超高エネルギーガンマ線観測

High-energy gamma-ray astrophysics

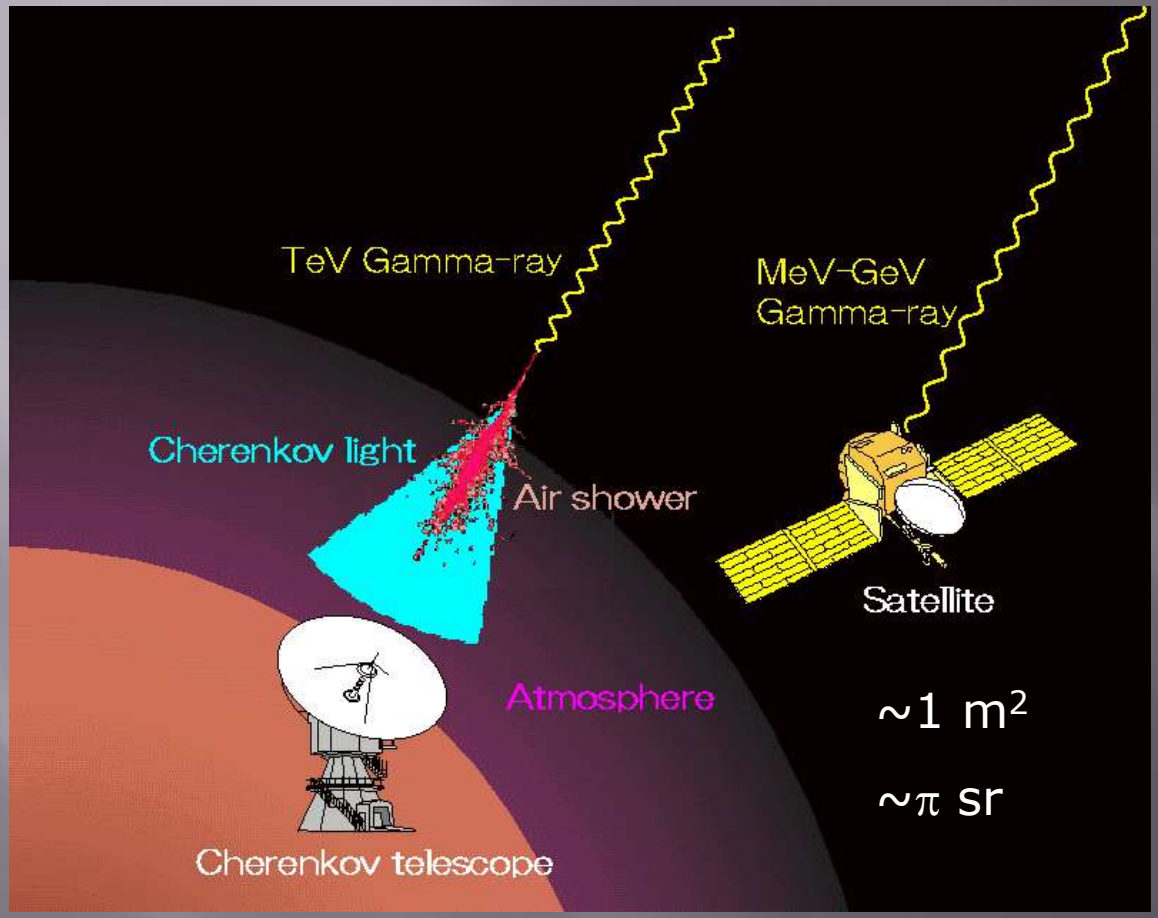
森　正樹

東京大学宇宙線研究所

第7 回高エネルギー宇宙物理連絡会研究会 「高エネルギー宇宙物理学の将来計画」

2007 年3 月12 日～14 日　東京大学宇宙線研究所

Detection of gamma-rays (1)



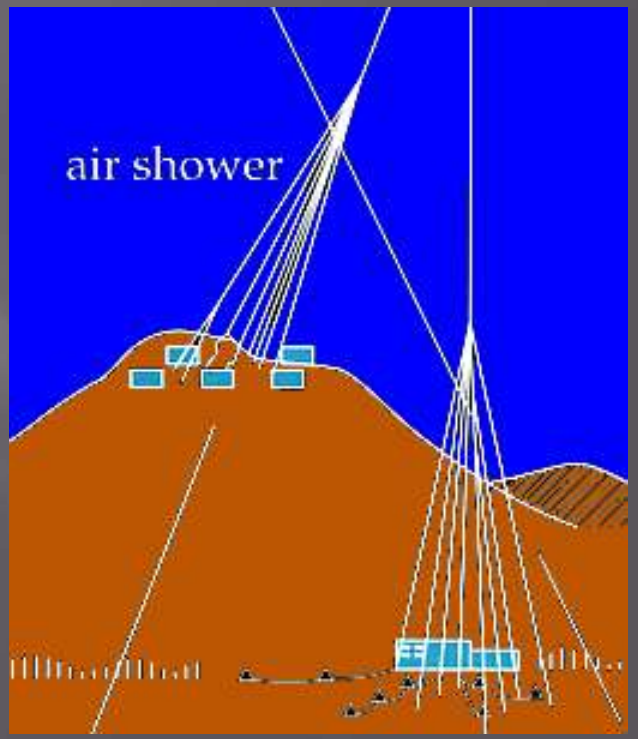
~1 m^2

~π sr

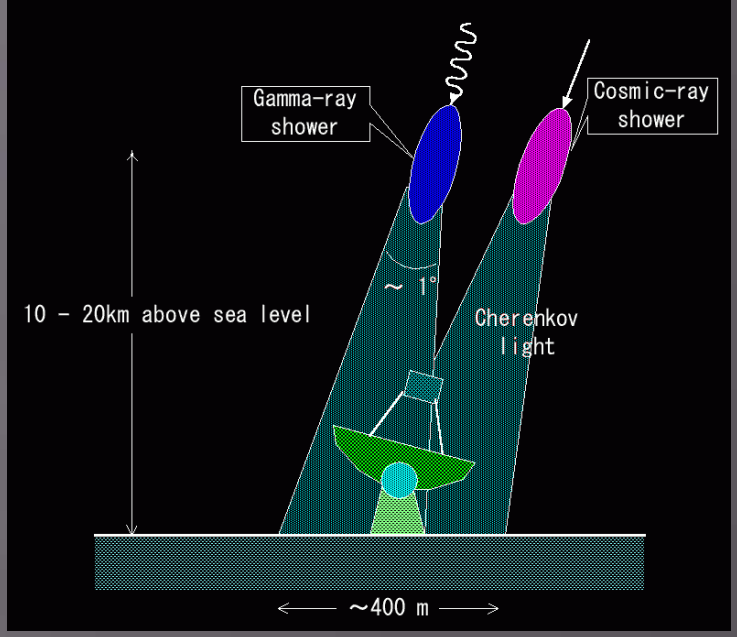
A ~$10^4 m^2$

Ω ~10^{-2}sr

> TeV gamma-rays

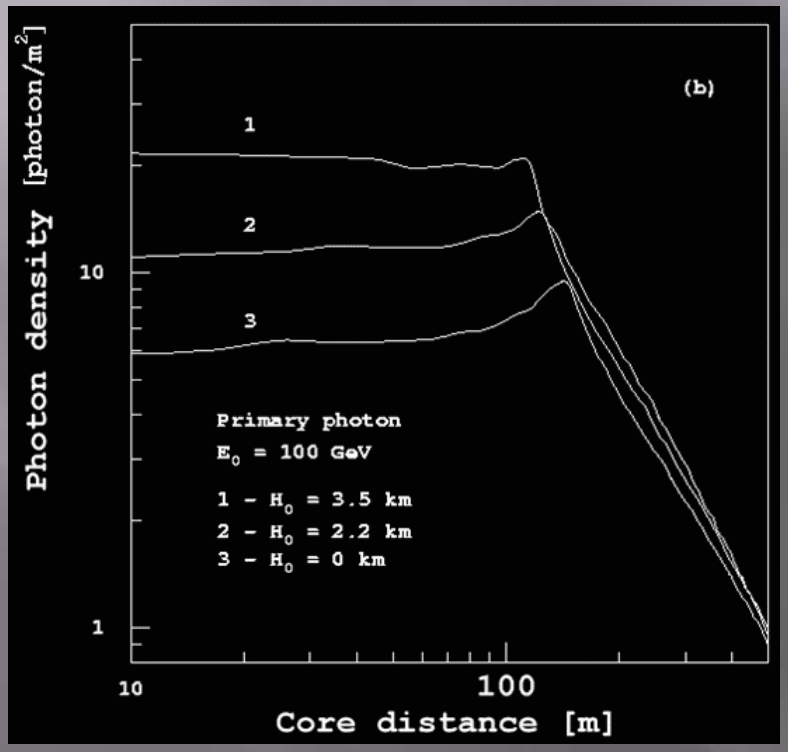


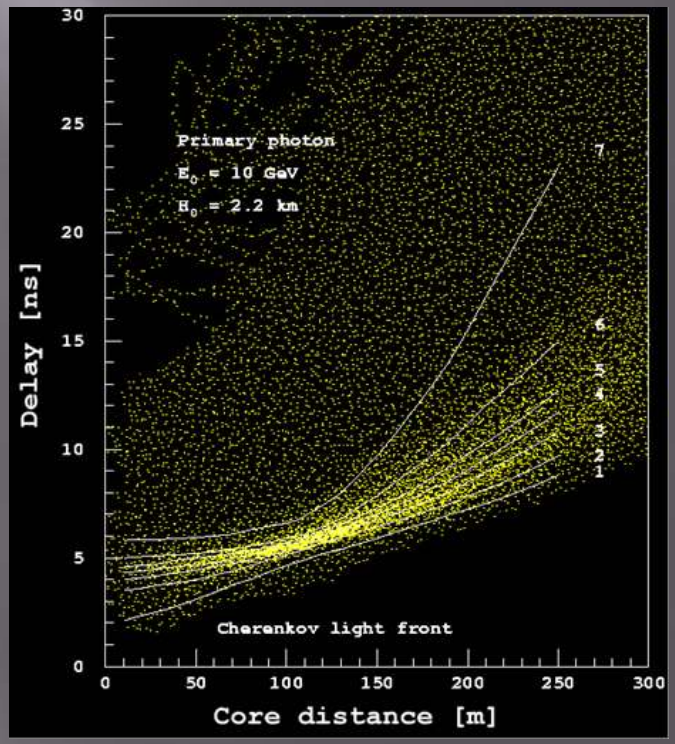
Atmospheric Cherenkov telescopes



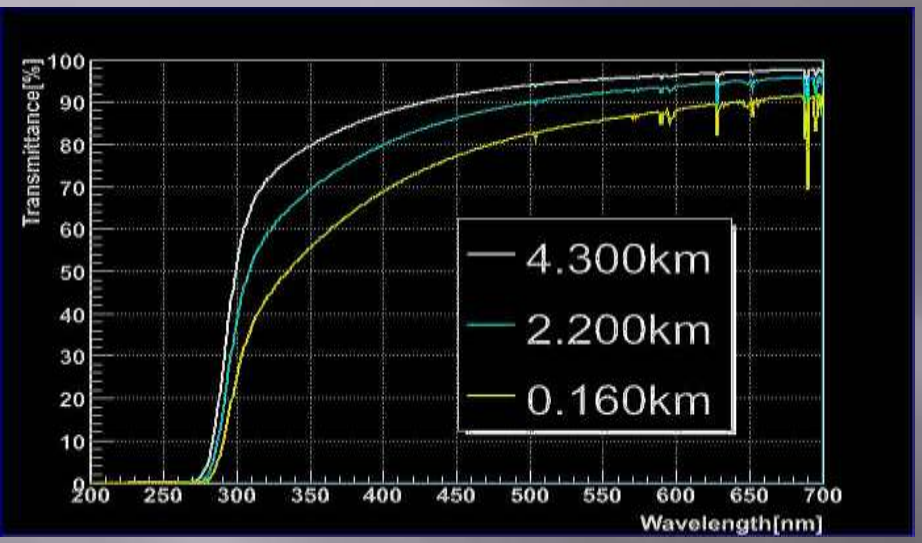
Cherenkov light from gamma-ray showers

Lateral distribution & Timing distribution

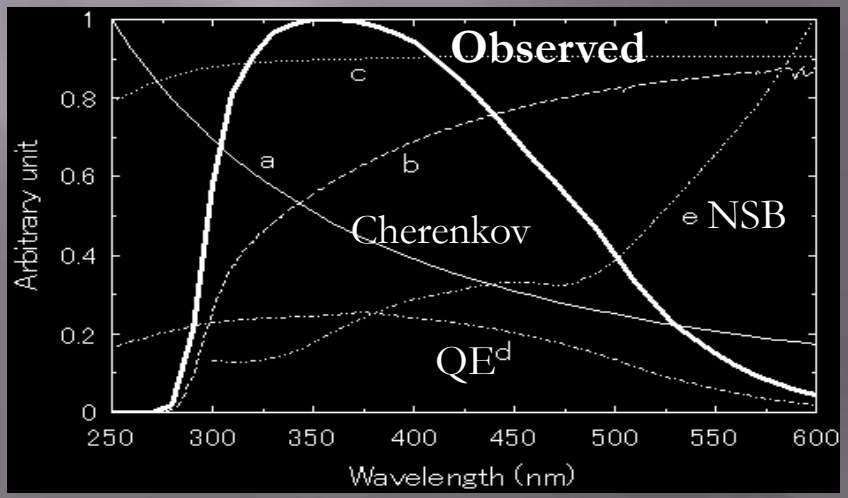


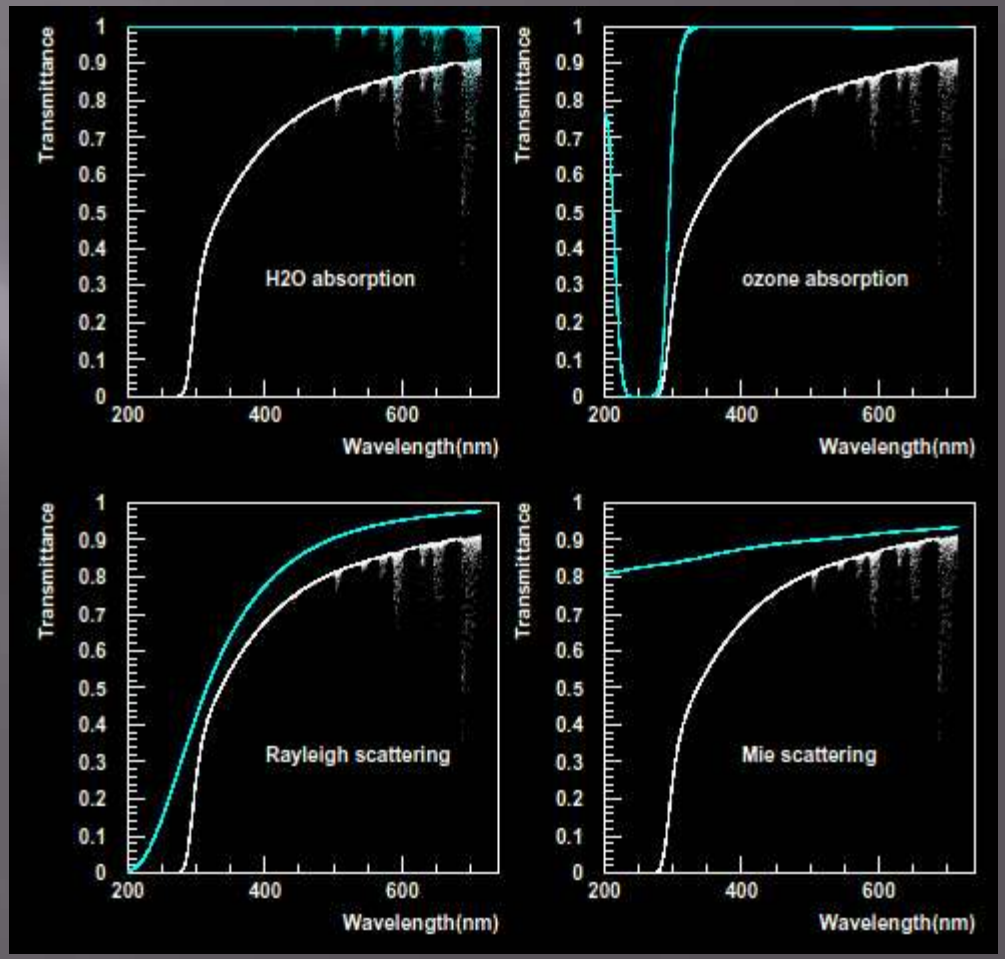


Atmospheric transmission



MODRAN4 calculation by M.Yuasa (2006)

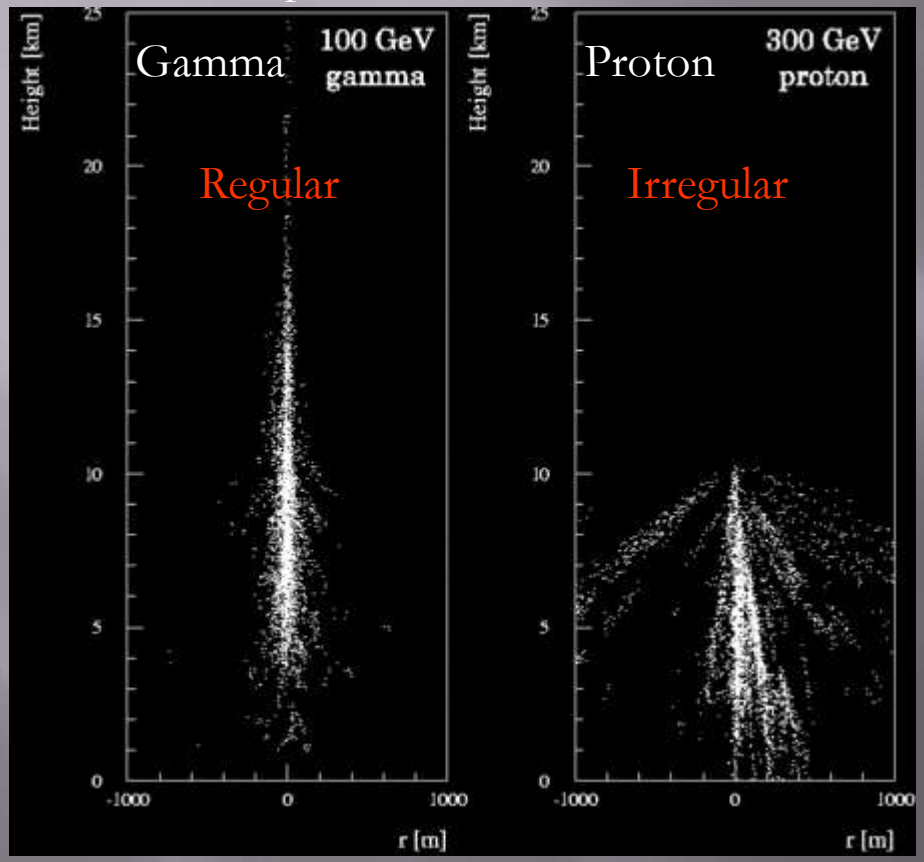




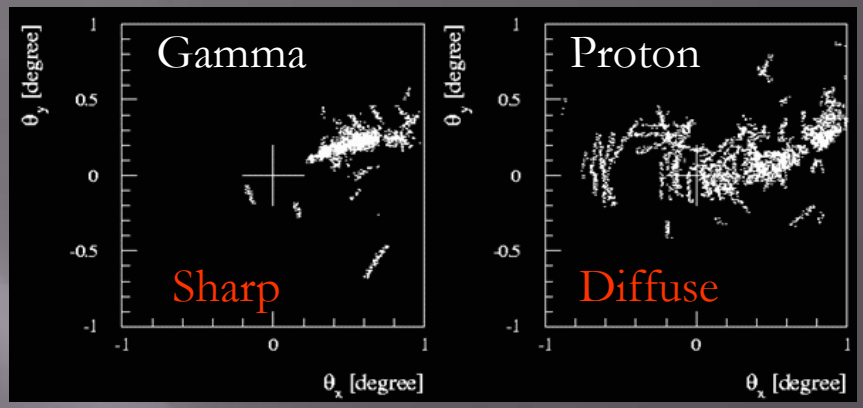
MODRAN4 calculation by H. Tsunoo (2002)

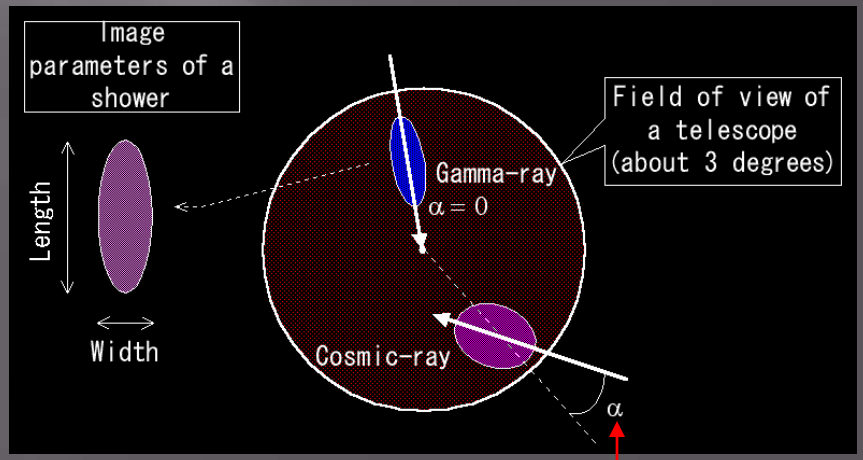
Imaging Cherenkov Telescopes

Shower profile



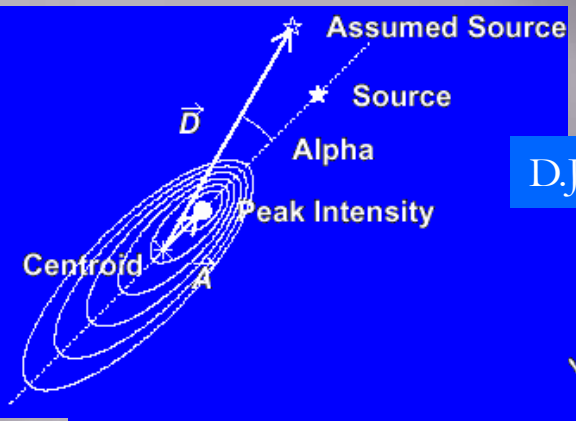
Focal plane image



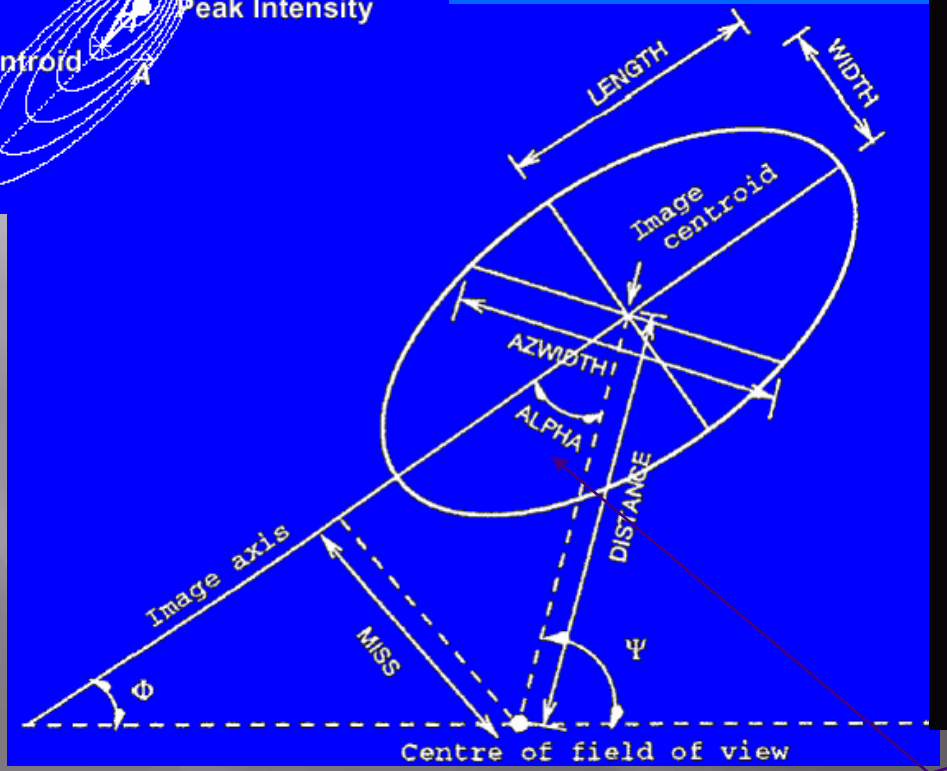


α (image orientation angle)

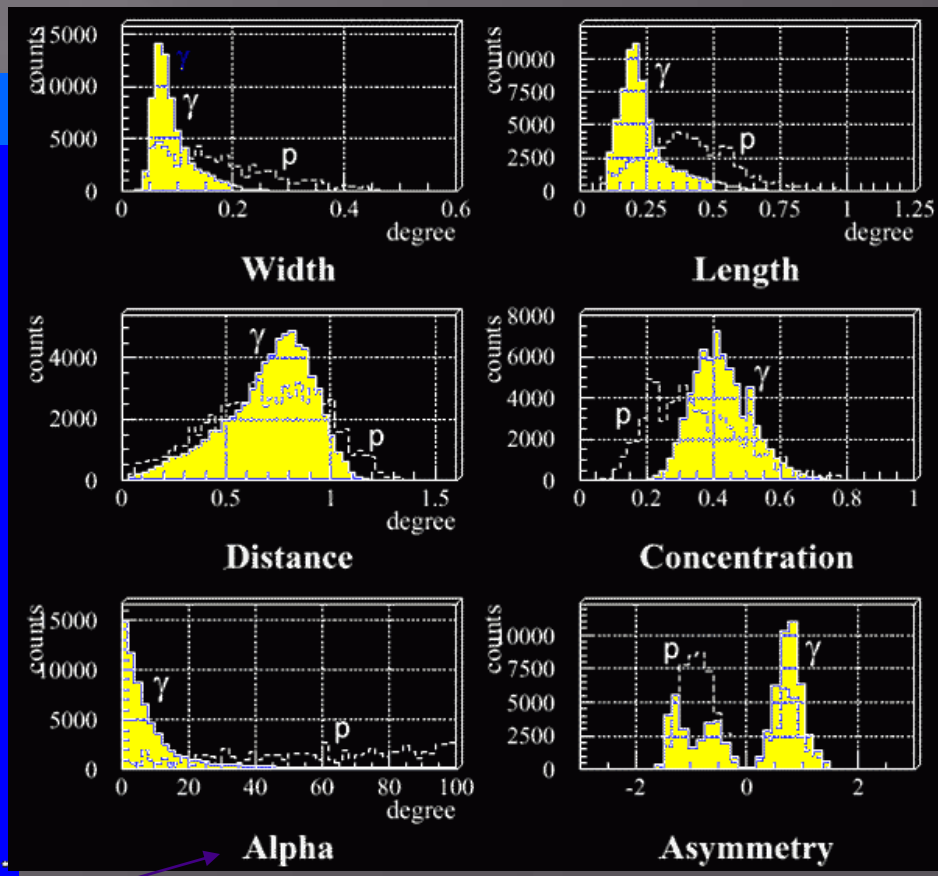
Imaging analysis



D.J. Fegan, J.Phys.G, 1997



Distribution of imaging parameters



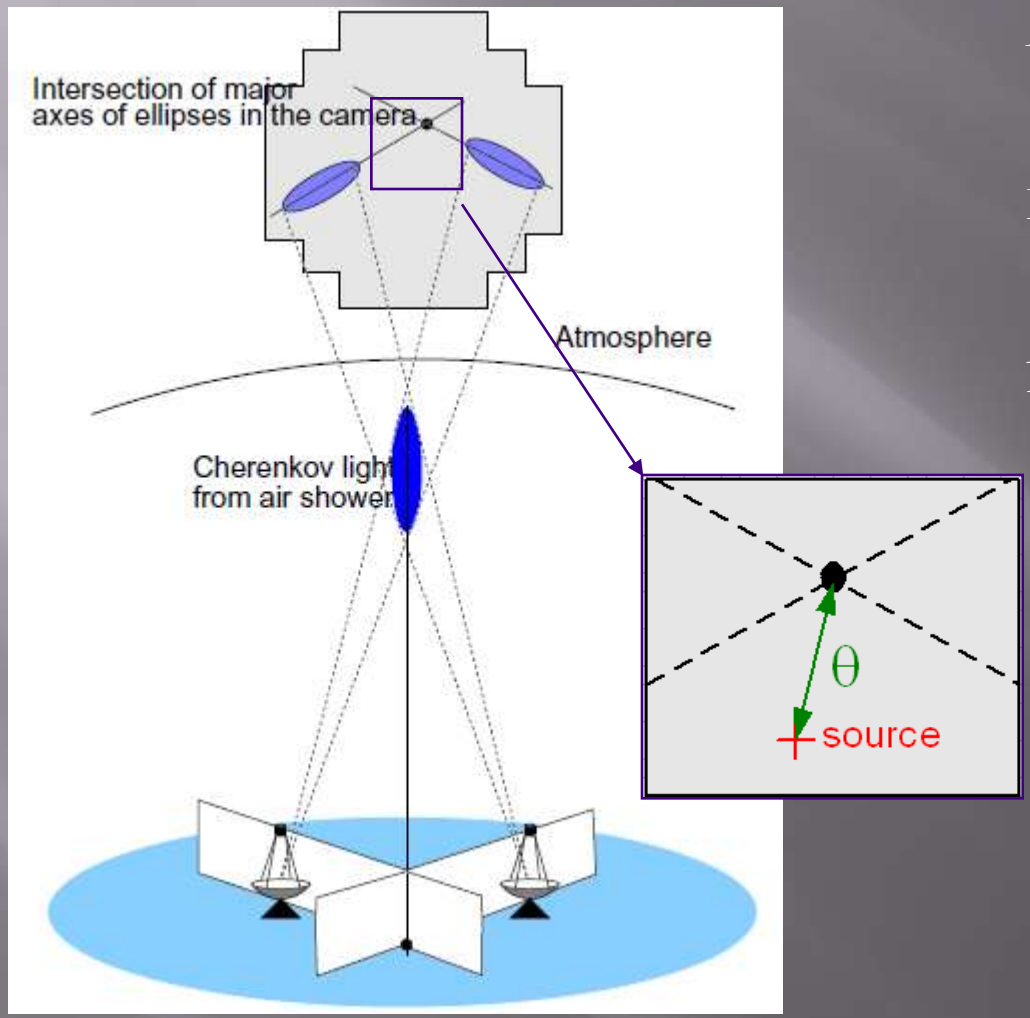
(Simulation)

α (image orientation angle)

"Image parameters": A.M. Hillas, 1983 ICRC

"Alpha": A.V.Plyasheshnikov and G.F.Bignami, N.C. 1985

Stereo observation



© S.Funk, 2005

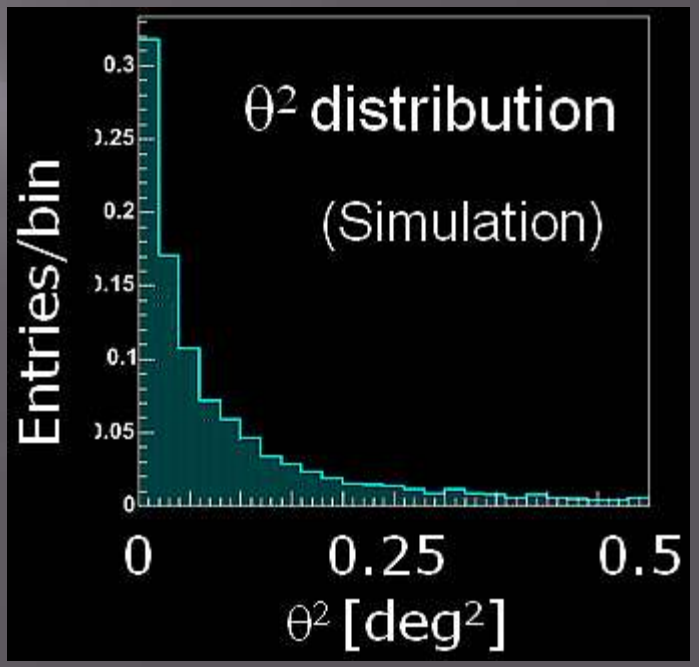
Angular resolution

0.25deg → 0.1 deg

Energy resolution

30% → 15%

Better S/N (no local muons)



Detection of gamma-rays (2)

Base	**Satellite**	**Ground**	**Ground**
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)	Indirect (shower array)
Energy	< 30 GeV ($\rightarrow$ 100 GeV)	>100 GeV ($\rightarrow$ 50 GeV)	>3 TeV ($\rightarrow$ 1 TeV)
Pros	High S/N Large FOV	Large area Good $\Delta\theta$	24hr operation Large FOV
Cons	Small area High cost	Low S/N (CR bkgd.) *(but imaging overcomes this!)* Small FOV	Low S/N (CR bkgd.) Moderate $\Delta\theta$

Rene Ong, ICRC2005 OG2 rapporteur talk

VHE Experimental World

OG 1

http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html

H.E.S.S.

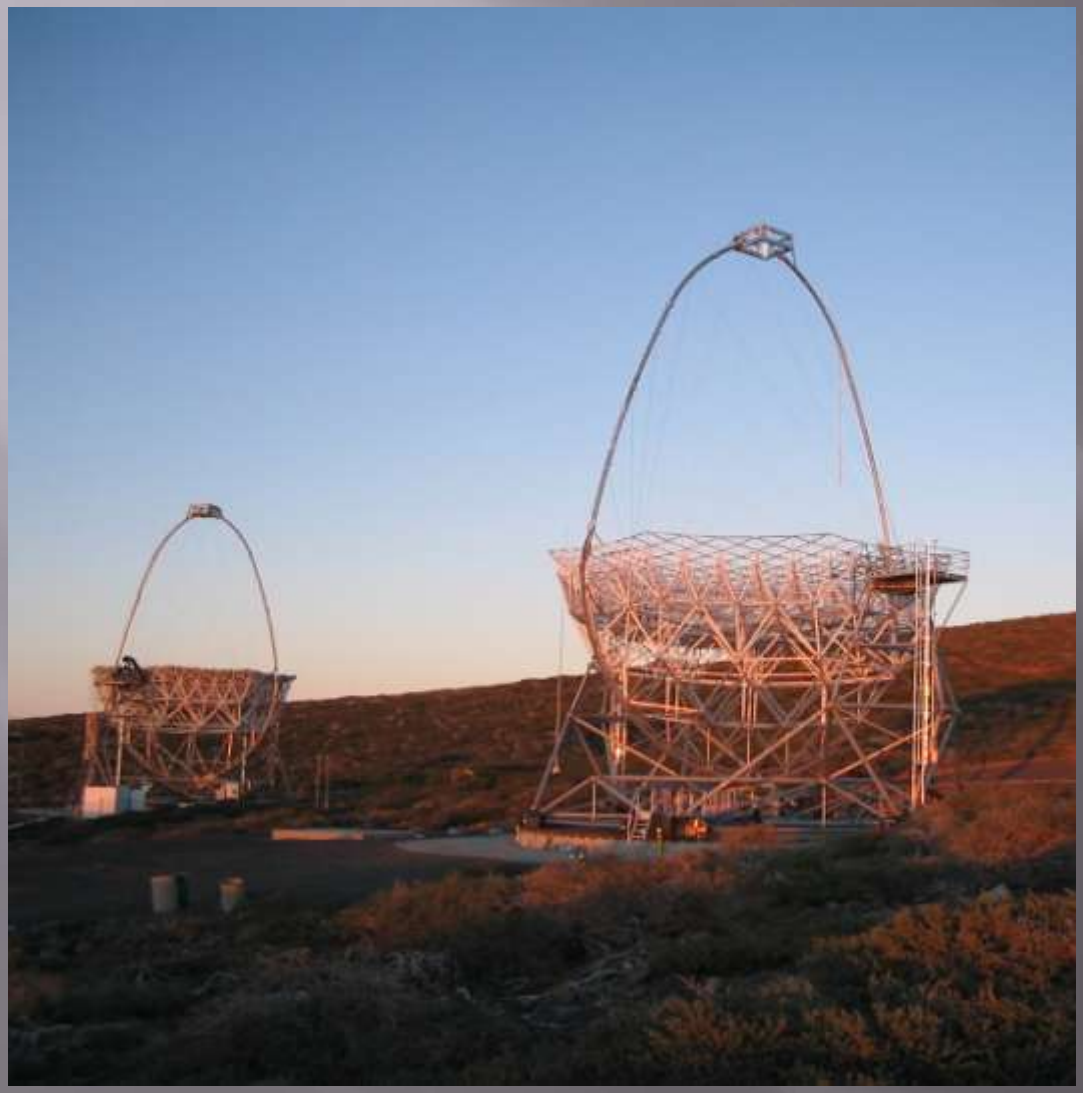
- 107 m² mirror area
  - 380 individual facets
- 15 m focal length
- 60 t structure
- Alt-Az mount

- 4 x 960 x 0.16° PMTs→ 5° field of view
- Integrated readout electronics
- 2-telescope coincidence

HESS-II 28mϕ telescope is to be built by 2008.

http://wwwmagic.mppmu.mpg.de/

MAGIC-I & MAGIC-II



576-pixel Camera

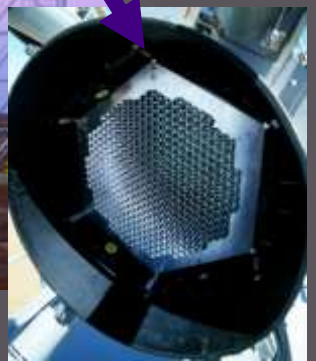
17m diameter largest dish
High resolution camera
Ultra fast read out system 300M → 2GHz
Analogue signal fiber transmission

MAGIC-II is under construction and will be completed in the fall of 2007.

http://icrhp9.icrr.u-tokyo.ac.jp/

CANGAROO-III

- Location:
  - 31°06'S, 136°47'E
  - 160m a.s.l.
- Telescope:
  - 114× 80cmϕ FRP mirrors (57m^2, Al surface)
  - 8m focal length
  - Alt-azimuth mount
- Camera:
  - T1: 552ch (2.7° FOV)
  - T2,T3,T4: 427ch (4° FOV)
- Electronics:
  - TDC+ADC

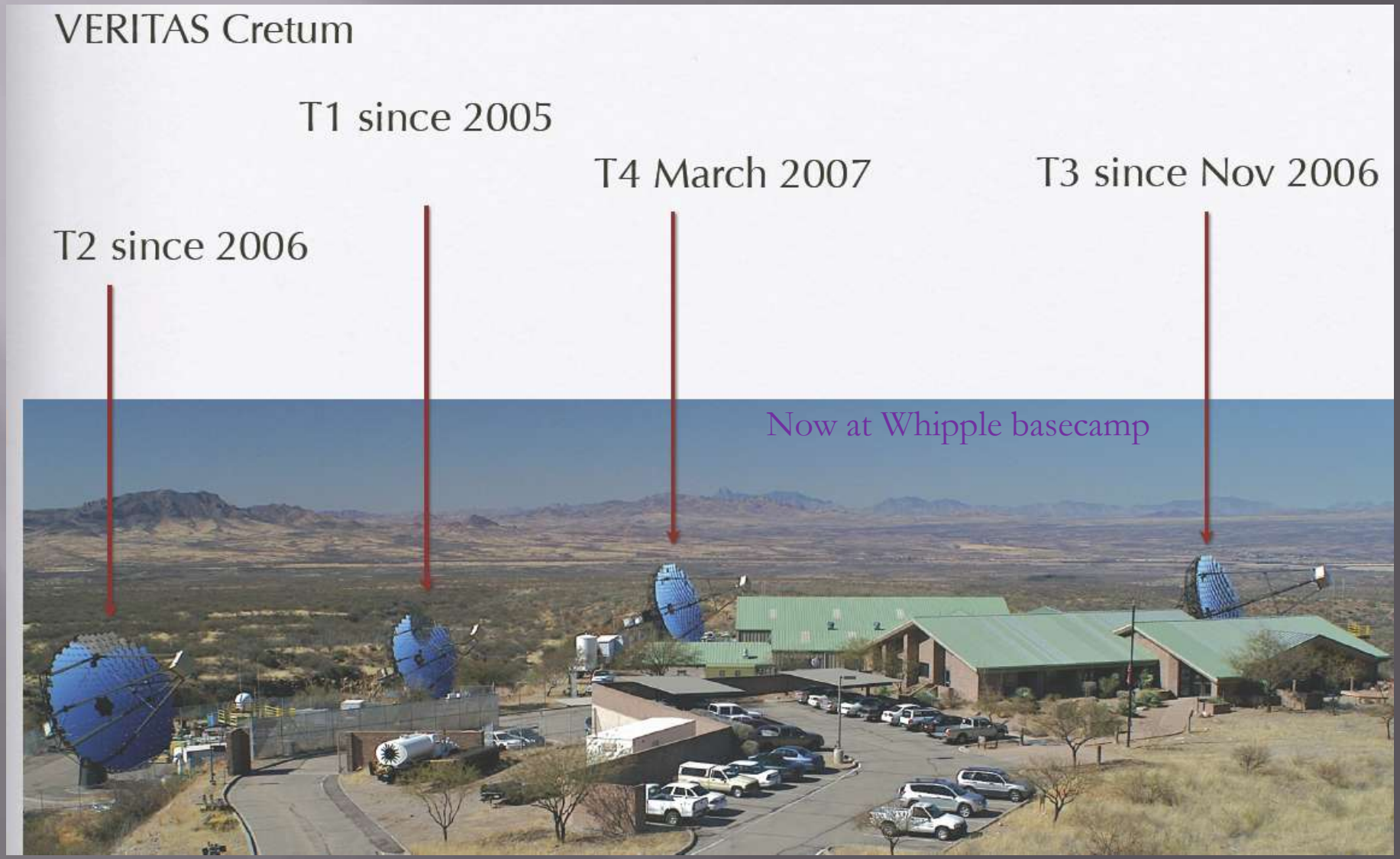


427-pixel Camera

http://veritas.sao.arizona.edu/

VERITAS

Four 12m telescopes in AZ



Aharonian et al., ApJ 636, 777 (2005)

H.E.S.S. Galactic plane survey

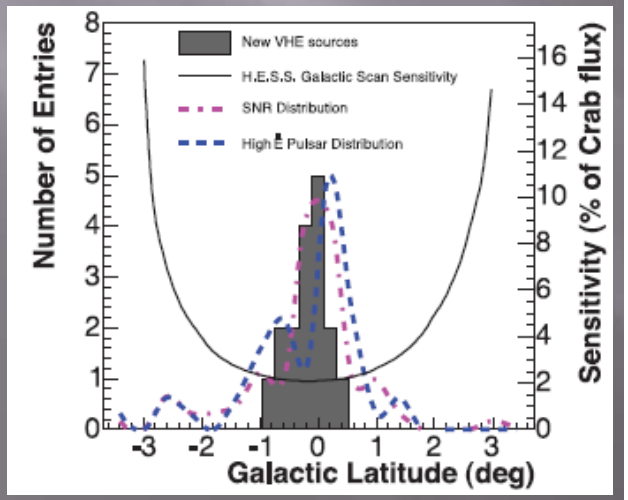
230 hr, 500 pointings

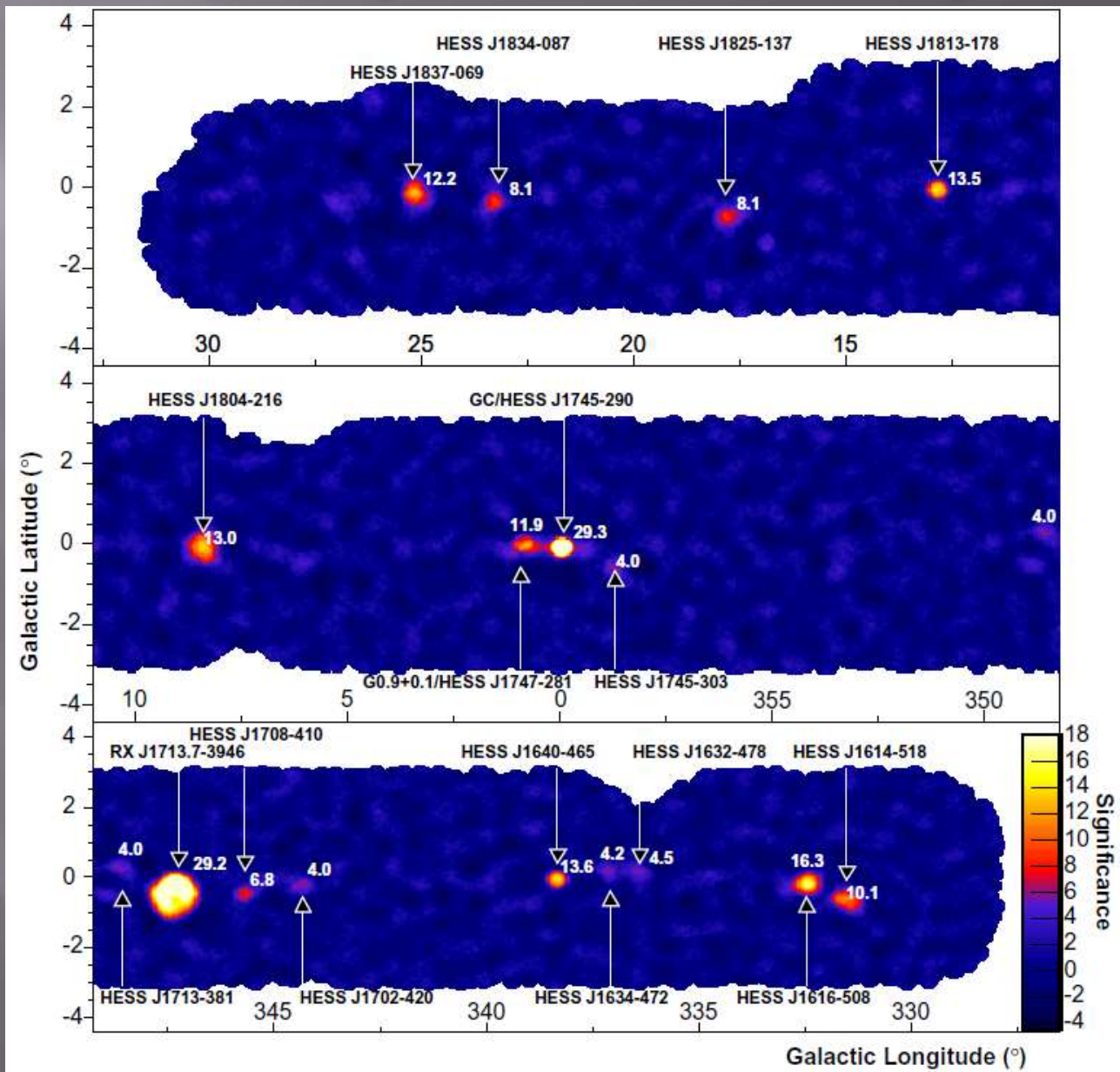
14 new TeV sources + 3 known

Scale height

~ 0.3deg RMS

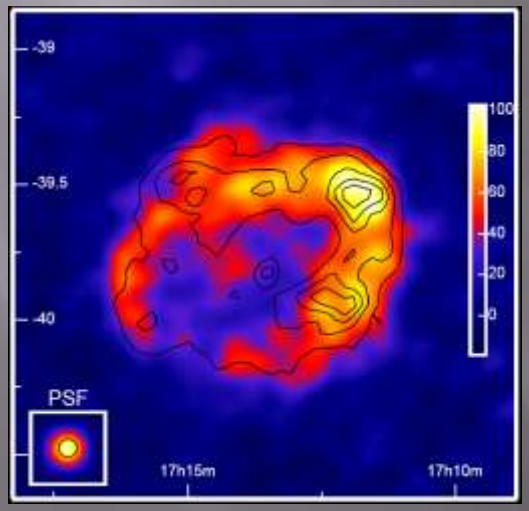
~ molecular gas

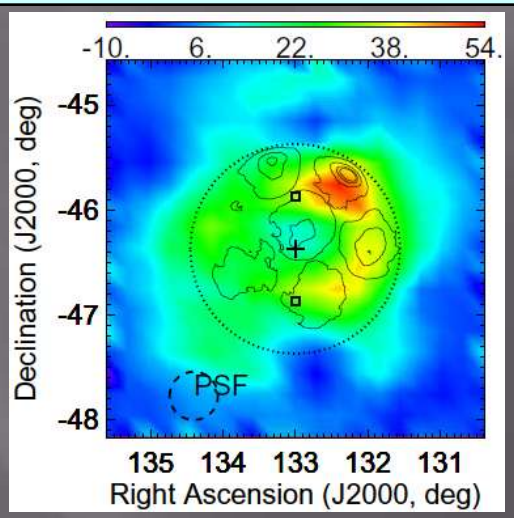


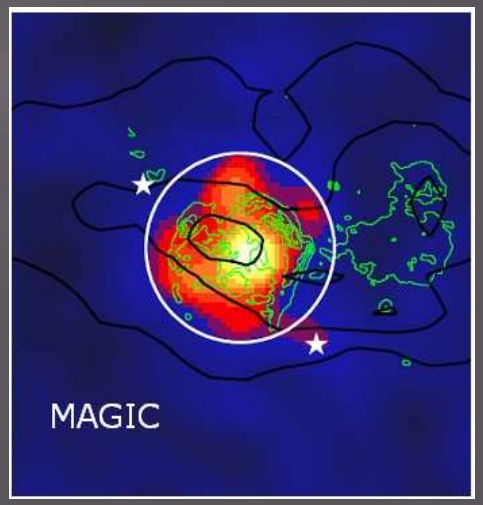


Supernova Remnants [9]

Category	Name	Discovery	Observ.
SNR	Cas A	HEGRA	
SNR	RX J0852.0−4622 (Vela Jr.)	CANGAROO	HESS
SNR/Un-ID	HESS J1640−465 (G338.3−0.0; 3EG J1639−4702)	HESS	
SNR	HESS 1713−381, G348.7+0.3 ?	HESS	
SNR	RX J1713.7−3946, G347.3−0.5	CANGAROO	HESS
SNR/PWN	HESS J1804−216 (G8.7−0.1 / W30; PSR J1803)	HESS	
SNR	HESS J1813−178 (G12.8−0.02; AX J1813−178)	HESS	MAGIC
SNR	HESS J1834−087 (G23.3−0.3 / W41)	HESS	MAGIC
SNR/PWN/Un-ID	HESS J1837−069 (G25.5+0.0; AX J1838.0−0655)	HESS	



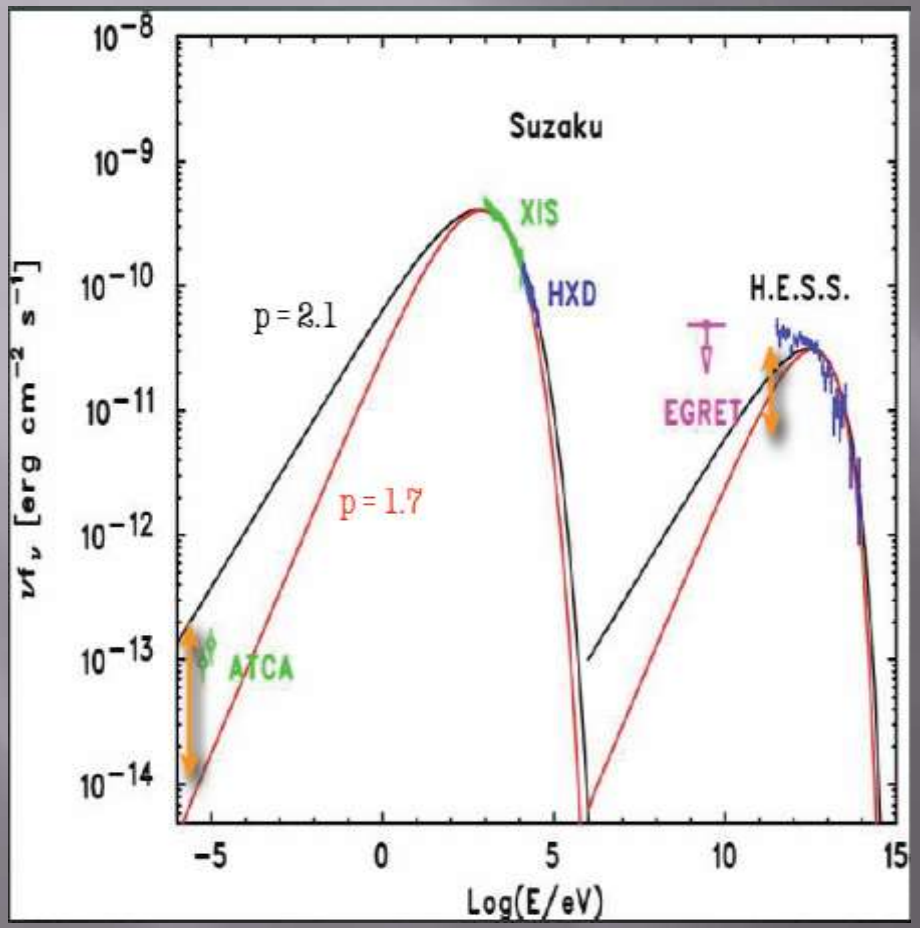


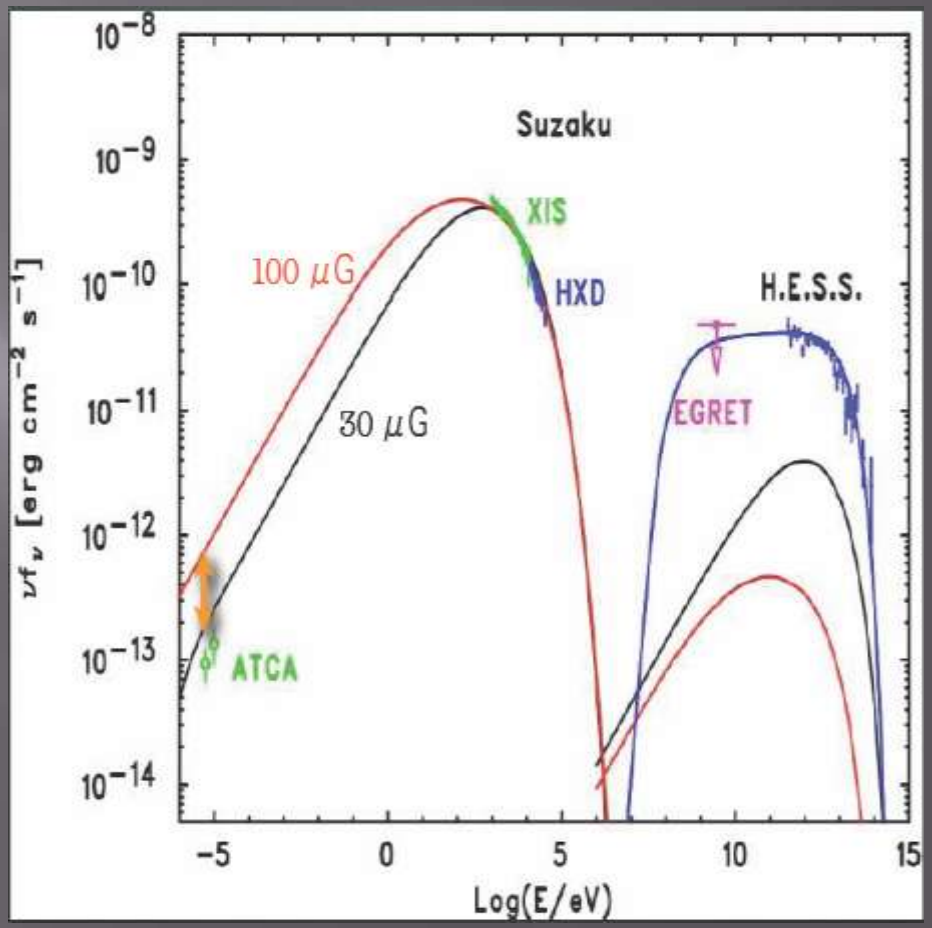


RX J1713.7-3946 (HESS) RX J0652.0-4622 (CANGAROO) HESS J1834-087 (MAGIC)

T.Tanaka, Ph.D. thesis (2007)

RX J1713.7-3946 spectrum





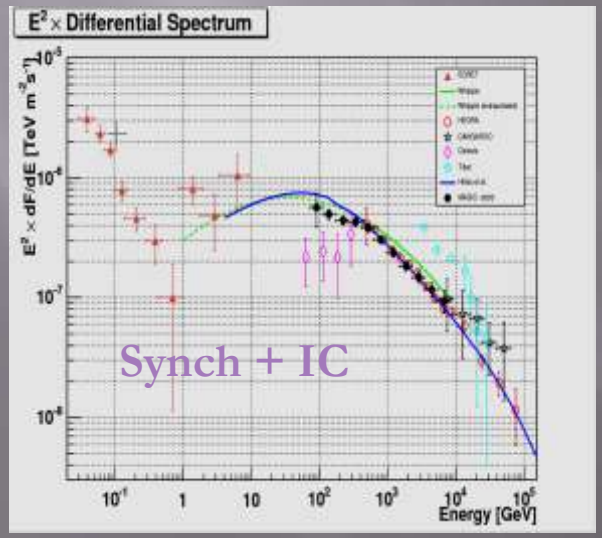
π^0 decay scenario – proton origin

Inverse Compton scenario – electron origin

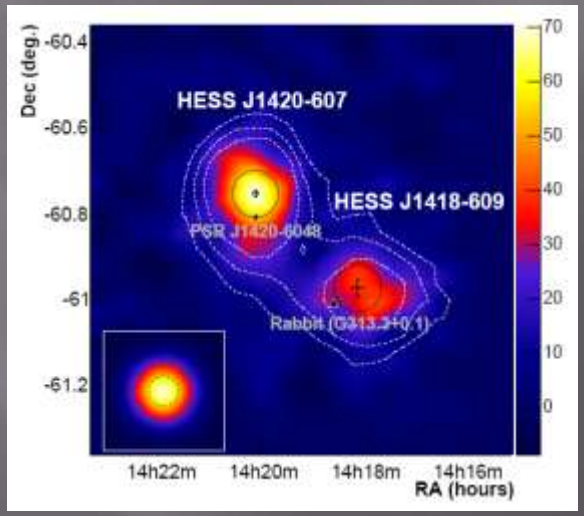
→ Proton origin favored? – but revised electron model viable…

Pulsar Wind Nebulae [8]

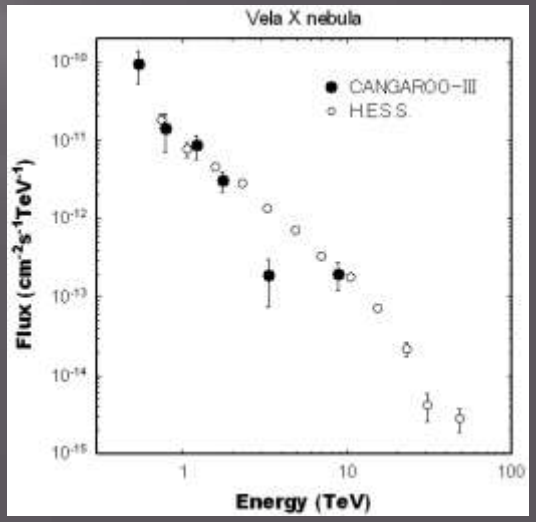
Category	Source	Discovery	Observation
PWN	Crab Nebula	Whipple	many
PWN	Vela X	CANGAROO	HESS
PWN	HESS J1418−609 (G313.3+0.1, Rabbit)	HESS	
PWN	HESS J1420−607 (PSR J1420−6048, Kookaburra)	HESS	
PWN	MSH 15−52, PSRB1509−58	CANGAROO	HESS
PWN	HESS J1616−508 (PSR J1617−5055)	HESS	
PWN	HESS J1747−281 (G0.9+0.1)	HESS	
PWN	HESS J1825−137 (PSR J1826−1334)	HESS	



Crab spectrum



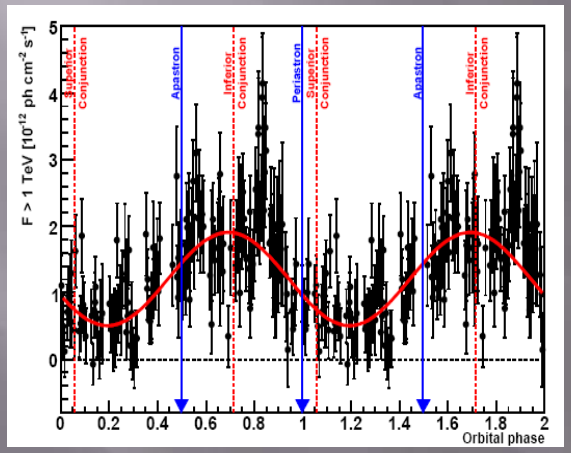
Kookaburra (HESS)



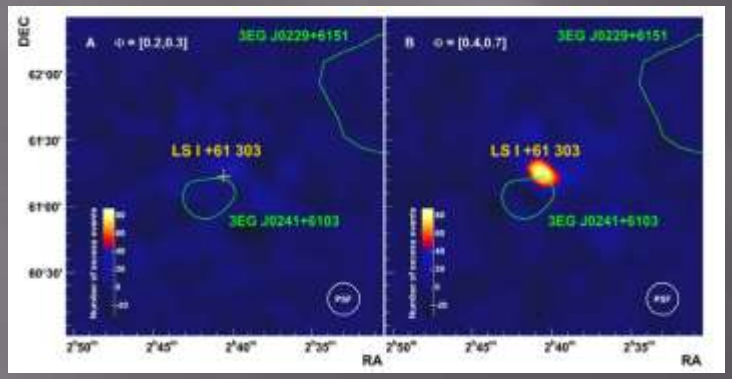
Vela X spectrum

Binary systems [5]

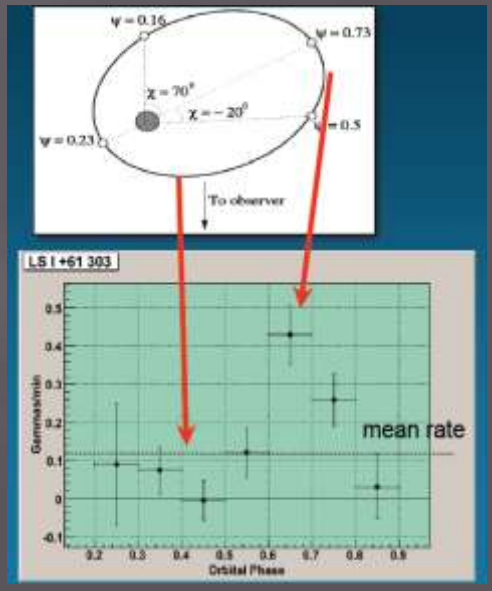
Category	Source	Discovery	Observation
Binary	PSR B1259−63 / SS 2883	HESS	
XRB	IGR J16320−4751	HESS J1632−478	
XRB/SNR	IGR J16358−4726 ?; G337.2+0.1 ?	HESS J1634−472	
XRB	LS 5039	HESS	
XRB	LSI+61 303	MAGIC	VERITAS



LS 5039 L.C.(HESS)



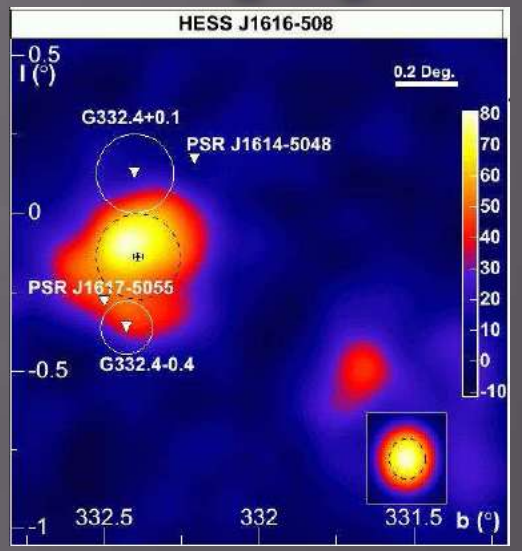
LSI+61 303 (MAGIC)



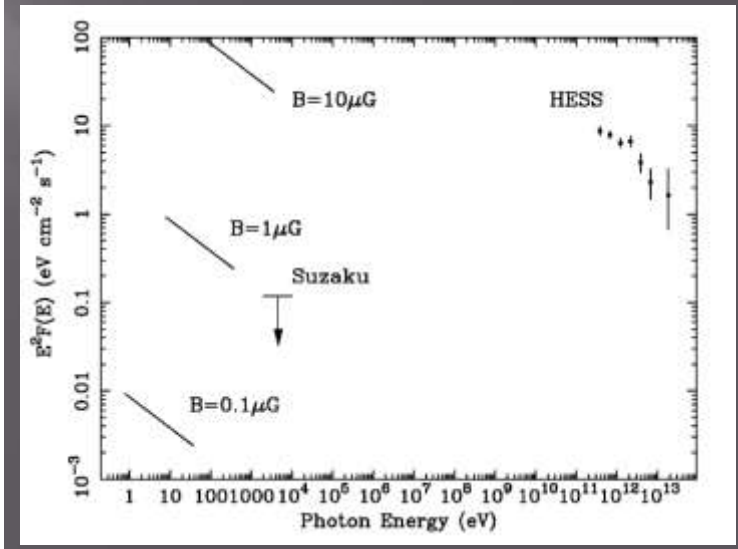
LSI+61 L.C.(VERITAS)

Unidentified sources [6]

Category	Source	Discovery	Observation
Un-ID	TeV J2032+4130	HEGRA	
Un-ID	HESS J1303-631	HESS	
Un-ID	HESS J1614-518	HESS	
Un-ID	HESS J1702-420	HESS	
Un-ID	HESS J1708-410	HESS	
Un-ID	3EG J1744-3011 ?	HESS J1745-303	

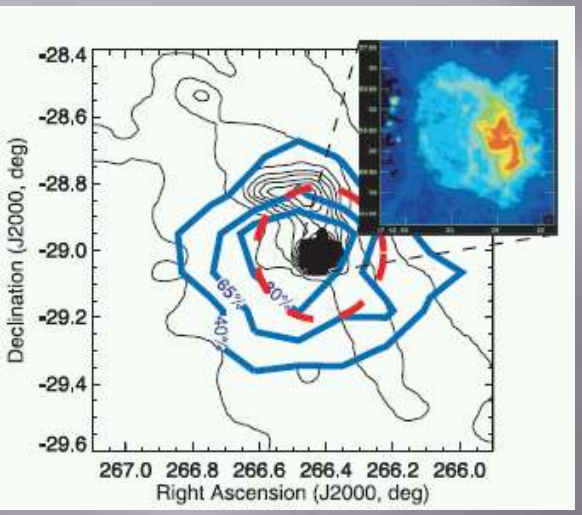


Name	Possible counterpart	Type[a]	Γ^b_{TeV}	f^c_{TeV}	N^d_H	Γ^e_X	f^f_X	f_{TeV}/f_X	Reference[g]
HESS J0852−463	RX J0852−4622	SNR	2.1	6.9	4	2.6	∼10	∼ 0.7	1, 2, 3
HESS J1303−631	—	?	2.4	1.0	20	2.0	<0.64	> 1.6	4, 5
HESS J1514−591	PSR B1509−58	PWN	2.3	1.6	8.6	2.0	3.2	0.5	6, 7
HESS J1632−478	AX J1631.9−4752	HMXB?	2.1	1.7	210	1.6	1.7	1.0	8, 9
HESS J1640−465	G338.3−0.0	SNR	2.4	0.71	96	3.0	0.30	2.4	8, 10
HESS J1713−397	RX J1713.7−3946	SNR	2.2	3.5	8	2.4	54	0.065	11, 12
HESS J1804−216	Suzaku J1804-2142	?	2.7	0.48	2	-0.3	0.025	19	8, 13
HESS J1804−216	Suzaku J1804-2140	?	2.7	0.48	110	1.7	0.043	11	8, 13
HESS J1813−178	AX J1813−178	?	2.1	0.89	110	1.8	0.70	1.3	8, 14
HESS J1837−069	AX J1838.0−0655	?	2.3	1.4	40	0.8	1.3	1.1	8, 15
TeV J2032+4130	—	?	1.9	0.20	?	?	<0.20	>1.0	16
HESS J1616−508	—	?	2.4	1.7	4.1	2.0	<0.031	>55	This work

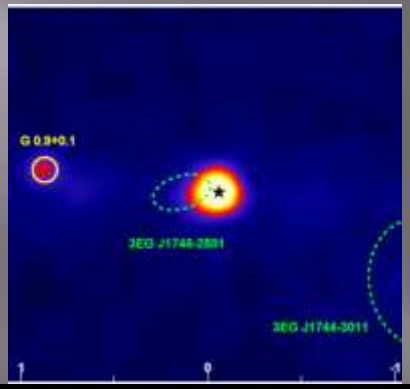


Suzaku (Matsumoto et al. 2006)

The Galactic center



H.E.S.S.: Aharonian et al., A&A 425, L13 (2004) /ICRC2005



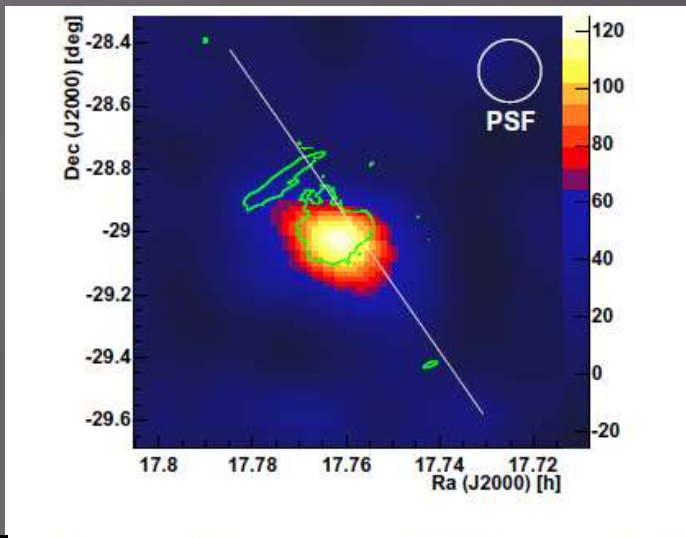
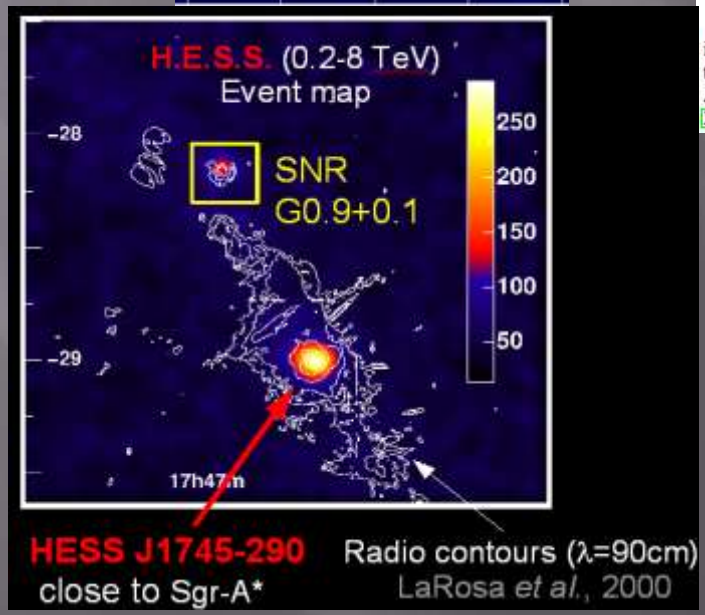


FIG. 1.— Smoothed sky map of γ-ray candidates (background subtracted) in the direction of the Galactic Center for SIZE ≥ 300 ph. el. (corresponding to an energy threshold of about 1 TeV). Overlayed are green contours (0.3 Jy beam^{-1}) of 90 cm VLA (BCD configuration) radio data (LaRosa et al. 2000). The white line shows the galactic plane.

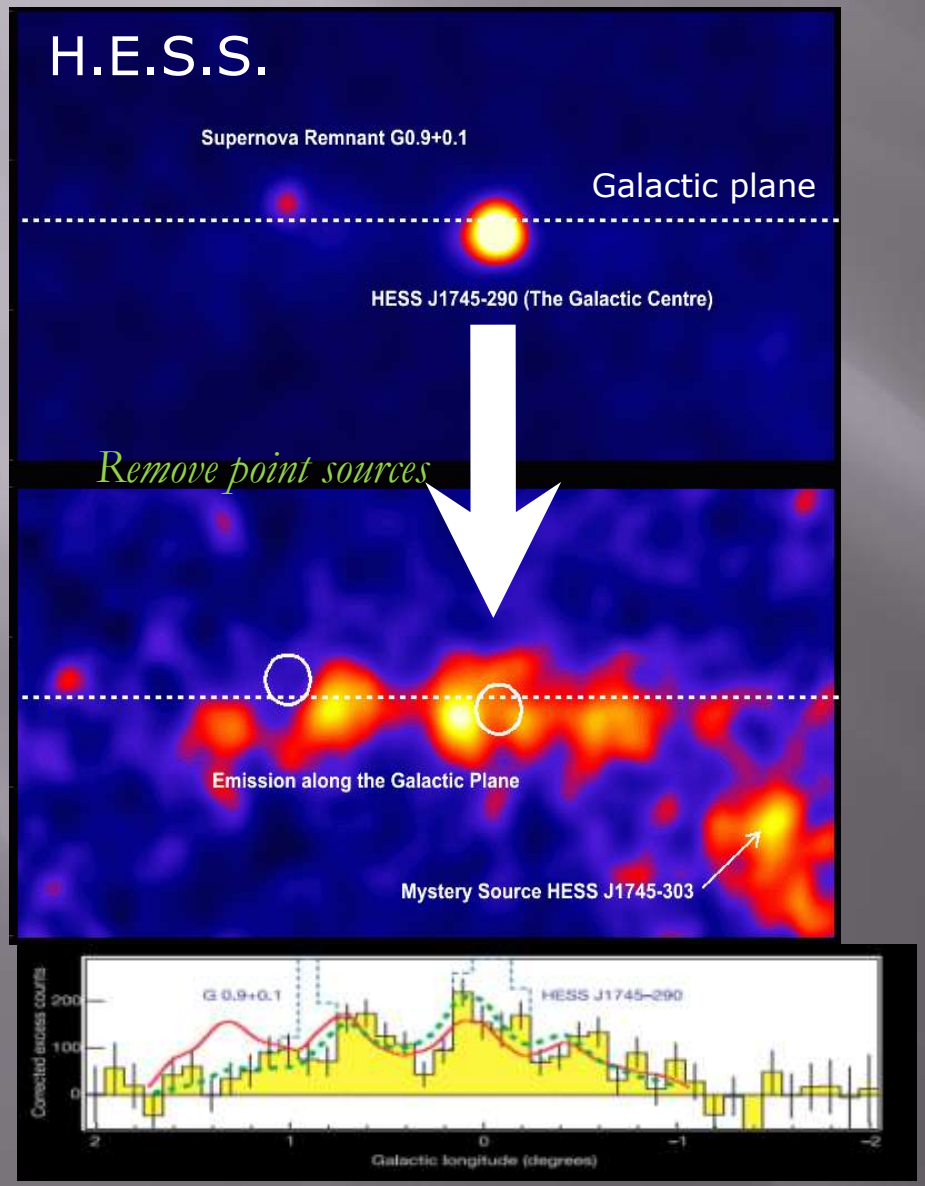
CANGAROO-II (Tsuchiya et al., ApJ 606, L115, 2004)



MAGIC, ApJ 638, L101 (2006)

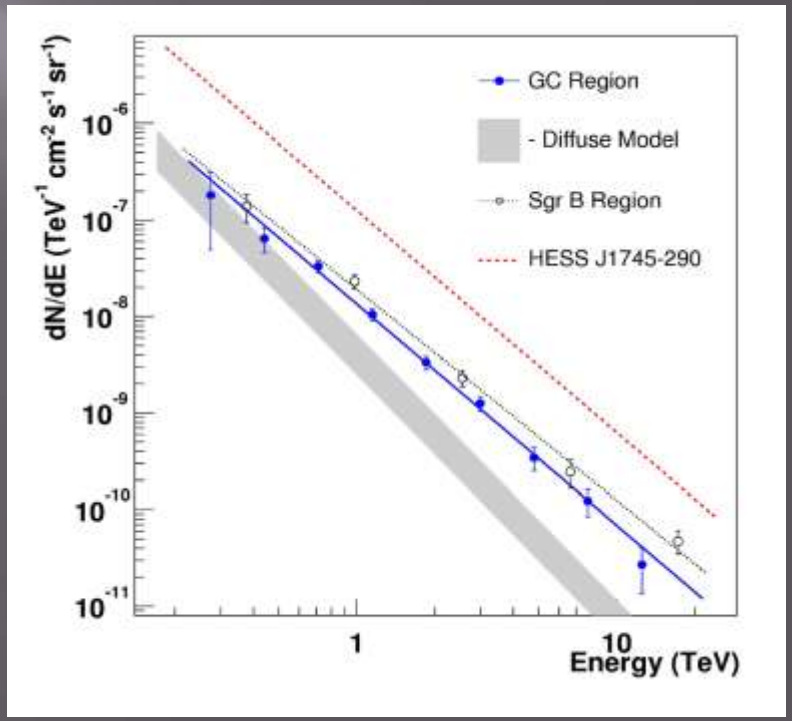
Aharonian et al., Nature 439 (2006) 695

Galactic diffuse emission

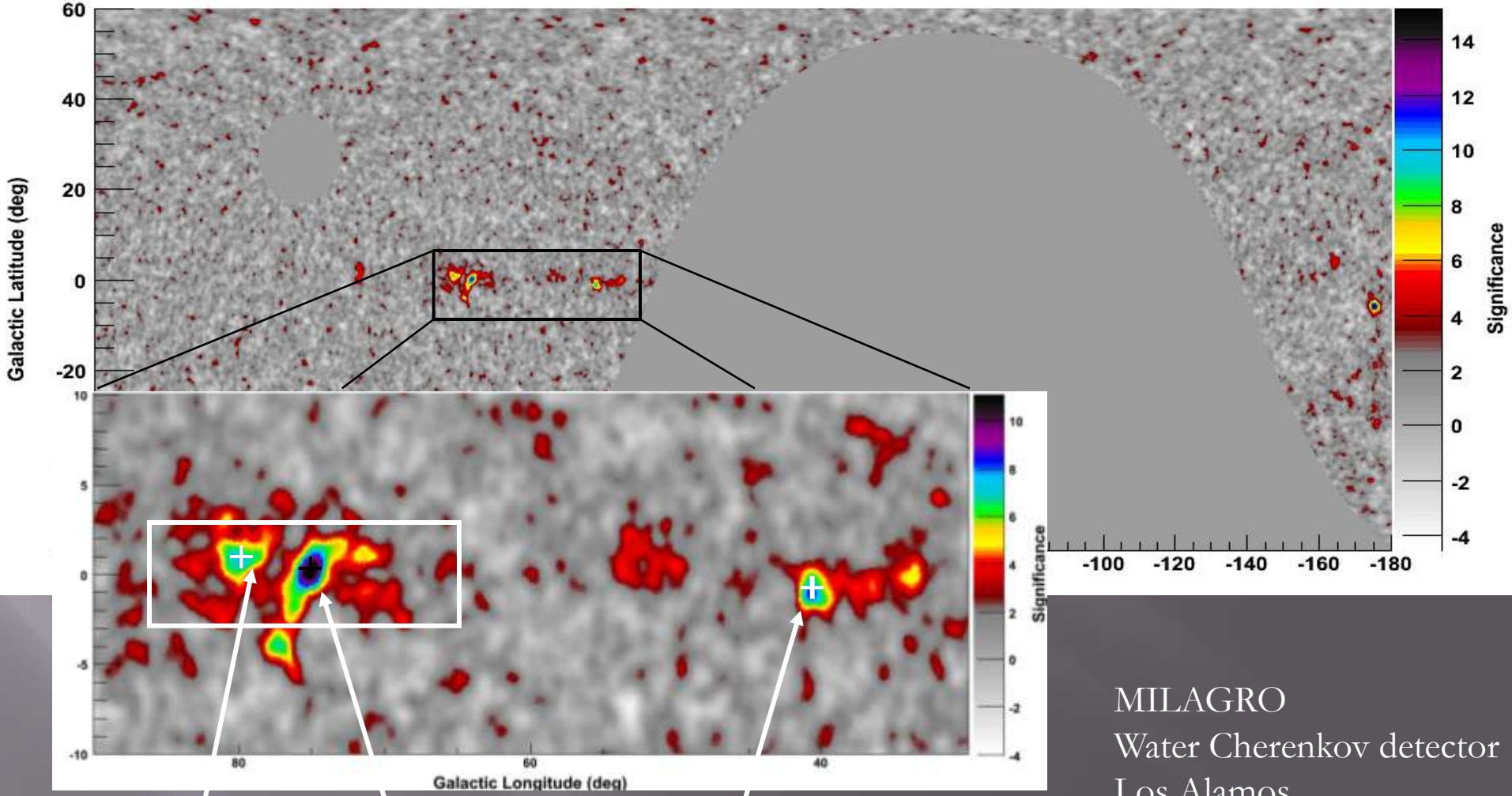


Spectral index
$-2.29 \pm 0.07 \pm 0.20$

Implies harder CR spectrum than in our solar system



The Cygnus region (1)

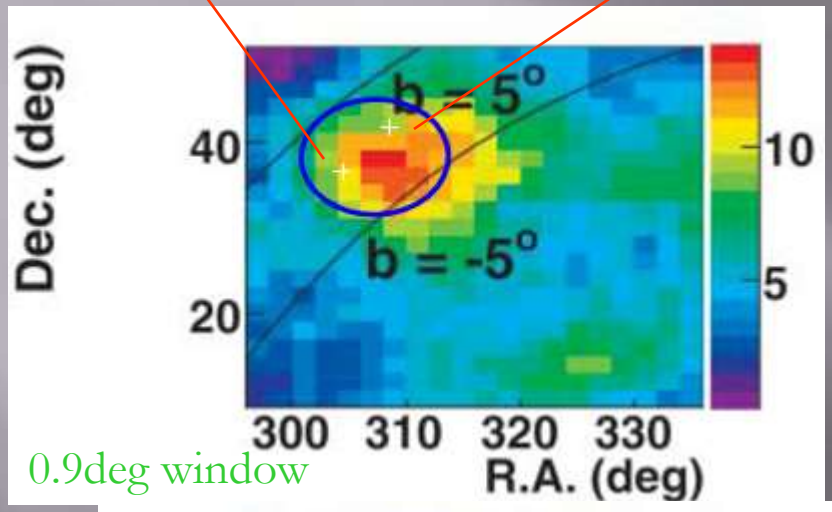


MILAGRO
Water Cherenkov detector
Los Alamos

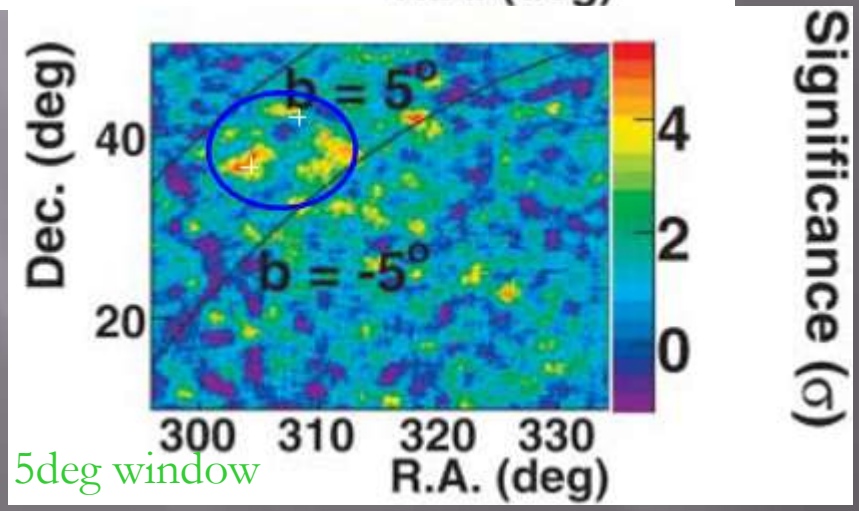
~12TeV

The Cygnus region (2)

MGRO J2033+42 MGRO J2019+37



0.9deg window



5deg window

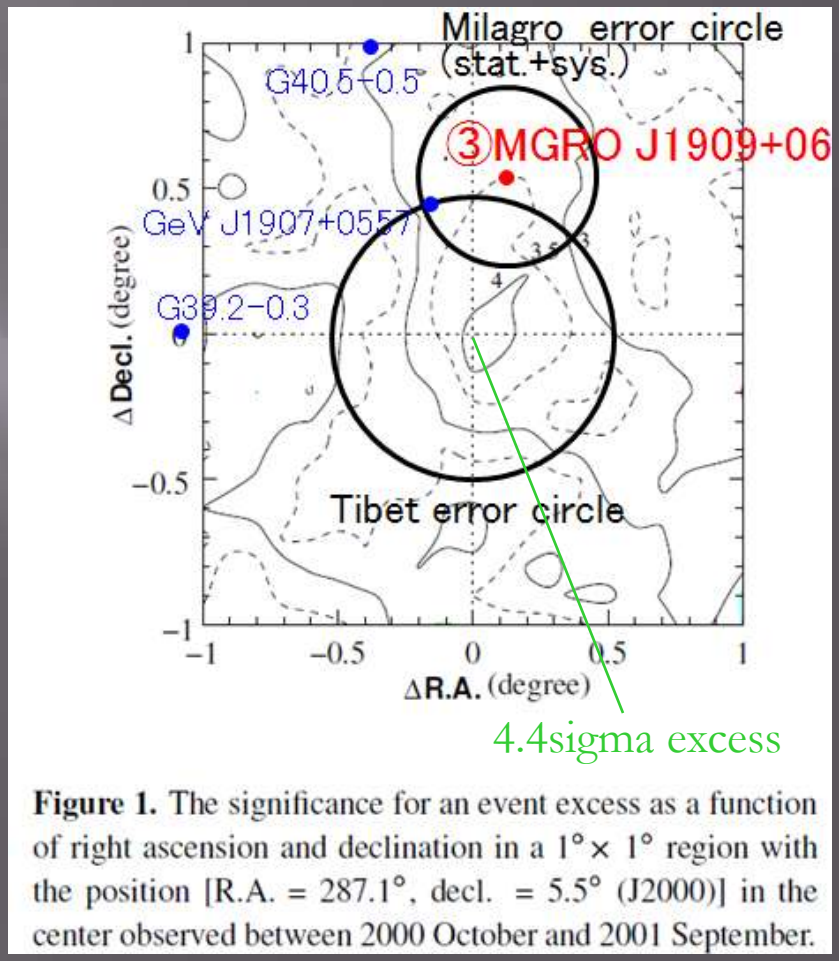


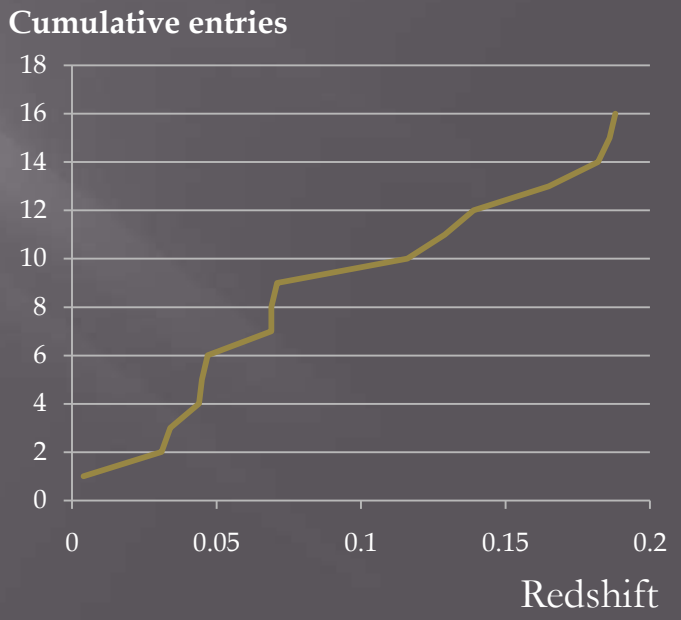
Figure 1. The significance for an event excess as a function of right ascension and declination in a 1°× 1° region with the position [R.A. = 287.1°, decl. = 5.5° (J2000)] in the center observed between 2000 October and 2001 September.

Tibet air shower array, Yangbajing, China

Extragalactic sources [17]

Source	Redshift	Sp. Index	Types	Discovery	Observation
M 87	0.004	2.9	FR-I	HEGRA	HESS
Mkn 421	0.031	2.2	HBL	Whipple	many
Mkn 501	0.034	2.4	HBL	Whipple	many
1ES 2344+514	0.044	2.9	HBL	Whipple	MAGIC
Mkn 180	0.045	3.3	HBL	MAGIC	
1ES 1959+650	0.047	2.4	HBL	7TA	many
BL Lac	0.069	3.6	LBL	MAGIC	
PKS 0548-322	0.069		HBL	HESS	
PKS 2005-489	0.071	4.0	HBL	HESS	
PKS 2155-304	0.116	3.3	HBL	Durham	HESS
1ES 1426+428	0.129	3.3	HBL	Whipple	HEGRA
1ES 0229+200	0.139		HBL	HESS	
H 2356-309	0.165	3.1	HBL	HESS	
1ES 1218+304	0.182	3.0	HBL	MAGIC	VERITAS
1ES 1101-232	0.186	2.9	HBL	HESS	
1ES 0347-121	0.188		HBL	HESS	
PG 1553	0.3?	4.0	HBL	HESS/MAGIC	

Mostly nearby, High-freq. peaked blazars (HBL) (only one LBL)



Gamma-ray absorption by EBL (1)

$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^-$

Extragalactic Background Radiation

Mean free path for e^+e^- pair production

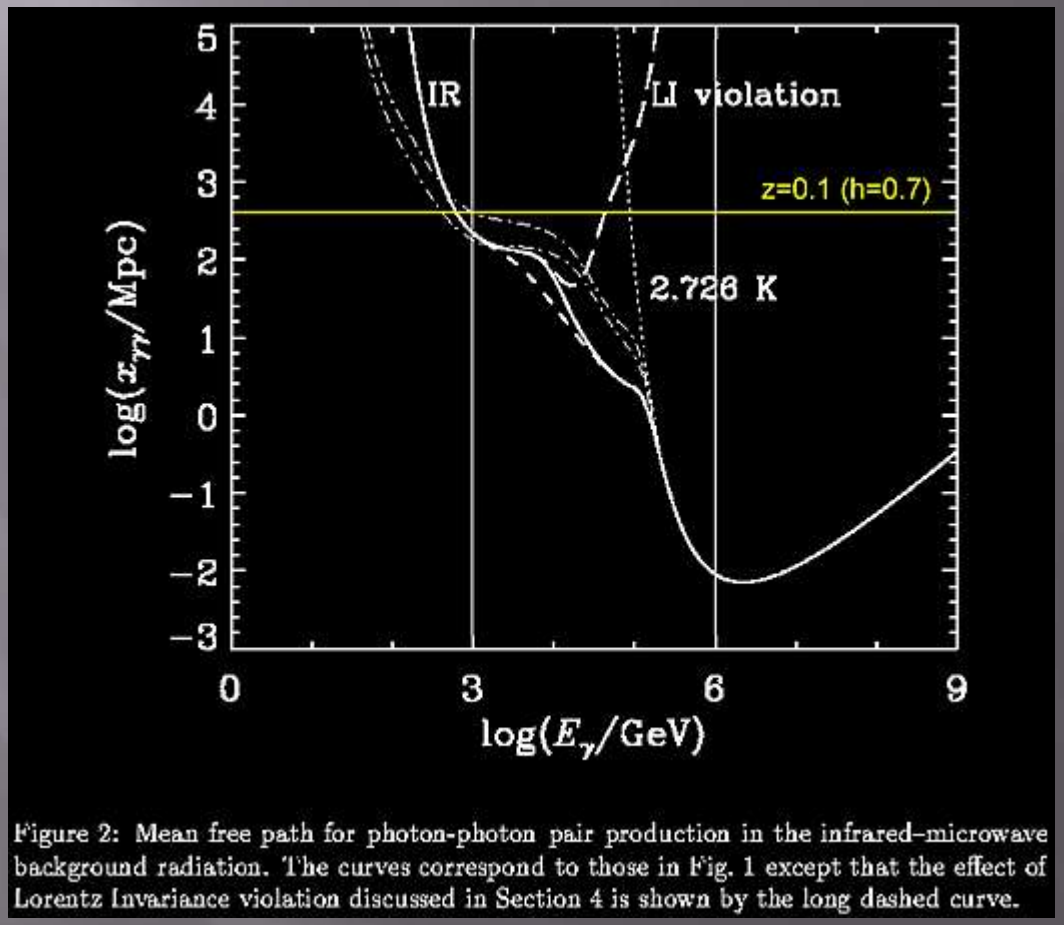
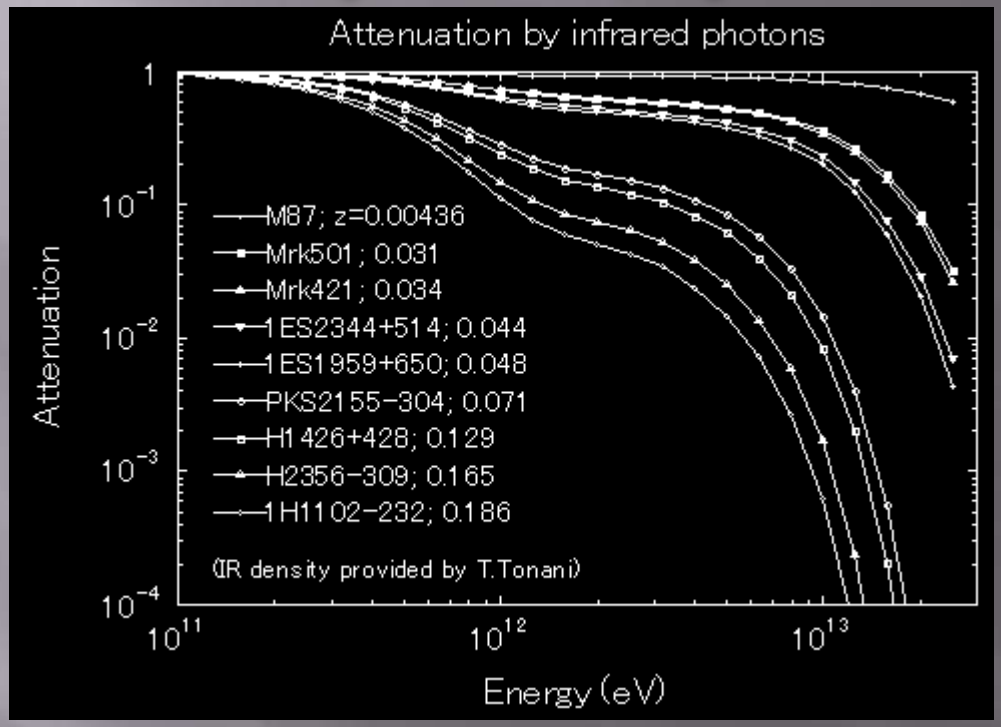


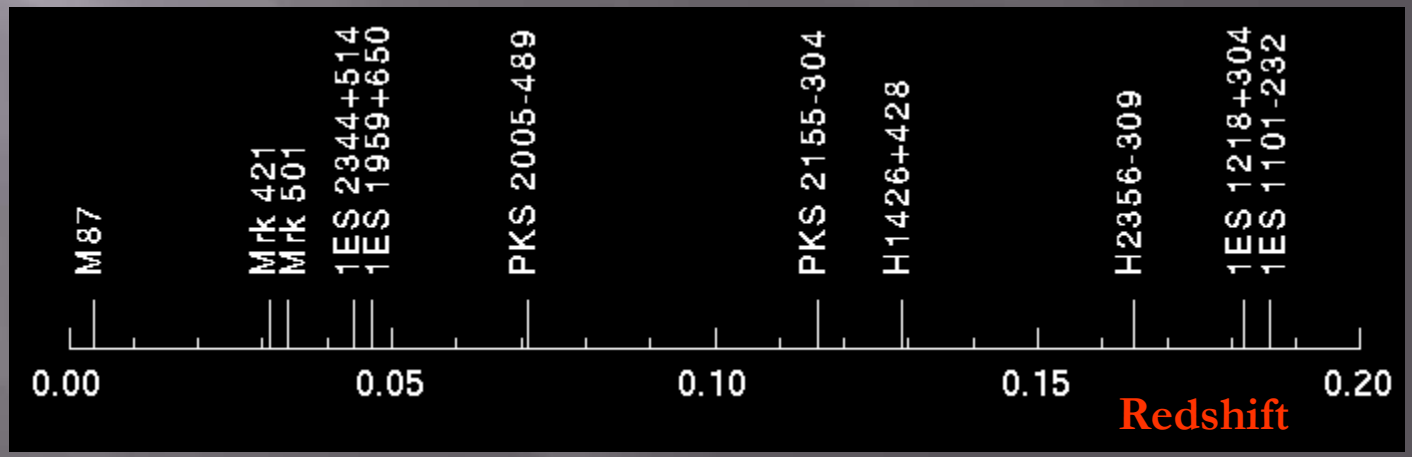
Figure 2: Mean free path for photon-photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz Invariance violation discussed in Section 4 is shown by the long dashed curve.

Protheroe & Meyer, Phys.Lett. B493 (2000) 1

Gamma-ray absorption on EBL (2)



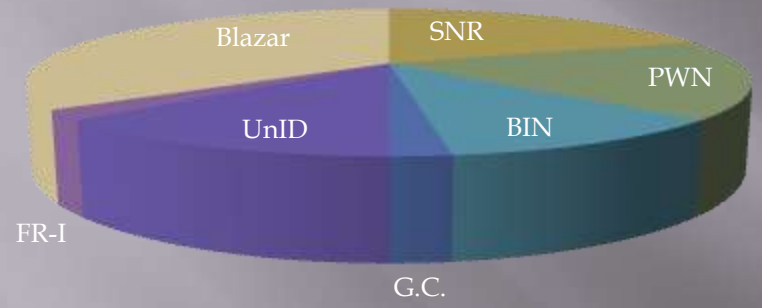
We need many samples of AGNs at various redshifts!

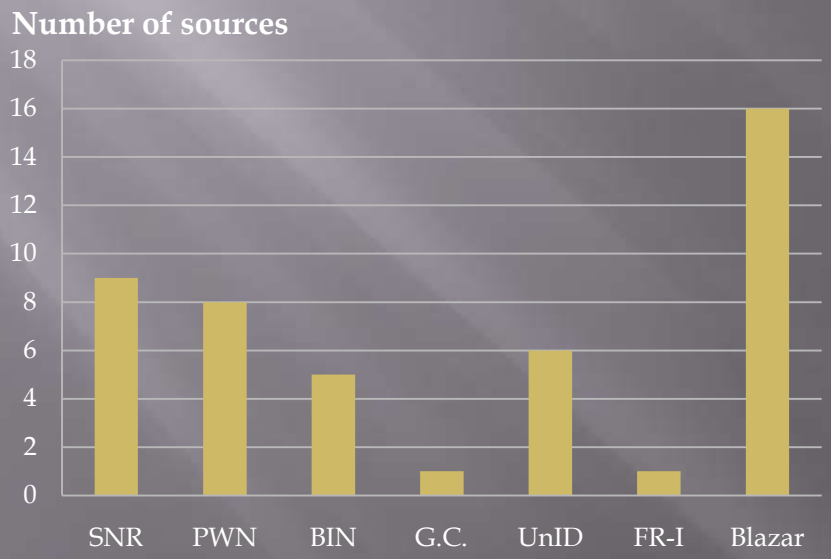


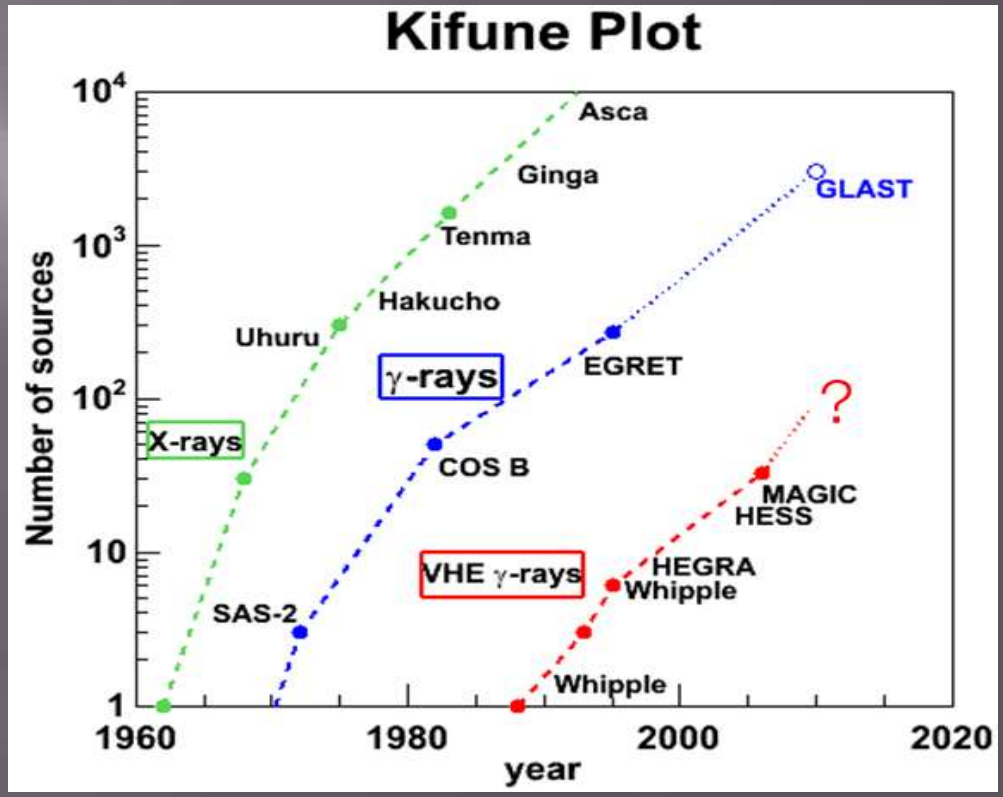
Classification by M.Teshima, CTA Workshop, Paris, March 2007

46 sources in the TeV region

(+ diffuse sources)

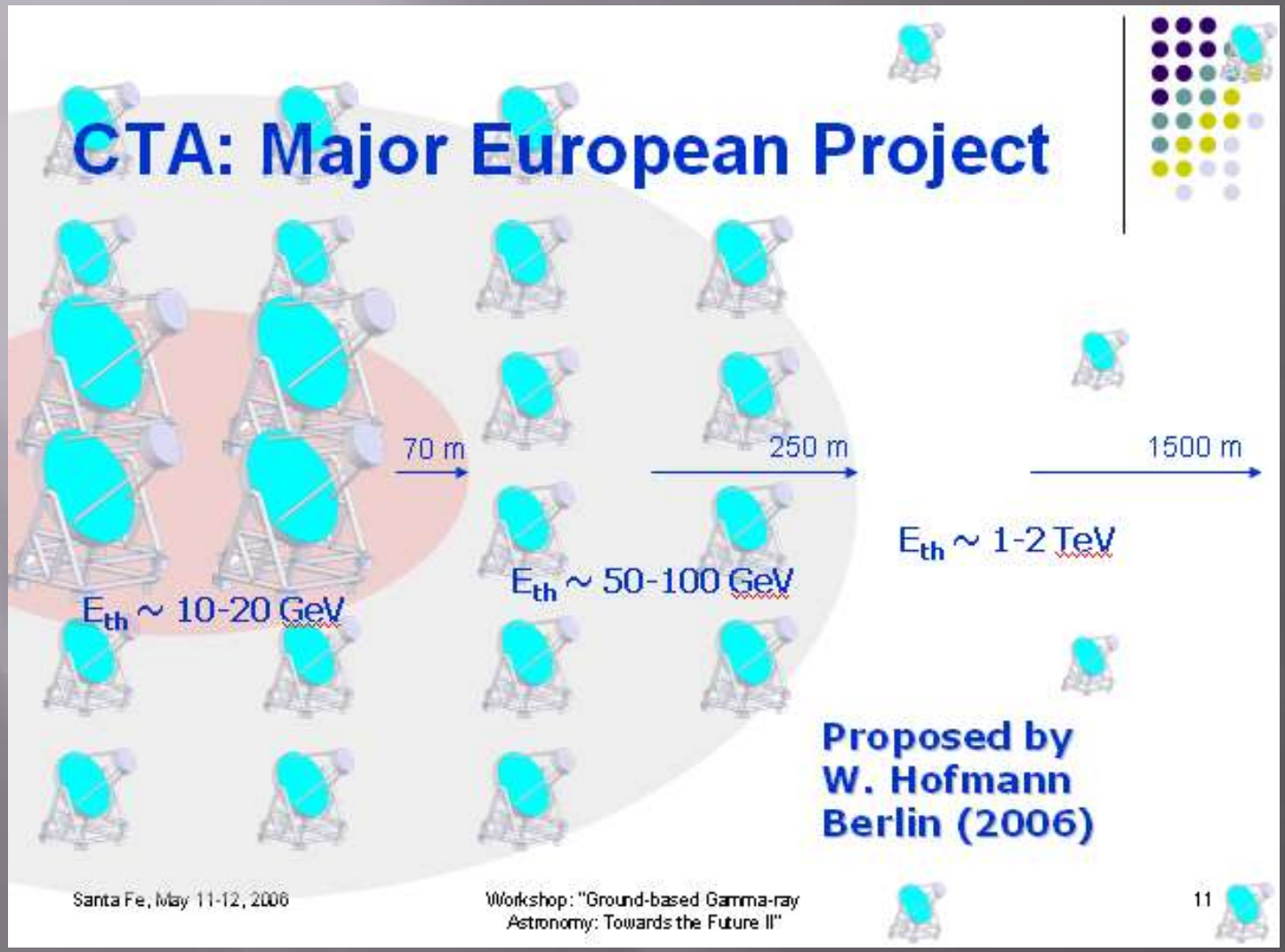






http://www.mpi-hd.mpg.de/hfm/CTA/

CTA (Cherenkov Telescope Array)



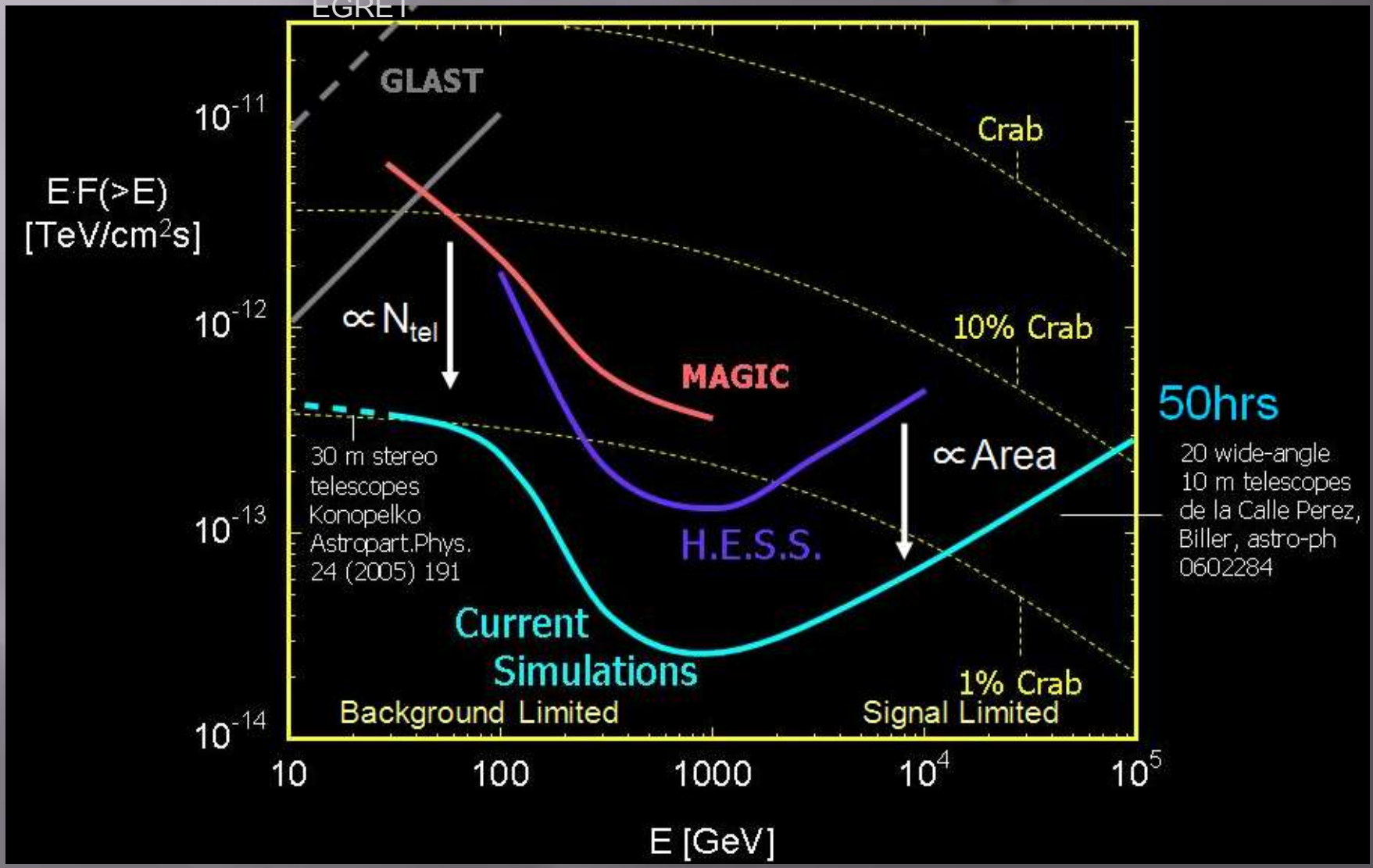
North array
(*10GeV-1TeV)
South array
(*10GeV-100TeV)

Total ~150M€

Konopelko, Santa Fe WS, May 2006

Hofmann; http://www.mpi-hd.mpg.de/hfm/CTA/

CTA sensitivity



Summary

- Very high energy gamma-ray sources may contain large varieties, including both Galactic and extragalactic objects.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- Supernova remnants are confirmed to be very-high-energy particle accelerators: an important evidence of cosmic ray origin! Plus others!
- Fundamental question in cosmic rays still remains: electron origin or proton origin?
- The "third generation" Cherenkov telescopes are working hard (and "fourth" ones are planned)– more fun!