Olaf Reimer Innsbruck University & KIPAC Stanford

GALAXY CLUSTERS AT GAMMA-RAYS – ARE WE GETTING THERE SOON?

8th Korean Astrophysics Workshop , 11 11 2014

Why observing at Gamma-rays?

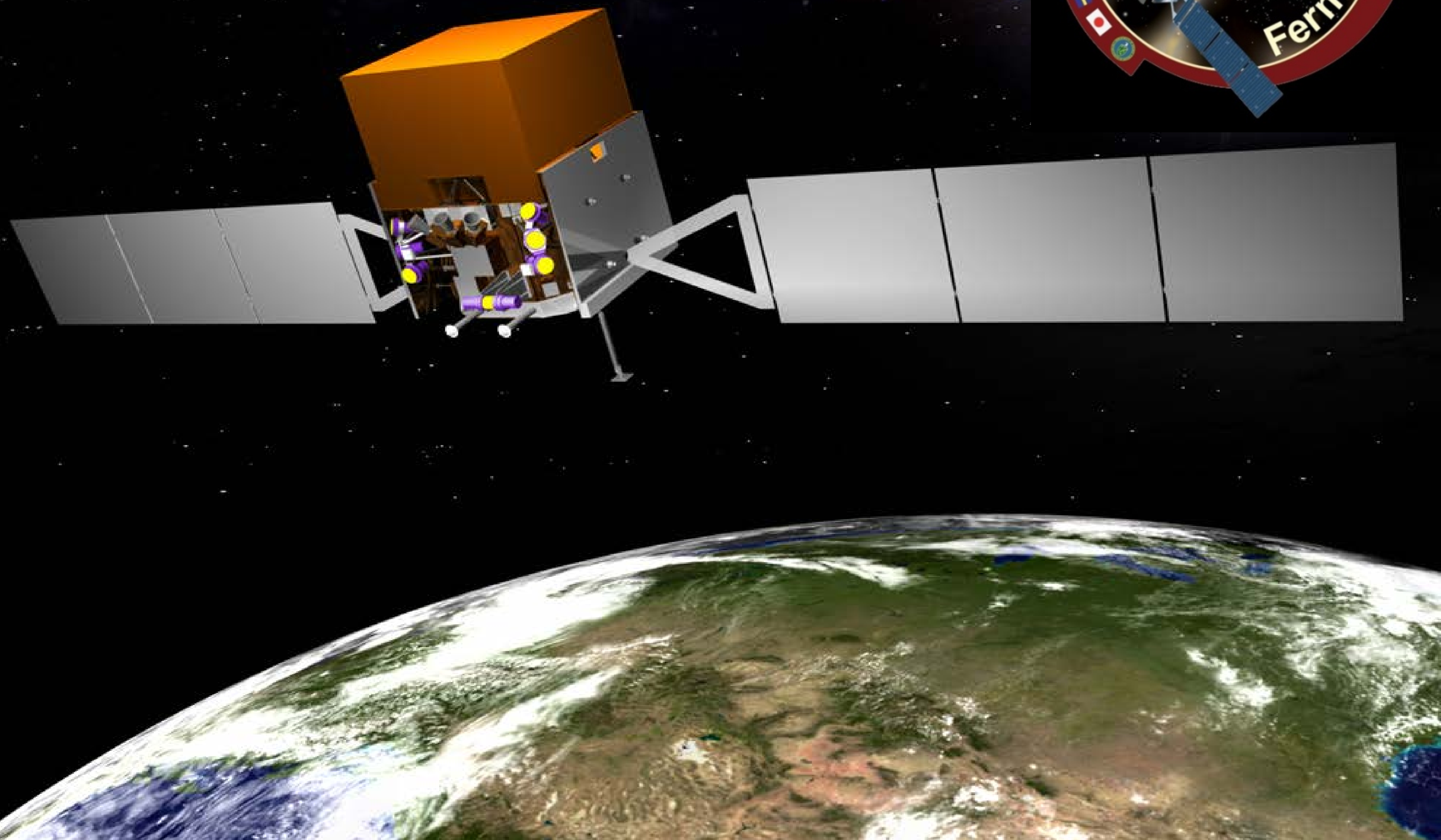
Think nonthermal, think CR!

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

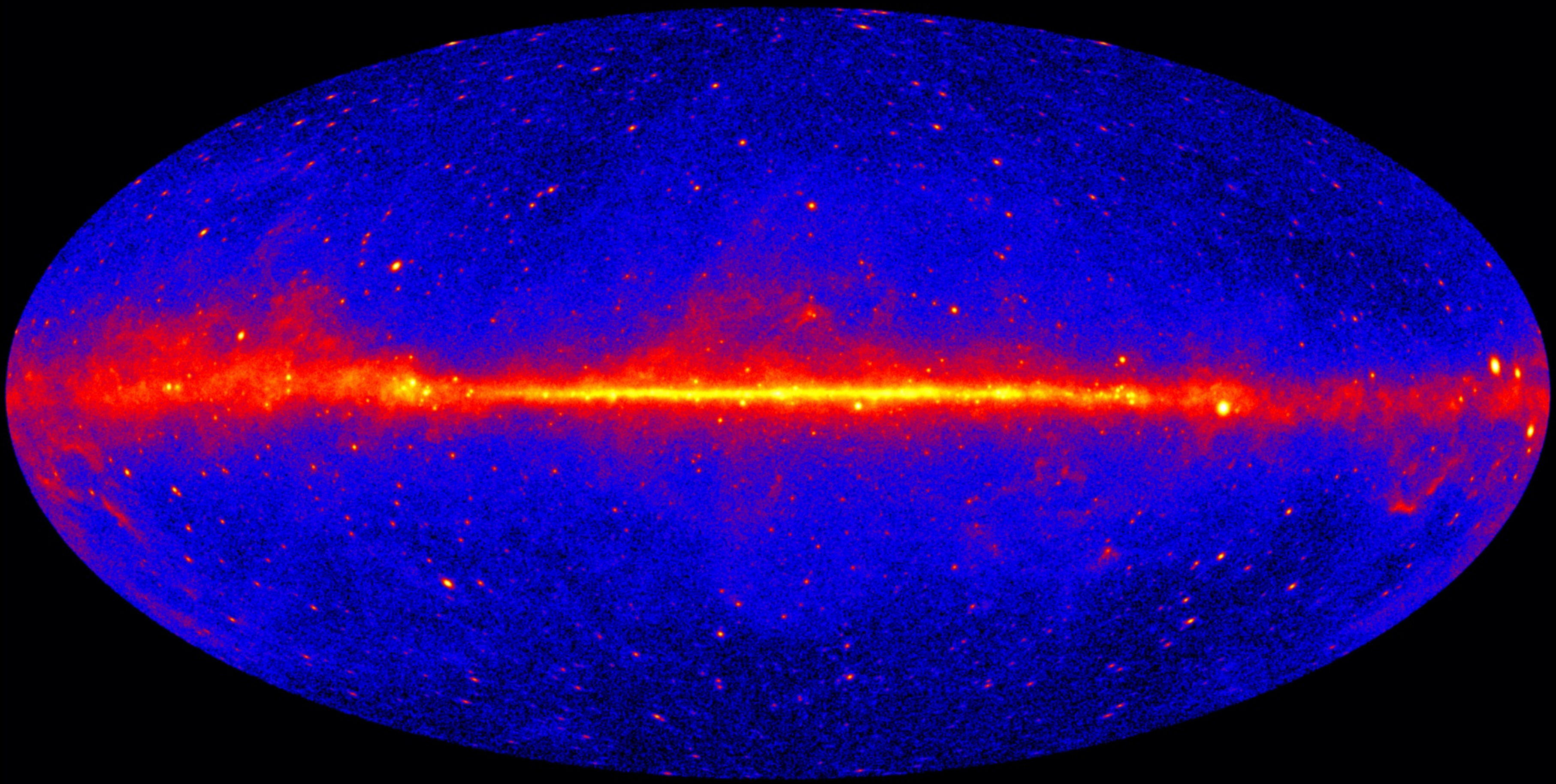
Principal processes to be considered:

- 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: $p\gamma$ -> π^0, π's, ...
  - -> Bethe-Heitler pair production: $p\gamma$ -> p, e^+, e^-
- secondary pair production through $\gamma\gamma$-interactions of VHE gammas from AGN / IC CMB γ (UV/OPT: GeV, IR: TeV)

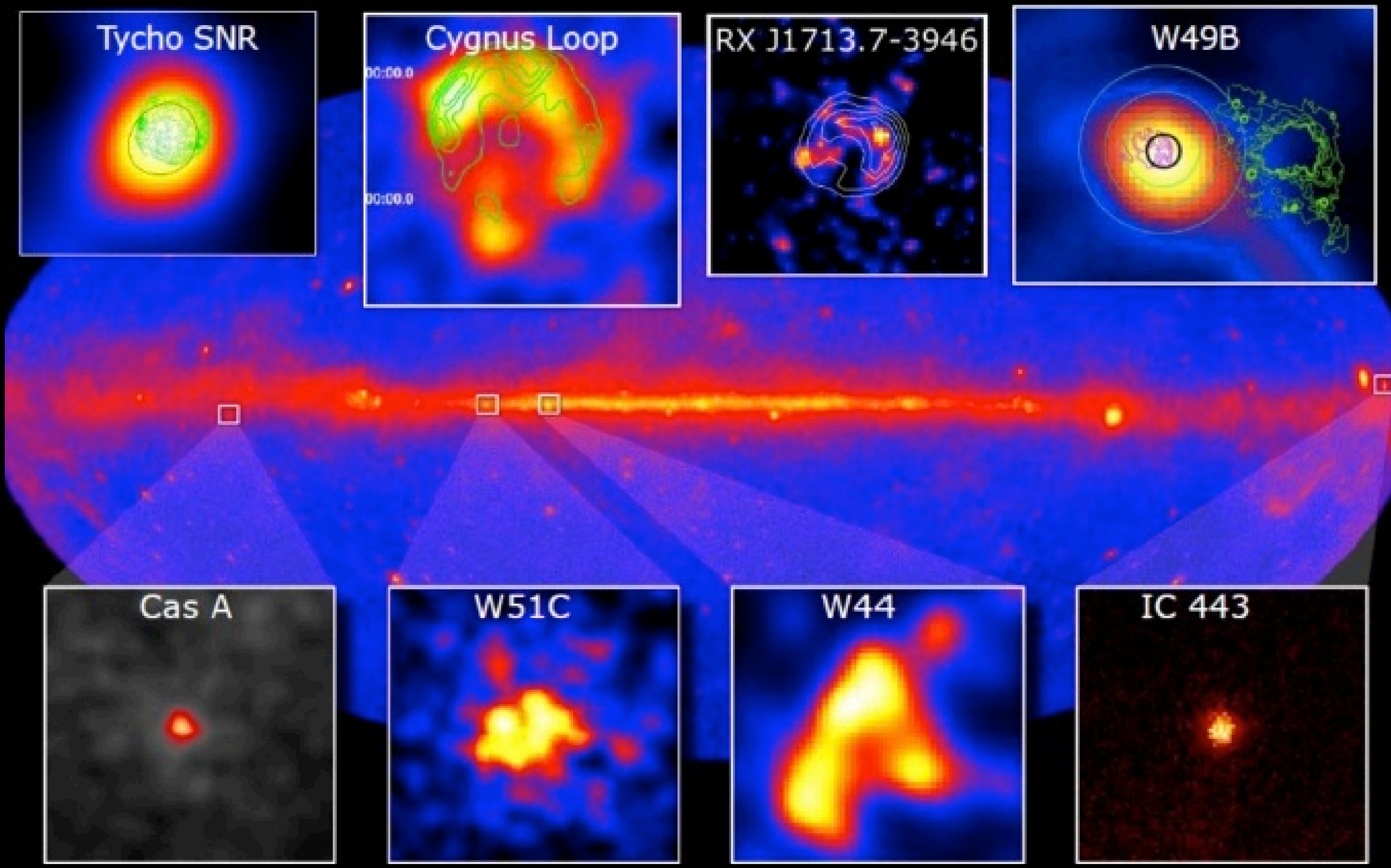
Player1: Fermi LAT



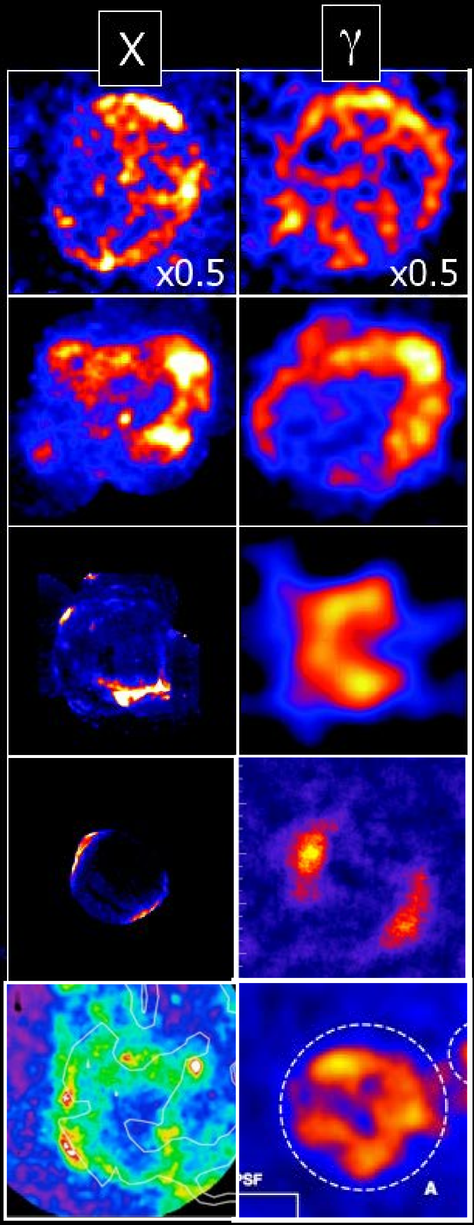
The GeV Sky after 5 years LAT



SNRs in the GeV regime



SNRs in the TeV regime



RX J1713.7-3946

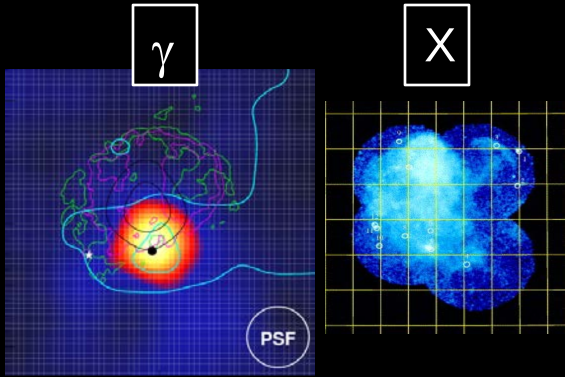
Vela Junior

RCW 86

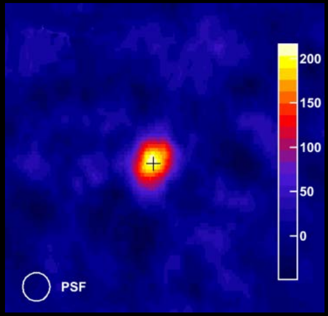
SN 1006

HESS J1731-347

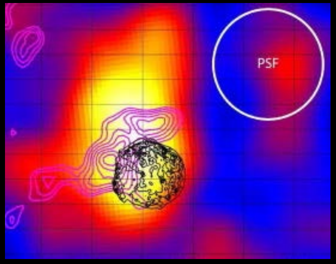
IC443

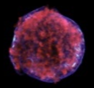


Cas A



Tycho

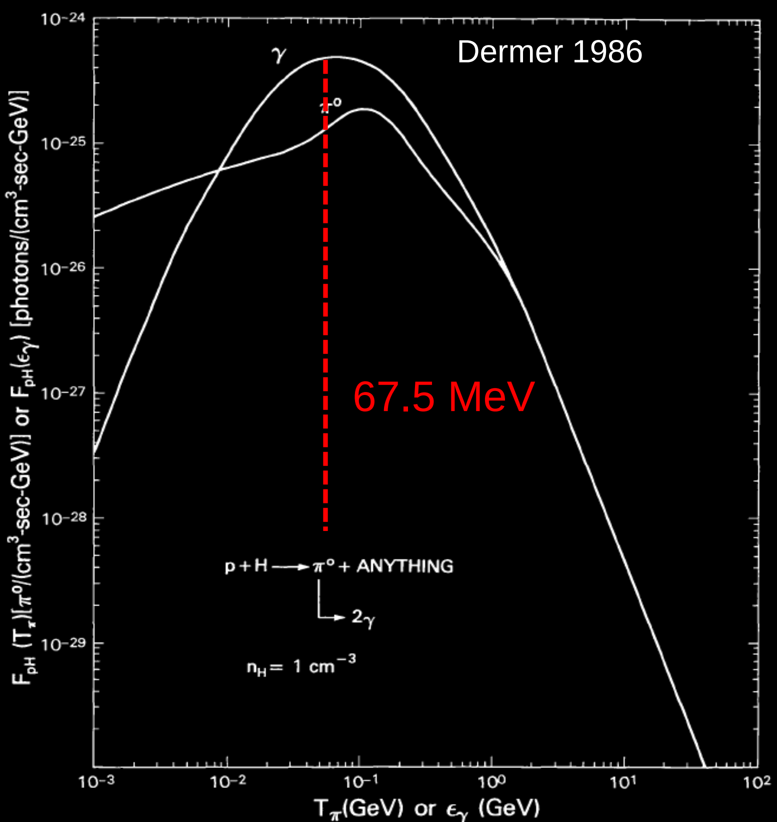




Generalities:
Leptonic vs. hadronic dominated emission

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 resemblence with Bremsstrahlung)

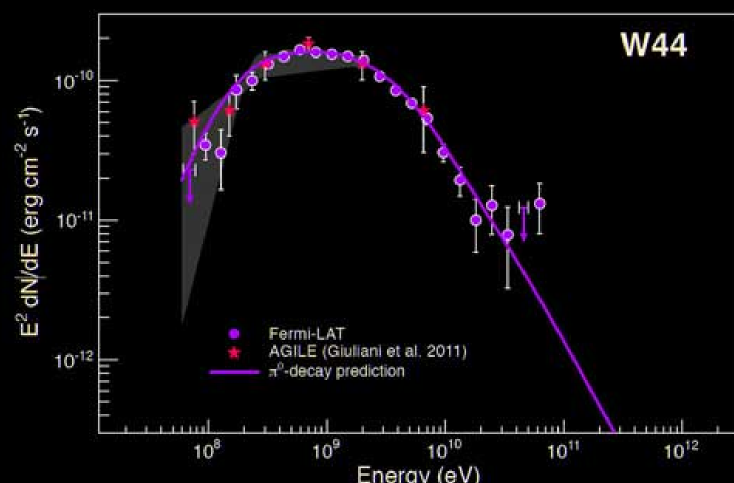


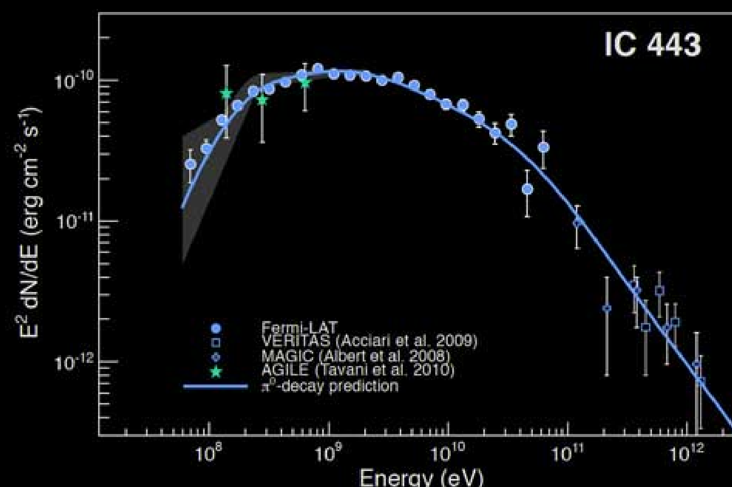
Science Vol.339, March 2013:

“Detection of the Characteristic Pion-Decay Signature in Supernova Remnants”

Image data from ESA Herschel and XMM-Newton

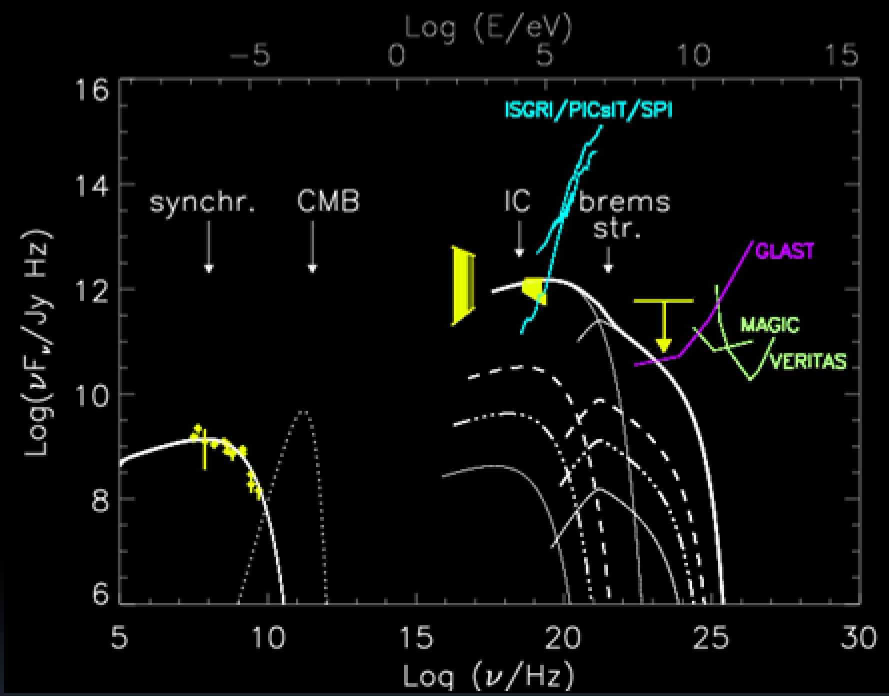
Image data from Chandra X-ray

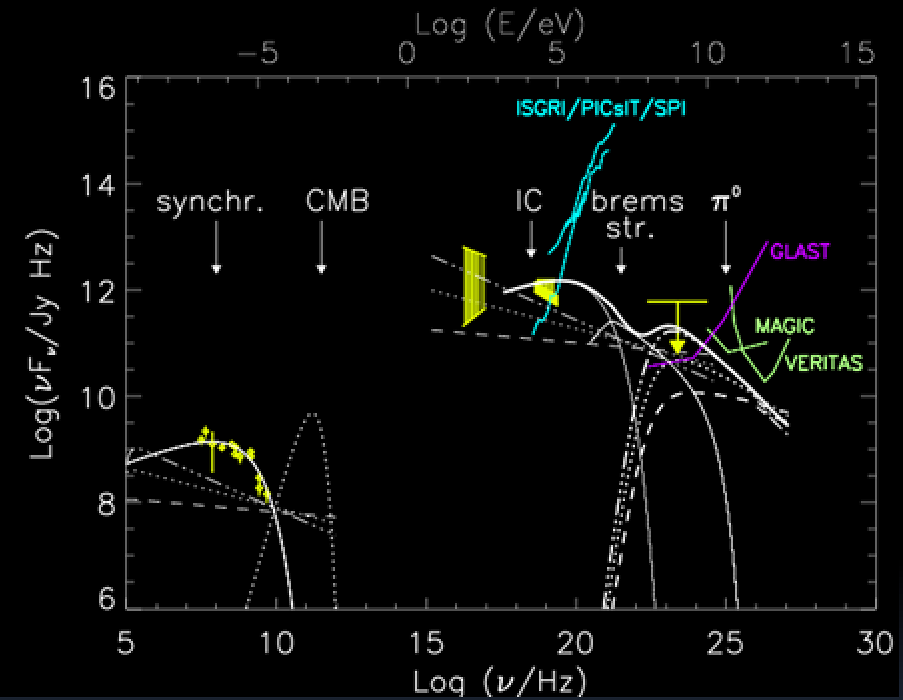




Galaxy Clsuter – γ by MWL priors

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+,…]

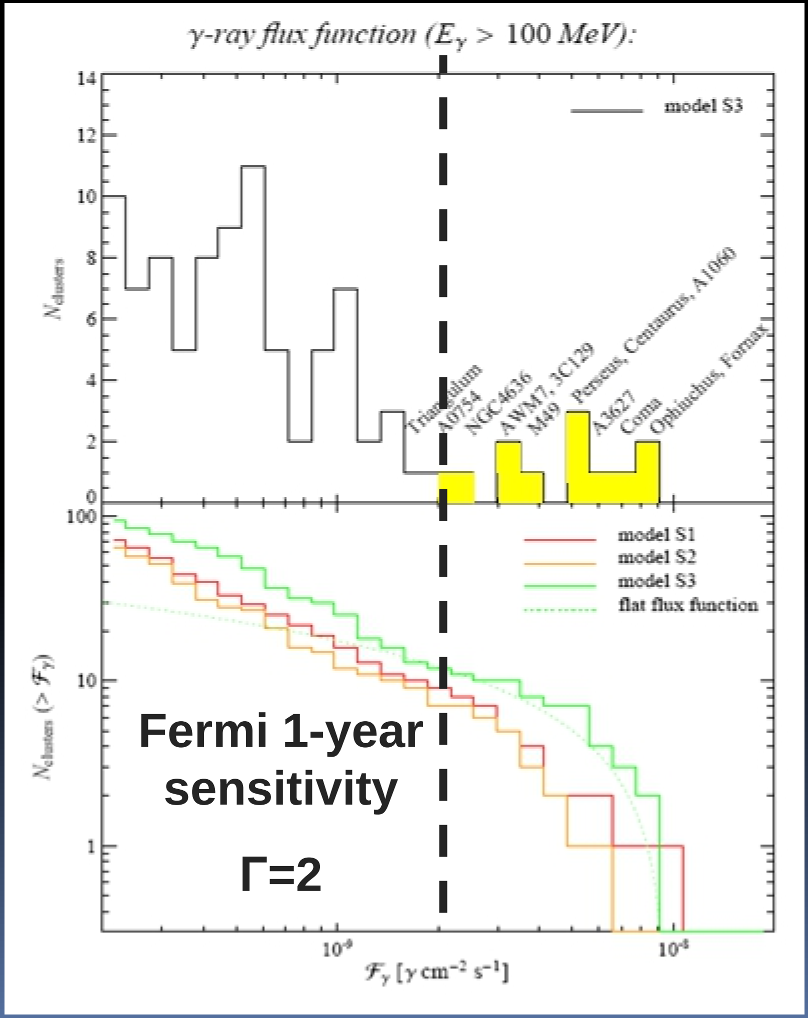
Best dark matter candidates similar; though expected flux **always** weaker than CR-based science case; detectability scaling follows roughly ~ M/d^2

MESSAGE : DM-annihilation related γ-ray flux always dominated by non-DM-related one ("conventional")*

Several clusters were anticipated over the LAT 1-year sensitivity (Pfrommer 2008):

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

…anticipation of AGN-related prominence in clusters



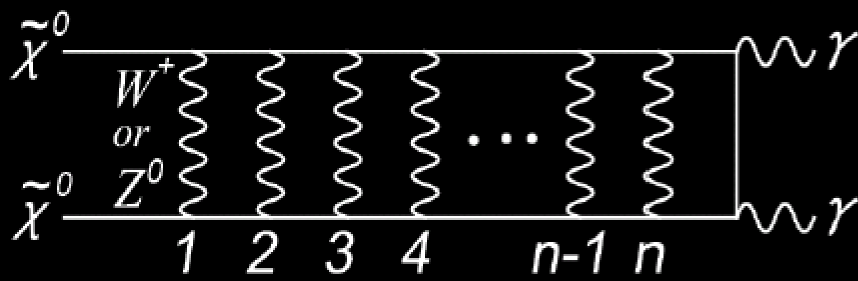
Gamma-ray from DM annihilation - high boostfactors?

1) nearby Dark Matter clump (not very likely)

2) non-thermal production (decay of heavy DM; collapse of cosmological defects, …).

3) interesting possibility for high-mass WIMPs: Sommerfeld enhancement

(Bergstrom & Ullio 1998 , Hisano, Matsumotoand Nojiri, 2003; Hisano, Matsumoto, Nojiriand Saito, 2004)



DM profile:

Fits to N-body simulations

$$\rho_{\text{Einasto}}(r) = \rho_s e^{\left(-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^{\alpha}-1\right]\right)}, \quad \alpha \approx 0.17$$

$$\rho_{\text{NFW}}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\text{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

$$\rho_{\text{CIS}}(r) = \frac{c}{a^2+r^2};$$

Galaxy clusters were considered part of the initial LAT science investigations, regarding both the DM- and a CR-related science case.

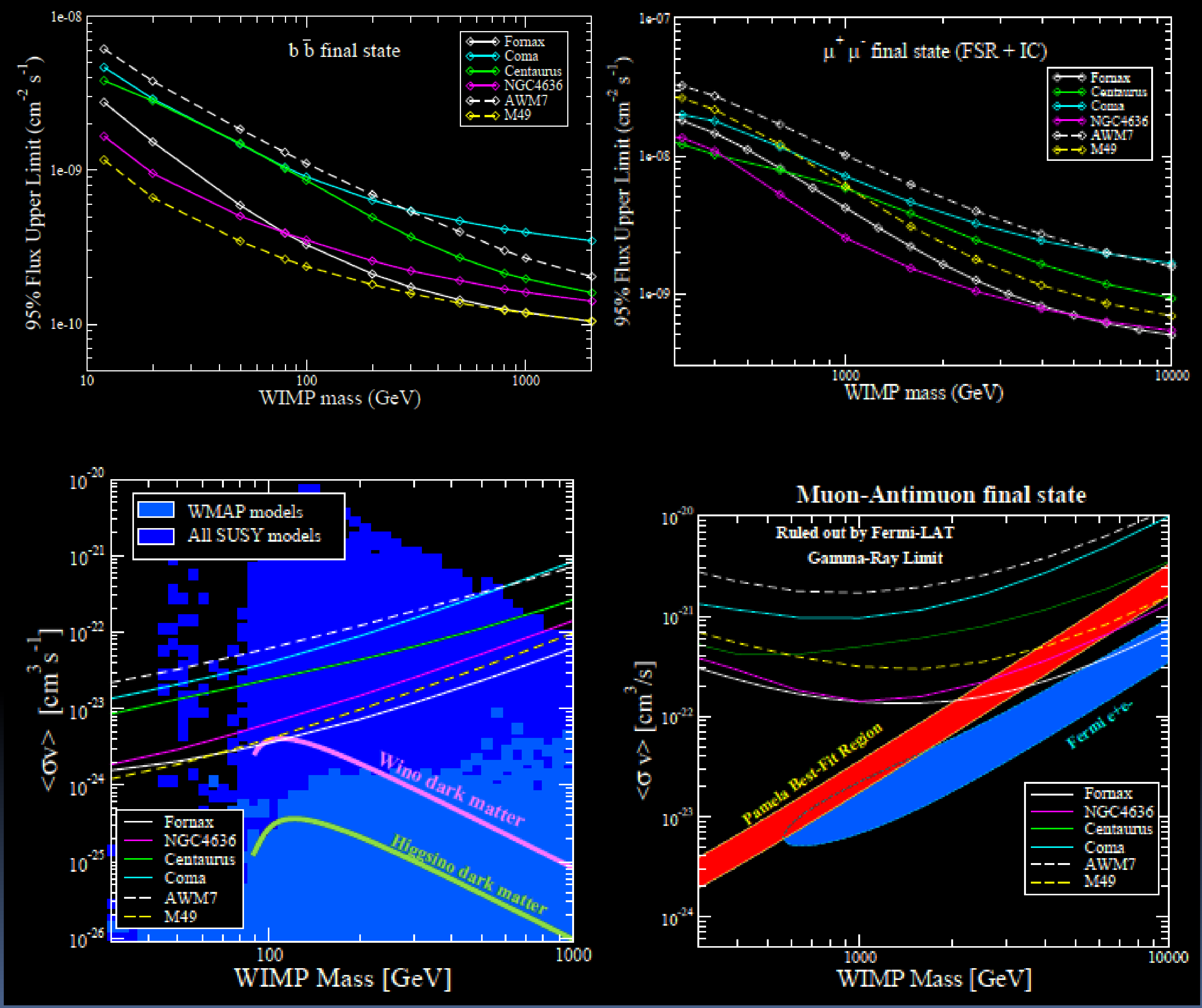
(1) Constraints on dark matter annihilation in clusters of galaxies with the Fermi Large Area Telescope

JCAP May 2010

Nearby clusters and groups of galaxies are potentially bright sources of high-energy gamma-ray emission resulting from the pair-annihilation of dark matter particles. However, no significant gamma-ray emission has been detected so far from clusters in the first 11 months of observations with the Fermi Large Area Telescope. We interpret this non-detection in terms of constraints on dark matter particle properties. … In this work, we focus on deriving limits on dark matter models; *a more general consideration of the Fermi-LAT data on clusters and clusters as gamma-ray sources is forthcoming.*

u.l.'s

<σν>



b b̄ final state
95% Flux Upper Limit (cm -2 s -1)
WIMP mass (GeV)
Fornax
Coma
Centaurus
NGC4636
AWM7
M49
μ+ μ- final state (FSR + IC)
95% Flux Upper Limit (cm -2 s -1)
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]

(2) GeV GAMMA-RAY FLUX UPPER LIMITS FROM CLUSTERS OF GALAXIES

Ackermann ea ApJ Letter June 2010

… we report on the search for GeV emission from clusters of galaxies using data collected by the Large Area Telescope on the *Fermi Gamma-ray Space Telescope* from 2008 August to 2010 February. Thirty-three galaxy clusters have been selected according to their proximity and high mass, X-ray flux and temperature, and indications of non-thermal activity for this study. We report upper limits on the photon flux in the range 0.2-100 GeV toward a sample of observed clusters (typical values (1-5) $\times 10^{-9}$ photon cm^{-2} s^{-1}) considering both point-like and spatially resolved models for the high-energy emission and discuss how these results constrain the characteristics of energetic leptons and hadrons, and magnetic fields in the ICM. The volume-averaged relativistic-hadron-to-thermal energy density ratio is found to be <5%-10% in several clusters.

Selection criteria

1) HIFLUGCS (X-ray brightest most nearby)
refined to M / d^2

→ 23

Cluster	l (deg)	b (deg)	z	θ_{500} (deg)	θ_{core} (deg)	M_{500}/d^2 (10^9 $M_\odot$/Mpc^2)	Diffuse radio	L_X (0.1-2.4 keV) (10^{44} erg s^{-1})	T_X (keV)
X-ray flux selection									
3C129	160.43	0.14	0.0223	0.67	0.14	29.1	...	2.27	5.57
A0754	239.25	24.75	0.0528	0.40	0.05	12.8	...	3.97	9.00
A1367	234.80	73.03	0.0216	0.77	0.18	42.7	...	1.20	3.55
A2199	62.94	43.69	0.0302	0.46	0.05	12.5	...	4.20	4.28
A2256	111.10	31.74	0.0601	0.33	0.10	8.5	Halo, Relic (1, 2)	9.24	6.83
A2319	75.67	13.58	0.0564	0.37	0.05	10.9	Halo (1, 2)	16.37	8.84
A3376	246.52	-26.29	0.0455	0.36	0.17	8.5	...	2.16	4.43
A3571	316.32	28.55	0.0397	0.45	0.05	14.5	...	8.08	6.80
Antlia (S636)	272.94	19.19	0.0116	0.85	0.29	31.6	...	0.38	2.06
AWM7	146.35	-15.62	0.0172	0.85	0.10	45.0	...	2.10	3.70
Centaurus (A3526)	302.41	21.56	0.0499	1.24	0.04	87.9	...	1.19	3.69
Coma (A1656)	58.09	87.96	0.0232	0.80	0.15	49.6	Halo, Relic (1)	8.09	8.07
Fornax (S373)	236.72	-53.64	0.0046	2.01	0.36	168.1	...	0.08	1.56
Hydra (A1060)	269.63	26.51	0.0114	1.02	0.08	52.5	...	0.56	3.15
M49	286.92	70.17	0.0044	1.68	0.02	95.5	...	0.02	1.33
NGC4636	297.75	65.47	0.0037	1.27	0.02	36.3	...	0.02	0.66
NGC5044	311.23	46.10	0.0090	0.74	0.01	16.6	...	0.18	1.22
NGC5813	359.18	49.85	0.0064	1.00	0.04	28.9	...	0.02	0.76
NGC5846	0.43	48.80	0.0061	0.78	0.01	13.3	...	0.01	0.64
Norma (A3627)	325.33	-7.26	0.0163	0.89	0.18	50.2	...	3.59	5.62
Ophiuchus	0.56	9.27	0.0280	0.10	0.10	131.6	Halo (3)	12.14	10.25
Perseus (A0426)	150.58	-13.26	0.0183	0.85	0.03	49.0	...	16.39	6.42
Triangulum	324.48	-11.63	0.0510	0.42	0.06	14.7	...	12.43	9.06

NT priors (radio halo or relic) → 8

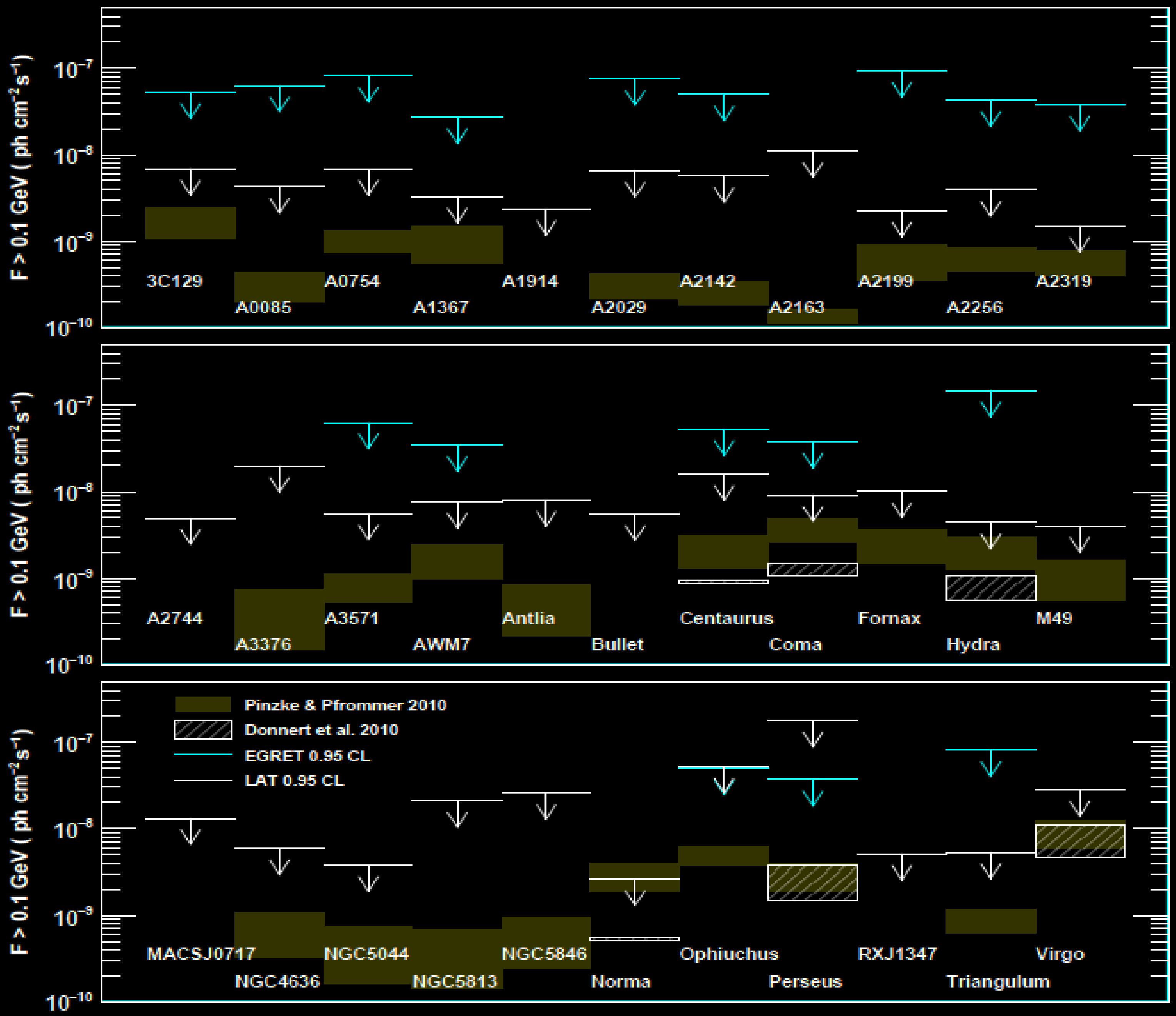
Non-thermal selection									
A0085	115.05	-72.06	0.0556	0.31	0.02	...	Relic (1, 4)	9.67	6.51
A1914	67.20	67.46	0.1712	0.13	0.02	...	Halo (1, 2)	17.04	8.41
A2029	6.51	50.55	0.0767	0.25	0.01	...	Halo (3)	17.07	7.93
A2142	44.21	48.70	0.0899	0.24	0.02	...	Halo (4)	21.05	8.46
A2163	6.75	30.52	0.2010	0.12	0.03	...	Halo (1)	32.16	10.55
A2744	8.90	-81.24	0.3080	...	...	...	Halo (1)	...	...
Bullet (1E 0657-56) (a)	266.03	-21.25	0.296	...	...	...	Halo (5)	...	14
MACSJ0717.5+3745 (b)	61.89	34.02	0.546	...	...	...	Relic (6)	24.6	11.6

Exceptional individual not included in the above defined criteria → 2

Other selection									
RXJ1347.5-1145 (c)	324.04	48.80	0.451	...	...	...	...	62.0	...
Virgo (M87 sub-clump) (d)	283.78	74.49	0.0036	...	0.05	...	...	...	...

Σ: 33

Fermi E > 200 MeV (Ackermann et al. 2010)



…and thus the galaxy cluster science case went colder!

Fermi-LAT team focus since then:

- ➢ continuous efforts to detect or improve constraints by using more data and/or explore methods to gain from multiobject analysis,
- ➢ improved instrumental response functions,
- ➢ meticulous control of analysis systematics
  - ☞ Ackermann ea ApJ 2014

…and outside the LAT team (list not comprehensive):

(1) Huang, Vertongen & Weniger JCAP 2011
(2) Ando & Nagai JCAP 2012

(3) Han, Frenk, Eke, Gao & S. White 2012 (arXiv)
then Han, Frenk, Eke, Gao, White, Boyarsky, Malyshev & Ruchayskiy JCAP 2012

(4) Huber, Farnier, Manalaysay, Straumann, Walter A&A 2012
(5) Dutson, White, Edge, Hinton, & Hogan MNRAS 2013
(6) Prokorov & Churazov A&A 2014
(7) Zandanel & Ando 2014

Han et al. 2012 (arXiv:1201:1003)

- maximum-likelihood analysis of the 3-year Fermi-LAT data
- Virgo, Fornax and Coma

RESULTS:

(1) For all three clusters, excess emission is observed within three degrees of the center, peaking at the GeV scale (missed in previous more or less point-source treatments)

(2) … cannot be accounted for by known Fermi sources or by the galactic and extragalactic backgrounds.

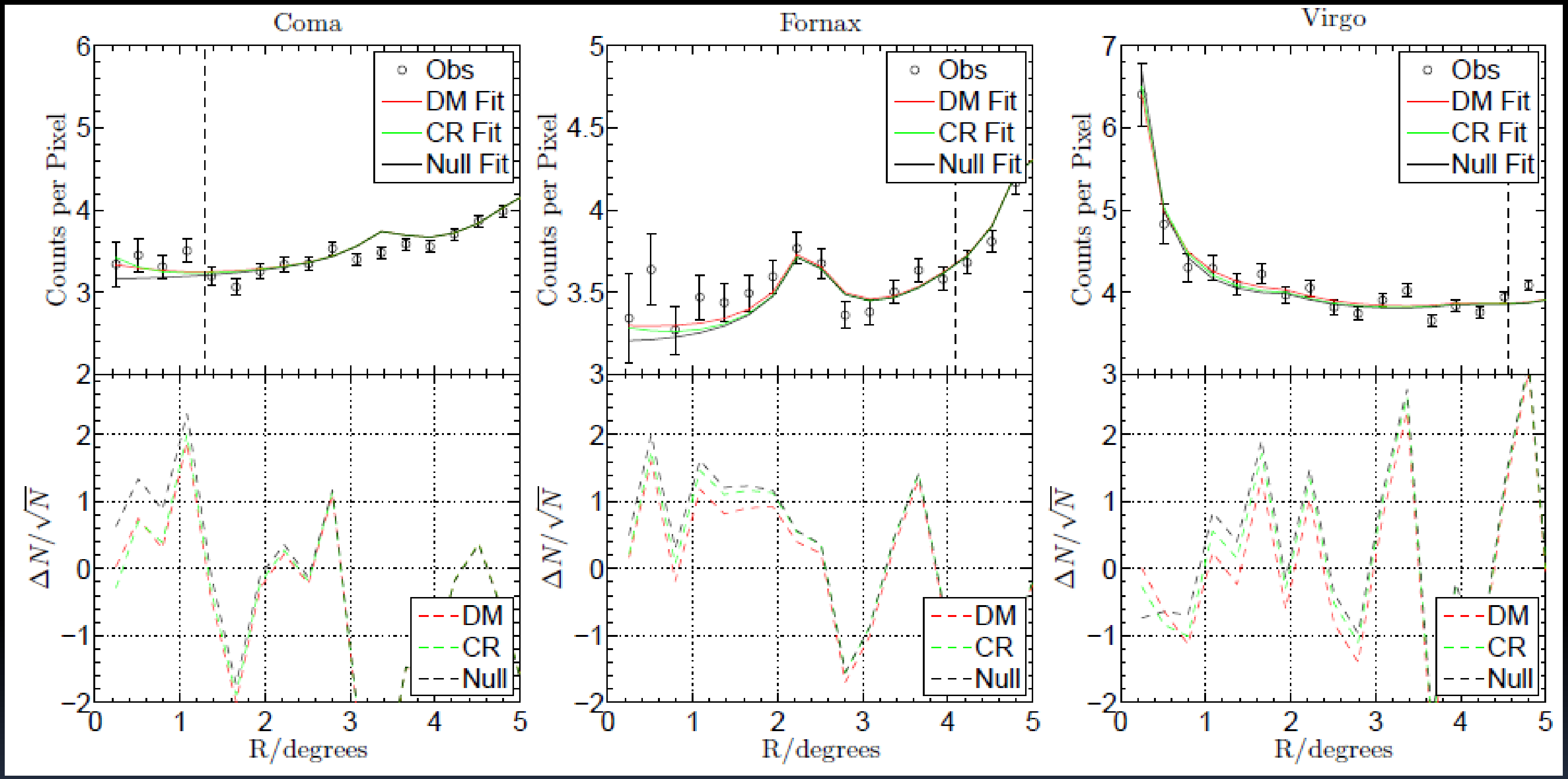
(3) significance of DM detection is 4.4 in Virgo and lower in the other two clusters

(4) different profiles used $\rightarrow$ significance of a CR component is lower than the significance of a DM component, and there is no need for such a CR component in the presence of a DM component in the preferred DM mass range

(5) DM signal best described by Particle with M=40 GeV in bbbar channel or 20 GeV for mu+ mu-

in layman's terms: GET ATTENTION RIGHTFULLY … OR TROUBLE?

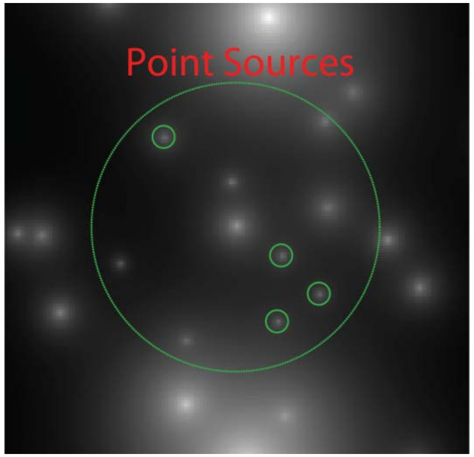
No intention to discuss the interpretation,
as this was about *analysis issues* in first place:



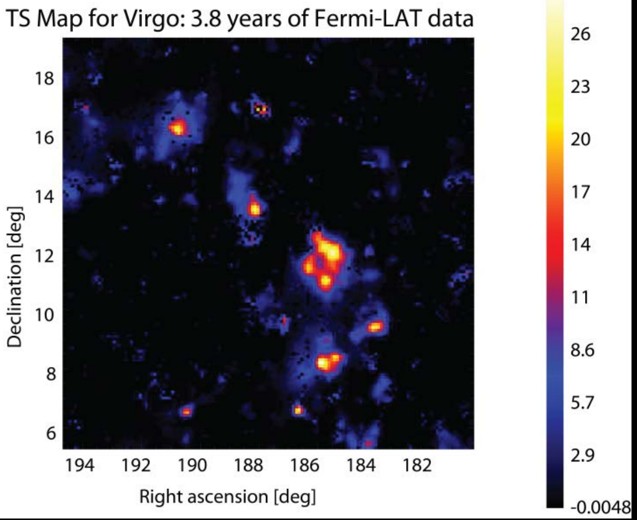
Jogler ea (Fermi-LAT) 2012

Macias-Ramirez et al. 2012 find 7 new point sources not in 2FGL catalog
Han et al. 2012 (arXiv 1207.6749) reported 4 new point sources

Han et al 2012
(July)



Macias-Ramirez et al 2012



Both groups explain extended excess due to missing point sources in the model of the original Han et al. 2012 (arXiv 1201.1003) work

It is possible that the point sources cause part or all of the emission.

Han et al then materialized as JCAP 2012,

no detection claim anymore!

	$\alpha_{CR,fit}$ [a]	$\alpha_{CR,UL}$ [b]	$F_{CR,UL}$ [c] $(\mathrm{ph \cdot cm^{-2}\ s^{-1}})$	TS	$TS_{corrected}$ [d]	$\alpha_{CR,UL,corrected}$ [e]
Coma	0.3 ± 0.1	0.5	2.4e-09	5.2	2.6	0.6
Fornax	0.9 ± 2	4.8	1.8e-09	0.2	0.1	6.4
Virgo	0.6 ± 0.3	1.2	2.1e-08	8.4	2.8	1.6

[a] Best fit normalization ($\alpha_{CR,fit} = 1$ is the theoretical prediction)

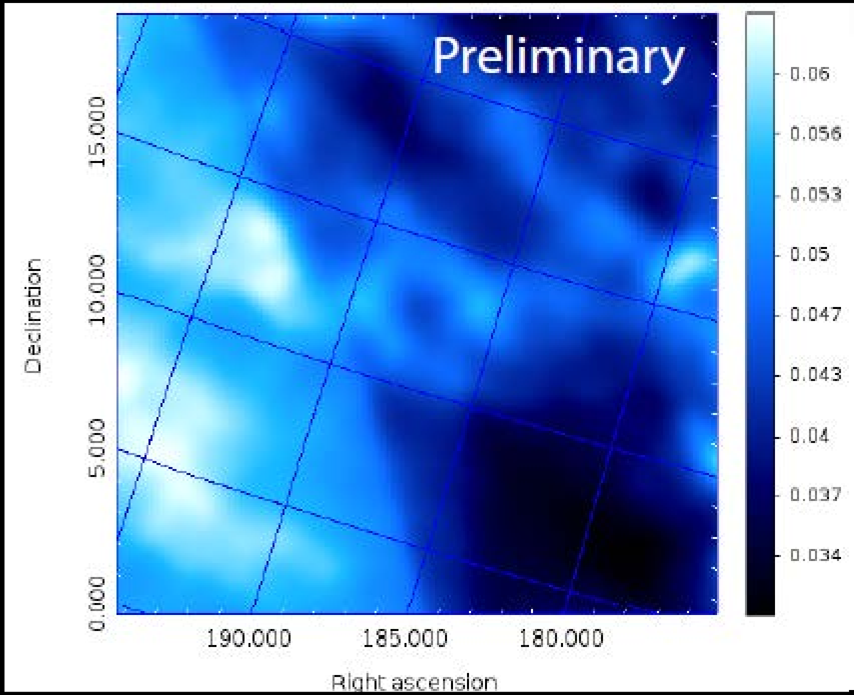
[b] 95% upper limit (UL) on the normalization

[c] 95% upper limit on the CR induced gamma-ray flux from 100 MeV to 100 GeV

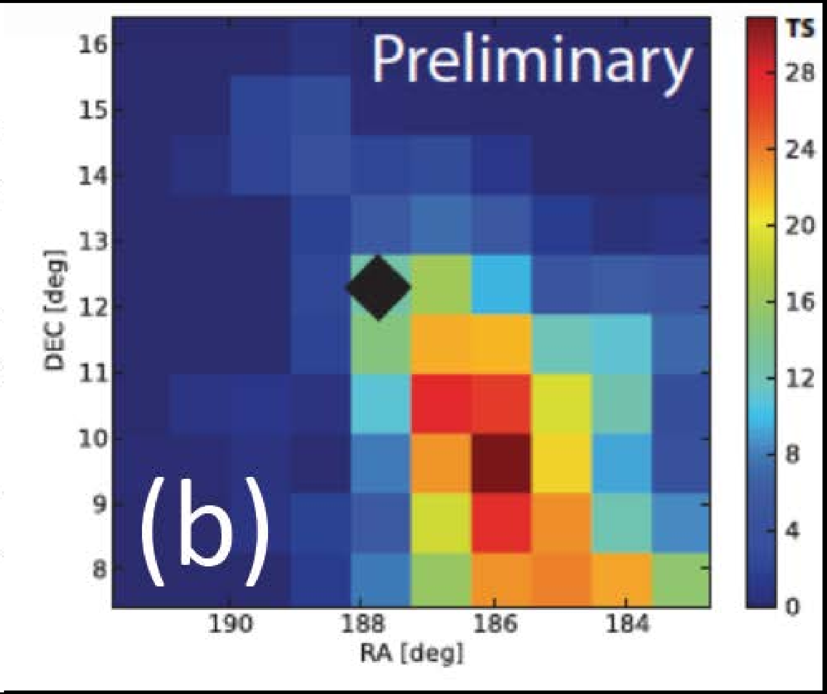
[d] TS after allowing for undetected point sources; see Section 3.3 for details

[e] Upper limit on the normalization factor after allowing for undetected point sources; see Section 3.3 for details

Fermi-LAT team's duty and pain



Standard diffuse model



TS map for searching extended emission

Zimmer ea (Fermi-LAT 2014)

Zimmer ea (Fermi-LAT) 2014

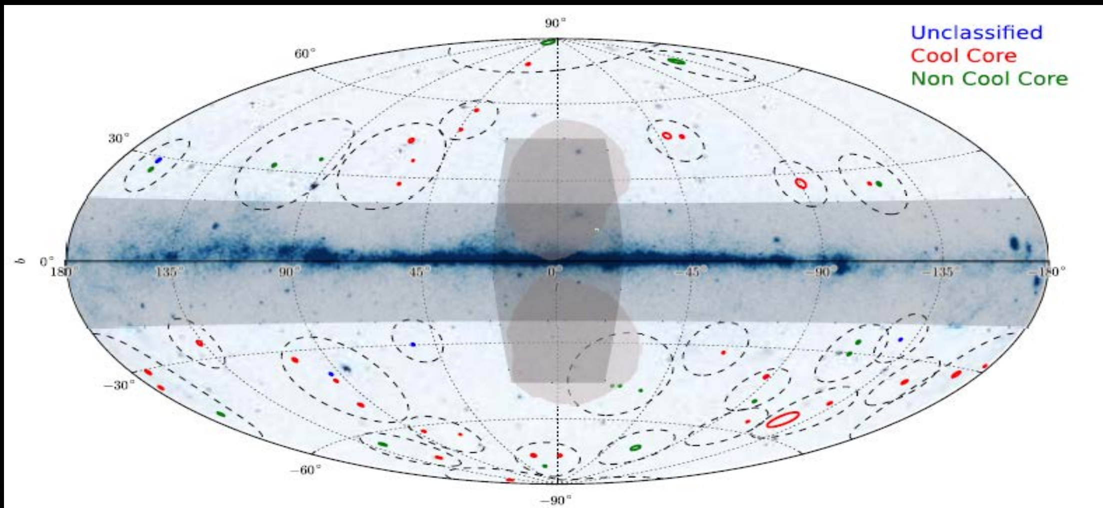
- No indication for DM or CR induced gamma-ray emission from the Virgo cluster
- Extended emission offset from the Virgo cluster center
  - significance depends strongly on the interstellar emission model

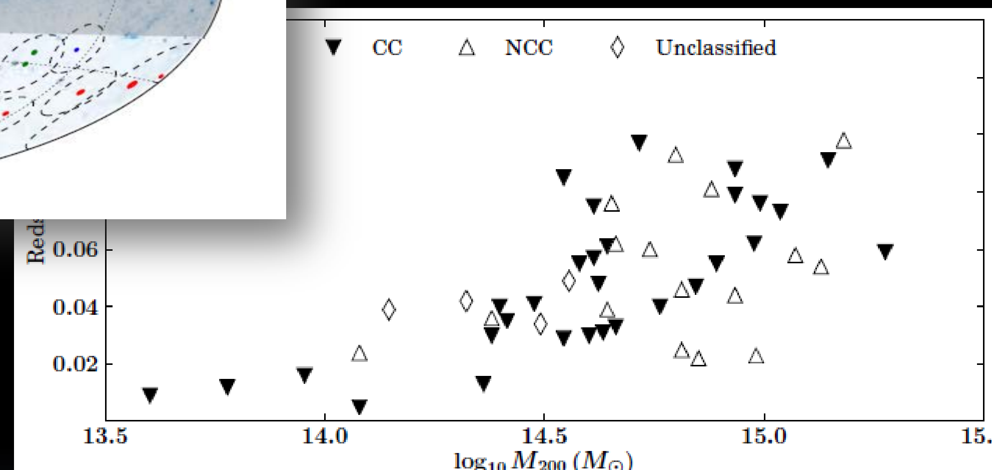
- Search for very extended emission is extremely difficult and requires a detailed study of systematic uncertainties especially of the interstellar emission model, even for extragalactic regions!

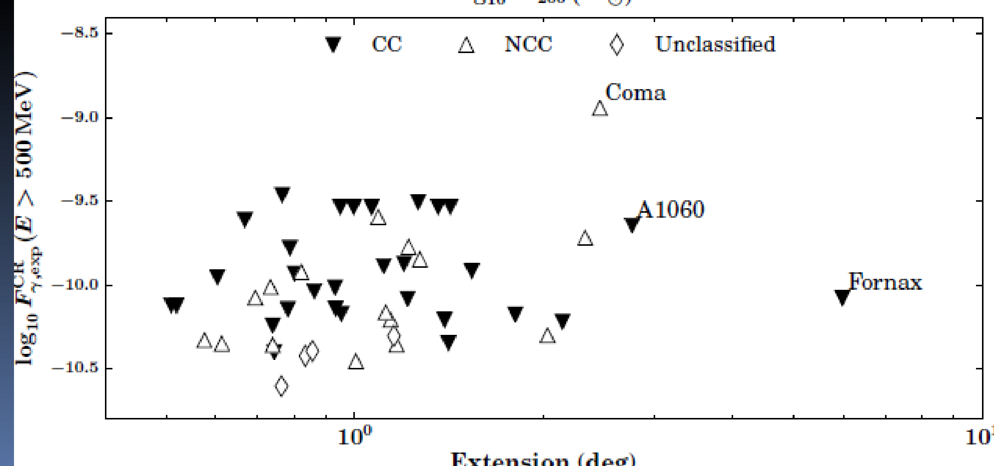
- The Virgo region is not a good site to search for DM/CR induced emission due to the complicated interstellar emission in this region

“Search for cosmic-ray induced gamma-ray emission in galaxy clusters”

Ackermann ea (Fermi-LAT + Christoph + Anders) 2014 May 20 ApJ

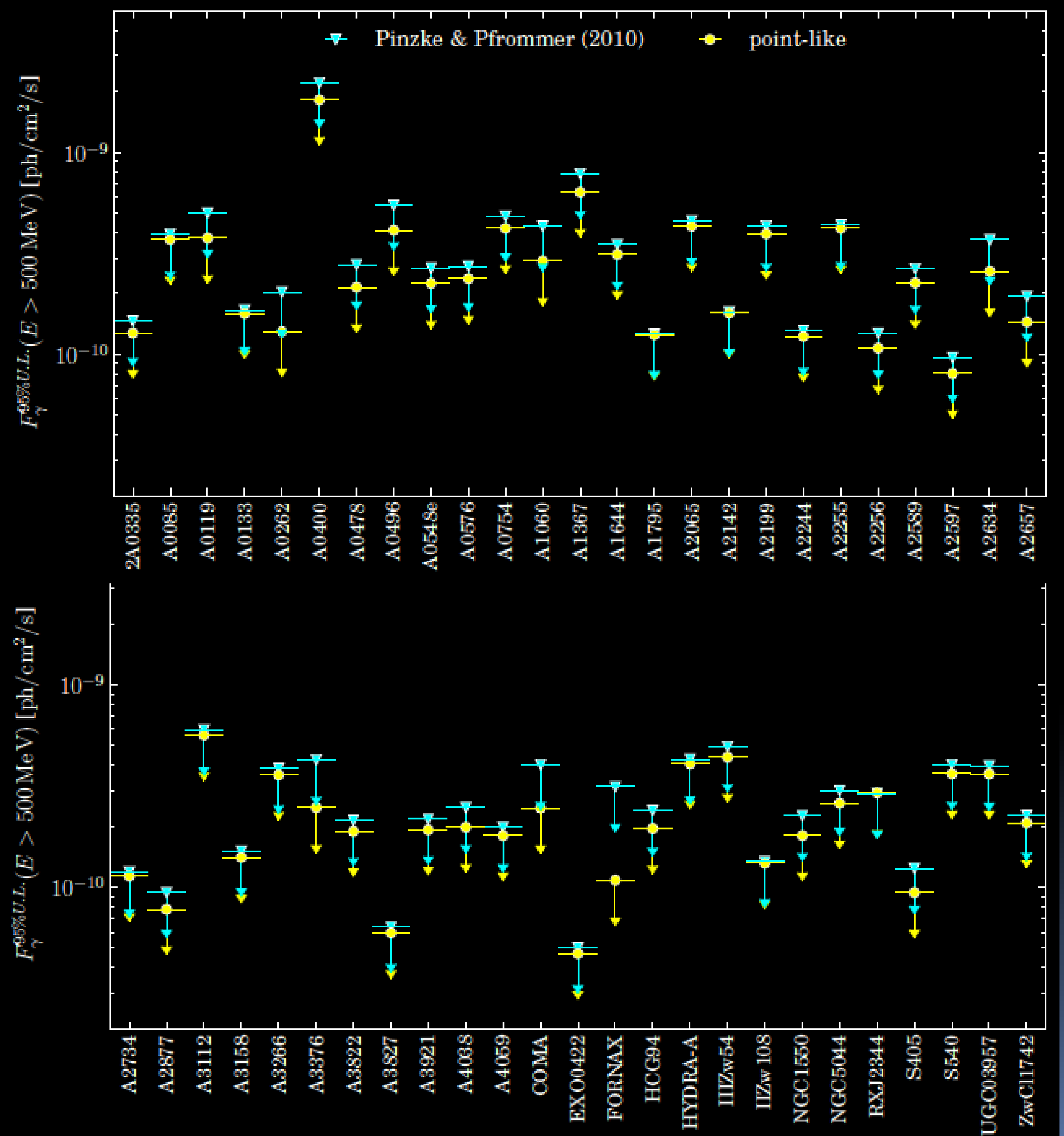






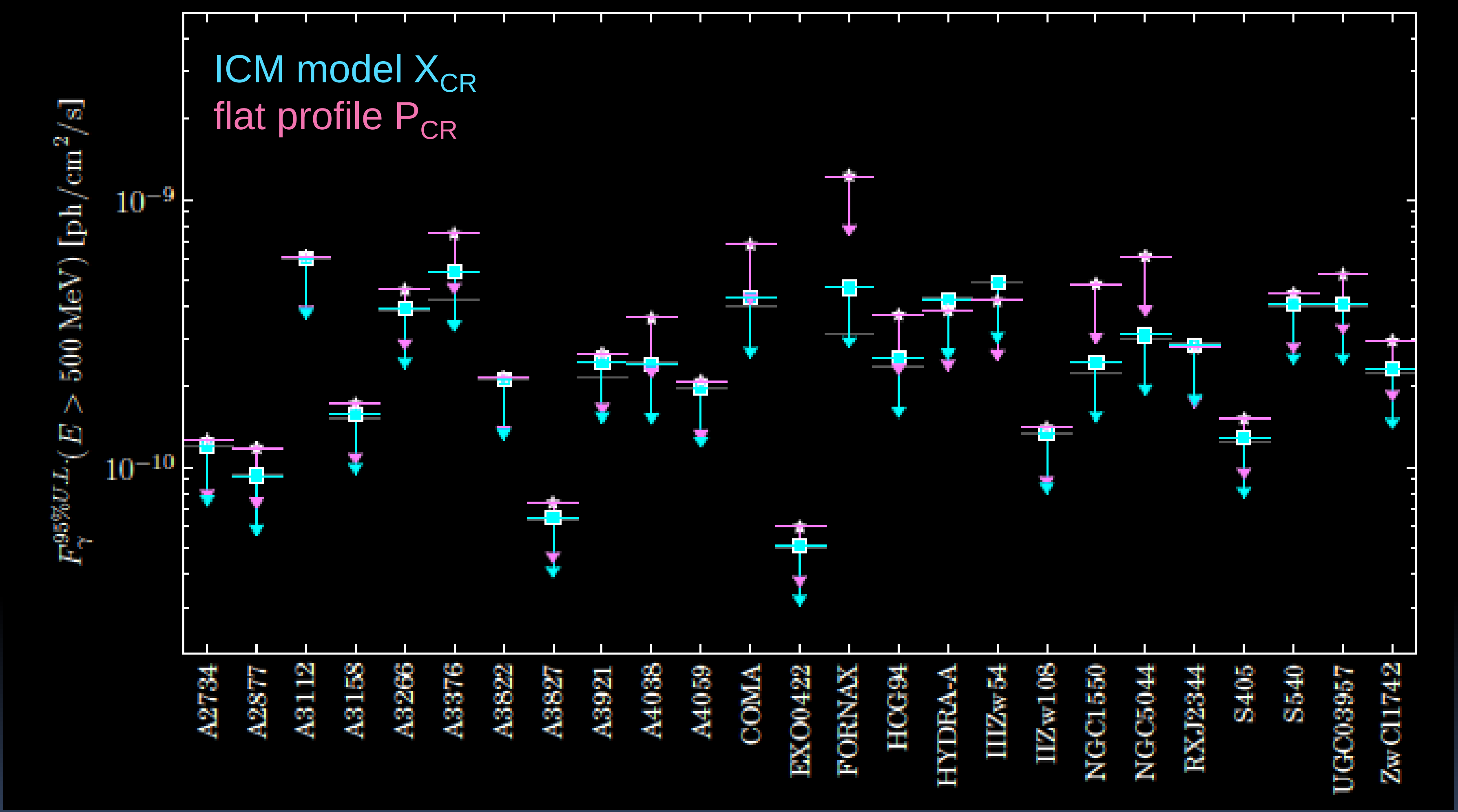
- 4 years of Fermi data
- individual cluster
- sample investigation
- CC vs. NCC split in sample

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



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

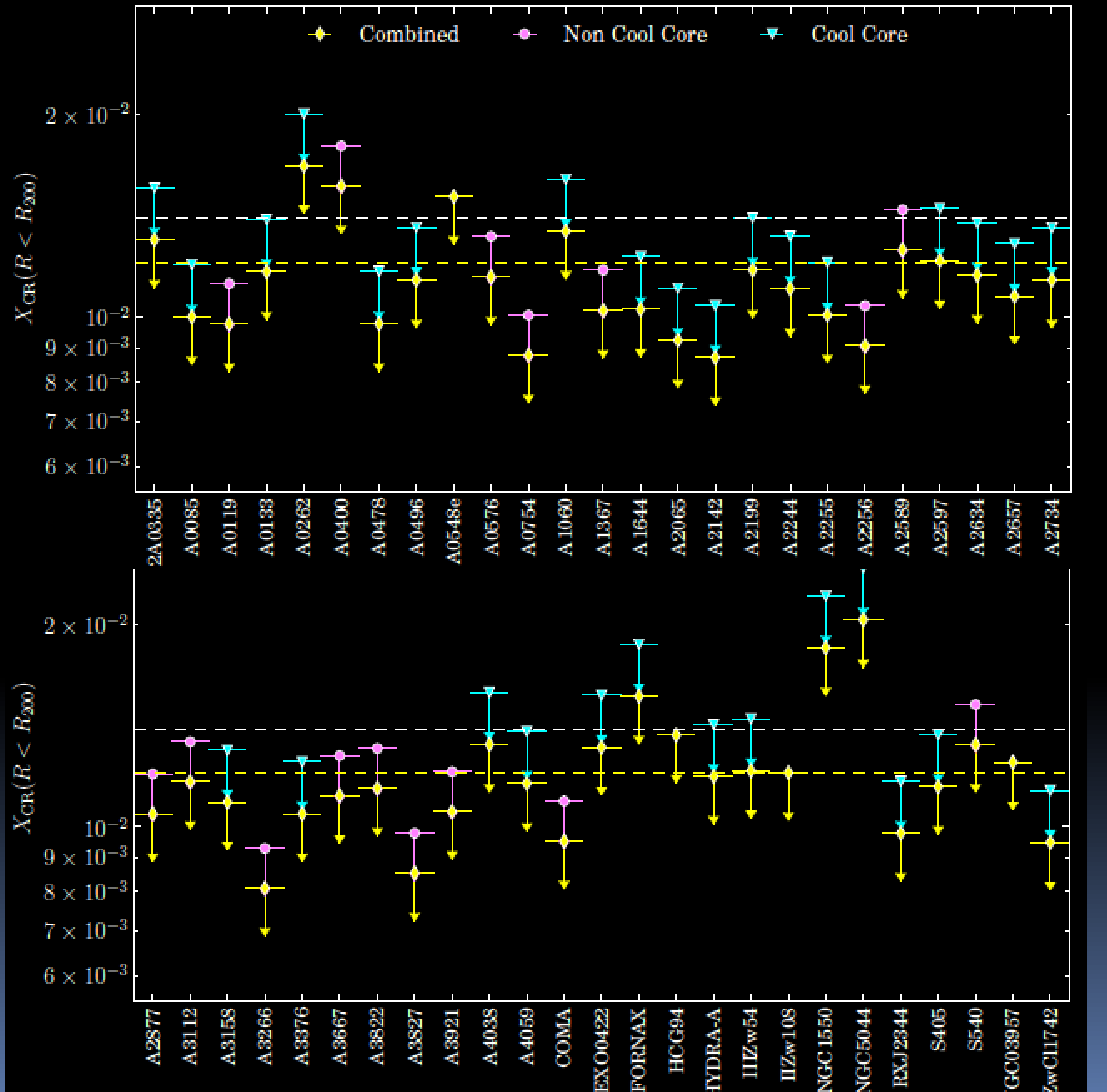
$$\langle X_{\rm CR} \rangle = \langle P_{\rm CR} \rangle_V / \langle P_{\rm th} \rangle_V$$



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

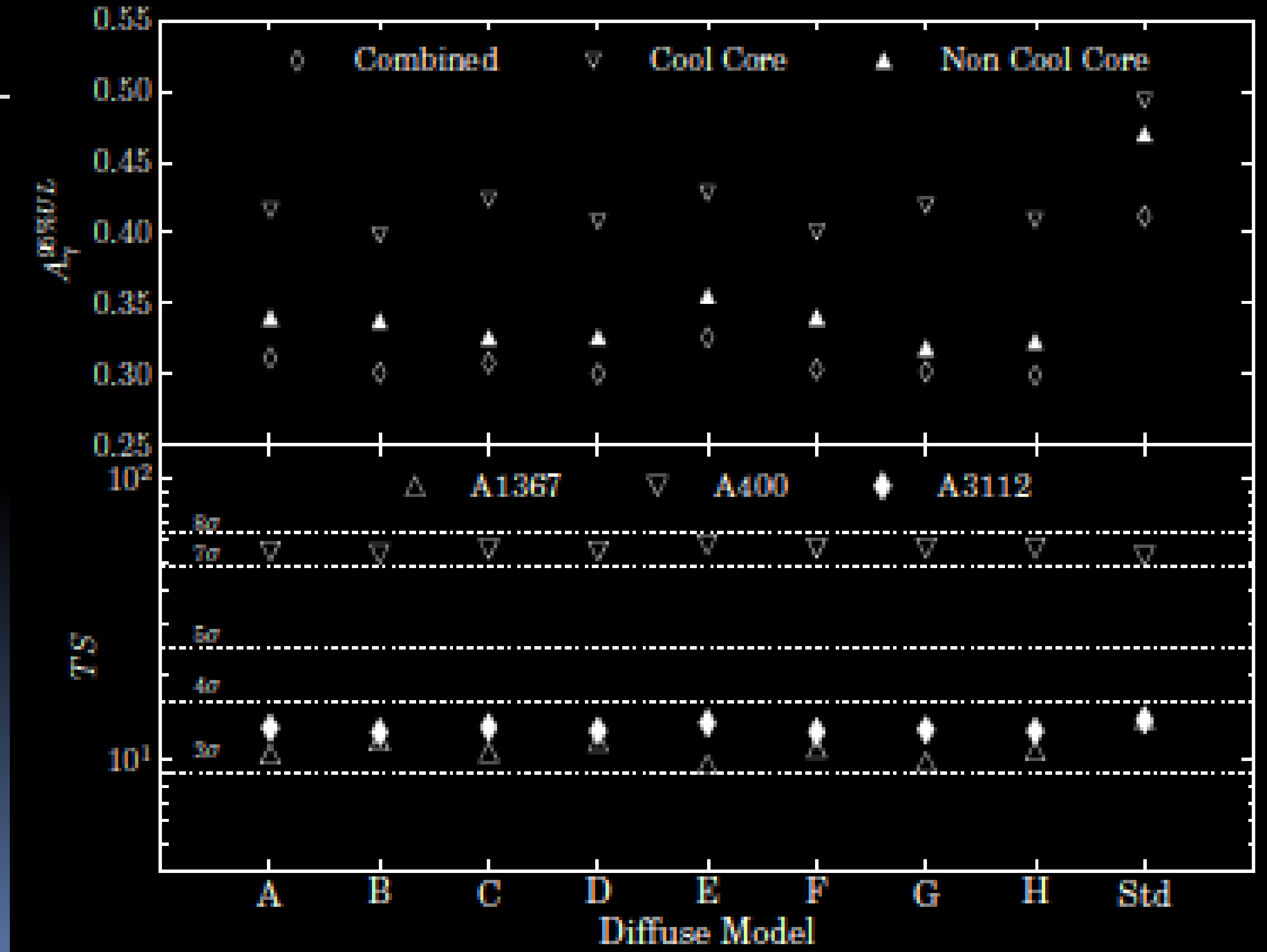
AVERAGE NCC, CC

TOTAL AVERAGE

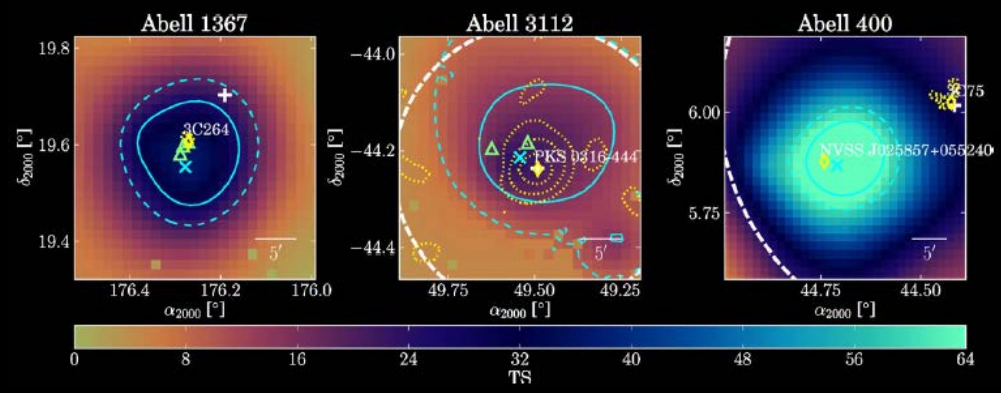


4th) Systematics, e.g. different galactic diffuse models

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	[illegible]	[illegible]
H	SNR	[illegible]	[illegible]



Conclusions

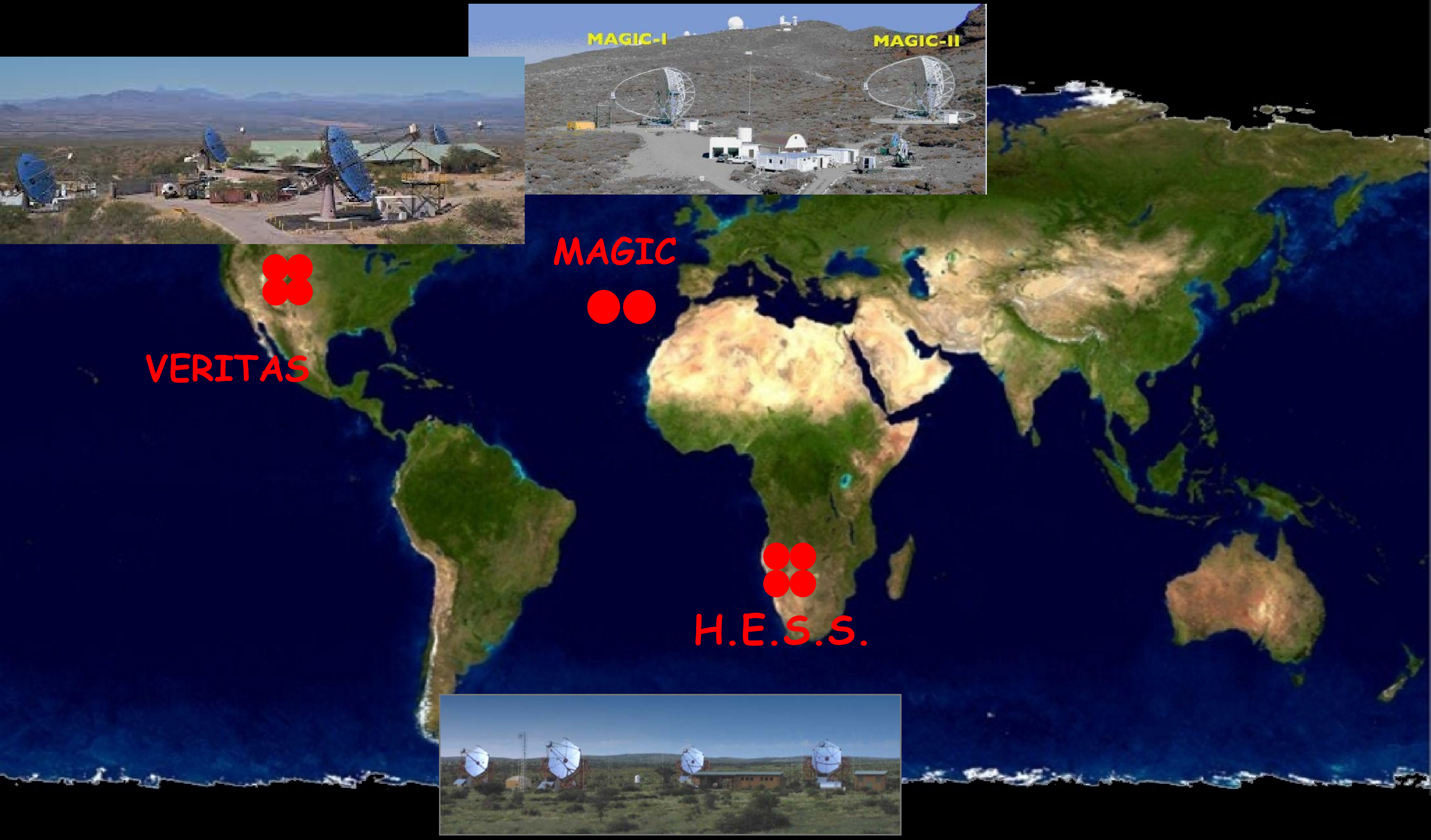


- no detection
- three suspicious cases
- bounds on the common scale-factor Aγ
- use jointly derived Aγ bound to calculate volume-averaged CR-to thermal pressure $<X_{CR}>$
- compute median upper limits within R_{200}

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

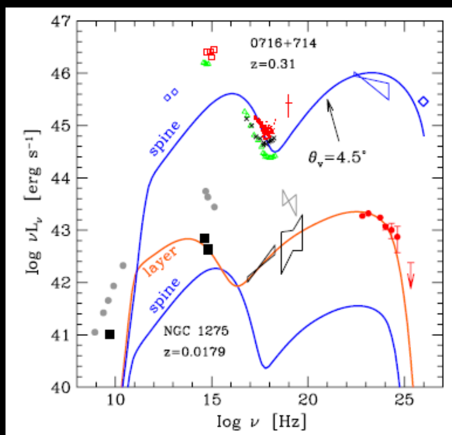
☞ **for the CC and NCC subsamples $<X_{CR}> <0.013$ and $<X_{CR}> <0.014$**

Player2: Major imaging atmospheric Cherenkov telescopes

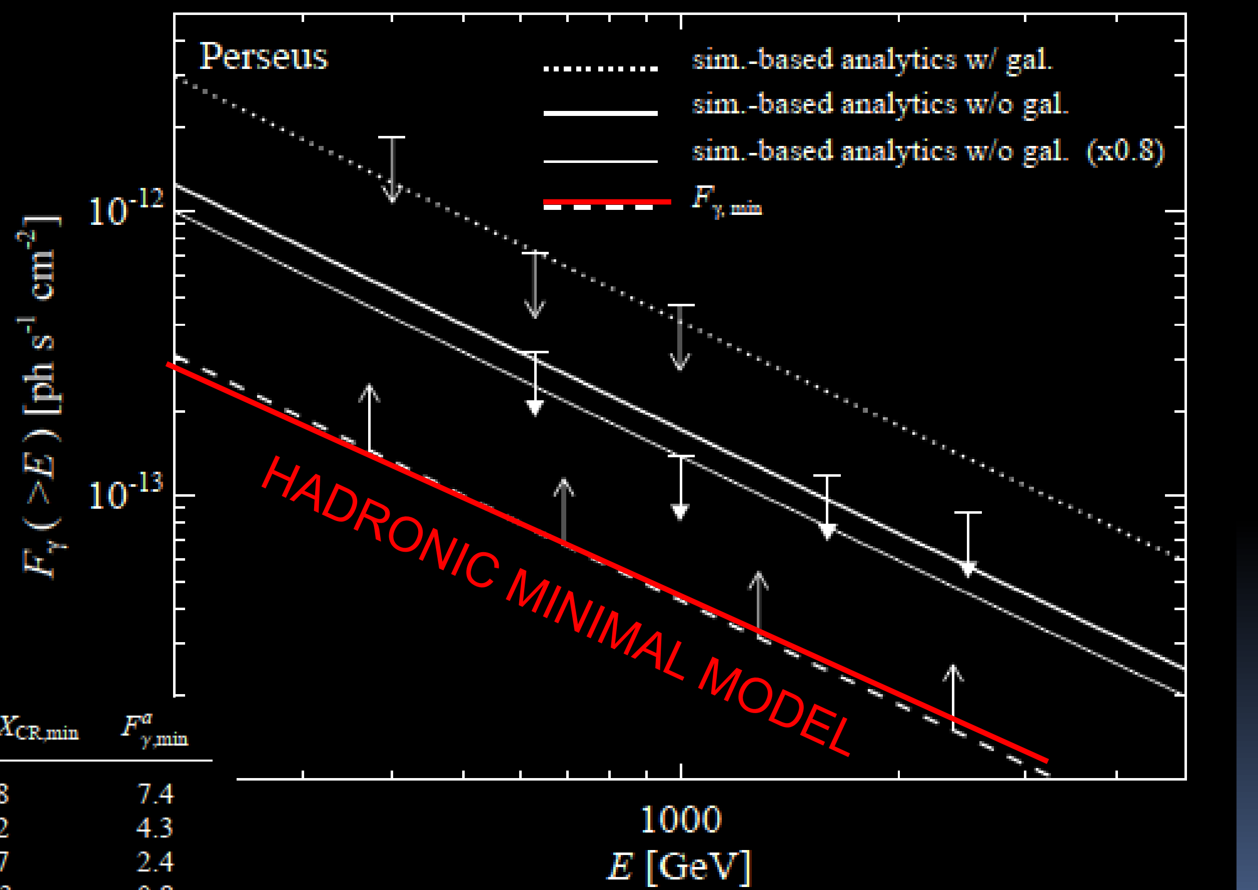


VHE observations of galaxy clusters

MAGIC Perseus u.l. (Aleksic et al. 2012) E_{CRp} ~ **1-2% depending on CR model and assumptions**



- NGC1275 : as prominent at TeVs as at GeVs !
- IC310 !

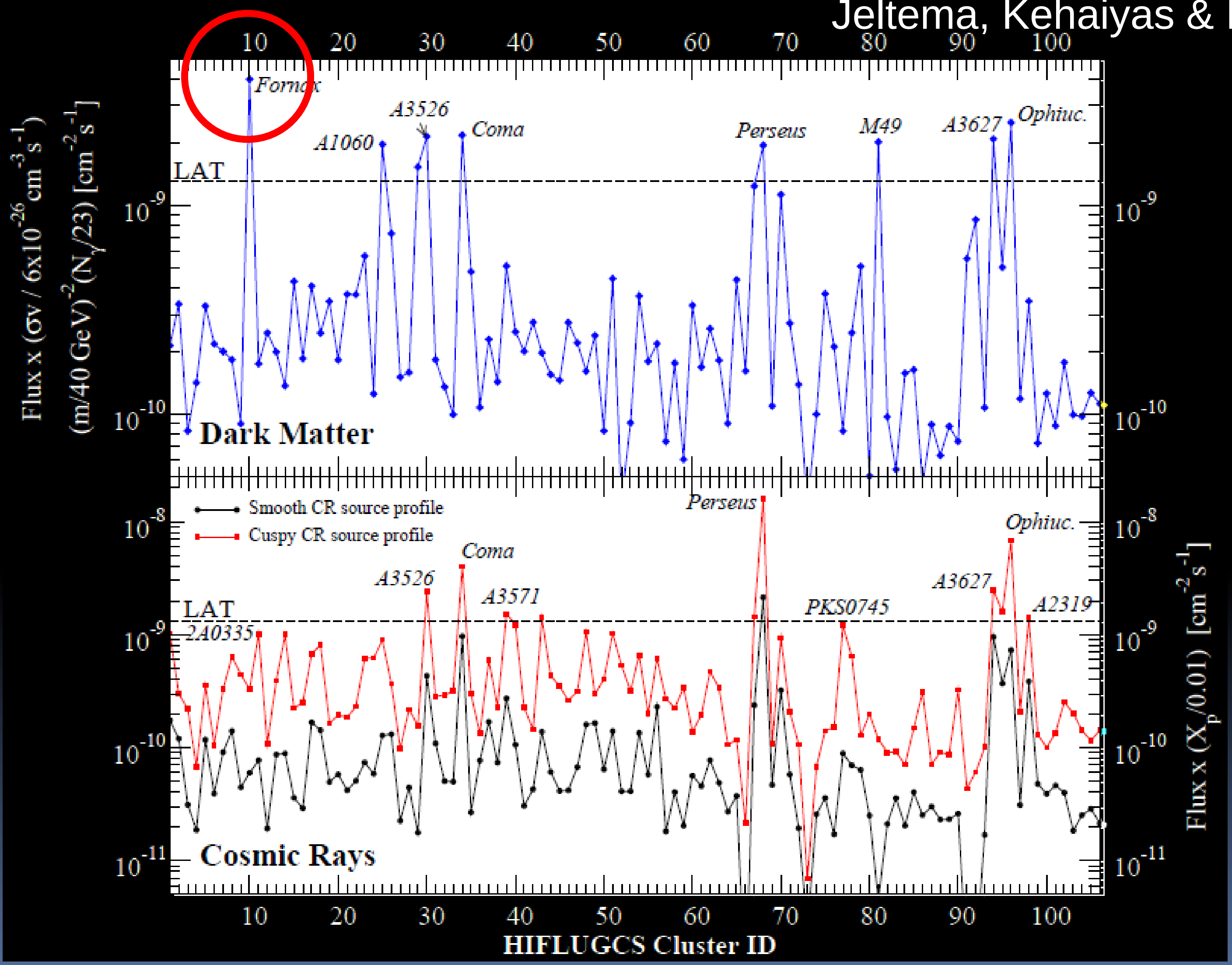


α	$X_{CR,max}$ [%]	$X_{CR,min}$ [%]	$X_{CR,max}/X_{CR,min}$	$F^a_{\gamma,min}$
2.1	0.77	0.42	1.8	7.4
2.2	1.12	0.35	3.2	4.3
2.3	2.17	0.38	5.7	2.4
2.5	11.6	0.67	17.3	0.8

VHE observations of galaxy clusters

Fornax (Abramowski ea – H.E.S.S. - 2012)

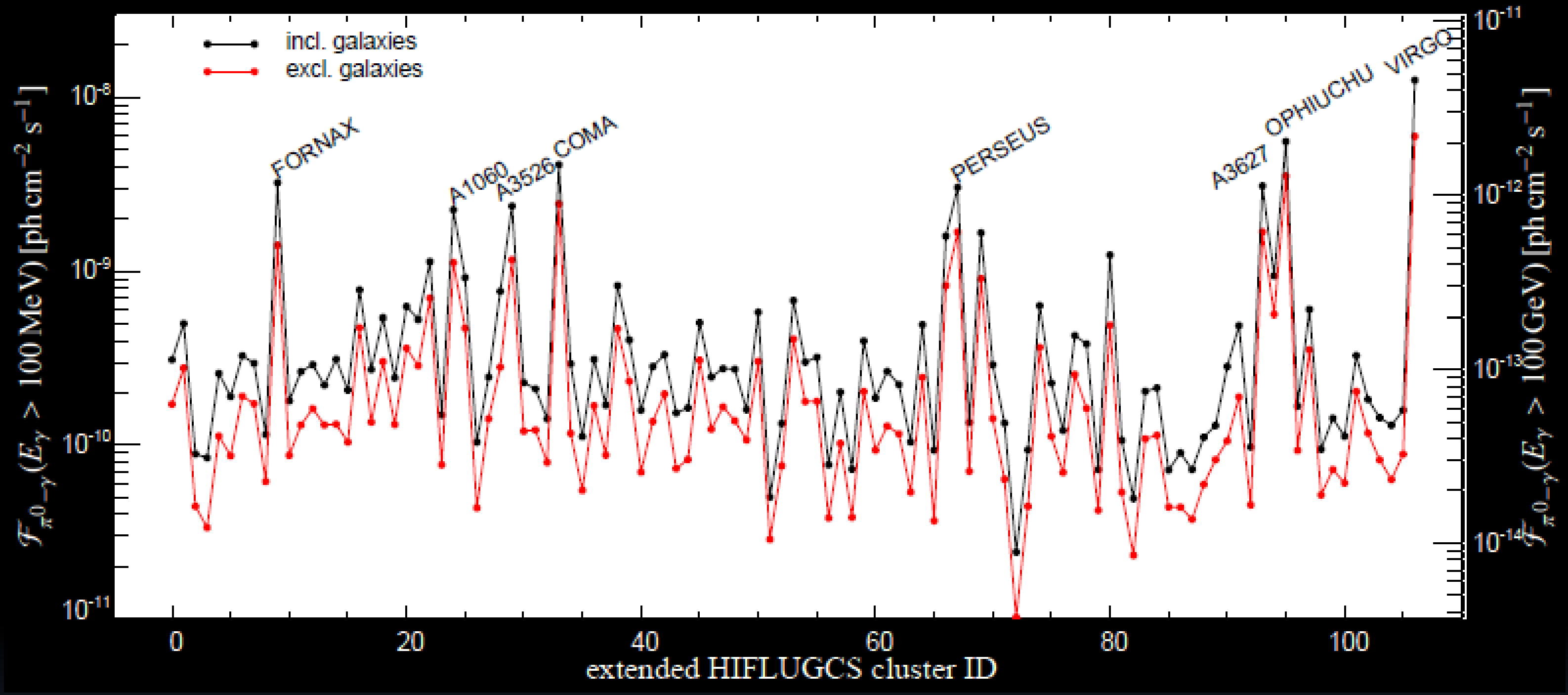
Jeltema, Kehaiyas & Profumo 2009



VHE observations of galaxy clusters

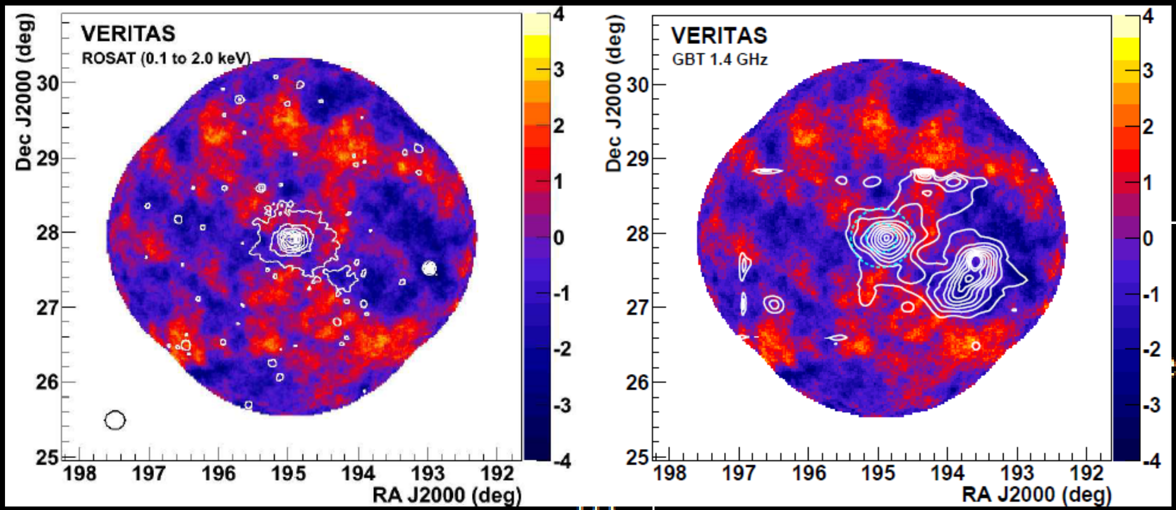
Fornax (Abramowski ea – H.E.S.S. - 2012)

Pinzke & Pfrommer 2010

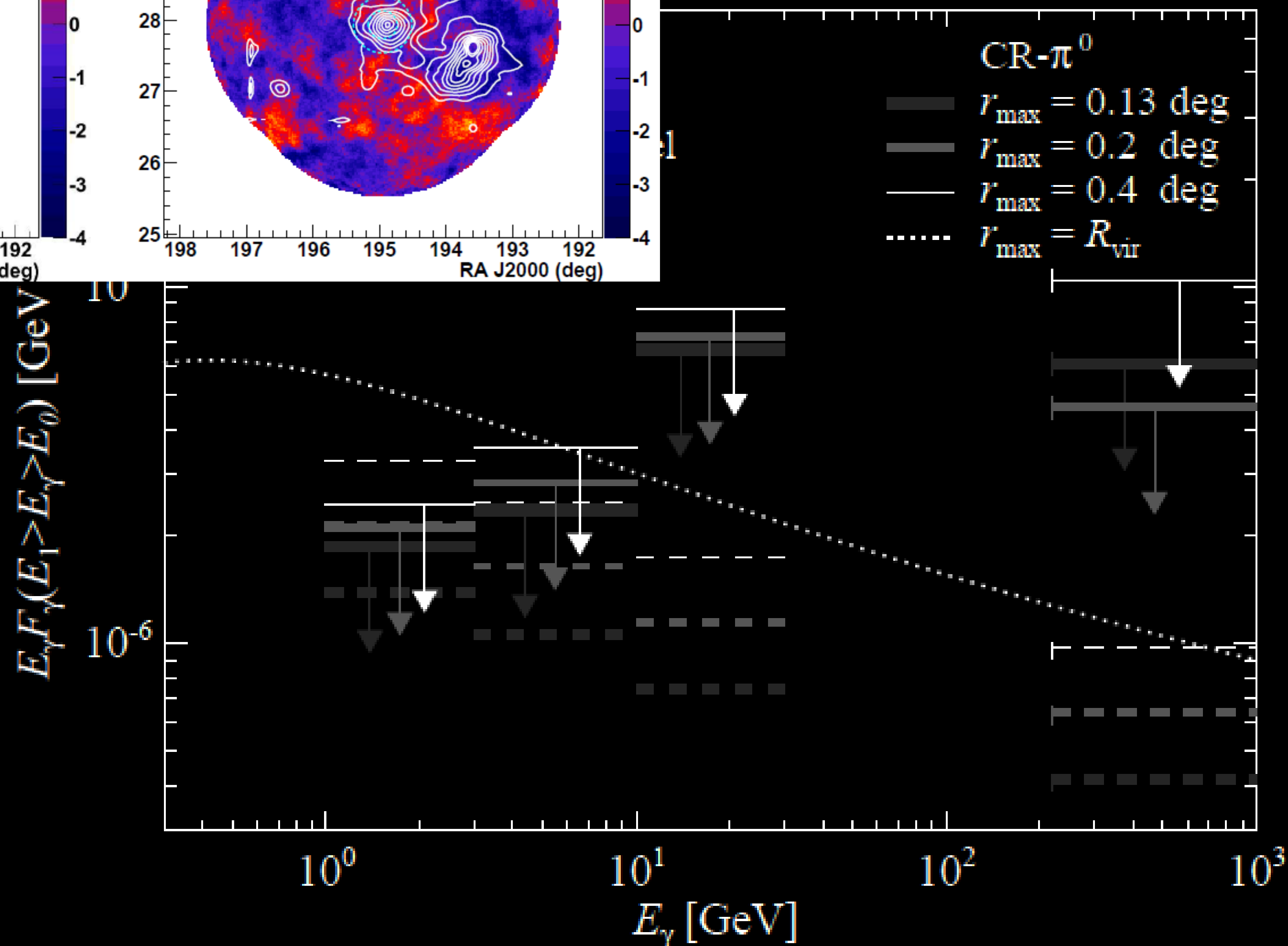


θ_{max}	$N_\gamma^{95\%\,\mathrm{C.L.}}(E_\gamma > E_{min})$	$\Phi_\gamma^{95\%\,\mathrm{C.L.}}(E_\gamma > E_{min})(10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$ $\Gamma = 1.5$	$\Gamma = 2.5$
0.1°	41.3	0.8	1.0
0.5°	135.1	2.3	3.3
1.0°	403.5	6.8	10.0

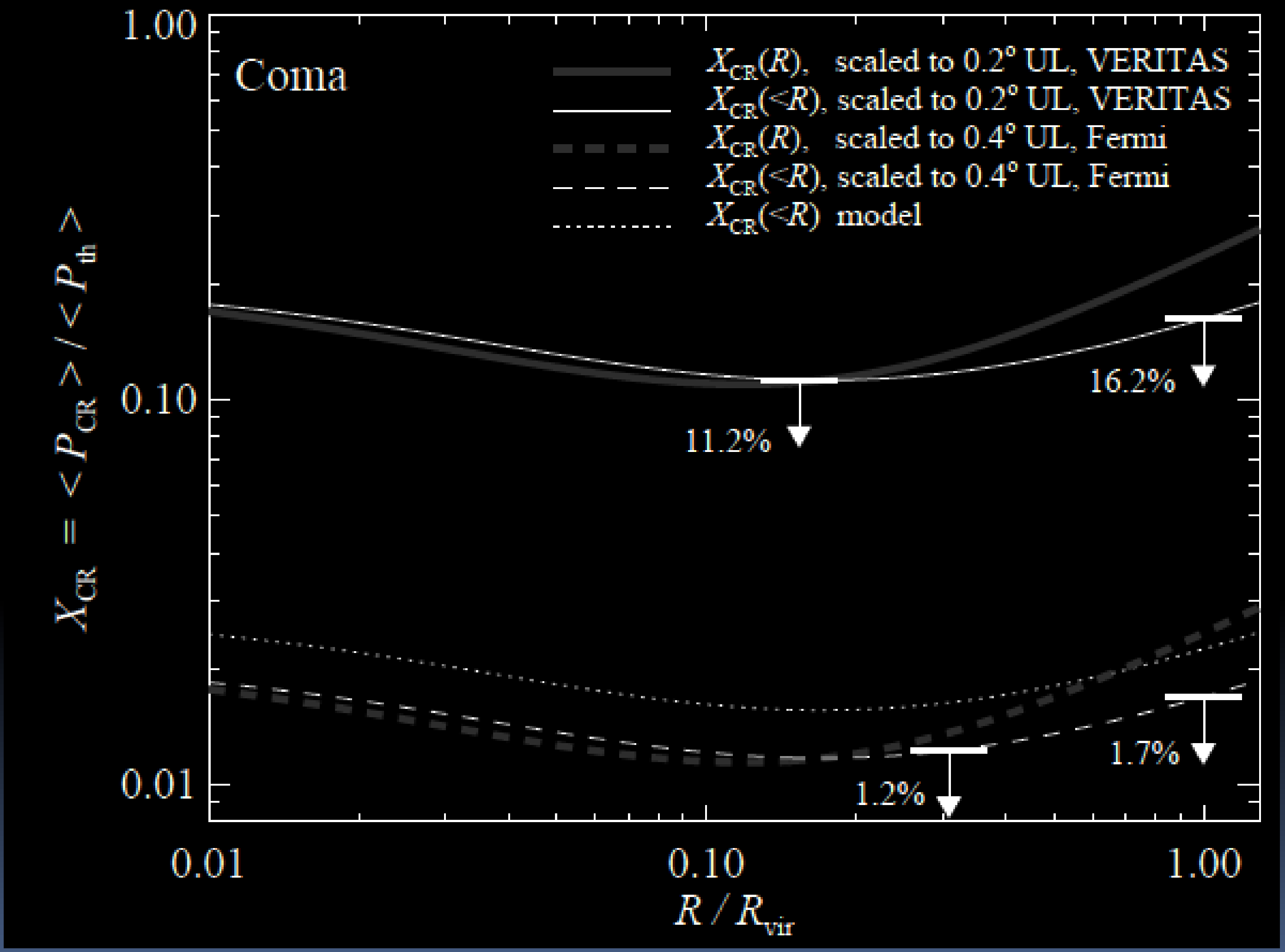
VHE observations of galaxy clusters



Arlen ea (VERITAS) 2012

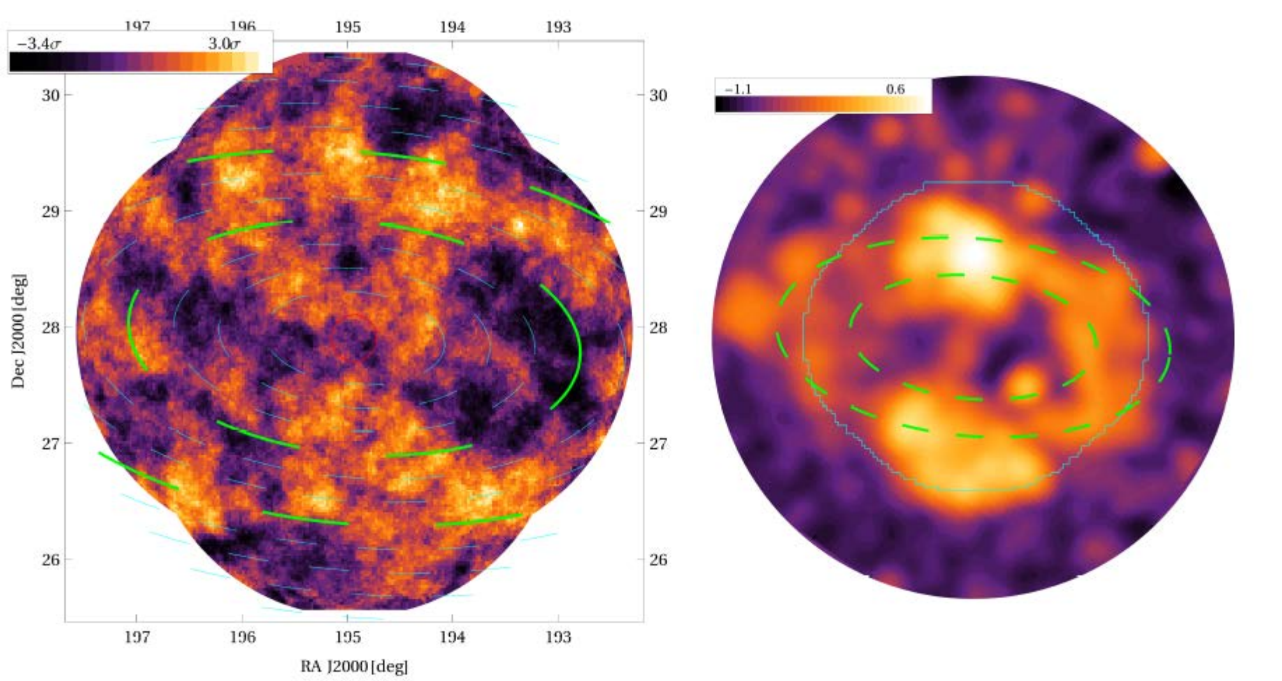


VERTITAS observations towards Coma (Arlen ea 2012)



Keshet ea 2012 (arXiv:1210.1574v1):

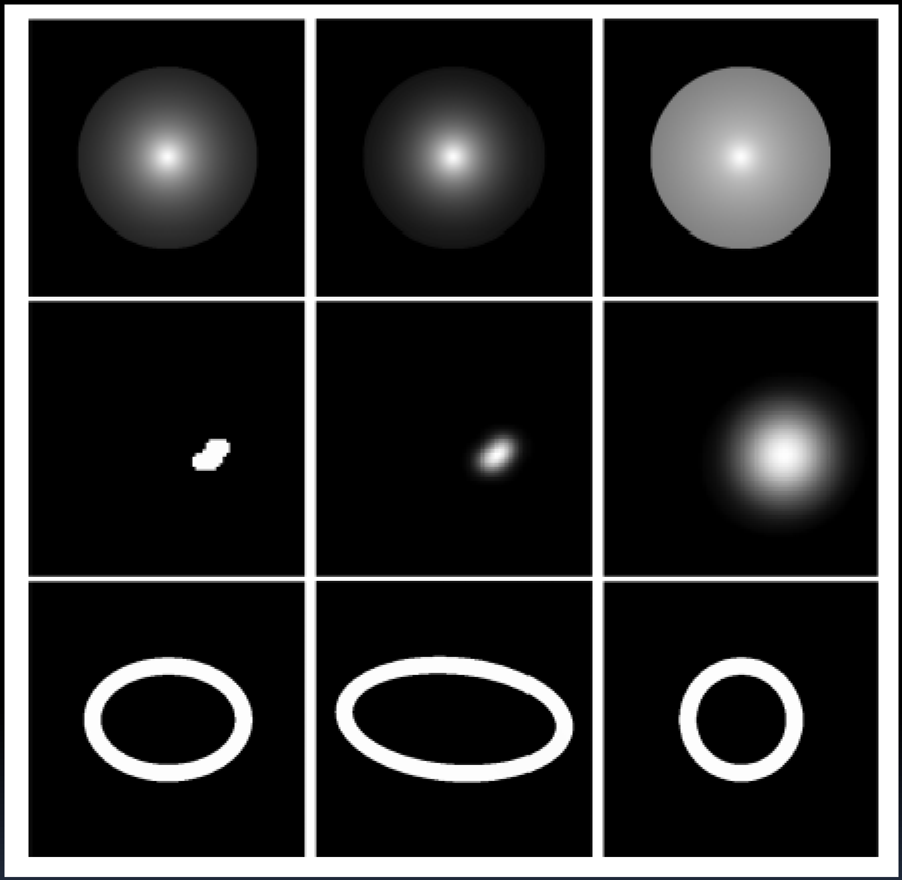
We report the discovery of a large, 5 Mpc diameter γ-ray ring around the Coma cluster, elongated towards the large scale filament connecting Coma and Abell 1367. The γ-ray ring correlates both with a synchrotron signal and with the SZ cutoff. The γ-ray, hard-X-ray, and radio signatures agree with analytic and numerical predictions, if the shock deposits a few percent of the thermal energy in relativistic electrons over a Hubble time, and 1% of the energy in magnetic fields. The implied IC and synchrotron cumulative emission from similar shocks dominates the diffuse extragalactic γ-ray and low frequency radio backgrounds.



(a) VERITAS significance map

(b) Simulated cluster in γ-rays

"Constraints on diffuse gamma-ray emission from structure formation processes In the Coma cluster" Zandanel & Ando MNRAS March 2014



- 5 years of Fermi data
- different emission templates

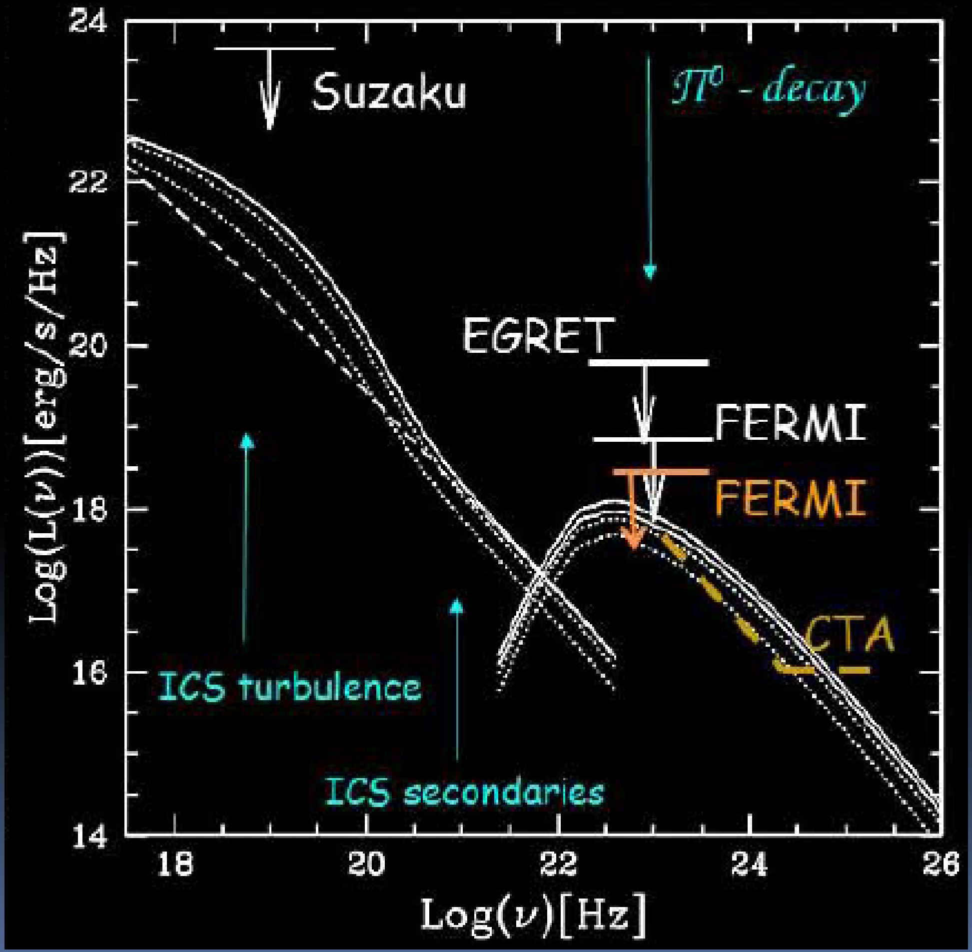
Model	Notes	TS	Γ	F_{UL} ($\times 10^{-9}$ cm^{-2} s^{-1})
PS		0.0	-2	0.62
PP		0.3	–	1.08
ZPP-100	$\gamma_{tu} = 100$	0.1	–	0.92
ZPP-2	$\gamma_{tu} = 2$	1.3	–	1.81
Relic		0.0	-1.18*	0.09
Ellipse		0.0	-2	2.49
Ellipse	Tilted	0.0	-2	1.74
Ring		0.2	-2	2.59
Disc		1.5	-2	2.91

- p acceleration efficiency less then 5%
- contribution to EGDB less then 1%
- nondetection of IC halo constraints CR electron efficiency to then 1%

Summary 1

No detection of GeV/TeV-scale gamma-ray emission whatsoever.

→ energy content CRp: η that small (~% level),
→ gamma as well as radio observations to allow to conclude that
nonthermal components are
dynamical not important/relevant

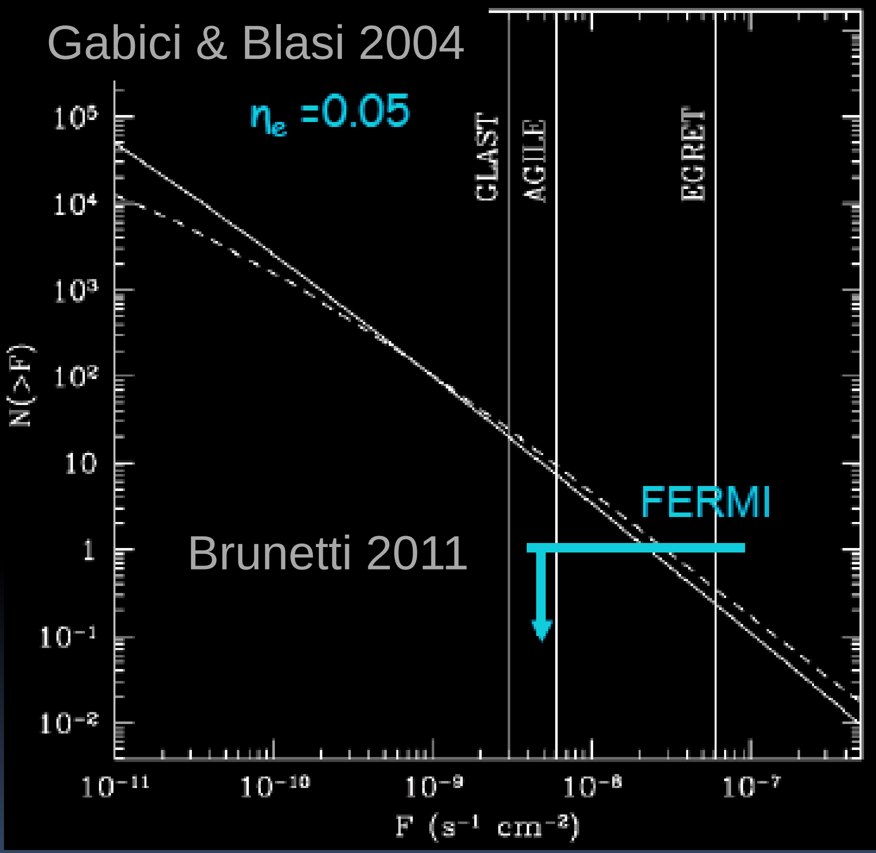


from review by
Brunetti & Jones 2014

Summary 2

No detection of TeV-scale gamma-ray emission whatsoever.

→ CRe: FERMI upper limits constrain the efficiency of electrons acceleration at shocks in galaxy clusters severly

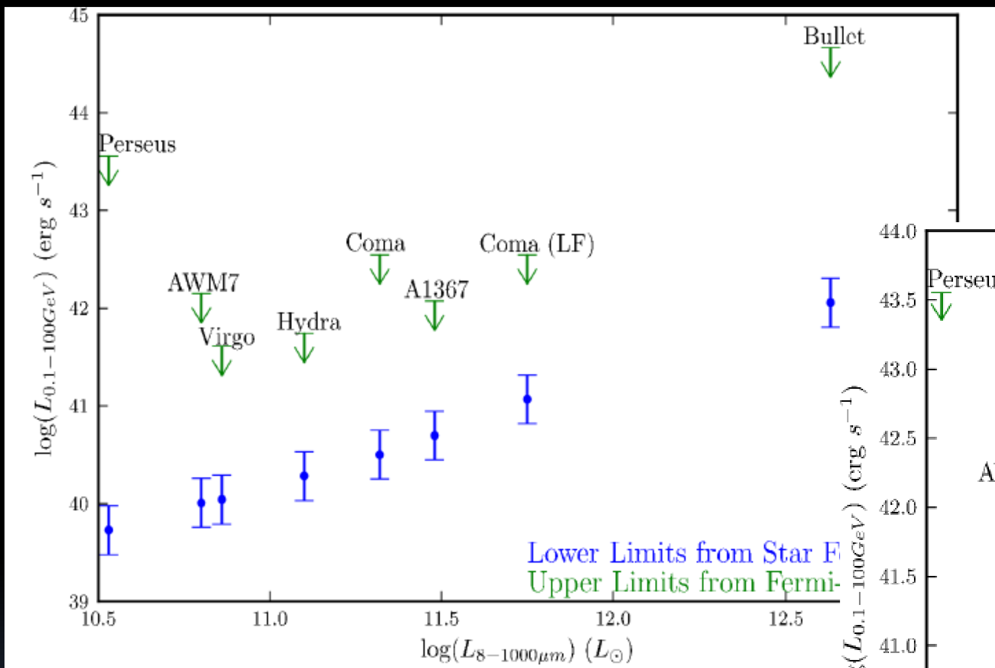


→ UHECRpγ and IC-dominance models are seriously challenged

Lower Limit from SF-related gamma-ray luminosity ?

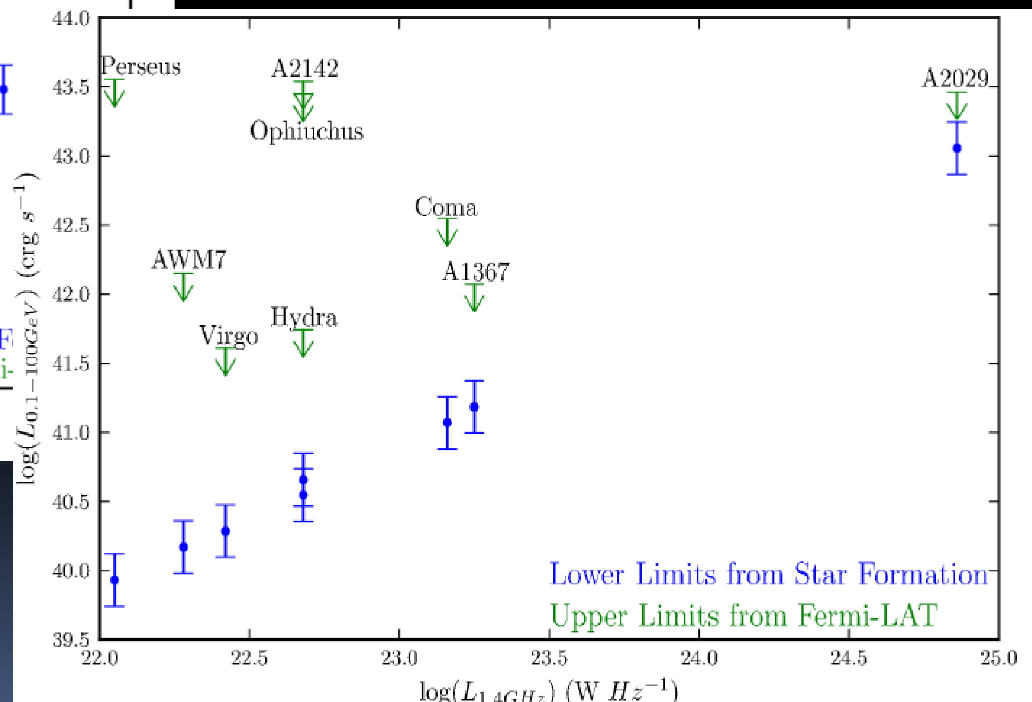
Storm Jeltema Profumo 2012

Infrared Luminosity (UV radiation from stars processed by dust into IR) and Radio Luminosity (synchrotron radiation from electrons accelerated by supernova remnants) are proxies for Star Formation Rate (SFR).



IR vs. gamma

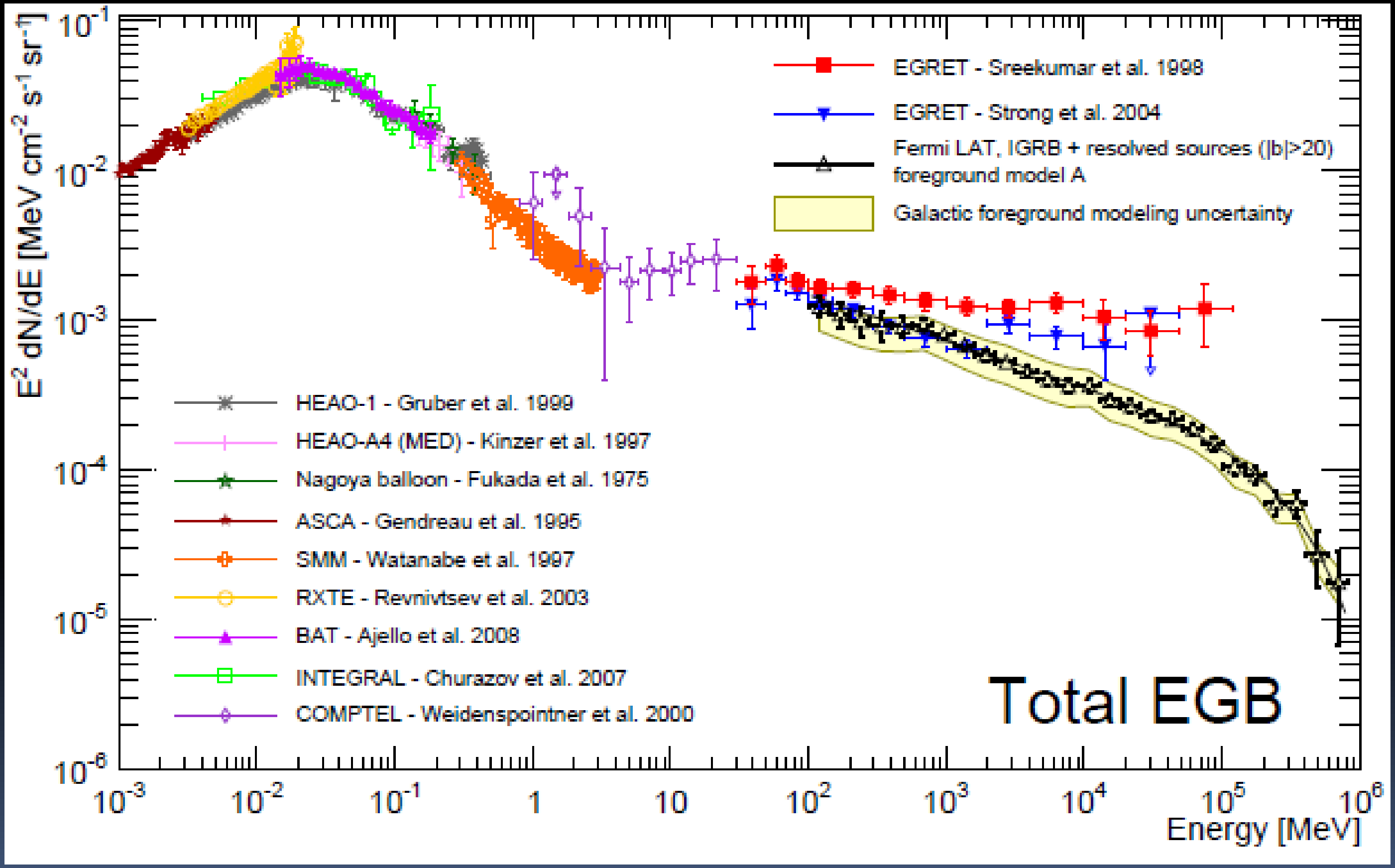
radio vs. gamma

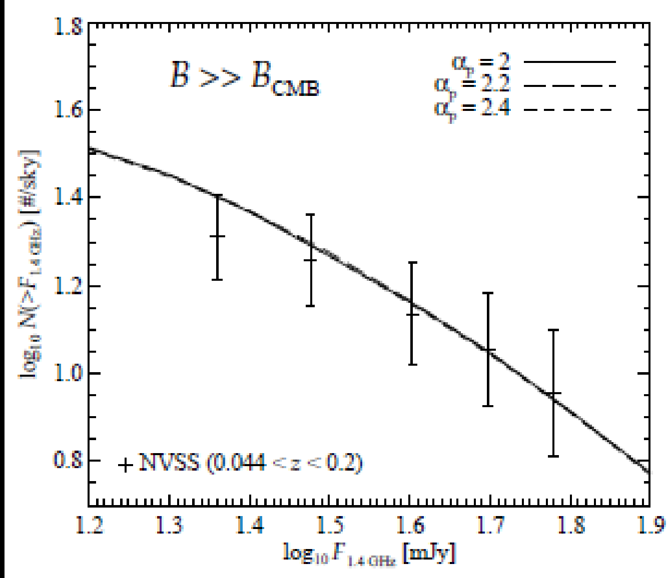


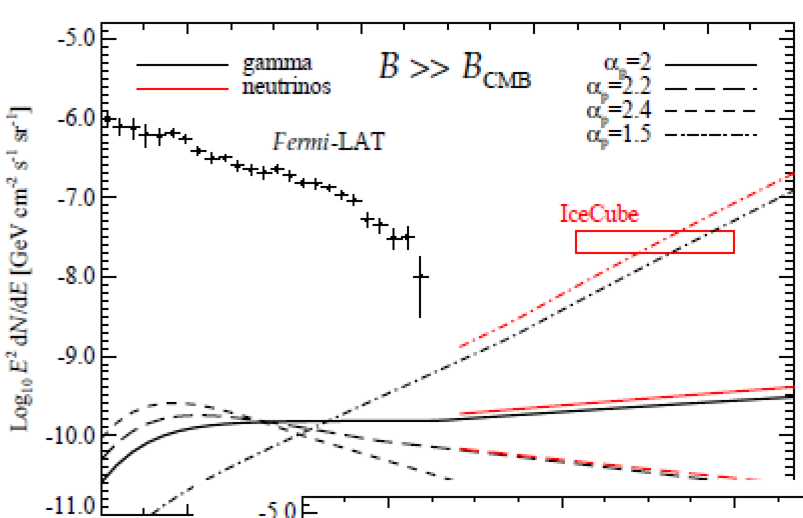
Ophiuchus, A2142 and A2029 have cool cores, which implies that their central galaxies may have elevated SFRs. For these clusters only the luminosity of the central, brightest cluster galaxy is considered. Warning: A2029 may host an AGN.

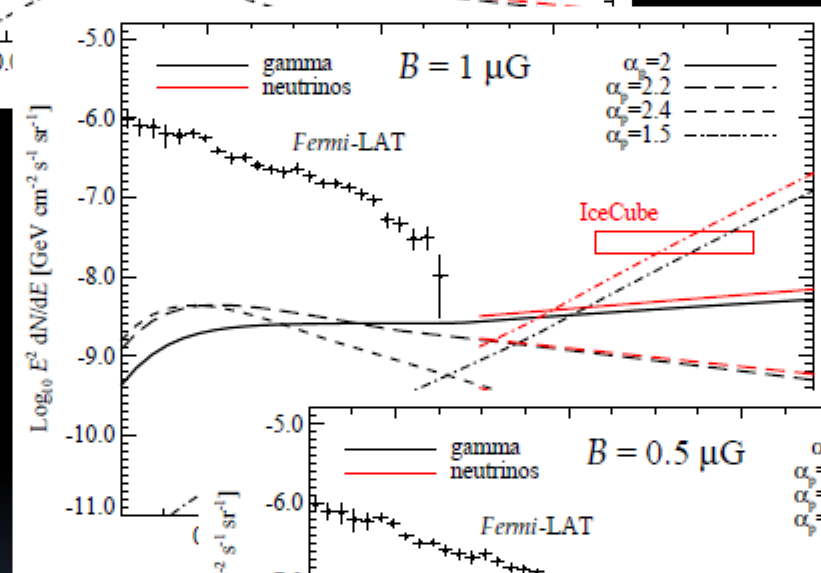
Contribution to the Extragalactic Diffuse Gamma-ray Background
(… a long way since Loeb &Waxman 2000)

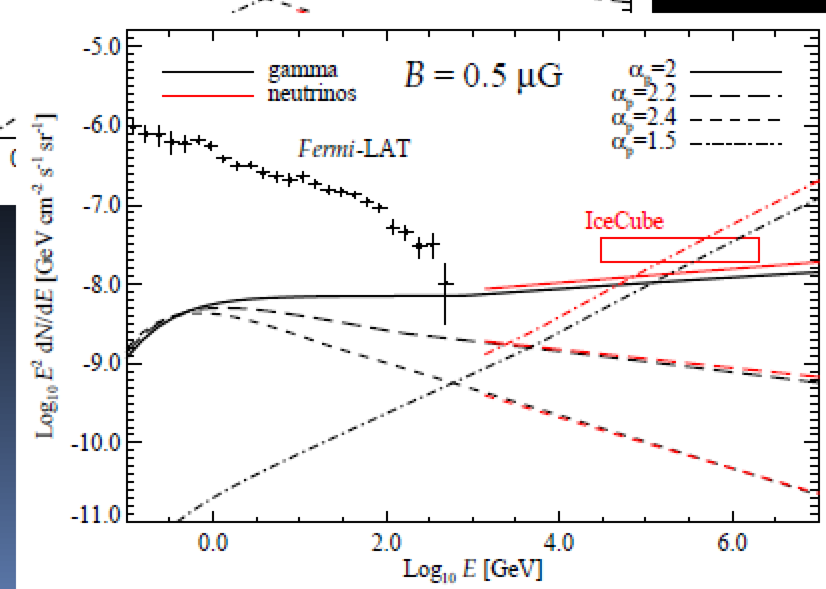
Ackermann ea (Fermi-LAT) 2014: Refined measurement







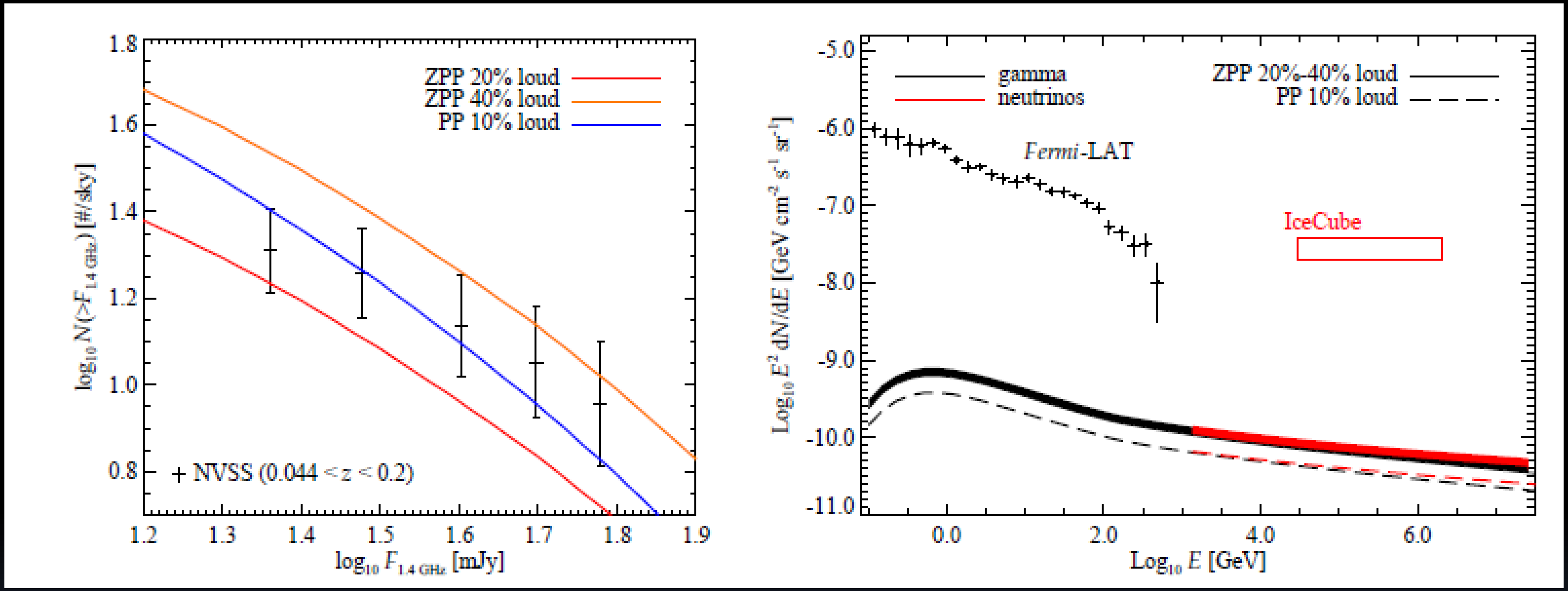




Zandanel ea 2014

hadronic interactions contribute less than 10% to the extragalactic diffuse background

Zandanel ea 2014



Assessment via secondaries:
According to semi-analytical model, galaxy clusters contribute less then 1% to extragalactic diffuse background

Conclusions regarding (lack of) detectable γ-ray emission in galaxy clusters

- disfavors lepton acceleration efficiencies in intracluster shocks > 0.001

- agrees with radio halo limits placed from constraints on secondary electrons (Brunetti et al. 2007, Churazov et al. 2008)

- volume-averaged CR-hadron-to-thermal energy density

$$\left\langle \frac{\epsilon_{CR}}{\epsilon_{TH}} \right\rangle \equiv \frac{\int N_p(E) E\, dE}{\frac{3}{2} n k T}$$

constrained to < 1-10% in many different cases, by different techniques, independent studies $\rightarrow$ serious!

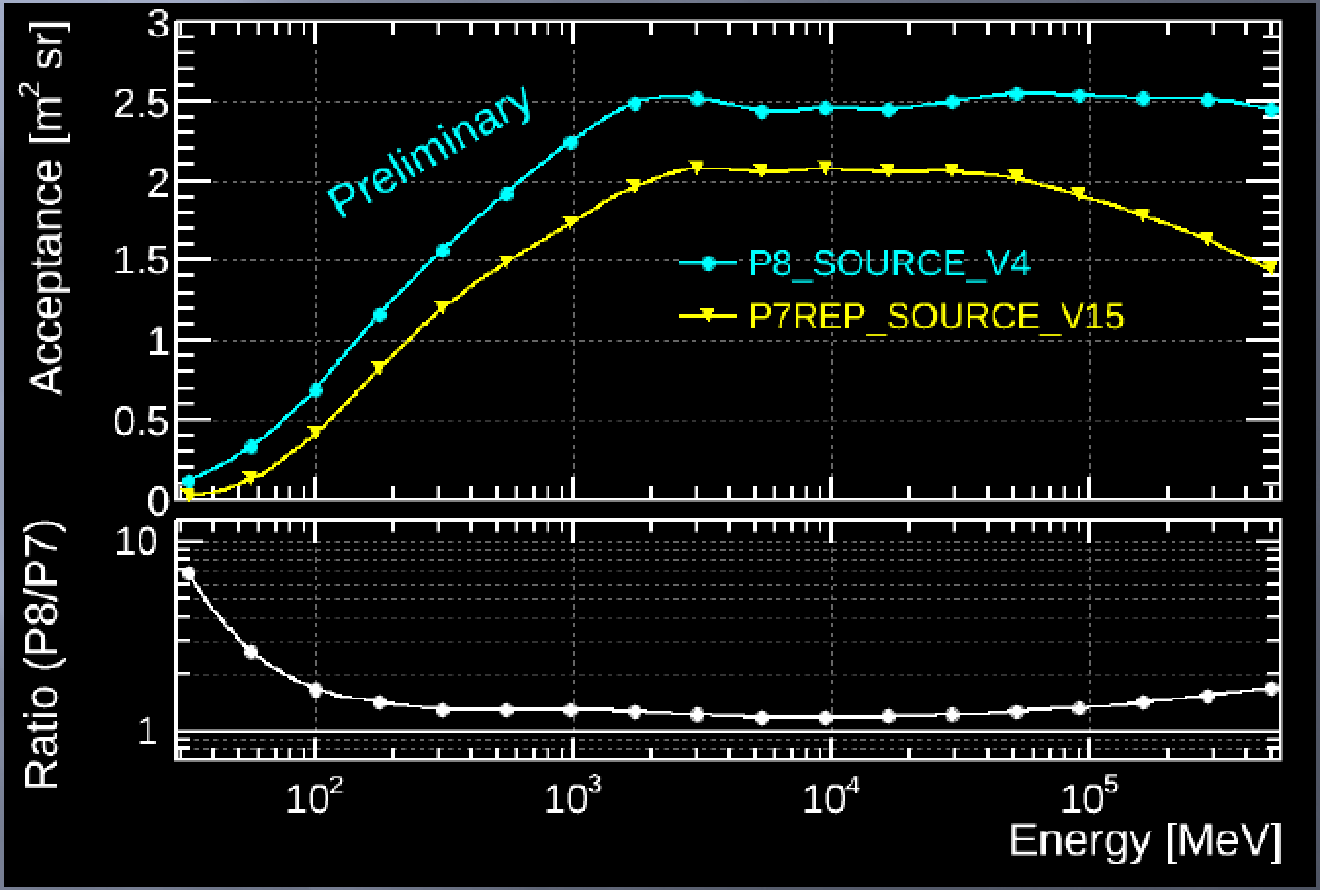
So are we getting somewhere?

- ☞ Fermi-LAT keeps observing!

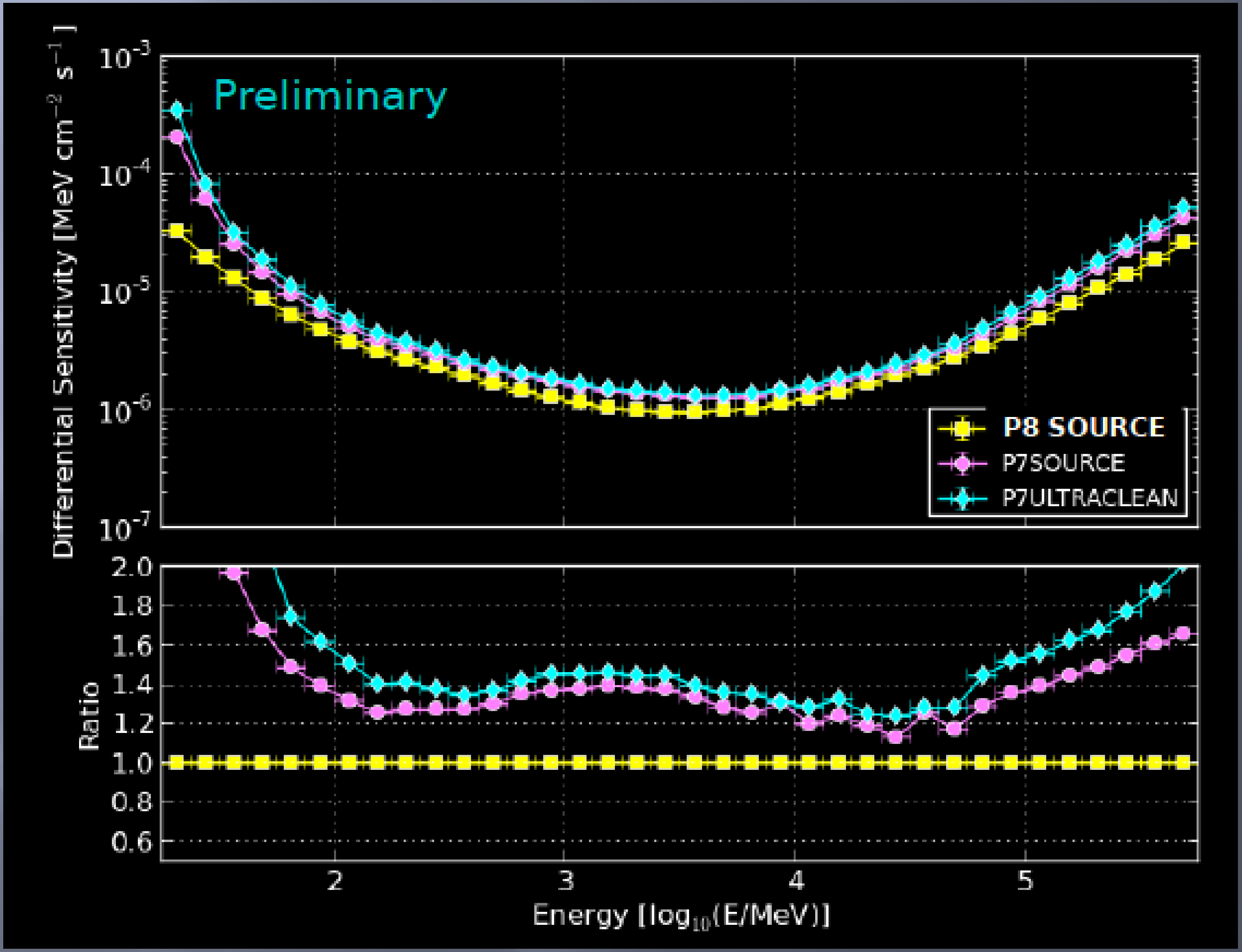
…provided that survey mode will be the default mode, it's an back-of-envelope exercise where instrumental sensitivity will be after 10 years …

modulo existence of matching source catalogs, improvements in the used diffuse emission model, further improvements in the IRFs, instrument status…

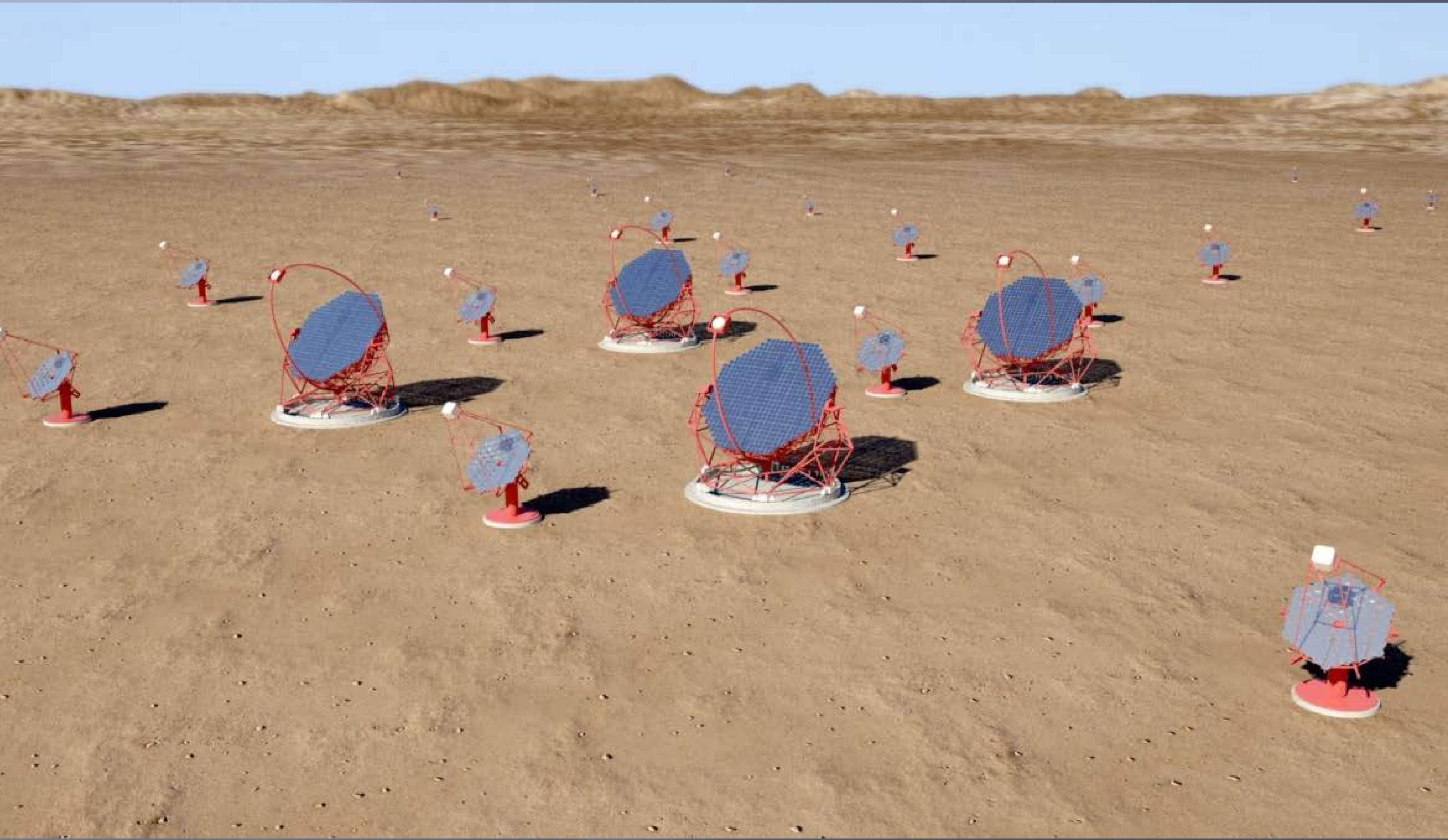
MAJOR NEWS: NEW IRF (PASS8) GETTING READY



MAJOR NEWS: NEW IRF (PASS8) GETTING READY

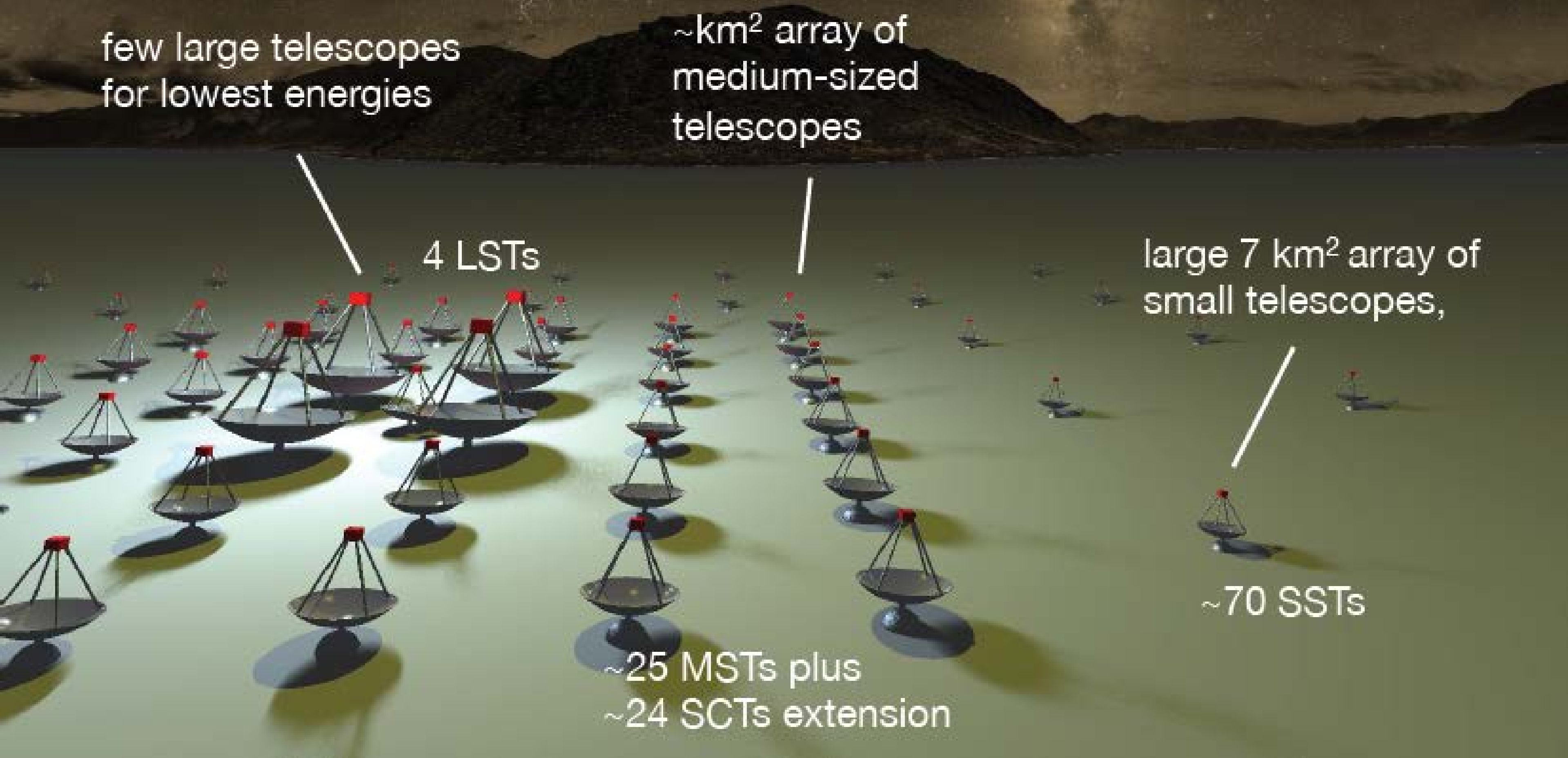


The CTA Observatory



Science-optimization under budget constraints:

- Low-energy γ high γ-ray rate, low light yield
  ➜ require small ground area, large mirror area
- High-energy γ low γ-rate, high light yield
  ➜ require large ground area, small mirror area



Theme 1: Cosmic Particle Acceleration

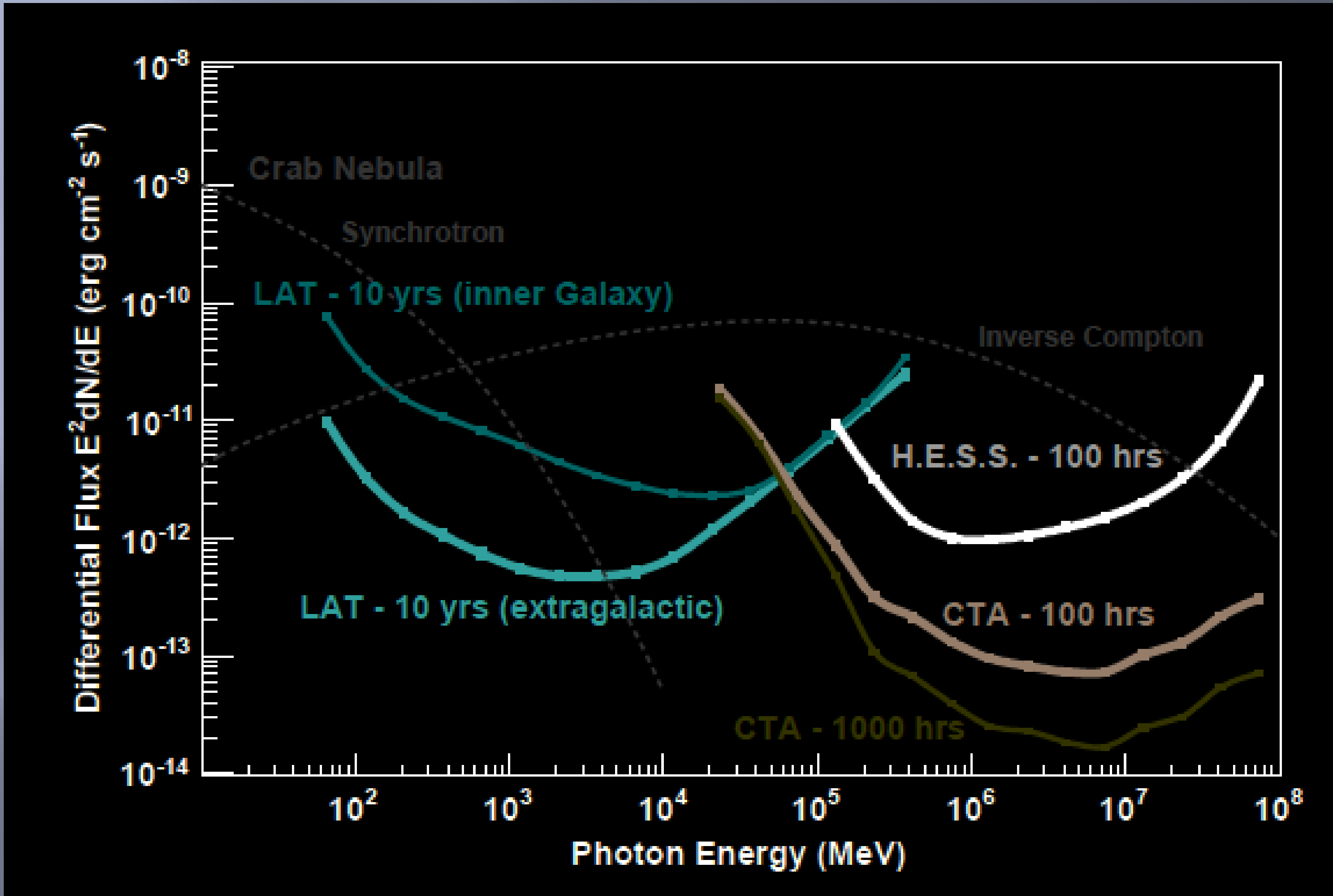
- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

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?

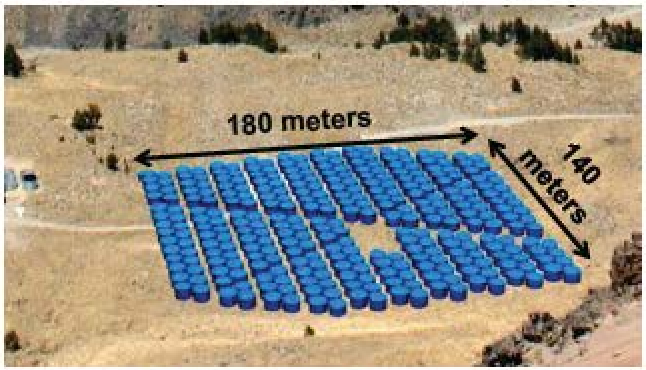


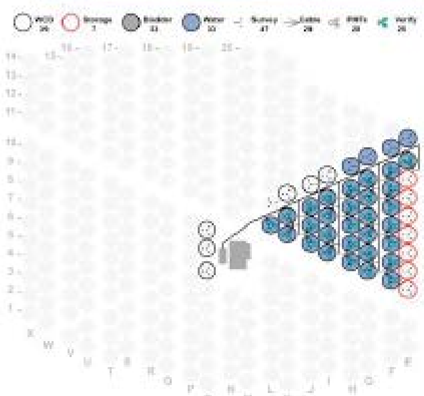
CTA consortium 2013

…but before CTA there will be HAWC

HAWC Design

300 close packed water tanks (7.3m dia x 4.5 m deep of 200,000 liters) each with 4 upward facing photomultiplier tubes at the bottom





Dingus ea 2012