Cosmic Ray Studies with MAGIC

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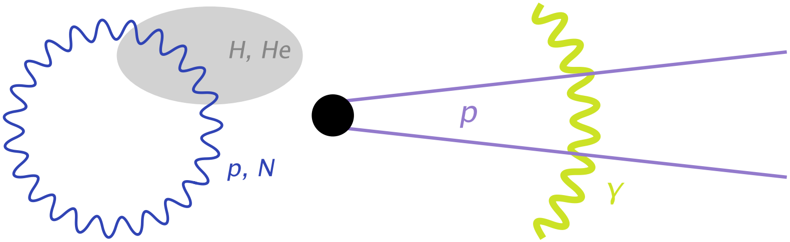
The Connection of γ rays with cosmic rays

All sites where **protons** and **nuclei** are accelerated and then interact radiating photons are candidate sources

1. $pN \rightarrow \pi^0, \eta^0 + X \rightarrow \gamma\gamma + X$ like in supernova remnant with molecular clouds
2. $p\gamma \rightarrow \Delta, ... + X \rightarrow \gamma\gamma + X$ like in jets of active galactic nuclei



The Connection of γ rays with cosmic rays

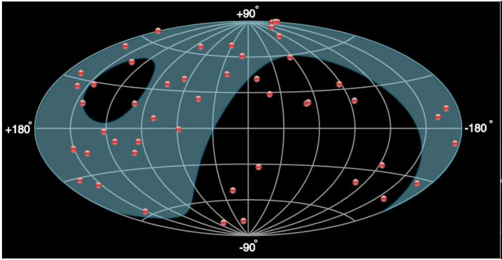
Cosmic ray **electrons** and **positrons** appear as diffuse emission; search cannot use direction information

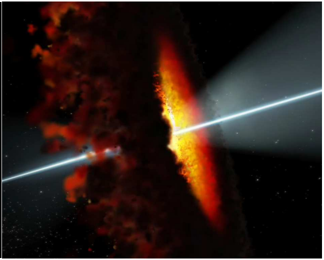
- Lifetime 10^5 ly $\Rightarrow$ propagation distance 1 kpc (they radiate photons through synchrotron, ionisation, bremsstrahlung or IC scattering)
- Spectrum is steeper than hadronic cosmic rays
- $e^{\pm}$, γ generate identical shower. Off-source observations or moon shadowed

Extragalactic cosmic ray sources

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 ....)



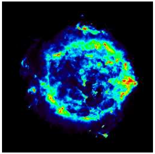


Spectral energy distribution contains information about possible proton component

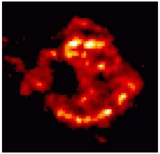
Galactic cosmic ray sources

Supernova remnants are one of the preferred candidates

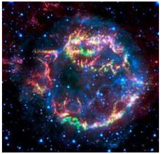
- Magneto-hydrodynamic interactions of the explosion blast wave with interstellar material originate strong shocks
- Some fraction of energy transferred into magnetic field
- Some into accelerated, non-thermal particles (Fermi acceleration)
- Radiation detected from radio to TeV.



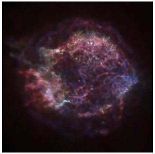
radio



IR



near IR

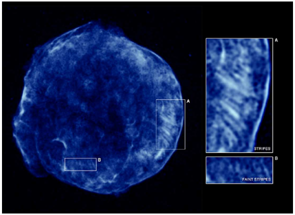


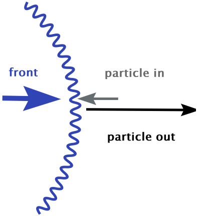
X rays

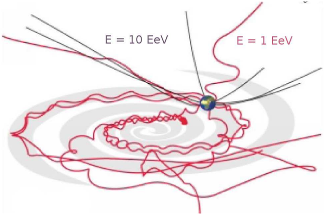
Acceleration of particles in SNRs

- **Free expansion phase (directly after the explosion)**
- **Sedov-Taylor or adiabatic expansion phase**
- Radiative cooling
- Dispersion phase

Fermi acceleration: scattering between particles and a **shock front** (charged matter, magnetic fields). Direct search or cosmic rays astrophysics is not feasible at TeV energies: deflections are large.

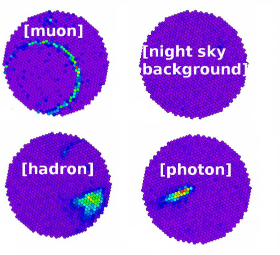






The detection of γ rays with telescopes

Extensive showers induced by photons in the atmosphere emit Cherenkov light.

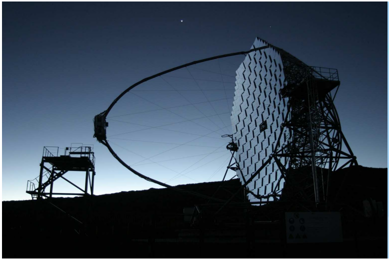
Light is caught by a photomultiplier camera in imaging atmospheric Cherenkov telescopes (pointed according to scheduled observations)

- filter out background made of: atmospheric hadrons, muons, night sky light, electronic noise.
- 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 on 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°



The supernova remnant W51C

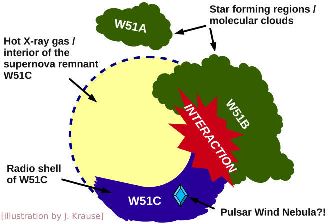
Sited in molecular complex with two nearby star forming regions and candidate pulsar wind nebula CX0J192318.5.

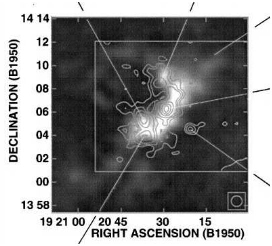
- age: 30000 years (Sedov phase)
- magnetic field of the order of 100 μG
- surrounding photons: cosmic microwave background, heated dust, reprocessed radiation, light of stars
- surrounding molecular material, partly ionised; observed interaction with the shell front of W51C with W51B

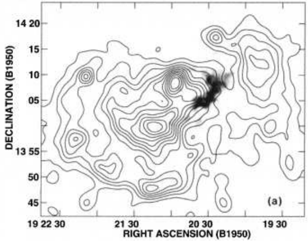
Crucial point is identifying hints of hadronic origin in γ ray emission

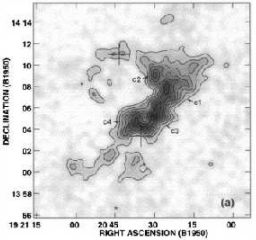
- Cut-off at pion mass
- Morphology of the emission, molecular clouds
- Models of spectral energy distribution, for identifying what species of particels are responsible for the emission.

Maps in HI and CO





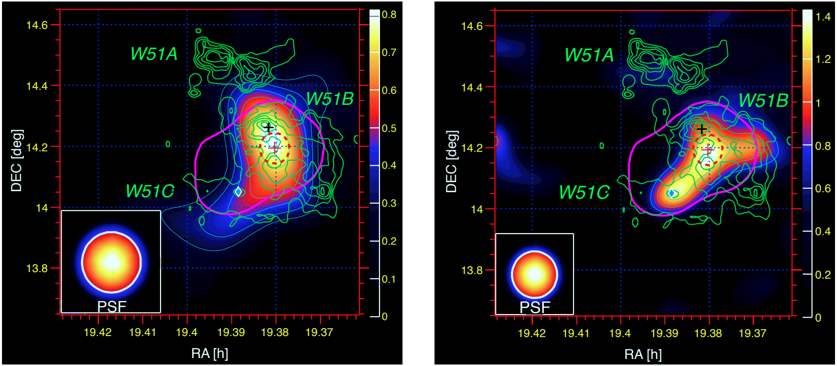




X rays contours with shocked HI (21 cm) and CO and HCO (H_2) from Koo & Moon ApJ475 (1997) Koo & Moon ApJ485 (1997)

Map in γ rays (in two energy ranges)

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



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

Colours: γ ray emission measured with MAGIC [A&A 541 (2012)];
Pink contours: extension of Fermi source [ApJL, 706 (2009)]; green: radio

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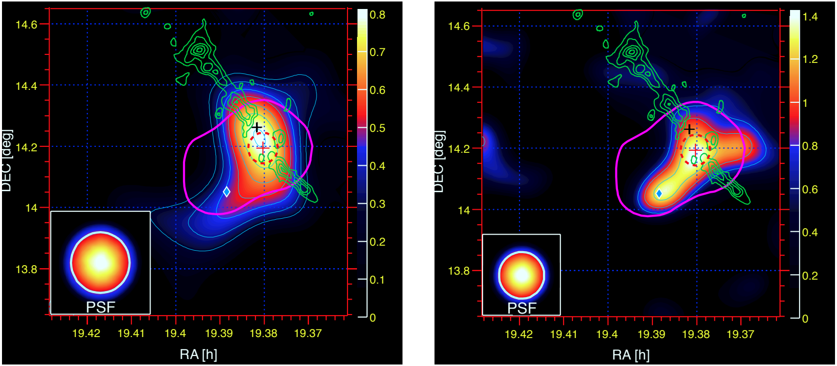

$300\ \text{GeV} < E < 1\ \text{TeV}$ $\qquad$ $E > 1\ \text{TeV}$

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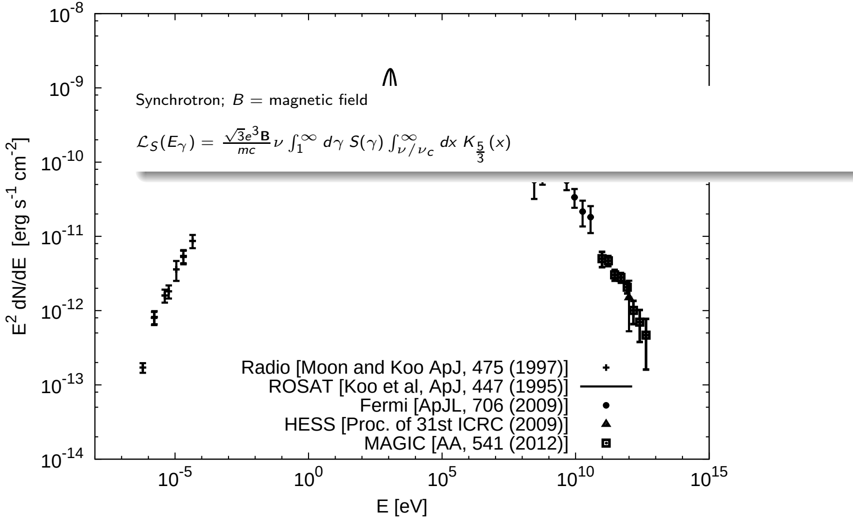
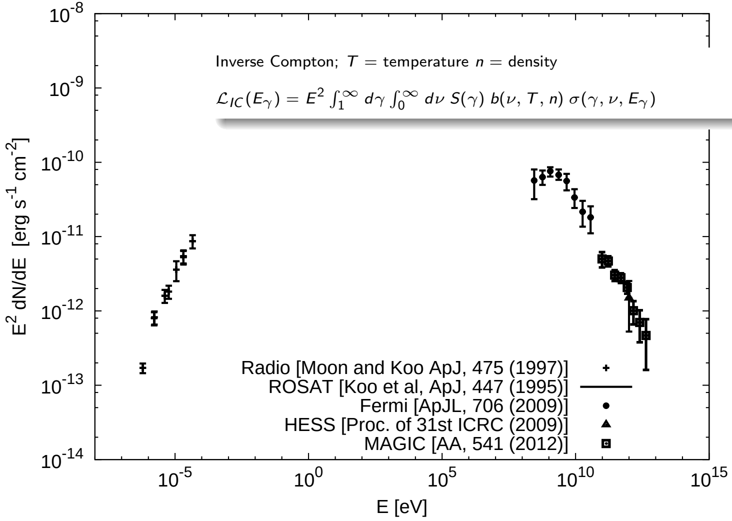
Spectral energy distribution



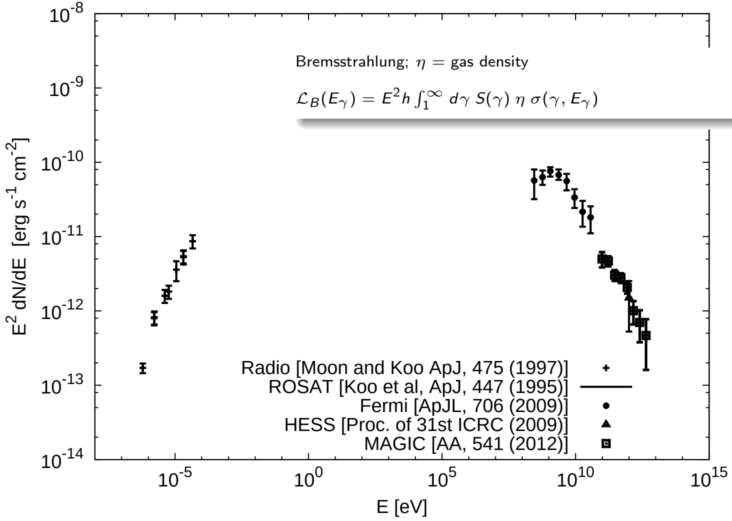
Spectral energy distribution



Inverse Compton; T = temperature n = density

$$\mathcal{L}_{IC}(E_\gamma) = E^2 \int_1^\infty d\gamma \int_0^\infty d\nu \; S(\gamma)\, b(\nu, T, n)\, \sigma(\gamma, \nu, E_\gamma)$$

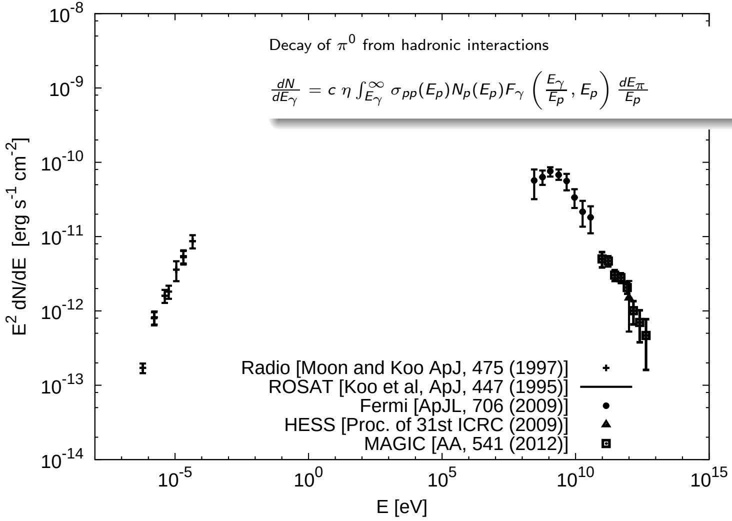
Spectral energy distribution



Bremsstrahlung; η = gas density

$$\mathcal{L}_B(E_\gamma) = E^2 h \int_1^\infty d\gamma\, S(\gamma)\, \eta\, \sigma(\gamma, E_\gamma)$$

Spectral energy distribution



Decay of π^0 from hadronic interactions

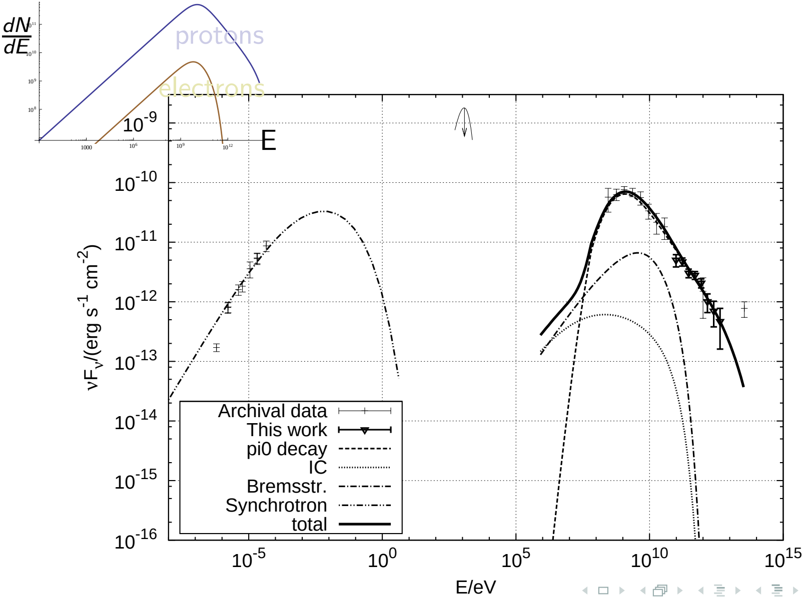
$$\frac{dN}{dE_\gamma} = c\,\eta \int_{E_\gamma}^{\infty} \sigma_{pp}(E_p) N_p(E_p) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right) \frac{dE_\pi}{E_p}$$

Fits of spectral energy distribution

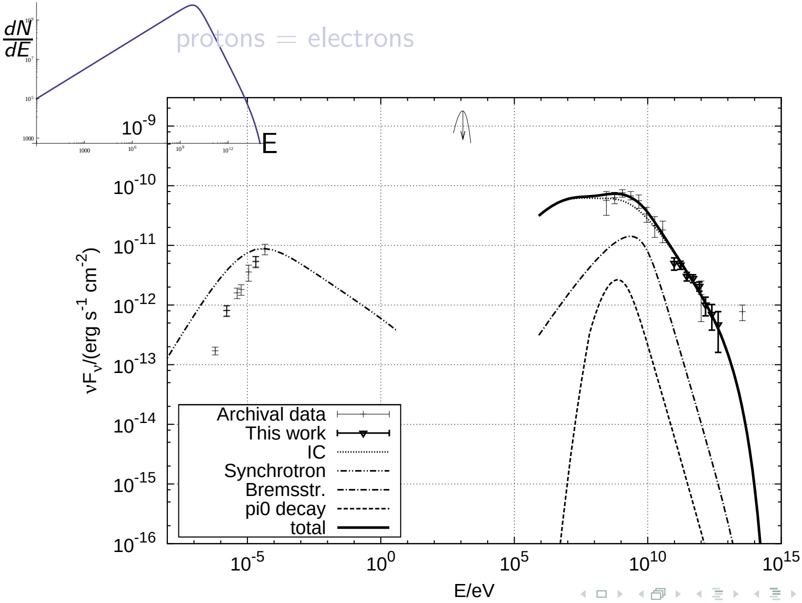
Parameters in fits belong to different classes:

- constrained with measurements:
  - B ambient magnetic field [Koo et al. (2010)]
  - d distance of the source [Sato et al. (2010)]
- input:
  - a_e, a_p electron, proton normalisation
  - η particle density of cloud
  - S_e, S_p spectra (implicitly contain breaks, indices, cutoffs)
- output:
  - amount of energy released in electrons and protons
  - nature of acceleration process

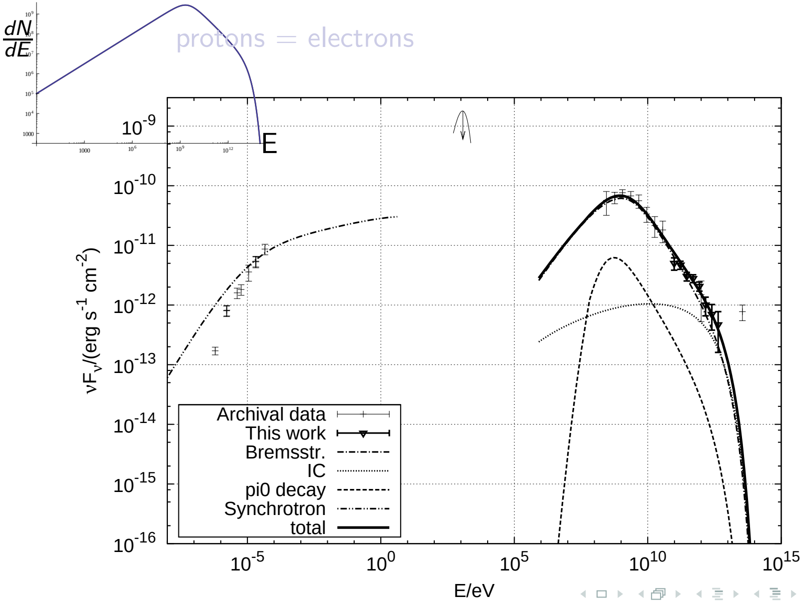
Fit of broad-band data: main contribution from pion decay



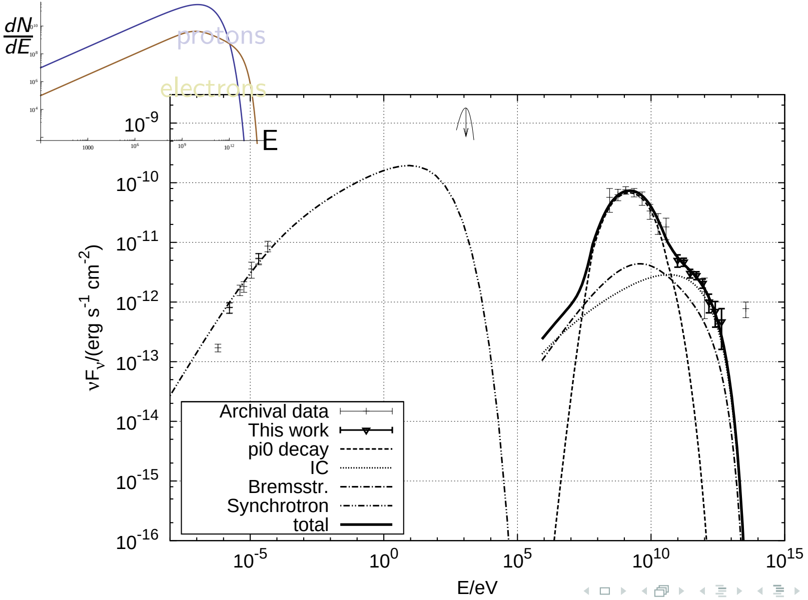
Fit: main contribution from inverse Compton scattering



Fit: main contribution from bremsstrahlung



Fit: mixed contribution



Best fit output

- luminosity, from integral of the emitted photon power

$$\mathcal{L} = \int_{\nu_0}^{\nu_1} d\nu \, \frac{dW(\nu)}{d\nu dt} \approx 10^{36}\text{erg/s (0.25 GeV - 5.0 TeV)}$$

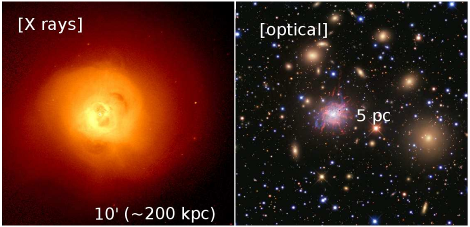
- energy released in particles, from integral of initial spectra

$$W_{e,p} = \int_{mc^2}^{\infty} dE \, S_{e,p}(E) \approx 17\%$$

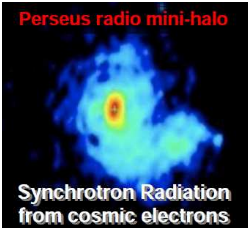
  $\approx 17\%$ of the energy of the supernova explosion converted into kinetic energy of protons and electrons
- density of the molecular cloud (target density) $\eta = 10 \text{ cm}^{-3}$
- proton to electron ratio $a_p/a_e \approx 100$ at 10 GeV.
- diffusion: γ emission has non spherical shape: are radiated in the shocked region, close to the acceleration site of their parent particles (in agreement with high ionisation, Ceccarelli et al. 2011); or re-acceleration of cosmic rays in forward shock (*'crushed cloud'*) (Uchiyama et al. 2010)

Perseus Cluster

Contains two high energy radio galaxies NGC 1275 and IC 310. Theoretical predictions: cosmic ray acceleration in cluster formation shocks; γ ray emission from cosmic ray interactions with the intra-cluster medium?



[Chandra] [Blackbird Obs.]

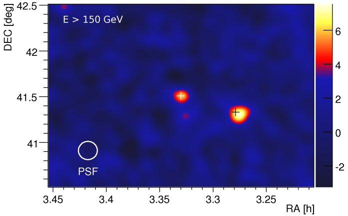


Radio Halo

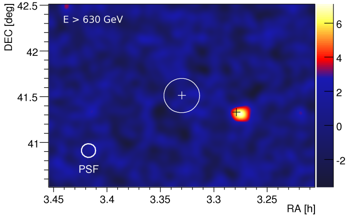
$$p_{CR} N_{ICM} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

$$p_{CR} N_{ICM} \rightarrow \pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow \mathbf{e}^\pm \nu_\mu \nu_e$$

Perseus Cluster; Constraints from γ ray observations



sky map above 150 GeV



sky map above 630 GeV

- average cosmic ray-to-thermal pressure ratio to be 1-2% and the maximum cosmic ray acceleration efficiency at structure formation shocks to be smaller than 50%. or
- non-negligible CR transport processes such as streaming and diffusion into the outer cluster regions
- assuming that the Perseus radio mini-halo is generated by secondaries created in hadronic cosmic ray interactions, the central magnetic field is larger than 4-9 μG.

Electron Spectrum

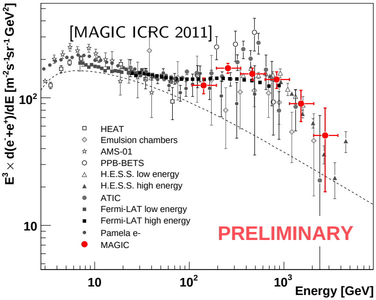
Cosmic ray electrons provide information about nearby sources.
The electron-induced showers survive the regular non-directional γ hadron separation cuts.

- $e^{\pm}$, γ generate identical shower. Separation would be possible only with height of first interaction point
- extragalactic sources (away from galactic halo), with no photon signal
- $e^{\pm}$ hadron separation with boosted decision tree based upon image parameters (number of islands, shpae of ellipse)
- background estimated with Monte Carlo

Electron and Positron Spectrum

Origin of high energy electrons

- **propagation** hypothesis: secondary $e^{\pm}$ generated in interactions of cosmic rays with interstellar medium
- **source** hypothesis: few, nearby pulsars
- **exotic physics** hypothesis: excess of high-energy $e^{\pm}$ measured in the range between 100 GeV and a few TeV not in agreement with ΛCDM model [Fan, Zhang, Chang, 2010]



Current Status: large data set accumulated (about 40 hours). New results soon.

Electron and Positron Ratio

Moon shadow observations: use moon as charge spectrometer

- distance to moon for $e^{\pm}$ shadow at 300-700 GeV: 4°
- sky brightness until 30 times night sky background, 50% moon phase

Strategy: choose source a few degrees off moon position, with special settings for high brightess (analysis is ongoing).

Summary

Cosmic ray accelerators are searched among γ ray sources

- Systems SNRs with molecular clouds: almost for sure acceleration sites of galactic cosmic ray protons and nuclei
- AGNs: promising engines for $p\gamma$ processes, thanks to dense radiation fields
- Electrons, positrons: analysis of diffuse specrum should be released soon