The MAGIC of FSRQs

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(and many MWL collaborators)

2018-06-28, 15y MAGIC anniversary meeting, La Palma

Photo credits:
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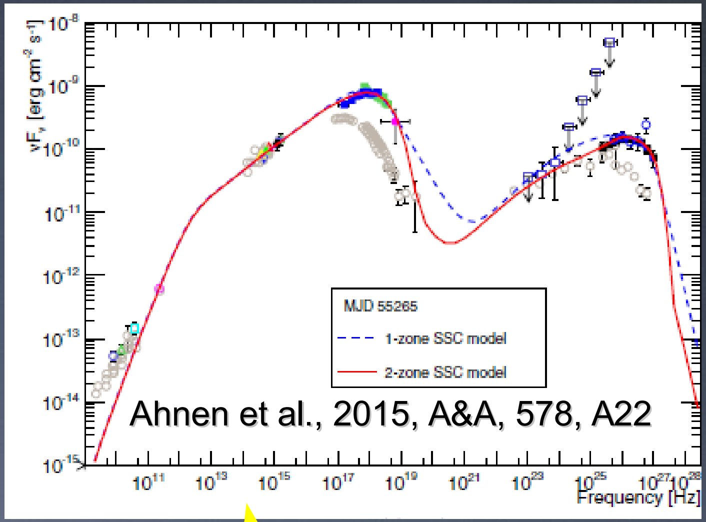
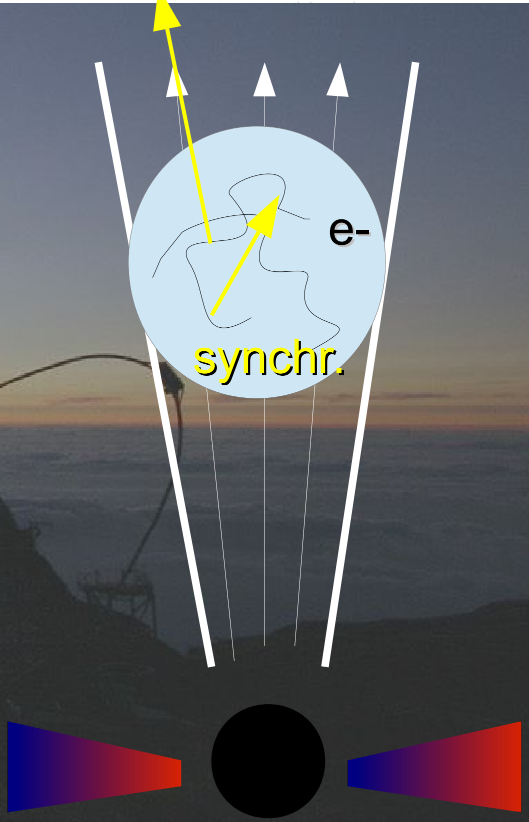
BL Lac objects

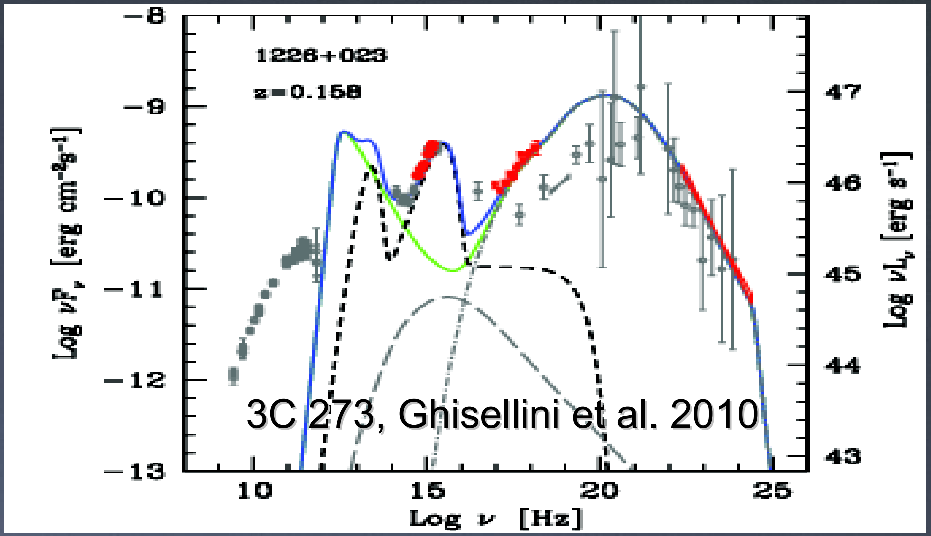
- BL Lac is a blazar, where no (or weak) optical emission lines are seen
- Modelling of BL Lacs is relatively simple, often the emission can be explained with a single blob moving along the jet filled with electrons and magnetic field

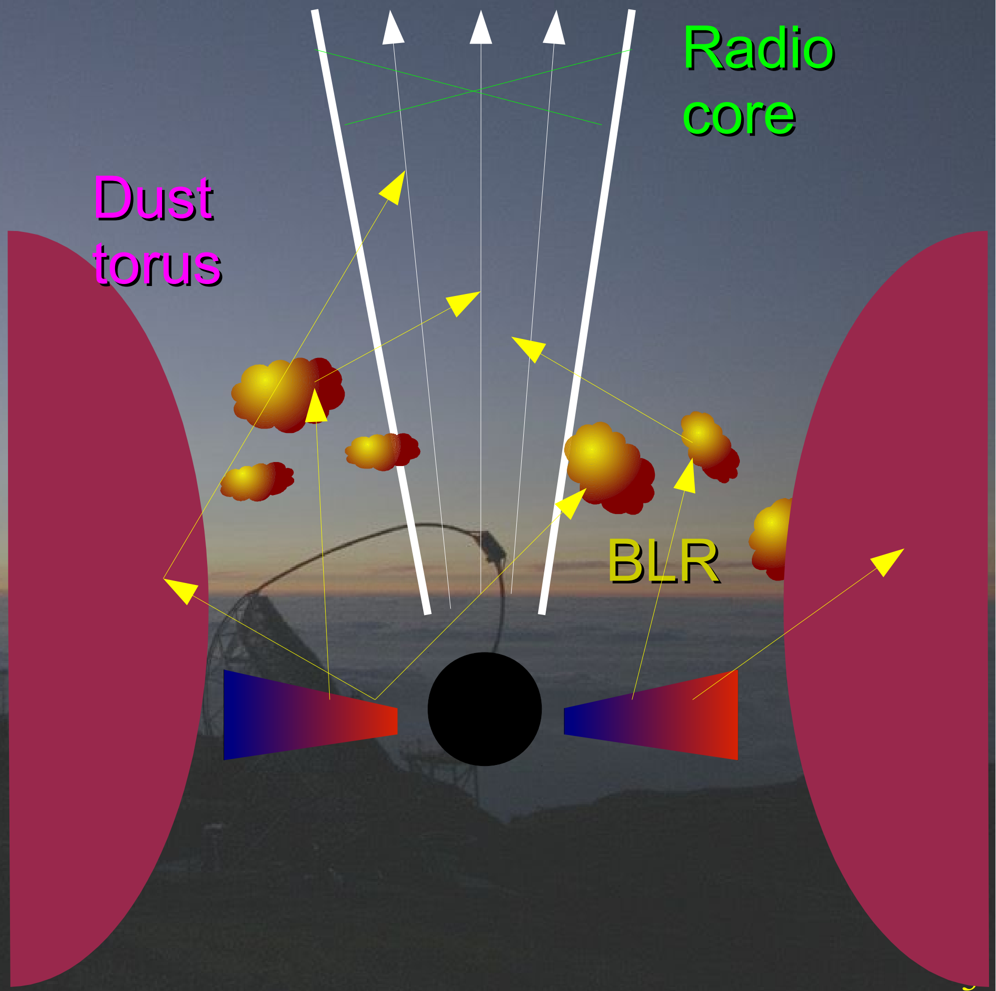




FSRQ objects

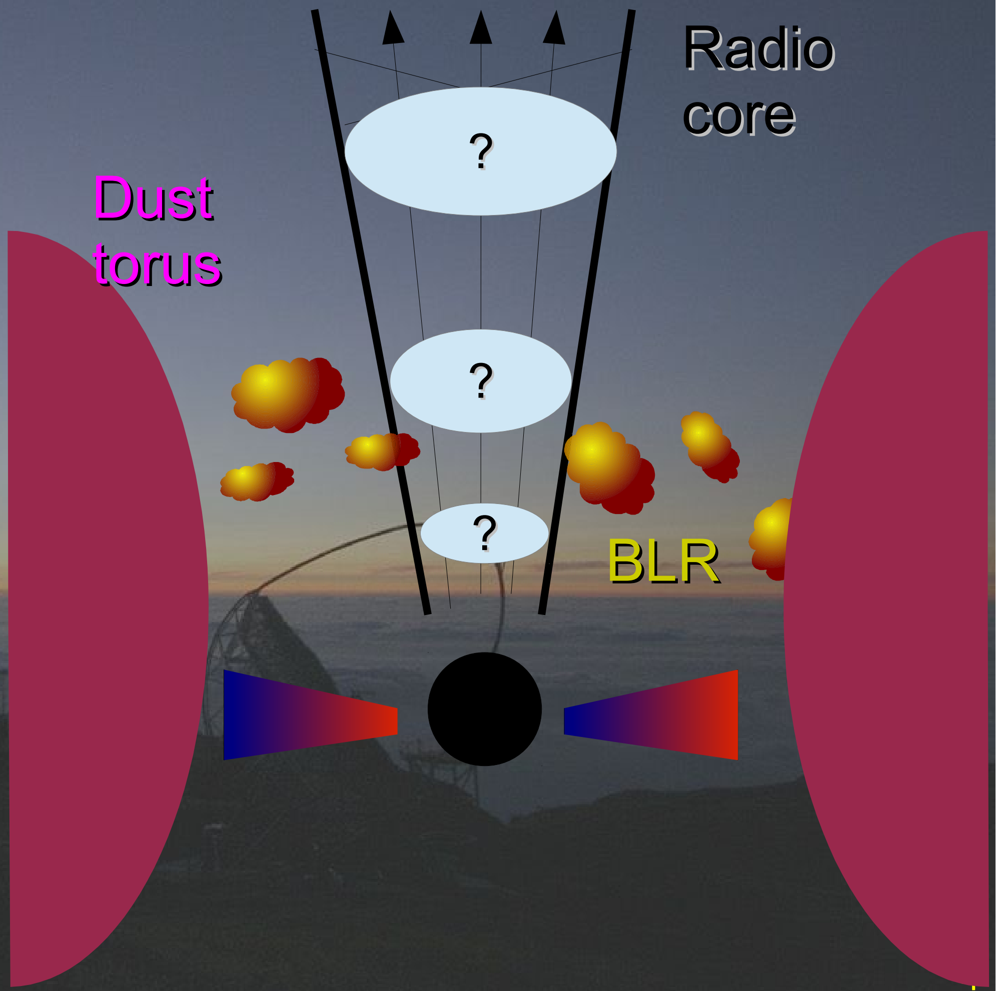
- FSRQ is a blazar with pronounced emission lines
- Very luminous (can be observed at high redshift)
- Direct evidences of accretion disk and broad line region
- Complicated sources: need a rich MWL coverage to understand them





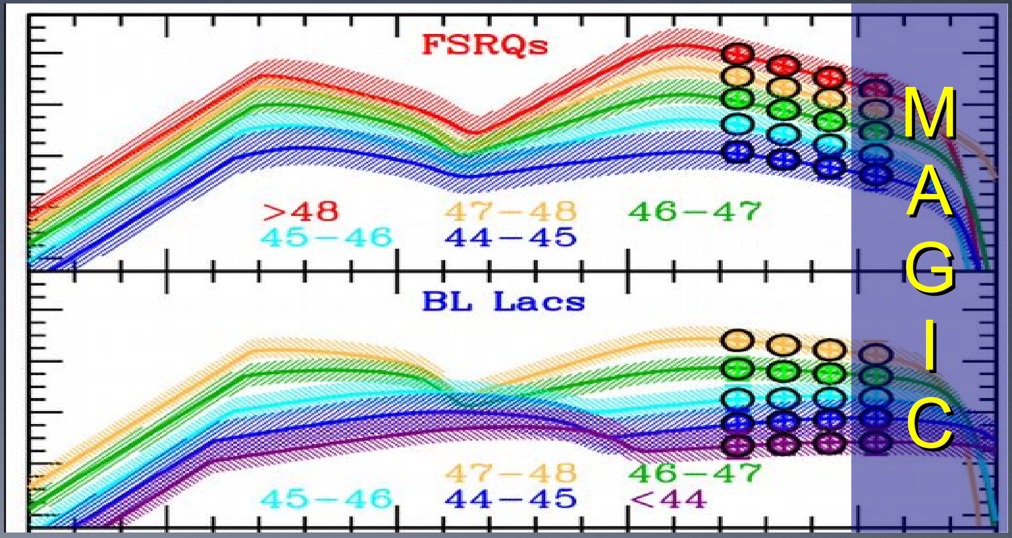
VHE gamma-ray emission region in FSRQ

- Gamma-ray emission region in FSRQ:
  - Within the BLR
  - In the radiation field of the dust torus
  - Near the radio core
- The closer to BH the easier to explain variability and luminosity, but the more problematic the absorption of sub-TeV gamma rays

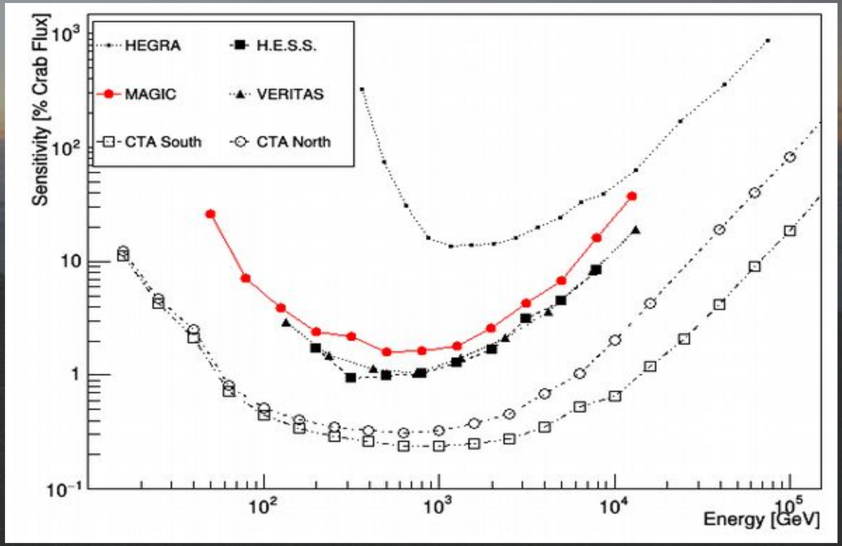


MAGIC: an instrument for VHE gamma ray studies of FSRQs

- FSRQs are intrisingly more powerful than BL Lacs and have higher Compton dominance, but the IC peak is shifted to lower energies
- FSRQ are a perfect target for *Fermi*-LAT, but difficult for IACTs
- Need an instrument with excellent low energy performance – MAGIC !

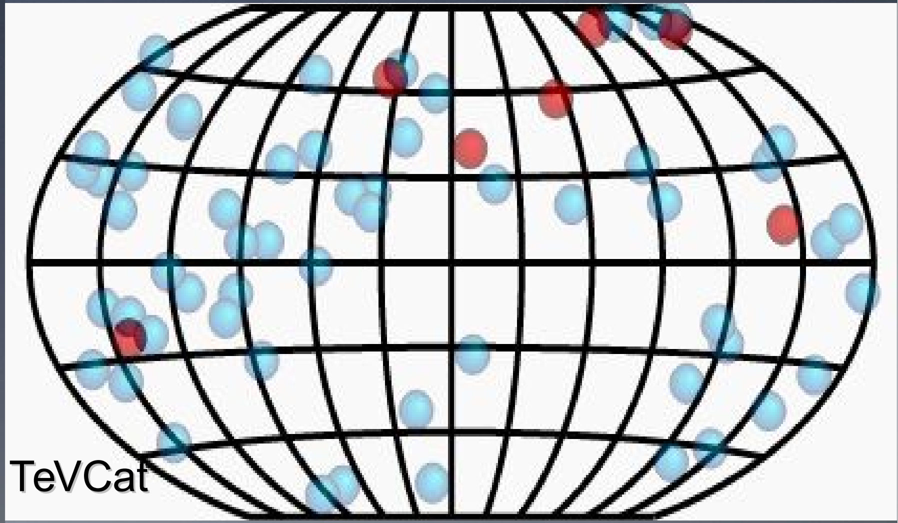


Ghisellini et al. 2017



Short history of VHE detections of FSRQs

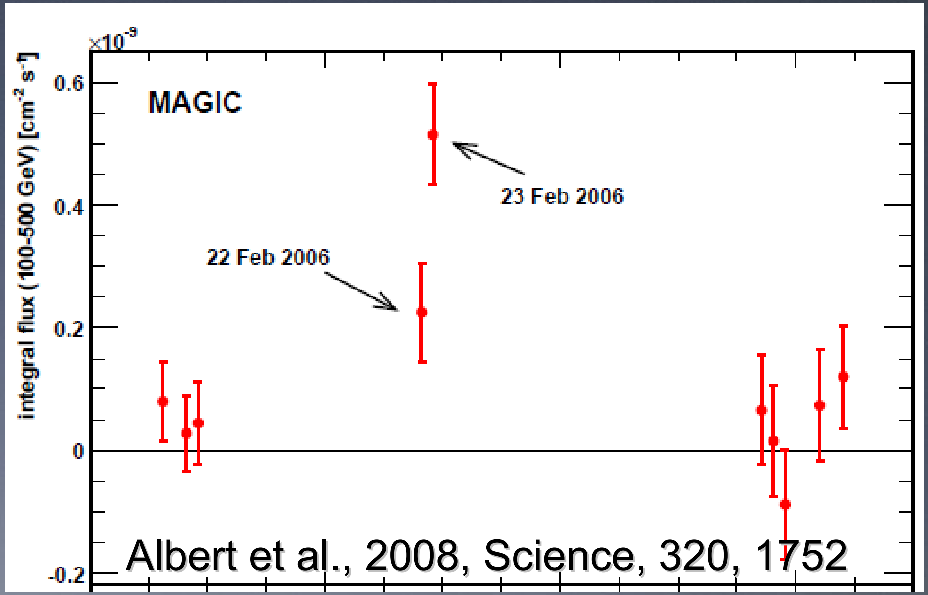
- 3C 279 (z=0.536): 2006 (by MAGIC)
- PKS1510 (z=0.361): 2009 (by H.E.S.S), 2012 (by MAGIC)
- PKS1222+216 (z=0.432): 2010 (by MAGIC)
- B0218+357 (z=0.954): 2014 (by MAGIC)
- PKS1441+25 (z=0.939): 2015 (by MAGIC), 2015 (by VERITAS)
- S4 0954+65 (disputed classification, unknown redshift): 2015 (by MAGIC)
- PKS0736+017 (z=0.189): 2016 (by H.E.S.S.)
- TON 0599 (z=0.725): 2017 (by MAGIC), 2017 (by VERITAS)



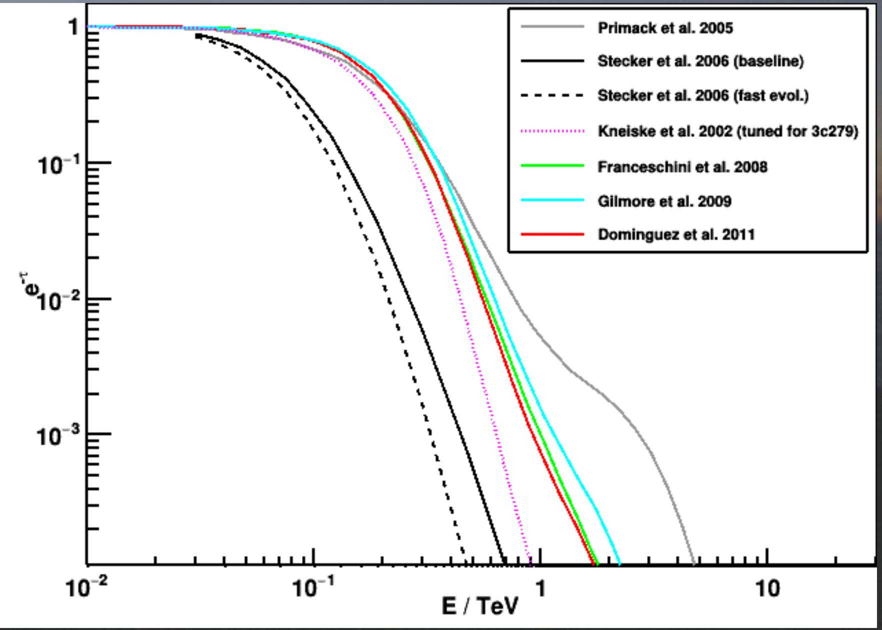
FSRQ, other AGNs

3C 279 detection revising EBL models

- First FSRQ seen at VHE gamma-ray energies
- It was surprising to detect the spectrum up to 500 GeV despite EBL absorption
- Detection of VHE gamma-ray emission triggered revision of EBL models

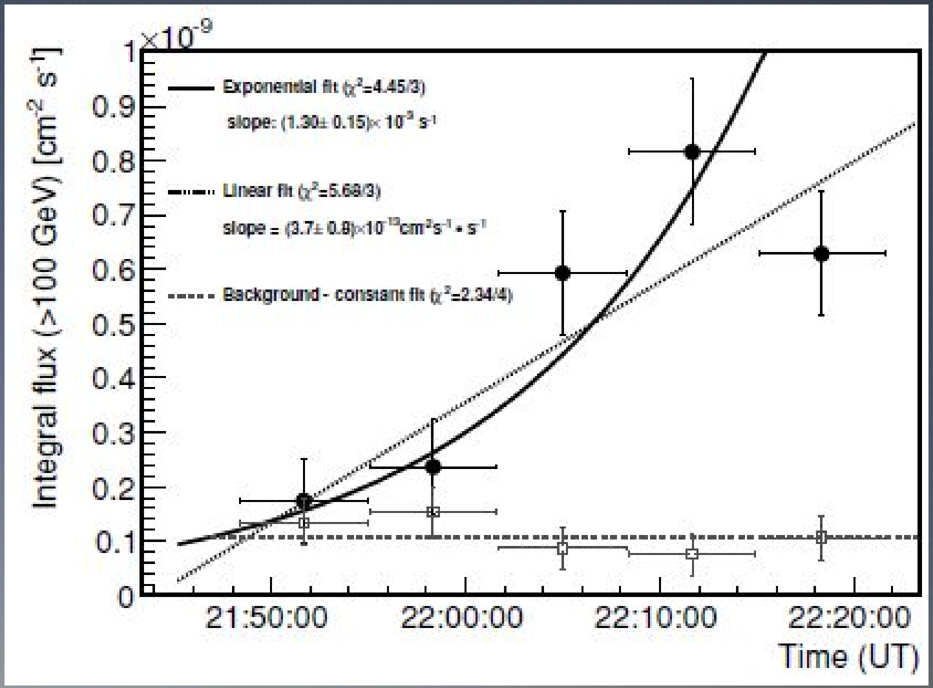


Albert et al., 2008, Science, 320, 1752



Fast variability of PKS1222+216

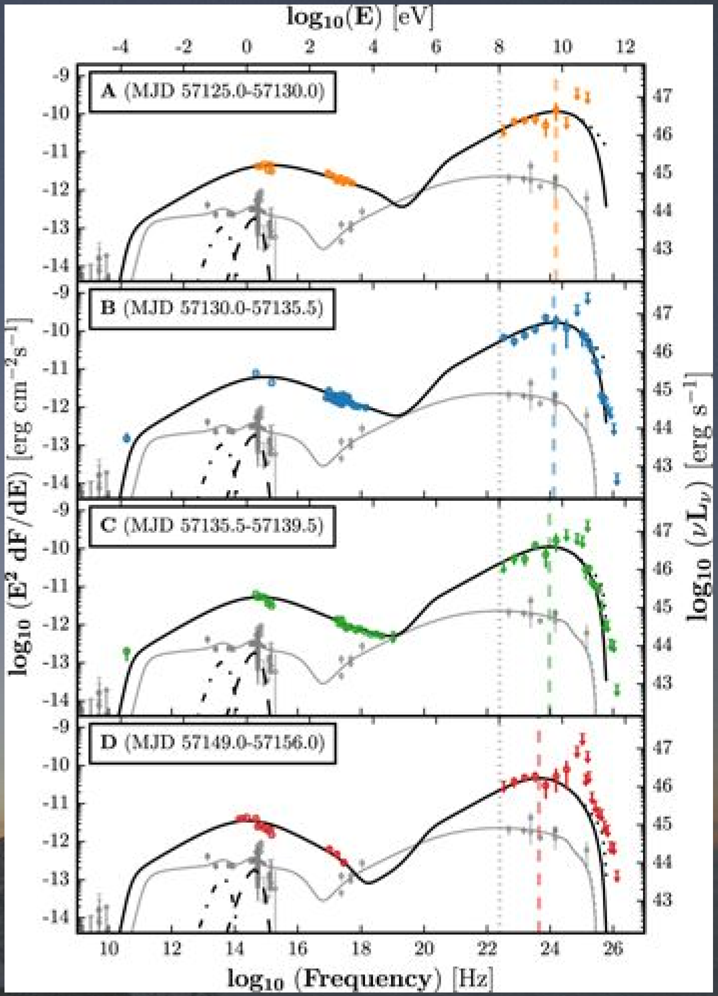
- FSRQ at z=0.432
- A VHE gamma-ray flare detected during high GeV state
- Flux doubling time of 10 min puts limits on the size of the emission region (or Doppler factor)



Aleksić et al. 2011, ApJL, 730, L8

PKS1441+25: FSRQ at z=0.94

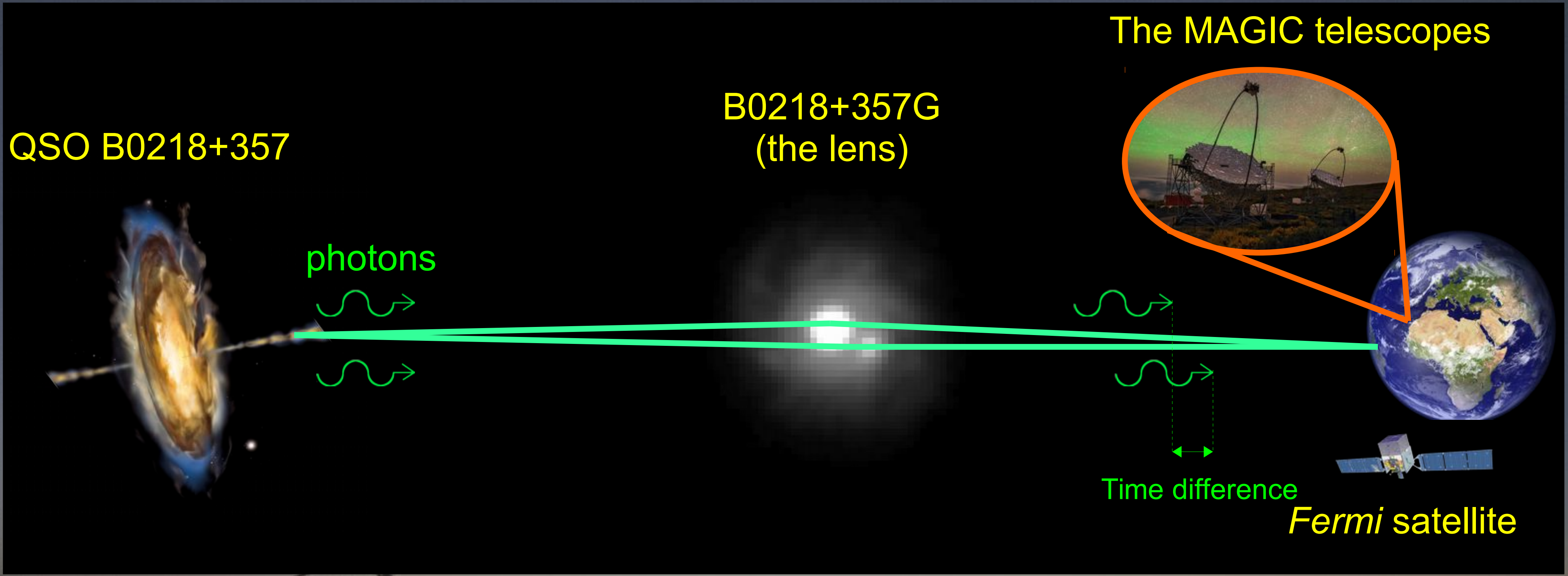
- GeV flare in April 2015 triggered an intense MWL campaign
- Emission region at fixed distance just beyond the BLR
- Variability caused by changing conditions of the plasma (EED and magnetic field) flowing through the emission region
- IR torus radiation:
  - IC target
  - Internal sub-TeV absorption



Ahnen et al., 2015, ApJ, 815, 23

Solid line: observed
Dotted: EBL-deabsorbed

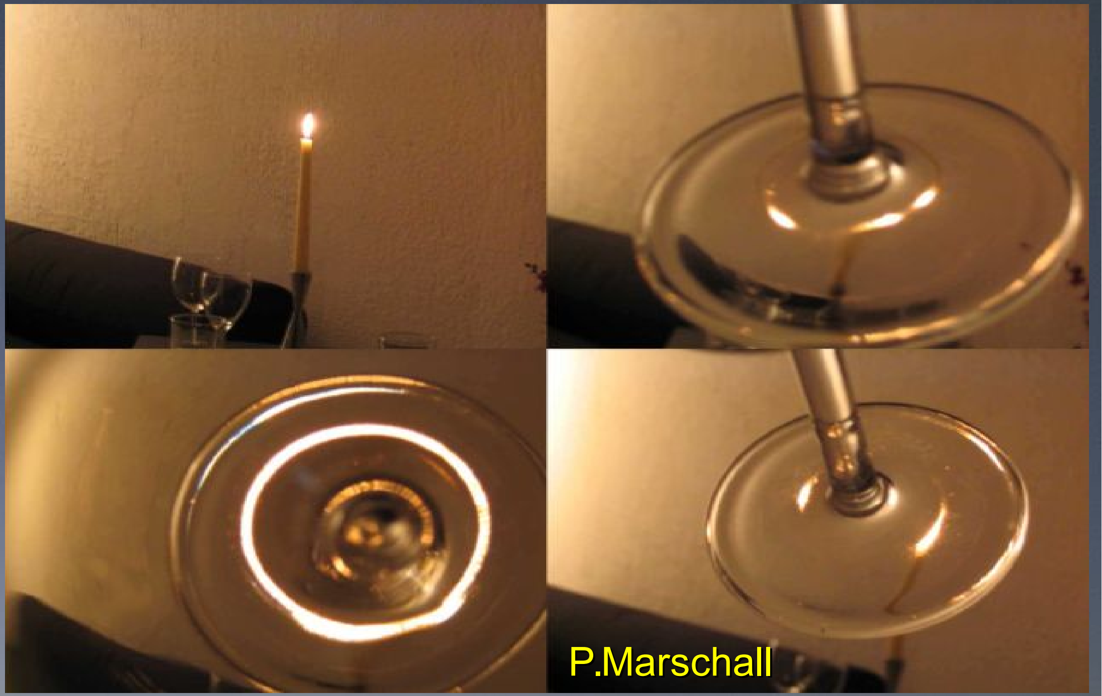
QSO B0218+357: gravitationally lensed blazar at z=0.95



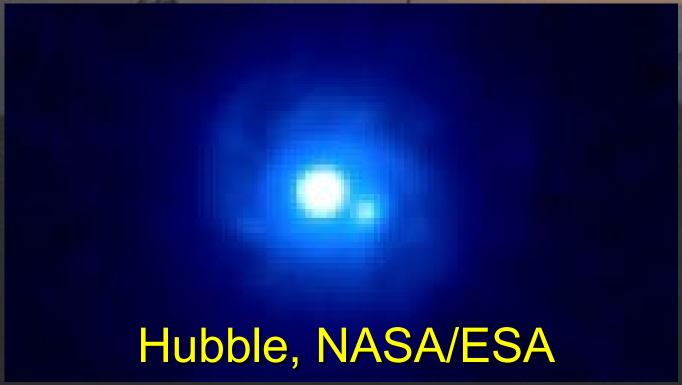
- The two images (seen in radio and optical) are formed by photons passing at a different distance to the center of the lens
- The two images arrive at Earth at a different time (~10-12 days)

Something to try at the MAGIC dinner...

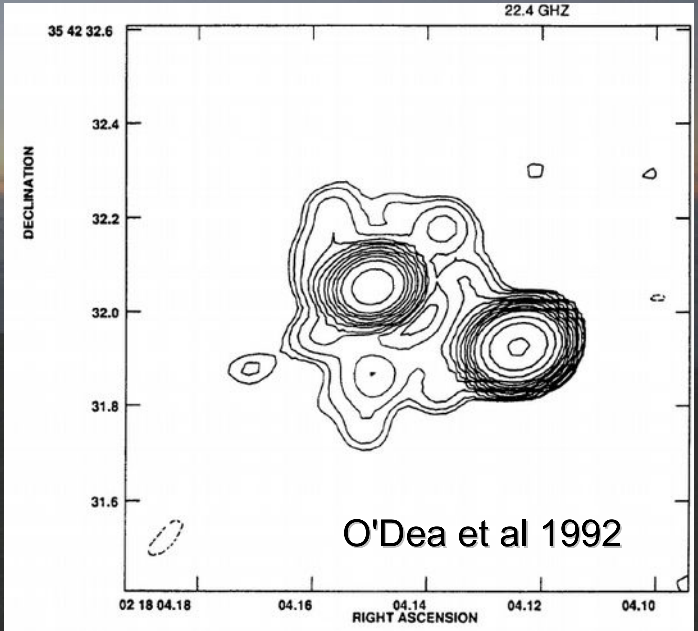
- In radio and optical the individual images can be directly seen
- In gamma rays we need to distinguish them by arrival time



P.Marschall



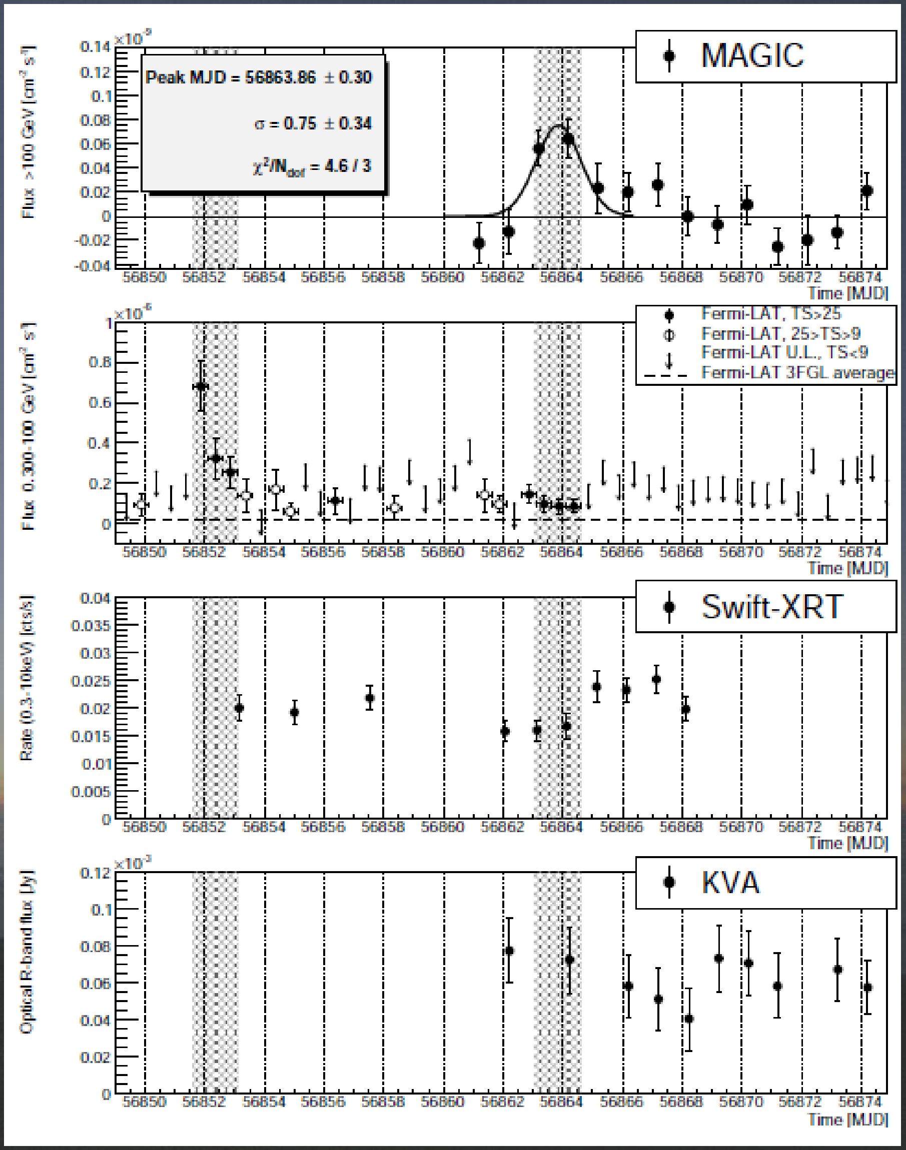
Hubble, NASA/ESA



O'Dea et al 1992

B0218+357 – first gravitationally lensed source detected in VHE gamma rays

- In July 2014 *Fermi*-LAT saw a GeV flare from B0218+357
- MAGIC detected a two day long flare at the expected time of arrival (photons seem to follow the same paths in the gravitational field up to at least 250 GeV)
- No increase during the second component of the flare in x-rays and optical range
- The only gravitationally lensed VHE gamma-ray source, nominally the farthest VHE source, one of only a few FSRQ detected in VHE

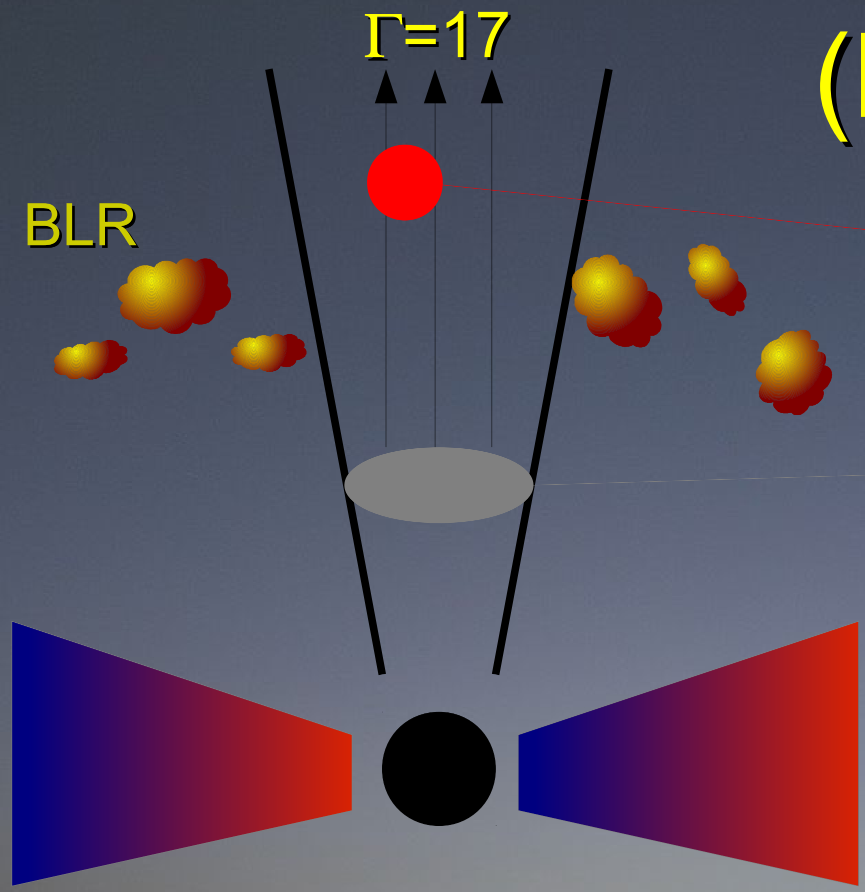


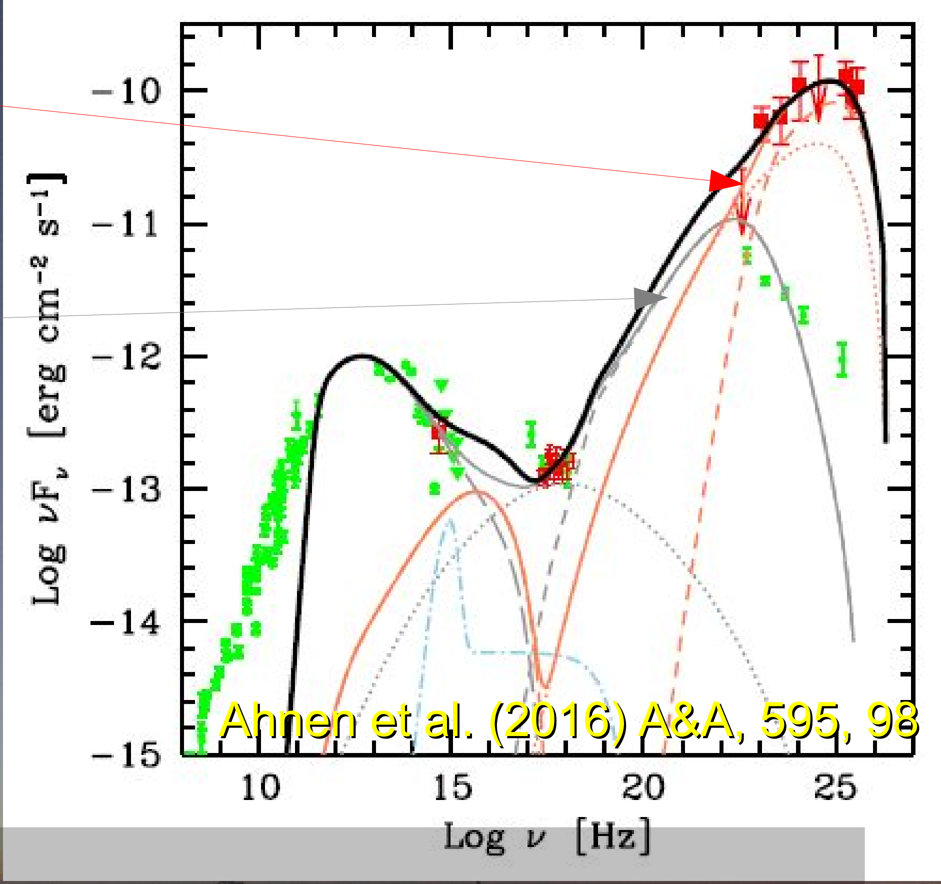
Ahnen et al. (2016) A&A, 595, 98

How to model a gravitationally lensed source ?

- Need to take into account:
  - If we are looking at emission of image A, image B, or sum of both
  - (strong lensing) magnification of individual images
  - Absorption in different images and different energy ranges

(Possible) SED model

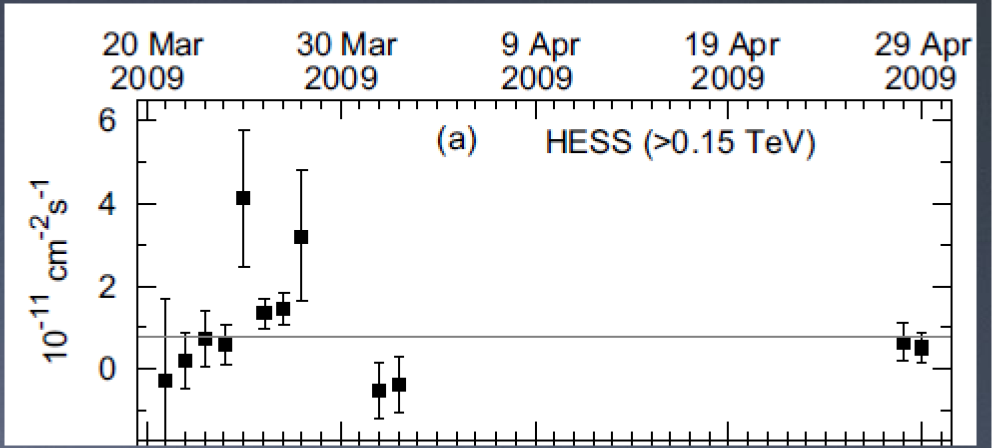




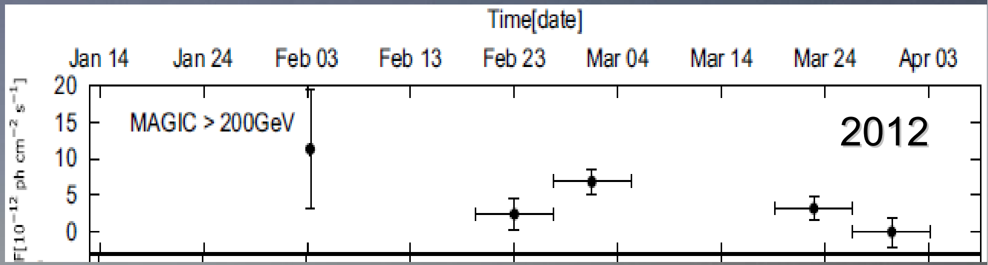
- Two zone model
  - "Jet in" zone: larger region within BLR, mostly responsible for low energy emission, quasi-stable and GeV emission at the level of long term *Fermi*-LAT measurements
  - "Jet out" zone: smaller region outside BLR(no strong absorption), mostly responsible for gamma rays (SSC + EC)

PKS1510-089

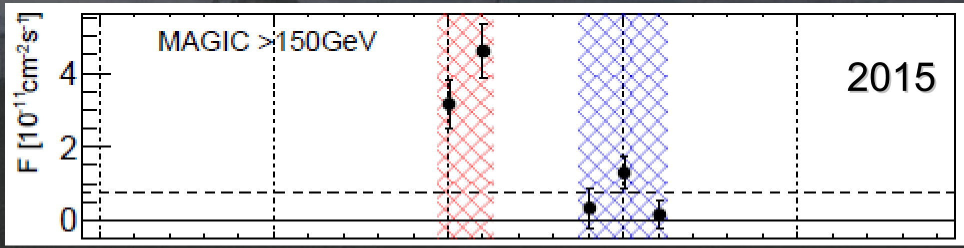
- Detected in VHE γ rays by H.E.S.S. during high optical and GeV state in 2009
- Confirmed by MAGIC during another high state in 2012
- Highly variable in optical and GeV gamma rays, but until 2015 no variability has been observed at VHE



Abramowski et al. 2013



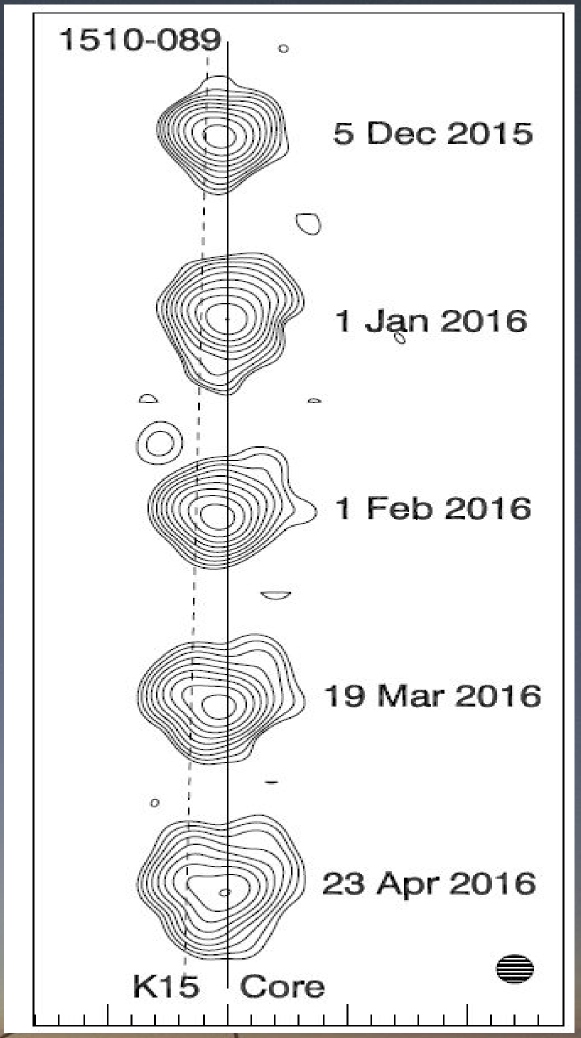
Aleksić et al. 2014, A&A, 569, 46

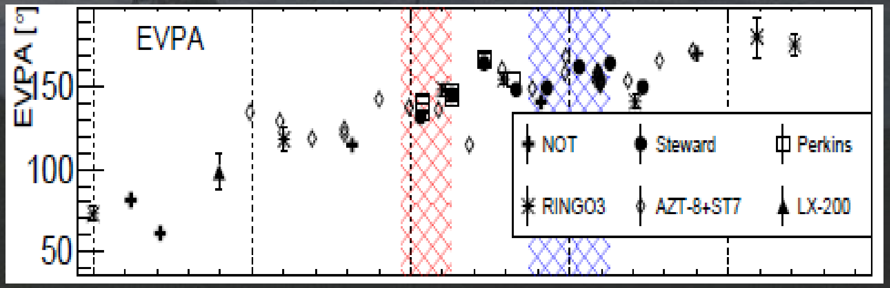


Ahnen et al 2017, 603, 29

What came together with the 2015 flare?

- Follow-up radio observations show a new jet component
- The zero separation epoch overlaps with the May 2015 high state, however with a large uncertainty
- Rotation of the optical polarization vector by 100° contemporaneous with the flare
- Similar behaviour also in 2009 and 2012 VHE detections

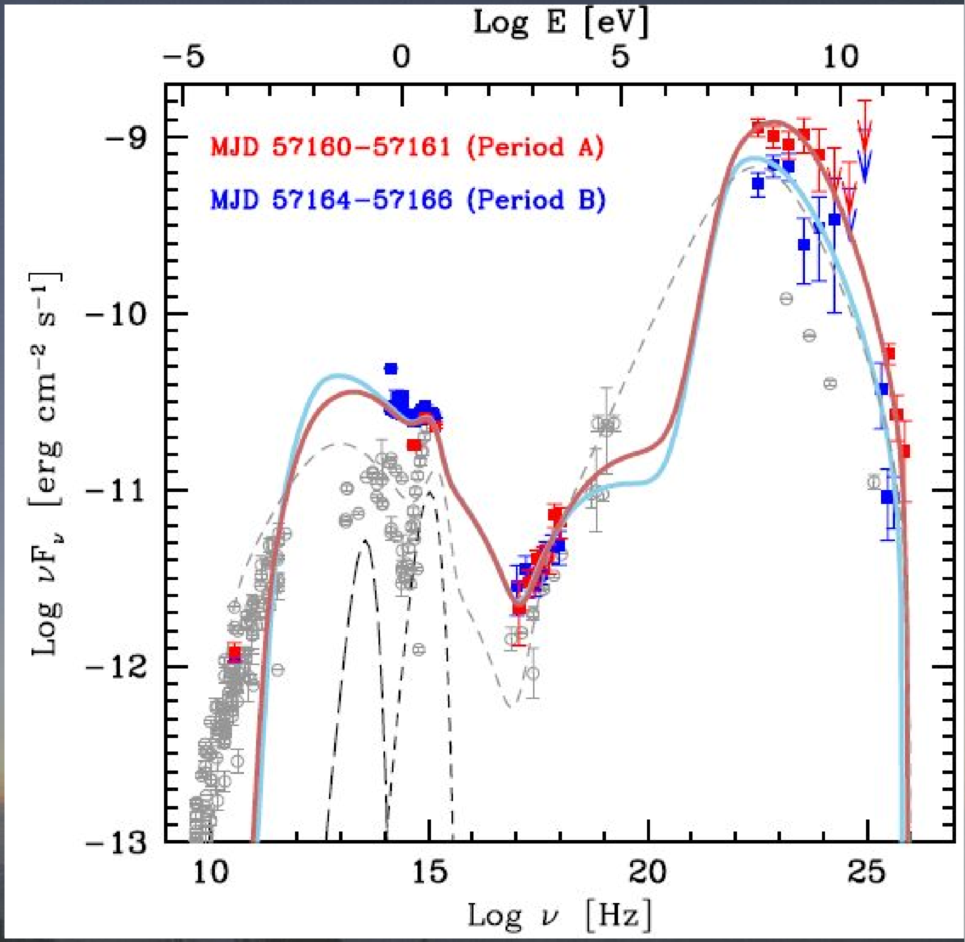




Ahnen et al 2017, 603, 29

A possible scenario of emission for 2015 flare of PKS1510-089

- EC scenario on BLR and dust torus photons
- Emission region placed just outside BLR
- Variability due to changes in *B* field and electron distribution flowing through the emission region



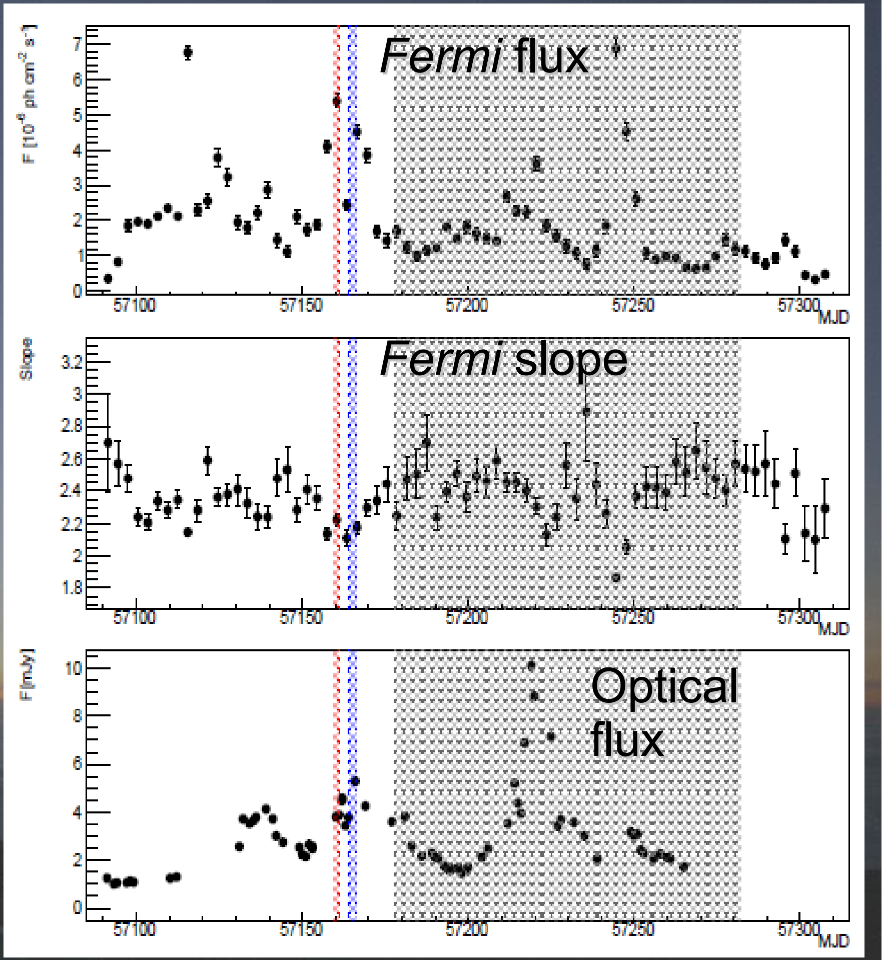
Ahnen et al 2017, 603, 29

In gray: 2012 emission model (Aleksić et al 2014)

How does the new radio component fit in the picture ?

(if it is connected with VHE)

- For a narrow jet (or a narrow spine) the VHE emission can be produced close to the radio core
- If the emission is produced upstream of the radio core, just beyond the BLR the electrons (after a lot of cooling and adiabatic energy losses) will reach the radio core after:
  $(1+z)d_{core}/(c\delta\Gamma)$ =
  $21(d_{core}/6.5pc)(\delta/25)^{-1}(\Gamma/20)^{-1}$ days
  still consistent (even more) with the timescale we saw

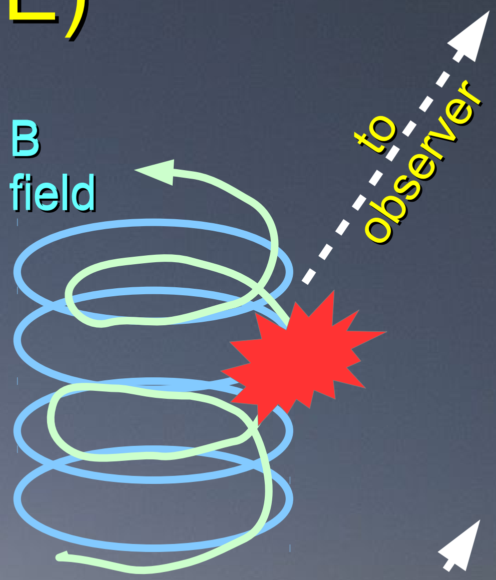


Ahnen et al 2017, 603, 29

How does the optical polarization rotation fit in the picture ?

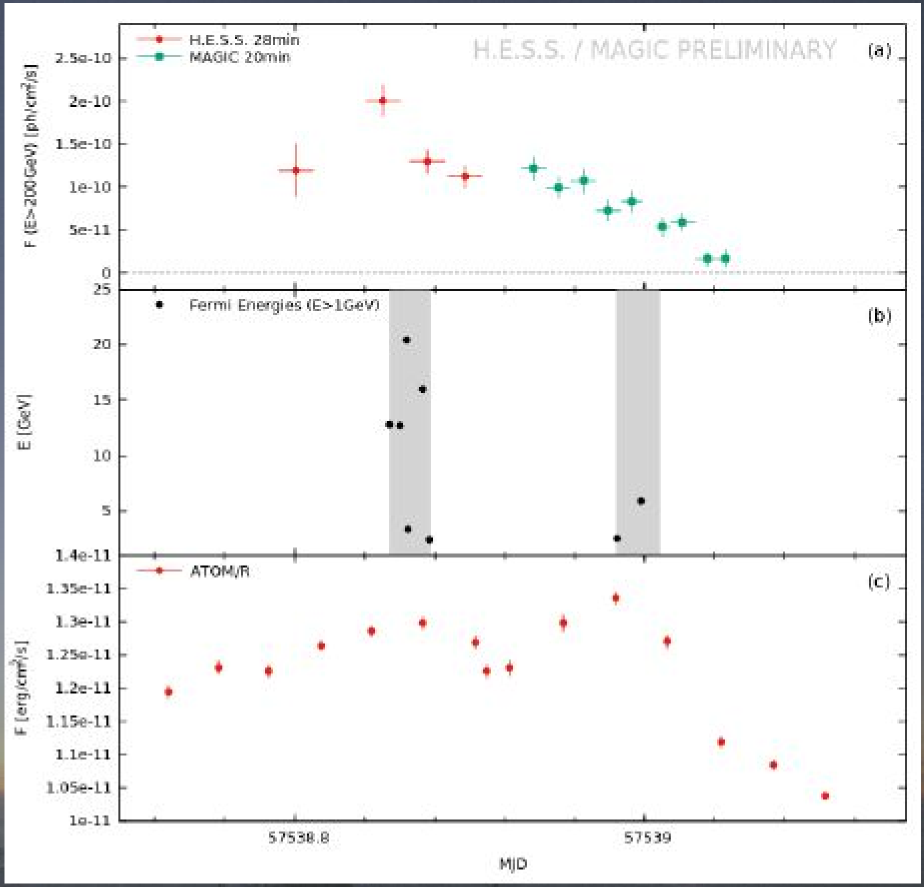
(if it is connected with VHE)

- Emission region following a spiral path in mainly toroidal magnetic field (Marscher et al 2010) – large swings of polarization are possible
- Alternatively light travel effects of axisymmetric emission region pervaded by helical magnetic field (Zhang et al. 2015) – swing of 180 deg is possible (sufficient for 2015 flare)



PKS 1510-089: intranight variability

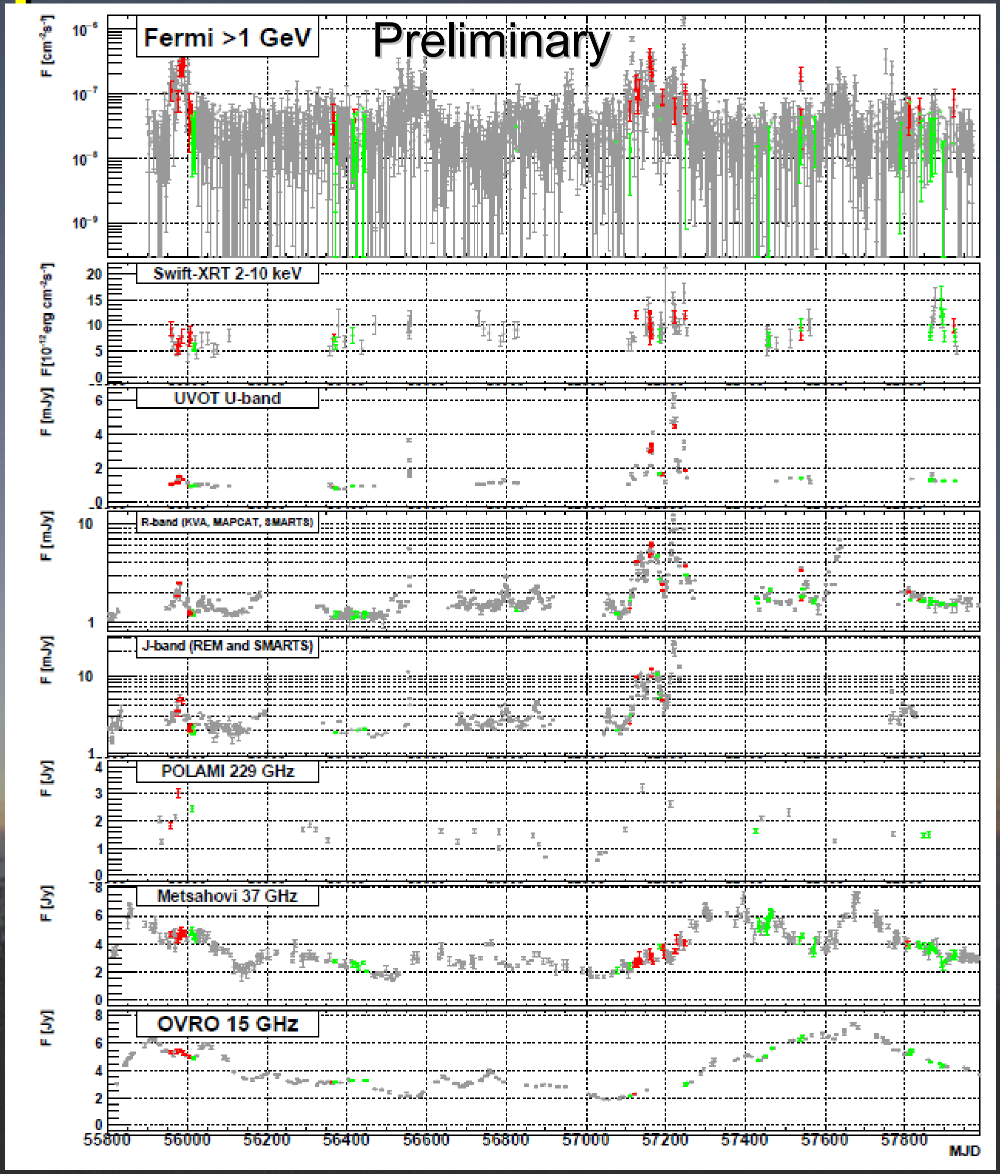
- In May 2016 H.E.S.S. and MAGIC saw a giant flare during high GeV state
- Intranight variability of VHE emission with time scale of the order of an hour (and a strong hint of switching off of the emission)
- Short variability time scale pushes the far dissipation scenario to the limits



Zacharias et al., ICRC2017

Is PKS1510-089 ever going VHE-quiet ?

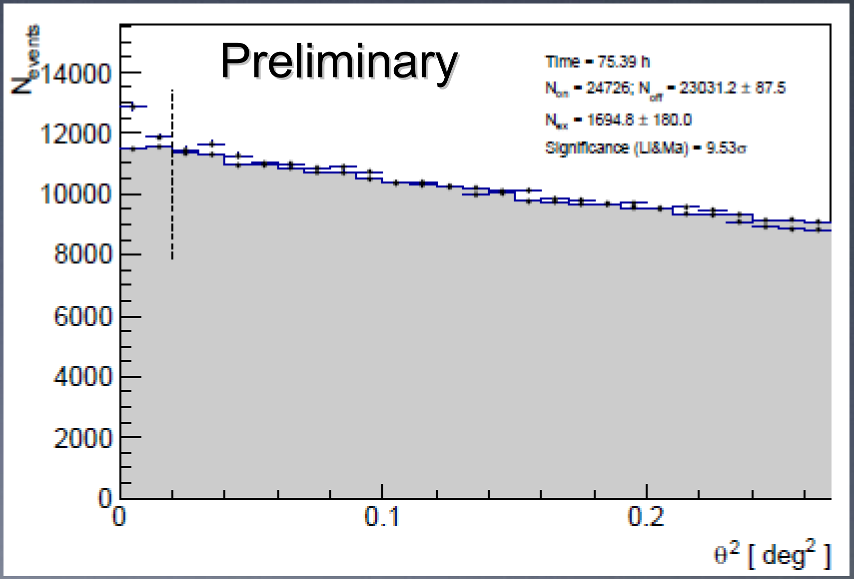
- Using *Fermi*-LAT we selected nights with low flux > 1 GeV
- Ample MWL coverage from radio to gamma-rays – we select data contemporaneous with MAGIC and taken during low GeV state



Acciari et al. subm. to A&A (arXiv: 1806.05367)

Detection of low state VHE gamma-ray emission

- Stacking 75h taken on 76 nights we can detect low state emission with 9.5σ
- The flux is ~0.6 of the one in 2012 high optical/GeV state and a factor 80 below the peak flux of the 2016 flare, but there is no significant change in spectral shape



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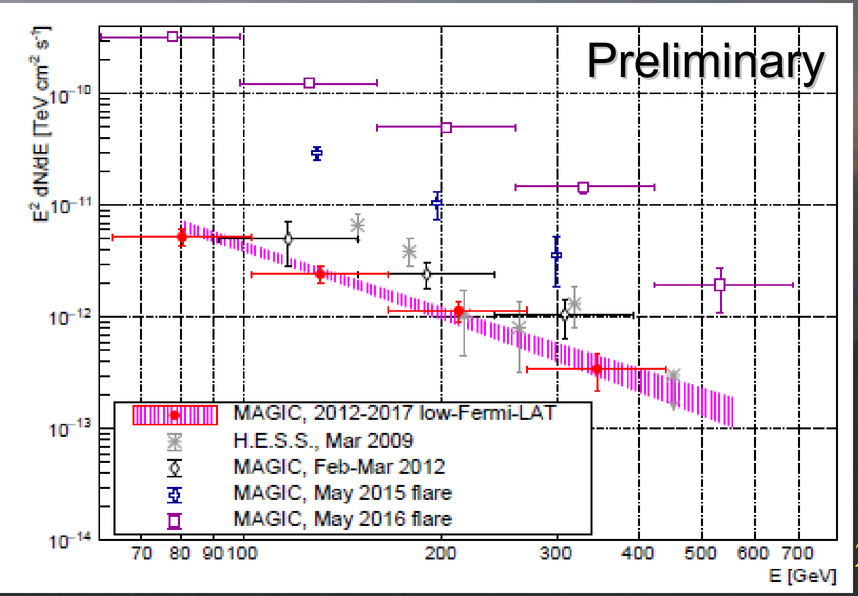
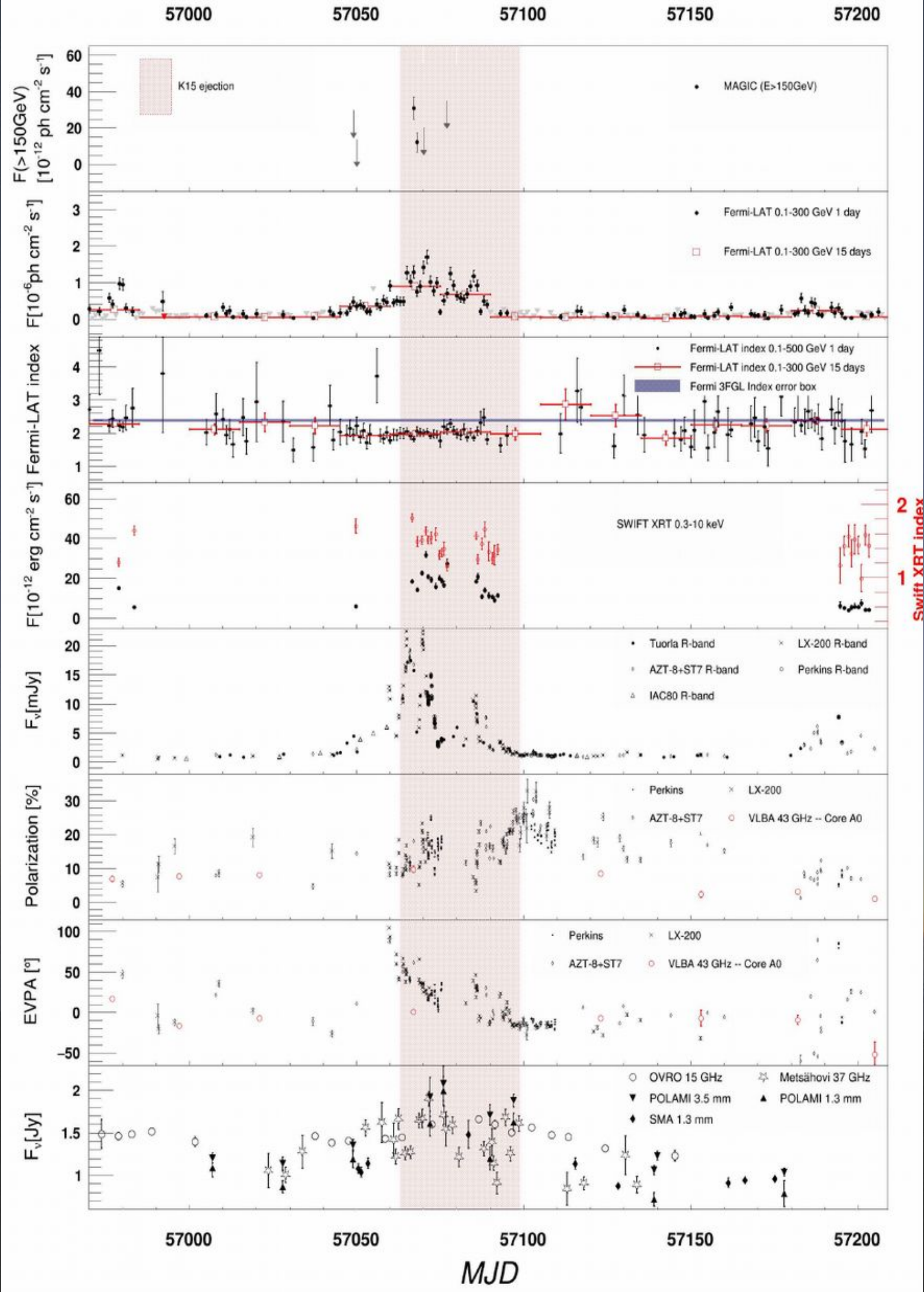




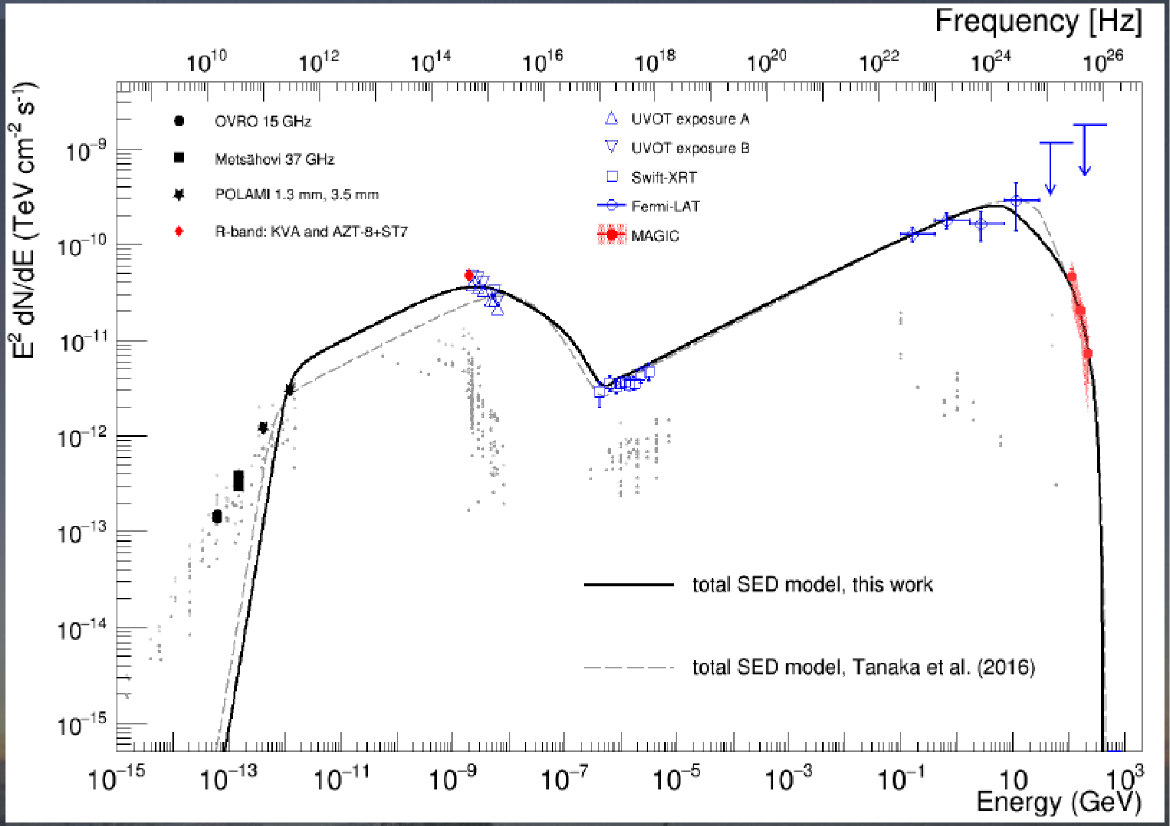
S4 0954+65: "*unknown*" blazar

- Unknown redshift
- Uncertain classification (FSRQ or BL Lac)
- Detection of VHE γ ray emission during GeV flare in Feb 2015
- Rotation of optical polarization vector by ~100°
- Emission of a new radio component

Ahnen et al., 2018 (A&A accepted), arXiv:1801.04138

S4 0954+65: broad band modelling

- External Compton scenario on dust torus photons (typical of FSRQ)
- High Compton dominance (SED_{IC}/SED_{synch}=7)
- If not a FSRQ: synchr. peak at 8 x 10^{14} Hz would classify it as an IBL



Ahnen et al., 2018 (A&A accepted), arXiv:1801.04138

Ton 599: a new member of the family

- A new distant (z=0.72) FSRQ detection in VHE γ rays during high optical and GeV state
- Stay tuned for more results from this source

Detection of very-high-energy gamma-ray emission from the FSRQ Ton 0599 with the MAGIC telescopes

ATel #11061; ***Razmik Mirzoyan (Max-Planck-Institute for Physics, Munich), on behalf of the MAGIC collaboration***
on ***15 Dec 2017; 16:21 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, TeV, VHE, Blazar

Referred to by ATel #: 11073, 11075, 11624

Tweet   Recommend 40

The MAGIC collaboration reports on the first time detection of very-high-energy (VHE; E>100 GeV) gamma-ray emission from Ton 0599 (RA:+11:59:31.83 DEC:+29:14:43.83, J2000). The object was observed with the MAGIC telescopes for ~1 hour on 2017/12/15 (MJD 58102.2). The preliminary analysis of these data resulted in the detection of Ton 0599 with a statistical significance of about 10 standard deviations. The VHE flux of this detection was estimated to be around 0.15x10^-9 [ph/cm2/s] (corresponding to about 0.3 CU) above 100 GeV, with a soft spectrum. TON599 is a gamma-ray FSRQ at z=0.72 which is in a remarkably high state from optical to gamma-ray since October 2017 (ATel #10931, #10932, #10937, #10938, #10948, #10949). MAGIC observations on TON 0599 will continue during the next days and multi-wavelength observations are strongly encouraged. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and A. Stamerra (antonio.stamerra@inaf.it)

ATel #11061

(note also ATel 11075 by VERITAS)

Conclusions

- MAGIC has significantly increased the population of known VHE γ-ray FSRQs, often due to follow up of GeV high states
- MAGIC observations of FSRQ expanded the visible VHE gamma-ray universe up to z~1
- Most of the FSRQ flares can be modelled in the EC scenario, with the emission region located beyond BLR in the DT radiation field
- Quite common (but not always) to have simultaneous ejection of a new radio component, rotation of the optical polarization vector and a VHE γ-ray flare
- FSRQ studies with PKS1510-089: MAGIC detected low state, high state, smaller and large flare

Backup

Magnification

- We *know* the flux magnification ratio of the two images μ_A/μ_B, but how much is μ_A and μ_B?
- Radio + optical image can be used for lens modelling, Single Isothermal Sphere model gives simple analytical formulas for flux magnifications in two independent ways:
  - From image positions: μ_A=2.7, μ_B=0.67
  - From flux ratio: μ_A=2.8, μ_B=0.77
- SIS is a very crude model, but careful lens modelling by Barnacka et al 2016 gave a model consistent with SIS

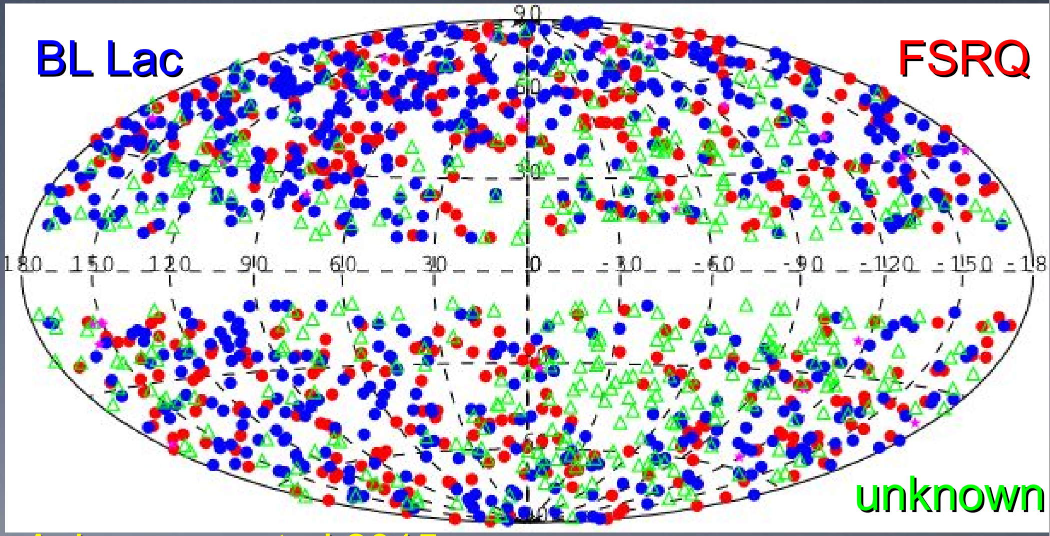
Absorption at the lens

- Can happen in any of the two images, independently!
- Hints of strong absorption in at least the A image:
  - Large reddening between the two images: $\Delta E(B-V)=0.90\pm0.14$ (Falco et al 1999) – Image A is weaker in optical than B !
  - Molecular absorption line gives column density of H2 of 0.5 – 5 x 10^{22} cm^{-2} (Menten & Reid 1996) – would affect soft X-rays

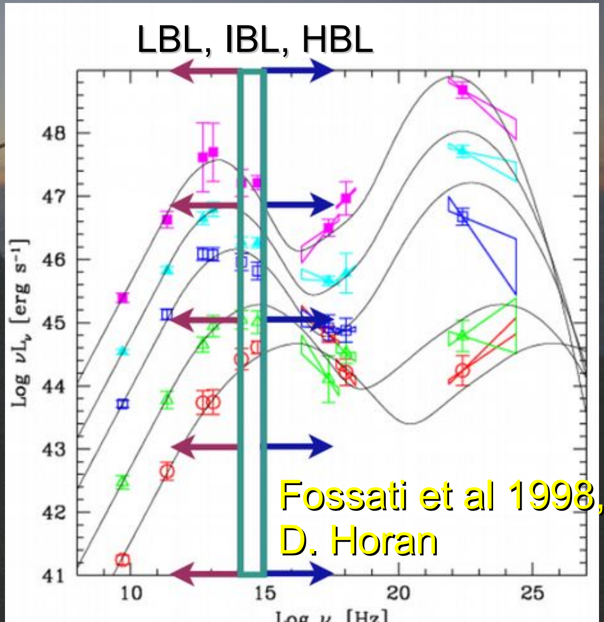
Parameter	Symbol	Model A Tanaka et al. (2016)	Model B this work
Redshift	z	0.368	
Bulk Lorentz Factor	Γ	30	35
Doppler factor	δ_D	30	35
Variability Timescale [s]	t_v	1.0×10^5	4×10^4
Comoving radius of blob [cm]	R'_b	$6.6{\times}10^{16}$	$3.0{\times}10^{16}$
Magnetic Field [G]	B	0.6	0.4
Low-Energy Electron Spectral Index	s_1	2.4	2.4
High-Energy Electron Spectral Index	s_2	4.5	3.6
Minimum Electron Lorentz Factor	$\gamma'_{\rm min}$	1.0	1.0
Break Electron Lorentz Factor	$\gamma'_{\rm brk}$	8.0×10^3	4.0×10^3
Maximum Electron Lorentz Factor	$\gamma'_{\rm max}$	2.0×10^4	4.0×10^4
Black hole Mass [$M_\odot$]	$M_{\rm BH}$	3.4×10^8	
Disk luminosity [erg s^{-1}]	$L_{\rm disk}$	3.0×10^{43}	
Inner disk radius [R_g]	$R_{\rm in}$	6.0	
Seed photon source energy density [erg cm^{-3}]	$u_{\rm seed}$	2.4×10^{-4}	4.4×10^{-5}
Seed photon source photon energy [$m_e c^2$ units]	$\epsilon_{\rm seed}$	7.5×10^{-7}	5×10^{-7}
Dust Torus luminosity [erg s^{-1}]	$L_{\rm dust}$	3.9×10^{42}	1.5×10^{42}
Dust Torus radius [cm]	$R_{\rm dust}$	2.1×10^{17}	6.1×10^{17}
Dust temperature [K]	$T_{\rm dust}$	1500	1000
Jet Power in Magnetic Field [erg s^{-1}]	$P_{j,B}$	1.0×10^{46}	1.4×10^{45}
Jet Power in Electrons [erg s^{-1}]	$P_{j,e}$	1.1×10^{45}	6.6×10^{45}

FSRQs at GeV gamma-rays

- In the 3rd AGN catalog of *Fermi*-LAT there are 467 FSRQs and 632 BL Lacs
- FSRQs are intrinsingly more luminous than BL Lacs and have IC peak at GeV energies – easy target for *Fermi*-LAT



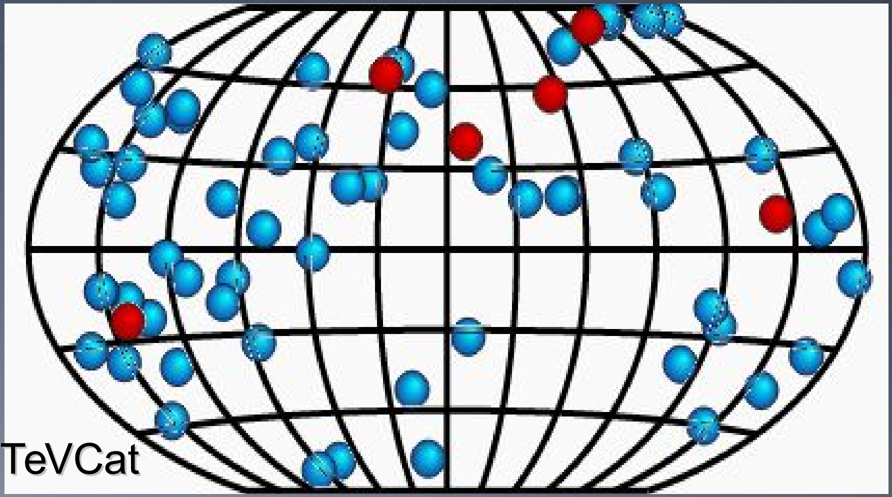
Ackermann et al 2015



Fossati et al 1998, D. Horan

FSRQ at (sub-)TeV energies

- Only a handful of FSRQs detected at VHE gamma rays and tens of BL Lacs
- FSRQs are difficult sources for IACTs:
  - Distant (absorption of higher energies in EBL !)
  - Intrinsingly steep at sub-TeV energies
  - Need an instrument with an excellent low energy performance: MAGIC

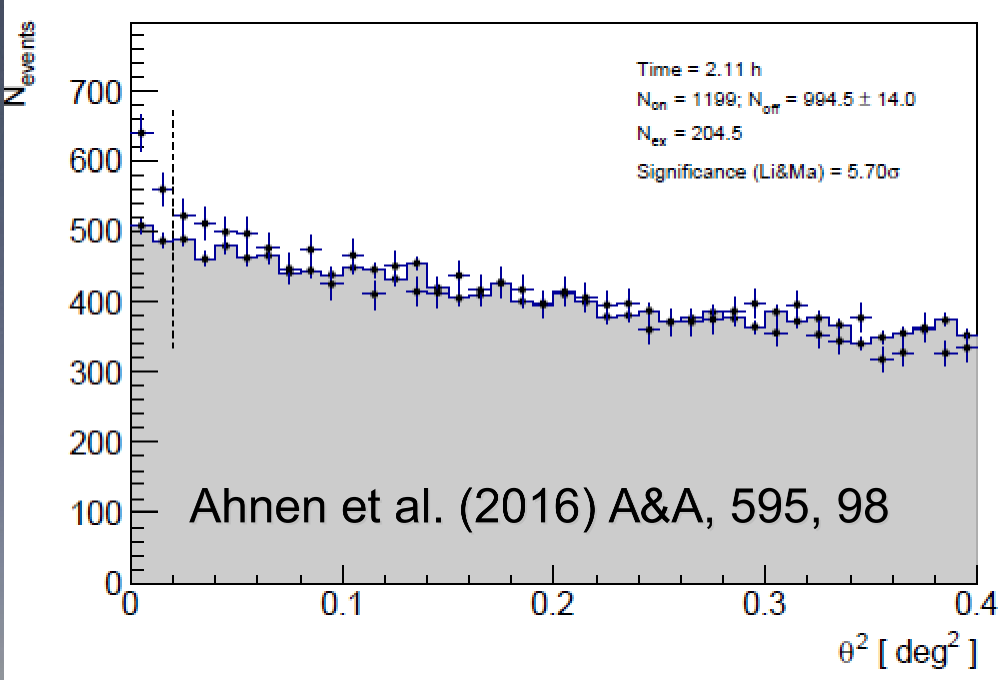


FSRQ, other AGNs

- Observations often during high states at lower frequencies to improve detection chances

B0218+357 flare in 2014

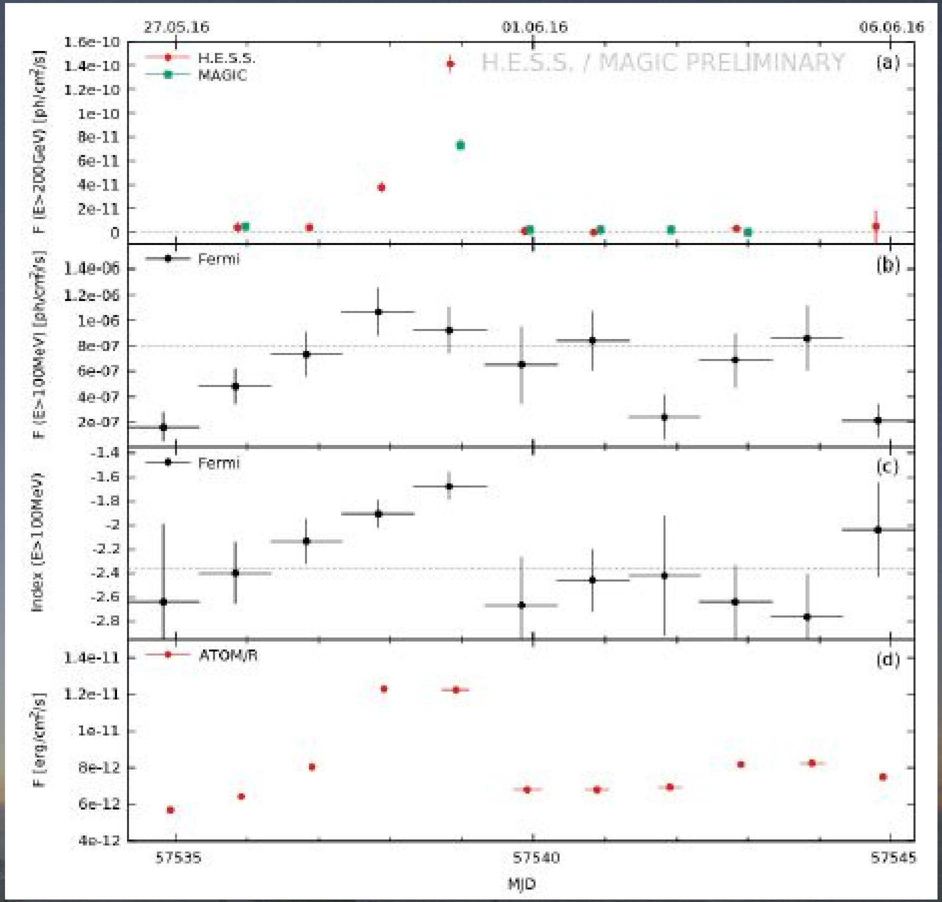
- On July 13/14 *Fermi*-LAT saw a flare from B0218+357, not as strong as in 2012, but with a much harder spectrum
- Flare lasted for 2 days more and then subsided
- MAGIC couldn't observe the original flare because of the full moon period
- Observations were scheduled during the expected delayed emission



- The two nights around the time of the expected delayed emission led to a detection with 5.7σ significance ==> expanded VHE sky from z 0.5-0.6 to 0.94

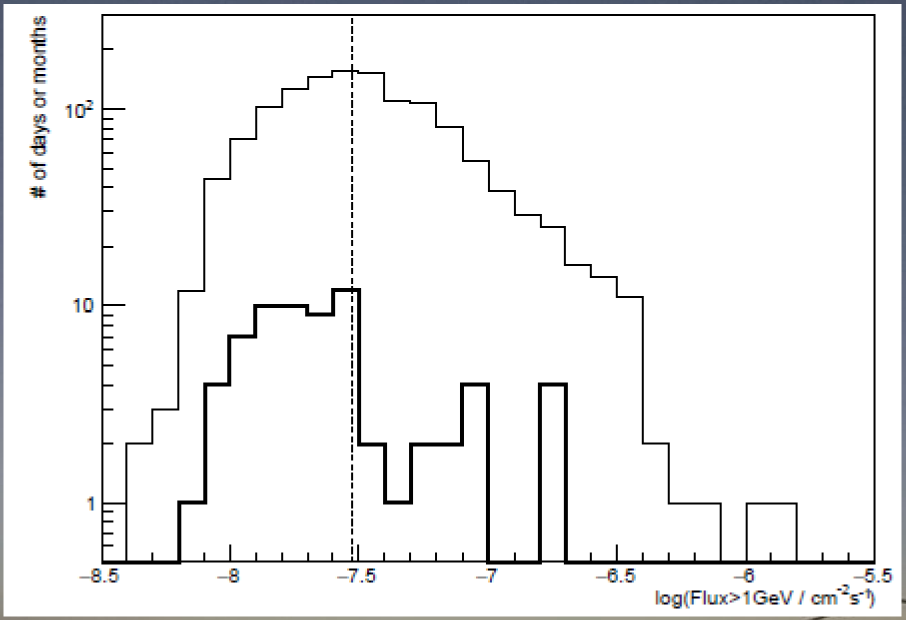
PKS 1510-089 keeps on surprising

- In May 2016 another gamma-ray high state happened
- H.E.S.S. and MAGIC detected a giant flare from PKS1510
- *Fermi*-LAT showed gradual hardening of the emission
- Also simultaneous somewhat higher optical state

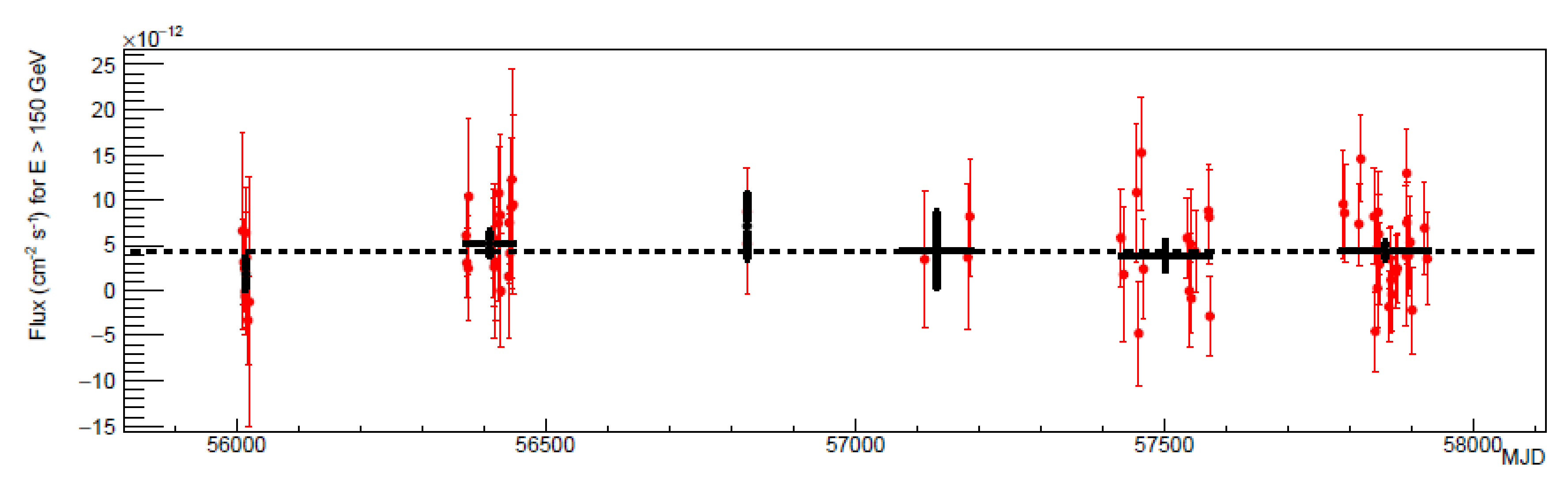


Zacharias et al., ICRC2017

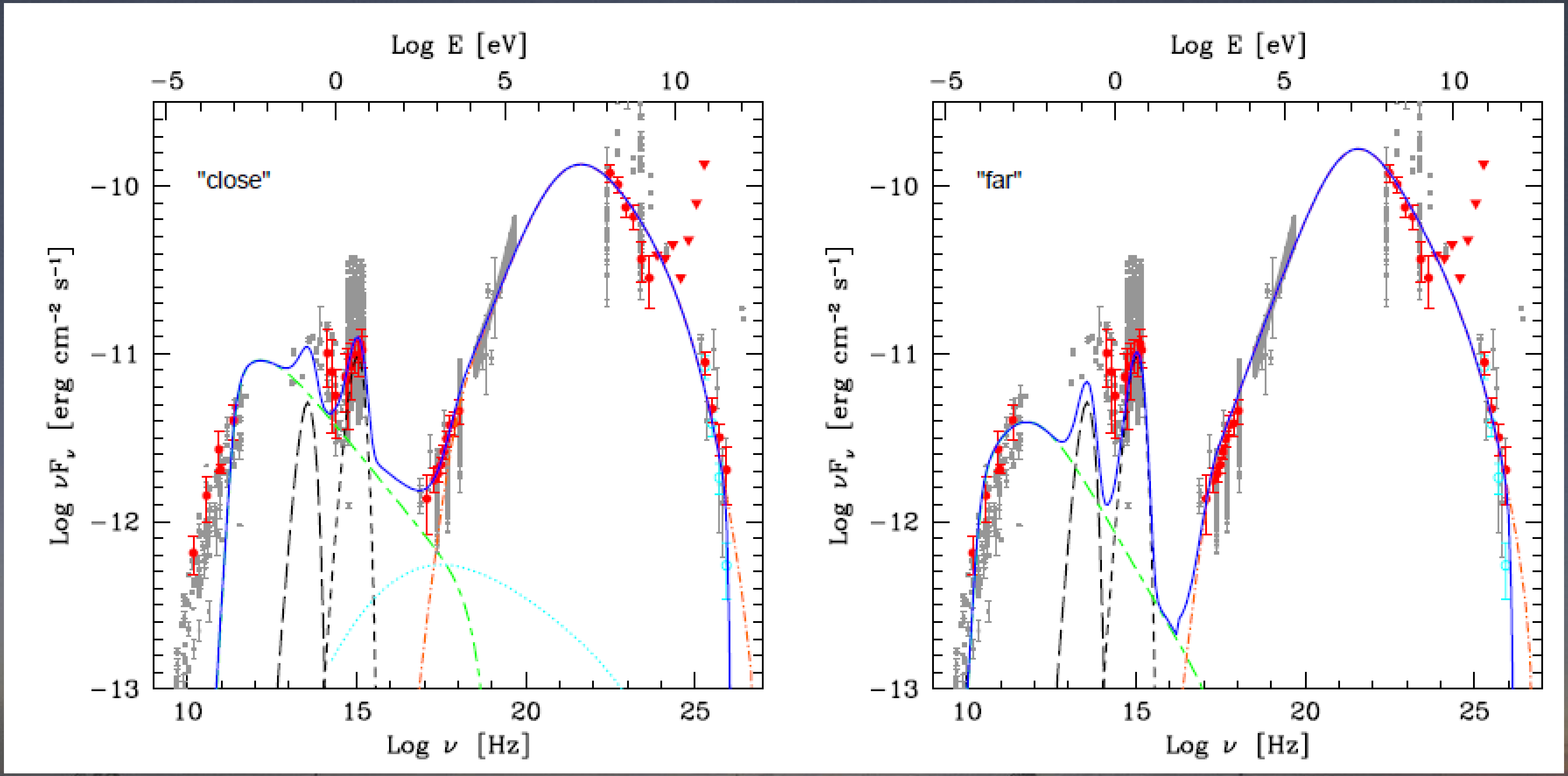
PKS1510-089 GeV flux distribution



PKS1510-089 low state VHE light curve



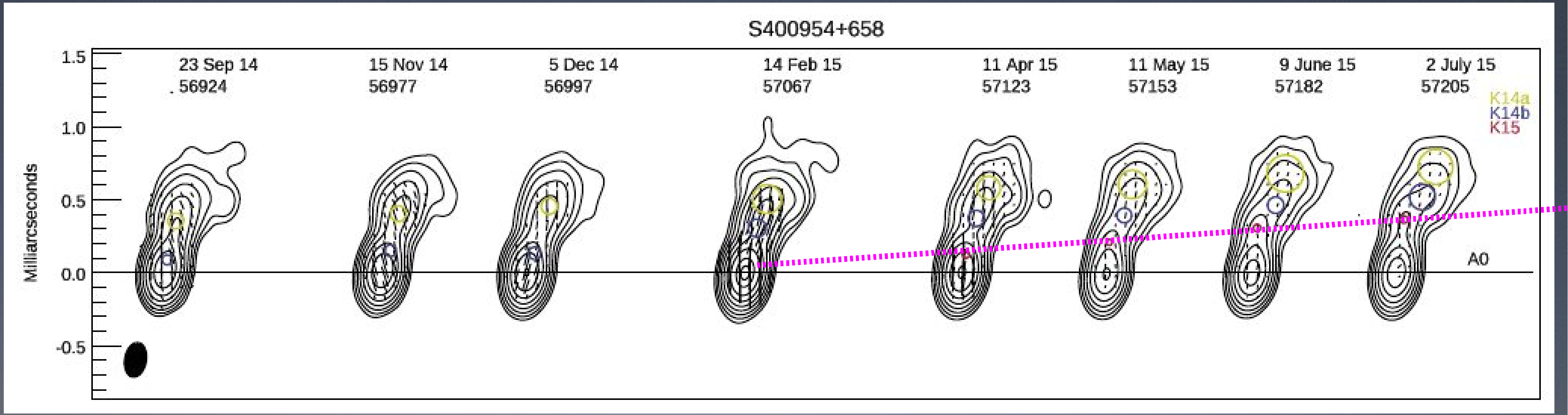
Model for low state

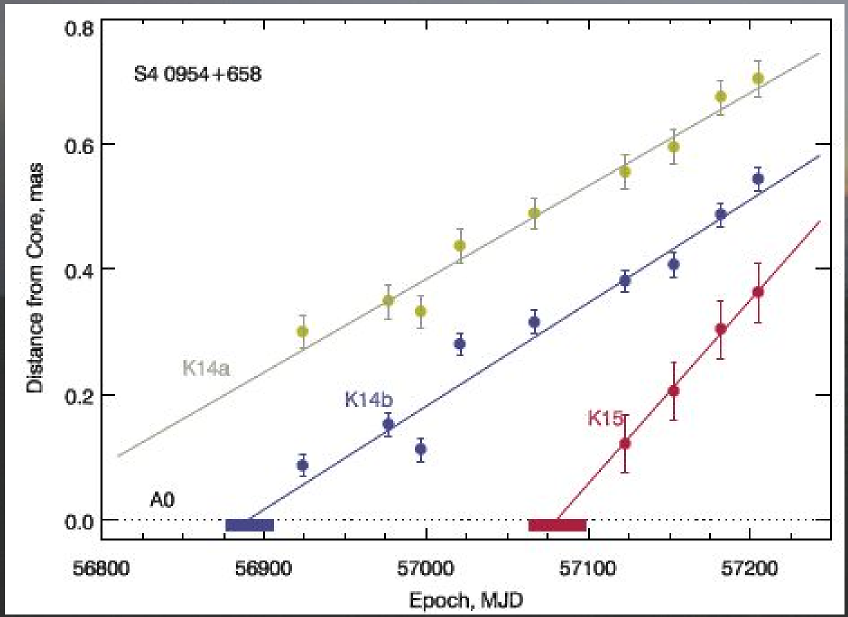


S4 0954+65 a blazar with many unknowns

- Disputed redshift: $z=0.368$ or $z>0.45$
- Uncertain classification
  - Small equivalent width of the emission lines: blazar-like
  - Broadband spectral features (flatter index in X-rays and γ rays, hint of blue-bump): FSRQ-like
- Until 2015 not detected at VHE γ rays

S4 0954+65: VLBA images after the flare





VLBA images show an appearance of a new radio component (K15) at the time of the flare

Ahnen et al., 2018 (A&A accepted), arXiv:1801.04138