LOFAR and the Transient Radio Sky

Amsterdam, 15-17 December 2008

MAGIC observations of galactic and extragalactic variable radio sources

Marc Ribó

UNIVERSITAT DE BARCELONA

ICCUB

Elina Lindfors and Nicola Galante

(for the MAGIC Collaboration)

MAGIC

OUTLINE

1. The MAGIC Cherenkov Telescope
2. Galactic variable radio sources
3. Extragalactic variable radio sources
4. MAGIC-II and LOFAR
5. Conclusions

MAGIC, with its 17 m diameter tesselated mirror, is the largest single-dish Cherenkov telescope in the world.

It started scientific operations in 2004 fall.

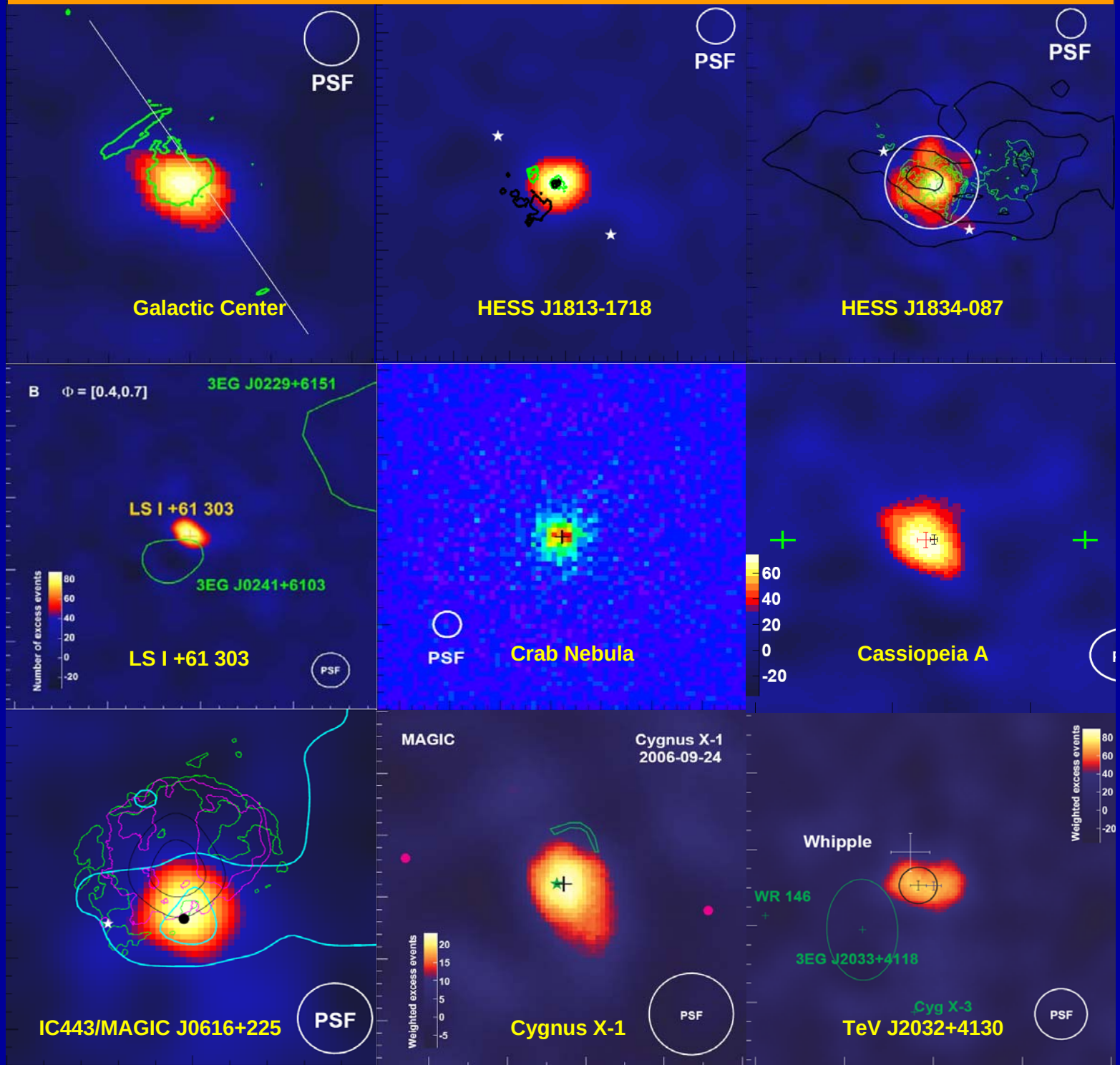
It is located in the **Observatorio del Roque de los Muchachos**, in the Canary Island of La Palma.

Basic parameters:

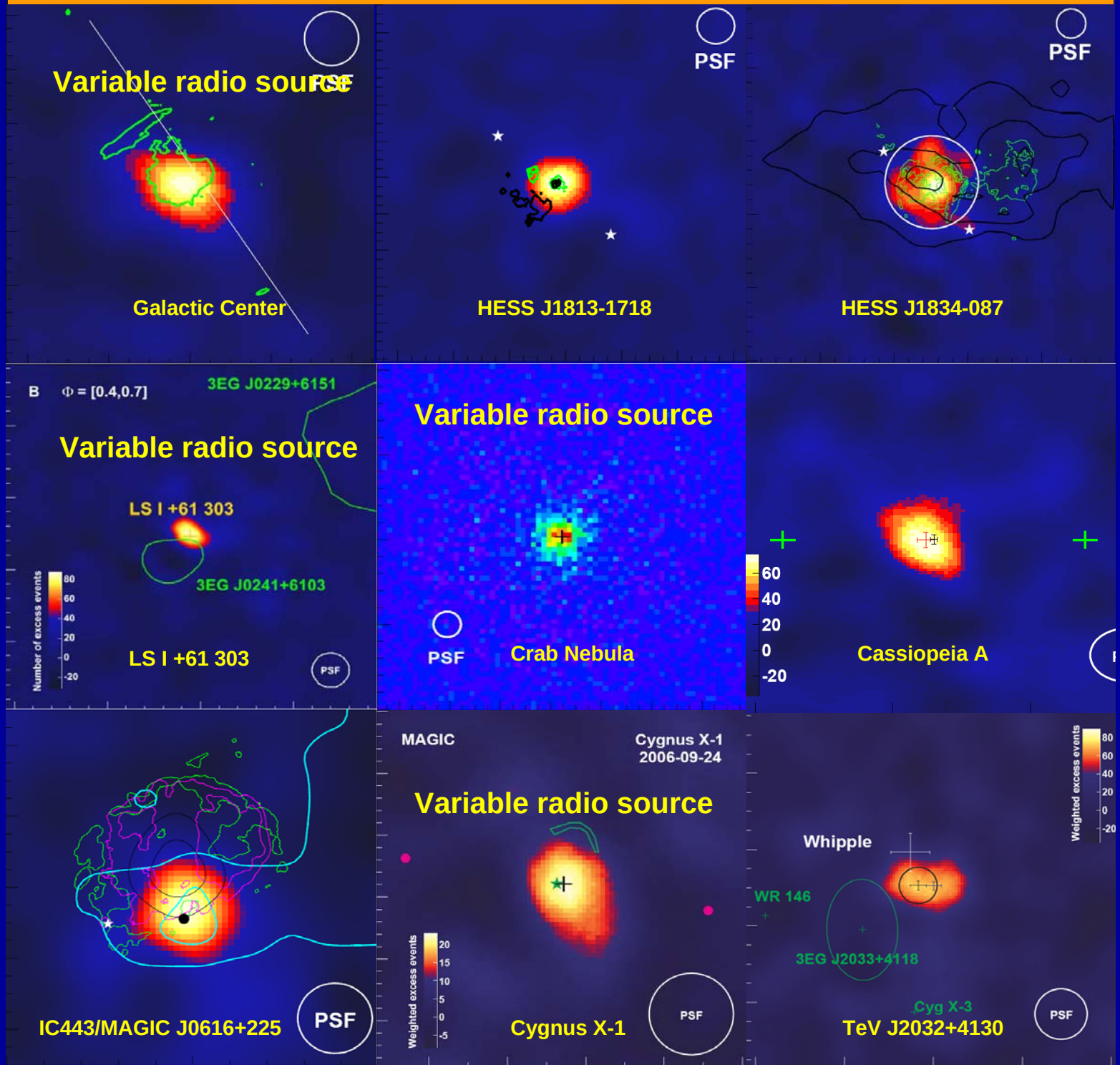
- Sensitivity: **1.6% Crab** Nebula in 50h.
- Angular resolution: **~ 0.1º**.
- Field of view: **3.5º**.
- Energy resolution: **~ 20%**.
- Energy threshold:
  55 GeV in normal operations
  25 GeV in sumtrigger mode

Stereoscopic observations with the **second MAGIC telescope starting in early 2009**.

GALACTIC SOURCES



GALACTIC SOURCES



Summary of Galactic sources observed by MAGIC

10 sources have been detected / 4 are new discoveries
4 upper limits

SNR:	**IC443/MAGIC J0616+225**
	Cassiopeia A
	HESS J1813–1718
	HESS J1834–087/W41
Pulsars and their nebulae:	**Crab Nebula**
	Crab pulsar
	PSR B1951+32/CTB 80
Galactic center:	**Galactic Center**
Unidentified sources:	**TeV J2032+4130**
X-ray binaries:	**LS I +61 303**
	Cygnus X-1
	Cygnus X-3
WR binaries:	**WR 146**
	WR 147

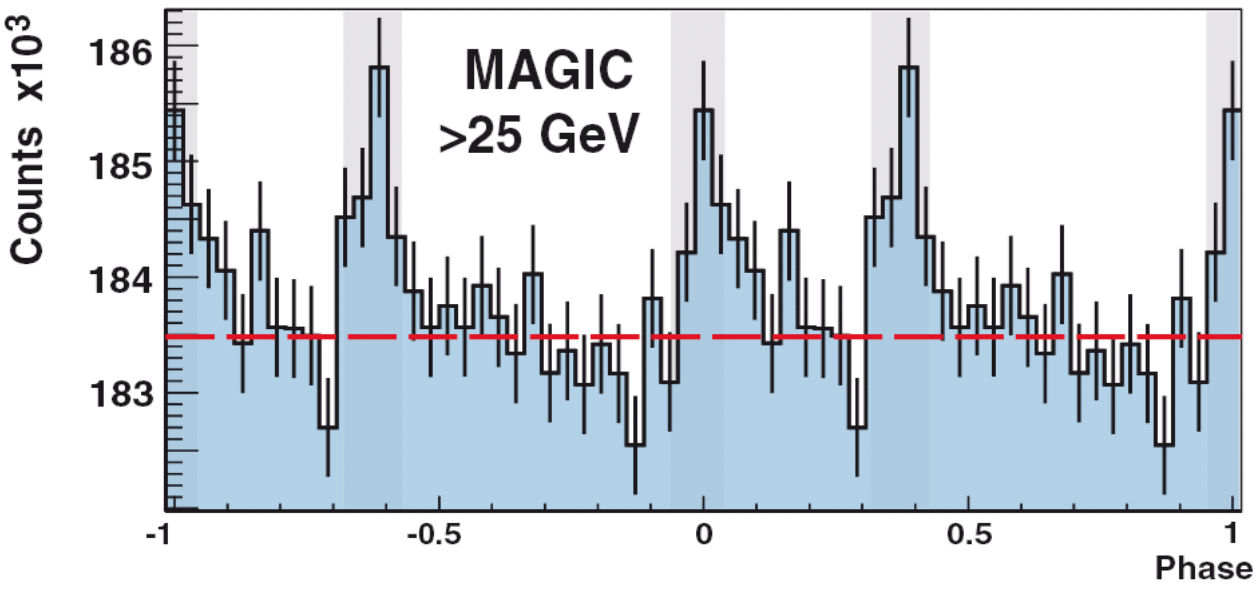
Summary of Galactic sources observed by MAGIC

10 sources have been detected / 4 are new discoveries
4 upper limits

SNR:	**IC443/MAGIC J0616+225**
	Cassiopeia A
	HESS J1813–1718
	HESS J1834–087/W41
Pulsars and their nebulae:	**Crab Nebula**
	Crab pulsar (variable radio source)
	PSR B1951+32/CTB 80
Galactic center:	**Galactic Center (variable radio source)**
Unidentified sources:	**TeV J2032+4130**
X-ray binaries:	**LS I +61 303 (variable radio source)**
	Cygnus X-1 (variable radio source)
	Cygnus X-3 (variable radio source)
WR binaries:	**WR 146**
	WR 147

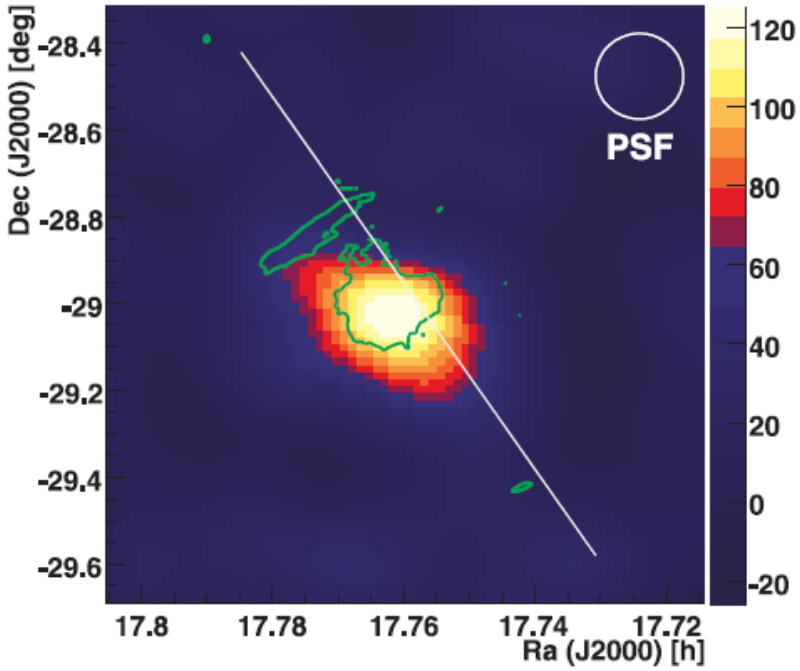
Crab Pulsar

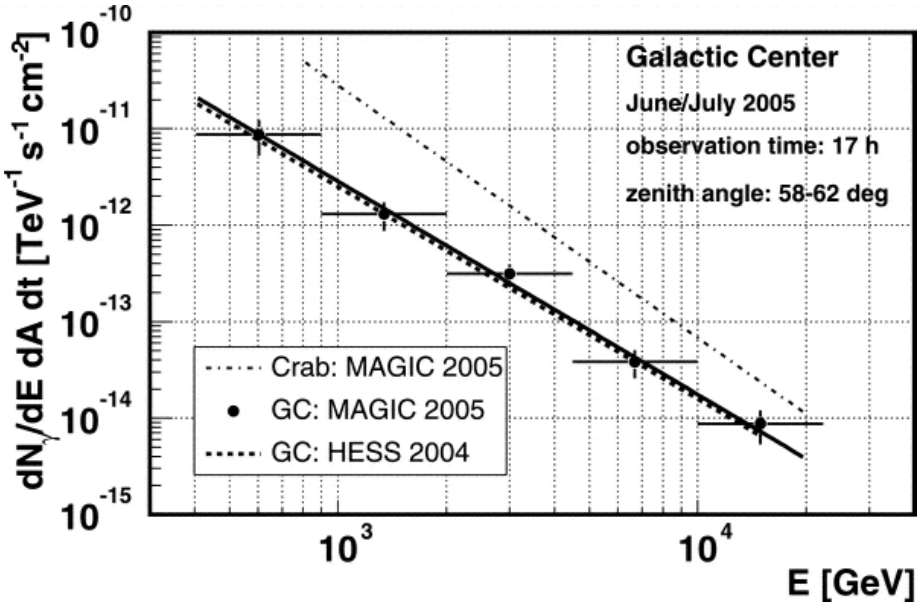
MAGIC has recently detected a pulsed signal from the Crab at $E > 25$ GeV with 6.4σ (Aliu et al. 2008, Science, 322, 1221).
First pulsar seen by a **Cherenkov Telescope**.
The pulsed signal occurs at the **same spin phases** as those observed with **EGRET** ($E>$ 100 MeV) and simultaneous MAGIC/optical data (central pixel).
This has been possible thanks to a **new trigger system** (sum-trigger).
Conclusion: The energy cut-off in the phase-averaged spectrum is relatively high. This indicates that **emission happens far out in the magnetosphere**. These results **exclude the polar cap model and challenge the slot gap model** for the Crab pulsar.



Galactic Center

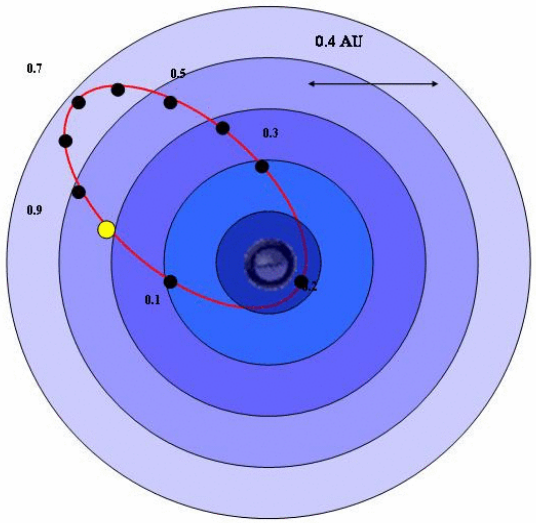
MAGIC has confirmed the HESS spectrum of the Galactic Center source (which is in contradiction with earlier CANGAROO results). **The source is steady (Albert et al. 2006, 638, L101)**.
The **power law spectrum** up to about 20 TeV **disfavors dark matter annihilation** as the main origin of the detected flux. The absence of flux variation indicates that the VHE gamma-rays are rather produced in a **steady object such as a SNR or a PWN**, and not in the central black hole.



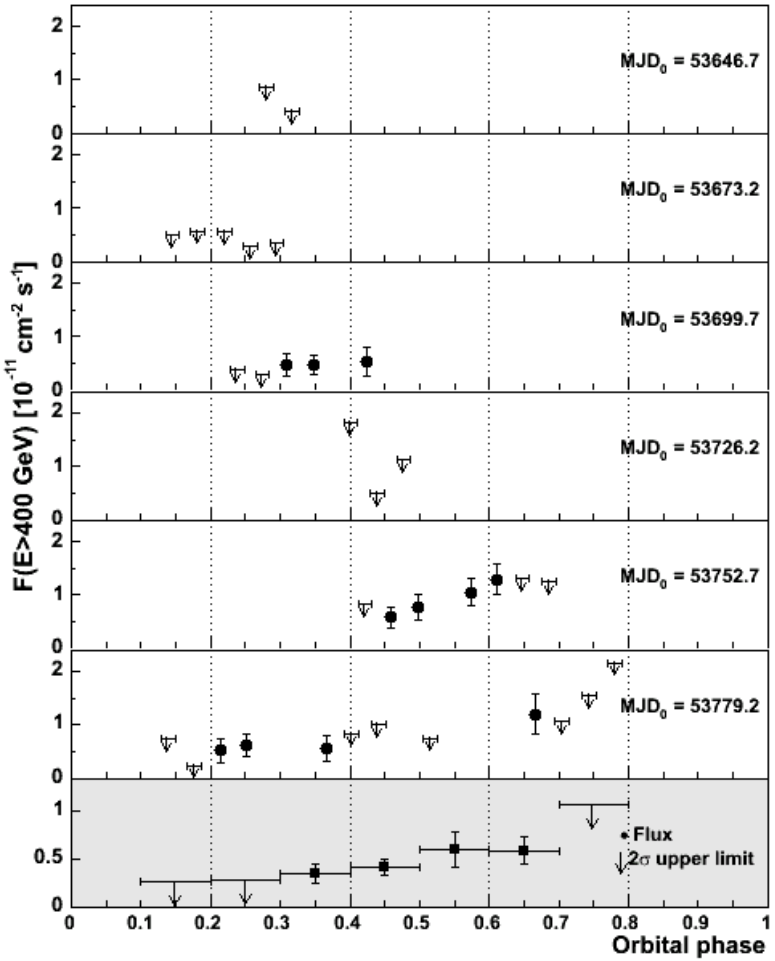


LS I +61 303

LS I +61 303 is an X-binary system containing a **B0.5Ve** donor and a compact object of unknown mass (upper limit of ~5 M_sun) orbiting it every **26.5 days**, in a very eccentric orbit with ***e*~0.5-0.7**. **No radio pulses are observed**. VHE gamma-rays are detected at apastron **(Albert et al. 2006, Science, 312, 1771)**.

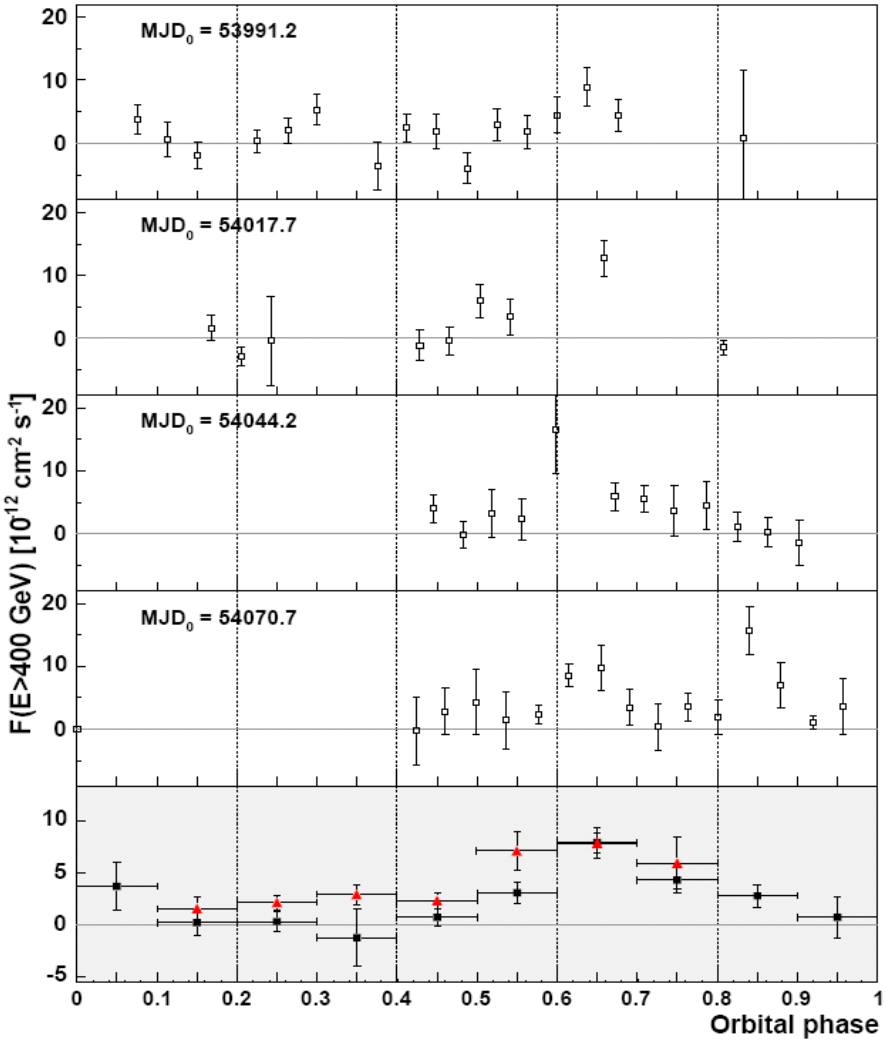


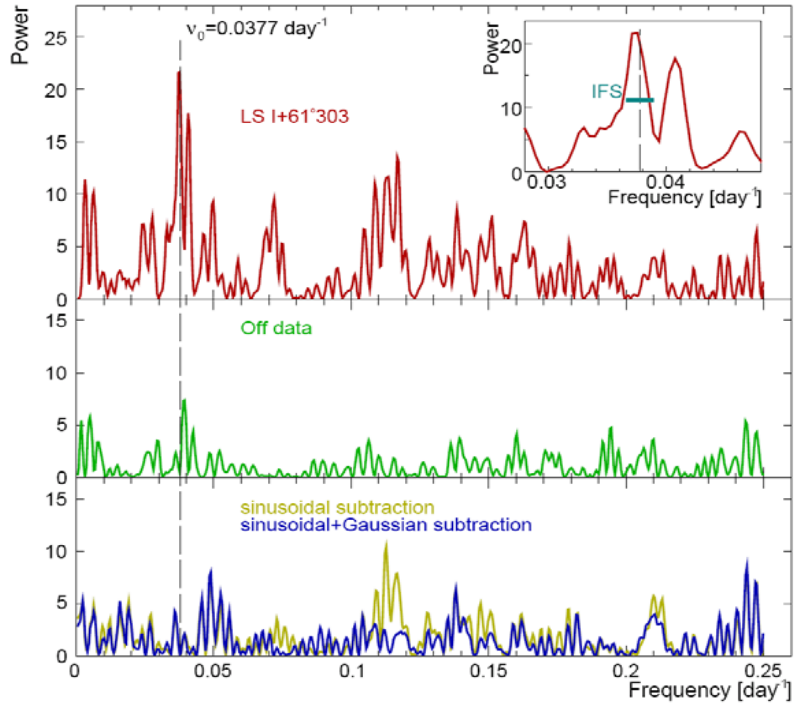
VERITAS has confirmed the earlier results reported by the **MAGIC** Collaboration **(Acciari et al. 2008)**.

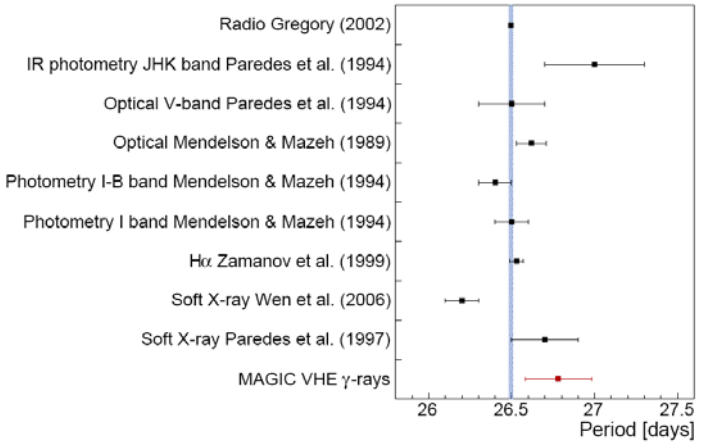


LS I +61 303

The **MAGIC** Collaboration has just reported the detection of **TeV periodicity** with 26.8±0.2 d from **LS I +61 303 (Albert et al. 2008, ApJ, in press, arXiv:0806.1865)**.

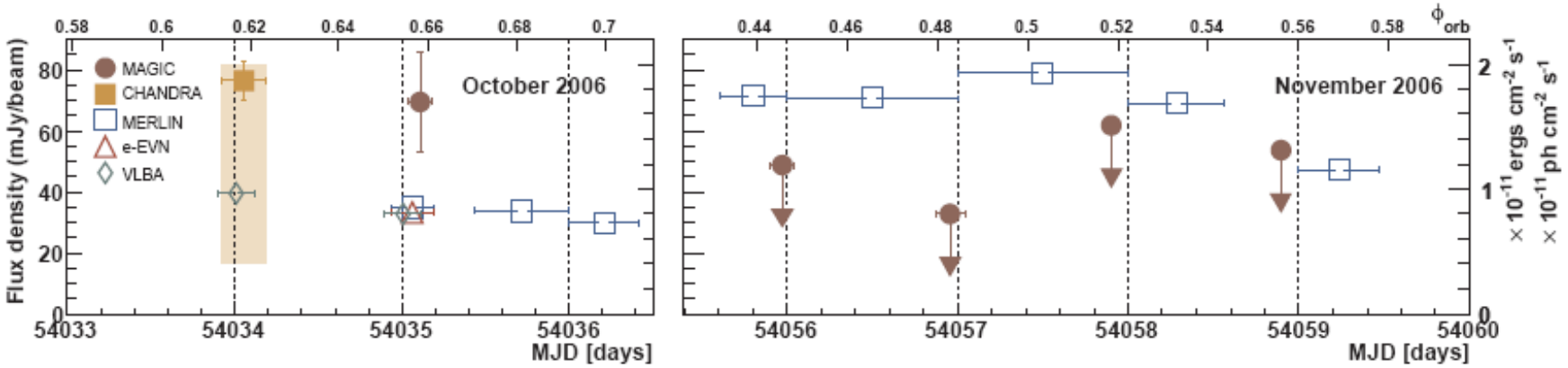




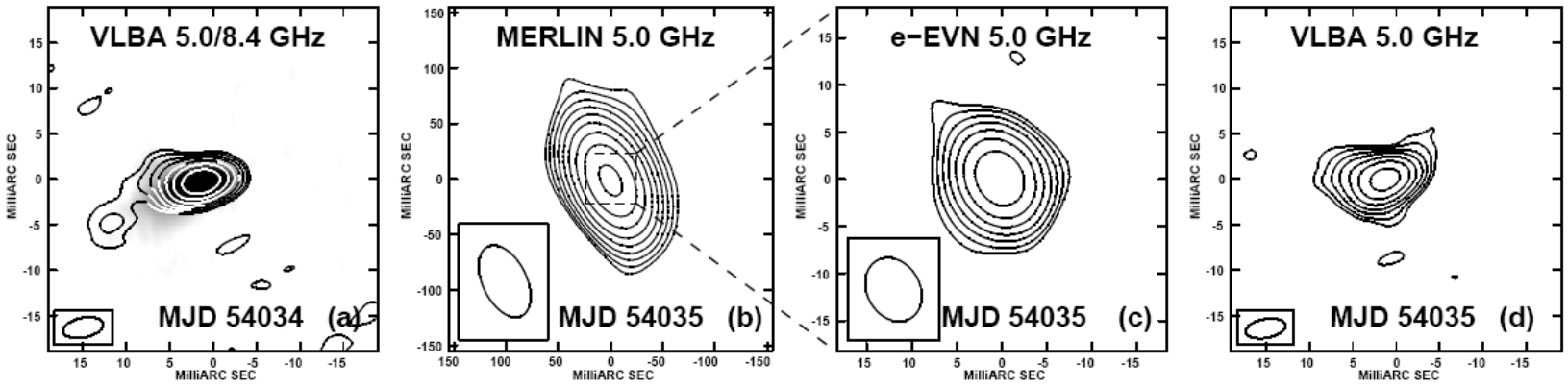


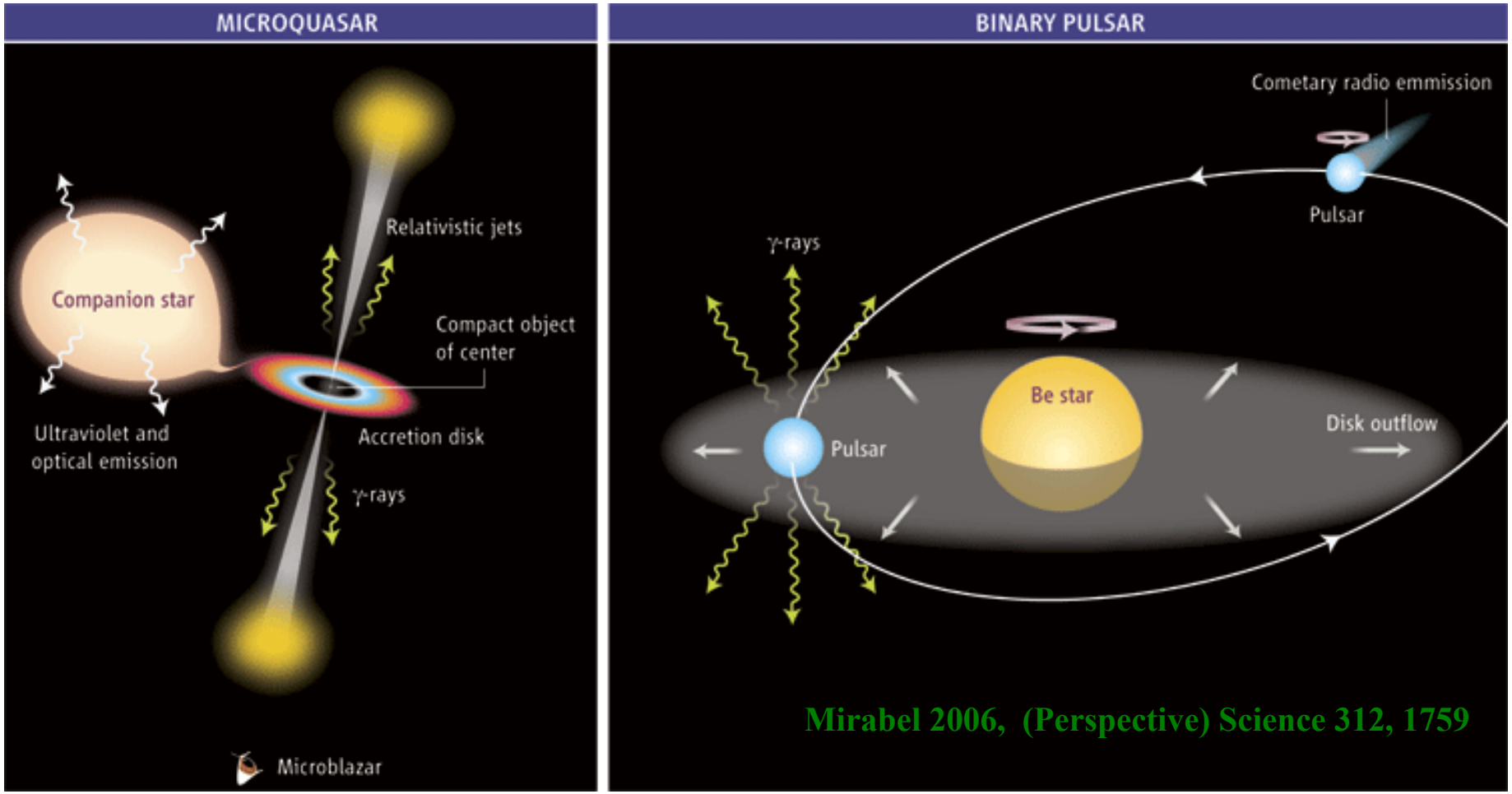
LS I +61 303

- **Multi-wavelength campaign** during October-November 2006 with VLBA, MERLIN, e-EVN, Chandra and MAGIC **(Albert et al. 2008, ApJ, 684, 1351)**.
- No clear gamma-ray/radio correlation, but **possible gamma-ray/X-ray correlation**.



- No large-scale (~100 AU) persistent jets.
- Highly stable morphology indicates **interaction of steady outflows**.





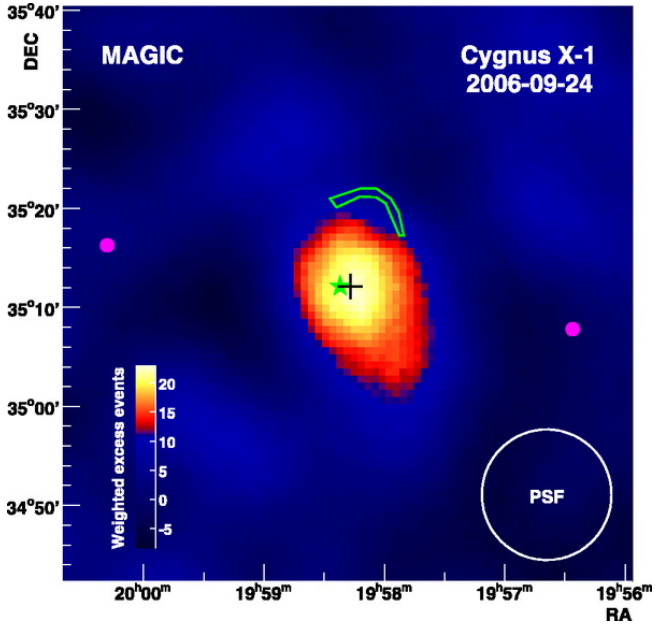
Cygnus X-1 **LS 5039 ?** **LS I +61 303 ?** **PSR B1259-63**

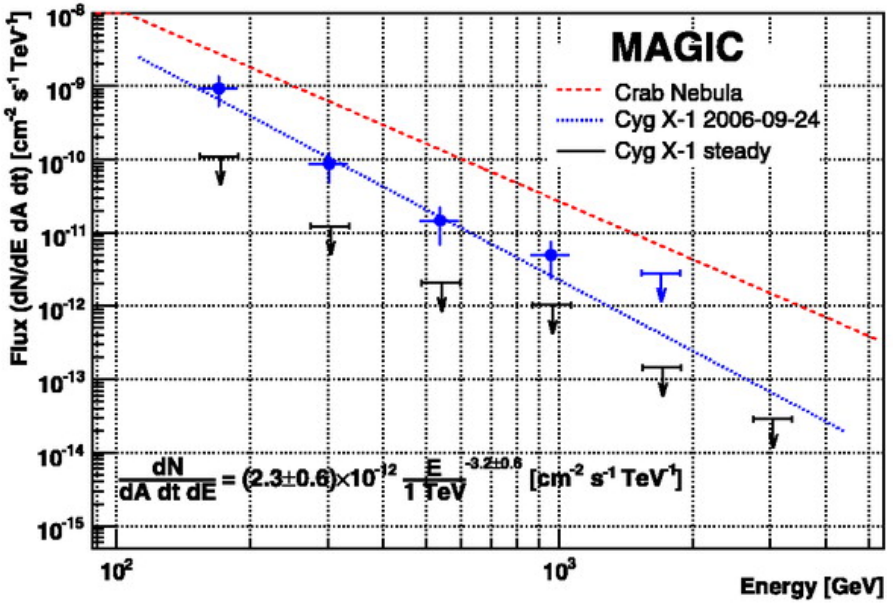
Cygnus X-1

Cygnus X-1, containing an **O9.7Iab** donor and an **accreting black hole** of at least 10 solar masses orbiting it every **5.6 days**, in a circular orbit.

- Steady flux below ~1% Crab Nebula flux.
- **Strong evidence** (4.1σ post-trial significance) **of intense short-lived [1h-24h] flaring episode** discovered by MAGIC on 24-09-2006.
- Soft spectrum (Γ = -3.2) between ~100 GeV and 1 TeV, with no break.
- Extension below MAGIC angular resolution (~ 0.1°).
- Radio-nebula produced by the jet interaction with the ISM excluded.

(Albert et al. 2007, ApJ, 665, L51).





Cygnus X-1

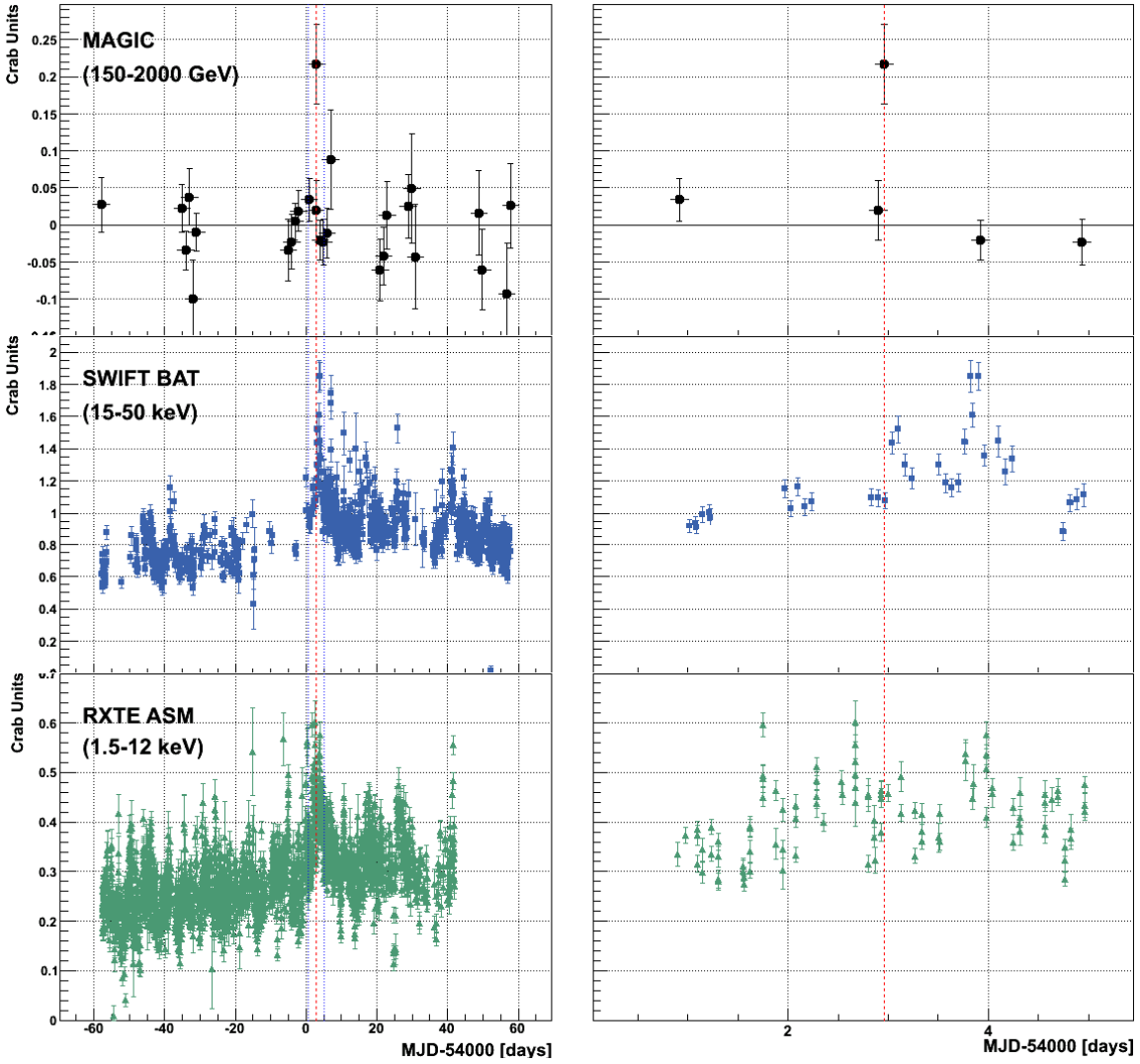
Detected up to 1 TeV. **Orbital phase 0.9-1.0**, when the BH is behind the star and photon-photon absorption should be huge: **τ~10 at 1 TeV (Bednarek & Giovannelli 2007)**. Away from the BH might be the solution: **flare in the jet?**

TeV excess right before the onset of a hard X-ray peak seen by *Swift*.

Observations one day later reveal that no TeV excess was found during the maximum and decay phase of another hard X-ray peak.

More simultaneous multi-wavelength data is necessary to build models.

(Albert et al. 2007, ApJ, 665, L51).



EXTRAGALACTIC SOURCES

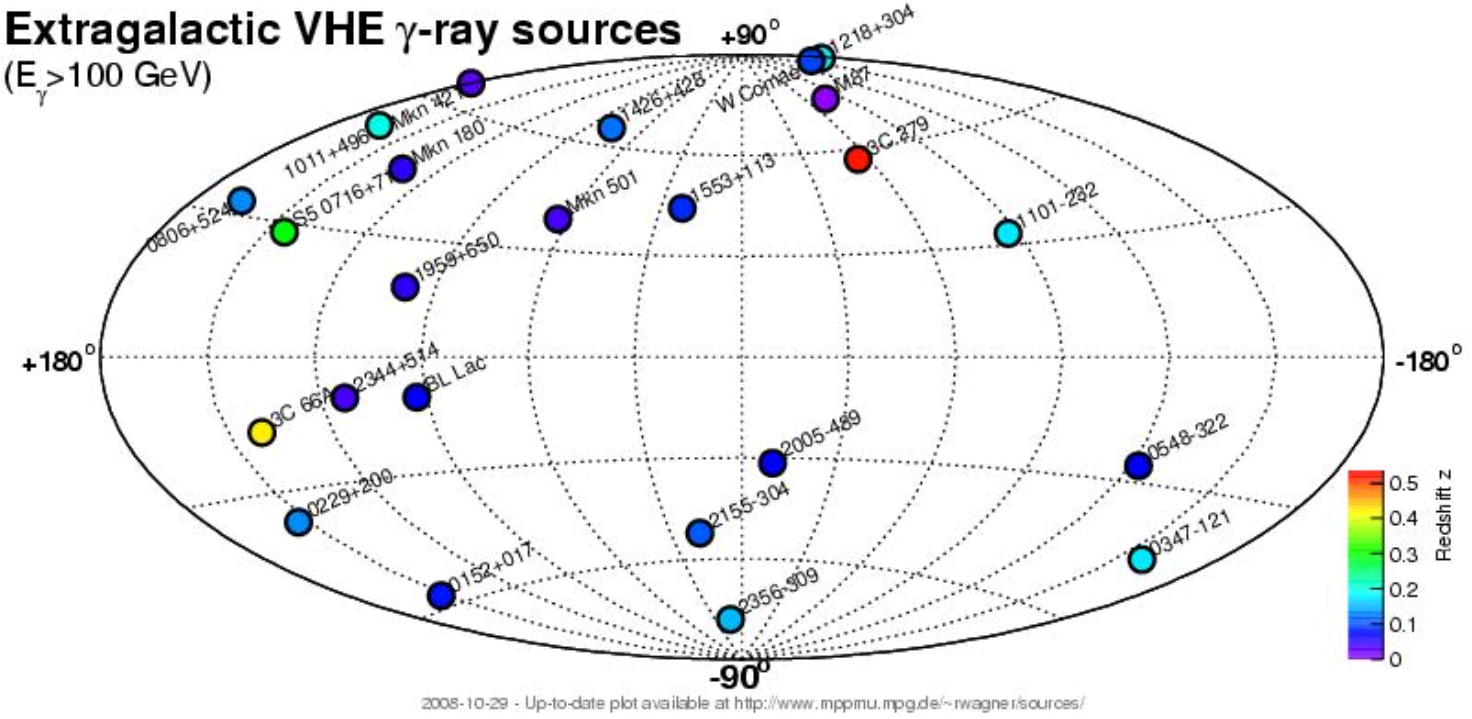
All known extragalactic VHE gamma-ray emitting sources (24) are AGN:

- 18 **high frequency peaked BL Lacs**, 4 **low frequency peaked BL Lacs**
- 1 **flat spectrum radio quasar** (3C 279)
- 1 **radio galaxy** (M87)

MAGIC 1) **Monitors** known sources.

2) Participates in **MWL campaigns**.

3) Performs **ToO observations**.



Summary of Extragalactic sources observed by MAGIC

12 sources have been detected / 7 are new discoveries
12 upper limits

Radio galaxies:	**M87**
HBLs:	**1ES 1959+650, 1ES 2344+514**
	Markarian 421, Markarian 501
	1ES 1218+304
	Markarian 180
	PG 1553+113
	1ES 1011+496
	1ES 0120+340, RX J0319.8+1845, 1ES 0323+022,
	1ES 0414+009, 1ES 0806+524, 1ES 0927+500,
	RX J1417.9+254, 1ES 1426+428, RXJ1725.0+1152
LBLs:	**BL Lac, S5 0716+714**
FSRQ:	**3C 279**
Starburst galaxies:	**Arp 220**

Dark Matter annihilation from dSph galaxies: **Draco, Willman 1**

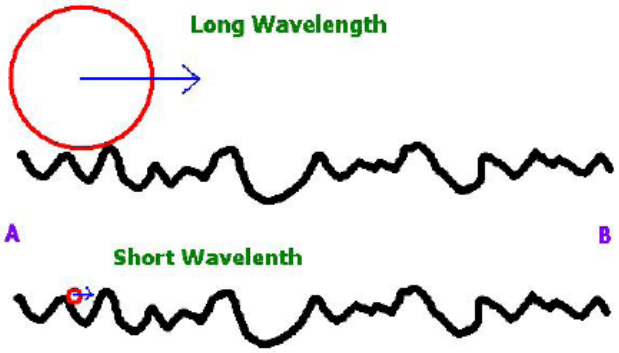
Summary of Extragalactic sources observed by MAGIC

12 sources have been detected / 7 are new discoveries
12 upper limits

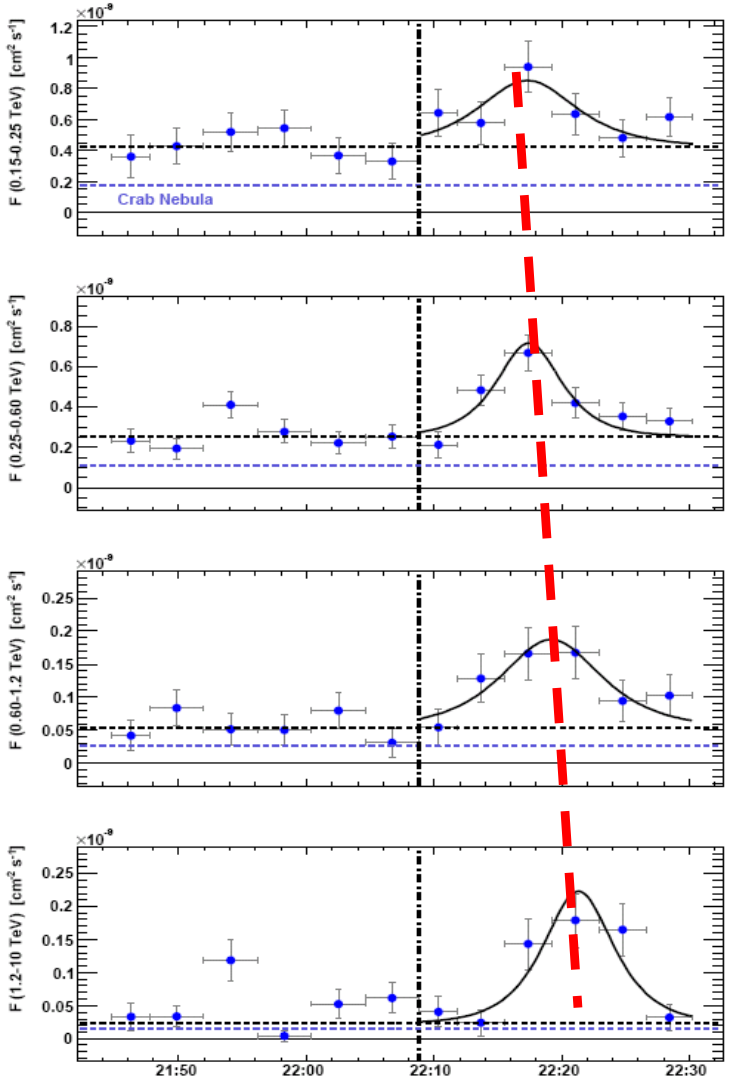
Radio galaxies: **M87**
HBLs: **1ES 1959+650, 1ES 2344+514**
Markarian 421, Markarian 501
1ES 1218+304
Markarian 180
PG 1553+113
1ES 1011+496
1ES 0120+340, RX J0319.8+1845, 1ES 0323+022,
1ES 0414+009, 1ES 0806+524, 1ES 0927+500,
RX J1417.9+254, 1ES 1426+428, RXJ1725.0+1152
LBLs: **BL Lac, S5 0716+714**
FSRQ: **3C 279**
Starburst galaxies: **Arp 220**
Dark Matter annihilation from dSph galaxies: **Draco, Willman 1**

Variable radio sources

Markarian 501



Retarded flare at higher energies of 4+/-1 minute may indicate **progressive acceleration of electrons (Albert et al. 2007, ApJ, 669, 862)**.



- It is widely speculated that **space-time is a dynamical medium**, subject to quantum gravitational **(QG) effects that cause space-time to fluctuate** on the Planck time and distance scales.

- A consequence of these fluctuations is the fact that the **speed of light in vacuum** becomes **energy dependent**.

- There is a **delay between γ-rays of different energies**, $\tau_l = (0.030 \pm 0.012)$ s/GeV, corresponding to a lower limit $M_{QG} > 0.21 \times 10^{18}$ GeV at the 95% C.L. **(Albert et al. 2008, PhLB, 668, 253)**.

Radio galaxy M87

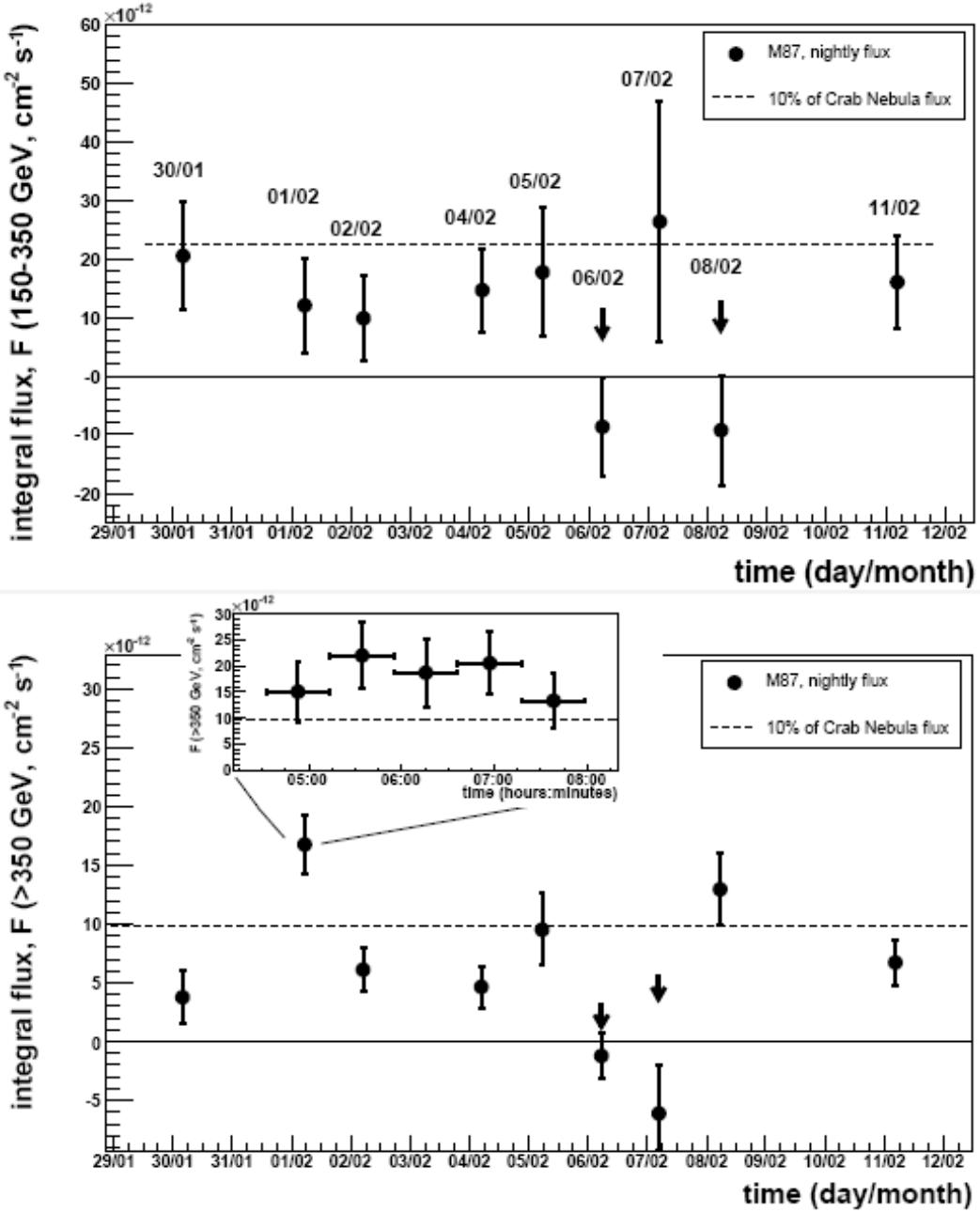
Shared monitoring between **MAGIC-VERITAS-HESS**.

MAGIC observed **fast flare** from **M87** in February 2008.

The flux was found to be **variable** above 350 GeV on a **timescale as short as 1 day** (significance level of 5.6 sigma). $R < 2.6\,\delta\,R_{Sch}$.

The highest measured flux reached 15% of the Crab Nebula flux.

(Albert et al. 2008, ApJ, 685, 23).



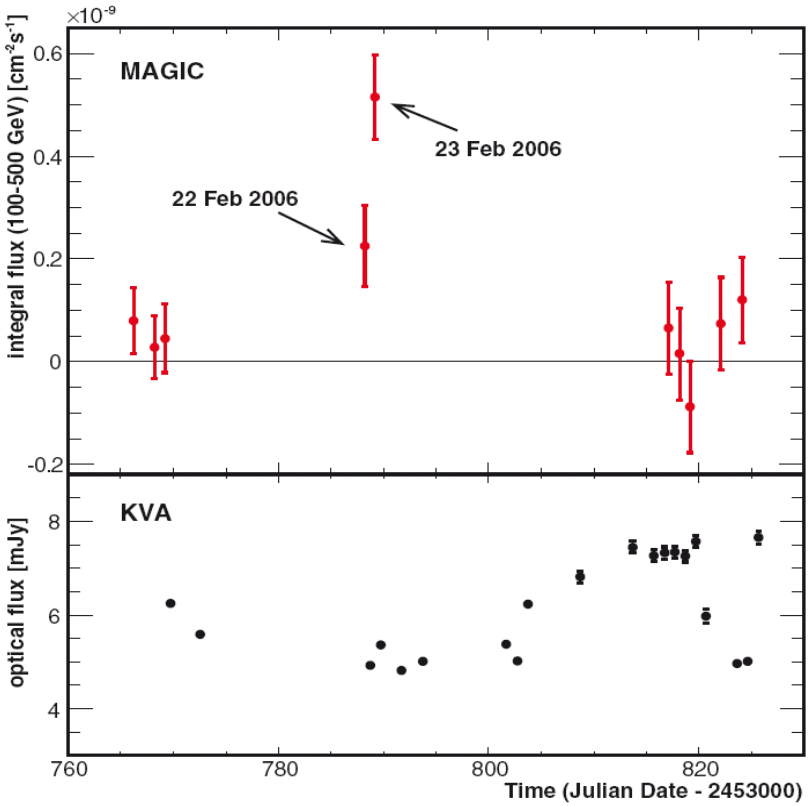
FSRQ 3C 279

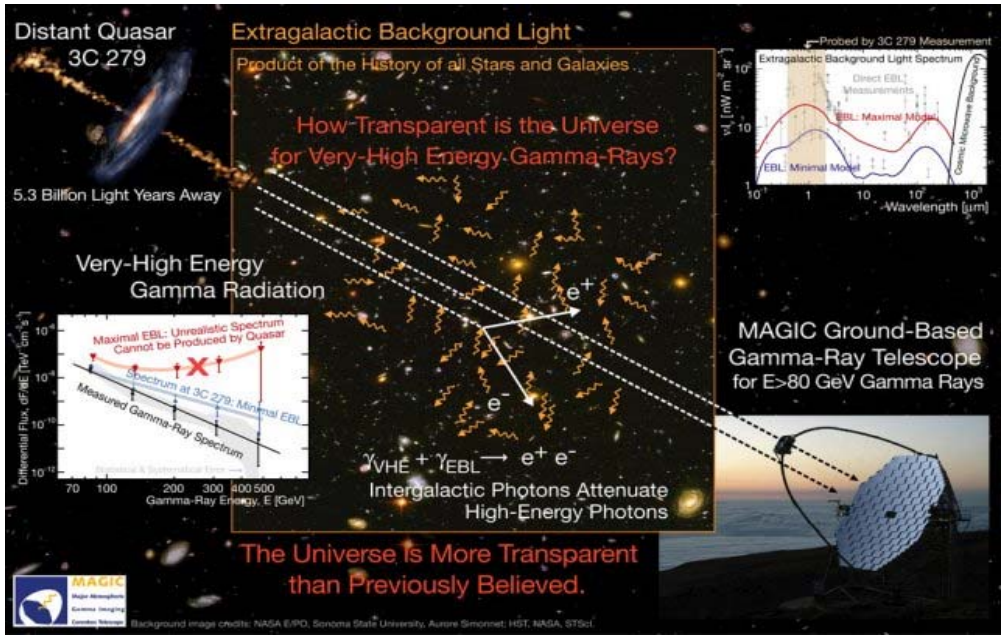
The Flat Spectrum Radio Quasar **3C 279**, at z=0.536, has been detected while flaring with **MAGIC**.

Discovery: Significant signal on 23rd of February, hint of signal from night before.

This is the **most distant object detected emitting gamma rays above 50 GeV**. These observations imply a **low amount of EBL in the infrared domain**, consistent with that known from galaxy counts.

(Albert et al. 2008, Science, 320, 1752).





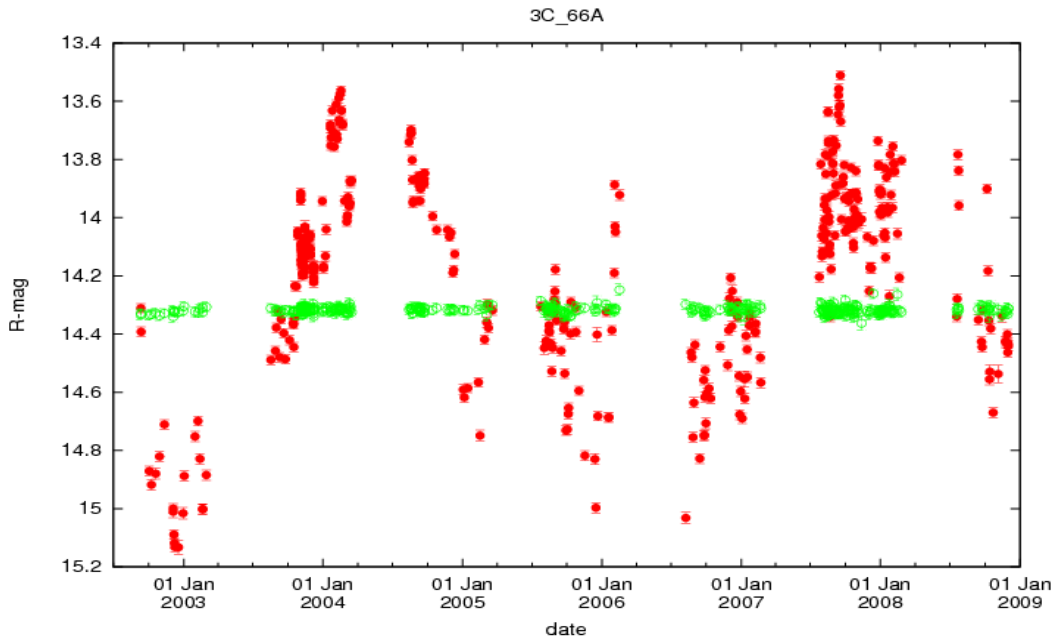
Optically triggered observations

Optical monitoring program of potentially VHE gamma-ray emitting blazars with the 60cm KVA (@La Palma, but remotely operated by Tuorla Observatory, Finland).

The program has resulted in a total of **3 discoveries**:

- Markarian 180
- 1ES1011+496
- S5 0716+714

Discovery of **MAGIC J0223+430** was triggered by optical outburst in **3C 66A**.



MAGIC J0223+430

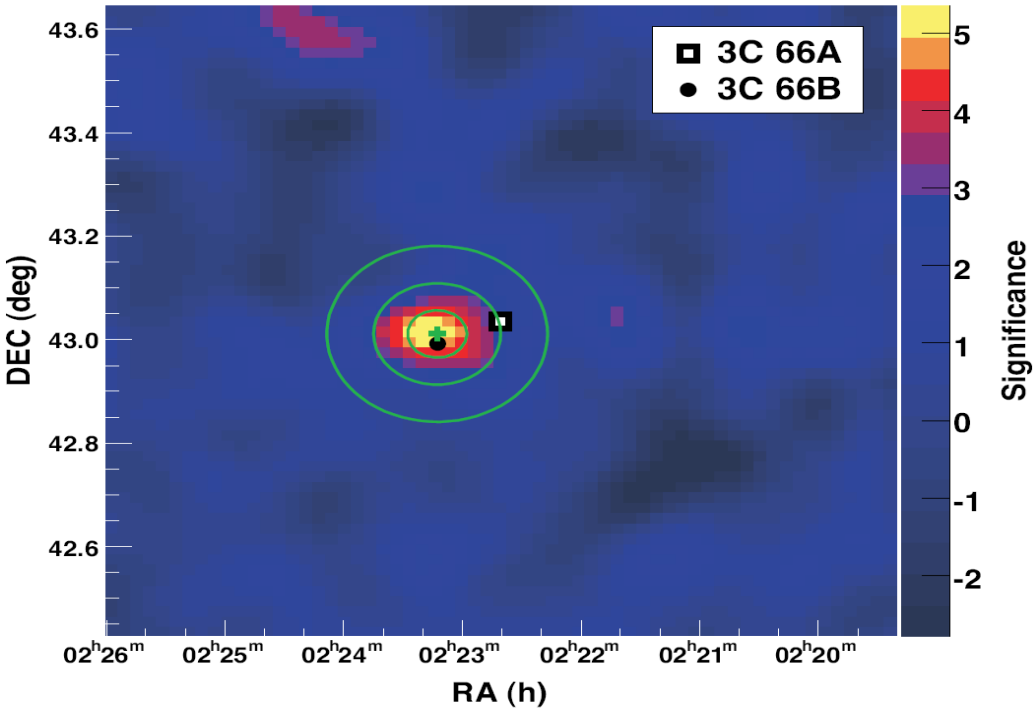
August 2007: **optical outburst in 3C66A**.

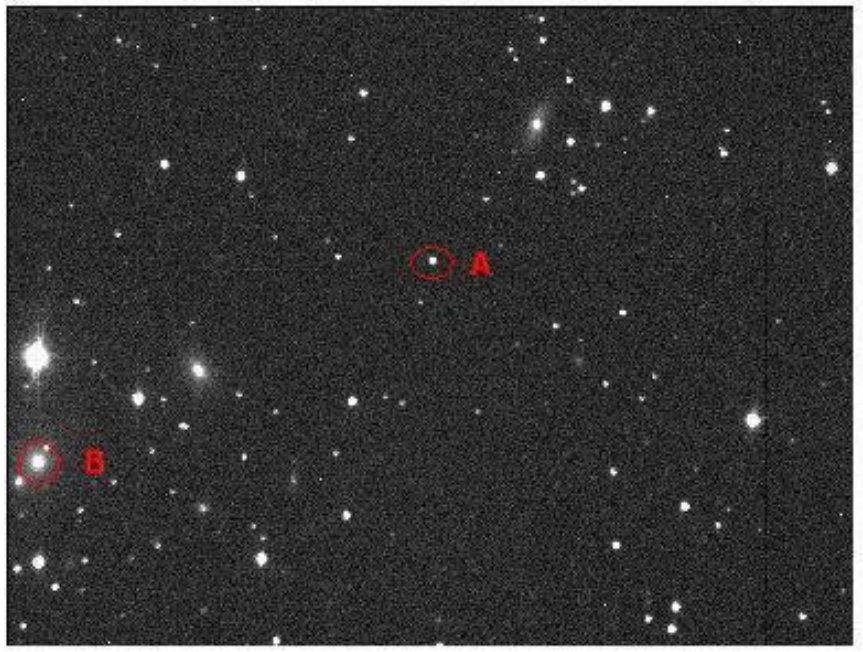
MAGIC observations August, September, December 2007

Clear signal: 5.4 sigma, flux ~2.2% Crab.

Position of the **signal is most likely not coincident with that of 3C 66A** (>150 GeV excluded at 85.4% c.l.), but rather with a **close (6') radio galaxy 3C 66B**.

(Aliu et al. 2008, ApJ, subm., arXiv:0810.4712).





S5 0716+714

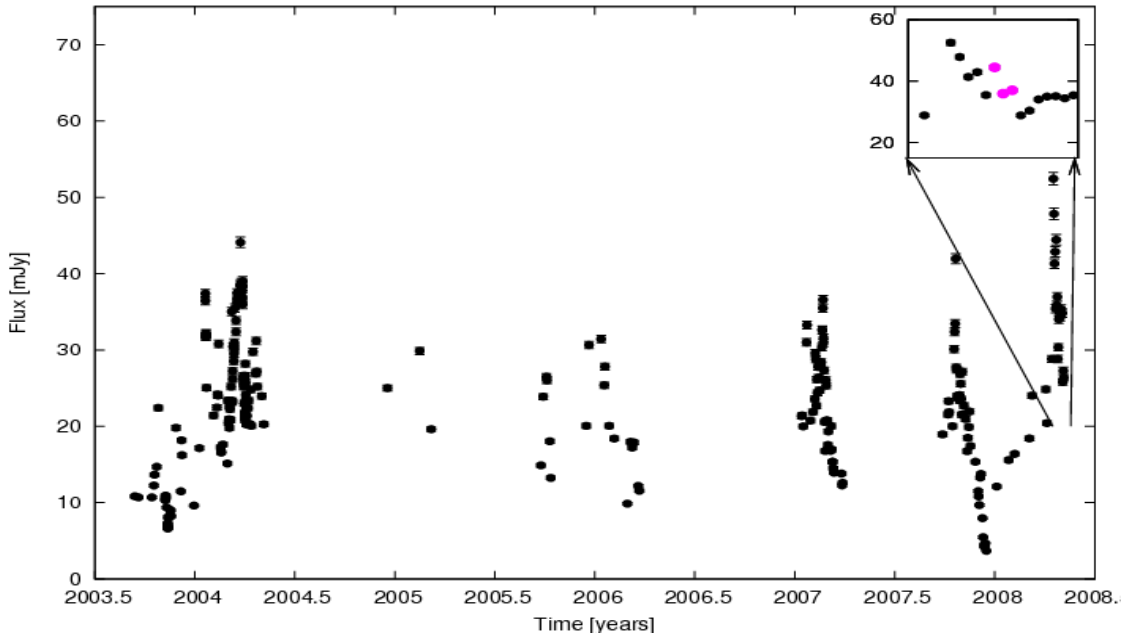
Famous BL Lac object. Host galaxy at z=0.31+/-0.08.

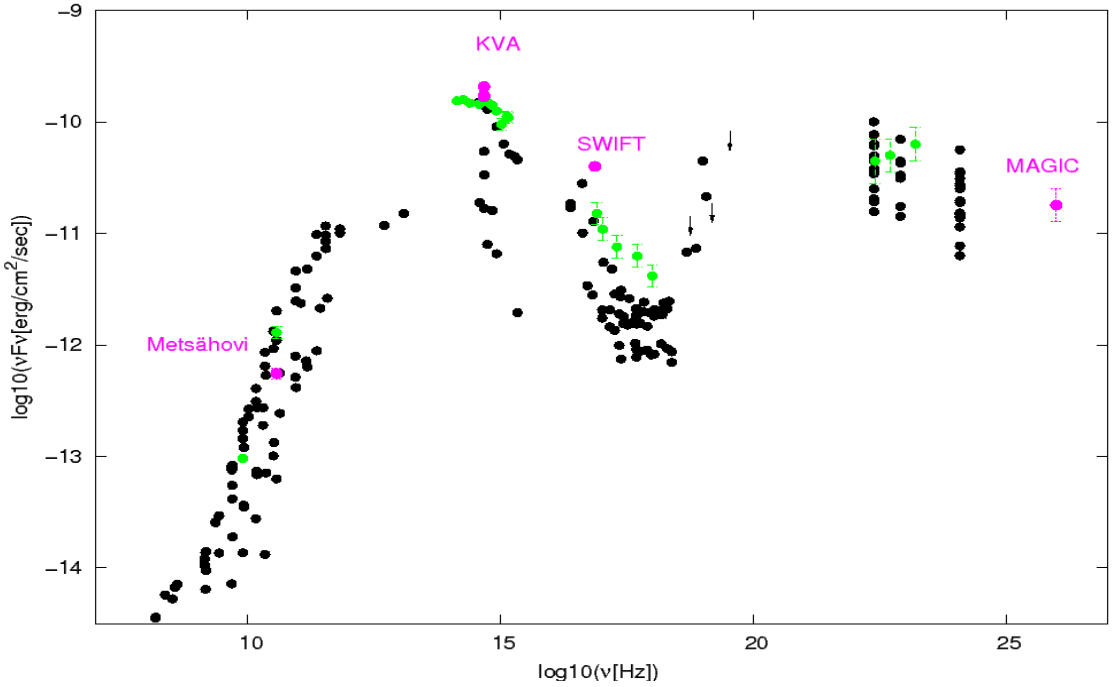
Optical outburst triggered MAGIC observations in April 2008.

A signal is clearly detected. Analysis of the data ongoing, preliminary flux estimation: $F(>400\ \mathrm{GeV})=10^{-11}$ph/cm2/s.

Also in very high state in X-rays (ATel#1495).

(Teshima et al. 2008, ATel#1500).

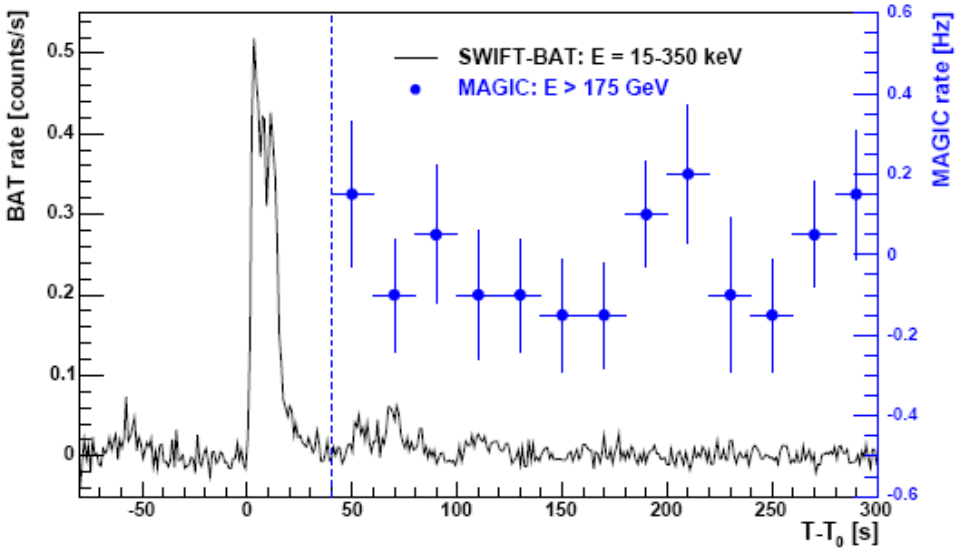




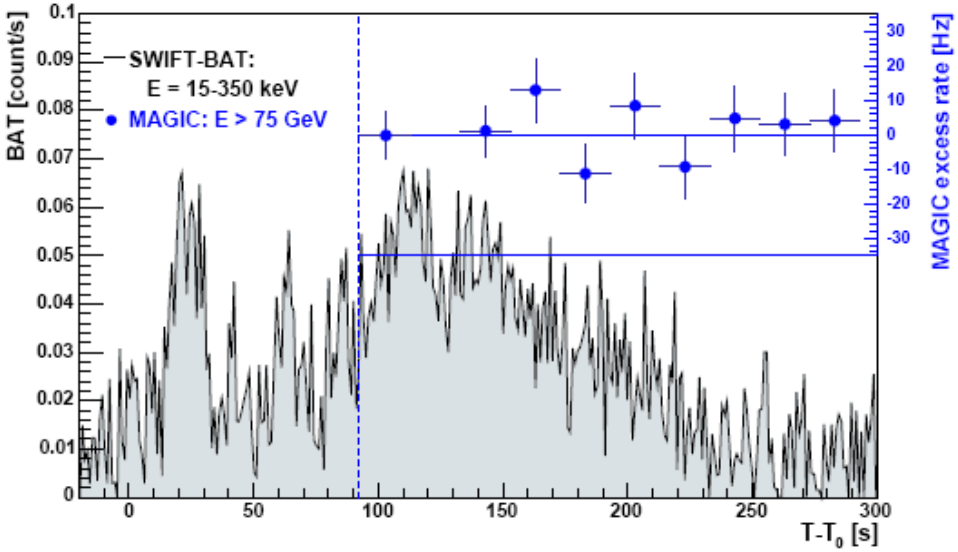
GRBs

The **MAGIC** telescope has been **specially designed to follow GRBs**: carbon fiber structure allows for a fast slewing. Typical **delay of 50 seconds** after receiving alert. **Fully automated triggering pipeline** since spring 2008.

GRB 050713a



GRB 050914



GRBs

Upper limits for 16 long duration GRBs have been obtained with MAGIC, some of them observed during the prompt emission, while others during the afterglow. **Only 1/3 of sources with $z<1$**, where the Universe is transparent to $E>50$ GeV, seen by MAGIC. For sources with known redshift, the data are **compatible with unbroken power laws from few hundred keV to TeV accounting for EBL (Albert et al. 2007, ApJ, 667, 358; Galante et al. 2008)**.

GRB name	$\Delta t_{\rm alert}$* [s]	$\Delta t_{\rm obs}$† [s]	T_{90} [s]	$\langle Z.A. \rangle$** [deg]	estimated $E_{\rm th}$‡ [GeV]	Fluence U.L. [10^{-8} erg cm^{-2}]	Fluence U.L. [C.U.]	Redshift z
GRB 050421	58	108	10	50°	290	3.8	0.2	-
GRB 050502	40	269	20	42°	190	6.2	0.3	3.8
GRB 050505	540	717	60	55°	400	14.8	0.8	4.3
GRB 050509a	16	131	12	50°	290	7.7	0.4	-
GRB 050713a	13	40	70	49°	270	16.8	0.8	-
GRB 050904	82	145	225	20°	95	10.6	0.3	6.3
GRB 060121	15	583§	2	42°	190	9.7	0.4	-
GRB 060203	171	259	60	44°	210	40.3	1.7	-
GRB 060206	16	52	7	10°	85	14.4	0.4	4.05
GRB 060825	19	57	8	28°	90	36.0	0.7	2.0
GRB 061028	140	169	106	38°	107	29.0	0.8	-
GRB 061217	13	786¶	0.4	56°	373	9.6	0.5	0.8
GRB 070412	674	701	34	35°	90	7.8	0.2	(0.034?)
GRB 070920a	539	680	56	52°	250	7.1	0.4	-
GRB 080319a	63	290	40	36°	175	10.3	0.5	-
GRB 080330	16	90	60	50°	313	6.4	0.4	1.51

MAGIC-II and LOFAR

LOFAR will monitor the sky in a relatively unexplored frequency, **opening a new observational window in the time/wavelength plane** and allowing for the discovery of new transient sources. If the accelerated particles producing non-thermal synchrotron radio emission have enough energy, **TeV emission can be expected**. There is an **ongoing program to trigger MAGIC** (and MAGIC-II) after receiving alerts from LOFAR. With this program we expect to detect:

- **Flares of X-ray binaries**
- **Flares of AGNs**
- **GRBs**

Trigger tests have already been conducted (thanks to Sera Markoff, John Swinbank, etc.). Although we are now using the protocol implemented to trigger GRB observations by MAGIC, we plan to change it into the **International Virtual Observatory Alliance (IVOA) voeventnet.org** protocol.
MAGIC can also be used to trigger LOFAR.

MAGIC-II and LOFAR

MAGIC can also be used to trigger LOFAR.

Significance levels:

3-4 sigma: marginal evidence
4-5 sigma: evidence
> 5 sigma: detection

Analysis levels:

- **Online analysis**: provides results with a limited sensitivity a few minutes after the data taking.
- **Onsite analysis**: provides results with nearly whole sensitivity the morning after the data taking.
- **Final double-check analysis: provides final double-check results with whole sensitivity a few weeks/months after the data taking**.

MAGIC-II and LOFAR

MAGIC can also be used to trigger LOFAR.

Significance levels:

3-4 sigma: marginal evidence
4-5 sigma: evidence
> 5 sigma: detection

Analysis levels:

Internal triggers on a shared risk basis

- **Online analysis**: provides results with a limited sensitivity a few minutes after the data taking.
- **Onsite analysis**: provides results with nearly whole sensitivity the morning after the data taking.
- **Final double-check analysis: provides final double-check results with whole sensitivity a few weeks/months after the data taking**.

Conclusions

- The **MAGIC** Cherenkov telescope has **discovered several variable TeV sources** after receiving alerts from other observatories.
- Among the **variable radio sources** we have **detected X-ray binaries and AGNs**. **Upper limits on GRBs** have been obtained.
- The new **MAGIC-stereo** system of telescopes will allow us to conduct **detailed follow-up studies of transient sources between 25-100 GeV**, not achievable with other Cherenkov telescopes, after receiving alerts from other facilities such as **LOFAR**.
- **We can also trigger LOFAR** using online/onsite analysis on a shared risk basis.
- TeV observations, combined with multi-wavelength data can help to **unveil the leptonic or hadronic nature of the accelerated particles**, their density and maximum energy, the magnetic fields, etc.