# Superorbital variability of the gamma-ray binary LS I +61 303 studied with MAGIC

HEPRO V

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La Plata

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes


***Josep M. Paredes,***

**A. López-Oramas, D. Hadasch, O. Blanch, D.F. Torres for the MAGIC Collaboration; J. Casares, A. Herrero**

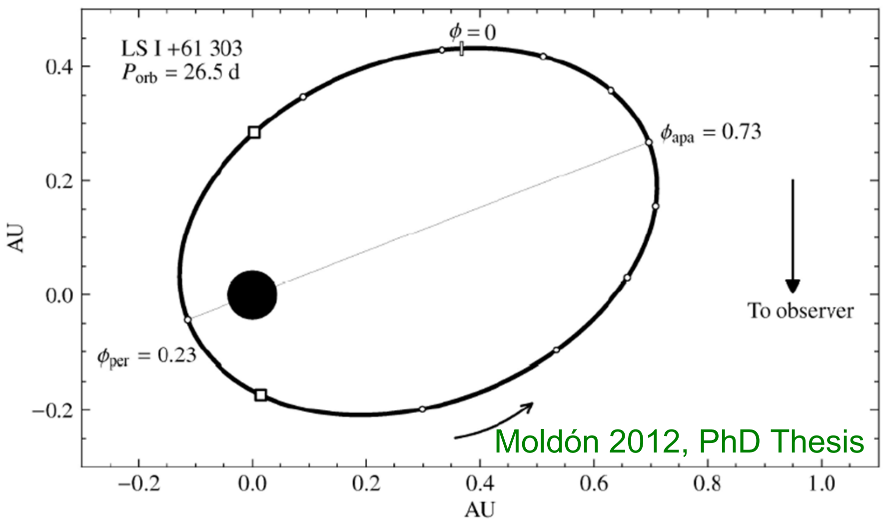

UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

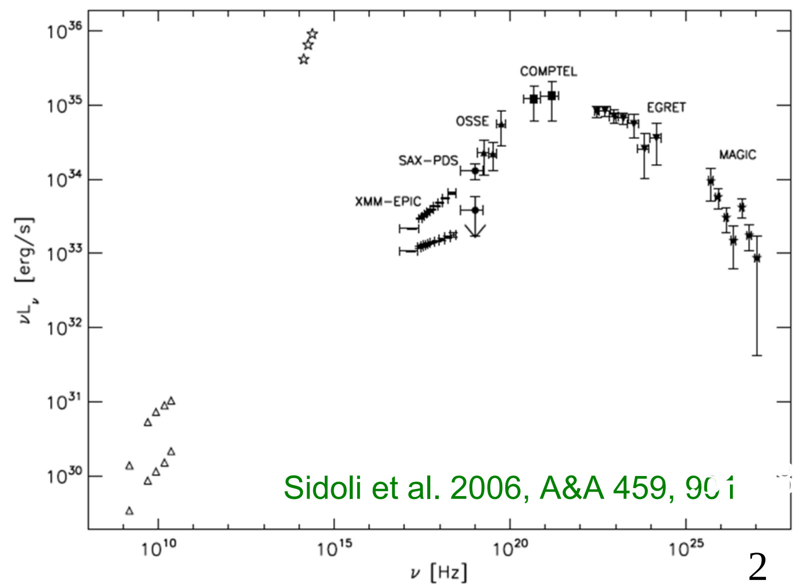
EXCELENCIA MARÍA DE MAEZTU

# LS I +61 303

- Be star (B0 Ve) with circumstellar disk+ NS or BH
- $P_{orb}$ = 26.4960 +/- 0.0028 d
- e = 0.5-0.7
- d = 2.0 +/- 0.2 kpc
- Gamma-ray binary

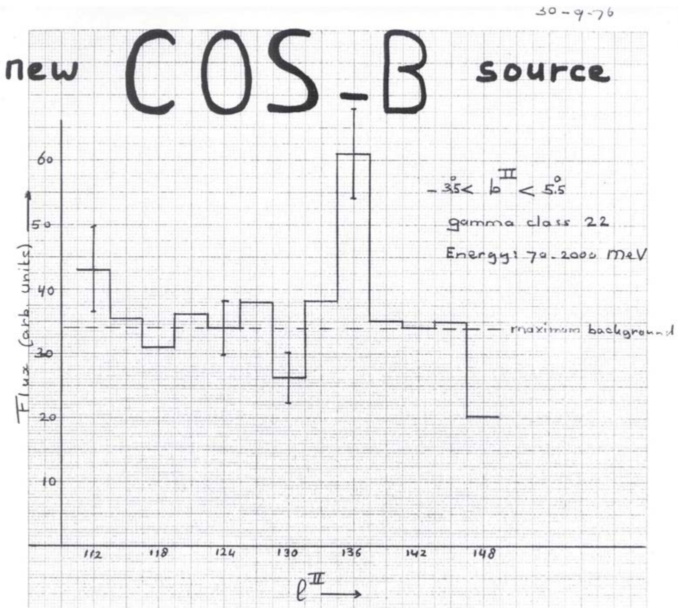



Moldón 2012, PhD Thesis



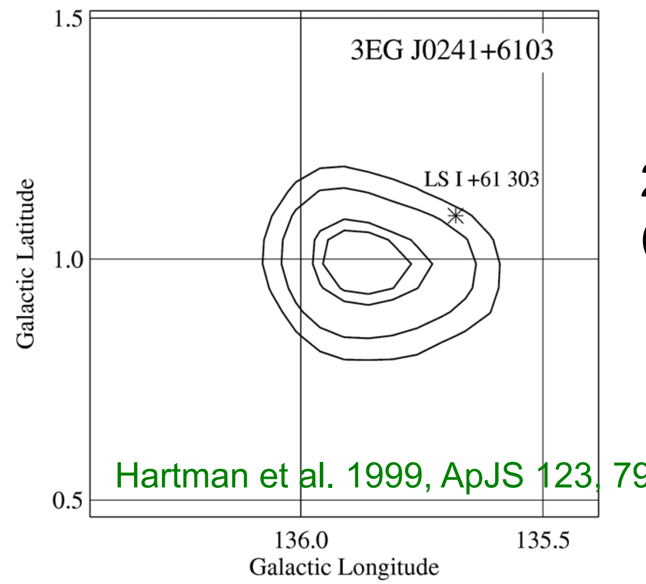

Sidoli et al. 2006, A&A 459, 901

# Historical association with a γ-ray source



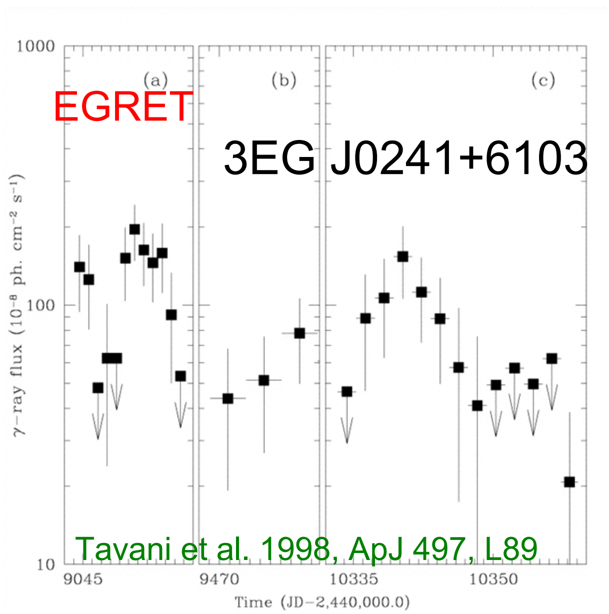

COS-B γ-ray source CG/2CG 135+01
Hermsen et al. 1977, Nature 269, 494

LS I+61 303 was proposed to be associated with the γ-ray source 2CG 135+01 Gregory&Taylor 1978, Nature 272, 704



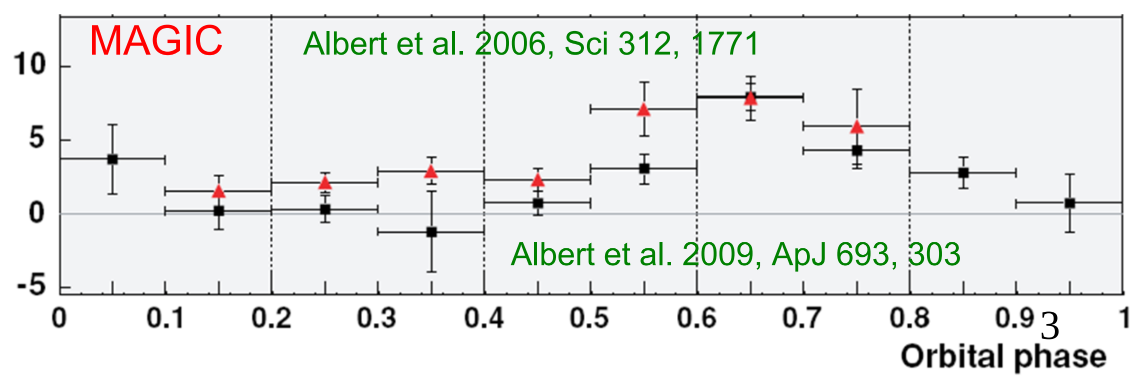

Hartman et al. 1999, ApJS 123, 79

2CG 135+01
(= 3EG J0241+6103)




Tavani et al. 1998, ApJ 497, L89

Variability on days and months timescales



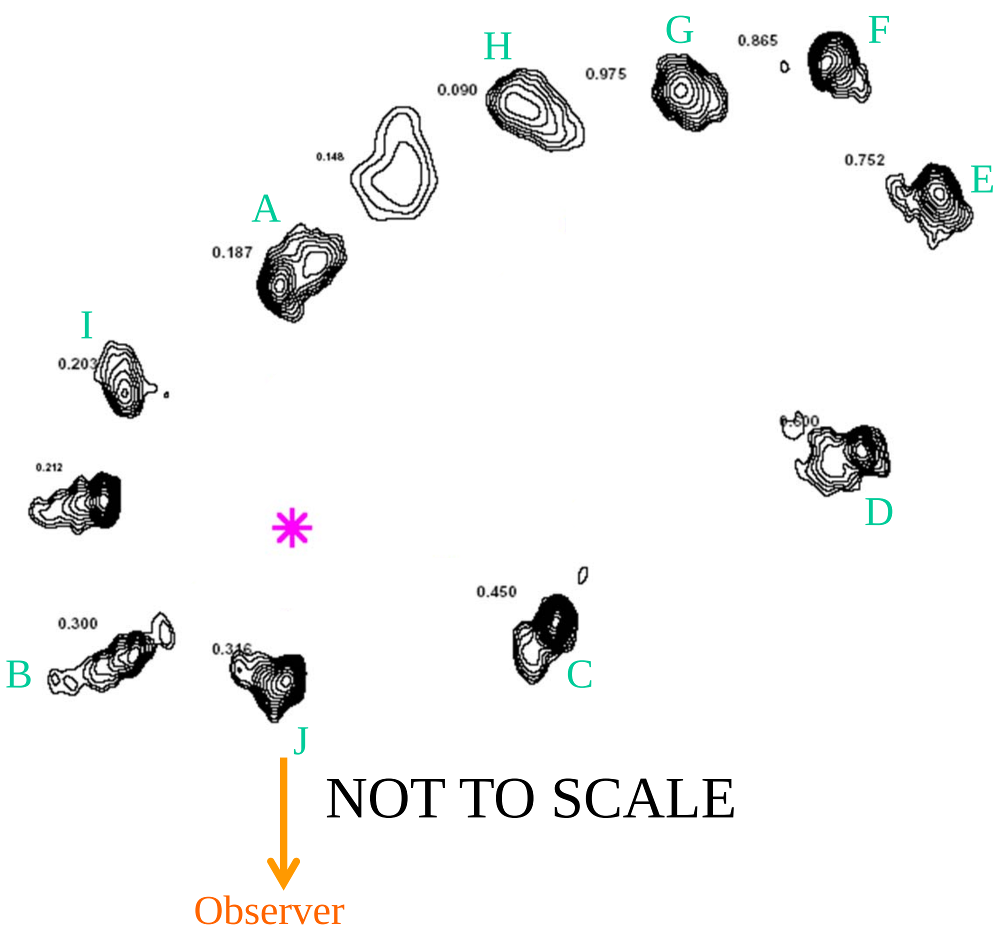

Albert et al. 2006, Sci 312, 1771

Albert et al. 2009, ApJ 693, 303

# A pulsar-wind scenario?

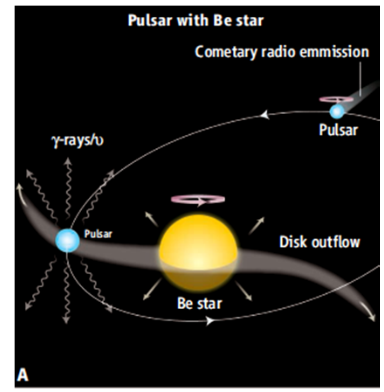
VLBA

Jet-like features have been reported several times, but show a puzzling behavior (Massi et al. 2001, 2004). VLBI observations show a rotating jet-like structure (Dhawan et al. 2006, VI Microquasars Workshop, Como, Setember 2006)




3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU.
Semi-major axis: 0.5 AU

Consistent with the pulsar wind scenario (Maraschi & Treves 1981)




Lack of pulsations. Pulsar search in
X-ray: Rea et al. 2010, MNRAS 405, 2206
radio: McSwain et al. 2011, ApJ 738, 105
Cañellas et al. 2012, A&A 534, 122

# Orbital periodicity (26.496 d)

Radio (**P=26.4960 +/- 0.0028 d)** Taylor & Gregory 1982, ApJ 255, 210

Optical and IR Mendelson & Mazeh 1989, MNRAS 239, 733;
Paredes et al. 1994 A&A 288, 519

X-rays Paredes et al. 1997 A&A 320, L25; Torres et al. 2010, ApJ 719, L104

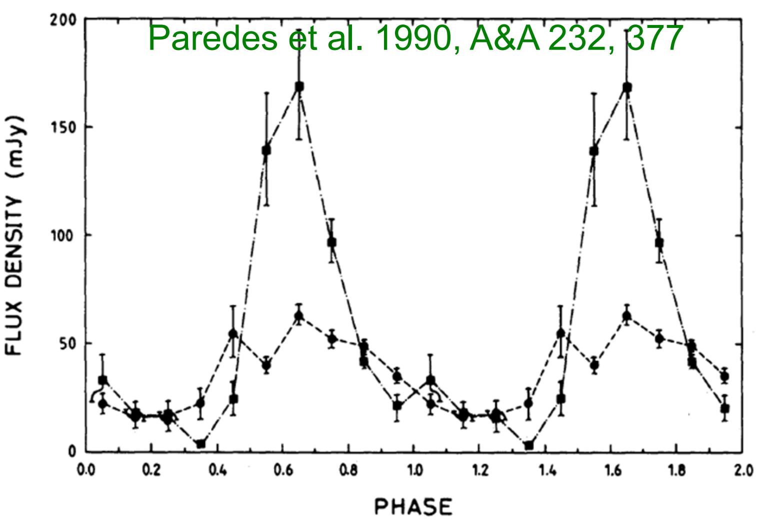
HE gamma-rays Abdo et al. 2009, ApJ 701, L123

VHE gamma-rays Albert et al. 2009, ApJ 693, 303

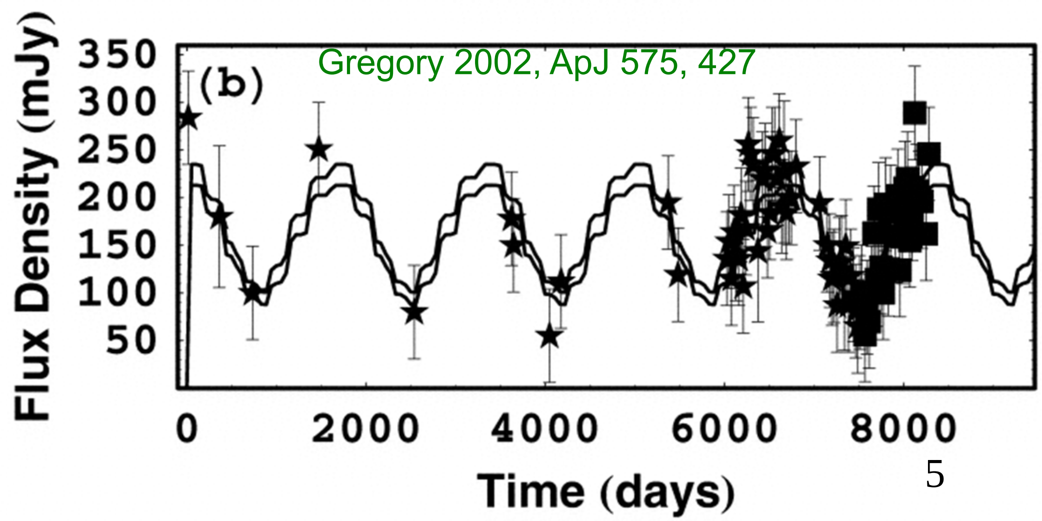
# Superorbital periodicity (1667 +/- 8 d)

**Radio**

**Radio** (~ 4.4 yr, **P=1667 d**) Paredes 1987, PhD Thesis; Gregory 2002, ApJ 575, 427

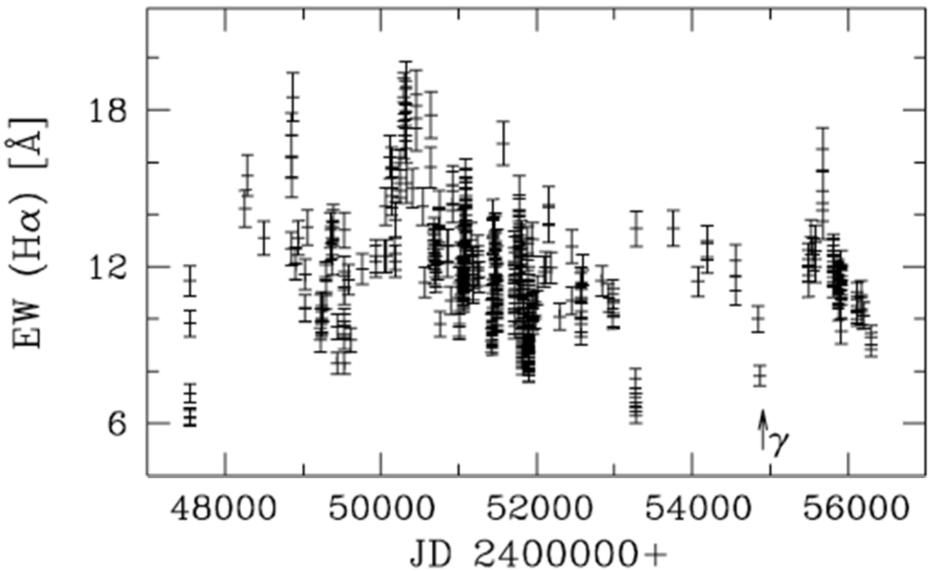



Paredes et al. 1990, A&A 232, 377




Gregory 2002, ApJ 575, 427

# Superorbital periodicity (1667 +/- 8 d)



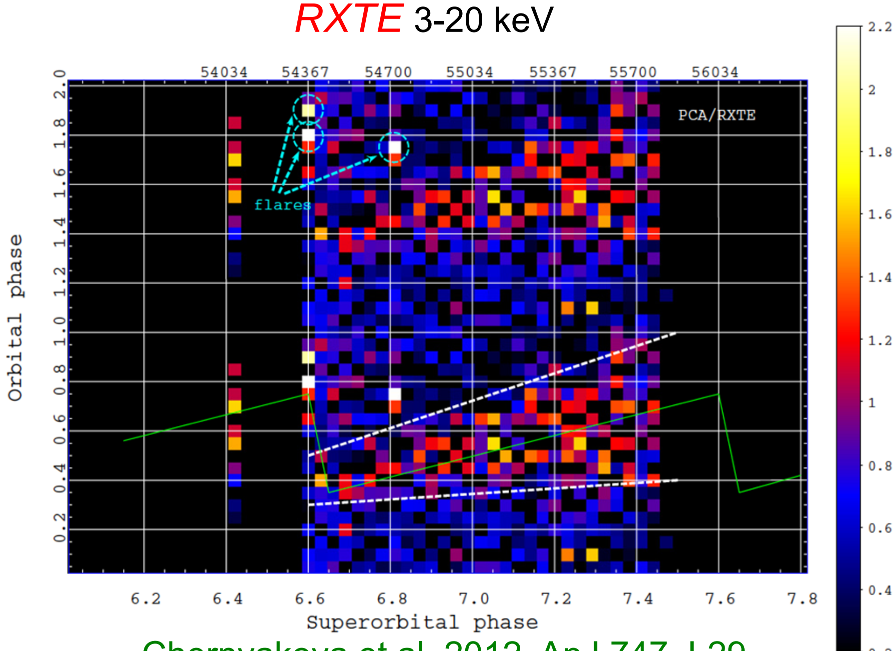

**Optical**

The Hα emission is modulated with the orbital and superorbital periods

Zamanov et al. 2013, A&A 559, 87
(Paredes-Fortuny et al. 2015, A&A 575. L6)

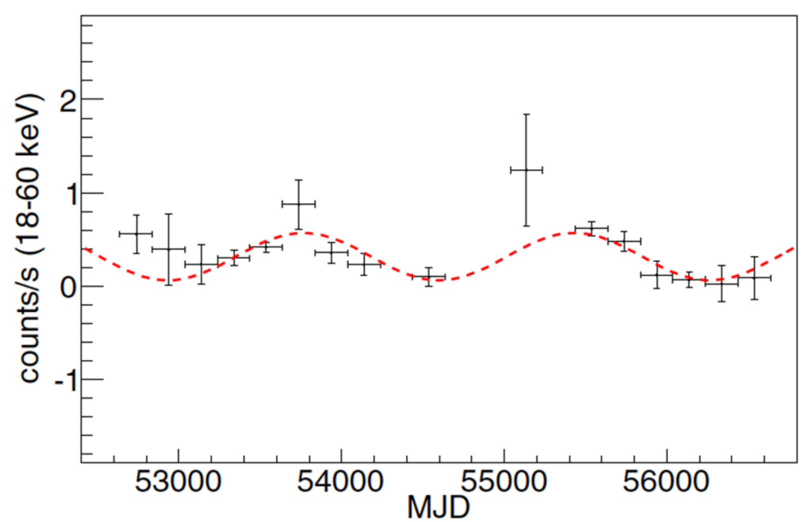
**X-ray**

*RXTE* 3-20 keV



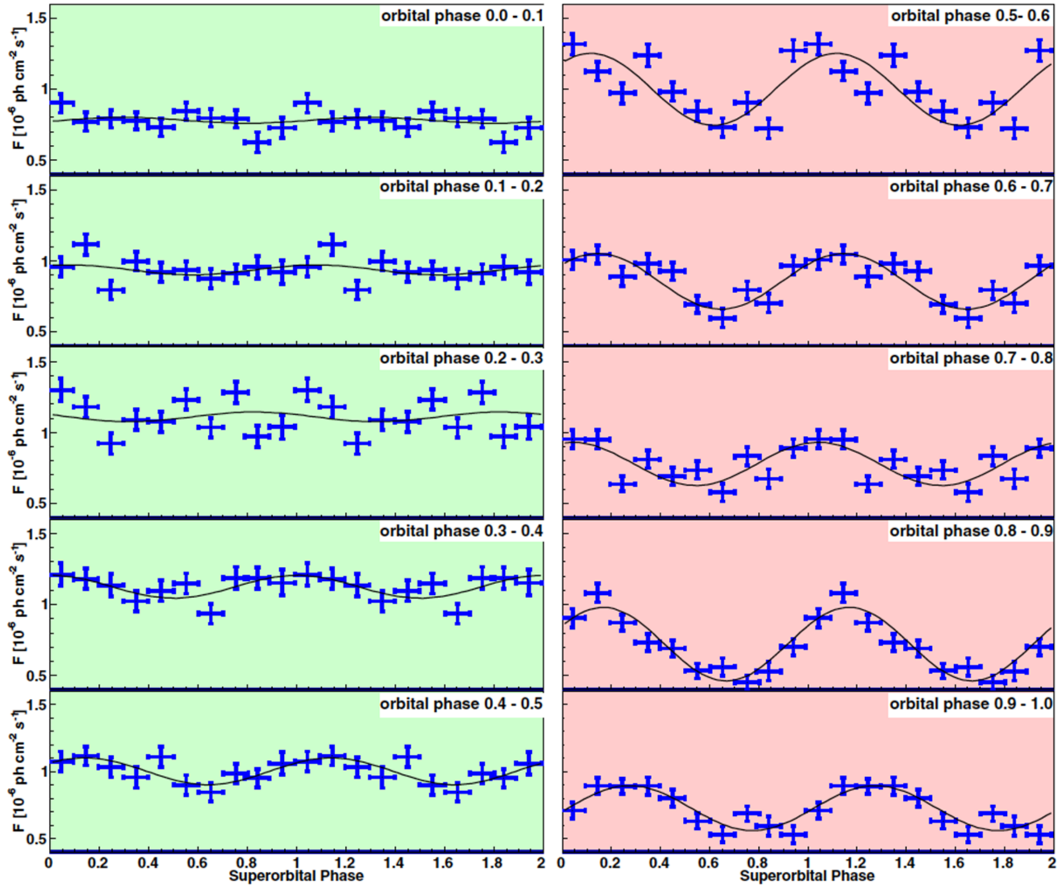

Chernyakova et al. 2012, ApJ 747, L29
(Li,J. et al. 2012, ApJ 744, L13)

*INTEGRAL* (18-60 KeV)




Li,J. et al. 2014, ApJ 785, L19

*Fermi*-LAT (>100 MeV)




**HE**

Ackermann et al. 2013, ApJ 773, L35

Superorbital modulation (radio and HE) of

1667±8 days

**Does it appear at VHE?**

# THE MAGIC TELESCOPES

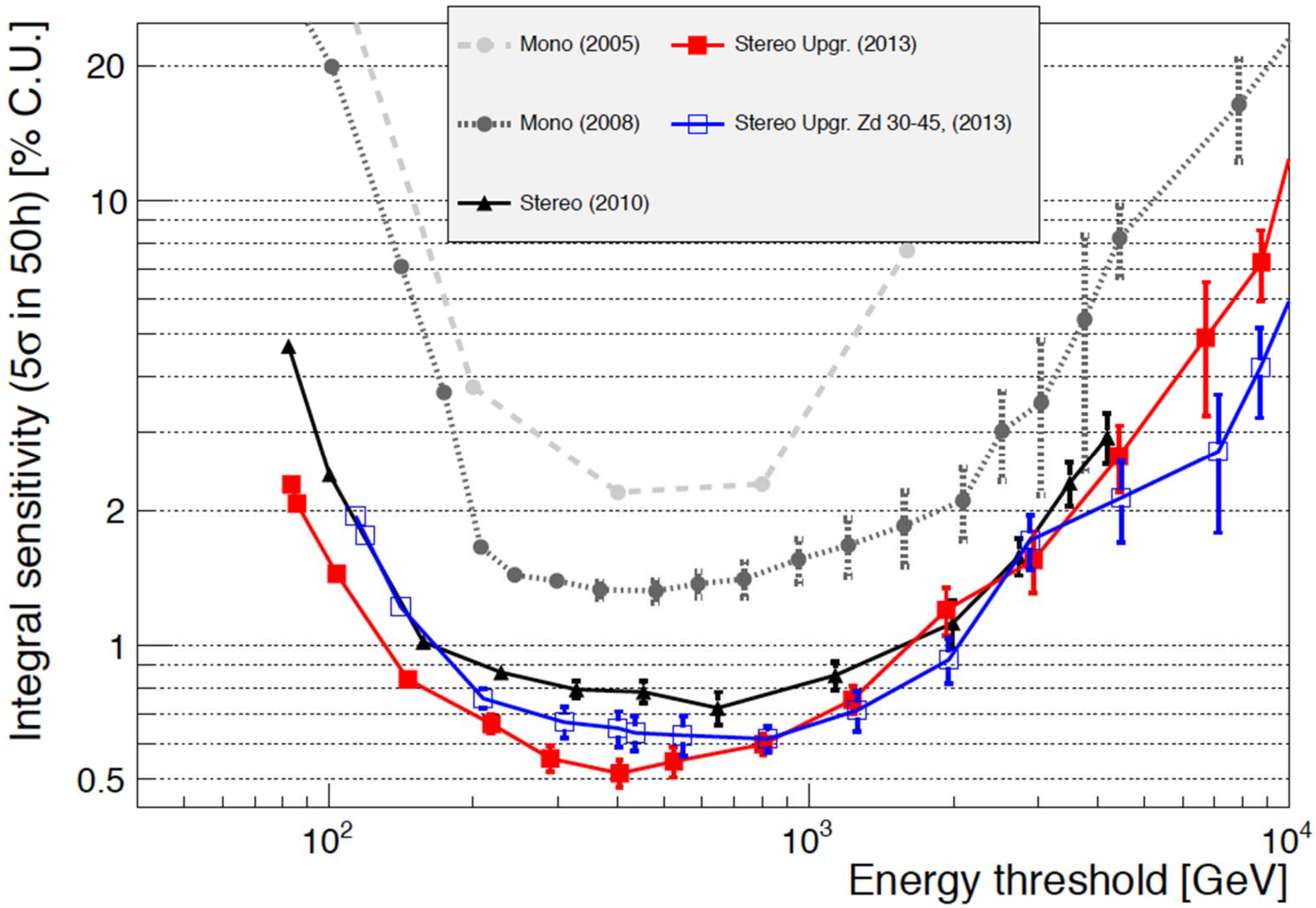
**Two Imaging Atmospheric Cherenkov Telescopes (IACTs) of 17 m diameter mirror dish**

- Operational energy range: 50 GeV → 50 TeV
- Sensitivity: 0.7% the Crab Nebula flux (above 220 GeV) after 50h observation
- Angular resolution: ~0.05-0.1 deg (energy dependent)
- Energy resolution: ~15-20% (energy dependent)
- Fast movement (points to any direction of the sky in less than 25 s)

# Overall evolution during the last decade

**4-fold improvement in sensitivity over the last decade**

**→ ~10---fold improvement at the lowest energies !!**




**Better sensitivity + Lower energy threshold = More science!!**

Aleksic et al. 2016, APh 72, 76 (arXiv:1409.5594)

# Observations

A four-year (August 2010-September 2014) campaign has been carried out with the MAGIC telescopes

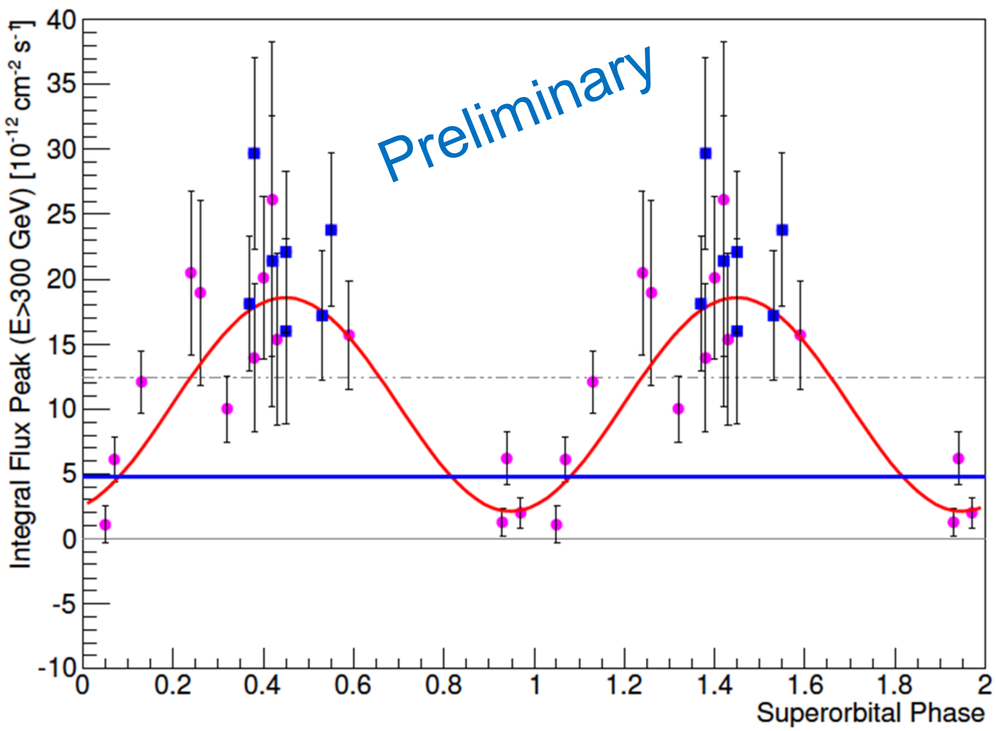
- **Study the superorbital behavior**
  Aug 2010-Sep 2014, $\phi_{\mathrm{orb}} = 0.5 – 0.75$
  + Archival MAGIC data (4-year, 2006-2010)
  + Published VERITAS data

- **Search of (anti-)correlation between TeV and H$\alpha$ emission**
  MAGIC data from $\phi_{\mathrm{orb}} = 0.8 – 1.0$
  LIVERPOOL optical data (simultaneous observations)

- **Spectral studies**
  Entire sample, data split according superorbital and orbital phase and flux level

# Results

## Superorbital modulation




- MAGIC (magenta dots) and VERITAS (blue squares)

- Each data point represents the peak flux emitted in one orbital period during orbital phases 0.5 – 0.75 and is folded into the superorbital period of 1667 days

| Function | Fit Probability |
|---|---|
| Constant | $4.5 \times 10^{-12}$ |
| Step function | $4.7 \times 10^{-3}$ |
| Sinusoidal | 0.08 |

- Fitting functions with the corresponding fit probabilities for MAGIC + VERITAS data of LS I +61303

There is a significant **superorbital signature** in the TeV emission of LS I +61303 and that it is compatible with the 4.5-year radio modulation seen in other frequencies

# Results

## Direct search for periodicity

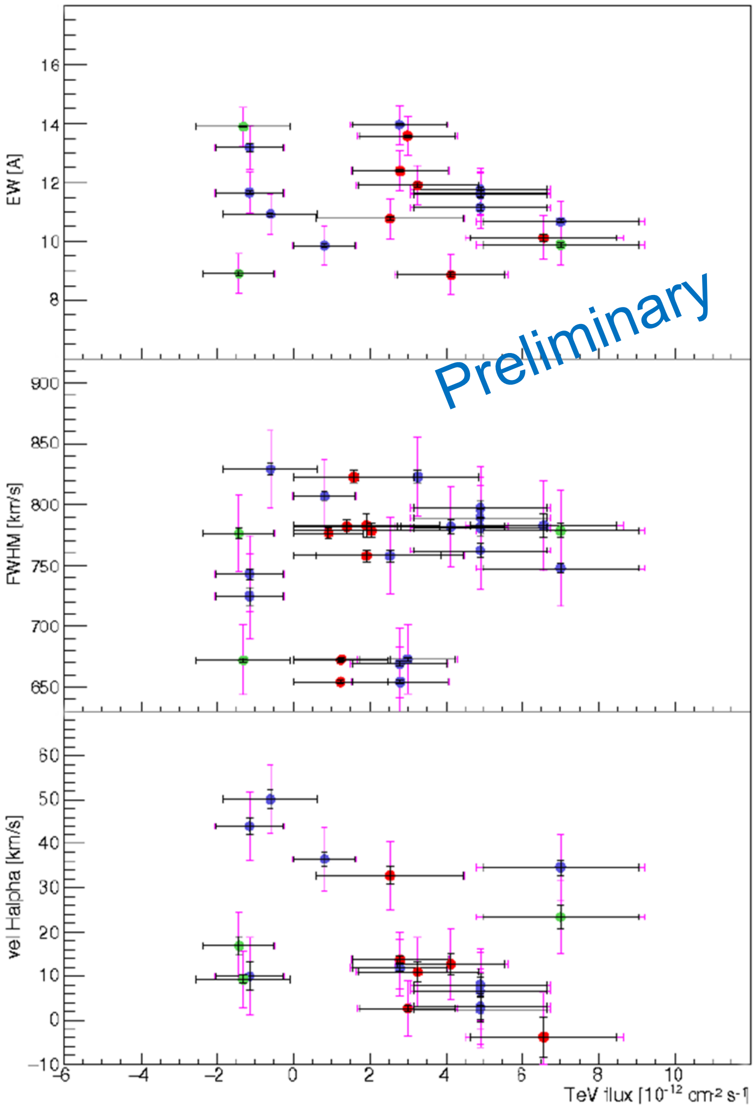
*Lomb-Scargle method*: Used over the complete set of observed peaks

A local maximum at the frequency of the superorbital period found in radio, with a probability of 10% to be produced by random fluctuations

Monte Carlo simulations show that this is the expected probability for an actual periodic signal, with the current number of measurements of the peak amplitude and their precision. To get probabilities well below 1%, about twice large data sample would be needed

# Results

## Search of (anti-)correlation between TeV and Hα emission




| Simultaneity | Parameters | $r$ | Prob |
|---|---|---|---|
| Nightly | TeV - EW | -0.23 | 0.84 |
| Nightly | TeV - FWHM | -0.14 | 0.72 |
| Nightly | TeV - vel | -0.44 | 0.97 |
| 3 hours | TeV - EW | -0.32 | 0.80 |
| 3 hours | TeV - FWHM | -0.24 | 0.74 |
| 3 hours | TeV - vel | -0.45 | 0.90 |

- Correlations between the TeV flux obtained by MAGIC and the Hα parameters (EW, FWHM and vel) measured by LIVERPOOL, for the extended orbital interval 0.75 – 1.0.
- r: Pearson correlation coefficient
- Prob: the associated probability for a non-correlation

No significant correlation is found from the statistical test performed over the sample at $\phi_{\rm orb}$ = 0.75 – 1.0

The **flip-flop model** (Zamanov et al. 2001; Torres et al. 2012; Papitto et al. 2012): Pulsar-composed binary that changes (driven by the influence of matter ) from a *propeller* regime in periastron to an *ejector* regime in apastron

Larger rate of matter {

- Larger pressure on NS magnetosphere → Disruption
  - Pulsar wind affected/disappears
  - Inter-wind shock that generates the **non-thermal emission goes off**
- Larger mass accumulation
  - A **larger EW** of Hα

**The optical emission shall be anti-correlated with the TeV flux**

*Viability of the **flip-flop scenario**:*

- The detection of **superorbital variability** inTeV confirms the predicted long-term behavior of the flip-flop model (Torres et al. 2012). The source was found in high and low states as expected. This result also confirms the earlier observational hints for this phenomenology discovered using smaller samples of TeV data (Li et al. 2012)

- **No (anti-)correlation found**. The relation can not be confirmed or denied due to different timescales between optical and TeV bands. The fast and extreme changes in the Hα data of the source (Zamanov et al. 2013), and the vastly different integration times (minutes vs several hours) in both frequencies, may blur finding any possible trend.

# Results

## Spectral stability

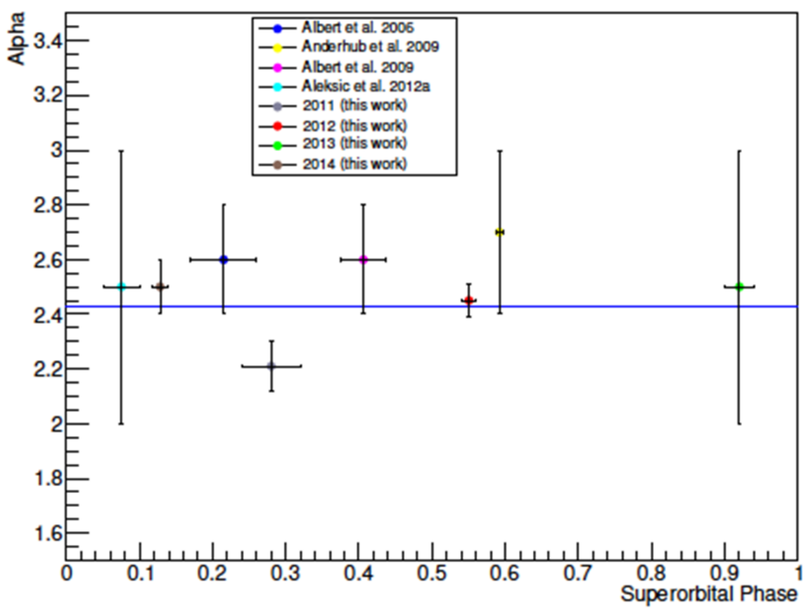
The VHE spectrum derived for the complete observed data set is:

$$\frac{dN}{dAdtdE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha}$$

$N_0 = (4.4 \pm 0.1_{stat} \pm 0.2_{sys}) \times 10^{-13}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$

$\alpha = 2.4 \pm 0.2_{stat} \pm 0.2_{sys}$

$E_0 = 1$ TeV




Blue line: average value

Is the mechanism of production of gamma rays the same, independently of the overall flux of the source and superorbital state ?

**Spectral index does not show variability** for :

- Each of the different observational campaigns
- Epochs when the source was in high (flux being at 5 – 10% of the Crab Nebula flux) or low (flux at 2 – 5%) state
- Orbital interval $\phi_{orb} = 0.5 - 0.75$ and $\phi_{orb} = 0.75 - 1.0$

# Conclusion

1. We achieved a first detection of superorbital variability inTeV.
   The superorbital signature is compatible with the 1667-day radio period with a chance probability of a 8%.

2. No intra-day correlation between $H_\alpha$ and TeV emission is visible, nor an obvious trend connecting the two frequencies.