The Secondary Universe

Secondary photons and neutrinos from distant blazars and the intergalactic magnetic fields

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UC Berkeley
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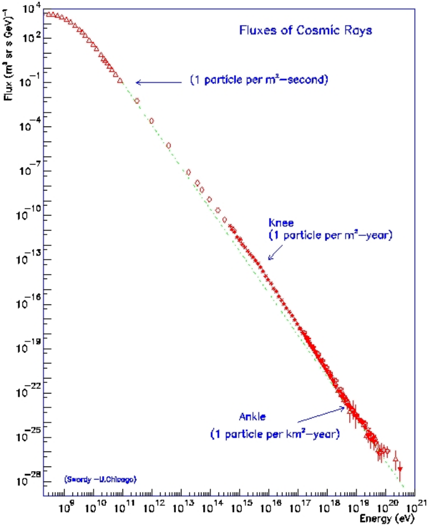
The Secondary Universe

The talk will be based on

- **A new interpretation of the gamma-ray observations of distant active galactic nuclei** - *WE and A. Kusenko - Astroparticle Physics 33, 81 (2010)*
- **Secondary photons and neutrinos from cosmic rays produced by distant blazars** - *WE, O.E. Kalashev, A. Kusenko and J.F. Beacom - Phys.Rev.Lett. 104, 141102 (2010)*
- **Role of line-of-sight cosmic ray interactions in forming the spectra of distant blazars in TeV gamma rays and high-energy neutrinos** - *WE, O.E. Kalashev, A. Kusenko and J.F. Beacom - ApJ, 731, 51 (2011)*
- **Determination of intergalactic magnetic fields from gamma ray data** - *WE, S. Ando and A. Kusenko - Astroparticle Physics 35, 3 (2011)*
- **Newer unpublished results**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 Active Galactic Nuclei (AGN) have been reported *(Tinyakov and Tkachev)*, but current results are inconclusive
- Composition (protons or heavy nuclei) still under debate



Gamma Ray Astronomy

- Extragalactic sources 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

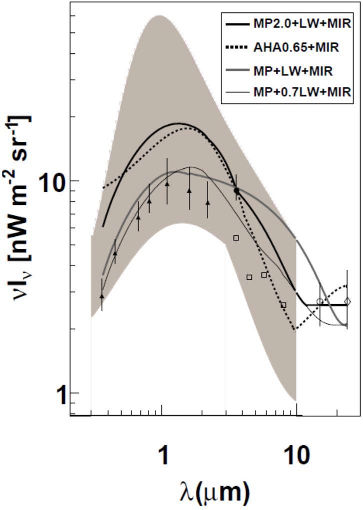
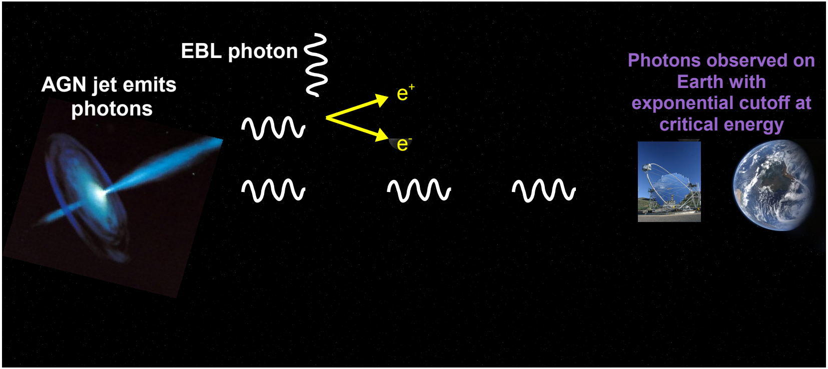


Figure from Krennrich et al 2008

Conventional Approach



Highest energy photons pair produce off extragalactic background light (EBL) and observed signal shows significant softening.

Conventional Approach

- Calculate optical depth $\tau(\mathrm{E})$ for a given EBL model.
- Observed spectrum will be $\frac{dN}{dE} = N_0 E^{-\Gamma_{int}} \times e^{-\tau(E)}$ where $N_0 E^{-\Gamma_{int}}$ is the intrinsic gamma ray spectrum.
- If best fit gives $\Gamma_{int} < 1.5$ then exclude EBL model and set EBL model with $\Gamma_{int} = 1.5$ as upper limit.
- If EBL model already at lower limits set by galaxy counts and $\Gamma_{int} < 1.5$ then conclude AGN has a particularly hard spectrum (this has lead to predicted intrinsic spectra as hard as $\Gamma = 0.5$).

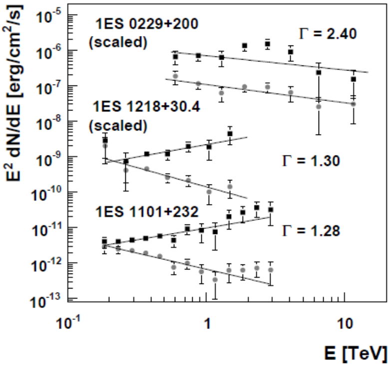


Figure from Krennrich et al 2008

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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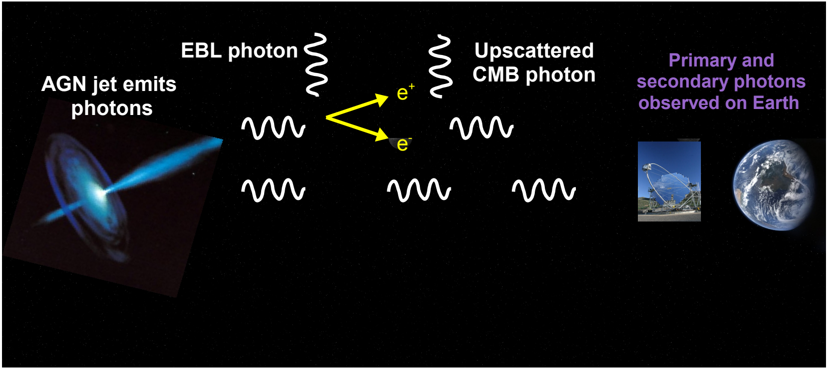
- **Can this suprising spectral behaviour be explained by using a new approach?**

New Approach



Highest energy photons pair produce off extragalactic background light (EBL) forming EM cascades. The secondary photons contribute to observed spectrum.

New Approach

- For distant sources secondary photons will be produced from EM cascades from interations with EBL and CMB photons.
- Start with intrinsic spectrum $\frac{dN}{dE} = N_0 E^{-\Gamma_{int}}$
- Use Monte Carlo to track individual photons and all secondary particles.
- Include effects from intergalactic magnetic fields (IGMF).
- Build observed spectrum on Earth.

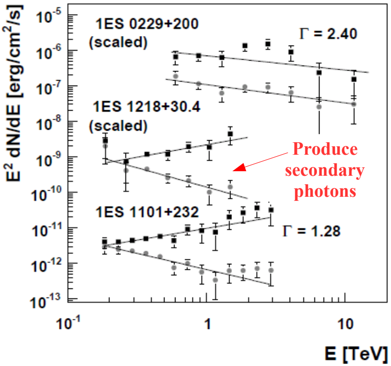
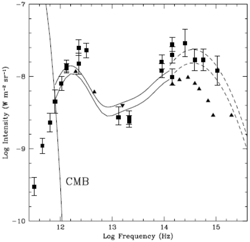


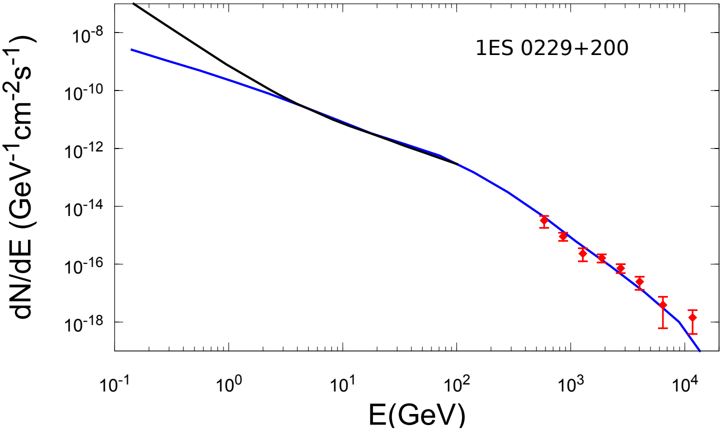
Figure from Krennrich et al 2008

The Simulation

- Ran a large scale Monte Carlo tracking individual particles
- Used intrinsic gamma ray spectra with power law spectrum $\frac{dN}{dE} \sim E^{-\Gamma}$ with $\Gamma \sim 0.5 - 2$
- Used EBL models ranging from a "high" one, based on observed luminosity functions *(Stecker et al)*, down to a "low" one based on lower limits from galaxy counts. EBL models include evolution with redshift
- Included intergalactic magnetic field (IGMF), random field with typical correlation length.

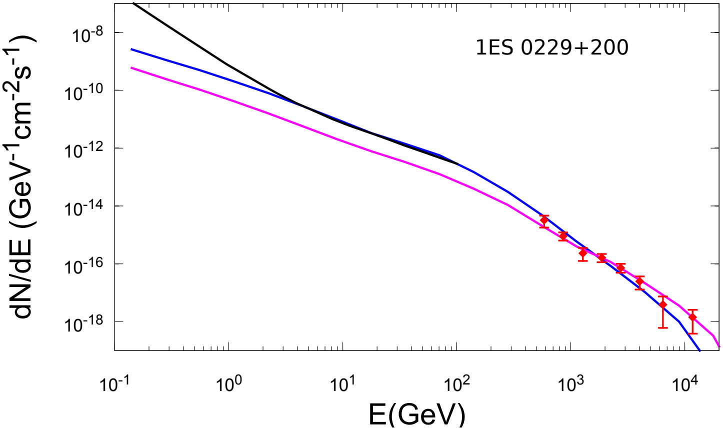


Results



Results fitted to Hess data for 1ES0229+0200 at $z = 0.14$ with intrinsic spectra $\Gamma = 1.5$ and intergalactic magnetic field (IGMF) $= 10^{-15}G$ for "high" EBL model from *Stecker et al*.

Results



Results fitted to Hess data for 1ES0229+0200 with intrinsic spectra $\Gamma = 1.5$ and IGMF $= 10^{-15} G$ for "high" EBL model (blue) from *Stecker et al* and "low" EBL (purple) based on lower limits from galaxy counts.

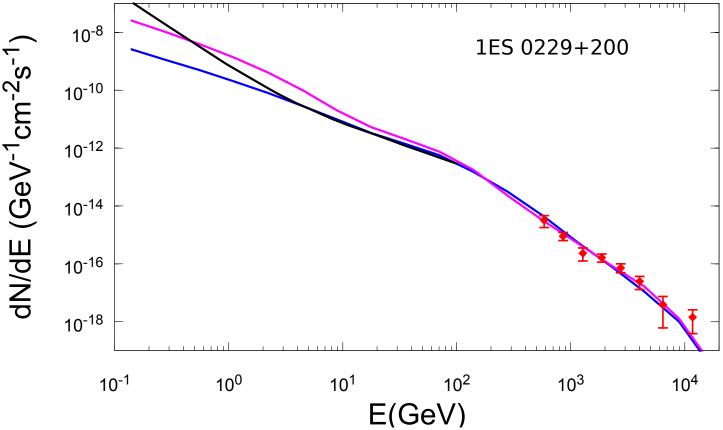
Results

- Results show a good fit to experimental results, reduced $\chi^2 < 1$.
- Intrinsic spectra with $\Gamma > 1.5$ also give good fit to data for a variety of parameters, in agreement with theoretical predictions.
- Good fit for a variety of EBL models, unlike conventional approach that excluded models such as Stecker et al for the case of $\Gamma > 1.5$.

Magnetic Fields

- Huge uncertainty in intergalactic magnetic fields (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
- Secondary gamma rays may provide a way to test this
- Intergalactic magnetic fields deflect electrons and positrons causing some of the secondary gamma rays to arrive outside the angular resolution of the detectors.
- Can use both Hess results and Fermi upper limits to place limits on intergalactic magnetic fields and AGN properties.

Results



Results fitted to Hess data for 1ES0229+0200 with intrinsic spectra $\Gamma = 1.5$ and intergalactic magnetic field (IGMF) $= 10^{-15}G$ (Blue) and $= 10^{-18}G$ (Purple) for "high" EBL model

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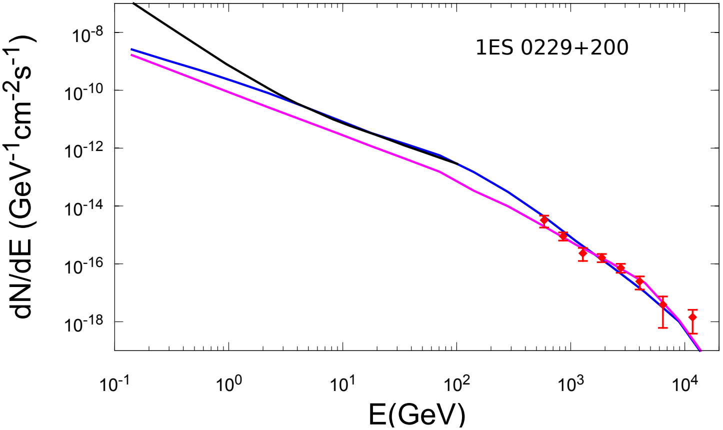

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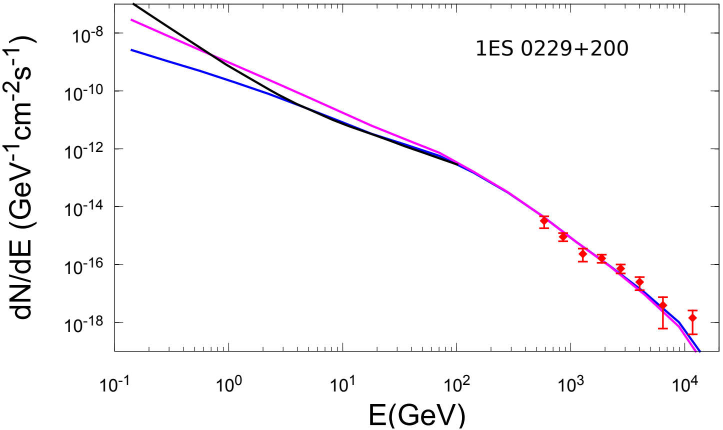


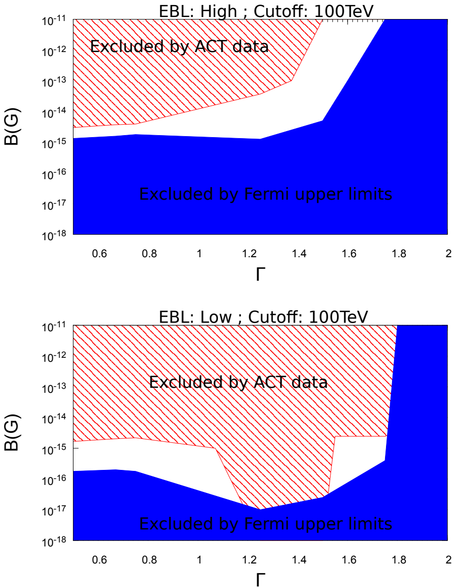
Results fitted to Hess data for 1ES0229+0200 with intergalactic magnetic field (IGMF) $= 10^{-15} G$ for intrinsic spectra Γ =1.5(Blue) and 1.8(Purple) for "high" EBL model.

Results

- Can set lower limit on intergalactic magnetic fields (IGMF) if too many GeV scale secondary photons arrive within Fermi's angular resolution.
- Can set upper limit on IGMF if magnetic field large enough to affect signal in Hess energy range. A χ^2 analysis on multiple sources can be performed to set upper limits.
- Can set limits on intrinsic spectra.

Results

- Intergalactic magnetic fields and intrinsic spectra Γ disallowed by spectral fits to Hess (Red shaded region) and Fermi data (Green shaded region).
- Two EBL models are shown, "high" EBL (top) and "low" EBL (bottom).
- A high energy cutoff of 100 TeV was used for primary photons.



Results

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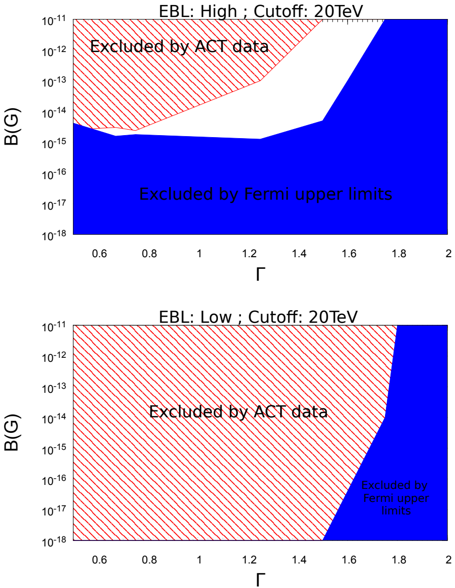
- Two EBL models are shown, "high" EBL (top) and "low" EBL (bottom).
- A high energy cutoff of 20 TeV was used for primary photons which improves limits.



Results

- Limits set on intergalactic magnetic fields (IGMF) and AGN properties for a wide range of models.
- Some model dependent lower limits on IGMF had been set using spectral data by other authors (Nerenov, Tavecchio, Dolag, Dermer), but not as comprehensive as our results
- First upper limits on IGMF using spectral data
- Limit of $\Gamma < 1.8$ for intrinsic spectra, much closer to Fermi's mean value for nearby AGN of 1.9 than previously reported by other authors.

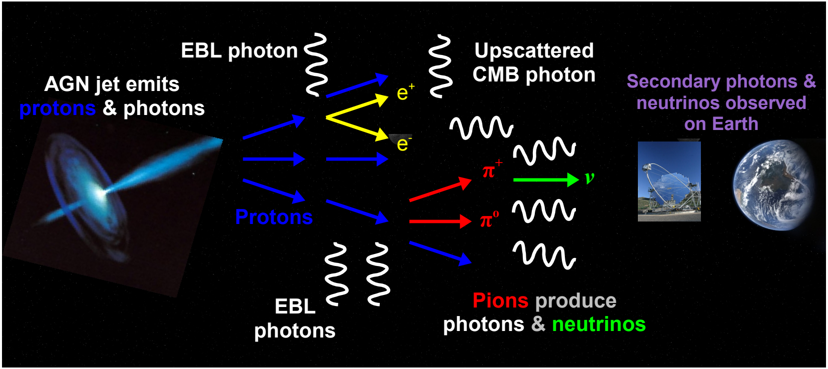
Secondaries from Cosmic Rays

- Limits on IGMF suggest magnetic field could be of the order of $10^{-12} - 10^{-18}$ G for a large section of parameter space.
- Magnetic fields of this order imply that cosmic rays will travel in almost a straight line from the source and it becomes necessary to include them in the analysis.
- Cosmic rays comprised of protons will interact with EBL and CMB along the way to Earth
- The dominate reactions will be

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

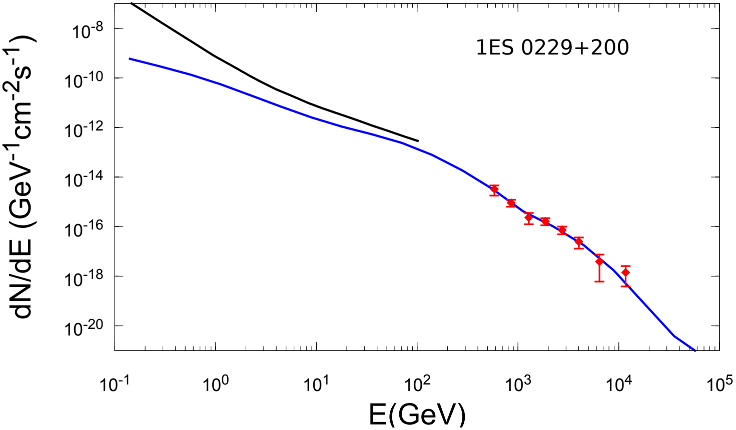
- Neutrons and pions decay very quickly
- e^+e^- pairs upscatter CMB photons to higher energies
- If intergalactic magnetic fields (IGMF) sufficiently low, then secondaries will point back to source

Secondaries from Cosmic Rays



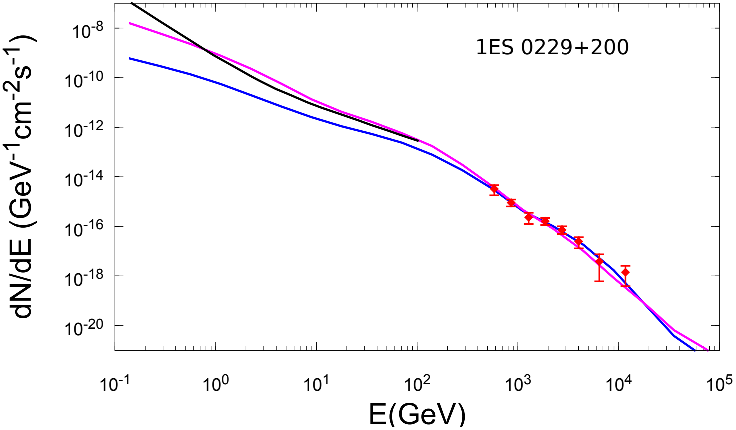
Cosmic ray protons undergo proton pair production off CMB and photopion production off EBL. These secondaries lead to high energy gamma rays and neutrinos.

Cosmic Ray Results



Results fitted to Hess data for 1ES0229+0200 with cosmic ray protons as primary source. An intrinsic spectra of $\Gamma = 2$ and intergalactic magnetic field (IGMF) $= 10^{-15} G$ were used with a "high" EBL model.

Cosmic Ray Results



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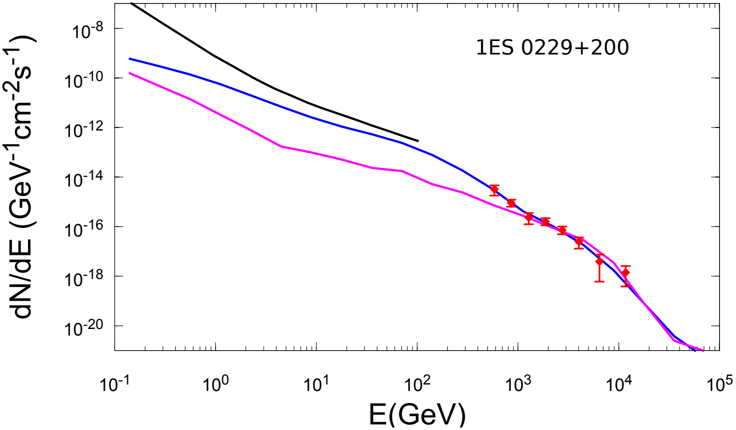

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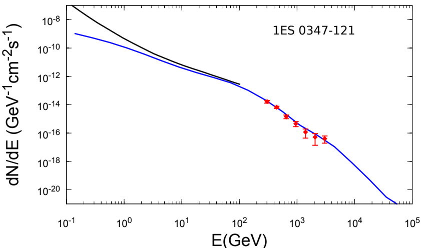
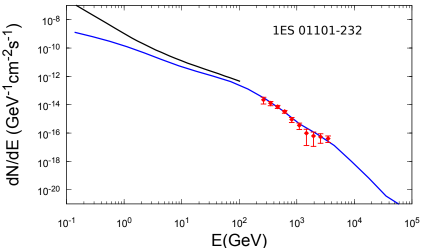


Calculated spectrum of 1ES 0347-121 normalized to Hess data



Calculated spectrum of 1ES 1101-232 normalized to Hess data

Source	Redshift	EBL Model	L_p	$L_{p,\mathrm{iso}}$	χ^2	DOF
1ES0229+200	0.14	High	3.1×10^{43} erg/s	1.1×10^{46} erg/s	1.8	7
1ES0347-121	0.188	High	5.2×10^{43} erg/s	1.9×10^{46} erg/s	3.4	6
1ES1101-232	0.186	High	6.3×10^{43} erg/s	2.3×10^{46} erg/s	4.9	9
1ES0229+200	0.14	Low	1.3×10^{43} erg/s	4.9×10^{45} erg/s	6.4	7
1ES0347-121	0.188	Low	2.7×10^{43} erg/s	1.0×10^{46} erg/s	16.1	6
1ES1101-232	0.186	Low	3.0×10^{43} erg/s	1.1×10^{46} erg/s	16.1	9

Model parameters for the spectra shown above. (Here we assumed $\mathrm{B} = 10^{-15}$ G, $E_{\max} = 10^{11}$ GeV, $\alpha = 2$, and $\theta_{jet} = 6^\circ$.)

Cosmic Ray Results

- Cosmic ray secondaries have slightly harder spectrum as no primary photons are present at lower energies.
- Results robust against changes in intrinsic spectrum and shape is determined by EBL structure. We considered $\Gamma = 1.5 - 3$.
- 95% CL limit on IGMF found to be

$$2 \times 10^{-16}\ \mathrm{G} < \mathrm{B} < 3 \times 10^{-14}\ \mathrm{G}\ (\text{“high”}\ \text{EBL})$$
$$1 \times 10^{-17}\ \mathrm{G} < \mathrm{B} < 8 \times 10^{-16}\ \mathrm{G}\ (\text{“low”}\ \text{EBL})$$

- Signal extends to very high energies with little suppression.
- Galactic magnetic fields make it hard to prove that AGN are source of cosmic rays, but lack of high energy cutoff could prove both this and low IGMF.

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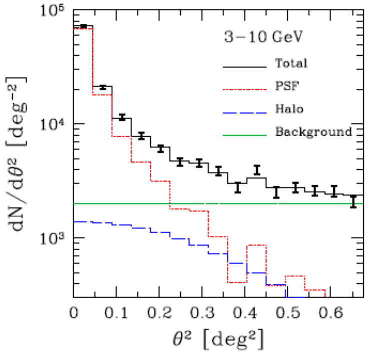
- For cosmic rays an accompanying high energy neutrino signal should be seen.

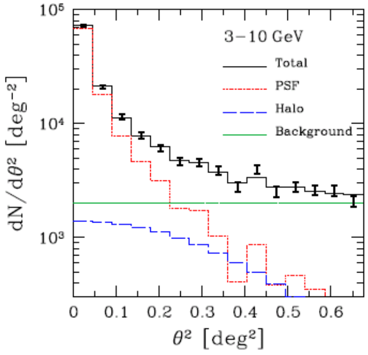
Halos



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

- Recent results hint at a magnetic field of the order of 10^{-15} G
- Calculations done with 2 seperate methods, first with Fermi prelaunch point spread function and second with Crab image. Both methods showed a halo with a 3.5σ significance.

Halos



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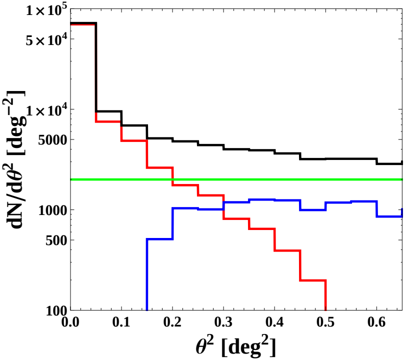
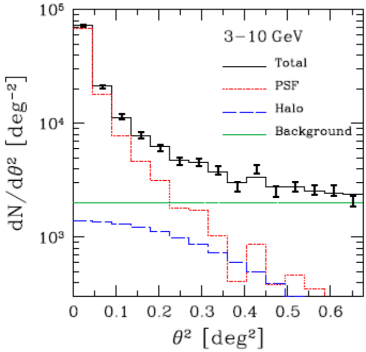
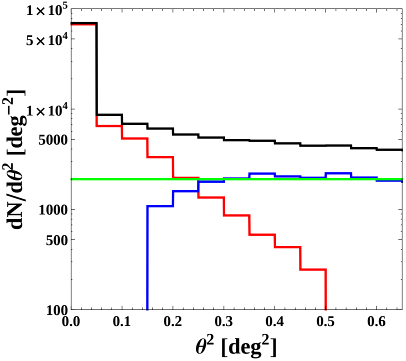


Calculated angular spectrum for secondary photons in the energy range 3 GeV - 10 GeV from high energy gamma rays for an AGN with IGMF $= 10^{-15}$ G. Results are normalized to data from *Ando, Kusenko 2010*

Halos





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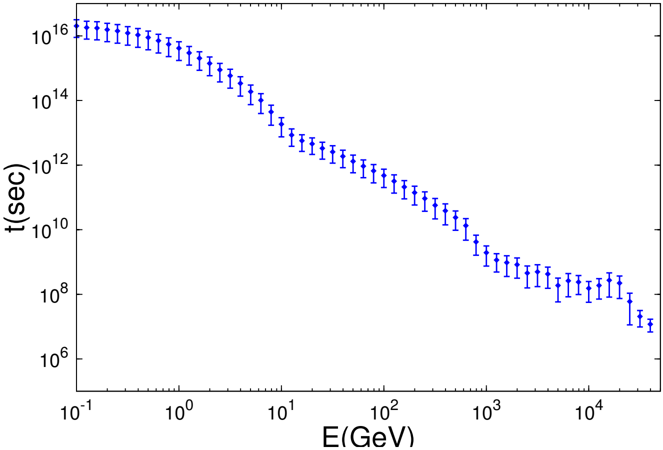
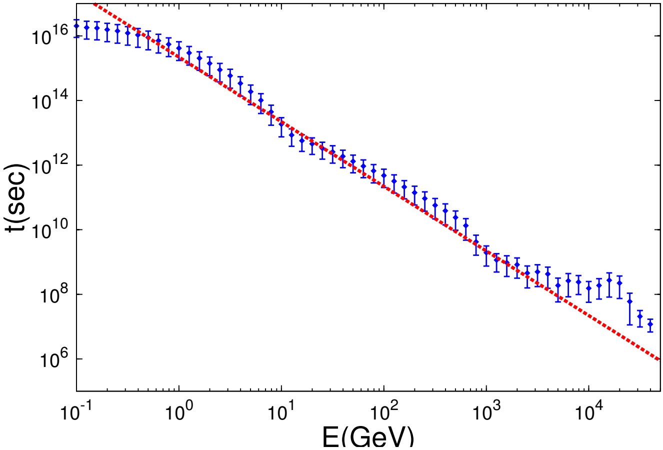
Timing and Variability



Calculated time delay with one sigma error bars of secondary gamma rays for a cosmic ray source at $z \sim 0.2$ and IGMF $= 10^{-15}$ G.

Timing and Variability



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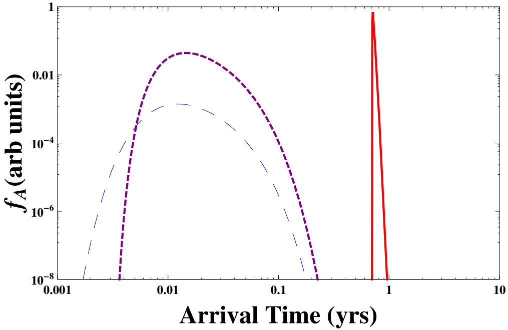
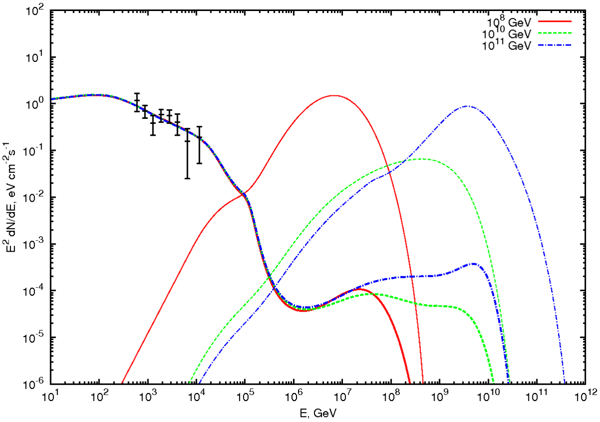
Timing and Variability

- Time delays from protons can dominate at high energies.
- Proton delays dependent on high energy cutoff.
- If sources are active on shorter timescales, signal may be suppressed at lower energies (Dermer et al 2011).
- Additional delays can occur at source for cosmic rays.



Arrival time probability distribution in arbitrary units for secondary gamma rays with energies 1 TeV (red, solid), 10 TeV (purple, short dashed) and 100 TeV (blue, long dashed). Results are shown for a cosmic ray source at $z = 0.2$ with a high energy cutoff of 10^8 GeV and an IGMF of 10^{-16} G..

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)

Neutrinos

- Secondary neutrinos have different scaling due to interactions along the way
  Expect $\frac{1}{D^2} \times$P(Interaction)$\sim \frac{1}{D}$, this allows more distant sources to be detectable

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- All neutrons decay, as opposed to primary neutrinos where neutrons at source can interact with photon field. Implies secondary flavor ratios should differ from 1:1:1.
- Signal close to IceCube's sensitivity.

Future Work

- Fit more sources to improve estimates on IGMF, EBL and AGN properties
- Improve estimates using halo structure.
- 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
- Improve timing estimates
- Improve code with GPU acceleration

Summary

- High energy gamma rays and 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 previously claimed to be excluded
  - Calculated spectra robust for various photon and proton injection models
- Secondary neutrinos should be visible with neutrino experiments like IceCube
- Unique scaling allowing possibility of detection of sources at higher redshift

Summary

- Limits set on IGMF and AGN properties for a wide range of models.
  - AGN spectral index $\Gamma < 1.8$ for this set of sources
  - Assuming cosmic ray component robust limit of

$$1 \times 10^{-17}\ \mathrm{G} < \mathrm{B}_{\mathrm{IGMF}} < 3 \times 10^{-14}\ \mathrm{G}$$

  - Assuming intrinsic gamma component dominates secondaries then a robust lower limit of $\mathrm{B}_{\mathrm{IGMF}} > 10^{-17}$ G is found and model dependent upper limits found using ACT spectral data
- Halo structure predicted and possibly observed.
- Lack of variability predicted and so far observed.
- Future work can provide information on EBL, IGMF, AGN properties and cosmic ray composition

THANK YOU!