Very-high-energy γ-rays from the Universe's middle age: detection of B0218+357 and PKS1441+25 with the MAGIC telescopes

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On behalf of the MAGIC and Fermi-LAT collaborations

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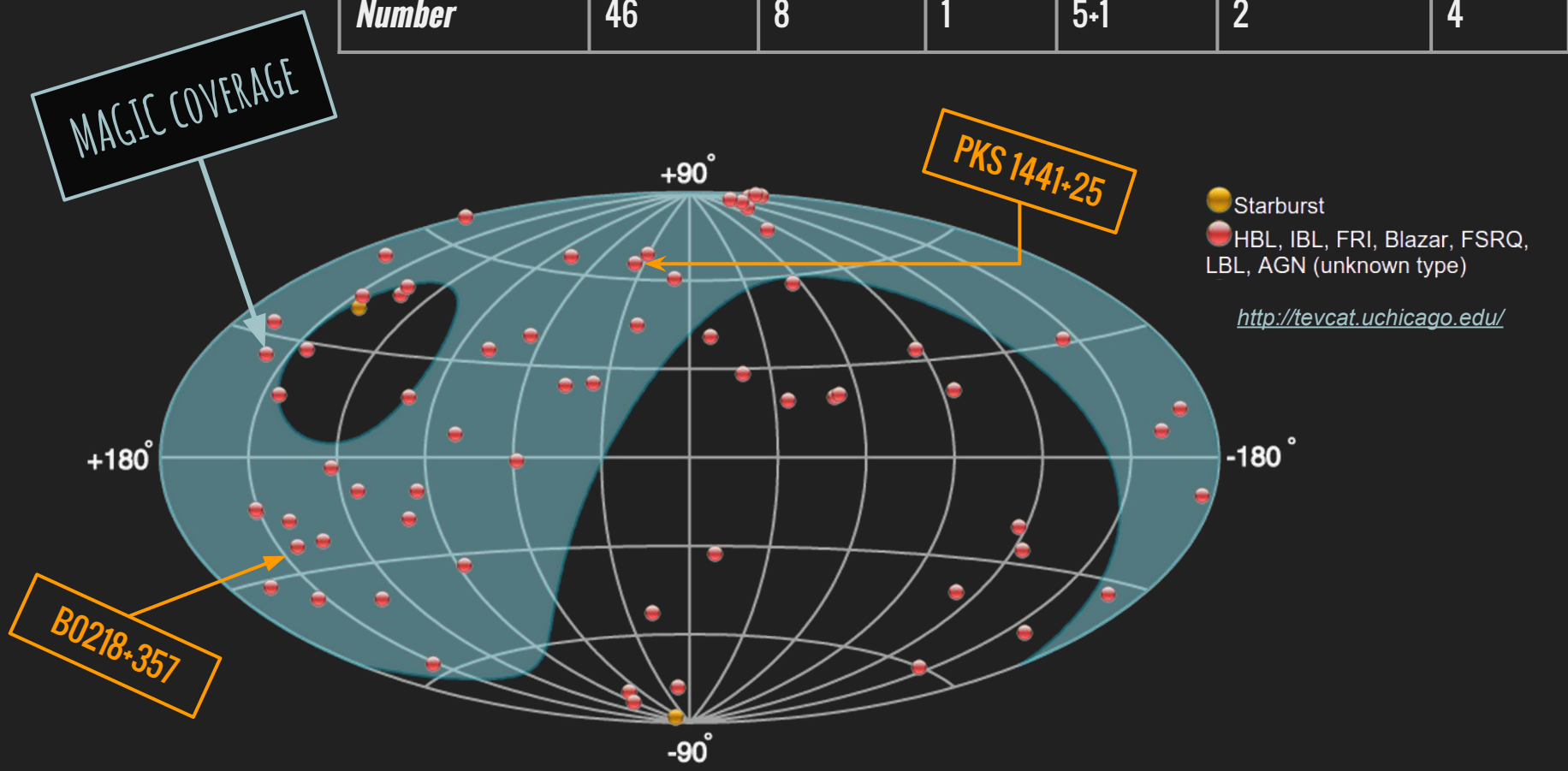
Lewes, Delaware - Fermi Summer School 2016

The very high energy gamma-ray sky

2016/06/03	HBL	IBL	LBL	FSRQ	Starburst	FRI
Number	46	8	1	5+1	2	4



- 67 extragalactic sources detected at very high-energy gamma-rays (VHE, E>100 GeV)
- 5+1 FSRQ at high redshifts, 0.36 < z < 0.94

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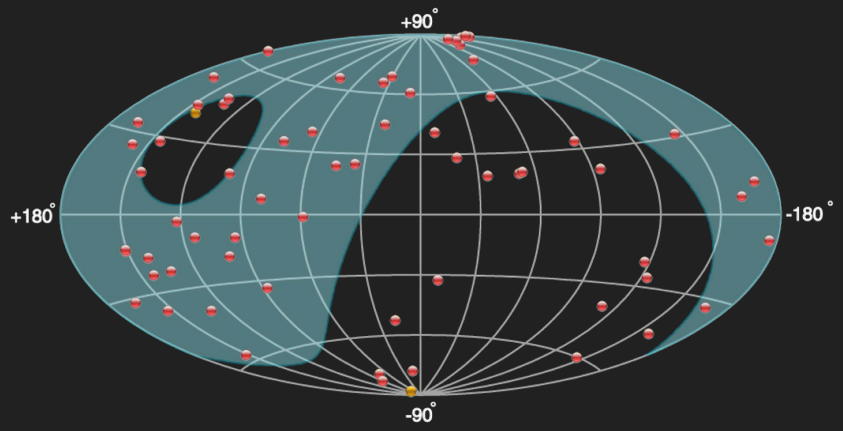

Source	z	Discoverer	Year
3C 279	0.5362	MAGIC	2006
PKS 1510-089	0.361	HESS	2009
PKS 1222+216	0.432	MAGIC	2010
B0218+367	0.944	MAGIC	2014
S4 0954+65	0.368	MAGIC	2015
PKS 1441+25	0.939	MAGIC	2015

Classification under debate.

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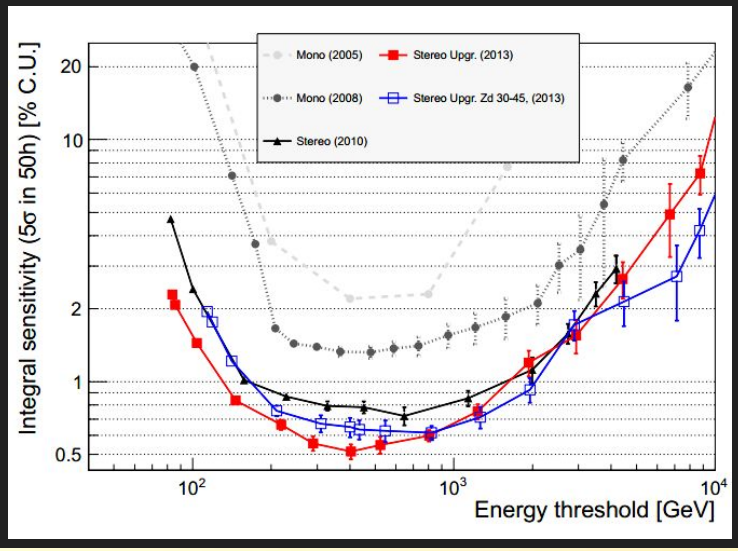
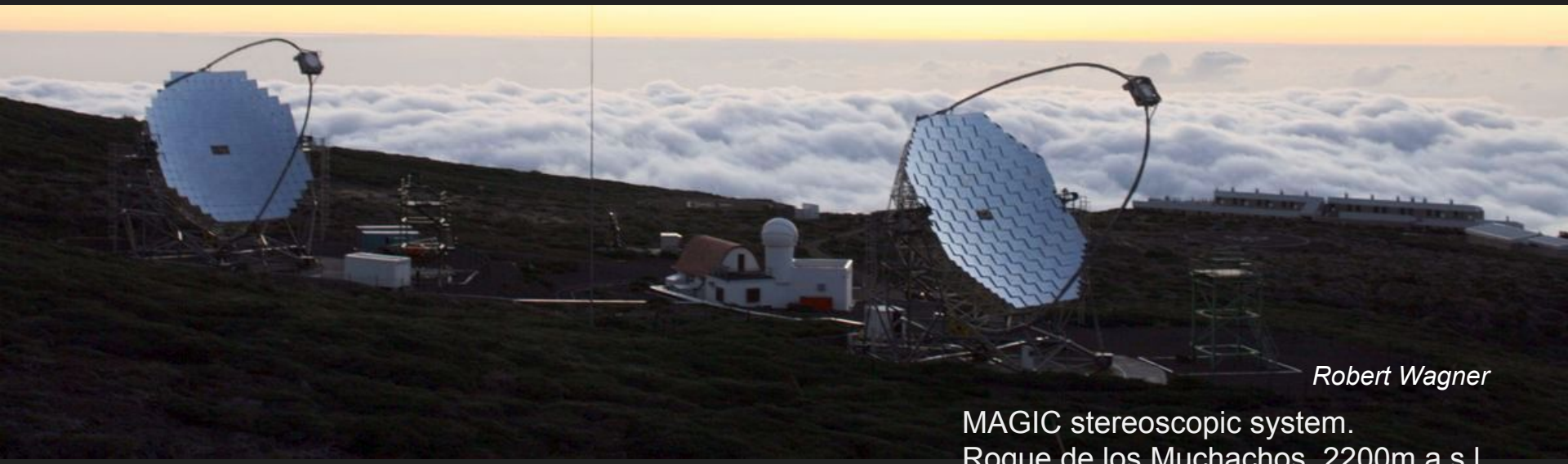
The MAGIC telescopes

- MAGIC I operating since 2004, MAGIC II since 2009.
- 17m diameter, 1039 PMTs cameras and a 3.5deg FOV.
- Performance after the major upgrade of 2011-2012:
  - ✓ Energy threshold of ~50GeV. Lower in pulsar analysis.
  - ✓ Sensitivity ~ 0.66% Crab units in 50h @ E>220GeV.
  - ✓ Energy resolution of 16% @ E~220GeV.
  - ✓ Angular resolution < 0.07° @ E>220GeV.
- Collaboration of >150 members from 10 countries.

J. Aleksić et al. (2016)

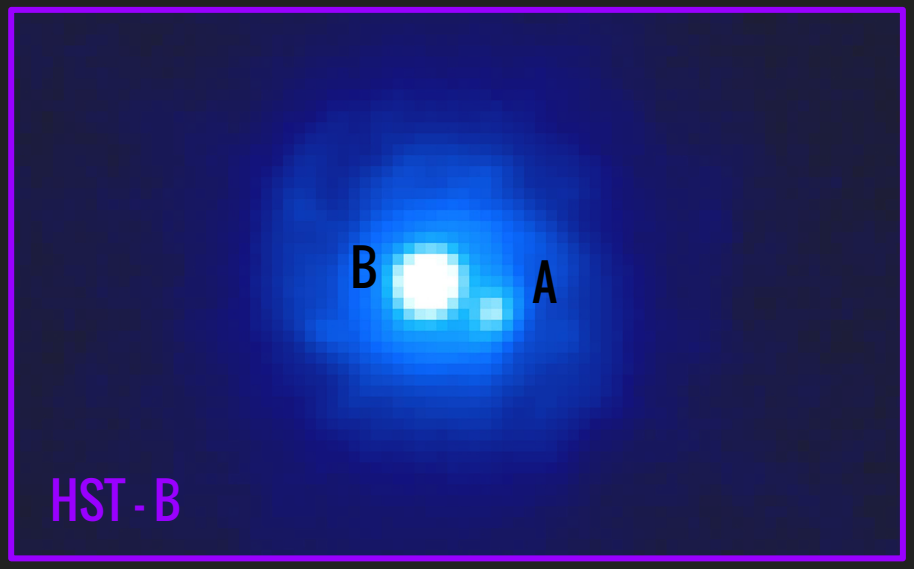




Robert Wagner

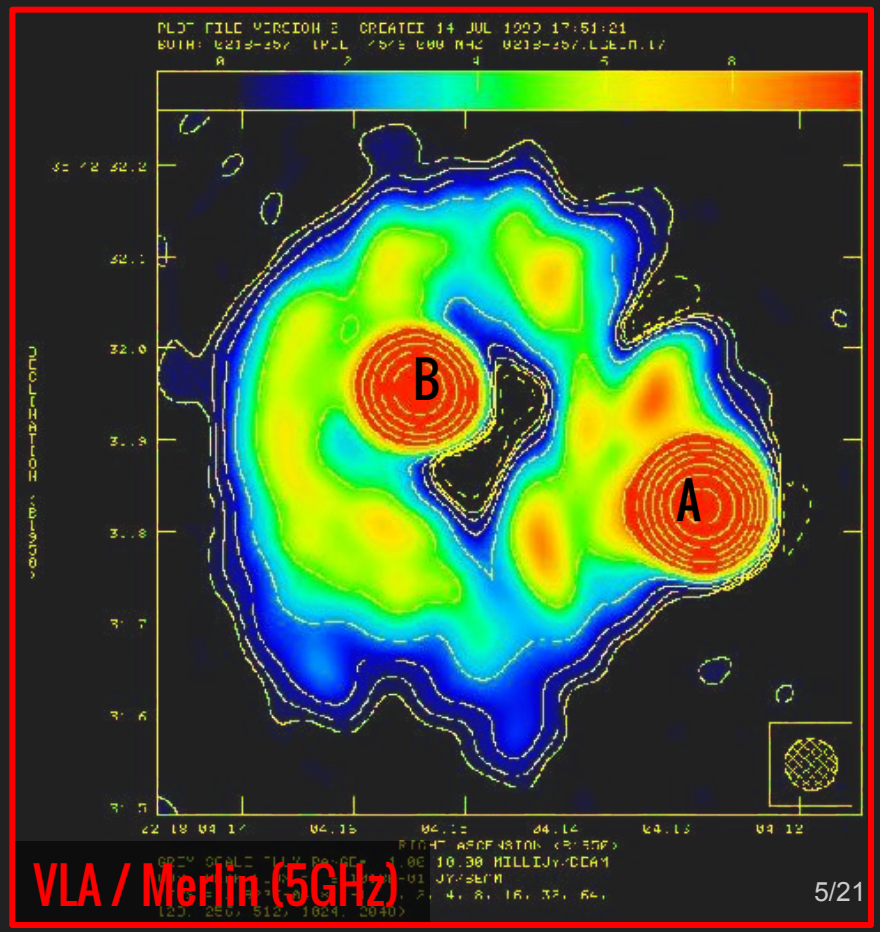
MAGIC stereoscopic system.
Roque de los Muchachos, 2200m a.s.l.
La Palma, Spain

B0218+357: The echo of a distant flare



- Lensing galaxy (Spiral): z = 0.68466 ± 0.00004
- Magnification ratio B/A:
  - Radio: 0.27-0.28 (changes with freq.)
  - HE gamma-rays: ~1 (2012)
- Magnification is wavelength dependent, interpreted as microlensing + changes in the star configuration + changes in the lens itself (free-free absorption in ratio).

- HST & Radio reveal 2 emission components, separated 335 mas + Einstein ring.
- Time delay 10.5 +/- 0.2 days



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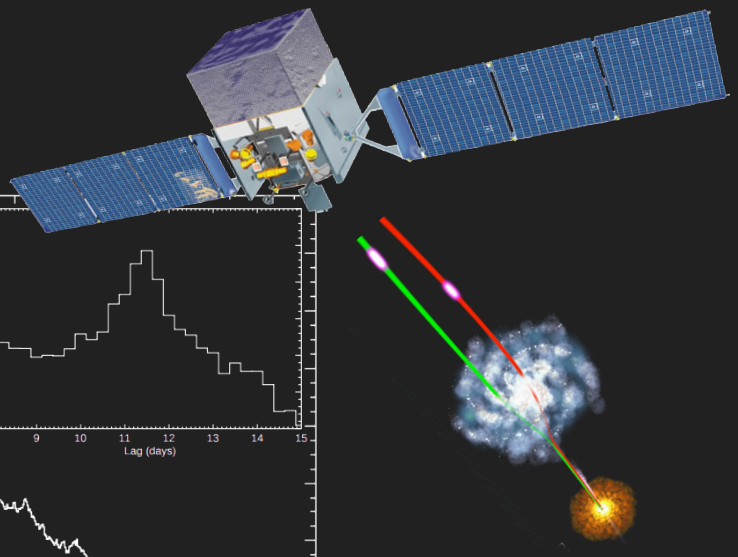
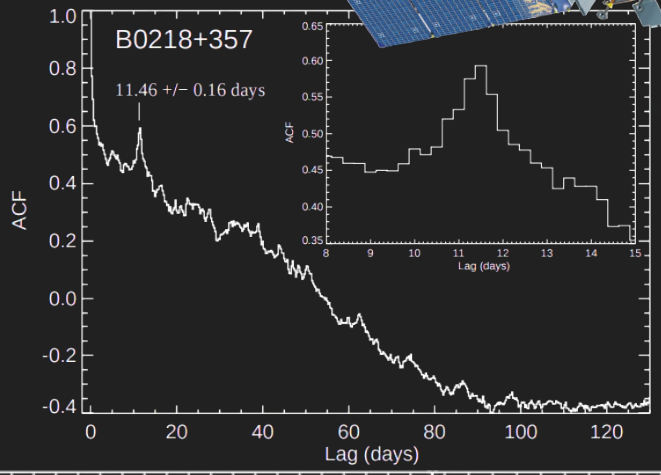
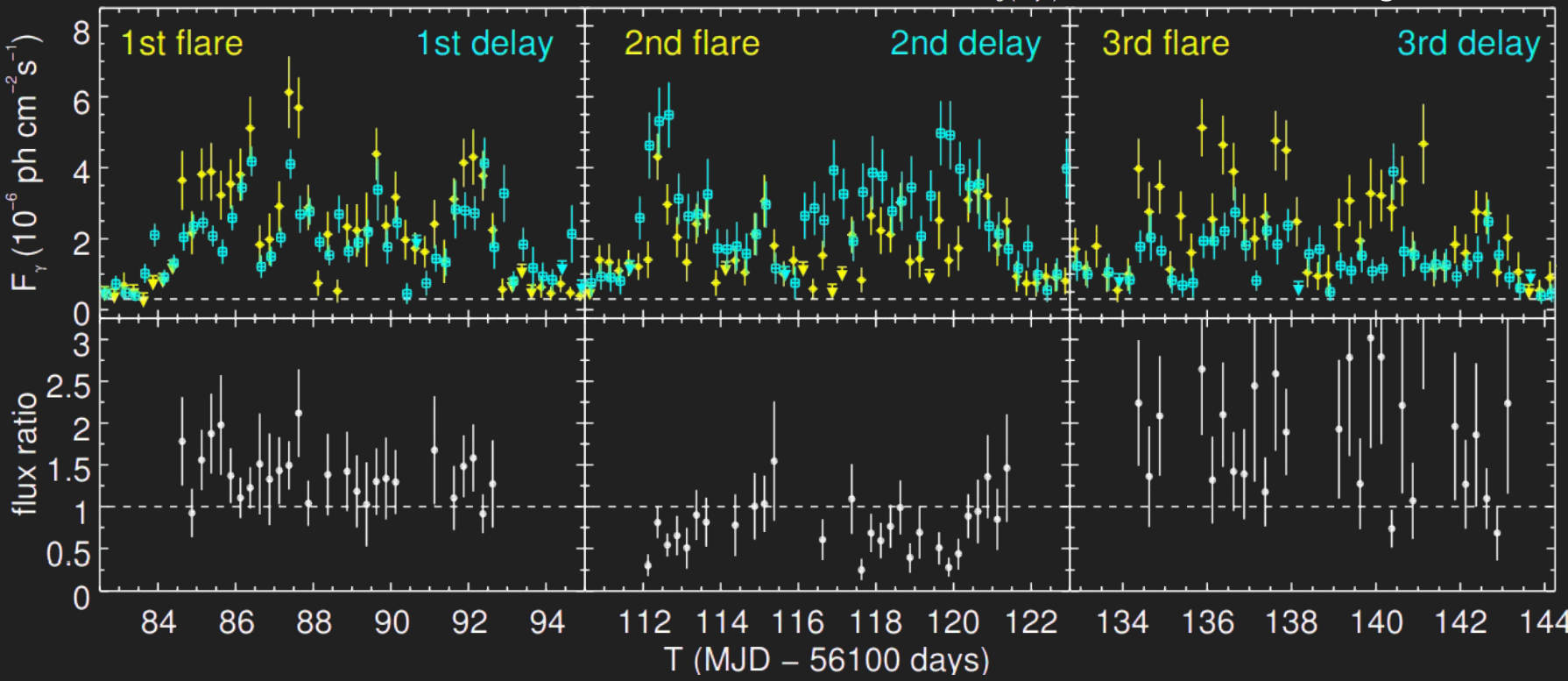


2012 Flare

- Series of outburst.
- ACF analysis: 11.46 ± 0.16 days (9σ)
- Magnification in HE ~1.
- Γ = 2.30 ± 0.03 (2.28 ± 0.03, 3FGL).



Cheung et al. 2014



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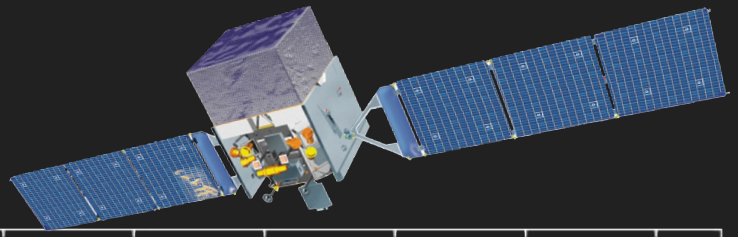

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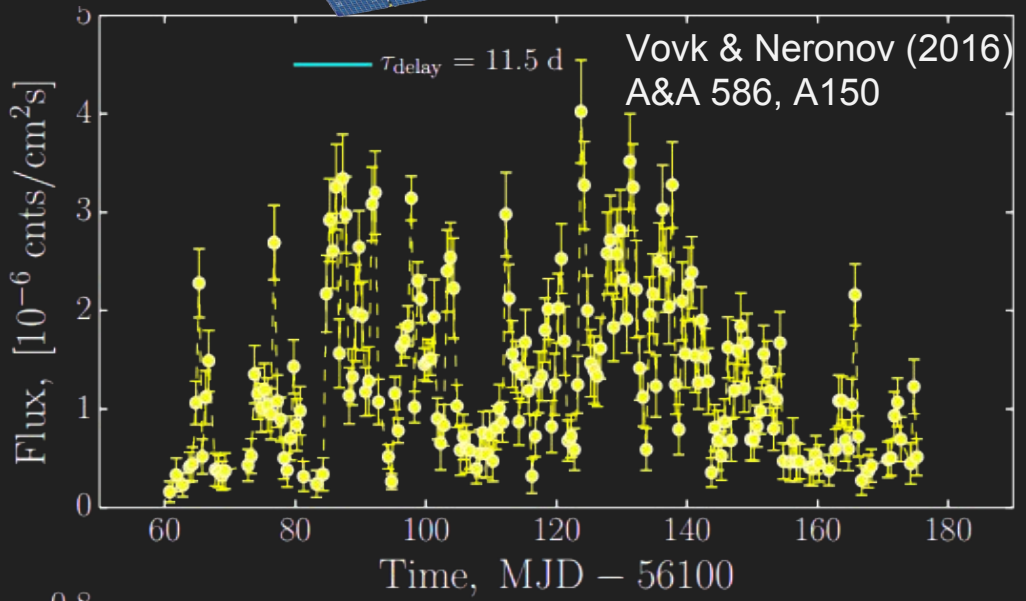
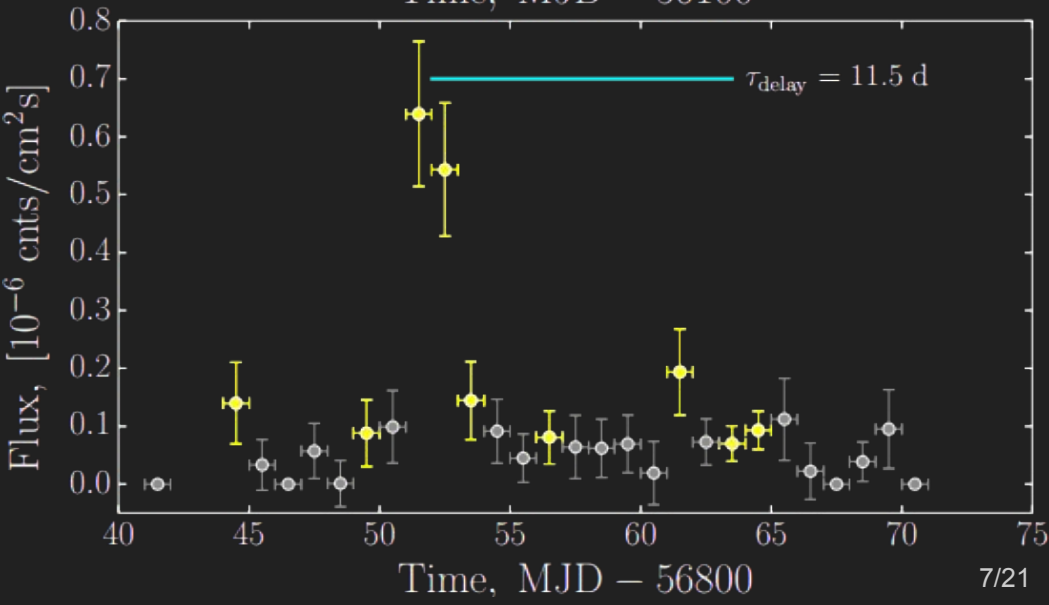


2014 Flare

- Short outburst (~2d) on July 13-14th.
- Leading comp:
  - Hard spectrum, α~1.4-1.6 (and a 94 GeV HE photon)
  - Magnification factor: ~ ¼ (LAT)
  - Not observable with MAGIC (Full Moon break).
- Trailing comp observations scheduled. **Detection by MAGIC, Swift-XRT & KVA.**



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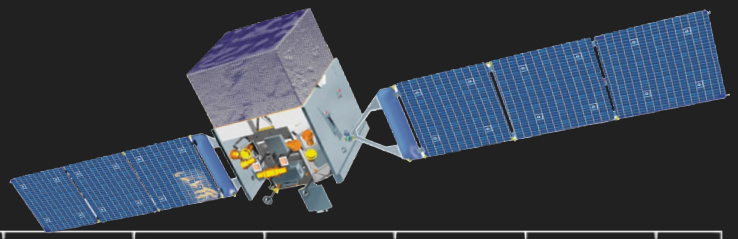

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2014

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  Detect GIC, Swift-XRT & KVA.

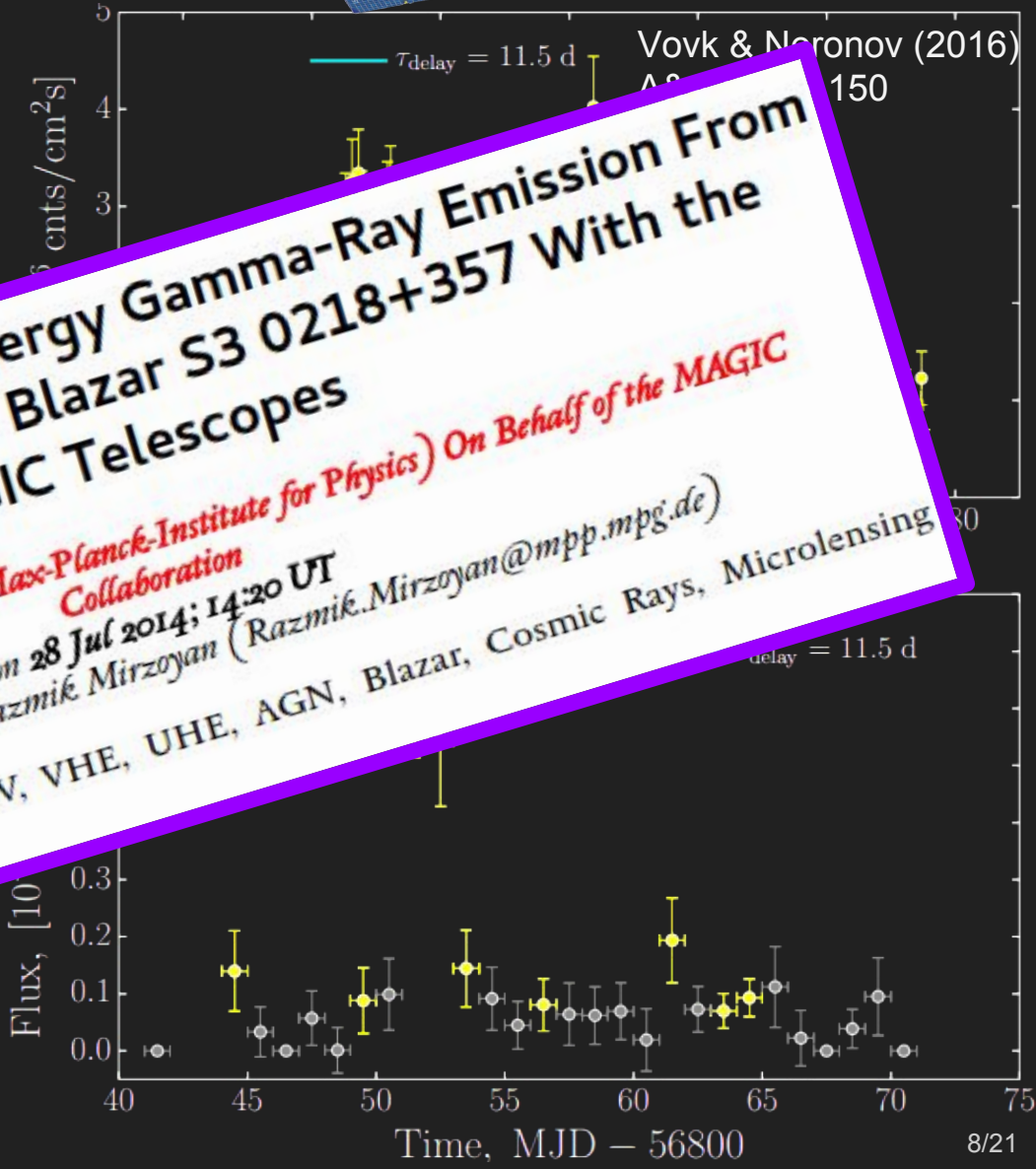
Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

ATel #6349; Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration
on 28 Jul 2014; 14:20 UT

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

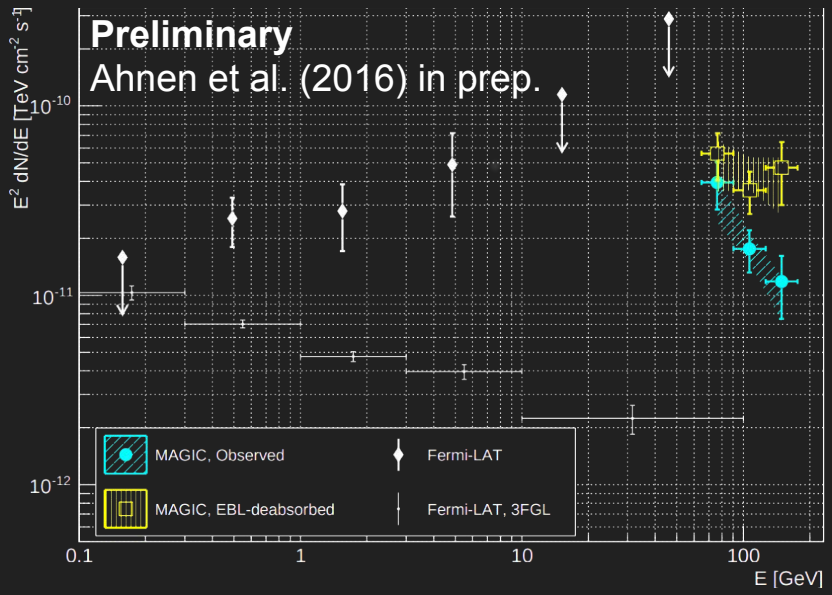
Subjects: Gamma Ray, >GeV, TeV, VHE, UHE, AGN, Blazar, Cosmic Rays, Microlensing

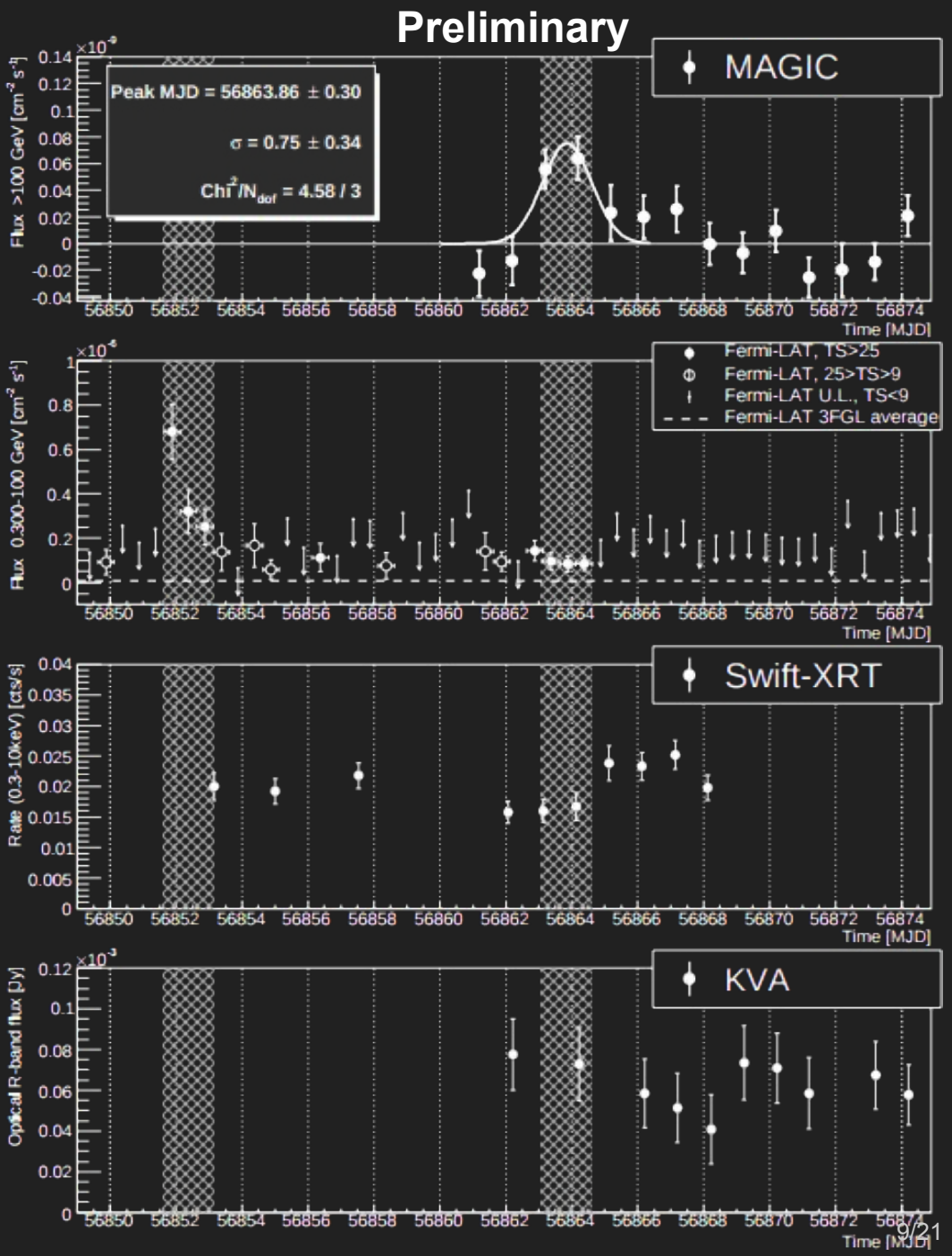
Event



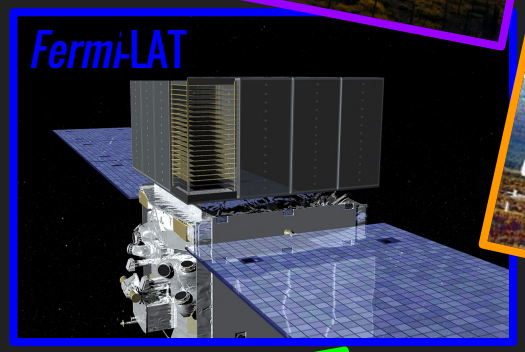
B0218+357: MAGIC + MWL

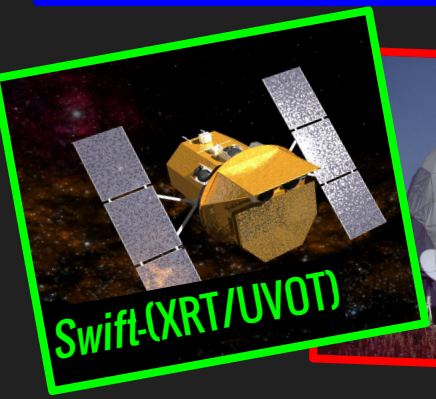
- MAGIC observed signal found in the 2 expected nights (assuming a delay of 11.5 days). High state not visible in other wavelengths.
- For the first time in VHE, we could anticipate a flaring state.
- VHE universe expanded from z=0.6 to z=0.94.
- Follow-up (~2 weeks) showed no signal.





PKS 1441+25. From VHE Gamma-rays to Radio





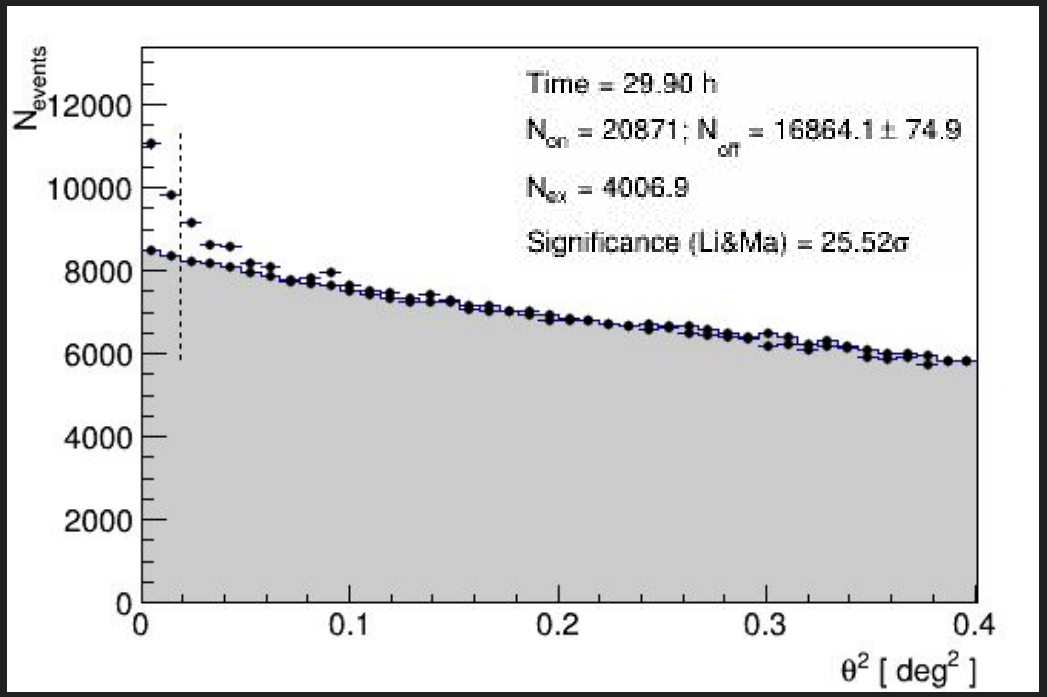
Source details

- **Classification**: FSRQ (Abdo et al. 2010a; Nolan et al. 2012; Ackermann et al. 2013).
- **Redshift**:
  - $z = 0.9397 \pm 0.0003_{stat}$ (SDSS)

Instruments

- **MAGIC** (VHE gamma-ray): E> 50 GeV
- ***Fermi*-LAT** (HE gamma-ray) : 0.1<E<300 GeV
- **NuSTAR** (Hard X-ray): 3<E<79 keV
- ***Swift*-XRT** (X-rays)
- ***Swift*-UVOT** (UV/optical)
- **KVA** (optical-R)
- **Hans-Haffner-Telescope** (optical-R)
- **CANICA** (IR: J, H, and K_S bands)
- **CARMA** (Radio. *27-270 GHz*)
- **Metsähovi** (Radio, *2-150 GHz*)
- **OVRO-40m** (Radio, *15 GHz*)

PKS 1441+25. VHE observations with MAGIC & LAT



- Observations started on Apr 17-18 2015 after a high state alert from *Fermi*-LAT (E>10GeV), optical and X-Rays.
- MAGIC detected the source with 6σ on Apr 17-18 (2h) and on Apr 18-19 (4h) again, with more than 11σ.
- After 10 days of continuous monitoring (30h), the significance >25σ (4010 ± 160 gamma-ray like events).
- No signal was detected in May (after the Moon break).

Results published in ApJL: http://iopscience.iop.org/article/10.1088/2041-8205/815/2/L23
http://arxiv.org/abs/1512.04435

- VERITAS observations were triggered by MAGIC results. VHE signal was confirmed with >5σ during the night of April 21, 2015

http://iopscience.iop.org/article/10.1088/2041-8205/815/2/L22
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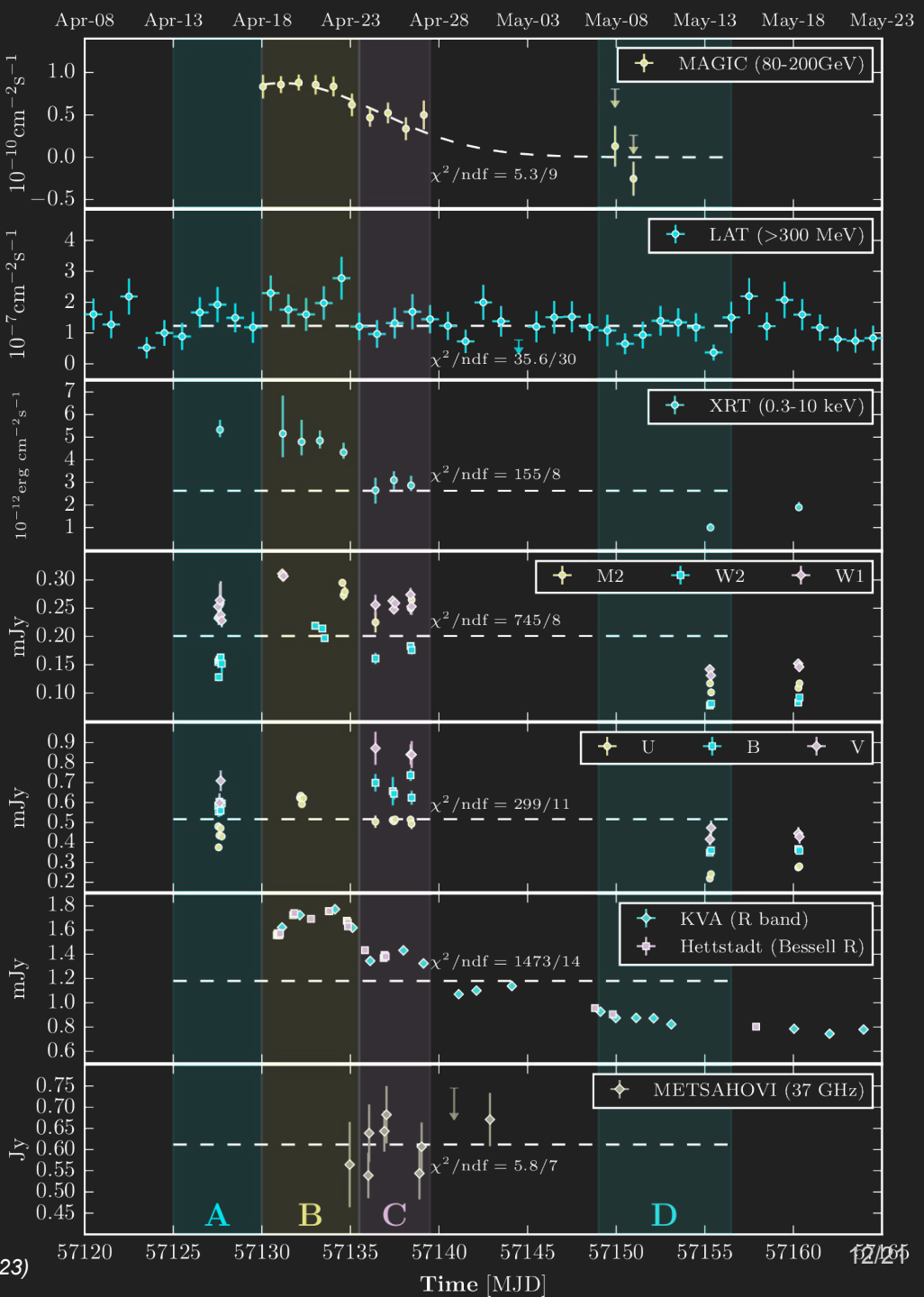
Multi-wavelength flux evolution.

- The data is divided in 4 periods: A, B, C, D according to the source flux level.

- No-variability hypotheses discarded:
  - B+C+D: χ^2/ndf = 52.5/11, P=2.2e-9
  - B+C: χ^2/ndf = 26.0/9, P=2.1e-3.
- Halving flux time (Gaussian):
  - 6.4 ± 1.9 d (VHE)
  - 7.6 ± 1.7 d (X-rays)
- Mean flux ratios among periods (F_B/F_C):
  - VHE: 1.80 ± 0.27
  - HE: 1.40 ± 0.29
  - X-rays: 1.58 ± 0.17
- No intra-night variability detected (VHE).

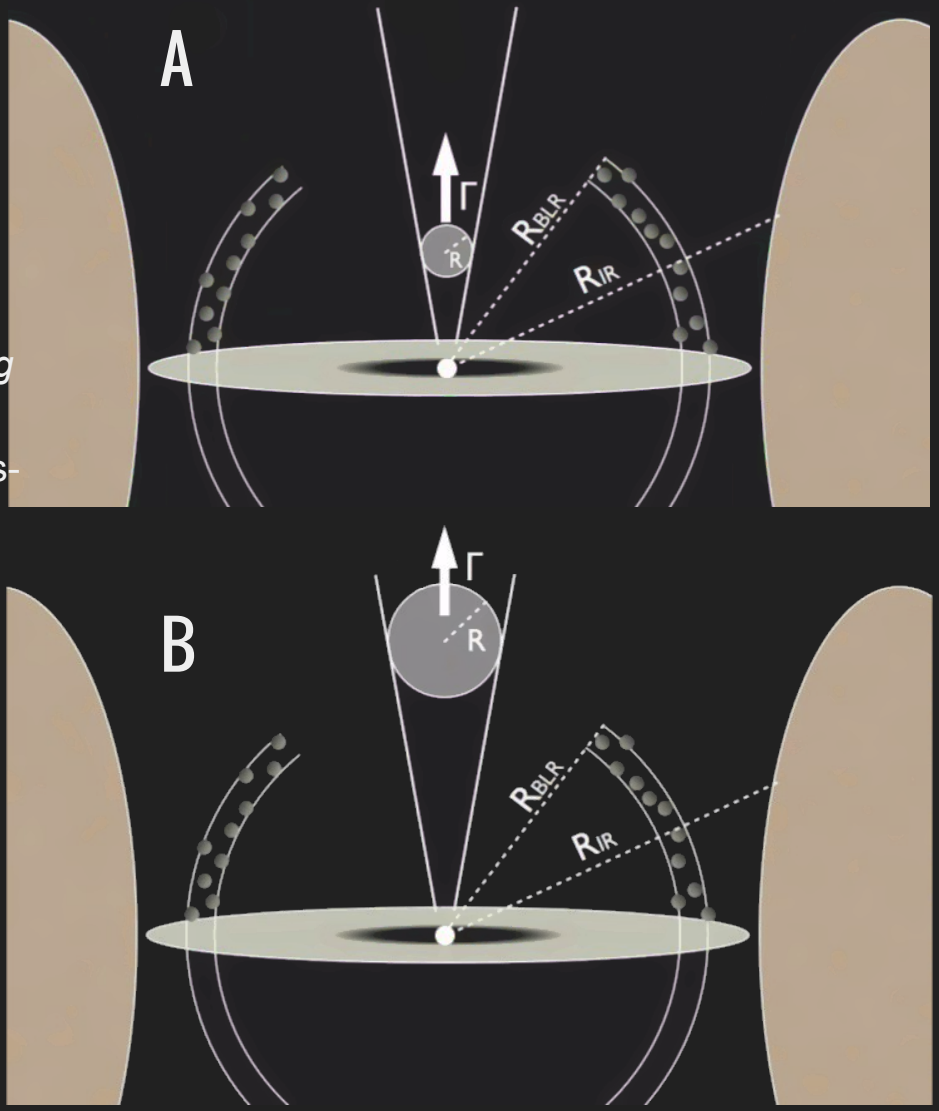


Ahnen et al. (ApJL, 2015, 815, L23)

Emission models for FSRQs

Ingredients:

- External radiation field (thermal rad. of the dusty torus / reprocessed disk radiation @ BLR).
- IC Scattering with relativistic e- in the jet. *Softening expected at ~ GeV (KN cutoff).*
- Spherical emission region with radius R ~ jet cross-section and bulk Lorentz factor Γ. Cases:
  A. Inside BLR
  B. Outside BLR



std one-zone model

Dermer et al. 2009
Ghisellini&Tavecchio 2009
Sikora et al. 2009

Emission models for FSRQs

Before EBL absorption!

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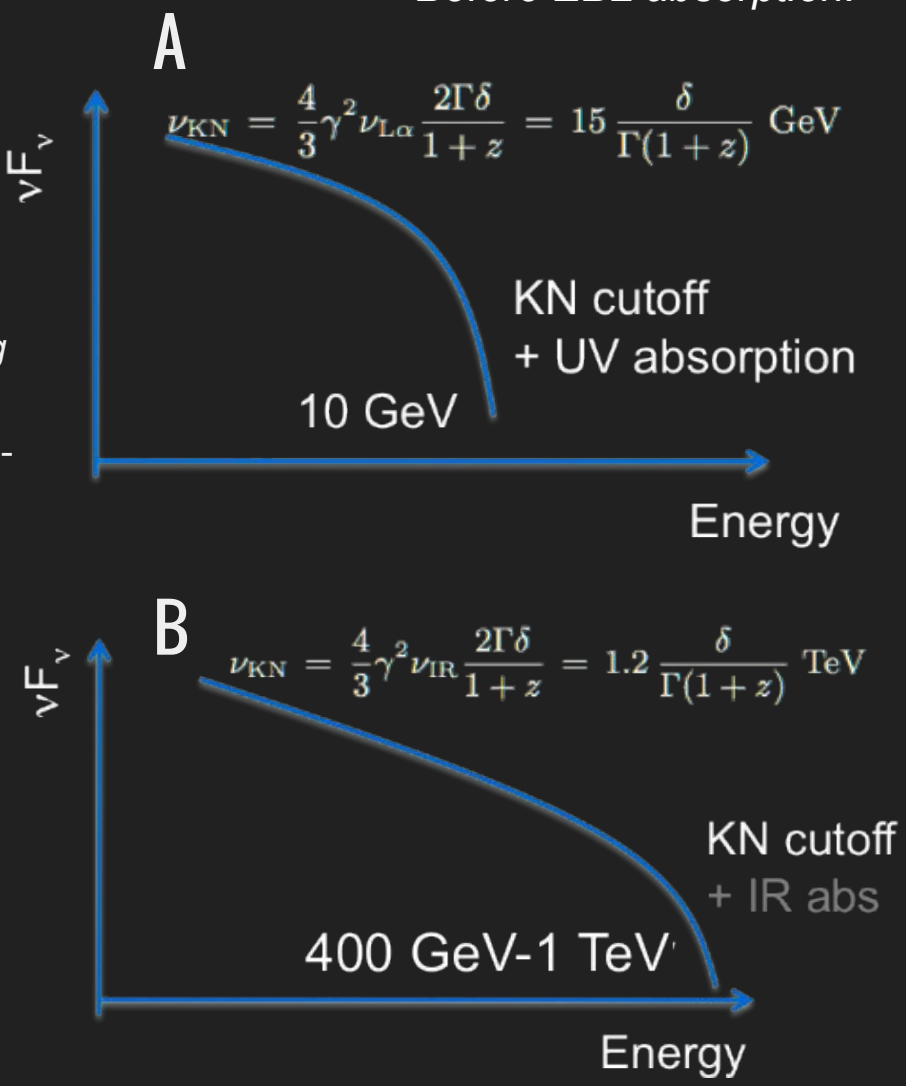
Case A:

- Gamma-rays interact with UV photons from the BLR → strong absorption at ~ GeV

Case B:

- Gamma-rays interact with IR photons from the torus → strong absorption at ~ TeV



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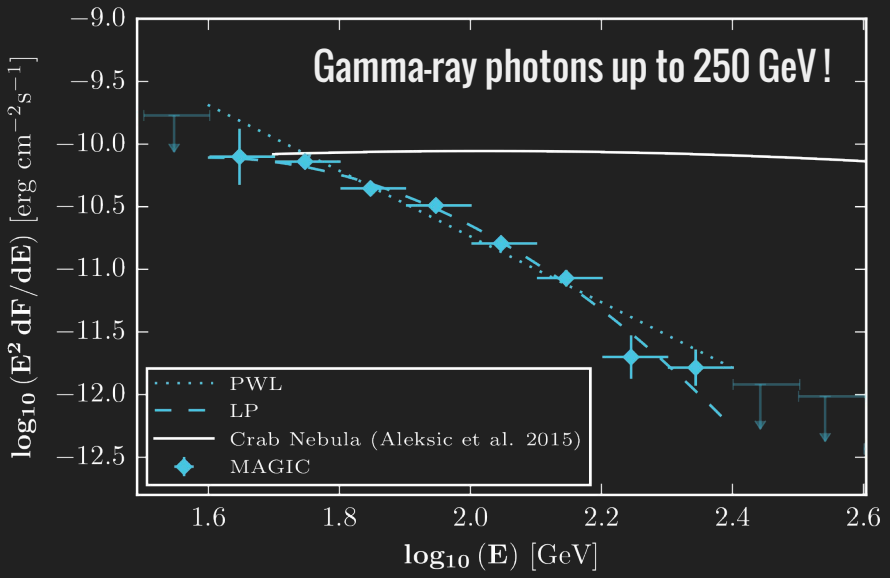

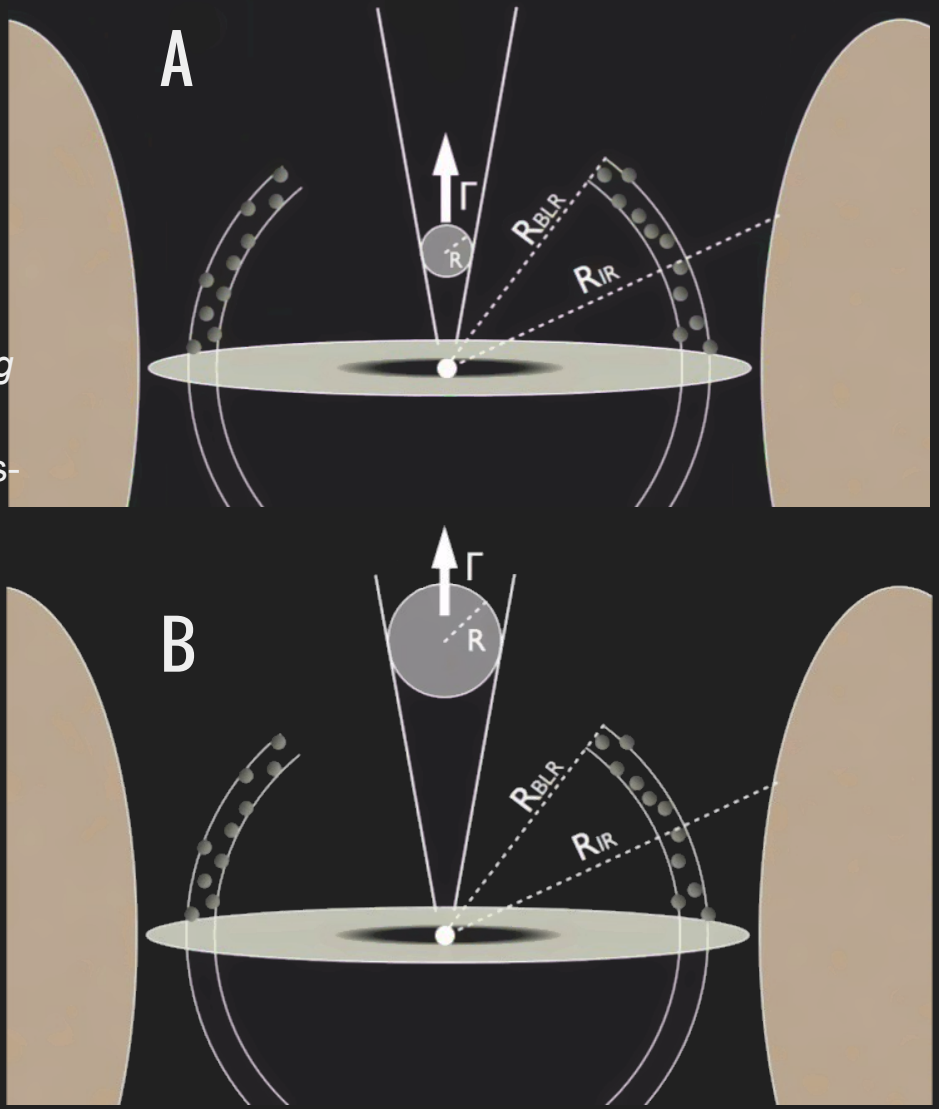

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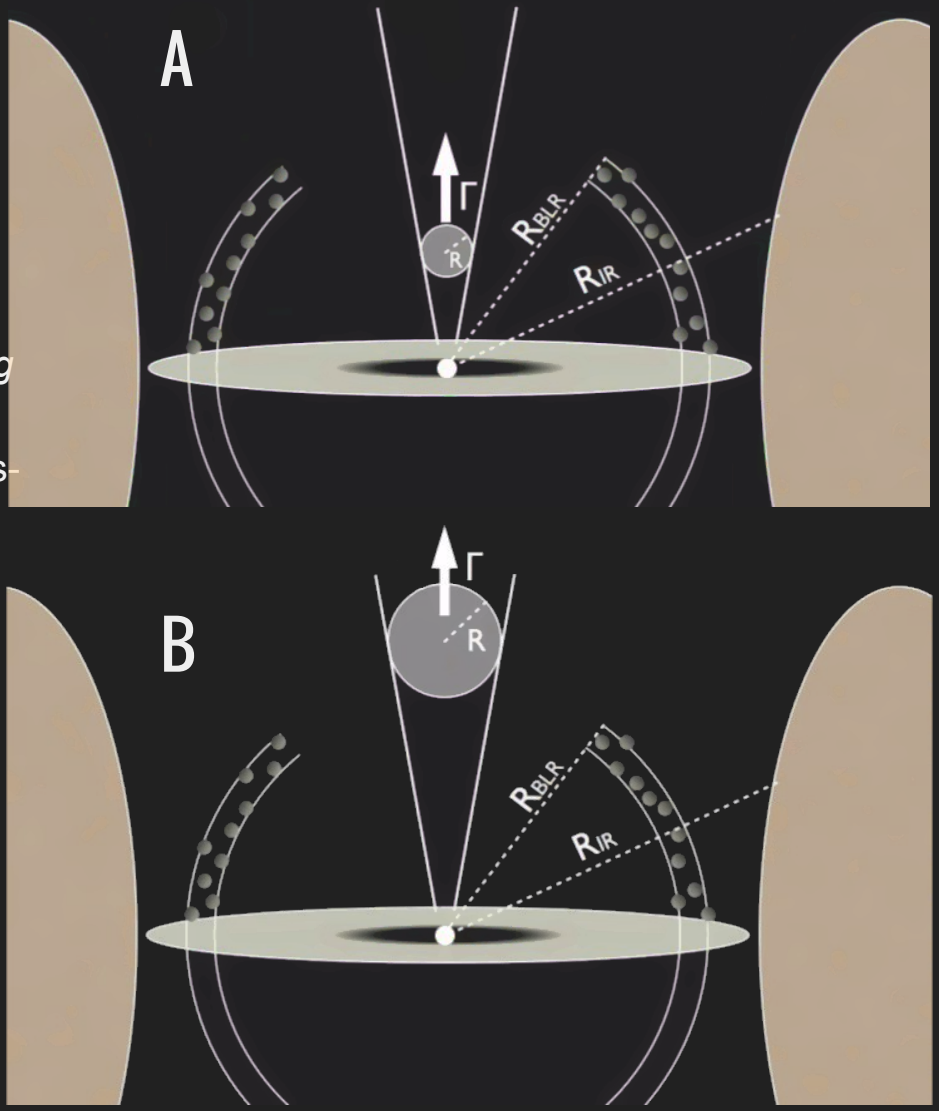

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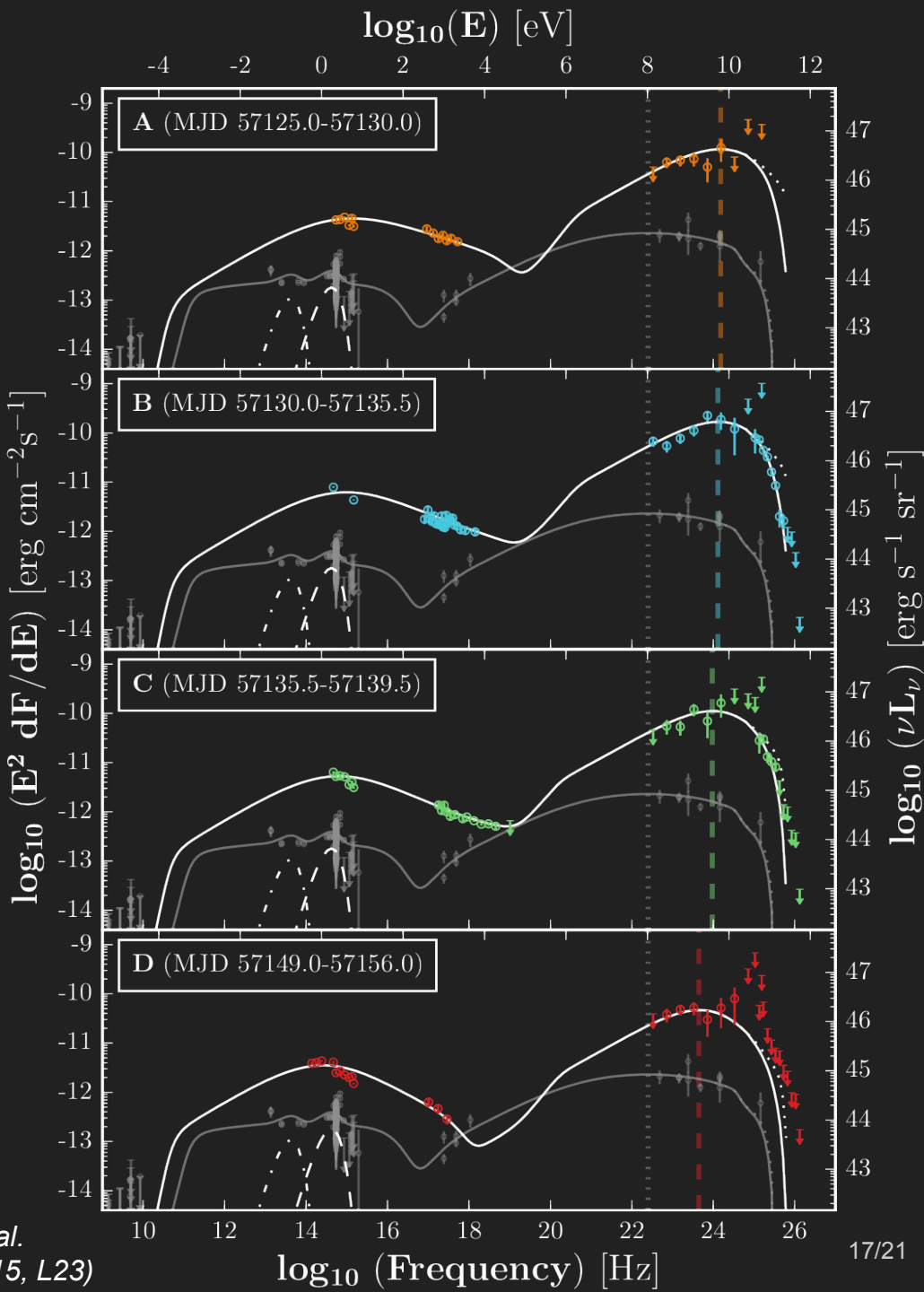
The ‘far dissipation’ scenario

MWL SEDs for PKS 1441+25 for the four states of the source indicated in Fig. 1.

- **Solid line:** Observed spectrum.
- **Dotted line:** EBL-deabsorbed spectrum (Dominguez et al. (2011)
- **Dashed:** Disk emission.
- **Dash-dotted:** Torus emission.
- **Vertical lines:** Inverse Compton (IC) peaks

Grey: Archival data extracted from ASDC (http://tools.asdc.asi.it) are shown in grey.

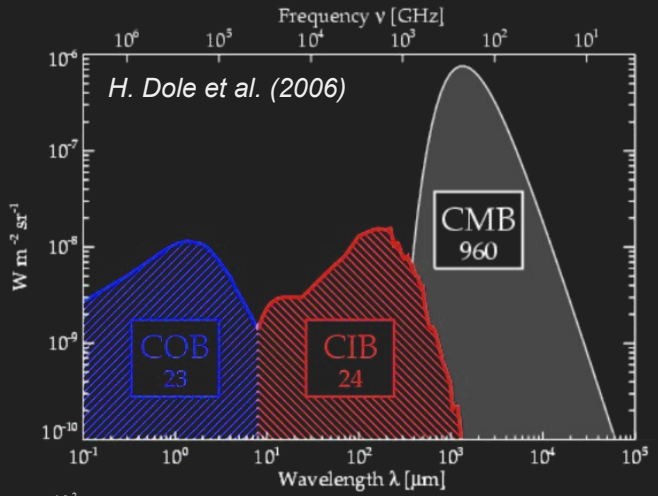
The VHE spectral points not corrected for EBL.

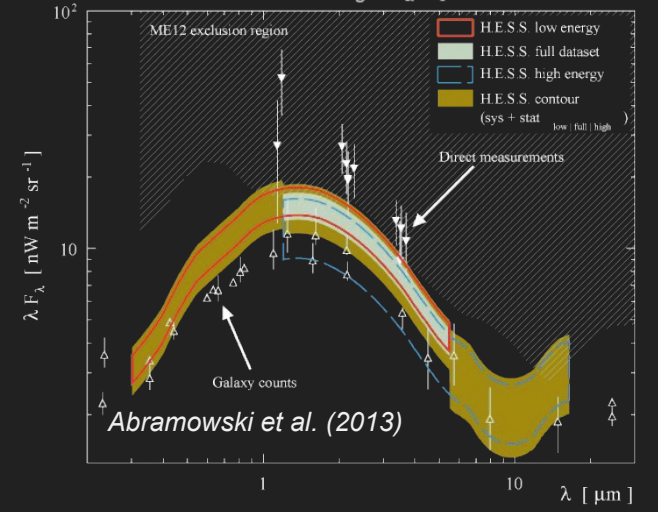


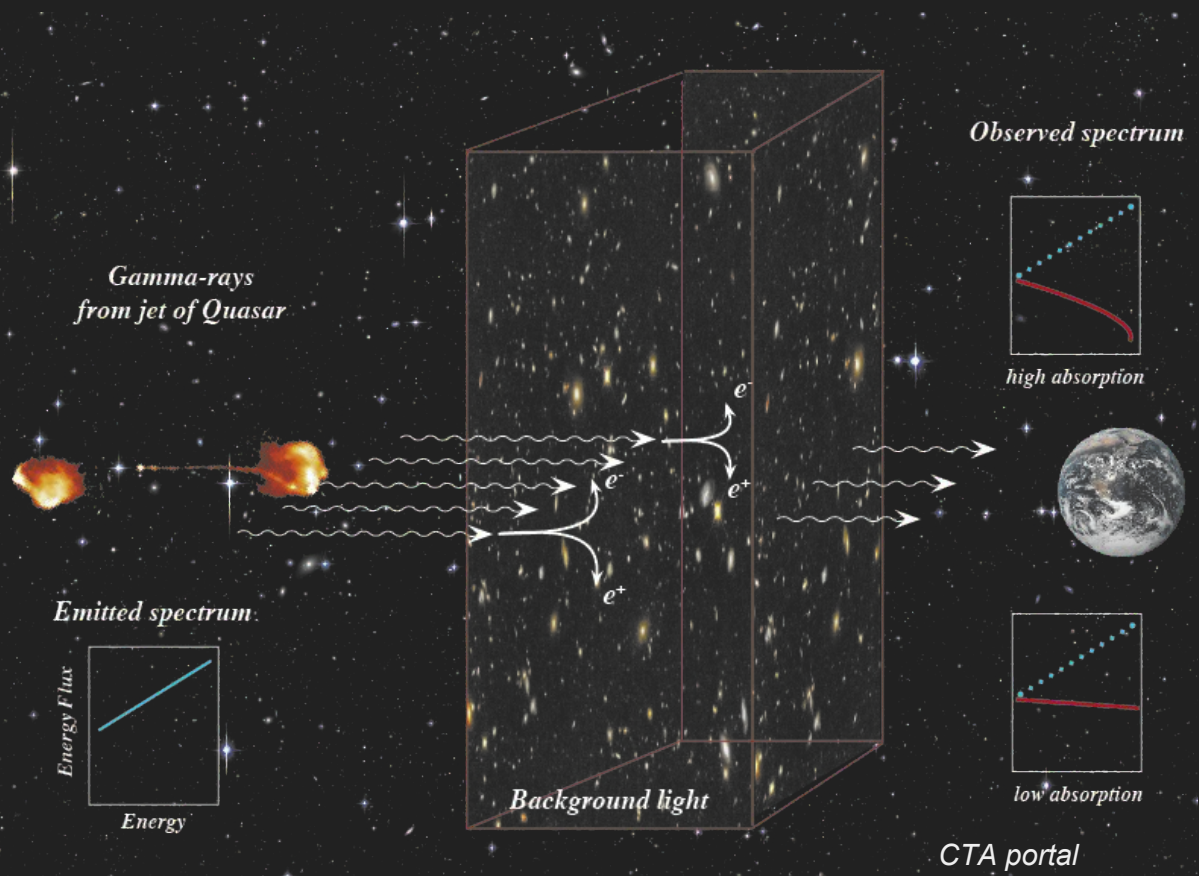
Ahnen et al. (ApJL, 2015, 815, L23)

Extragalactic Background Light

Well known for the local Universe
Worse characterized at high redshift.

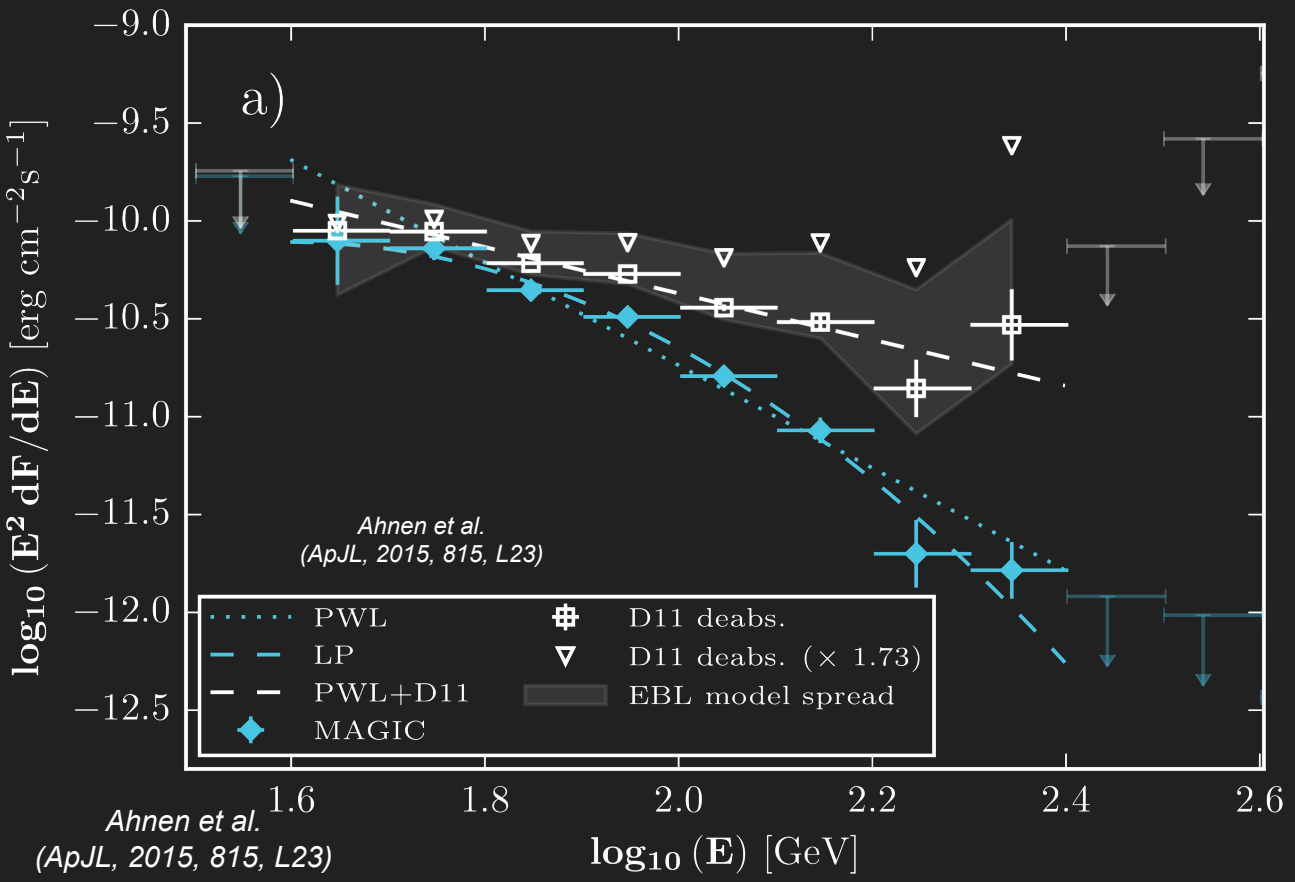






EBL: diffuse radiation (COB+CIB) which absorbs GeV-TeV radiation via pair e^+ e^- production.
Direct measurement, galaxy counts (lower limits), indirect measurements (IACT + Fermi, γ-rays absorption).

Extragalactic Background Light



Ahnen et al.
(ApJL, 2015, 815, L23)

Likelihood Ratio Test (LRT)

$\tau(z,E) = \alpha\, \tau_{model}$

EBL Models considered:

- Dominguez et al. (2011)
- Franceschini et al. (2008)
- Gilmore et al. (2012).
- Scully et al. (2014).

Spectral shapes tested:

- Power-law.
- Log-parabola.
- Power-law with sub/sup. exponential cutoff.

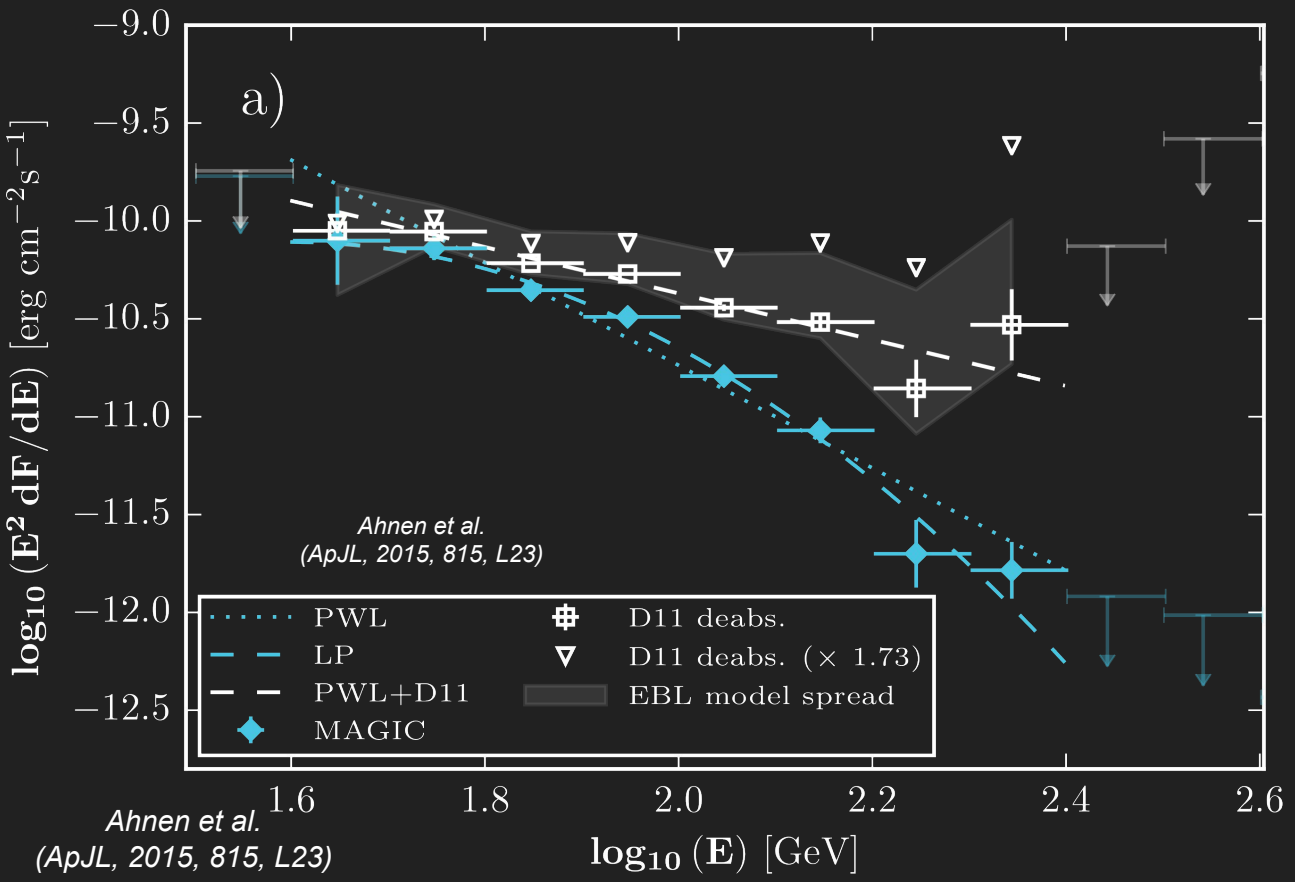
Worst case UL:

$\alpha_{F08} < 1.72$

$\alpha_{F08} = 1.3 \pm 0.4$ ($0.5 \le z \le 1.6$)
[*Ackermann et al. 2012*]

Pros: Strong signal, lack of fast variability (data stacking), high redshift (significant EBL suppression) ...
Cons: Soft spectrum (FSRQ - KN regime), possible cutoff at ~ 1 TeV (source/z=0.94 reference frame) . . . .

Extragalactic Background Light



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$\lambda f_{\lambda=0.45\mu m} < 7.3$ nW cm^{-2}sr^{-1}

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Conclusions

- Fermi-LAT is essential to trigger Cherenkov telescopes!.
- MAGIC detected for the first time VHE emission from the z=0.94 blazars B0218+357 (July 2014) and PKS 1441+25 (April 2015). They are the most distant known VHE sources until date.
- B0218+357 is the first gravitationally lensed QSO detected in VHE, and the first one with a prediction in the flare arrival.
- PKS1441+25's MWL SED is modeled with an External Compton model.
  - The emitting region is constrained to be just outside the BLR by the absence of intrinsic absorption in the HE and VHE regimes.
- Both sources provide the first indirect probes of the EBL at z~1 with a VHE ground based instrument.
  - Measured VHE spectrum is fully consistent with the attenuation caused by the EBL.
  - Upper limits to the EBL density are derived by assuming state-of-the-art EBL models: $\tau(z,E) < 1.73\ \tau_{D11}$