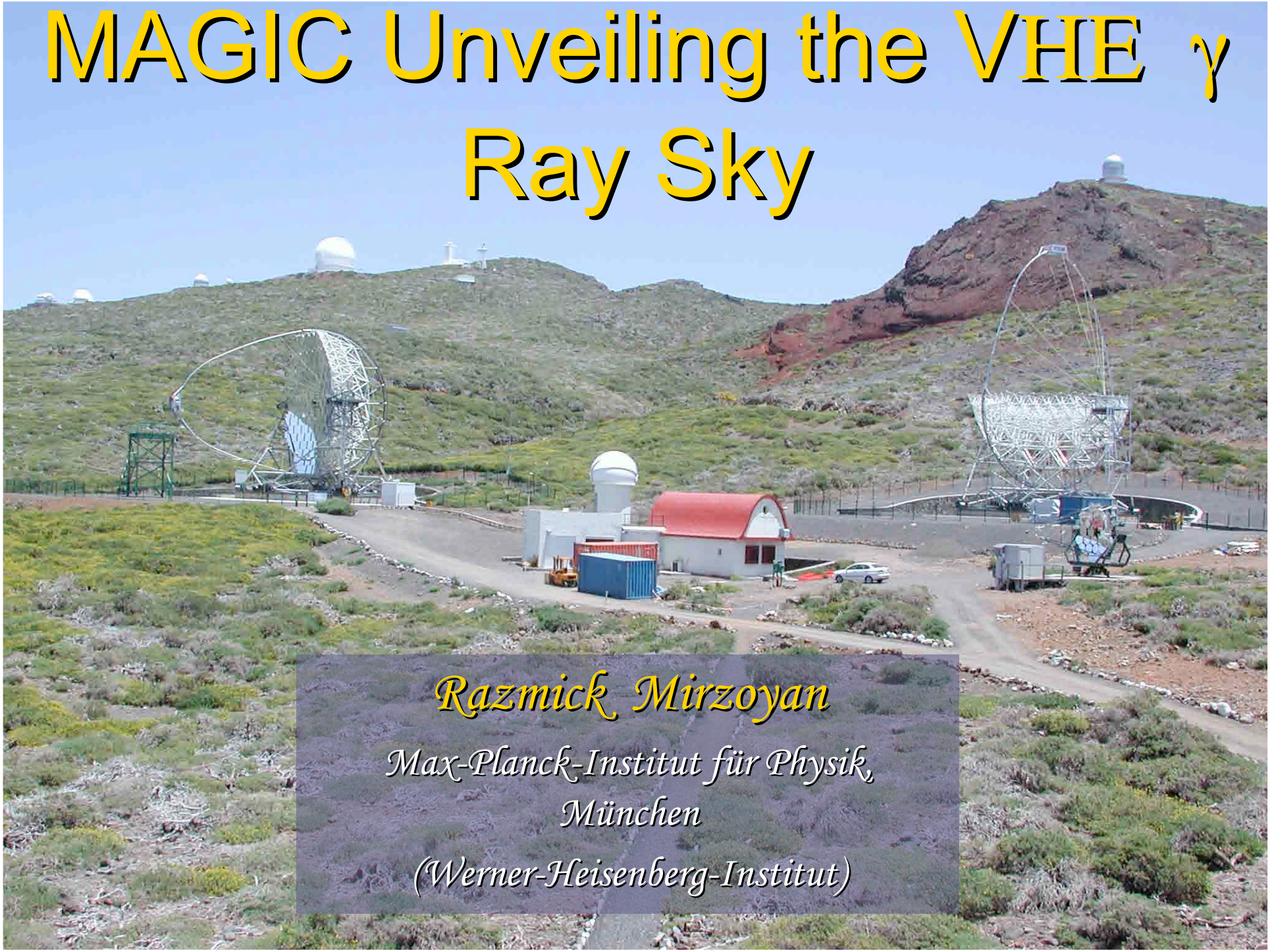
# MAGIC Unveiling the VHE γ Ray Sky



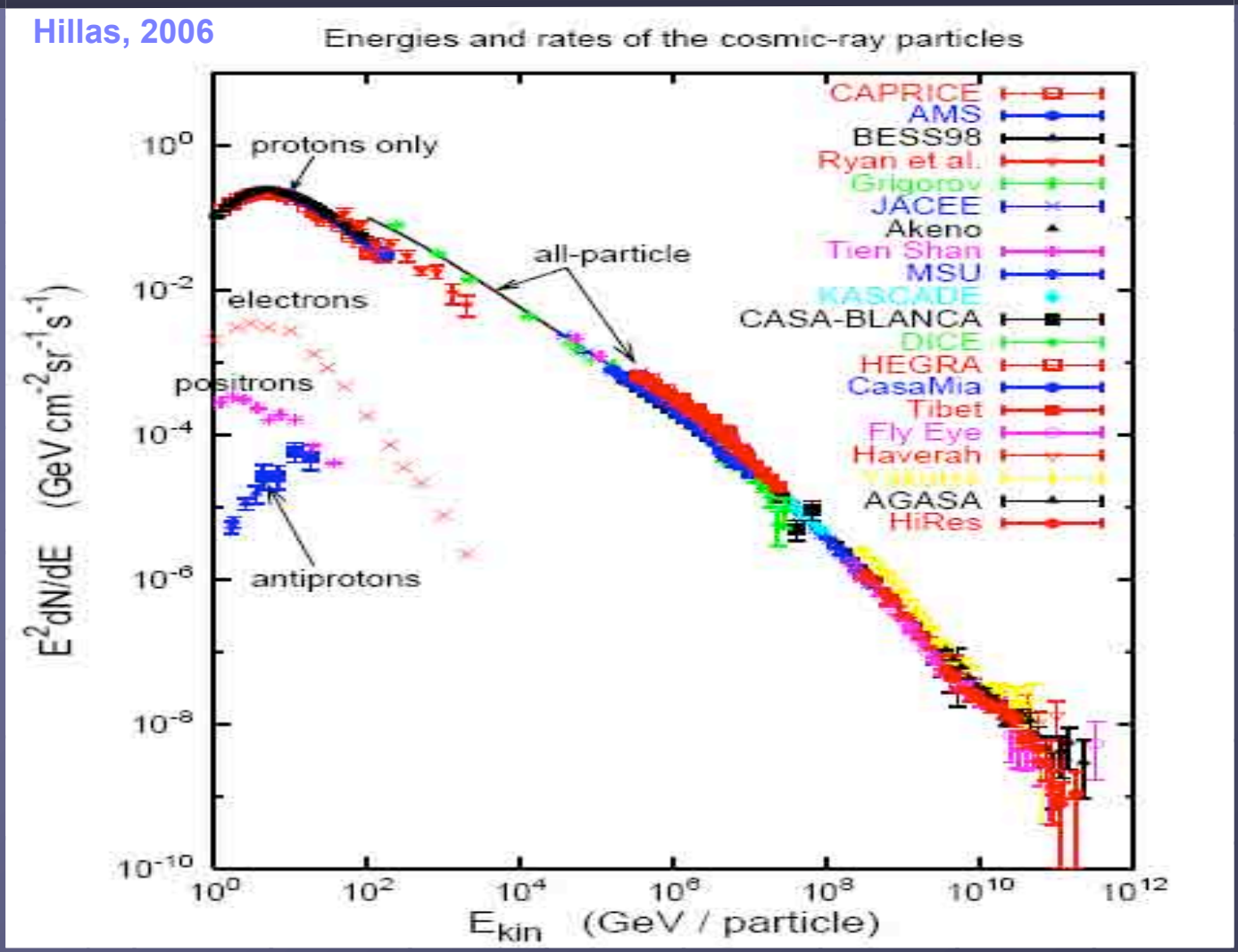
*Razmick Mirzoyan*

*Max-Planck-Institut für Physik, München*

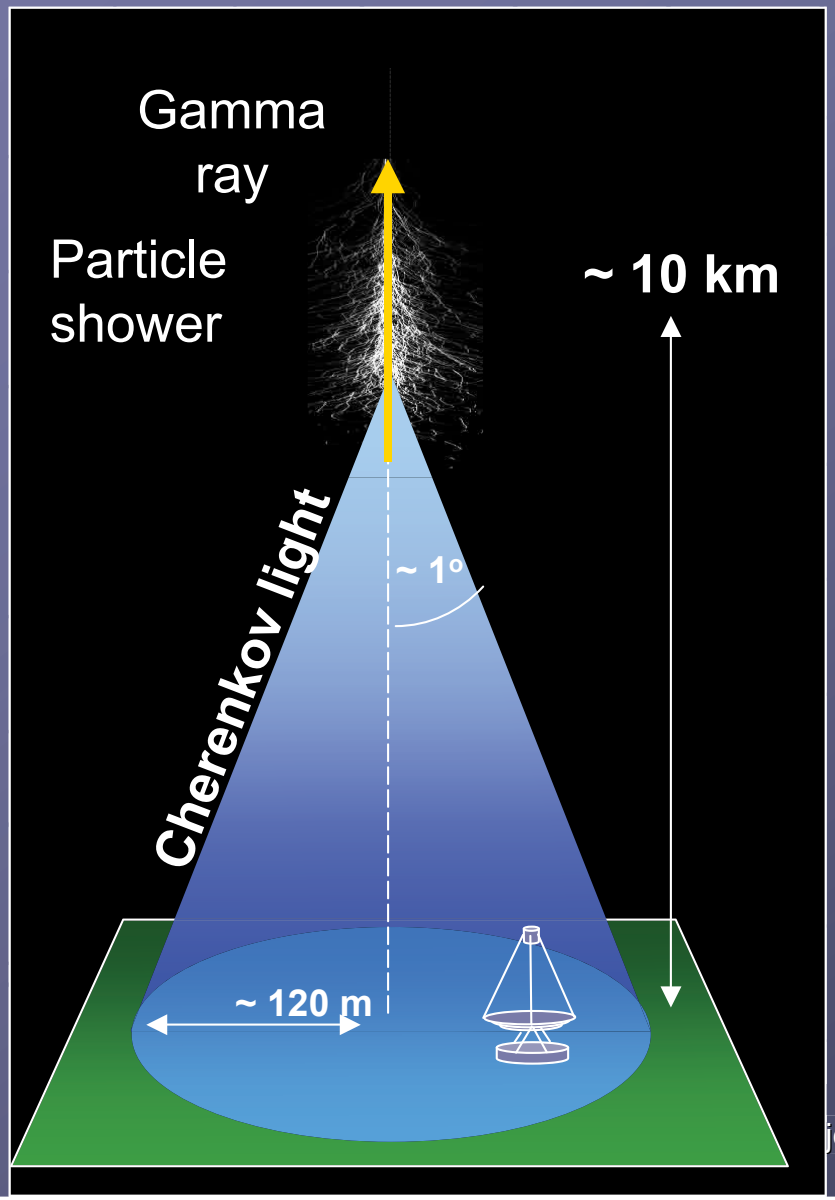
*(Werner-Heisenberg-Institut)*

# The Cosmic Ray Spectrum

Hillas, 2006

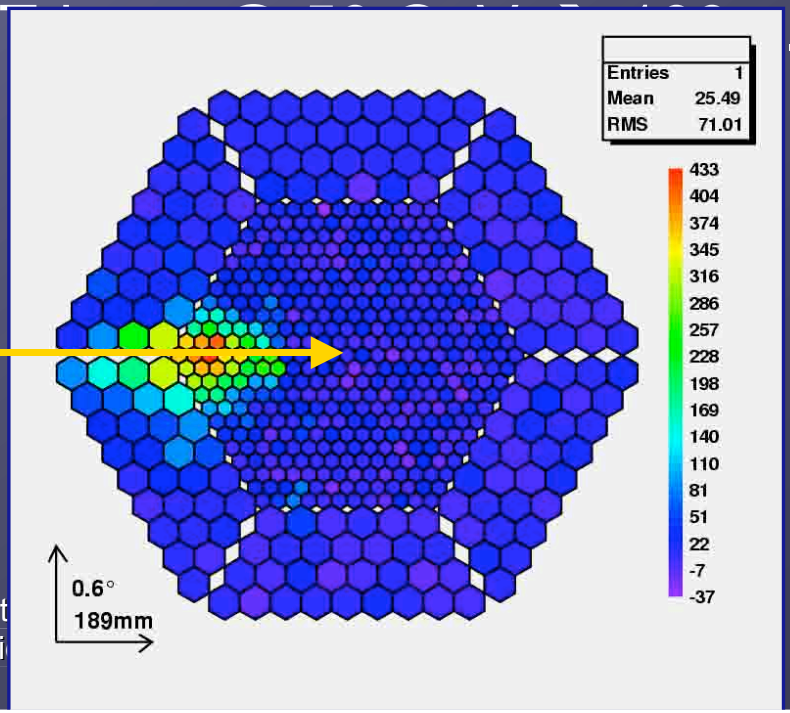


# Atmospheric Imaging Cherenkov Telescope




Cherenkov light from γ showers:

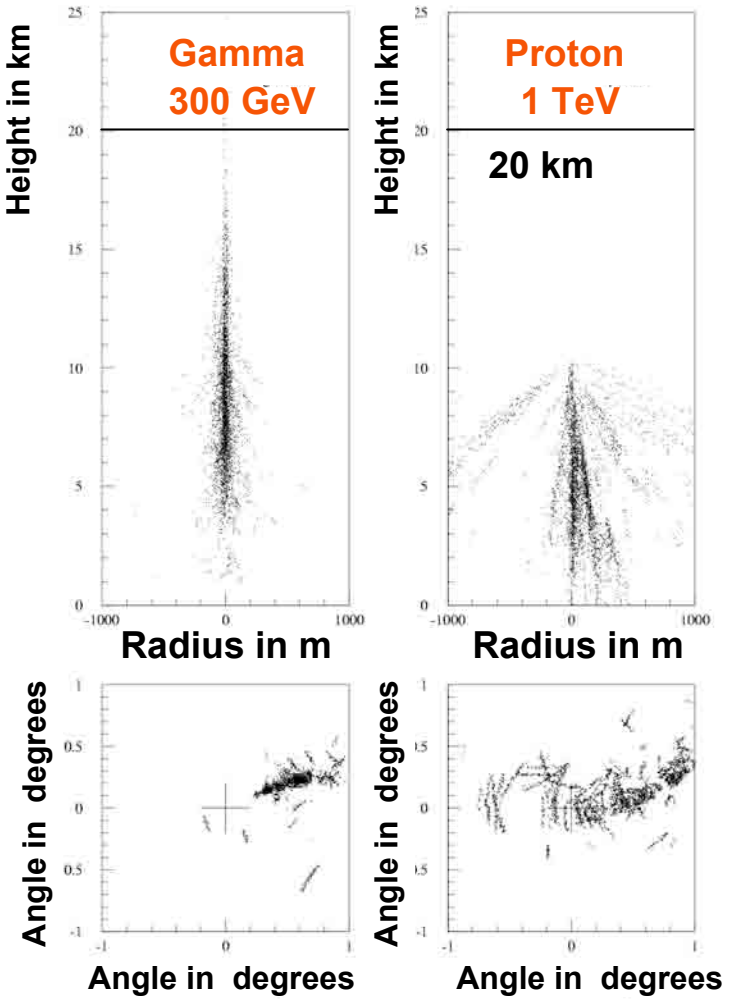
- ~10 photons/m² @ 100 GeV
- ➔ scarce photon statistics
- MAGIC @ 100 GeV ➔ 200p.e.
- .e.



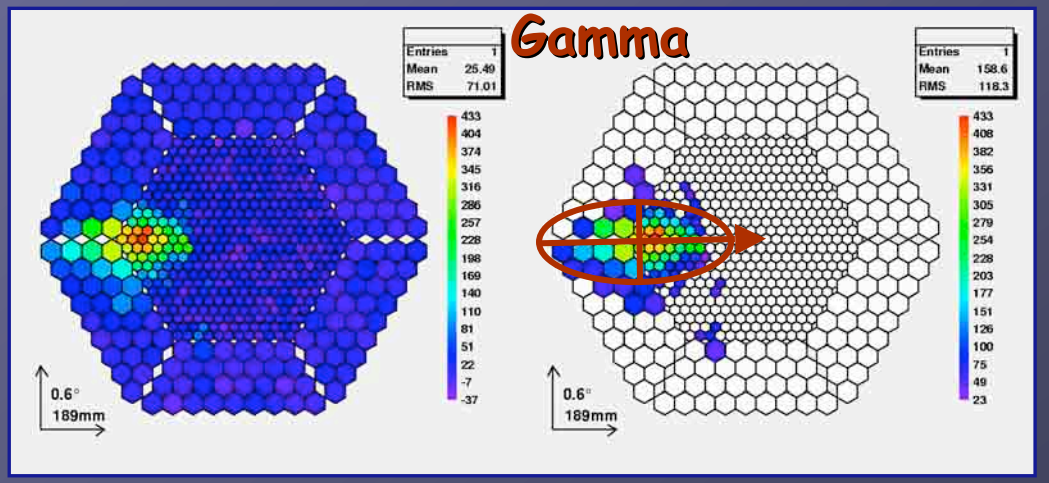

Highlight
ject Revi

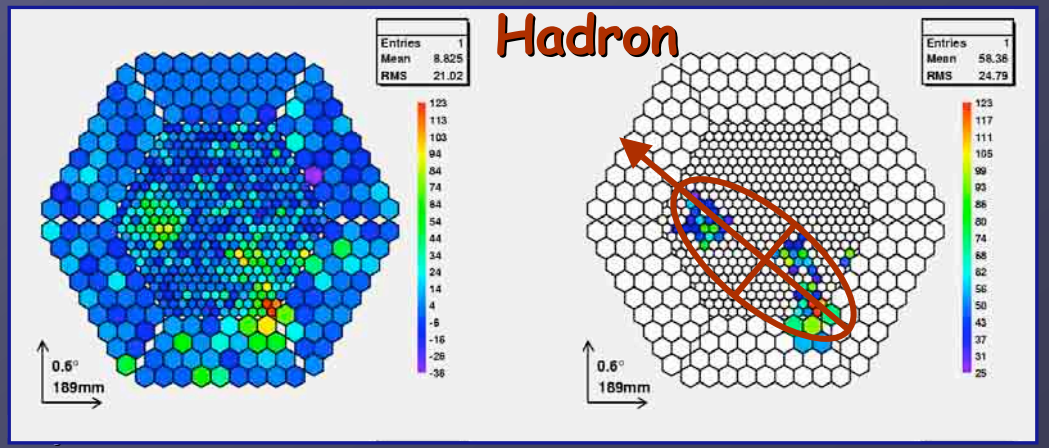
# Gamma/Hadron separation

## MC Simulation of Shower

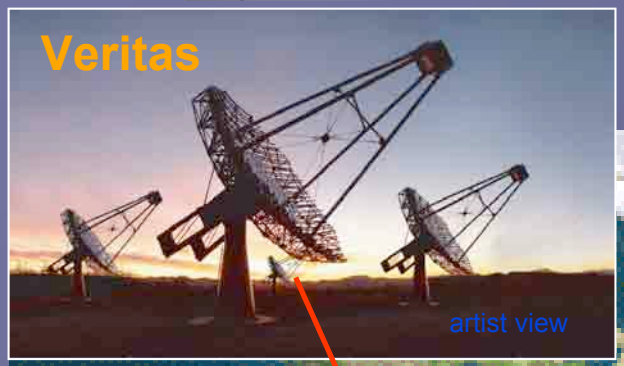



## Hadron Rejection by Image Shape + Orientation ~ 99.9 %

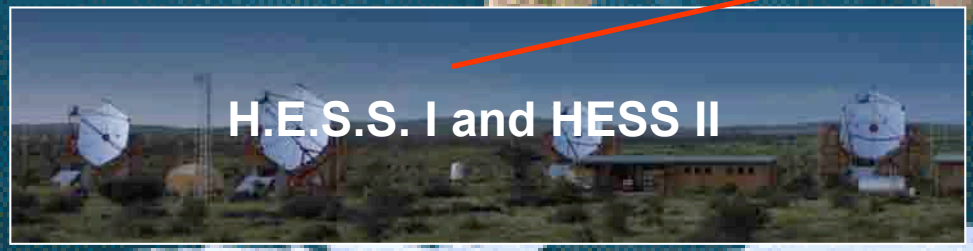


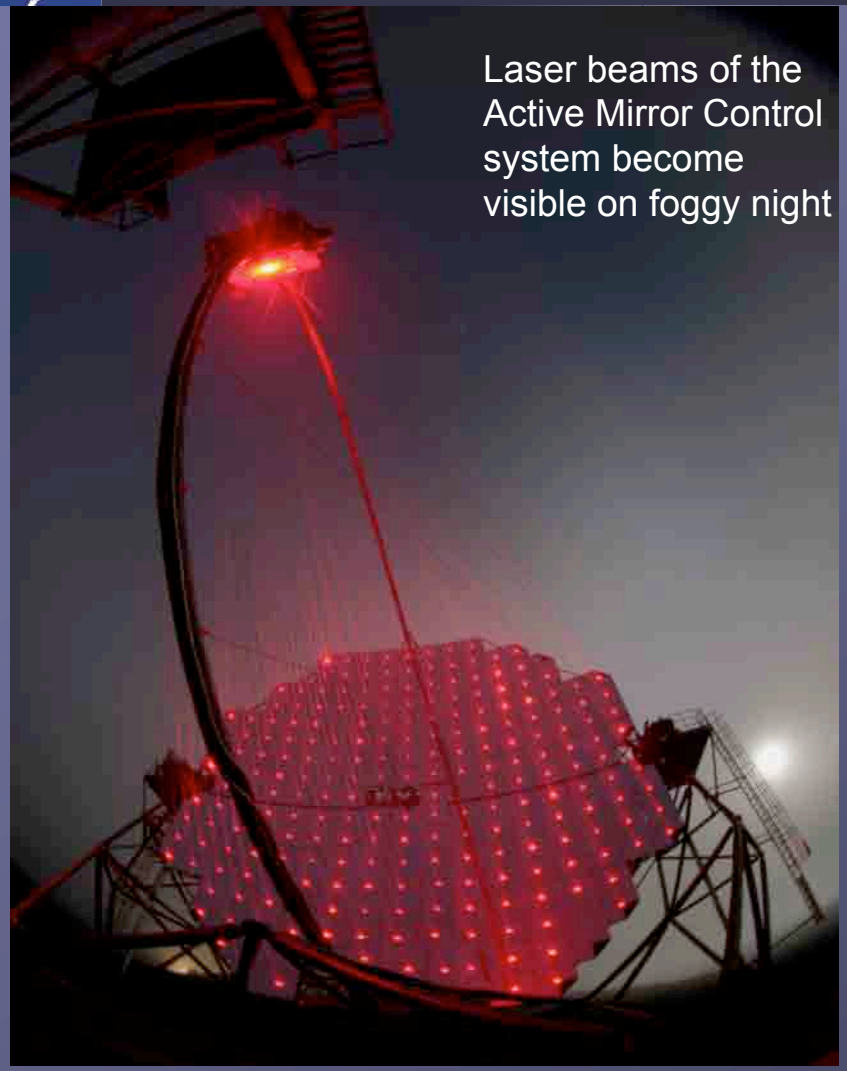
# Major IACTs in the world








# The MAGIC collaboration



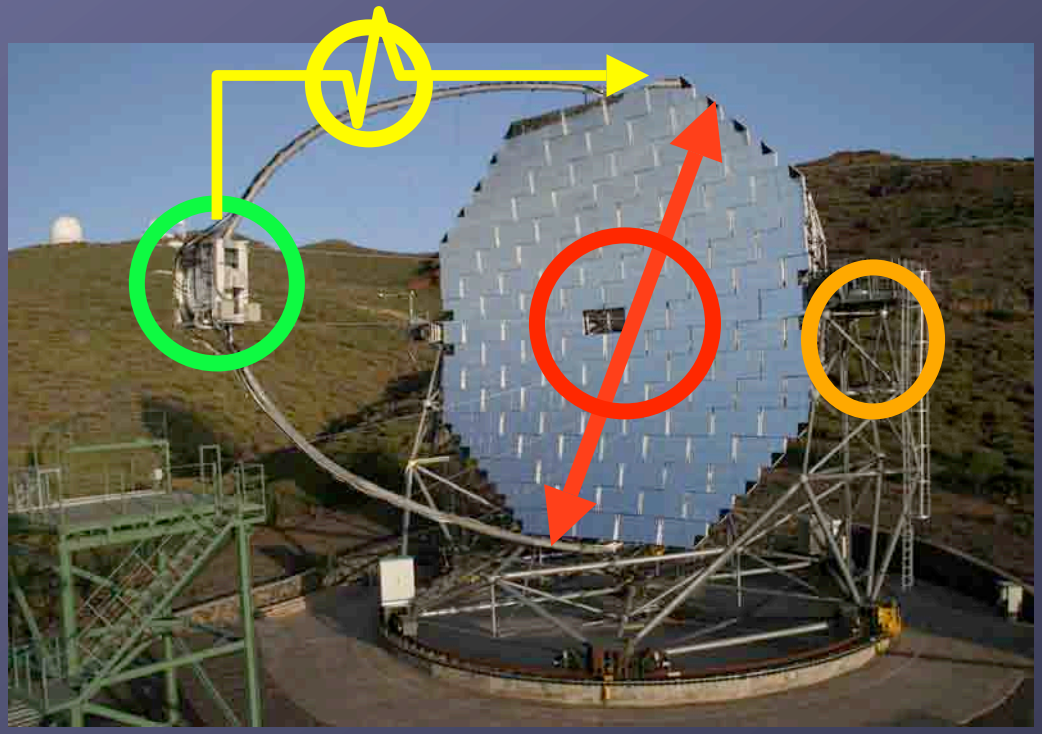

- International collaboration: 20 institutions, ~180 members ➔ still increasing
- Germany: MPI Munich, Humboldt Berlin, DESY-Zeuthen, Dortmund, Wuerzburg
- Italy: Padova, Siena-Pisa, Udine (INFN), INAF
- Spain: IFAE, UAB, UB, ICE, IAA, IAC, UC Madrid
- Switzerland: ETH, Finland: Tuorla
- Poland: Lodz, Bulgaria: Sofia, Armenia: Yerevan, USA: UCDavis

# MAGIC: a pioneering telescope

## *new threshold & technology standards*

## The key elements are:

- 17 m Ø reflector, Al mirrors
- CF frame, fast rotation 180°/50s
- Active mirror control
- 577 pixels, ~ 2.0° FOV camera (3.5°geometrical)
- Analogue signal transport via 162m long optical fibres
- 2 GSample/s readout



# The MAGIC Project

**MAGIC-I performance :**

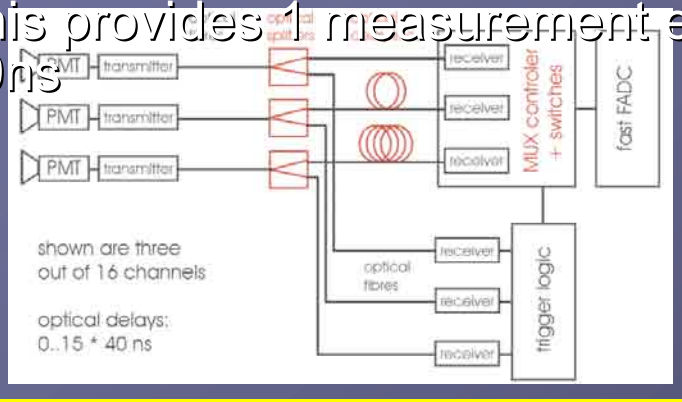
- Fast rotation for GRB < 50 secs
- Trigger threshold ~ 50 GeV
- Sensitivity ~ 1.6 % Crab (50 h)
- Angular resolution ~ 0.1°
- Energy Resolution 20-30 %

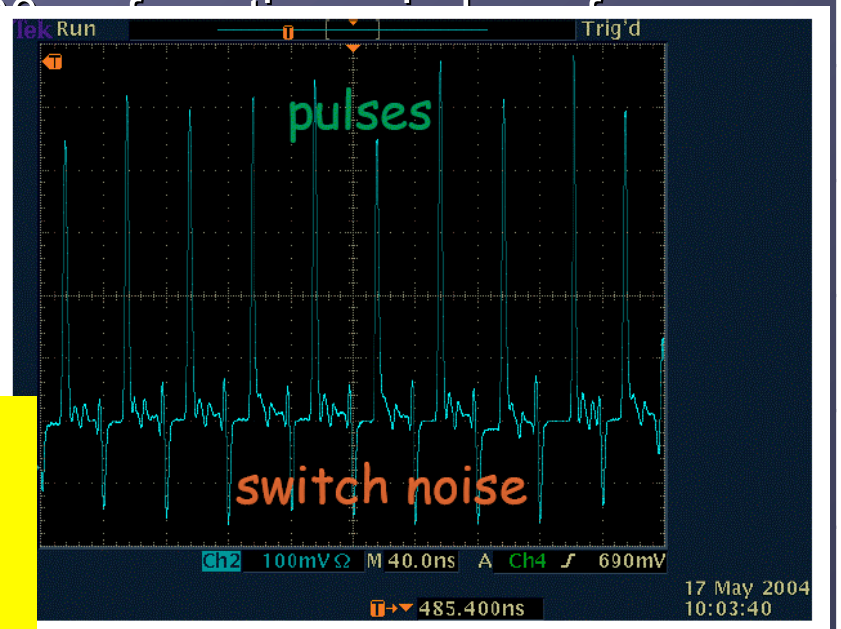
**MAGIC-II: under construction, t be completed (& inaugurated) i fall (September) 2008**

- M-I + M-II: 2-3 times higher sensitivity
- Effectively lower the threshold energy towards 40 GeV
- Details in the next talk by F. Goebel

# Multiplexing 2 GSamples/s FADC

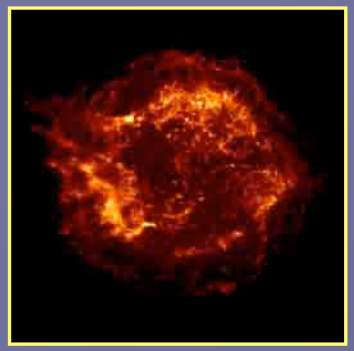
- By using multiplexing of analog signals in optical fibres we developed at MPI a system allowing one to read out 16 signal channels in 1 channel of commercial ultra-fast FADC (packing the 16 channels in a sequence)
- With a bank of 40 channel FADCs from Acqiris we are reading out 640 (576-signal) channels of the MAGIC-I imaging camera.
- This provides 1 measurement every 500 [illegible] 30ns



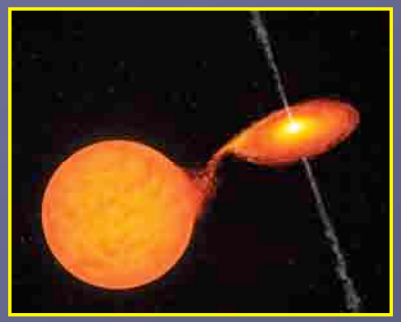

This ultra-fast readout allowed us, in the 1st time, to strongly reject background and thus to increase the sensitivity of the telescope
by 40 % @ high energies and
by 70% @ low energies ! (quasi-stereo 3D-mode)

# Scientific Objectives

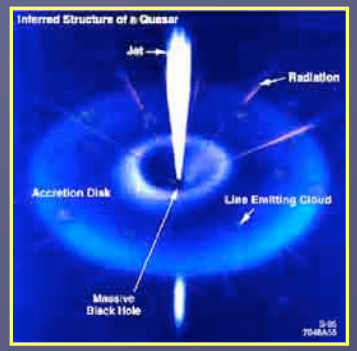


SNRs

Pulsars and PWN



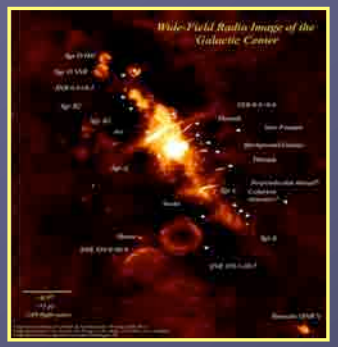
Micro quasars X-ray binaries



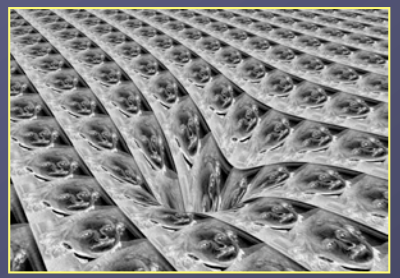

AGNs

GRBs

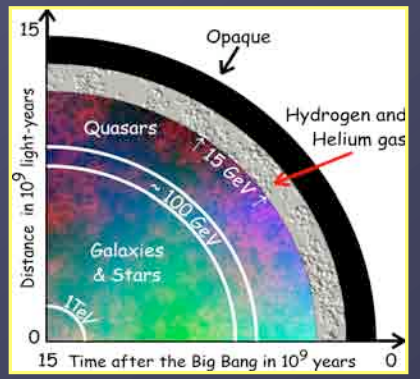
Origin of cosmic rays




Dark matter

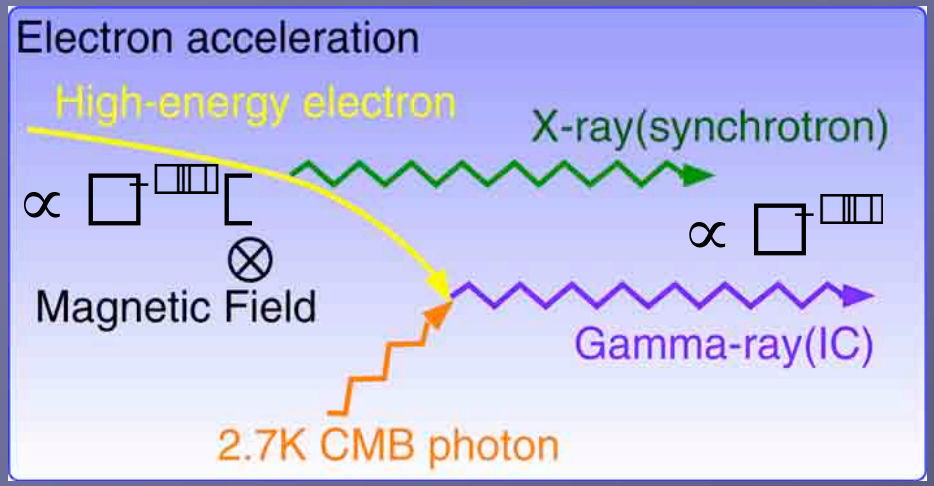


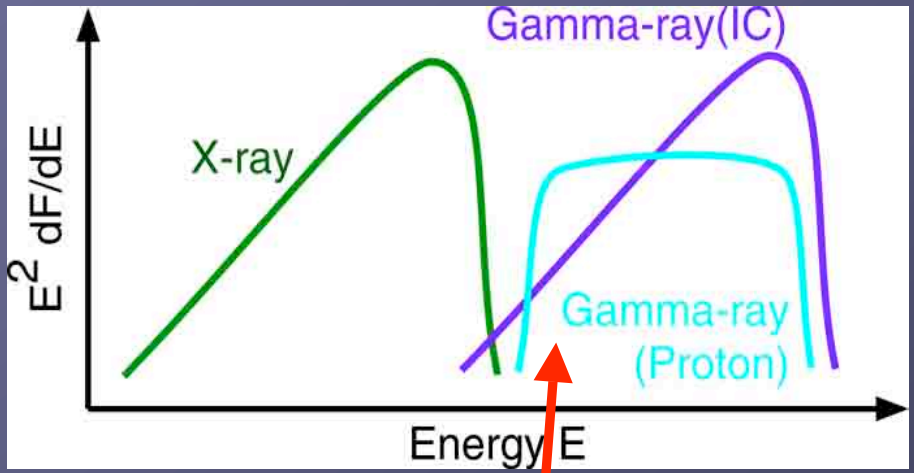
Space-time & relativity

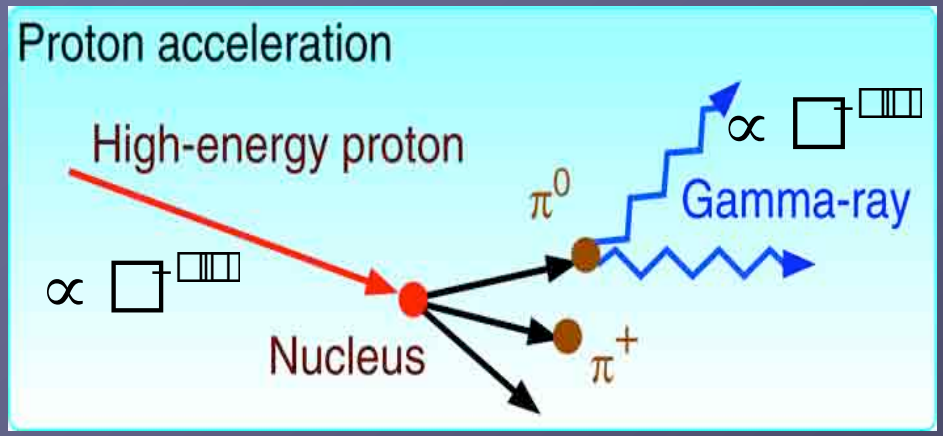



Cosmology

# γ-Ray Emission Processes

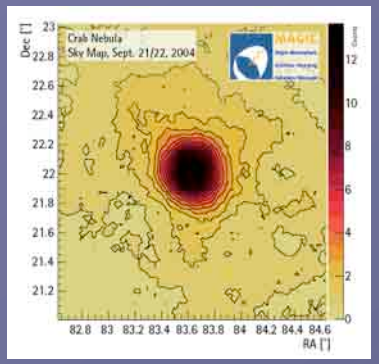


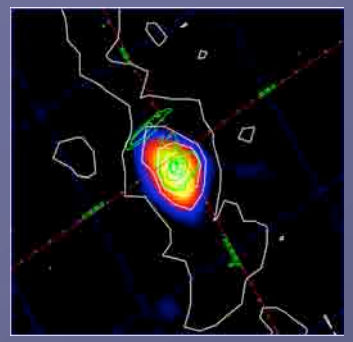




A major test on the accelerated *particle type and process* is to measure the very low energies < 100 GeV where the left 2 mechanisms much differ.

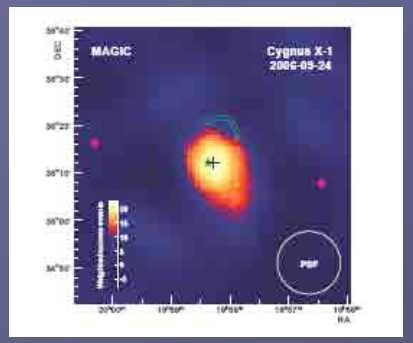
# Galactic Source Observations



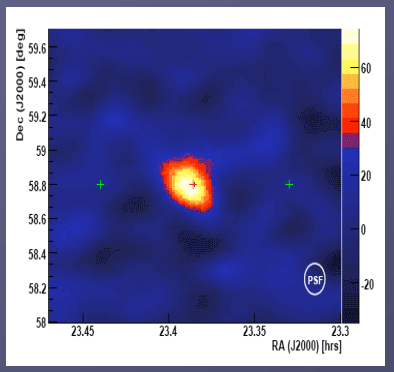

**Crab Nebula**



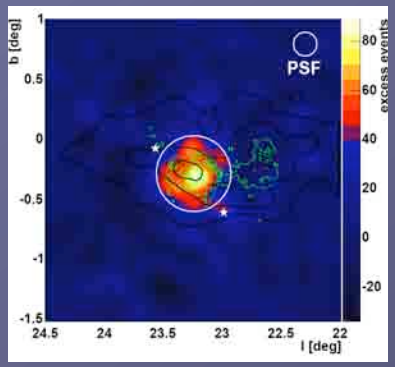
**Galactic Center**



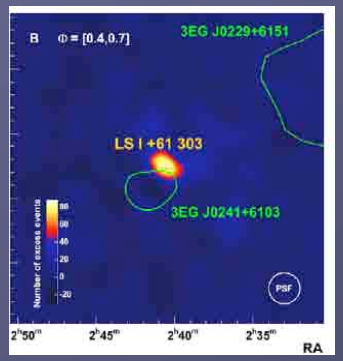

**Cyg-X1 binary**
**Discovered by MAGIC**



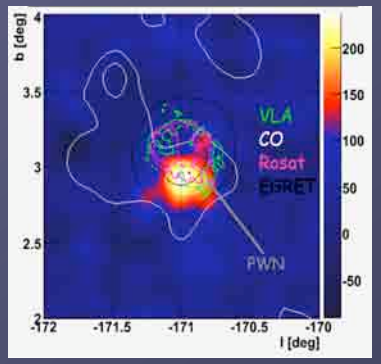

**Cas A**



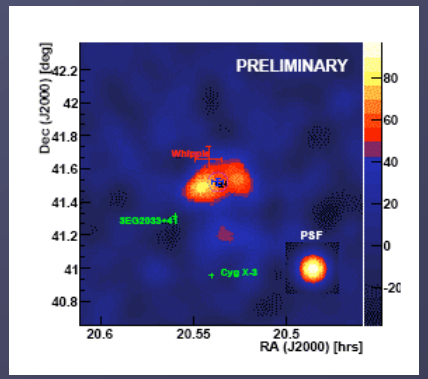

**HESS J1834**
**$^{13}$CO cloud**




**LSI+61 303 Binary**
**Discovered by MAGIC**



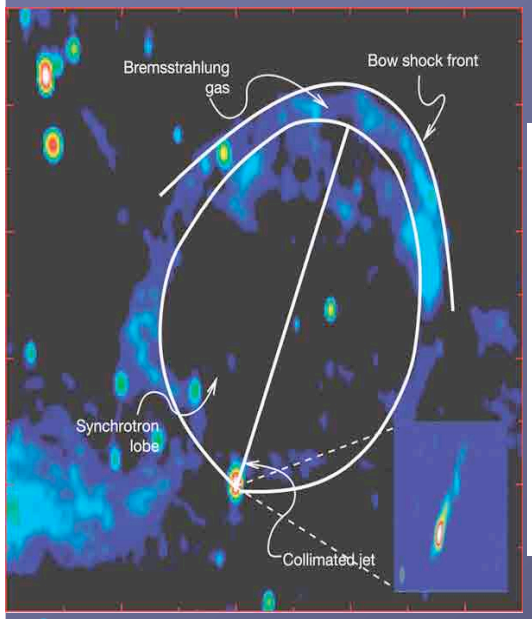

**IC-443**
**Discovered by MAGIC**




**J2032+4130**

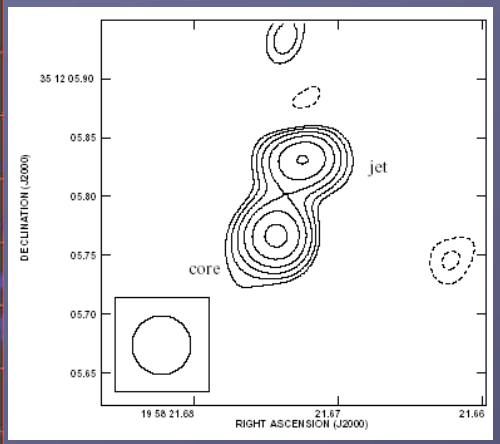
# Cyg X-1

Single-sided jet (microblazar?) resolved at milli-arcsec scales with VLBA in hard state. Opening angle < 2°, bulk velocity is $\beta > 0.6c$




Gallo et al. 2005, Nature

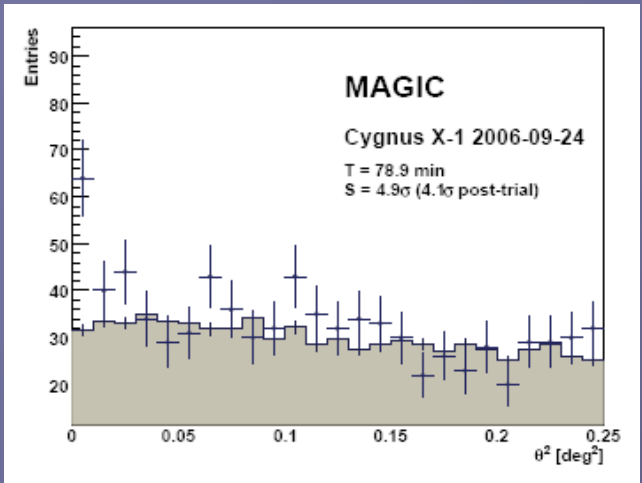
MERLIN, 5 GHz

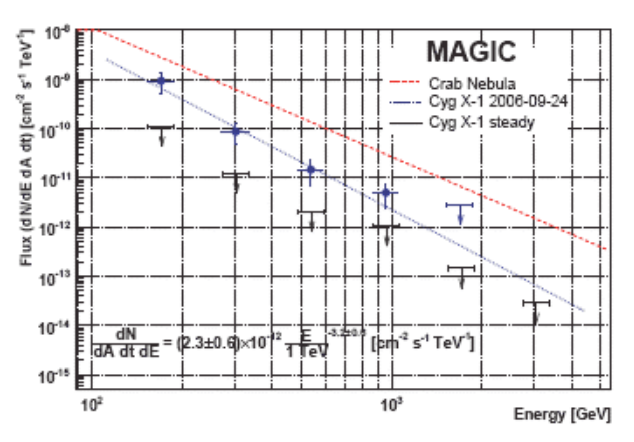



Cyg X-1. On the other hand, it is intringuing that Cyg X-1 does appear surrounded by several clumps of extended emission. All these clumps also appear in maps made from the individual visibility data sets. At a marginal level, their disposition reminds an elliptical ring-like shell with Cyg X-1 offset from the center by a few arcminutes.

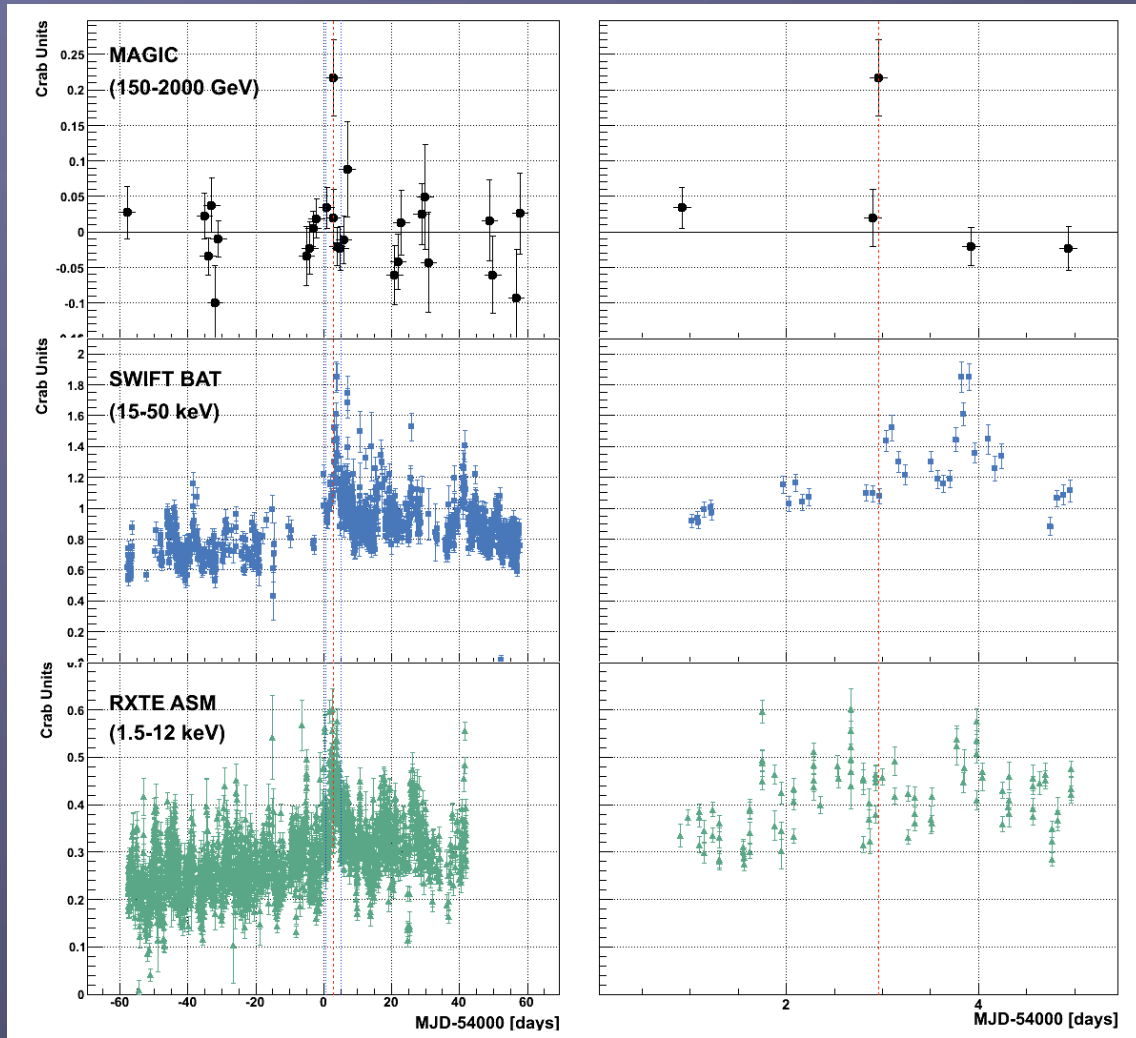
- CygX-1 is the best established candidate for the stellar mass black hole (BH) and one of the brightest X-ray sources in the sky.
- It is located at ~2.2 kpc and is composed of 21 ±8 $M_o$ BH orbiting a companion of 40 ±10 $M_o$
- It was observed by MAGIC for a total of 40h on 26 nights

# Cygnus X-1



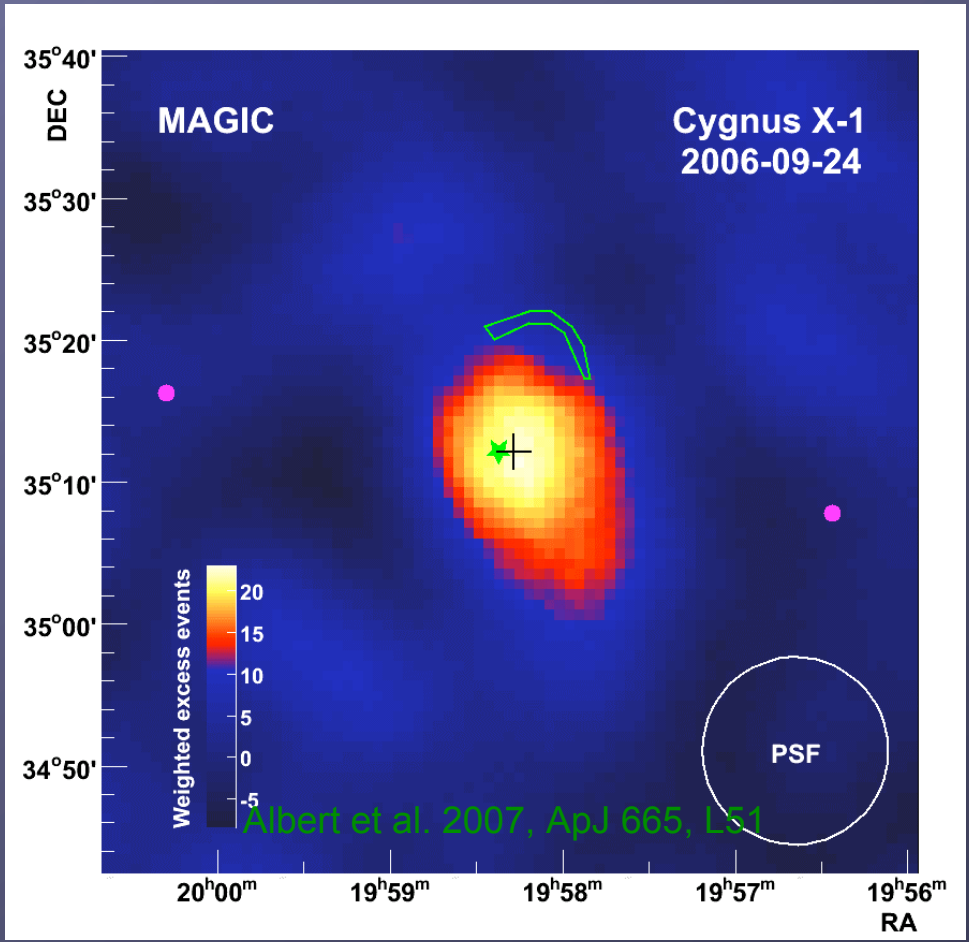




Albert et al. 2007, ApJ 665, L51



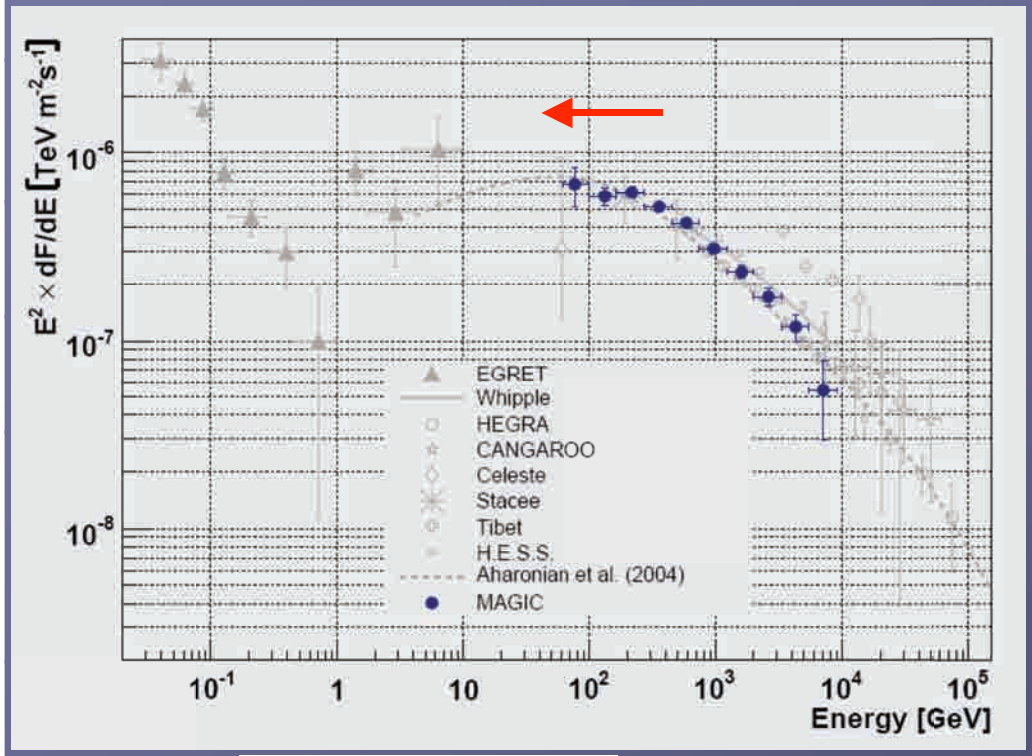
# Cygnus X-1

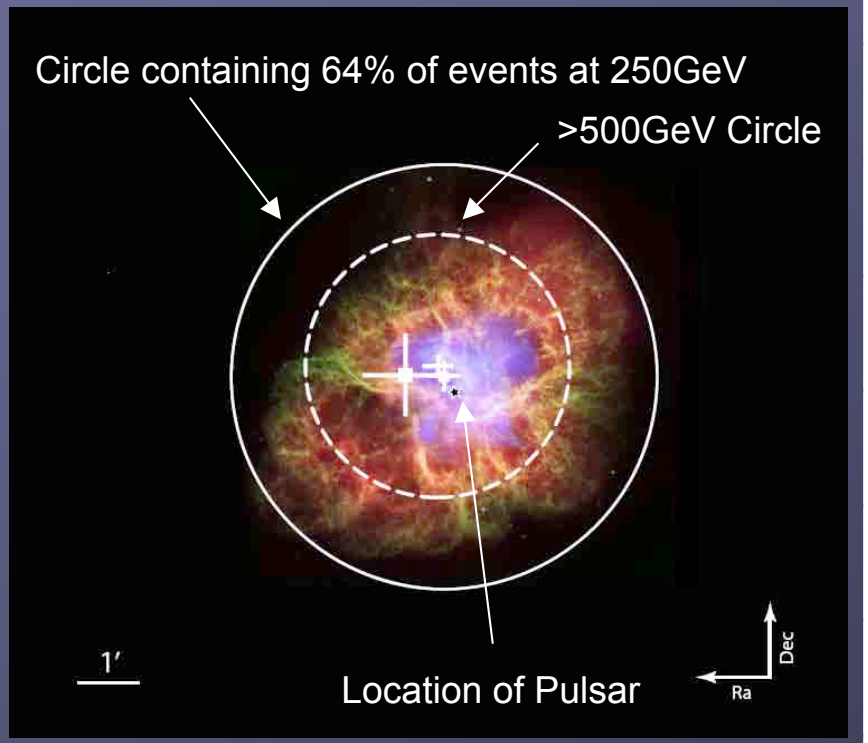
- Source location compatible with the position of Cygnus X-1 and exclude radio ring
- 4.9$\sigma$ for the second halve of the night (at phase 0.9-1.0, when the black hole is behind the star)
- For the 1st time we have found experimental evidence that a galactic stellar mass BH is producing VHE $\gamma$ rays
- This is also the 1st evidence that the VHE $\gamma$ rays are produced in an accreting binary system.

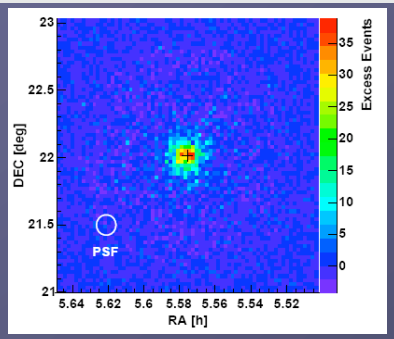


# Crab Nebula (PWN)

## Gamma Ray Signals from Crab ~ 0.4Hz



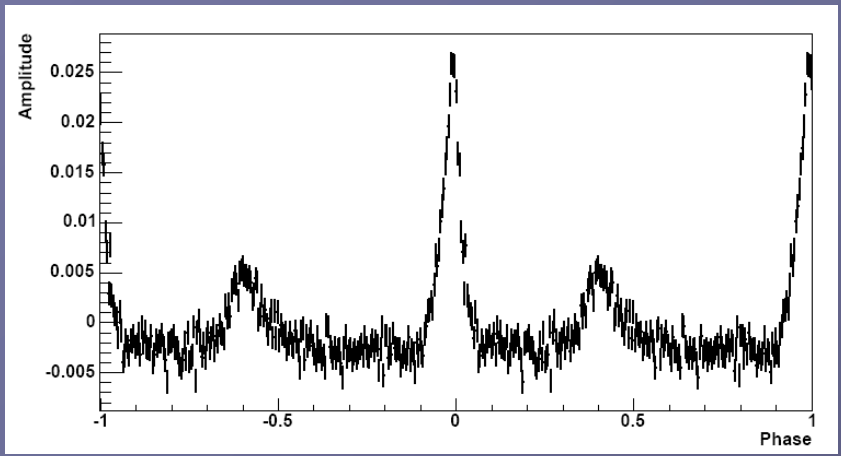




- Extended the spectrum from 400 GeV down to ~ 70-80 GeV.
- Hint on peaked distribution with peak @ 77 ± 45 GeV

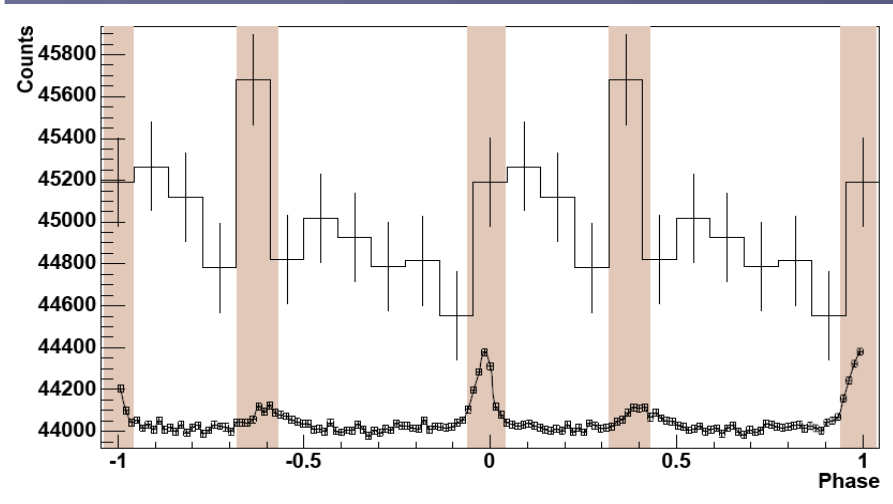
# Crab Pulsar Observations

Optical light curve of Crab Pulsar observed by MAGIC

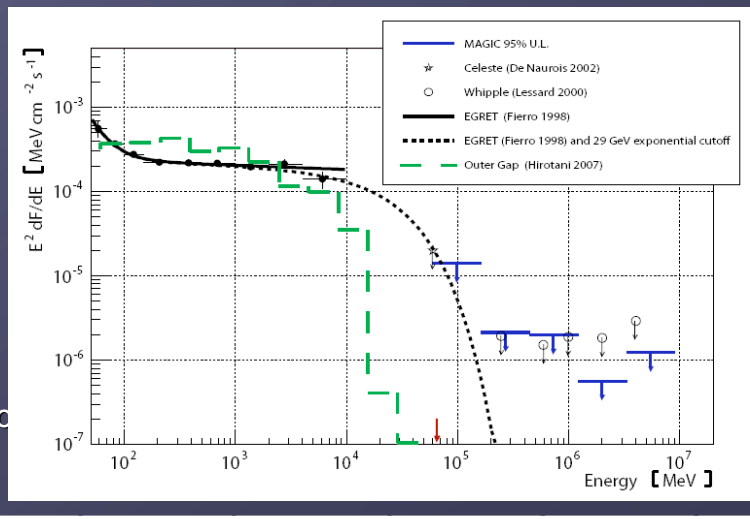



Central pixel readout optical light intensity (not Cherenkov light)

Some 2.9 σ 'excess' at EGRET phase at ~65GeV




95% Upper Limit for H.E. Gamma ray pulsed emission from Crab Pulsar




Highlights o
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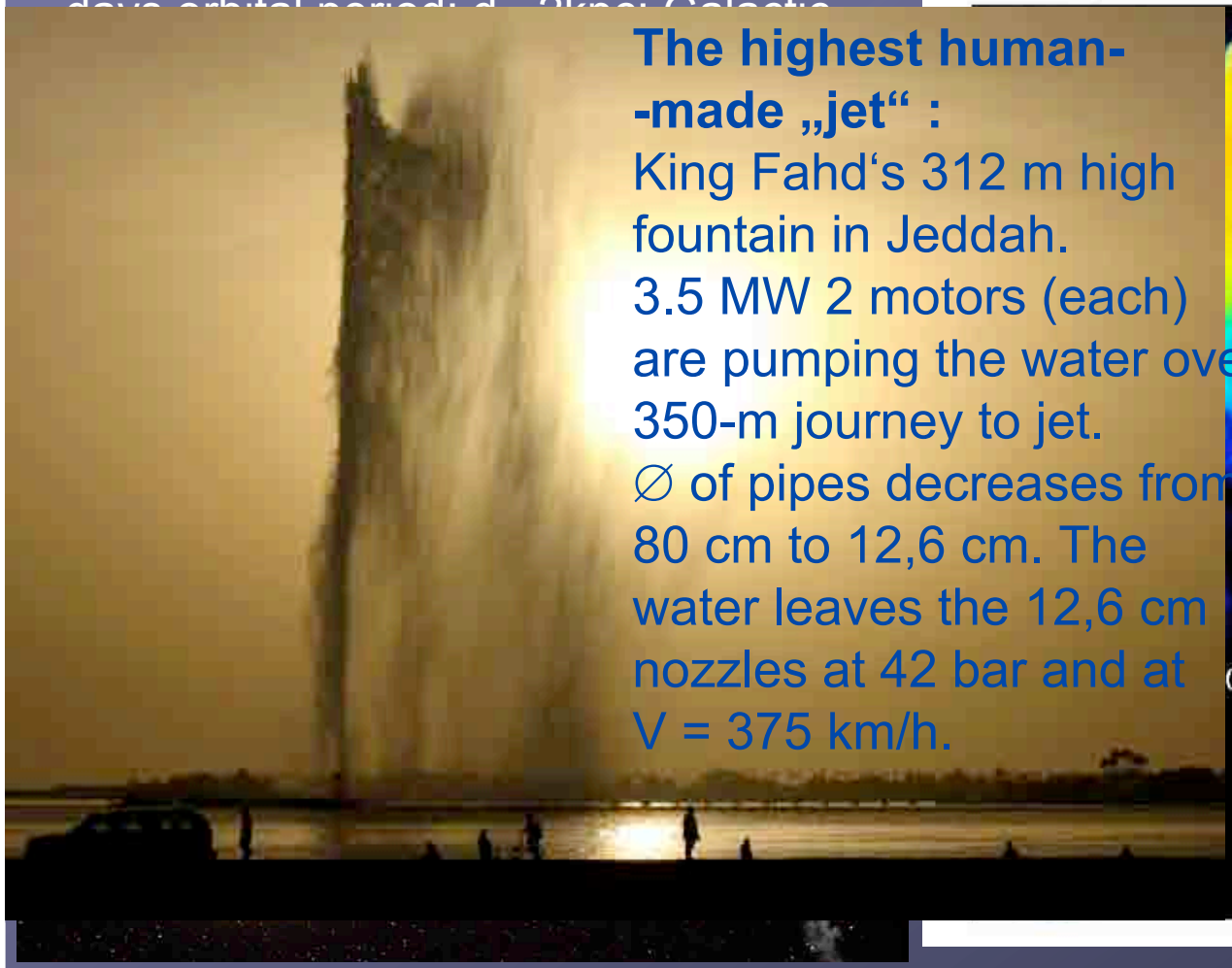
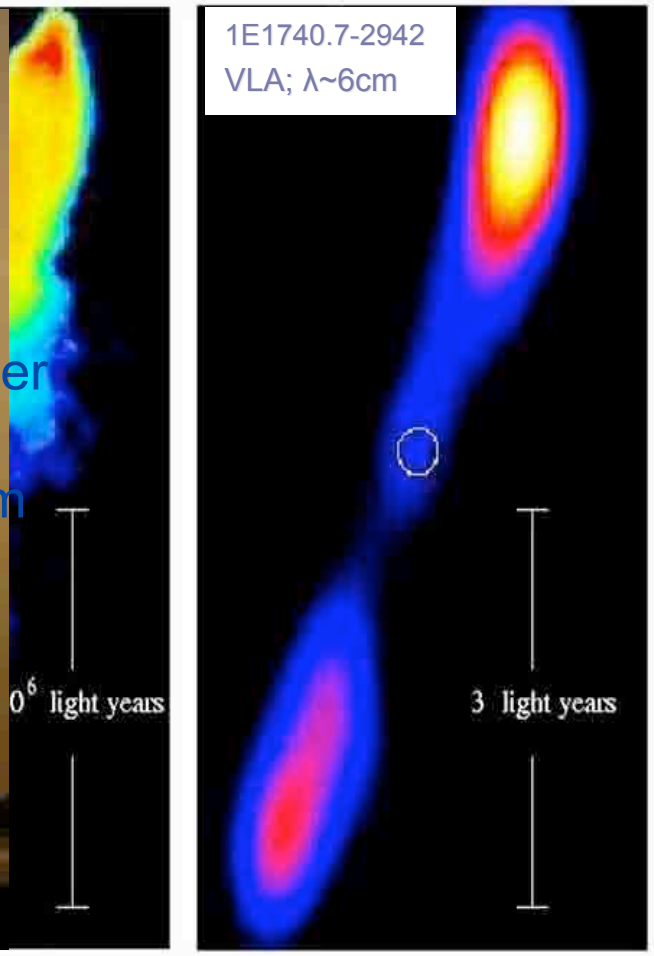
# Micro-quasar LS I +61 303

X-Ray Binary System, Radio jet; 26.5 days orbital period; d ~2kpc; Galactic

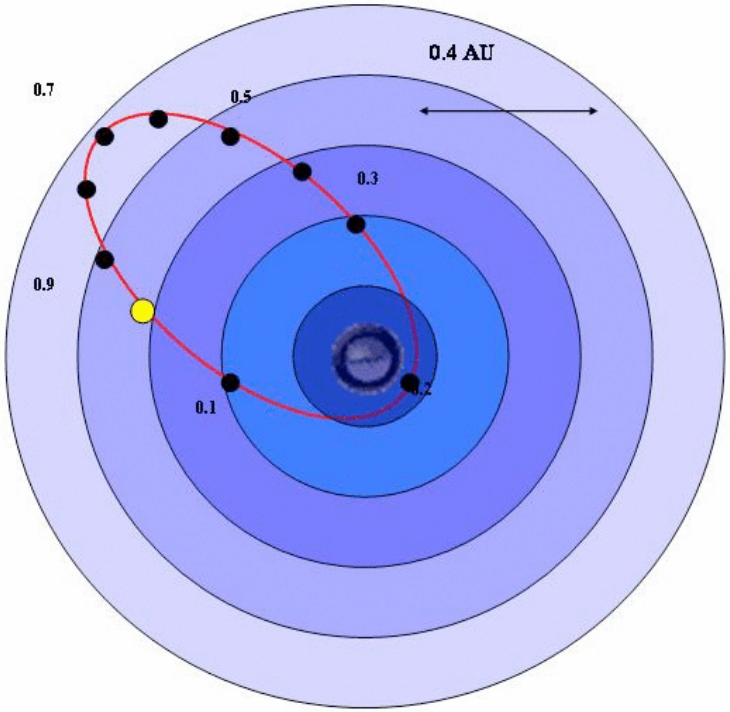


**The highest human-made „jet“ :**
King Fahd‘s 312 m high fountain in Jeddah.
3.5 MW 2 motors (each) are pumping the water over 350-m journey to jet.
∅ of pipes decreases from 80 cm to 12,6 cm. The water leaves the 12,6 cm nozzles at 42 bar and at V = 375 km/h.

Quasar Microquasar



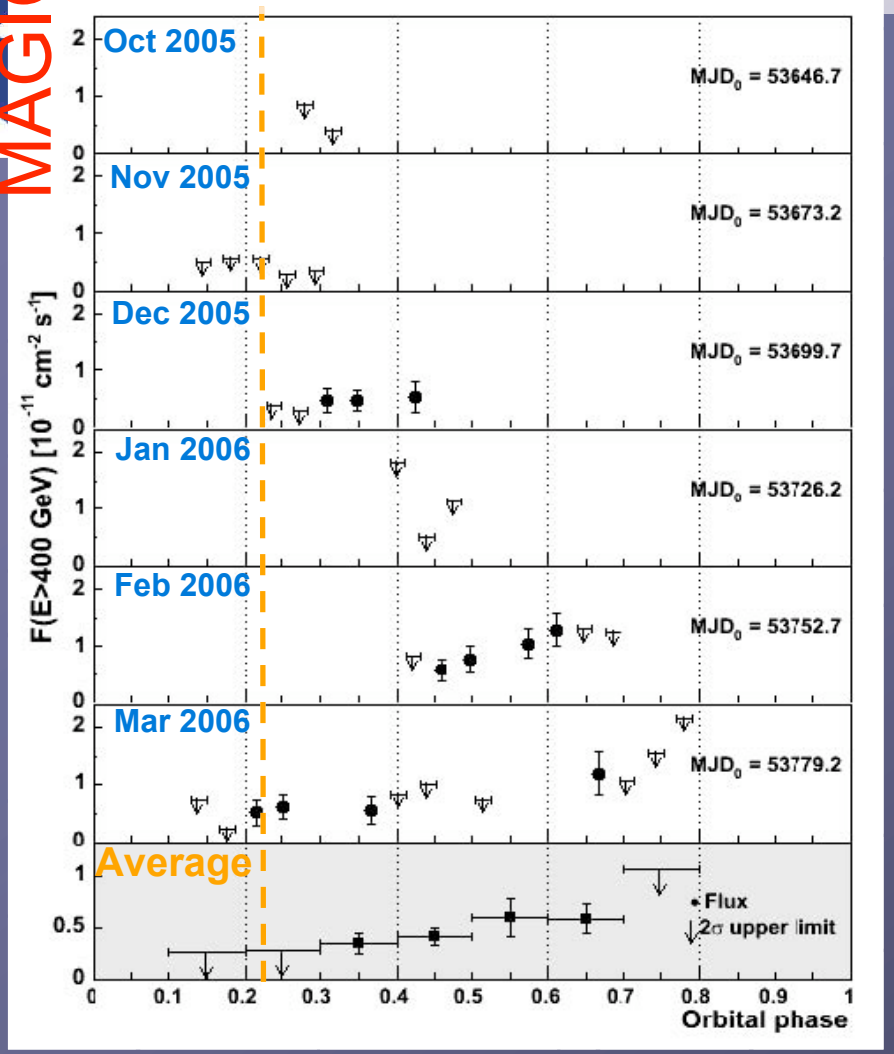
# TeV Binary System LS I +61 303




- **Discovered by MAGIC in 2005**
- The average emission has a **maximum at phase 0.6**.
- No hint for **intra-night flux variations** (observed in radio and x-rays)
- **Marginal detections** occur at lower phases.

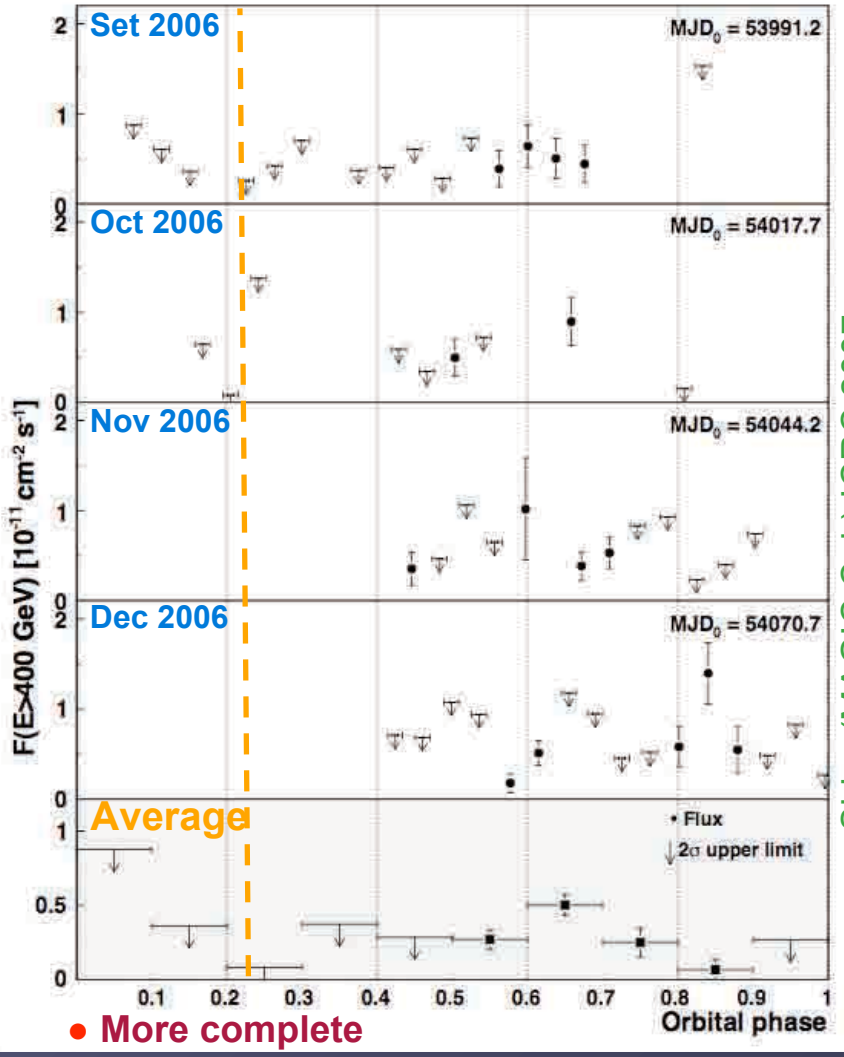
MAGIC

## Season I : ~54 hours



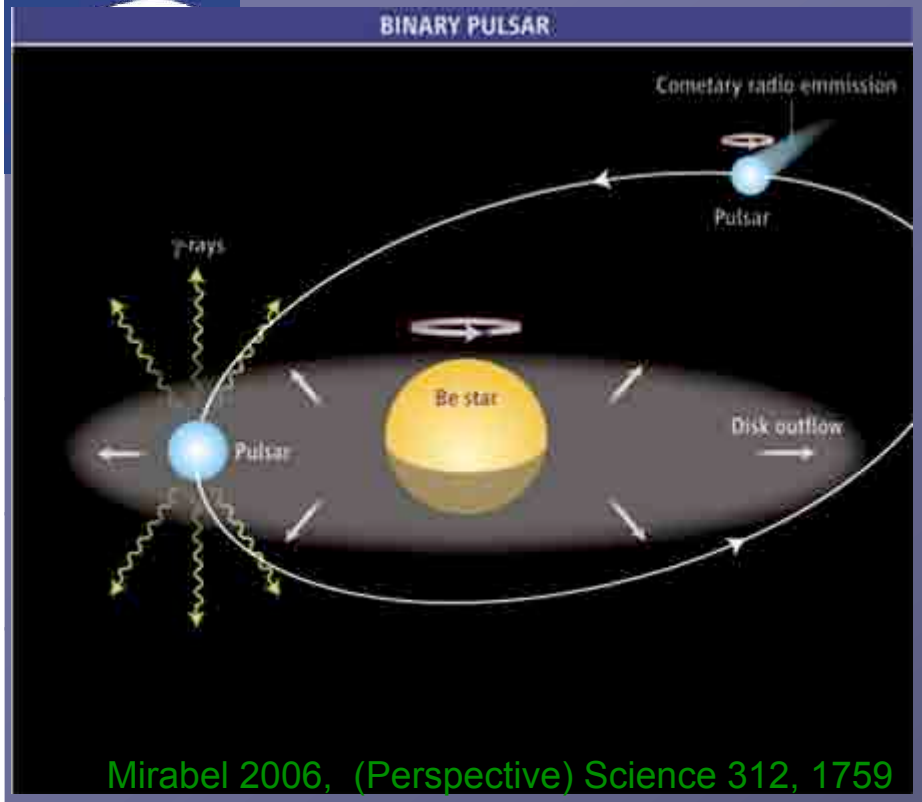

- A **variable flux** (prob. stat. fluctuation $3 \cdot 10^{-5}$)
- **Maximum flux** @ phase 0.6-0.7 (16% Crab flux)
- No **intra-night flux variations** (but seen in radio, & X)

## Season II: ~112 hours



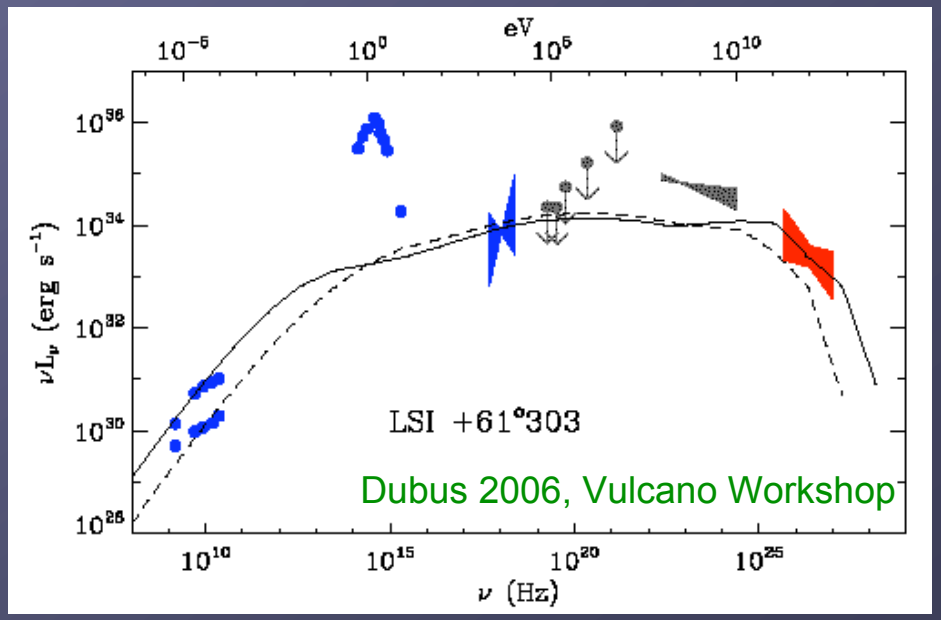

Sidro (MAGIC Col.) ICRC 2007

- **More complete**
- Similar behaviour as before
- Maximum flux detected at phase 0.6-0.7
- Exception one point at Φ~0.85




Mirabel 2006, (Perspective) Science 312, 1759

A possible scenario comes from the interaction of the relativistic wind from a young pulsar with the wind from its stellar companion, as in PSR B1259-63. A cometary nebula of radio emitting particles is formed. It rotates with the orbital period of the binary system. We see this nebula projected (Dubus 2006, A&A 456, 801).

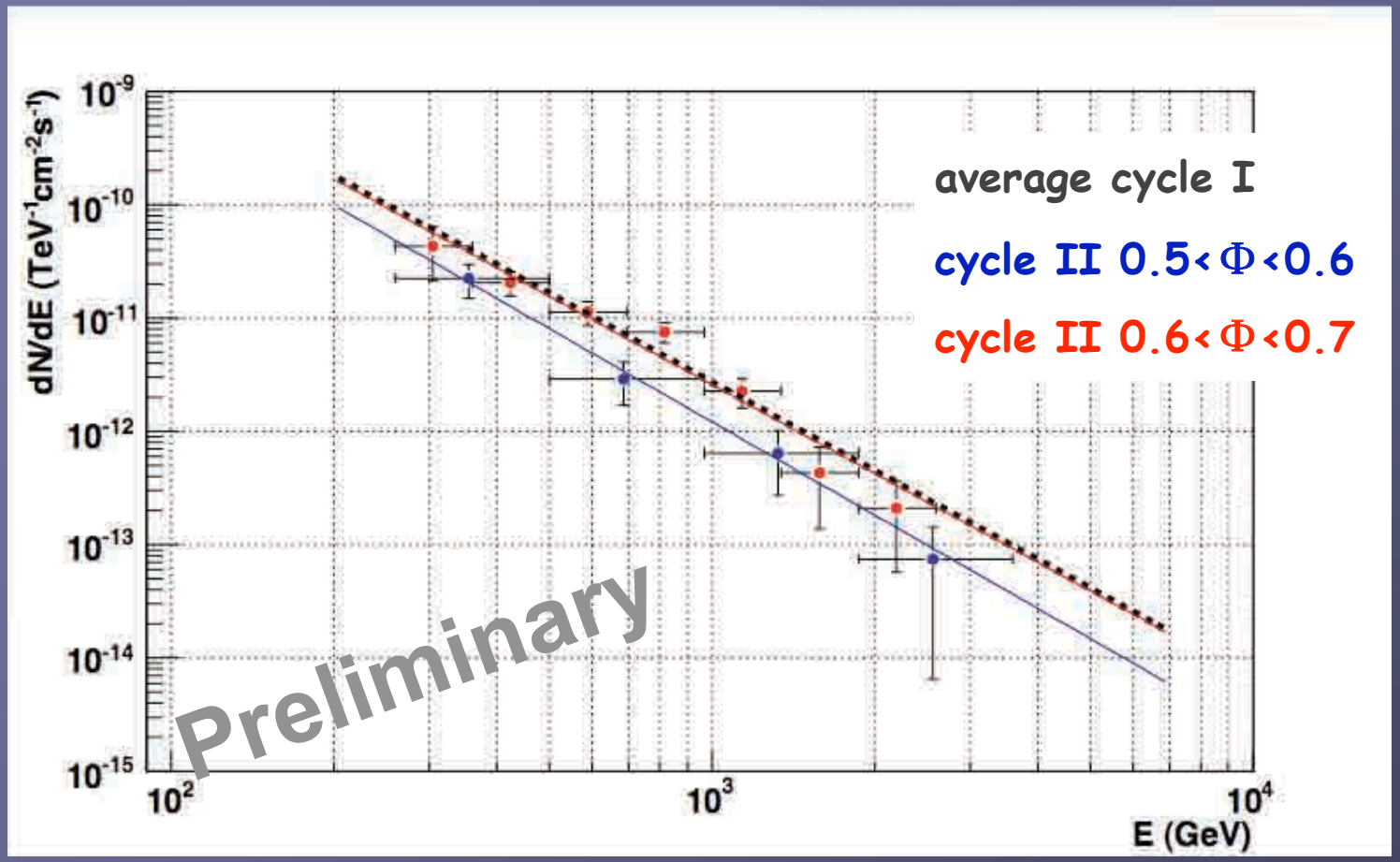



Dubus 2006, Vulcano Workshop

UV photons from the companion star suffer inverse Compton scattering by the same population of non-thermal particles, leading to emission in the GeV-TeV energy range.

(Dubus 2006, A&A 456, 801; Maraschi & Treves 1981).

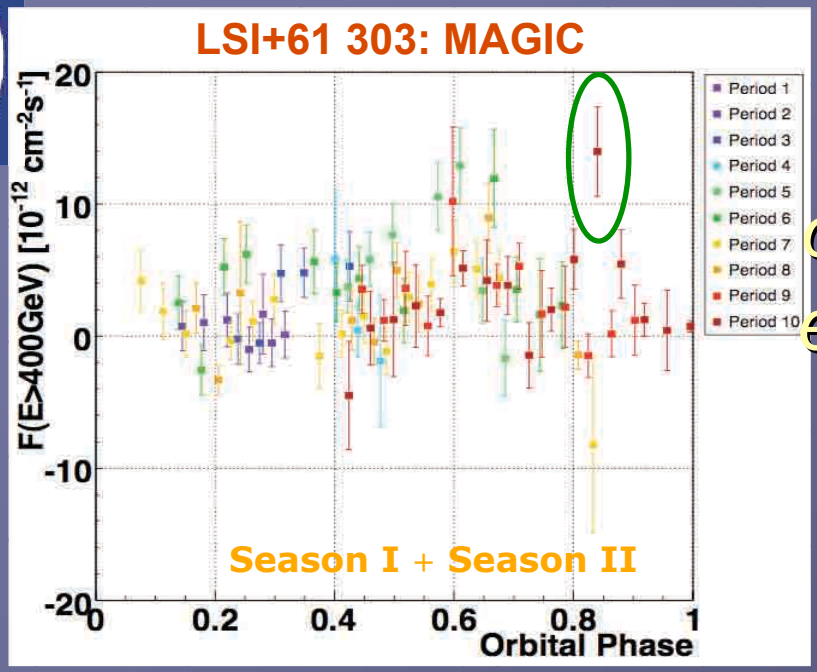
# Energy Spectrum




- The **average energy spectrum** from 200 GeV to 4 TeV is well fitted by a power law with spectral index $\alpha$ = -2.6 ± 0.2 (stat) ± 0.2 (syst)
- The luminosity above 200 GeV is ~7 x $10^{33}$ erg $s^{-1}$ (if distance ~2 kpc)
- **It is more luminous at TeV** energies than at **X-rays**
- **Spectral stability**: both cycles (over 1 year) / different measured phases / days

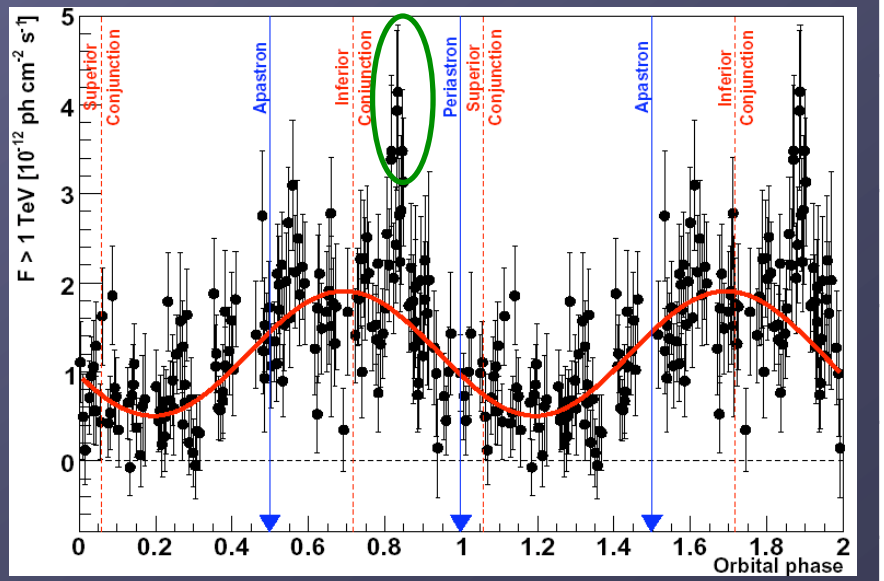
Sidro (MAGIC Col.) ICRC 2007

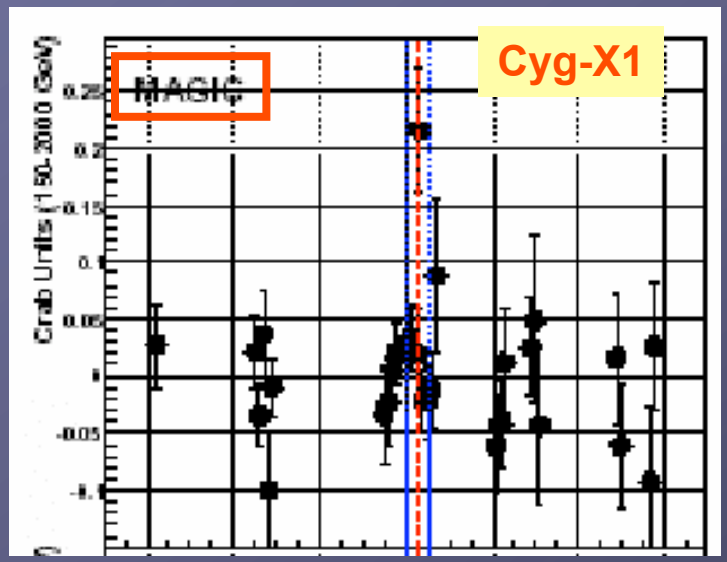
## LSI+61 303: MAGIC



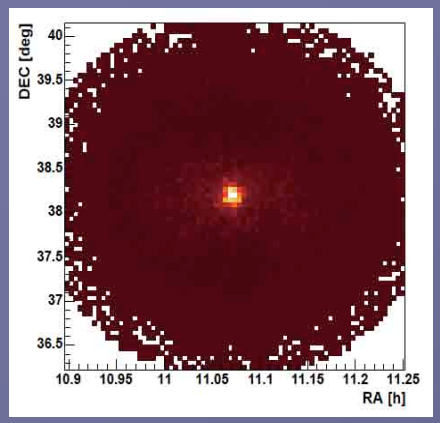

*Could it be that the flaring of binary systems @ VHE γ energies is not an exception but rather a "rule" ?*

## LS 5039: H.E.S.S.

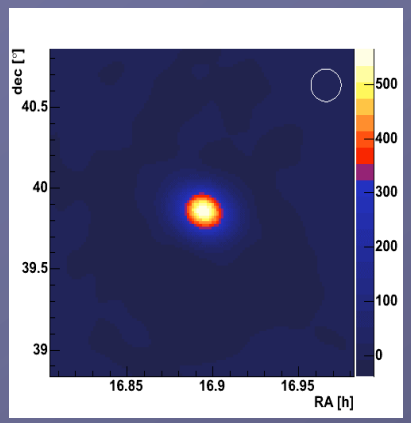


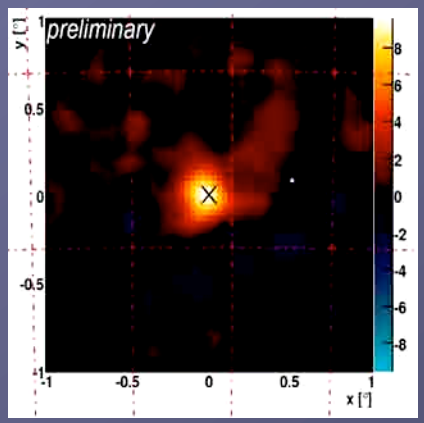
# Highlights in extra-galactic source observations



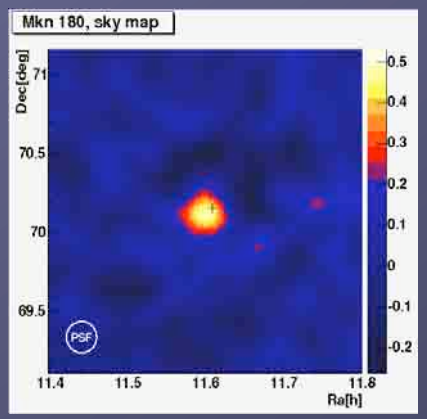

Mrk421 (0.031)



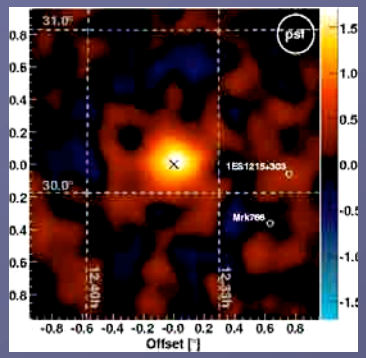

Mrk501 (z=0.034)
Very fast flare



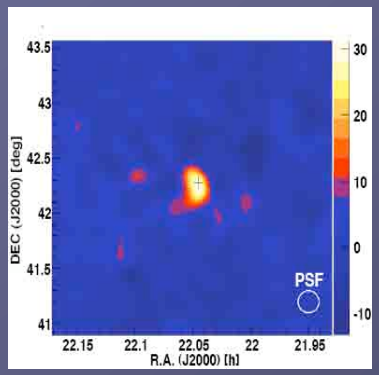

1ES2344 (z=0.044)



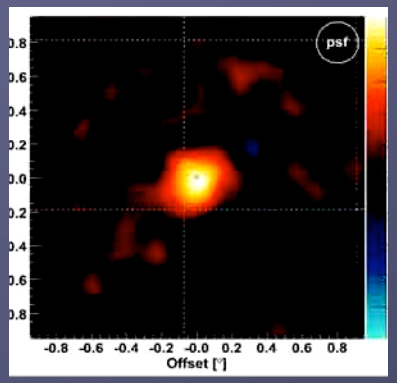

Mrk180 (0.045)
MAGIC discovery



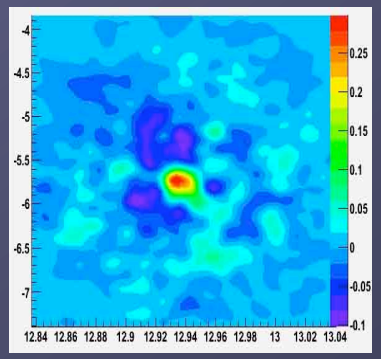

1ES1218 (z=0.18)
MAGIC discovery



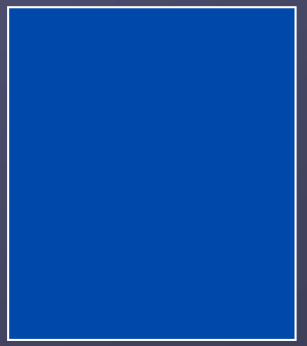

BL-Lacertae (0.069)
MAGIC discovery




PG 1553 (Z>0.25)
MAGIC discovery

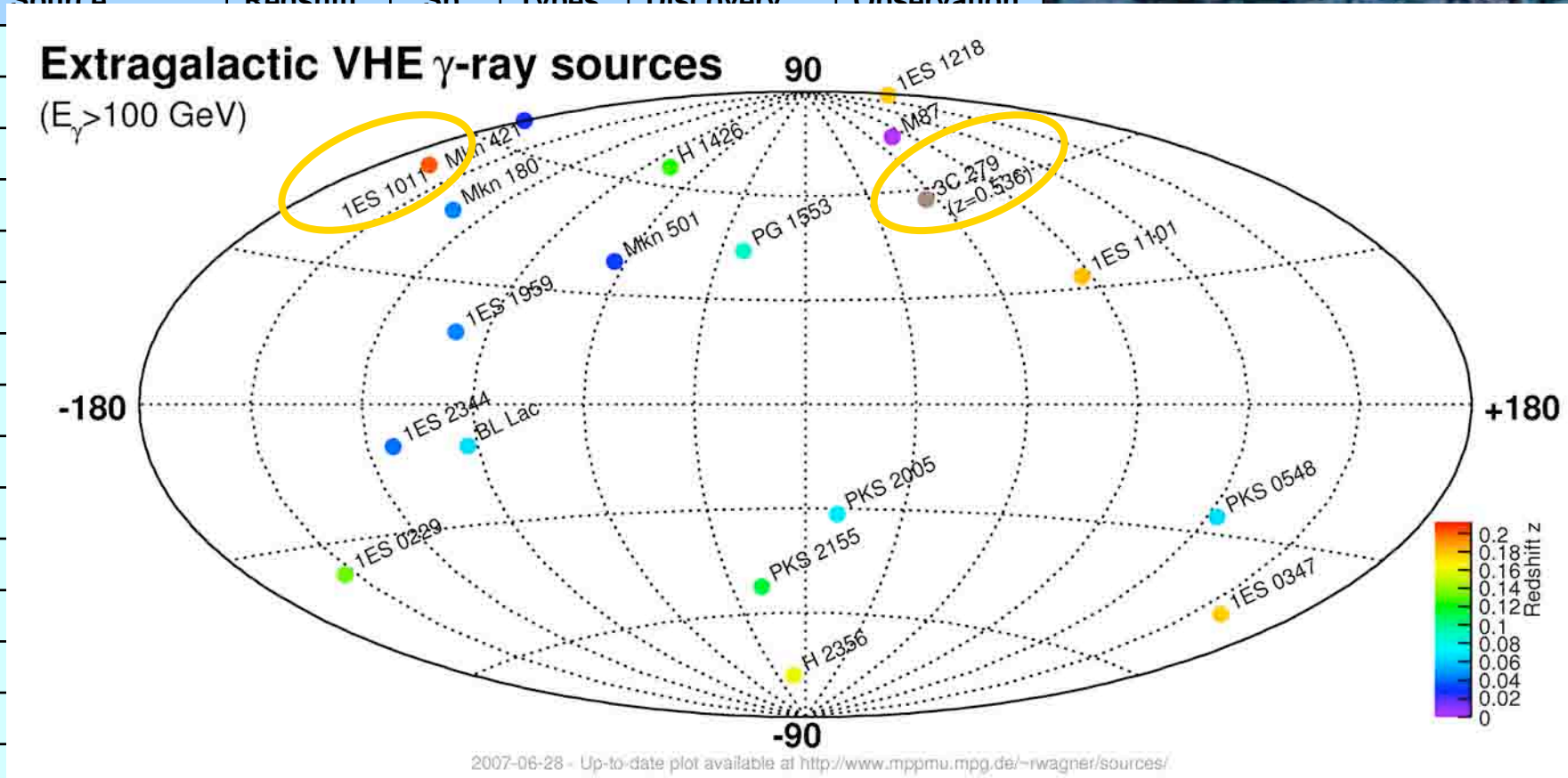


3C 279
MAGIC discovery



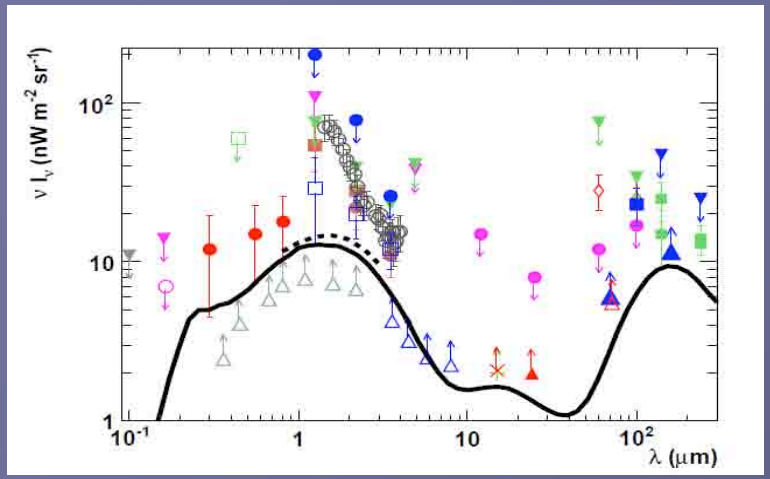
NEW ! 3C XYZ
MAGIC discovery

# Extragalactic VHE γ-Sources 19 (20)



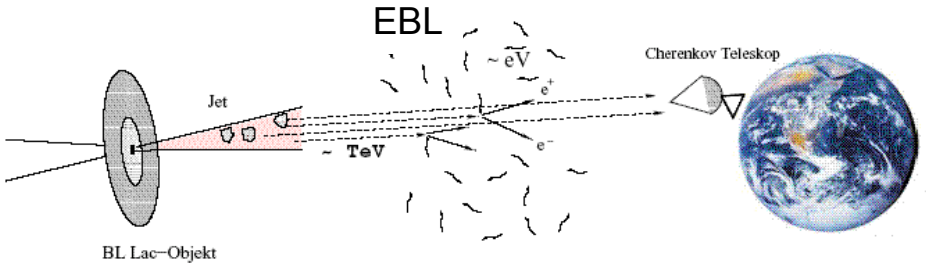

| Source | Redshift | Sp | Types | Discovery | Observation |
|---|---|---|---|---|---|
| 1ES 0347-121 | 0.188 | | HBL | HESS | |
| 1ES 1011+496 | 0.212 | 4.0 | HBL | MAGIC | |
| 3C 279 | 0.538 | | FSRQ | MAGIC | |
| PG 1553 | ? | 4.0 | HBL | HESS/MAGIC | |

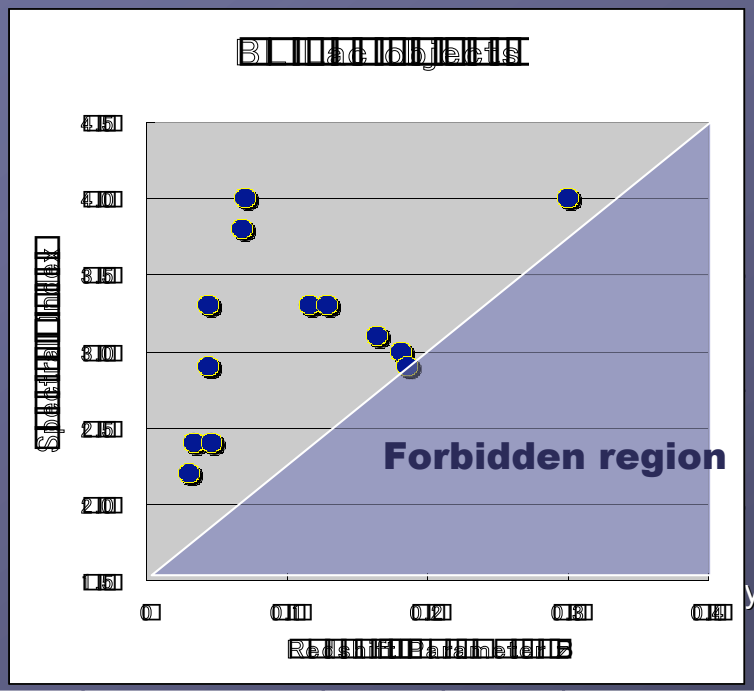
# Absorption of γ's in Universe

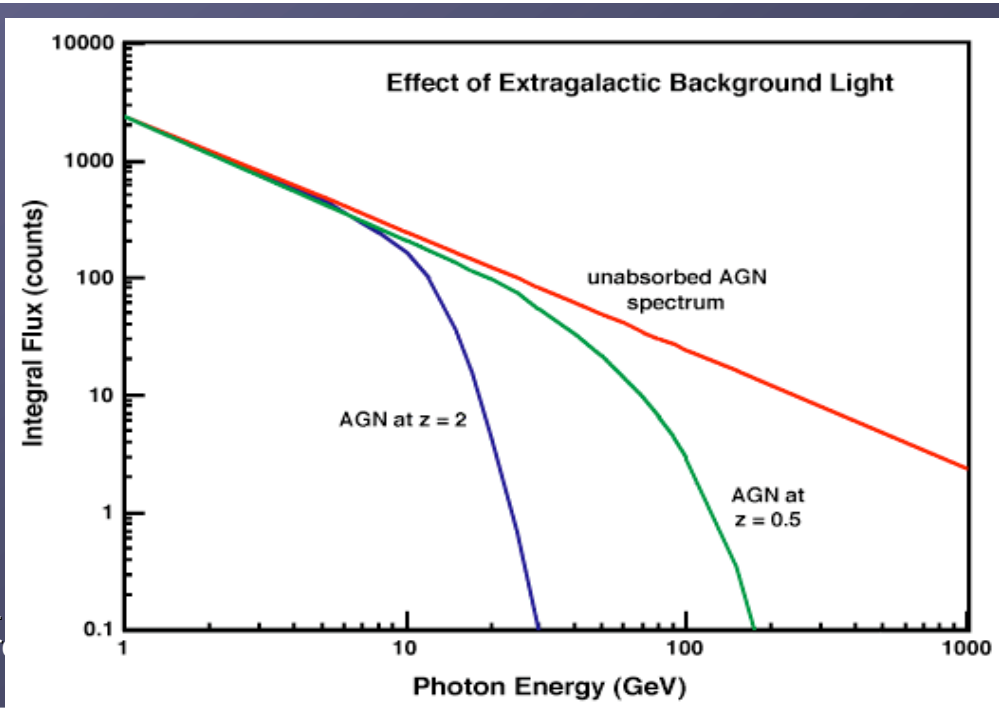



Pair Creation:

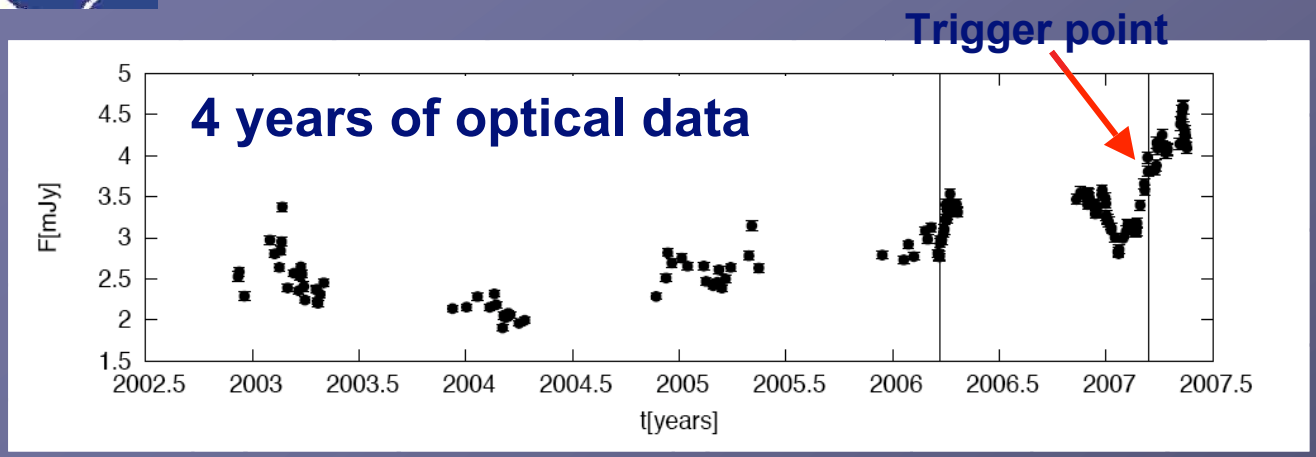
$\gamma \square \gamma_{EBL} \rightarrow e^+ + e^-$

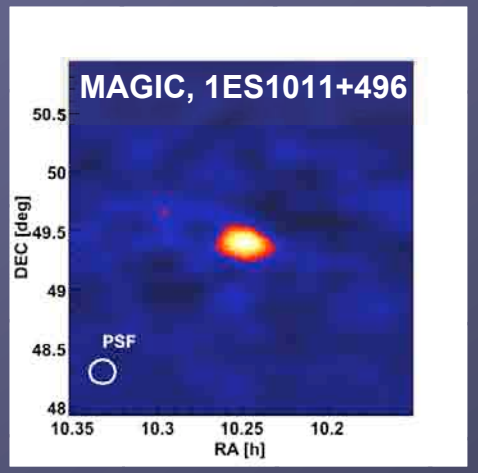


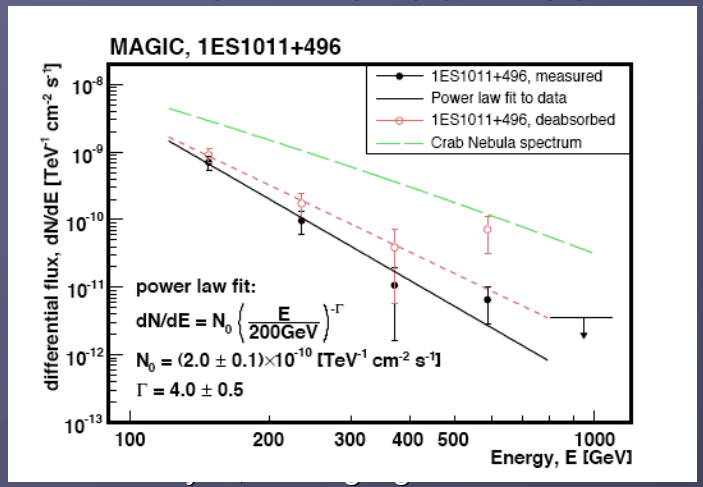
# 1ES 1011+496

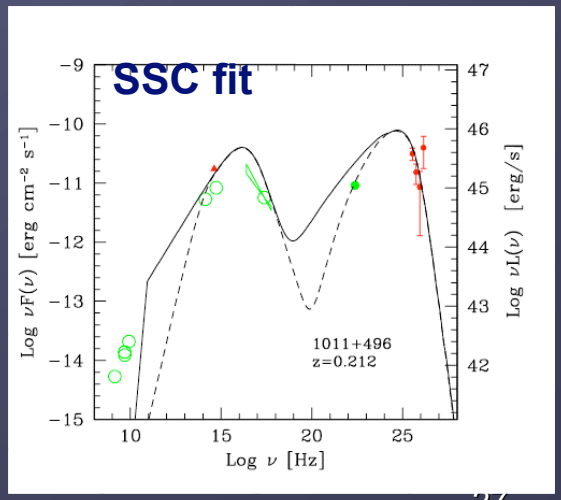


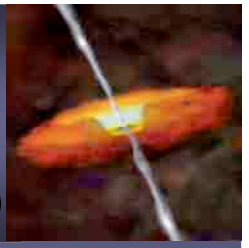

**Optical trigger: MAGIC observations in March-May 2007, 18.7h of data, clear signal (6.2 σ): discovery !** ApJ Lett. 667 (2007) , arXiv:0706.4435

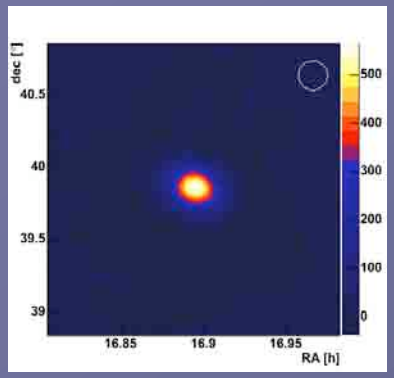
- Soft spectrum: Γ=3.3 after deabsorption
- 10% crab at 200 GeV
- No significant variability
- 3 σ in 2006 data. If it was due to genuine signal, then 40% lower flux then in 2007

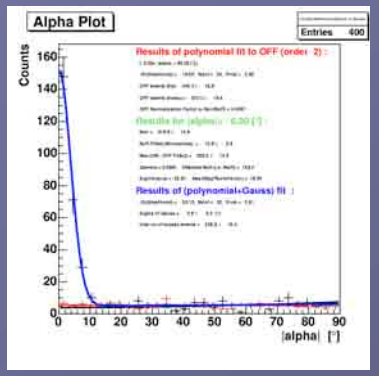


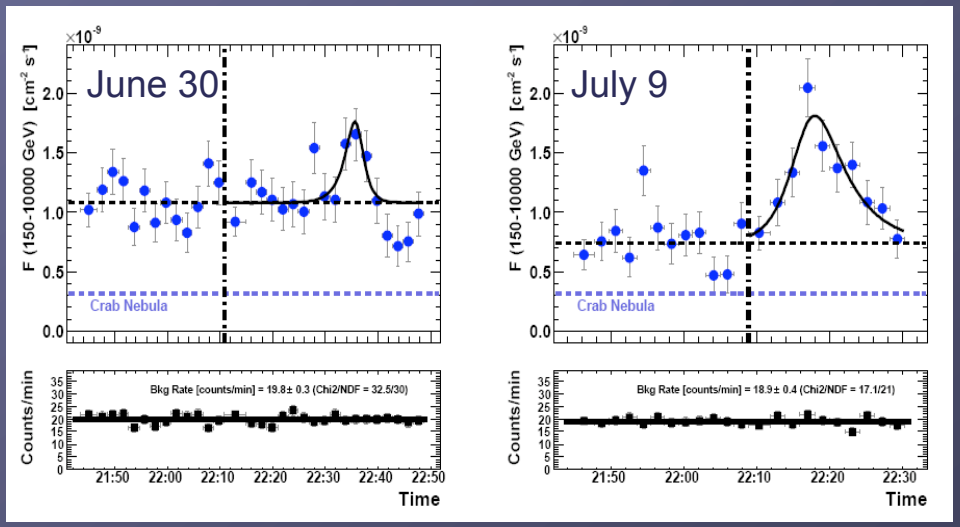
# Mrk-501 Flares on June 30 and July 9 in 2005



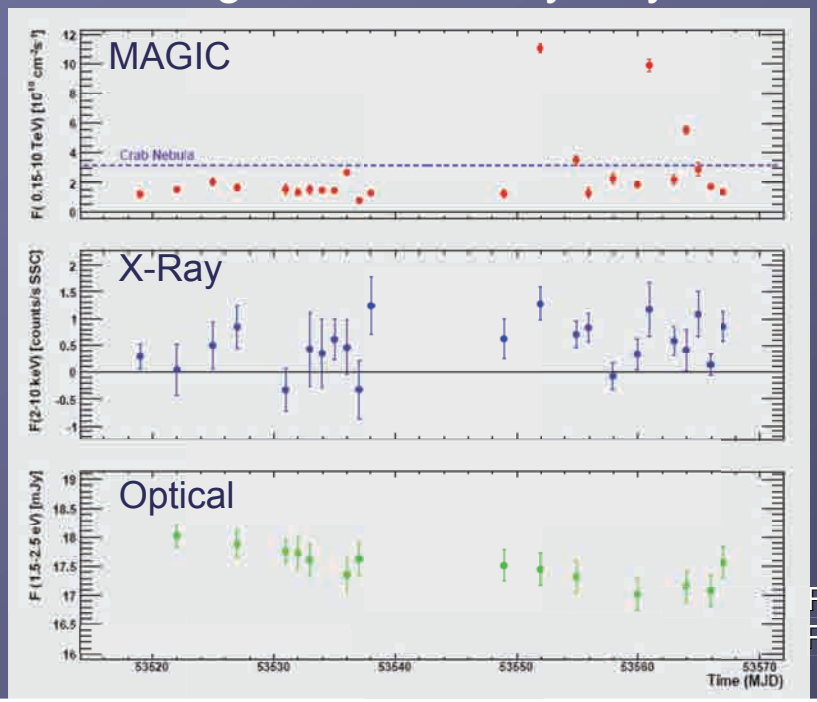


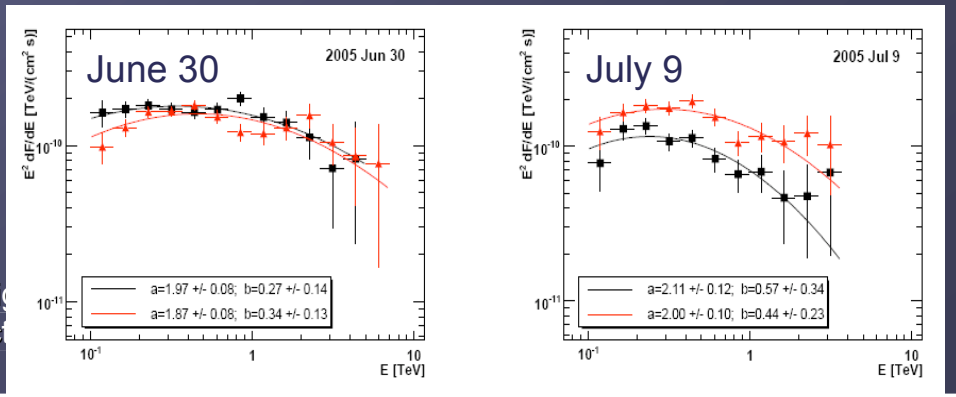

## Intra-night light curve in 2mins bin



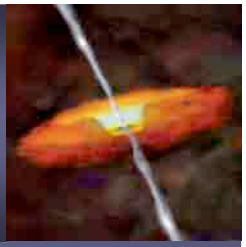

## Light curve in May-July 2005

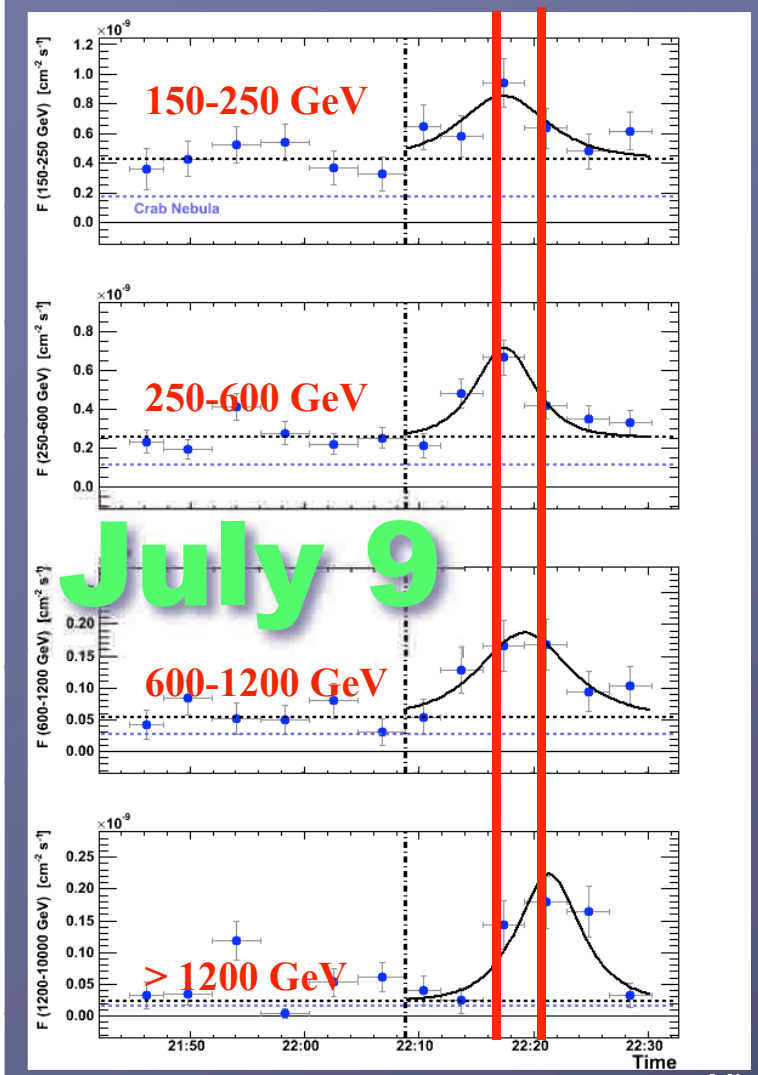



## Energy Spectra in pre-burst state and burst state



# Mrk-501: July 9 outburst
# Time lag for higher energies






4min bin

arXiv:0708.2889v1 [astro-ph] 21 Aug 2007

This time lag may be explained by the particle acceleration process.

**IF**

**Photons at different energies were emitted simultaneously**

**30 sec.**

~~$\Delta T = 4 \pm 1\ min;\ \Delta E \sim 1\ TeV$~~

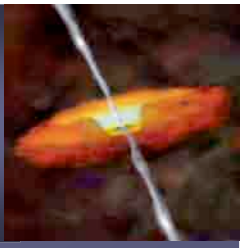
$$E_{QG} = \frac{L}{c} \cdot \frac{\Delta E}{\Delta t} = \sim\!\!(0.6 \pm 0.2) \cdot 10^{17}\ GeV\!\!\sim$$

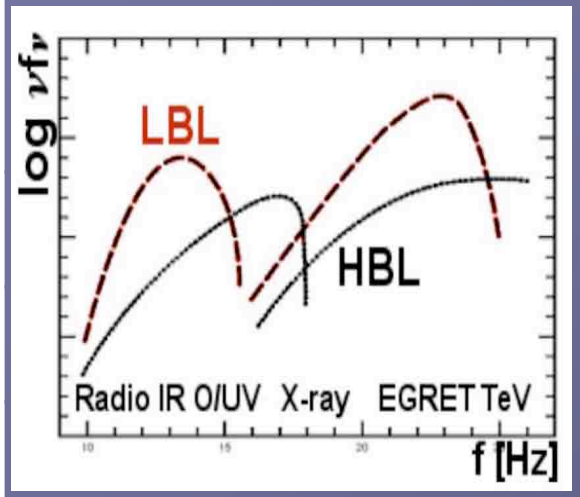
Our data provides a stringent lower limit of Q.G. energy scale: $\mathbf{M_{QG} > 0.26 \cdot 10^{18}\ GeV}$ at 95% CL. The Q.G. energy scale is estimated to be $10^{17}$~$10^{19}$GeV.

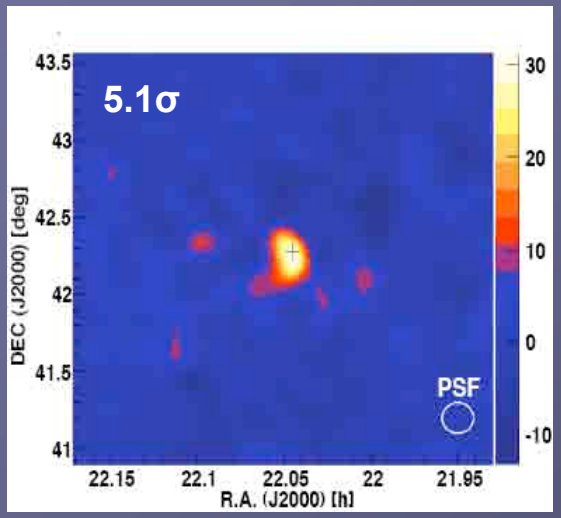
Mrk501 BH ~ $3 \times 10^9$Msolar ➔ Rsh/c ~$3 \times 10^4$sec=10 light hours

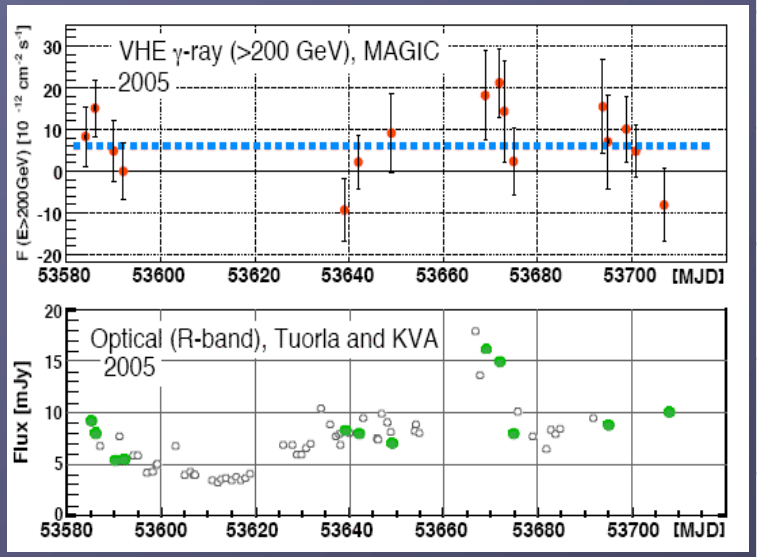
Order of 100sec time variation requires extreme jet / blob emission of Γ-factor of 100. Perhaps new theory/explanation is necessary.

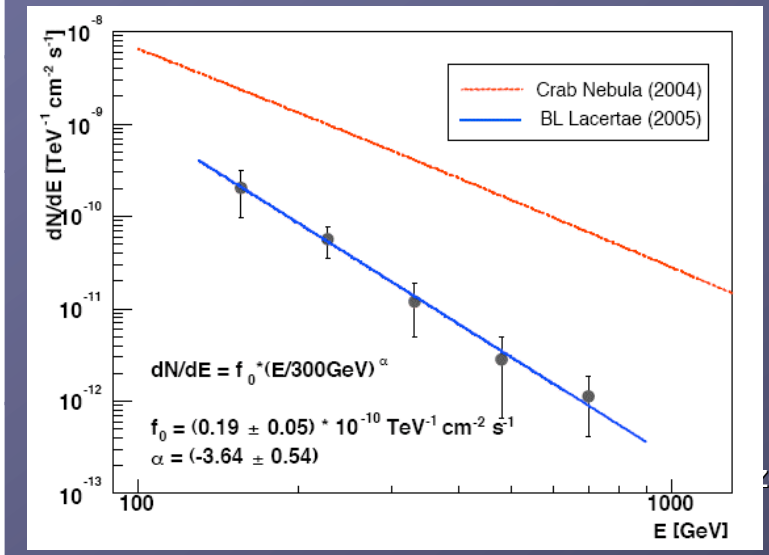
# New Source, BL Lacertae (New class: LBL, z=0.069)

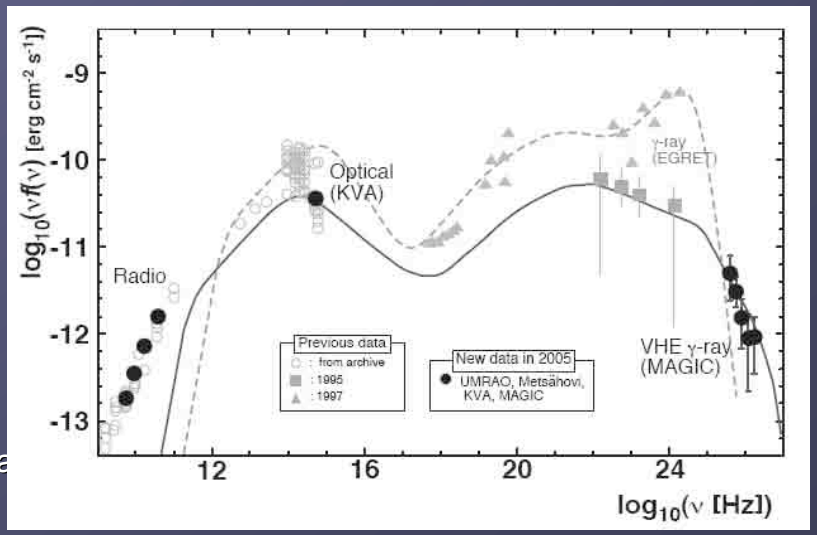




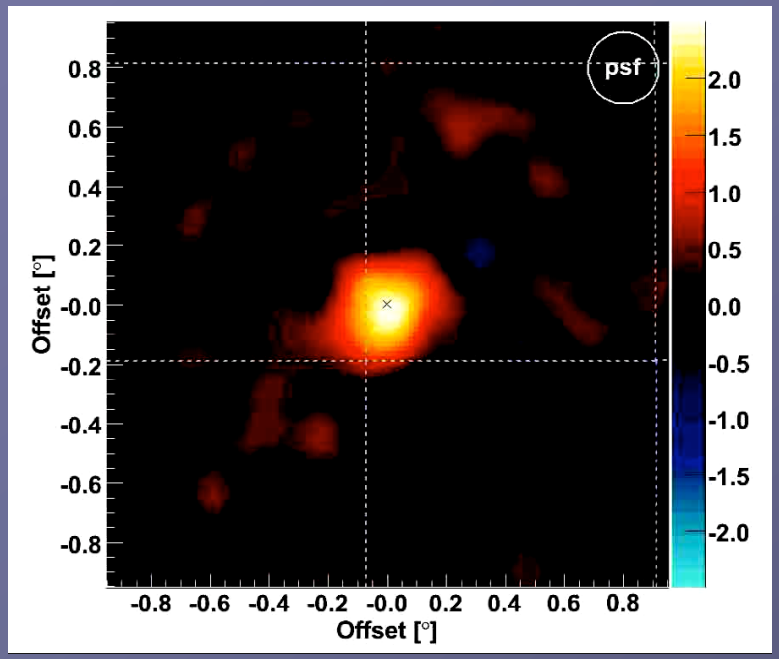



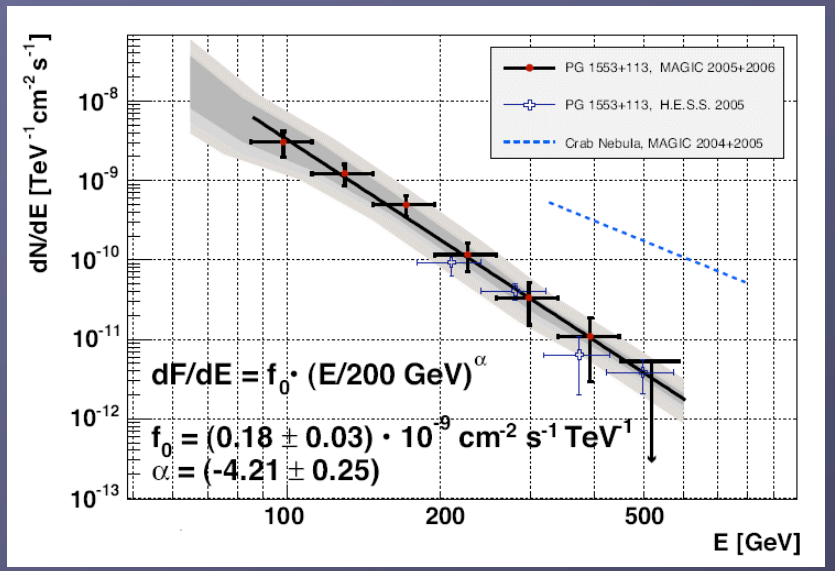




~ 3%Crab

Very steep Spectrum

# PG 1553 (z>0.25 unknown)




## Very Soft energy spectrum

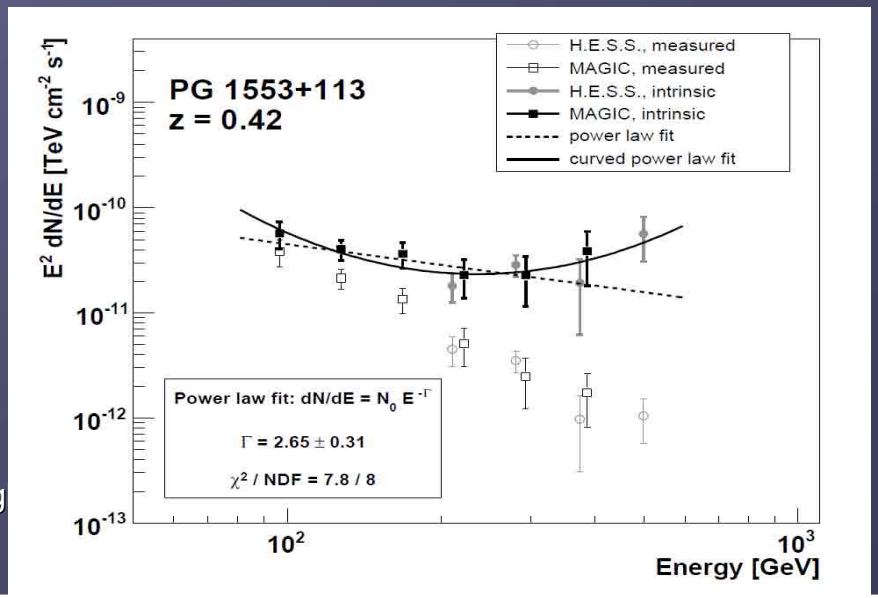
Due to EBL attenuation

or

nature of SSC mechanism

MAGIC ➔ Z < 0.42

(D.Mazin and F.Goebel)

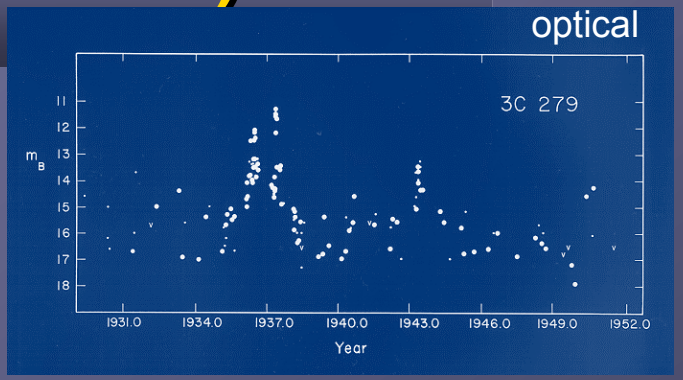



December 17, 2007

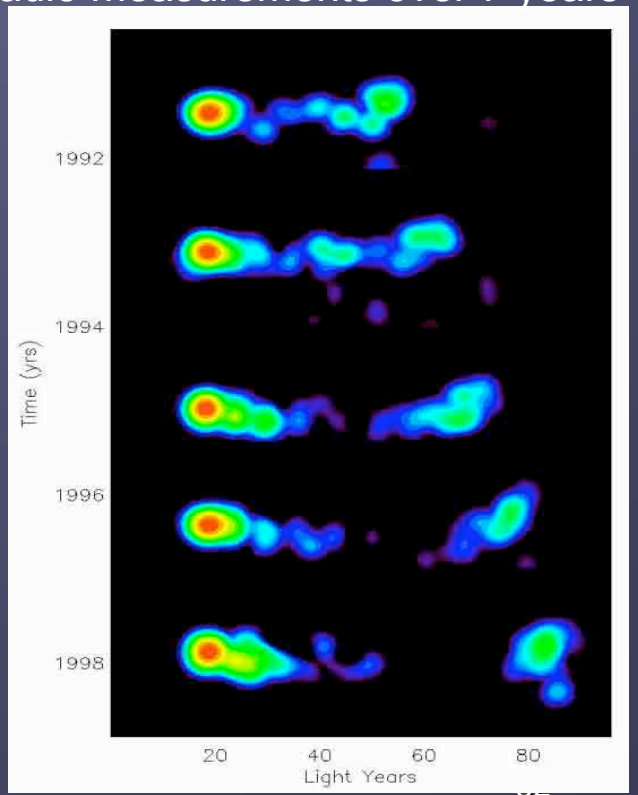
Mirzoyan, R.: Hig
Project

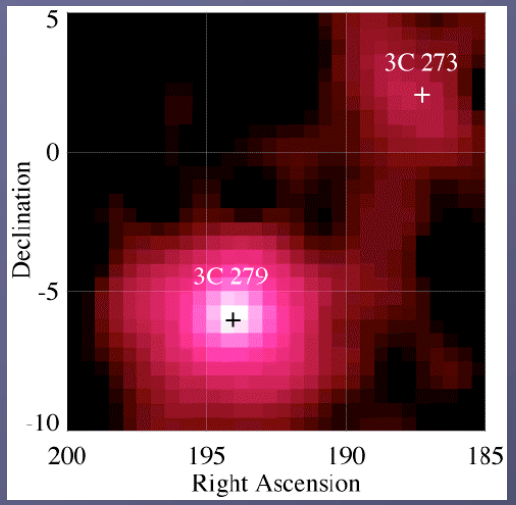
# 3C 279 (z = 0.536)

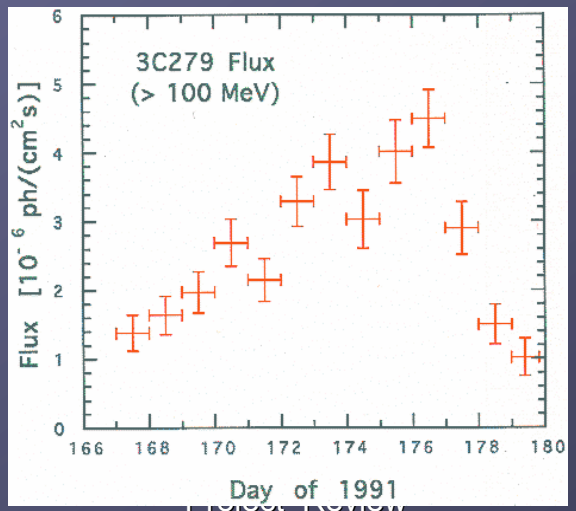
- EGRET brightest AGN
  - Gamma-ray flares in 1991 and 1996
  - Apparent luminosity ~ $10^{48}$erg/s
  - First time variation □□~ 6hr in 1996 flare
- Typical OVV quasar (Optically violent variable)
  - Categorized as a FSRQ (Flat Spectrum Radio Quasar)
- Superluminal motion, γ~ 20~30
- z = 0.538, Ld ~ 3Gpc



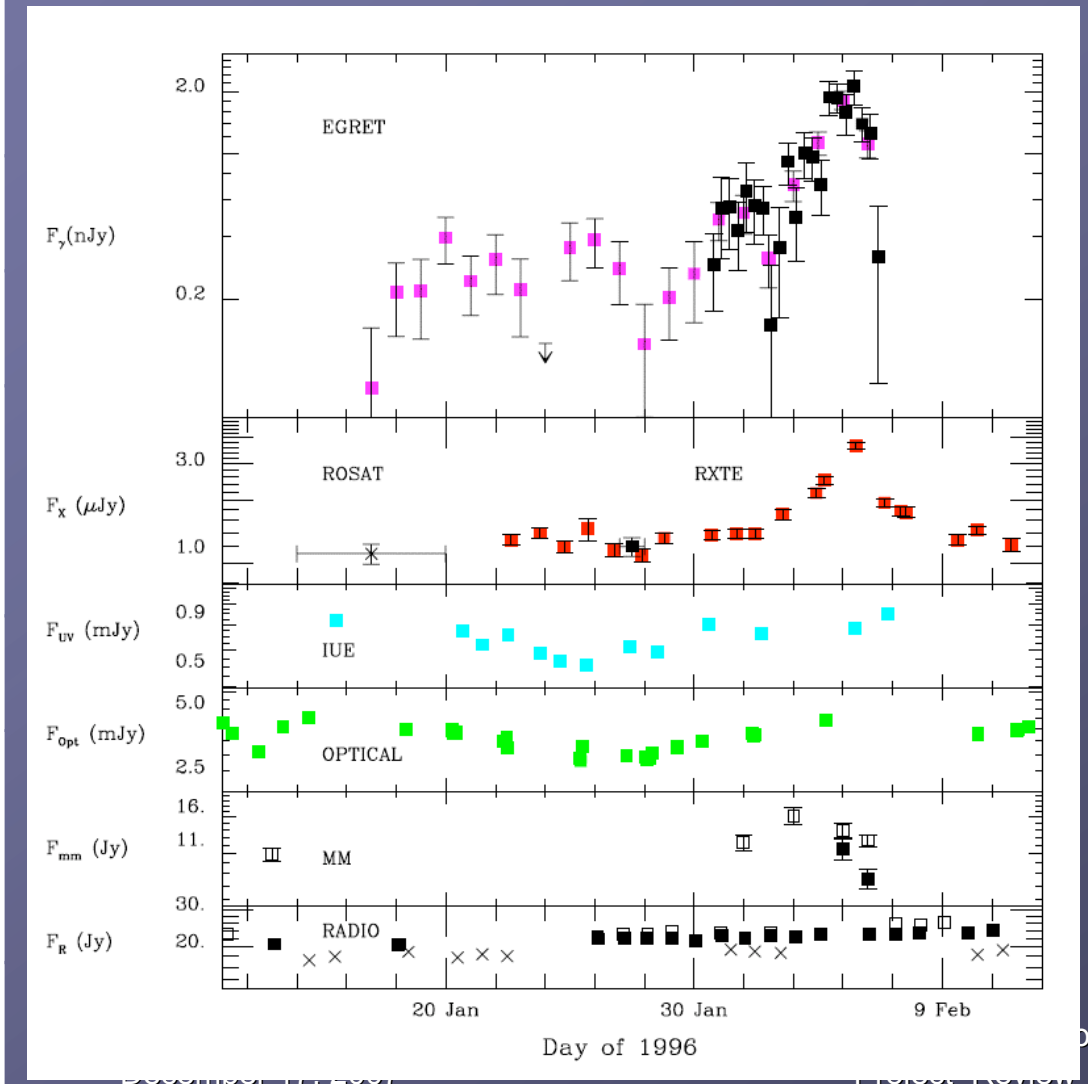

Radio measurements over 7 years

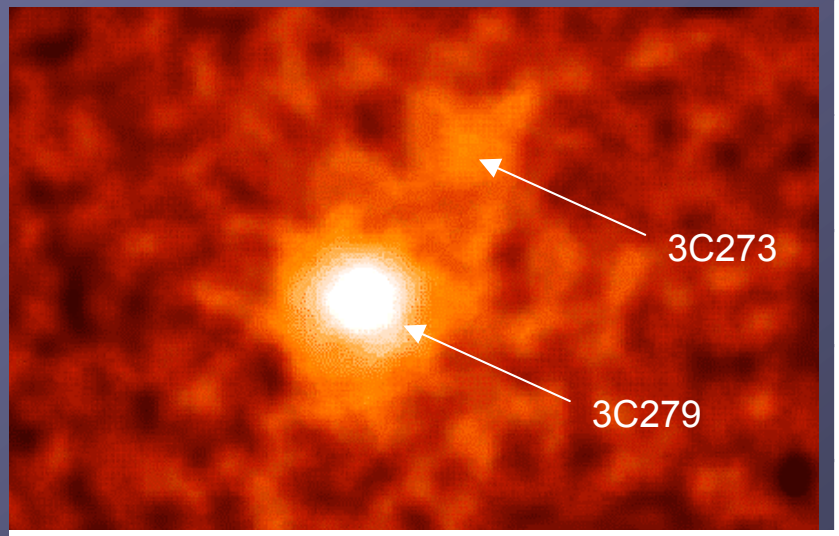


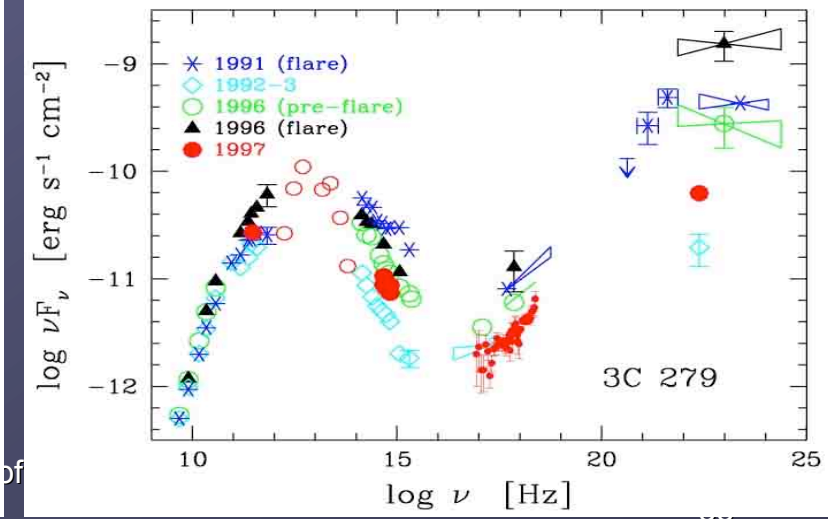



# 3C 279 Flare in 1996



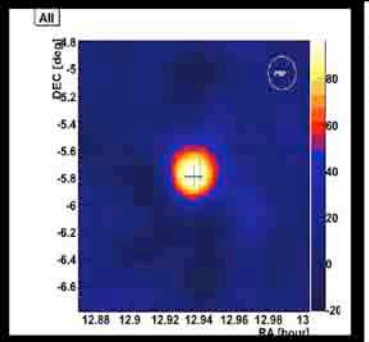



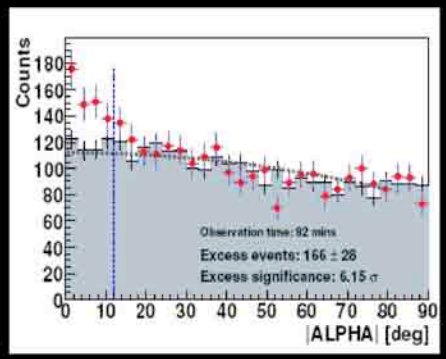
# MAGIC Discovery: 3C 279

## Sky-map and alpha plot on 23rd Feb 2006

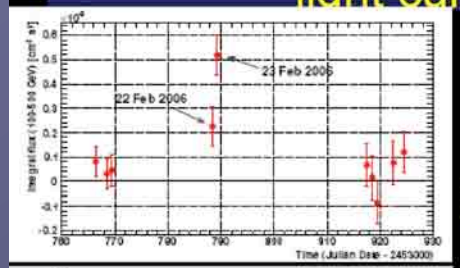
Sky map of 3C279

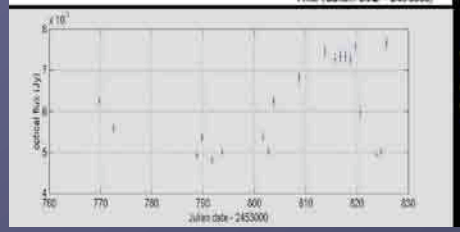



Clear detection on 23rd night




## 3C279 VHE gamma-ray light curve

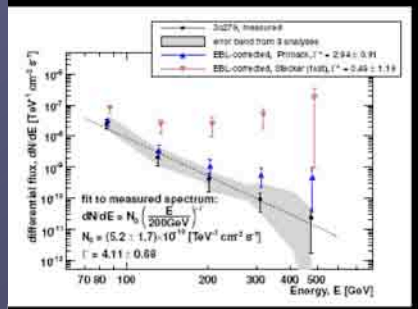



3C279 was active in optical in 2006
2~3 times brighter than 2005.
Marginal detection on 22nd night

We did not see any apparent correlation between optical and VHE gamma-rays.

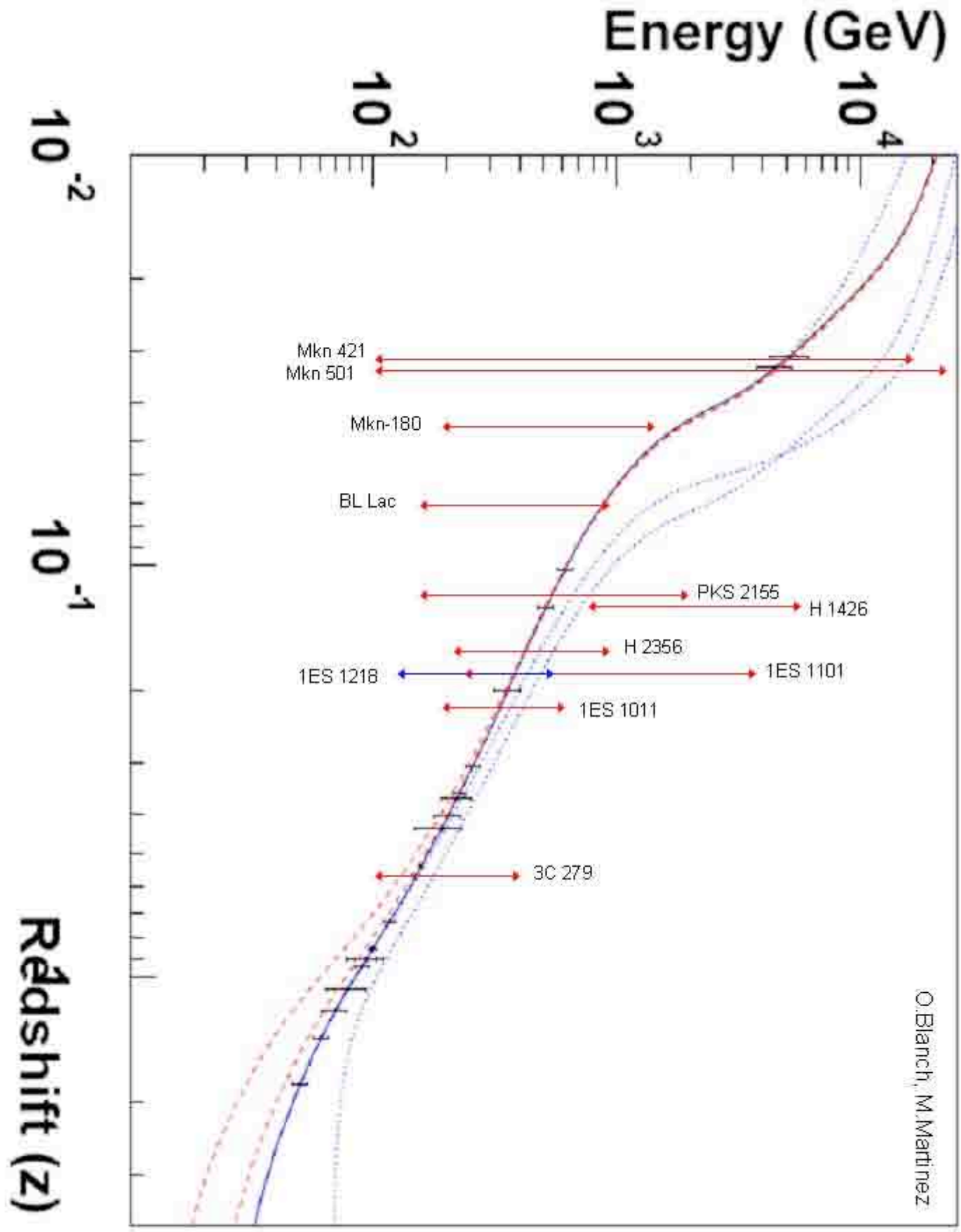
## Spectrum of 3c279




Stecker (Fast) model gives unphysical intrinsic spectrum.

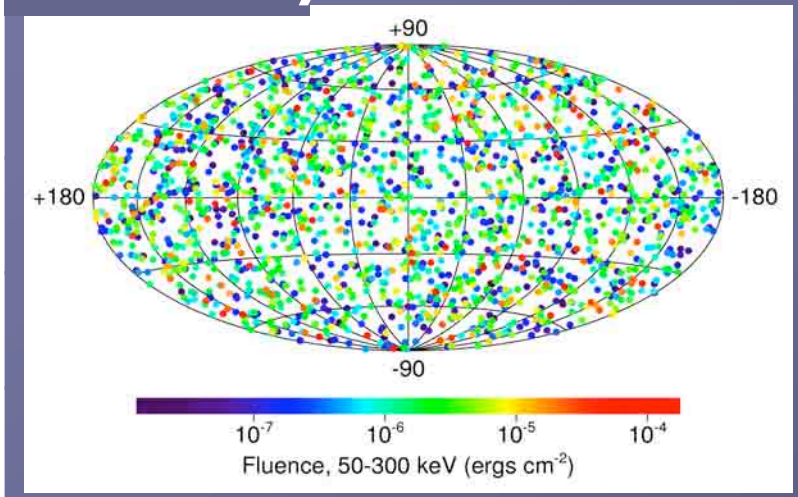
Kneiske Low Model gives hard intrinsic spectrum → additional component in SED required.

Primack (2005) gives acceptable results.

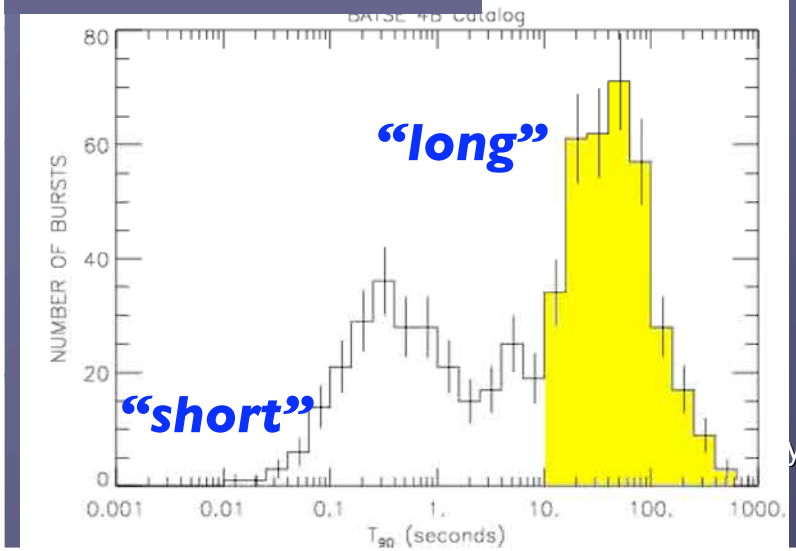


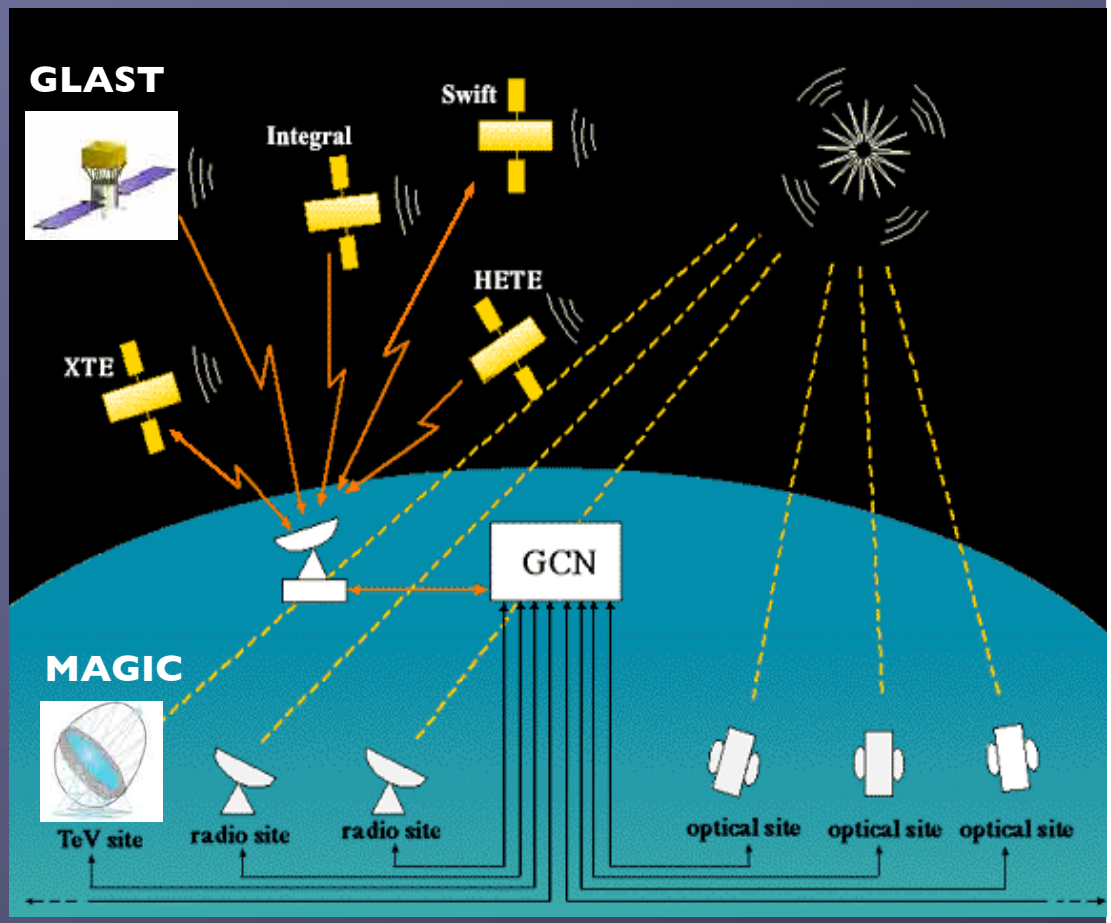
# GRB observations by MAGIC

## Uniformity



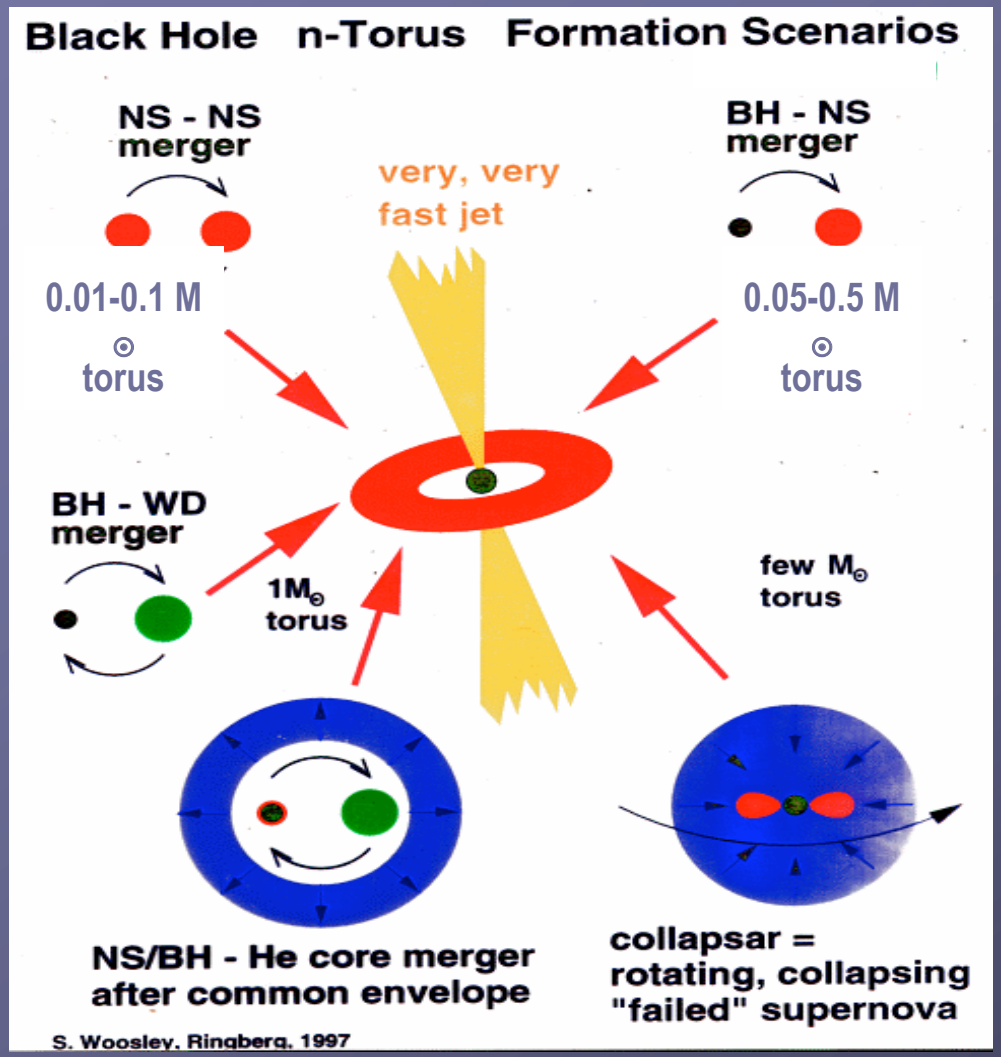

## Duration of Burst




GRB trigger from a satellite to MAGIC: 13 sec
Capability: slew to any position in ≤ 50 sec

# GRBs




- GRBs are the most energetic phenomenon in the Universe, with $10^{51}$ erg released in few sec. (equivalent to explosion of ~$10^{30}$ atomic bombs)
- Most of long duration (> 2s) class events seem to be related to the collapse of massive (> 40-50 $M_\odot$) stars in the last stages of their evolution
  ⇒ formation of a BH and a jet
- The short duration class (< 2 s) events seem to be related to mergers of compact (neutron stars) binary systems

# Observation of GRBs

## MAGIC follow-up observations

M. Garcz @ София

| | Redshift | $T_{90}$ [s] | Start data taking [s] | Observation time [min] |
|---|---|---|---|---|
| GRB060522 | 5.11 | 69 | 2752 | 13 |
| GRB060602b | - | 9 | 4230 | 26 |
| GRB060825 | - | 8.1 | 57 | 33 |
| GRB060904a | - | 80 | 5434 | 119 |
| GRB060912 | 0.94 | 5 | 24291 | 18 |
| GRB060926 | 3.21 | 8 | 12834 | 23 |
| GRB061028 | - | 106 | 169 | 100 |
| GRB061110b | 3.44 | 128 | 715 | 59 |
| GRB061217 | 0.83 | 0.2 | 786 | 66 |
| GRB070411 | 2.95 | 101 | 2652 | 128 |
| GRB070412 | - | 34 | 701 | 124+180 |

## GRB - Observed GRB locations

GRB WG: ApJ 667, 358

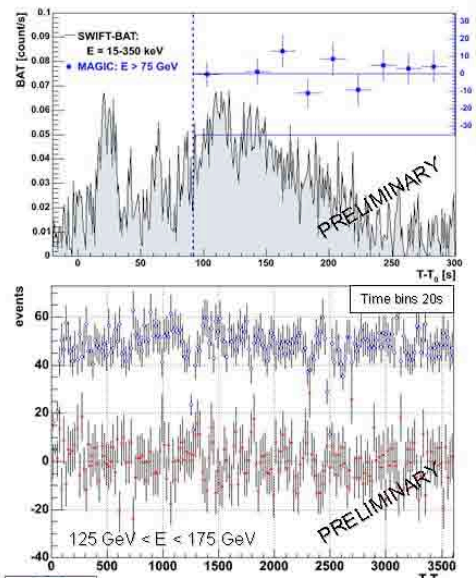
| GRB | $t_0$ | $\Delta t_{alert}$ | $\Delta t_{oss}$ | $t_{90}$ | <ZA> |
|---|---|---|---|---|---|
| 050421 | 04:11:52 | 58 s | 83 s | 10 s | 50° |
| 050502a | 02:14:18 | 18 s | 990 s | 20 s | 42° |
| 050505 | 23 | | | 0 s | 55° |
| 050509a | 01 | | | 2 s | 50° |
| 050509b | 04 | | | 13 s | 49° |
| 050528 | 04:06:45 | 43 s | 77 s | 11 s | 50° |
| 050713a | 04:29:02 | 13 s | 40 s | 27 s | 49° |
| 050904 | 01:51:44 | 82 s | 92 s | 225 s | 20° |
| 060121 | 22:24:54 | 15 s | 583 s | 2 s | 42° |
| 060203 | 23:53:35 | 171 s | 185 s | 83 s | 40° |
| 060206 | 04:46:53 | 16 s | 25 s | 11 s | 10° |

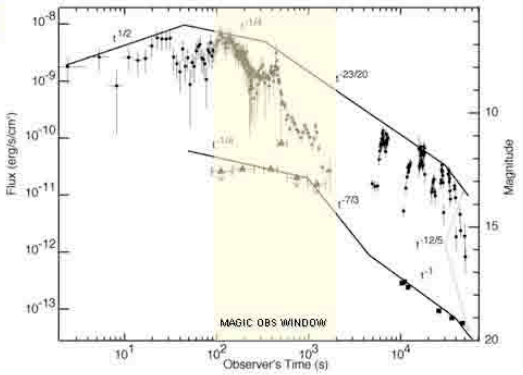
Typical repointing 10÷30 s

Denis Bastieri - Collaboration Meeting - Madrid, 22 Nov 2006 11

## The Case of GRB050904

**later we learnt that z = 6.3**



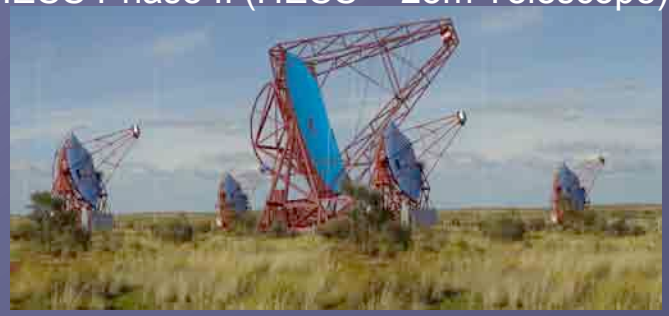
# From EGRET (all years) to GLAST (1 year)

# Outlook : the next 7-10 years

## Next generation VHE γ ray Observatory: CTA

MAGIC Phase II (MAGIC-I + MAGIC-II) in 2008
50-100 sources will be discovered

HESS Phase II (HESS + 28m Telescope) in 2009

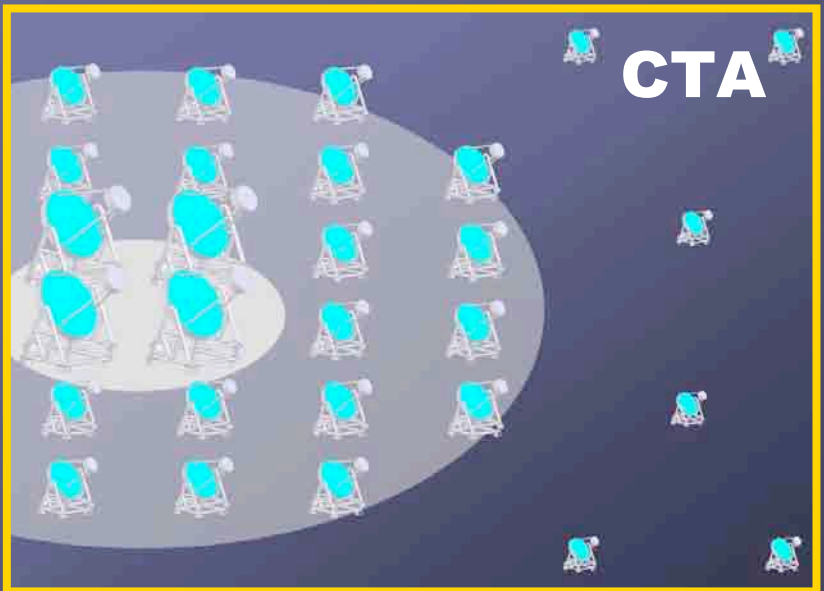


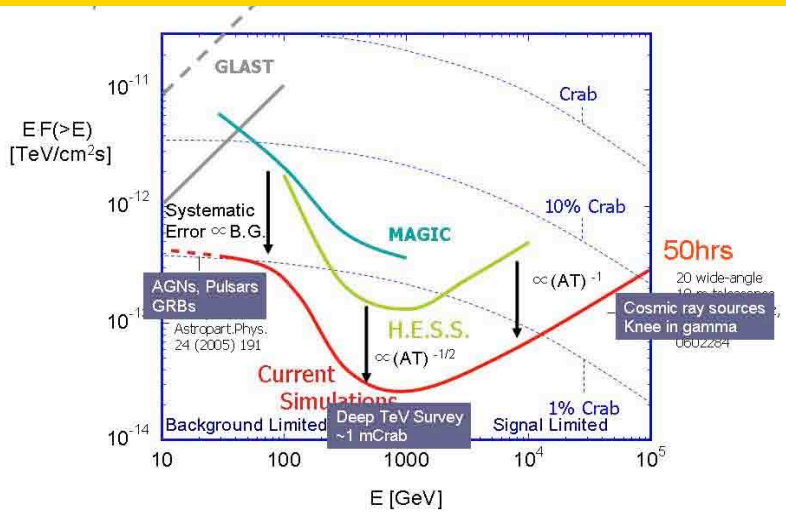
~400 scientists
~50 institutions

Astronomers in EU

JAPAN, US

Cherenkov Telescope Array
1000's of sources will be discovered




Mirzoyan, R.: Highlights
Project Review

# Summary: coming close to solve the puzzle of cosmic rays !

- We detected γ ray emission from > 22 sources, some 30 publications in peer reviewed journals
  - New discovered sources
    - TeV Binary LSI +61 303
    - Cyg X-1
    - IC 443
    - LBL (Low peaked BL Lac Objects) BL-Lacertae
    - 1ES 1011 +496
    - 3C 279
    - 3C XYZ
    - 1 O…..
  - Most new extra-galactic Blazars show steep spectra
    - Constraints on EBL ➔ Cosmology (star and galaxy formations)
  - Flaring sources
    - Detail of flare, intra night light curves, evolution of spectra
    - Limit on Quantum Gravity Scale
  - GRB observations
    - > 10 GRBs were observed and 2 were in prompt phase, but no positive results

- The golden age of the VHE γ hunting of MAGIC has started !

# Number of sources vs. year