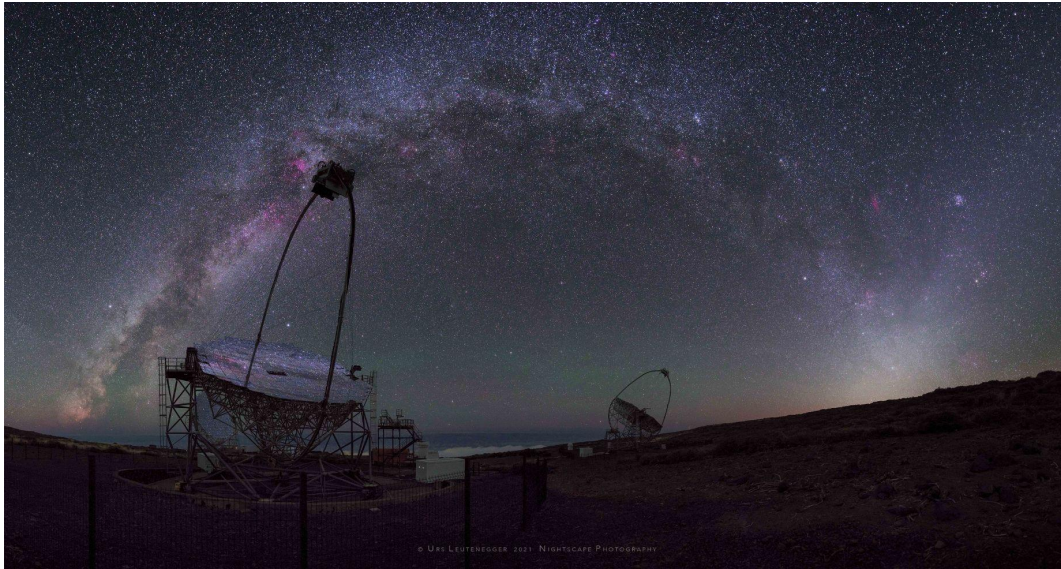




# Overview of MAGIC results



Marina Manganaro,  
University of Rijeka



([marina.manganaro@uniri.hr](mailto:marina.manganaro@uniri.hr))

Image Credit: Urs Leutenegger  
([@urs.leutenegger](https://twitter.com/urs.leutenegger))



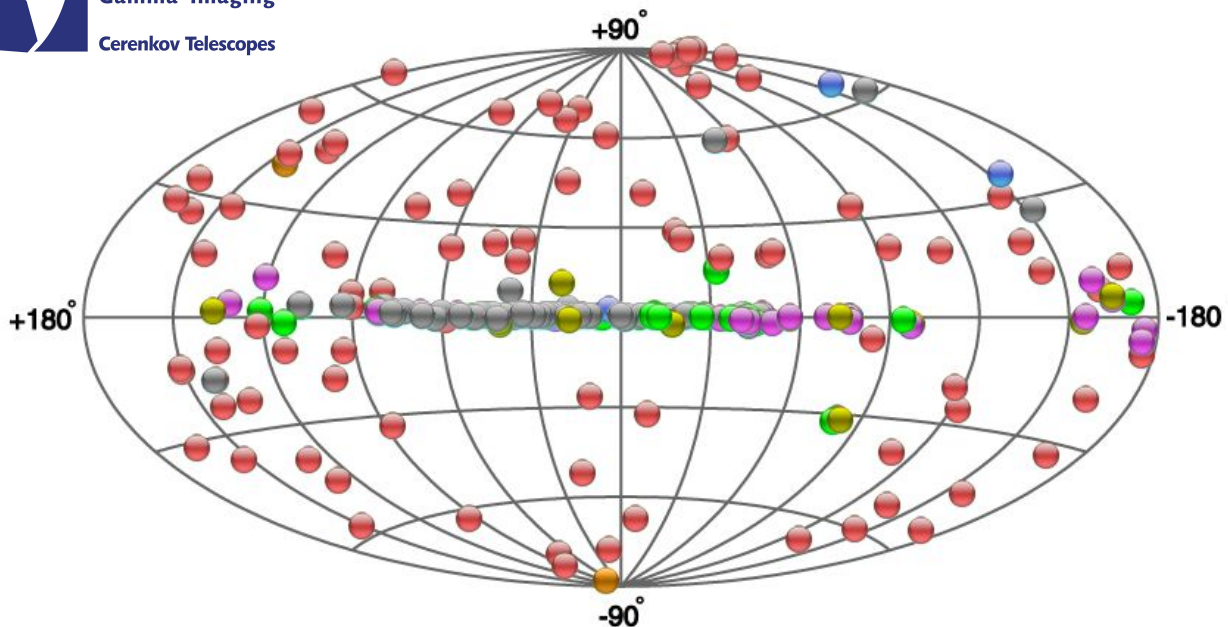
**MAGIC**

Major Atmospheric

Gamma Imaging

Cerenkov Telescopes

# The Very-High-Energy gamma-ray sky



## Source Types

-  PWN TeV Halo  
PWN/TeV Halo
-  XRB Nova Gamma BIN  
Binary PSR
-  HBL IBL GRB FSRQ LBL  
AGN (unknown type) FRI  
Blazar
-  Shell Giant Molecular  
Cloud SNR/Molec. Cloud  
Composite SNR  
Superbubble SNR
-  Starburst
-  DARK UNID Other
-  Star Forming Region  
Globular Cluster Massive  
Star Cluster BIN  
uQuasar Cat. Var. BL  
Lac (class unclear) WR

TeVCat: <http://tevcat.uchicago.edu/>

## MAGIC telescopes: Characteristics



- MAGIC I from 2004, MAGIC II from 2009
- Located in the Canary island of La Palma, 2200m a.s.l
- Mirror dish diameter: 17 m
- Active reflective mirror surface: 236<sup>2</sup> m
- Upgrade of MAGIC I camera and readout system in 2012
- 1039 PMTs cameras (FoV 3.5°)
- Energy range: 30 GeV to 100 TeV
- Fast repositioning (180° in less than 30s)
- Energy threshold can be lowered to 15 GeV
- Sensitivity above 220 GeV is ~0.66% of the Crab nebula flux (for 50 hs)
- In total 300 MAGICians from 12 countries



# MAGIC

Major Atmospheric  
Gamma Imaging  
Cerenkov Telescopes

## Extensive Air Showers (EAS)

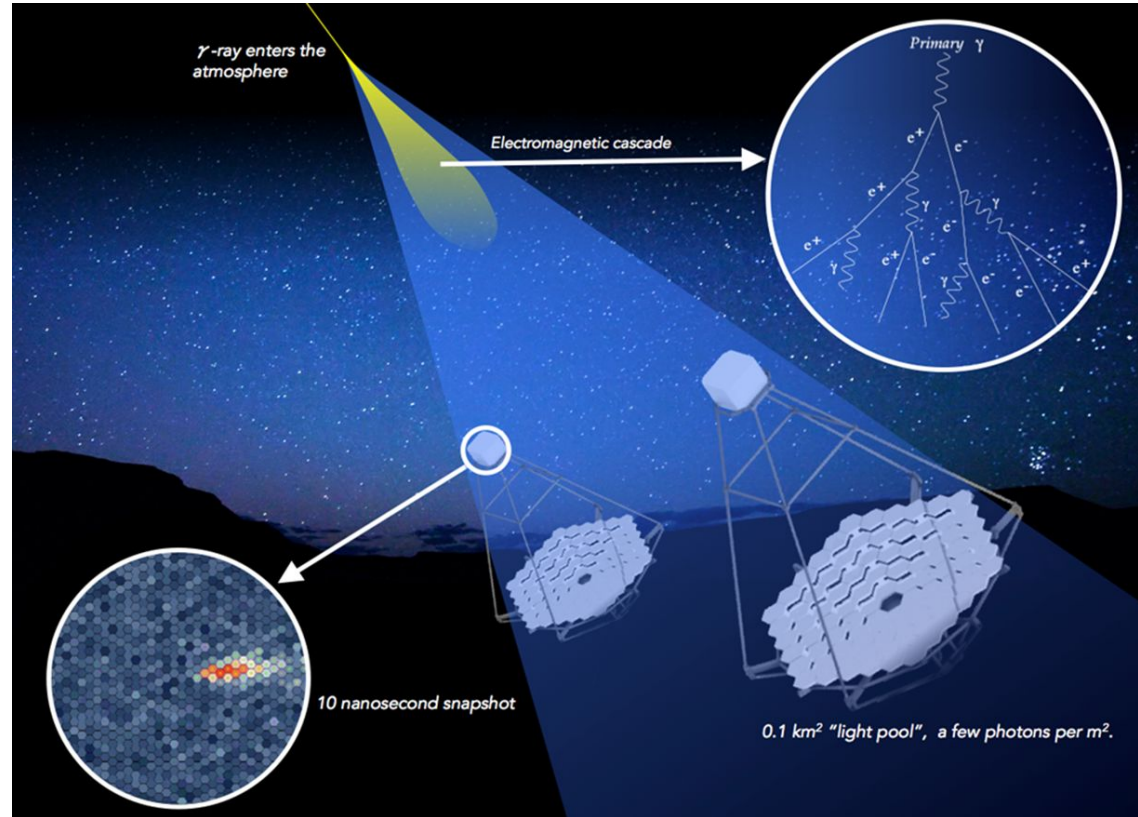
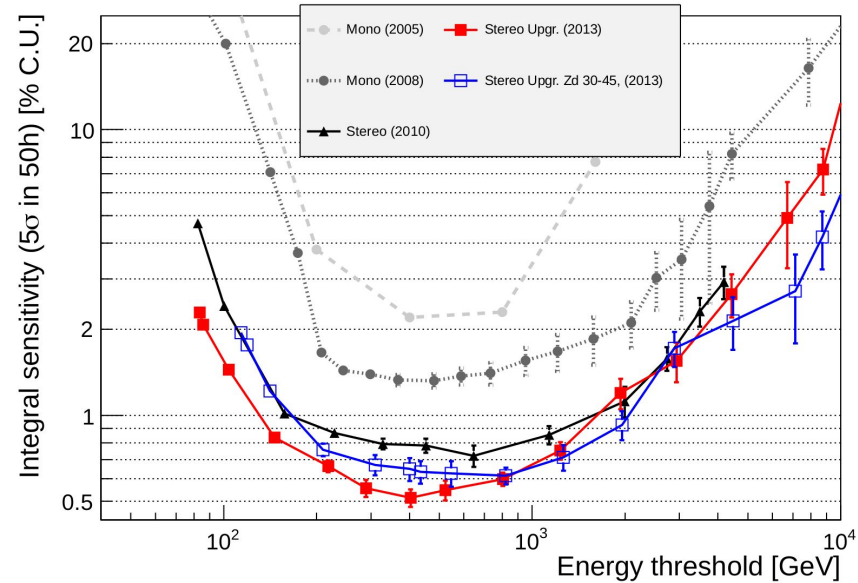


Image credit: CTAO

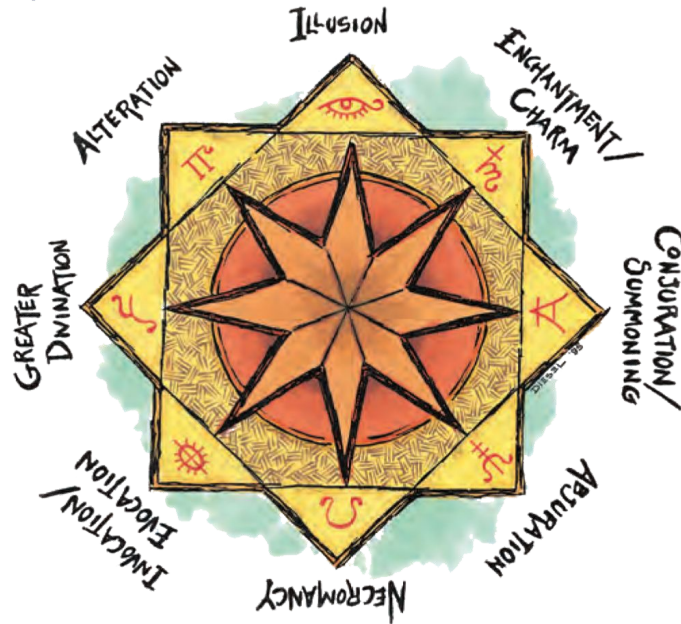
# MAGIC telescopes: Sensitivity



-Astroparticle Physics, Volume 72, p. 76-94



## Schools of MAGIC



## Physics working groups

- Astroparticle and Fundamental Physics
- Transients objects
- Galactic objects
- Extragalactic objects

## Grimoire of the MAGIC telescopes



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## Evocation: Gamma-Ray Bursts studies

First GRB detected  
by MAGIC:  
Long GRB 190114C

- after more than 100 observations of GRB alerts, finally the first GRB was detected!
- years of preparation, coordination with other facilities, software development, technical maintenance to allow fast repositioning...
- a long wait that was finally worth it

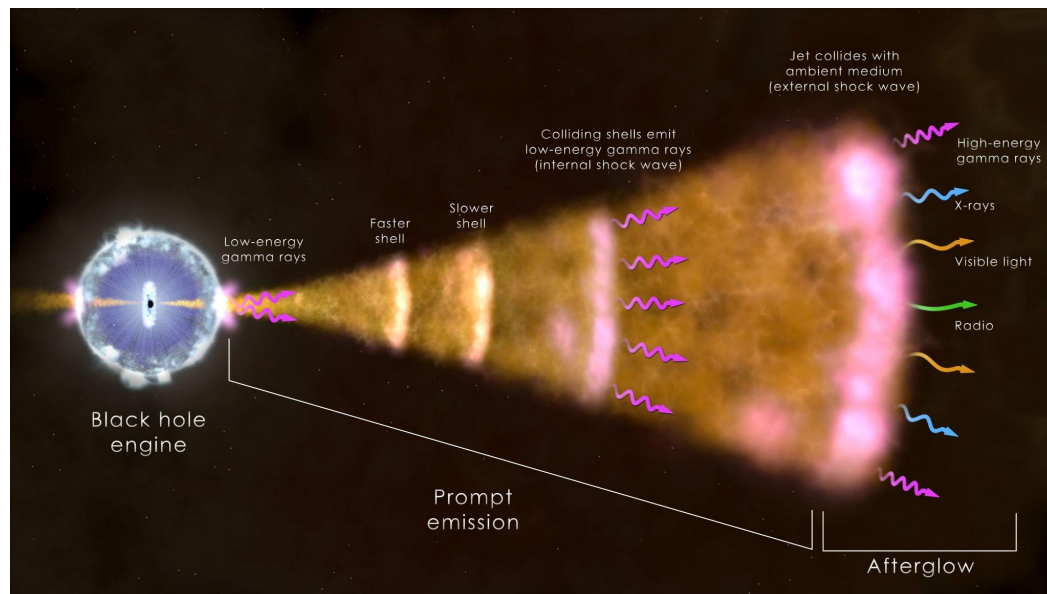


Image Credit: NASA's Goddard Space Flight Center

**Nature 575, 459 (2019)** and **Nature 575, 455 (2019)**



## Evocation: Gamma-Ray Bursts studies

First GRB detected by MAGIC:  
Long GRB 190114C

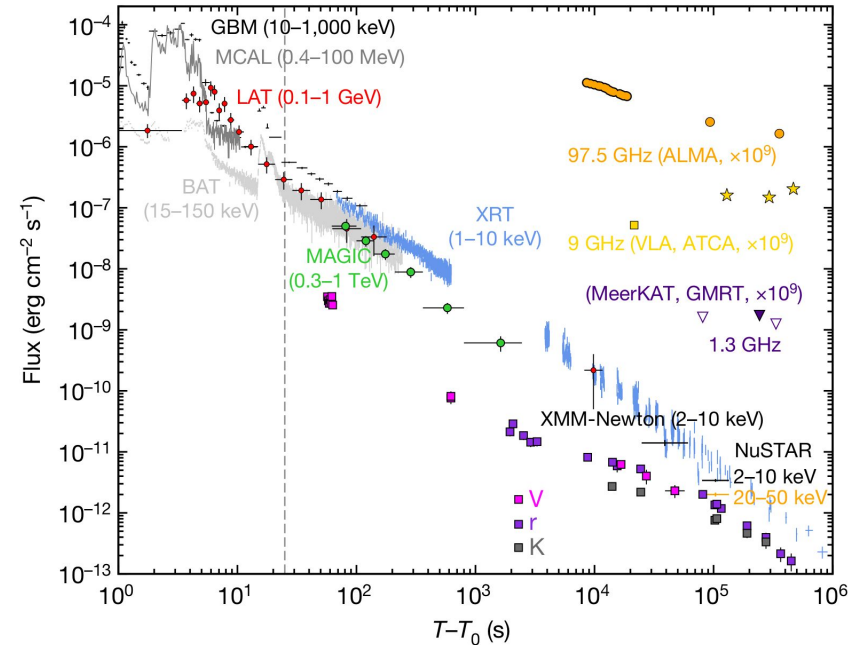
$T_0 = 20:57:03$  UT : Swift-BAT and Fermi-GBM  
triggered on GRB190114C\*

$T_0 + 22$ s: MAGIC received the alert

$T_0 + 50$ s: MAGIC started tracking

$T_0 + 57$ s: MAGIC started data acquisition  
(35s after the alert)

$T_0 + 62$ s: MAGIC data acquisition stabilised



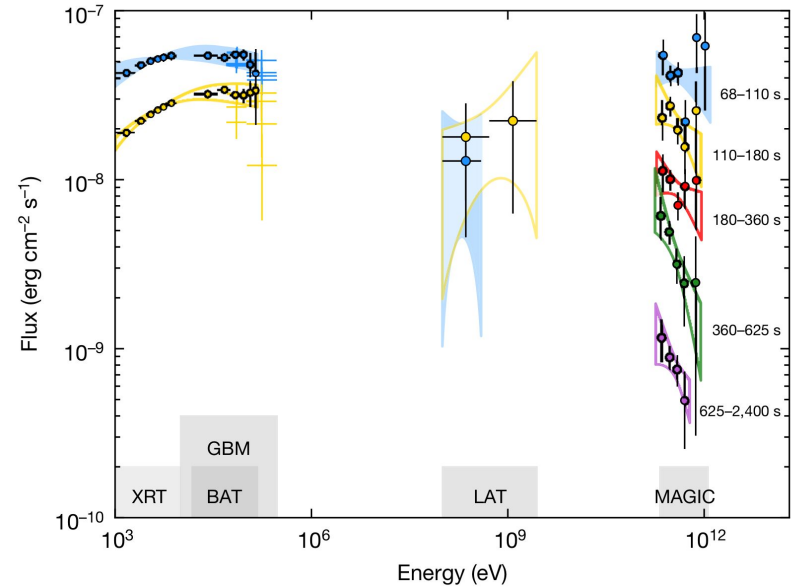
**Nature 575, 459 (2019)** and **Nature 575, 455 (2019)**

<https://gcn.gsfc.nasa.gov/other/190114C.gcn3>

## Evocation: Gamma-Ray Bursts studies

### First GRB detected by MAGIC: Long GRB 190114C

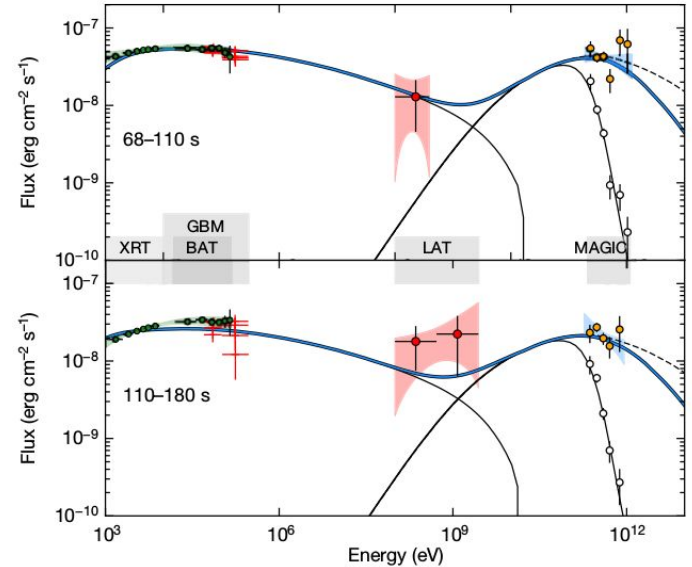
- MAGIC spectra in 5 different time intervals
- For the first two time intervals, observations in the gigaelectronvolt and X-ray bands are also available
- During the first time interval Swift-XRT, Swift-BAT and Fermi-GBM data show that the afterglow synchrotron component peaks in the X-ray band
- Up to 1 GeV, the SED is a decreasing function of energy
- At higher energies, the MAGIC flux above 0.2 TeV implies a spectral hardening
- The newly discovered teraelectronvolt radiation is not a simple extension of the known afterglow synchrotron emission, but a separate spectral component.



\*[Nature 575, 459 \(2019\)](#) and [Nature 575, 455 \(2019\)](#)

## Evocation: Gamma Ray Bursts studies

- The prompt phase lasts for ~25s
- MAGIC start observing in the early afterglow phase
- VHE gamma-rays have been detected up to 1TeV.
- First evidence of an extra component beyond synchrotron emission in the afterglow of a GRB
- The new emission component in the afterglow has a power comparable to that of the synchrotron component.
  - flat energy flux,  $d\phi/dE \sim E^{-2}$  (after EBL de-absorption),
  - incompatible with synchrotron (burnoff limit  $E > 100$  GeV),
  - compatible with synchrotron self Compton (SSC).



modelling of the multi-band data in the synchrotron and SSC afterglow scenario

**Nature 575, 459 (2019)**

**MAGIC detected another GRB, 201216C at  $z=1.1$ !?**

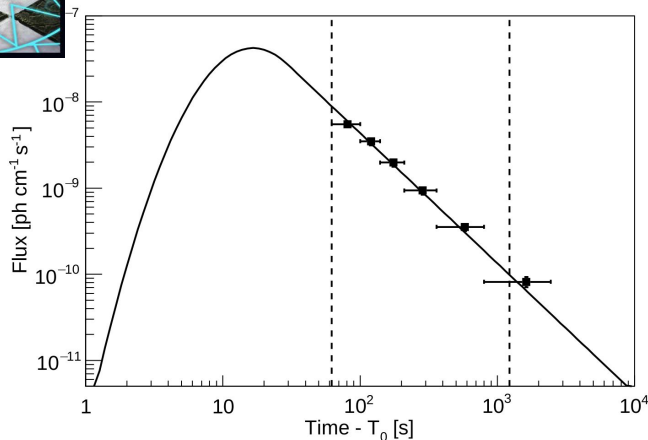
ATel #14275

(<https://www.astronomerstelegam.org/?read=14275>)



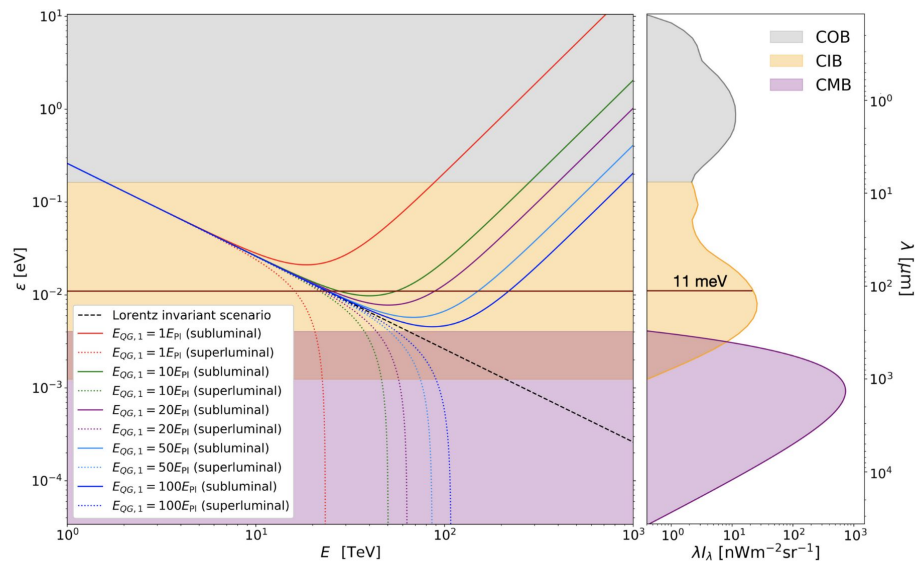
## Illusion: LIV studies with GRB 190114C

Probing Quantum Gravity  
with MAGIC Light curve



- Competitive Lower limits for the QG energy scale derived in this work using an unbinned analysis

**Phys. Rev. Lett. 125, 021301 (2020)**



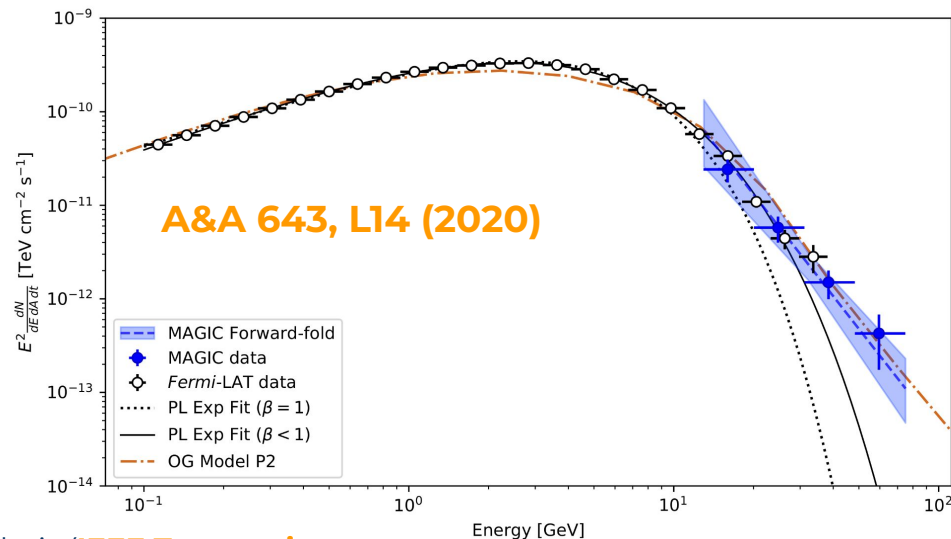
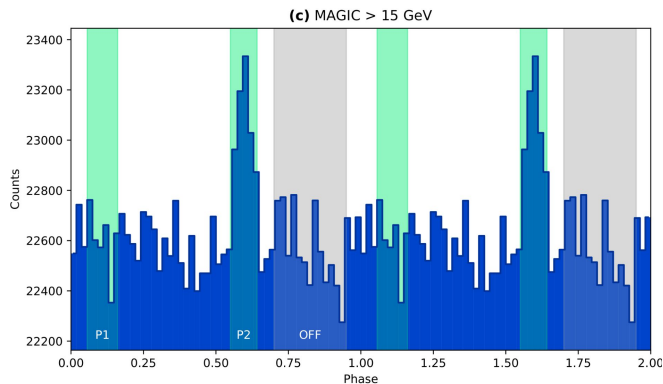
Energy of the background photons at threshold ( $\epsilon_{th}$ ) for the pair-production reaction as a function of a gamma-ray energy ( $E$ )

Plot by J. Strišković,  
Terzić et al., *Universe*, vol. 7, issue 9, p. 345 (2021)





# Enchantment: Geminga pulsar detection hints at a power-law tail emission beyond 15 GeV



- Energy range: between **15 GeV** and 75 GeV thanks to the Sum-Trigger II system and the dedicated analysis ([IEEE Transactions on Nuclear Science, Volume 68, Issue 7, pp. 1473-1486](#))
- First time a middle-aged pulsar has been detected up to these energies
- P2 is detected in the MAGIC energy range, with a significance of  $6.3 \sigma$  with 80 hours of data
- The power-law tail emission detected by MAGIC is interpreted as the transition from curvature radiation to Inverse Compton scattering of particles accelerated in the northern outer gap.



**MAGIC**

Major Atmospheric

Gamma Imaging

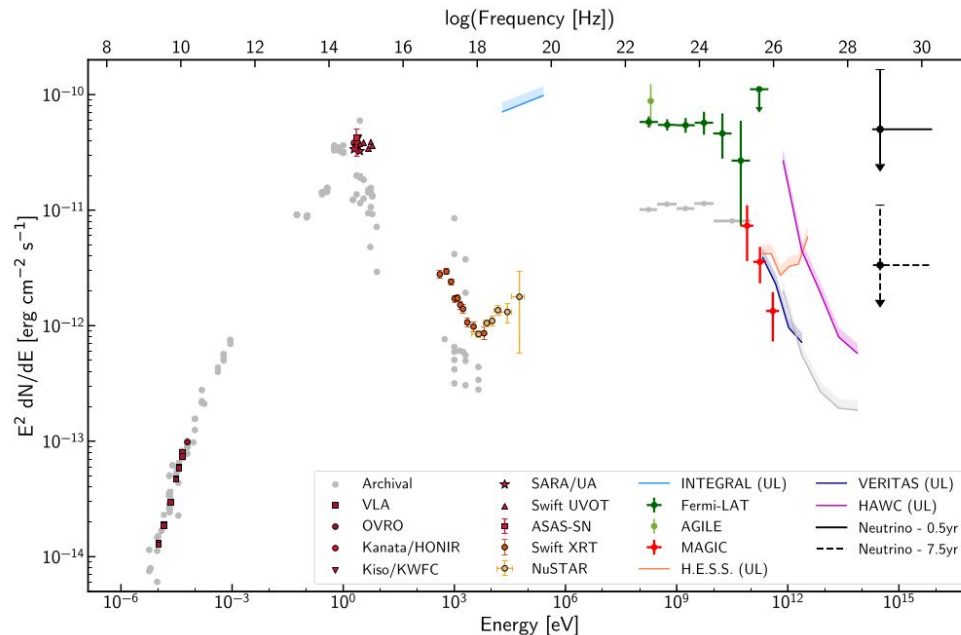
Cerenkov Telescopes



Image Credit: Mikolaj Lasota

# Summoning: Multimessenger astrophysics: the first neutrino blazar, TXS 0506+056

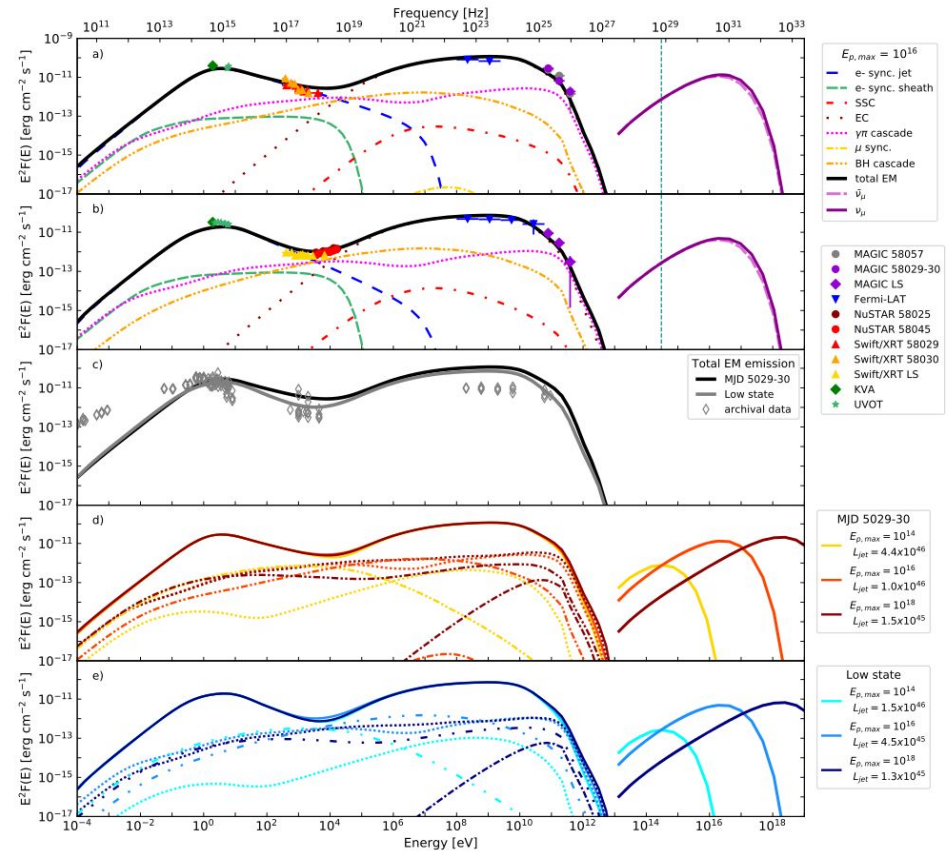
- First time observation of VHE  $\gamma$ -rays in coincidence with a high energy neutrino
- Impressive multi-collaboration effort
- Firm detection of the blazar TXS 0506+056 by MAGIC
- Complex observational strategies for following neutrino alerts rewarded
- Still waiting for the next neutrino blazar or other neutrino sources to be detected



Science 361, eaat1378 (2018)

- Jet-sheath scenario with  $E_{p,max} = 10^{16}$  eV
- hadronic emission components
- The neutrino and MWL data can be interpreted with a one-zone model and external photons from structured jets
- The inferred proton luminosity is in the range  $\approx 10^{45} - 4 \times 10^{46}$  erg/s and
- maximum CR energies in the comoving frame of  $10^{14}$  to  $10^{18}$  eV

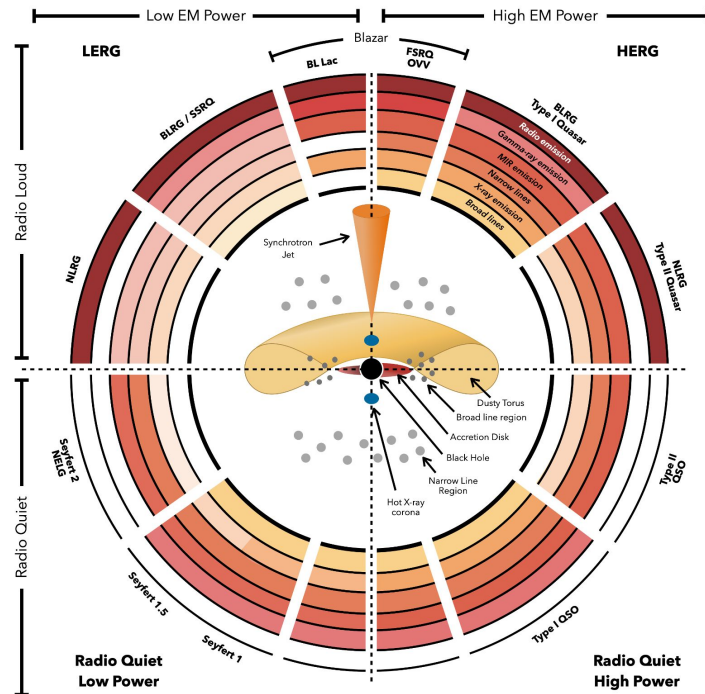
**Astrophysical Journal Letters, 863 (2018) L10**





## Divination: High redshift sources

- Farthest sources detected in VHE gamma rays are both FSRQs at a redshift of 0.9
- PKS 1441+25  $z=0.939$
- QSO B0218+357 (gravitational lens)  $z=0.944$
- Important for EBL studies
- At the limit of the Gamma-ray horizon
- Remarkably the GRB 201216C is located at  $z=1.1$ !



J. E. Thorne

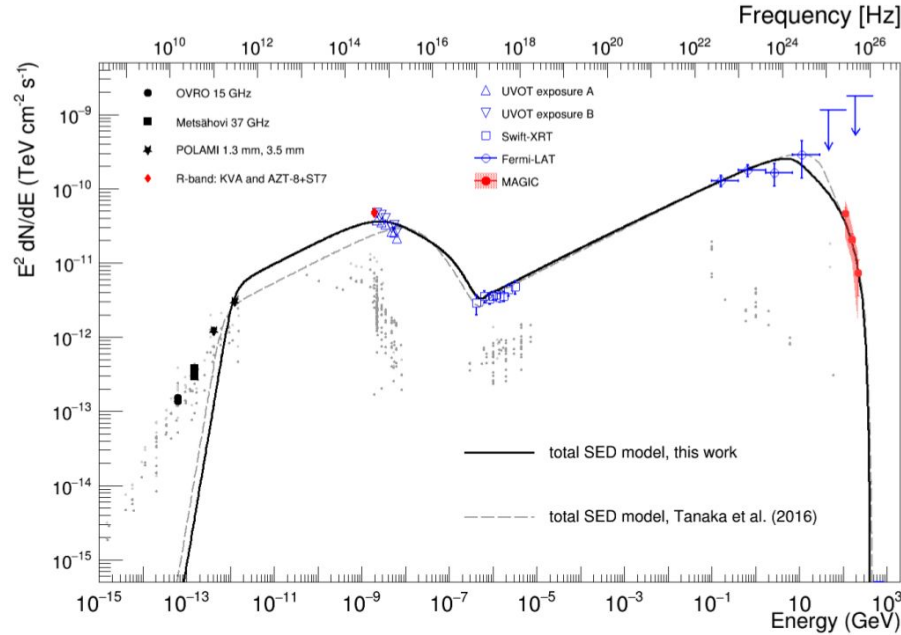
AGN unification scheme by J.E. Thorne



# Divination: Transitional blazars

Blazars looking like BL Lac but presenting FSRQs characteristic. Challenging to be modelled. Very interesting!

S40954+56



A&A 617, A30 (2018)

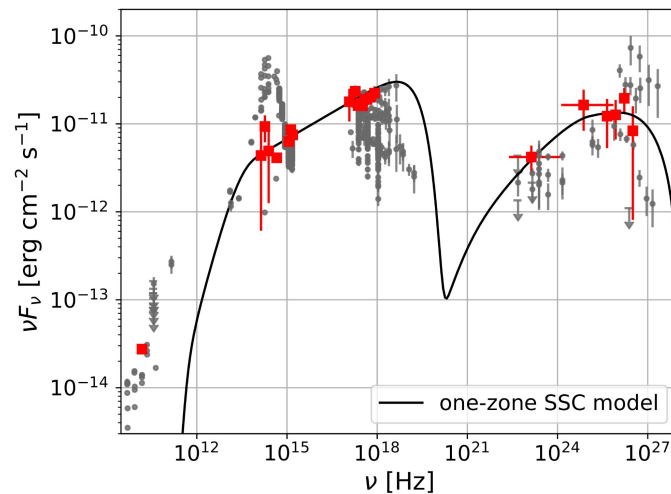


## Transmutation: Extreme sources

-First definition by Costamante 2001  
(A&A, 371, 51)

-EHBLs (extremely High Energy peaked BL Lacs)

- Synchrotron peak shifted towards high energies
- IC peak in the VHE gamma-ray range
- Expected to be very faint according to the blazar sequence
- Recently some of them, detected in the VHE gamma-ray range, have shown an intermittent nature making the hunt more intriguing
- A first systematic study of such very interesting objects has been published recently by MAGIC ([ApJ 88, 247, 16, \(2020\)](#))
- Both leptonic and hadronic models are able to describe the observations at the cost of extreme parameters.



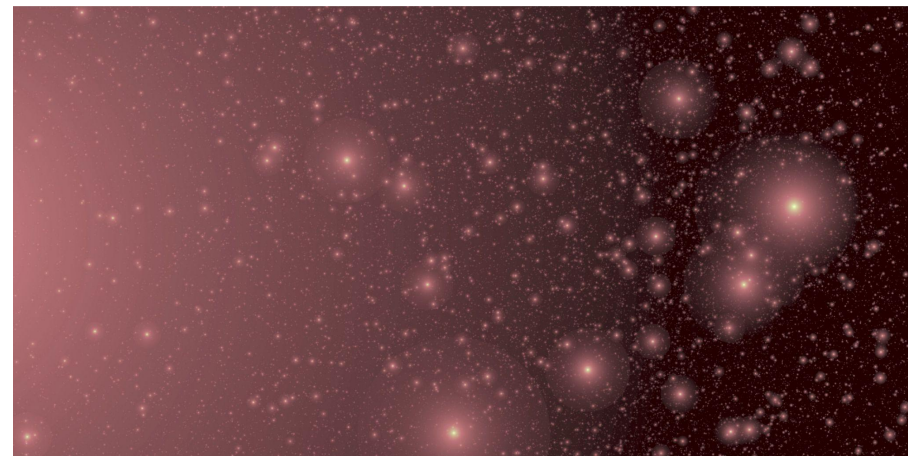
SED of 1ES2344+514, an “intermittent” EHBL  
([MNRAS 496, 3912 \(2020\)](#))



## Necromancy: Dark Matter

Dark MAGIC is practised  
within many different  
projects:

- Dark Matter lines in the Galactic Center
- Dwarf spheroidal satellite galaxies observations
- Multi-dSphs combined analysis
- Galaxy clusters
- Axion-like particles hunting



[http://clumpy.gitlab.io/CLUMPY/\\_images/DMSky\\_pink.png](http://clumpy.gitlab.io/CLUMPY/_images/DMSky_pink.png)





## Necromancy: Vampire stars

MAGIC detection of VHE  
gamma rays from the nova  
RS Ophiuchi

- Classical novae: cataclysmic binary star systems in which the matter of a companion star is accreted on a white dwarf
- Symbiotic binary: the donor star is a red giant (RG). The white dwarf is immersed in the RG wind. Some novae show repeated outbursts within a human lifetime: recurrent novae (RN)

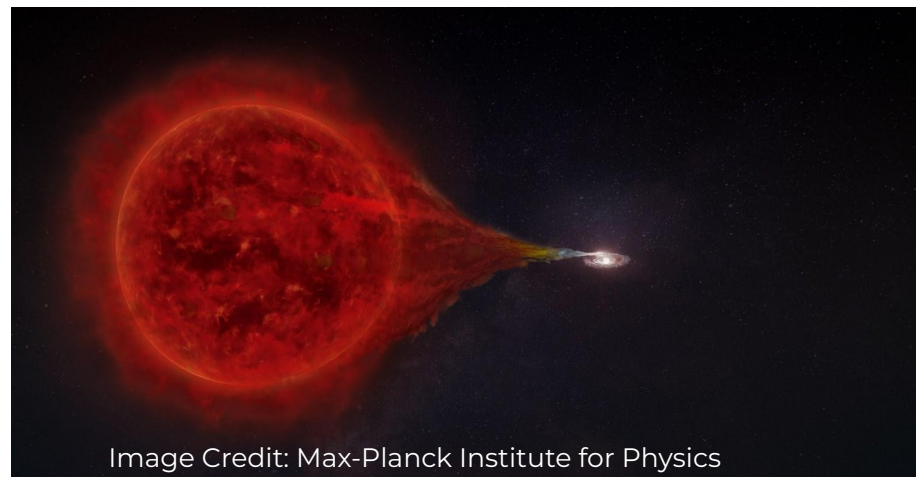


Image Credit: Max-Planck Institute for Physics

- Accumulation of hydrogen in a layer eventually causes a thermonuclear explosion on the surface of the white dwarf brightening the white dwarf to  $\sim 10^5$  solar luminosities and triggering ejection of the accumulated matter
- extreme conditions required to accelerate particles, electrons or protons, to high energies



# MAGIC detection of VHE gamma rays from the nova RS Ophiuchi

- RS Ophiuchi, a recurrent symbiotic nova with a red giant companion
- Outburst discovered by the amateur astronomer Keith Geary\*
- MAGIC observations in August 2021 allowed to characterize the emission from a nova in the 60 GeV to 250 GeV energy range
- The theoretical interpretation of the combined Fermi LAT and MAGIC data suggests that protons are accelerated to hundreds of gigaelectronvolts in the nova shock. Such protons should create bubbles of enhanced cosmic ray density, of the order of 10 pc, from the recurrent novae.

Acciari et al., *Nature Astronomy*, 6, 760 (2022)

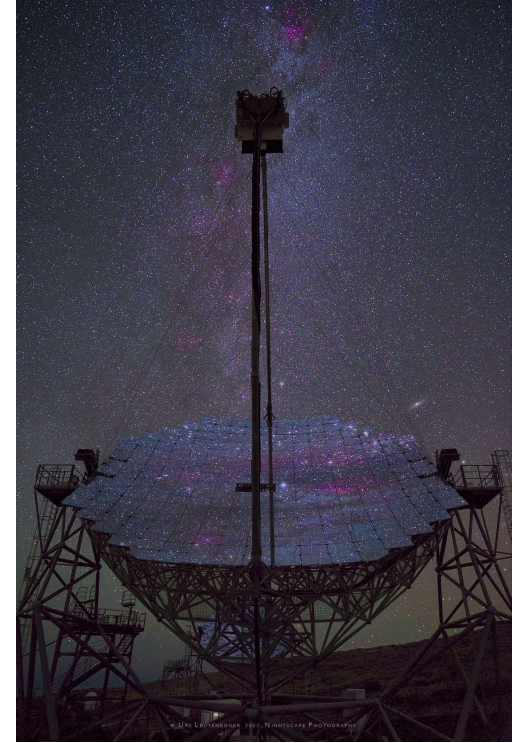


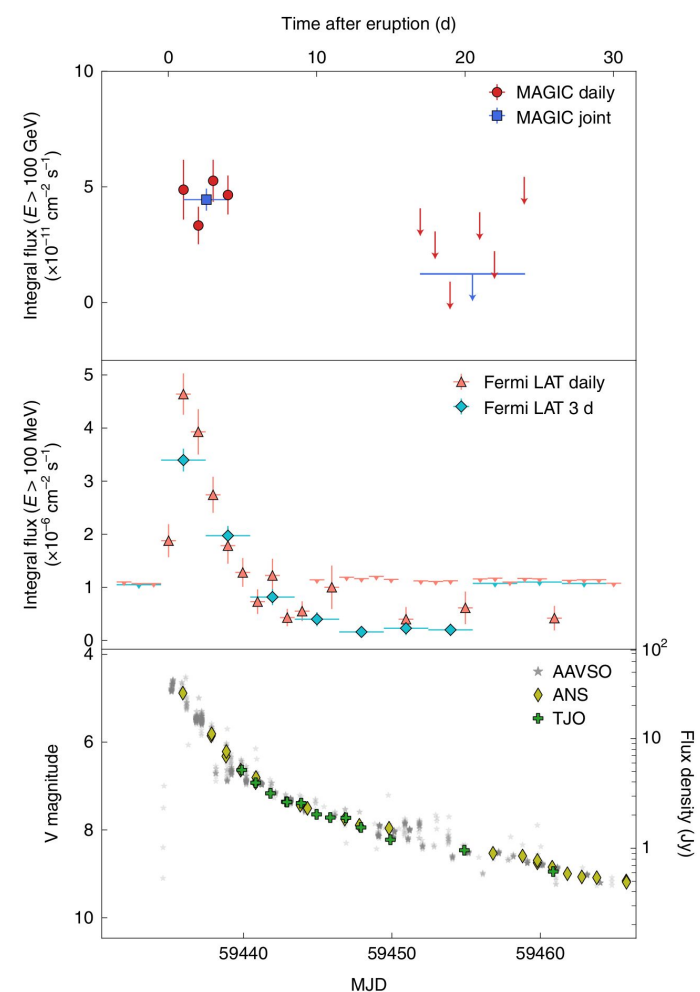
Image Credit: Urs Leutenegger (@urs.leutenegger)

\*<http://ooruri.kusastro.kyoto-u.ac.jp/mailarchive/vsnet-alert/26131>

# MAGIC detection of VHE gamma rays from Ophiuchi

Acciari et al., *Nature Astronomy*, 6, 760 (2022)

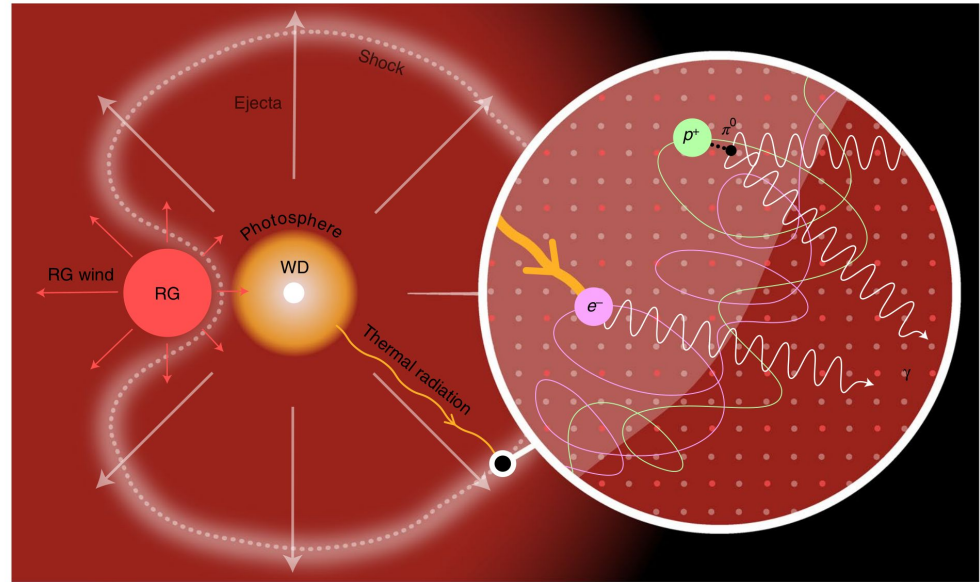
- Multiwavelength light curve of RS Oph
- VHE (MAGIC, top)
- high-energy (Fermi LAT, middle)
- optical (Joan Oró Telescope (TJO), Asiago Novae and Symbiotic Stars Collaboration (ANS) and American Association of Variable Star Observers International Database (AAVSO), bottom) bands.
- The lack of MAGIC data between MJD 59440 and MJD 59454 is due to the presence of bad weather conditions and strong moonlight.
- Error bars represent  $1\sigma$  statistical uncertainties in the data points, and arrows are 95% confidence level upper limits.



# MAGIC observations of RS Ophiuchi

Acciari et al., *Nature Astronomy*, 6, 760 (2022)

Schematic representation of RS Oph during an outburst. A photosphere (yellow circle) surrounds the WD (white small circle). Its companion star, an RG (red circle), emits a slow wind (red arrows). Ejecta of the nova explosion (grey arrows) propagate into the surrounding medium, causing a shock wave encompassing the binary system (grey dashed line).



In the shock wave, energetic electrons and protons (magenta and green wavy lines, respectively) are trapped by a magnetic field and accelerated. Gamma rays (white arrows) are produced either by electrons scattering the thermal radiation of the photosphere (yellow arrow) or by protons interacting with the surrounding matter (grey and red dots).

## Conclusions

- Detection of 2 GRBs and other 2 at the edge of detection: one of the goal of MAGIC from the beginning is now a reality!
- Evidence of proton acceleration from a nova explosion
- Quantum gravity has been probed with the GRB 190114C MAGIC lightcurve
- The strategies of real-time follow-up of neutrino events have been successfully! Now we wait for the next neutrino blazar...
- The development of Sum-Trigger II allowed MAGIC to reach a lower threshold of only 15 GeV... Geminga pulsar has been detected and studied in a range of 15GeV-75 GeV and farthest AGNs are waiting to be detected!
- 18 years of observations...the magic is still here!



Thanks for your attention!



@MAGICtelescopes



Image Credit: Chiara Righi (@chirighi)