Some contributions of MAGIC to the physics of cosmic rays

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Introduction: γ ray astronomy and cosmic rays

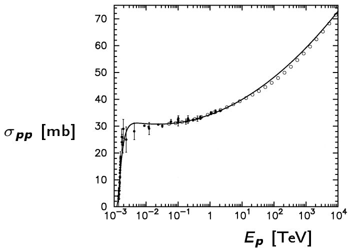
High energy photons are produced by particles (electrons or hadrons) accelerated at sources: indirect access to the parent particle spectra through photon spectra measured at Earth.

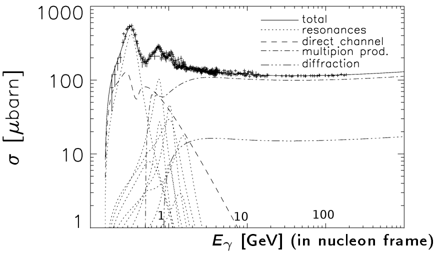
- electrons: via bremsstrahlung or inverse Compton
- hadrons: via inelastic collisions on hadrons or photons

$$pp \to \pi^0, \eta^0 + X \to \gamma\gamma + X$$

$$p\gamma \to \Delta, ... + X \to \gamma\gamma + X$$

- target hadrons (protons, nuclei): in interstellar medium, molecular clouds, etc
- target photons: ambient (cosmic microwave background, accretion disk) or internal (synchrotron radiation, stellar/interstellar/circumstellar emission)





$pp \rightarrow X$ (SIBYLL, QGSJET)

[Phys.Rev.D80,2009], [Phys.Rev.D83,2011]

[par. Phys.Rev.D.74,2006 or J.Phys.31,2005]

$p\gamma \rightarrow X$ (SOPHIA)

[Comp.Phys.Commun.,124, 290]

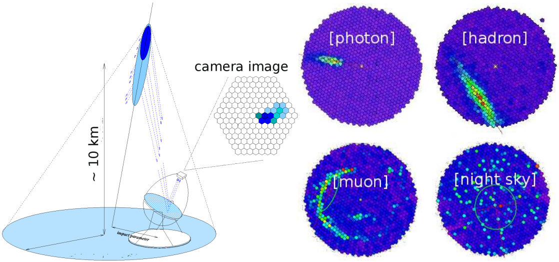
[par. Phys.Rev.D.78, 2008]

Cross sections for $pp, p\gamma$ processes are obtained with Monte Carlo simulations and often used in form of parametrisations.
However: in computation of photon spectra the main unknown is the **spectral parameters set** of accelerated hadrons

$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{1}{4\pi d^2}\left[a_p \frac{dN_p}{dE}(E_p, \textbf{indices}, \textbf{breaks}, \textbf{cutoffs}) * \sigma(E)\right]$$

The detection of γ rays with telescopes

Photon induced showers in the atmosphere emit Cherenkov light.



Light is caught by a photomultiplier camera in imaging atmospheric Cherenkov telescopes (pointed according to scheduled observations)

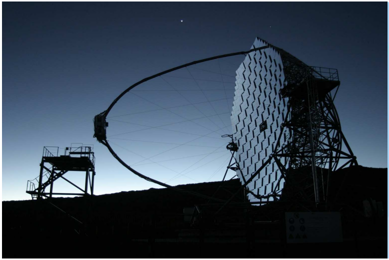
- filter out background made of: atmospheric hadrons, muons, night sky light, electronics.
- reconstruct arrival direction, energy spectrum, and resolve morphology when possible.

The MAGIC telescopes

MAGIC is a stereo system of two dishes (17 m diameter) located at La Palma (Canaries) with energy window: 50 GeV - 30 TeV.

Its performance at energies > 300 GeV:

- sensitivity 0.8% Crab in 50 hours
- angular resolution 0.07°
- energy resolution 17%
- field of view 3.5°



The MAGIC telescopes: status of the art

MAGIC I: commissioned in 2001, MAGIC stereo: since 2009

upgrade of camera and readout is being carried on summer 2012

- system becomes symmetric
- lower readout dead time, improved electronics and computing
- **increase sensitivity to extended sources (larger trigger area of MAGIC I)**
- **lower energy threshold (analogue sum trigger)**

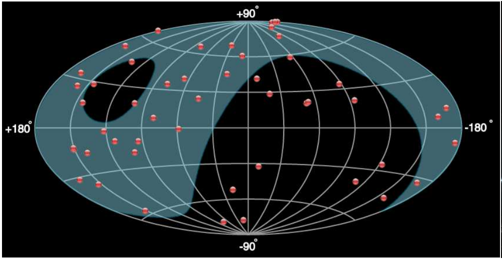
In what follows: selection of sources that could be hadronic accelerators / *that at least have problems with leptonic interpretation*

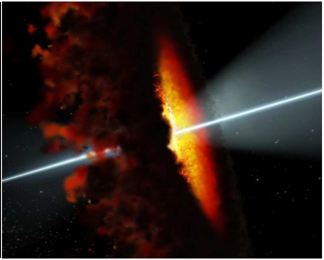
- two 'historical' blazars
- two radio galaxies
- two flat spectrum radio quasars
- two BL Lacs with uncertain models
- one supernova remnant

Extragalactic sources and accelerated hadrons

Candidate accelerators are AGN (engine: presumed super-massive black hole; feature: collimated relativistic jets), further classified as

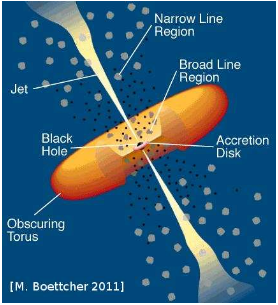
- blazars (BL Lacs and flat spectrum radio quasars)
- others (radio galaxies, clusters of galaxies ....)

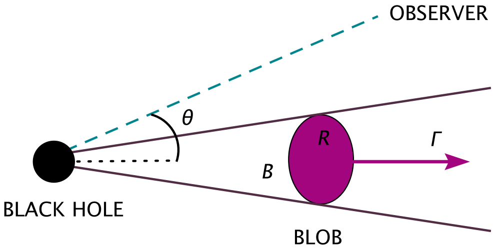




Extragalactic sources and accelerated hadrons

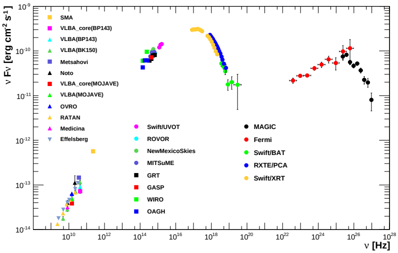
- Hadronic emission happens through $p\ \gamma$ interactions
- Study of interaction models through analysis of spectra (morphology not available: far sources appear point-like)
- Emission properties change with different inclinations of the relativistic jet to the line of sight
- All blazars are variable: models must be time dependent





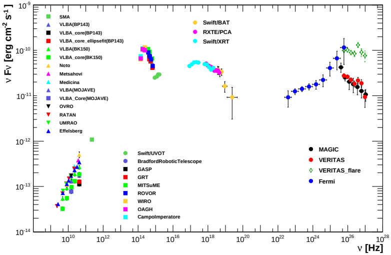
Markarian 421 and Markarian 501

BL Lacs observed with complete campaigns (several instruments and many years of coverage)



Markarian 421

[Fermi-LAT and MAGIC, Aph. J. 736, 2011]



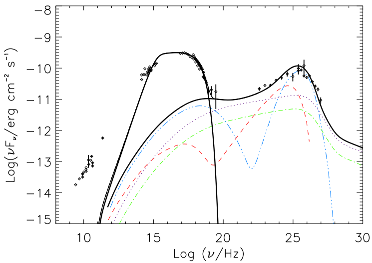
Markarian 501

[Fermi-LAT, MAGIC, VERITAS, Aph. J. 727, 2011]

Models constrain at once: magnetic field, size of emission region, variability time scale, spectral shape of accelerated particles

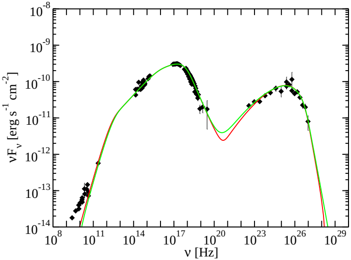
Markarian 421

hadrons accelerated at source
γ from photo-meson and cascades



$B = 50$ G
Blob radius $= 4 \cdot 10^{14}$ cm
Jet Power $4.5 \cdot 10^{44}$ erg s^{-1}

electons accelerated at source
γ from synchrotron self-Compton



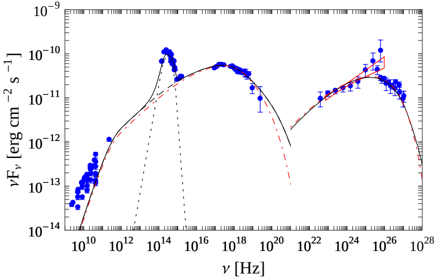
$B = 8.2 \cdot 10^{-2}$ G
Blob radius $= 5.3 \cdot 10^{15}$ cm
Jet Power $1.0 \cdot 10^{44}$ erg s^{-1}

Jet power in agreement with weak accretion disk of BL Lac objects
Broad-band variability: flux variations on timescales of one day [ApJ, 736,131, 2011]

Markarian 501

Hadronic model for flares, seed photons from the synchrotron emission enhanced during the flare [Mücke et al APh 18, 593M, 2003]

- target photons: synchrotron spectrum observed during flaring
- emission region: blob size $\Rightarrow$ variability scale

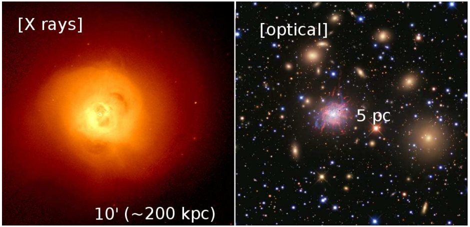


average broad-band emission interpreted with synchrotron self-Compton

are flares caused by a different composition or just a different population?

Radio galaxies: Perseus Cluster

Bright in X rays; contains two radio galaxies visible at very high energies NGC 1275 and IC 310



[Chandra [MNRAS, 418, 2011]] [Blackbird Obs.[MNRAS, 418, 2011]]

γ radiation from cosmic ray interactions with ambient cluster gas (model uncertainties: acceleration efficiency and transport)
Constraints on interactions between cosmic rays and the interstellar medium from no γ ray excess above 630 GeV [MAGIC A&A, 541, 99A, 2012]

- cosmic ray to thermal pressure smaller than a few percent
- central magnetic field larger than 4-9 μG .

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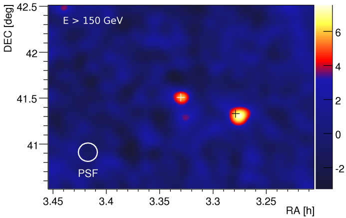
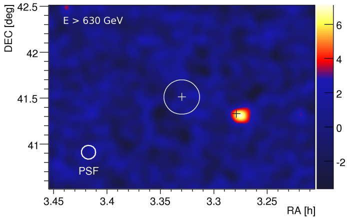


sky map above 150 GeV



sky map above 630 GeV

γ radiation from cosmic ray interactions with ambient cluster gas (model uncertainties: acceleration efficiency and transport)

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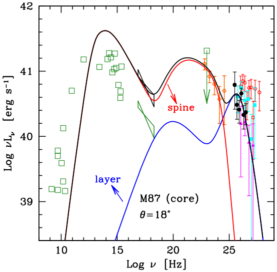
Radio galaxies: M87 (Virgo cluster)

Extended sources, radio lobes and large scale jets have been looked at as interesting accelerators [M. Hillas, APh 32, 160H, 2009]



- Monitoring campaign with MAGIC, leptonic models for the low emission state [MAGIC coll. arXiv:1207.2147]
- Flow increase seen in multi-wavelength campaign [ApJ 746, 2012]. Emission interpreted with accelerated electrons (emitting through synchrotron and inverse Compton processes)

two components of the jet: inner fast core (spine) and slower layer; both interpreted with electron synchrotron and inverse Compton

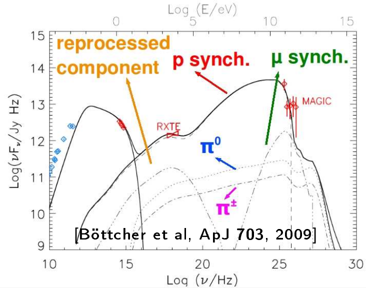
Flat spectrum radio quasars

Class of blazars with emission lines

- strong accretion disk
- additional target photon field from broad line region

3C 279 ($z = 0.536$)

[MAGIC, Science 320, 2008]

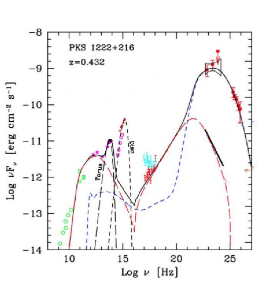


most distant flat spectrum radio quasar

uncertain emission model

PKS 1222+216 ($z = 0.432$)

[MAGIC, Fermi S. 2011]

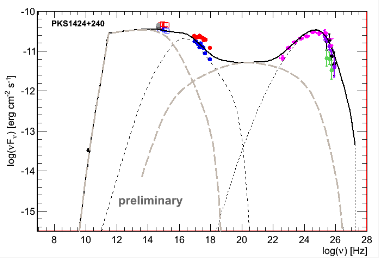


γ ray emission region lies outside the broad line region

Blazars whose emission model is uncertain

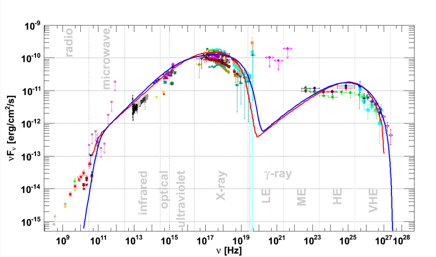
- Jet along the line of sight, no emission lines
- Some new sources, whose spectral energy distribution is not explained with accelerated electrons

PKS 1424+240 [Gamma 2012]



BL Lac with uncertain red shift, estimation z=0.24; two zone model

1ES1959+650 [Gamma 2012]



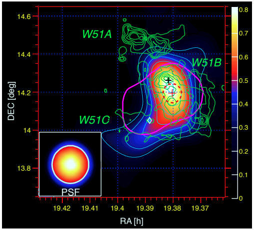
shape and parameters are not explained; origin of emission unclear

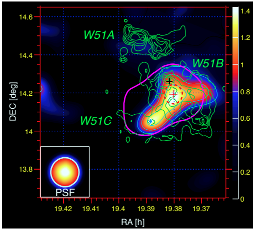
Sources connected with galactic cosmic rays

Supernova remnants are thought to be the sources of galactic cosmic rays with energies up to the knee (10^{15} eV)

- Supernova explosion rate in the Milky Way matches the observed flux of cosmic rays at Earth
- Fermi acceleration of first order (diffusive shock): scattering between upstream turbulence and shock front (charged matter, magnetic fields).
- Hadronic emission occurs through $p\ p$ interactions (presence of molecular material offers nuclear target)
- *nuclear enhancement factor (average)* accounts for nucleus-nucleus collisions

Hints in favour of a hadronic component in W51C



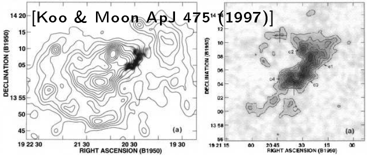


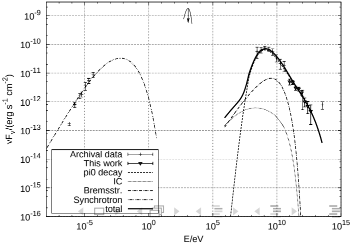
300 GeV $< E <$ 1 TeV $E >$ 1 TeV

Maximum of the emission coincides with interaction between the explosion front and the molecular cloud in nearby star forming region

Spectral energy distribution is best fit with π^0 decay [MAGIC A&A 541, 2012]

[Koo & Moon ApJ 475 (1997)]





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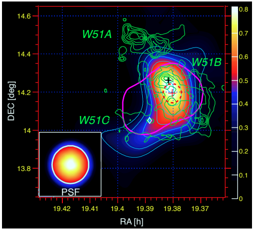
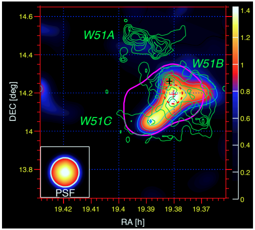


$300\ \mathrm{GeV} < E < 1\ \mathrm{TeV}$



$E > 1\ \mathrm{TeV}$

Interpretation of γ ray emission

- disfavoured: cosmic rays diffusing away from the shell [Gabici et al. 2010], in a sphere with radius 350 pc. It would produce uniform emission, for instance W51A illuminated
- possible: γ are radiated in the shock regions, close to the acceleration site of their parent particles. In agreement with high ionisation [Ceccarelli et al. 2011]
- possible: re-acceleration of cosmic rays in forward shock [Uchiyama et al. 2010]

Electron Spectrum

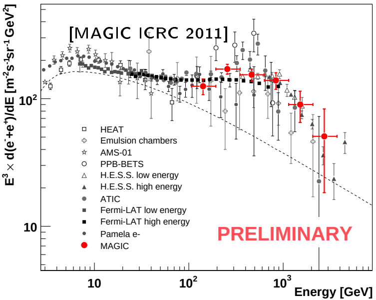
Cosmic ray electrons provide information about nearby sources

- Lifetime 10^5 light years $\Rightarrow$ propagation distance 1 kpc (they radiate photons through synchrotron, ionisation, bremsstrahlung or inverse Compton scattering)
- Spectrum is steeper than hadronic cosmic rays

Electrons initiate electromagnetic showers in the atmosphere; seen with Cherenkov telescopes as 'standard' background

Origin of high energy electrons

- secondary electrons generated in interactions of cosmic rays with interstellar medium
- supernova explosions
- pulsars



Neutrinos

Hadron acceleration in sources would be confirmed with coordinated observation of neutrinos from decay of charged pions (same parametrisation as for π^0 [Kelner et al PhysRevD. 74, 2006])

$$pp, p\gamma \rightarrow \pi^{\pm} + X$$

$$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu} \rightarrow e^{\pm}\nu_e\nu_{\mu}$$

Cooperation of γ ray and neutrino telescopes with multi-messenger observations: neutrino events with coordinates close to preselected candidate sources are used to alert γ ray observations [Ackermann, Bernardini, Galante ICRC 2008].

To date, only upper limits have been produced by the TeV observations

Conclusions

Possibilities of MAGIC in the study of cosmic ray physics:

+/-	cosmic ray **sources**	single source or classes
+/-	cosmic ray **spectra**	from models
-	cosmic ray **composition**	(protons and nuclei are averaged)
+/-	cosmic ray **propagation**	from models and sky maps

Cosmic ray **interactions**: we use existing models for hadronic cross sections (*use*, not *constrain*, as limited by uncertainties)
access to the cross section folded with uncertainties in spectral and ambient parameters

- spectral shape, indices, cutoffs of accelerated particles
- spectral normalisation
- magnetic fields
- target density (of photons in the source vicinity, or hadrons in interstellar medium)

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Chances for MAGIC

- Spectral modelling of active galactic nuclei; hadronic processes via photo-meson production
- Hadronic collisions in galactic sources, in interaction points with interstellar medium
- Hints favouring hadronic scenarios from morphology (high resolution maps of systems supernova remnant-molecular cloud)
- Connection between γ ray and neutrino telescopes