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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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 $\boldsymbol{\Gamma \geq 1.5}$ 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

- 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 $\Gamma = 0.5$).

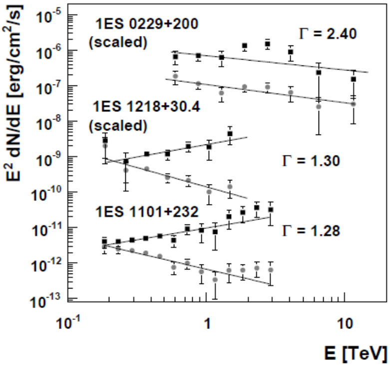


Figure from Krennrich et al 2008

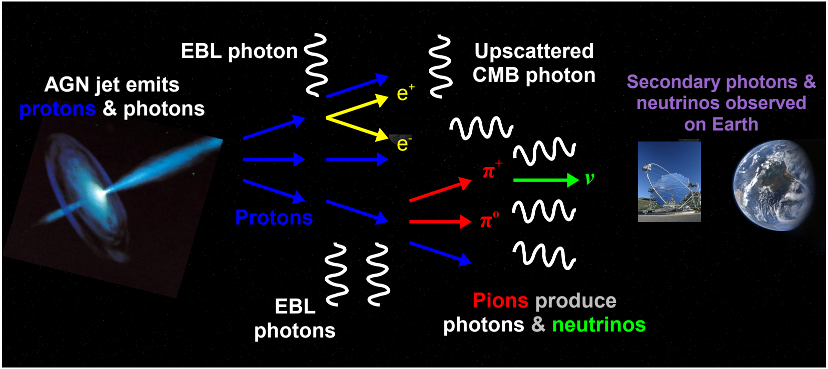
Secondaries from Cosmic Rays

- 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

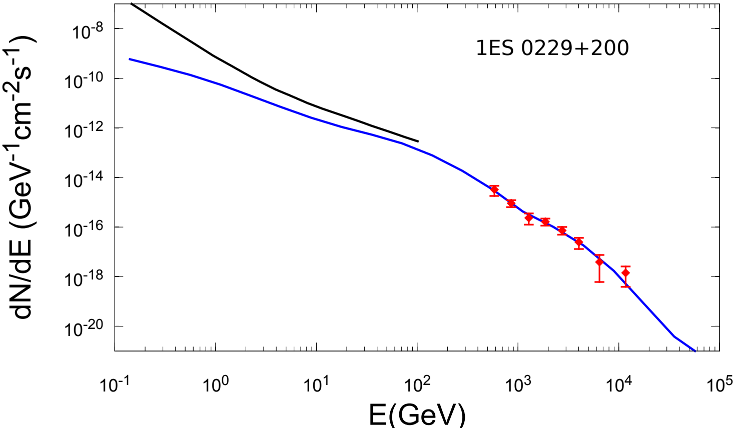


Cosmic ray protons undergo proton pair production off CMB and photopion production off EBL. These secondaries lead to high energy gamma rays and neutrinos.

Secondaries from Cosmic Rays

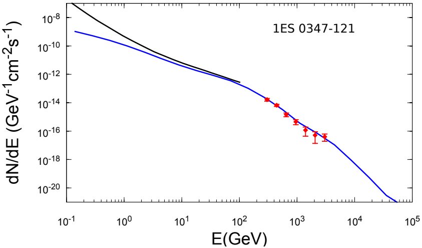
- Ran large scale Monte Carlo to track secondary photons and neutrinos.
- Used a variety of EBL models from low level to high.
- Used 3D intergalactic magnetic fields (IGMF) with fixed correlation length, average strength and randomized direction.
- Angular resolution for Fermi and HESS or Veritas folded into predicted observed spectra.

Cosmic Ray Results (The Past)

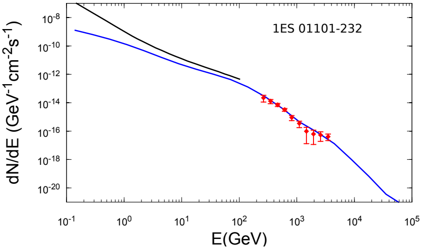


Results fitted to Hess data for 1ES0229+0200 with cosmic ray protons as primary source. An intrinsic spectra of $\Gamma = 2$ and intergalactic magnetic field (IGMF) $= 10^{-15}G$ were used with a "high" EBL model.

Cosmic Ray Results (The Past)



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, $E_{\mathrm{max}} = 10^{11}$ GeV, $\alpha = 2$, and $\theta_{jet} = 6^{\circ}$.)

Cosmic Ray Results (The Past)

- 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

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

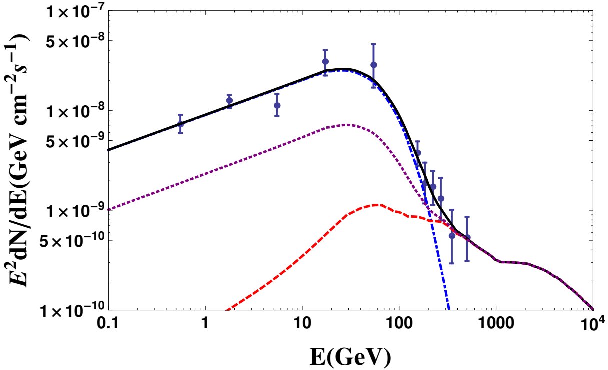
- Signal extends to very high energies with little suppression.
- Galactic magnetic fields make it hard to prove that AGN are source of cosmic rays, but lack of high energy cutoff could prove both this and low IGMF.

Consequences of Model

Secondary gamma rays with low IGMF have some testable consequences:

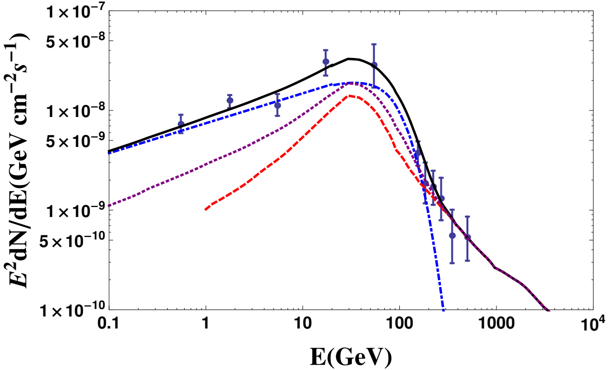
- For $\mathrm{B} > 10^{-15}$ G halos will be present around source, more significant for cosmic rays.
- No short scale time variabilty
  For sources with $z > 0.1$ variability has been observed at E$\sim$200GeV but never in the TeV range.
- For cosmic rays an accompanying high energy neutrino signal should be seen.

New Sources (The Present)



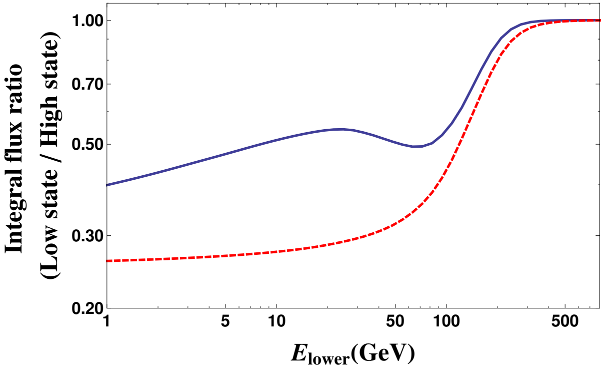
Predicted spectrum of PKS 1424+240 (solid black line), assuming z = 0.6, for Stecker et al EBL model. The blue dot-dashed line is primary spectrum (spectral index = 1.65); red dashed line is secondary gamma rays for the mean IGMF of $B = 10^{15}$ G with a correlation length of 1 Mpc; black solid line is the combined spectrum of primary and secondary gamma rays. Also shown are the VERITAS and Fermi data points. The purple line represents the total spectrum with primary signal suppressed by a factor of 4 (low state).

New Sources (The Present)



Predicted spectrum of PKS 1424+240 (solid black line), assuming z = 1.3, for Franceschini et al EBL model. The blue dot-dashed line is primary spectrum (spectral index $= 1.7$); red dashed line is secondary gamma rays for the mean IGMF of $B = 10^{15}$ G with a correlation length of 1 Mpc; black solid line is the combined spectrum of primary and secondary gamma rays. Also shown are the VERITAS and Fermi data points. The purple line represents the total spectrum with primary signal suppressed by a factor of 4 (low state).

New Sources (The Present)

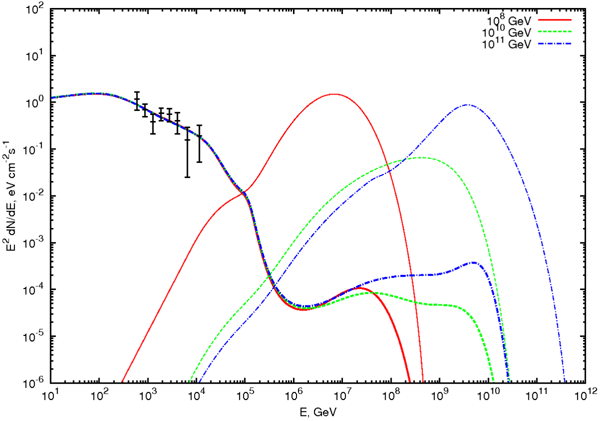


Ratio of integral flux of flaring state to low state, where the integral ux is integrated from E_{lower} to 1 TeV. In each the ux contains both a primary and secondary gamma ray component. The primary component is suppressed by a factor of 4 for the low state whereas the secondary component remains constant. The blue solid line shows the results for a source at $z = 1.3$ and low EBL model and the red dashed line shows the results for a source at $z = 0.6$ and high EBL mode.

New Sources (The Future)

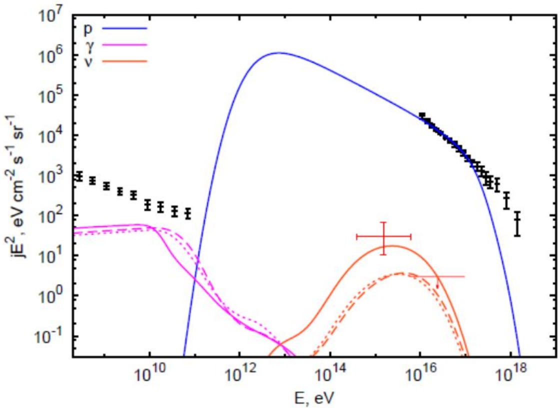
- New experiments and more observing time on current generation experiments will detect more distant sources.
- Starting to probe EBL levels at higher redshifts. With accurate redshift data should be able to set meaningful limits on EBL levels for $z > 0.6$.
- Complimentary to this, once more robust EBL limits exist, redshift limits can be placed on sources with uncertain redshifts.
- Limits on IGMF can be further improved.

Neutrinos (The Past)



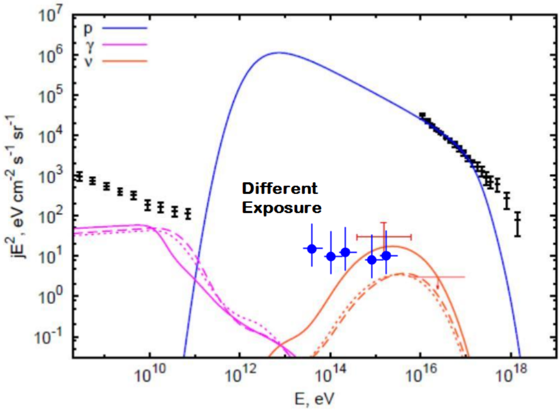
Calculated gamma ray and neutrino spectra for 1ES 0229+200 for various high energy cutoffs in the proton spectrum. A proton spectrum with $\Gamma = 2$ was used.

Neutrinos (The Present)



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.

Neutrinos (The Future)



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.

Summary

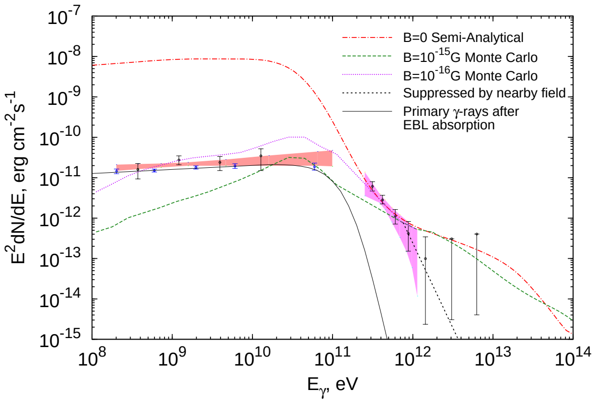
- High energy cosmic rays from AGN produce seconday gamma rays and neutrinos on the way to Earth
- The secondary gamma rays give a good fit to TeV sources at high redshift and energy
  - Calculated spectra robust for various photon and proton injection models
  - Agrees well with new, very distant sources.
- Secondary neutrinos agree with current IceCube results
- Limits set on IGMF for a wide range of models.

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

- Future work can provide information on EBL, IGMF, AGN properties and cosmic ray composition

THANK YOU!

New Sources (The Present)



Spectra of secondary gamma rays produced by protons from a source at z = 1.3, calculated using semianalytical and Monte Carlo techniques. Points shown are for PKS 0447-439 which has a redshift limit of $z > 1.246$.