The Secondary Universe

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

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(And Google, but not for this talk)
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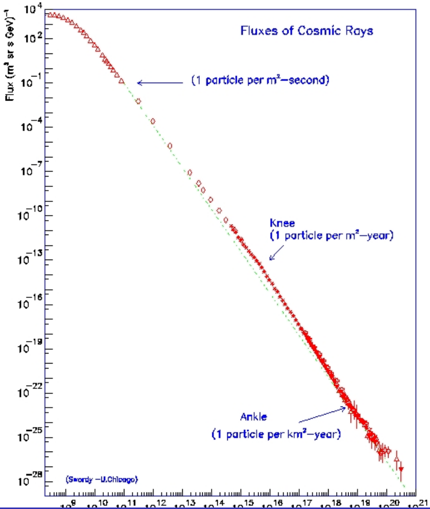
The Secondary Universe

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- **Newer unpublished results**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

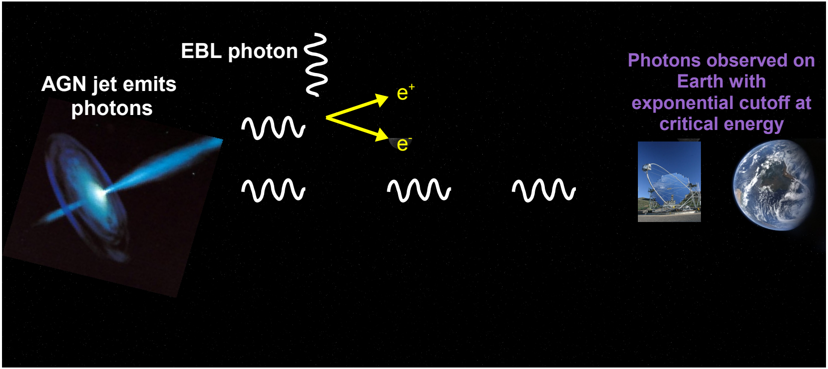
- Cosmic rays detected over a very wide energy range up to E$\sim 10^{11}$GeV
- Source of highest energy cosmic rays unknown, but thought to be extragalactic
- No significant attenuation below GZK cutoff
- Composition (protons or heavy nuclei) still under debate



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

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 $\Gamma = 0.5$).

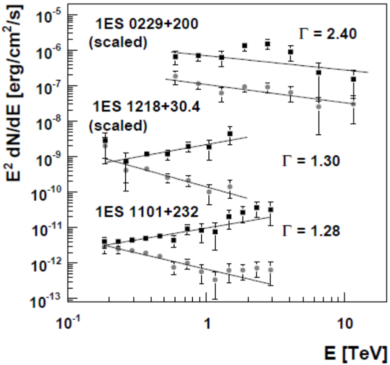


Figure from Krennrich et al 2008

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?**

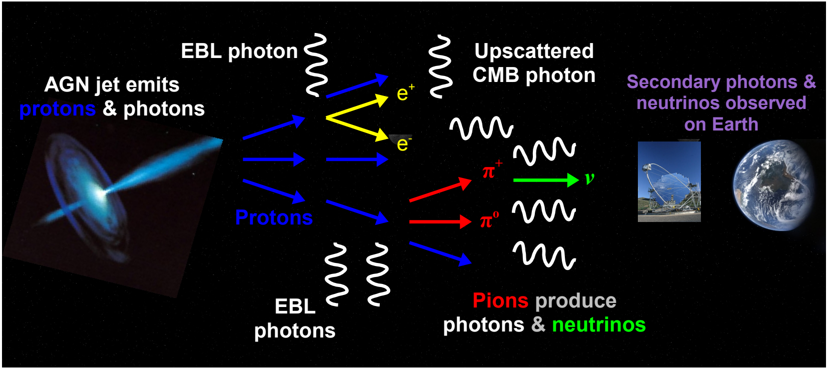
Secondaries from Cosmic Rays

- 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

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

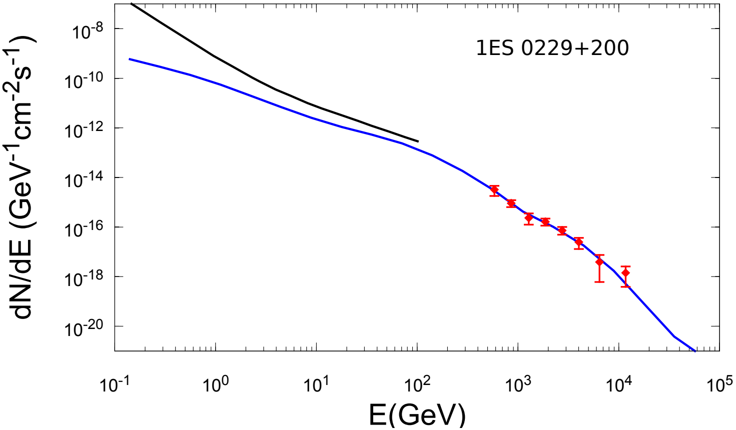
- Neutrons and pions decay very quickly
- e^+e^- pairs upscatter CMB photons to higher energies
- If intergalactic magnetic fields (IGMF) sufficiently low, then secondaries will point back to source

Secondaries from Cosmic Rays



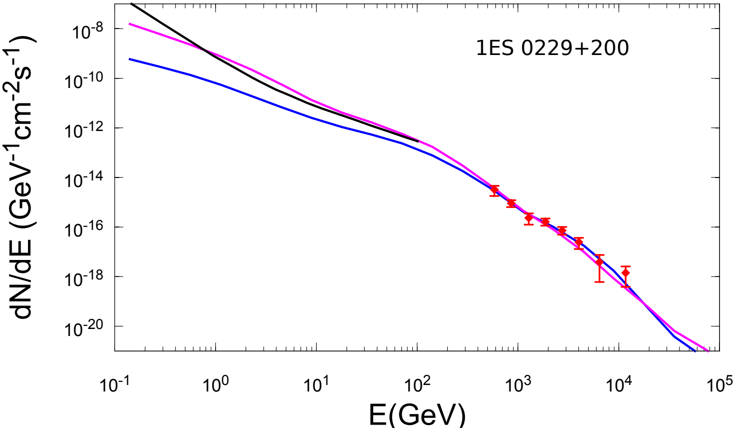
Cosmic ray protons undergo proton pair production off CMB and photopion production off EBL. These secondaries lead to high energy gamma rays and neutrinos.

Cosmic Ray Results



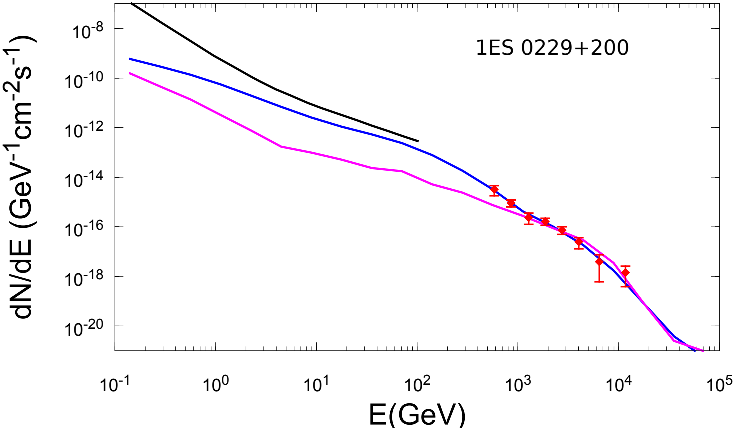
Results fitted to Hess data for 1ES0229+0200 with cosmic ray protons as primary source. An intrinsic spectra of $\Gamma = 2$ and intergalactic magnetic field (IGMF) $= 10^{-15}G$ were used with a "high" EBL model.

Cosmic Ray Results



Results fitted to Hess data for 1ES0229+0200 with cosmic ray protons as primary source for intergalactic magnetic field (IGMF) $= 10^{-15}$ G(Blue) and $= 10^{-18}$ G(Purple) were used with a "high" EBL model.

Cosmic Ray Results



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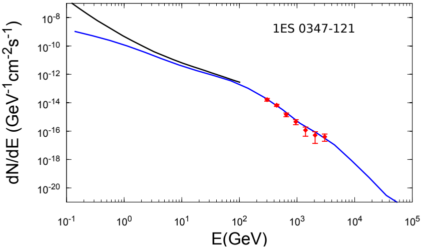
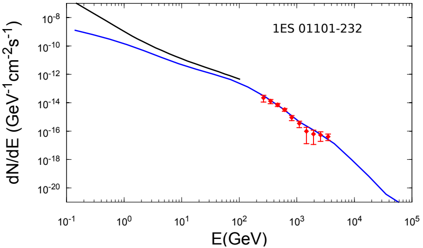


Calculated spectrum of 1ES 0347-121 normalized to Hess data



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 provide an excellent fit to highest energy points of distant blazars.
- 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.

Consequences of Model

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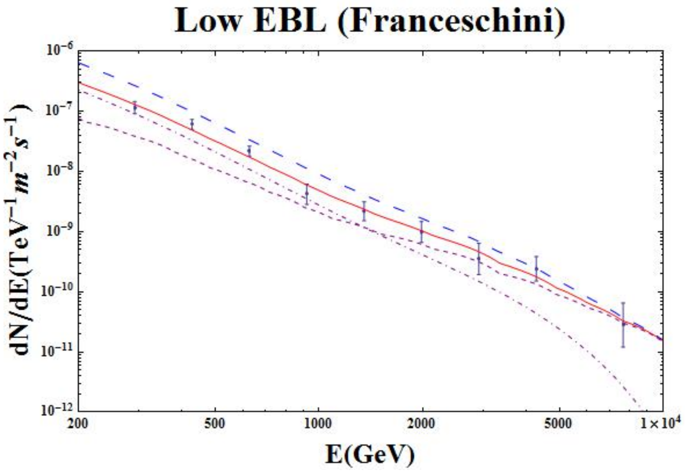
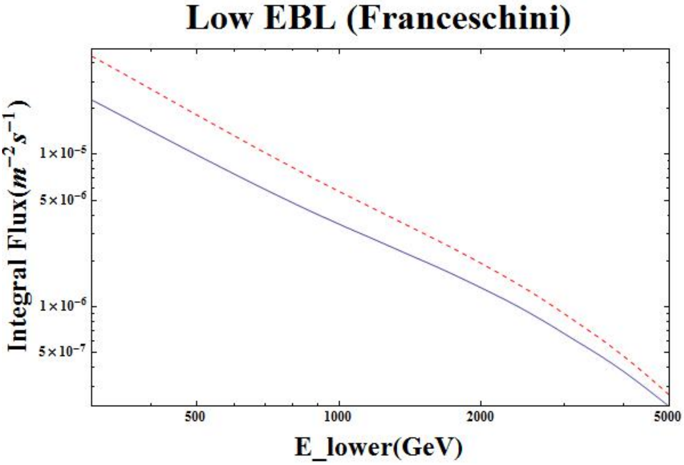
  For sources with $z > 0.1$ variability has been observed at E$\sim$200GeV but never in the TeV range.
- For cosmic rays an accompanying high energy neutrino signal should be seen.

Flaring and Variability



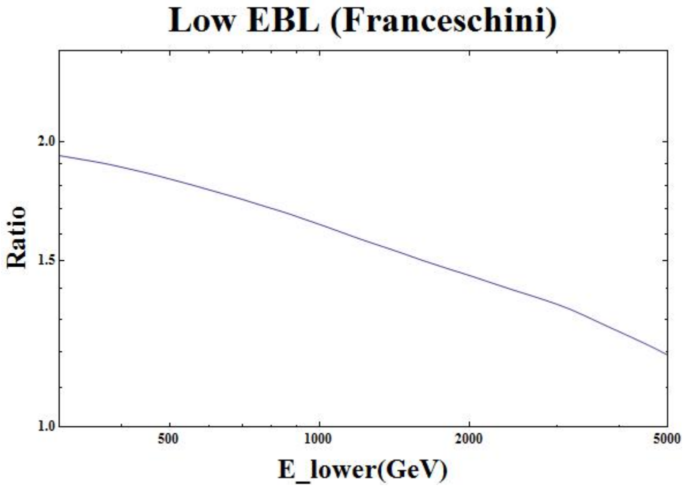
Calculated spectra for 1ES0229+200 wirh a secondary signal from cosmic rays, a primary gamma ray signal and IGMF $= 10^{-15}$ G. A flaring component is shown for the primary signal.

Flaring and Variability



Integral flux of flaring state vs non-flaring state for 1ES0229+200.

Flaring and Variability



Integral flux of flaring state vs non-flaring state for 1ES0229+200 with low EBL model.

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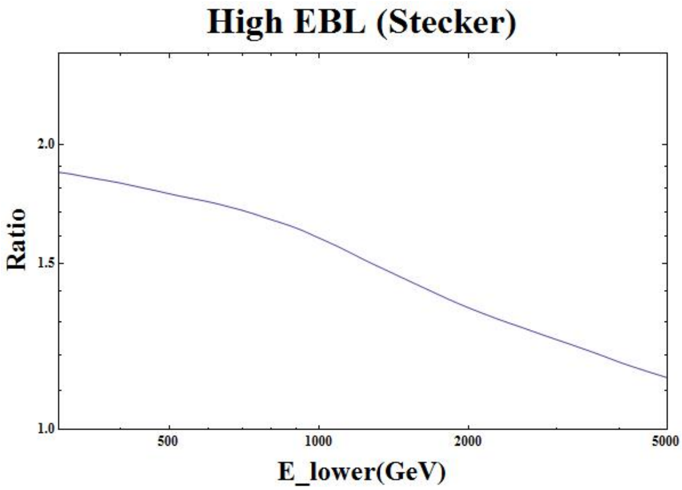
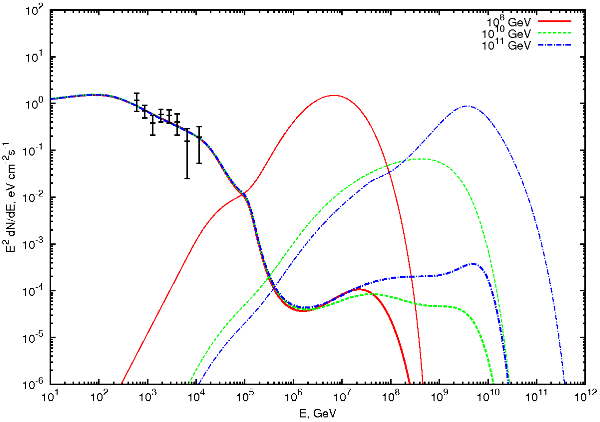


Integral flux of flaring state vs non-flaring state for 1ES0229+200 with high EBL model.

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 $\frac{1}{D^2} \times \mathrm{P(Interaction)} \sim \frac{1}{D}$, this allows more distant sources to be detectable

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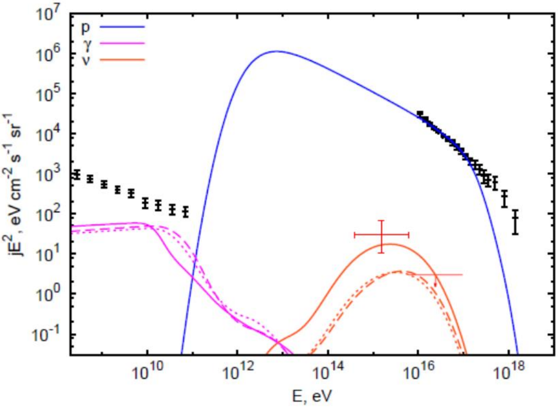
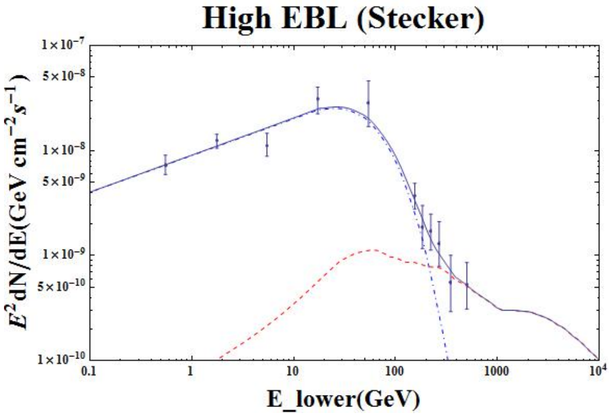
- Could IceCube detect these neutrinos?

Neutrinos



Predicted spectra of PeV neutrinos (red lines) compared with the ux measured by the IceCube experiment. The IceCube data points (red) are model-dependent 68% condence level ux estimates obtained by convolving the IceCube exposure with the predicted neutrino spectrum.

New Sources



Primary gamma ray spectra fitted to spectrum of PKS1424 for z=0.6 and Stecker et al EBL. A secondary component is shown to improve the fit.

Summary

- High energy 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 for a wide range of models.
    - Assuming cosmic ray component robust limit of

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

- Halo structure predicted.
- Lack of variability predicted and so far observed.
- Possible detection of secondary neutrino signal by IceCube.
- Future work can provide information on EBL, IGMF, AGN properties and cosmic ray composition

THANK YOU!