Selected Studies of Celestial γ-ray Sources with MAGIC

Razmik Mirzoyan

Max-Planck-Institute for Physics
Munich, Germany
On behalf of the MAGIC Collaboration

National Academy of Sciences of
Republic Armenia, Yerevan, Armenia

Gamma-ray Astronomy, the beginning

Seminal paper by Phillip Morrison, 1958

AN AIR SHOWER TELESCOPE

AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

5). Here are some numerical estimates.

The Crab Nebula: Visual magnitude of polarized light m = 9.

Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.

Therefore: $U_{\gamma} = 10^{12} eV$ and $R(10^{12} eV) \approx 10^{-3.2}\ m^{-2} s^{-1}$.

The signal is thus about 10^{3} times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

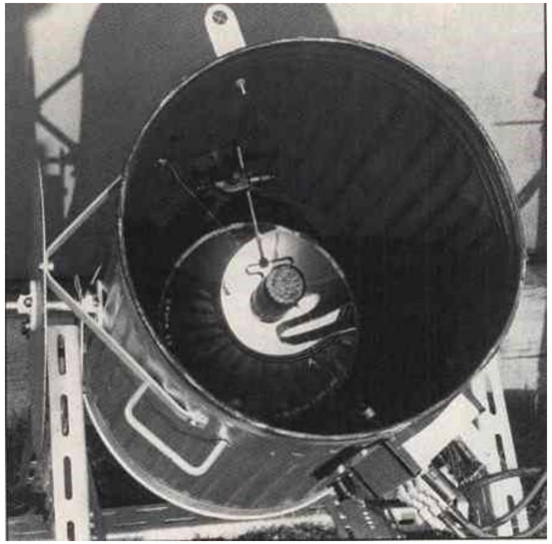
487, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.

$R(10^{12} eV) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

Also proposed at higher energies independently by Giuseppe Cocconi, 1959

Important stages in the development of ground-based γ-ray astronomy

1952-1953 – discovery of Cherenkov pulses in atmosphere with a 0,25m ø mirror and a 2'' PMT



1959-1964 - Chudakovs experiment in Crimea
12 x 1,55m ø parabolic mirrors (total 26,5 m^2)

1968-2003 - 10m ø Whipple telescope
AZ, USA

Discovery of γ-Rays from the Crab Nebula, 1989

THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

I. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as con-

Subsequent to the discovery of PSR 0531 in the nebula, TeV gamma-ray observations concentrated on the pulsar because greater sensitivity could be achieved by the assumption of syn-

37-pixel imaging camera

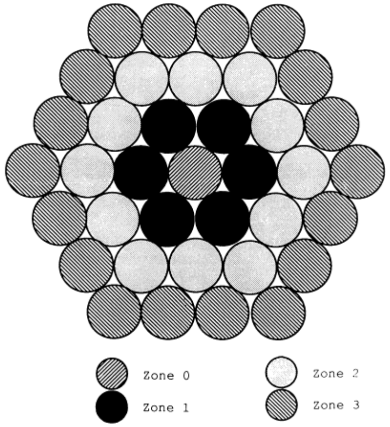


FIG. 1.—Layout of phototubes in the focal plane of the 10 m optical reflector. Each phototube has a sensitive area defined by a diameter of 0°.4; the spacing between phototubes is 0°.5. The full field of view is 3°.5. The center phototube is defined as zone 0; the surrounding ring of six phototubes is zone 1, the ring of 12 zone 2, and

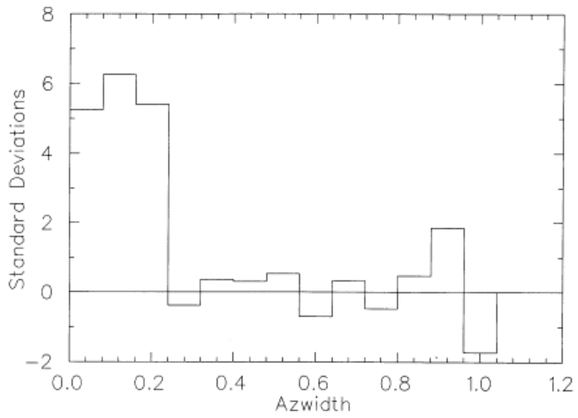
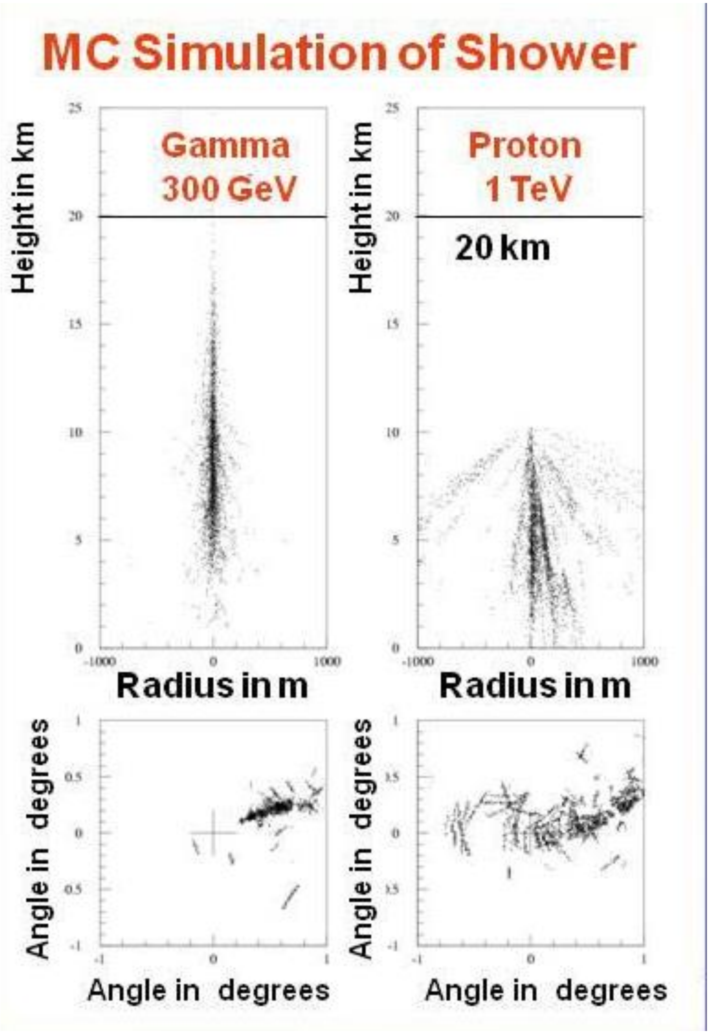


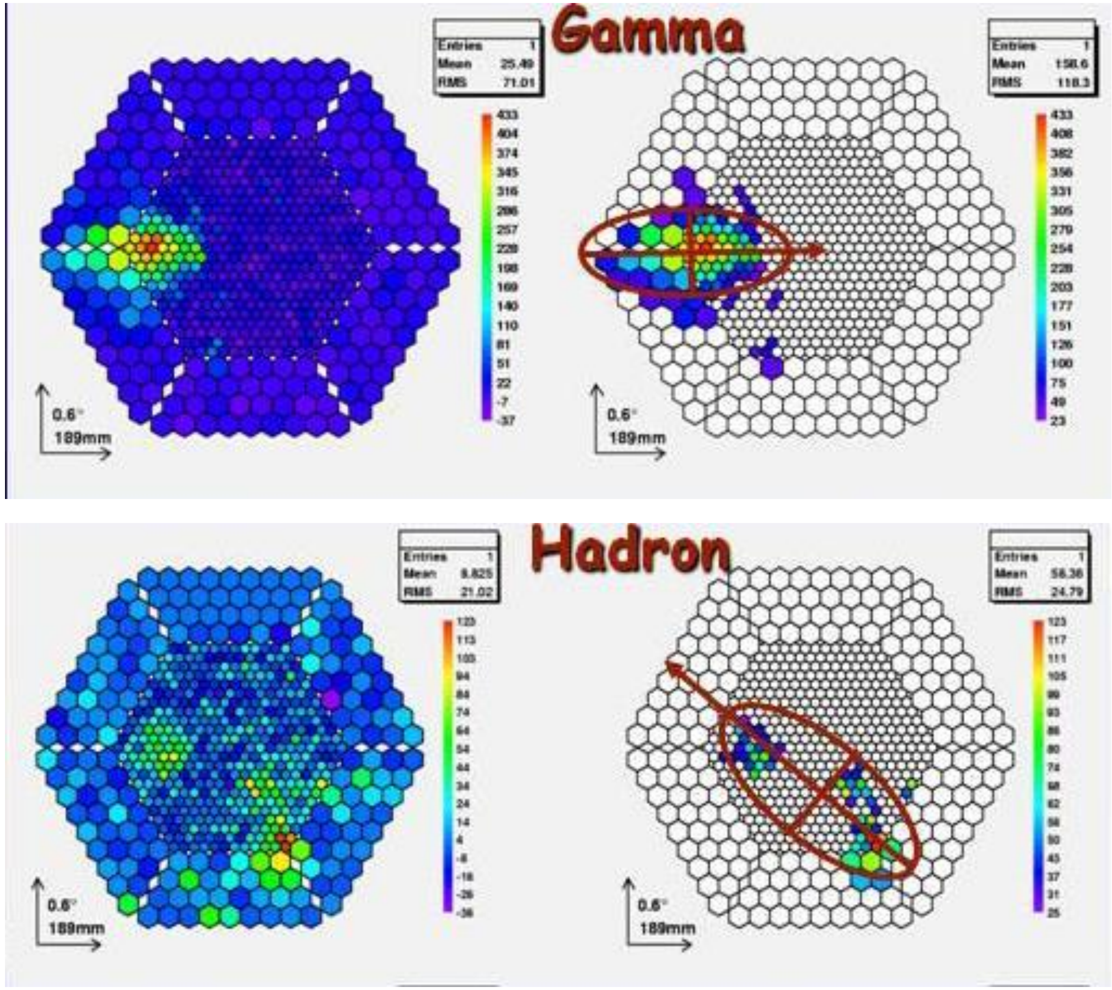
FIG. 7.—Distribution of *azwidth* (ON − OFF) in terms of standard deviations as a function of *azwidth*

The HEGRA detector included
6 air Cherenkov imaging telescopes
@ ORM in La Palma, Canary islands
Operation 1992 - 2002

VERITAS, H.E.S.S., MAGIC and also the 1st 23m Ø CTA/LST: at the frontier of VHE γ-astro-physics

γ-hadron separation by the image shape + orientation; for a point source hadrons can be rejected at > 99.98 % level





MAGIC: ~300 Astro-Physicists From 13 Countries

Armenia	ICRANet and Alikhanian Broth. NL
Bulgaria	Sofia nuclear Physics Institute
Brazil	CBPF Rio de Janeiro
Croatia	Consortium (Zagreb, Split, +…)
Finland	Consortium (Tuorla, +…)
Germany	DESY Zeuthen, U. Dortmund, MPI Munich, U. Würzburg
Japan	Consortium (Univ. Tokyo, Kyoto, +…)
Italy	INFN & U. Padova, INFN Pisa & U. Siena, INFN Como/Milano Bicocca, INFN Udine/Trieste & U. Udine, INAF (Consortium: Rome, Milan, +…)
Norway	U. of Bergen
Poland	U. of Lodz
Spain	U. Barcelona, UAB Barcelona, IEEC-CSIC Barcelona, IFAE Barcelona, IAA Granada, IAC Tenerife, U. Complutense Madrid, CIEMAT Madrid
Switzerland	ETH Zurich, Univ. Geneva
India	Kolkata

First association of a ~300 TeV neutrino to a γ-ray source

Science 361, July 2018

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

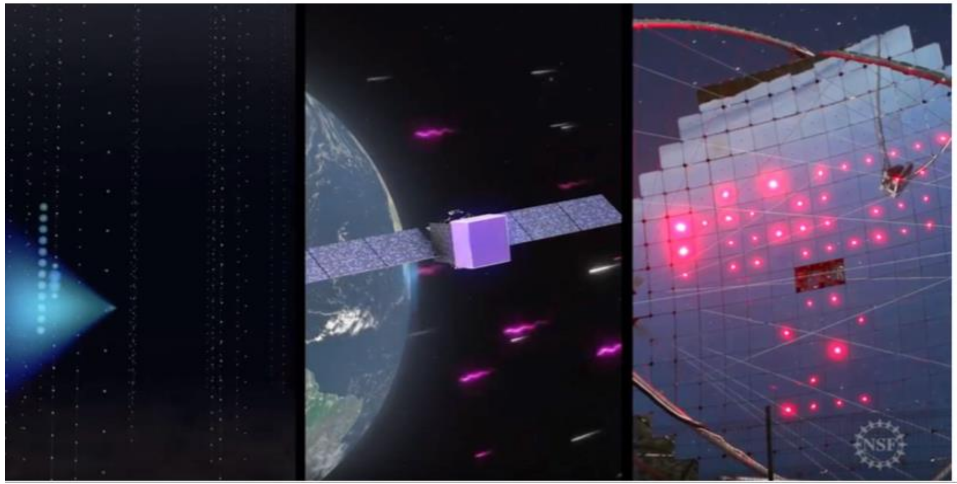
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

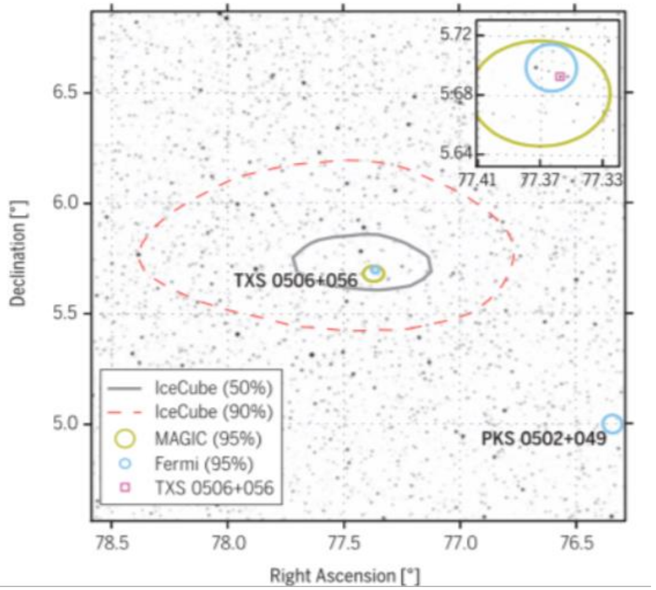
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

evaluated below, associating neutrino and γ-ray production.

The neutrino alert

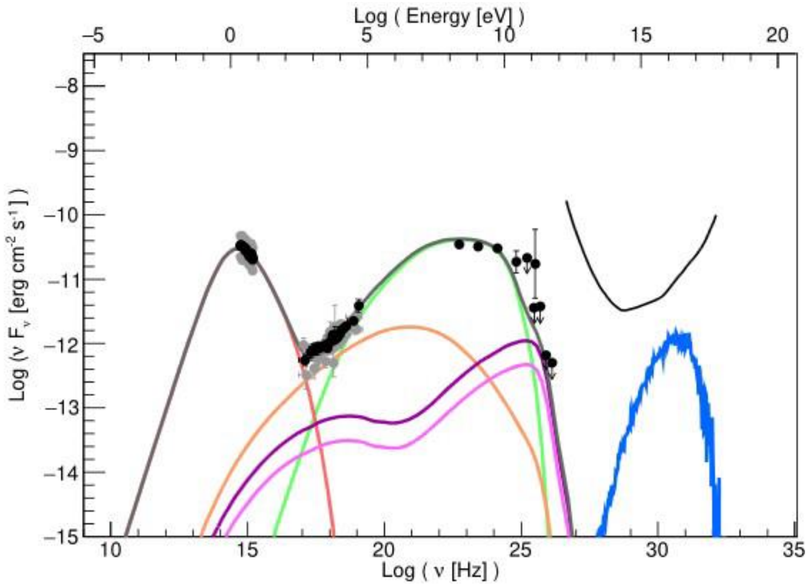
IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths 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



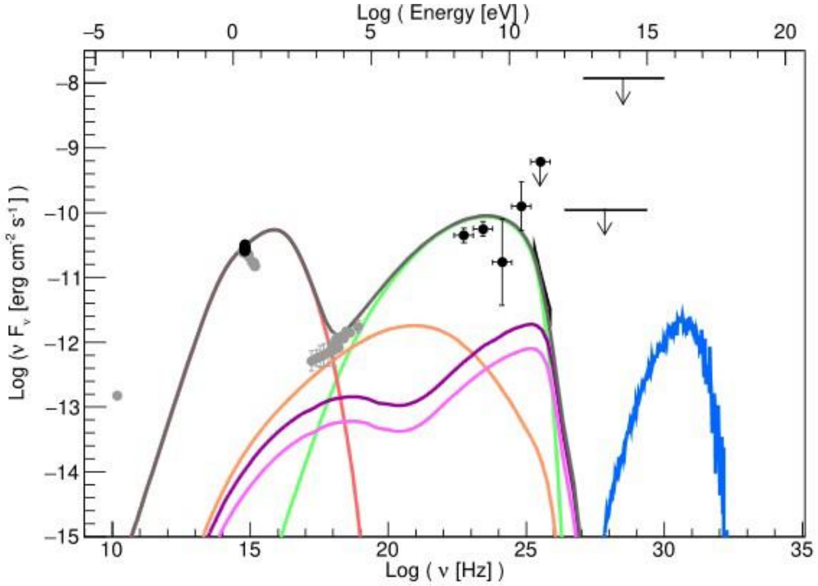


Blazar TXS 0506+056

ApJ 927 (2022)



Low-state Nov. 2017 – Feb. 2019



High-state Dec. 2018

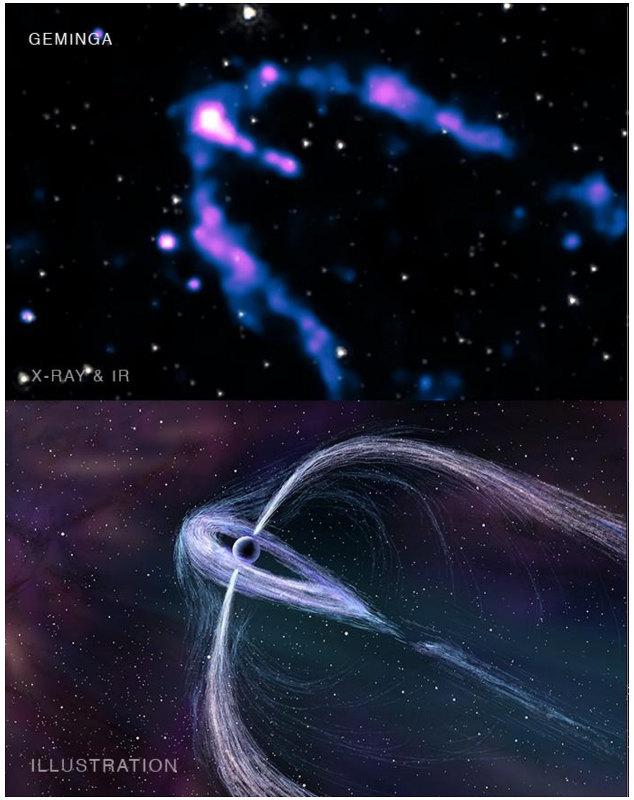
2017-2019

- MWL campaign, source in a different state than in 2017
- Mostly low state (74 hours)
- In December 2018 high state (4h) was measured, similar to the 1st detection, but no associated neutrino was detected
- Low and high state flux differ by one order of magnitude

Pulsed γ-ray signal measured by MAGIC @ 6.3σ from Geminga pulsar at **E ≥ 15 GeV**

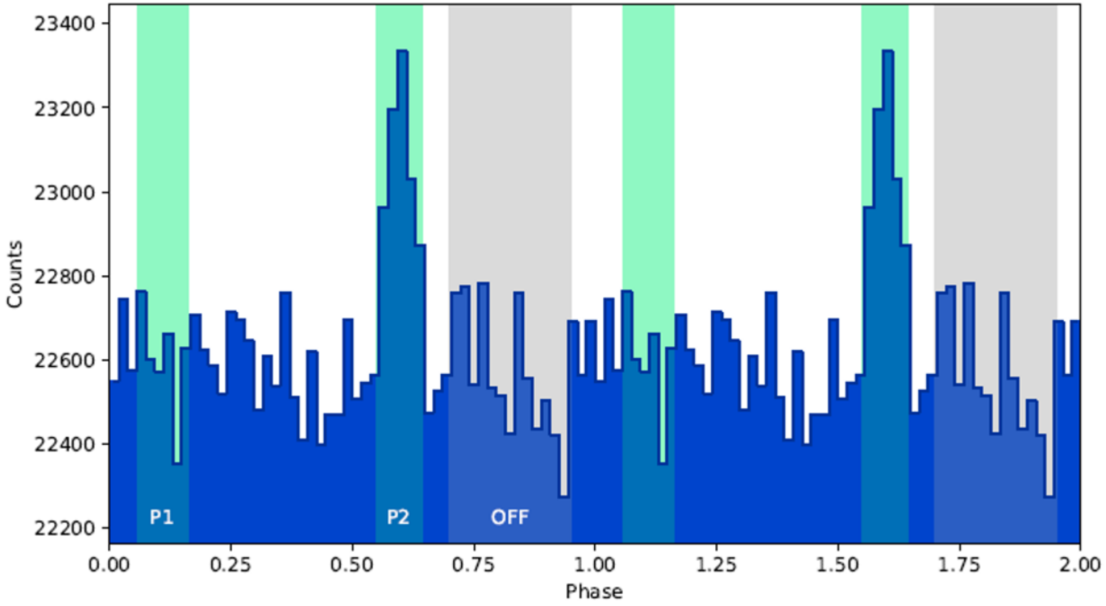
(the 3rd pulsar revealed in the VHE domain)

Acciari et al, A&A 2020



X-ray: NASA/CXC/GWU/N.Klingler et al;
IR: NASA/JPL-Caltech; Illst: Nahks TrEhnl

Age ~340ky; estimated distance ~ (175 – 250) pc



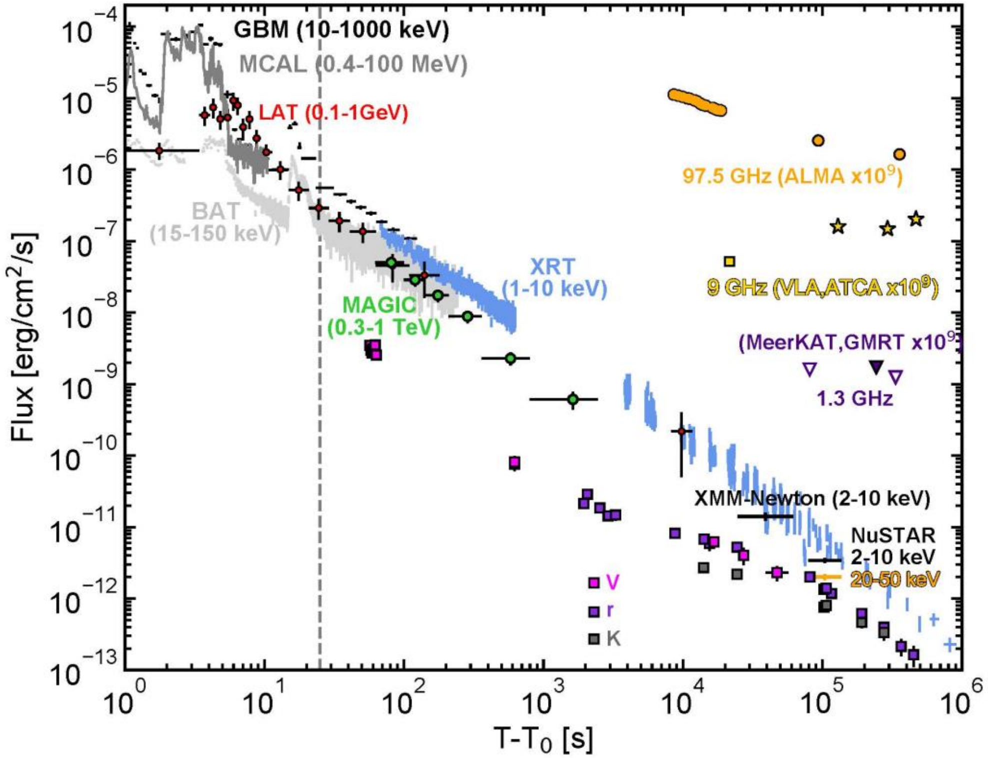
80h of data taken under *Sum-Trigger-II* low-energy trigger

GRB190114C MWL light curves by MAGIC & 2 dozen space- and ground-based instruments measured on 14.01.2019

MAGIC published 2-papers in *Nature, 575 Nov. 2019*

- For the first time GRB measured @ TeV
- Measurements started 57 s after onset
- T_{90}~ 360 s, bright, long GRB
- E_{iso}~ 3×10^{53} (1keV - 10 MeV)
- Red shift z = 0.4245
- Detected ~ 60σ in afterglow, the energy range 200 GeV – 2 TeV
- TeV flux similar to that in X-rays
- Intensity > 130 Crab in the first minute
- Purest ever gamma-ray sample

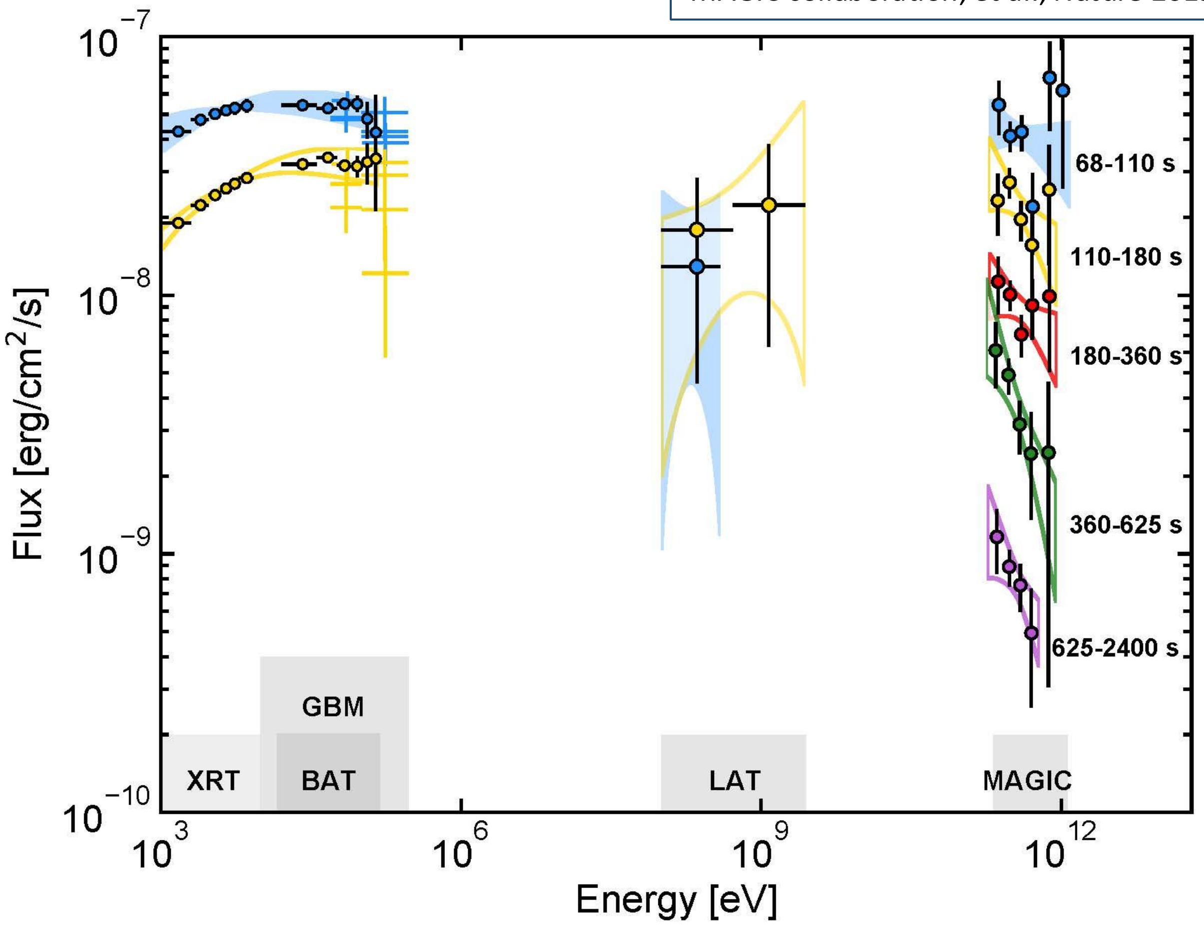
Acciari, et al., Nature 2019



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

Evolution of GRB 190114C could be followed with ultra-short time resolution

MAGIC collaboration, et al., Nature 2019

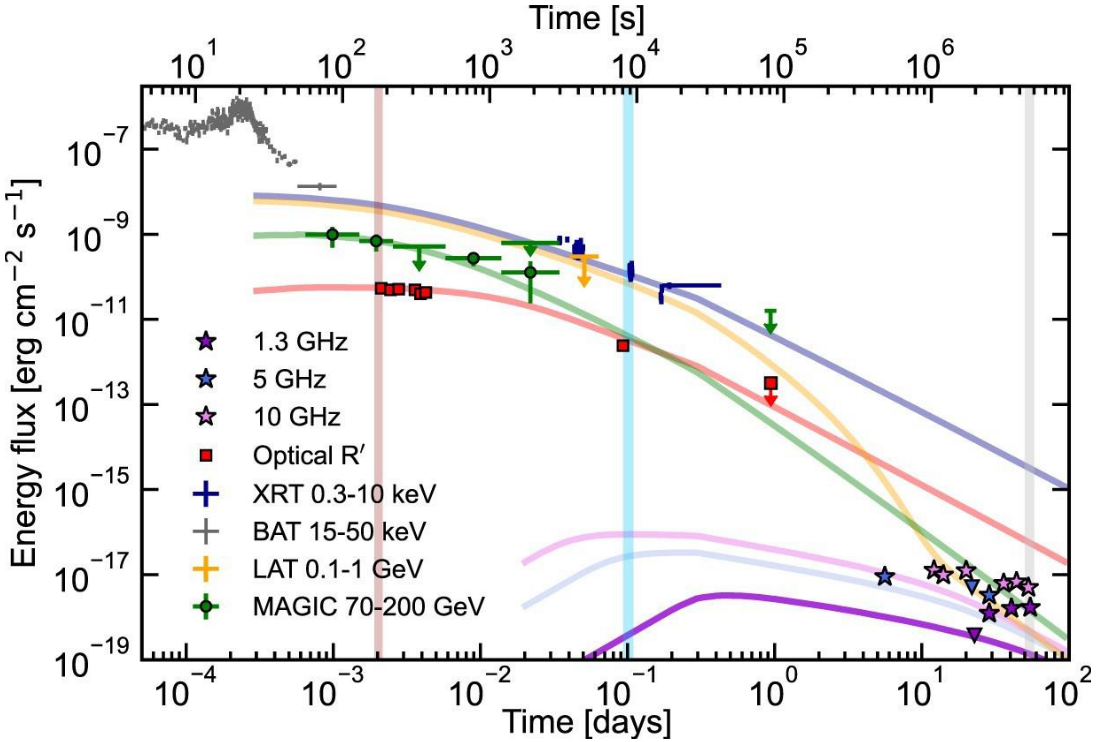


Nature, 575
November 2019

- The incredible intensity @ TeV allowed us to follow the spectral evolution in extremely short time intervals
  - 42s (1st bin)
  - 70s (2nd bin)
  - 180s (3rd bin)
- The SSC process with two-bump structure could successfully explain the TeV emission
- GRBs even more powerful than assumed before the discovery of the TeV emission

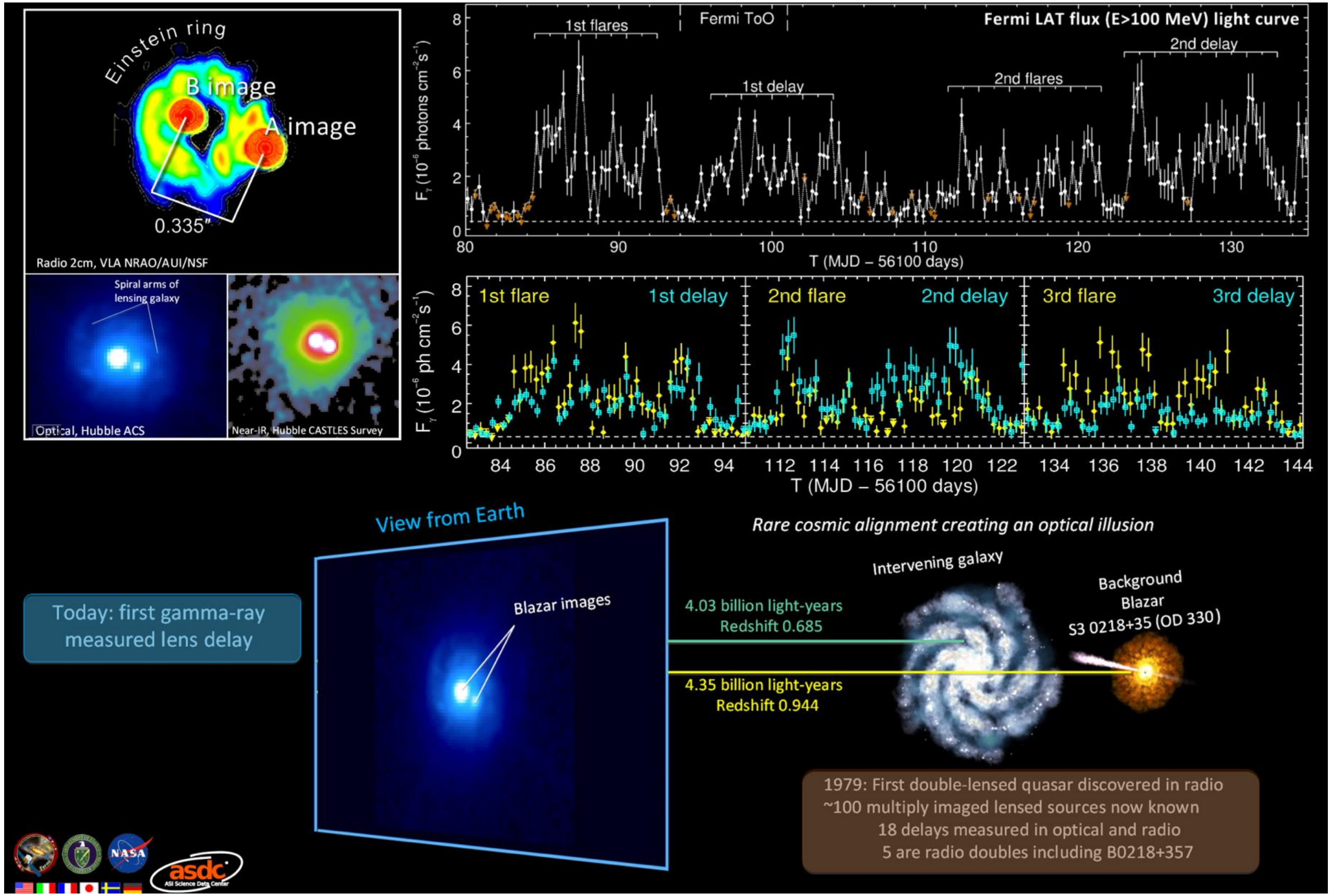
Long GRB 201216C at red shift 1.1 with MAGIC

- Quite bright: $E_{iso} \sim 5\cdot10^{53}$ erg; T_{90} = 48s
- Yet the most distant VHE source (GCN29075)
- Strong absorption of TeV γ on EBL; model differencies contribute to flux uncertainties
- 5σ > 70 GeV in the first 20 min of observations
- Good MWL coverage
- The SSC model provides a reasonable description, like for GRB 190114C
- Late radio data requires to invoke an additional component



MAGIC, MNRAS 527 (2024)

Gravitational lense system B0218 (also known as S3 0218+357)



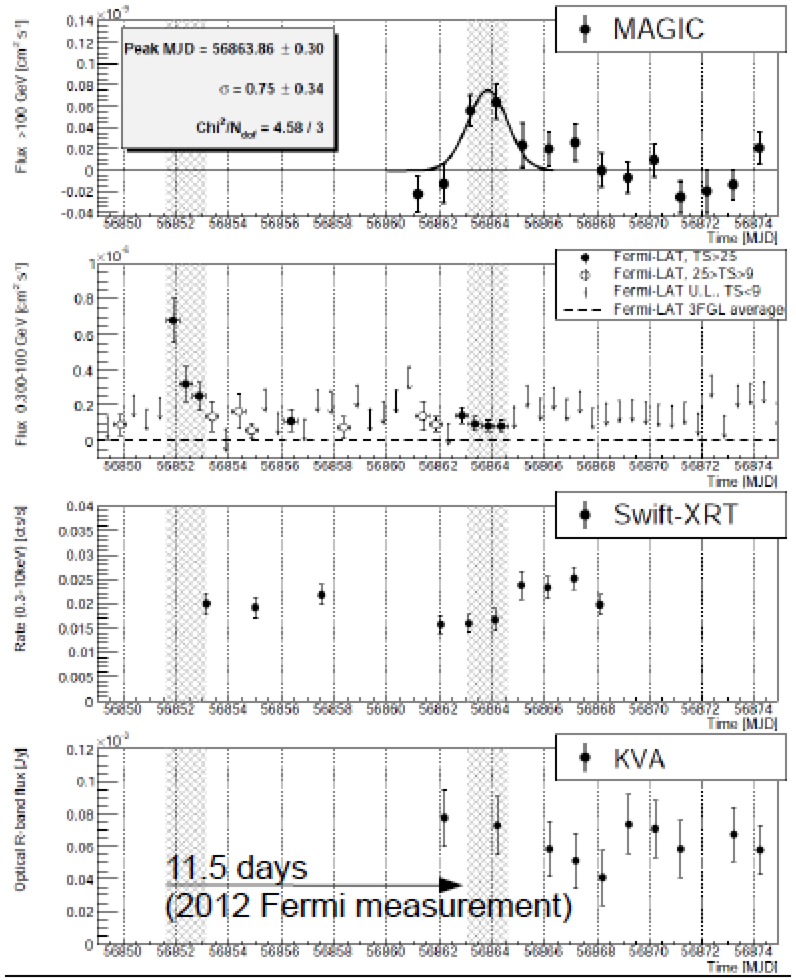
MAGIC B0218 & MWL

A&A 595 (2016)

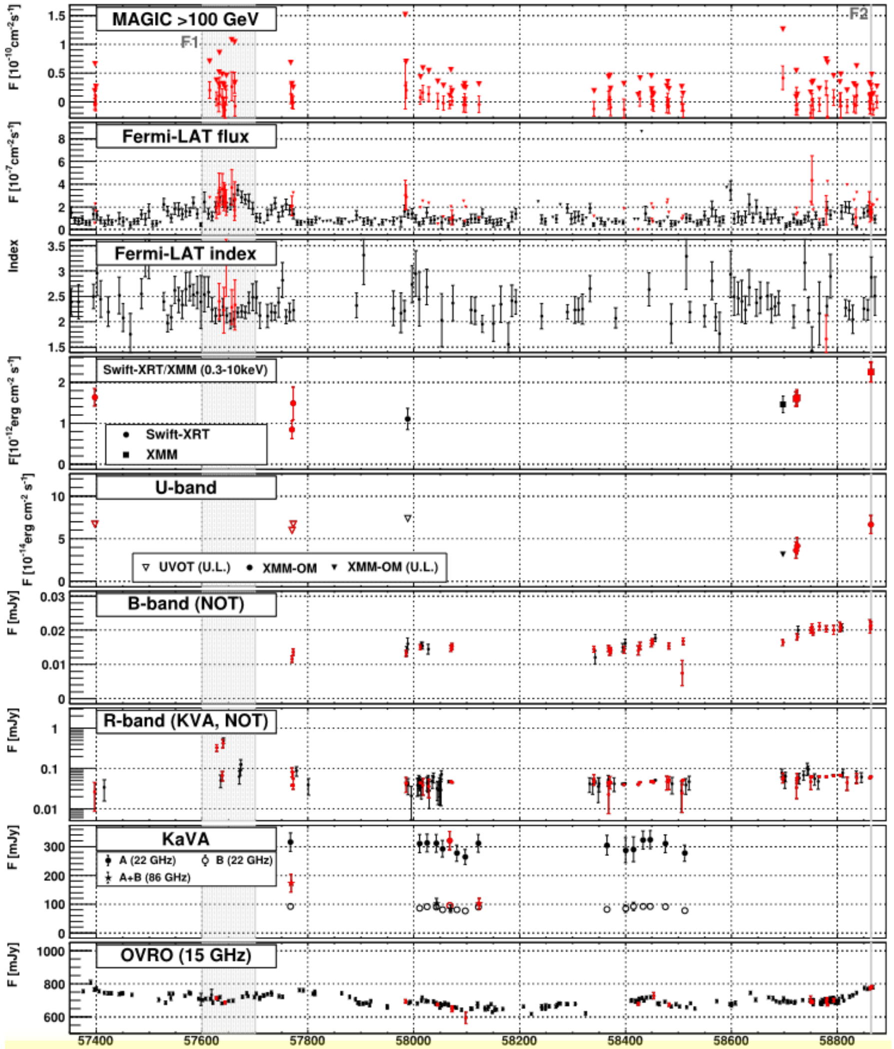
MAGIC: a single ~2 day long flare at the expected time of arrival

● *Fermi*-LAT: Clear leading flare, detected also significant emission during the trailing flare, but difficult to prove that the emission really larger than between the two components

● No enhanced emission during the second component of the flare in X-rays and optical range



Gravitational lensed blazar B0218



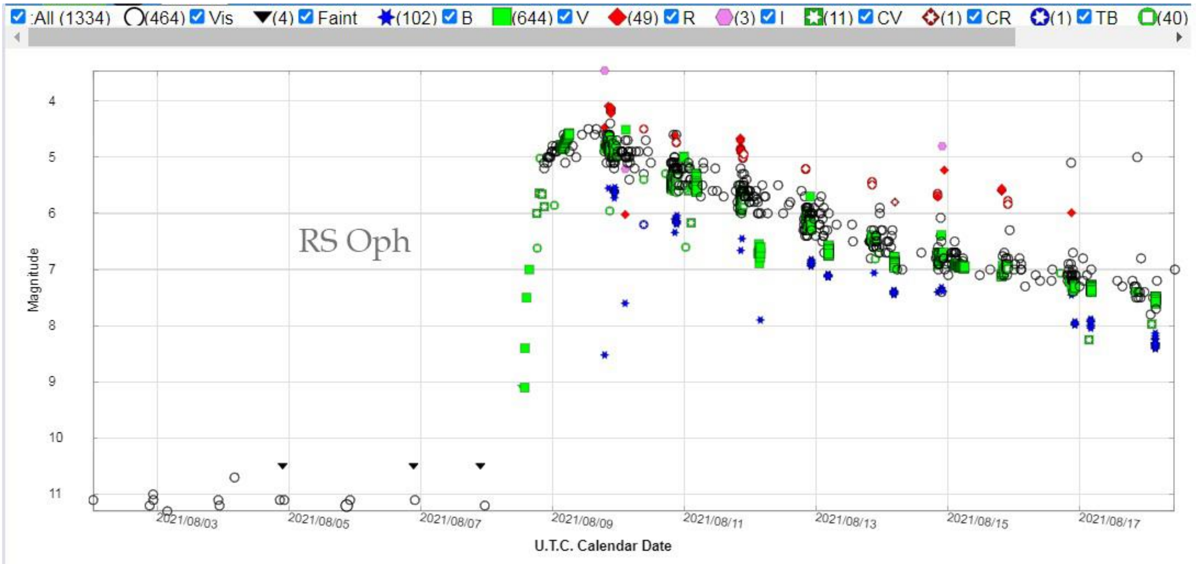
MNRAS, 510 (2022)

- Multiwavelength monitoring 2016-2020 in radio, optical, X-rays and gamma rays
- Enhanced GeV and optical state
- MAGIC 72 hours in 72 nights
- No significant emission detected => No detection at VHE in low-state
  - Improved lens model
  - Measurement of column density of absorbing material in lens galaxy
  - MWL low sate emission fitted with two zone model

=> Still most promising lensed candidate

Outburst of RS Ophiuchi in 2021

- RS Ophiuchi is a recurring nova that has had nine outbursts since 1898, with each sudden jump in visual magnitude from 12.5 to about mag 5.
- Such a burst was observed on August 8th 2021 by Irish amateur Keith Geary



Here is a picture from August 10, 2021 with the QHY 268C on the 10 inch f/5 Newton. 10 minutes total exposure time. AstronomyForum, Rene112

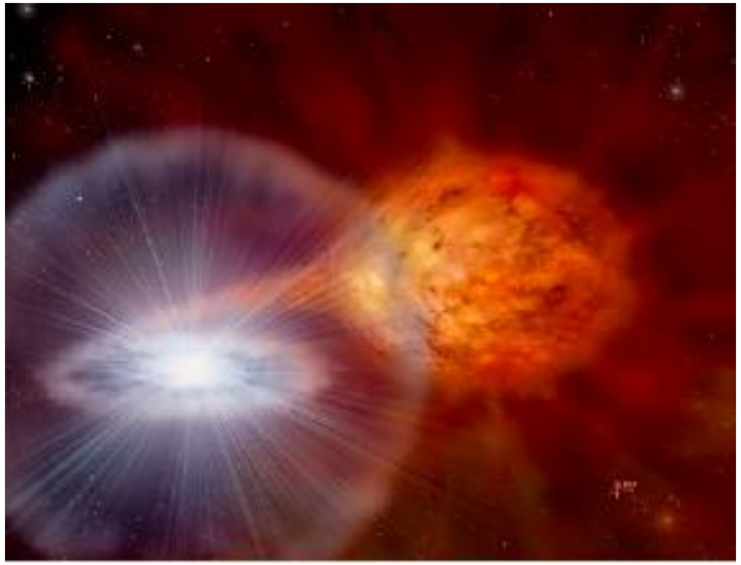
RS Oph

MAGIC coll., Nature Astronomy, 2022

- Classical novae are cataclysmic binary star systems, in which the matter of a companion star is accreted on a white dwarf (WD). Accumulation of the matter in a layer eventually causes a thermonuclear explosion on the surface of the WD, brightening the WD to 10^5 solar luminosities and triggering ejection of the accumulated matter. They provide extreme conditions required to accelerate particles, electrons or protons, to high energies.
- A symbiotic nova can be formed when the companion star of the WD is a red giant (RG)
- Following these alerts, MAGIC began observations of RS Oph as part of its nova follow-up program, on August 09, 2021 at 22:27 UT, i.e., about 1 day after the first optical and GeV detections.
- In parallel, the H.E.S.S. collaboration announced VHE gamma rays from RS Oph
- The MAGIC observations reveal VHE emission contemporaneous to the Fermi-LAT and optical maxima, and a decrease below the VHE detection limit two weeks later
- The first four days of **MAGIC observations (August 09-12) yield** a VHE signal with a **significance of 13.2 σ, spanning from 60 GeV to 250 GeV**, well fitted by a single power-law
- Intriguingly, while the GeV emission subsides with a halving time scale of 2,2 days, the flux measured by MAGIC over the first four days is consistent with being constant
- This suggests a migration of the gamma-ray emission towards higher energies, in line with an increase of the maximum energies of the parent particles.

RS Oph detected and characterised over ist peak emission by MAGIC telescopes

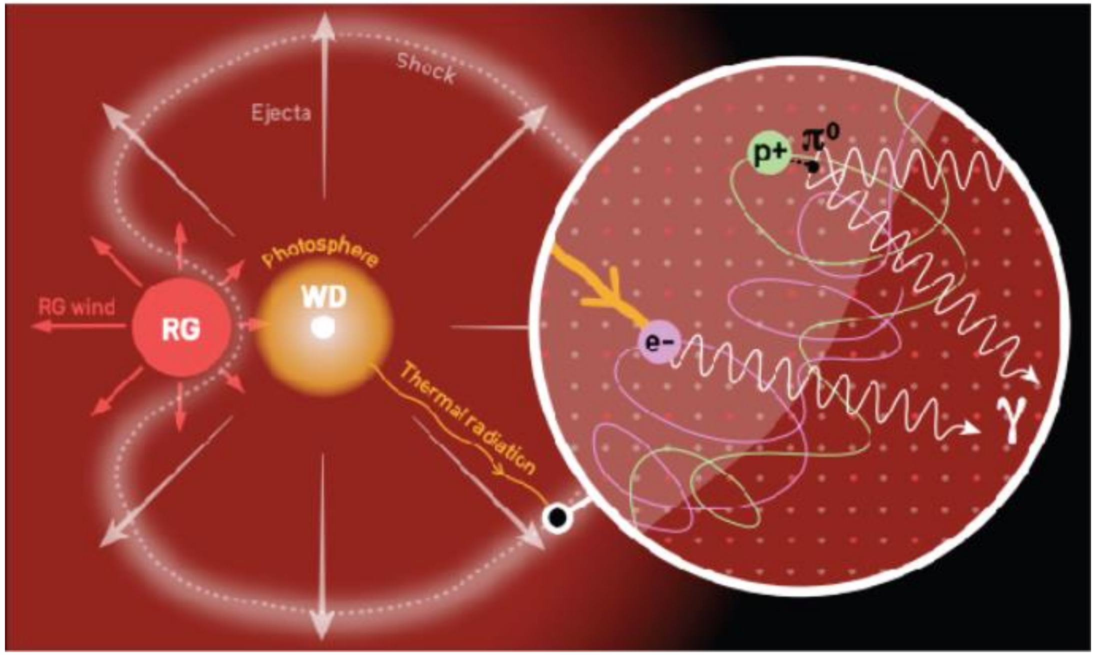
MAGIC coll., Nature Astronomy, 2022



- Recurrent nova in a symbiotic binary
- Outbursts once every 15-20 years
- Previous outburst in 2006 (no gamma-satellite in orbit)
- Distance under debate, from 1.4 - 4.3 kpc in literature
- Used value 2.45 kpc

Why do we see gamma-ray emission ?

MAGIC coll., Nature Astronomy, 2022



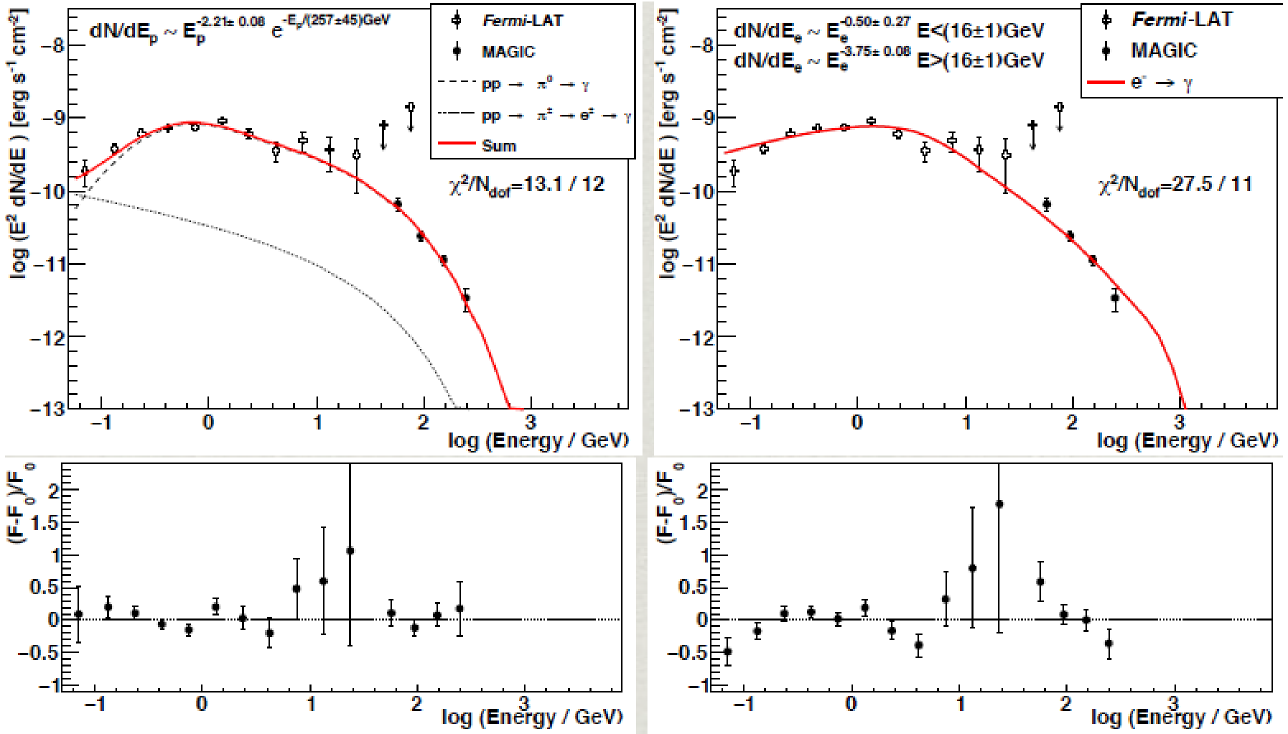
A photosphere (yellow circle) surrounds the White Dwarf (WD, white small circle). Its companion star, a red giant (RG, red circle) emits a slow wind (red arrows). Ejecta of the nova explosion (gray arrows) propagate into the surrounding medium causing a shock wave encompassing the binary system (gray dashed line). In the shock wave, energetic electrons and protons (magenta and green wavy lines, respectively) are trapped by a magnetic field and accelerated.

- A correlation between optical and gamma-ray emission has confirmed that a substantial part of the novae explosion's power goes into shocks. In such shocks, energetic electrons and protons can be produced
- Gamma-ray emission can arise from photosphere thermal radiation up-scattered to the high energy range by relativistic electrons via *inverse Compton* scattering.
- Alternatively, the *ambient matter* (nova ejecta and RG wind) *can act as a target for hadronic interaction of protons or Bremsstrahlung radiation of electrons*
- The maximum energies of high-energy particles will depend on the efficiency of the acceleration mechanism, duration of the nova, and the cooling energy losses
- Production of high energy photons via leptonic mechanisms is much more demanding on the acceleration processes efficiency than for proton models
- The total contribution of novae is in any case < 0.2 % compared to that of supernovae (remnants)

Proton Acceleration

- The proton acceleration is the preferred option because
  - These can be injected with the natural -2 spectrum, while electrons need an ad-hoc spectral brake in the injection spectrum
  - The chi² of the fit is better for protons
  - There is a hint of spectral hardening in the energy for protons
  - Optical and high-energy emission decay similar → while IC emission should decay faster because of the photosphere expansion

MAGIC coll., Nature Astronomy, 2022



The expected next explosive result:

Thermonuclear explosion in T Corona Borealis

T Coronae Borealis (T CrB), is recurrent symbiotic nova.
Erupted in 1866 and 1946 (**80years**), and predicted (AAVSO) to explode in the year 2024 (because of preeruption dip in optical LC)

T CrB is 3 times closer to the Earth than RS Oph (0.9kpc vs 2.7kpc)

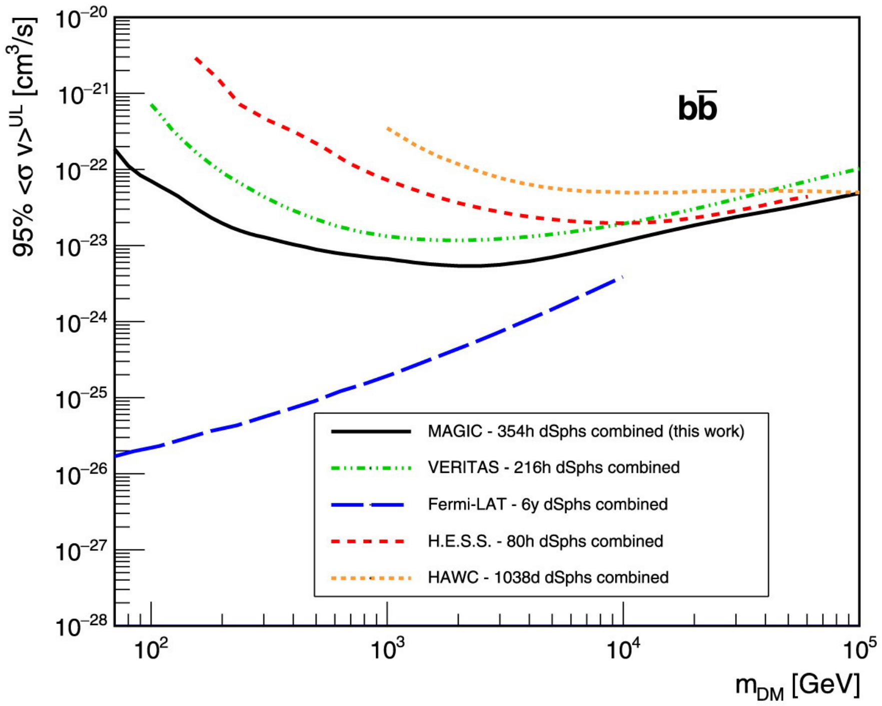
→9 times brighter !
→once in a lifetime opportunity !
→Large expectation and commitment to observe from many groups

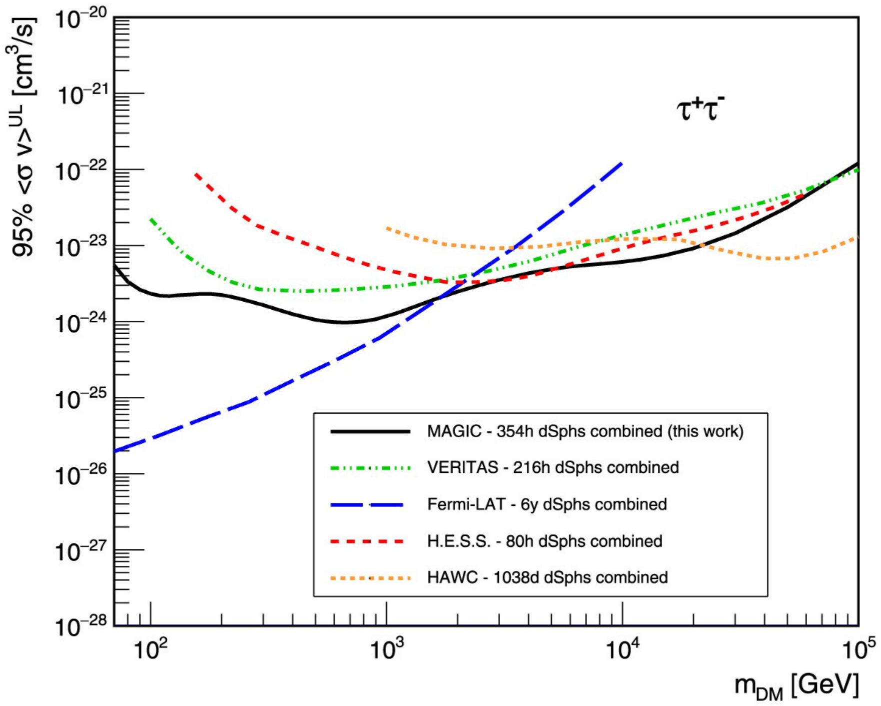
T CrB also caught attention of Neil deGrasse Tyson in youtube video with more than 3M visits in few weeks:

https://www.youtube.com/watch?v=5i6aEA-RkOQ&list=PLnaXrumrax3Wyn1oMYWYlpcwrc76Nm40Q

Dark Matter Search

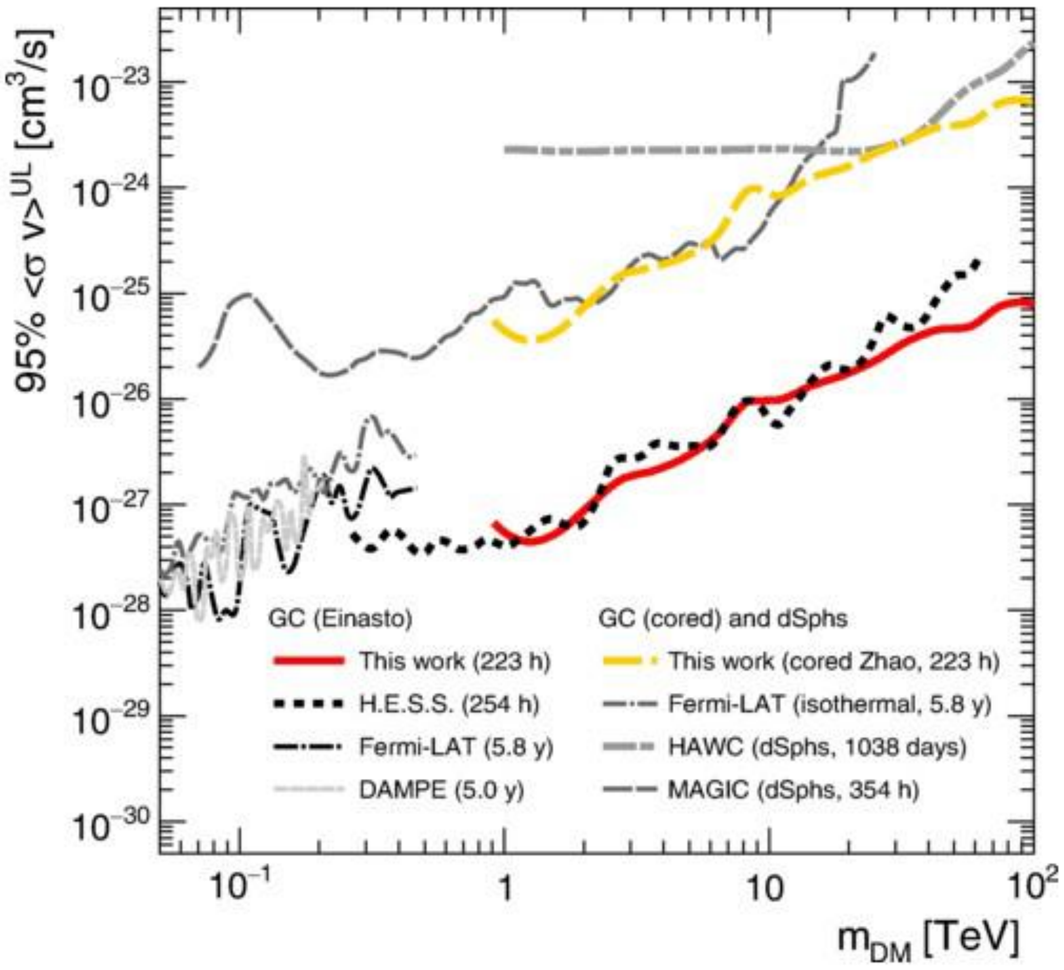
Phys. Dark. Univ., 2022





4 dwarf spheroidal (dSph) galaxies were observed for 354 h
=> No excesses measured
=> Dark matter annihillation cross section constrained
=> Most stringent limits on dSph at multi-TeV energies

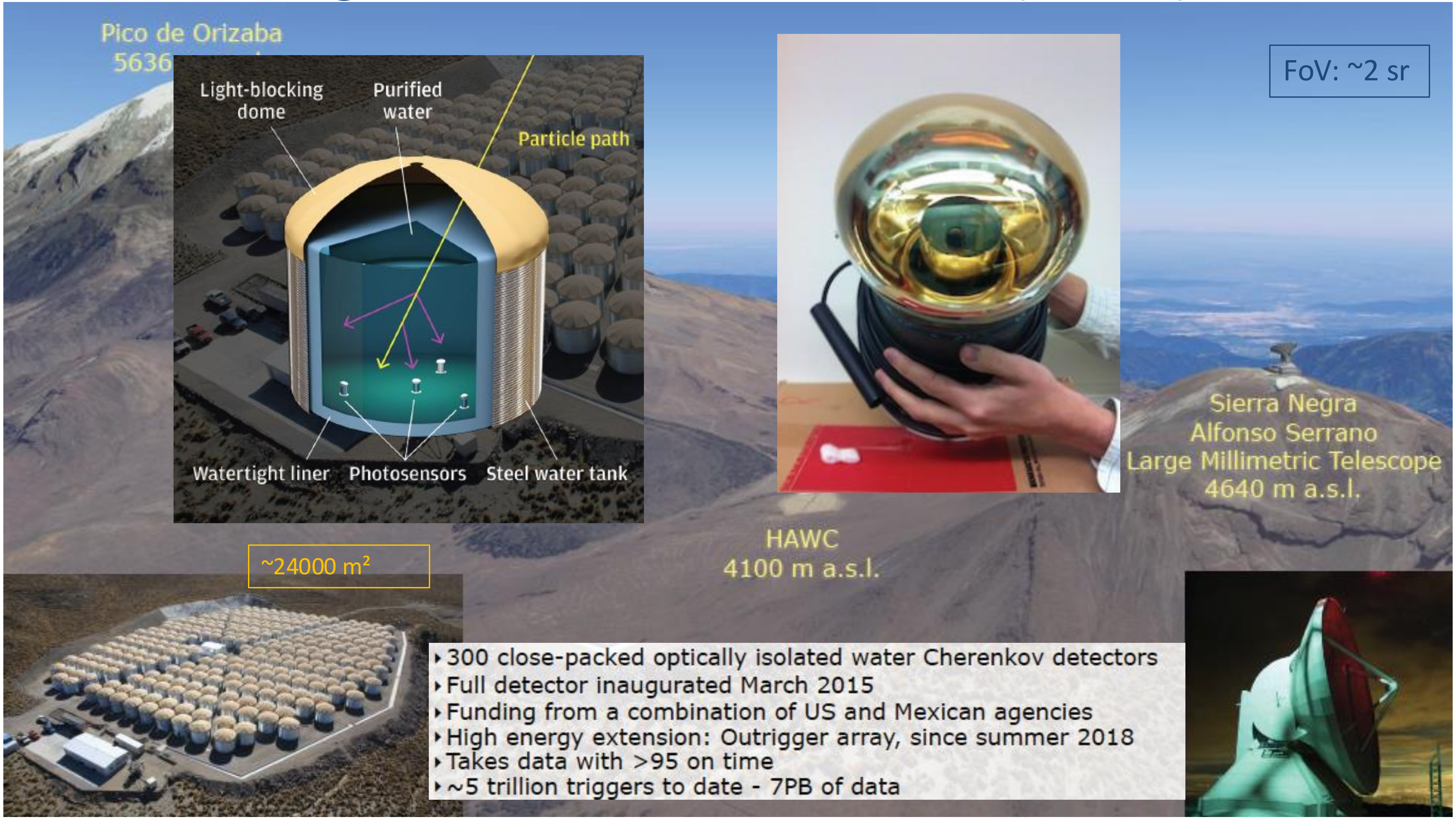
Dark Matter Line Searches



PRL 130 (2023)

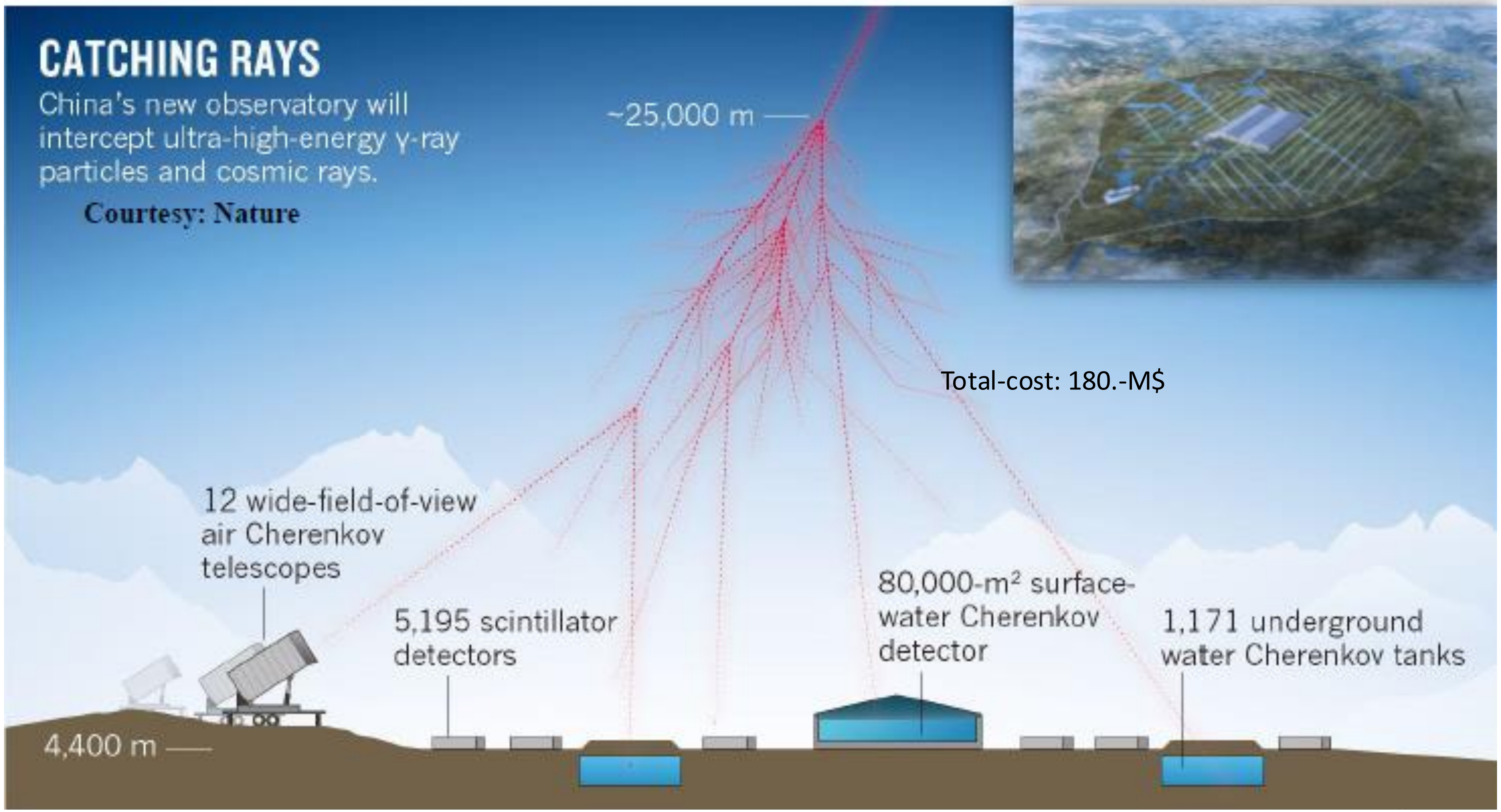
- DM line searches from the Galactic Center region
- No line feature found in 223 h observations
- Use large zenith angle observation technique for increasing the sensitivity > 20 TeV
- Strongest constrains

High Altitude Water Cherenkov (HAWC) detector



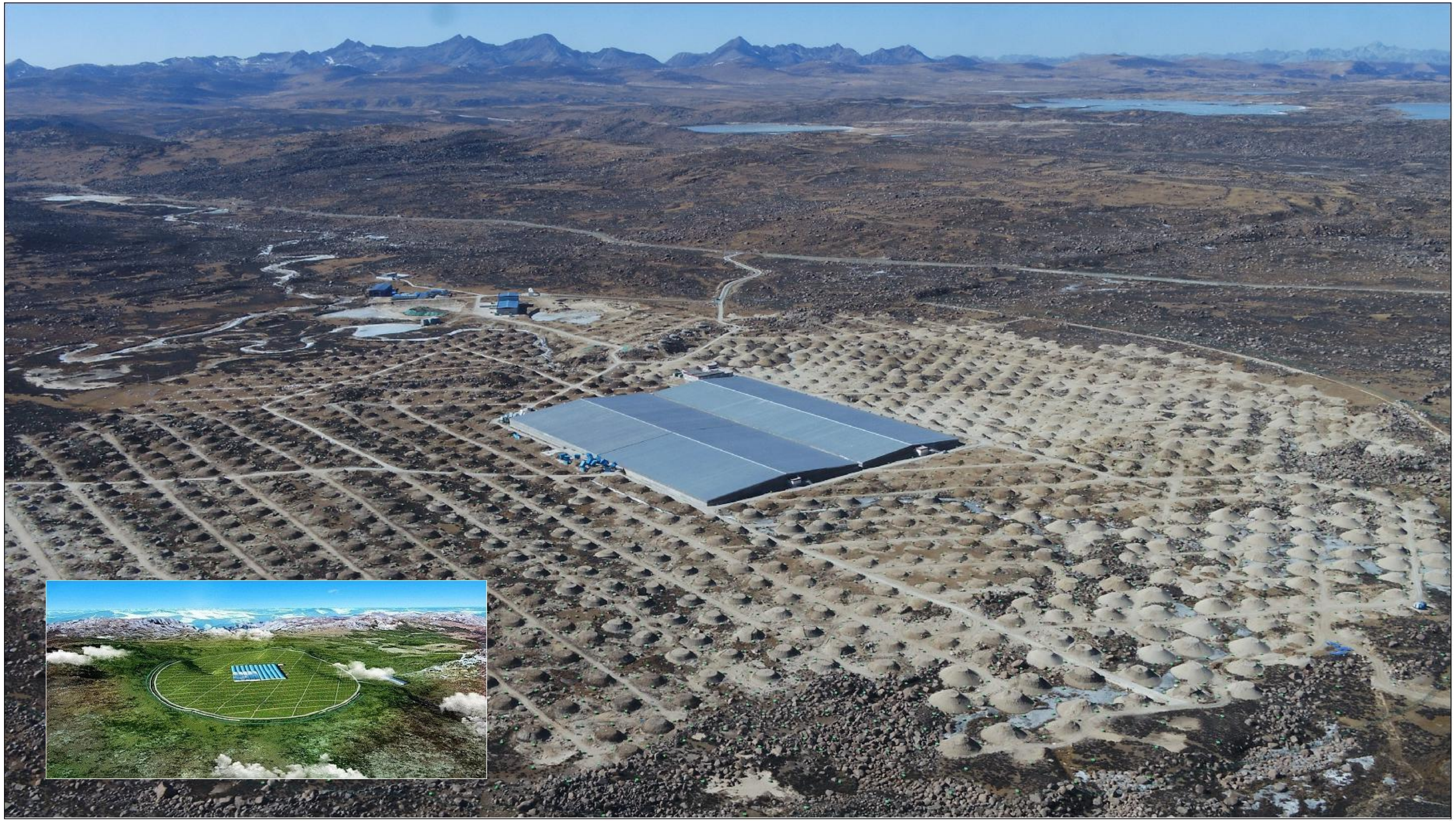
- 300 close-packed optically isolated water Cherenkov detectors
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018
- Takes data with >95 on time
- ~5 trillion triggers to date - 7PB of data

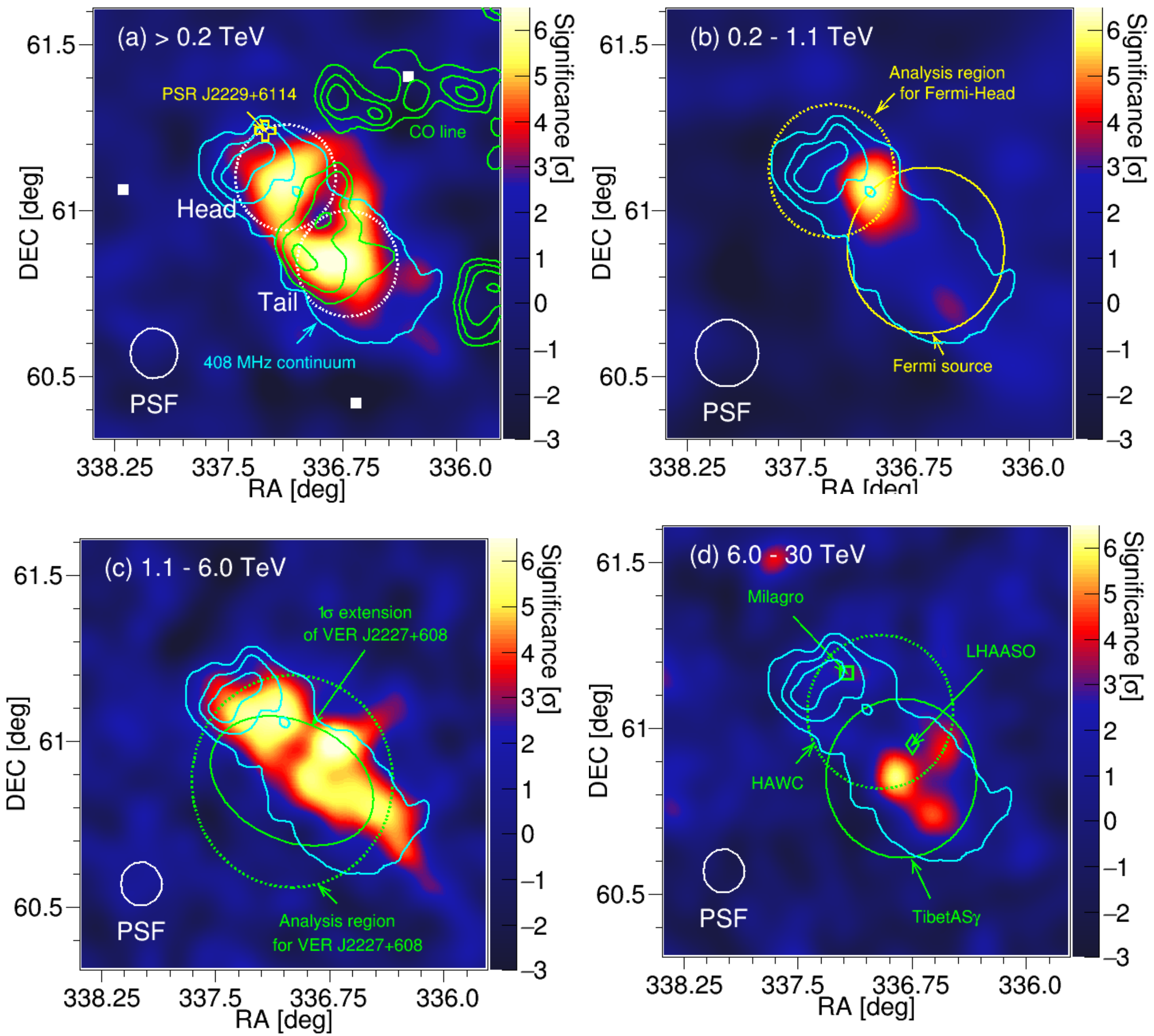
Hybrid Detection of EASs by LHAASO



LHAASO in China

Last couple of years LHAASO discovered several tens of PeVatrons





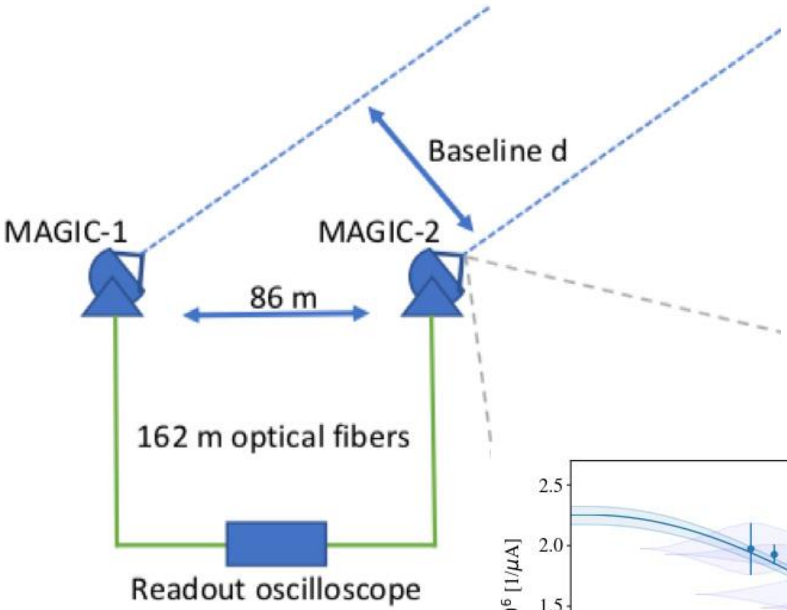
SNR G106.3+2.7

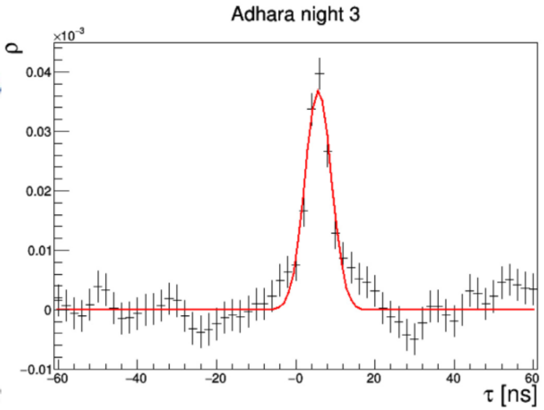
MAGIC, A&A 2023

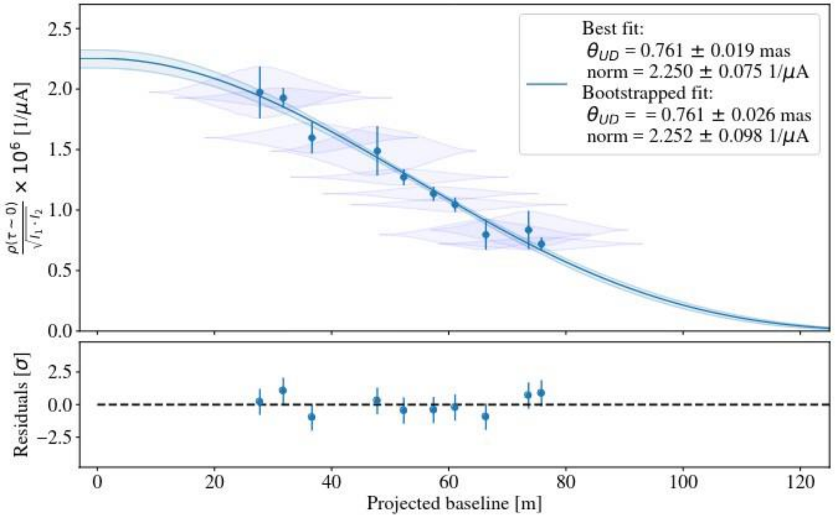
MAGIC observations provide compelling evidence of hadronic multi-TeV emission from the putative PeVatron

The γ-ray emission region detected with the MAGIC telescopes in the SNR G106.3+2.7 is extended and spatially coincident with the radio continuum morphology. The multi-wavelength spectrum of the emission from the tail region suggests proton acceleration up to ∼PeV, while the emission mechanism of the head region could either be hadronic or leptonic.

Intensity Interferometry with MAGICs +LST1



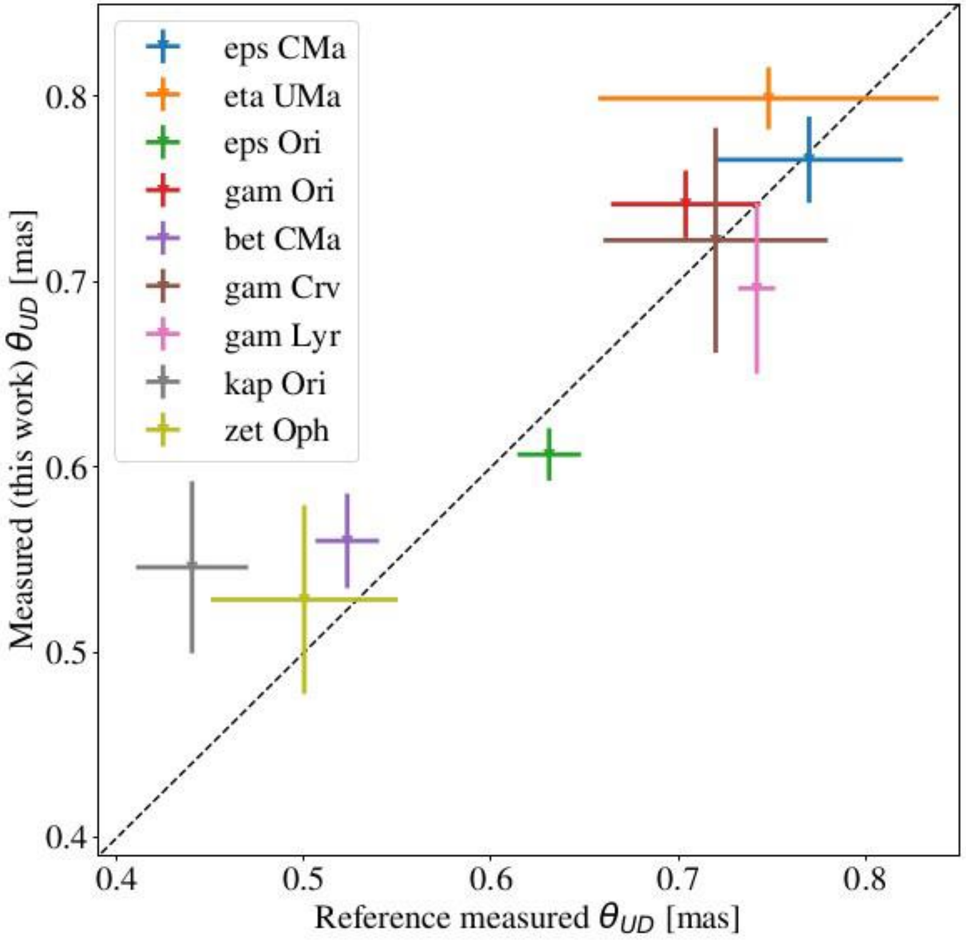




Using interference filters with central wavelength Λ = 425 nm, with ~ 20 nm bandwidth

- IACTs feature large mirrors and ~ a few ns time response to photons. They fit well for stellar intensity interferometry (SII)
- In visible light, long baseline optical SII with IACTs can allow one to reach an **angular resolutions** on the order of several **tens of micro-arcseconds**.
- We have installed an optical setup on top of the cameras of the two 17 m diameter MAGICs and observing coherent fluctuations in the photon intensity measured at the two telescopes for a number of celestial objects. Currently best sensitivity for SII among IACTs

Stellar Intensity Interferometry with MAGICs + LST1



- Diameters of 9 stars measured with MAGIC agree well with other experiments
- New measurements of 13 stars have been performed and published in MNRAS, 2024
- Inclusion of nearby LST-1 quadrupled the sensitivity
- Potentially one can measure shape of stars, of binary systems and hopefully also recurrent novae explosions

CONCLUSIONS

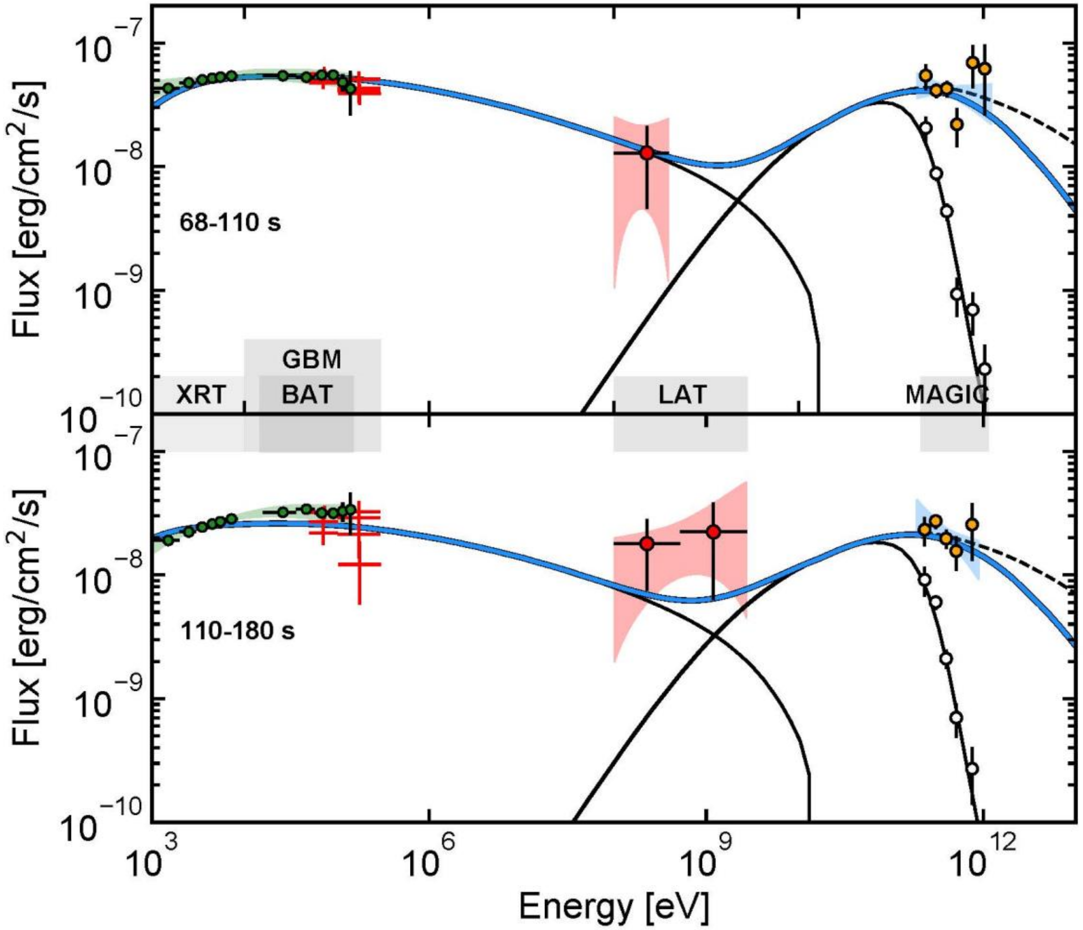
Photo of ORM site in La Palma taken a couple of months ago

- In a time scale of a few years the ORM observatory with 4 LSTs of 23m diameter, along with a number of MSTs, twin MAGICs and the array of 4m class SSTs on Tenerife will become the most sensitive IACT array in the Northern hemisphere

Backup slides

IC Emission from GRB 190114C

MAGIC collaboration, et al., Nature 2019



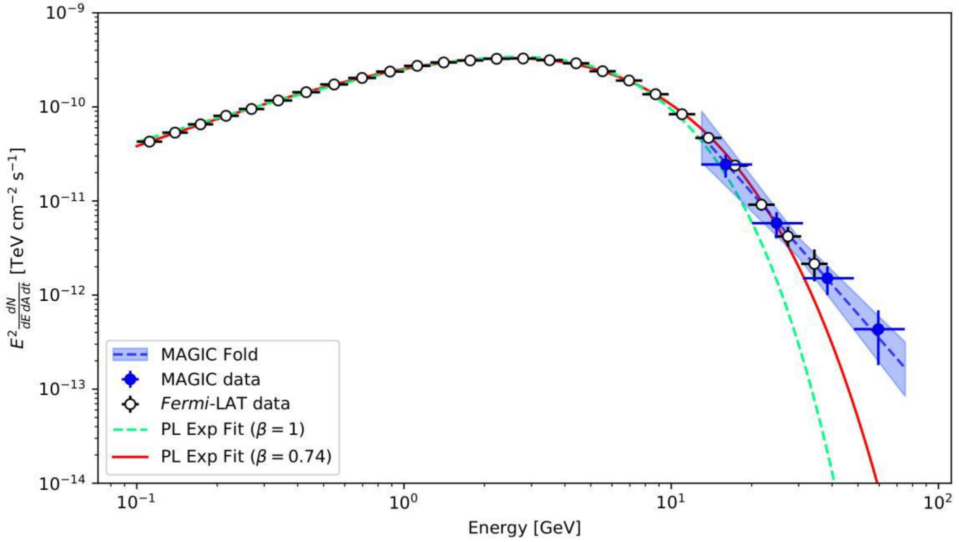
Discovery of a new, TeV emission component in the afterglow of a GRB!

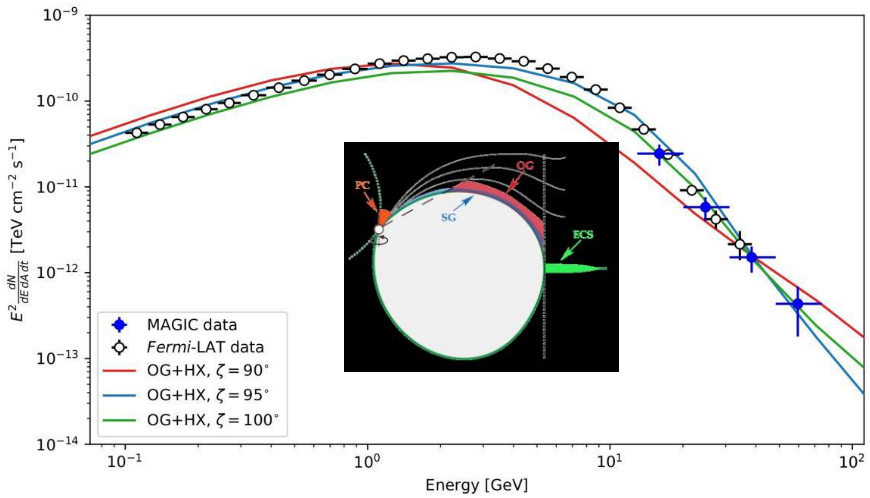
- The double-peak structure is well-known from blazar SEDs
- The energy in the SSC peak is comparable to the energy in synchrotron
- A non-negligible part of GRB energy is released @ TeV energies
- Modeling parameters in agreement with previous GRB aferglow studies, GRB 190114C not exceptional

➡ VHE emission should be a common effect

MAGIC + Fermi Spectrum of Geminga

Acciari et al, A&A, 2020; **Highlight Letter**





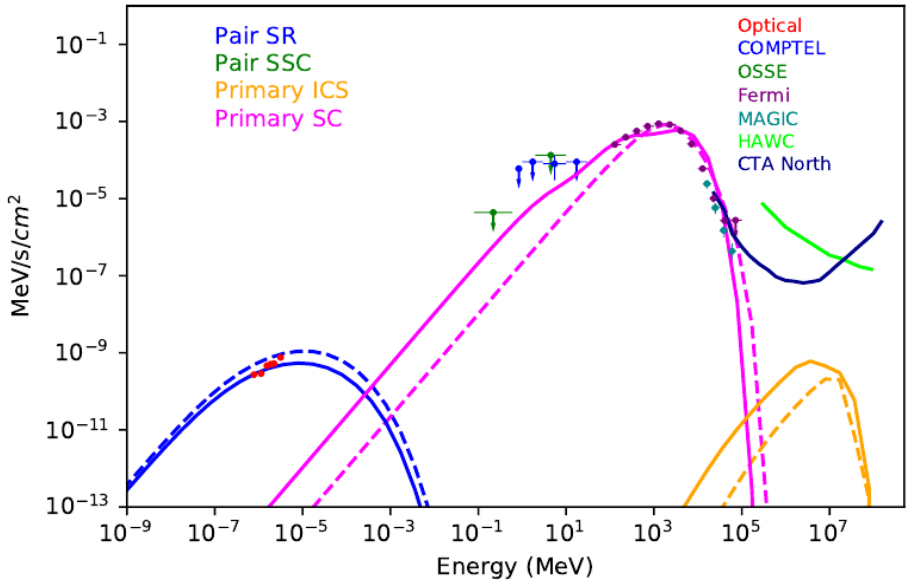
- Power law spectrum @ (15 – 75) GeV with Γ = -5.2
- MAGIC & Fermi data overlap for E ≤ 40 GeV
- No cutoff observed
  - Exponential cutoff ruled out
  - Sub-exponential disfavored @ 3.5 σ level
  - Power law behavior compatible with IC

- Modeling with Outer Gap
  - IC with inward-going e^-
- Observation challenges the model
  - Contribution from Heated Polar Cap (Caraveo, 2004)

Geminga Pulsar

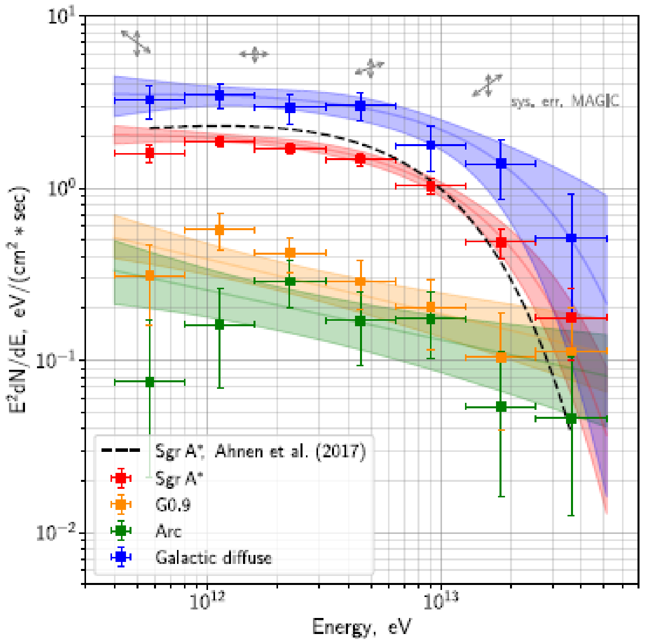
- Novel **class of models** supported by extensive **numerical simulations**.
- Acceleration **just beyond** the **light-cylinder**
- Geminga emission explained as **primary SC**, **no need to invoke IC component**.
- Challenging target also for CTA/LST.

Harding et al., 2021



Diffuse γ-ray emission from the GC region and acceleration of particles by SMBH

Acciari et al., A&A 2020



Centre of our galaxy harbours the yet closest known super-massive black hole. Due to proximity this is a unique laboratory, also for studying comic ray acceleration near black holes.

MAGIC GC observations confirm the peaked towards the position of the central SMBH cosmic-ray density profile, similar to H.E.S.S. (2016). This could be seen as an evidence that until relatively recently the SMBH was still accelerating particles

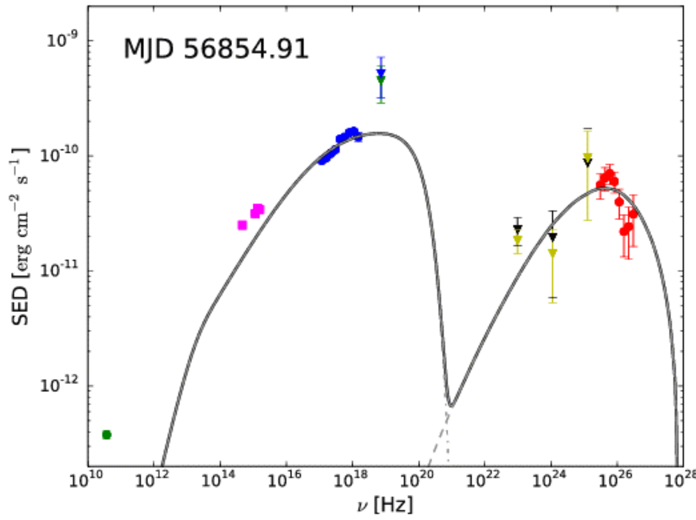
MAGIC data shows that the spectrum of diffuse gamma-ray emission is hard (Γ ~ 2) and extends to several 10's of TeV.

Our analysis, however, shows a **2σ hint for a spectral turnover** at around those energies

Mrk 501: extreme X-ray flares & a hint of a narrow spectral feature @ 3 TeV

MAGIC coll., A&A 2020

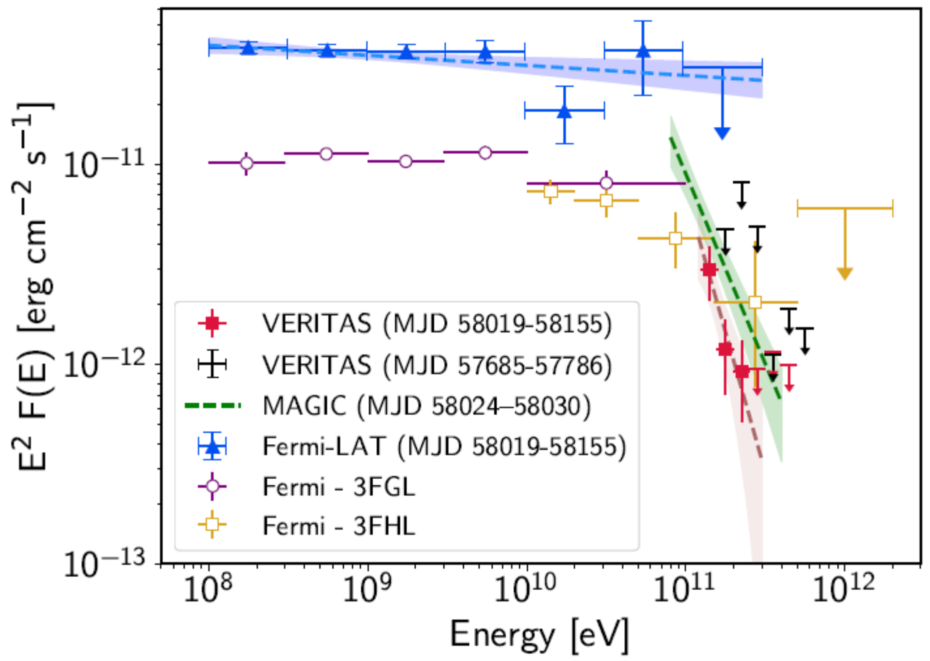
- Markarian 501 (Mrk 501) is one of the brightest very high energy (VHE, E> 100 GeV) gamma-ray blazars. It is located at nearby redshift z=0.034.
- During a multi-wavelength campaign in July 2014, Mrk 501 displayed the highest X-ray activity observed by the Neil Gehrels Swift X-ray telescope (XRT) since its launch.
- The X-ray spectra displayed during this flaring episode were very hard, and showed variability on nightly timescales.
- On 2014 July 19, in coincidence with the peak of the X-ray activity, **a hint of a narrow feature at 3 TeV** was observed with the MAGIC telescopes.
- Such feature makes the VHE spectrum inconsistent with the "classical" analytic functions used to describe the measured VHE spectra.



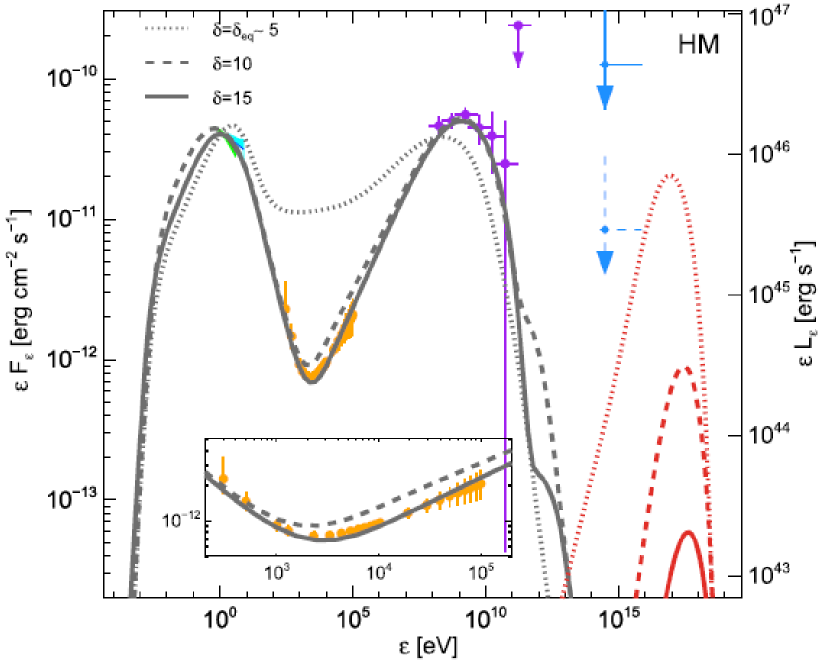
3 different scenarios to produce such effect: (a) a pileup in the e^- energy distribution due to stochastic acceleration; (b) a structured jet - two-zone SSC emission model;
(c) magnetospheric vacuum gap model + one zone SSC; a pair cascade model.

TXS 0506+056 - What Did We Learn ?

Santander PoS(ICRC2019)782



Keivani, et al.,ApJ, 2018



- VHE γ-rays and hard X-rays essential for constraining the models
- Spectrum change from Fermi energies to TeV could be due to internal absorption or primary spectral break or production inefficiency, or…
- Favored scenario: leptonic with some admixture of hadronic; pure hadronic is ruled out
- One-zone models result in a very high *p* luminosity → two-zone or external fields help

Recent fireworks in the sky: Supernova 2023ixf

• First reported observation of a new stellar object in M101 very late on May 19th by Koichi Itagaki (a „supernova hunter“)
• Afterwards confirmed as supernova
• Well observable by MAGIC at this time
• Distance is about 21 million light years, very close as far as supernovae go
• Quick organisation by MAGIC teams beginning on the morning of May 20th (Weekend !!)
• Large number of MW observations happening across the community
(e.g. Swift, HST foreseen)

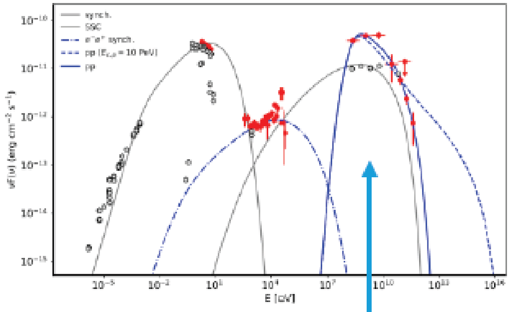
The Blazar TXS 0506+056 Associated With a High-Energy ν: Insights Into Extragalactic Jets & Cosmic-Ray Acceleration

Ansoldi et al., ApJL 2018

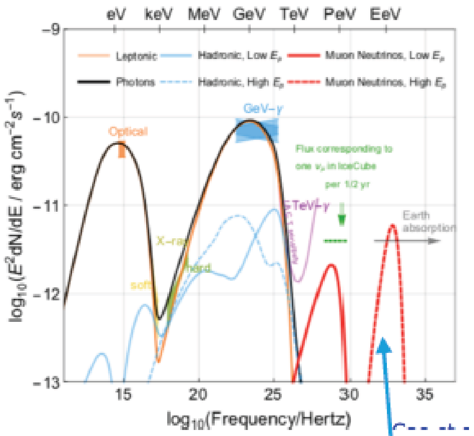
The maximum E_p in the blazar emission region is consistent with a contribution to UHECRs from protons and/or heavy nuclei accelerated in a blazar

TXS 0506+056

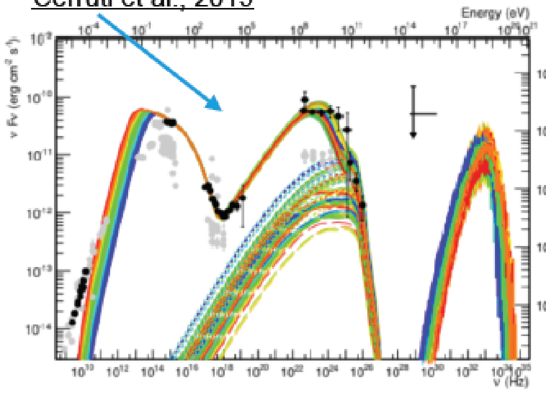
Theoretical interpretations



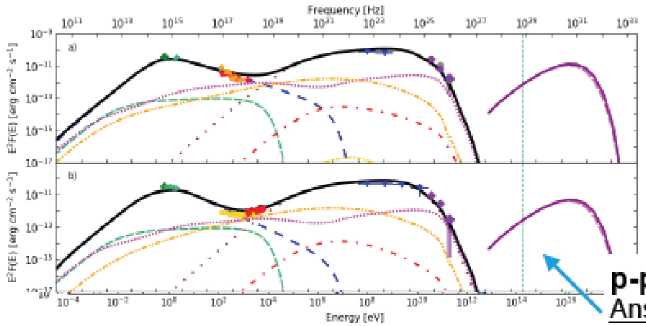
Jet+cloud (pp)
Sahakyan et al., 2018
Liu et al., 2019



Proton-synchrotron
Keivani et al., 2018
Gao et al., 2018
Cerruti et al., 2019



Hadro-leptonic
Gao et al., 2018
Cerruti et al., 2019

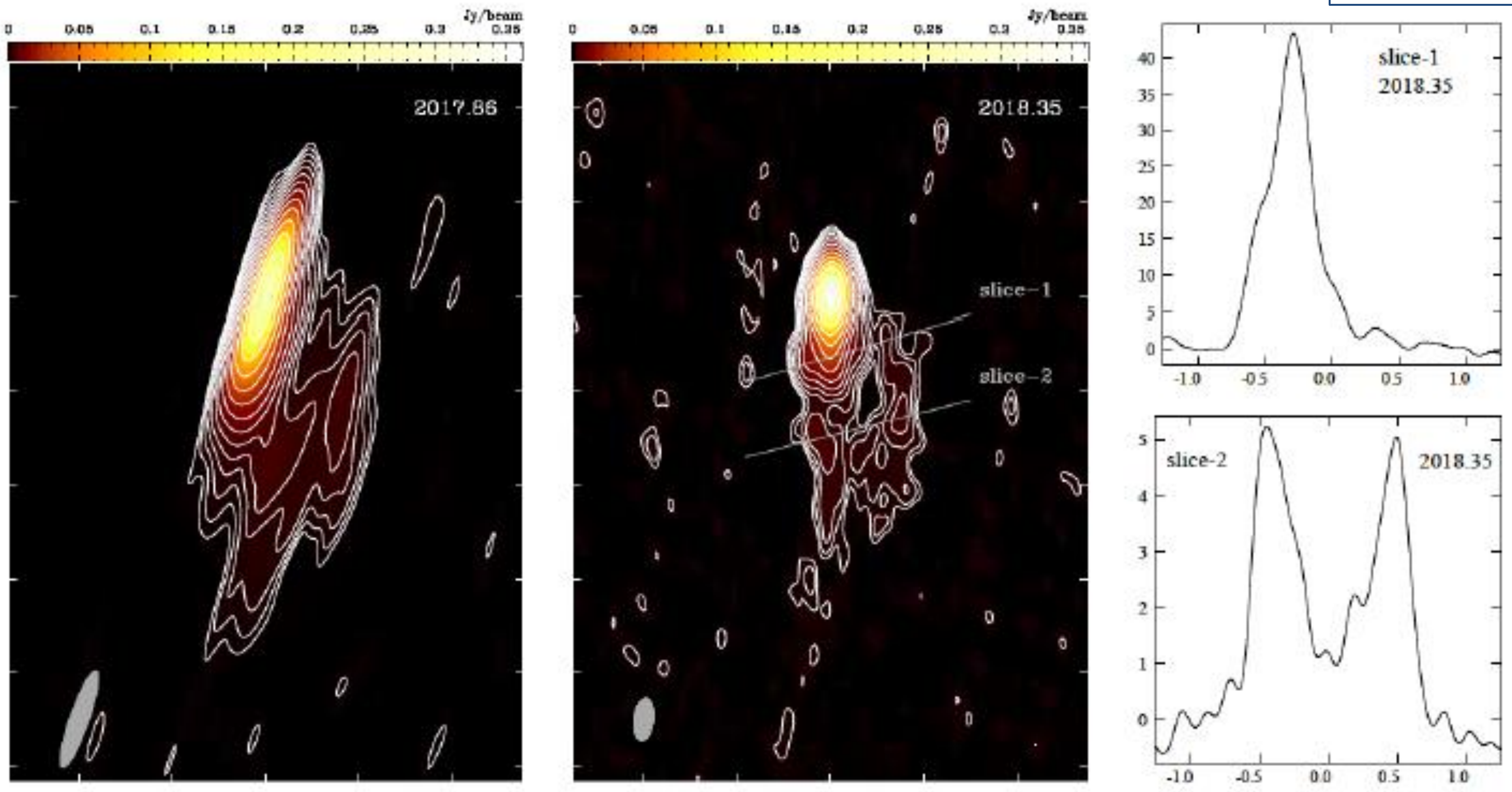


p-ph on external ph field
Ansoldi et al., 2018 (jet layer)
Keivani et al, 2018 (BB)
Righi et al., 2019 (RIAF)

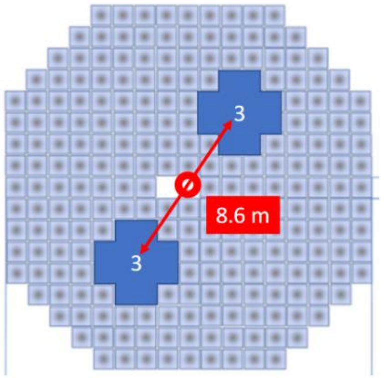
The TXS 0506+056 Story is On-Going

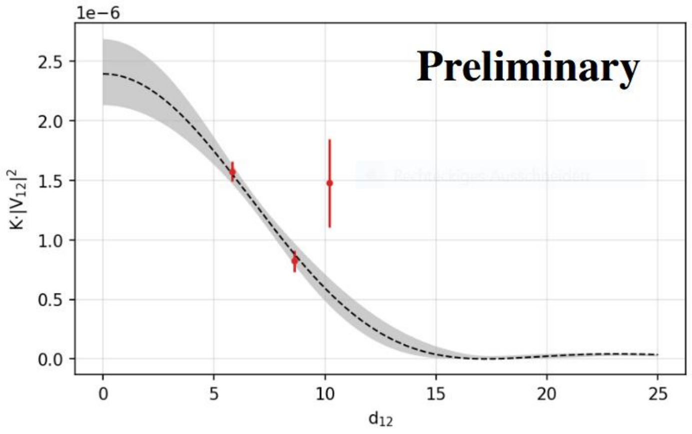
VLBI radio measurements confirm the suggested structured (shear) jet model proposed in the MAGIC paper Ansoldi et al., ApJL 2018

Ros et al., A&A 2020



Advantages due to the Active Mirror Control System

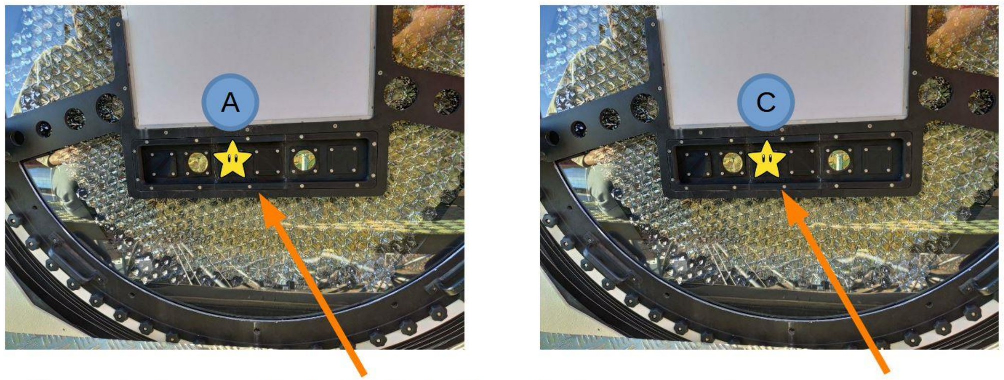




Sub-groups of mirrors can be selected to focus on a single light sensor (PMT), imitating independent telescopes, thus scanning distance range defined by the reflector diameter

MAGIC-SII setup: The power of AMC

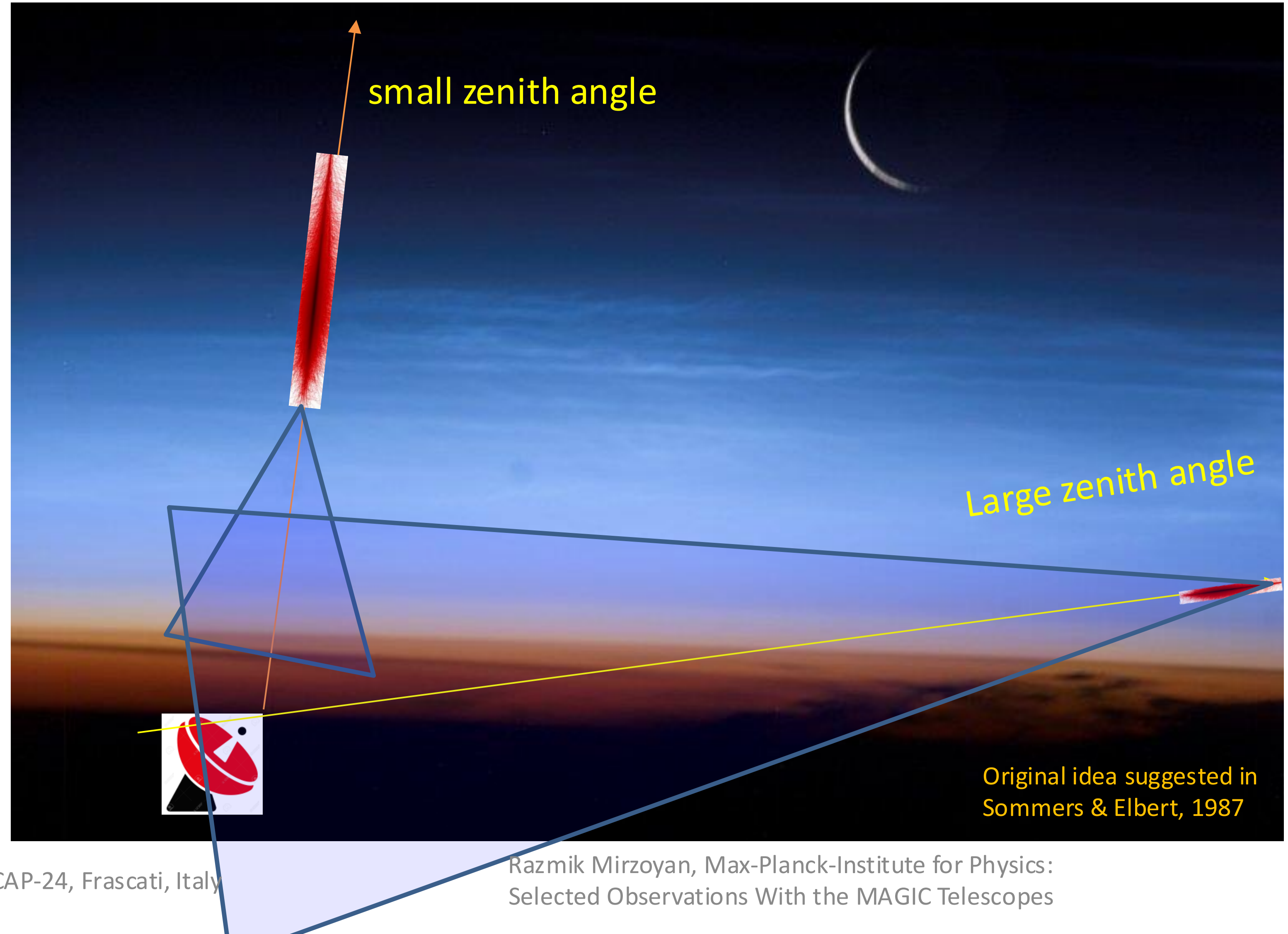
- This functionality adds enormous versatility to MAGIC: **full-mirror**



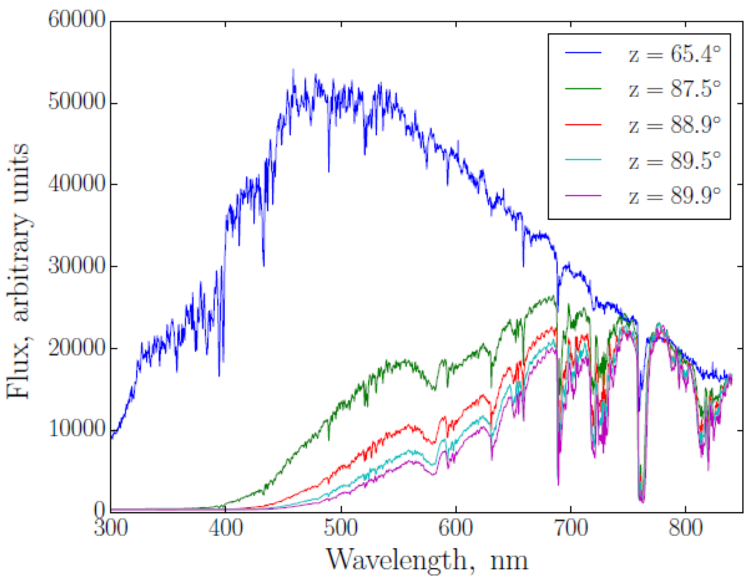
AMC allows to focus all starlight in the pixel you want

LST1 taking data

Cartoon on larger collection area for EAS measured by IACT @ large zenith angles



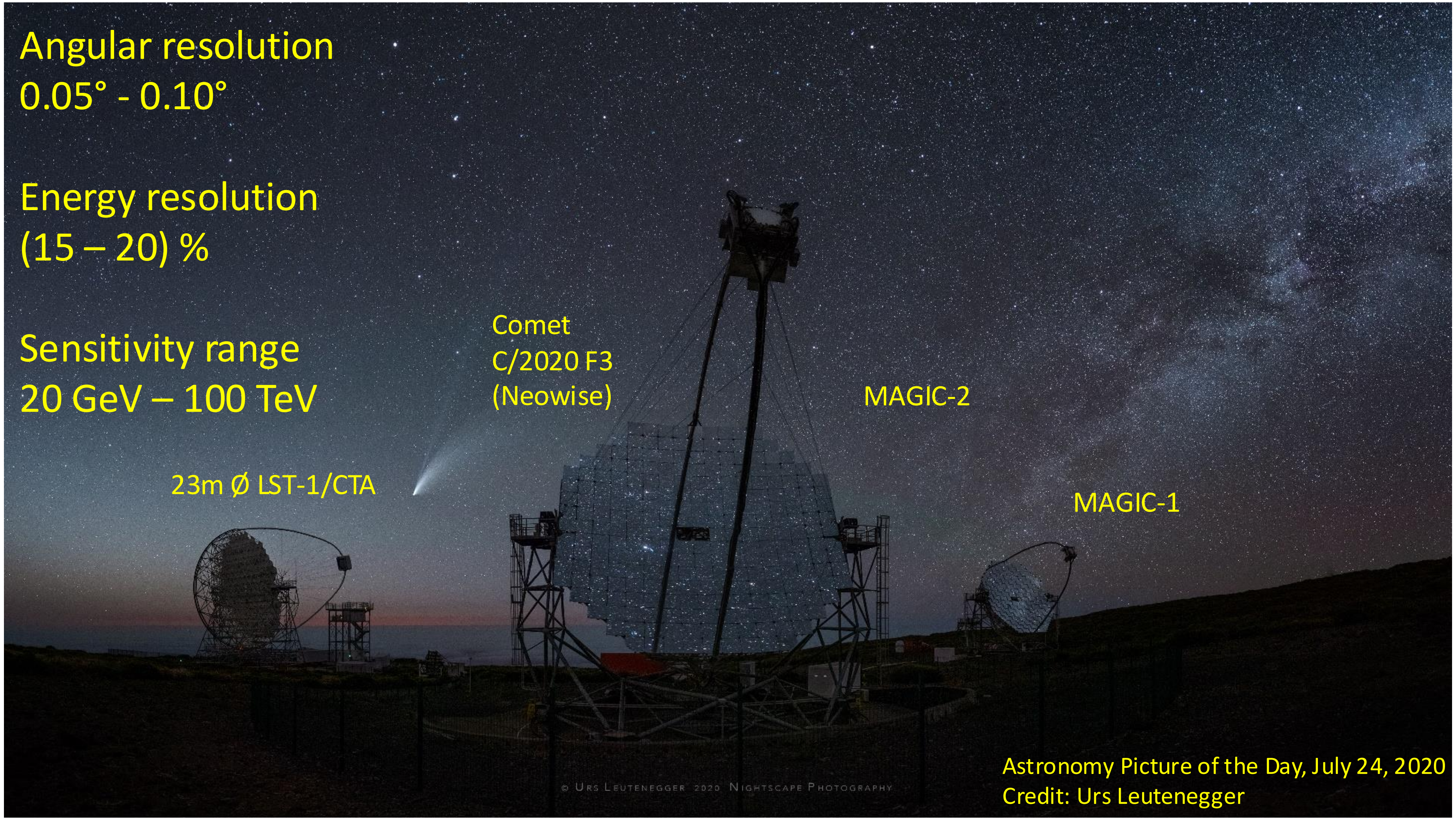
MAGIC Got 2nd Wind at ≥ 100 TeV With VLZA Observation Technique



Left: spectra of the Sun measured at ORM in La Palma at increasing zenith angles, 65° → 90°
Right: photo of the setting Sun in La Palma, taken from the ORM observatory (2200 m a.s.l.)

→ even from horizon Cherenkov light of $\lambda \geq 500$ *nm* can reach a telescope
Accurate calibration of atmospheric transmission along the long path length is essential

The MAGIC VHE γ-ray Imaging Air Cherenkov (Hi-Tech) Telescopes



CASA-MIA (and link to LHAASO)

- The **CASA-MIA** array was located at Dugway, Utah, USA, at 1450m a.s.l.
- It consisted of 2 major components:
  - the Chicago Air Shower Array (**CASA**), 1089 scintillation detectors placed on a 15 m square grid and **covering an area of 0.23 km²**, and
  - the Michigan Array (**MIA**), a buried at a depth of ~ 3.5 m array of 1024 scintillation counters **for the muon component of air showers with an active area of 2400 m²**

The underground muon detectors covered only ~1% of the total area, which prevented them to discover PeVatrons already ~30 years ago.

LHAASO increased the total area 4-fold and increased the relative share of muon detectors to 4%. And that had a magnificent effect; **LHAASO** discovered several **dozens of PeVatrons**