The MAGIC Telescopes: a look into the Extreme Universe

David Paneque

On behalf of the MPP gamma-ray group

MPP Project Review 2018

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MAX-PLANCK-GESELLSCHAFT

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Outline

1 – The MAGIC telescopes *(15th anniversary !)*

2 – The MAGIC MPP group (and overall contributions)

3 – Hardware/Software activities in 2018

4 – Scientific results in 2018

5 – Conclusions

1 – The MAGIC telescopes (and collaboration)

The MAGIC Stereoscopic system

- **MAGIC: Two Imaging Atmospheric Cherenkov Telescopes (IACTs) of 17 meter diameter mirror dish to perform Very High Energy (VHE) gamma-ray astronomy**
  - **Operational energy range ; from 50 (30) GeV to >50 TeV**
  - Sensitivity: 0.7% the Crab Nebula flux (above 220 GeV) after 50 hours observation
    - → About 5% of the Crab Nebula flux in 1 hour of observation
- **The strategy** : *operate until (at least) CTA is in scientific operation (**> 2022**)*
  - 2004 : the Crab Nebula Start scientific operation of MAGIC 1 (Single telescope)
  - 2006 : MAGIC upgraded with the MUX-DAQ system (More stable and Better pulse-information)
  - 2009 : MAGIC upgraded with a second telescope (stereo observations)
  - 2012 : Large Hardware of upgrade of the system (*improved sensitivity and reliability*)

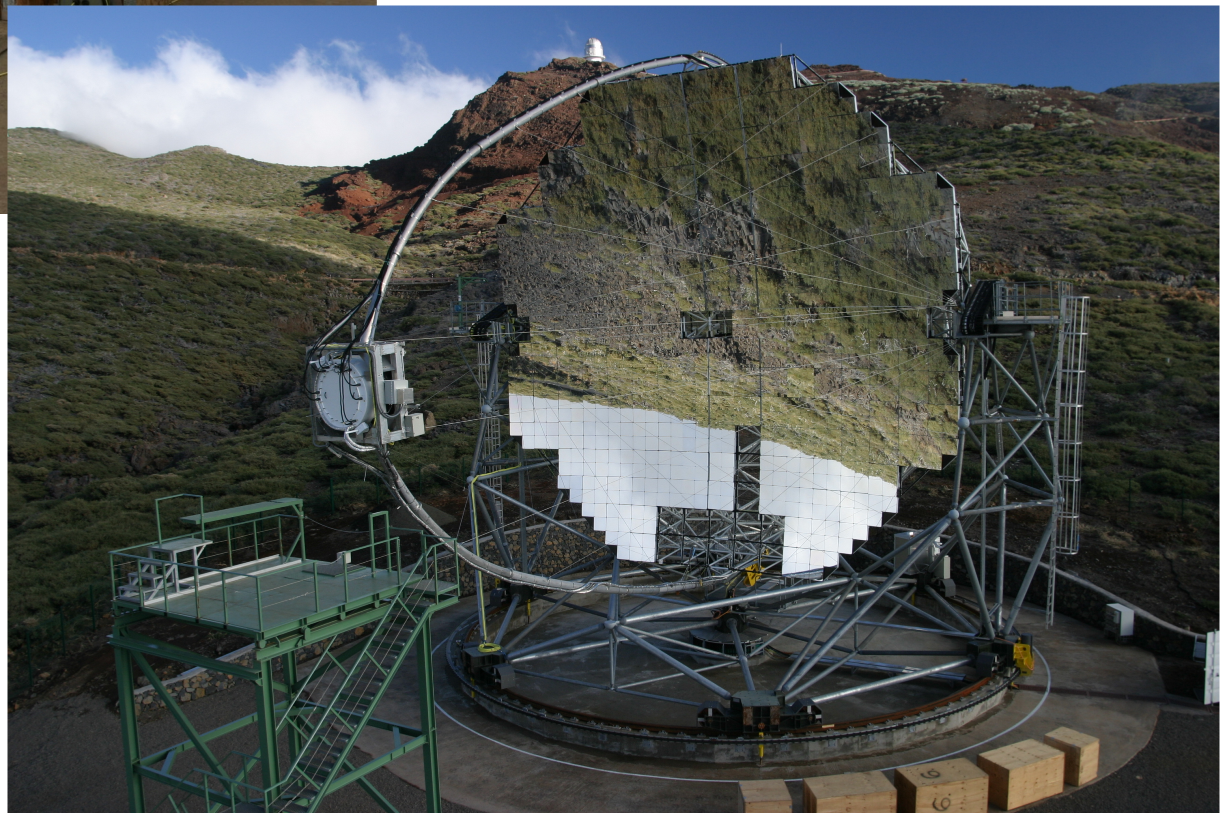

Observatorio Roque de los Muchachos (2200 meter a.s.l.)
La Palma, Canary islands (Spain)

The MAGIC Collaboration

The **MAGIC Collaboration** is composed by ~150 physicists (230 members in total, including technical and administrative staff) from **12 countries**

MAGIC inauguration (@Palma, 2003/10)

October 10, 2003
MAGIC Site
(Roque de los Muchachos,
La Palma)



The basic elements were there, but telescope was actually not fully operational at that moment

15th Anniversary of MAGIC (@Palma, 2018/06)

https://indico.mpp.mpg.de/event/5698/overview

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

Astrophysics + MAGIC

26-29 June 2018
H10 Hotel Taburiente Playa

Europe/Lisbon timezone

- Overview
- Scientific Programme
- Timetable
- Contribution List
- Author List
- My Conference
  - My Contributions
- Registration
  - Registration Form
- Scientific Organizing Committee
- Local Organizing Committee
- Conference Fee
- Accommodation
- Travel
- Confirmed Speakers
- Participants

Hotel Taburiente Playa, La Palma, Ca

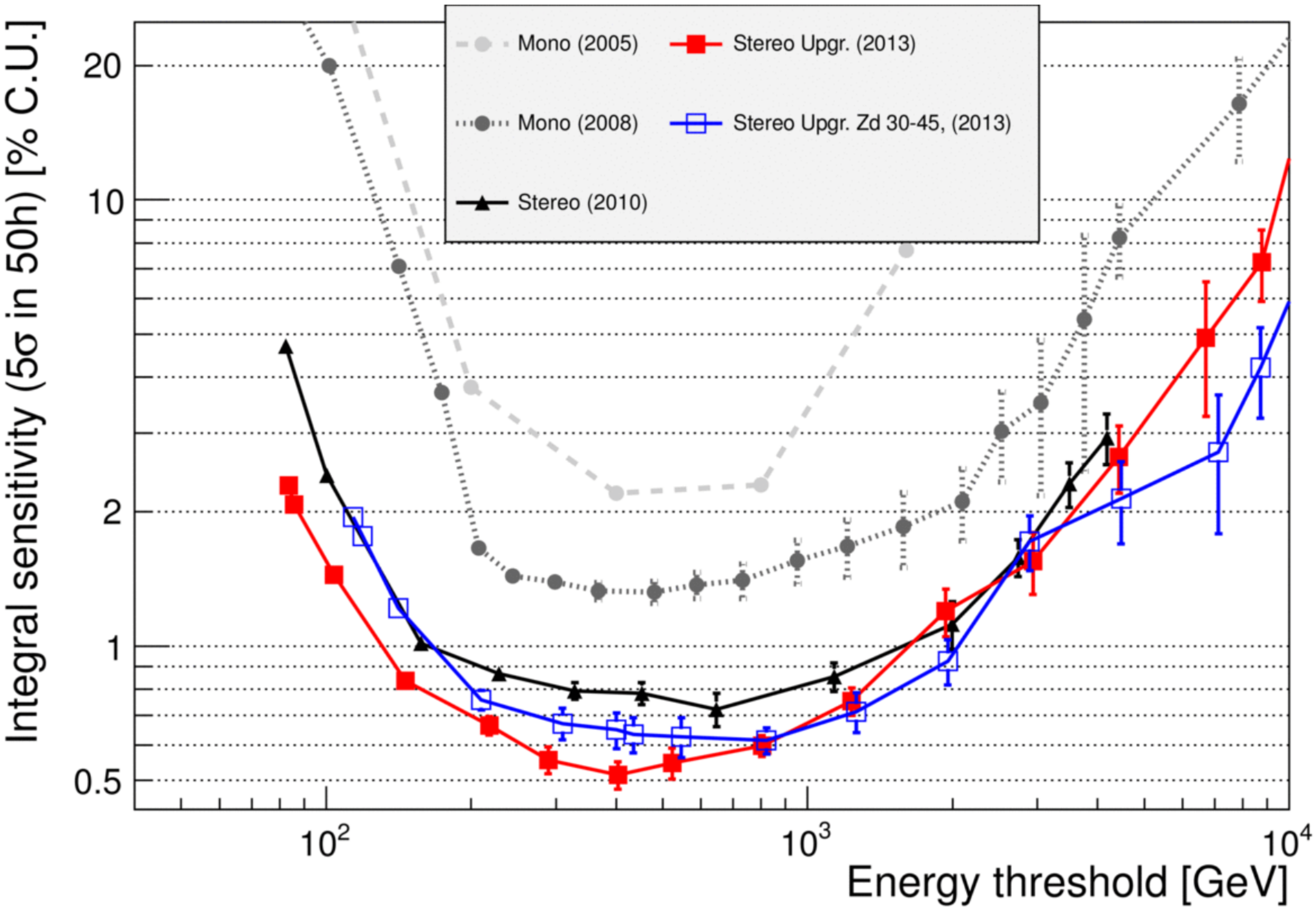
If you want to join us, please register o

Starts 26 Jun 2018 18:30
Ends 29 Jun 2018 23:00
Europe/Lisbon

We cordially invite you to attend the A+M 'Astrophysics and MAGIC (A+M)' Conference, which will focus on presentations highlighting the technical and scientific accomplishments in physics of cosmic and gamma rays, in cosmology, neutrino and gravitational waves and the newly born multi-messenger astronomy. We consider a scientific conference to be a most suitable setting for celebrating 15 years of MAGIC IACT operation.

Evolution of the MAGIC Performance

4-fold improvement in sensitivity over the last 15 years



Aleksic et al., (MAGIC collab.) Astroparticle Physics 72, 76-92, 2016

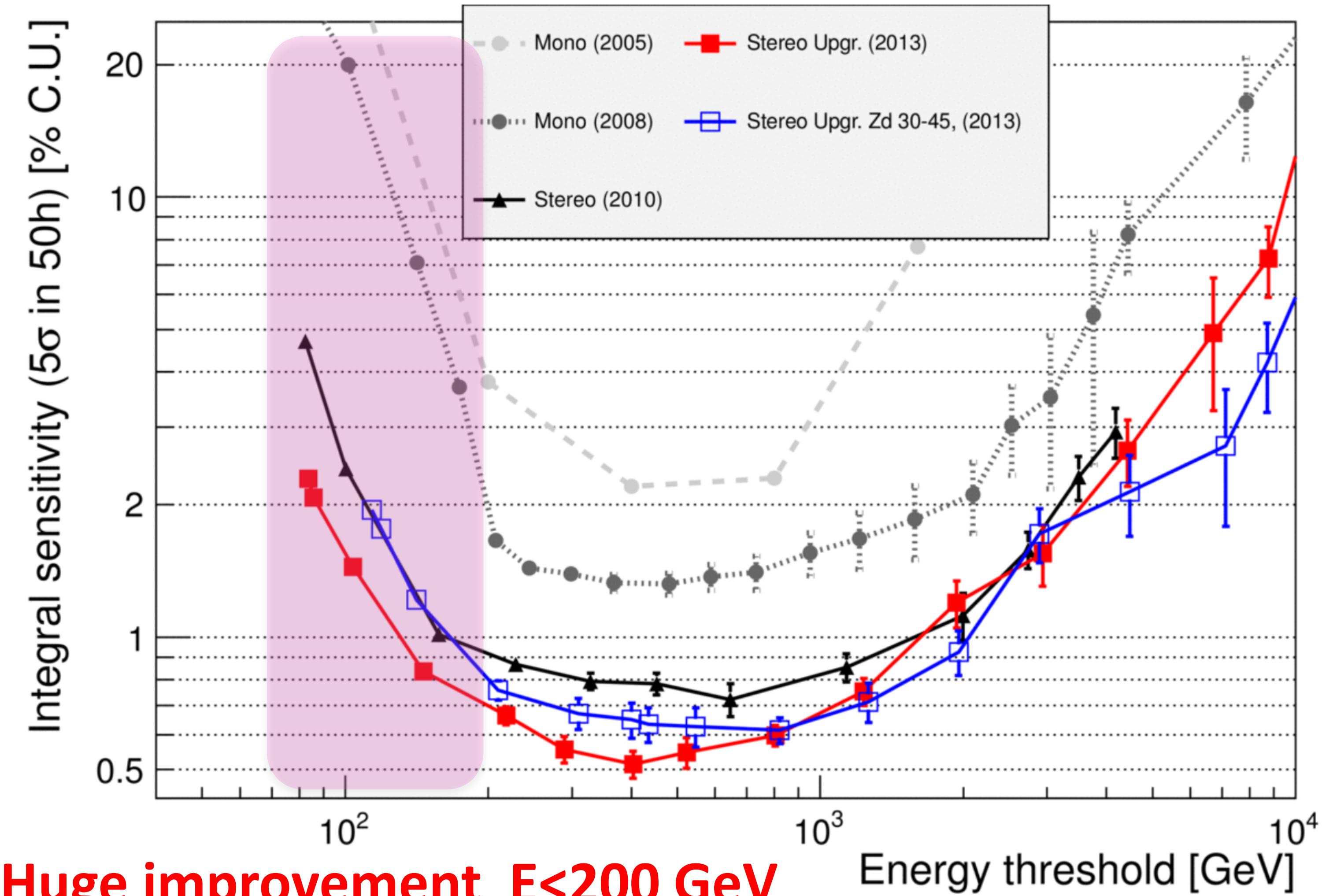
Better sensitivity + Lower energy threshold = More science !!

Evolution of the MAGIC Performance

4-fold improvement in sensitivity over the last 15 years

→ More than 10-fold improvement below 200 GeV

→ Obs. time for detection reduced 100 times below 200 GeV



Aleksic et al., (MAGIC collab.) Astroparticle Physics 72, 76-92, 2016

Huge improvement E<200 GeV

Better sensitivity + Lower energy threshold = More science !!

2 – The MAGIC MPP group
(and overall contributions)

The MPP experimental gamma-ray group

Scientists : 20 physicists (2018)

Director: Masahiro Teshima

Senior (3): Razmik Mirzoyan, Thomas Schweizer, David Paneque

Postdoc (5+2): Ievgen Vovk, David Green, Moritz Huetten, Martin Will, Yusuke Suda, *Derek Strom, Giacomo D'Amico*

PhD Students (7): Uta Colin (*Menzel*), Yating Chai, Juliane van Schenperberg, Alexander Hahn, Kazuma Ishio, Giovanni Ceribella, Marcel Strzys

Undergraduate (2): Stefan Keller, Daniel Hoff

Visitors: *Michele Peresano, Darko Zaric, Tomohiro Inada, Yuki Iwamura, Satoshi Fukami, B. Banerjee …*

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Undergraduate (2): Stefan Keller, Daniel Hoff

MAGIC (and CTA) gets a CRUCIAL support from the mechanical and electrical engineer departments from MPP

O. Reimann, T. Haubold, D. Fink, M. Fras, H. Wetteskind, S. Horn, S. Tran C. Jablonksi, R. Stadler, W. Haberer, S. Schmidl, T. Dettlaf, J. Schlammer …

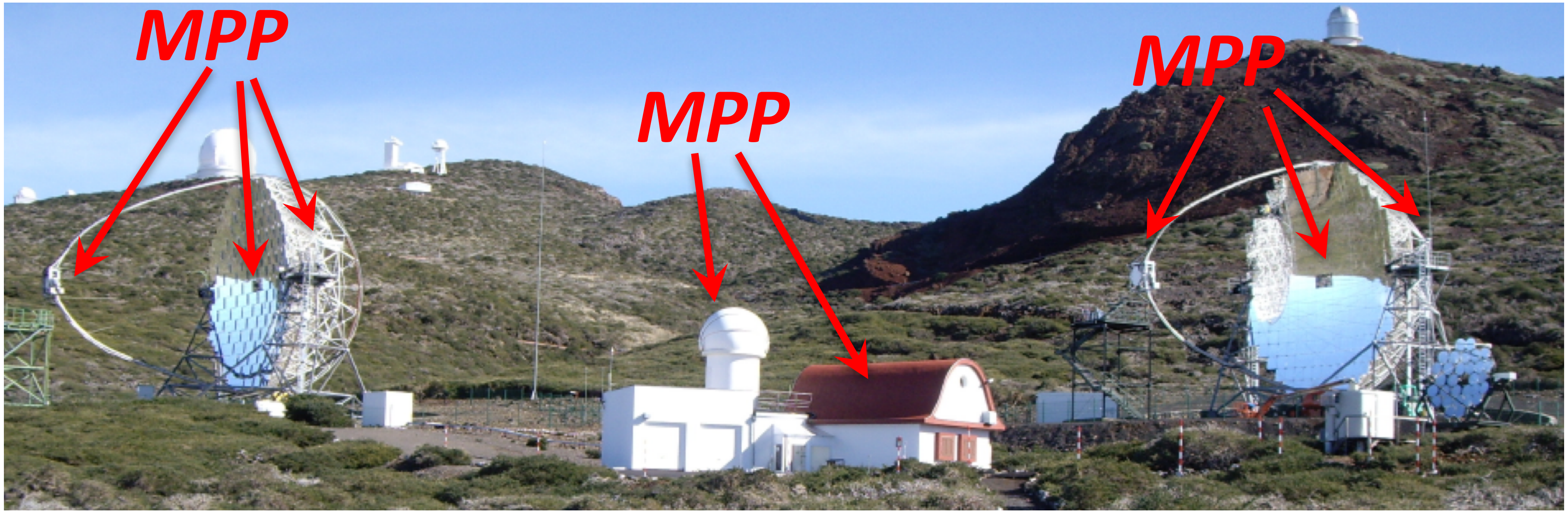
MPP activities with/within MAGIC

MPP is the group with most resources within the MAGIC collaboration

→ ***MAGIC was born at MPP (E. Lorenz & R. Mirzoyan in mid 90s)***

→ ***Most hardware was designed, built and now maintained by MPP***

2 Telescope structures (cooperation with company MERO)
2 Telescope cameras + 2 Calibration systems
LIDAR (for monitoring atmospheric conditions)
Sum-Trigger-II (for lowering energy threshold)
Support instrumentation for Very Large Zenith Angle observations
Starting to produce also mirrors (with novel technology)



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Involvement at all levels: Organizational, hardware, software, science

Spokesperson (Razmik Mirzoyan)
Contact MAGIC-LST (Masahiro Teshima)
Physics coordinator (David Paneque)
Technical coordinator (Martin Will)

→ **4 MPP members in MAGIC Executive Board (*11 members in total*)**

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→ **4 MPP members in MAGIC Executive Board (*11 members in total*)**

Astroparticle and fundamental physics coordinator (Moritz Huetten)

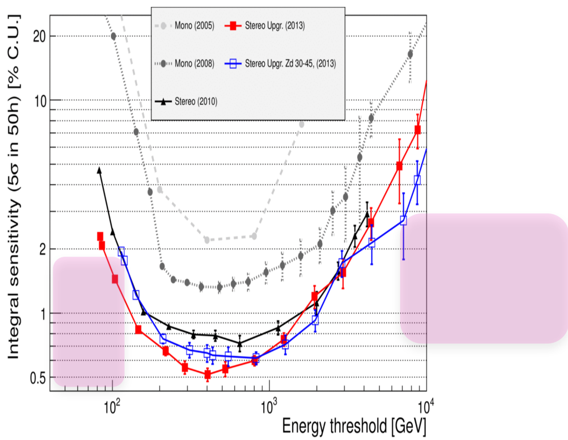
Galactic group coordinator (David Green)

Sum-Trigger coordinator (Thomas Schweizer)

→ *improve performance at lowest Energies*

Very Large Zenith Angles coordinator (Ievgen Vovk)

→ *improve performance at highest Energies*



3 – Hardware/software activities in 2018

Remark:

Because of limited time for this talk, I will not report about the regular (yearly) activities related to the maintenance of the telescope structure, camera, calibration system, LIDAR …

All these activities are CRUCIAL for the standard operation of the MAGIC telescopes, and are done, mostly, by MPP mechanical&electronic engineers and technicians (*H. Wetteskind, D. Fink, M. Fras, T. Dettlaf, J. Schlammer …)*

I will only (very briefly) report activities that are non-conventional, and explore new ways of improving the current system, or aim to make path for new future systems

Development of strategies to improve the performance at the lowest energies : Sum-Trigger-II system.

Work coordinated by Thomas Schweizer

(+Derek Storm, Giovanni Ceribella, Toni Dettlaff …)

Allows MAGIC to decrease energy threshold down to 30 GeV
→ Crucial for pulsars and distant sources (z>1)

Commissioned and started some scientific observations in 2016/2017. But Technical problems hampered its performance during the first 9 months of 2018.

Fixed after Intervention in August+September 2018
(Thomas Schweizer, Derek Strom and Giovanni Ceribella)

Sum-Trigger is starting to deliver new exciting results
First detection of Geminga pulsar at VHE (*preliminary*)

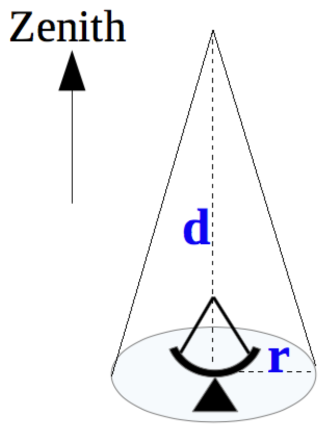
Development of strategies to improve the performance at the highest energies : Very Large Zenith Angle Obs.

Work coordinated by Ievgen Vovk

(+J. van Scherpenberg, M. Peresano, D. Zaric…)

Vertical observations

typical for IACTs

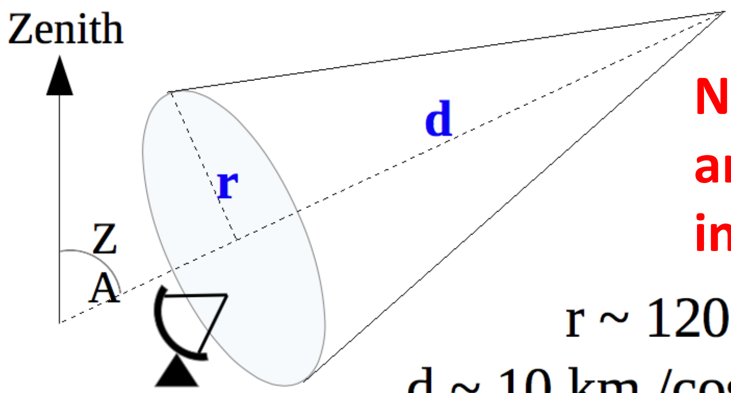


d ~ 10 km

r ~ 120 m

Large zenith angle observations

proposed



Need small pixels and good time information

r ~ 1200 m

d ~ 10 km /cos(ZA) ~ 100 km

MAGIC has this possibility. HESS and VERITAS have difficulties because of larger pixel sizes and worse time information

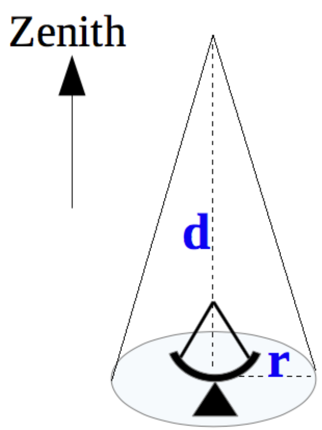
Development of strategies to improve the performance at the highest energies : Very Large Zenith Angle Obs.

Work coordinated by Ievgen Vovk

(+J. van Scherpenberg, M. Peresano, D. Zaric…)

Vertical observations

typical for IACTs



d ~ 10 km

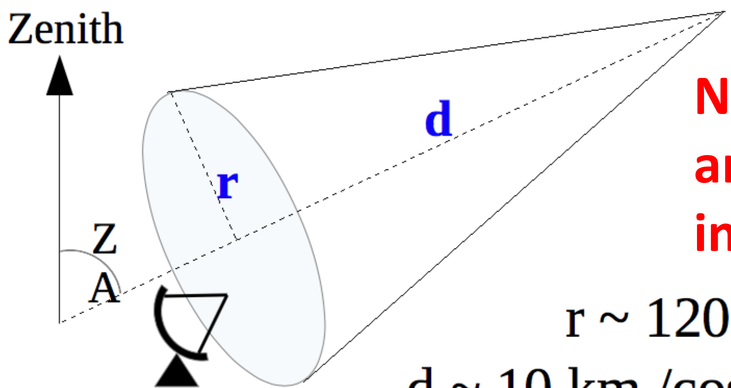
r ~ 120 m

Possibility to get effective areas comparable to those of CTA

(although with larger cosmic bkg and worse energy and angular resolution)

Large zenith angle observations

proposed



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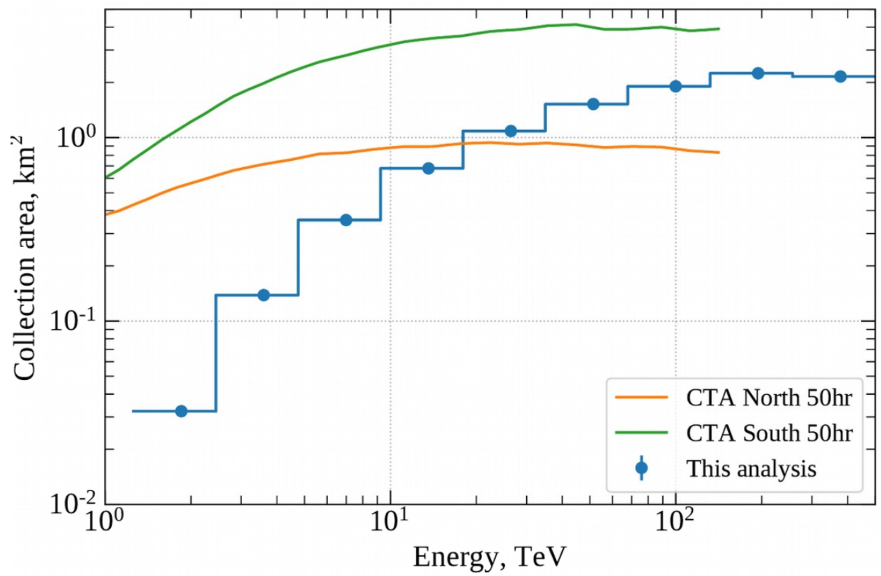


Detection of Crab nebula up to 100 TeV in ~50 hours

Development of software packages to further improve MAGIC performance for extended sources

A&A 619, A7 (2018)
https://doi.org/10.1051/0004-6361/201833139

Astronomy & Astrophysics

Skyprism: developed by I. Vovk, M. Strzys, and C. Fruck

Spatial likelihood analysis for MAGIC telescope data

From instrument response modelling to spectral extraction

MAGIC prize in June 2018

I. Vovk[1], M. Strzys[1], and C. Fruck[2,1]

[1] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany
e-mail: Ievgen.Vovk@mpp.mpg.de; strzys@mpp.mpg.de; fruck@mpp.mpg.de
[2] Technische Universität München, Physik-Department, James-Franck-Str. 1, 85748, Garching

Received 30 March 2018 / Accepted 31 May 2018

ABSTRACT

Context. The increase in sensitivity of Imaging Atmospheric Cherenkov Telescopes (IACTs) has lead to numerous detections of extended γ-ray sources at TeV energies, sometimes of sizes comparable to the instrument's field of view. This creates a demand for advanced and flexible data analysis methods that are able to extract source information using the photon counts in the entire field of view.

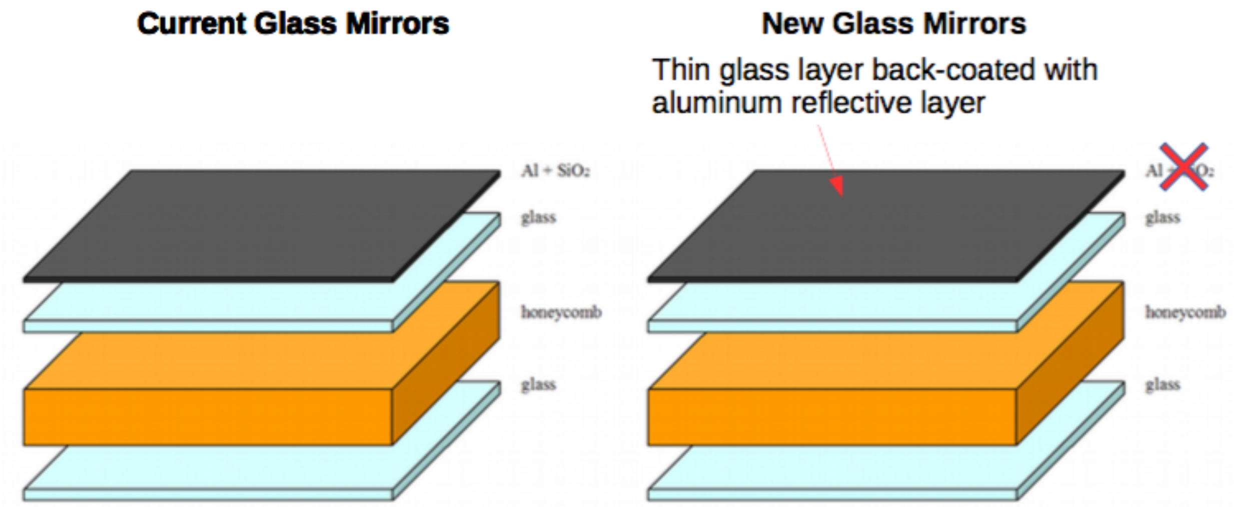
Aims. We present a new software package, "SkyPrism", aimed at performing 2D (3D if energy is considered) fits of IACT data that possibly contain multiple and extended sources. The fits are based on sky images binned in energy. Although the development of this package was focused on the analysis of data collected with the MAGIC telescopes, it can further be adapted to other instruments, such as the future Cherenkov Telescope Array.

Methods. We have developed a set of tools that in addition to sky images (count maps) compute the instrument response functions of MAGIC (effective exposure throughout the field of view, point spread function, energy resolution, and background shape) based on the input data, Monte Carlo simulations, and the pointing track of the telescopes. With this information, the package can perform a simultaneous maximum likelihood fit of source models of arbitrary morphology to the sky images providing energy spectra, detection significances, and upper limits.

Results. We demonstrate that the SkyPrism tool accurately reconstructs the MAGIC point spread function, on- and off-axis performance as well as the underlying background. We further show that for a point source analysis with the MAGIC default observational settings, SkyPrism gives results compatible with those of the standard tools while being more flexible and widely applicable.

Hardware to improve the performance in long-round: development of novel back-coated ultra-thin glass mirrors

Coordinated by Razmik Mirzoyan ***(+Martin Will, J. van Scherpenberg …)***



In collaboration with
Media Lario Technologies

Their performance (reflectivity & PSF) is similar to that of the MAGIC mirrors

Advantages of back-coated glass mirrors:

Long lifetime: *Glass is robust against corrosion from dust and rain*

Stable performance over long time: ~ *lifetime of a telescope*

Easy to clean from dust and dirt: *it does not get scratched*

Status

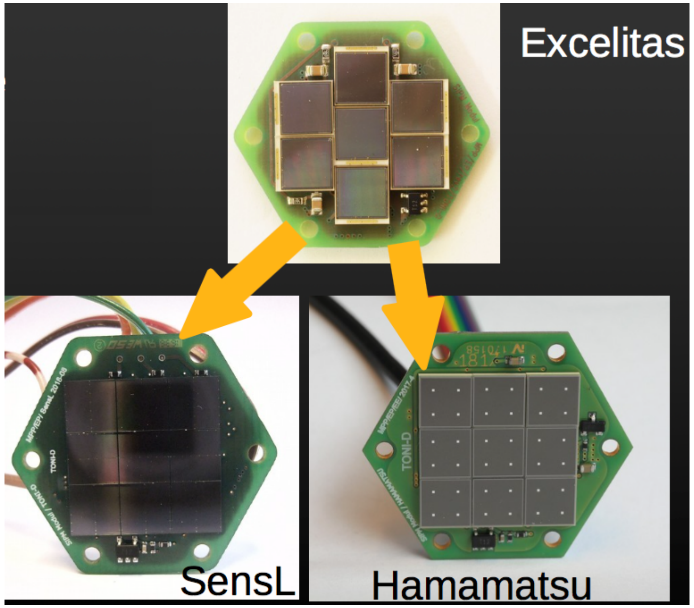
Two 1m^2 mirrors installed on MAGIC for in-field tests (October 2018)

Four 1m^2 mirrors in Germany for further evaluation (MPP+ Tübingen)

30 mirrors for MAGIC ordered from Media Lario Technologies

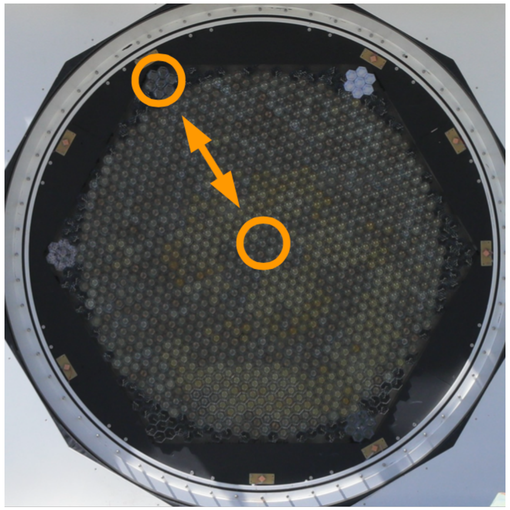
Hardware to improve the performance in long-round: development & test of large-size SiPM modules

Coordinated by Razmik Mirzoyan ***(+D. Mazin, A. Hahn, D. Strom, D. Fink, …)***



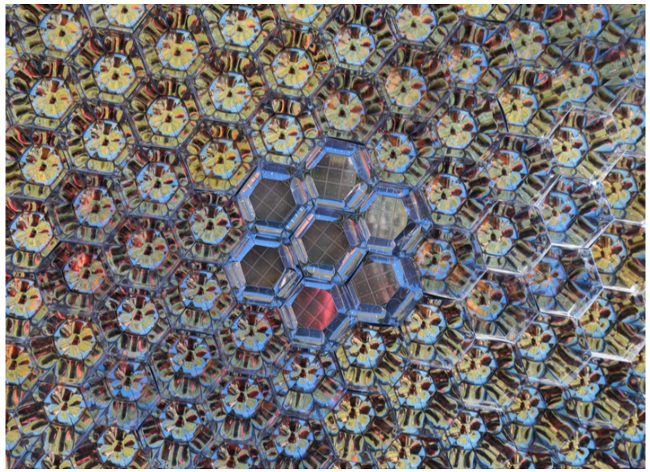
Improved pixel design to reduce dead areas, optimize heat flow and lower breakdown voltage

SiPMs installed in MAGIC are outside trigger region; typically do not get light from events
→ difficult to compare to PMTs



July 1st 2018

Swap SiPM cluster with PMT cluster in centre of camera
→ Results being understood



4 – Scientific results in 2018

- Brief overview
- Some highlights from publications in 2018

Science with the MAGIC telescopes

GOAL: provide experimental basis for the understanding of the *extreme Universe*

High-Energy particles will end up producing **gamma rays**

Hadronic high-energy particles → $\pi^{o} \rightarrow \gamma\gamma$, $\pi^{\pm} \rightarrow \mu^{\pm}\,\nu$

Leptonic high-energy particles → *Bremsstrahlung*, *Synchrotron*, *Inverse Compton*

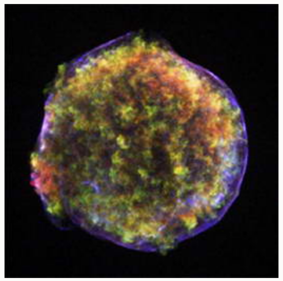
Information brought by the gamma rays:

1 - Location of the high energy particles
→ source direction

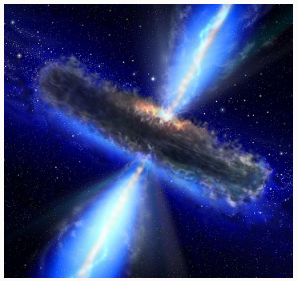
2 - Lower limit to the energy of the high energy particles

3 - Time information

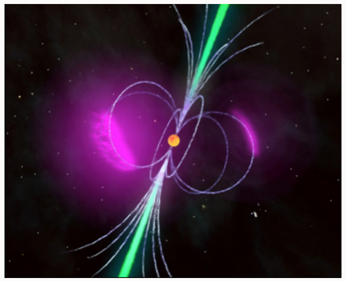
Energy Sources



Explosions



Accretion



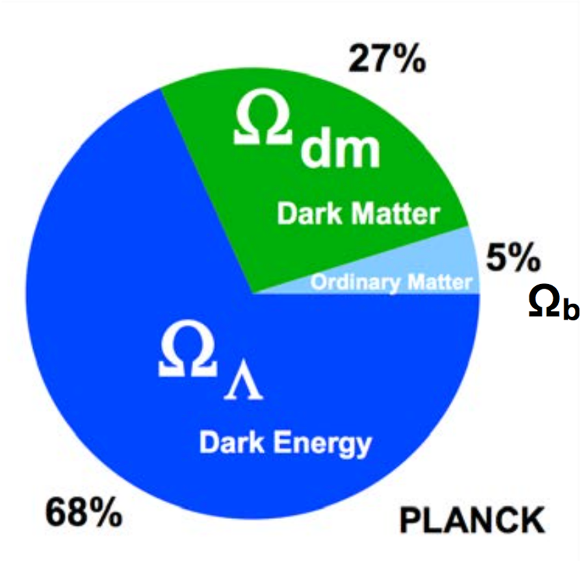
Extreme EM Fields

Many extreme particle accelerators in the Universe

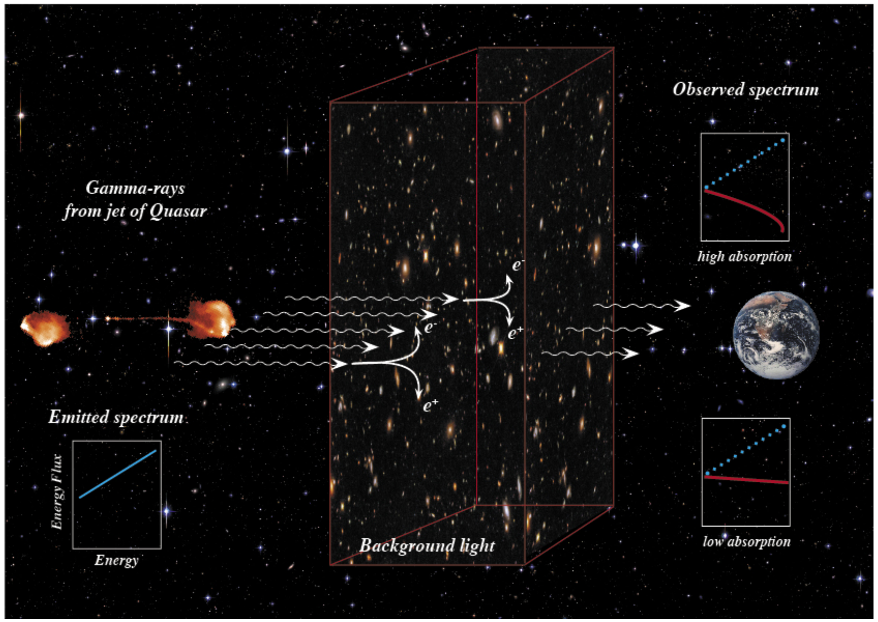
High-energy gamma rays are excellent means to probe these physical conditions, which are *not-reproducible at the Earth*

Science with the MAGIC telescopes

Also look for non-conventional astrophysics



Indirect searches of DM particles



Additional fundamental physics related to the propagation of the gamma-rays from the (distant) sources to the Earth

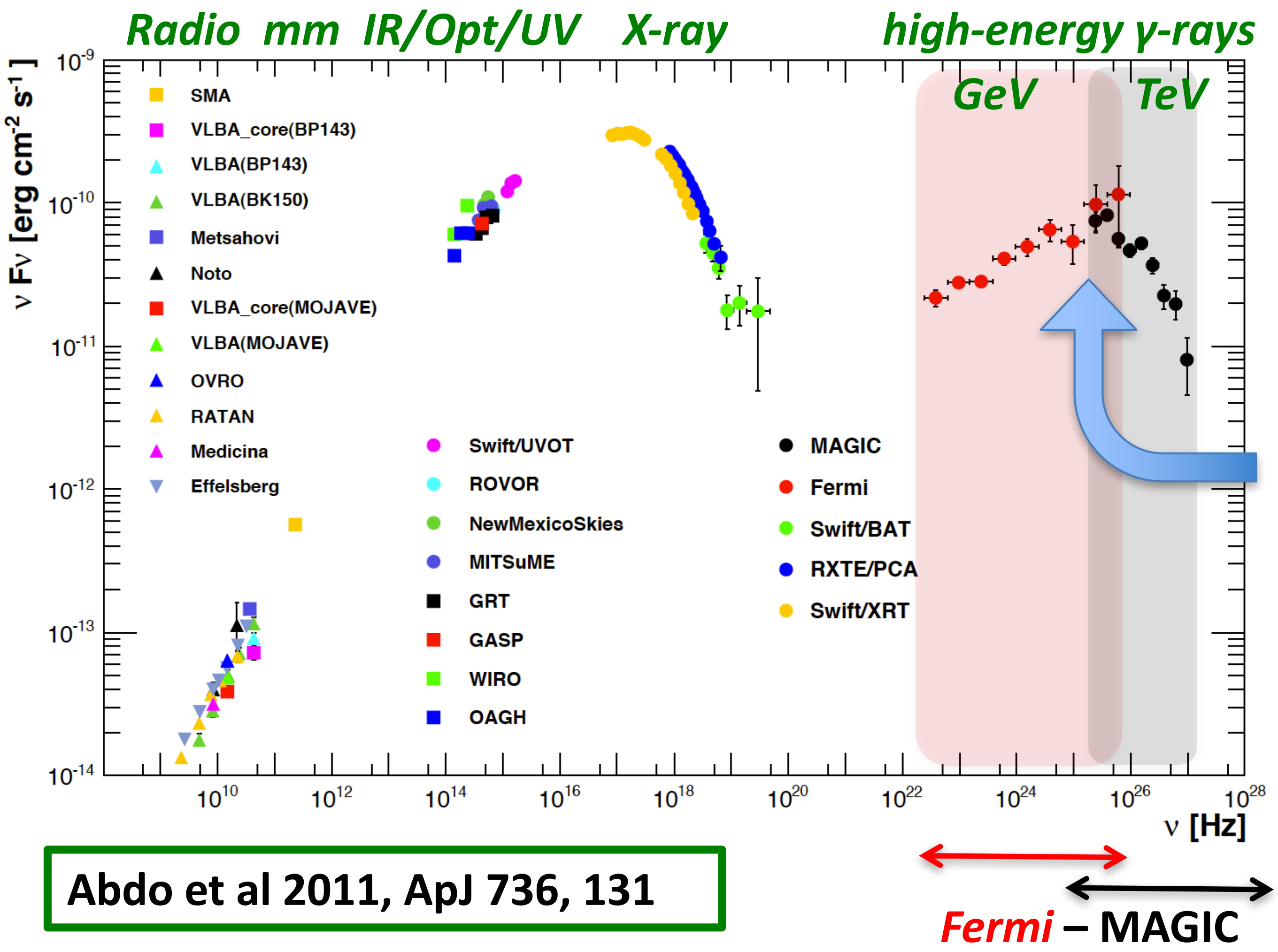
- Extragalactic Background Light (EBL)
- Intergalactic Magnetic Fields (IGMF)
- Lorentz Invariance violation (LIV)
- Search for Axion Like Particles (ALPs)

Synergy of MAGIC and Fermi-LAT

Many cosmic sources emit radiation over a wide energy range

Emission at different energies could be produced by same particles

→ *The gamma-ray emission fully characterized <u>"only" since 2009</u>*



Abdo et al 2011, ApJ 736, 131

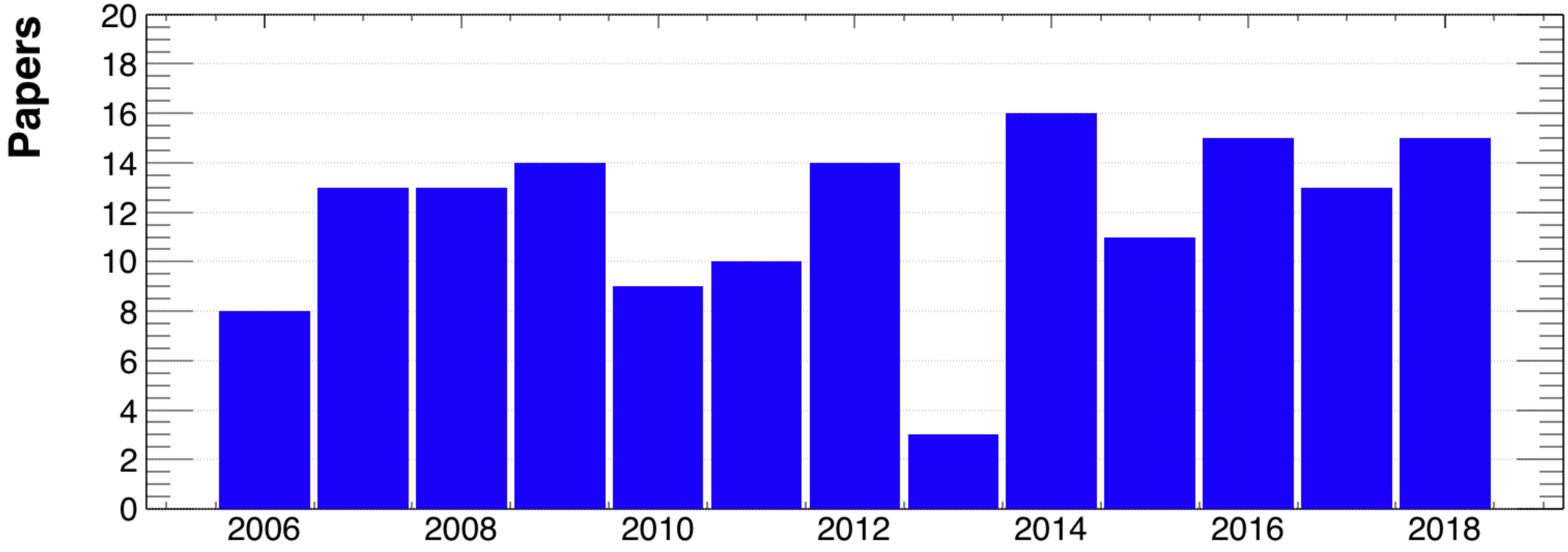
***Fermi*–MAGIC** spectra cover the complete high energy component over 5 orders of magnitude without gaps

→ *Crucial for the theoretical modeling of the broad emission of many sources*

MAGIC data used for publications over a wide range scientific topics

→ *from "conventional" astrophysics to dark matter searches*

After 15 years of scientific operation, MAGIC produces ~14 papers/year



Most publications benefit from the large synergy with Fermi-LAT

→ *All-sky capability of LAT crucial for many VHE source discoveries*

The most significant (~3σ) association of a high-energy neutrino to a gamma-ray source to date

Probably the hottest publication out of the 15 MAGIC publications in 2018

Science 361, July 2018

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

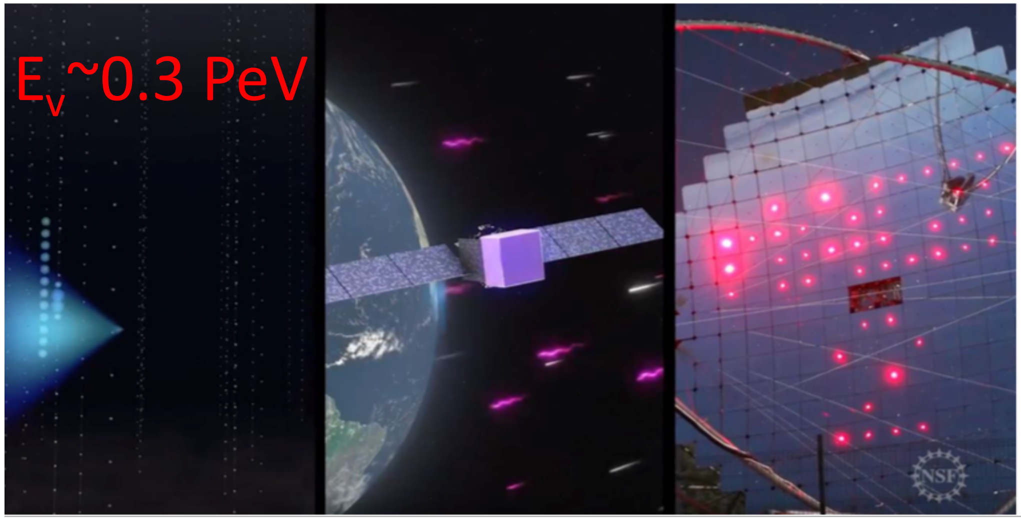
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

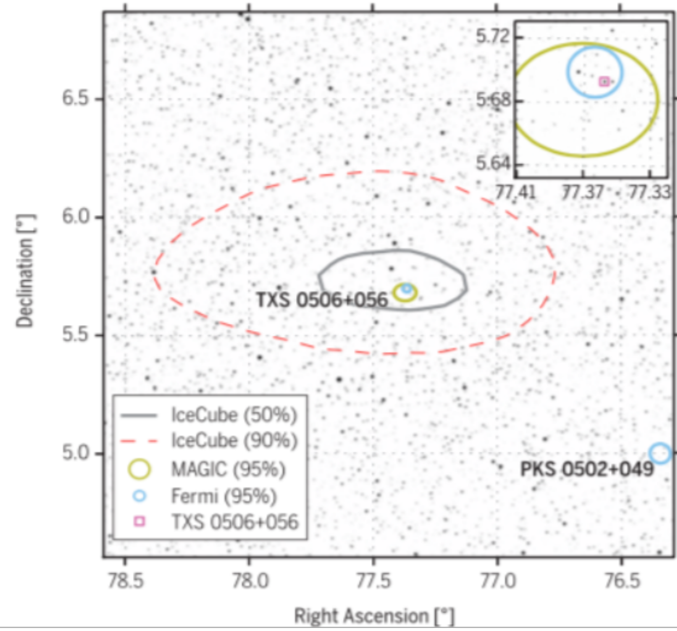
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

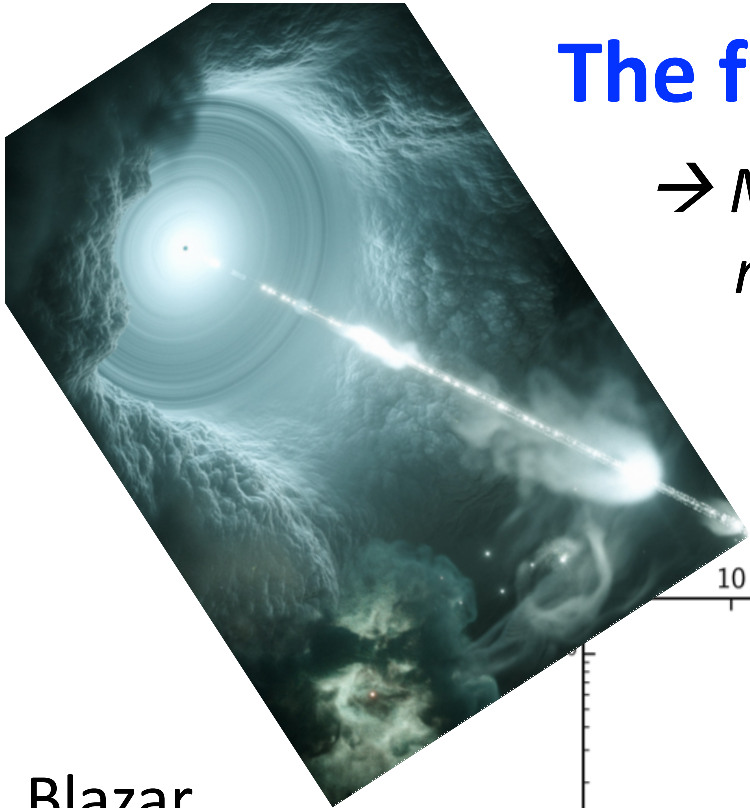
evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced moving through





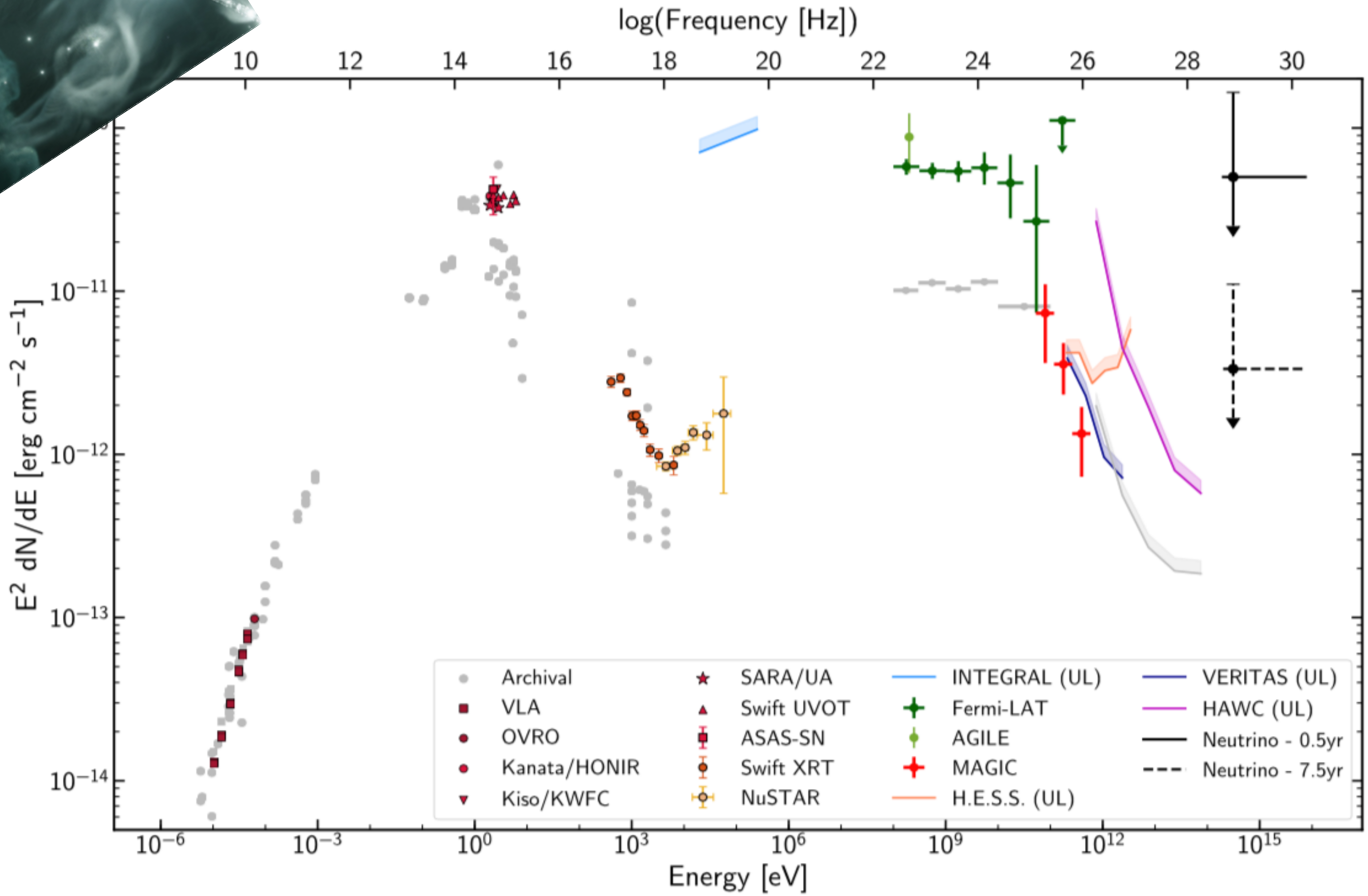


The first multi-messenger spectrum

→ *MAGIC was crucial for characterizing the most energetic electromagnetic emission*

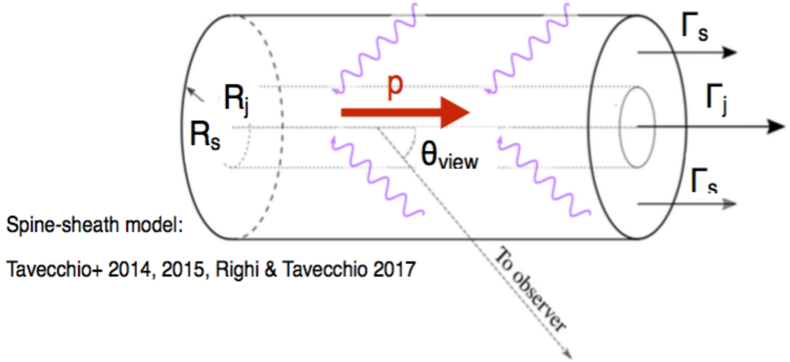
IceCube + Fermi+MAGIC ++, Science 361, 146 (2018)

Blazar
TXS 0506+056
z ~ 0.34



The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray accel.

Spine-sheath model



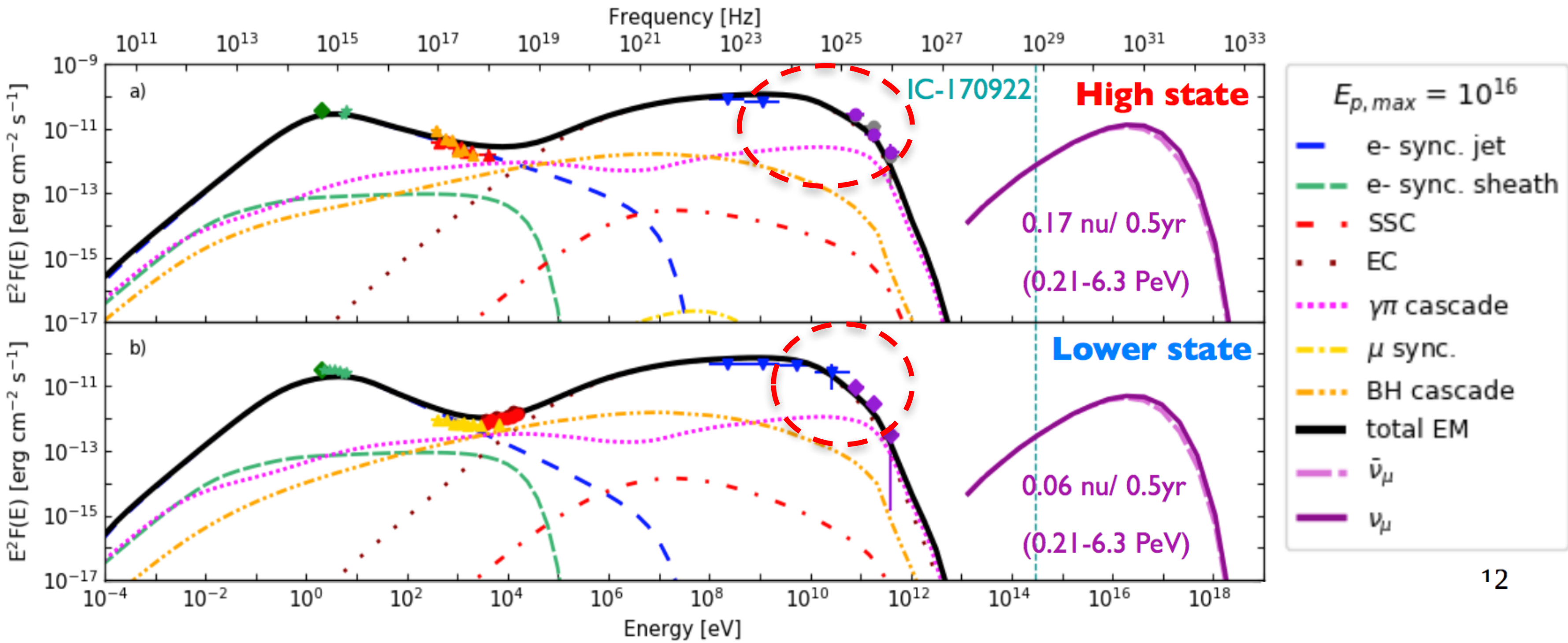
MAGIC collab. ApJL 863, 10 (2018)

Lepto-hadronic model consistent with broadband spectrum and neutrino flux

Leptonic: synchrotron, SSC, EC

Hadronic: synch. rad. from pions and muons, photo-meson cascade, BH cascade

Internal absorption at ~100 GeV consistent with the Fermi-MAGIC break



The most significant (~3σ) association of a high-energy neutrino to a gamma-ray source to date

MAGIC involved in 2 publications related to this event:

1) Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

IceCube+Fermi+MAGIC+… et al., 2018
Science 361, 1378

2) The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic-Ray Acceleration

MAGIC collab + …, 2018
ApJ 863, 10

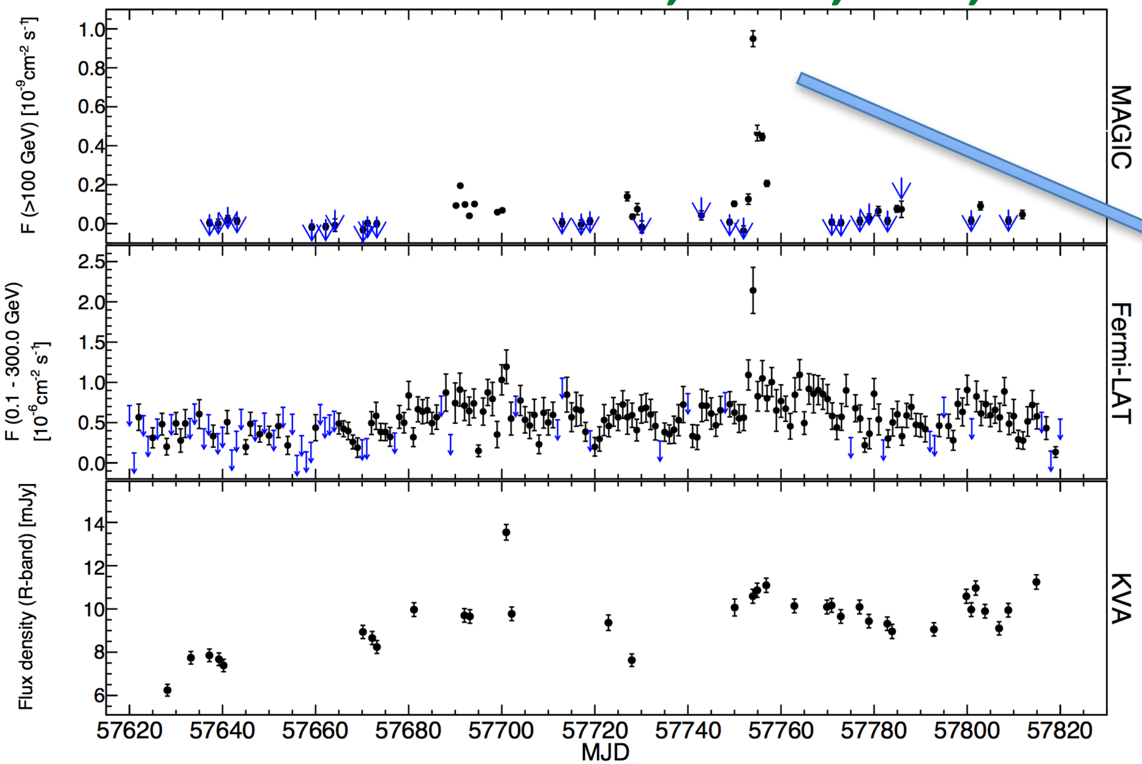
+ various press conferences in and various press releases

Many publications about this event by a large number of scientists

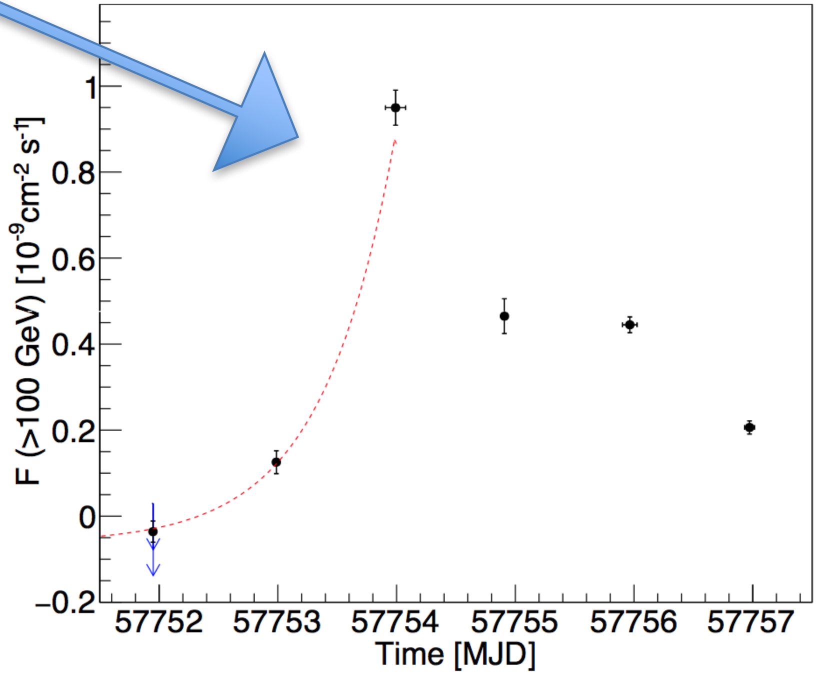
One of the hottest topics in astrophysics summer conferences in 2018

Fast variability @VHE in radio galaxy NGC1275

MAGIC Collab. 2018, A&A, 617, 91



Multi-instrument campaign from 2016/2017



Flux doubling time of ~10 hours can be used to set constraints to the size of the emitting region R

$$R_B \leq \frac{c t_{\rm var} \delta}{1+z}$$

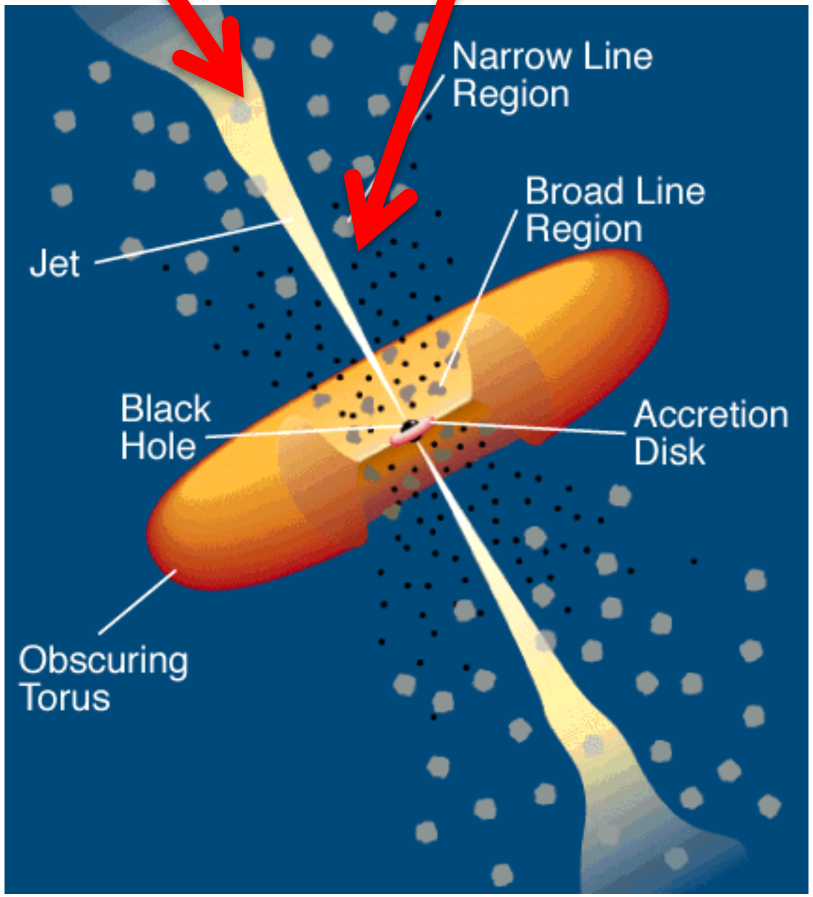
$$\mathbf{R < 20\ \delta \times r_g}$$

Event horizon $r_g \sim 3km \frac{M_{BH}}{M_{Sun}}$

Radio galaxies as gamma-ray emitters

Blazars are radio loud AGNs with the jet pointing towards the Earth (*e.g. TXS 0506+056*)

Radio galaxies are radio loud AGNs where the jet is observed from a large angle (Theta>10 deg)



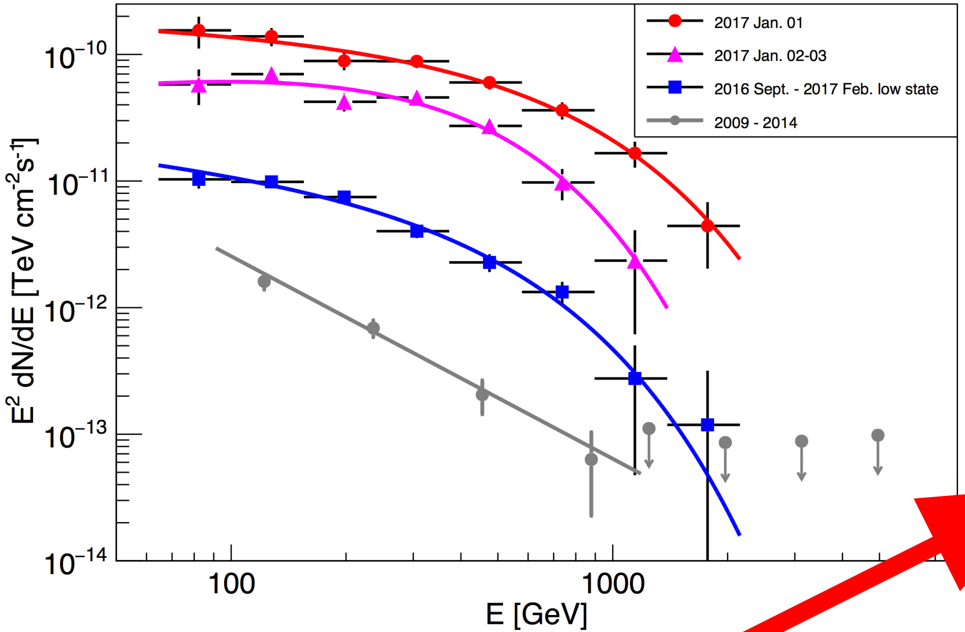
Pictorial description of an AGN

Image Credit: C.M.Urry & P. Padovani

MAGIC Spectra during these fast flares show gamma rays with energies larger than 1 TeV

NGC 1275

MAGIC Collab. 2018, A&A, 617, 91



Opacity due to gamma-gamma absorption in the source

$$\tau_{\gamma\gamma} \sim \frac{\sigma_T {D_L}^2 F_0 \varepsilon_\gamma (1+z)}{10 R {m_e}^2 c^5 \delta^5}$$

NGC 1275: **Tau (1TeV) <1** → **Doppler > 4** → **Theta < 16 deg**

Theta=Viewing angle with respect to jet

→ Inconsistent with measured Theta>30 deg at radio

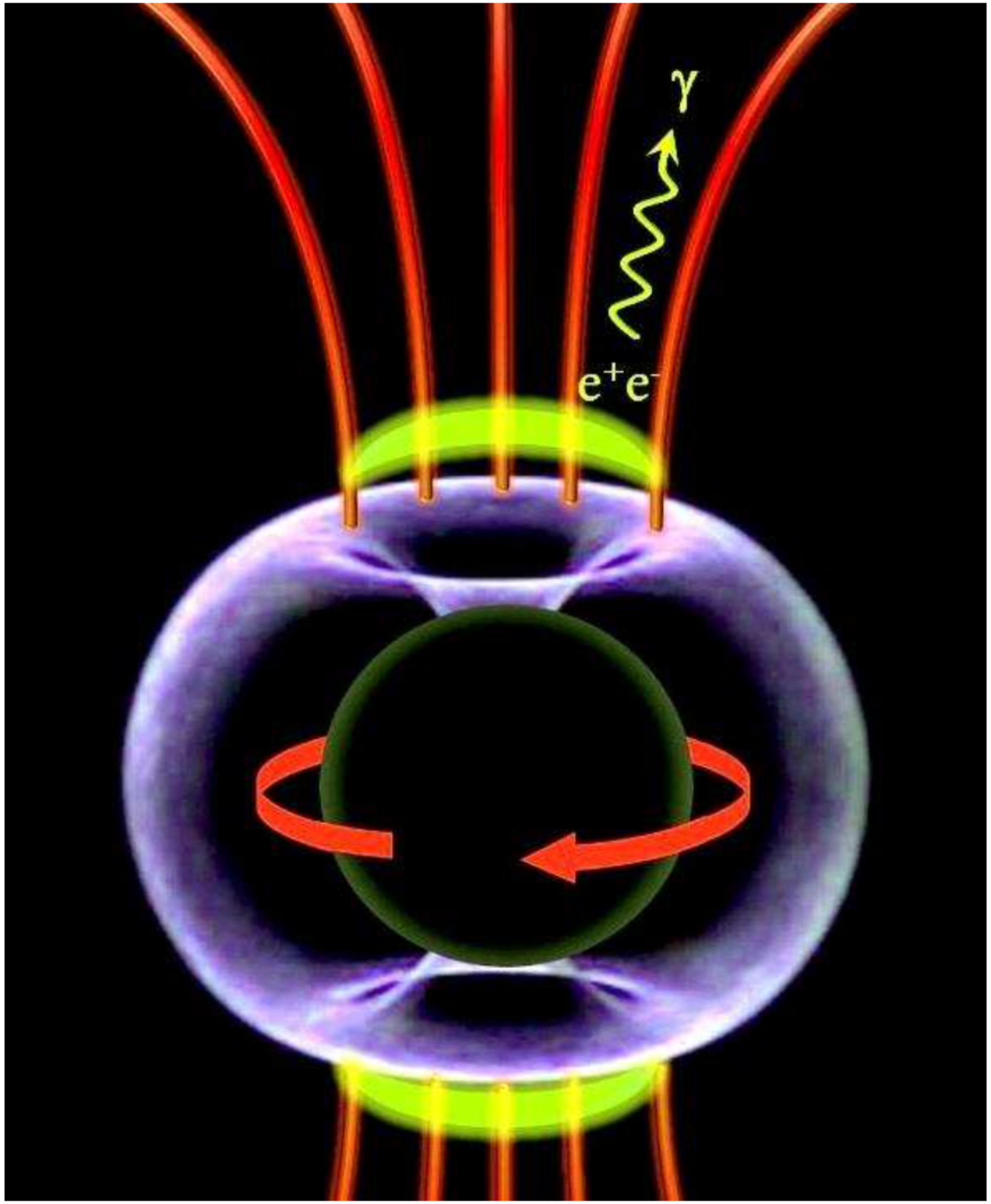
MAGIC puzzle for radio galaxies … how to explain it ?

Data could be explained with "**Magnetospheric models**":
by e.g. Levinson & Rieger 2011;
Aleksic et al. 2014, *Science*
Hirotani & Pu 2016

e+e− accelerated in an electric field in vacuum gap regions

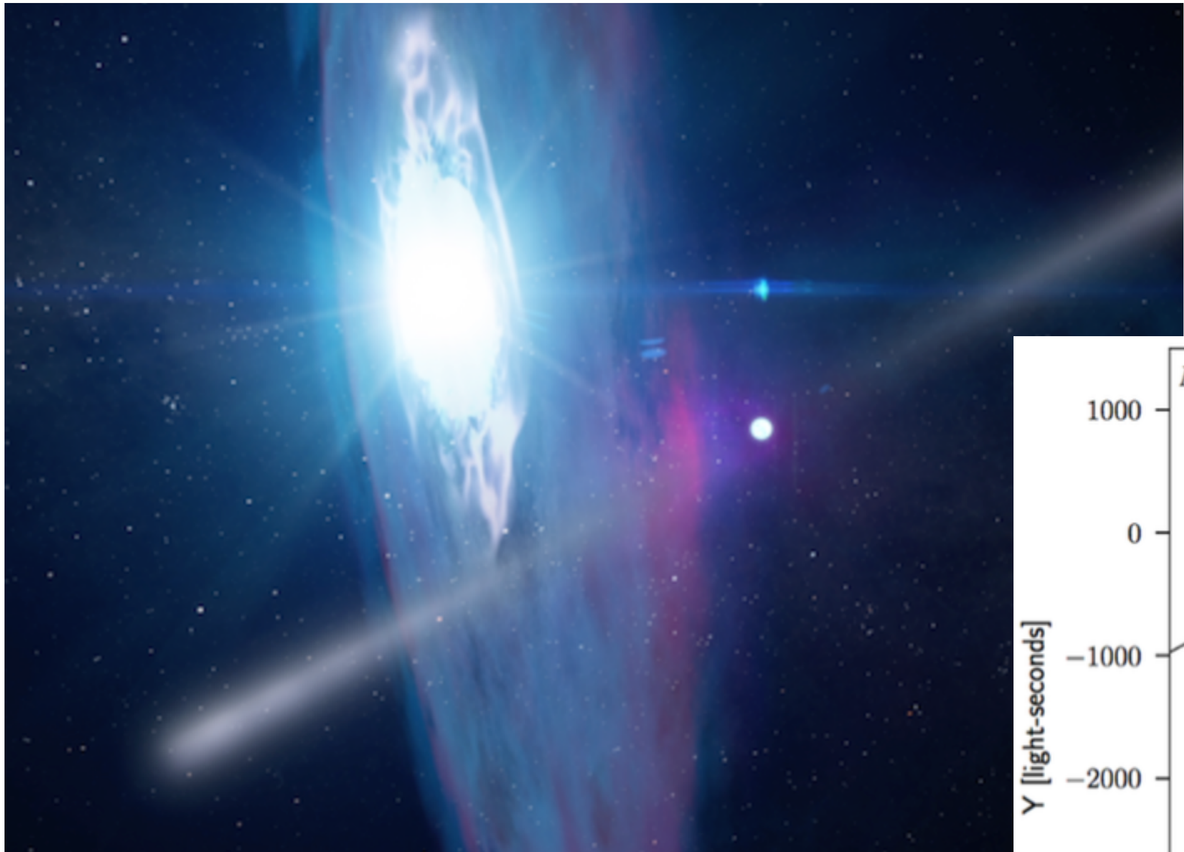
Similar to "aligned magnetic rotator models" for pulsars

Could produce anisotropic particle beams at angles 10-20 deg to the jet axis



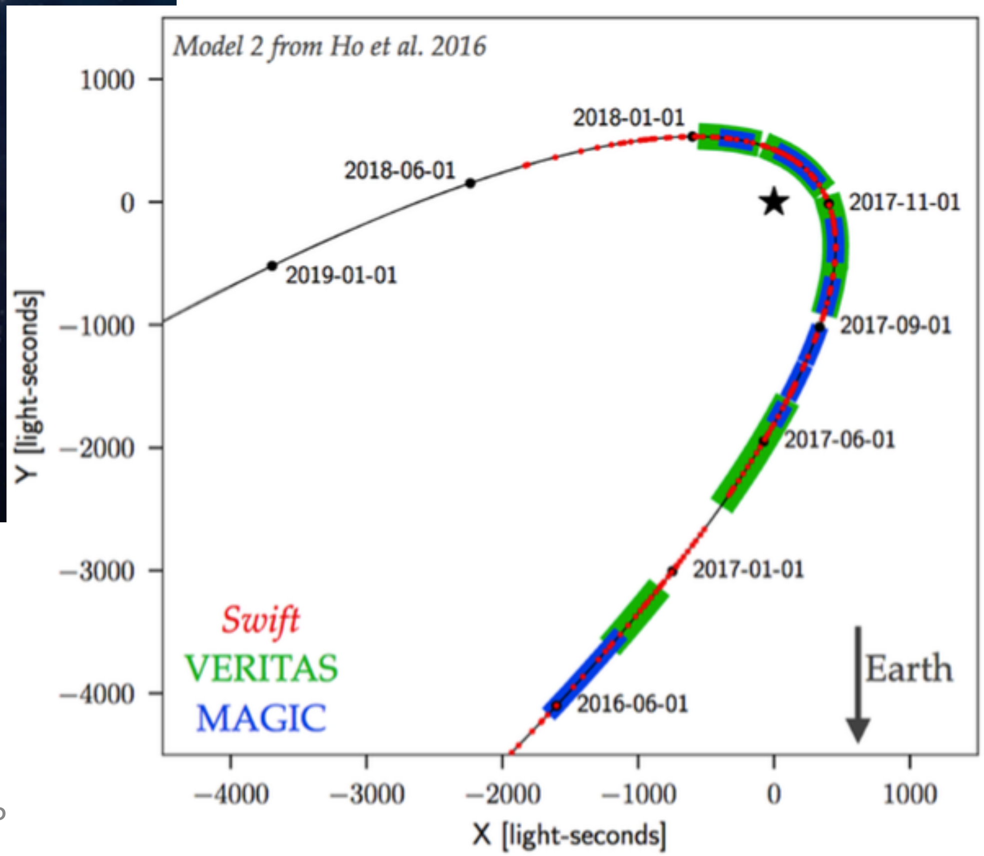
Pulsar / Be star binary system PSR J2032+4127 / MT91 213, observed at periastron in November 2017

(period of ~50 years; once in a half century opportunity)



VERITAS+MAGIC 2018, *ApJ*, 867, 19

+ Several press releases



Large observing campaign, including Swift, MAGIC & VERITAS

David P

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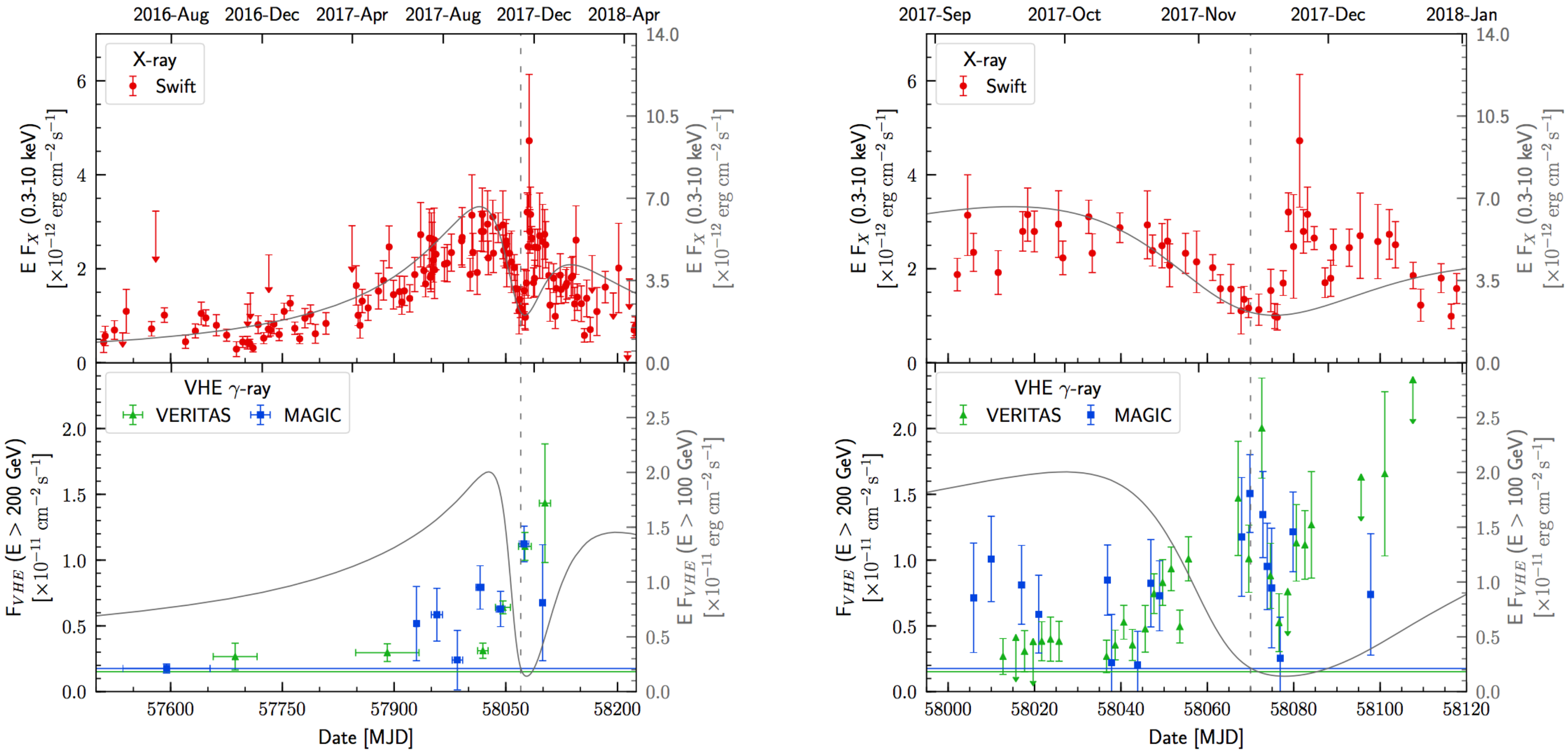

(a) Full Dataset

(b) Periastron

Observational data does not match what models had predicted

5 - Conclusions

MAGIC is 15 years old, and operates better than ever, under leadership of MPP at all levels (organization, science & technical)

- Factor of 4 improvement in sensitivity since beginning of science operation
  → *More than one order of magnitude better sensitivity below 200 GeV*

- First Cherenkov Telescope that uses atmospheric corrections with LIDAR
- Sum-Trigger-II improving performance at energies below ~100 GeV
- Very Large Zenith Angle observations improving performance above ~10 TeV
- Skyprism sofware package improve performance for extended objects
- *Keep exploring new hardware possibilities (e.g. SiPMs & Mirrors)*

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The collaboration is big (~200 people) and diverse (12 countries) and regularly publish on a broad range of scientific topics

→ In 2018 we published exciting results about multimessenger cosmic sources, radio galaxies and binary systems

→ Many more interesting results in preparation (review or submitted)
  → Detection of Geminga pulsar at VHE, hints of TeV bumps in spectra blazars …

MAGIC is a key player in the study of the Extreme Universe