# TeV gamma-ray variability and duty cycle of Mrk 421 as determined by 3 Years of Milagro monitoring

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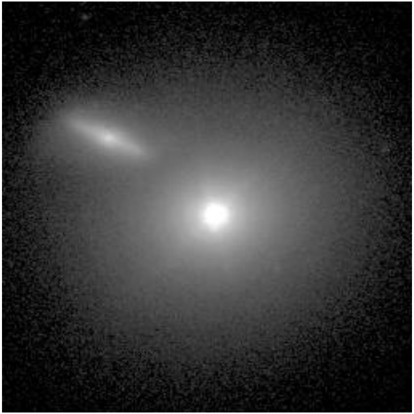
# Summary

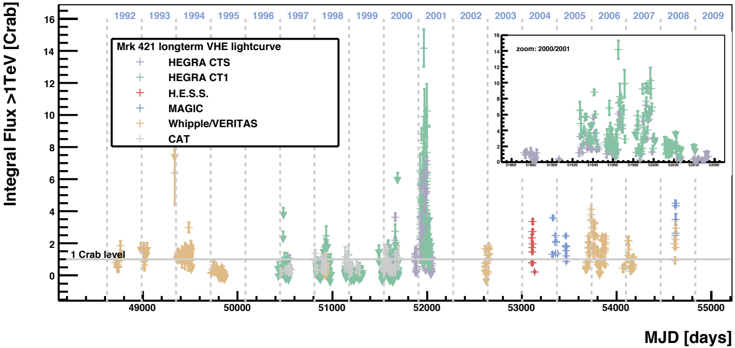
# Markarian 421 (Mrk 421): generalities

- R.A=166.11 deg, Dec=38.21 deg
- It is the closest blazar known, with z=0.03 (de Vaucouleurs et al. 1991)
- It was the first extragalactic object detected at VHE (Punch et al. 1992)

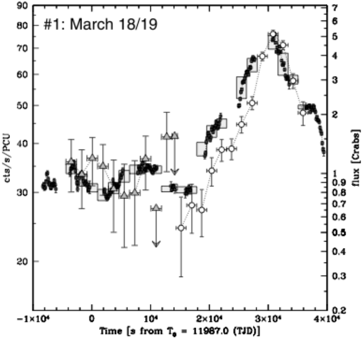


# Mrk 421: the light curve

It presents major outbursts accompanied by rapid flares with timescales from tens of minutes to several days (see e.g. Tluczykont et al. 2010)

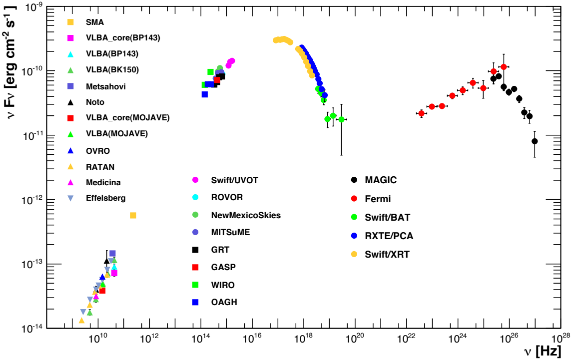


A correlation has been observed between the X-ray and the TeV emissions (Fossati et al. 2008)...




...although not all X-ray flares have been associated with a simultaneous increase in the TeV flux (Rebillot et al. 2006), and **a possible orphan TeV flare has been detected on 2004 (Blazejowski et al. 2005)**

# Mrk 421: the spectrum



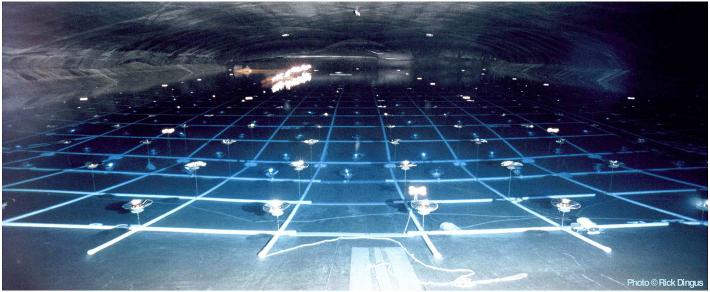

Multiwavelength campain from January to June 2009: **both leptonic and hadronic models describe well the spectrum (Abdo et al. 2011)**

# The Milagro detector - I

- Milagro was a water Cherenkov detector designed for VHE gamma-ray astronomy
- It was located near Los Alamos, New Mexico, USA, at an elevation of 2630 meters a.s.l.
- It operated from 2000 to 2008

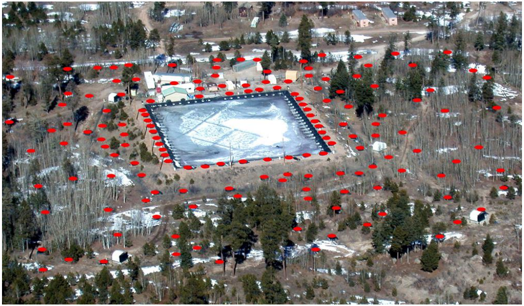
# The Milagro detector - II

- Central 80 m x 60 m x 8 m water reservoir, containing two layers of PMTs:
  450 PMTs at 1.4 m below the surface (top layer)
  273 PMTs at 6 m below the surface (bottom layer)



# The Milagro detector - III

- From 2004: Outrigger Array, consisting of 175 tanks filled with water and containing one PMT, distributed on an area of 200 m x 200 m around the central water reservoir.



Milagro reached its final configuration in September 2005

# The Milagro detector - V

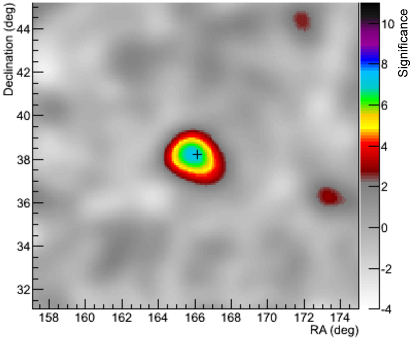
- Detector Performances:
  - It operated with a duty cycle $\geq$ 90 %
  - Its field of view was of $\sim$ 2 sr
  - It was sensitive between 100 GeV to 100 TeV
- These characteristics made Milagro well suited to study the VHE emission from
  - Extended sources
  - Transient sources (GRBs, **AGN** flares)
  - Sun

# Mrk 421 observation by Milagro

- Observation period:

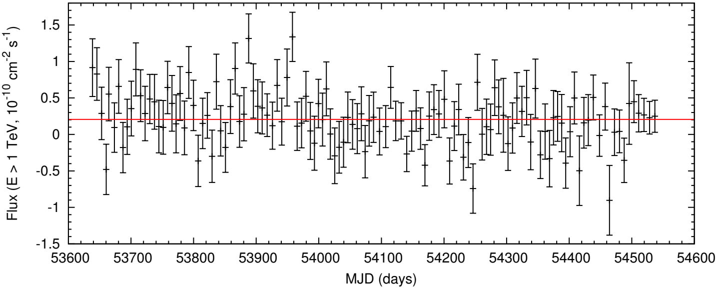
  From September 21, 2005 to March 15, 2008

- Significance: $\sim 7.1\ \sigma$




Abdo et al., submitted to ApJ

## Light curve above 1 TeV




Abdo et al., submitted to ApJ

Milagro flux consistent with being constant along the 3-year monitoring period:

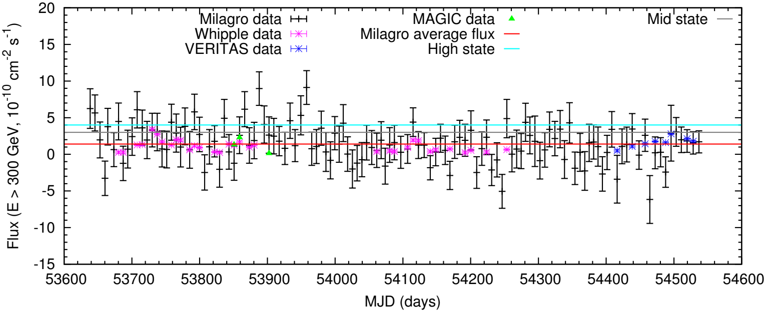
$$\bar{f}(\mathrm{E} > 1\ \mathrm{TeV}) = (2.052 \pm 0.304) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} = \mathbf{0.85 \pm 0.13\ Crab}^{*}$$

$$\chi^2 = 134 \text{ for 122 degrees of freedom}$$

* Crab flux measured by Milagro, Abdo et al. 2012

# Light curve above 300 GeV

Comparison with Whipple, VERITAS and MAGIC
(Acciari et al. 2011, Aleksíc et al. 2010)




Abdo et al., submitted to ApJ

All the data have a significance above $\bar{f}$ less then 3 $\sigma$

# The $\gamma$-ray Duty Cycle

- The duty cycle $DC$ gives an estimate of the level of activity of the source:

$$DC = \frac{\sum_i t_i}{\sum_i t_i + T_{\text{baseline}}} = \frac{T_{\text{flare}}}{T_{\text{flare}} + T_{\text{baseline}}}$$

- For Mrk 421 the X-ray duty cycle has been estimated to be in the range between 22 % (Krawczynski et al. 2004) and 27.3 % (Wagner 2008)
- ...a comparison with the TeV duty cycle is useful to test the correlation of the TeV emission with the X-ray emission ⇒ **constraints about the emission mechanisms**

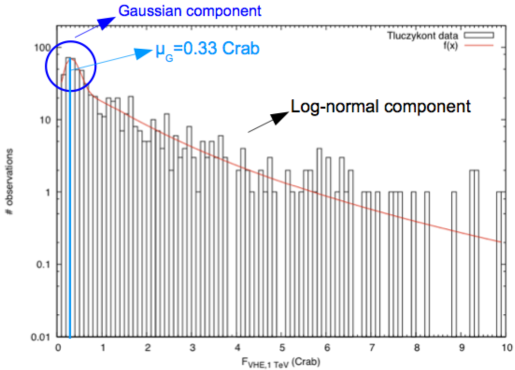
- Milagro average flux $\bar{f}$ results from the composition of the flux of Mrk 421 in the low baseline state and the flux in any other higher state $i$:

$$\bar{f} \times T_{\mathrm{Milagro}} = F_{\mathrm{baseline}} \times T_{\mathrm{baseline}} + \sum_i f_{\mathrm{flare},i}\, t_i$$

- the same high state fluence could be obtained by considering many long-duration low-flux flares or a few short-duration high-flux flares
- $\Rightarrow$ To estimate $T_{\mathrm{flare}} = \sum_i t_i$ and then the duty cycle $DC = \frac{T_{\mathrm{flare}}}{T_{\mathrm{Milagro}}}$ also the distribution of flux states of Mrk 421 is needed

## Distribution of VHE flux states

Tluczykont et al. 2010 collected data taken by different VHE experiments (IACT: Whipple, VERITAS, MAGIC, HESS, HEGRA, CAT) from 1992 to 2009




Best fit: f(x) = Gaussian + log-normal function

# The $\gamma$-ray Duty Cycle

With $f(x)$ we can calculate the average flare flux as:

$$< f_{\text{flare}} >= \frac{\int_{F_{\text{min}}}^{F_{\text{lim}}} x\, f(x)\, dx}{\int_{F_{\text{min}}}^{F_{\text{lim}}} f(x)\, dx}$$

$$\Rightarrow DC = \frac{(\bar{f} - F_{\text{baseline}})}{< f_{\text{flare}} > - F_{\text{baseline}}}$$

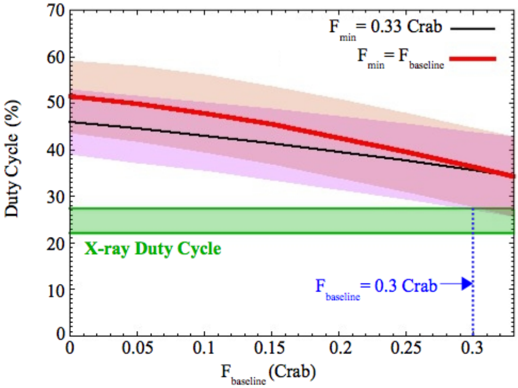
I calculated $DC$ for:

a) different values of $F_{\text{baseline}}$

b) different values of $F_{\text{min}}$ ( $< f_{\text{flare}} >$)

- i $F_{\text{min}} = F_{\text{baseline}}$
- ii $F_{\text{min}} = 0.33$ Crab ($< f_{\text{flare}} >=$1.84 Crab)

# The $\gamma$-ray Duty Cycle




- TeV $DC$ between $34^{+9}_{-8}\%$ and $51^{+8}_{-7}\%$
- X-ray $DC$ between $22\%$ and $27.3\%$
- $F_{\text{baseline}} <$ 0.3 Crab:

  TeV $DC >$ X-ray $DC$

Abdo et al., submitted to ApJ

# Conclusions

- For almost all value of $F_{\mathrm{baseline}}$ the TeV $\gamma$-ray $DC$ is higher than the X-ray $DC$
- $\Longrightarrow$ not all TeV $\gamma$-ray flares are associated with a corresponding X-ray flare (orphan TeV flares)
- $\Longrightarrow$ There should be a mechanism, additional to SSC, responsible for the extra VHE emission, likely to be hadronic

# Future: from Milagro to HAWC

## HAWC (High Altitude Water Cherenkov Observatory)

- Higher altitude: from 2630 to 4100 mt a.s.l.
- Larger area: from 4000 to 20000 $m^2$
- 300 individual tanks instead of a big water reservoir

with its higher sensitivity (10-15 times the sensitivity of Milagro) HAWC will be able to better measure the fluxes of AGN flares

See talks by A. Marinelli (Parallel Session E, today, h:15:05) and G. Sinnis (Plenary Session, Friday, h:9:40)

# Backup slides

# The distribution of flux states of Mrk 421

$$f(x) = f_{\mathrm{G}}(x) + f_{\mathrm{ln}}(x)$$

with

$$f_{\mathrm{G}}(x) = \frac{N_{\mathrm{G}}}{\sigma_{\mathrm{G}}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu_{\mathrm{G}}}{\sigma_{\mathrm{G}}}\right)^2\right]$$

and

$$f_{\mathrm{ln}}(x) = \frac{N_{\mathrm{ln}}}{x\,\sigma_{\mathrm{ln}}\sqrt{2\pi}} \exp\left[-\frac{(\log(x)-\mu_{\mathrm{ln}})^2}{2\sigma_{\mathrm{ln}}^2}\right]$$

## The duty cycle calculation

$$\bar{f} \times T_{\rm Milagro} = F_{\rm baseline} \times T_{\rm baseline} + \sum_i f_{{\rm flare},i}\, t_i$$

We can rewrite this equation as:

$$\bar{f} \times T_{\rm Milagro} = F_{\rm baseline} \times (T_{\rm Milagro} - T_{\rm flare}) + T_{\rm flare} \times < f_{\rm flare} >,$$

with $T_{\rm Milagro} = T_{\rm baseline} + T_{\rm flare}$

$$\Rightarrow T_{\rm flare} = \frac{\left(\bar{f} - F_{\rm baseline}\right) T_{\rm Milagro}}{< f_{\rm flare} > - F_{\rm baseline}}$$

$$DC = \frac{T_{\rm flare}}{T_{\rm Milagro}} = \frac{\left(\bar{f} - F_{\rm baseline}\right)}{< f_{\rm flare} > - F_{\rm baseline}}$$