Special photography of the universe: γ ray astrophysics and the MAGIC telescopes

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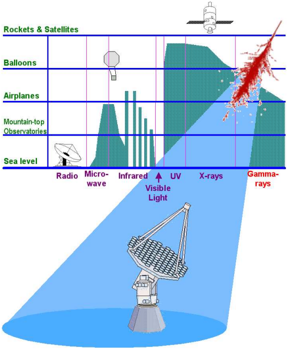
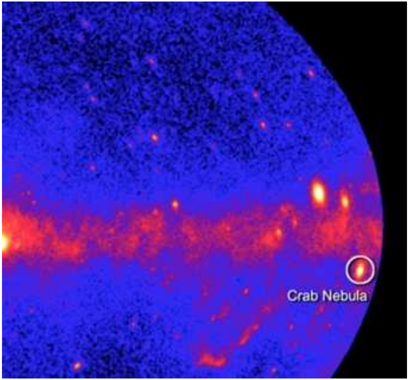
Introduction: physics of γ rays

γ ray astrophysics is astronomy in the GeV - TeV range. Most similar to traditional astronomy, among astroparticle messengers disciplines (cosmic rays, neutrinos).





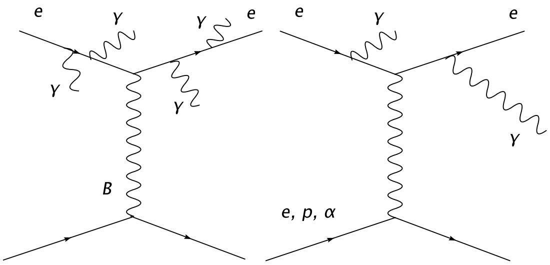
Creation of γ rays

γ ray emission is non thermal: needs particle physics processes to be explained. Channels yielding photons from 'common' particles (e^-, p, nuclei) accelerated at sources:

- **Synchrotron radiation** $e^- B \rightarrow e^- B\gamma$
- **Inverse Compton scattering** $e^-\gamma \rightarrow e^-\gamma$
- **Bremsstrahlung** $e^- N \rightarrow e^- N\gamma$
- **Proton-hadron collisions**
  - meson decays $pN \rightarrow \pi^0, \eta^0 + X \rightarrow \gamma\gamma + X$
  - cascades
- **Proton-photon collisions**
  - meson, baryon decays $p\gamma \rightarrow \Delta, ... + X \rightarrow \gamma\gamma + X$
  - cascades

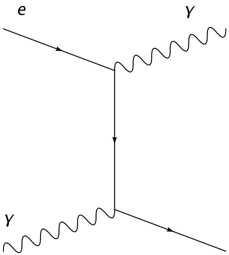
Creation of γ rays (from leptons)

- **Synchrotron radiation** $e^- \to e^- \gamma$
  coherent radiation; happens in presence of magnetic field; negligible for protons. for low magnetic fields, the synchrotron peak is located in the optical-X ray region.
- **Bremsstrahlung** $e^- N \to e^- N\gamma$
  happens on charged target



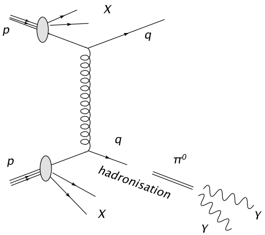
Creation of γ rays (from leptons)

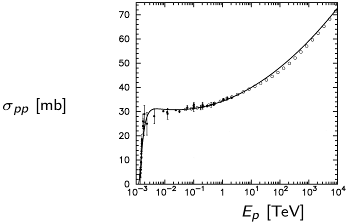
- **Inverse Compton scattering** $e^-\gamma \rightarrow e^-\gamma$
  happens on synchrotron or external seed photons: the cosmic microwave background, infra-red emission (heated dust), interstellar emission.



Creation of γ rays (from neutral meson or baryon decays)

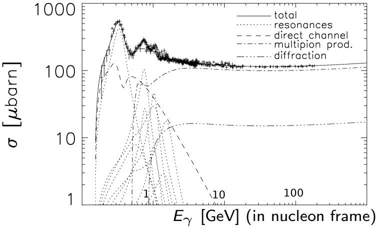
- **Proton-hadron collisions**
  $pN \rightarrow \pi^0, \eta^0 + X \rightarrow \gamma\gamma + X$
  on nuclear target (gas in interstellar medium)
- **Proton-photon collisions**
  $p\gamma \rightarrow \Delta, ... + X \rightarrow \gamma\gamma + X$
  on synchrotron or photons in the source ambient: cosmic microwave background, accretion disk, interstellar emission.





$pp \rightarrow X$ (SIBYLL, QGSJET)

[Phys.Rev.D**80**,2009], [Phys.Rev.D**83**,2011]



$p\gamma \rightarrow X$ (SOPHIA)

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

Creation of γ rays (from neutral meson or baryon decays)

Source environment is dense and contains magnetic field: **transport inside the source** originates synchrotron radiation of secondaries and cascades.

- π-**synchrotron** $p\gamma_{\textbf{soft}}B \to \pi^{\pm}BX \to \pi^{\pm}BX\gamma$
- μ-**synchrotron** $p\gamma_{\textbf{soft}}B \to \pi^{\pm}BX \to \mu^{\pm}BX \to \mu^{\pm}BX\gamma$
- **Bethe-Heitler** $p\gamma_{\textbf{soft}} \to pe^{+}e^{-}$
- **proton synchrotron** $pB \to pB\gamma$
- **pair creation** $\gamma\gamma_{\textbf{soft}} \to e^{+}e^{-}$
- **pair creation** $\gamma N \to e^{+}e^{-}N$
- **bremsstrahlung** $e^{\pm}N \to e^{\pm}\gamma N$

Propagation of γ rays

γ rays are absorbed, depending on their energy, through pair conversion onto the *extragalactic background light*

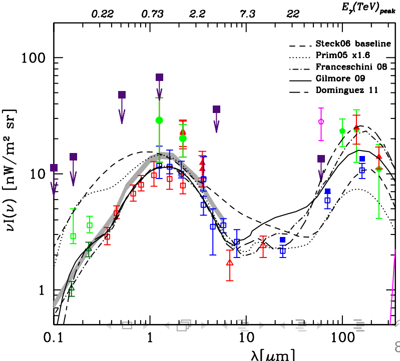
$$\gamma\gamma_{EBL} \rightarrow e^+ e^-$$

the spectrum of γ_{EBL} is modeled to quantify the transparency of the path from the source to the Earth.

Sources contributing to EBL: mostly stars

- direct emission: UV to optical
- absorbed and re-emitted (reprocessed) radiation from dust: IR

small contributions from active galactic nuclei



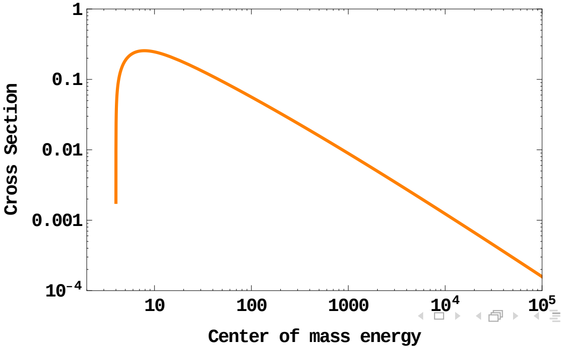
Propagation of γ rays

Cross section for photon-photon scattering has sharp peak

$$\sigma(E_\gamma, \epsilon_{EBL}, \theta) = \frac{3}{16}\left(1-\beta^2\right)\left[\left(3-\beta^4\right)\ln\left(\frac{1+\beta}{1-\beta}\right) + 2\beta\left(2-\beta^2\right)\right]$$

$$\beta = \sqrt{1 - \frac{2}{E_\gamma \epsilon_{EBL}(1-\cos\theta)}}$$

Sharp peak $=$ each γ ray energy has specific preferred absorber

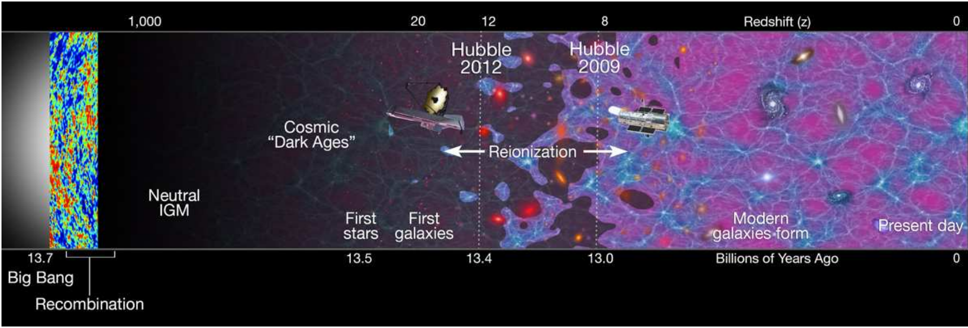


Extinction of γ rays on the EBL field: optical depth, integrated over distance, angle, EBL energy

$$\tau(E_\gamma, z) = \int_0^{z'} dz \, \frac{dl}{dz} \int_{-1}^{1} d\cos\theta \, \frac{1-\cos\theta}{2} \int_{\epsilon'}^{\infty} d\epsilon \, n(\epsilon, z)(1+z)^3 \sigma(E_\gamma, \epsilon, \theta)$$

contains **cosmology** or *metric* of the universe

$$\frac{dl}{dz} = \frac{c}{H_0(1+z)\sqrt{\mathbf{\Omega_m}(1+z)^3 + \mathbf{\Omega}_\lambda}}$$

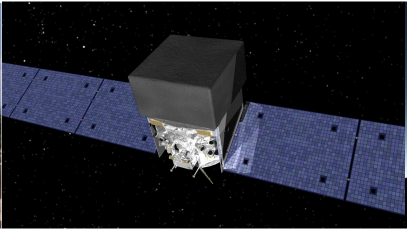
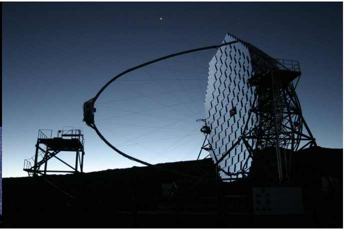


EBL is the integrated star light over the history of the universe

The detection of γ rays

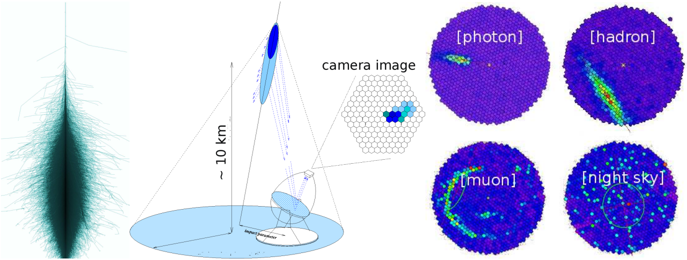
Complementary observations

- satellites (Fermi): **calorimeter** that works on pair conversion 30 MeV - 300 GeV
- ground **Cherenkov Imaging** telescopes (HESS, VERITAS and MAGIC): 50 GeV – 10 TeV

The detection of γ rays with telescopes

Photon-induced showers in the atmosphere emit Cherenkov light which is caught by a photomultiplier camera.



Imaging atmospheric Cherenkov telescopes are 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

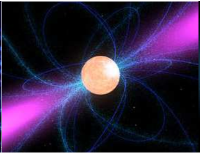
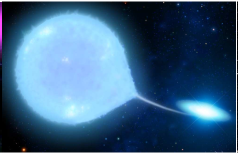
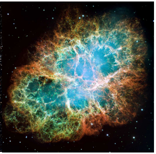
MAGIC is a stereo system of two dishes (17 m diameter) located at La Palma (Canaries) with energy window: 50 GeV - 30 TeV.
Its performance at energies above 300 GeV:

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

γ rays sources

Sources are searched among **high energy accelerators of particles** (electrons, protons, nuclei) that subsequently radiate photons

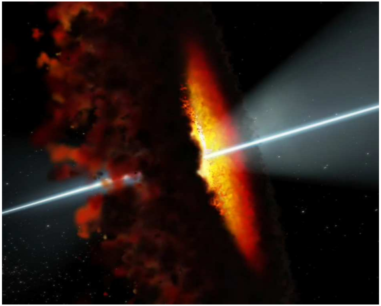
- Active galactic nuclei (here belong: blazars, radio galaxies): accretion power of very massive black hole
- Pulsars: strong rotating magnetic field
- Binary systems: mass accretion from companion star
- Supernova remnants: explosion producing shocked plasma (Fermi acceleration)
- Pulsar wind nebulae: magnetised relativistic wind

Extragalactic sources: AGNs

Super-massive black hole ($10^7 - 10^9 M_\odot$) powers the acceleration

- active accretion disk
- powerful, relativistic highly collimated jets



AGN unified model: emission properties change with different inclinations of the relativistic jet to the line of sight

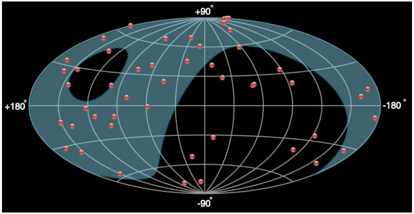
- blazars (BL Lacs and flat spectrum radio quasars)
- others (radio galaxies, clusters of galaxies ....)

AGN emission

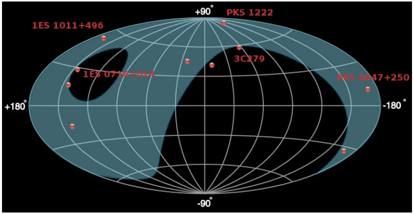
Acceleration and radiation is confined inside a blob along the jet. γ rays originate

- from electrons: via inverse Compton
- from hadrons: via inelastic collisions of hadrons on photons
  $p\gamma \rightarrow \Delta, ... + X \rightarrow \gamma\gamma + X$

About 50 AGNs have been seen at high energy; $\sim$ 20 discovered by MAGIC; special interest on distant ones ($z = 0.2$) for the study of γ propagation



AGNs



AGNs ($z > 0.2$)

Spectral signatures

Study of interaction models through analysis of spectral energy distribution. Theoretical curve is obtained as a folding of initial acceleration spectra with cross sections, transport equation and estimated distance

$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{1}{4\pi d^2}\left[\frac{dN}{dE}(E; \textbf{indices}, \textbf{breaks}, \textbf{cutoffs}, \textbf{normalisation}) * \sigma(E, \mathbf{B})\right]$$

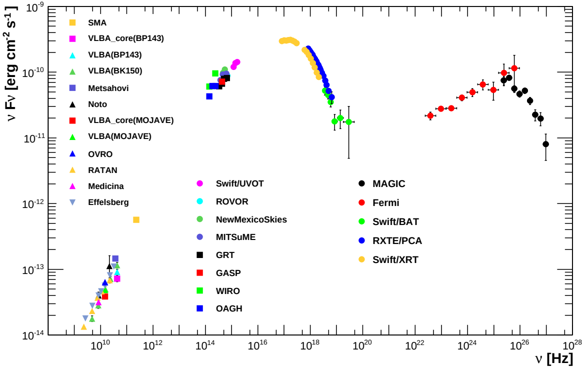
Cross sections for leptonic processes are analytically known; for $pp, p\gamma$ are obtained with Monte Carlo simulations.

Emission feature:

- Size of emission region is related to variability time scale; simultaneaous measurements needed
- magnetic fields $10^{-2} - 10^{2}$ G (fit parameters)

BLLac: Markarian 421

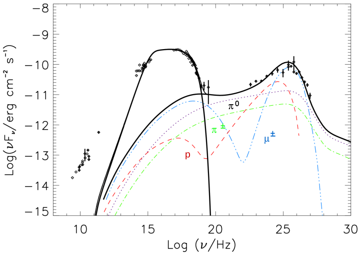
BL Lacs observed with complete campaigns (several instruments and many years of coverage) [Fermi-LAT and MAGIC, Aph. J. **736**, 2011]



Spectral energy distribution shows typical double peak shape

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

hadrons accelerated at source
γ from photo-meson and cascades

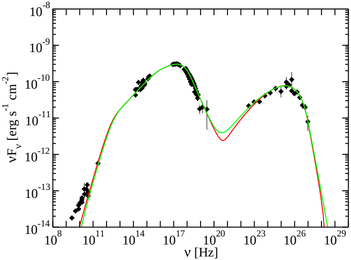


$B = 50$ G

Blob radius $= 4 \cdot 10^{14}$ cm

Jet Power $4.5 \cdot 10^{44}$ erg s^{-1}

electrons accelerated at source
γ from synchrotron self-Compton



$B = 8.2 \cdot 10^{-2}$ G

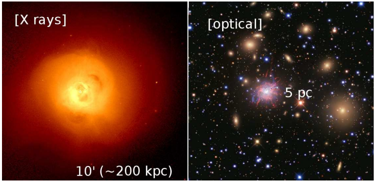
Blob radius $= 5.3 \cdot 10^{15}$ cm

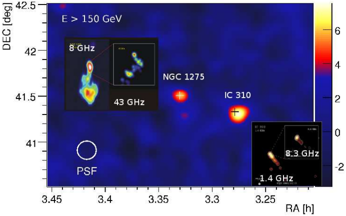
Jet Power $1.0 \cdot 10^{44}$ erg s^{-1}

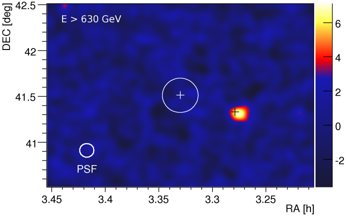
Jet power in agreement with weak accretion disk of BL Lac objects; flux variations on timescale of one day [ApJ, **736**,131, 2011]

Radio galaxies: Perseus Cluster

Brightest cluster in X rays; contains two radio galaxies visible at very high energies NGC 1275 and IC 310 [MAGIC A&A, **541**, 99A, 2012]



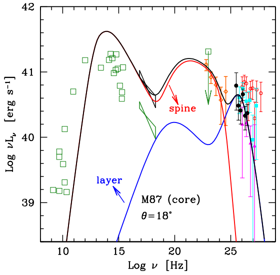




Sets constraints on interactions between cosmic rays and the interstellar medium from no γ ray excess from NGC 1275 above 630 GeV; IC 310: hard spectrum, fast variability

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]



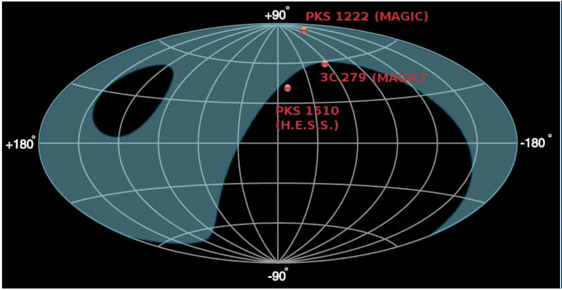
M87 is a giant elliptical galaxy in Virgo cluster

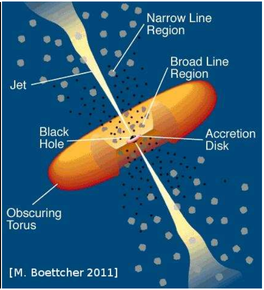
- Monitoring campaign with MAGIC, leptonic models for the low emission state [MAGIC coll. arXiv:1207.2147]
- Flow increase seen in multi-wavelength campaign [ApJ **746**, 2012]. Emission interpreted with accelerated electrons (emitting through synchrotron and inverse Compton processes)

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

Flat spectrum radio quasars

Main difference with respect to BL Lac objects: strong accretion disk, extra photon field from so called *broad line region* (show emission lines)

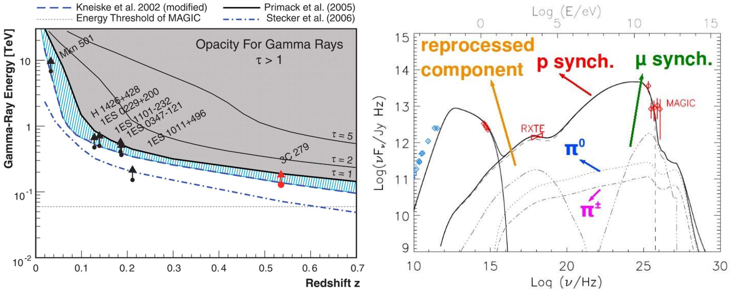




- less populated class of blazars (MAGIC has seen 3)
- emission lines ⇒ precise measurement of red-shift

How transparent is the universe?

MAGIC has seen the flat spectrum radio quasar 3C 279 ($z = 0.536$), most distant very-high energy source [MAGIC, Science **320**, 2008]

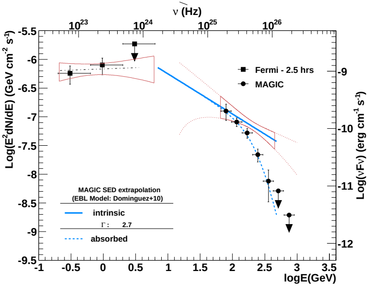


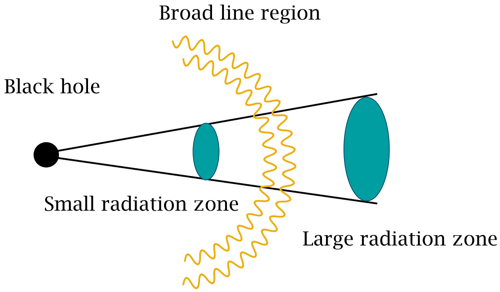
improved existing limits on extragalactic background light; uncertain emission model [Böttcher et al, ApJ **703**, 2009]

Flat spectrum radio quasars

PKS 1222+216 ($z = 0.432$) [MAGIC, ApJ**730**, 2011]; puzzling source

- observed fast variability (10 minutes): small emission region, inside broad line region
- observed no cutoff (no absorption): emission region lies outside the broad line region

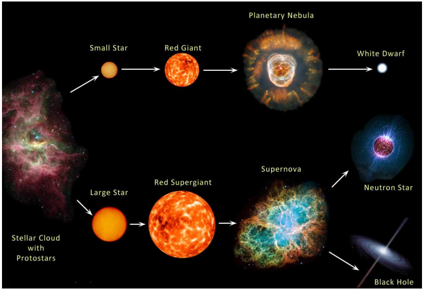




Stellar end products and galactic sources

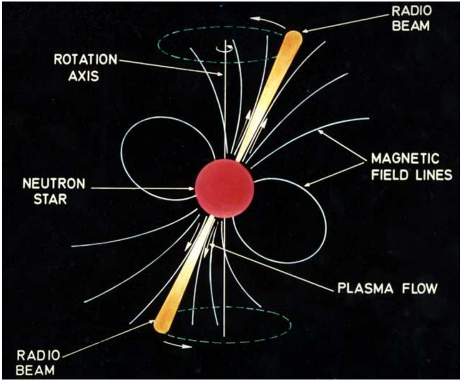
Star runs out of fuel for thermonuclear reactions, infalling material recoils outwards and is ejected with huge velocities producing strong shock wave that interacts with ambient medium (blast wave). This turbulence sweeps and heats circumstellar matter, creates an expanding shell of hot plasma

- accelerates particles up to very high energies **shell supernova remnant**
- with associated **expanding gaseous nebula** that cools in neutron star;
- fast rotation and strong magnetic fields: **pulsar**



Pulsars

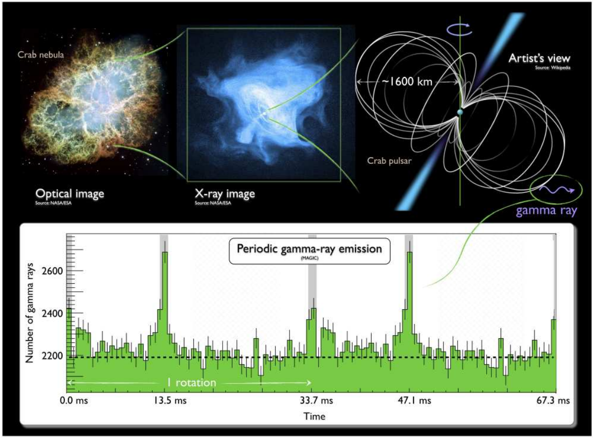
Neutron stars with fast rotation and strong magnetic fields that produce intense electrical potentials (electrons, positrons), beamed along magnetic field lines.



Pulse is caused by beam crossing our line of sight ('lighthouse'-like)

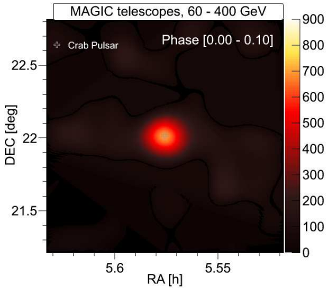
Crab Pulsar

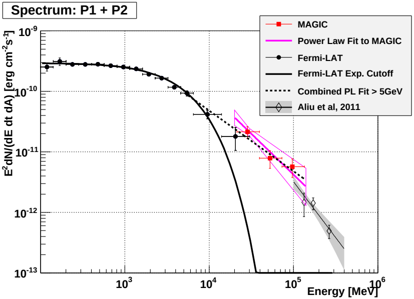
MAGIC discovered gamma rays from the Crab pulsar at energies 25 GeV (special trigger for low energies) – 400 GeV [MAGIC A&A 540, (2012)]



Crab Pulsar

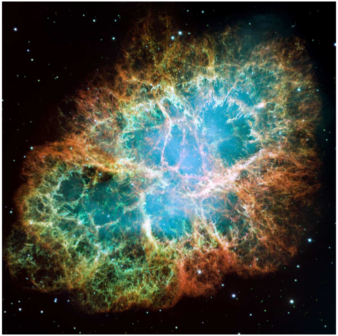
MAGIC discovered gamma rays from the Crab pulsar at energies 25 GeV (special trigger for low energies) – 400 GeV [MAGIC A&A 540, (2012)]
Curvature radiation, period = 33 ms, $B = 10^{12} G$

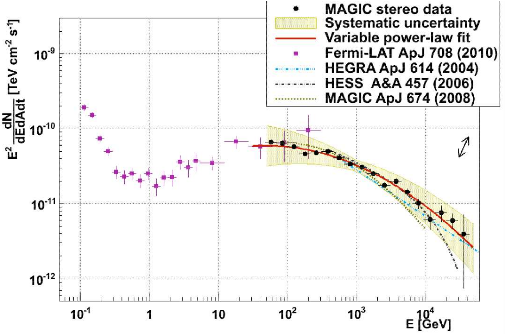




Pulsar wind nebulae

Crab Nebula: the standard candle of γ ray astronomy; particles are accelerated in standing shock powered by pulsar wind. Emission happens through inverse Compton scattering on synchrotron photons. MAGIC spectrum between 50 GeV and 45 TeV





Supernova remnants

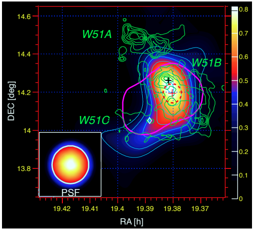
Sources connected with cosmic rays of galactic origin (10^{15} eV)

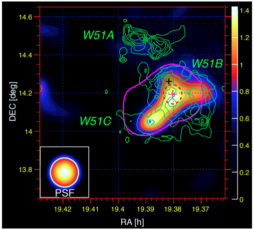
- Supernova explosion rate in the Milky Way matches the observed flux of cosmic rays at Earth [Baade and Zwicky (1934)].
- Fermi acceleration of first order (diffusive shock): scattering between upstream turbulence and shock front (charged matter, magnetic fields).

Often surrounded by molecular clouds in star froming region, which offer nuclear target for hadronic interactions

$$pN \to \pi^0 X \to \gamma\gamma X$$

Hints in favour of a hadronic component in W51C

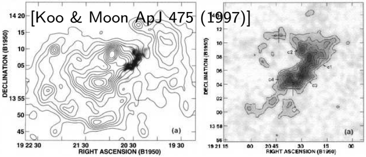




300 GeV $< E <$ 1 TeV

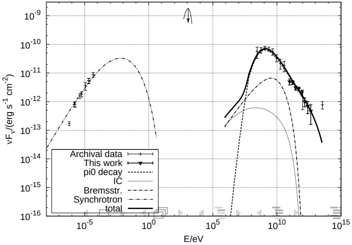
$E >$ 1 TeV

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



[Koo & Moon ApJ 475 (1997)]

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



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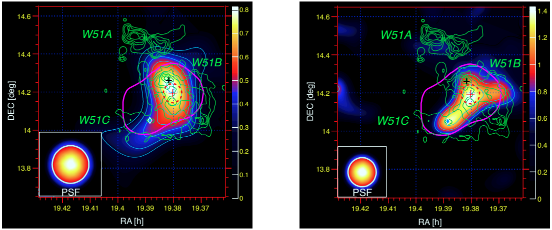


300 GeV $< E <$ 1 TeV $\qquad$ $E >$ 1 TeV

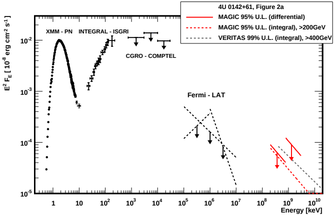
Interpretation of γ ray emission

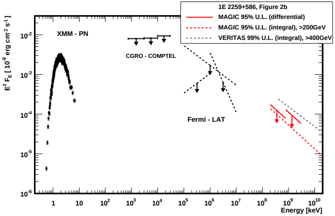
- disfavoured: cosmic rays diffusing away from the shell [Gabici et al. 2010], in a sphere with radius 350 pc. It would produce uniform emission, for instance W51A illuminated
- possible: γ are radiated in the shock regions, close to the acceleration site of their parent particles. In agreement with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

Magnetars

Highly magnetized neutron stars very luminous in X-rays

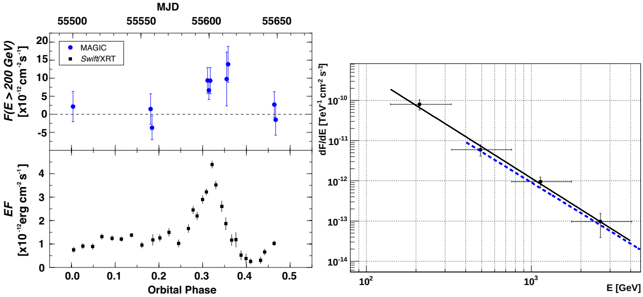
- Just recently identified as a class of sources, magnetic field a thousand trillion times stronger than Earth's.
- Never seen in gamma rays.
- MAGIC observed without signal 4U 0142+61 and 1E 2259+586 above 100 GeV: upper limits





Binary Systems

- HESS J0632+057, γ ray binary composed of Be star MWC 148 (optical) and counterpart of unknown nature with long orbital period (321 days) and high eccentricity.
- MAGIC detected emission from HESS J0632+057 coincident in time with X-ray outburst
- other 3 γ ray binaries: LS 5039, LSI 61-303, PSR B1259-63



Light curve shows γ ray variability of 1-2 months
Spectrum indicates no turnover of the spectrum at low energies.

Multi-messenger astronomy

Hadronic sources wanted!

- acceleration of protons, nuclei means **cosmic rays** (whose sources are still not seen)
- hadron acceleration yields **neutrinos** from decay of charged pions

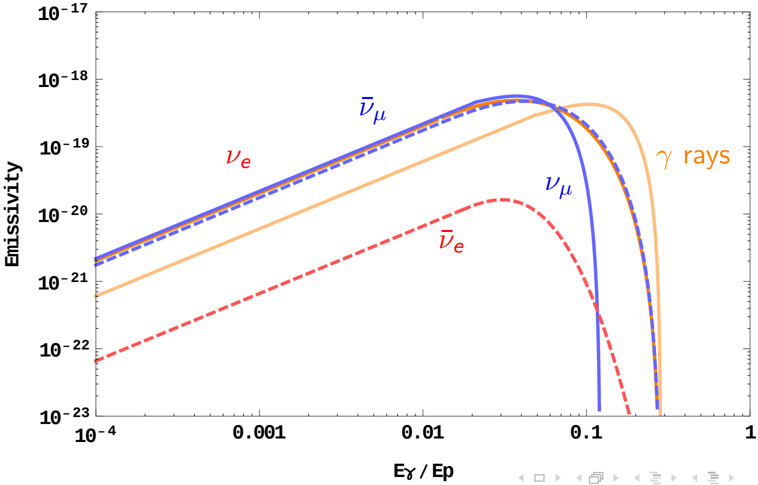
$$pN, p\gamma \to \pi^{\pm} + X$$

$$\pi^{\pm} \to \mu^{\pm}\nu_{\mu} \to e^{\pm}\nu_{e}\nu_{\mu}$$

MAGIC is part of a cooperation between γ ray and neutrino telescopes: 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

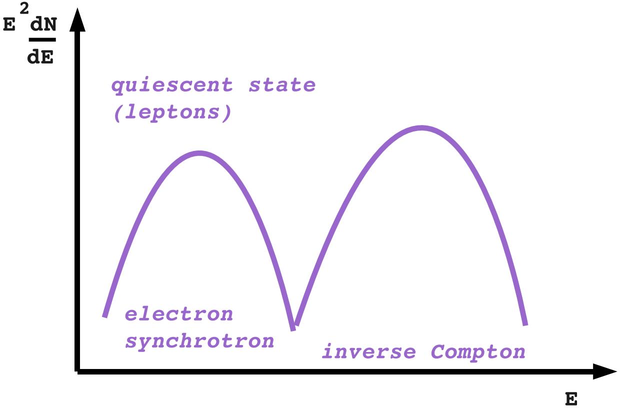
Multi-messenger astronomy

Neutrino spectra are obtained with parametrisations, once absolute normalisation and input spectral parameters are obtained (from spectral energy distributions of sources)



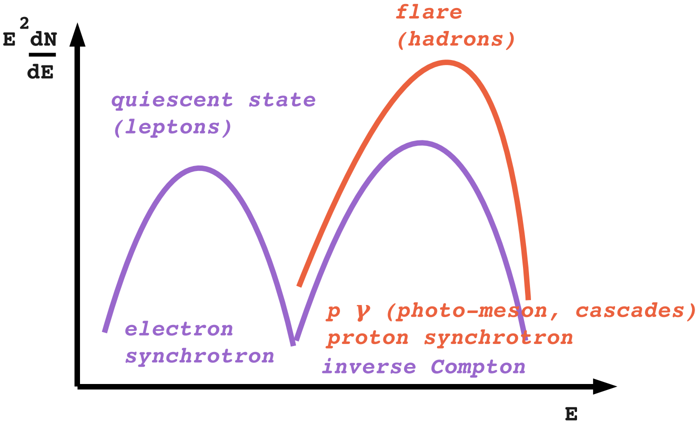
Multi-messenger astronomy

Example: orphan flares (flares in very high energies that have no X-ray or radio counterpart) explained with second population of particles.



Multi-messenger astronomy

Example: orphan flares (flares in very high energies that have no X-ray or radio counterpart) explained with second population of particles.



Conclusions

Latest main results from MAGIC

Active galactic nuclei

- BL Lacs (Mrk 421, leptons or hadrons?)
- Radio galaxies (Perseus cluster, M87)
- Flat spectrum radio quasars (3C 279, PKS 1222)

Galactic sources

- Pulsars (Crab pulsar)
- Pulsar wind nebulae (Crab nebula: best measured source)
- Supernova remnants (W51, galactic cosmic ray accelerator?)
- Binary system (HESS J0632)
- Magnetars (not seen)

Fundamental physics, cosmology, others

- EBL Studies (distant AGNs)
- Dark matter (limits on dark matter particles annihilation - not mentioned here)

Conclusions

MAGIC will keep taking data until 'new generation' takes over.
CTA under construction: array of Cherenkov telescopes of different sizes

- 10 GeV – 100 TeV
- angular resolution $\sim$ arcminutes
- temporal resolution $\sim$ seconds
- usable in 'pointing' or 'survey' mode