

# The MAGIC of acceleration

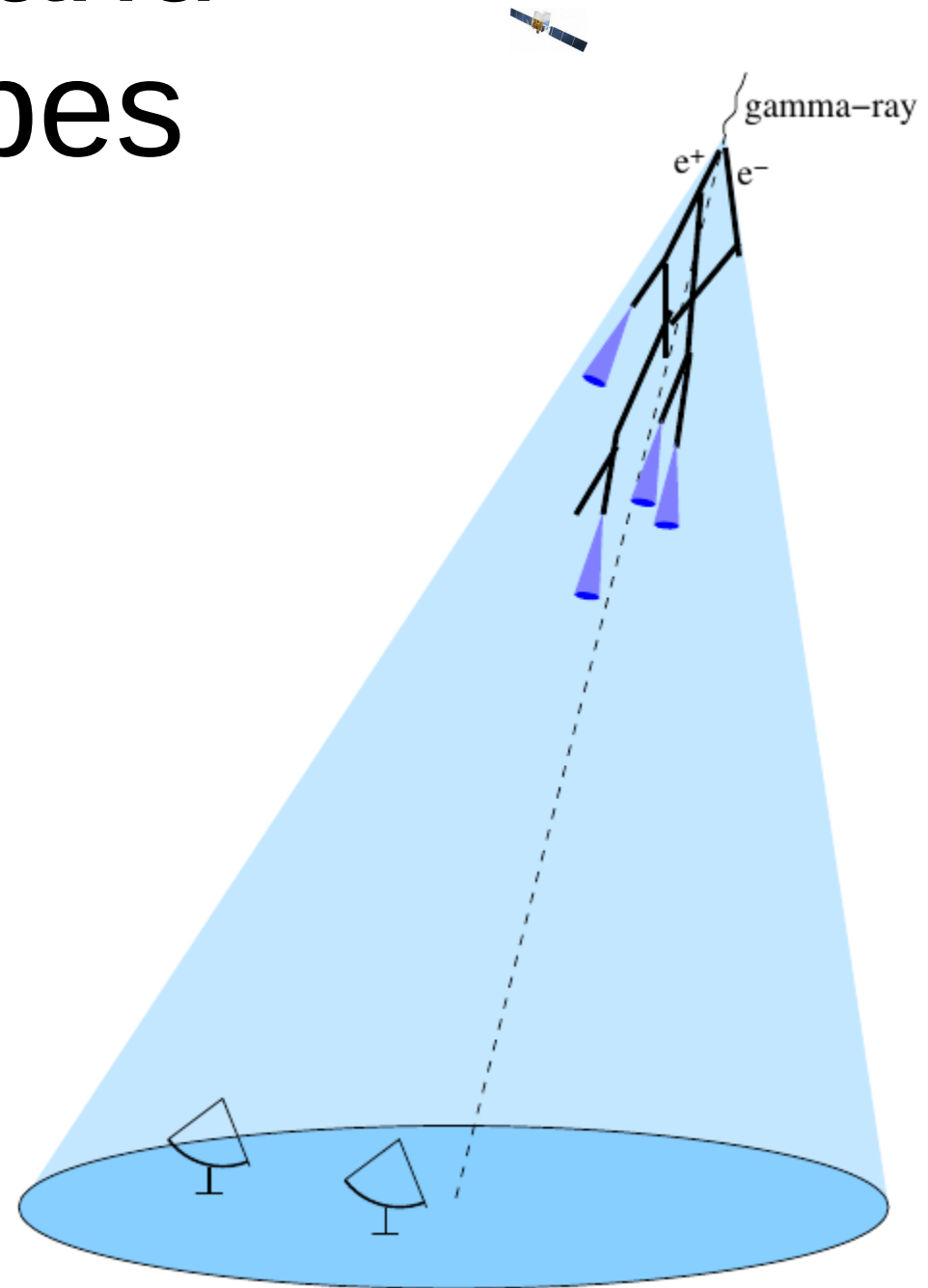
J. Sitarek on behalf of the MAGIC Collaboration

2022.01.11, 28<sup>th</sup> Epiphany Conference

# IACT technique and MAGIC telescopes

- MAGIC: two 17-m diameter Cherenkov telescopes located at La Palma, Spain
- Energy range: from a few tens of GeV to a few tens of TeV
- Sensitivity in the best energy range  $\sim 0.7\%$  of the Crab Nebula flux in 50 hr

**Combination of stereoscopy and large mirror diameter results in optimal low-energy performance**



# Physics with MAGIC

**Galactic Science:**  
SNRs, PWNe, Gal.  
Cent., Pulsars, ...

**Extragalactic Science:**  
AGNs and beyond

**Transients and  
Multi-Messenger:**  
Follow up of GRBs,  
GW,  $\nu$ , ...

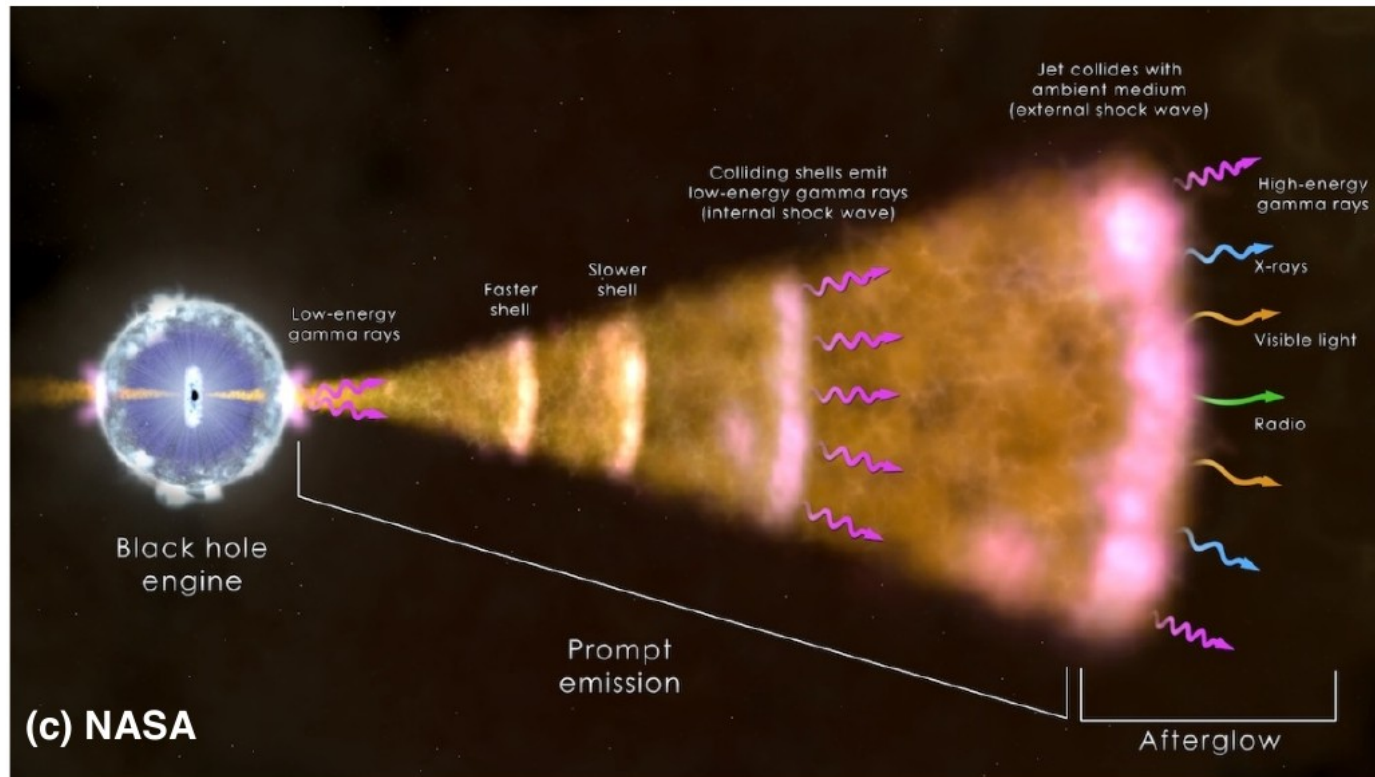
**Fundamental Physics  
and Cosmology:**  
Probing Dark Matter,  
LIV, EBL, IGMF, ...



**“Exotic applications”:**  
Cosmic Rays, Intensity  
Interferometry

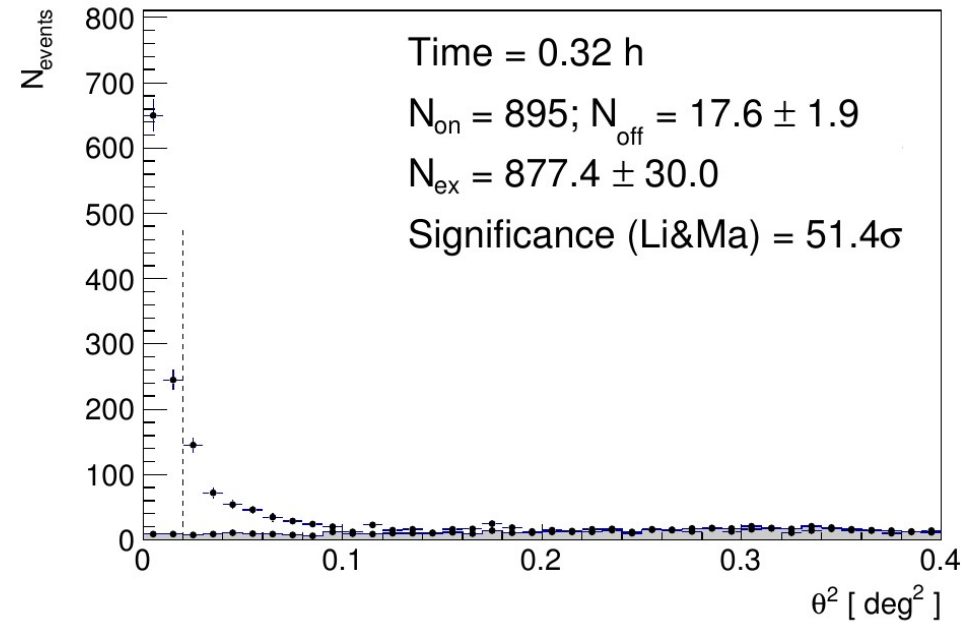
- **Typical scenario:** acceleration of charged particles ( $e^{\pm}$ ,  $p$ ) in cosmic sources, subsequent production of gamma rays in radiative processes => **by studying gamma rays we study  $e^{\pm}$  and  $p$**
- **Low energy threshold of MAGIC:** allows us to study:
  - Inefficient accelerators (low maximum energy)
  - Sources where highest energies are absorbed (inside the source or on the way to the observer)
  - Good sensitivity to transients (large statistics at low energies)

# GRB 190114C



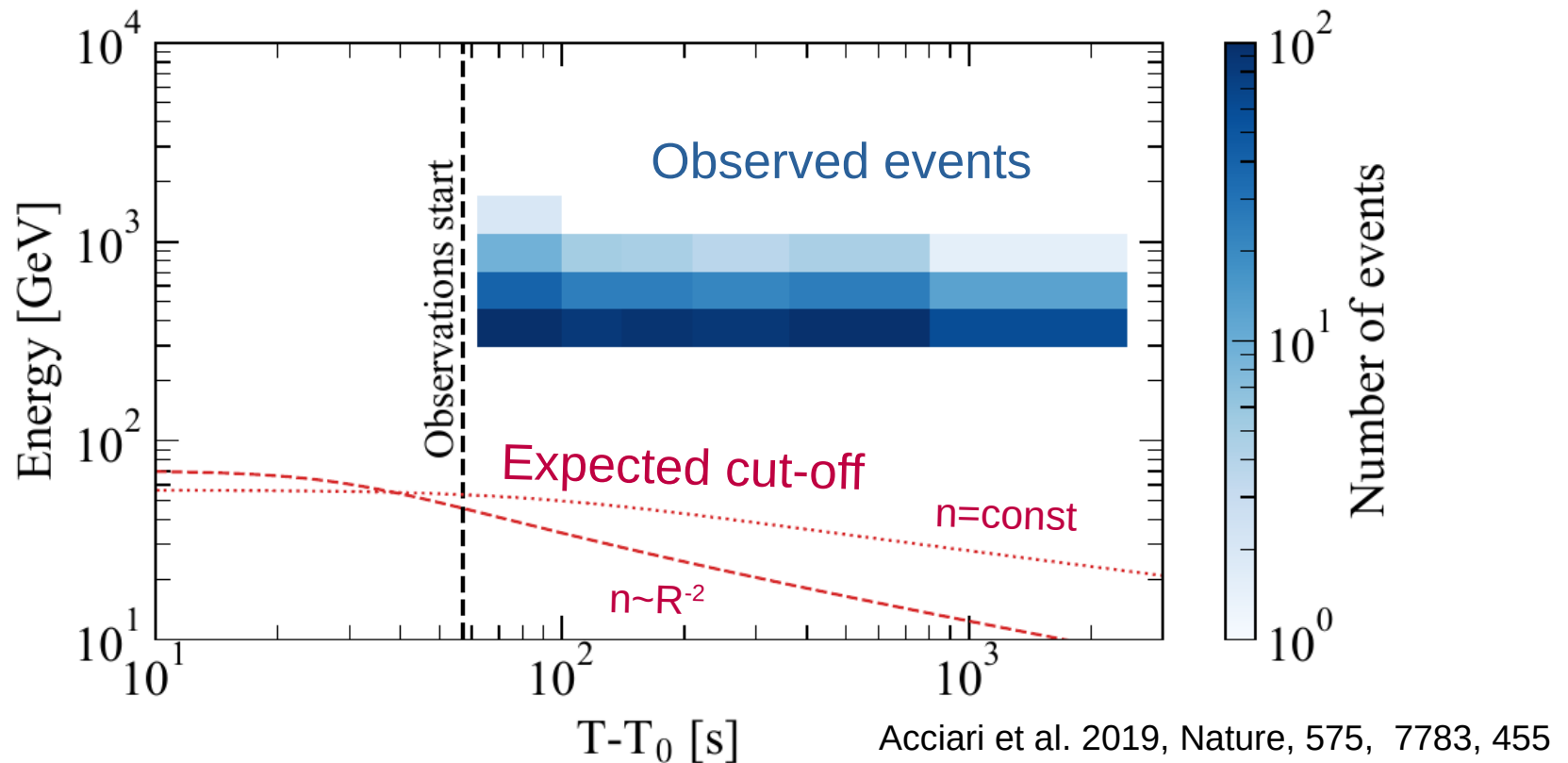
# GRB 190114C

- After decades of search of VHE gamma-ray emission from GRBs, the first claim of detection came from MAGIC observations of GRB 190114C
- Long GRB with  $T_{90}=361$  s
- MAGIC observations already 50s after the X-ray (*Swift*-BAT) trigger.
- **The brightest VHE gamma-ray source ever:** reached 0.1 kCrab level in the first seconds of observations



Acciari et al. 2019, Nature, 575, 7783, 455

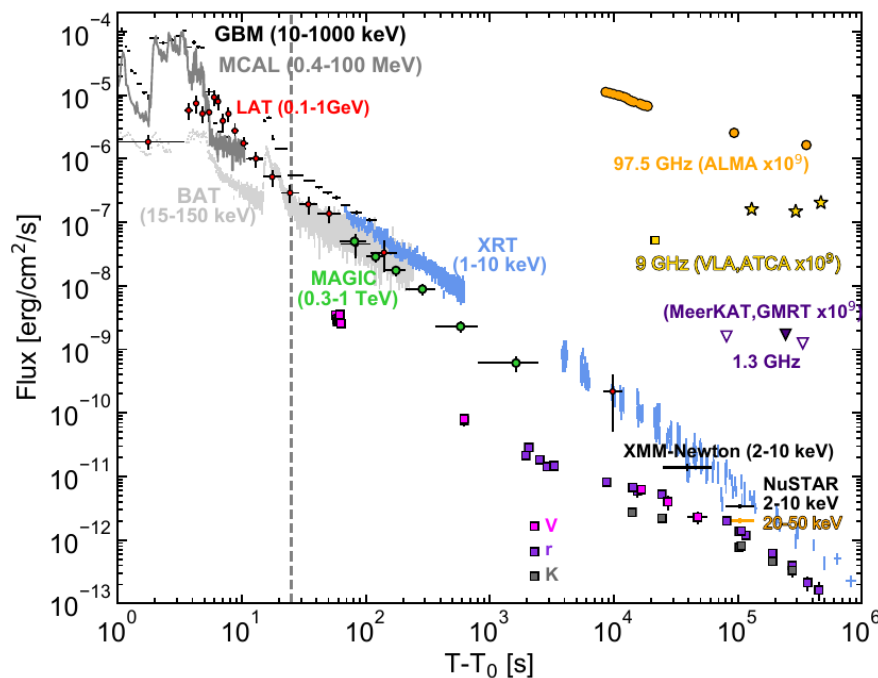
# First clear evidence of non-synchrotron origin of gamma rays



Observed energies an order of magnitude larger than expected cut-off of synchrotron emission – clear evidence for the suspected second emission mechanism

# Including multiwavelength information

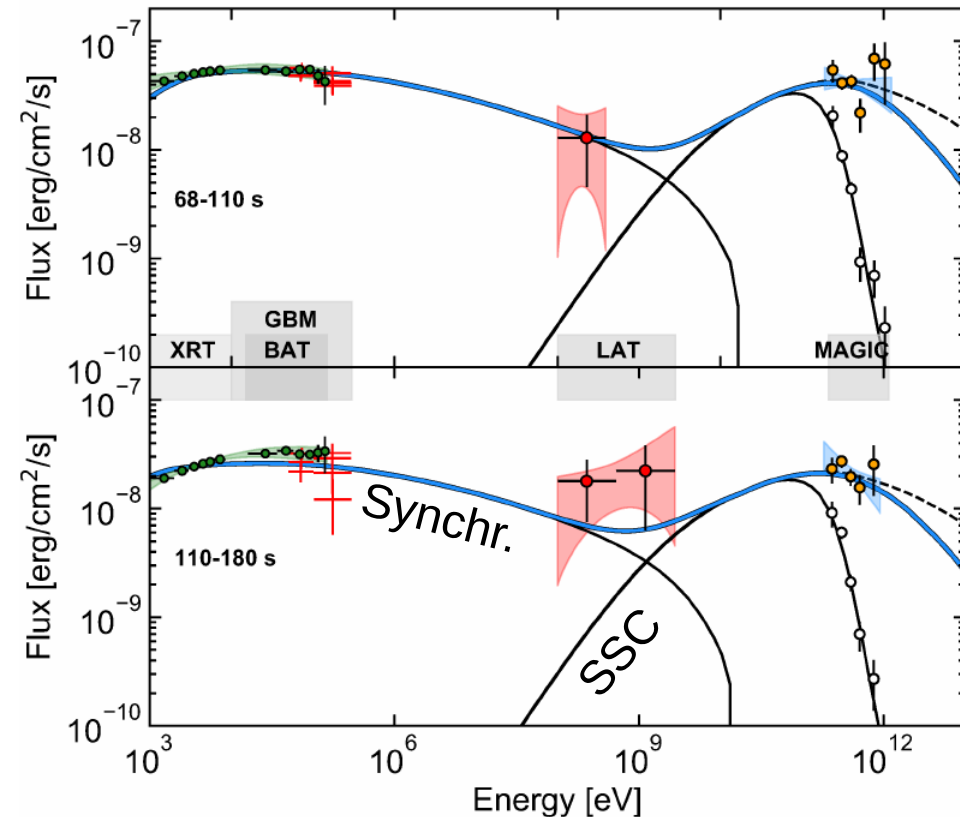
- MAGIC observations in the early afterglow phase
- TeV decay with  $\sim t^{-1.51 \pm 0.04}$ , faster than X-rays (synchrotron emission,  $\sim t^{-1.36 \pm 0.02}$ , *Swift*-XRT )



Acciari et al. 2019, Nature, 575, 7783, 459

# Combination of synchrotron and SSC emission

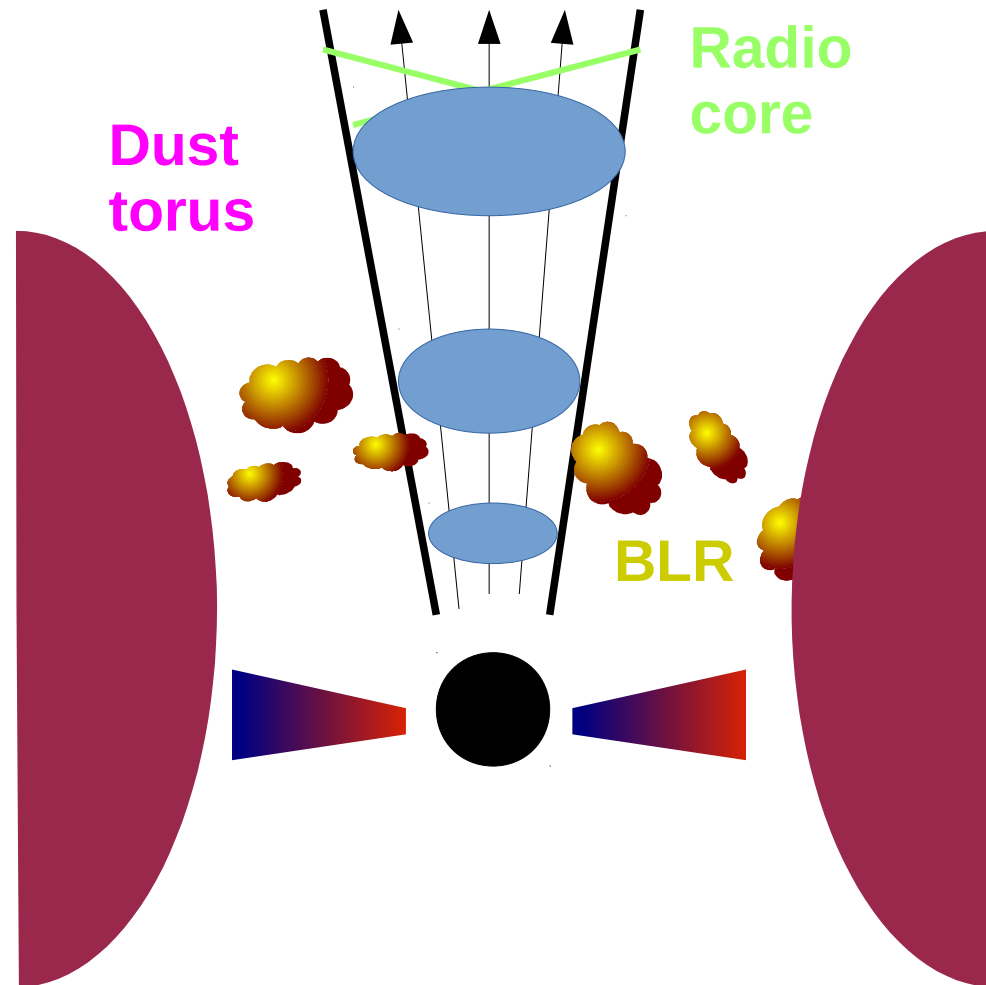
- The emission can be modeled in a SSC scenario
- The highest energy emission strongly absorbed by EBL



Acciari et al. 2019, Nature, 575, 7783, 459

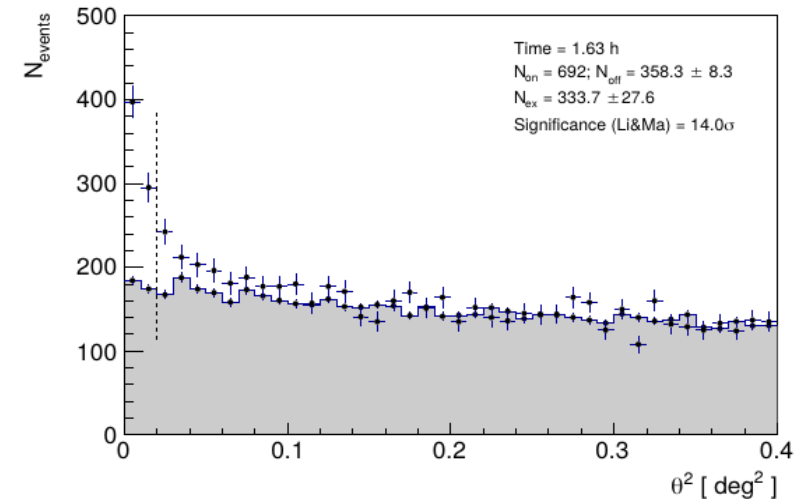


# Flat Spectrum Radio Quasar QSO B1420+326



# QSO B1420+326 (a.k.a. OQ 334)

- 8th FSRQ detected at VHE gamma rays
- distant source ( $z=0.682$ )
- Strongly variable in gamma rays
- Detected by MAGIC during follow-up of flaring activity started in December 2019.



Acciari et al. 2021, A&A, 647, A163

# Rich MWL campaign

- Flux measurements in radio, NIR, optical, UV, X-ray, HE and VHE gamma rays
- Optical polarimetry
- Optical spectroscopy
- Follow-up with radio interferometry

4 periods selected for detailed analysis:

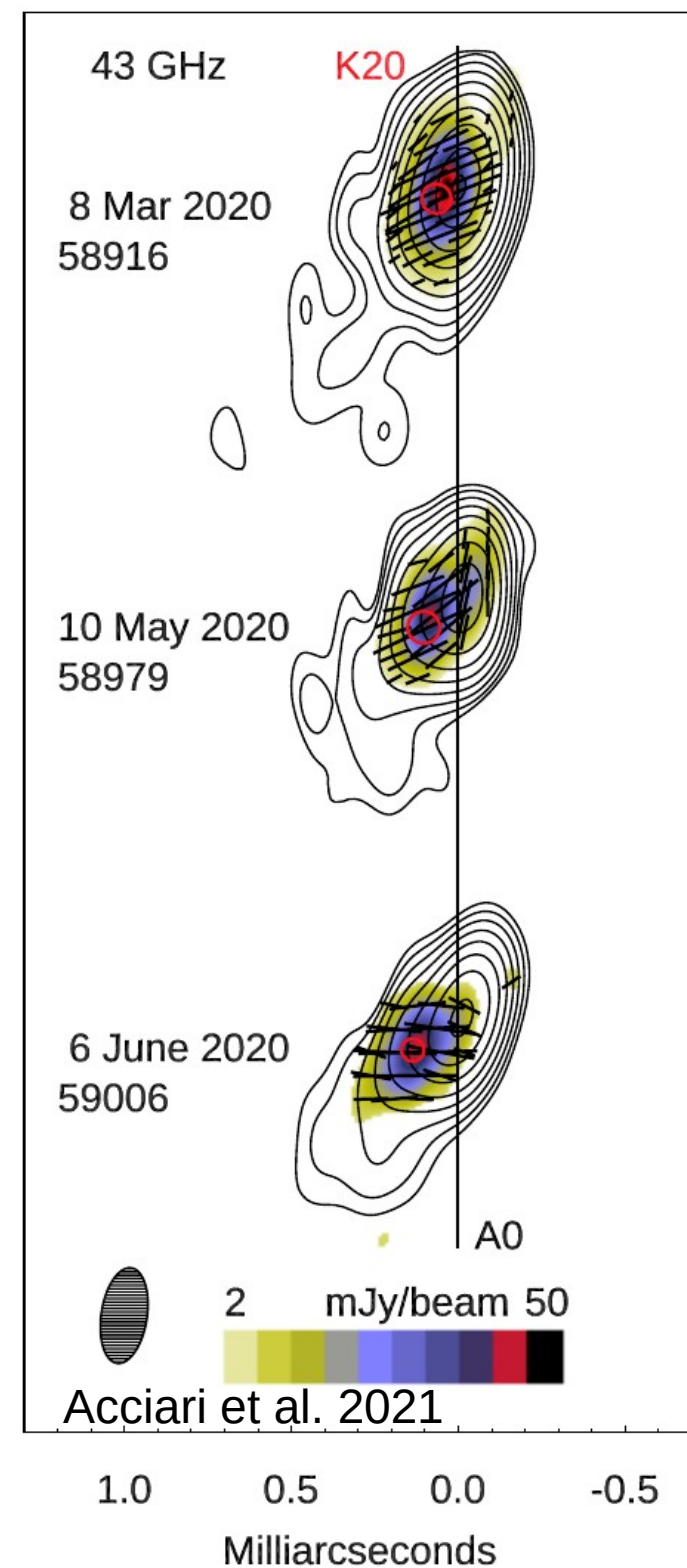
Period	MJD	comment
A	58846.5 - 58853.5	pre-flare
B	58867 - 58868	optical flare
C	58868.3 - 58870.3	VHE flare
D	58873.5 - 58880.5	post-flare

Acciari et al. 2021



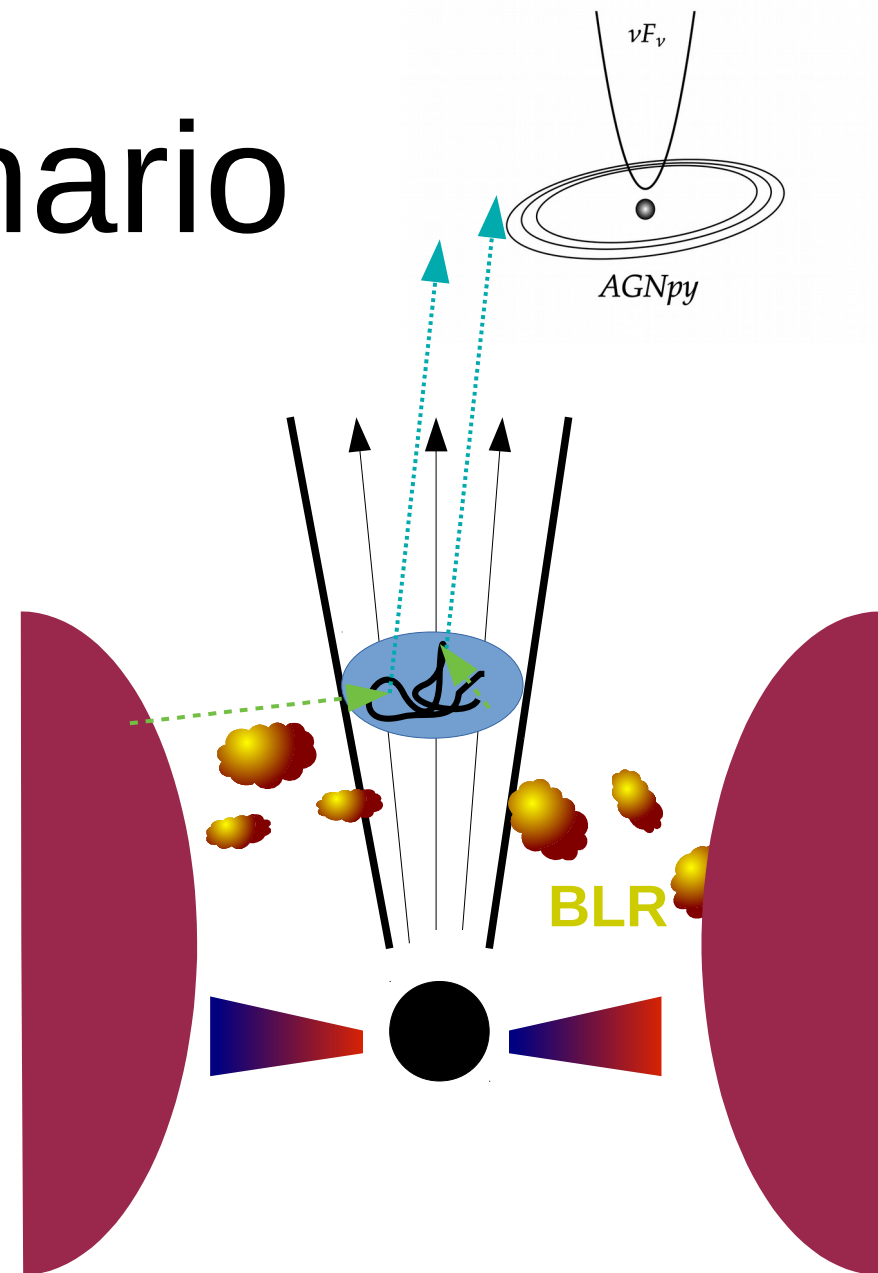
# VLBA images

- Follow-up radio interferometry measurements shown a new knot (K20) ejected from the core with  $\Gamma=19\pm 9$  and  $\delta=33\pm 9$
- During the time of VHE emission the upstream edge of the knot was passing through the centroid of the core

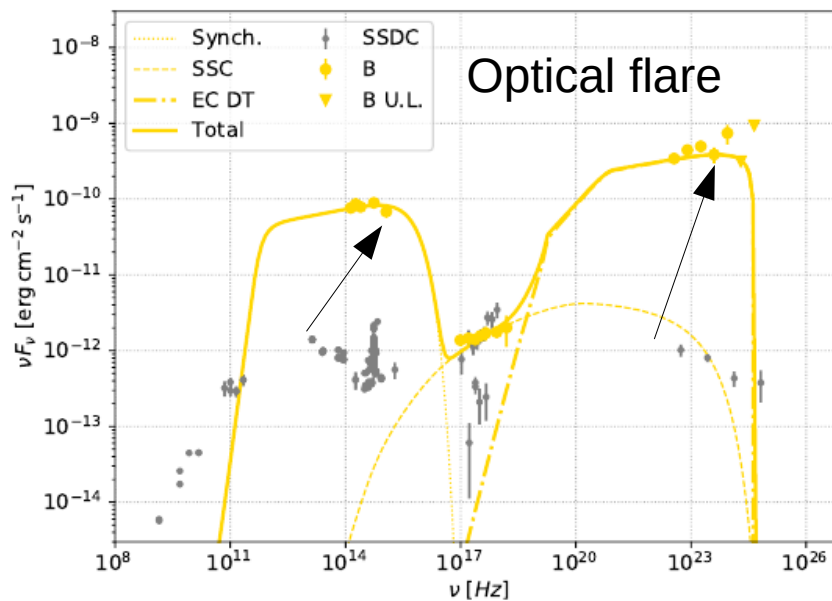
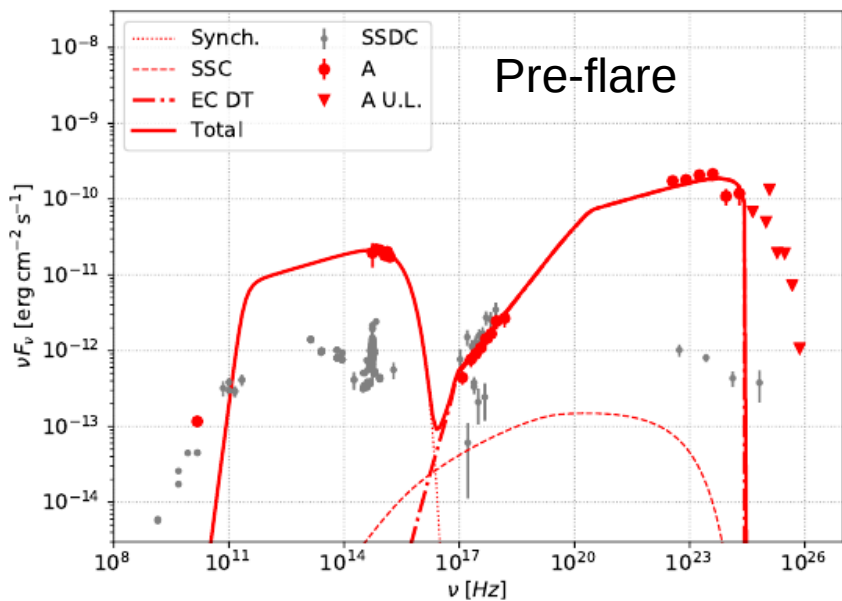


# Modeling scenario

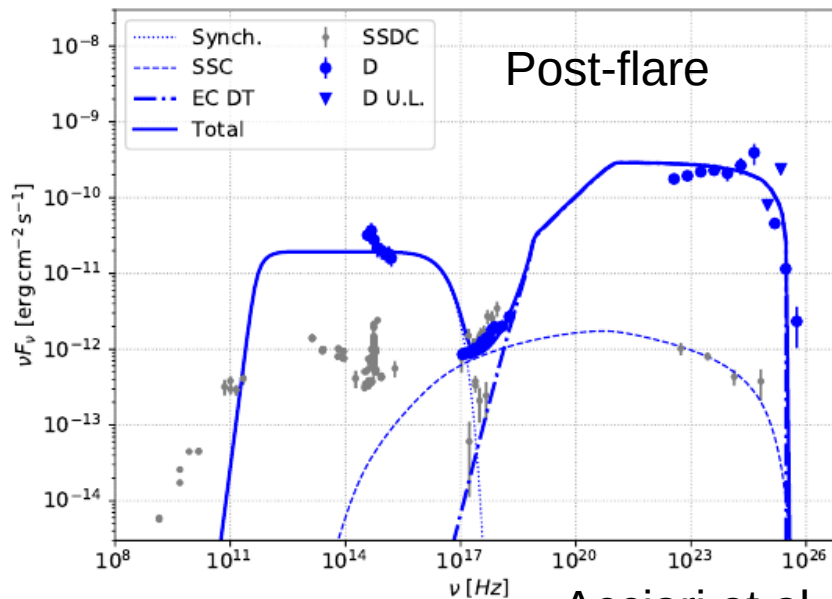
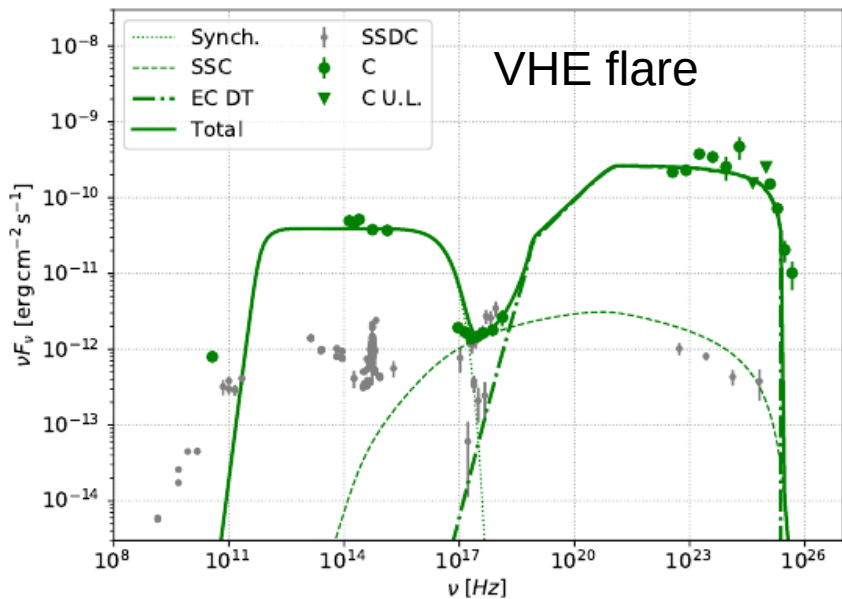
- Leptonic model, FSRQ have likely pronounced External Compton emission
- Large increase of optical flux  $\implies$  SSC component
- Size of the emission region  $r_b \implies$  limited by  $\sim 1$  day time scale variability
- VHE gamma-rays  $\implies$  emission region beyond BLR
- Electron energy distribution determined by balance of the cooling, acceleration and dynamic time scale
- Modeling performed with agnpy (<https://agnpy.readthedocs.io>) code, each period modeled independently



# SED modeling



Shift of position and flux of both peaks by at least 1-2 orders of magnitude during enhanced state

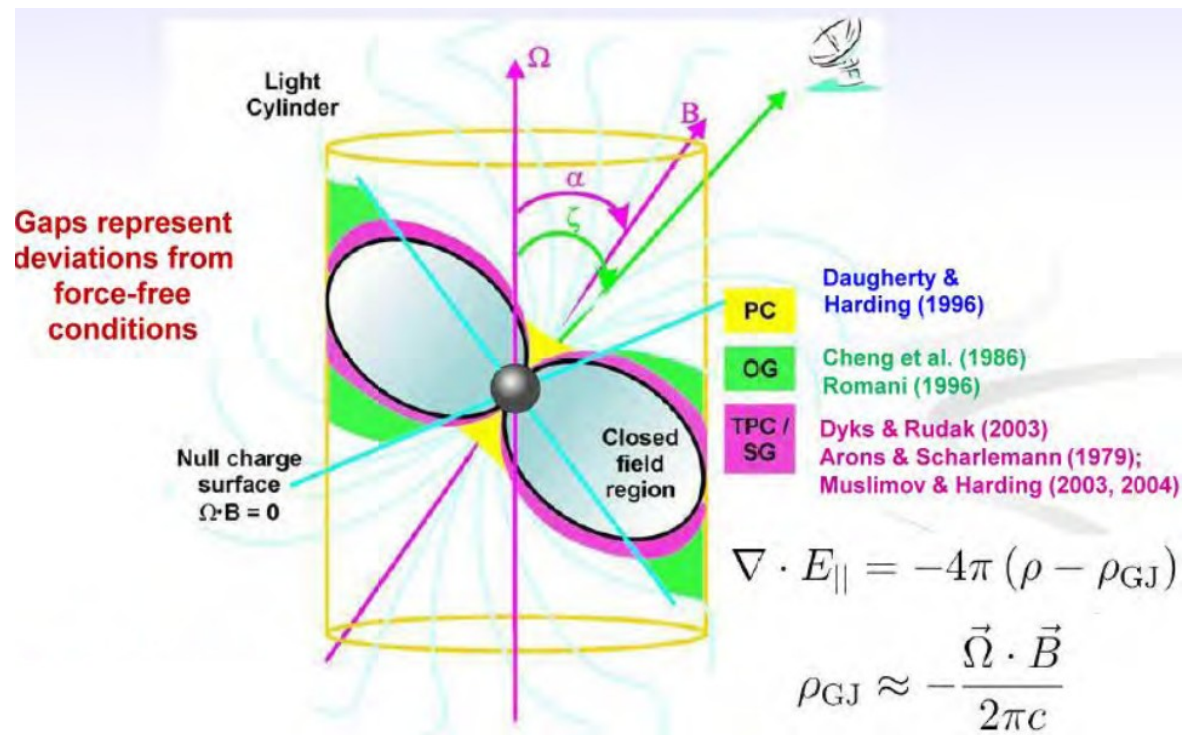


Classification of the source changes with the emission of a newly accelerated particles.

# Conclusions from the modeling

- Acceleration of electrons in a shock beyond the Broad Line Region
- Gamma rays explained as External Compton emission on Dust Torus radiation field
- (highly variable in shape) X-ray emission explained as a combination of falling edge of synchrotron, bulk of SSC and rising edge of EC emission
- Proposed solution is close to  $u_e/u_B$  equipartition (0.06 – 1.6)

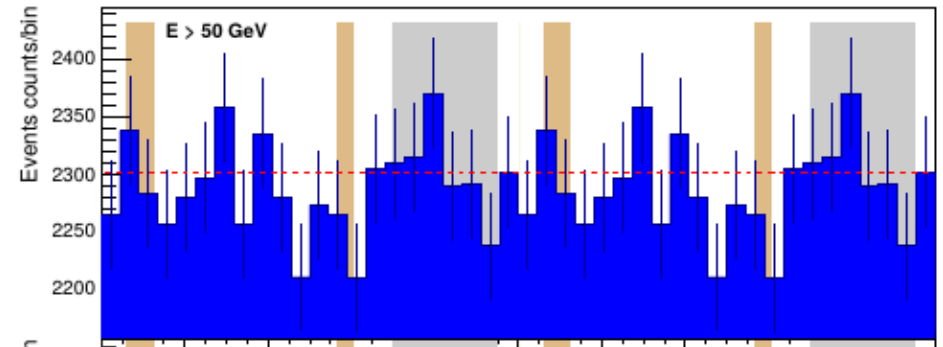
# Geminga pulsar



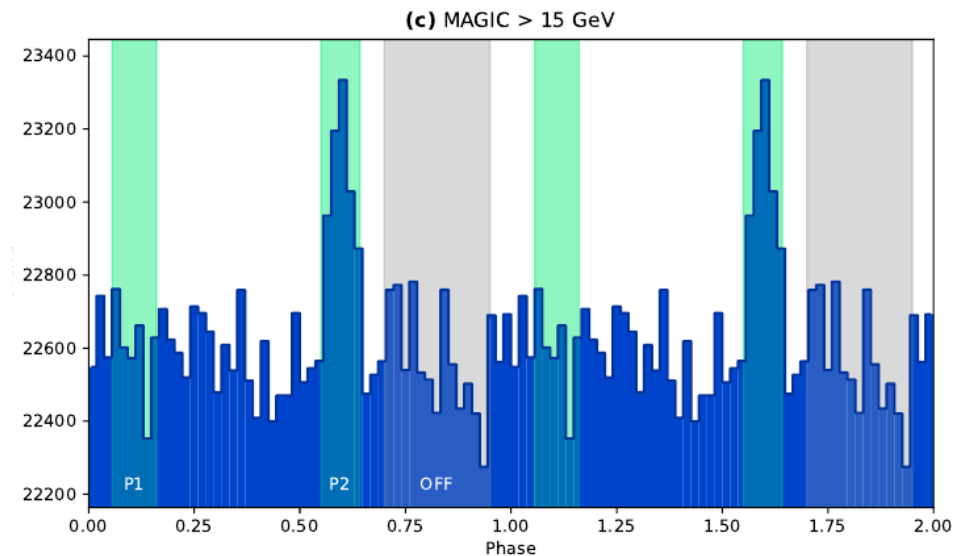


# Geminga

- Classical, radio-quiet pulsar
- Very bright at GeV gamma-rays
- 63 hrs of observations with standard MAGIC trigger resulted only in upper limits (Ahnen et al. 2016)
- Detected by MAGIC with  $6.3\sigma$  signal in 80 hrs of special SumTrigger-II observations



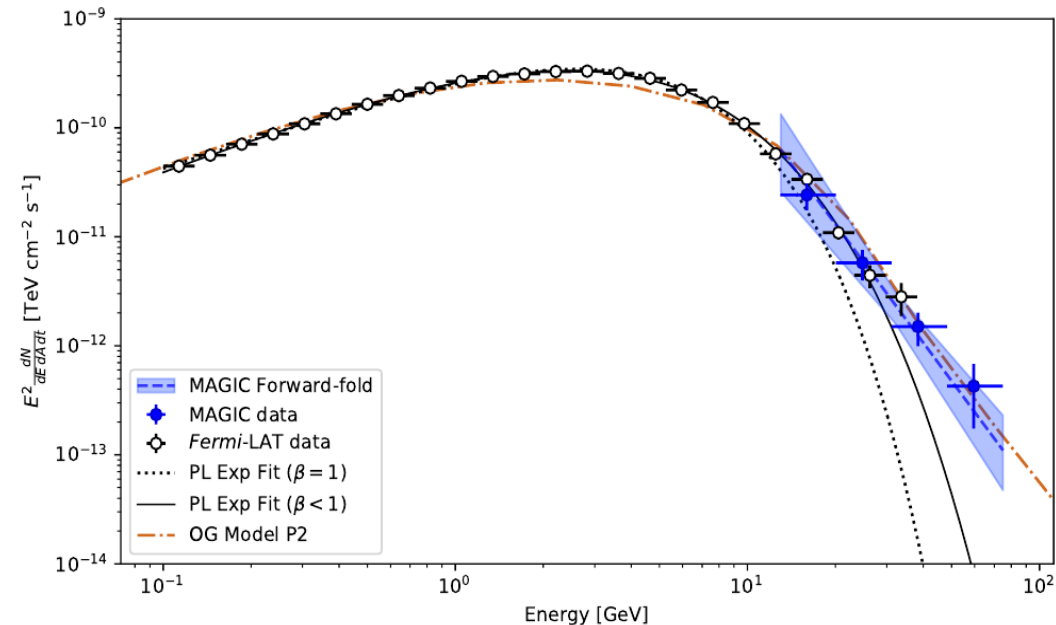
Ahnen et al. 2016, A&A, 591, A138



Acciari et al. 2020, A&A, 643, L14

# Challenging source

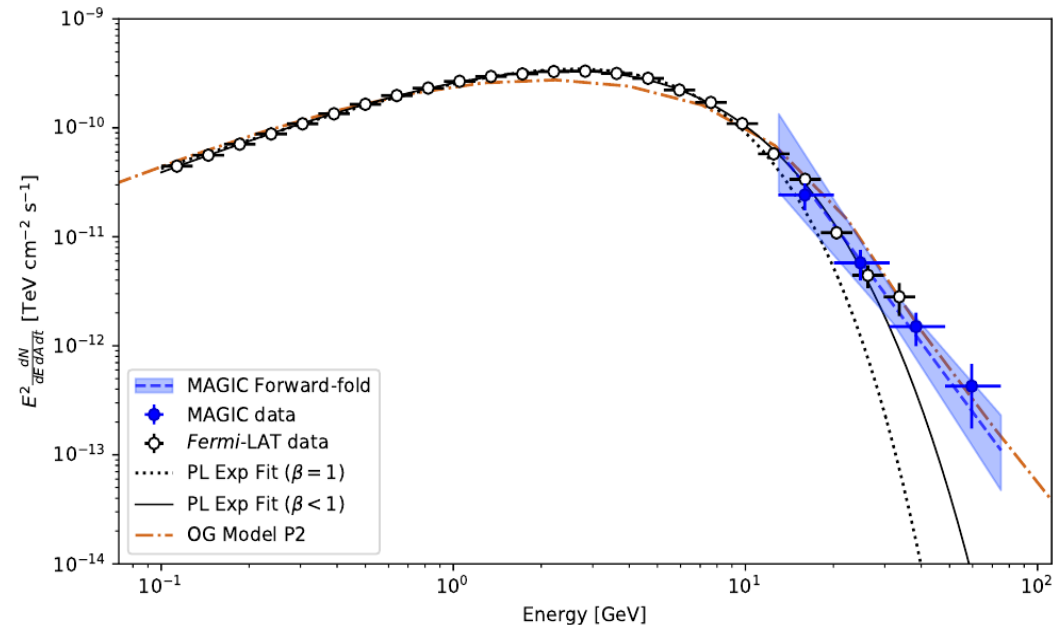
- Extremely soft spectrum at VHE gamma rays: spectral index of  $-5.62 \pm 0.54$
- Spectrum reconstructed between **15 GeV** and 75 GeV



Acciari et al. 2020, A&A, 643, L14

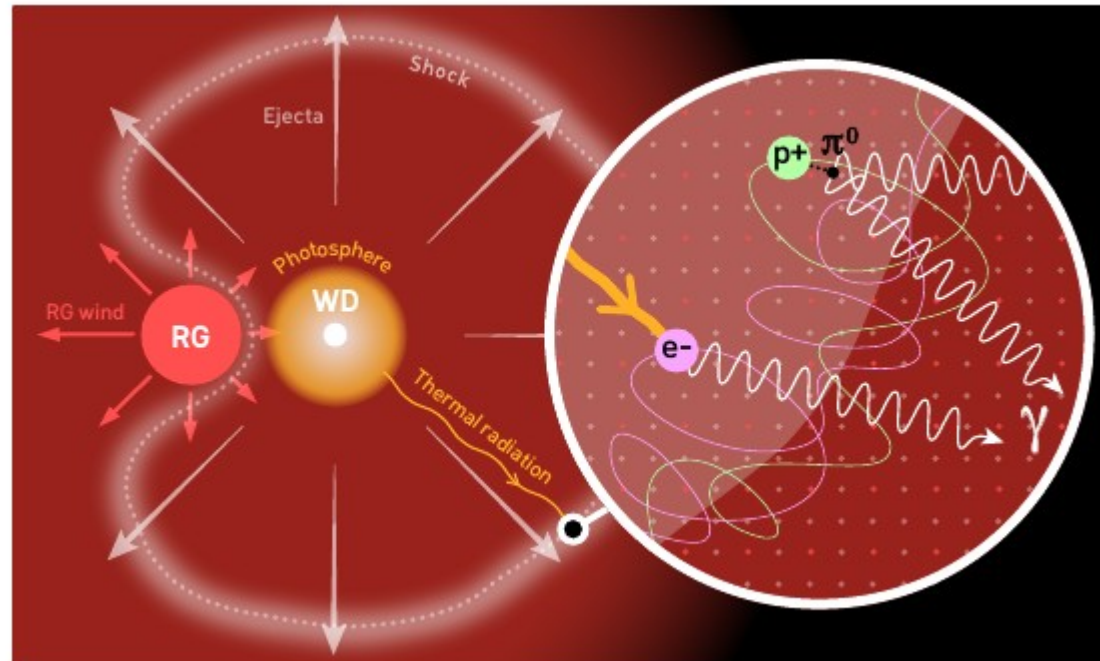
# Emission model

- Joint MAGIC/Fermi-LAT rules out the sub-exponential cut-off at a 3.6 sigma level => Hinting a power-law tail emission at  $E > 15$  GeV
- $e^{\pm}$  accelerated in an outer gap scenario
- Flux  $< 40$  GeV dominated by curvature radiation
- $> 40$  GeV dominated by IC scattering of soft X-rays from the surface of the NS (inward going electrons)



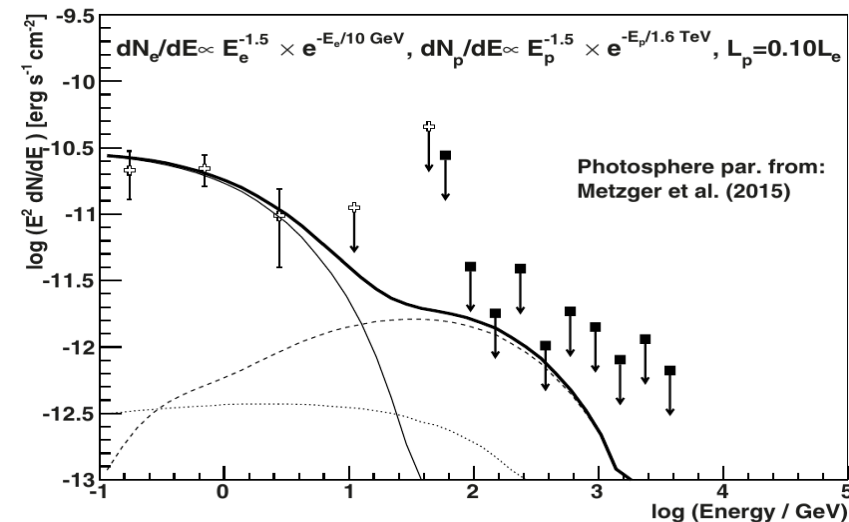
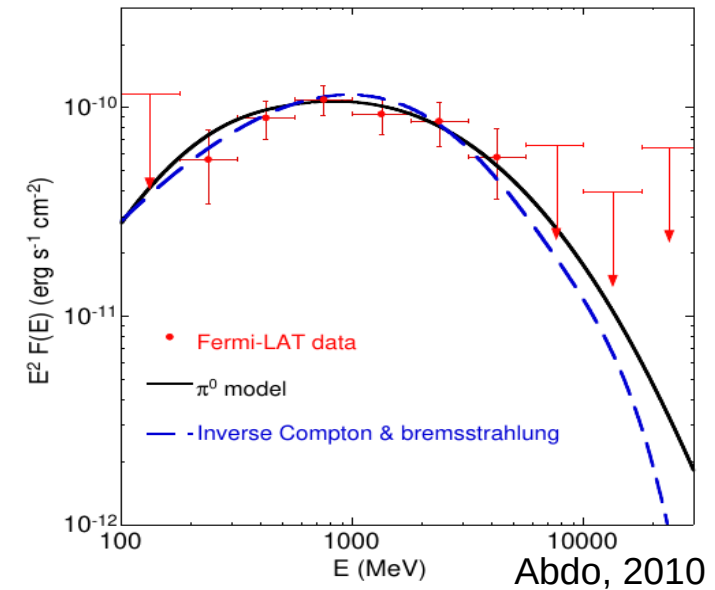
Acciari et al. 2020, A&A, 643, L14

# Nova RS Ophiuchi



# Novae at GeV energies

- Since over 10 years novae are known GeV emitters
- GeV data alone are not sufficient to disentangle electron and proton acceleration models
- 10-years-long nova follow-up program in MAGIC

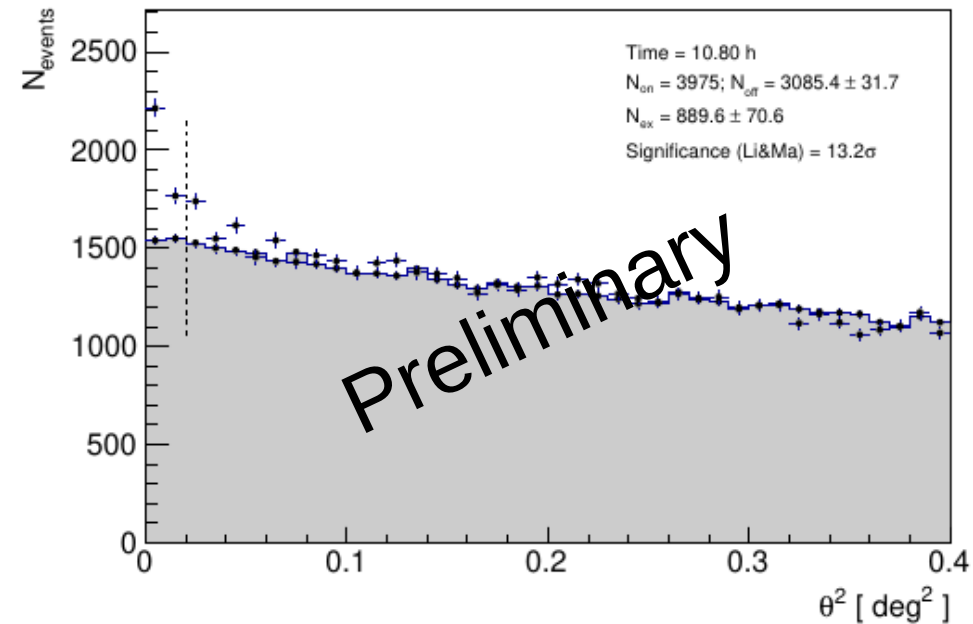


# RS Oph

- Recurrent nova in a symbiotic binary
- Outbursts every 15-20 years
- Latest outburst on 2021.08.8 UT ~22:20
- First nova from which the VHE gamma ray emission has been reported (H.E.S.S. ATel #14844)
- Independently, MAGIC observed the source following the Fermi-LAT alert already one night after the nova onset.

# MAGIC observations of RS Oph

- The source was detected in the first four nights after the optical detection
- Follow-up data taken 3 weeks after the detection do not show a significant signal



# MAGIC in MWL view

- Despite fast decline ( $\sim 3$  day time scale) in *Fermi*-LAT, the MAGIC emission is consistent with being constant over the first 4 days.

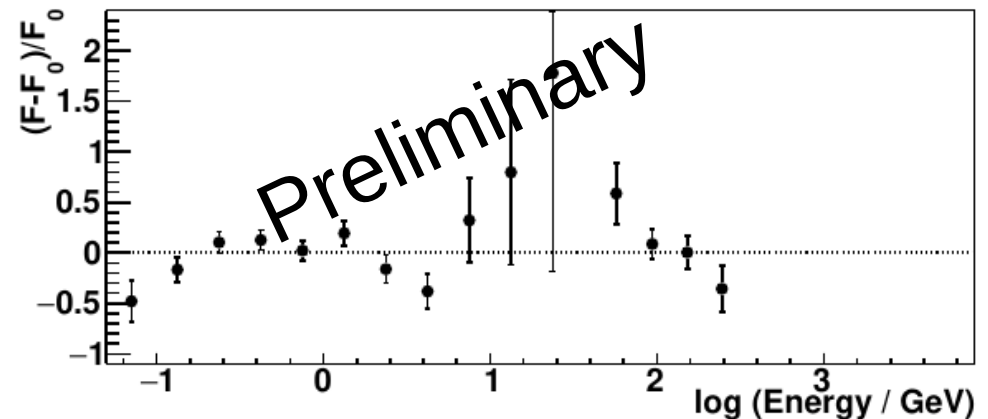
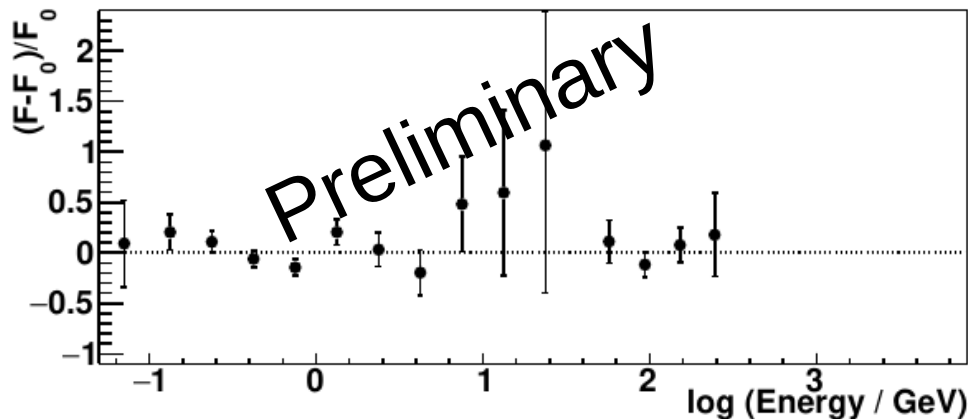


# Two modeling scenarios

- Protons – pp interaction on mainly nova ejecta (with some contribution from RG wind)
- Electrons – IC on thermal radiation of a photosphere
- Particles are **injected** and either cool down completely (electrons) or we gather their emission during the acceleration time (protons)
- Since we deal with injected spectra any cooling breaks should automatically be taken into account – the injection spectrum should be simple and directly reflect the acceleration of particles

# Protons or electrons?

- Combined fit to the Fermi and MAGIC data reveals preference for proton acceleration:
- natural  $\sim -2$  slope spectrum with a cut-off, while electrons need a strong **acceleration** break
- much better  $\chi^2/N_{\text{dof}}$  of the fit (13.2/12 vs. 27.5/11), AIC test gives electrons only  $4.7 \times 10^{-4}$  times as likely as protons



# Conclusions

- MAGIC telescopes provide insight into the acceleration and radiation processes of relativistic particles via observations of gamma rays
- MWL information needed for full picture of the source models
- GRB 190114C: first claim of VHE gamma-ray emission from a GRB
- B1420+326: extreme shifts of the peak position during a high state of a FSRQ
- Geminga pulsar: extremely soft source measured down to 15 GeV
- RS Oph: first firm evidence for acceleration of protons in novae