Very High-Energy Gamma-ray Astronomy

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University of Hong Kong,
21st June 2010

References

- Aharonian et al. 2008 (review in 2008)
- Hinton and Hofmann 2010 (ARA&A)
- Voelk and Bernloehr (Experimental Astronomy, 25:173-191, 2009, arXiv:0812.4198)
- Online catalogs, e.g. TeVCat

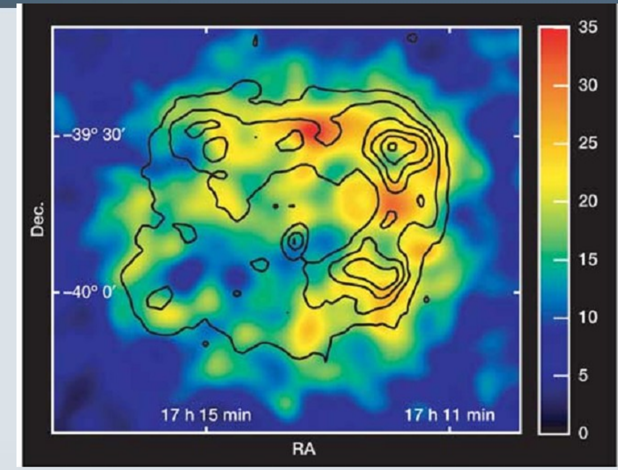
- My biased, personal collection of some VHE highlights....

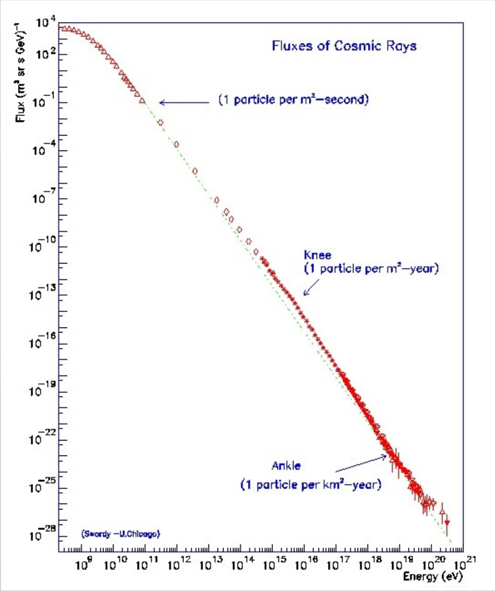
Contents

- The questions in VHE (>100 GeV) astronomy
- VHE observation techniques
- Galactic objects: pulsar wind nebulae (PWNe) and shell-type SNRs
- Extragalactic objects: AGN, radio galaxies
- GRBs
- Globular clusters
- Future VHE experiments

The questions in VHE Astronomy

- Astrophysics
  - Probing the physics and the environment of "cosmic accelerators": *neutron stars, SNRs, massive stars, supermassive black hole, jets, etc.*
  - Origin of *cosmic rays*
- Astroparticle Physics
  - Indirect search for *dark matter*
  - Search for energy dependence of the speed of light: break of "Lorentz invariance" or not?
- Cosmology
  - Indirect measure of the Extragalactic Background light: Help us to understand star formation history
  - Non-thermal content of *galaxy clusters*



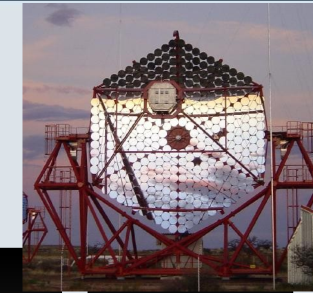


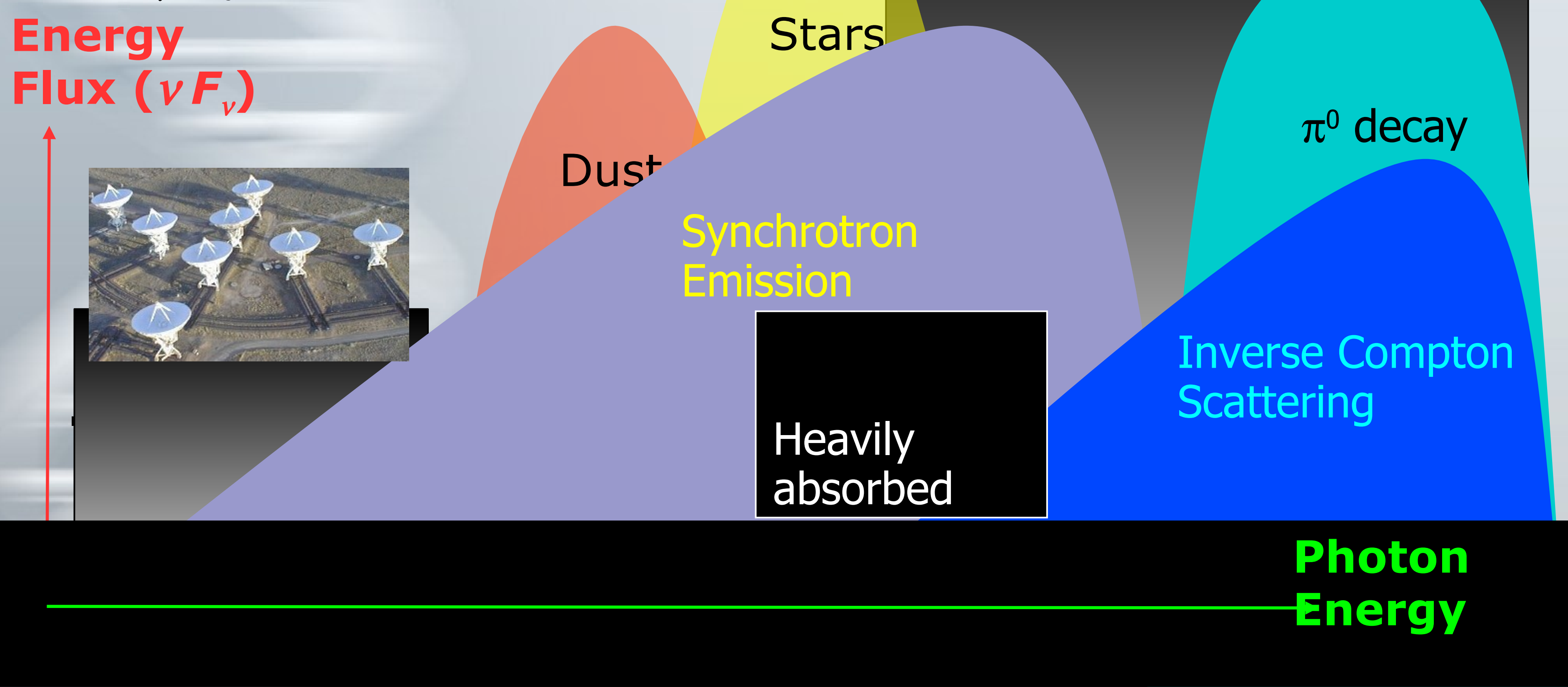
The 'Non-Thermal Windows'

- Tracers for ultra-relativistic electrons and hadrons
  - Non-thermal windows
    - Radio (low energy electrons)
    - Hard X-ray
    - γ-ray

Satellites

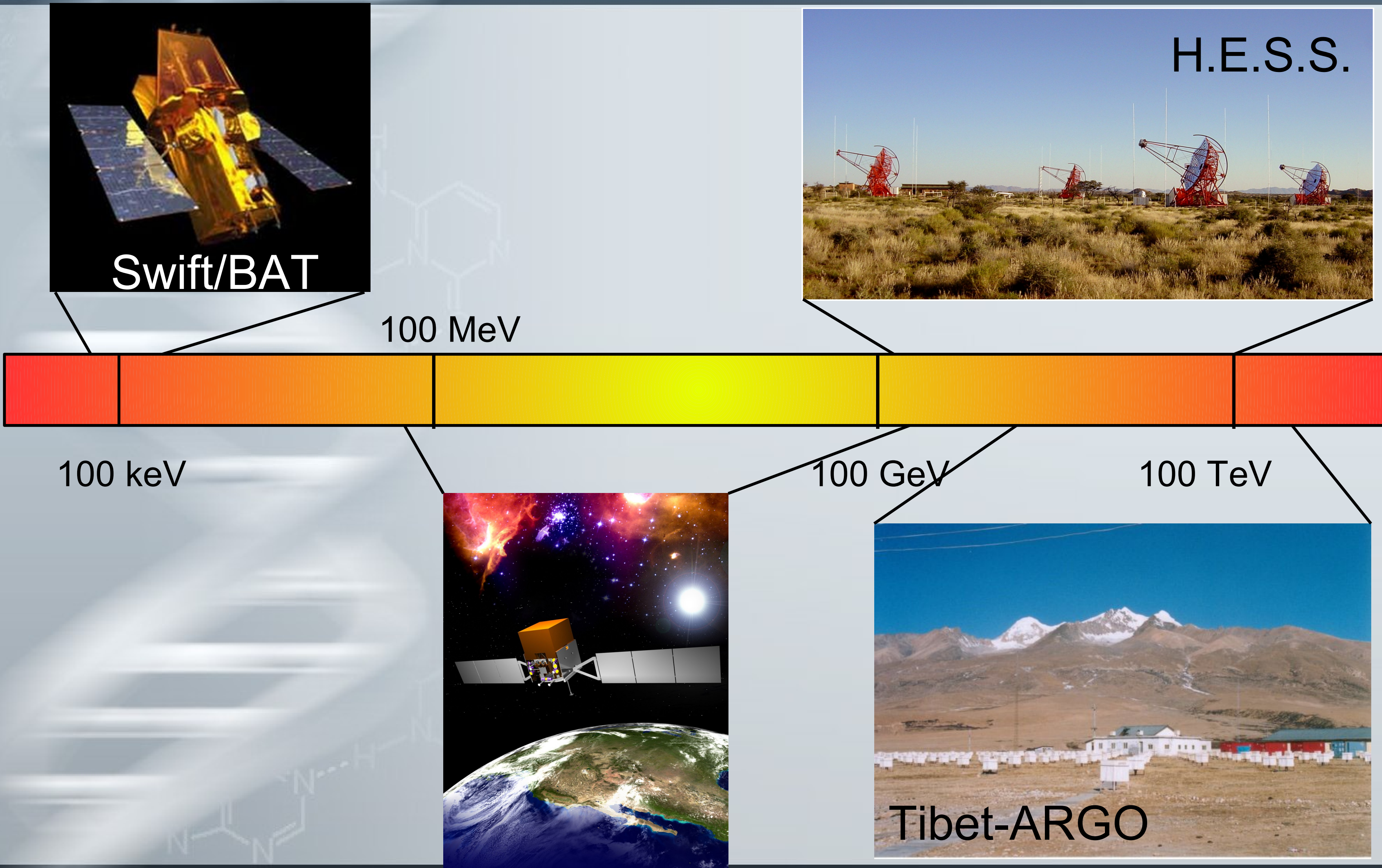
Cherenkov Telescopes

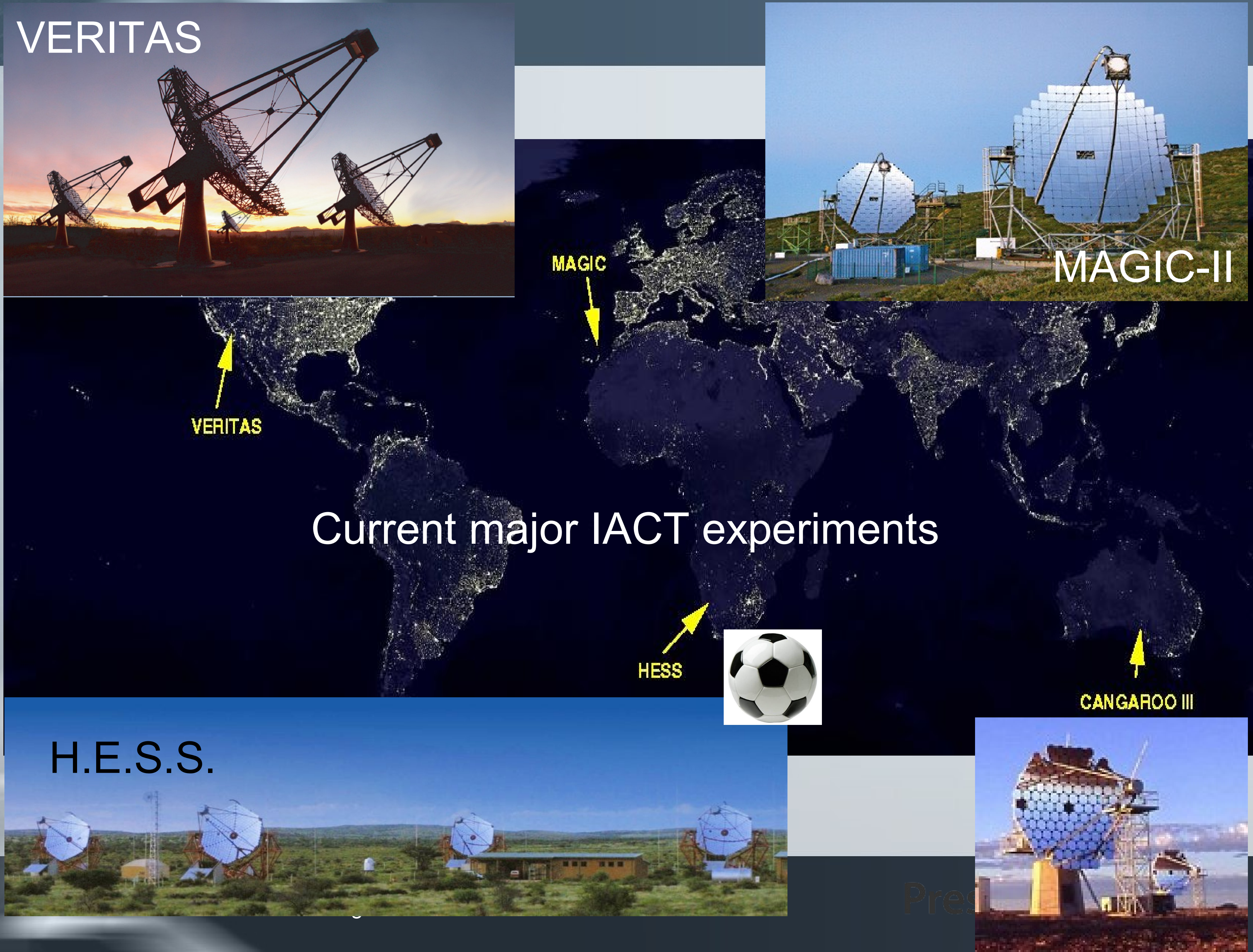




The detectors

A family of (selected) γ-ray detectors




VERITAS
MAGIC-II
MAGIC
VERITAS
Current major IACT experiments
HESS
CANGAROO III
H.E.S.S.

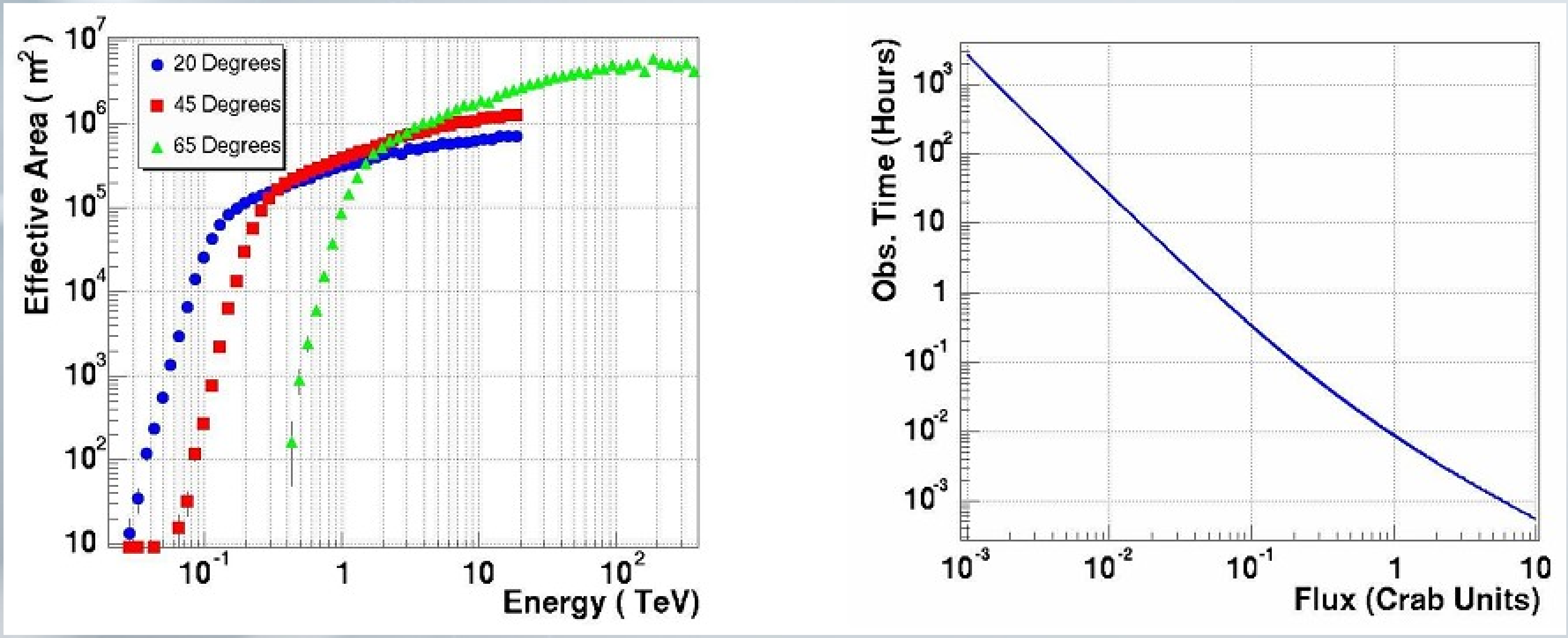
Performance of Fermi/LAT and IACTs

Gamma-ray detectors in space and on ground

Advantages of IACTs over Fermi:
(a) collection area higher by a factor of 10^4 ;
(b) better angular resolution;
(c) much lower background photons for sources located at the Galactic plane.

Disadvantages of IACTs over Fermi:
(a) Lower duty cycle;
(b) smaller field of view.

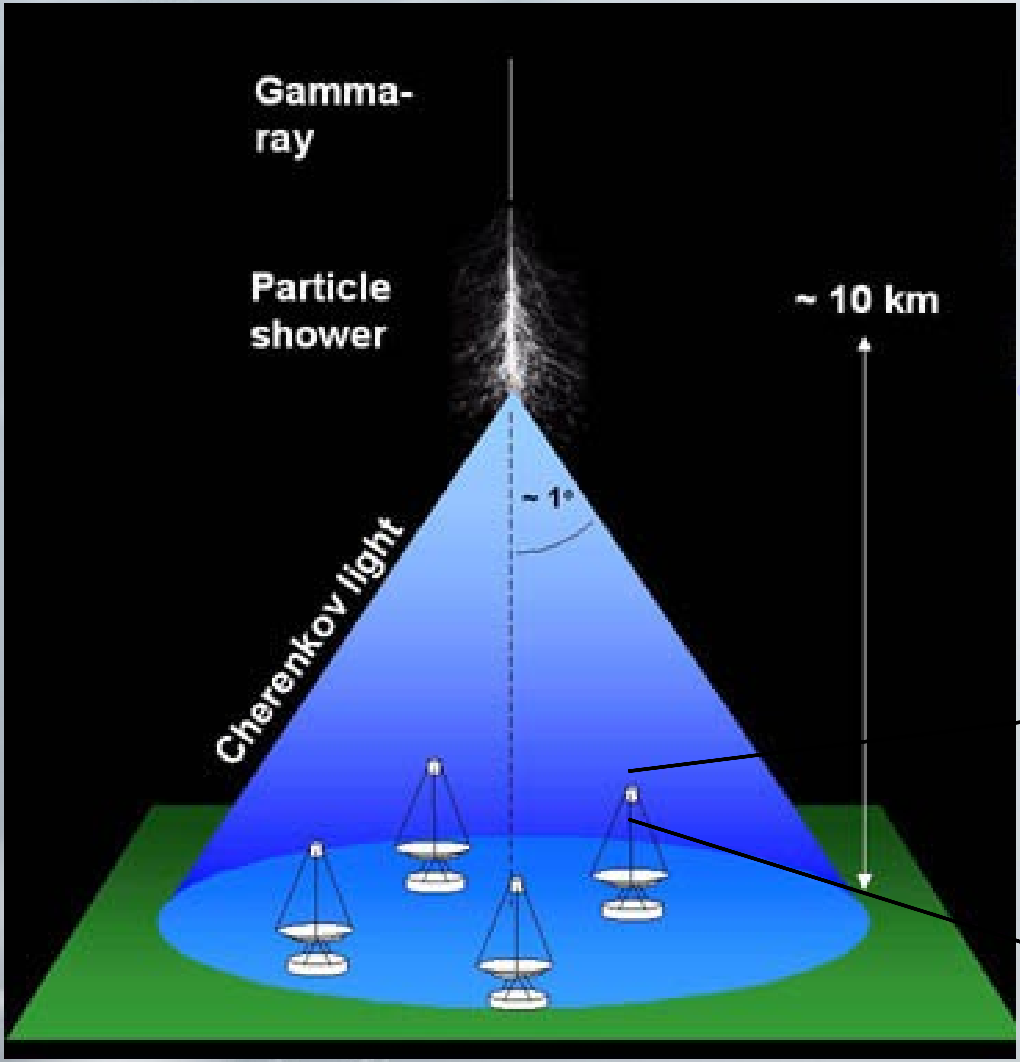
Effective collection area & sensitivity of H.E.S.S.



Aharonian, et. al. (H.E.S.S. Collaboration), 2006

Observation principle

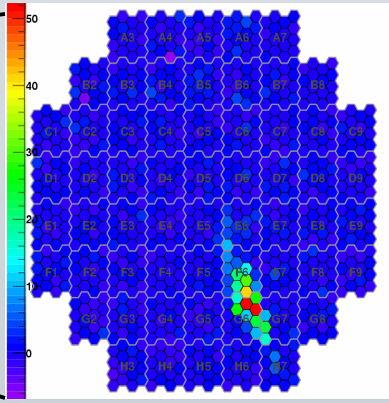
Air shower and Cherenkov light



- Pair production
  - $\gamma \rightarrow e^+ e^-$
- Bremsstrahlung
  - $e^- + (\gamma) \rightarrow e^- + \gamma$
- Cascade develops

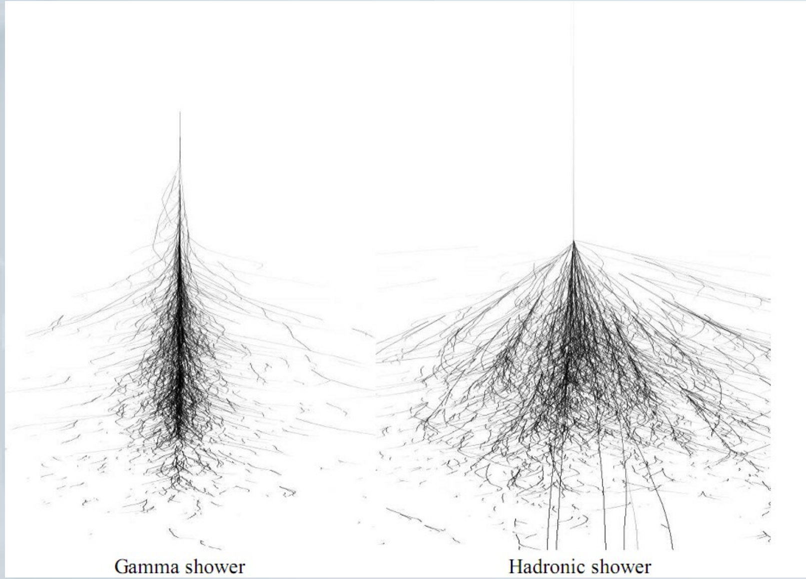
Cherenkov light

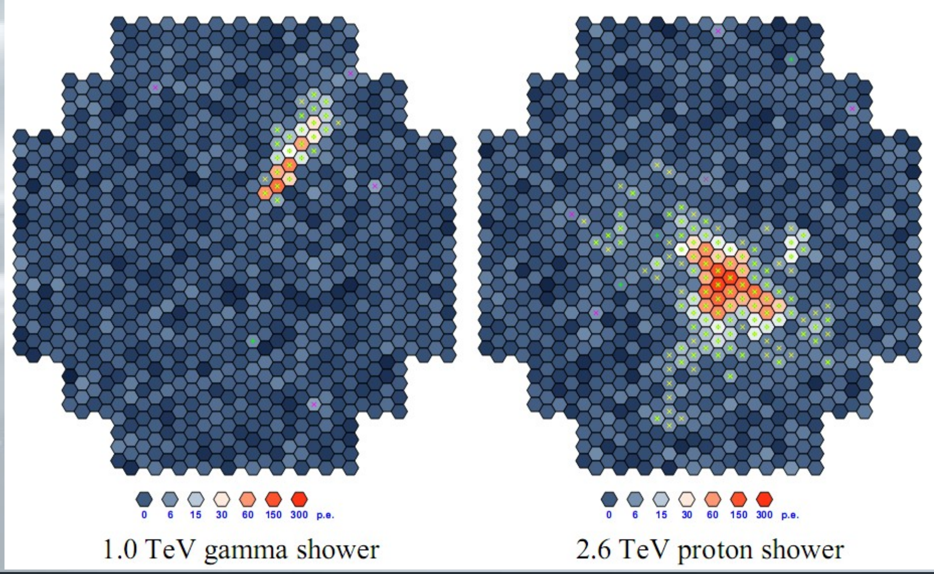
- ~10 ns light ‘flash’
- 1° angle at 10 km height → 100 m radius ‘light-pool’



A γ-ray image in one of the cameras

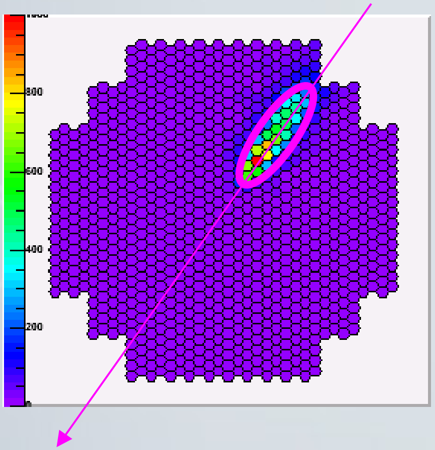
Disentangle γ-ray showers from that of cosmic rays

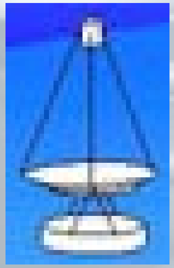




Voelk & Bernloehr, 2009

Stereo technique

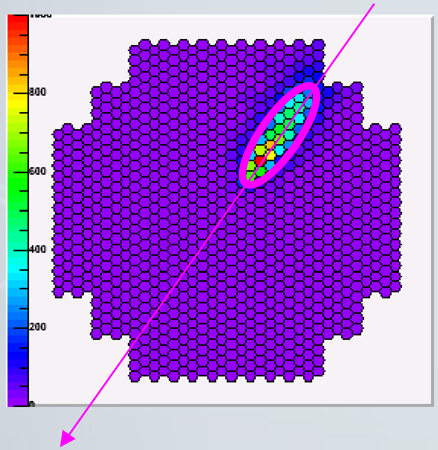


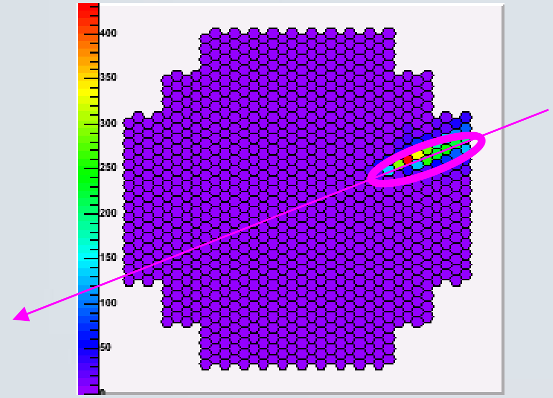


PresentationPoint

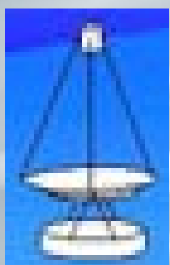
Stereo technique

X 2

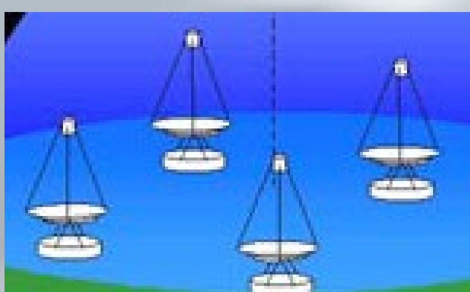


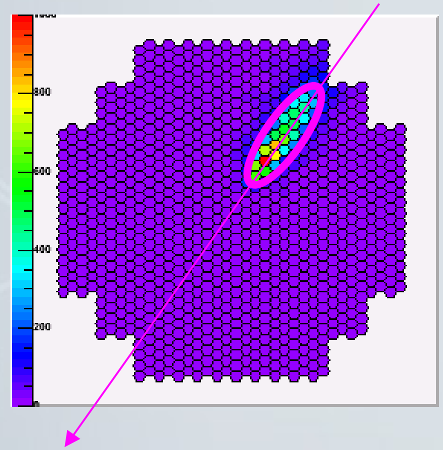


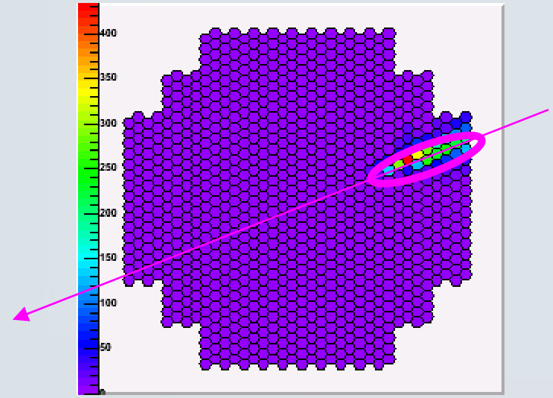
Stereo technique



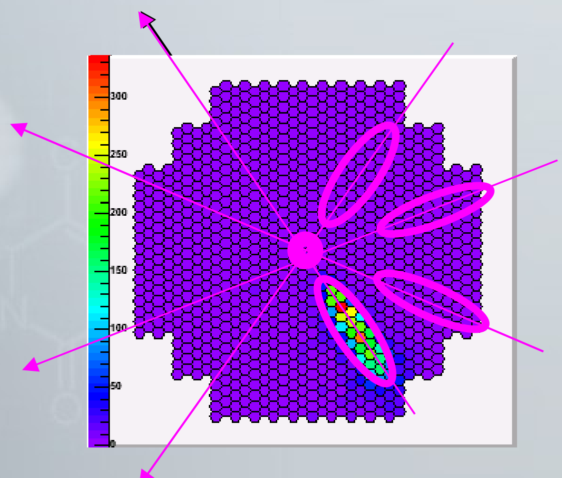
X 4 =

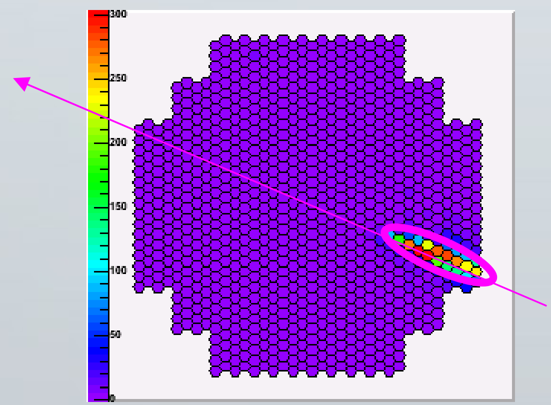




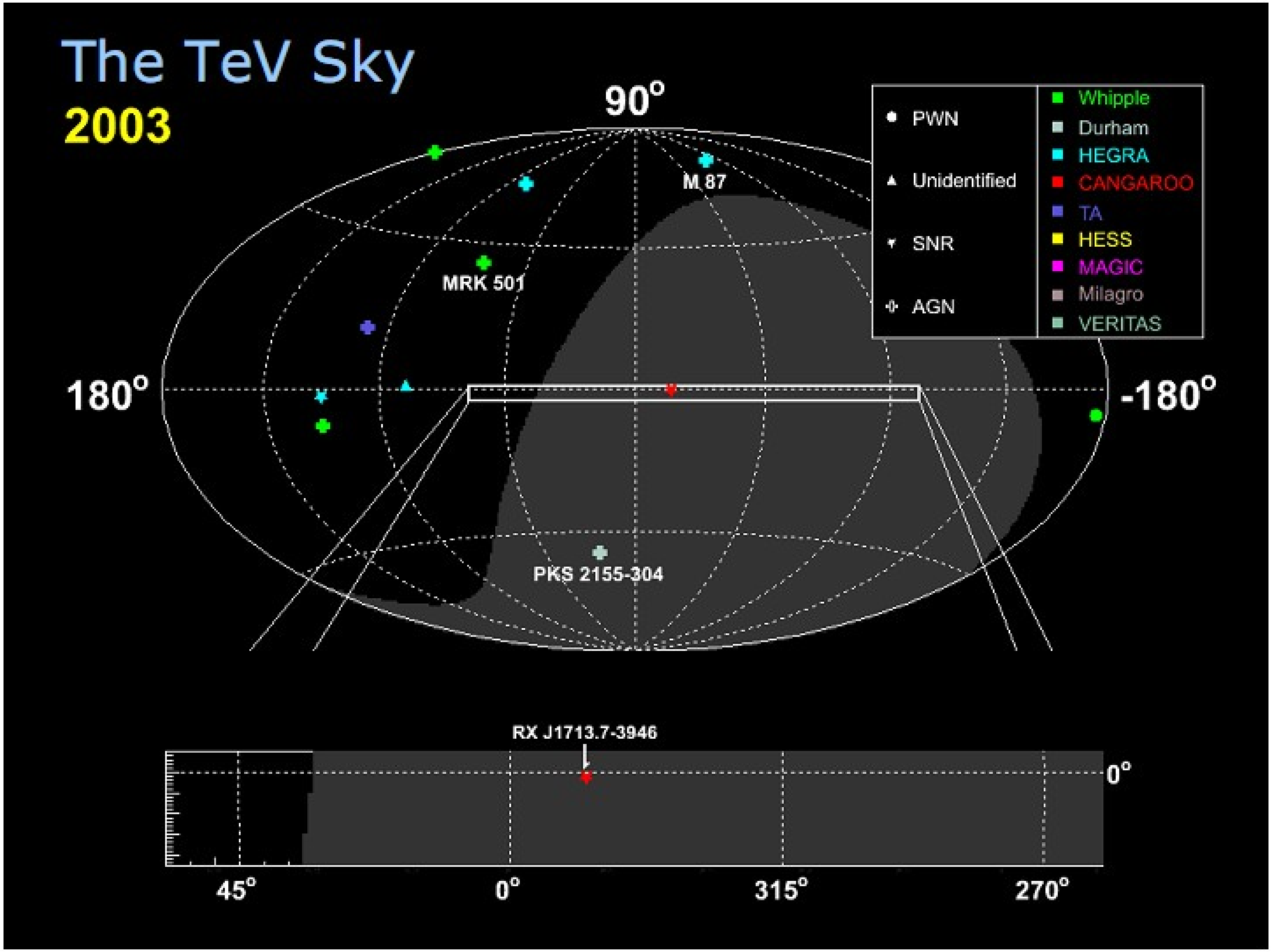


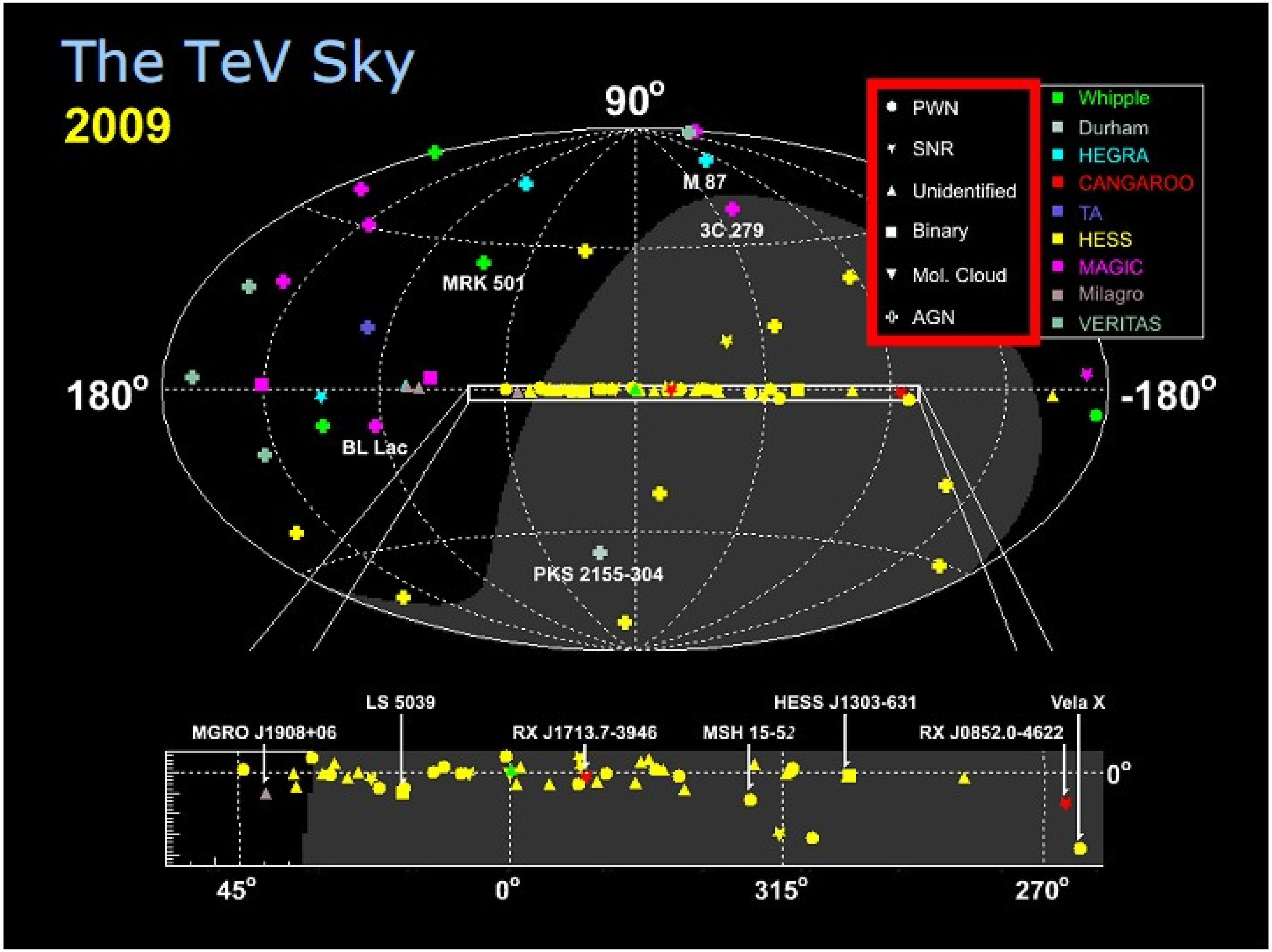
Reconstruct the source position in the camera





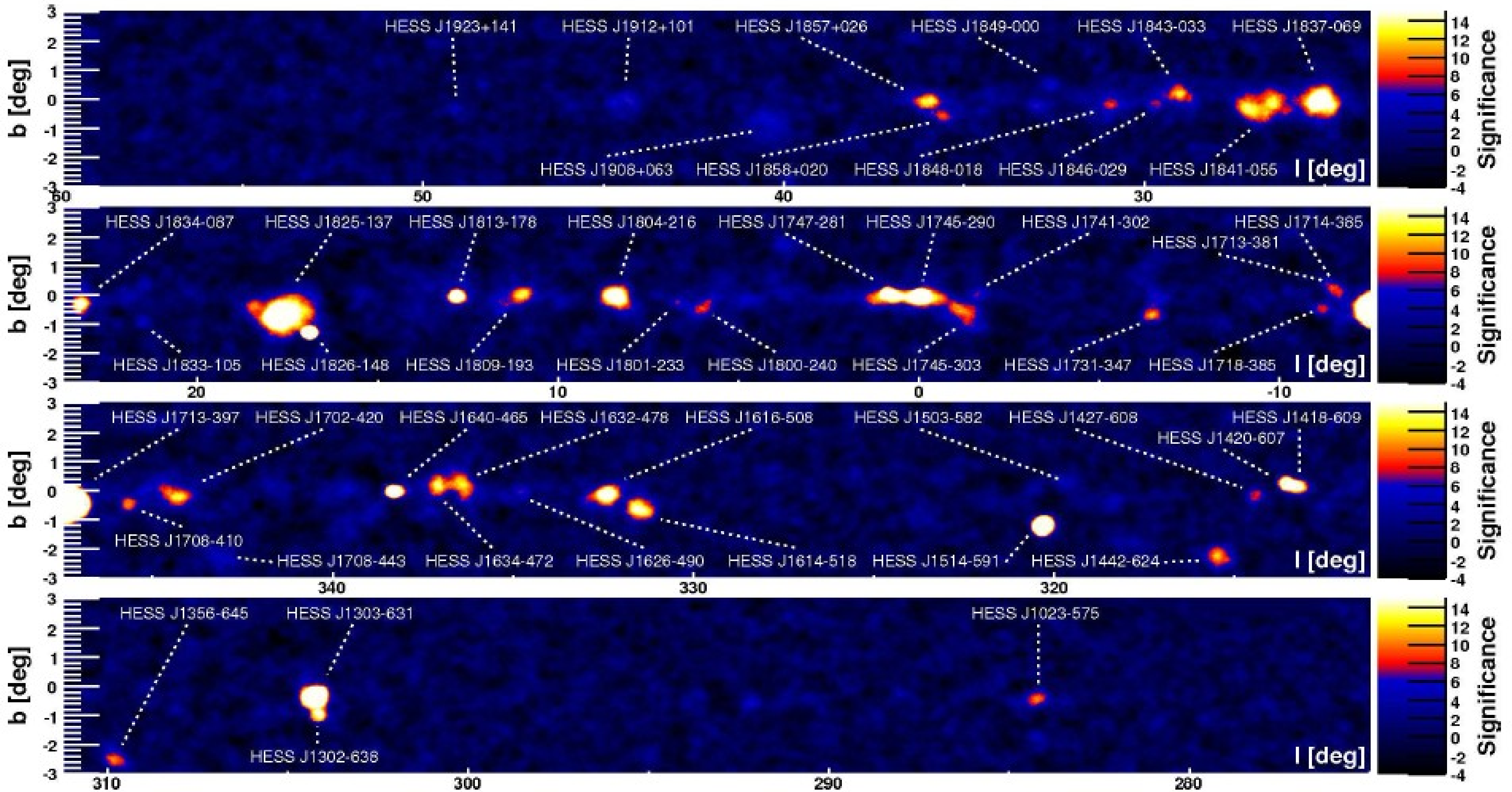
What have we seen?


The TeV Sky
2003
90°
180°
-180°
M 87
MRK 501
PKS 2155-304
PWN
Unidentified
SNR
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
RX J1713.7-3946
0°
45°
0°
315°
270°


The TeV Sky
2009
90°
180°
-180°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
LS 5039
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
HESS J1303-631
Vela X
RX J0852.0-4622
0°
45°
0°
315°
270°

I. Galactic sources

H.E.S.S. galactic plane survey (2003-2009)



Chaves+ @ ICRC 2009

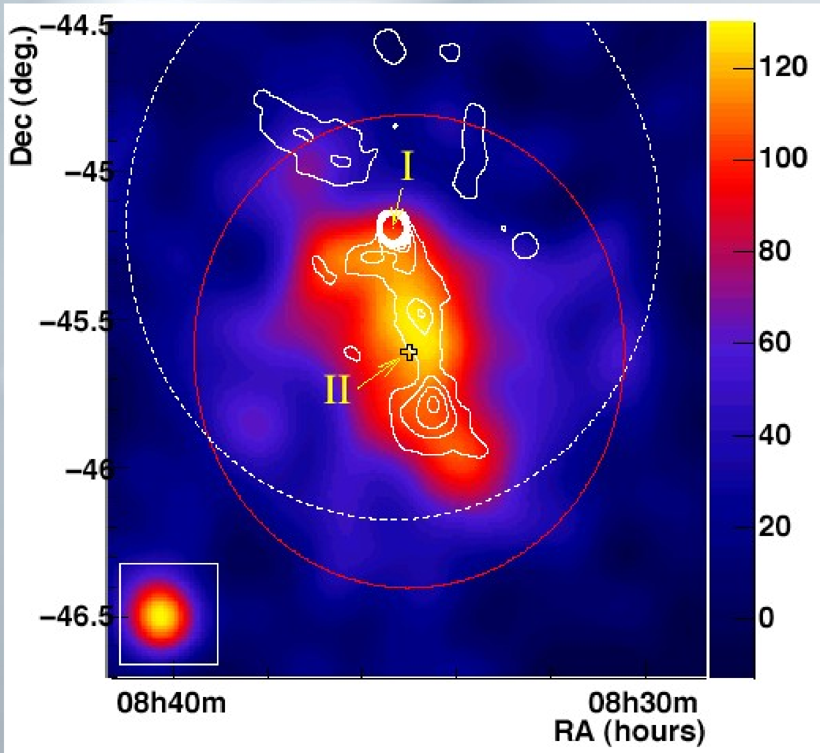
Selected Galactic VHE sources

Table 2 Selected Galactic VHE γ-ray sources with well-established multiwavelength counterparts

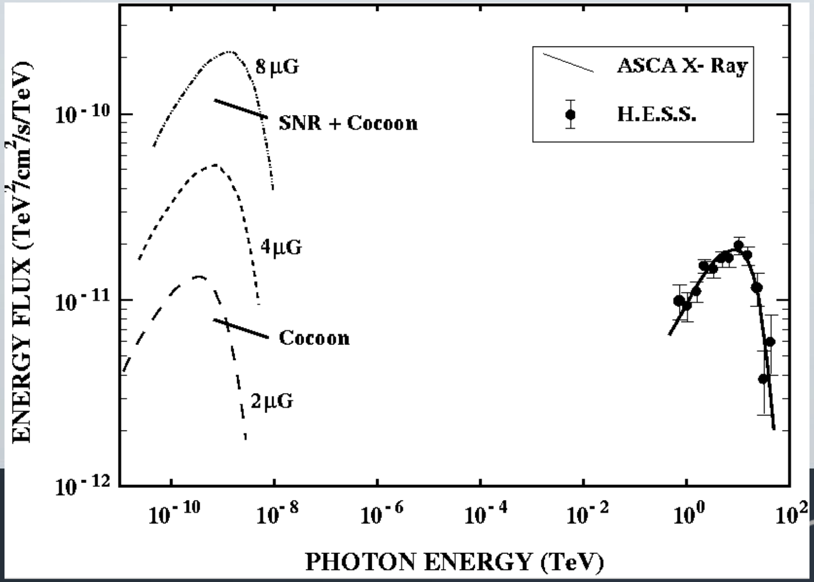
Object	Type	Method	Flux	Reference
PSR B1259-63	Binary	Pos/Var	7*	Aharonian et al. (2005b)
LS 5039	Binary	Pos/Per	3*	Aharonian et al. (2006a)
LS I +61 303	Binary	Pos/Var	16*	Albert et al. (2006b)
RX J1713.7–39046	SNR	Mor	66	Aharonian et al. (2004)
Cassiopeia A	SNR	Pos	3	Aharonian et al. (2001)
Vela Junior	SNR	Mor	100	Katagiri et al. (2005)
RCW 86	SNR	Mor	5–10?	Aharonian et al. (2008)
SN 1006	SNR	Mor	?	Naumann-Godo et al. (2008)
Crab Nebula	PWN	Pos	100	Weekes et al. (1989)
G 0.9+0.1	PWN	Pos	2	Aharonian et al. (2005d)
MSH 15–52	PWN	Mor	15	Aharonian et al. (2005a)
HESS J1825-137	PWN	EDMor	12	Aharonian et al. (2006e)
Vela X	PWN	Mor	75	Aharonian et al. (2006g)

Hinton and Hofmann (2010)

Pulsar Wind Nebulae: Vela X

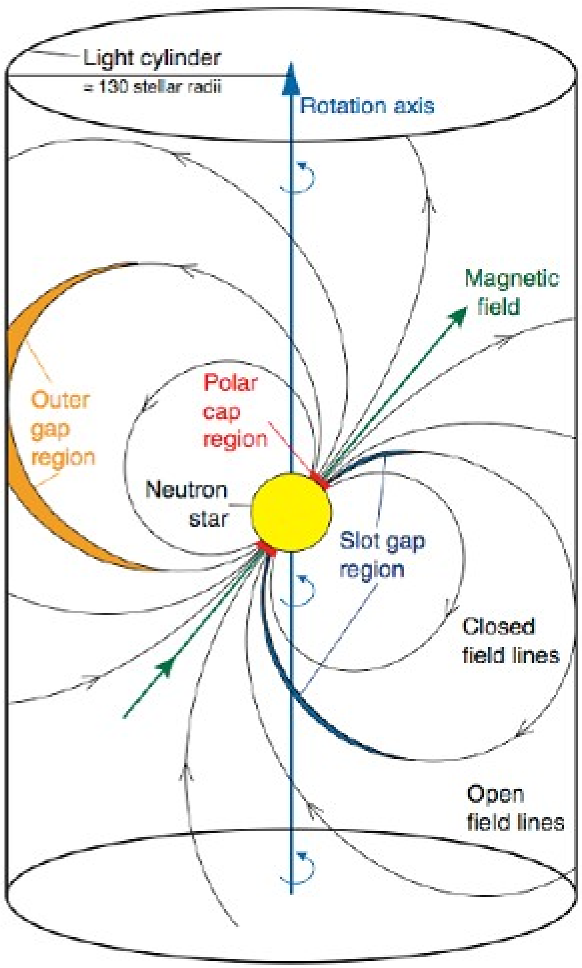


- Spectral curvature : νF_{ν} peaks in VHE, first clear indication
- *"VHE observations of inverse Compton scattering of the CMBR allow direct inference of the* ***spatial*** *and* ***spectral*** *distribution of non-thermal electrons"*
- PWN spatially displaced from the pulsar
- Environmental effects, e.g. nearby molecular clouds

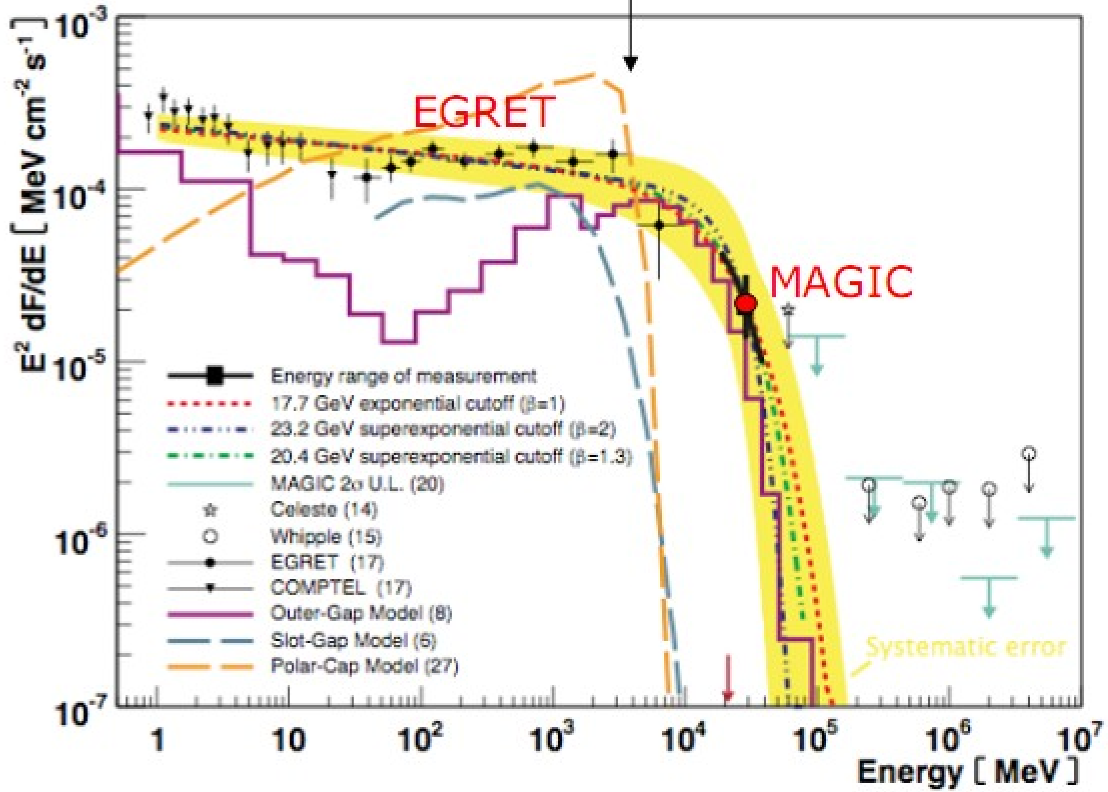


Aharonian, et al. (H.E.S.S. collaboration), 2006

MAGIC detection of the Crab pulsar above 25 GeV

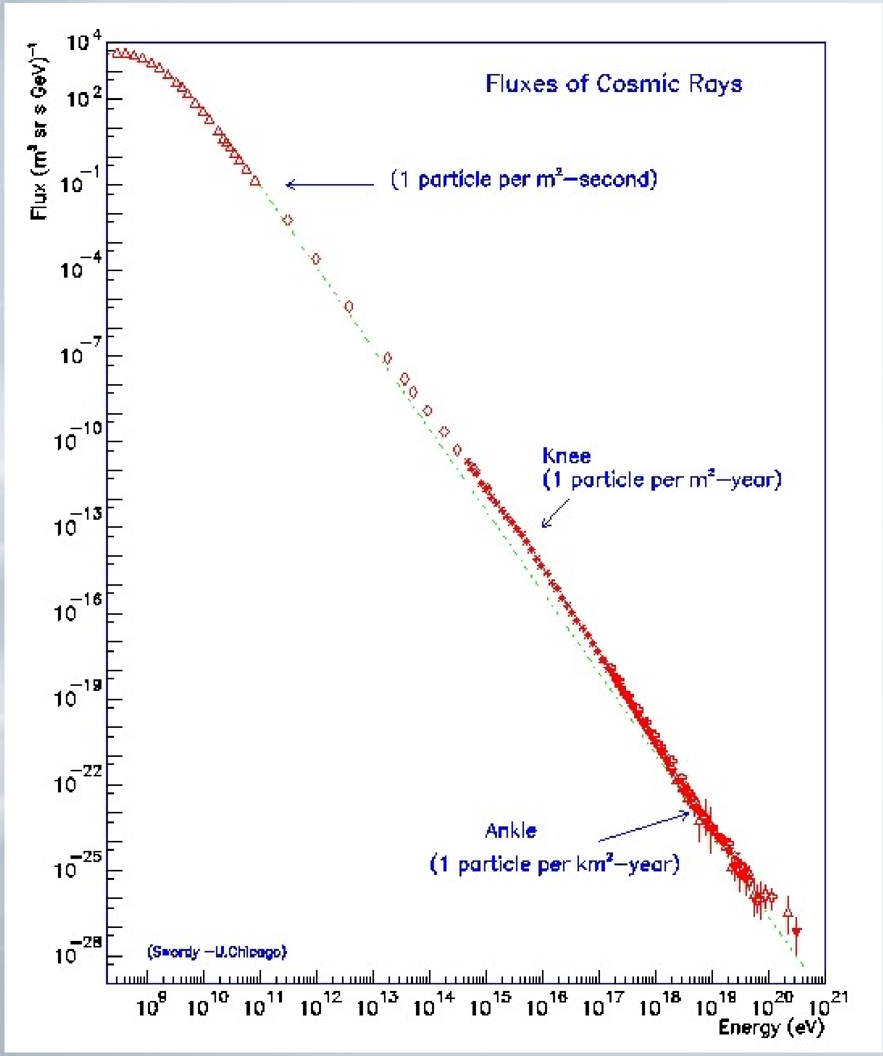


Emission from polar cap and slot gap cut off around 10 GeV due to pair production



Aliu, et al. (MAGIC collaboration), 2008, Science

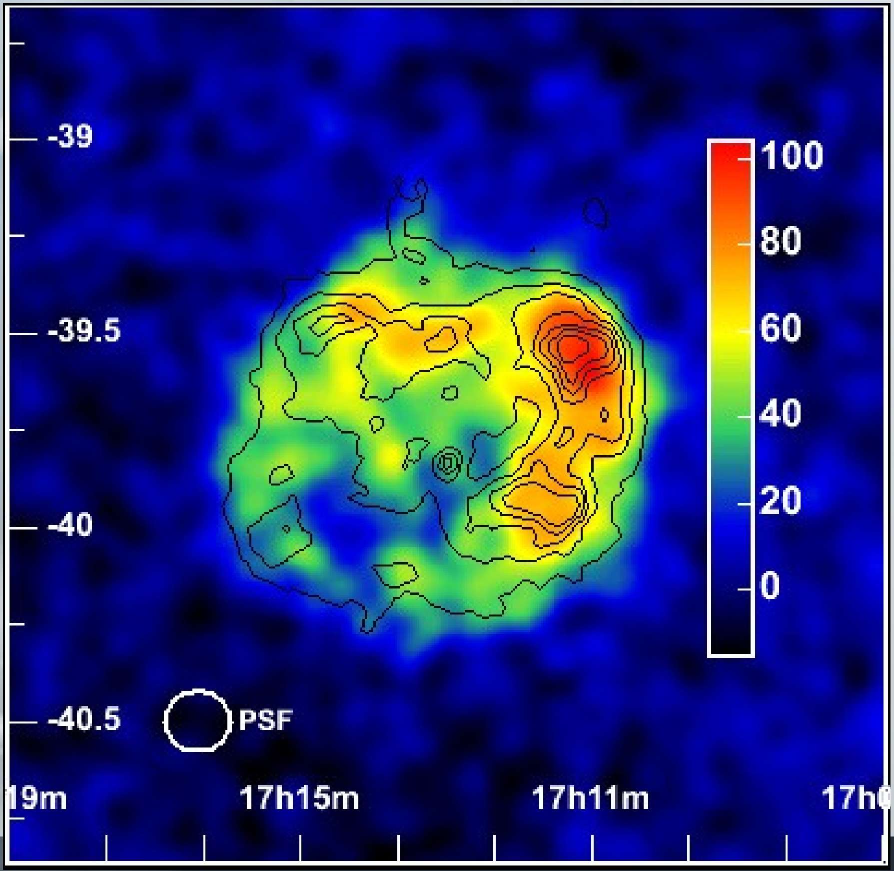
Origin of Cosmic-ray



Cosmic-ray spectrum

Resolved supernova-remnant: **RX J1713.7-39.46**

- Cosmic-rays up to 10^{15} eV has long been believed to come from Galactic supernova remnants
- Direct evidence hard to obtain: charge particles -> direction unknown
- Gamma-rays can be used to trace particle acceleration sites



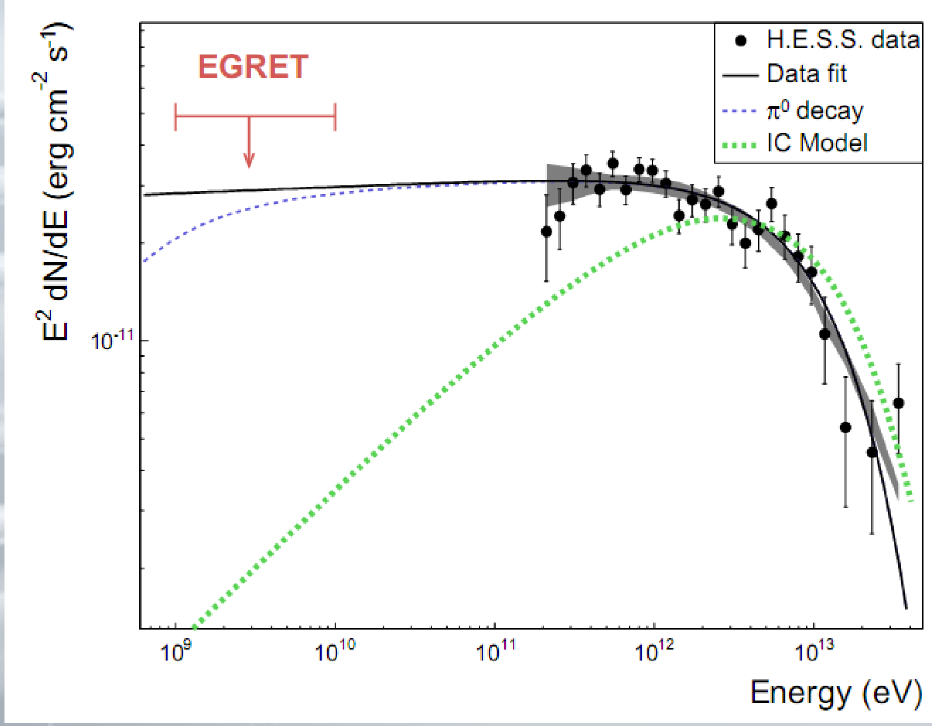
Color: HESS excess image

Contour: ASCA 1-5 keV smoothed

Aharonian et al., (H.E.S.S. collaboration), 2005, Nature

Have we seen the site of cosmic-ray acceleration?

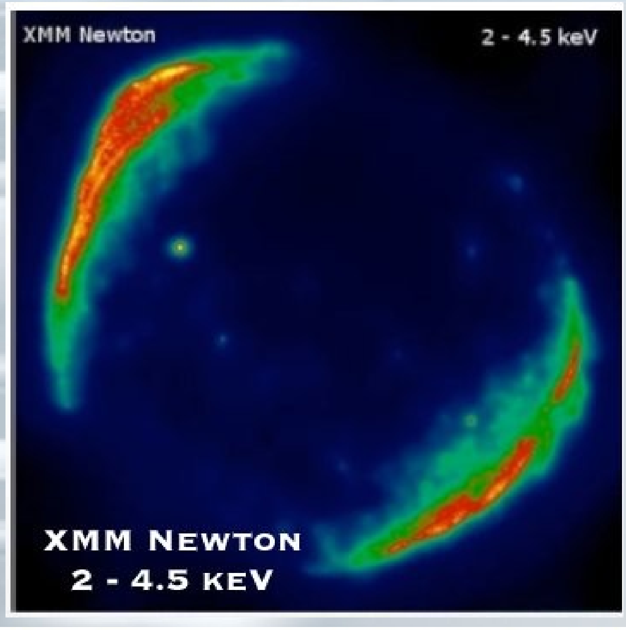
- Both electrons and protons can radiate gamma-rays
- To distinguish hadronic models against leptonic models, detailed modeling is needed
- Fermi/LAT results should give a more definitive answer

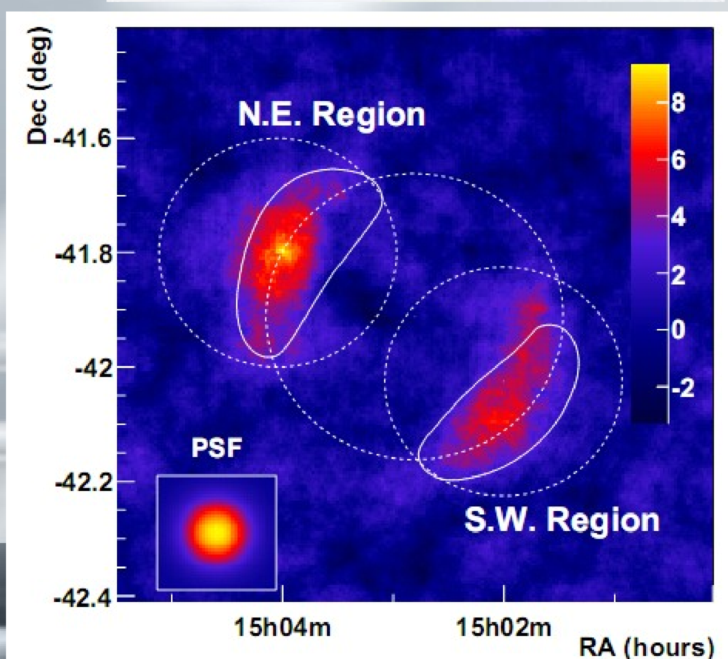


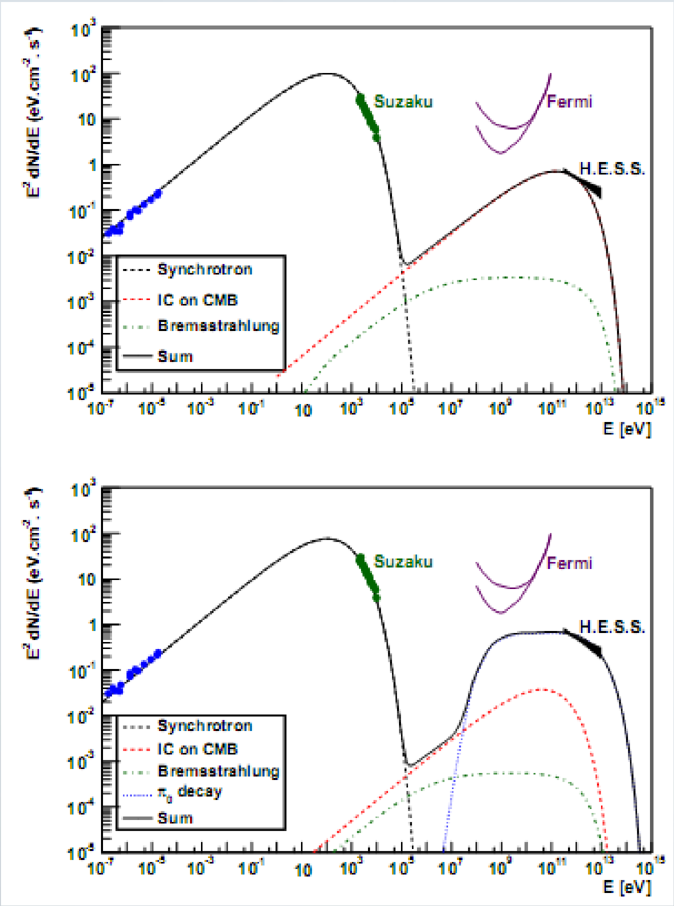
(David Berge, PhD thesis)

γ-ray spectrum of RX J1713.7-3946

SN 1006: recently discovered in VHE γ-rays







Aharonian, et al. (H.E.S.S. collaboration), 2010, accepted by A&A, arXiv: 1004.2124

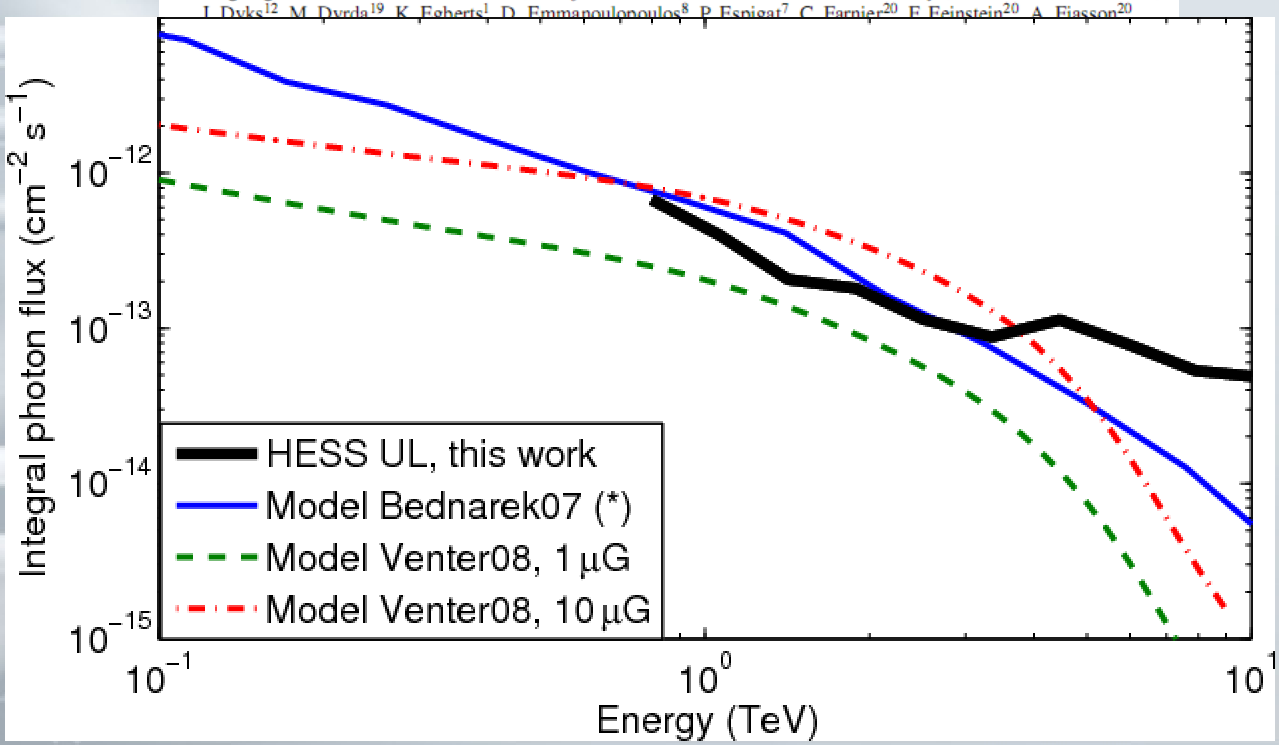
H.E.S.S. upper limits on 47 Tucanae

A&A 499, 273–277 (2009)
DOI: 10.1051/0004-6361/200811564

Astronomy & Astrophysics

HESS upper limit on the very high energy γ-ray emission from the globular cluster 47 Tucanae
(Research Note)

F. Aharonian[1,2], A. G. Akhperjanian[3], G. Anton[4], U. Barres de Almeida[5,⋆], A. R. Bazer-Bachi[6], Y. Becherini[7], B. Behera[8], K. Bernlöhr[1,9], C. Boisson[10], A. Bochow[1], V. Borrel[6], I. Braun[1], E. Brion[11], J. Brucker[4], P. Brun[11], R. Bühler[1], T. Bulik[12], I. Büsching[13], T. Boutelier[14], P. M. Chadwick[5], A. Charbonnier[15], R. C. G. Chaves[1], A. Cheesebrough[5], L.-M. Chounet[16], A. C. Clapson[1], G. Coignet[17], M. Dalton[9], M. K. Daniel[5], I. D. Davids[18,13], B. Degrange[16], C. Deil[1], H. J. Dickinson[5], A. Djannati-Ataï[7], W. Domainko[1], L. O'C. Drury[2], F. Dubois[17], G. Dubus[14], J. Dyks[12], M. Dyrda[19], K. Egberts[1], D. Emmanoulopoulos[8], P. Espigat[7], C. Farnier[20], F. Feinstein[20], A. Fiasson[20]



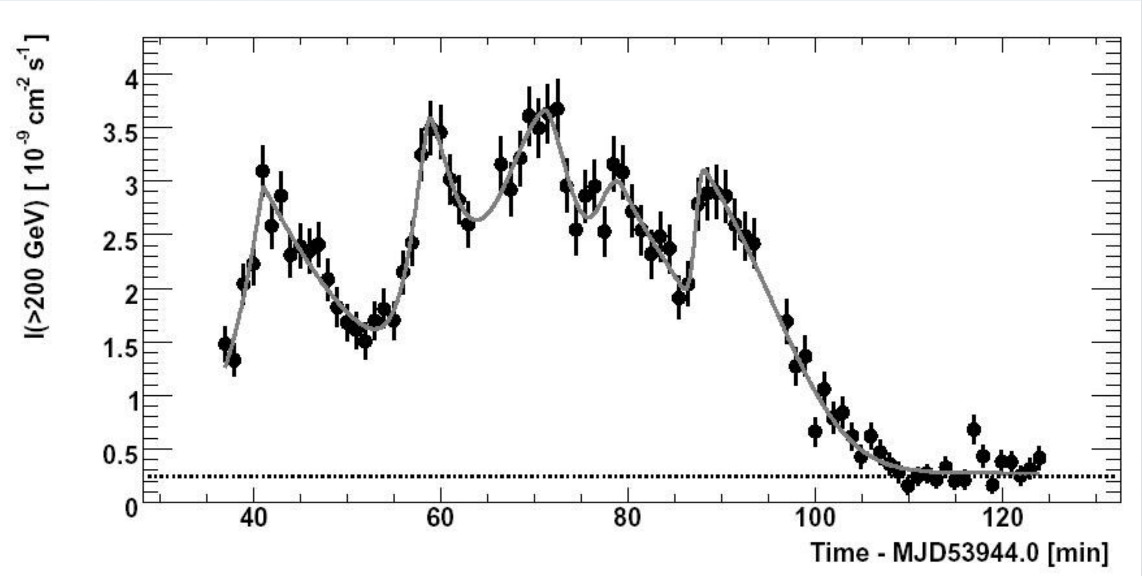
II. Extragalactic sources

PKS 2155-304 in 2006: extremely bright flares

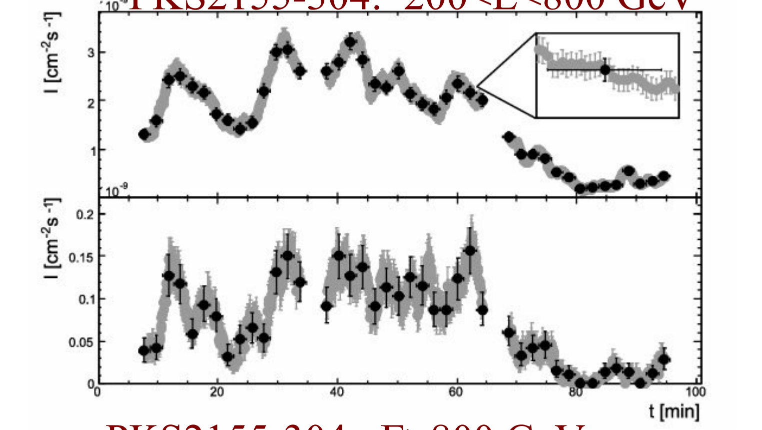
Doubling time scale ~ 3min

suggests
Lorentz factor > a few

Aharonian, et al. (H.E.S.S. collaboration), 2006



PKS2155-304: 200<E<800 GeV



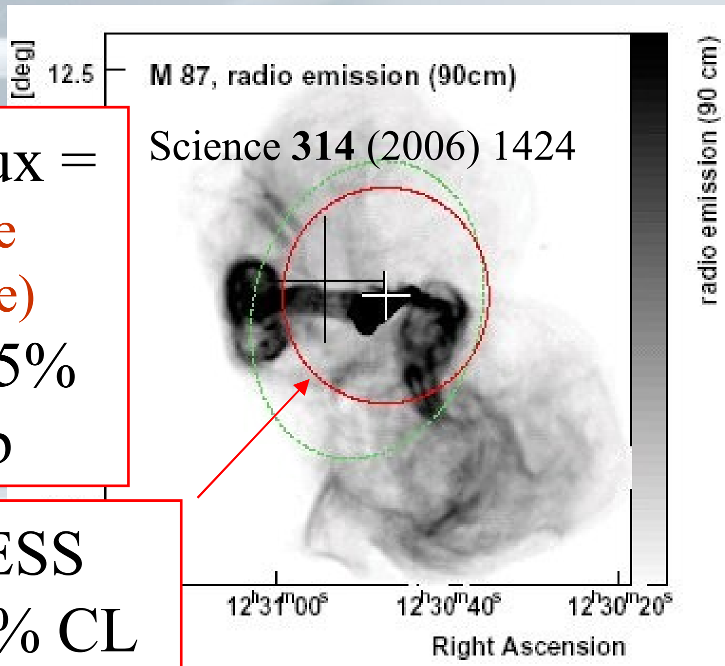
PKS2155-304: E>800 GeV

- No differences (time-lags) between light-curves in different energy ranges was found

M_{QG} > 7% Planck mass

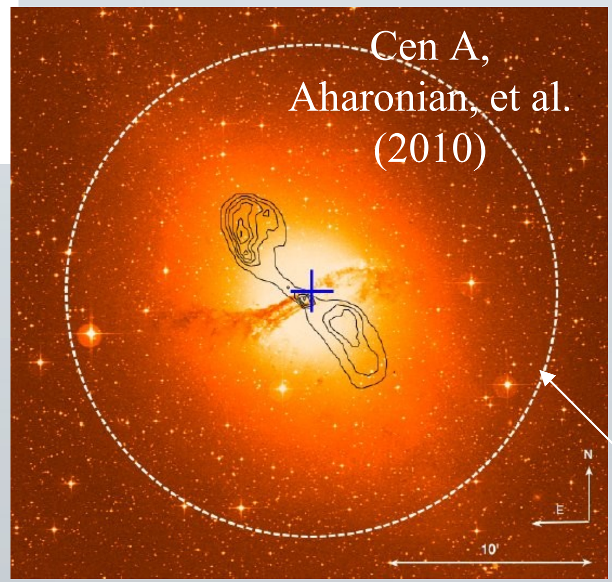
Radio-galaxies: emission region compatible with radio core

M87 flux = variable (day-scale) 1% to 5% Crab



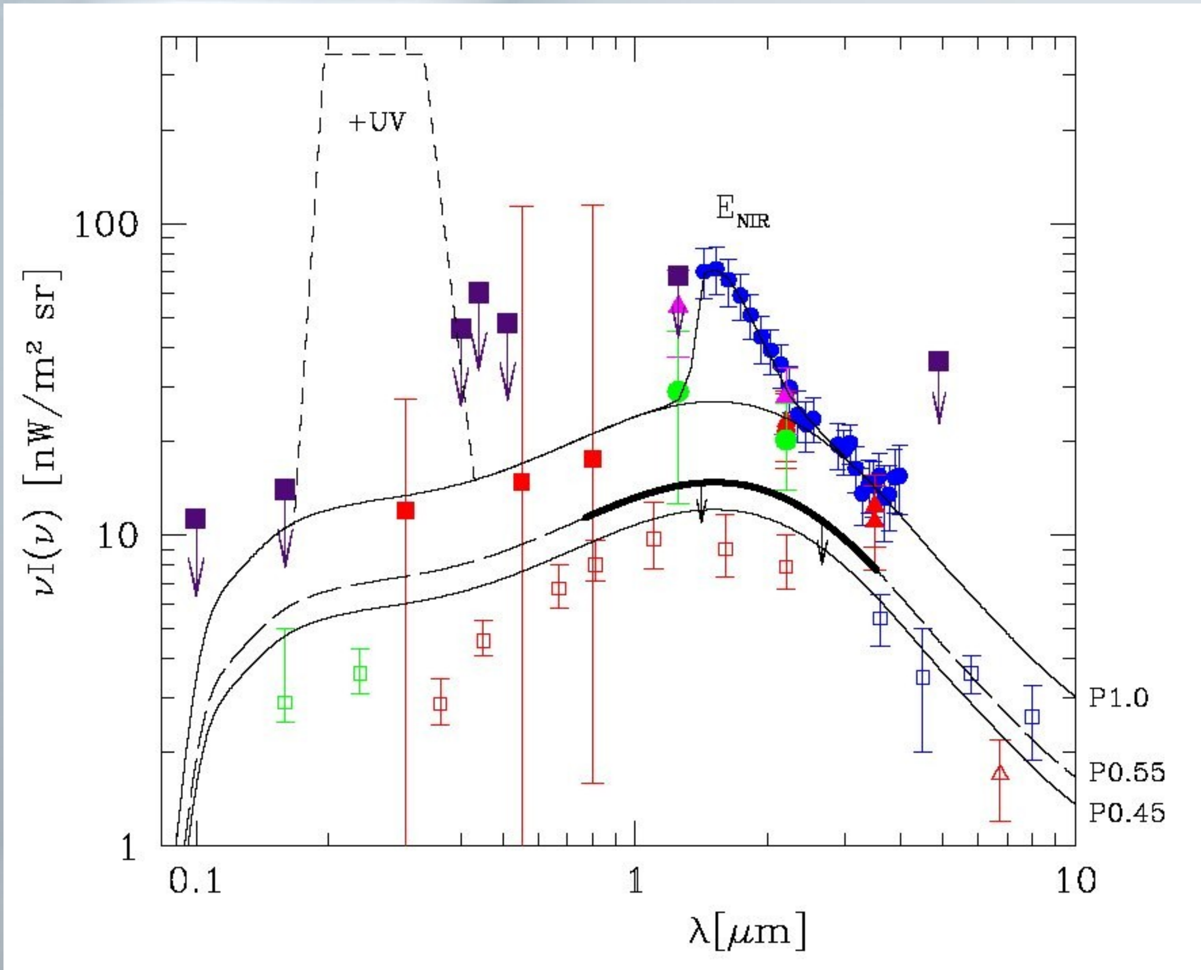
HESS 99.9% CL limit

Cen A flux (E>250 GeV) = 0.8% Crab



HESS 95% CL limit

Constraint on Extragalactic Background Light



Aharonian, et al. (H.E.S.S. collaboration), 2006, Nature

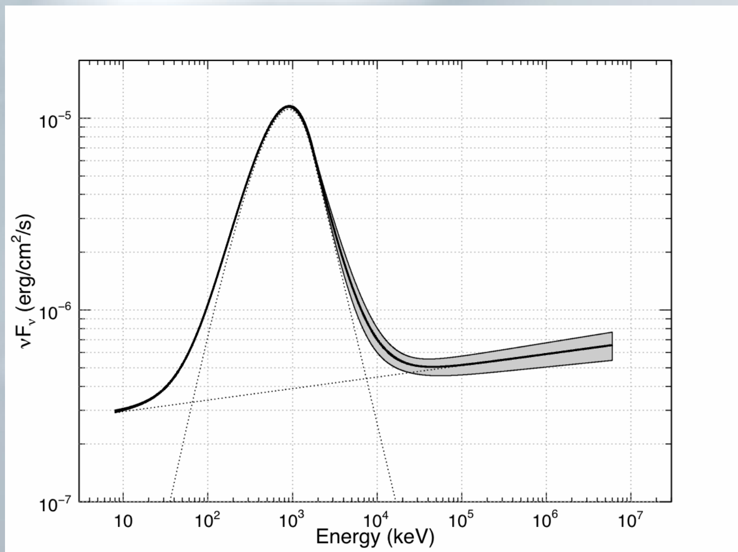
Based on blazar spectra measurements of 1ES1102-232 and H2356-306

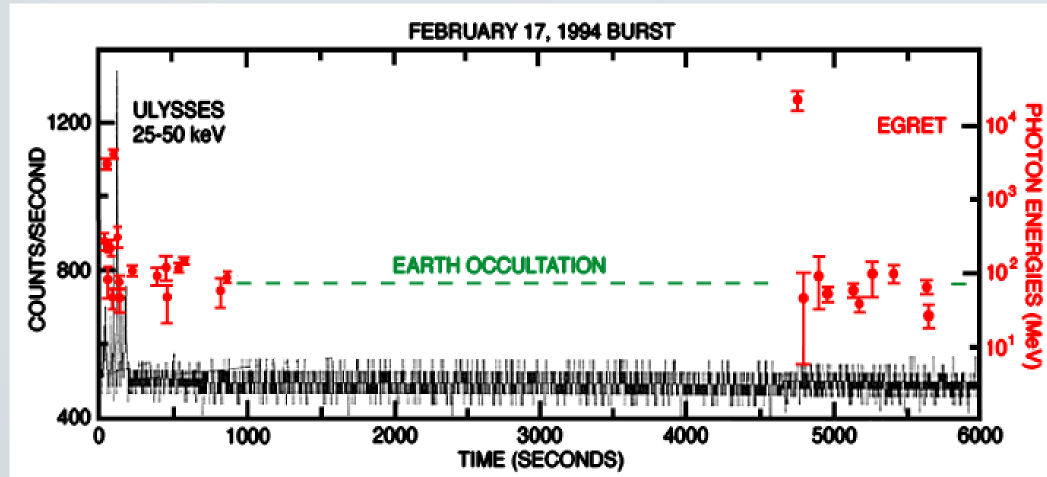
After correcting for the absorption, the spectrum at the source must have a spectral index > 1.5

suggests a low level of EBL

GeV emission from GRBs

GRB 090902B, Abdo et al. 2009



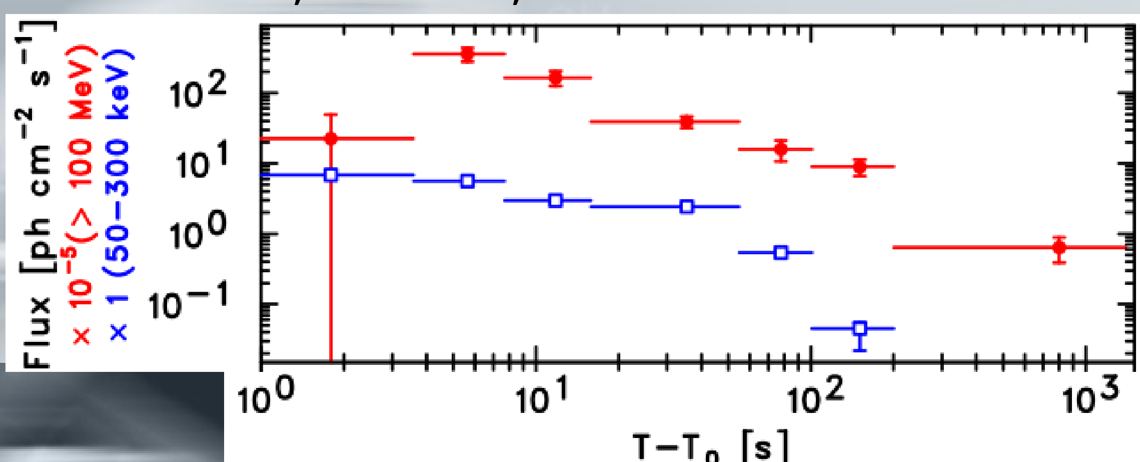


GRB 940217

Hurley et al., Nature, 1994

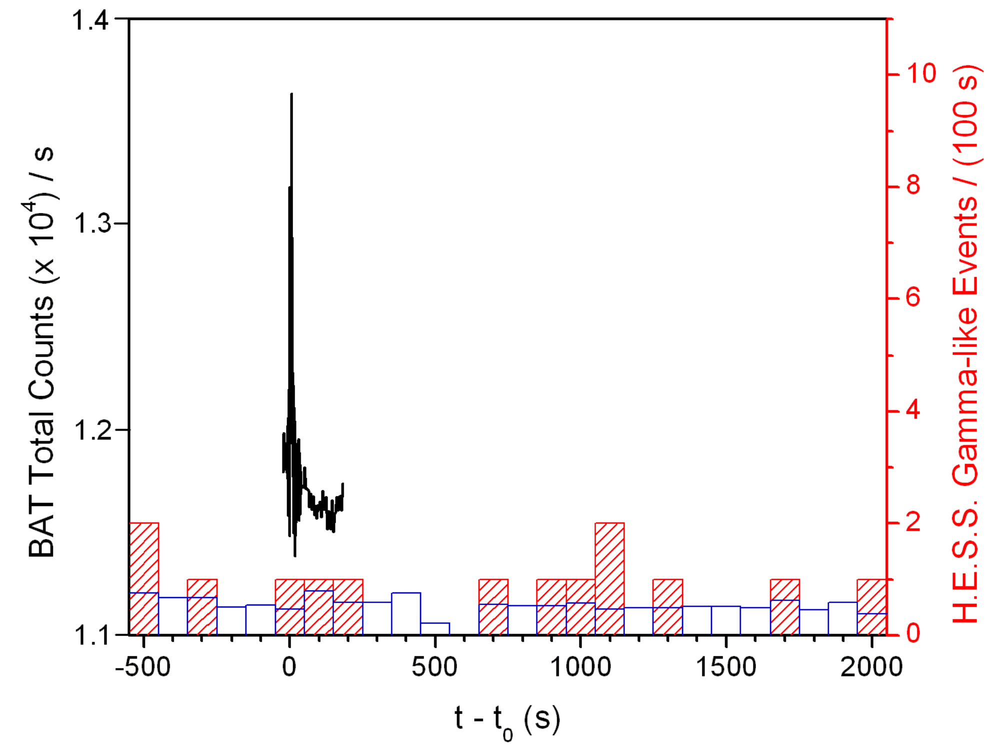
GRB 080916C

Abdo et al., Science, 2009



5-σ detection @ 200-1400 s

Simultaneous Obs of GRB 060602B by H.E.S.S.



- GRB060602B occurred in the H.E.S.S. FoV during the prompt phase
- Complete coverage
- First kind of its type:

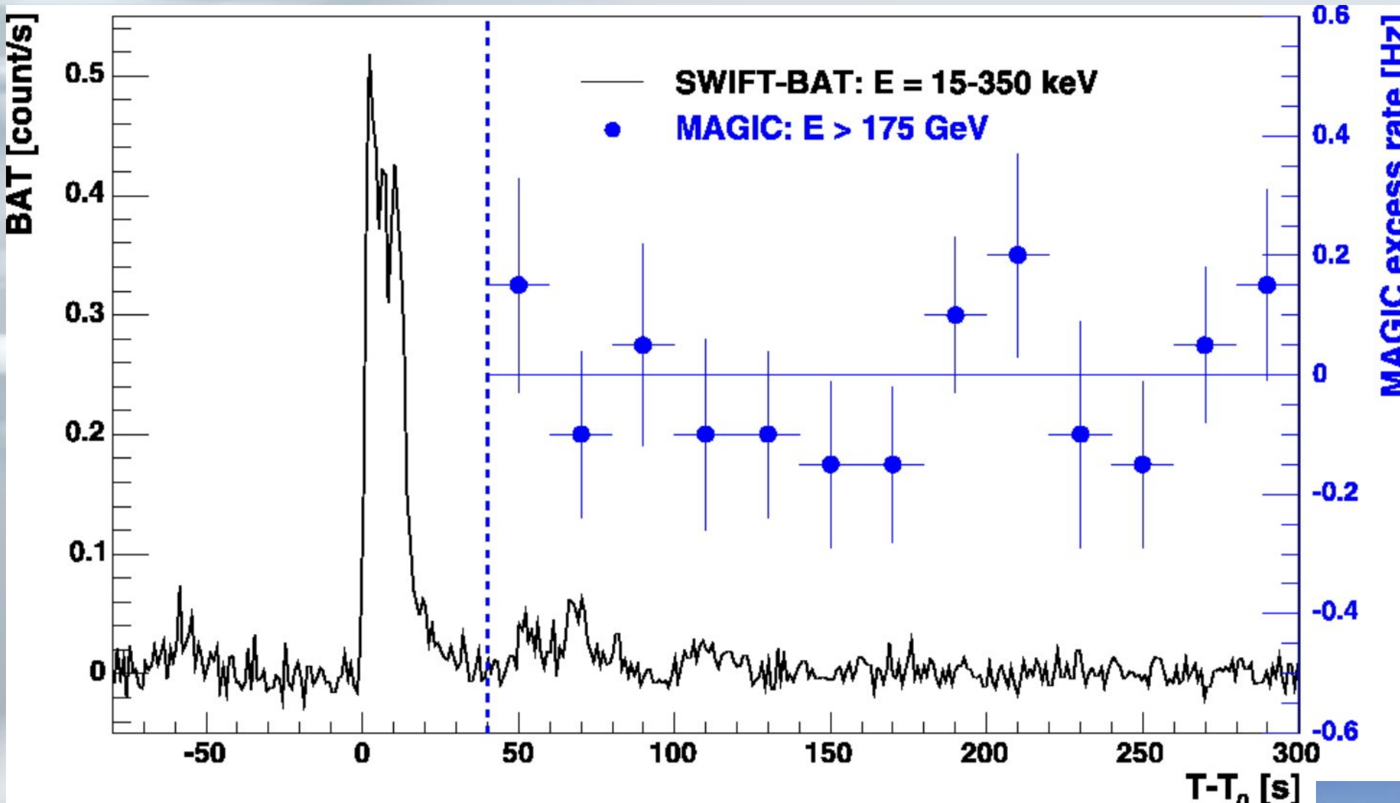
a burst in gamma-ray (15-150 keV) observed with an air Cherenkov instrument

- T_{90} = 9 sec
- No detection

H.E.S.S. Events in the proximity of burst time window (Aharonian et al., H.E.S.S. collaboration, 2009)

H.E.S.S. has observed over 40 GRBs but no detection yet..

Obs of GRB 050713A by MAGIC: fast-slewing

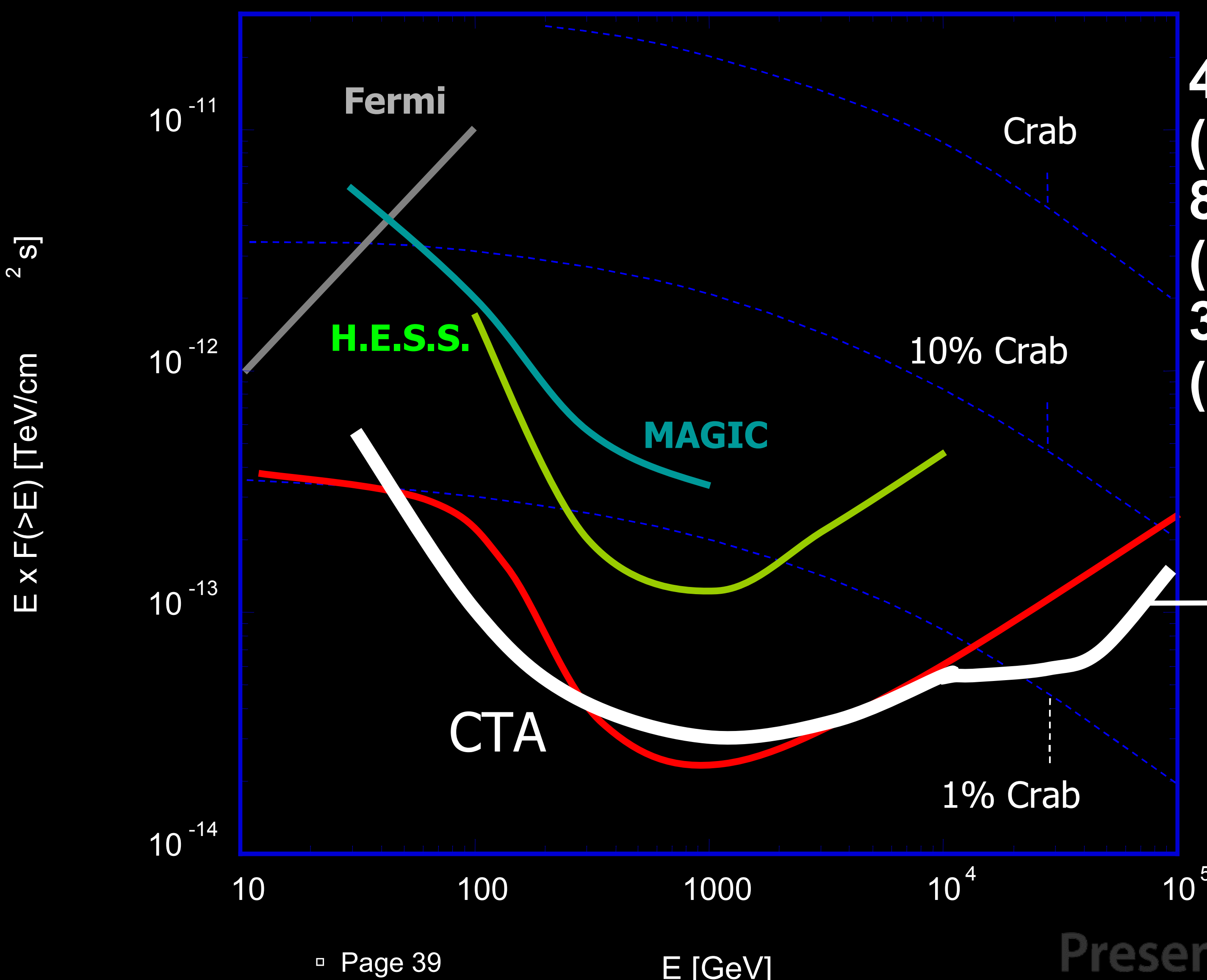


Albert, et al. (MAGIC collaboration), 2006

A plan of a future IACT experiment

Cherenkov telescope array (CTA)

CTA sensitivity



4× 600m²
(0.08°/ 5°) +
85× 100m²
(0.16°/ 7°)
39x 37m²
(0.25°/ 7°)

Summary

- VHE astronomy is a well-established field of astronomy: spectrum, images, light curves
- One can do cosmology, astroparticle physics with VHE detectors
- MAGIC-II, H.E.S.S.-II, VERITAS, CTA (future)
- Number VHE sources is approaching 100
- Galactic sources include PWN, SNR, helps our understanding of the origin of cosmic rays
- Extragalactic sources include AGN and radio galacties (and starburst galaxies), GRBs are yet to be detected
- Still waiting for detection on Globular clusters...