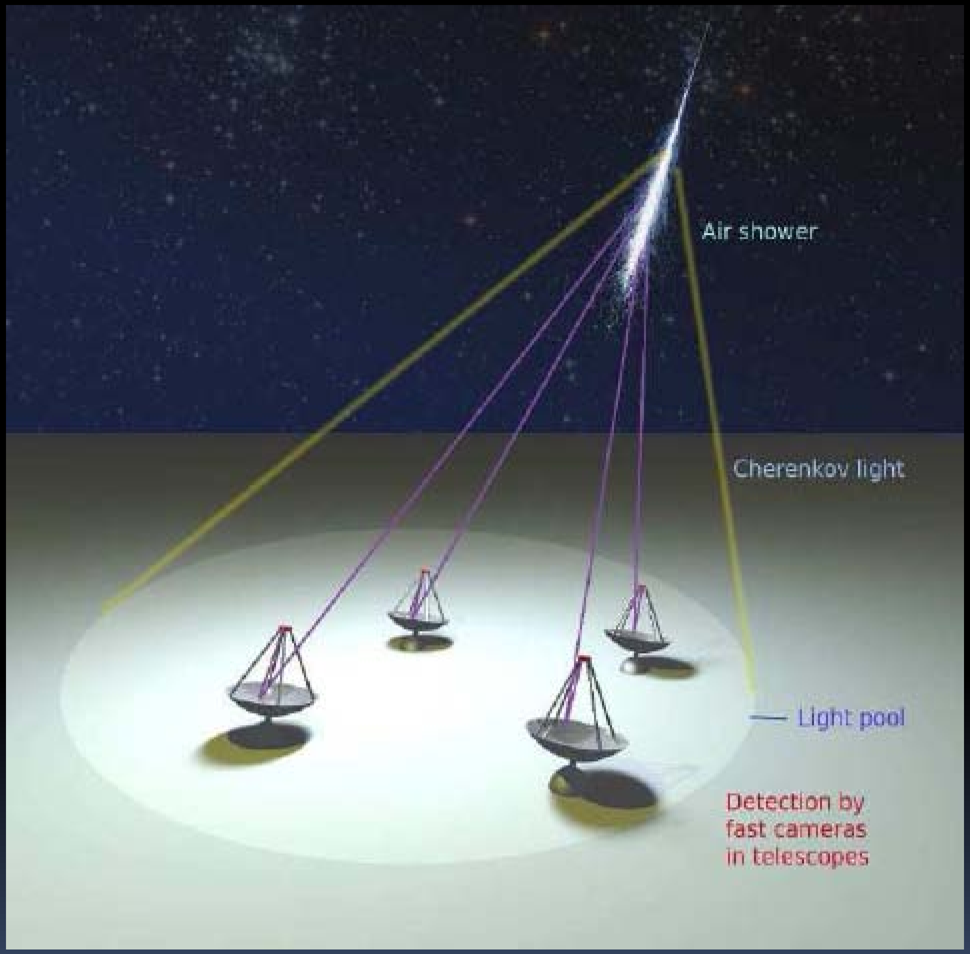
Olaf Reimer Leopold-Franzens-Universität Innsbruck & KIPAC Stanford

GALAXY CLUSTERS AT TEV ENERGIES
- FROM NOW TO CTA -

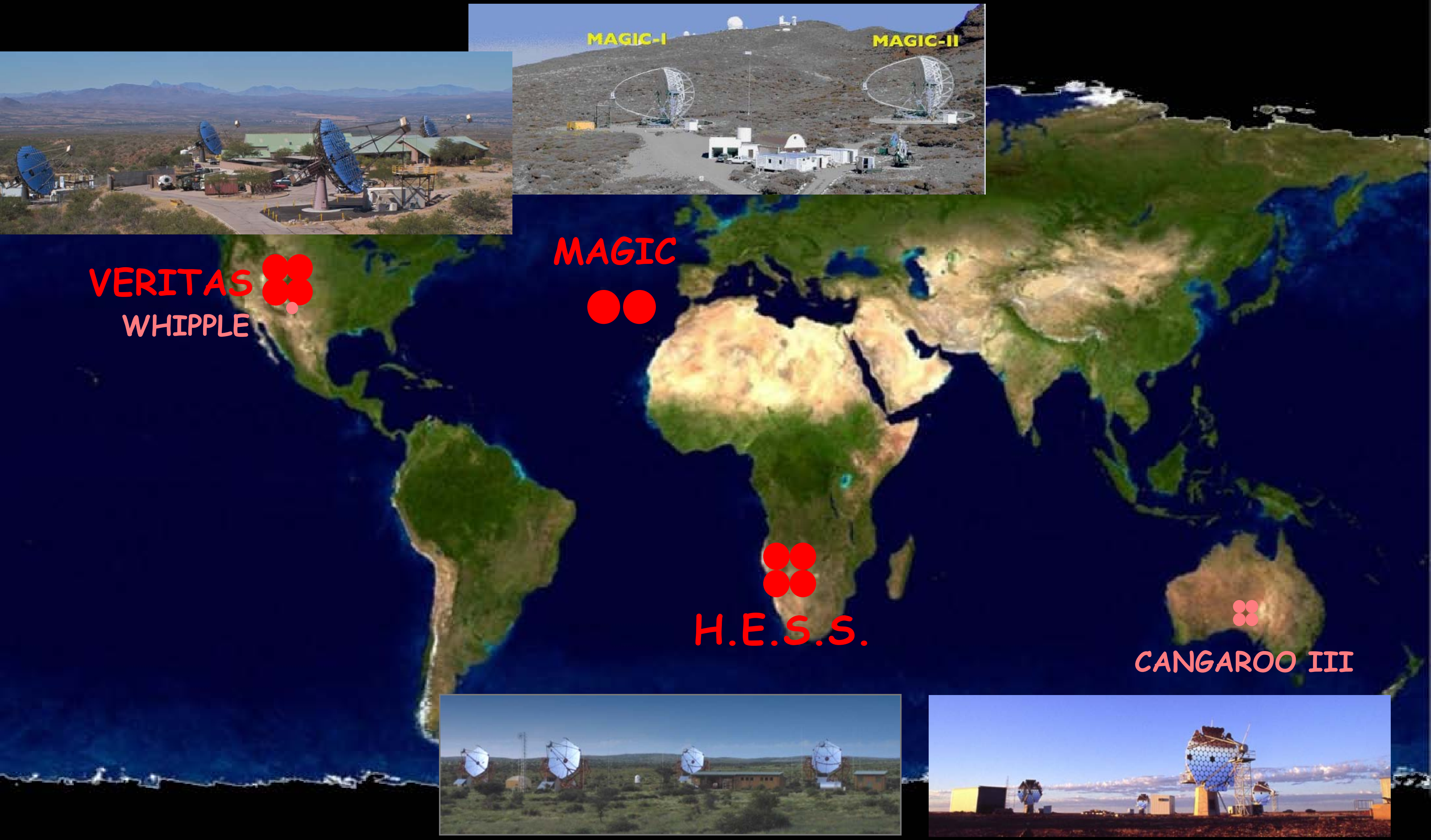
Stockholm, September 12 – 14 , 2011

Imaging atmospheric Cherenkov telescopes - technique

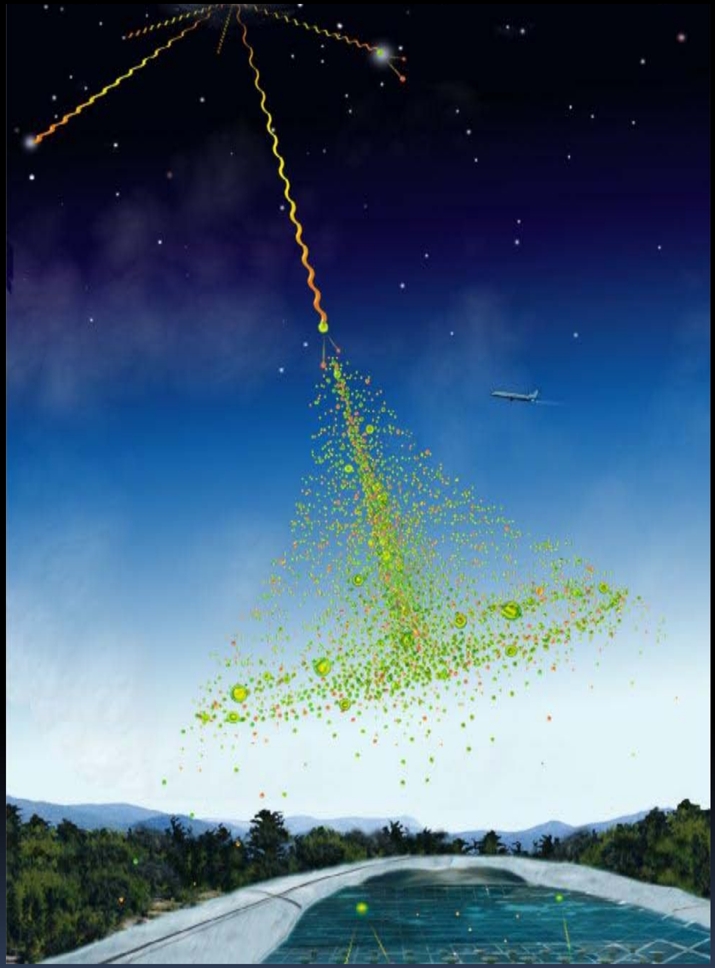


- CR primary particle enters Earth's atmosphere and develops cascade
- Forward propagating faint, bluish Cherenkov light cone can be caught by reflecting telescopes, that focus on a highly/-pixelated camera (single PE resolution and few ns-time resolution)
- (multiple) camera images are fitted to shower parameter and allow determination of arrival direction, energy, primary particle identification

Major imaging atmospheric Cherenkov telescopes

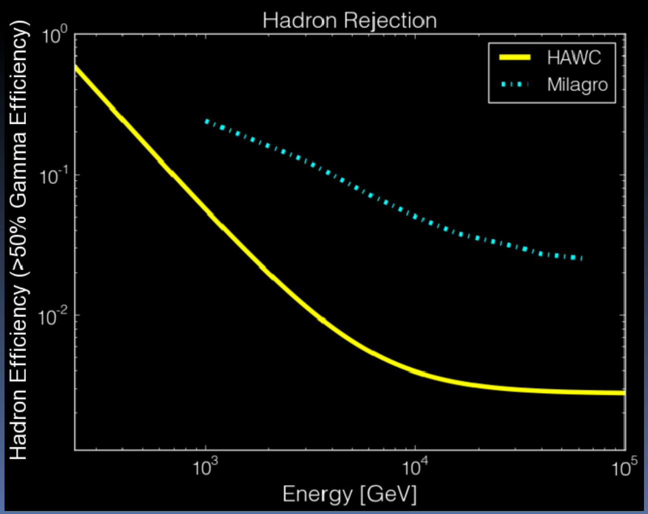


Air Shower Detectors with γ-ray aim - technique

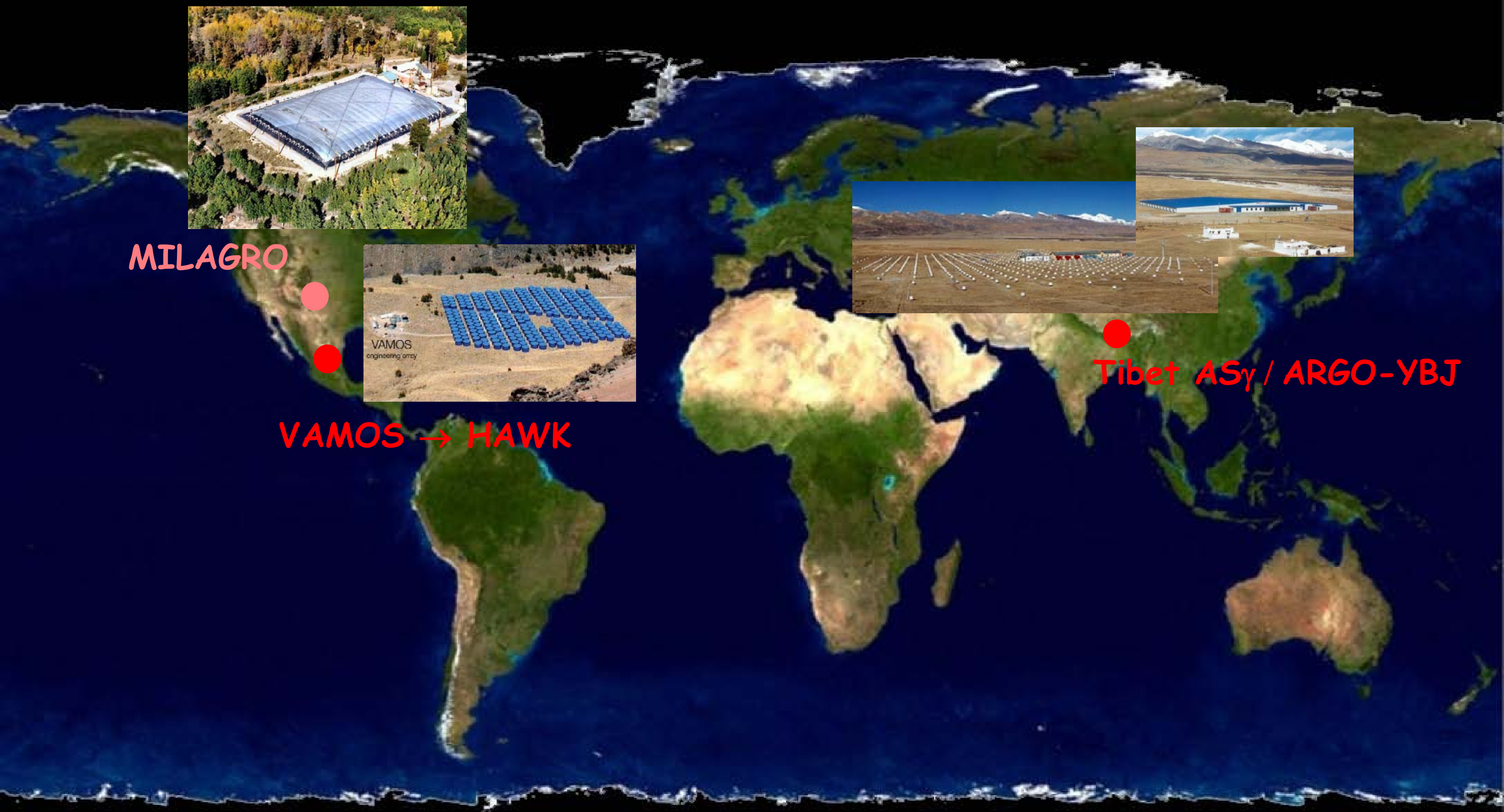


- CR primary enters Earth's atmosphere
- particle cascade develops & ultimately hit surface detector
- time differences in arriving shower front is used to reconstruct arrival direction, image to reveal energy and ID of primary particle

main challange for γ-ray application: hadron rejection $\rightarrow$ no MILAGRO-like single pond solution considered anymore



Major Air Shower Detectors with γ/hadron discrimination



Why observing at Gamma-Rays?

Think nonthermal, think CR!

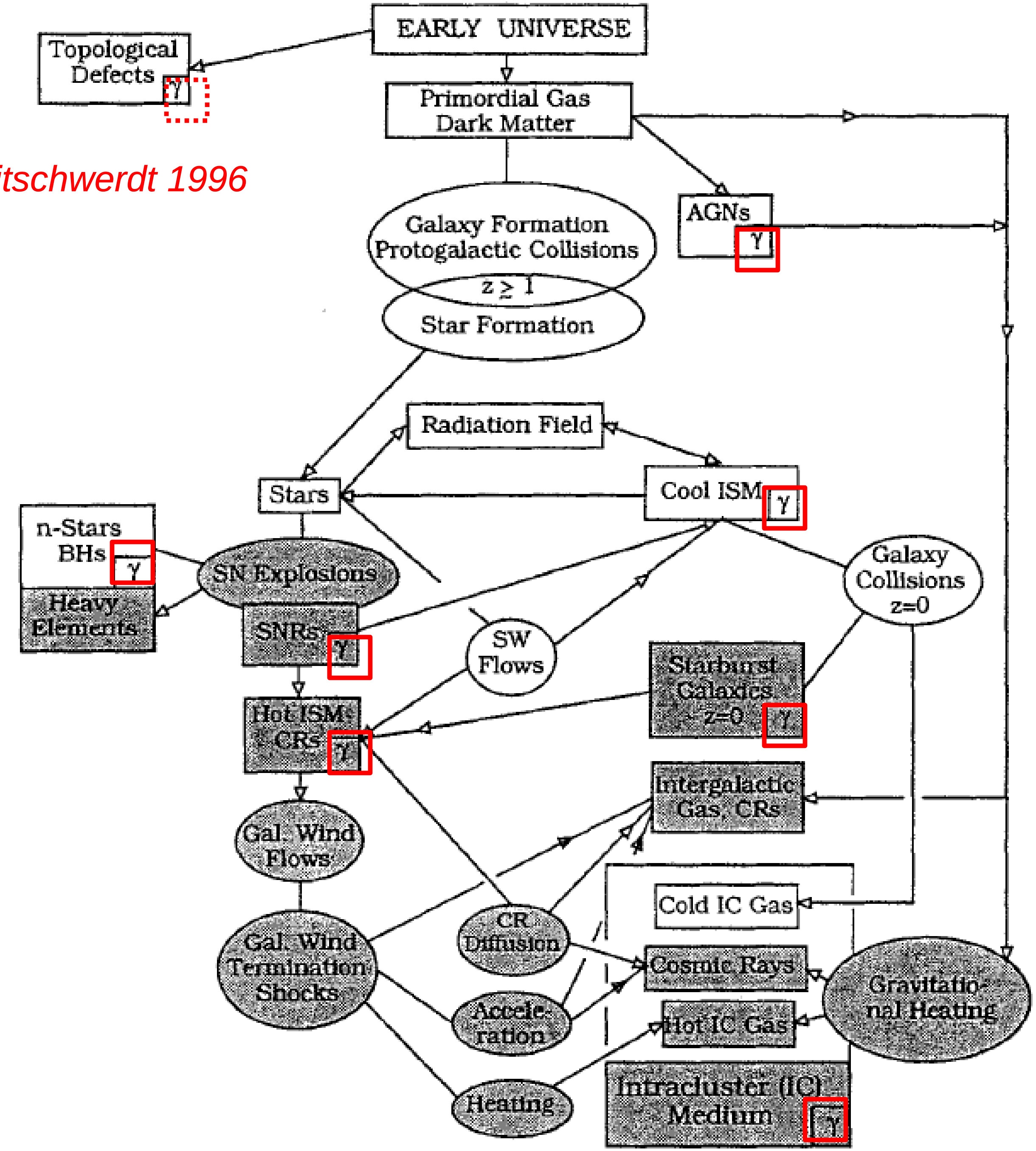
Galaxy Clusters contain significant populations of Cosmic Rays, stored over cosmological timescales
-> largest non-thermal sources in the Universe

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

Physical processes to be considered:

- pp-interactions -> π^0 decay -> HE γ's
- TeV electrons -> IC photon upscattering on CMB -> HE γ's
- p-acceleration up to 10^{18} eV -> CMB interaction /injection into ICM -> photomeson production: $p\gamma \rightarrow \pi^0, \pi$'s, ...
  -> Bethe-Heitler pair production: $p\gamma \rightarrow p, e^+, e^-$
- secondary pair production through $\gamma\gamma$-interactions of VHE gammas from AGN / IC CMB γ (UV/OPT: GeV, IR: TeV)

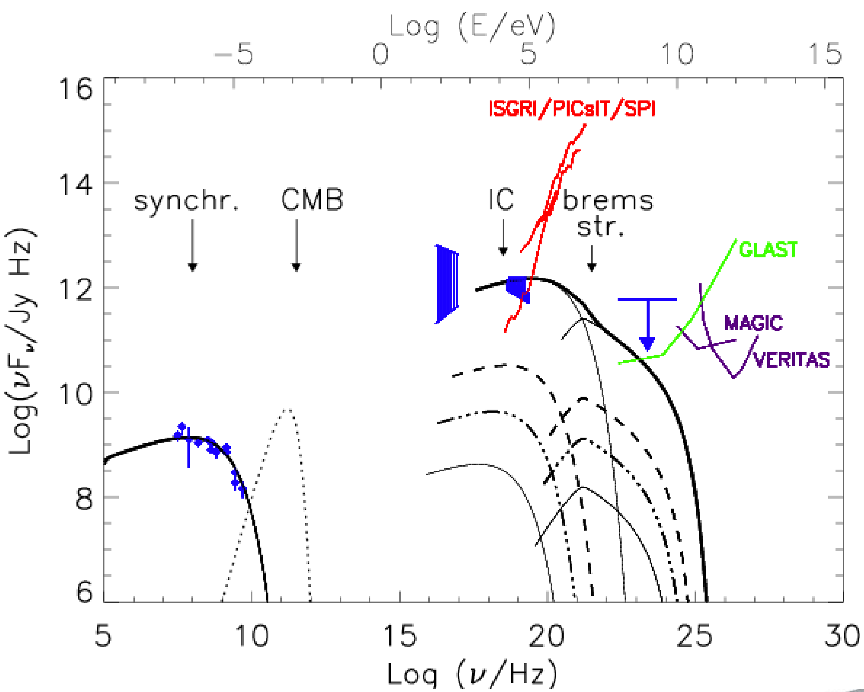
Völk, Aharonian & Breitschwerdt 1996

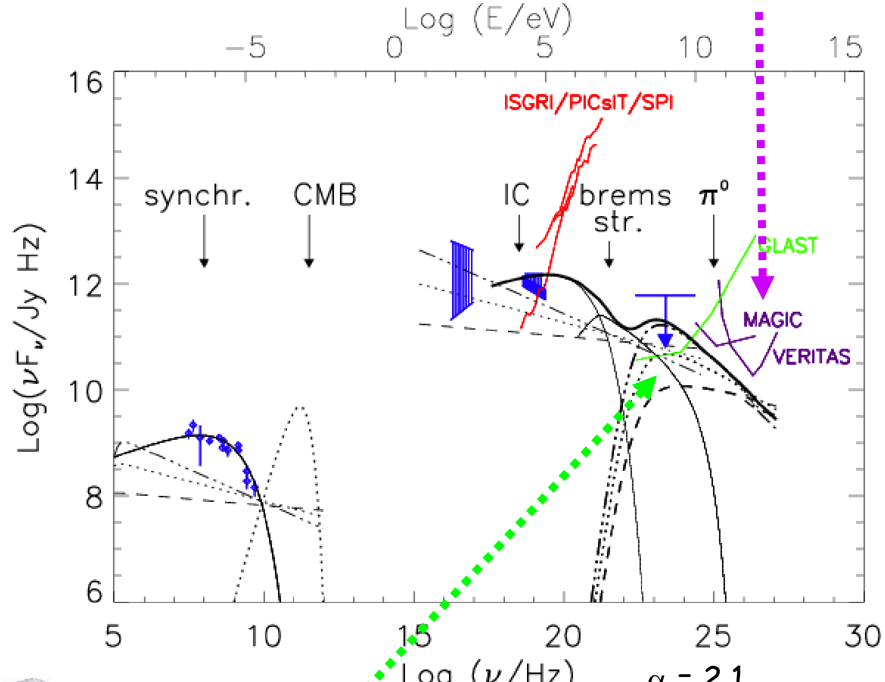


MWL modeling: radio + X-ray allows to predict gamma-ray emission

archetypal case: Coma

(Aharonian; Dermer & Berrington;
Völk & Atoyan; Blasi & Gabici;
Brunetti etc...
- here: Reimer et al. 2004:)





B= 0.1 μG

B= 0.7 μG

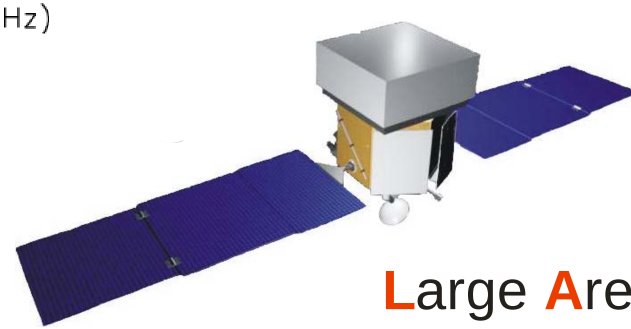
B= 1.9 μG

B= 6 μG

α = 2.1

α = 2.3

α = 2.5



E_{CRp} ~3%,8%,28% E_{kT}

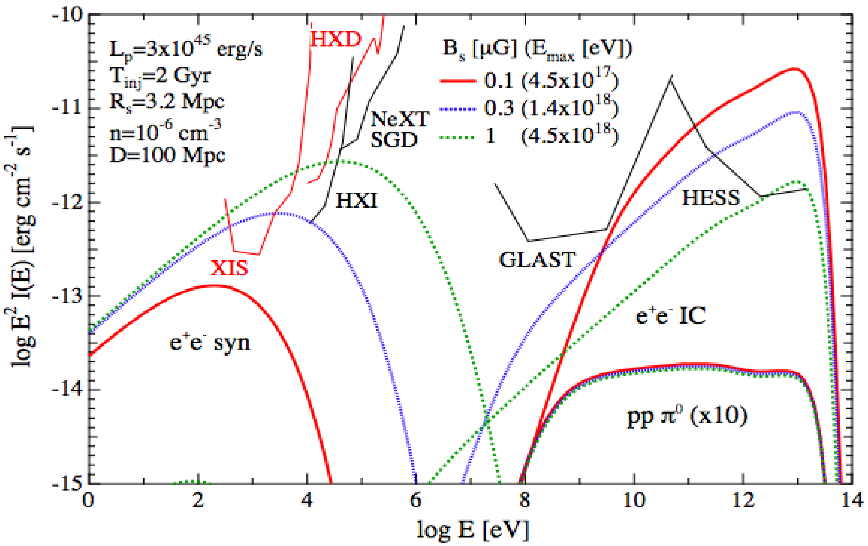
Large Area Telescope

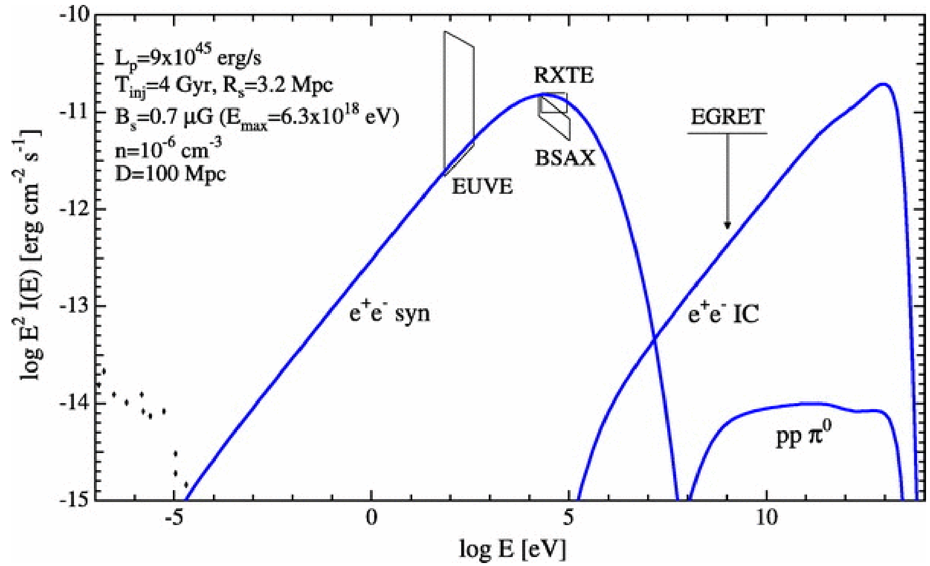
UHECR-induced (secondary) pair emission injected by powerful radio galaxy

Aharonian 2002; Rohrdorf, Grasso & Dolag 2004

UHECR-induced pair emission from cluster accretion shocks

UHE proton – photon (CMB) pair syn.+IC





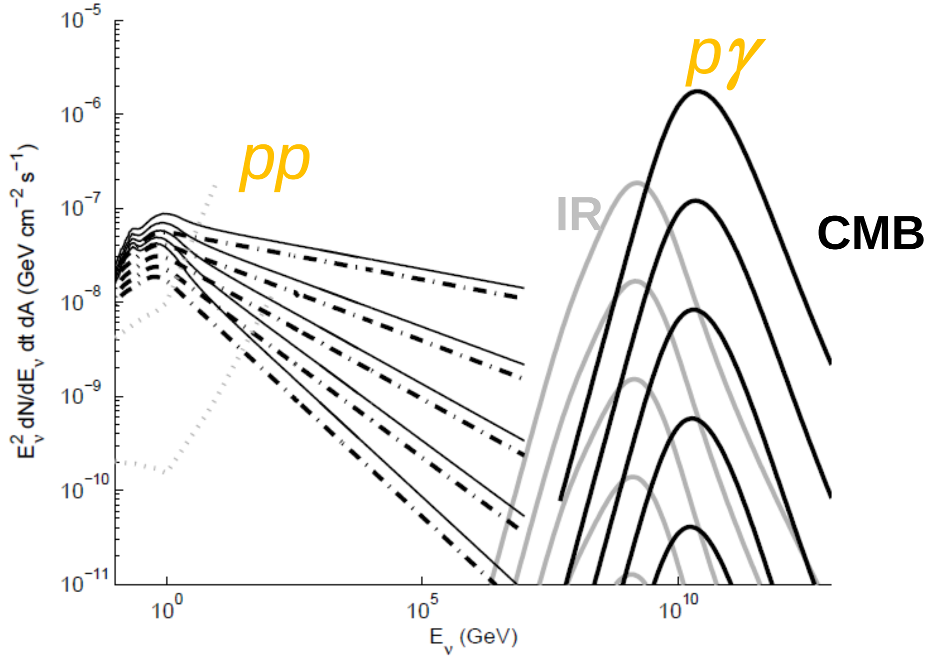
Inoue, Aharonian & Sugiyama 2005

$p+\gamma_{CMB} \rightarrow p+ e^+e^-$

$E_p \sim 10^{18}$eV $E_{+-} \sim k_{+-} E_p \sim 10^{15}$eV

$\rightarrow e^+e^- + B(\sim\mu G) \rightarrow$ syn. $E_\gamma \sim$keV-MeV

$e^+e^- + \gamma_{CMB} \rightarrow$ IC $E_\gamma \sim$TeV-PeV

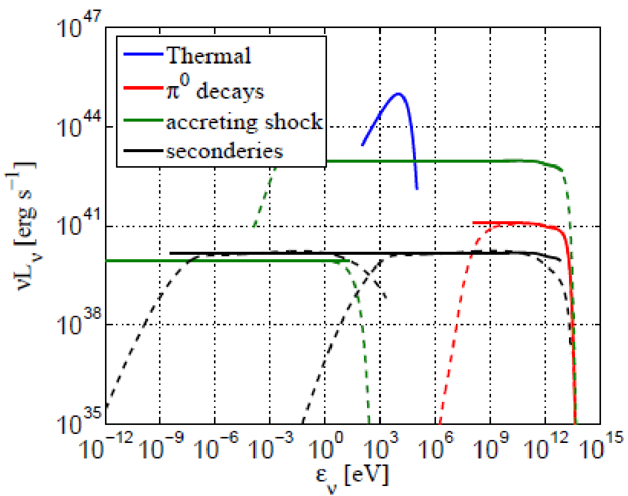


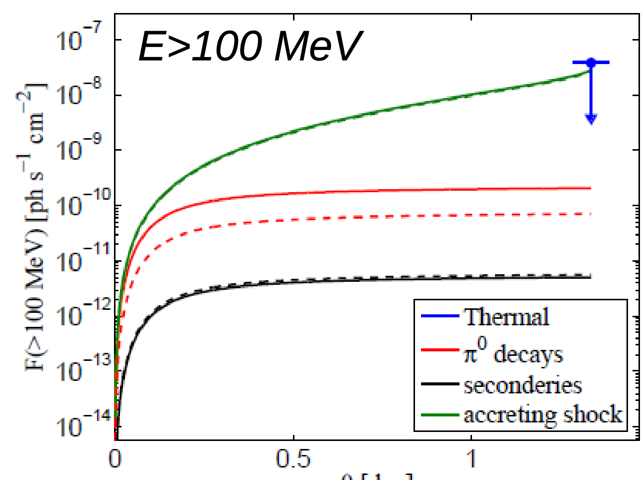
Wolfe, Melia, Crocker & Volkas 2008

secondary model with varying Spectral index $2.1 < \Gamma_p < 2.5$

IC-dominance models (Kushnir, Katz & Waxman, Kushnir & Waxman 2010)

IC of CMB photons by electrons accelerated in accretion shocks (primary electrons) exceed the luminosities produced by secondary particles

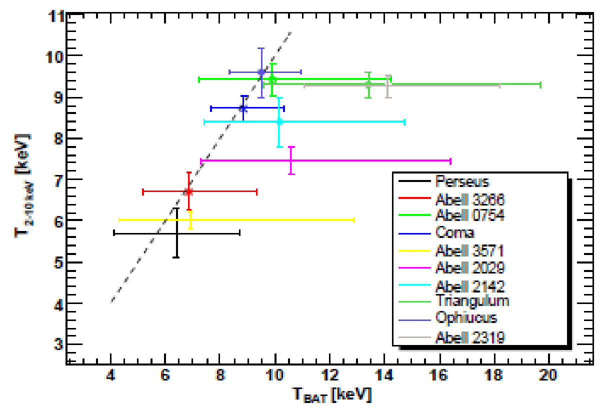




***REMARK**: NT priors from X-ray not safe anymore – NuStar / Astro-H will have next word!*

Ajello, Rebusco, Cappelluti, OR, et al. 2008 (E > 15 keV SWIFT/BAT)

NAME	$F_{50-100\,keV}$ [a] $(10^{-12}$ erg cm^2 s$^{-1})$	B [b] (μG)
Perseus	...	...
Abell 3266	<0.57	>0.55
Abell 0754	...	...
Coma	...	...
Abell 3571	$1.4^{+0.4}_{-0.4}$	~ 0.08
Abell 2029	<1.27	>0.42
Abell 2142	<1.50	>0.10
Triangulum Australis	<0.65	>0.39
Ophiucus	<2.80	>0.15
Abell 2319	<0.67	>0.15



NAME	$F_{50-100\,keV}$ [a] $(10^{-12}$ erg cm^2 s$^{-1})$	B [b] (μG)
Abell 85	<2.51	~ 0.6
Abell 401	<0.22	~ 0.4
Bullet	$1.58^{+0.43}_{-0.47}$	~ 0.16
PKS 0745-19	<1.6	~ 0.5
Abell 1795	<1.38	/
Abell 1914	<1.08	~ 0.3
Abell 2256	<0.19	~ 0.6
Abell 3667	$2.98^{+4.17}_{-0.73}$	/
Abell 2390	<0.25	~ 0.8

Ajello, Rebusco, Cappelluti, OR, et al. 2010

serious consideration that multi-kT components mimic NT emission!

→ accordingly MWL modeling advocates then <u>lower</u> γ-ray fluxes

Galaxy clusters - CR calorimetry?

Criteria based on non-DM induced astrophysical processes [e.g. Reimer et al. ‘03, Blasi et al. ’07, Pfrommer ’08+]

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

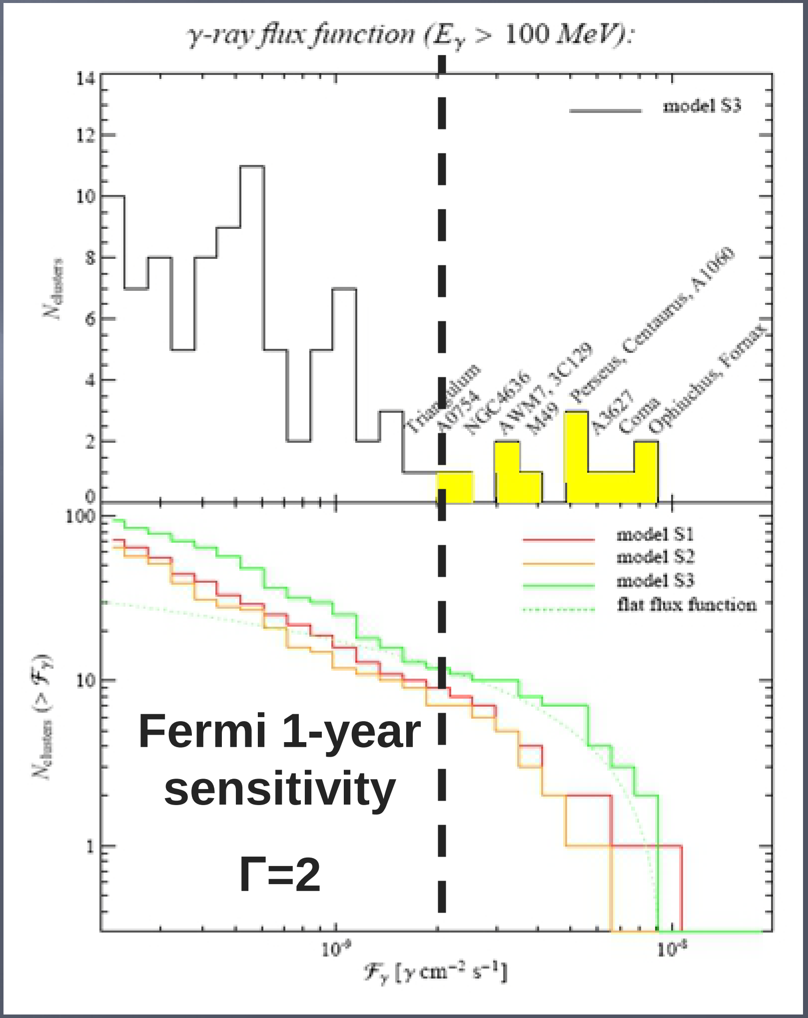
MESSAGE : DM-annihilation related γ-ray flux always dominated by non-DM-related one (“conventional”)*

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

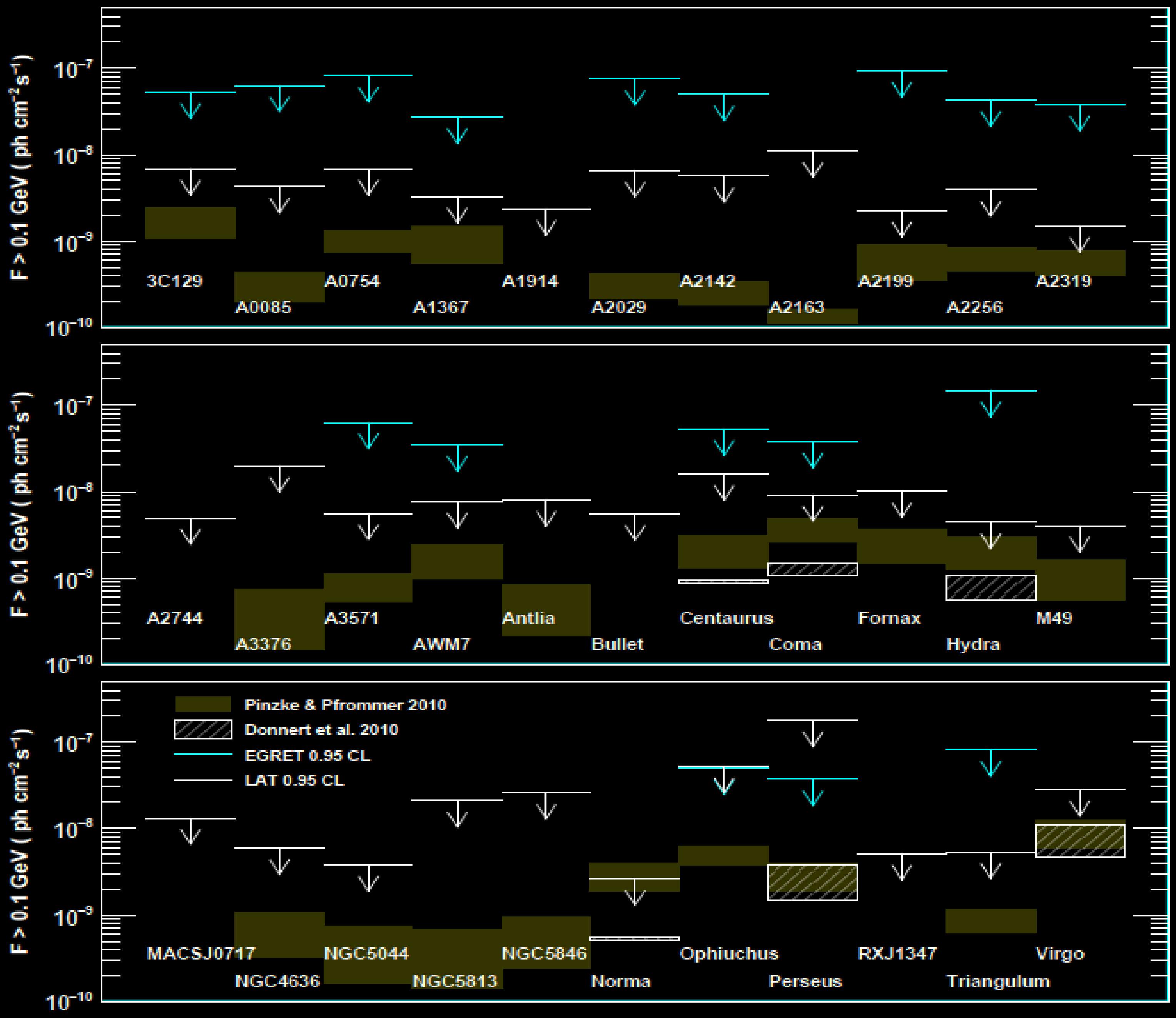
Ophiuchus, Fornax, Coma, Perseus, Norma, Centaurus, …

…anticipation of AGN-related prominence in clusters

(NGC1275: Abdo et al. 2009,
M87: Abdo et al. 2009)…



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



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

- disfavors lepton acceleration efficiencies in intracluster shocks > 0.001

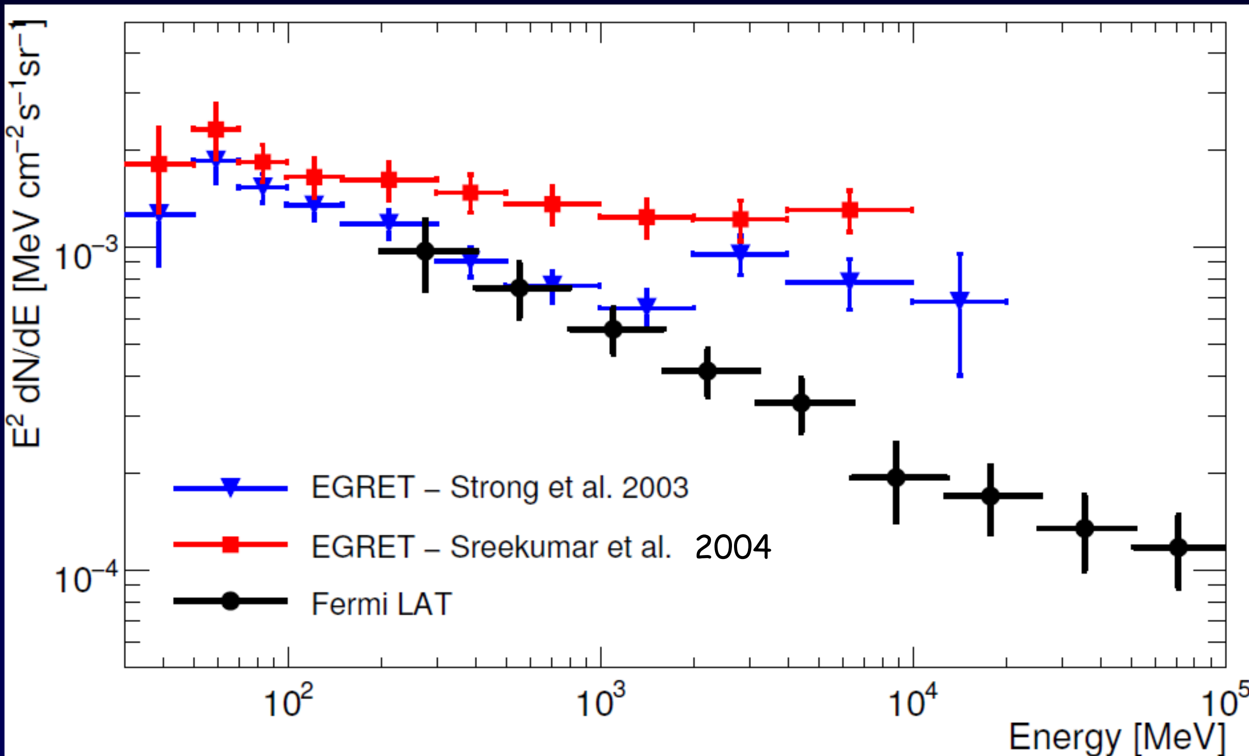
- agrees with radio halo limits placed from constraints on secondary electrons (Brunetti et al. 2007, Churazov et al. 2008)

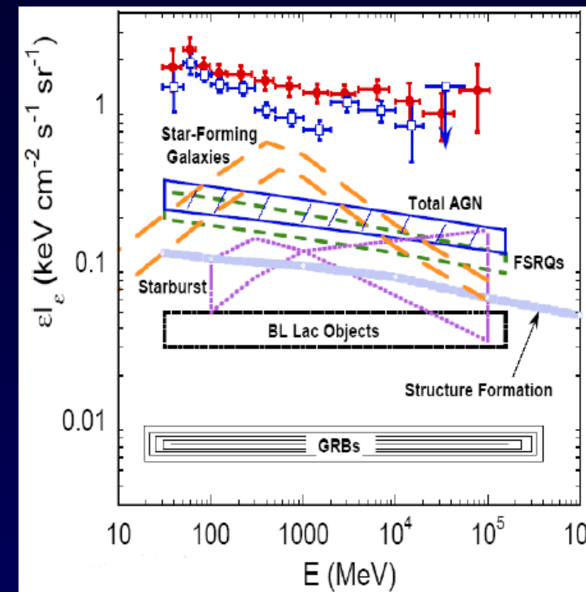
- volume-averaged CR-hadron-to-thermal energy density

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

  constrained to < 4-10% in many different cases

Is there a cumulative imprint from galaxy clusters in the EGDB?





Dermer 2007

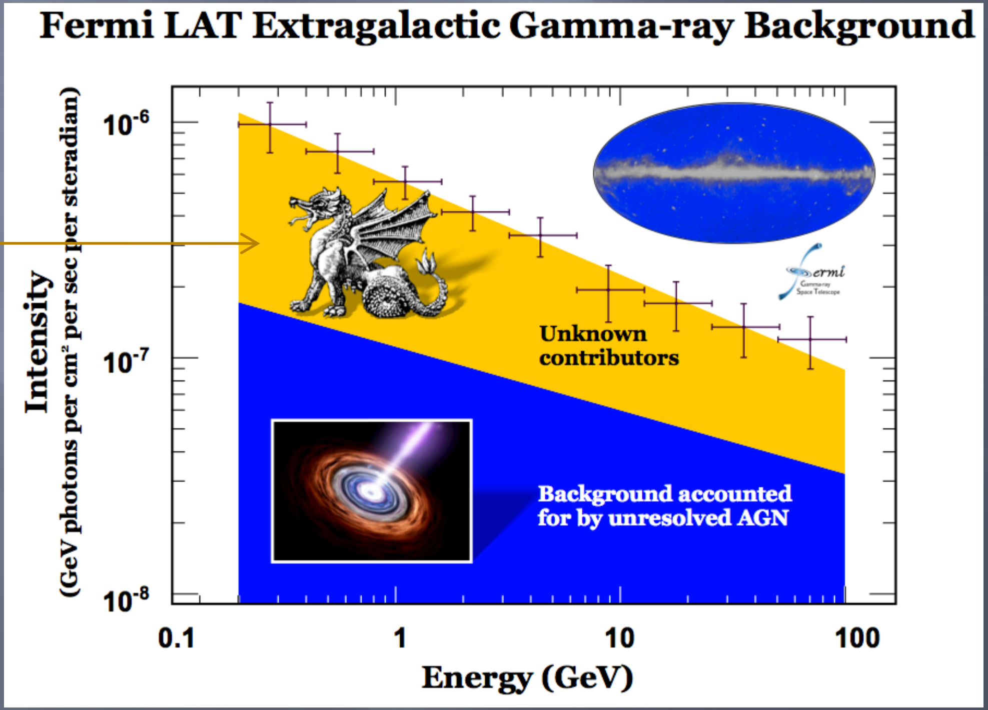
	Flux, E>100 MeV	spectral index
LAT (Abdo et al. 2010)	**1.03 +/- 0.17**	**2.41 +/- 0.05**
EGRET (Sreekumar et al. 1998)	1.45 +/- 0.05	2.13 +/- 0.03
EGRET (Strong Moskalenko Reimer 2004)	1.11 +/- 0.10	
LAT + resolved sources below EGRET sensitivity	1.19 +/- 0.18	2.37 +/- 0.05
	x 10^{-5} cm^{-2} s^{-1} sr^{-1}	

We're left with 70% unknowns in the EGDB

- LAT EGB in the 0.2-100 GeV band: consistent with $E^{-2.4}$
- Blazars account for no more than 30% of the EGB
- BL Lacs dominate emission above 10 GeV
- 70% of the EGB currently unexplained :

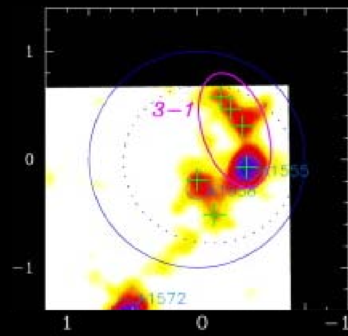
Where are the bright new ideas for that?
(we had already LSSF/GC, GRB, DM, SFG, RG)

NASA PressRelease "Dragons"



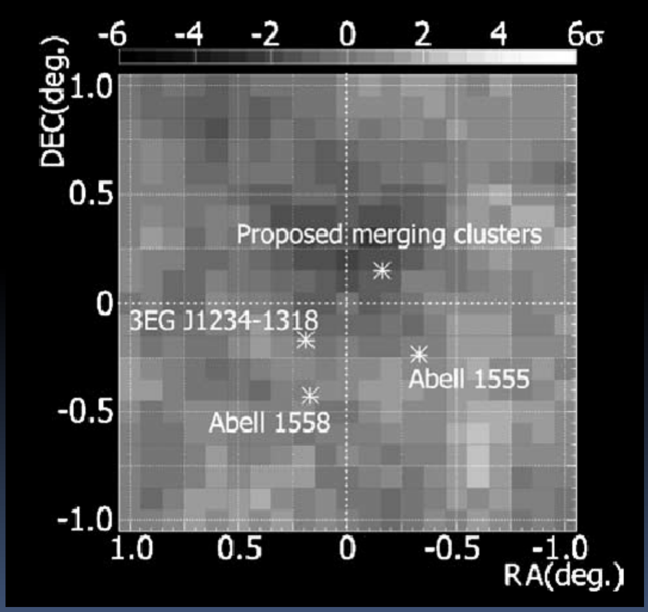
IACT observations of galaxy clusters

Cangaroo II: 3EG J1234-1318/APMcat cluster (Hattori & Nishijima 2005)



Kawasaki & Totani 2002
Follow-up of EGRET high-lat UNIDs

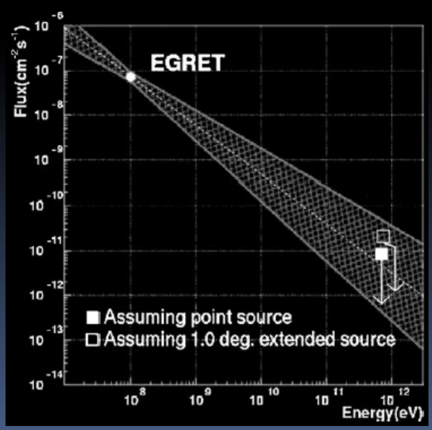
A1558 & A1555, (A1572)



significance map E > 700 GeV

$8.3 \times 10^{-12}\ cm^{-2}\ s^{-1}$ for E > 700 GeV and point source

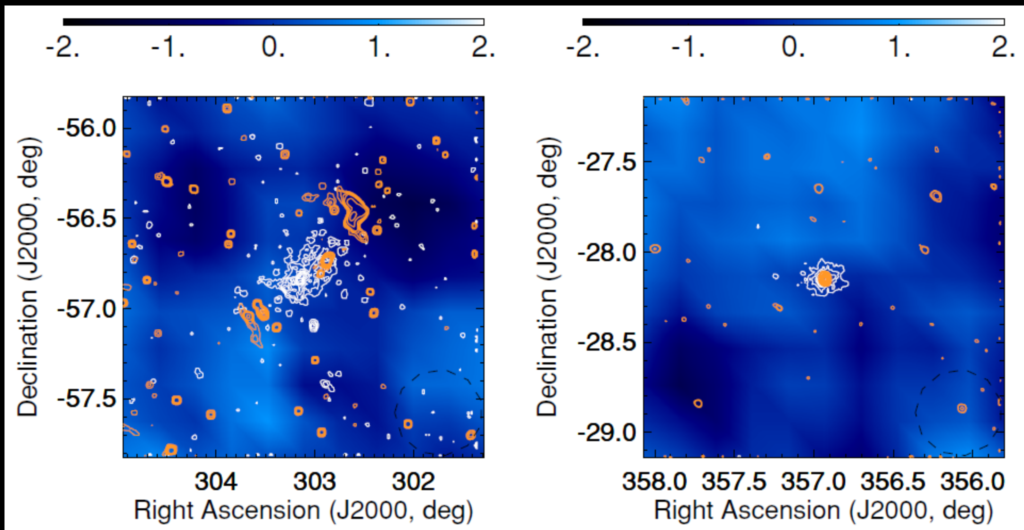
$2.1 \times 10^{-11}\ cm^{-2}\ s^{-1}$ *for E > 750 GeV and* 1° extended source

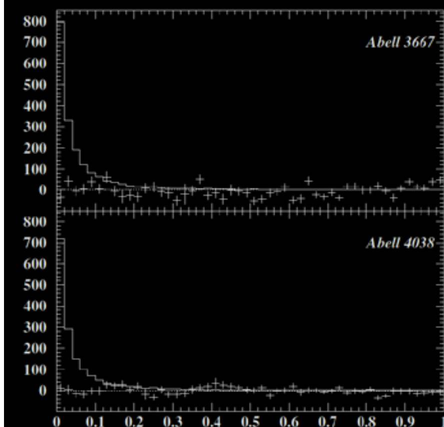


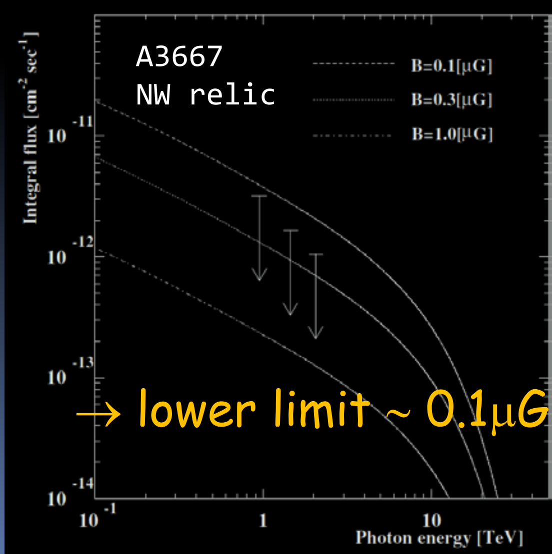
$B \leq 0.1\ \mu G$
(from E_{max} electrons)

IACT observations of galaxy clusters

Cangaroo III: Abell 3667, Abell 4038 (Kiuchi et al. 2008)

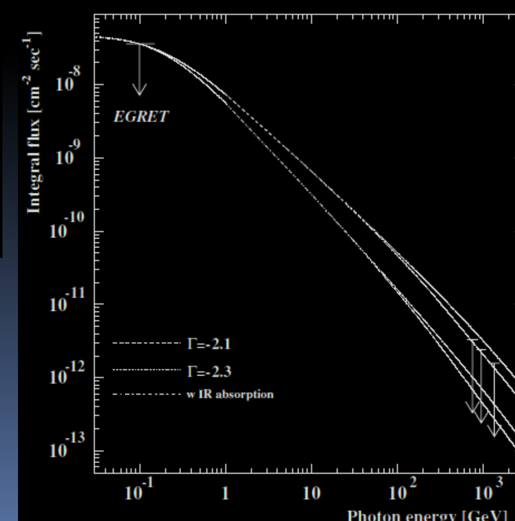






→ lower limit ~ 0.1μG

Region		2σ Upper Limit[a] (cm^{-2} s^{-1})	Magnetic Field (μG)	Energy Density (eV cm^{-3})
A3667 *NW Relic*		3.19×10^{-12}	>0.1	...
A3667 *SE Relic*		5.69×10^{-12}	>0.1	...
A3667 *Cluster Core*	I.[b]	5.52×10^{-12}	...	<20
	II.[c]	2.03×10^{-12}	...	<40
A4038 *Cluster Core*		3.30×10^{-12}	...	<40

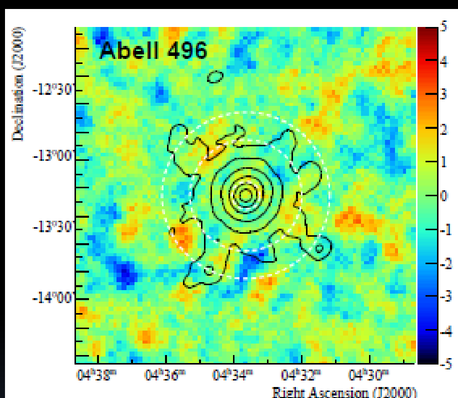


IACT observations of galaxy clusters

H.E.S.S.: A496, A85 (Aharonian et al. 2009a)

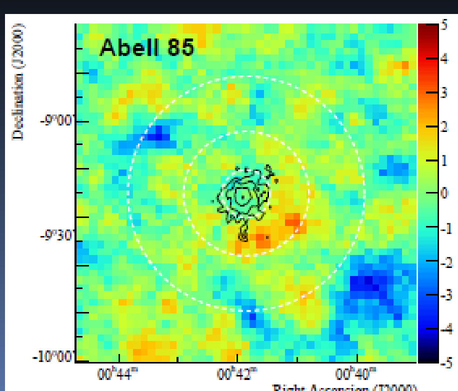
strategy: A496 – nearby relaxed cooling core cluster, central high gas $t_{cool} < t_H$, favorable for hadronic gamma-ray production, southern object, REFLEX: Fx/Rx -> Fγ-brightness scaling (~15h)

A85 – accretion power scaling $M^{5/3}$ (Gabici & Blasi 2003, 2004) , converted to accretion flux via d^{-2}, source extension in complex morpholog: two subcluster but one has cooling core (~33h)



Abell 496

Analysis	Radius [°]	Radius [Mpc]	E_{th} [TeV]	Assumed Γ	$F_{\rm ul}(>E_{th})$ [10^{-12} ph. cm^{-2} s^{-1}]	$F_{\rm ul}(>E_{th})$ [% Crab flux]
Core	0.1	0.2	0.57	2.1	0.48	0.9
				2.3	0.52	1.0
1 Mpc	0.4	1.0	1.0	2.1	0.72	3.2
				2.3	0.75	3.3
Extended	0.6	1.4	0.57	2.1	2.4	4.6
				2.3	2.6	5.0
Very extended	1.5	3.5	0.57	2.1	5.8	10.9
				2.3	6.2	11.7



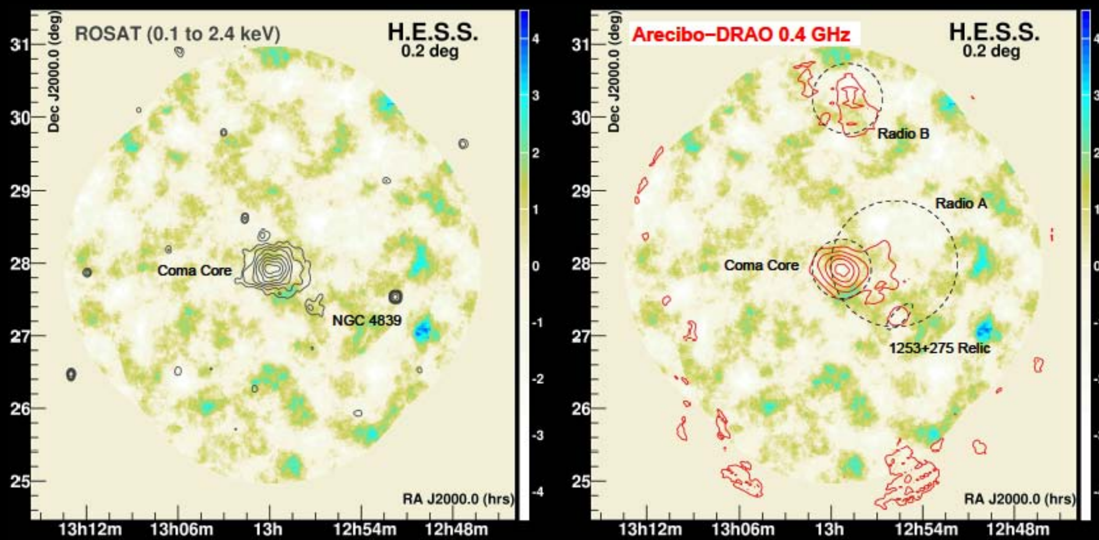
Abell 85

Analysis	Radius [°]	Radius [Mpc]	E_{th} [TeV]	Assumed Γ	$F_{\rm ul}(>E_{th})$ [10^{-12} ph. cm^{-2} s^{-1}]	$F_{\rm ul}(>E_{th})$ [% Crab flux]
Core	0.10	0.4	0.46	2.1	0.39	0.5
				2.3	0.41	0.6
95% X-ray containment	0.13	0.5	0.46	2.1	0.34	0.5
				2.3	0.36	0.5
1 Mpc	0.26	1.0	1.0	2.1	3.2	1.4
			1.0	2.3	3.3	1.4
Extended	0.49	1.9	0.46	2.1	1.5	2.0
				2.3	1.6	2.2
Very extended	0.91	3.5	0.46	2.1	9.9	13.6
				2.3	11.0	15.1

IACT observations of galaxy clusters

H.E.S.S. Coma (A1656) (Aharonian et al. 2009b)

strategy: no need to elaborate, ~8h exposure probably need some explanation



Name	^{3}S [σ] ($E>1,5,10$ TeV)			Flux U.L. $^{4}\Phi^{99\%}$ ($E>1,5,10$ TeV)		
Coma Core	-0.5	-1.2	-1.4	6.1	0.3	0.1
	+0.4	-0.4	-0.6	10.8	0.9	0.5
	+1.1	-0.5	-1.5	25.5	1.7	0.6
1253+275-Relic§	+1.3	+2.0	+1.0	15.9	2.6	1.2
Radio-A	+2.0	-2.2	-2.0	78.7	2.3	1.4
Radio-B	+2.5	+0.7	+0.0	77.8	7.0	3.4
NGC 4839	+0.4	+1.7	+1.2	9.0	1.9	1.0
	-1.8	+0.3	+0.1	6.7	2.0	1.3

Constraints† on the ratio of CR (non-thermal) to thermal energy (E_{CR}/E_{th}) for the Coma cluster core region (within two radii) and assumed cosmic-ray distribution models A and B

Radius	α	Model	$\eta = E_{CR}/E_{th}$	E_{CR} [erg]
0.2° (0.33 Mpc)	2.1	A	<0.19	$<7.4\times10^{61}$
0.4° (0.67 Mpc)	2.1	A	<0.18	$<2.5\times10^{62}$
0.4° (0.67 Mpc)	2.1	B	<0.25	$<3.5\times10^{62}$
0.4° (0.67 Mpc)	2.3	A	<0.55	$<7.7\times10^{62}$

† The upper limit for $E>5$ TeV has been used here.

Model A – CR density follows thermal density with $E_{CR}/E_{th} \leq 0.2$

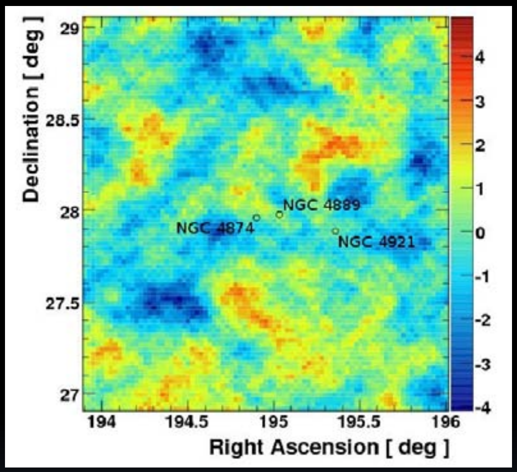
Model B – spatial homogeneous CR density

Limit on η comparable to radio limits but probe CR > 50 TeV instead of < 0.1 TeV (GeV or radio), aim for testing UHE pγ interaction scenario

IACT observations of galaxy clusters

Veritas (Whipple): Perseus, A2029 u.l. (Perkins et al. 2006)
E_{CRp} **<8%** E_{kT} (for Γ = 2.1) -> discussed on MAGIC results

Veritas (Veritas): Coma u.l. (Perkins et al., γ2008) (~20h)



reached ~3% Crab for extended central region

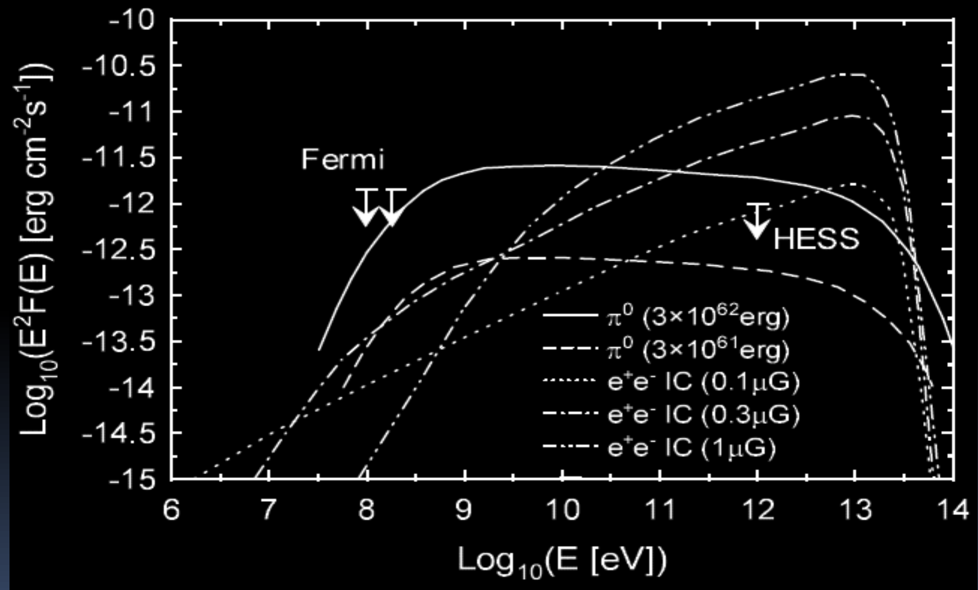
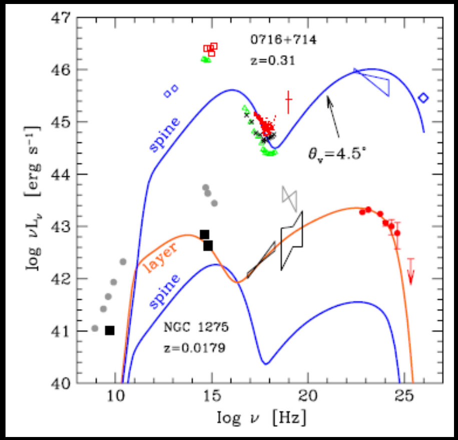


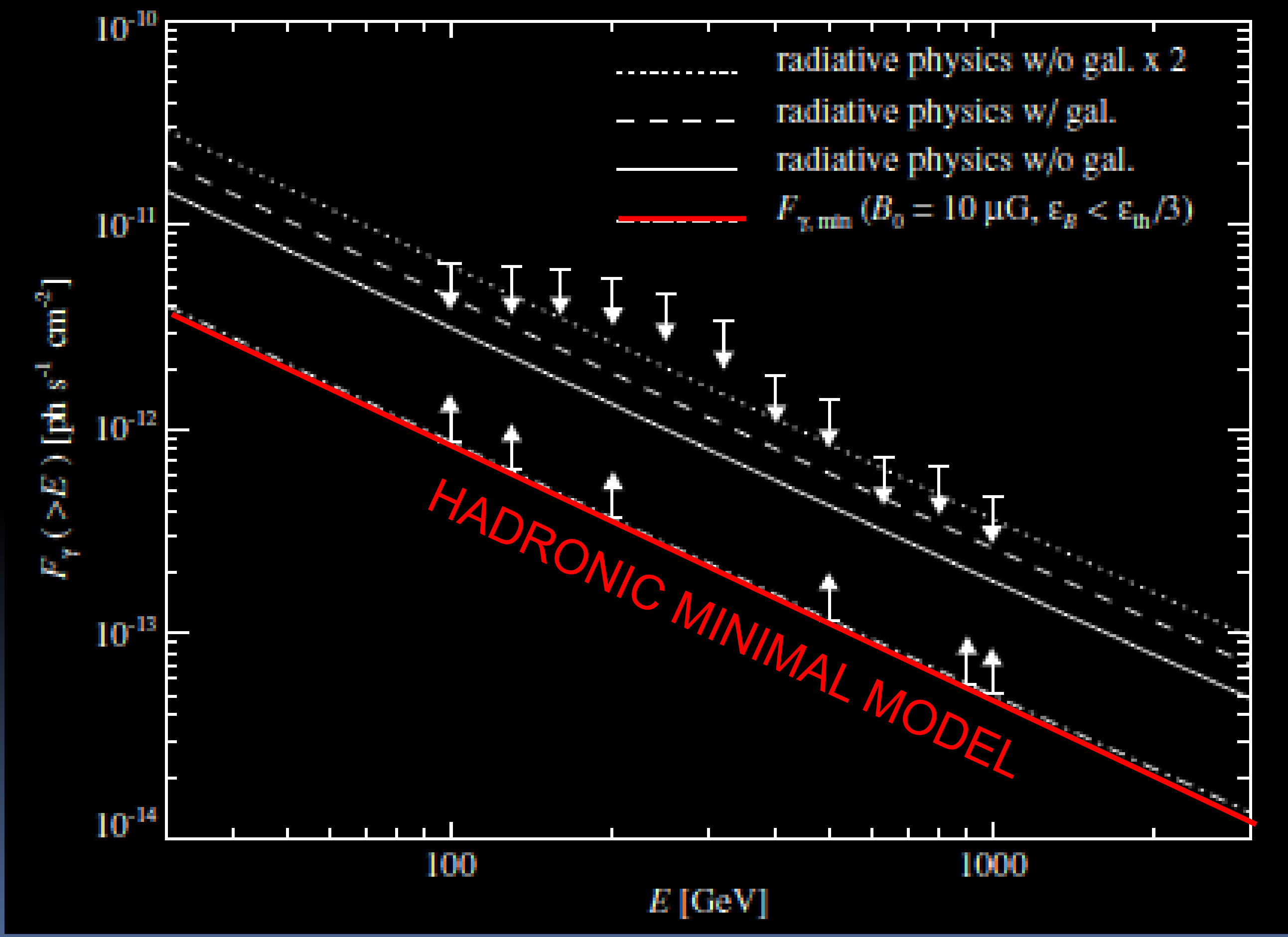
FIG. 8: Model predictions and upper limits on the gamma-ary emission from the Coma cluster. π^0 model curves are taken from Völk and Atoyan [17] and e^+e^- IC from Inoue, Sugiyama and Aharonian [18]. Mori 2009, Fermi Symposium

IACT observations of galaxy clusters

MAGIC Perseus u.l. (Aleksic et al. 2010) E_{CRp} <4%(core) E_{kT} (for Γ = 2.1)
<8%(entire)



NGC1275 : as prominent at TeVs as at GeVs !



IACT observations of galaxy clusters

Deepest survey of any cluster ever made so far at VHE

- MAGIC-I observation

  ~25 h (Nov - Dec 2008)

  Flux upper limits above 100 GeV (*MAGIC Coll., APJ 710, 634, 2010*)

- STEREO observation

  ~40 h (Oct 2009 - Feb 2010)

  Discovery at VHE of IC 310

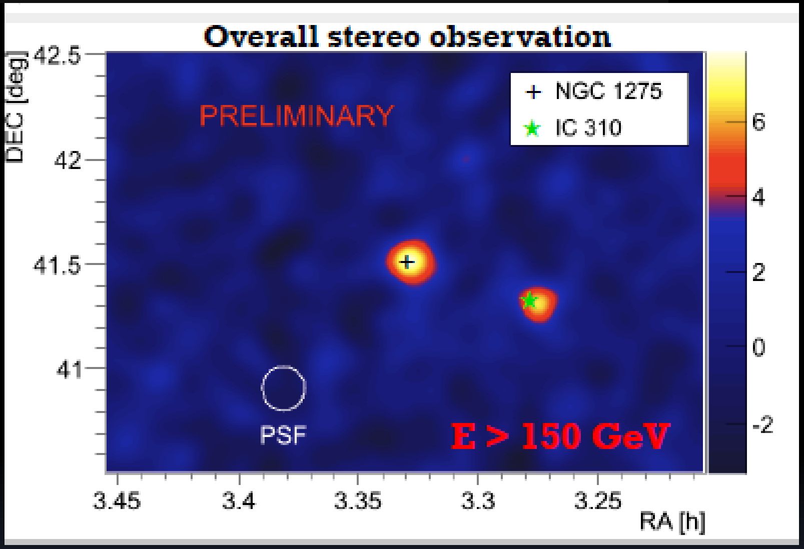
  (*MAGIC Coll., APJ 723, 207, 2010*)

- STEREO observation

  ~45 h (Aug 2010 - Feb 2011)

  Discovery at VHE of NGC 1275

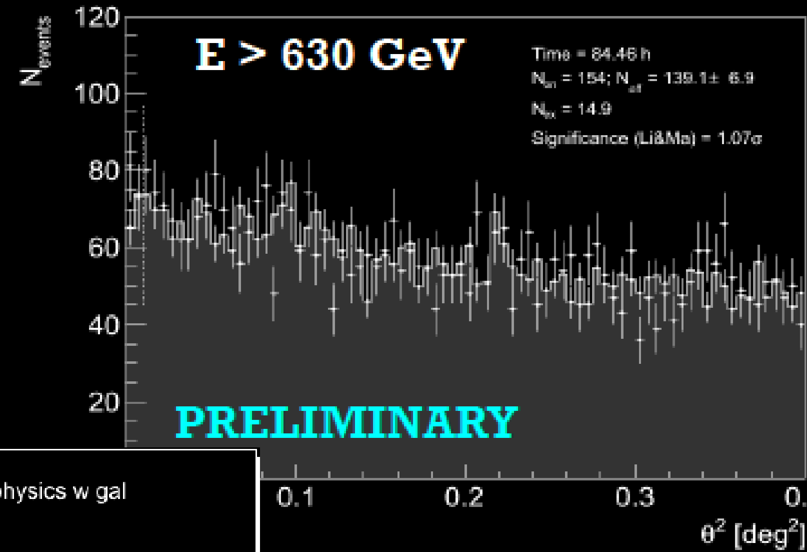
  (*Atel#2916; MAGIC Coll., in preparation*)



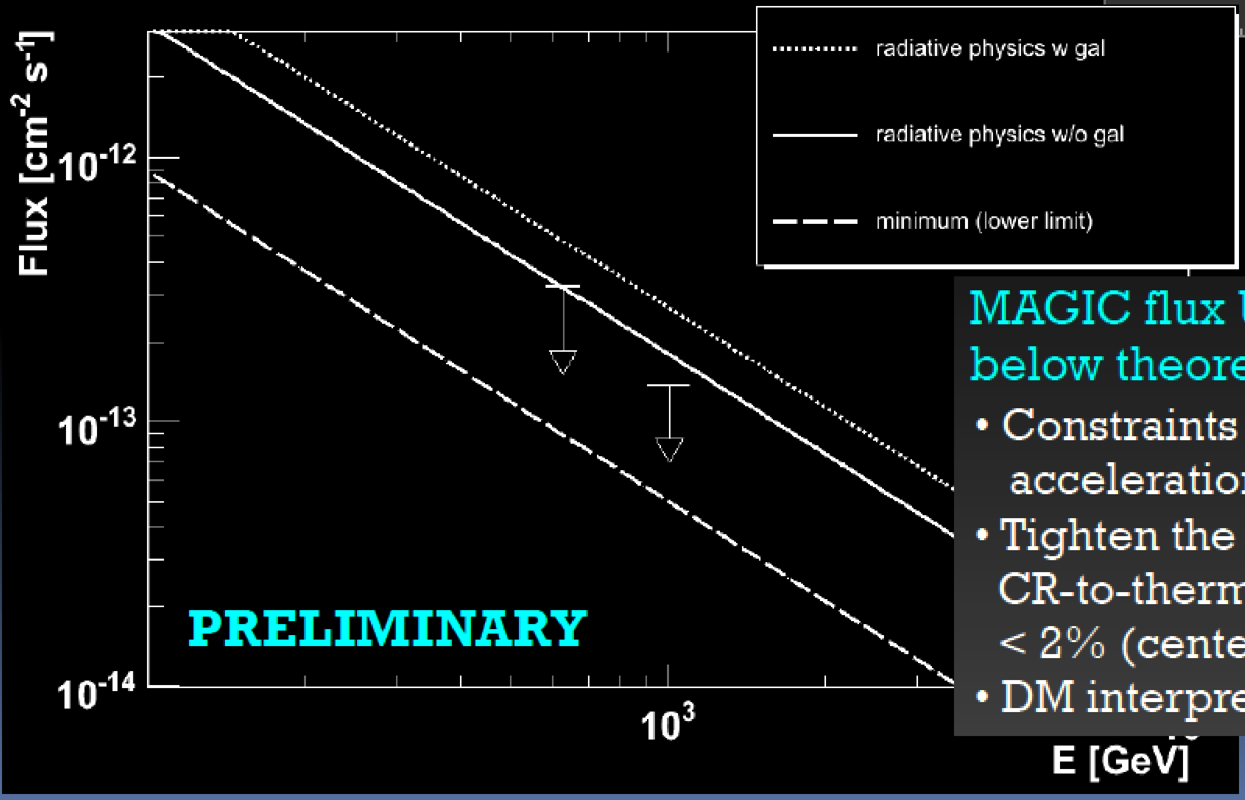
Hildebrand et al. ICRC 2011

IACT observations of galaxy clusters

- ~40 h (Oct 2009 – Feb 2010)
- ~45 h (Aug 2010 – Feb 2011)
- Overall Stereo observation: ~85 h
- CR and DM studies above ~600 GeV (where NGC 1275 is no longer detected)



Lombardi et al. ICRC 2011



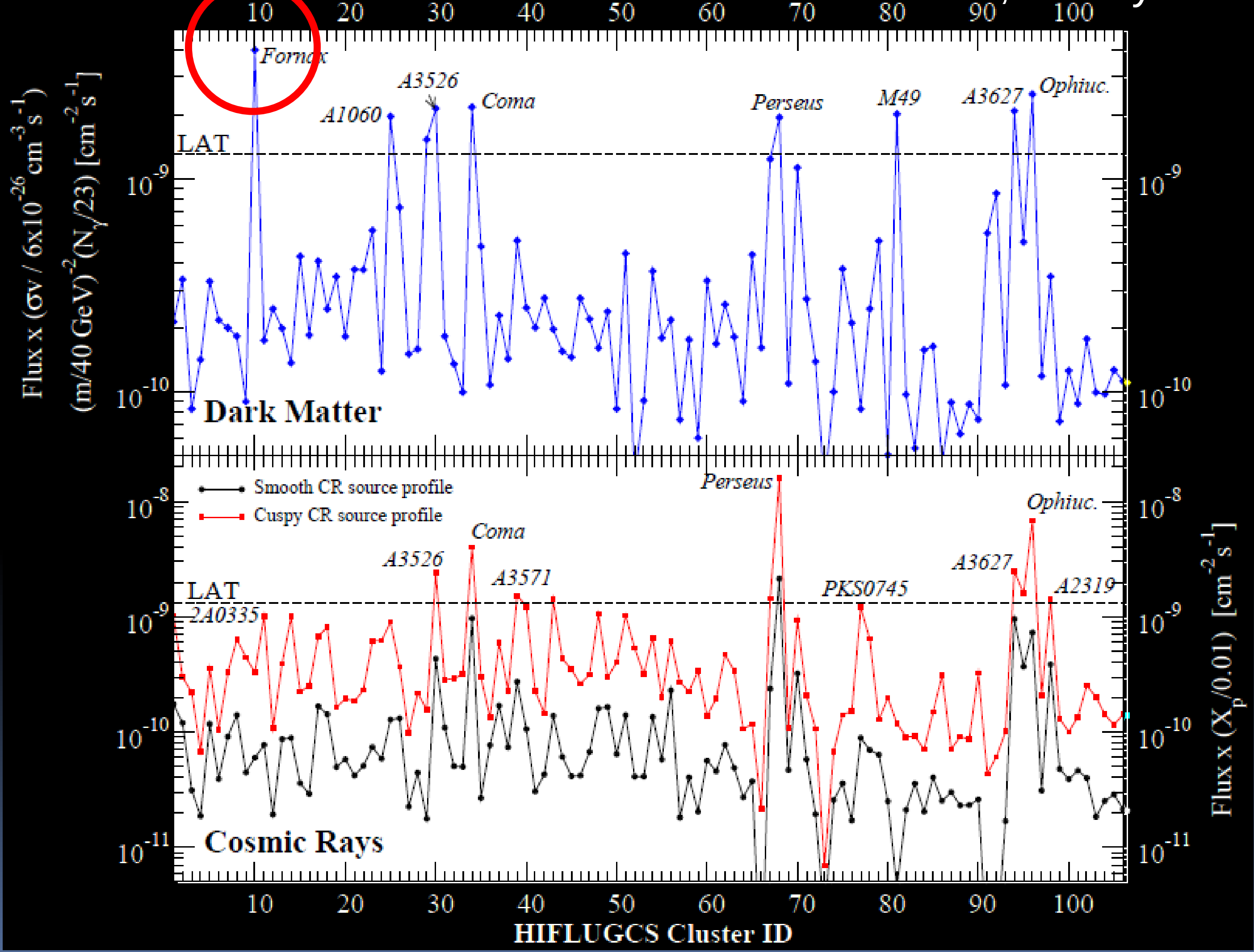
MAGIC flux ULs (95% CL) are below theoretical expectations:

- Constraints on maximum CR acceleration efficiency in simulations
- Tighten the constraints on the CR-to-thermal pressure to < 2% (center) - 4% (whole cluster)
- DM interpretation challenging

IACT observations of galaxy clusters

H.E.S.S.: Fornax (Abrawoski et al. 2011) (~11h)

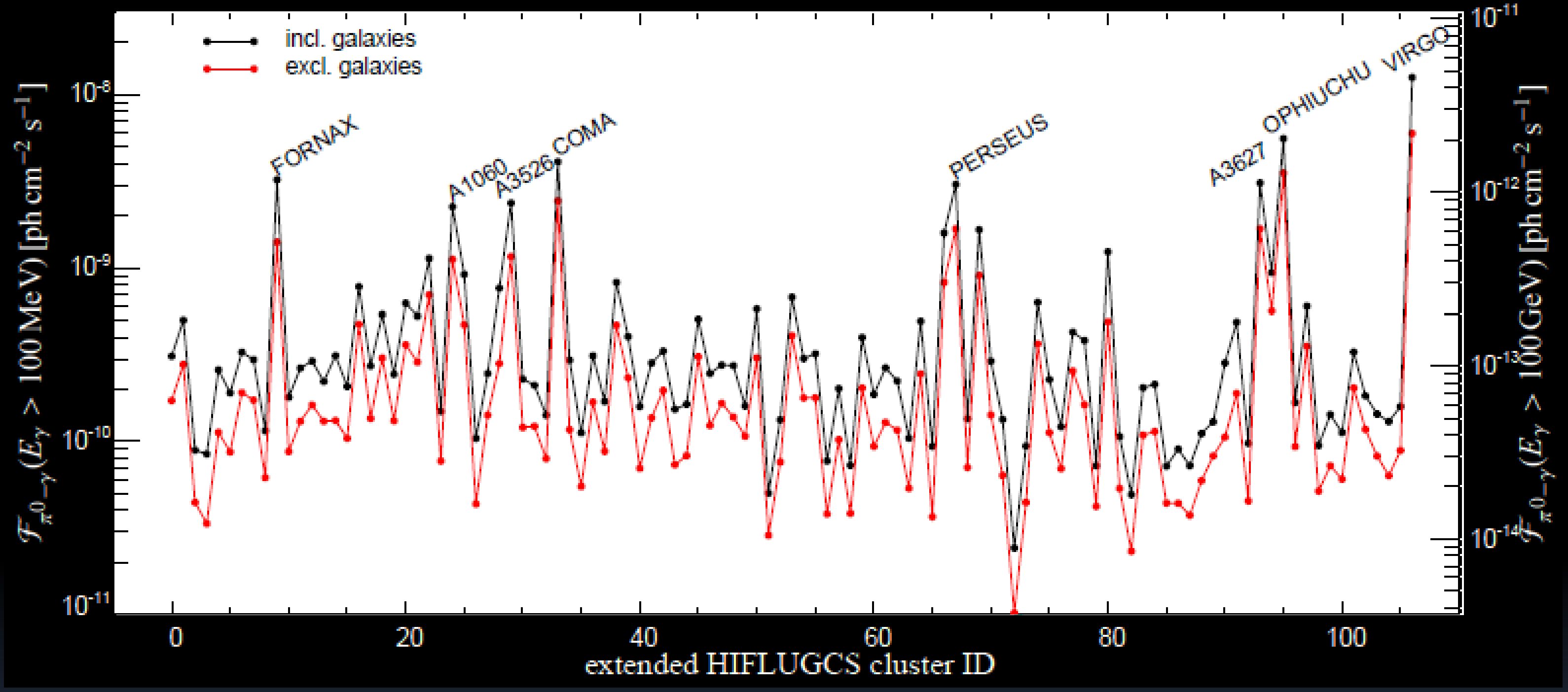
Jeltema, Kehaiyas & Profumo 2009



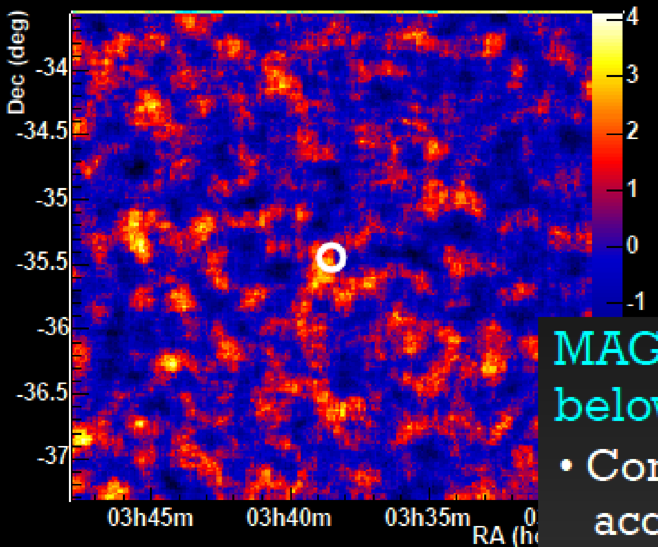
IACT observations of galaxy clusters

H.E.S.S.: Fornax (Abrawoski et al. 2011)

Pinzke & Pfrommer 2010



IACT observations of galaxy clusters



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

MAGIC flux ULs (95% CL) are below theoretical expectations:

- Constraints on maximum CR acceleration efficiency in simulations
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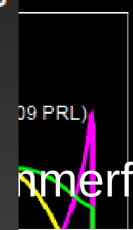
- DM interpretation challenging

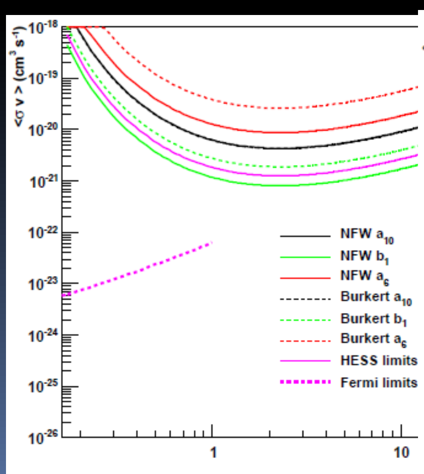
DM focussed interpret

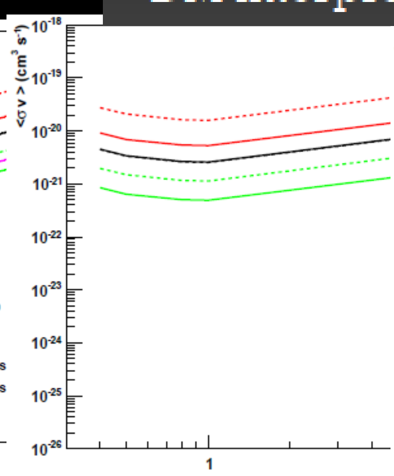
Neutralino DM

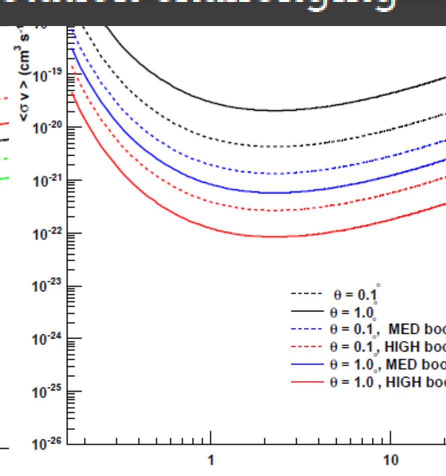
Kl

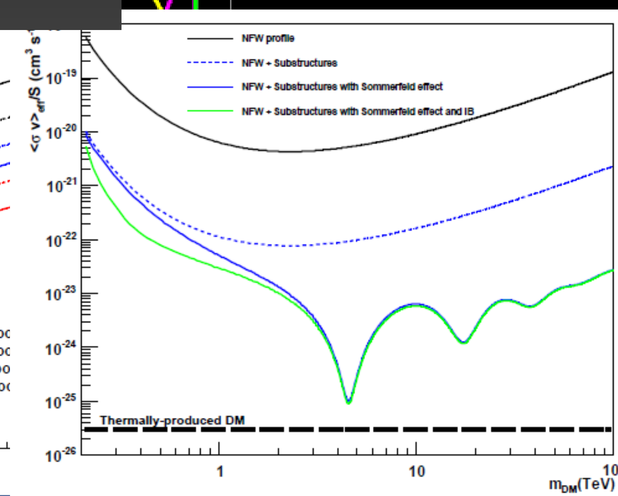


mmerfeld enhancement





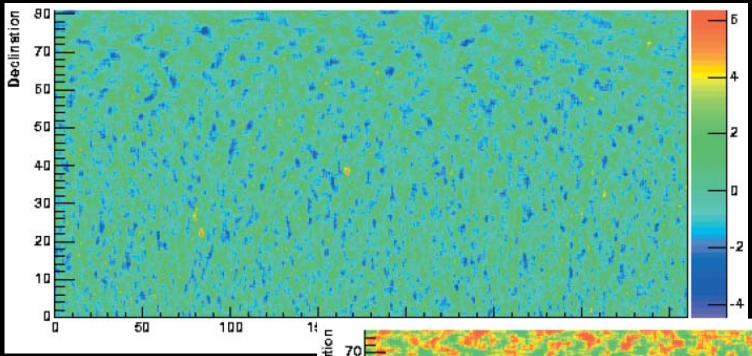




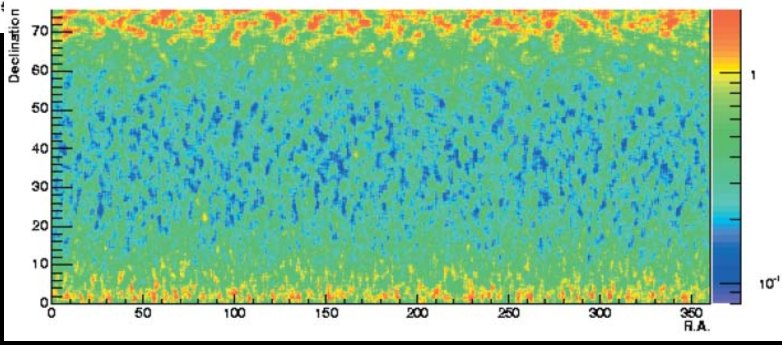
The only non-IACT word as of today

Atkins et al. (Milagro) 2004:

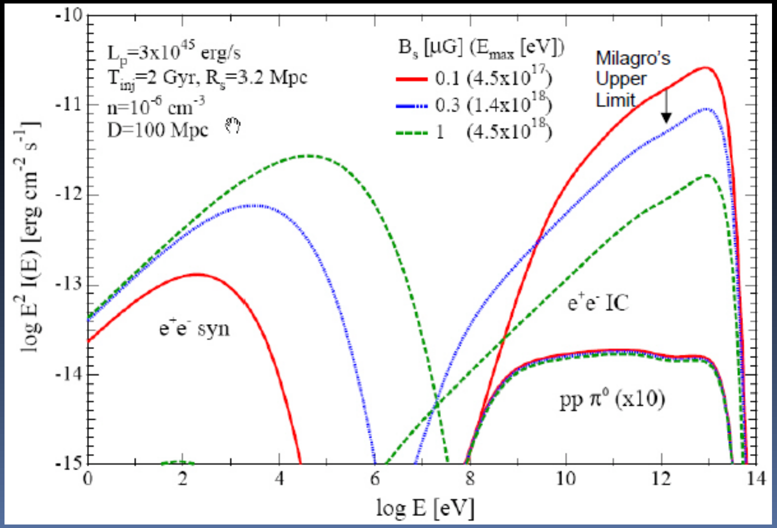
- gamma-ray excess map
- generally 275-600 mCrab u.l.



Dingus et al. (Milagro) 2005:



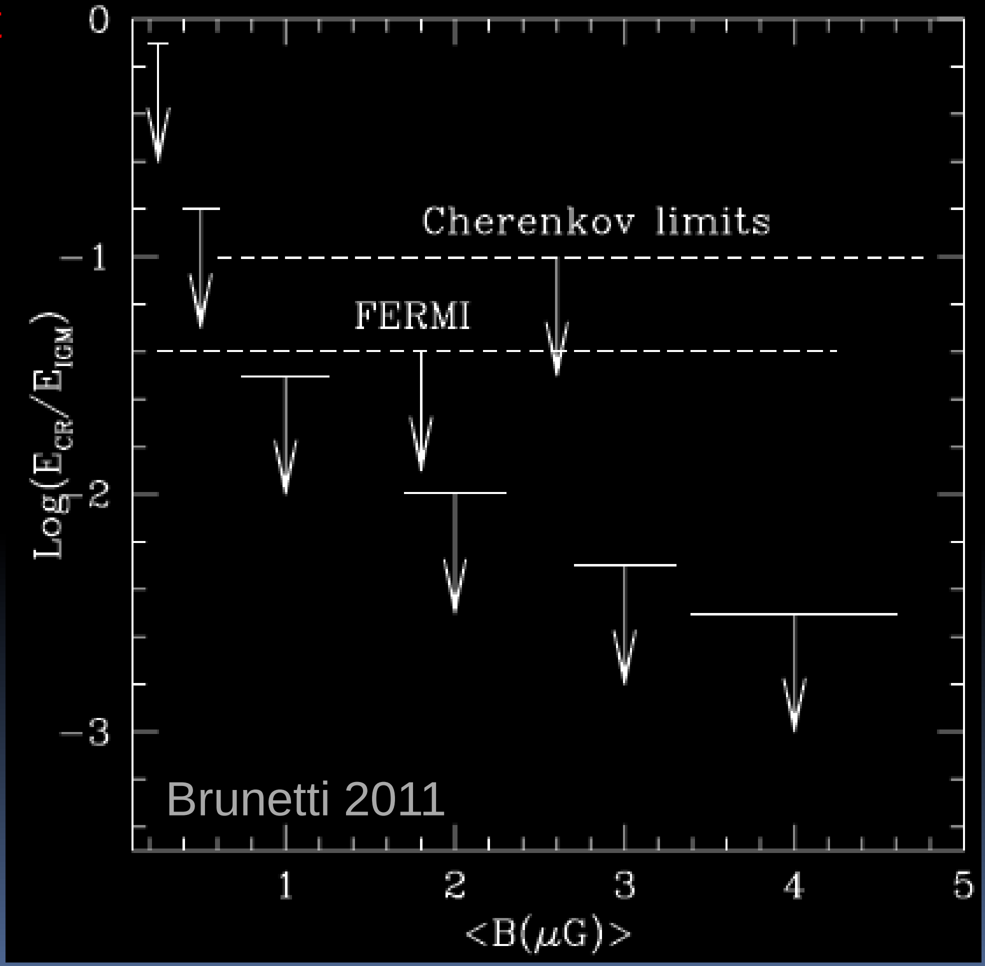
Cluster Characteristic	# of Clusters	Point Source Bin Size of side 2.1°		Larger Bin Size which varies with redshift	
		Statistical Excess *(sigma)*	E^2 dN/dE @ 1 TeV Upper Limit *(ergs/cm^{-2}s^{-1})*	Statistical Excess *(sigma)*	E^2 dN/dE @ 1 TeV Upper Limit *(ergs/cm^{-2}s^{-1})*
Coma Cluster	1	1.8	1.6×10^{-11}	1.2	2.3×10^{-11}
All Clusters	307	0.2	2.0×10^{-12}	1.9	5.1×10^{-12}
All Clusters with x-ray flux>10	52	1.5	5.6×10^{-12}	1.6	9.3×10^{-12}
All Clusters with optical richness ≥ 2	28	1.7	1.0×10^{-11}	2.0	1.6×10^{-11}
All Clusters with redshift<0.04	56	0.9	2.6×10^{-12}	1.6	6.0×10^{-12}



Summary 1st part

No detection of 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

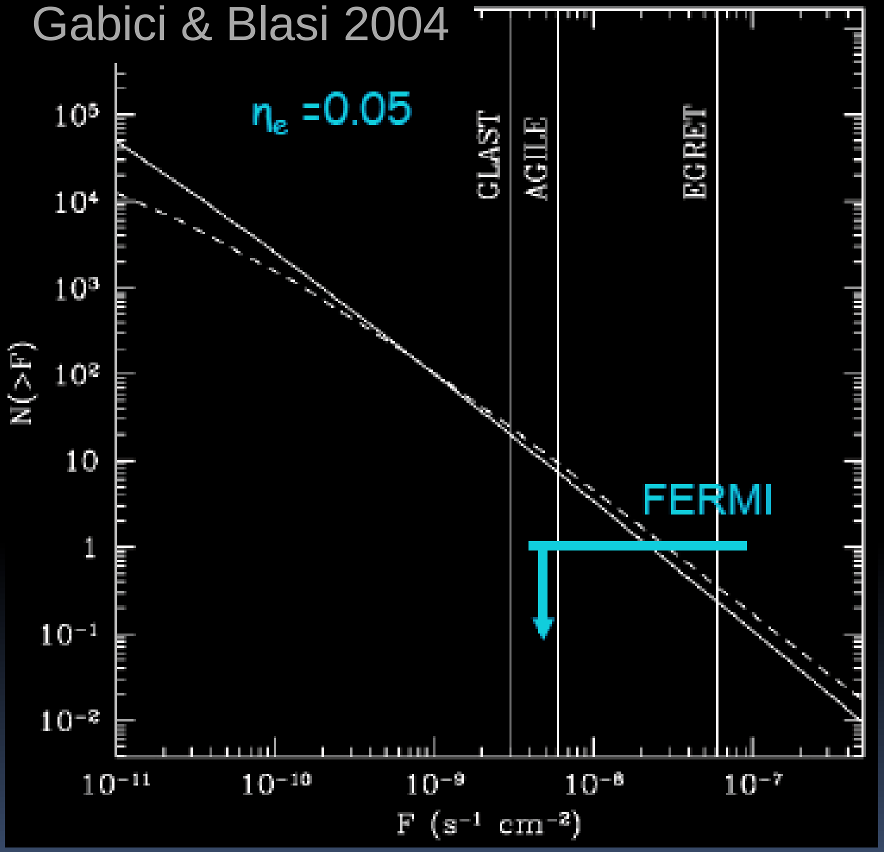


Summary 1st part

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

→ CRe: FERMI upper limits constrain the efficiency of electrons acceleration at shocks in galaxy clusters $\eta_e < 0.001$

Gabici & Blasi 2004



→ UHECRpγ and IC-dominance models are certainly challenged

Summary 1st part

Observation strategy:

We witnessed a change of paradigm in TeV observations!

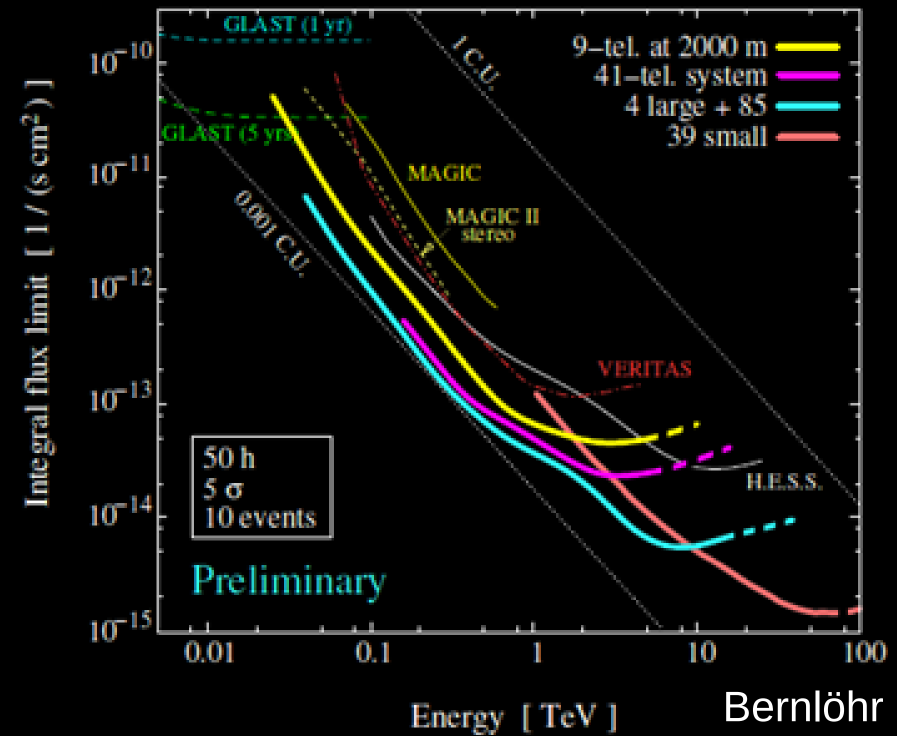
No more fishing with small exposure snapshots (mind small FoV for IACTs)
Why? Fermi-limits on allsky cluster sample (Ackermann et al. 2010)
EGRET limits on allsky cluster sample (Reimer et al. 2003) did not do the trick, with most of the limits about order-of-magnitude in flux less stringent
(mind Perseus / NGC1275, however!)

Focus is rightfully back on archetypal clusters (Coma, Perseus, Fornax)

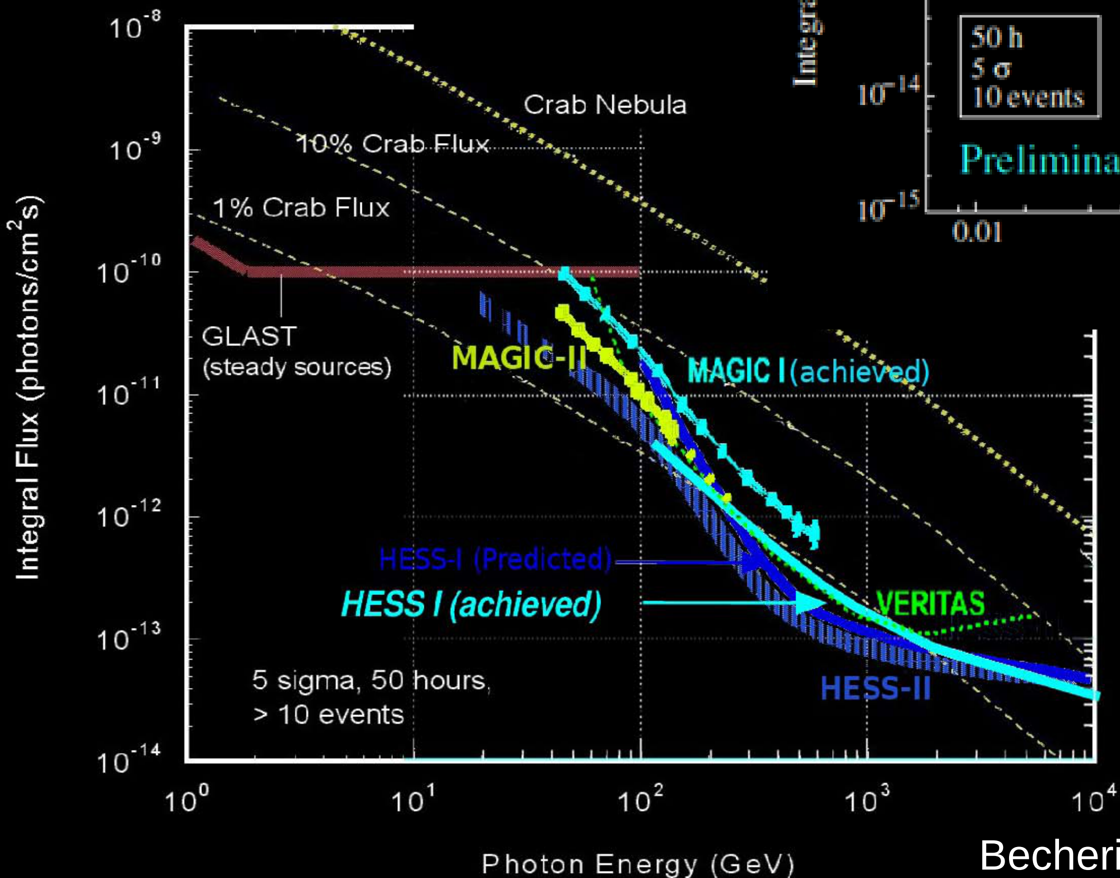
Deep observation made the obs program (as exemplified by MAGIC/MAGIC II) on Perseus.

Therefore the 2nd part will now focus on instruments, sensitivities & expectations.

Talking sensitivities now:

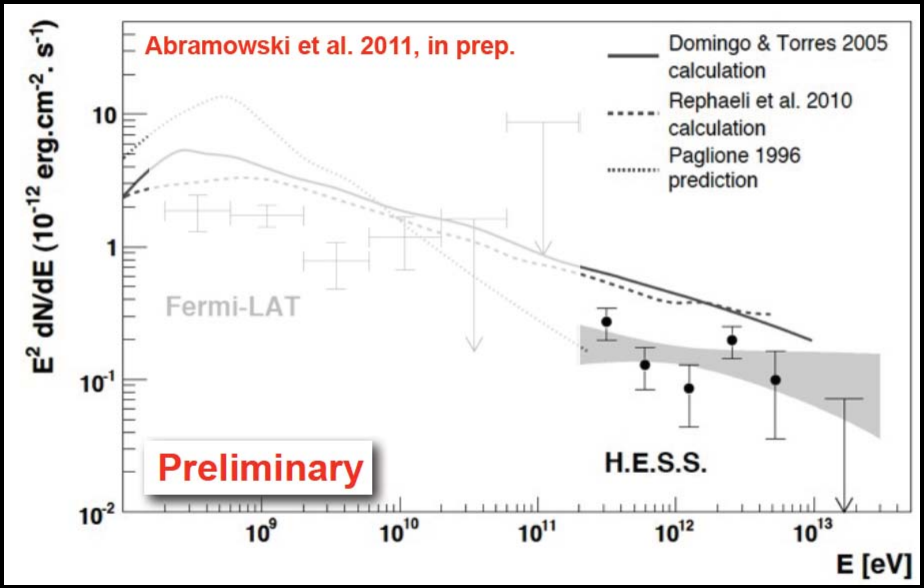


Bernlöhr 2009



Becherini 2009

Weakest TeV detection today: NGC 253



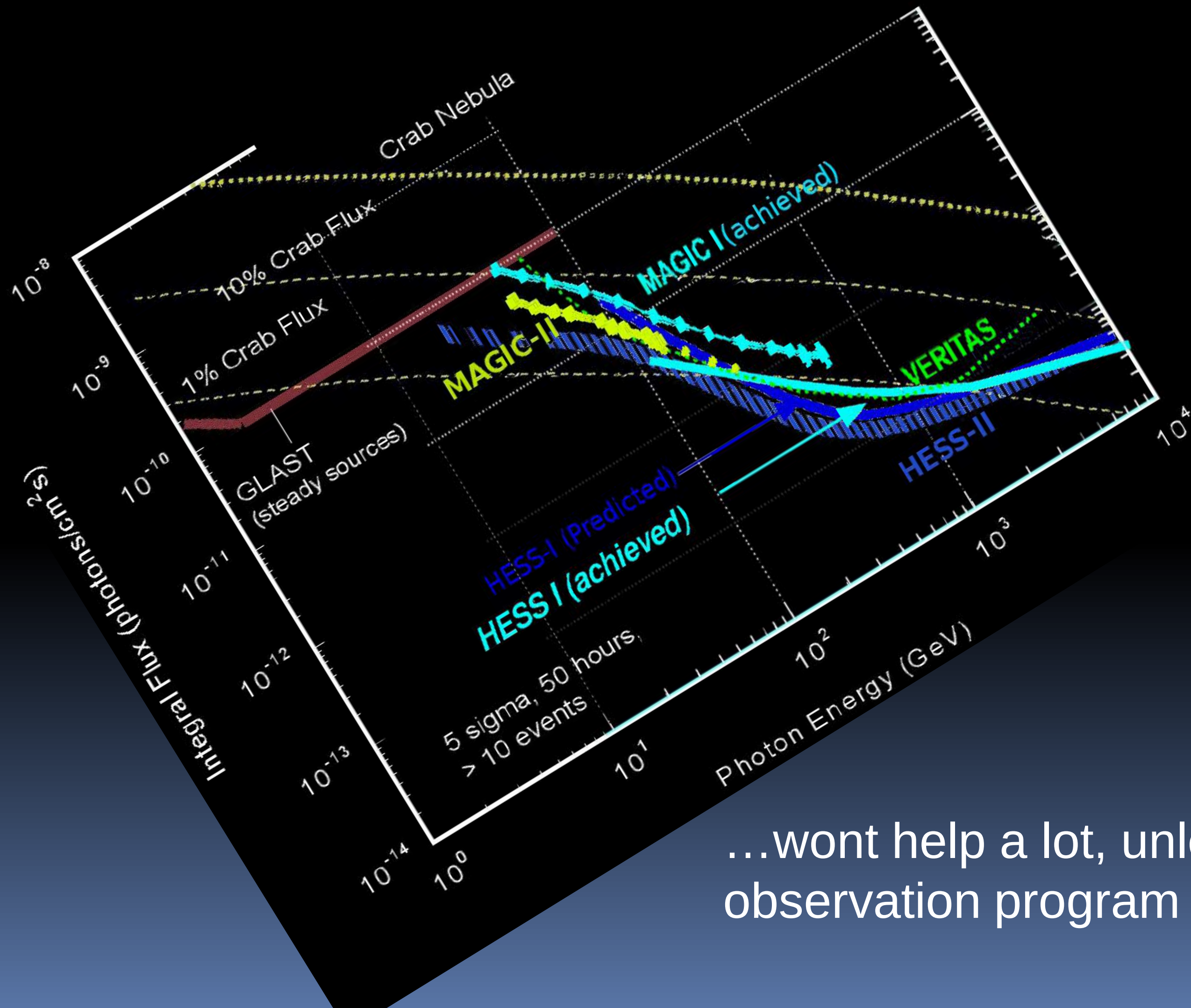
HESS data set comprises 170h of data!

HESS - Spectrum

- $\phi_0 = (0.97 \pm 0.20) \cdot 10^{-13}\ cm^{-2}\ s^{-1}\ TeV^{-1}$
- $\Gamma = 2.14 \pm 0.18_{stat} \pm 0.30_{sys}$
- $F_{>190GeV} = (5.6 \pm 1.2) \cdot 10^{-13}\ cm^{-2}\ s^{-1}$

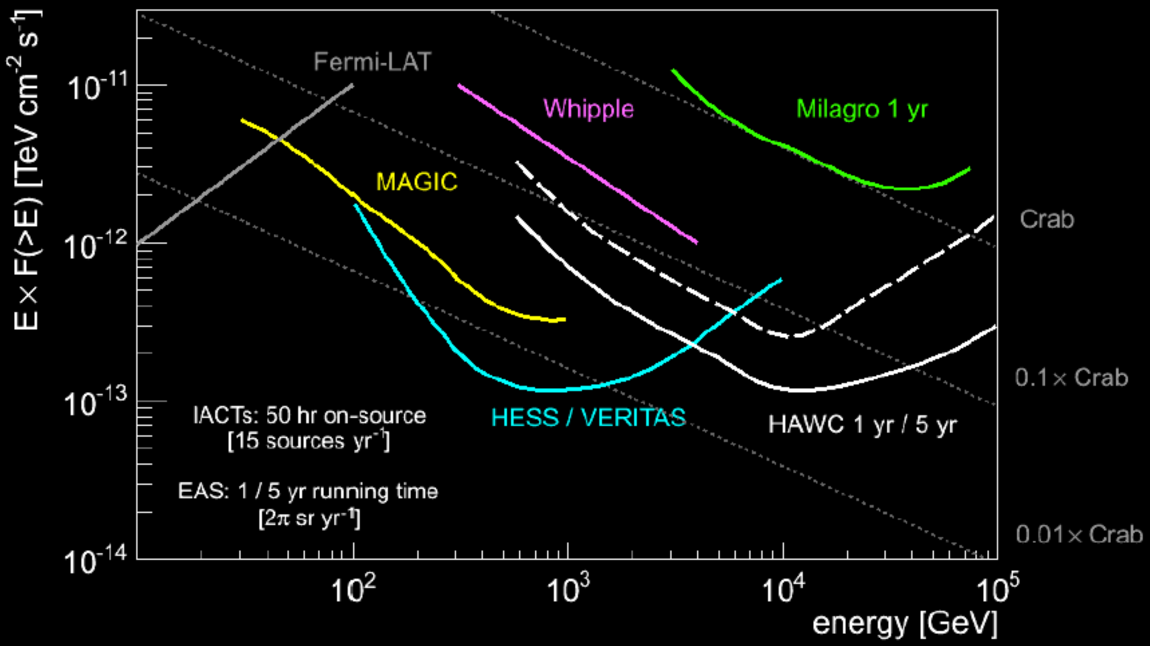
The accomplished depth of observation is at the limit where time allocation constraints, independent verification of analysis, systematic uncertainties and quality of calibration have to be considered simultaneously.

MAGIC-2, HESS-2, VERTIAS PMT upgrade



…wont help a lot, unless an *unusual* observation program is acceptable

Therefore next in line: HAWC



5σ sensitivity:

10 Crab in 3 min

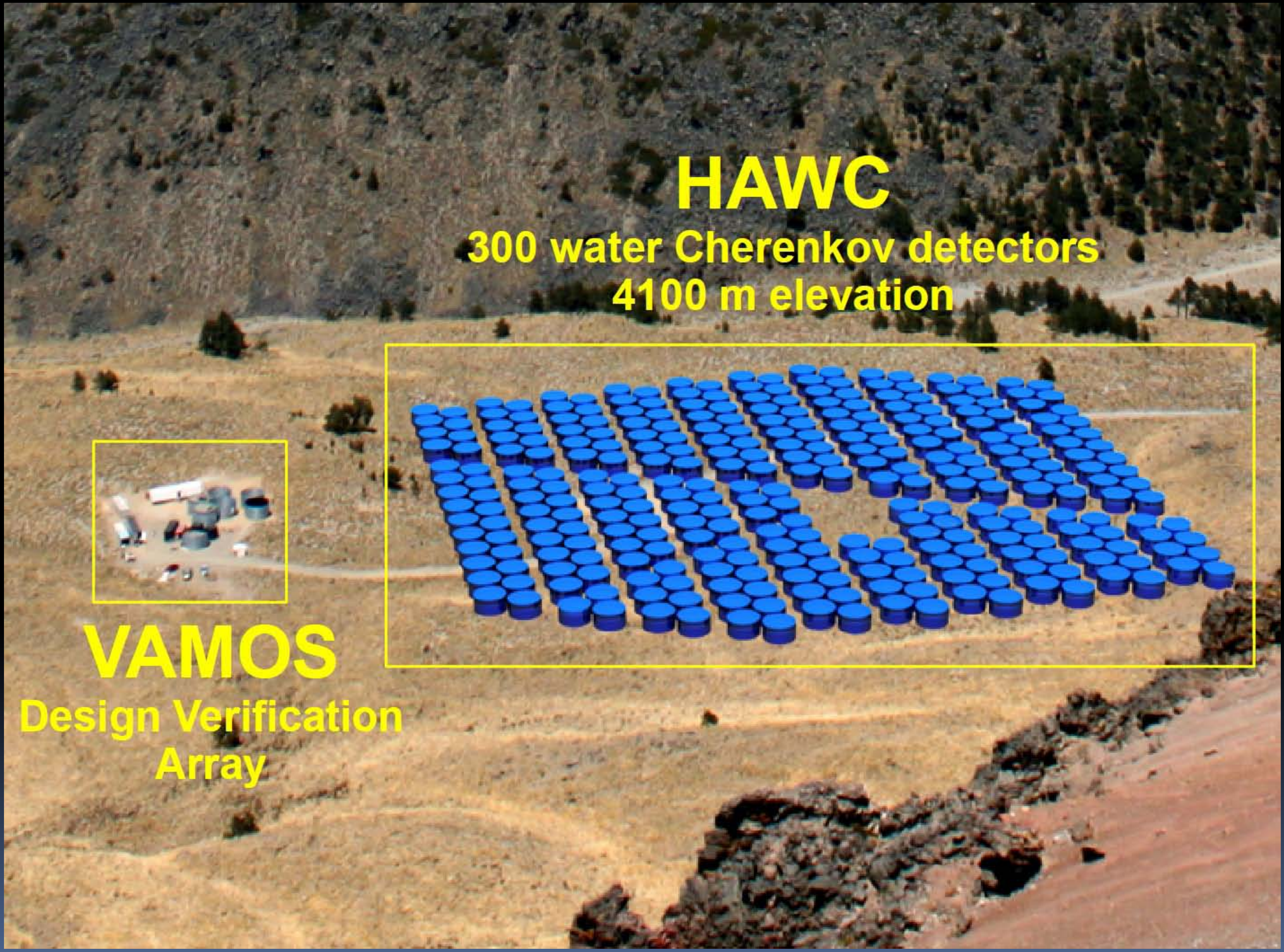
1 Crab in 5 hr

0.1 Crab in 4 months

Continuum sensitivity still behind IACTs, but large field of view.
→ will permanently take data, and on all clusters in hemisphere
→ If performance is stable and relieable, stacking techniques are anticipated to be used

Interesting prospects, but not too exciting for the science case of galaxy clusters

Anticipation of HAWC



Anticipation of HAWC

Schedule

Feb. 2011: Construction began

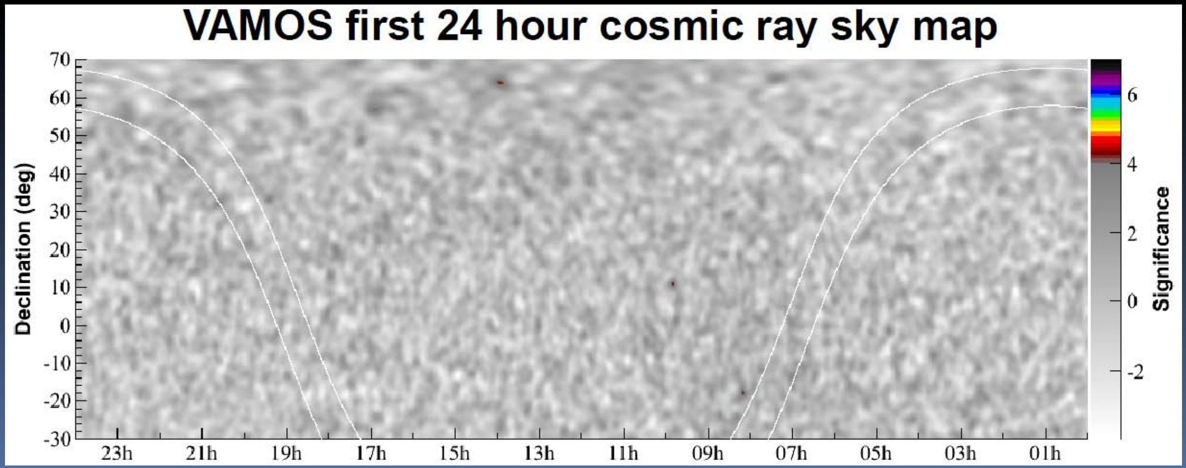
Spring 2012: 30 tanks
Sensitivity comparable to Milagro

Spring 2013: 100 tanks
Begin regular science operations

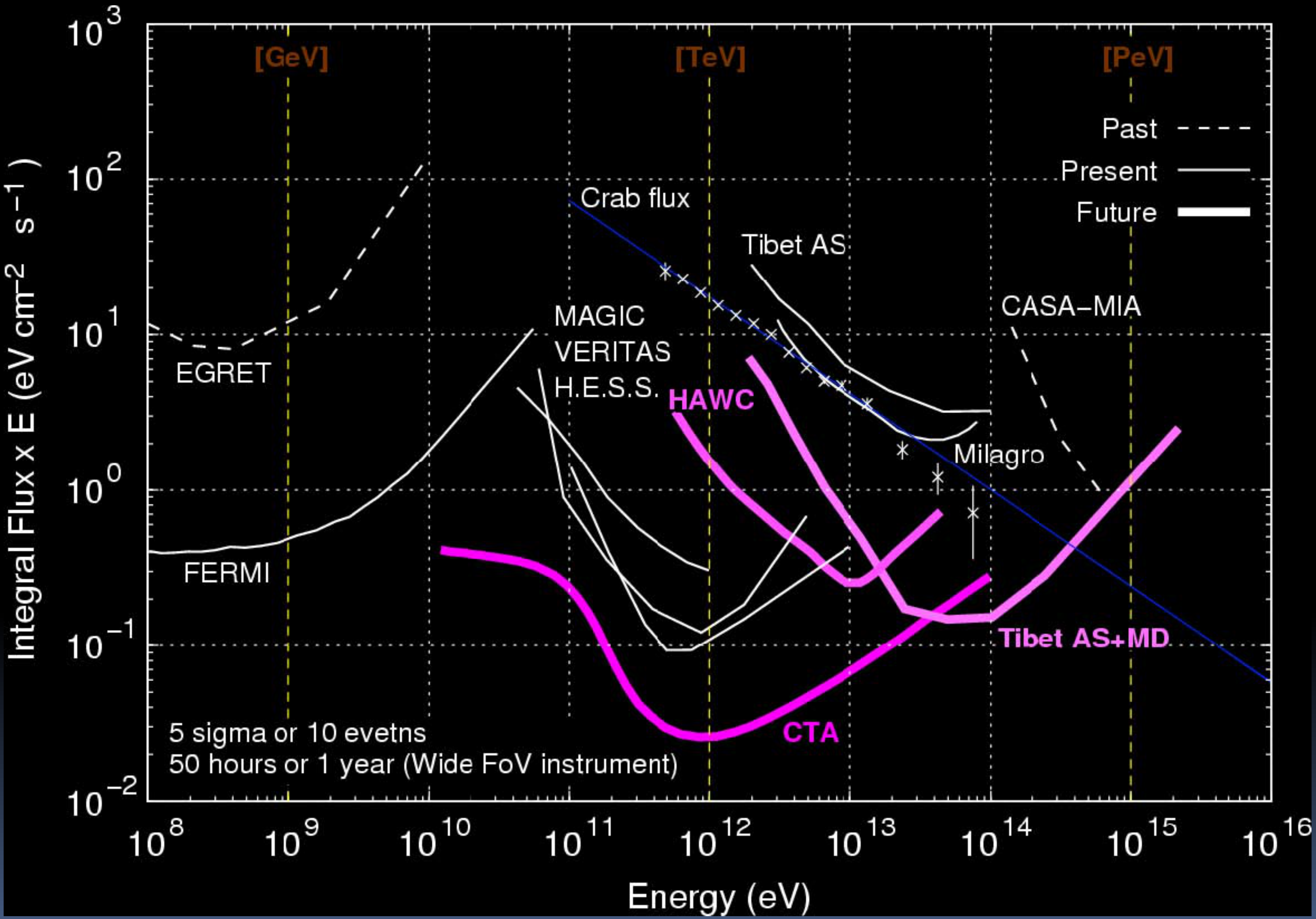
Fall 2014: 300 tanks

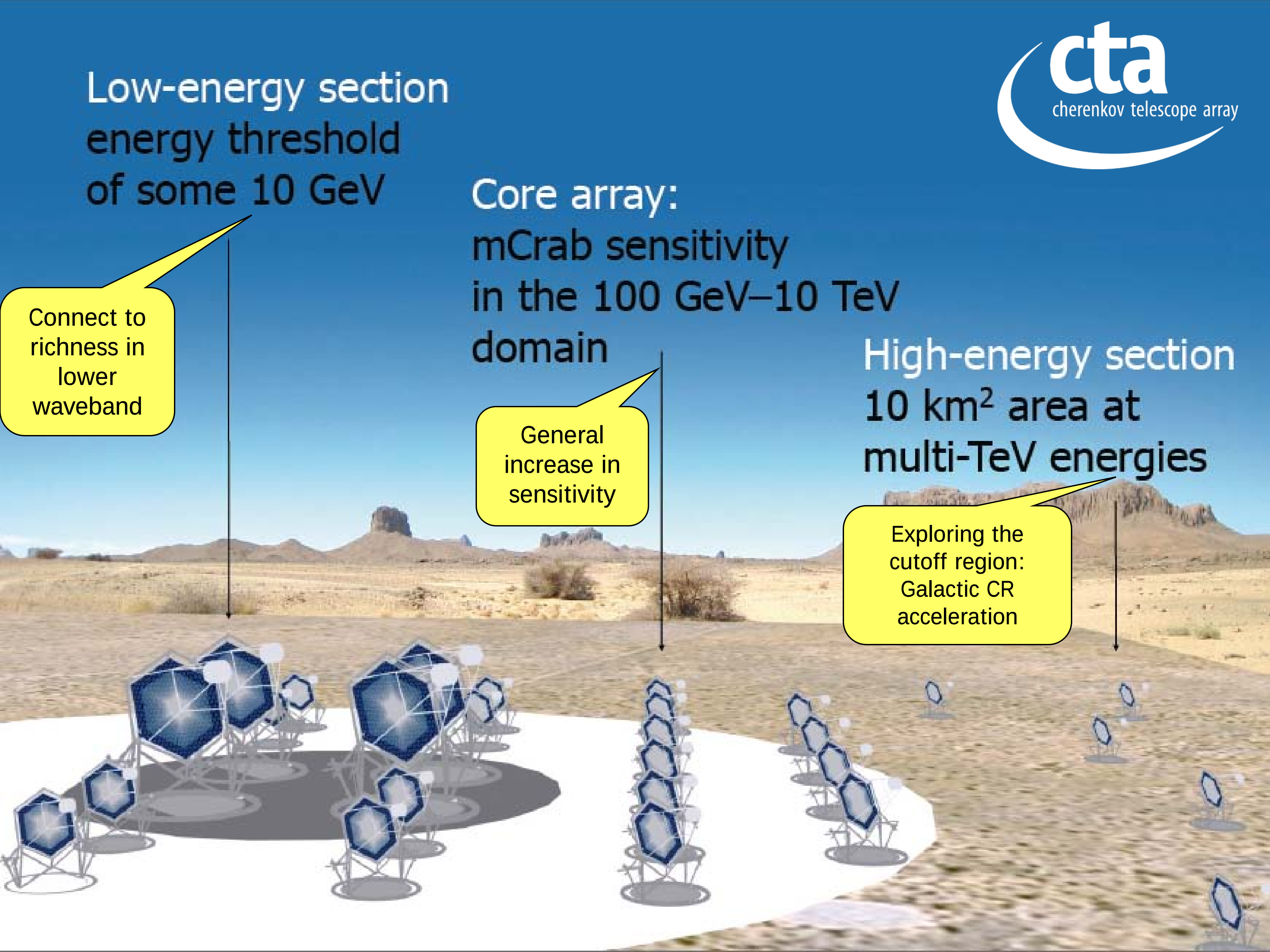
Completed in June 2011

7 tanks; 6 instrumented
36 total PMTs



Ultimatively: Chernkov Telescope Array

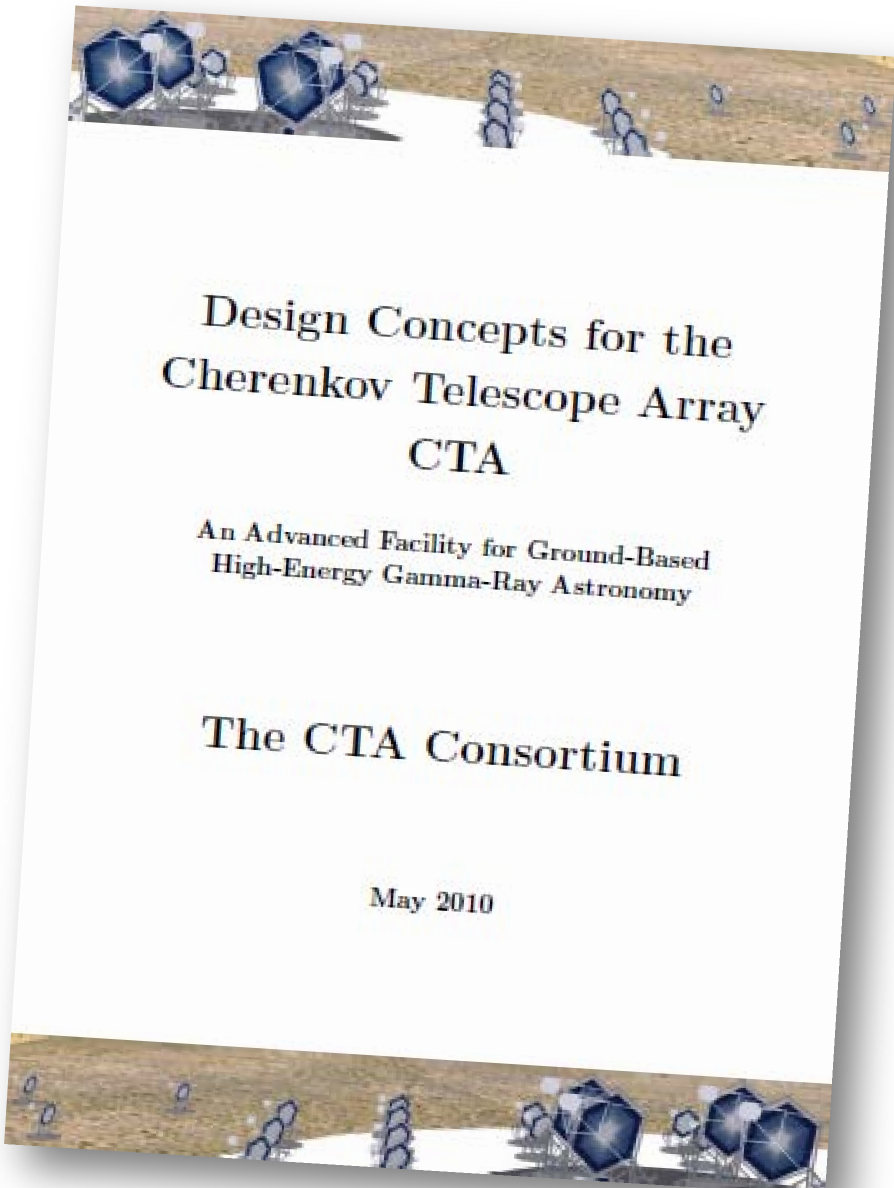




cta
cherenkov telescope array
Low-energy section
energy threshold
of some 10 GeV
Connect to richness in lower waveband
Core array:
mCrab sensitivity
in the 100 GeV–10 TeV
domain
General increase in sensitivity
High-energy section
10 km² area at
multi-TeV energies
Exploring the cutoff region: Galactic CR acceleration

…is now in PreparatoryPhase (EU + consortium supported)

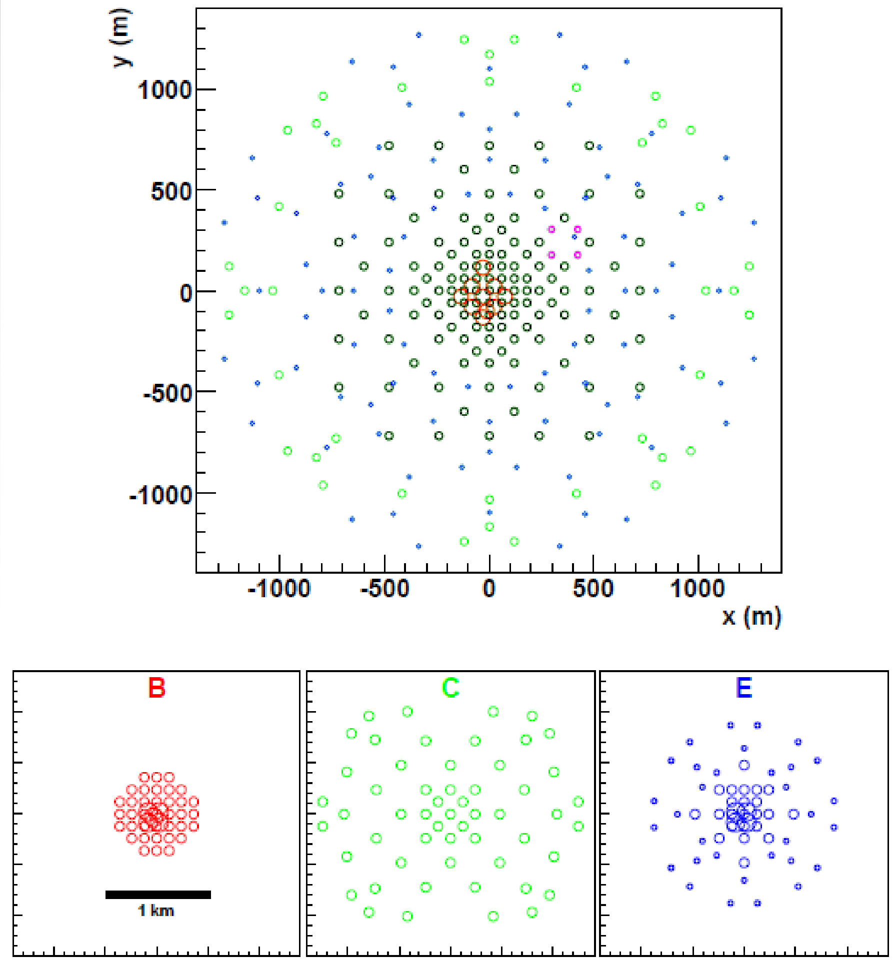
cta
cherenkov telescope array


Design Concepts for the
Cherenkov Telescope Array
CTA

An Advanced Facility for Ground-Based
High-Energy Gamma-Ray Astronomy

The CTA Consortium

May 2010



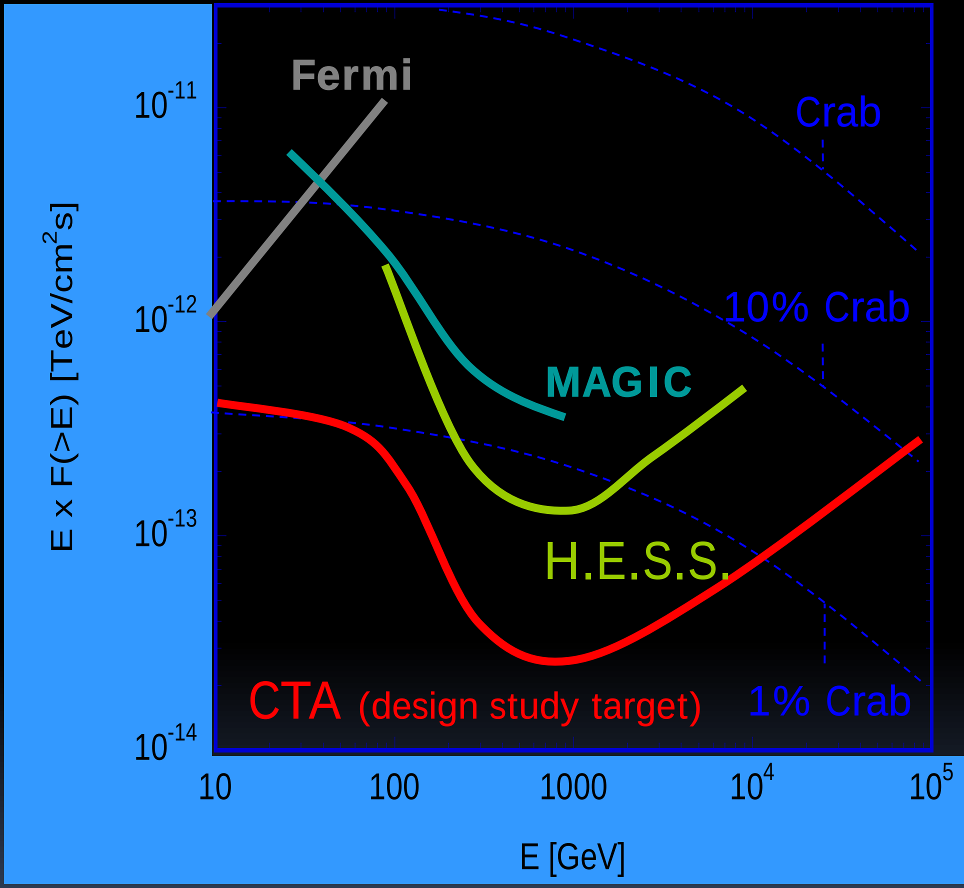
e.g. performance simulation of alternative array configurations

Improvement over existing arrays is within reach when considering:

- Large Telescopes (E_{thres})
- Dense central core
- High altitude site
- Advanced photo detectors (QE)
- … and larger arrays of small(ish) telescopes for highest energies

Gain:

- Threshold down to 5-10 GeV
- Angular resolution ~ factor 10
- Sensitivity ~ factor 10
- Reach the “knee” by E_{photon}



Subarray configurations will allow to obtain deep exposure without sacrifying the general obs program.

Summary 2nd part

→ Performance for Fermi/LAT is very much predictable, up into anticipated η
(will probably calculate that with Keith reg. 5y/10y/15y sensitivity for continuous sky-survey observation regime)

→ Upgraded 3rd generation Cherenkov telescopes do not promise breakthrough, although substantial gains can still be expected if ultra-deep observations are attempted (very challenging: systematic uncertainties, instrument stability, observation program acceptable for all science working groups, particle injection into cluster ?)

→ HAWC will come into business. Although transient science advocated, interesting prospects owing to survey capability and related analysis techniques.

→ CTA will pursue galaxy cluster observation (SWG CTA/CR-EXGAL)
will hopefully acknowledge learning process of TeV observations
thinkable are full array snapshots to nominal sensitivity and sub-array steering configurations to accumulate exposure elsewise impossible to justify

Until then, we'll keep a good eye on the radio observations of the SKA-pathfinders, large-scale structure formation simulations, turbulence, magnetic field assessments…