MAGIC highlights

VIA lecture 4 April 2008

Manel Martinez

Outline:

0- Introduction

1- The MAGIC telescope

2- Extragalactic highlights

3- Galactic highlights

4- MAGIC II

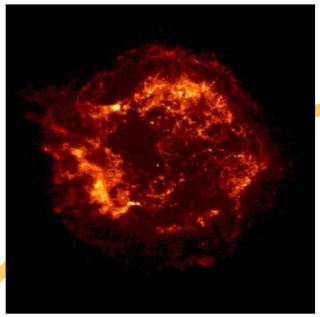
Thanks to Florian Goebel, Michael Rissi,
Robert Wagner and Juan Cortina for many slides

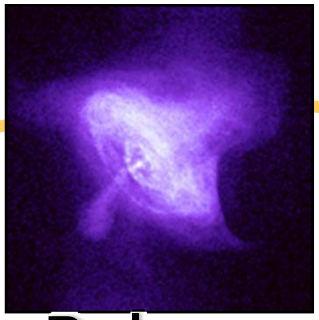
0- Introduction

The VHE γ-ray Physics Program

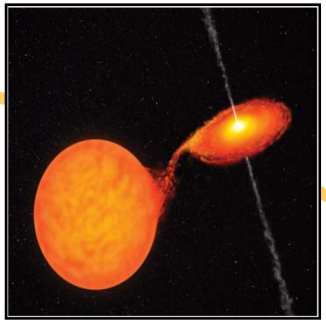
SNRs

Origin of Cosmic Rays



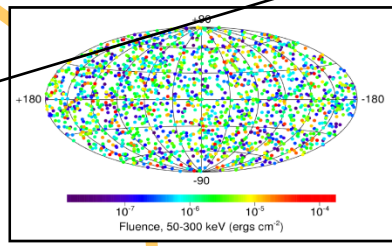


Pulsars

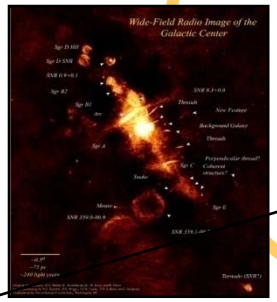


Binary systems

Galactic

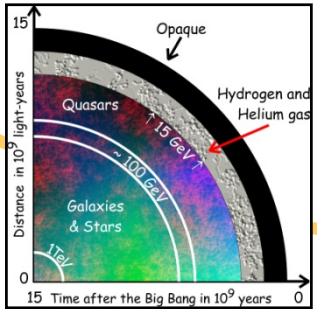


GRBs

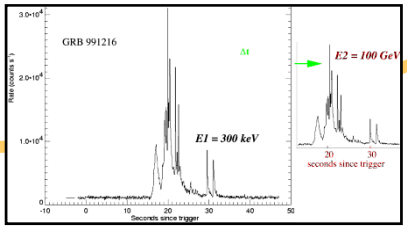


Cold Dark Matter

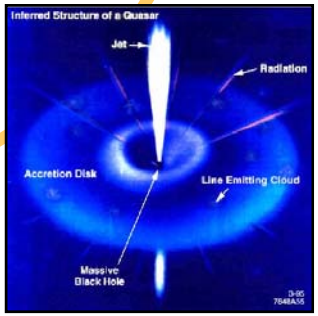
Extragalactic



Cosmological γ-Ray Horizon



Test of the speed of light invariance



AGNs

1- The MAGIC telescope

The MAGIC Collaboration

Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope

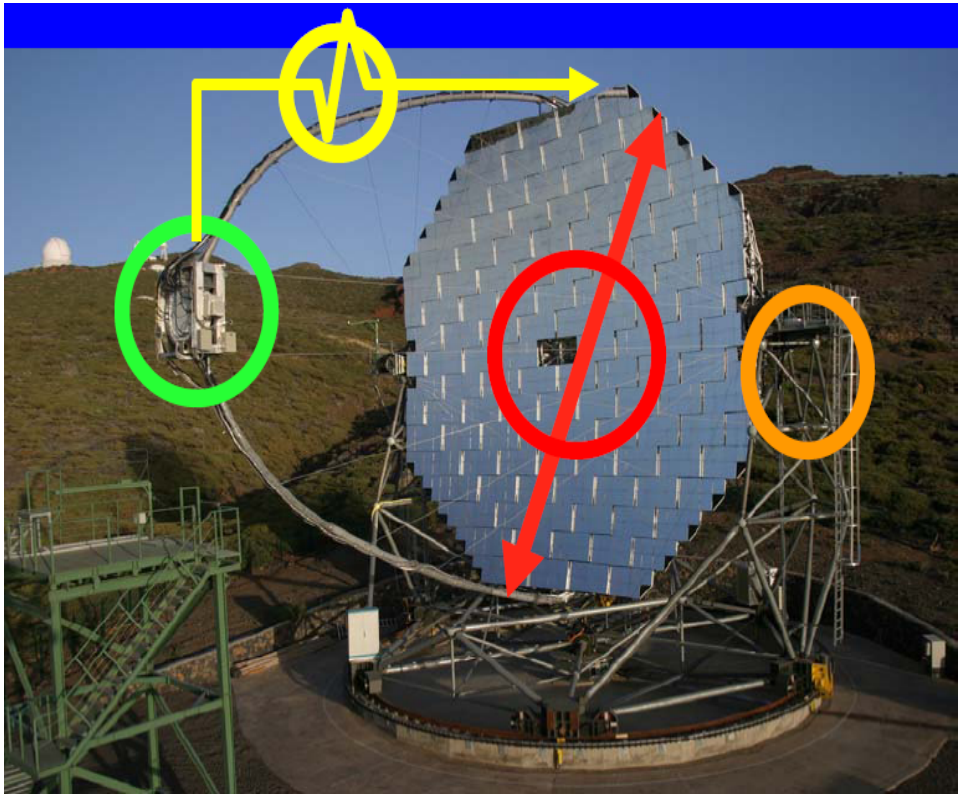
International collaboration of over 20 institutions from more than 10 countries (~180 collaborators, updated list at http://wwwmagic.mppmu.mp.de)

IAA, Granada, Spain
IAC, Tenerife, Spain
IEEC, Barcelona, Spain
INAF, Italy
Institut de Física d'Altes Energies, Barcelona, Spain
Institute for Research and Nuclear Energy, Sofia, Bulgaria
Institute for Particle Physics, ETH Zürich, Switzerland
DESY–Zeuthen, Berlin, Germany
Max-Planck-Institut für Physik, München. Germany
Tuorla Observatory, Pikkiö, Finland
Universidad Complutense, Madrid, Spain
Università di Padova, and INFN Padova, Italy
Università di Siena, and INFN Pisa,Italy
Università di Udine, and INFN Trieste, Italy
Universitat Autònoma de Barcelona, Spain
Universitat de Barcelona, Spain
Universität Dortmund, Germany
Universität Würzburg, Germany
University of Lodz, Poland
University of California, Davis, USA
Yerevan Physics Institute, Cosmic Ray Division, Yerevan, Armenia

Main aim: to detect γ–ray sources in the unexplored energy range: 30 $\rightarrow$ 3 TeV

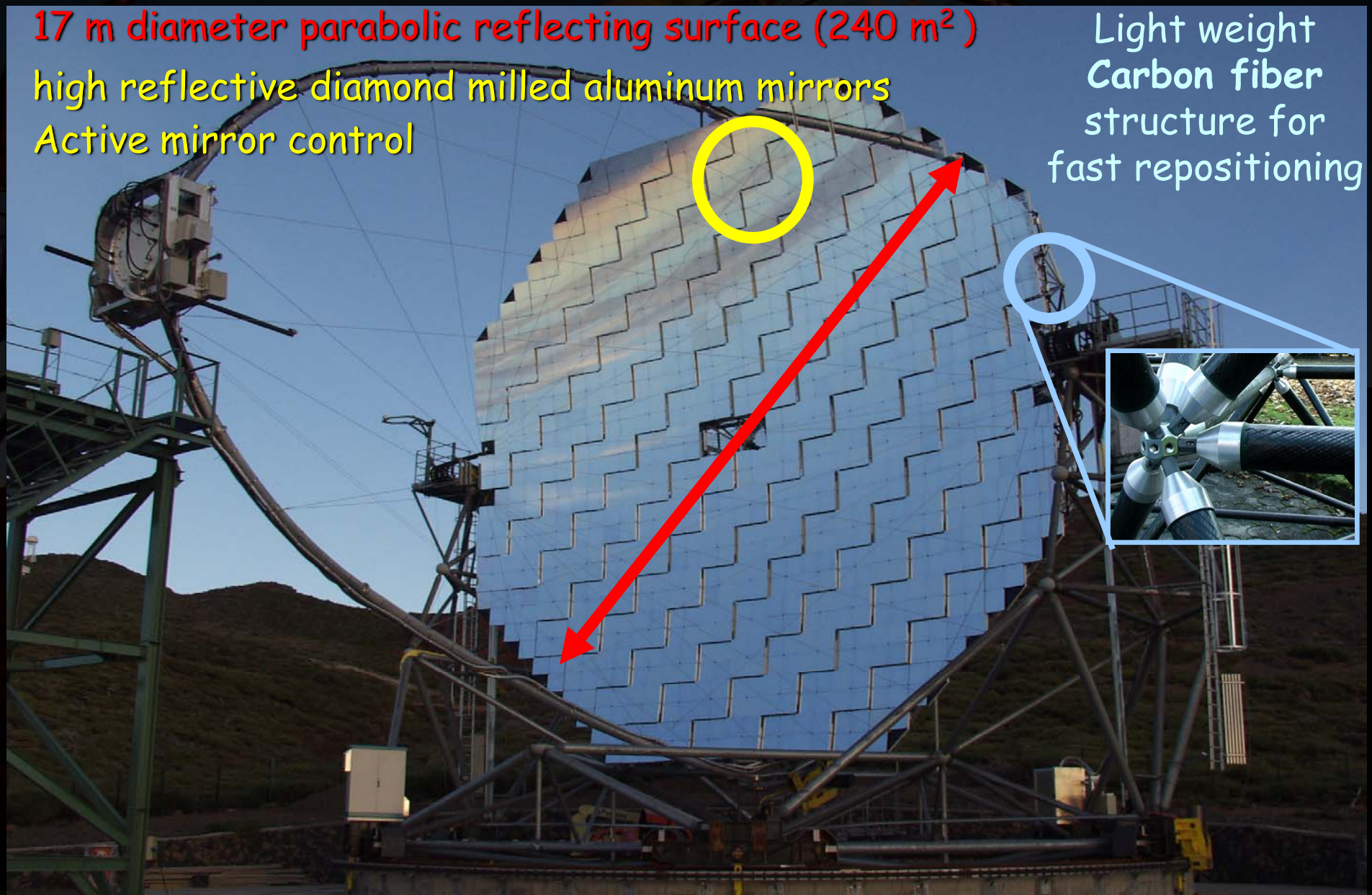
Technological innovations:

1) Lightweight structure for fast repositioning
2) Large and light reflector(ϕ = 17m)
3) Improved optics (AMC)
4) 577 pixels, enhanced QE, ~3.5° FOV camera
5) Improved transmission (analog optical fibers)
6) 3-level trigger system
7) Ultra-fast readout (300 MHz FADCs)



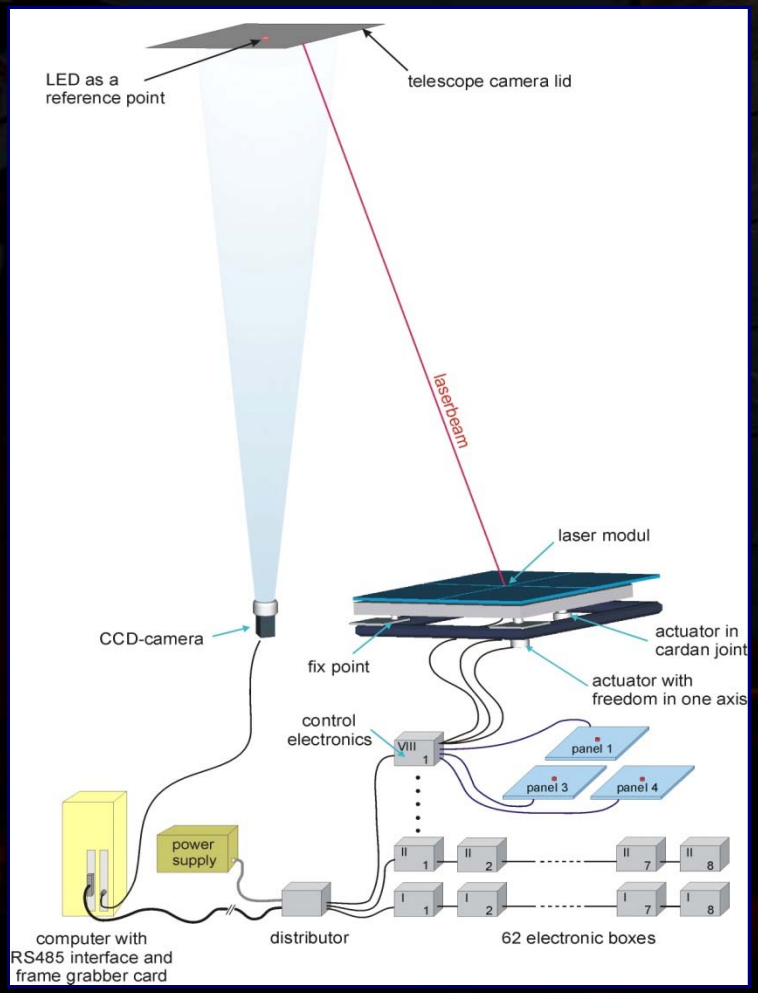
MAGIC has the lowest threshold of all IACTs

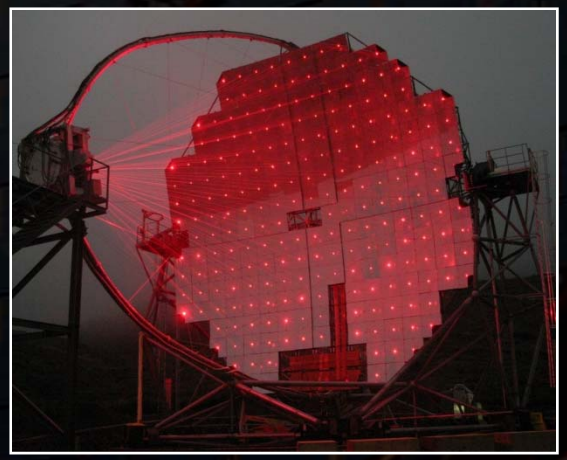
Key technological elements for MAGIC

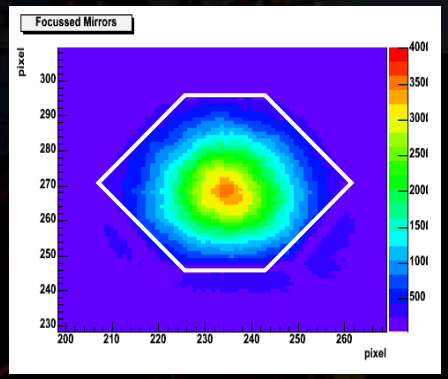


Active Mirror Control

light weight structure requires corrections for small residual deformations of mirror



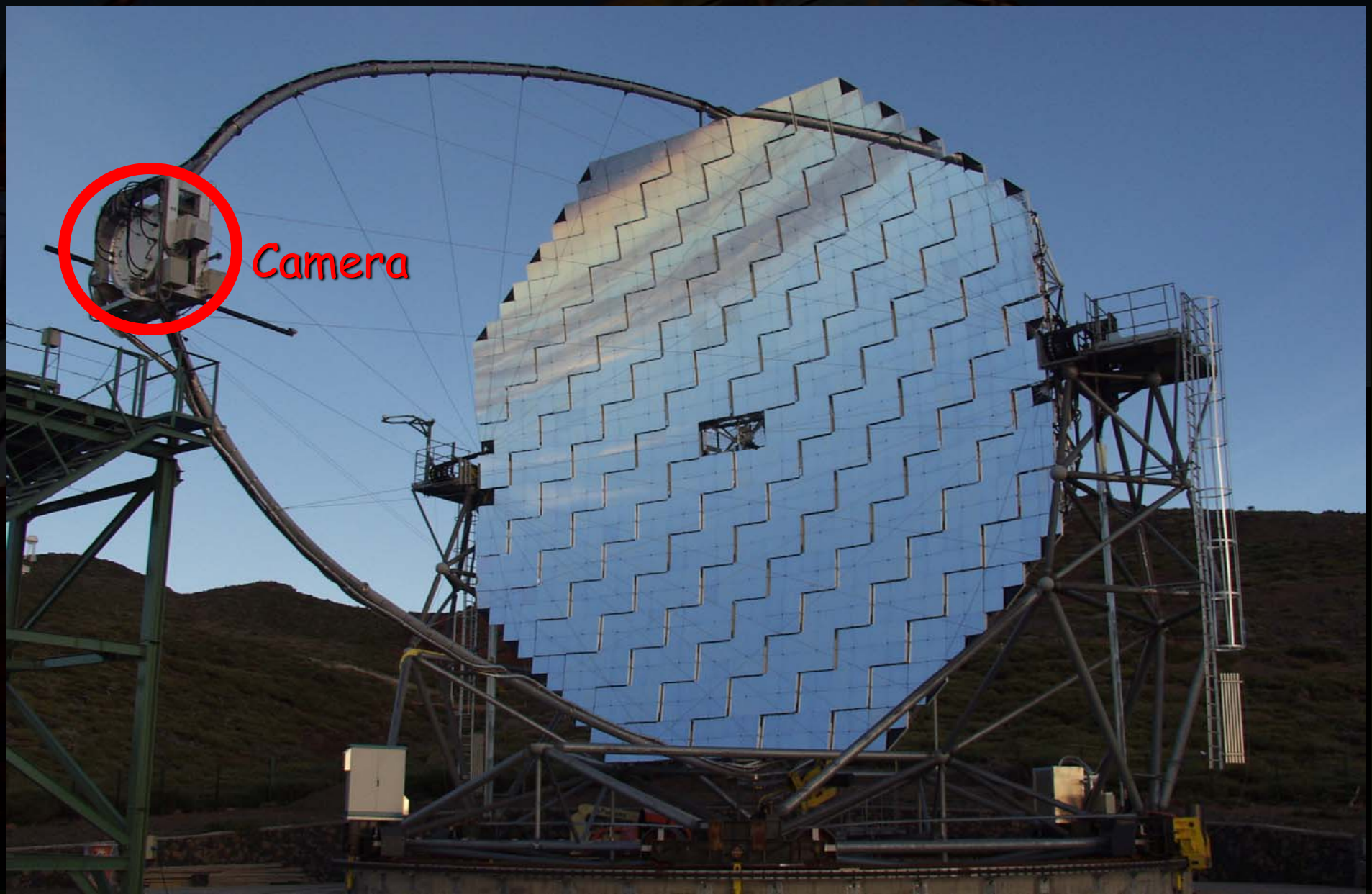




achieved PSF:

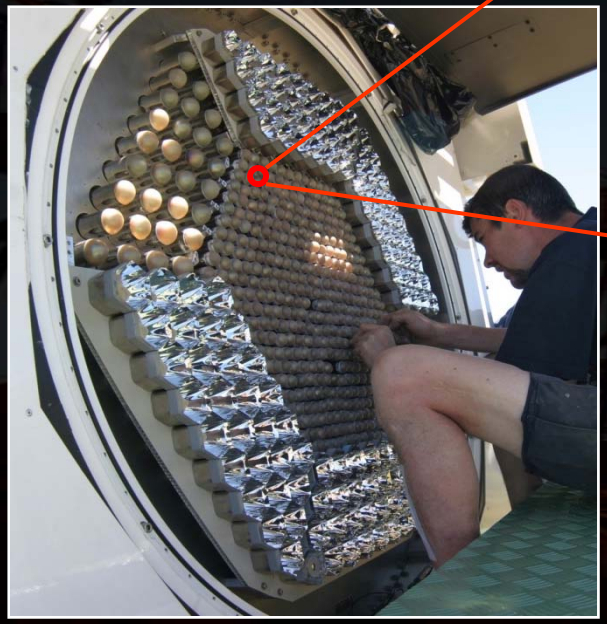
90% of light contained in 0.1 inner pixel

Key technological elements for MAGIC



High QE Camera

- Matrix of 577 PMTs
- Field of View: 3.5^{0}

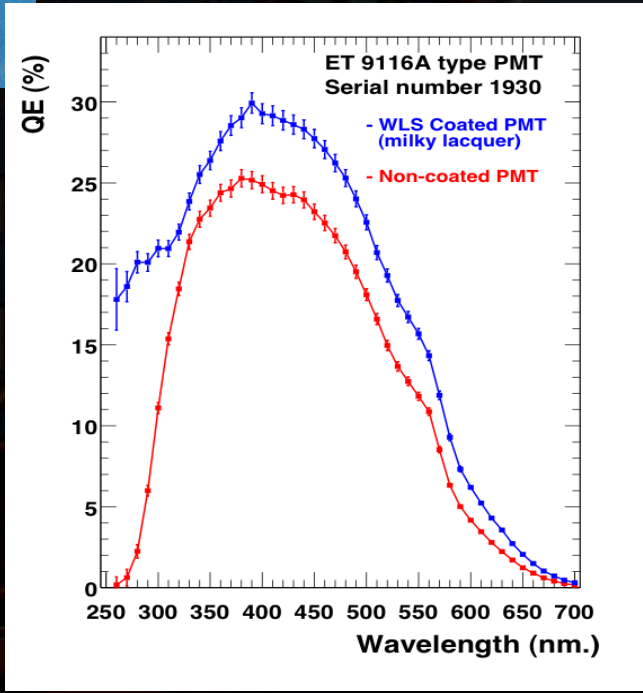


6 stage PMTs (low gain)

- ET 9116A (1") : 0.1^{O}
- ET 9117A (1,5") : 0.2^{O}

Quantum Efficiency increased up to 30 % with diffuse scattering coating

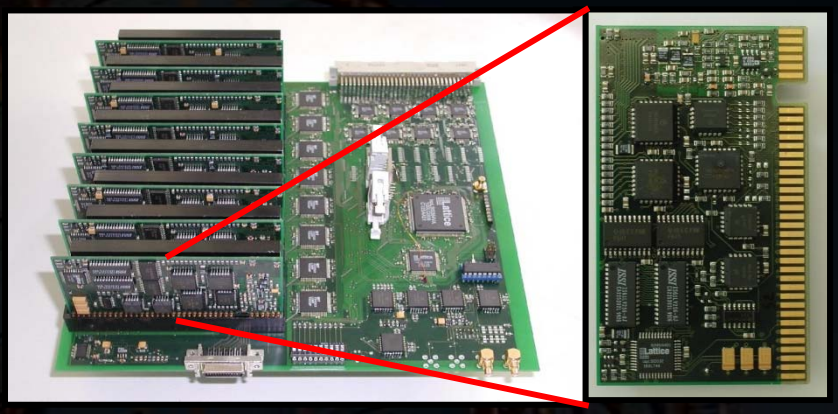
extended UV sensitivity using wavelength shifter coating



Signal Processing

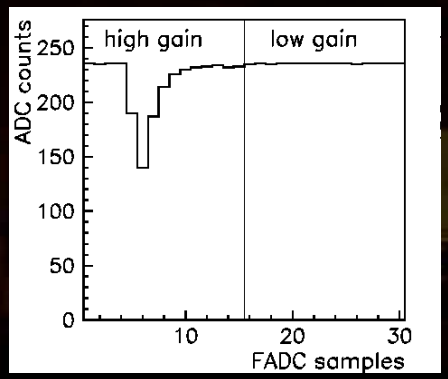
- Analog signals transmitted over 162 m long optical fiber
  => no signal dispersion

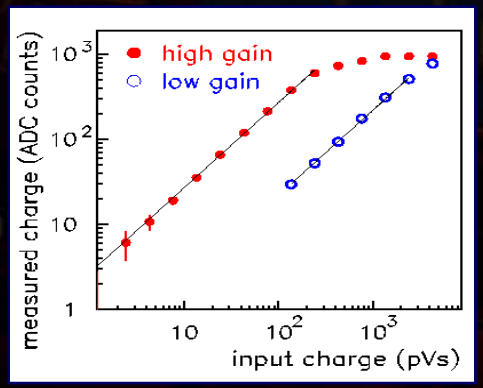
- Stretch pulse to 6 nsec
- Split to high & low gain (dynamic range > 1000)
- 300 MSamples/s 8 bit FADCs

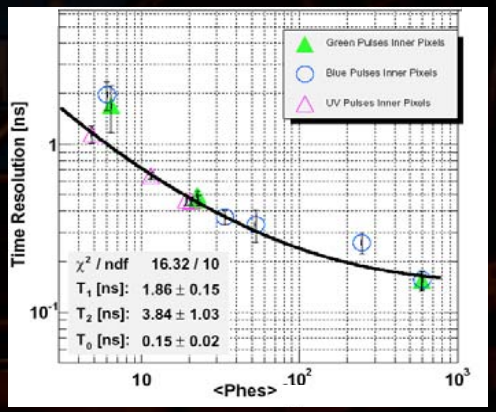


optimized signal reconstruction

- time resolution < 1 nsec
- small integration time
  => improved S/N





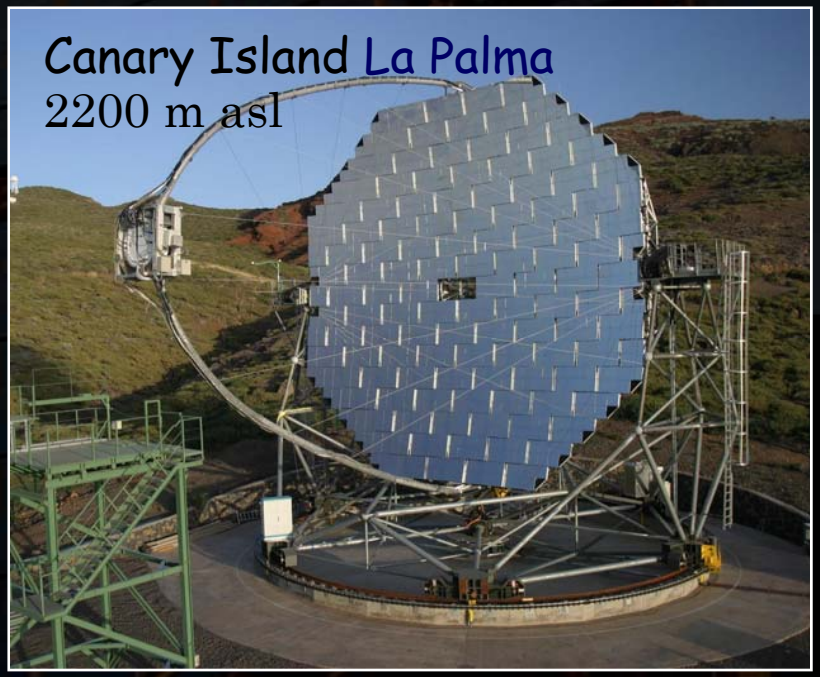


Current Status of MAGIC

Regular observation mode since fall 2004

- Largest single dish Cherenkov Telescope:
  17 m ø mirror dish
- Fast repositioning for GRBs:
  average < 40 s
- Can observe during moon

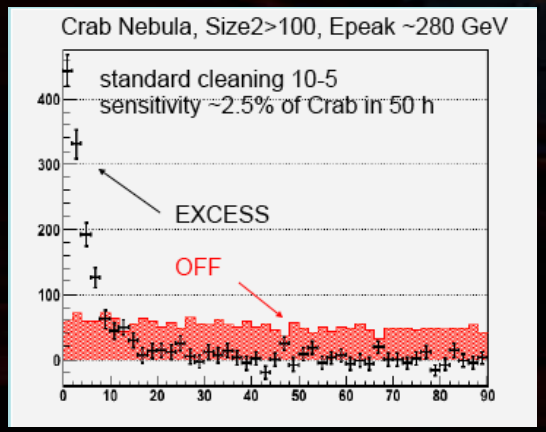
- Low energy trigger threshold:
  50 - 60 GeV
- Sensitivity: 2% Crab (5σ,50h)
- γ-PSF: ~ 0.1°
- Energy resolution: 20-30%

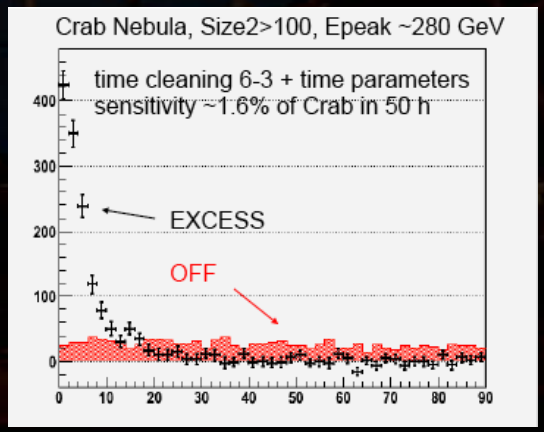


Upgrade 1: 2GSamples/s readout => increase sensitivity

- Ultra-fast inexpensive readout
  - Multiplex 16 channels using optical delays
  - Use commercial (expensive) 2GSamples/s, 10bit FADCs
  - Fully commissioned: Feb 2007
- Improved analysis
  - Use time evolution parameters of shower
  - Improved rejection of night sky background

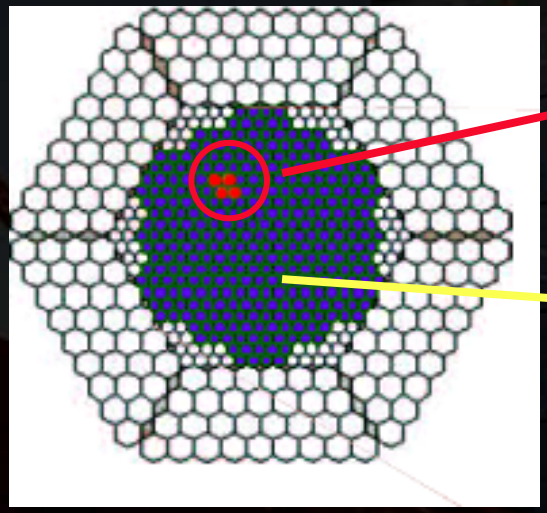
=> **Sensitivity improved to 1.5% Crab (5σ,50h)**





Upgrade 2: A new trigger concept => decrease threshold

- The standard MAGIC trigger consists of 2 Levels:
  - Level 0: Discriminating the signal of a single photomultiplier.
  - Level 1: The discriminator of at least 4 neighboring pixels fires.



Example for a 4NN trigger cell

Trigger area (diameter of ~2°)

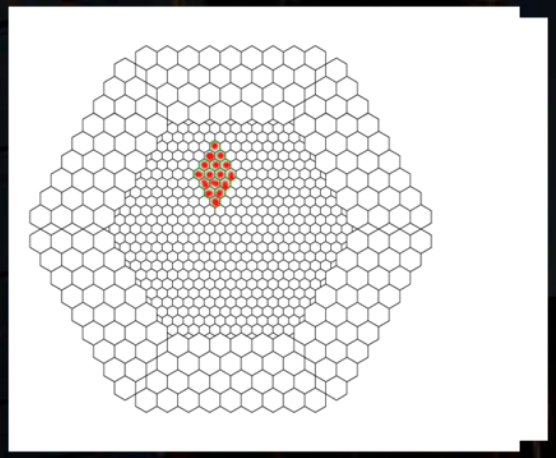
Energy threshold: ~50 GeV. Lowering the discriminator threshold results in a huge trigger rate due to accidental triggers from the night sky background. Maximal allowed trigger rate limited by maximal DAQ rate (~1.2kHz).

Typical trigger rate 200-300 Hz.

A DIFFERENT IDEA: AN ANALOG SUM TRIGGER

- Build clusters of several pixels
- Sum up the analog signals from the individual pixels
- discriminate on the summed signal

Example for one patch:

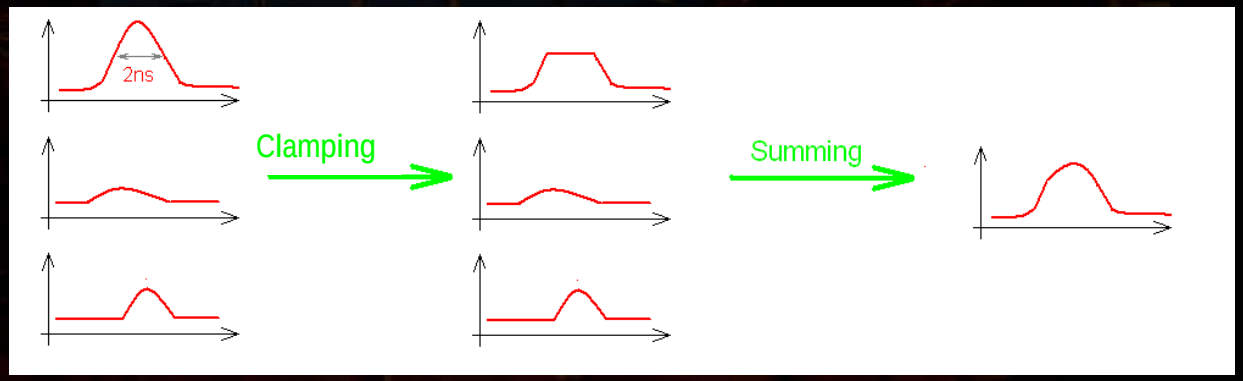


Features:

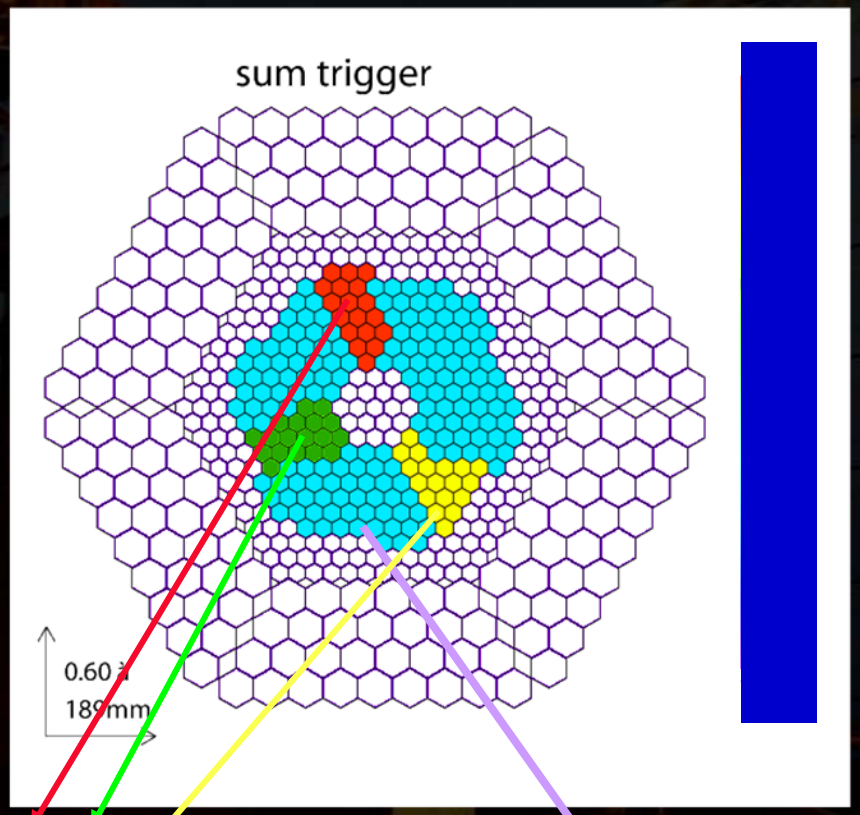
- Analog sum improves signal/noise ratio. Optimum patch size required Monte Carlo studies.
- Within one trigger patch: Free choice of pattern, no bias for shower shape
- Small acceptance window in time (~ns)
- Also small signals contribute to the trigger signal

Problem:

- Before summing up the individual signals, the signal must be clamped due to after pulses of the PMTs.



Configuration of the trigger patches: Optimization by Monte Carlo Simulations



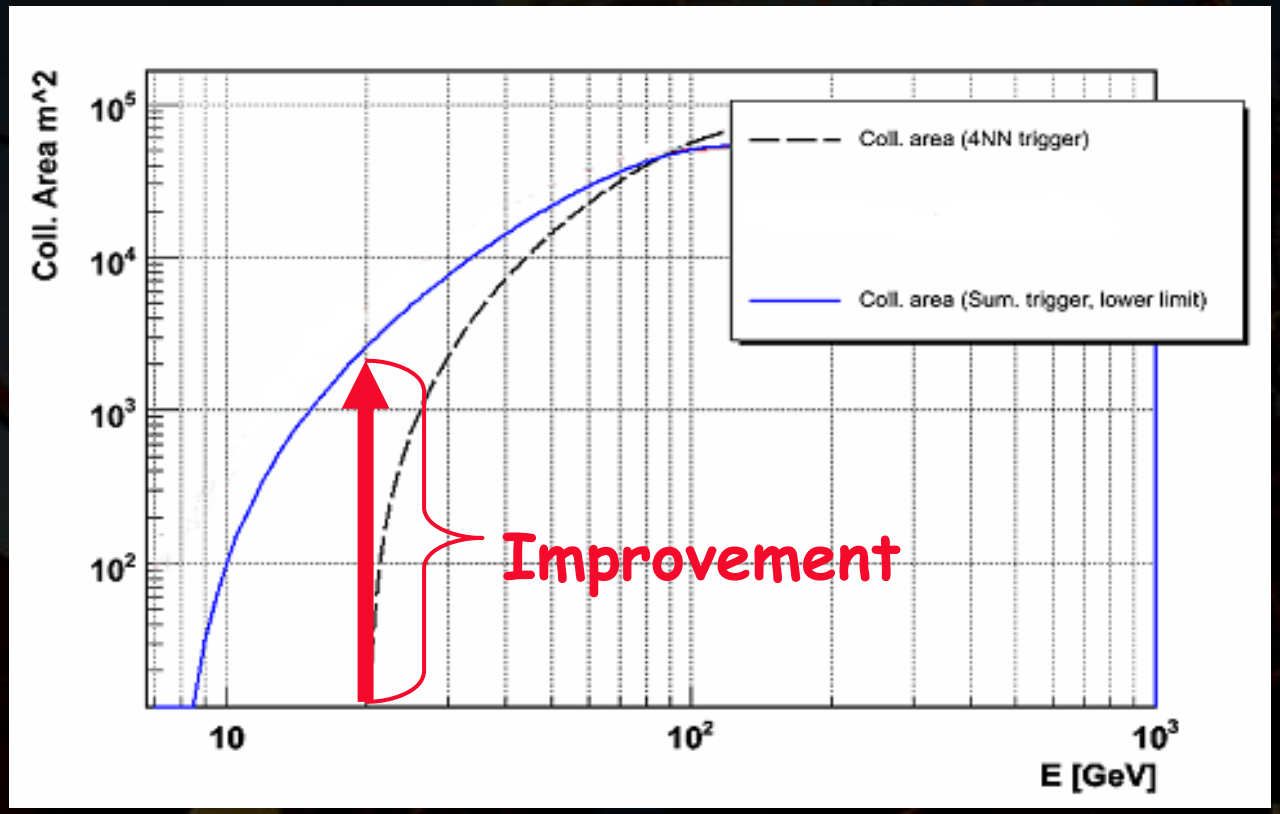
Example patches

Sum Trigger area (0.2°-0.8°)

- Several settings were simulated.
- Optimization criteria: maximize effective area at 20, 25 and 30 GeV.

- Results:
  - Patch Size 18 pixels
  - Total number of patches: 24
  - Clamping level: 6 phe
  - Differential energy threshold: ~30-40 GeV (for a spectral index of -2.7)

RESULTS: SENSITIVITY FOR DIFFERENT CONFIGURATIONS



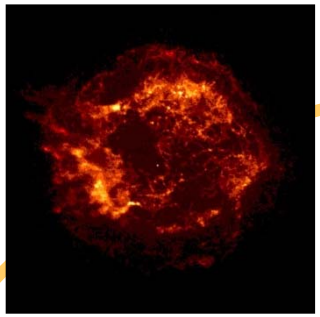
- Large improvement for energies < 80 GeV
- For energies > 100 GeV, the effective area of the standard trigger is higher than for the sum trigger. This is due to the higher trigger area.

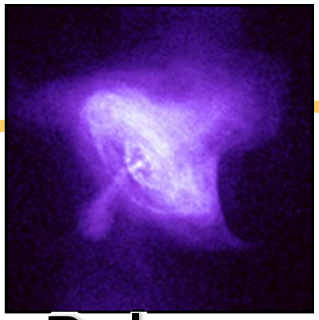
3- Extragalactic highlights

The VHE γ-ray Physics Program

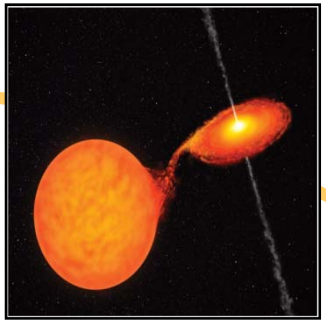
SNRs

Origin of Cosmic Rays



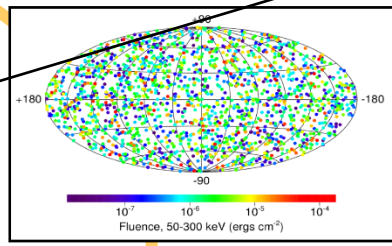


Pulsars

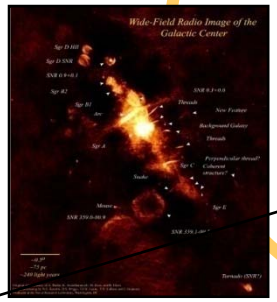


Binary systems

Galactic

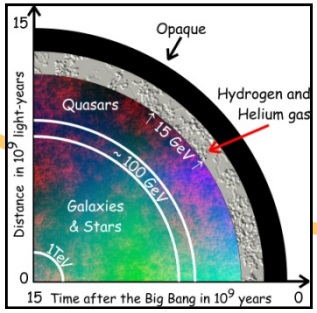


GRBs

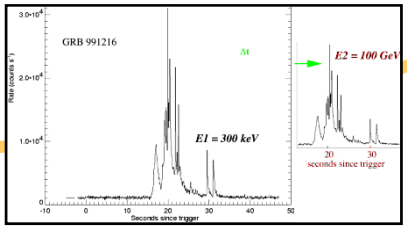


Cold Dark Matter

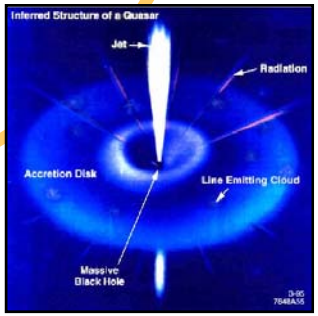
Extragalactic



Cosmological γ-Ray Horizon

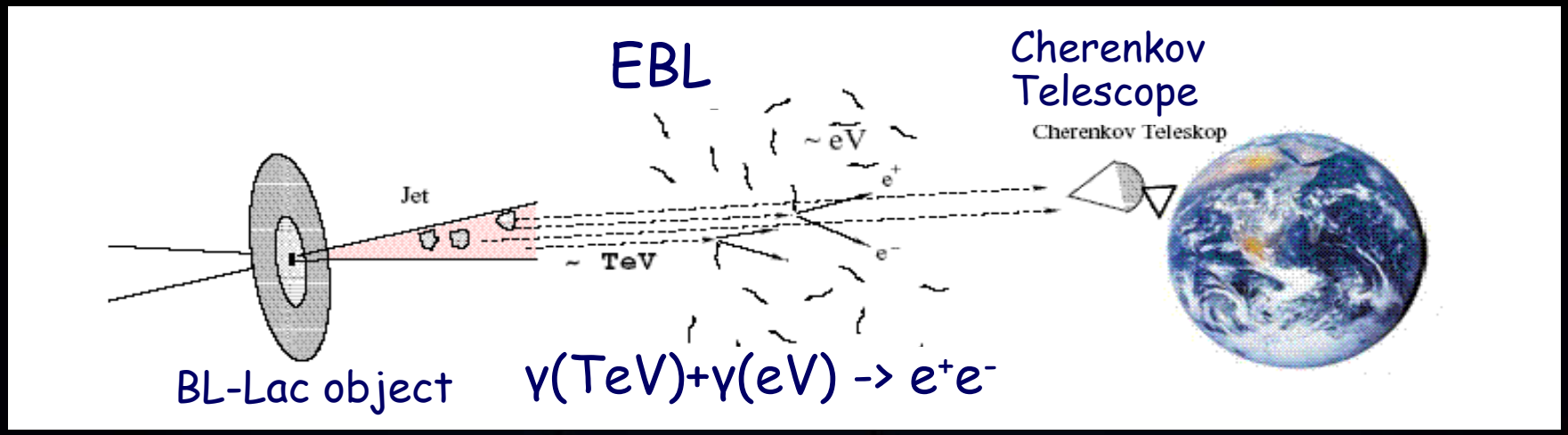


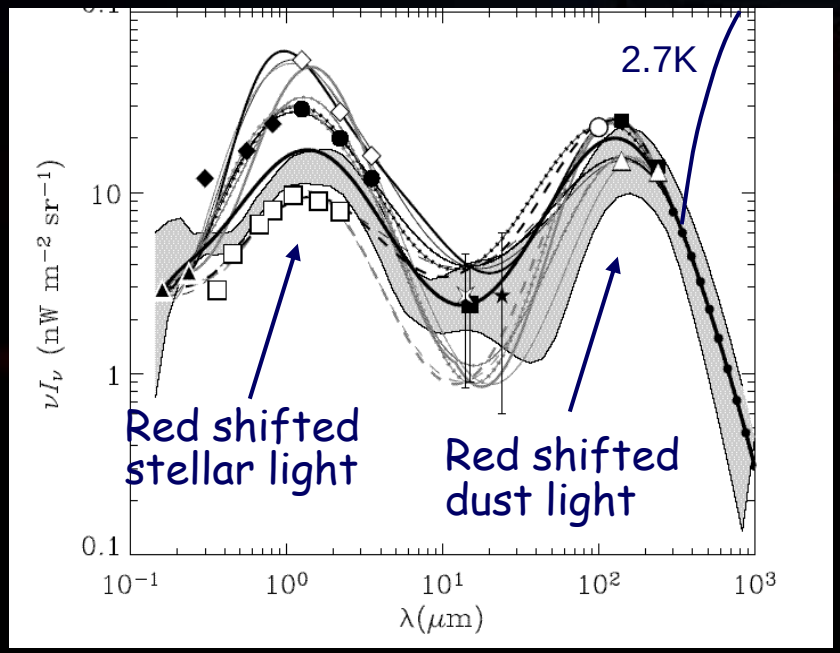
Test of the speed of light invariance

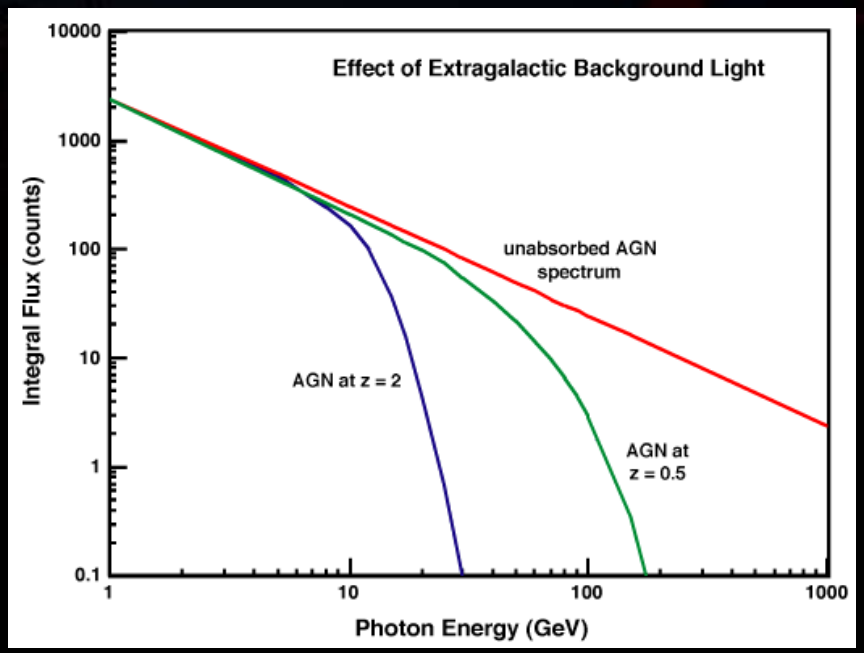


AGNs

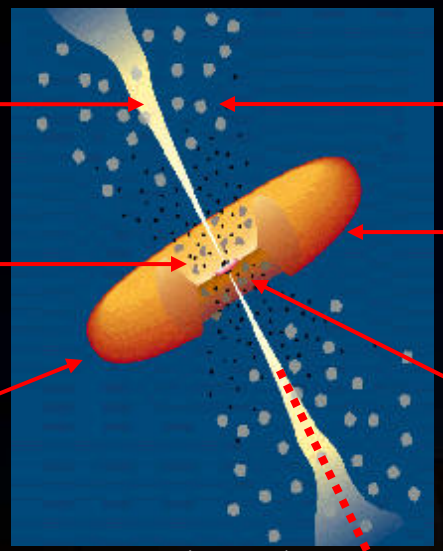
Attenuation of VHE γ-rays







Extragalactic VHE γ-ray sources:



Urry & Padovani (1995)

Blazar

MAGIC detections:

Source	Redshift z	type
Mrk 421	0.030	HBL
Mrk 501	0.034	HBL
1ES 2344+514	0.044	HBL
Mrk 180	0.045	HBL
1ES 1959+650	0.047	HBL
BL Lac	0.069	LBL
PKS 2155-304	0.117	HBL
1ES 1218+308	0.182	HBL
1ES 1011+496	0.212	HBL
3C 279	0.536	FSRQ
PG 1553+113	> 0.09	HBL

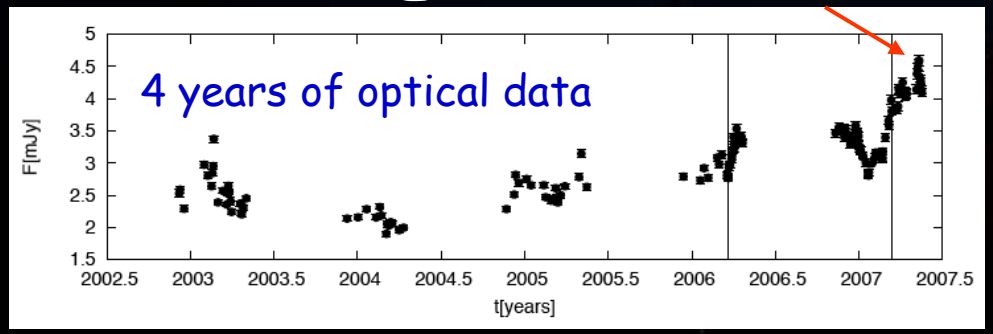
Blazars:

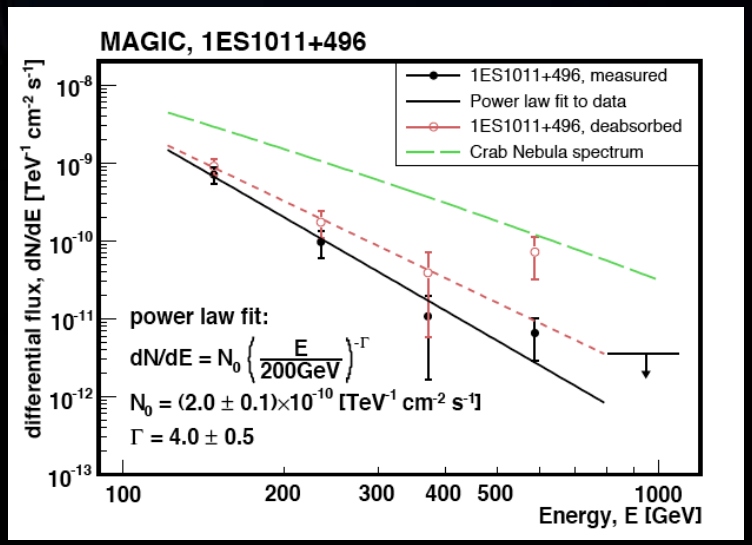
- AGN with relativistic jet aligned with observer's line of sight of observer
- non-thermal emission, highly variable
- AGNs: sources of extragalactic CRs ?
- VHE γ-rays: leptonic or hadronic origin ?

Search for new VHE Blazars

- Optical monitoring
- Use 35cm KVA (La Palma) & 1m Tuorla telescopes
- Following historical high optical flux
  => Discover Mrk180 (z=0.045) &
  1ES1011+496 (z=0.212, most distant AGN at that time)

1ES 1011 Trigger point



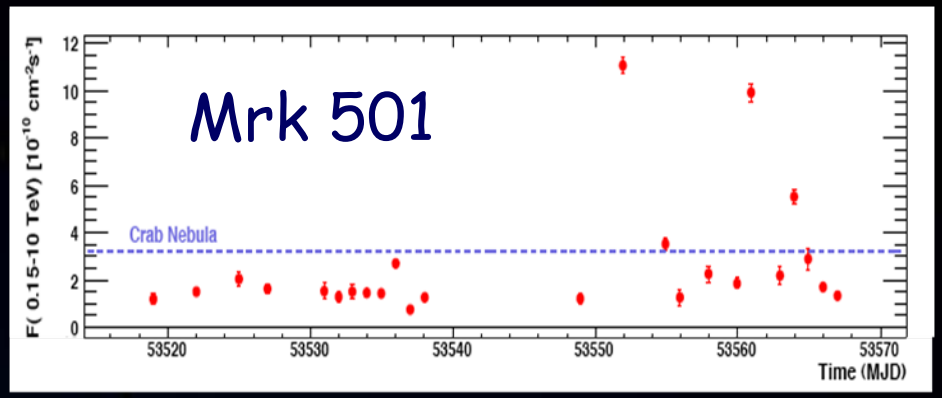


- Soft spectrum
  Γ=4.0 (Γ=3.3 after EBL deabsorption)
- Optical easier than X-ray monitoring

ApJL accepted, astro-ph/0606630

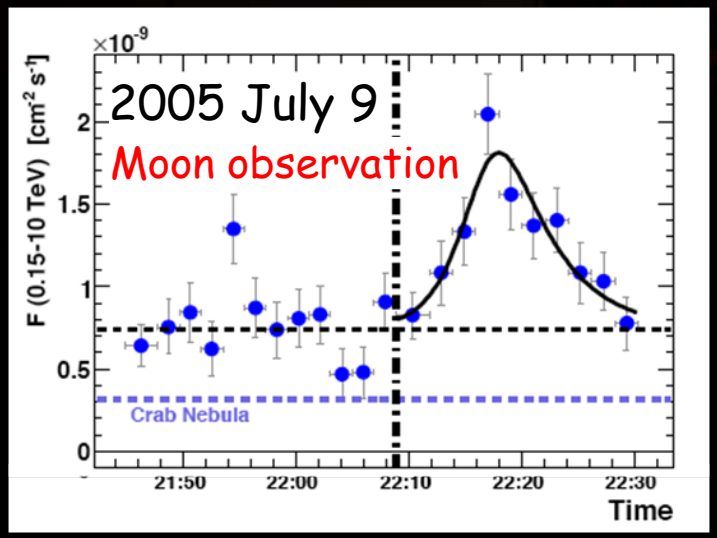
Mrk 501 (z=0.034)

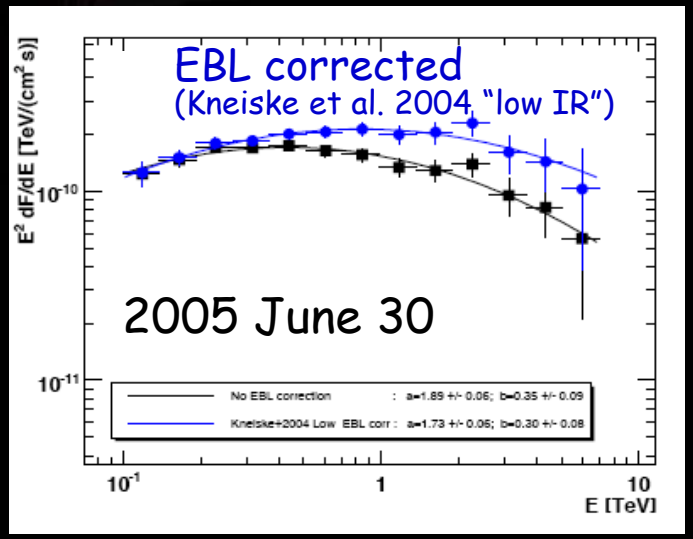
- Study know nearby AGNs
  => monitor Mrk 501
- Well know but far from understood & full of surprises



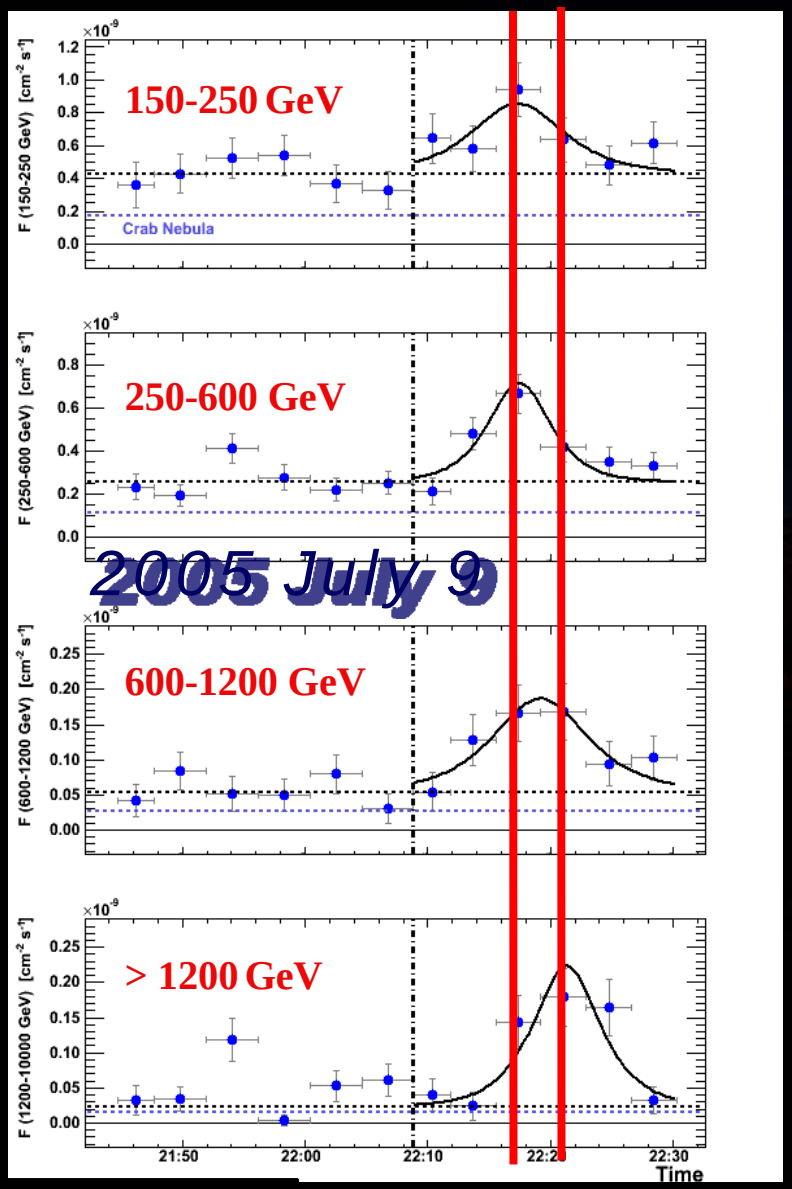
- Flare on June 30 & July 9 '05
- Doubling time less than 5 min
  => emission region << R_{BH}

Spectrum down to E>100GeV
=> Spectral peak detected
- IC peak ?





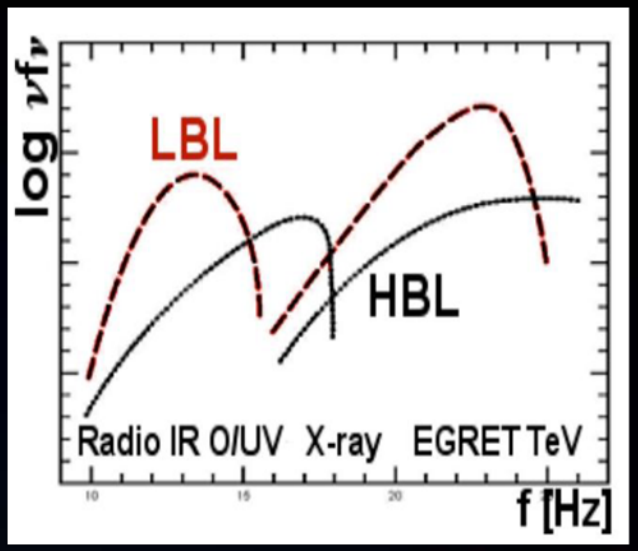
Mrk 501: Energy dependence of flare



- Energy dependent time lag: 4±1 min
- Gradual acceleration of electrons to high energies ?
- IF photons of different energy emitted simultaneously:
  - Refractive index of vacuum predicted by some Quantum Gravity models:
  - $M_{QG1} \sim 0.4 \times 10^{18}$ GeV
- Need more observations of rapid flares

BL Lac

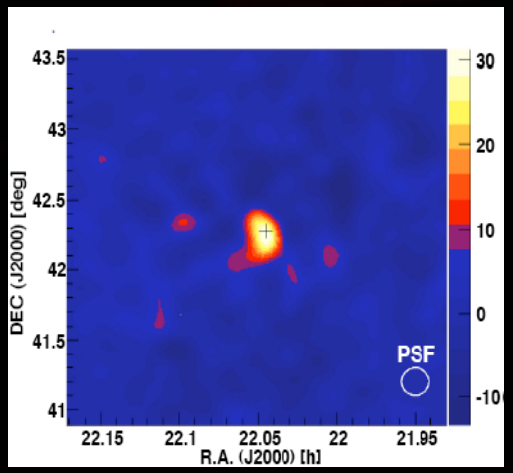
- Prototype of "BL Lac object"
- z=0.069
- Synchrotron peak @ 2.2×10^{14} Hz
  => *LBL*
- No LBL observed in VHE so far

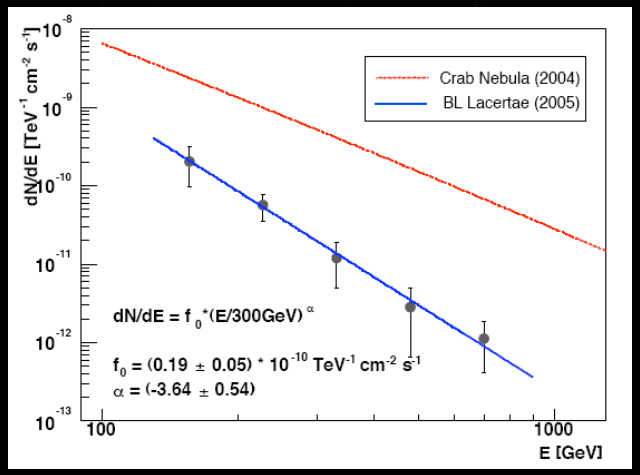


MAGIC detection (2005)

=> First discovery of VHE emission from LBL

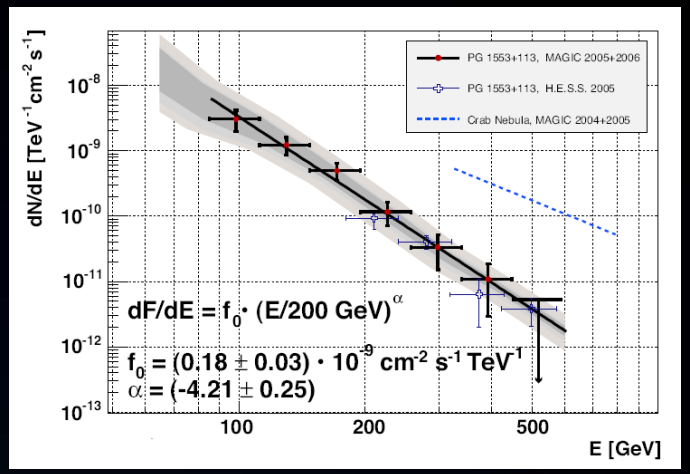
- Steep Γ = 3.6 spectrum
- Not detected during low optical state (2006)





PG1553

- VHE γ-ray emission discovered by H.E.S.S. & MAGIC
- Very steep spectrum Γ=-4.21 ± 0.25



- No spectral line found

=> Only lower limit: z > 0.09

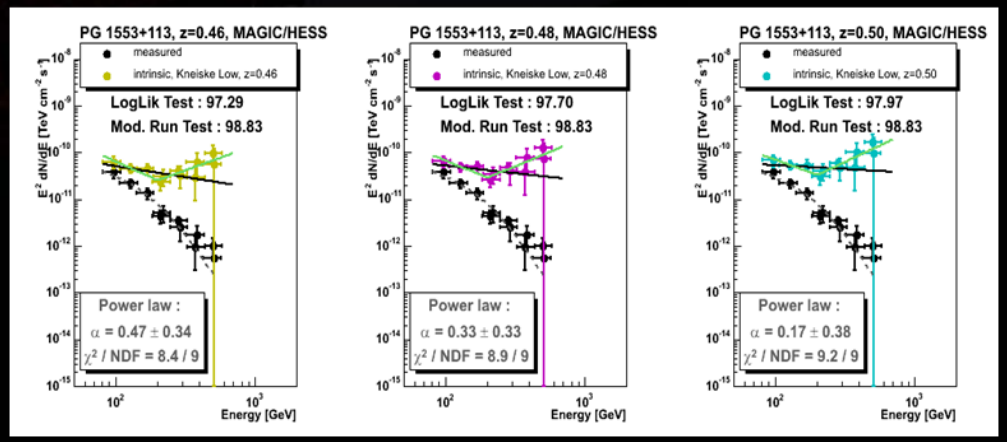
Assume:

- EBL (conservative)

Require:

- dN/dE ~ $E^{-\Gamma}$, Γ > 1.5

=> Upper limit on z



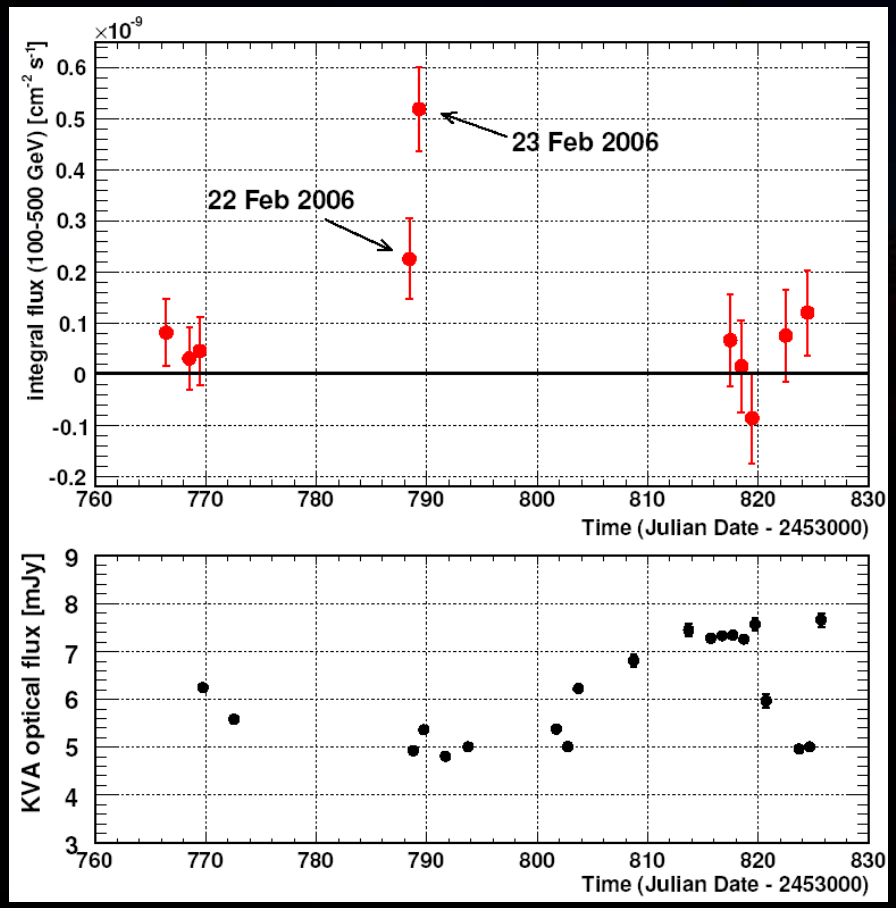
- Combined MAGIC & H.E.S.S. (Mazin & Goebel)

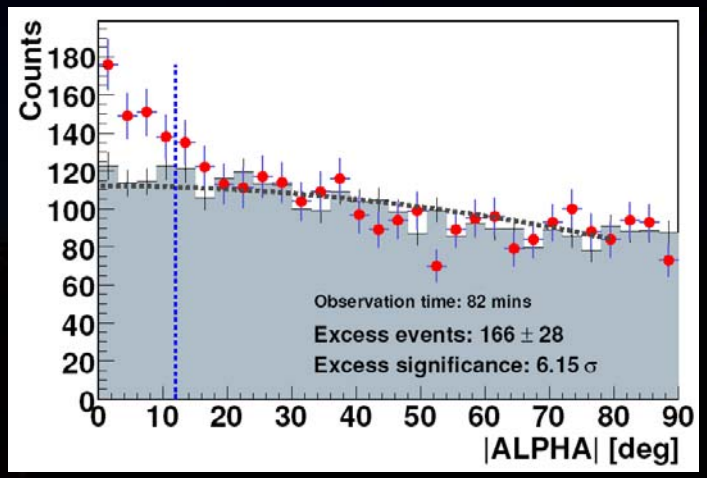
=> z < 0.42

3C 279 (z = 0.538)

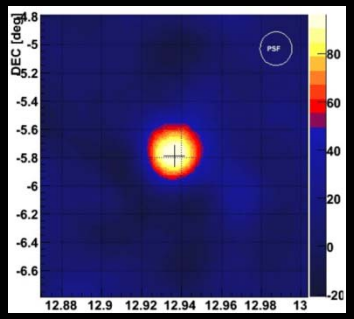
- Brightest EGRET AGN
- Flat Spectrum Radio Quasar

MAGIC excess on 23 Feb. 2006





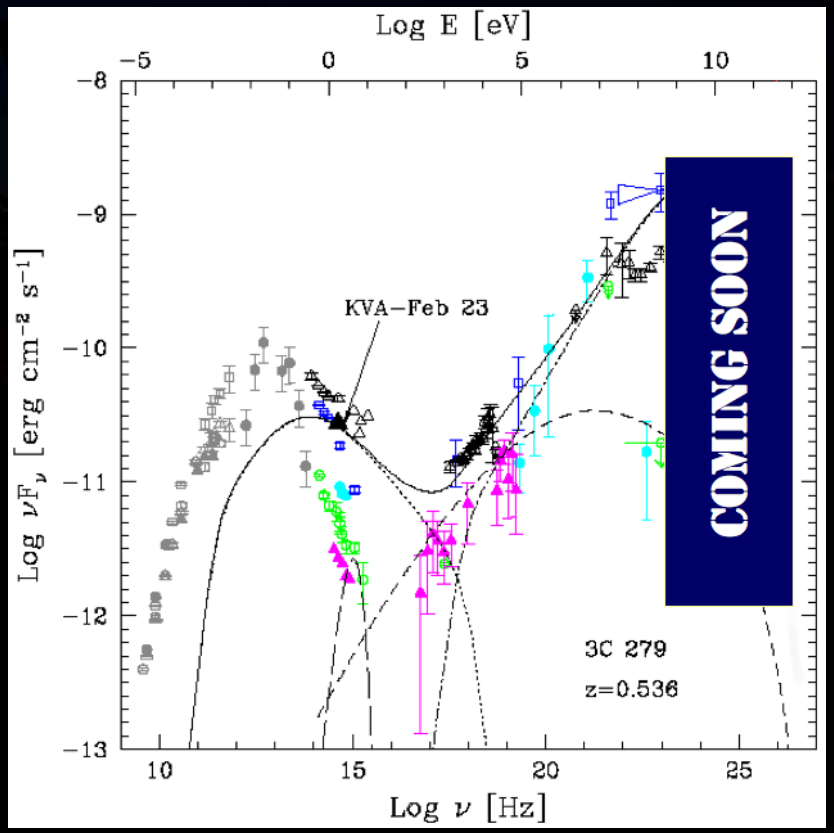
VHE distance Champion !!



3C 279: What's the relevance?

- z=0.536! Major jump in redshift of VHE sources
- First FSRQ in TeV gamma-rays: All source classes of the „blazar sequence" detected in VHE

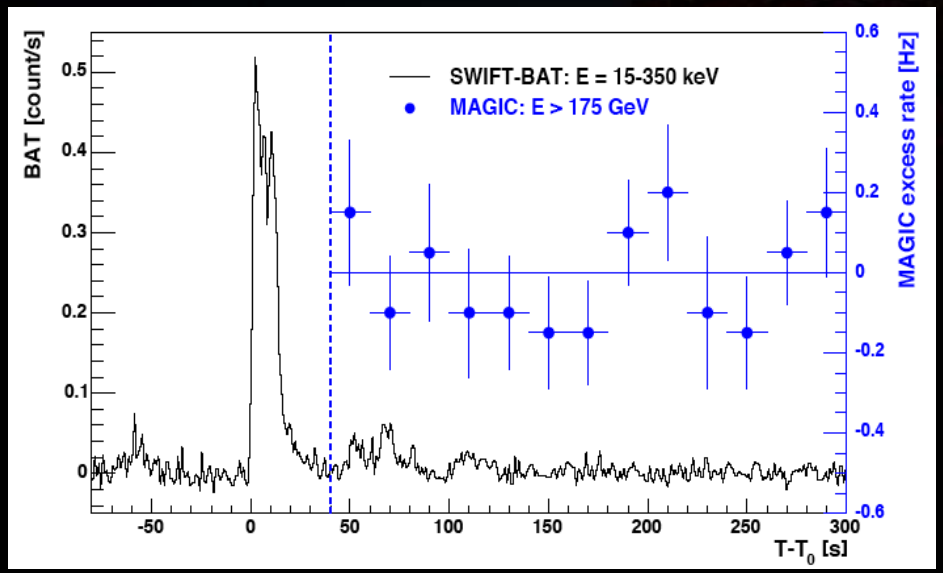
- Modeling of 3C 279 non-trivial:
  - FSRQ → bright emission lines: External photon fields important (Dermer+93, Sikora+94)
  - External-Inverse Compton Modeling required, more free parameters
  - VHE will provide vital input!

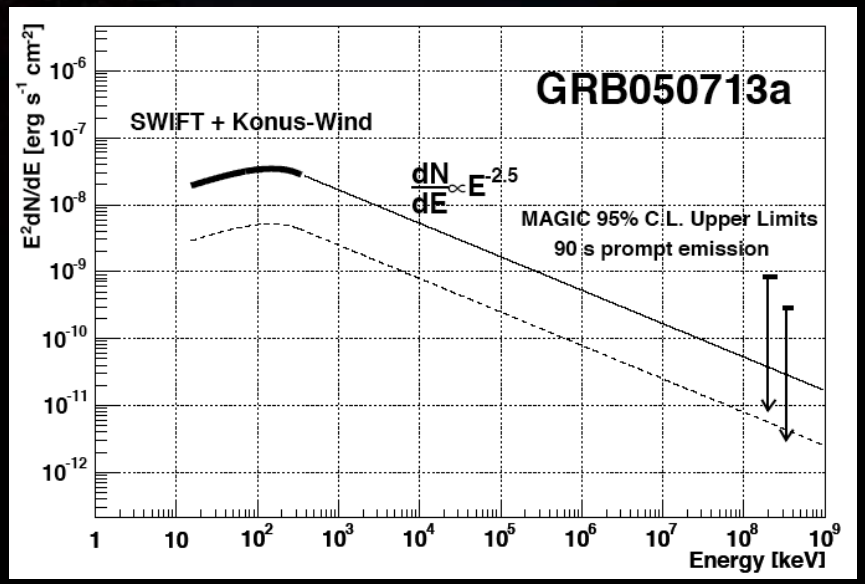


- And finally...
  Why do we see it at all?
  Is the universe more transparent to VHE g-rays than assumed?
  → Extragalactic Background Light

GRB 050713a

- fast response of MAGIC
- measured GRB050713a after 40s
- no γ emission seen
- wait for stronger GRB





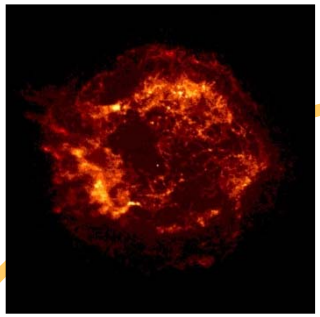
ApJL 638 (2006)

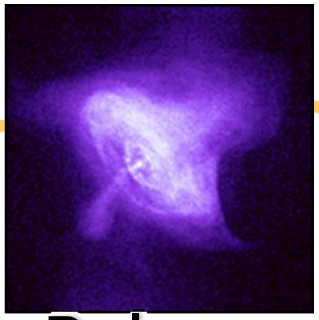
2- Galactic highlights

The VHE γ-ray Physics Program

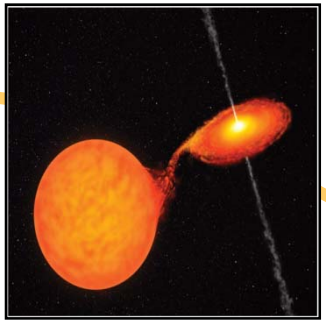
SNRs

Origin of Cosmic Rays



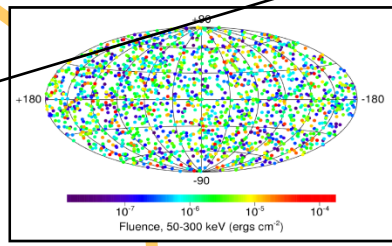


Pulsars

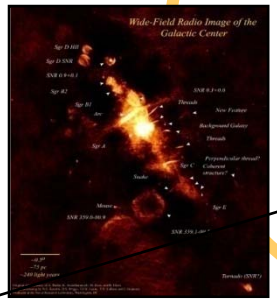


Binary systems

Galactic

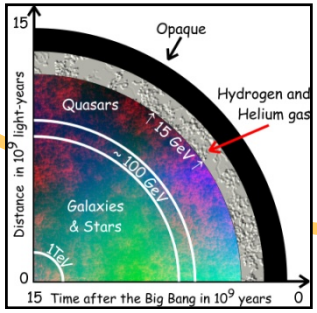


GRBs

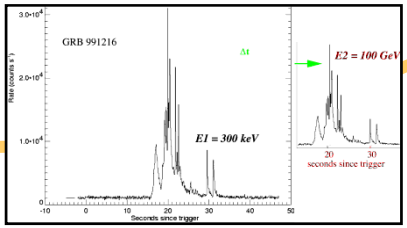


Cold Dark Matter

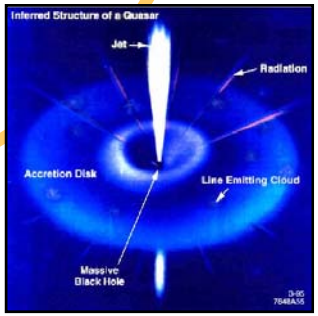
Extragalactic



Cosmological γ-Ray Horizon

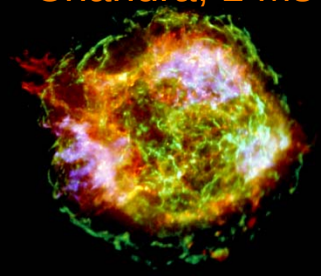


Test of the speed of light invariance



AGNs

Cas A: archetypal shell-type SNR

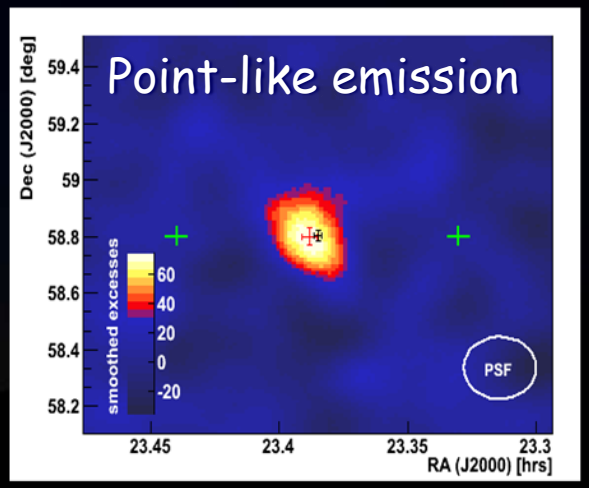


- Bright Synchrotron radiation in radio & X-rays
- Good candidate for dominant hadronic emission

MAGIC: 47h observation

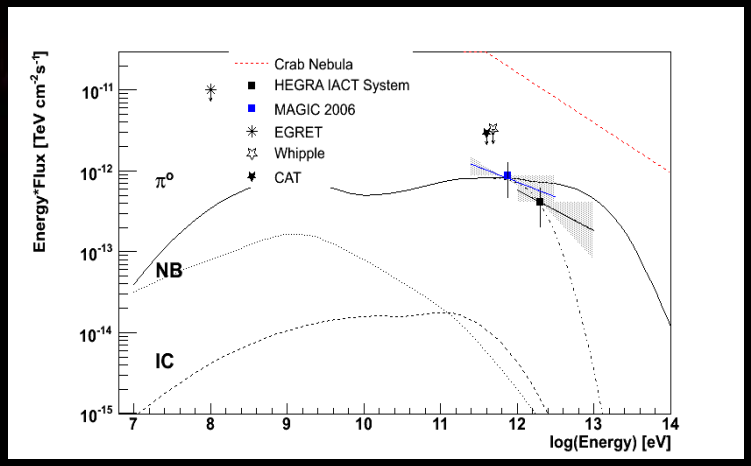
- 5.2σ detection @ E > 250 GeV
- Flux: 3% Crab level
- Γ = 2.4

confirms HEGRA detection @ E>1TeV



- Results favour hadronic origin (e.g. Berezhko et al. 2003)

  but … need more data at higher and lower E for definite answer



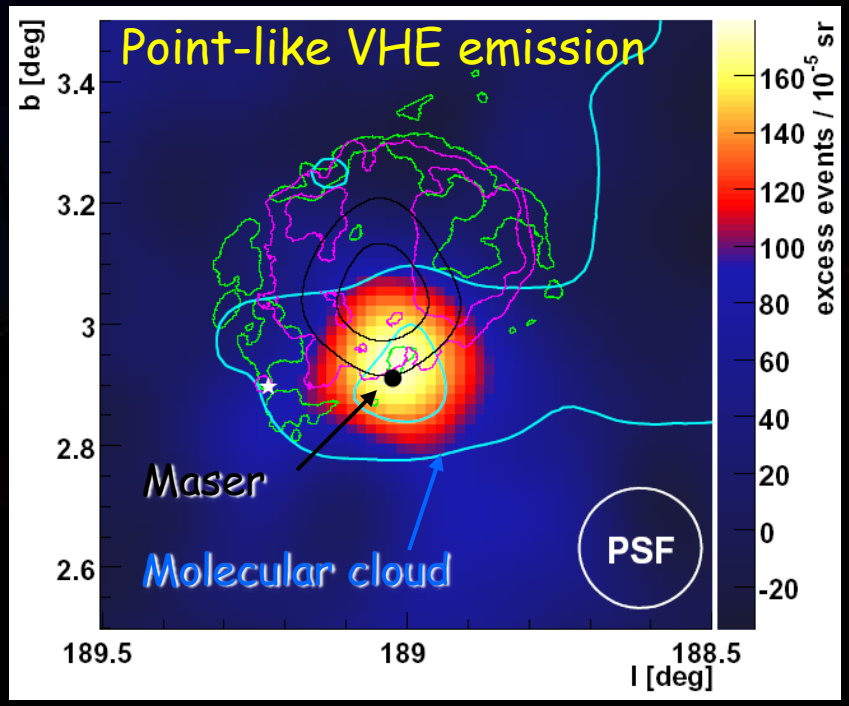
IC443 (MAGIC J0616+225)


Composite picture
APOD 2006/06/02

- Asymmetric shell-type SNR (Radio, X-ray & EGRET)
- Maser (1720 MHz)
- Dense molecular cloud (~10^4 $M_\odot$)

MAGIC: 37h observation

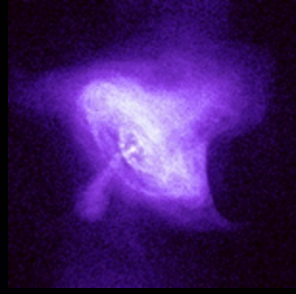
- 5.7σ discovery
- E > 90 GeV
- Γ = 3.1 (much steeper than Cas A)



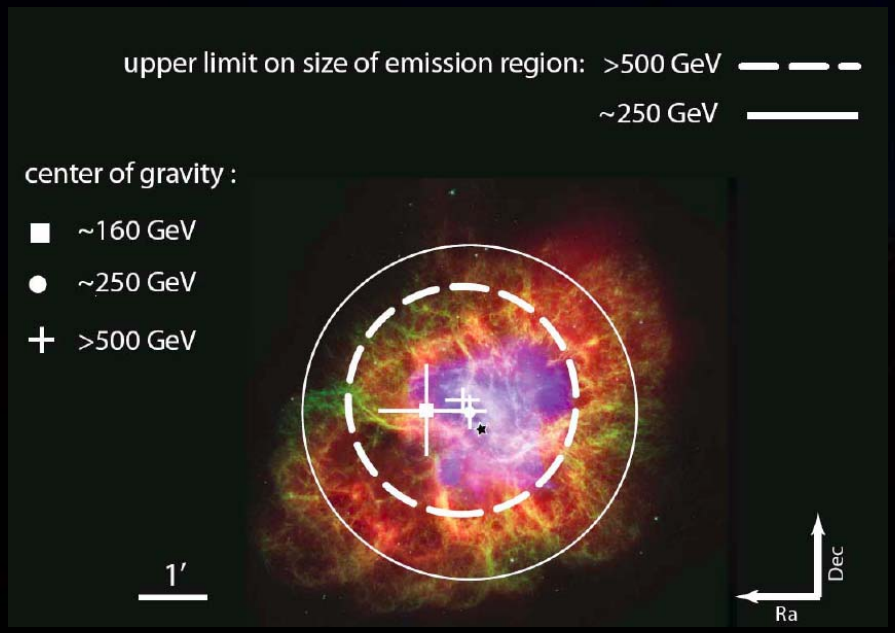
- Correlation with 3EG J0617+2238 ?
- Spatially coincident with
  - high density molecular cloud
  - maser emission

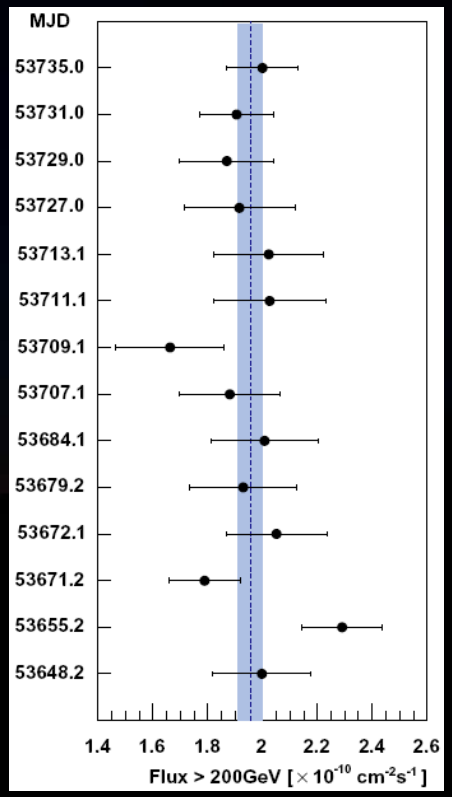
- γ-ray emission of π^0-decay from interaction of CR accelerated in IC443 with molecular cloud ?

Crab - The VHE standard candle



- Strongest, stable VHE source
- Cross calibration between instruments
- MAGIC trigger rate: ~0.4 Hz





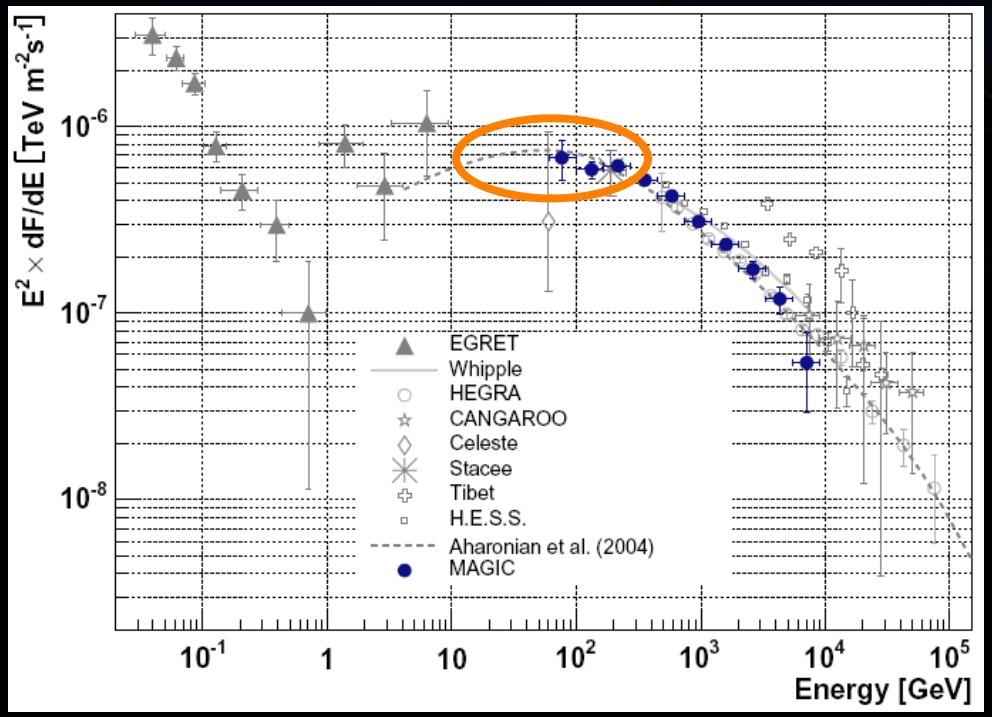
- Point-like VHE emission (r < 2′)
- Coincident with Pulsar position
- Systematic uncertainty ~ 1′

- Stable emission

Crab - Nebula

Prominent Pulsar Wind Nebula

- Relativistic electrons emitted by Pulsar
- Shock acceleration to $E_e > 1000$ TeV
- Synchrotron (X-ray) & Inverse Compton (IC, γ-ray) emission

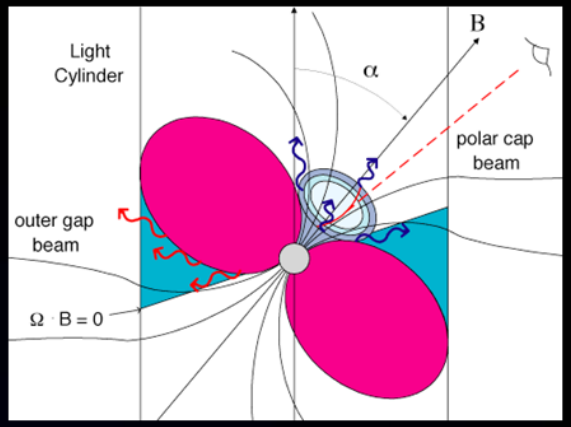


MAGIC observations

- Spectrum measured down to $E > 60$ GeV
- Well described by Self Synchrotron Compton (SSC) model
- IC peak estimated to be at $E_{IC} = 77$ GeV

Crab - Pulsar

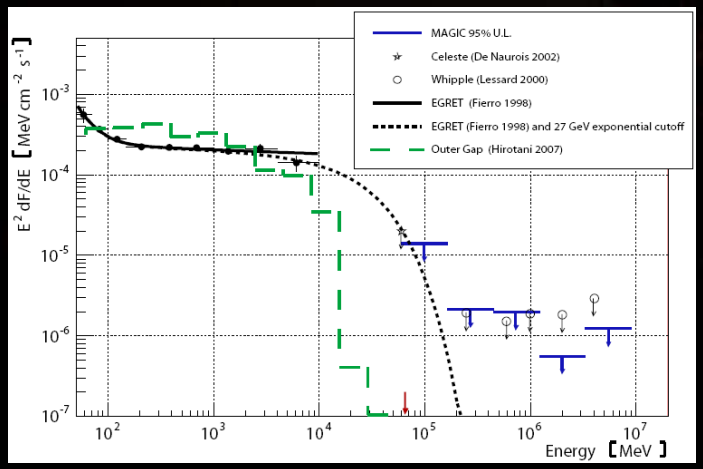
- Pulsed emission in Radio to γ-ray (<10GeV)
- Complex relativistic electrodynamics
- Challenge for theory



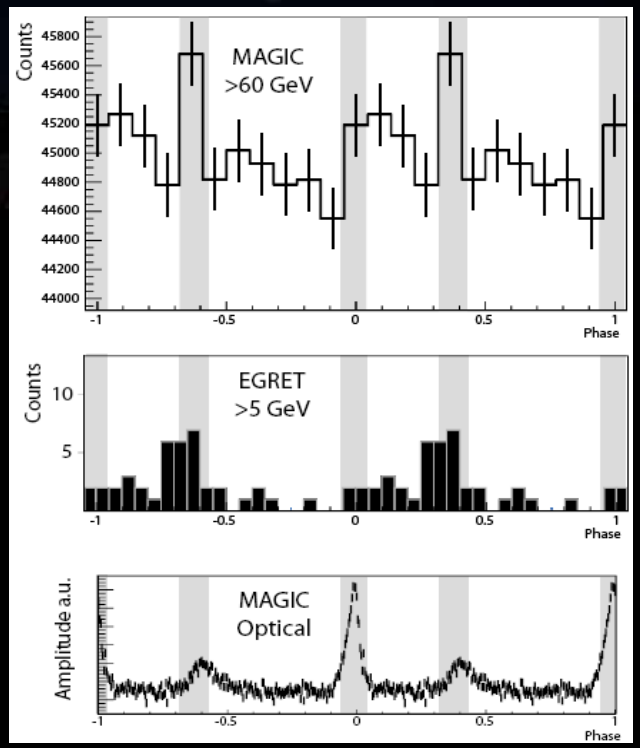
MAGIC search for pulsed emission

- No detection

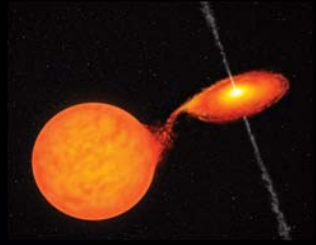
=> exponential cutoff @ E<27 GeV



2.9 σ hint in
EGRET (>100MeV) region

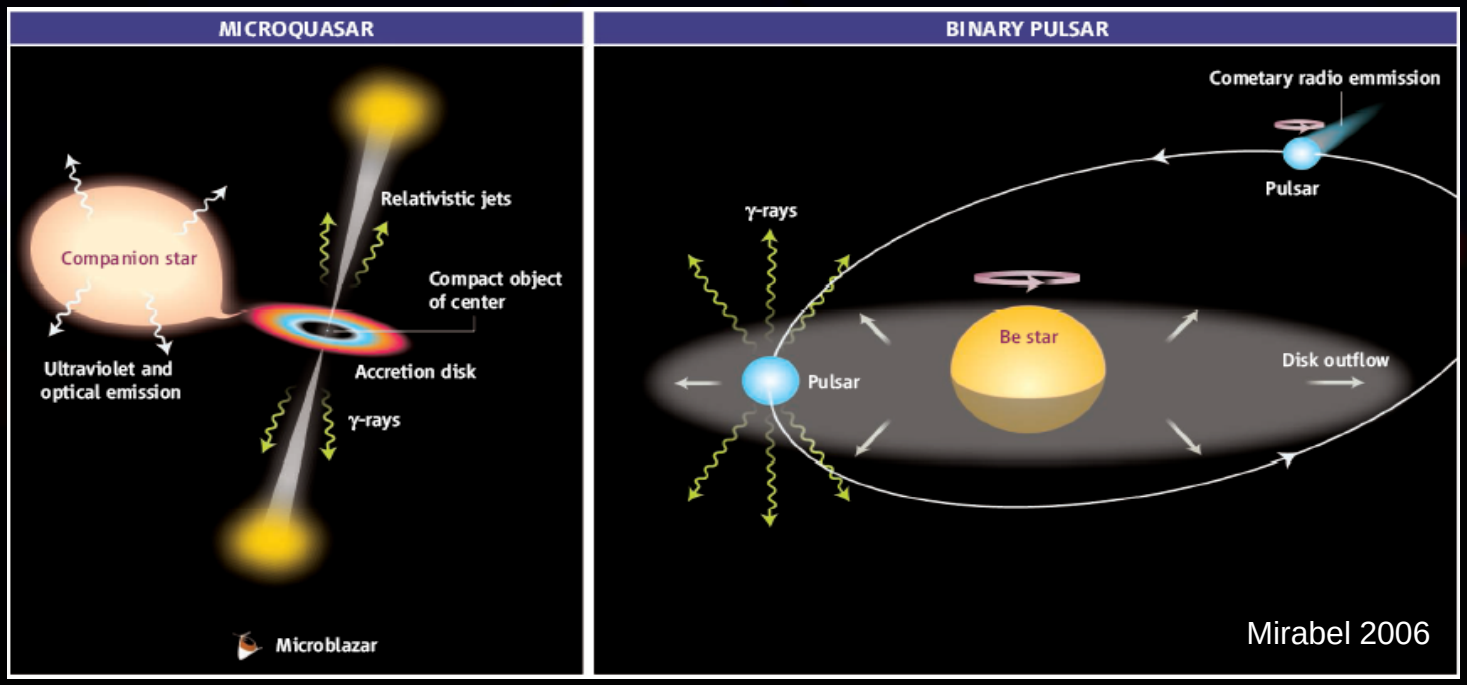


X-ray Binary Systems



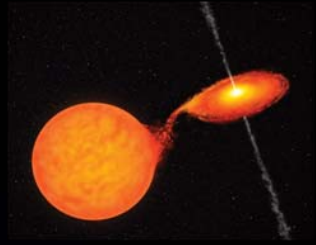
X-ray & γ-radiation (?) from binaries consisting of:

- Compact object (neutron star or black hole)
- High mass companion star

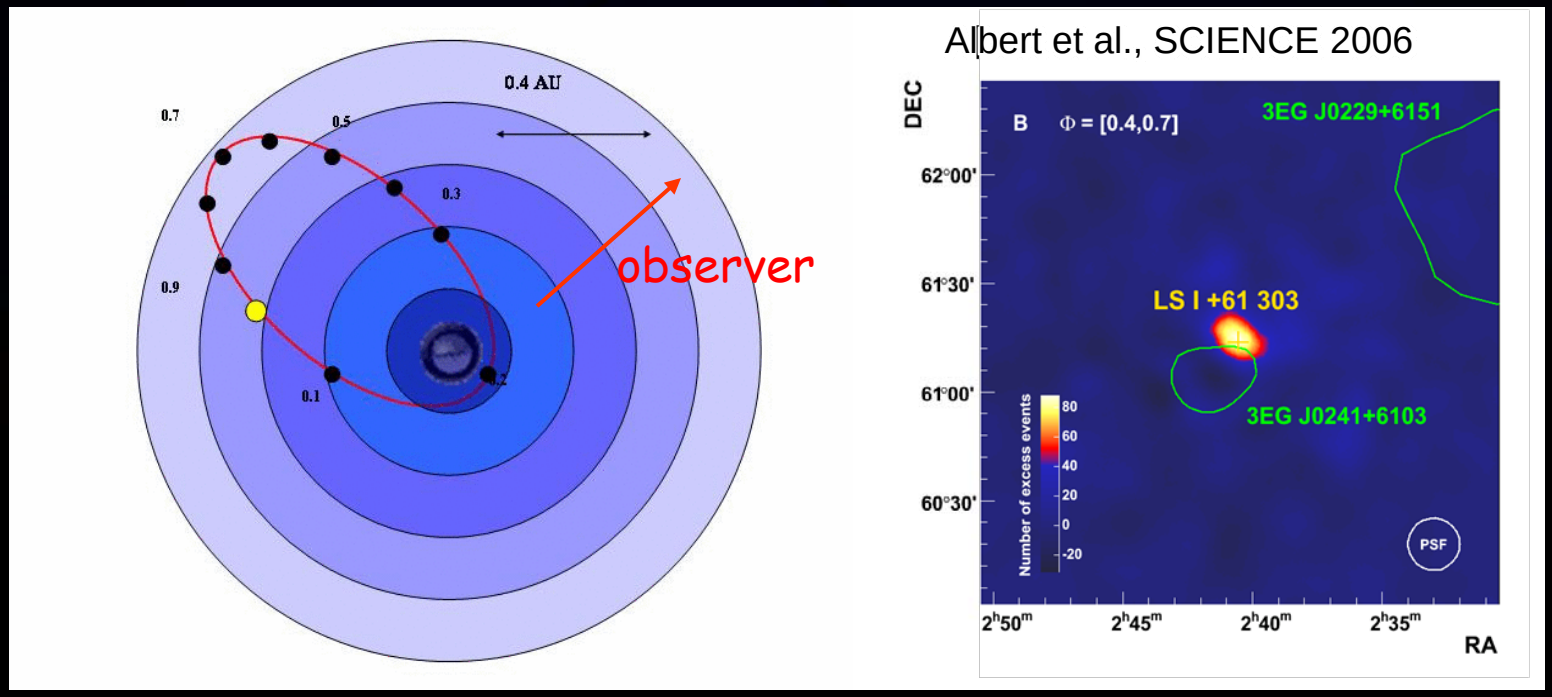


- Binary Pulsars: rel. electrons from rotational energy of pulsar
- Microquasars: rel. electrons (& hadrons) from accretion powered jets

LS I +61 303

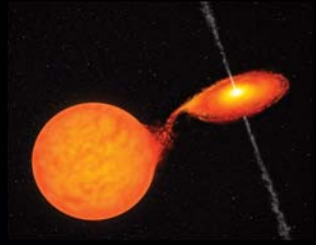


- Companion ~18 $M_\odot$ Be Star, compact object <4 $M_\odot$
- 26.5 day, highly eccentric (ε~0.7) orbit
- Variable radio, optical & X-ray emission



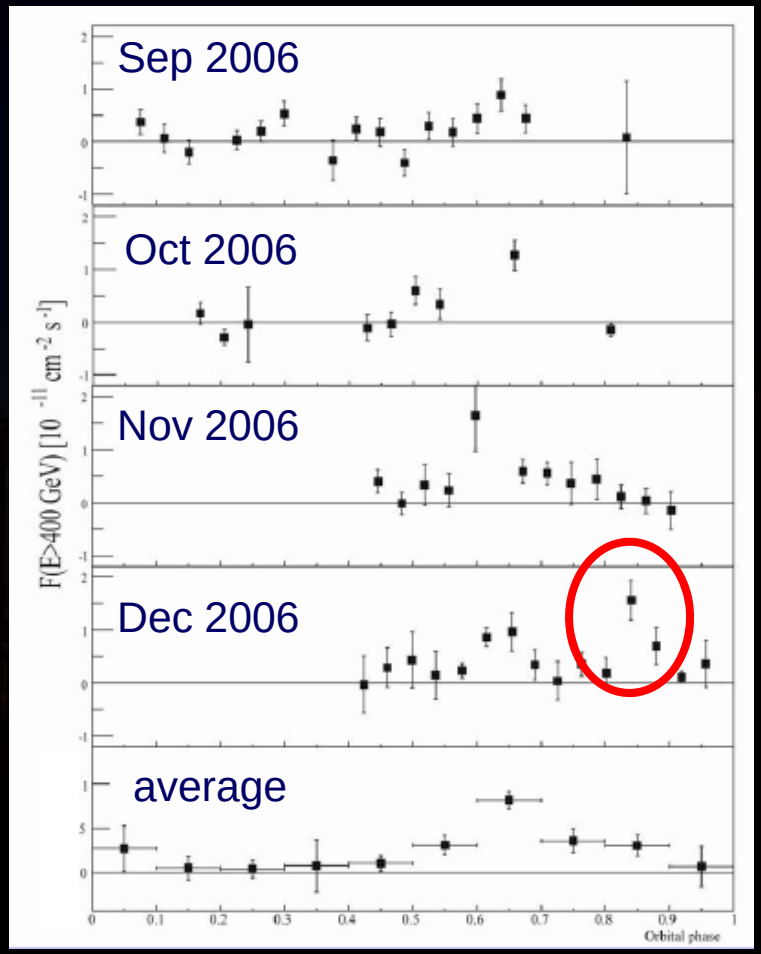
- MAGIC 9σ Discovery of variable VHE emission

LS I +61 303



MAGIC observation:

- 166h in 2005 & 2006
- Hint of periodic emission
  - Highest emission at φ = 0.6-0.7
  - Quite at periastron
- Flare in Dec 06 at φ = 0.8-0.9
- Spectral index stable (Γ = -2.6 $\pm$ 0.2) although flux changes by factor 3

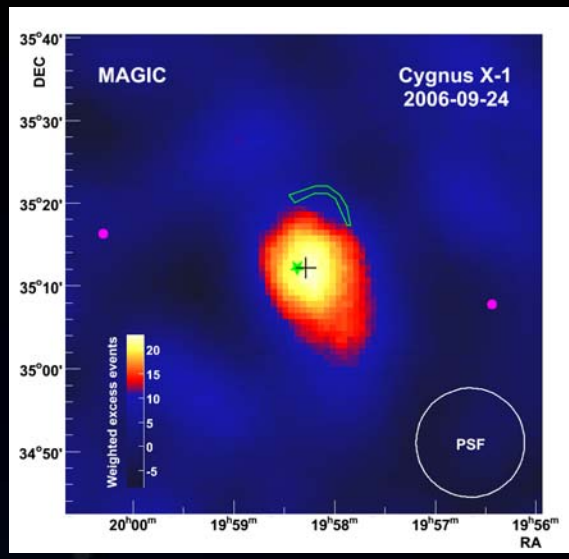


- Microquasar ?
  - no hint for accretion disc
  - Radio jets ?
- Binary pulsar ?
  - No pulsar observed

Cygnus X1

X-ray binary

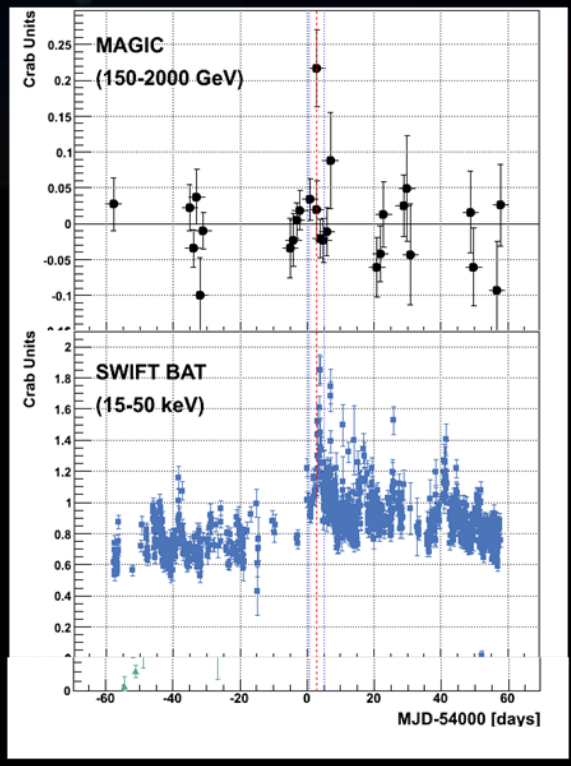
- Black hole ($M > 13M_\odot$)
- Super giant ($M \sim 40M_\odot$) companion O9.7 star
- Quasi circular 5.6 day orbit
- Single sided jet => microquasar ?



40h, 26days observations with MAGIC in 2006

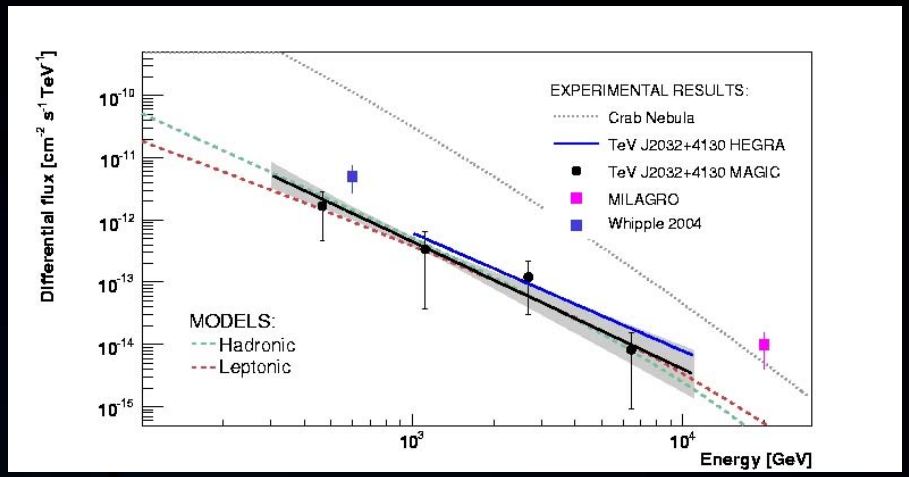
- Search for steady emission => no detection

- 4.9σ (4.1σ after trial) excess for 79min on Sept 24
- Excess right before (~1h) SWIFT peak
- Emission region compatible with Cyg-X1 excludes nearly radio nebula
- Excess during phase 0.9-1.0 (BH behind star)



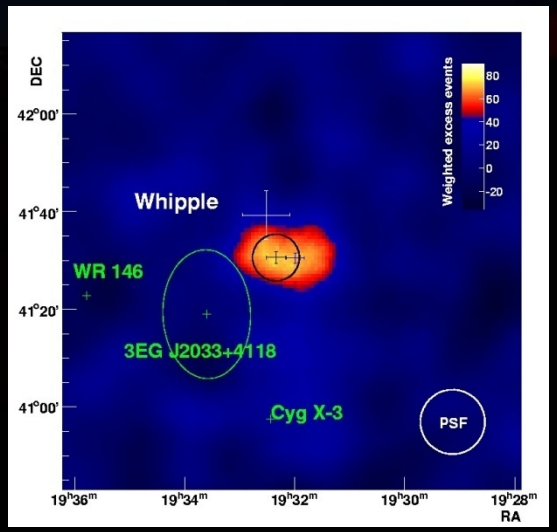
TeV 2032

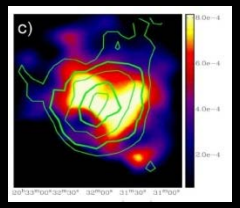
- HEGRA: First TeV unidentified source, weak (~5% crab at 1 TeV, Aharonian et al 2002) and slightly extended. Detected also by Whipple.
- Recent claim by MILAGRO of an extended source in the same direction.



MAGIC: 94h over 3 years (2005-2007).

- Spectrum consistent with HEGRA above 1 TeV and extends with the same spectral index (2.0 ± 0.3) down to 250 GeV. Flux ~3% crab.
- No indication of variability in 3 years of observation.
- Hardly compatible with flux at 20 TeV of co-directional MILAGRO source. Most probably it's a different source.
- Extended source. Hint at an asymmetric distribution…





keV diffuse emission
Horns et al, 2007

4- MAGIC II

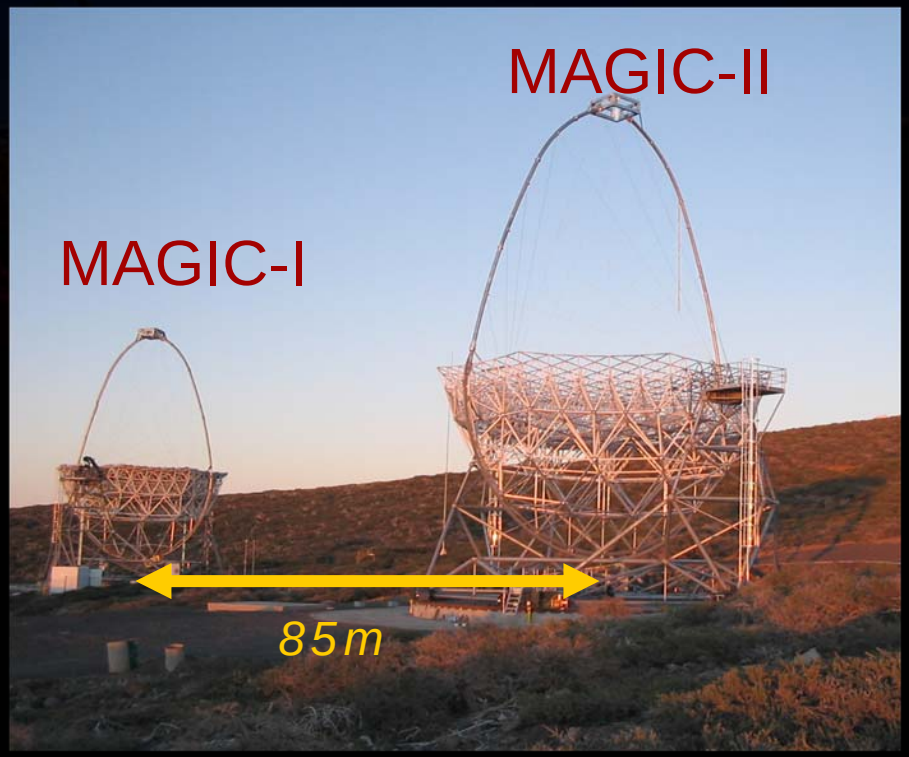
Aim:

- Increase sensitivity (particularly below 100 GeV)
- Lower energy threshold further

Second telescope: MAGIC-II

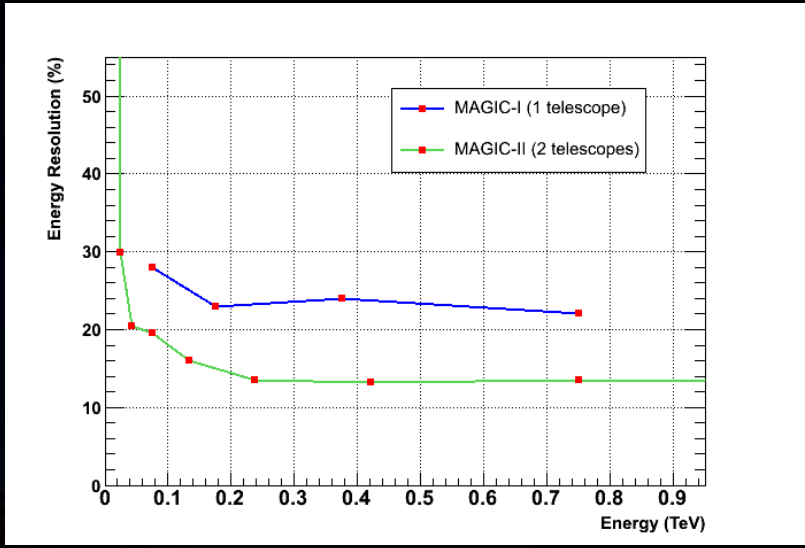
"Improved clone"

- Most fundamental parameters identical to MAGIC-I
- Use improved technology where available:
  - High QE photosensors
  - Fast sampling readout

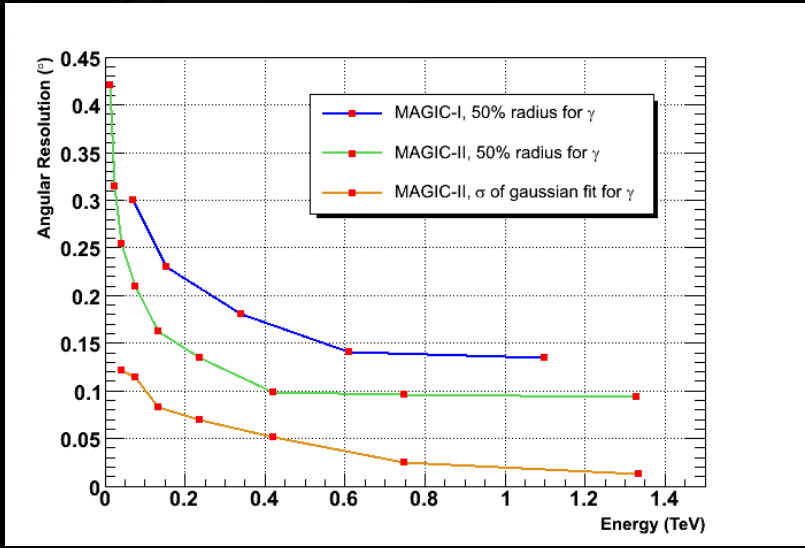


Improved Reconstruction

- Energy resolution
  - MAGIC-I: ~25%
  - MAGIC-II: 14-20% (2 telescopes)



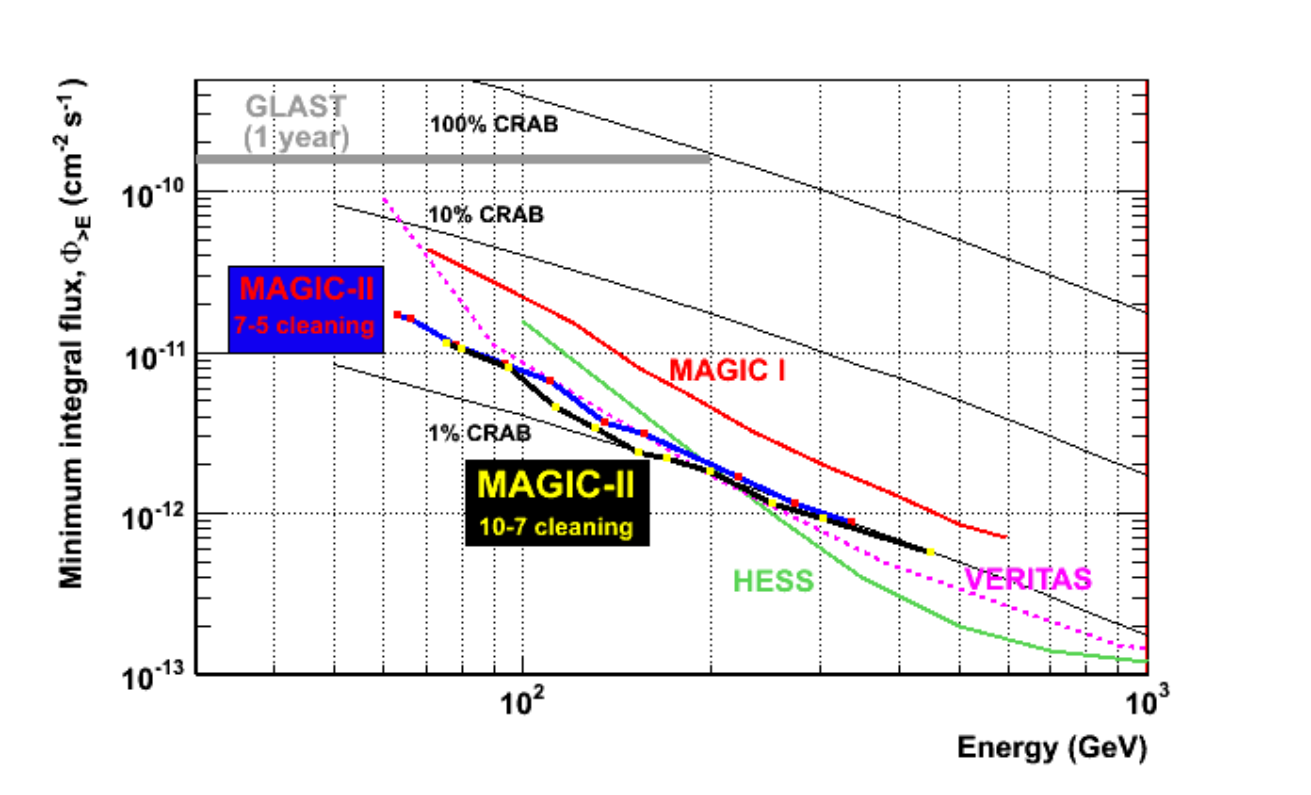
- Angular resolution
  - Substantial (~50%) improvement since source position is obtained from intersection point of both showers



Improved Sensitivity

Using Stereo Analysis

- better background rejection down to low energies
- increase sensitivity by up to factor 3
  => reduce observation time by factor 9
- Large gain in sensitivity at low energies (< 100 GeV)



Summary

- MAGIC is pioneering the quest for low-threshold Cherenkov Telescopes and delivering many scientific results
  - Discovered several galactic & extra-galactic sources
  - Addresses many exciting physics topics

- MAGIC-II operational second half of 2008 (inauguration 21 Sept 2008)

  => Improve sensitivity by factor ~3

  => Lower analysis threshold