The Secondary Universe

Cosmic Ray Astronomy with Secondary Gamma Rays and Neutrinos

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UCLA
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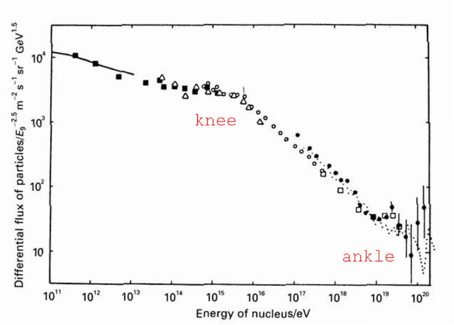
The talk will be based on

- **A new interpretation of the gamma-ray observations of distant active galactic nuclei**
  W. Essey and A. Kusenko - Astroparticle Physics 33, 81 (2010)
- **Secondary photons and neutrinos from cosmic rays produced by distant blazars**
  W. Essey, O.E. Kalashev, A. Kusenko and J.F. Beacom - Phys.Rev.Lett. 104, 141102 (2010)
- **New unpublished results**

Cosmic Rays

- Cosmic rays detected over a very wide energy range up to E$\sim 10^{11}$GeV
- Source of highest energy cosmic rays unknown, but thought to be extragalactic
- Some correlations with AGN have been reported *(Tinyakov and Tkachev, and Pierre Auger Observatory)*



Gamma Ray Astronomy

- Observed at energies up to ~ 10 TeV
- Best described by diffusive shock model *(Malkov & Drury 2001)*
- Can be described by hadronic or leptonic models
- Gamma ray power law spectra $\frac{dN}{dE} \sim E^{-\Gamma}$ with $\mathbf{\Gamma \geq 1.5}$ predicted by most models *(Aharonian et al. 2006; Malkov & OC Drury 2001)*
- Numerical simulations show harder electron spectra for relativistic shocks *(Stecker et al 2007)*, but for Synchrotron-Self-Compton (SSC) scenario the resulting spectra would experience substantial softening from Klein-Nishina effects making $\Gamma \geq 1.5$ *(Böttcher et al 2008)*
- Gamma rays pair produce with Extragalactic Background Light (EBL) to soften observed spectra

The EBL

- Many competing models using many differing philosophies
- Strict lower limit set by galaxy counts
- Gamma ray data could give upper limits due to attenuation from pair production

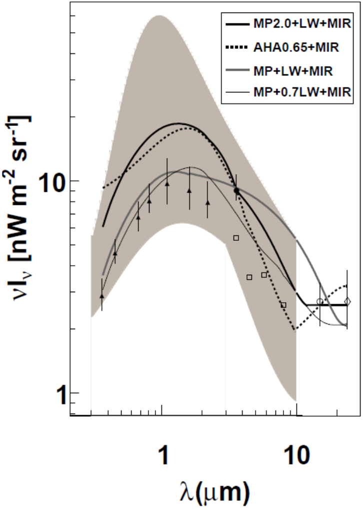
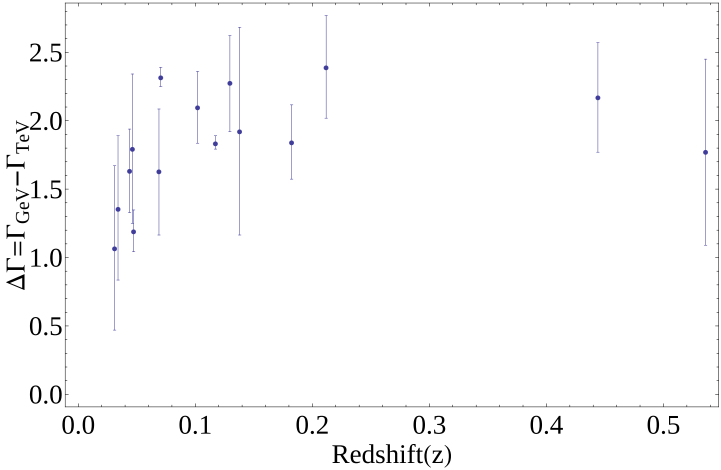


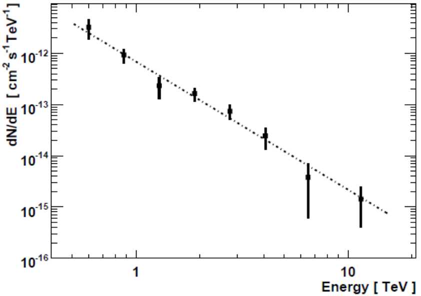
Figure from Krennrich et al 2008

Gamma Ray Spectra

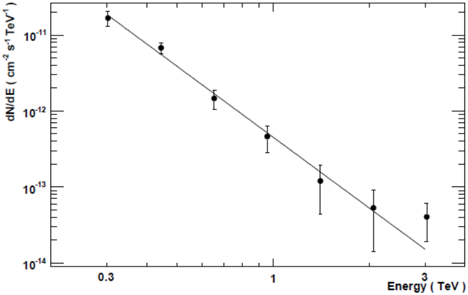


The change in gamma ray spectral slope $\Delta\Gamma$ from the GeV to TeV energy range for BL Lac objects seen by Fermi. Points taken from *(Abdo et al 2009)*

Gamma Ray Spectra



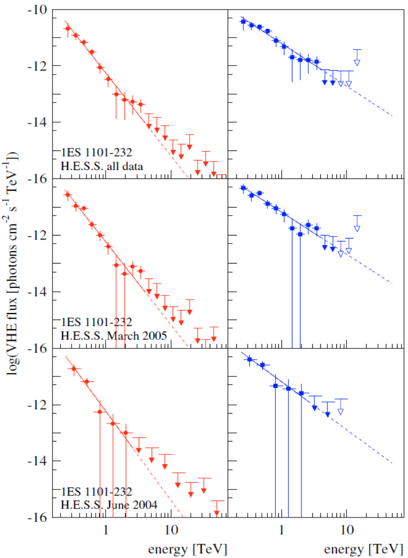
Measured spectrum of blazar 1ES 0229+200 at z=0.140. Fitted power law spectrum of $\Gamma = 2.5 \pm 0.19_{stat} \pm +0.10_{syst}$ which implies intrinsic spectrum $\Gamma_{int} = 0.6 - 1.5$ depending on EBL model. *(Aharonian et al 2007)*



Measured spectrum of blazar 1ES 0347-121 at z=0.188. Fitted power law spectrum of $\Gamma = 3.1 \pm 0.23_{stat} \pm +0.10_{syst}$ which implies intrinsic spectrum $\Gamma_{int} = 1.69$ using EBL model close to lower limits. *(Aharonian et al 2007)*

Gamma Ray Spectra

Measured spectrum of blazar 1ES 1101-232 at z=0.186. Fitted power law spectrum of $\Gamma = 2.94 \pm 0.21$ which implies intrinsic spectrum $\Gamma_{int} = 1.51 \pm 0.19$ depending on EBL model. *(Aharonian et al 2007)*



Gamma Ray Spectra

- Blazars at redshifts $\gtrsim 0.1$ have particularly hard spectra
- Krennrich et al used a set of 3 such blazars to show $\Gamma = 1.28 \pm 0.20$ or harder using lower limits on EBL
- Nearby blazars show softer spectra and Fermi measured a median $\Gamma \sim 1.9$ for blazars in the GeV energy range *(Abdo et al 2009)*

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- **Can this suprising specral behaviour be explained by some new effect?**

Secondaries from Cosmic Rays

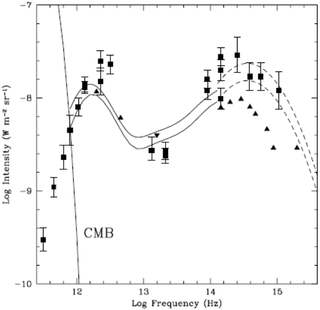
- Cosmic rays comprised of protons will interact with EBL and CMB along the way to Earth
- The dominate reactions will be

$$
\begin{aligned}
p + \gamma_b &\Rightarrow p + e^+ + e^- \\
p + \gamma_b &\Rightarrow N + \pi' s \Rightarrow \gamma' s + \nu' s
\end{aligned}
$$

- Neutrons and pions decay very quickly
- e^+e^- pairs upscatter CMB photons to higher energies
- If intergalactic magnetic fields (IGMF) sufficiently low, then secondaries will point back to source

The Simulation

- Ran a large scale Monte Carlo tracking individual particles
- Outgoing distribution functions for photopion production produced using Sophia package *(Mucke et al 2000)*
- Used protons as primary constituent of cosmic rays with power law spectrum $\frac{dN}{dE} \sim E^{-\Gamma}$ with $\Gamma \sim 2 - 2.5$
- Included gamma rays with power law spectrum $\frac{dN}{dE} \sim E^{-\Gamma}$ with $\Gamma \sim 1.5 - 2$
- Used an EBL model based on observed luminosity functions *(Stecker et al)* rather than lower limits, including evolution with redshift
- Included intergalactic magnetic field (IGMF)



Choice of Sources

Conditions for an ideal source to test model

- Observed at high redshift and high energies to allow attenuation of primary gamma rays
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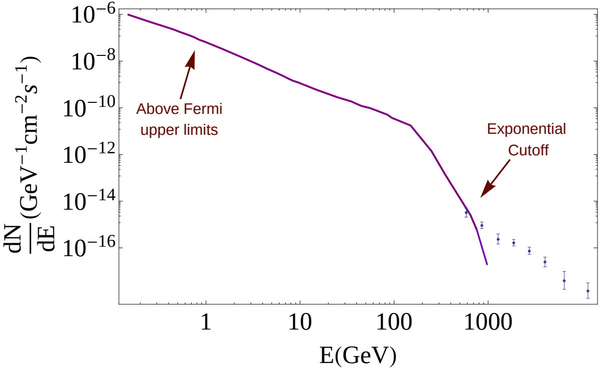
- 6 such sources, we chose 1ES 0229+200 at $z = 0.14$ as it extends all the way to ~ 10 TeV *(Aharonian et al 2007)*

Results



The differential flux of primary gamma rays for a source located at z=0.14 (such as 1ES 0229+200).An instrincic power law spectrum with $\Gamma = 1.5$ and IGMF of 10^{-15} G with a 10 kpc correlation length were used. Points shown were measured by HESS collaboration

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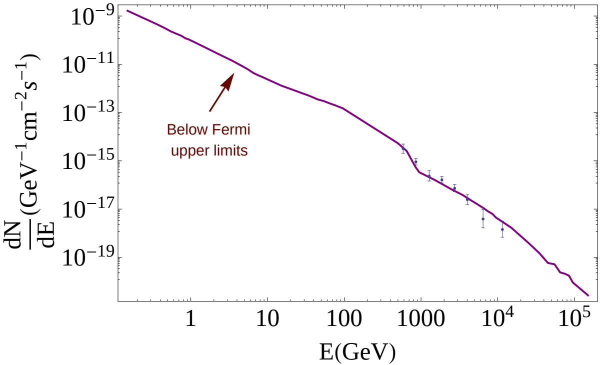
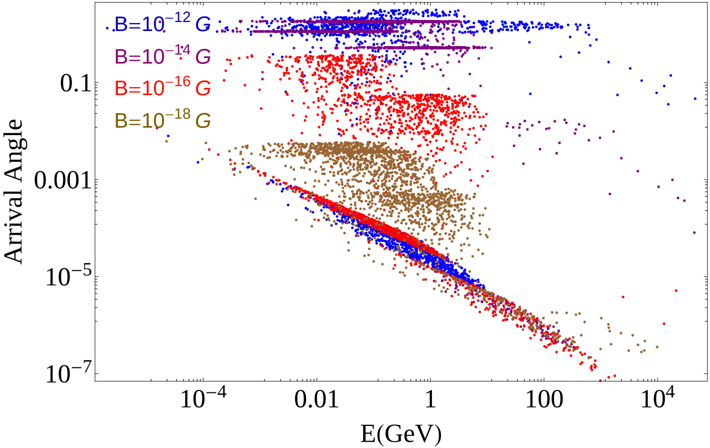


The differential flux of secondary gamma rays for a source located at z=0.14 (such as 1ES 0229+200) with a luminosity $\sim 10^{47}$erg/s. An IGMF of $B_{IGMF} \sim 10^{-15}$ G with a 10 kpc correlation length. Points shown were measured by HESS collaboration. Spectrum hardens at low energies due to IGMF.

Magnetic Fields

- Huge uncertainty in IGMF with current upper limits set to 10^{-6} - 10^{-12} G depending on model (Dolag et al 2004)
- Important to note that only upper limits exist for IGMF and perfectly consistent with current models down to 10^{-18} G
- Cosmic rays may provide a way to test this
- For our set of sources the TeV gamma rays are observed which places an upper limit on IGMF
- Lower energy gamma rays are not seen by Fermi which sets a lower limit on IGMF

Magnetic Fields



Photons arrving at $z = 0$ surface from a 10^6GeV electron starting at $z = 0.01$. The arrival direction is with respect to the electrons initial direction. The different colors correspond to different IGMF strengths ranging from $10^{-12} - 10^{-18}$ G

Magnetic Fields

- Hess detection of 1ES 0229+200 sets $\mathrm{B_{IGMF}} \lesssim 10^{-14}$G
- Fermi upper limits set $\mathrm{B_{IGMF}} \gtrsim 10^{-18}$G
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- Thus $\mathrm{B}_{\mathrm{IGMF}} \sim 10^{-17} - 10^{-15}$G
- **This gives a good estimate of the IGMF based on experimental data that is not just an upper limit.**
- **Consistent with Fermi images of distant AGN (Ando and Kusenko, 2010; Ando's talk)**

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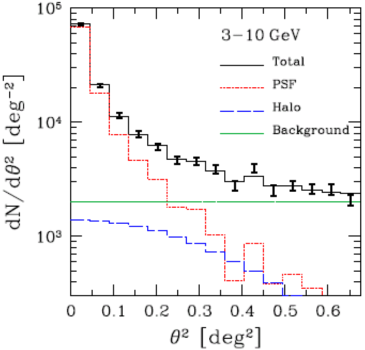
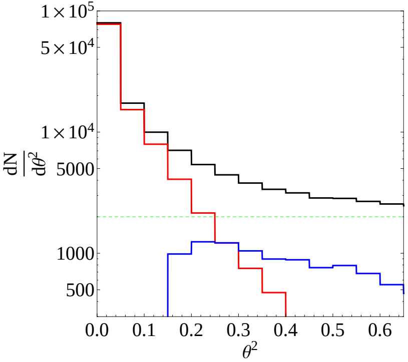
- Halos should be seen around the source at the GeV scale.
- An accompanying high energy neutrino signal should be seen.

Halos

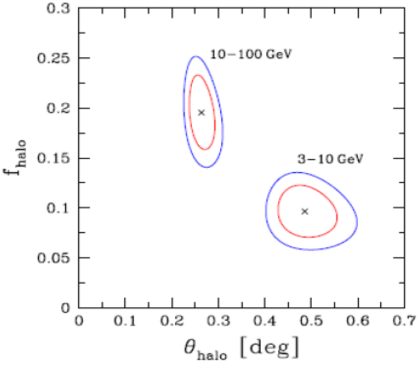


Measured angular distribution of stacked set of Fermi AGN *(Ando, Kusenko 2010)*



Calculated angular distribution for AGN at $z = 0.1$ with an IGMF of 10^{-15} G with a correlation length of 10 kpc normalized to data

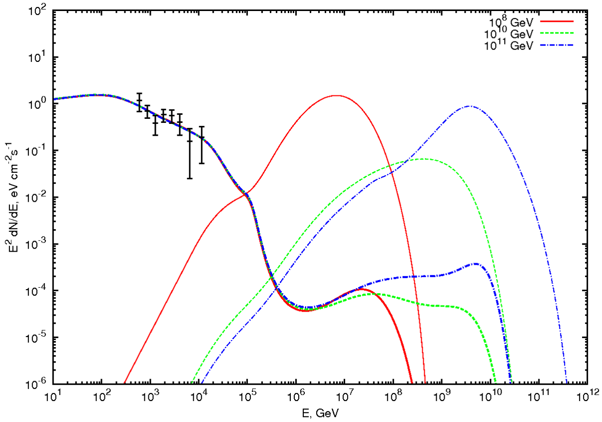
Halos



Measured fraction of photons arriving outside Fermi PSF for stacked set of Fermi AGN *(Ando, Kusenko 2010)*

- Results from simulation match experimental results well
- $f_{halo} \sim 0.10$ for $3 - 10$ GeV bin
- $f_{halo} \sim 0.17$ for $10 - 100$ GeV bin

Neutrinos



Calculated gamma ray and neutrino spectra for 1ES 0229+200 for various high energy cutoffs in the proton spectrum. A proton spectrum with $\Gamma = 2$ was used (arXiv:0912.3976v1)

Future Work

- Fit more sources to improve estimates on IGMF, EBL and AGN properties
- Extend code to include heavy nuclei
  - Different threshold and nuclear photo-disintegration
  - Different neutrino signature
  - Might be able to set limits on composition of cosmic rays from gamma ray and neutrino signals
- Include more realistic magnetic fields
- Extend to GRB cosmic rays

Summary

- Cosmic rays from AGN produce seconday gamma rays and neutrinos on the way to Earth
- The secondary gamma rays give a good fit to TeV sources at high redshift and energy, even for EBL models that were claimed to be excluded
  - Calculated spectra robust for various proton injection models
  - One parameter fit to data
- Secondary neutrinos should be visible with neutrino experiments like IceCube
- Unique scaling allowing possibility of detection of sources at higher redshift
- First ever estimate of intergalactic magnetic field, showing the magnitude is $\sim 10^{-17}$ G - 10^{-15} G
- Halo structure similar to newly detected AGN halos from Fermi data with correlation length ~ 10 kpc
- Future work can provide information on EBL, IGMF, AGN properties and cosmic ray composition