MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

IFAE
Institut de Física d'Altes Energies

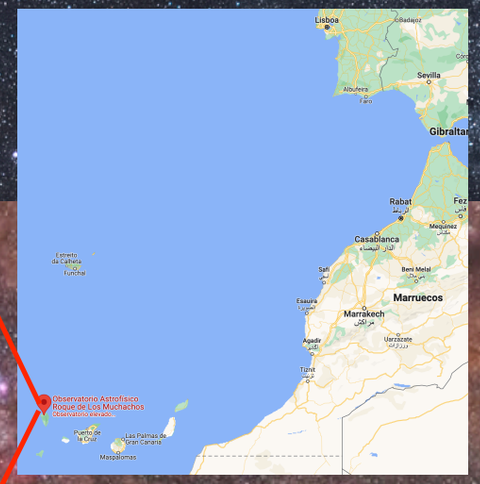
Scientific highlights from the MAGIC gamma-ray telescopes

J. Rico
Institut de Física d'Altes Energies, Barcelona, Spain
(on behalf of the MAGIC Collaboration)

27th European Cosmic Ray Symposium, Nijmegen 25-29 July 2022

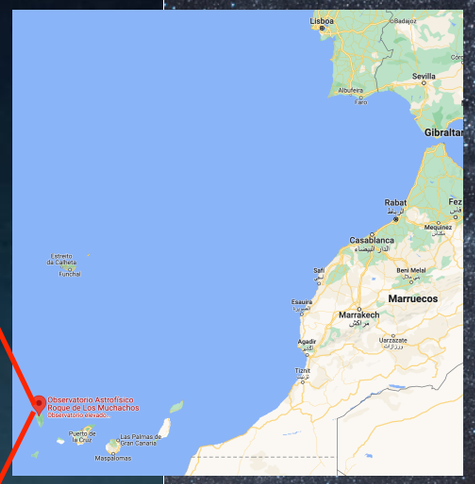
The MAGIC telescopes

- ★ Two Cherenkov telescopes at Roque de los Muchachos Observatory (La Palma, Spain)
- ★ 17 m diameter reflectors
- ★ Very-High-Energy (VHE) i.e. $E_\gamma \in$ [20 GeV-200 TeV]; ~20% resolution
- ★ PSF ~ 0.1°
- ★ Fast repositioning (<40s)



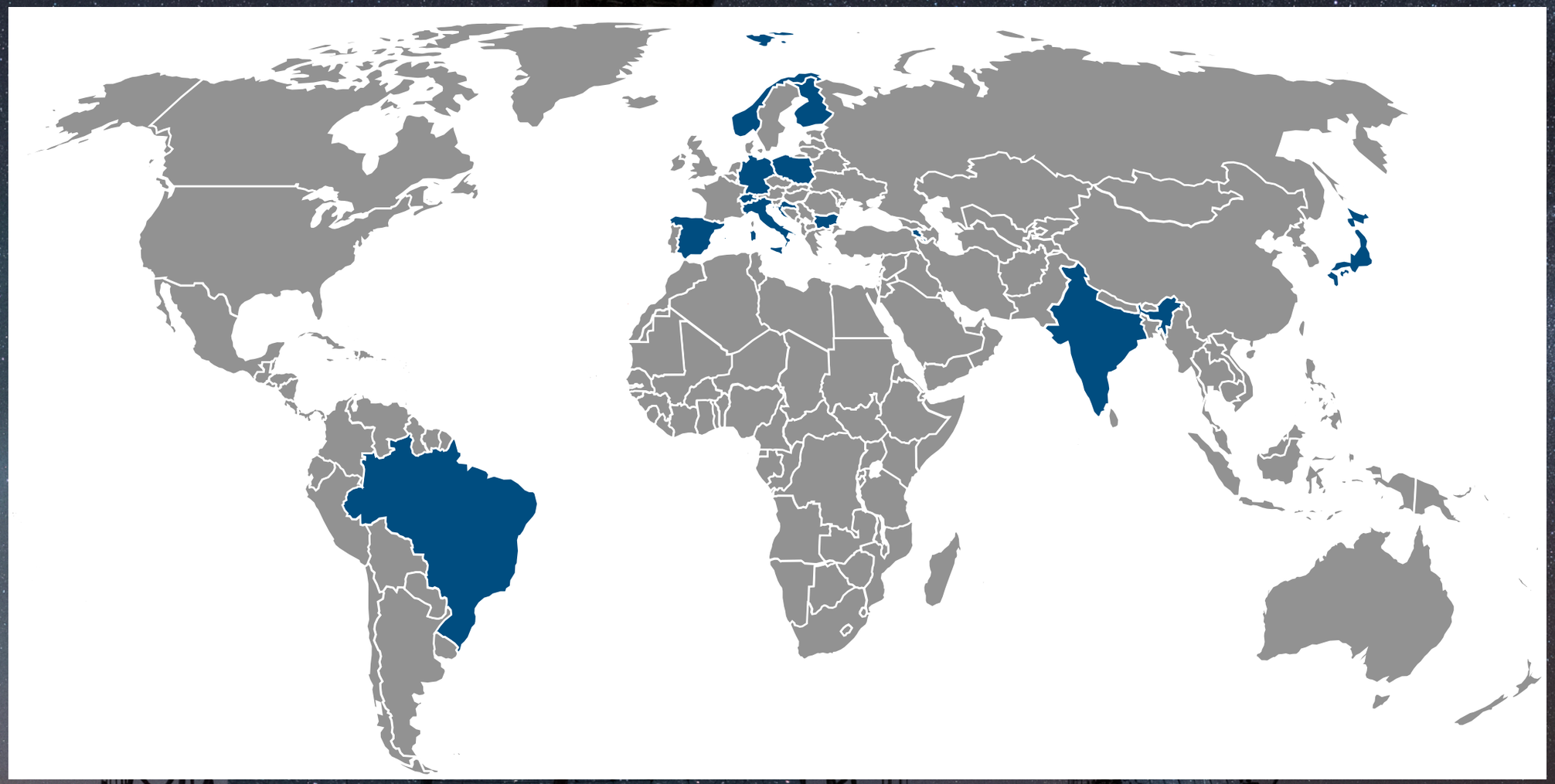
The MAGIC telescopes

- ★ 3-month covid shutdown:
  March 13 - June 18, 2020
- ★ 3-month volcano shutdown:
  September 19 - December 25, 2021



Credit: N. Mang

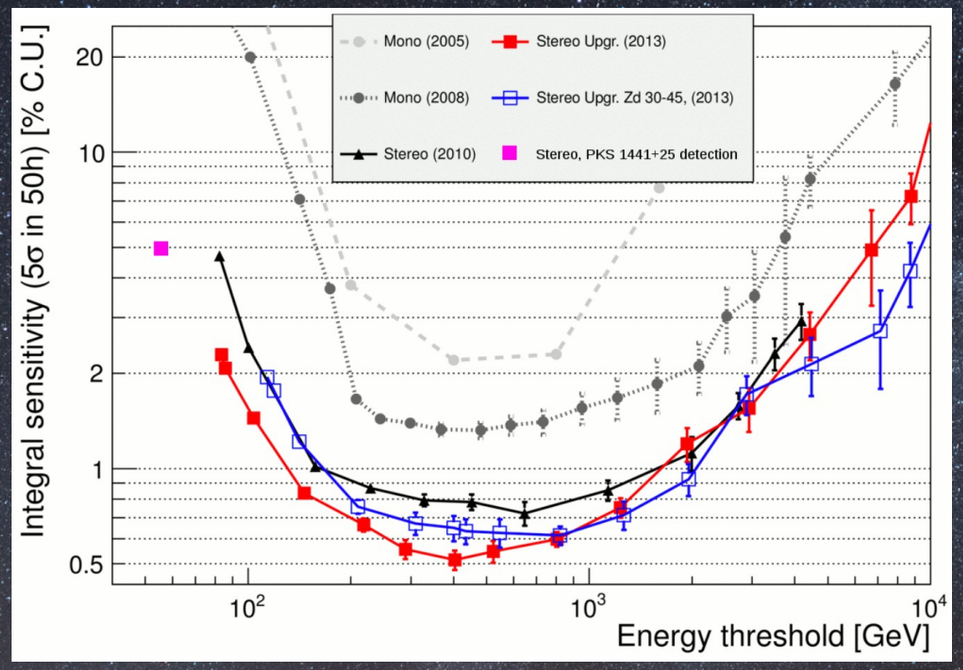
The MAGIC Collaboration



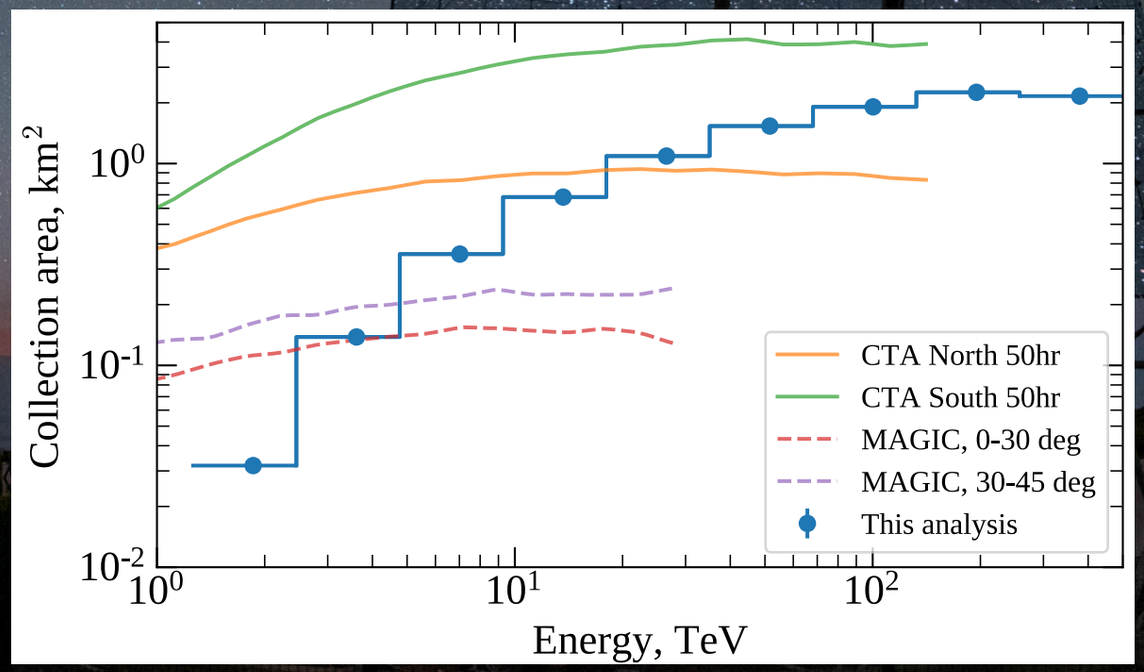
- ★ >200 scientists
- ★ 30 research institutions
- ★ 13 countries: Armenia, Brazil, Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Norway, Poland, Spain and Switzerland

MAGIC performance

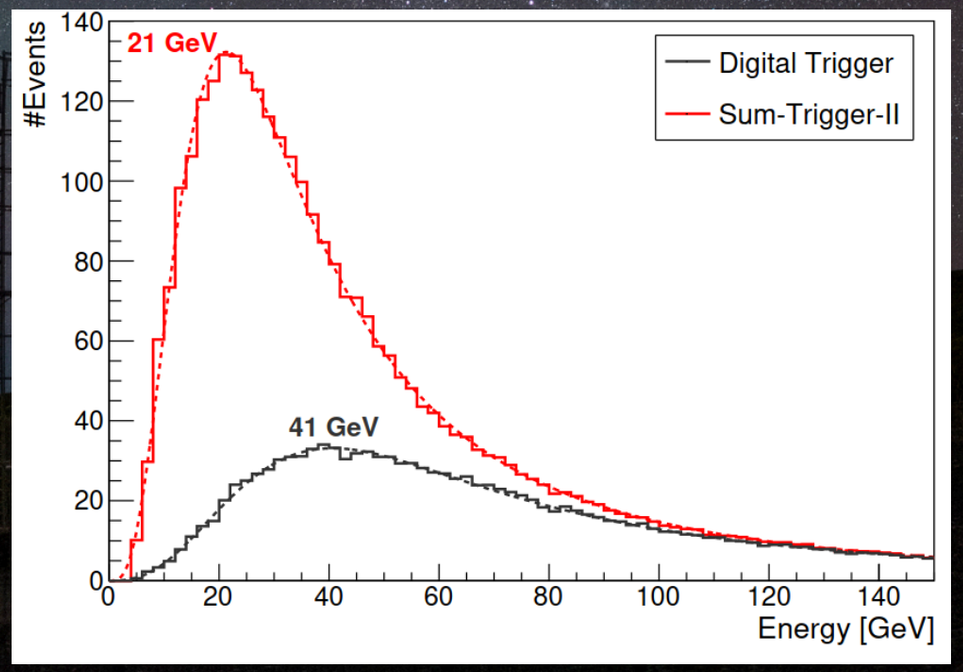
- ★ 2004 → one telescope
- ★ 2009 → two telescopes
- ★ 2012 → major upgrade
- ★ Pushing limits of energy range by special trigger and observational mode



Aleksić et al. Astropart. Phys. 72 (2016) 76



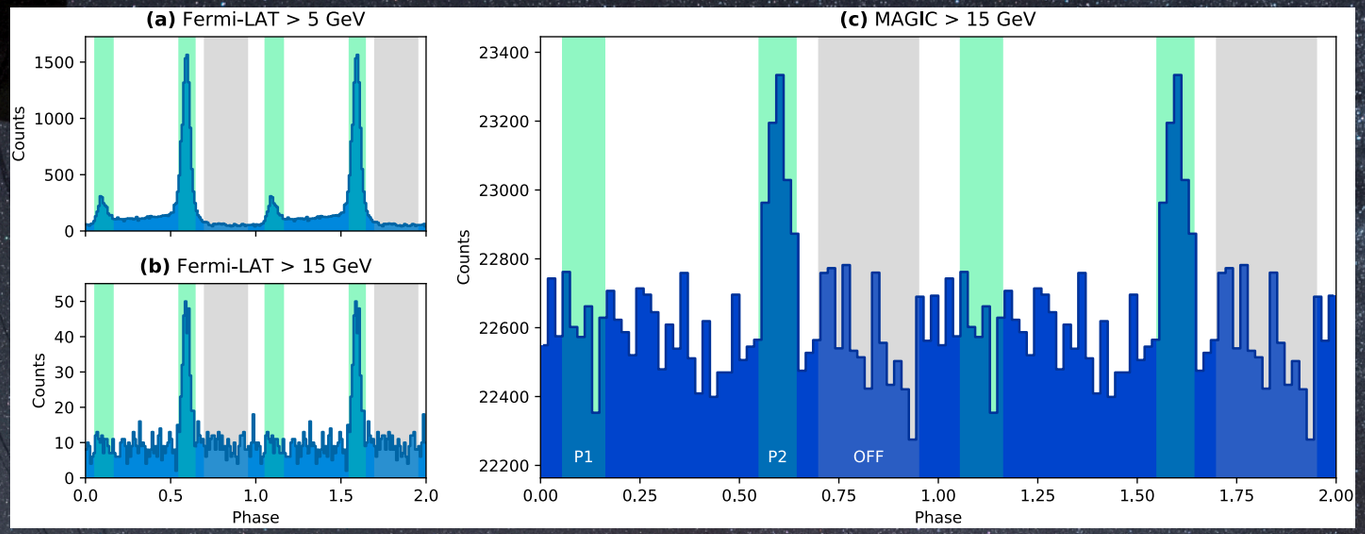
MAGIC Coll. A&A 635 (2020) A158

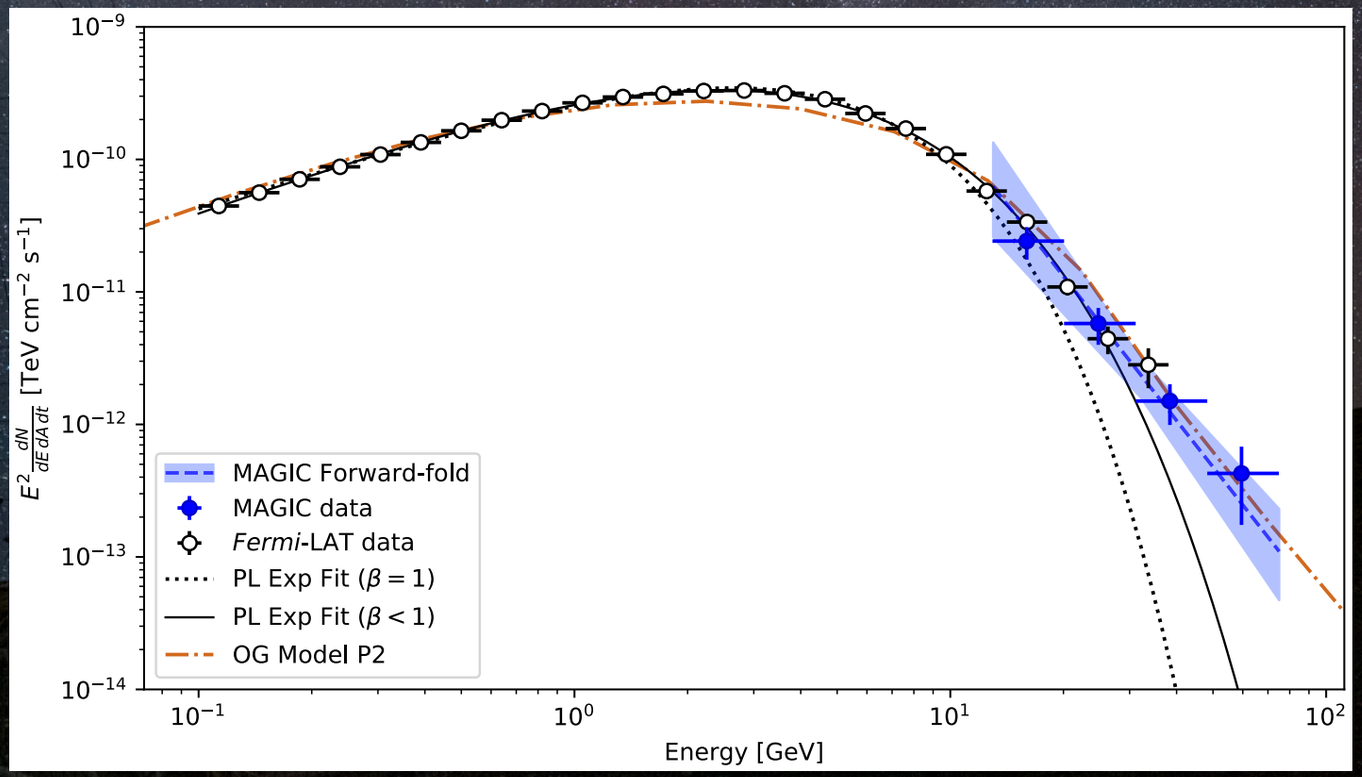


Dazzi et al. IEEE T Nuc. Sci. 68 (2021) 7

Geminga pulsar

- ★ Detection between 15 and 75 GeV
- ★ P2: 6.3σ detection
- ★ Third known VHE pulsar (300 kyear, oldest one)
- ★ Full exploitation of MAGIC low energy capabilities with special trigger (Sum-Trigger-II)
- ★ Power-law extension of Fermi spectrum, interpreted as
  - ✦ Inverse Compton of soft X-rays by electrons from NS surface
  - ✦ Transition from curvature and IC radiations? Or primary synchro-curvature emission with no IC? [ApJ 923 (2021) 194]



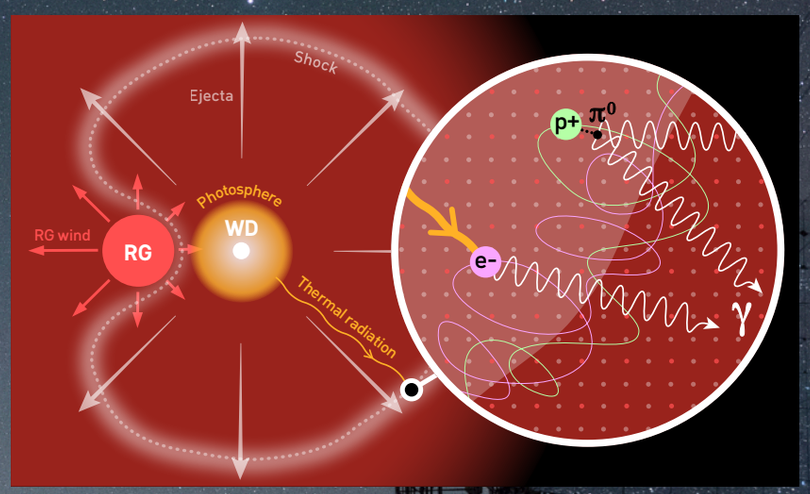


MAGIC Coll et al. A&A 643 (2020) L14

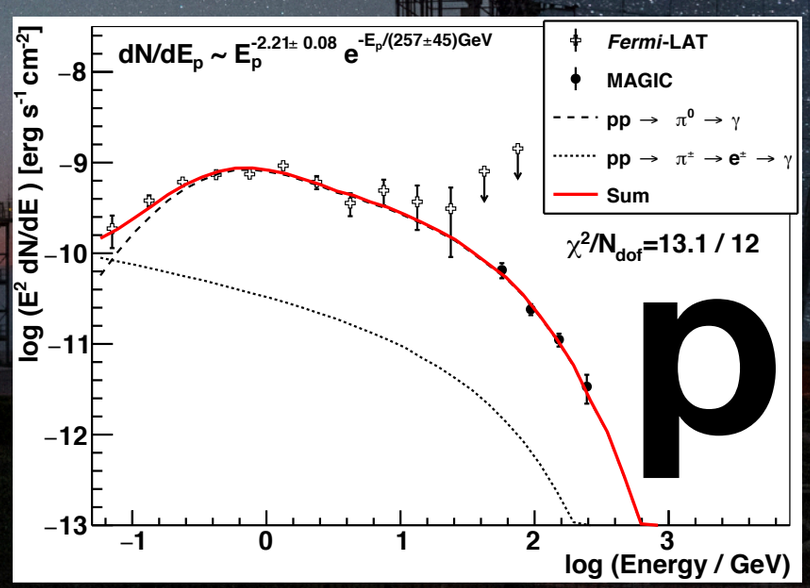
RS Ophiuchi

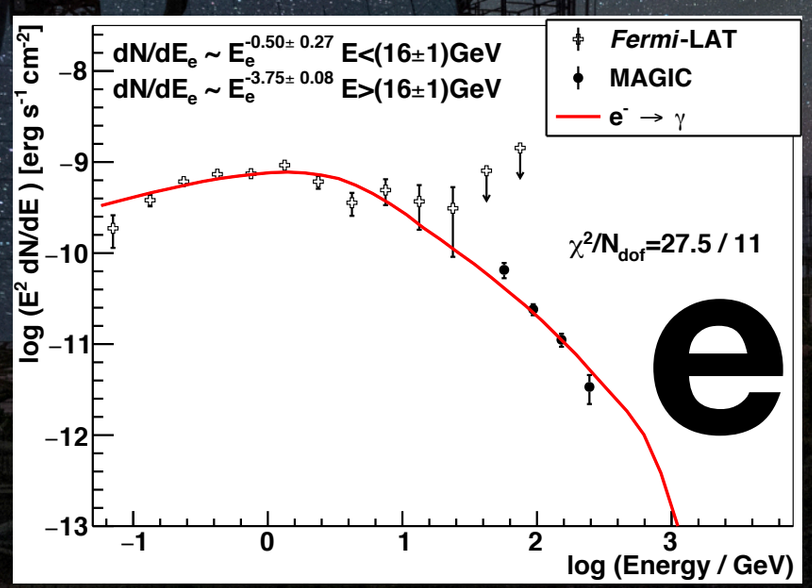
- ★ RS Ophiuchi recurrent symbiotic nova
- ★ August 2021 outburst detected by MAGIC
- ★ Proton acceleration strongly favored by fitting Fermi-LAT + MAGIC spectra
- ★ Minor contribution to Galactic cosmic rays & indirect support to bulk CRs from SNRs
- ★ New type of VHE gamma-ray emitter

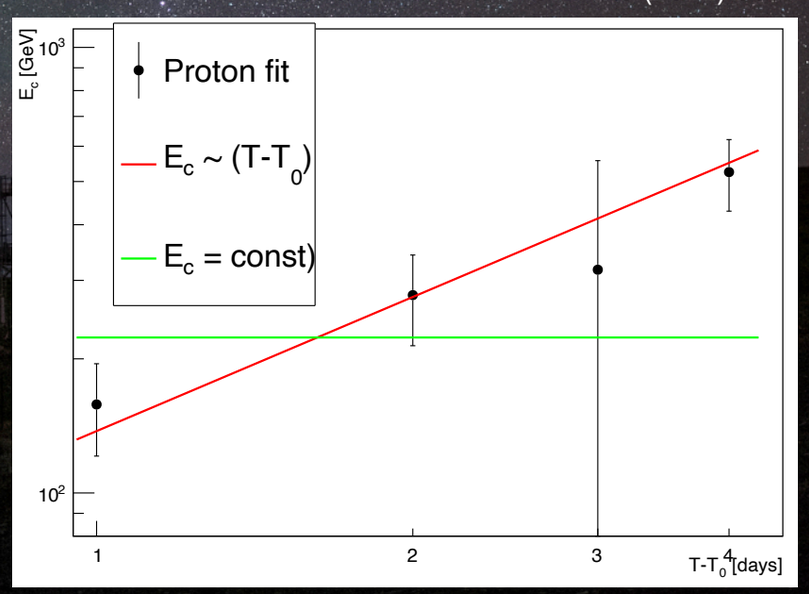
?



Acciari et al. Nat. Astron. 6 (2022) 689







M87: a broad MWL view

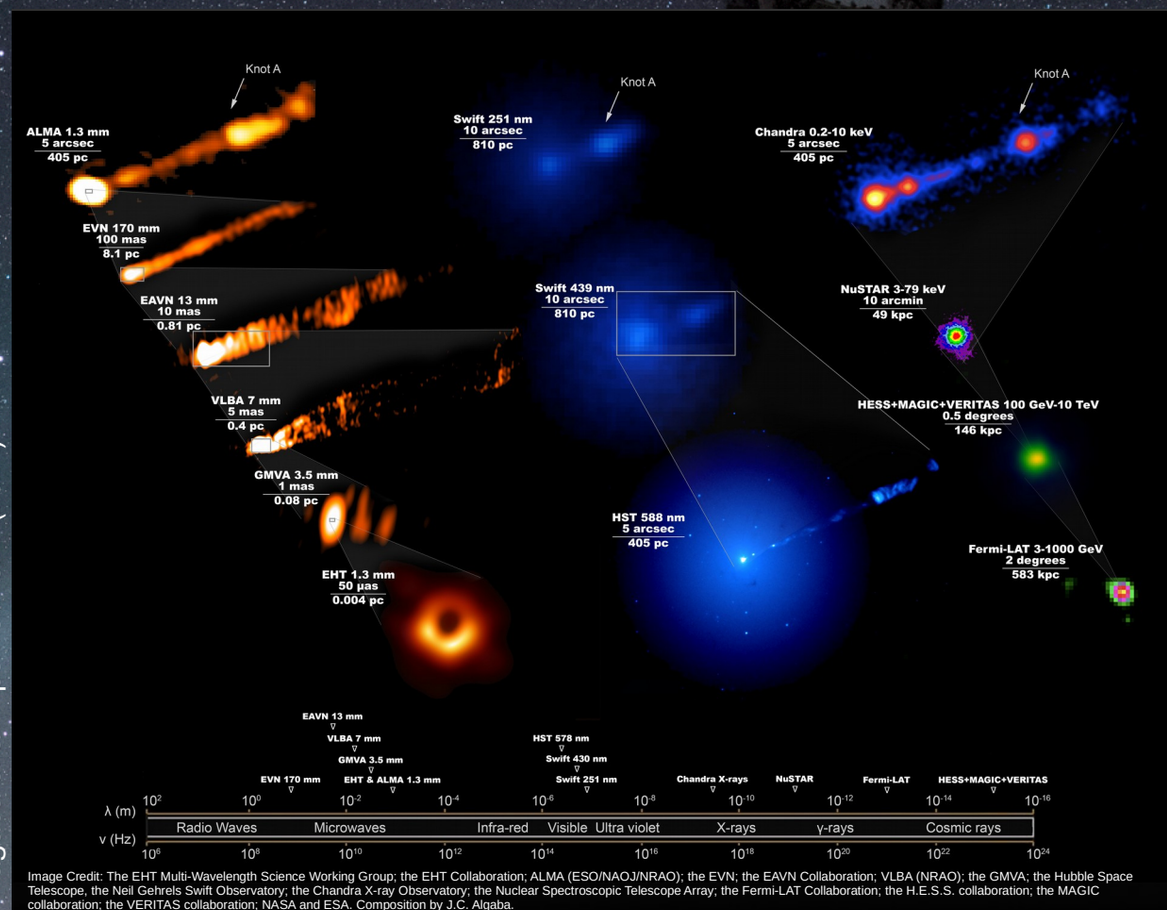
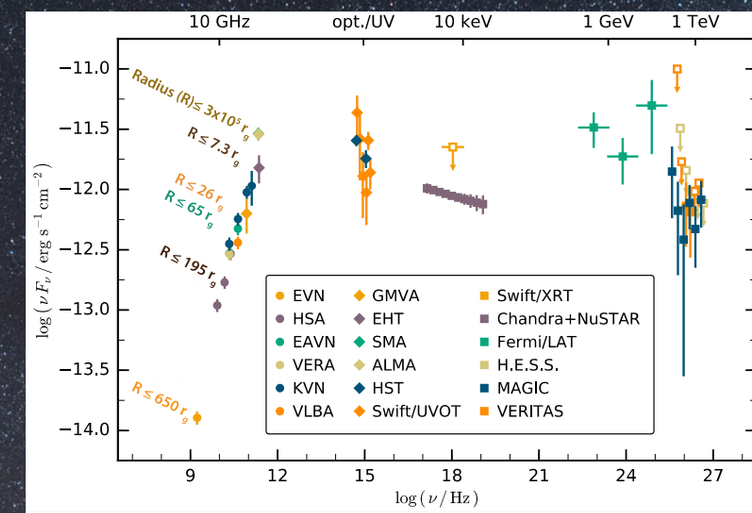
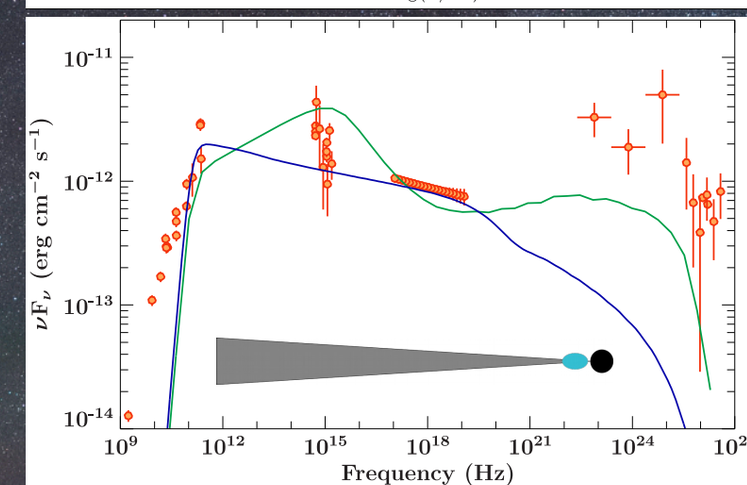
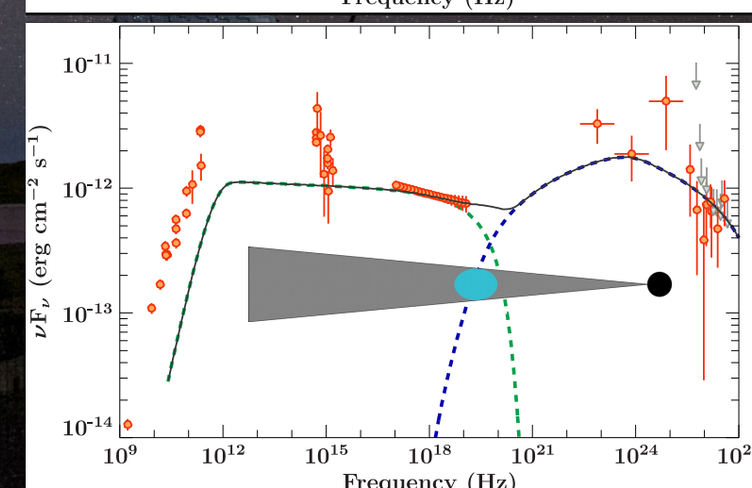


Image Credit: The EHT Multi-Wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope, the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S. collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J.C. Algaba.

Alagaba et al. ApJ Lett. 911 (2021) L11





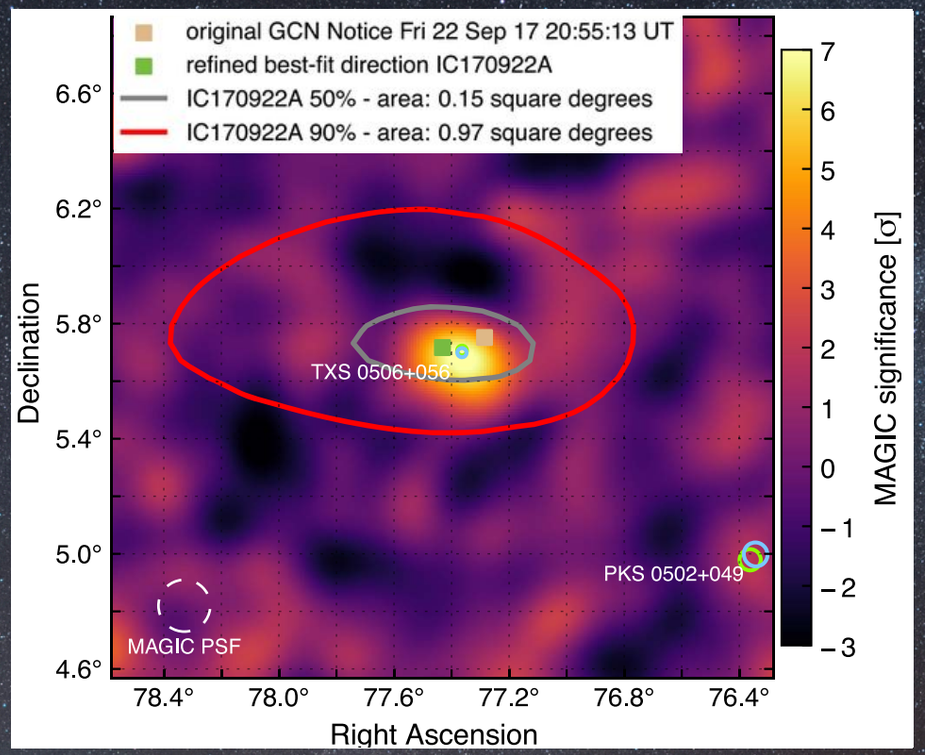


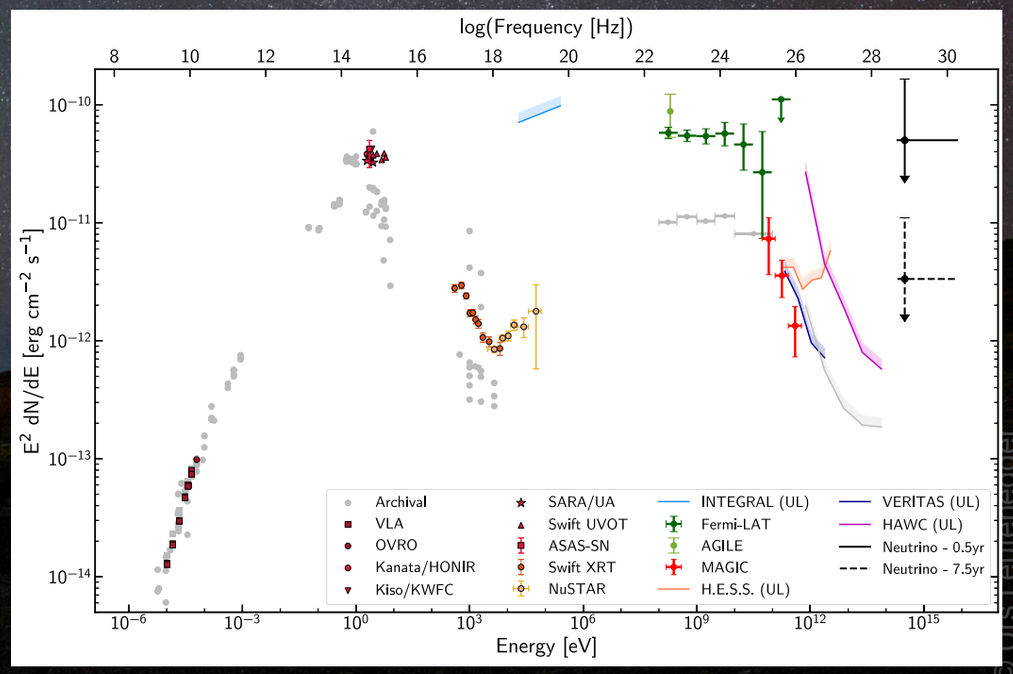
- ★ Broadband coordinated observations in 2017 during quiescent state (19 facilities in 15 decades of energy)
- ★ Cannot be modeled by single zone
- ★ Structured jet and time dependence are key

© Urs Leutenegger

TXS 0506+056

- ★ First evidence for an electromagnetic counterpart (flaring blazar, z=0.34) of a neutrino source
- ★ 3σ association of a high-energy (290 TeV) neutrino with a high-energy (90-400 GeV) gamma-ray source (MAGIC)
- ★ Multi-messenger SED
- ★ Deep monitoring (120h, 2017-2021) with MAGIC reveals several flares compatible with no further neutrino detection [Acciari et al. Astroph. J. 927 (2022) 197]

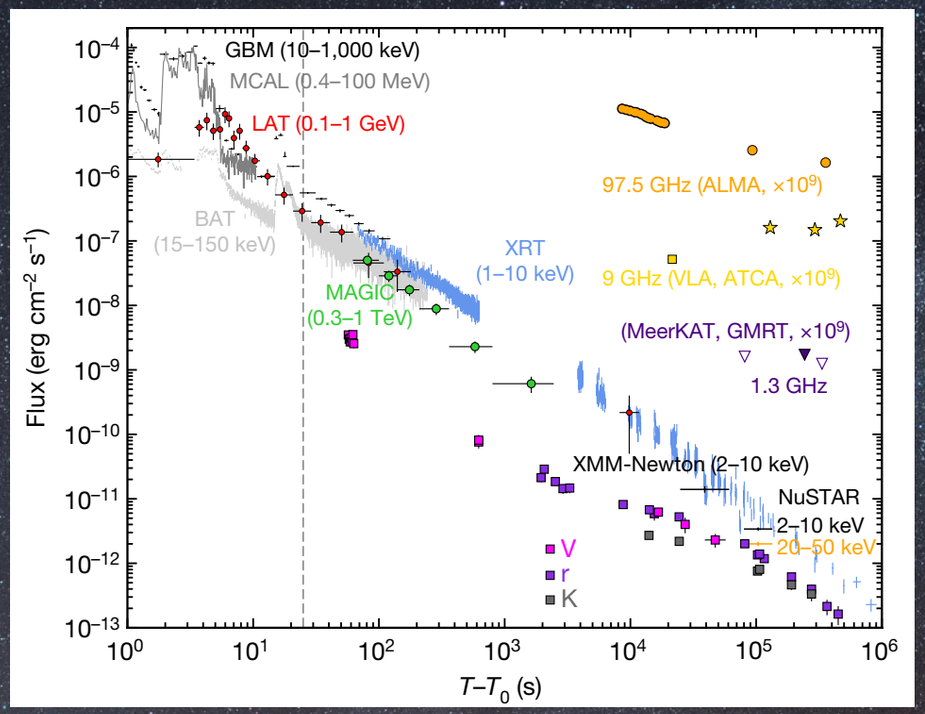


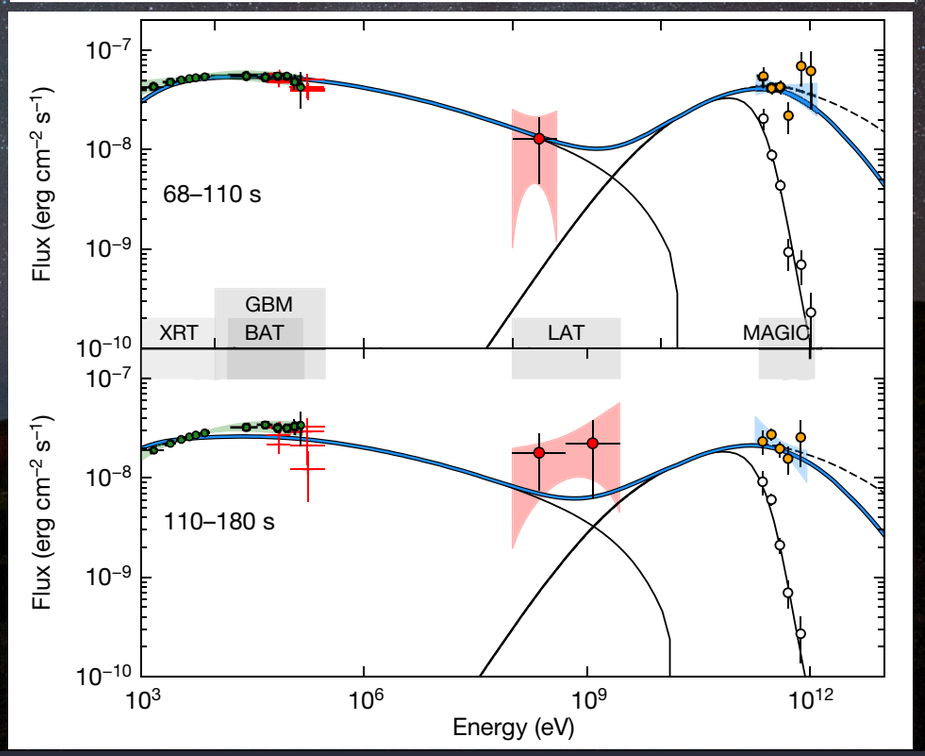


Aartssen et al. Science 361 (2018) eaat1378

GRB 190114C

- ★ Long gamma-ray burst (T_{90} = 361s)
- ★ First detection of VHE emission from GRB (>50σ)
  - ✦ MAGIC observation started at T_0+50s
  - ✦ Brightest VHE source ever → 100×Crab
  - ✦ Emission above 100 GeV strongly absorbed by interaction with extragalactic background light
- ★ Exhaustive MWL coverage
  - ✦ Synchrotron emission excluded, SSC favored

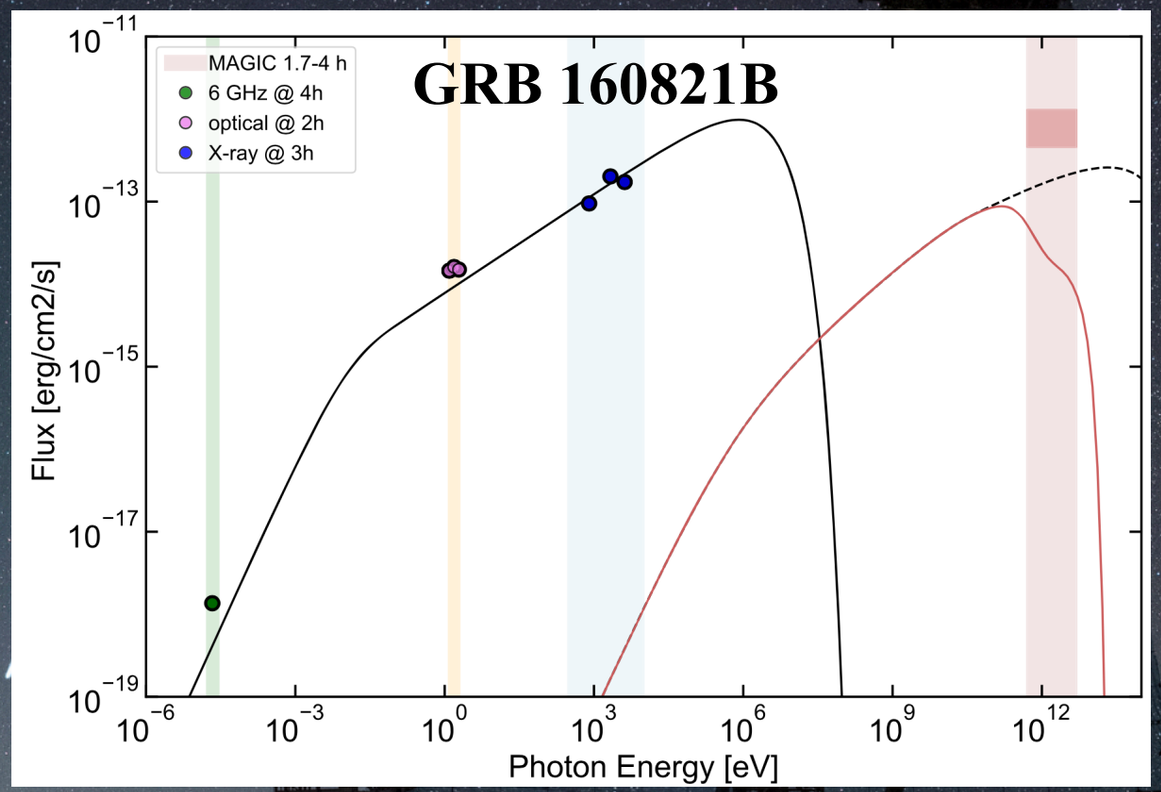




MAGIC Coll. Nature 575 (2019) 455
MAGIC Coll. et al. Nature 575 (2019) 459

Other GRB detections

Acciari et al. ApJ 908 (2021) 90



GRB 201216C: MAGIC detection in very high energy gamma rays

ATel #14275; ***Oscar Blanch (IFAE-BIST) on behalf of the MAGIC Collaboration***
*on **17 Dec 2020; 17:23 UT***
Credential Certification: Oscar Blanch (blanch@ifae.es)

Subjects: Gamma Ray, >GeV, TeV, VHE, Gamma-Ray Burst

Referred to by ATel #: 14277

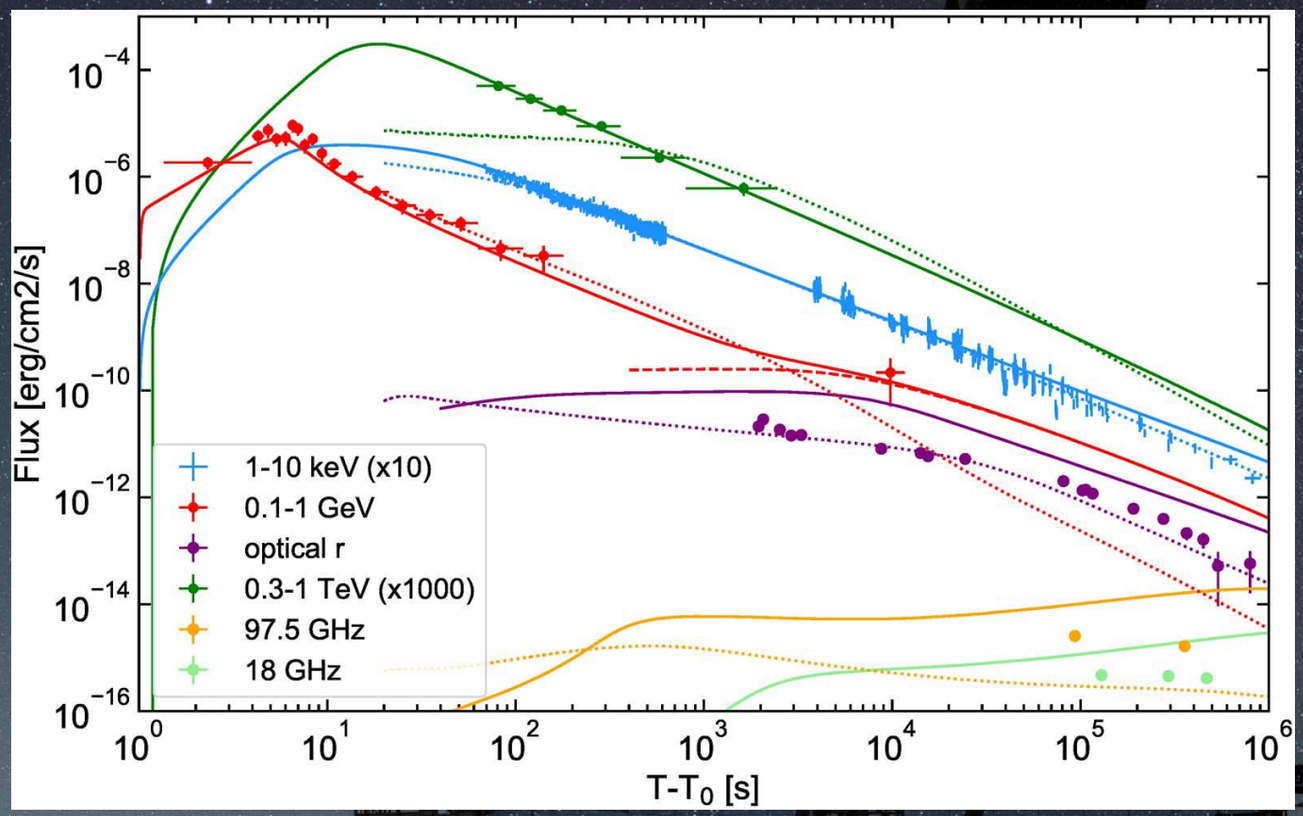
Tweet

On December 16, 2020, the MAGIC telescopes observed GRB 201216C following the trigger by Swift-BAT and Fermi-GBM (Beardmore et al., GCN 29061, Fermi/GBM team GCN 29063). MAGIC started observations under good conditions about 57 seconds after the GRB onset. The preliminary off-line analyses show an excess above 5 sigma, compatible with the GRB position reported by the Swift and Fermi teams. Refined off-line analyses of the data are ongoing.

- ★ 3σ hint of detection for short gamma-ray burst GRB160821B
  - ✦ Emission difficult to explain with one-zone synchrotron-self-Compton models
- ★ GRB 201216C detected with high (>5σ) significance -> Stay tuned for publication
- ★ The firm detection of GRB190114 have opened the can for almost routine GRB detections (4.5 detections so far by MAGIC and HESS)

LIV in GRBs

MAGIC Coll. et al. Nature 575 (2019) 459



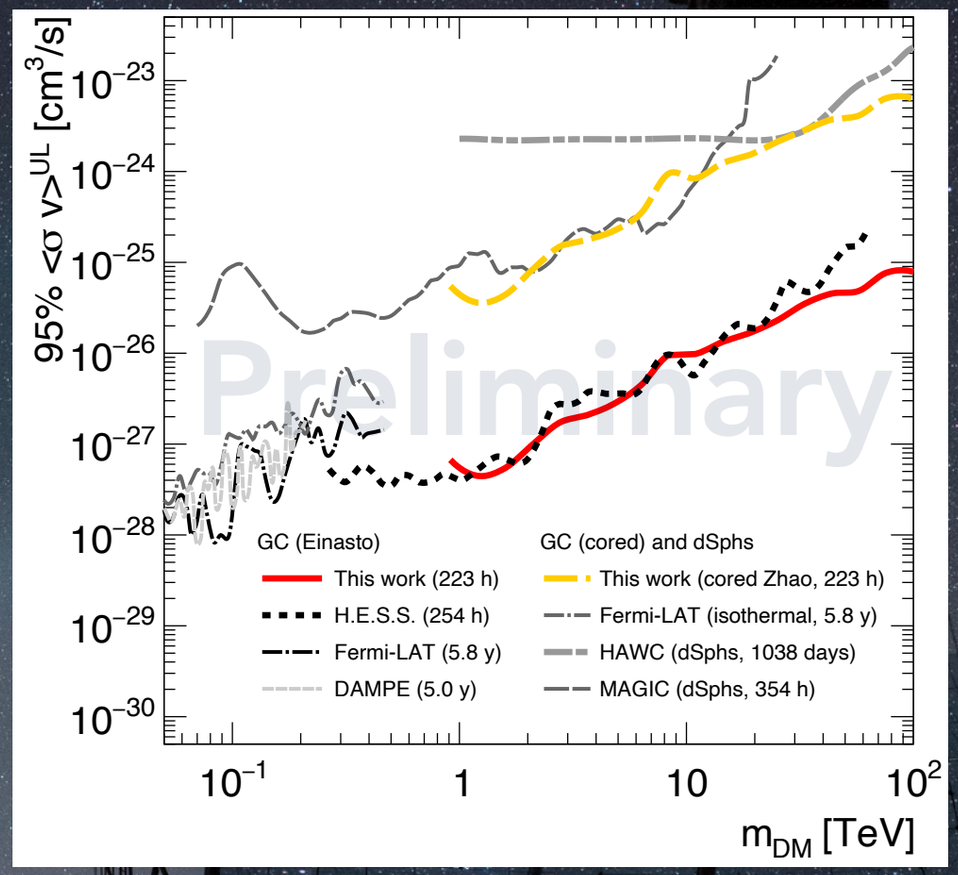
Acciari et al. Phys. Rev. Lett. 125 (2020) 021301

LC model	Minimal (step function)	Theoretical ([19])		
	η^{UL}	η^{LL}	η^{BF}	η^{UL}
η_1	4.4	-2.2	0.3	2.1
η_2	2.8	-4.8	1.3	3.7
	subl.	superl.		subl.
$E_{QG,1}$ [10^{19} GeV]	0.28	0.55		0.58
$E_{QG,2}$ [10^{10} GeV]	7.3	5.6		6.3

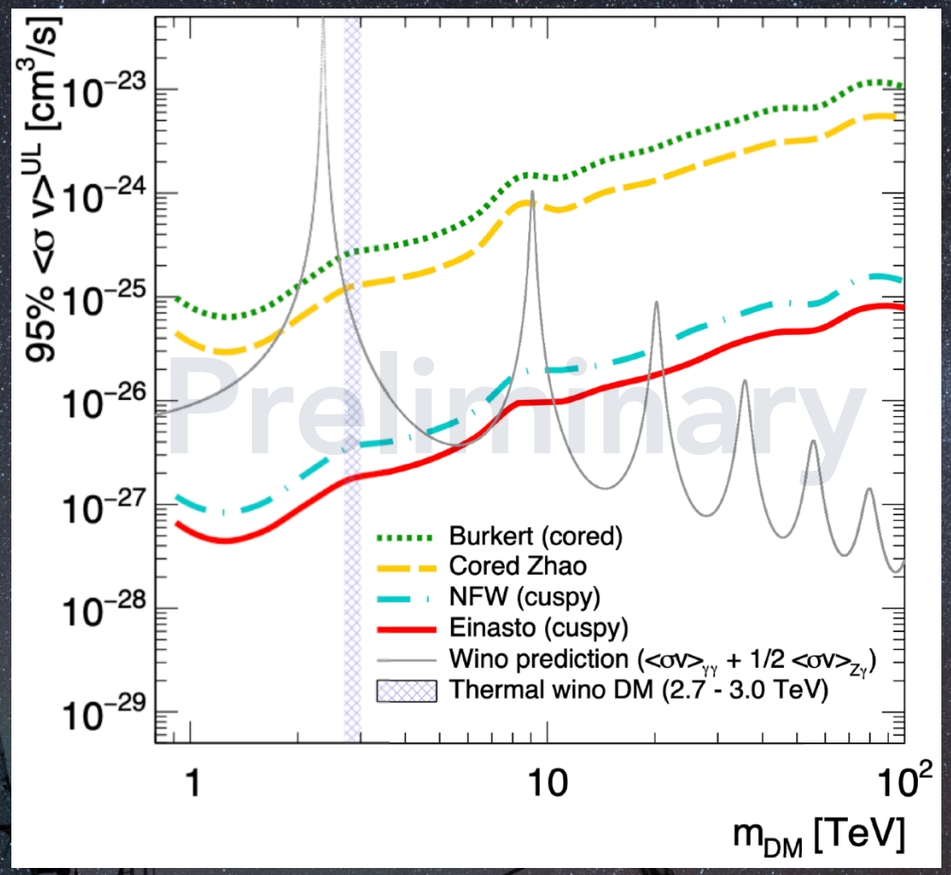
$$\Delta t = s\frac{n+1}{2}D_n(z)\left(\frac{\Delta E}{E_{QG,n}}\right)^n$$

- ★ No dependence of observed light curve on energy for VHE gamma rays
- ★ No correlation of photon arrival time with gamma-ray energy
- ★ Derive limits to quantum gravity scale
  - ✦ Competitive for the quadratic leading order even for a featureless light curve

Dark matter gamma-ray lines



Inada et al. Gamma 2022 conference



- ★ 220 h observations of the Galactic Center region
- ★ High zenith angle observations to increase the maximum dark matter mass (100 TeV)
- ★ Competitive limits for cusp and cored DM distribution
- ★ Excluding/tensioning specific DM models

Combined DM search

- ★ Stack likelihood functions of 20 dwarf satellite galaxies by 5 gamma-ray telescopes (Fermi-LAT, MAGIC, HESS, VERITAS, HAWC)

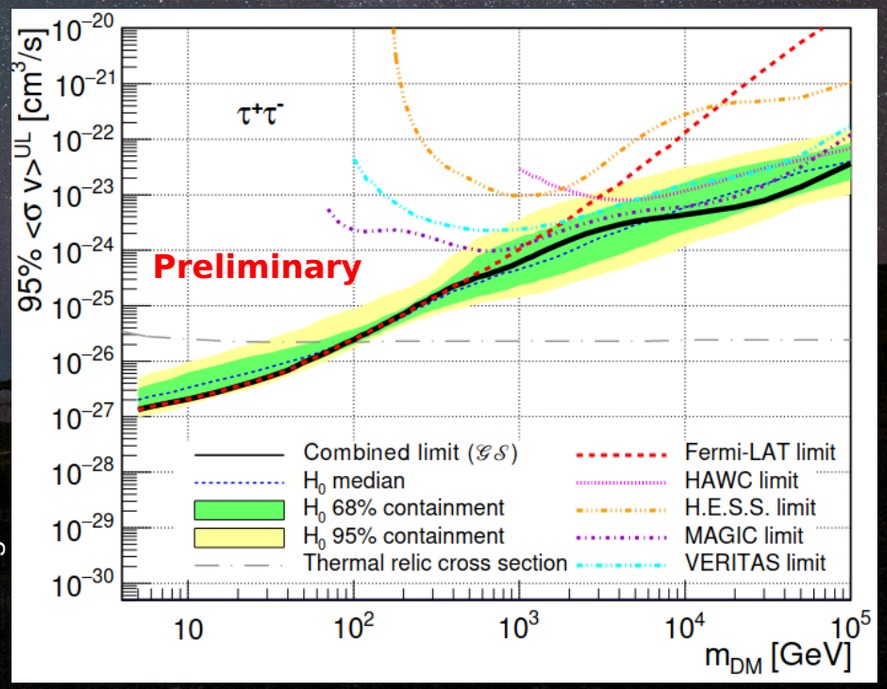
$$\mathcal{L}(\alpha;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{l=1}^{N_{\mathrm{dSph}}} \mathcal{L}_\gamma(\alpha\bar{J}_l;\boldsymbol{\mu}_l|\boldsymbol{\mathcal{D}}_{\gamma_l}) \cdot \mathcal{L}_J(\bar{J}_l|\boldsymbol{\mathcal{D}}_{J_l})$$

$$\mathcal{L}_\gamma(\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\gamma) = \prod_{k=1}^{N_{\mathrm{meas}}} \mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}_k|\boldsymbol{\mathcal{D}}_{\gamma,k})$$

$$\mathcal{L}_J(\bar{J}\,|\,\bar{J}_{\mathrm{obs}},\sigma_J) = \frac{1}{\ln(10)\bar{J}_{\mathrm{obs}}\sqrt{2\pi}\sigma_J}\, e^{-\left(\log_{10}(\bar{J})-\log_{10}(\bar{J}_{\mathrm{obs}})\right)^2/2\sigma_J^2}$$

- ★ Combined limits:
  - ✦ Wide mass range: [5 GeV — 100 TeV]
  - ✦ Coherent statistical treatment, easy to compare
  - ✦ up to 2-3 times more constraining
- ★ Extension to neutrinos ongoing…!

Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2cm^{-5}sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2cm^{-5}sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$



Kerszberg et al. Gamma 2022 conference

© Urs Leutenegger

Conclusions

- ★ MAGIC operating smoothly since last major upgrade in 2011-2012
- ★ Good scientific harvest, e.g.:
  - ✦ Discovery of new types of VHE gamma-ray emitters
  - ✦ Help unveiling the origin of Galactic cosmic rays and Ultra-High-Energy neutrinos
  - ✦ Understanding particle acceleration in shocks, jets and extreme environments
  - ✦ Fundamental Physics issues:
    - ✳ Lorentz Invariance tests
    - ✳ Search for Dark matter
- ★ Multi-wavelength/multi-messenger/multi-collaboration projects getting increasingly important