γ-Ray Opacity of the Universe and High Energy Tests of Lorentz Invariance

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Absorption of Cosmic Gamma Rays from Blazars

Electron-Positron Pair Production Interactions with Intergalactic Low Energy Photons; Stecker, et al. 1992, Astrophys. J. 390, L49

High Redshift Absorption

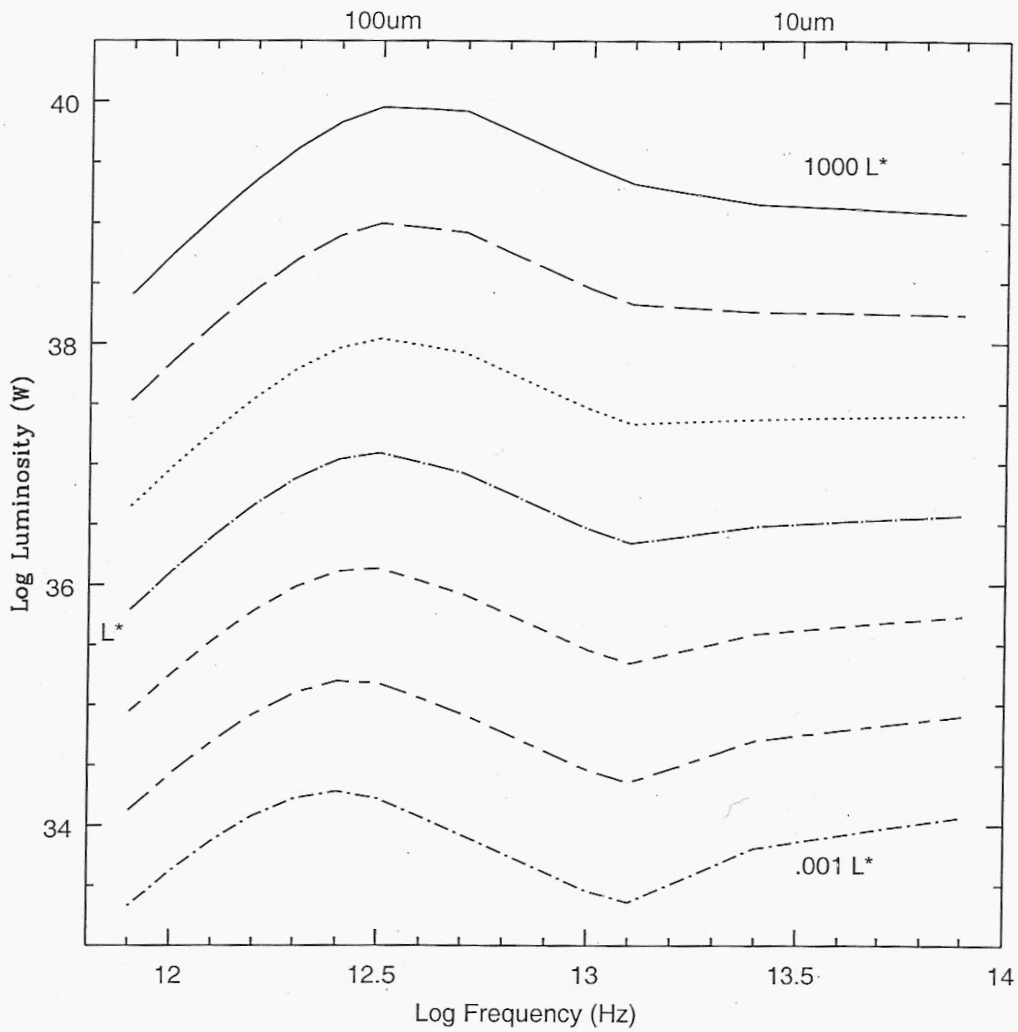
Salamon & Stecker 1998, ApJ 493, 547;

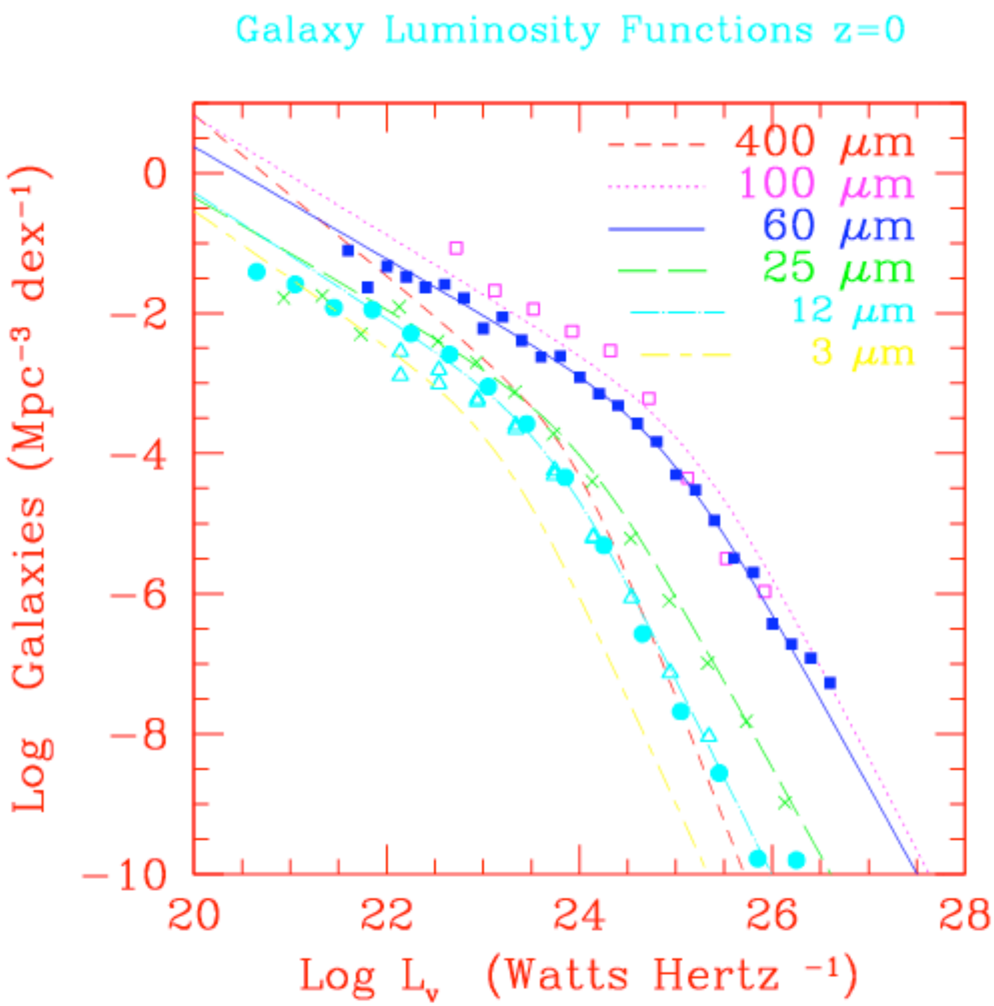
Stecker, Malkan & Scully 2005

Theoretical Calculations: Input

- Spectral Energy Distributions of Galaxies
- Galaxy Luminosity Functions (LF)
- Redshift Dependence of Galaxy LFs

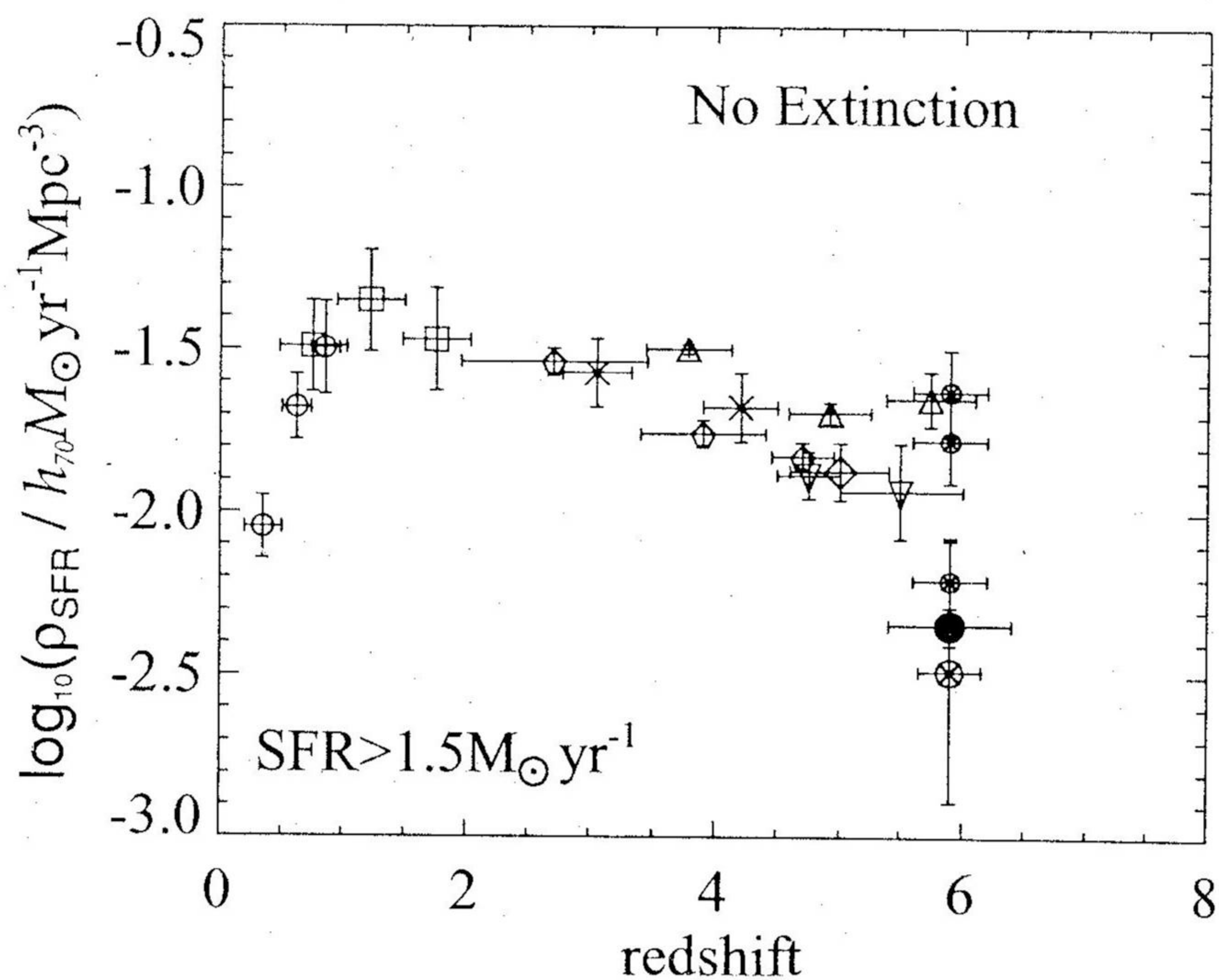
Spectral Energy Distributions vs. Luminosity



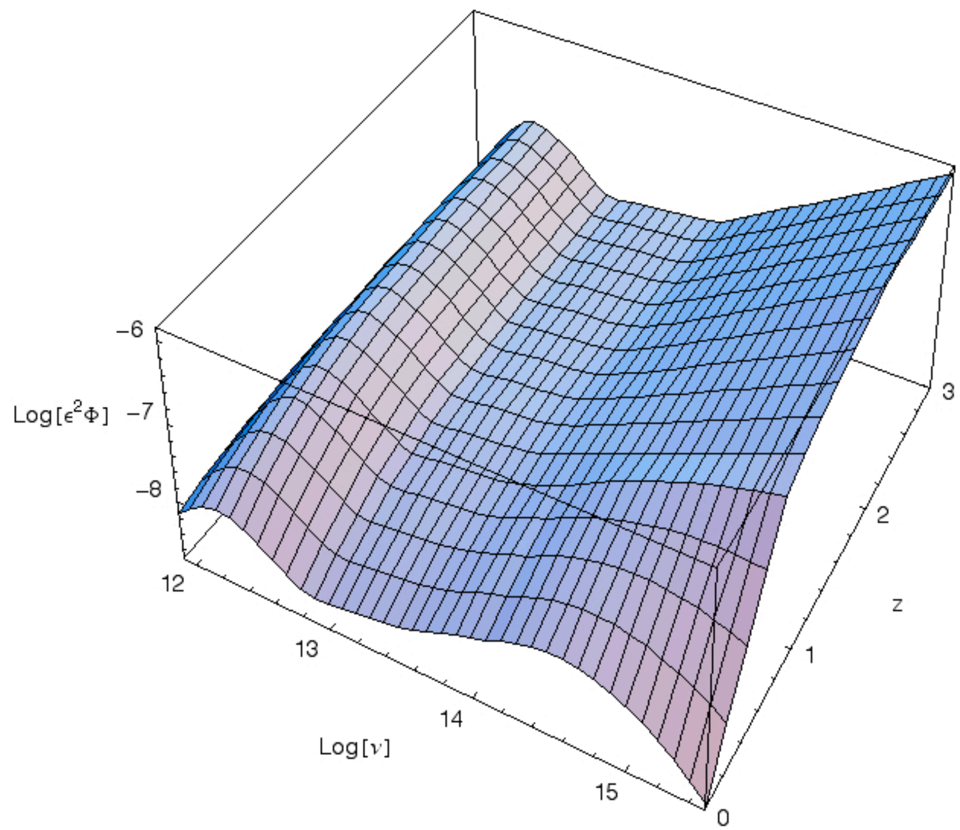


Galaxy Luminosity Functions z=0
400 μm
100 μm
60 μm
25 μm
12 μm
3 μm
Log Galaxies (Mpc⁻³ dex⁻¹)
0
−2
−4
−6
−8
−10
20
22
24
26
28
Log Lν (Watts Hertz ⁻¹)

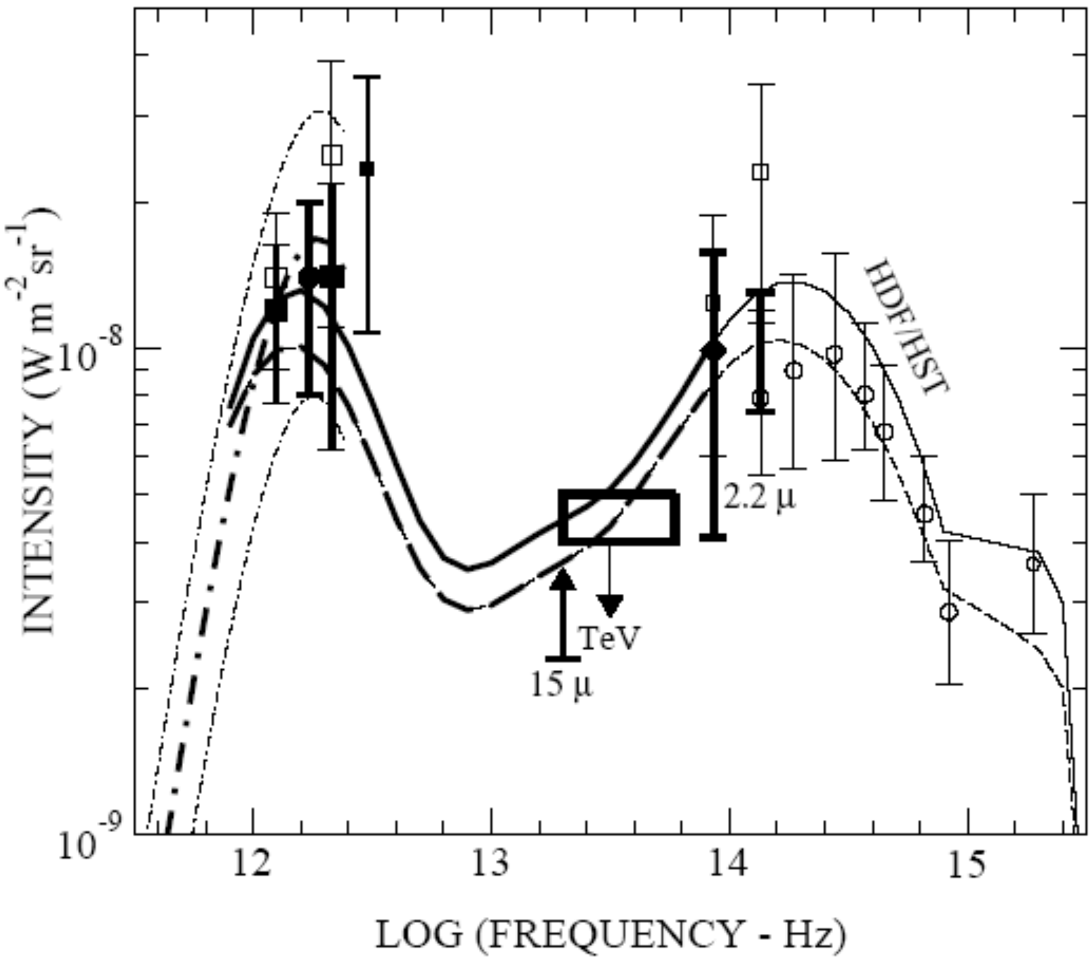
Star Formation Rate vs Redshift



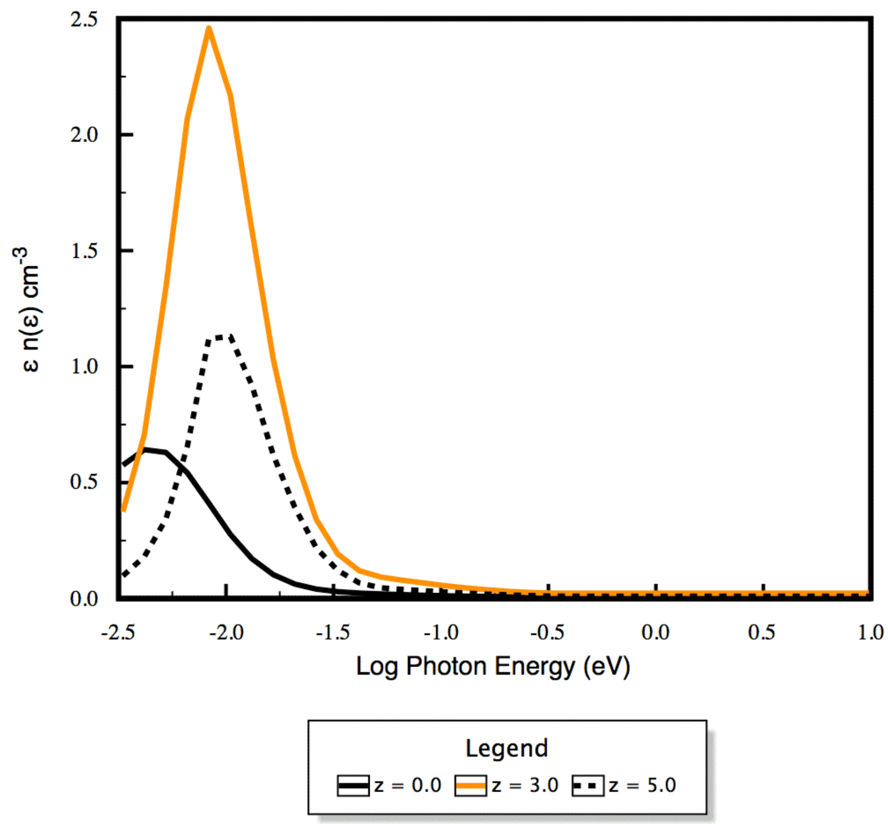
IR-UV Spectral Energy Distributions



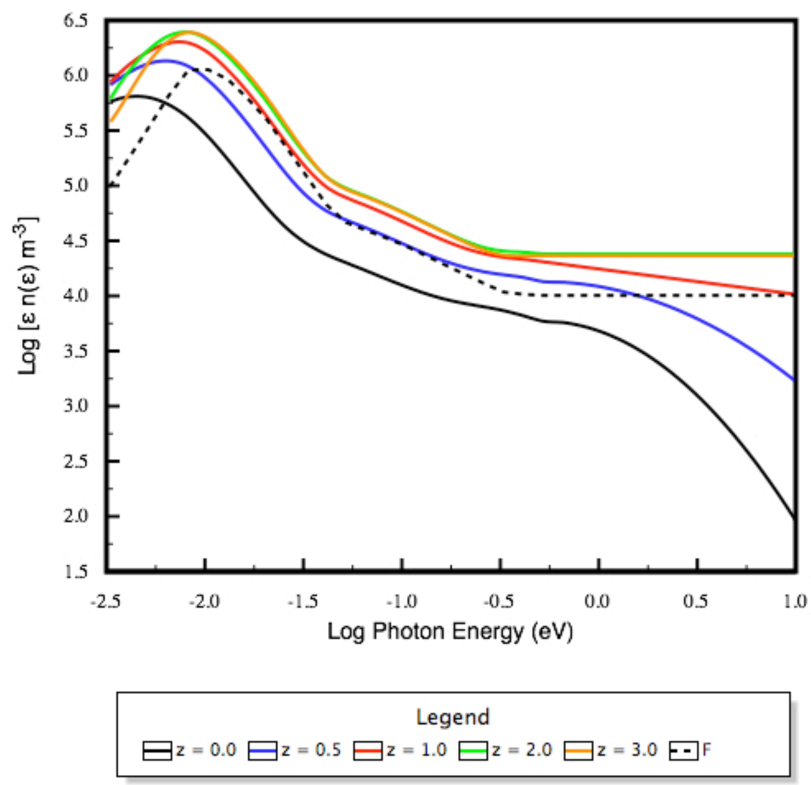
Range of z=0 EBL SED (SD98)



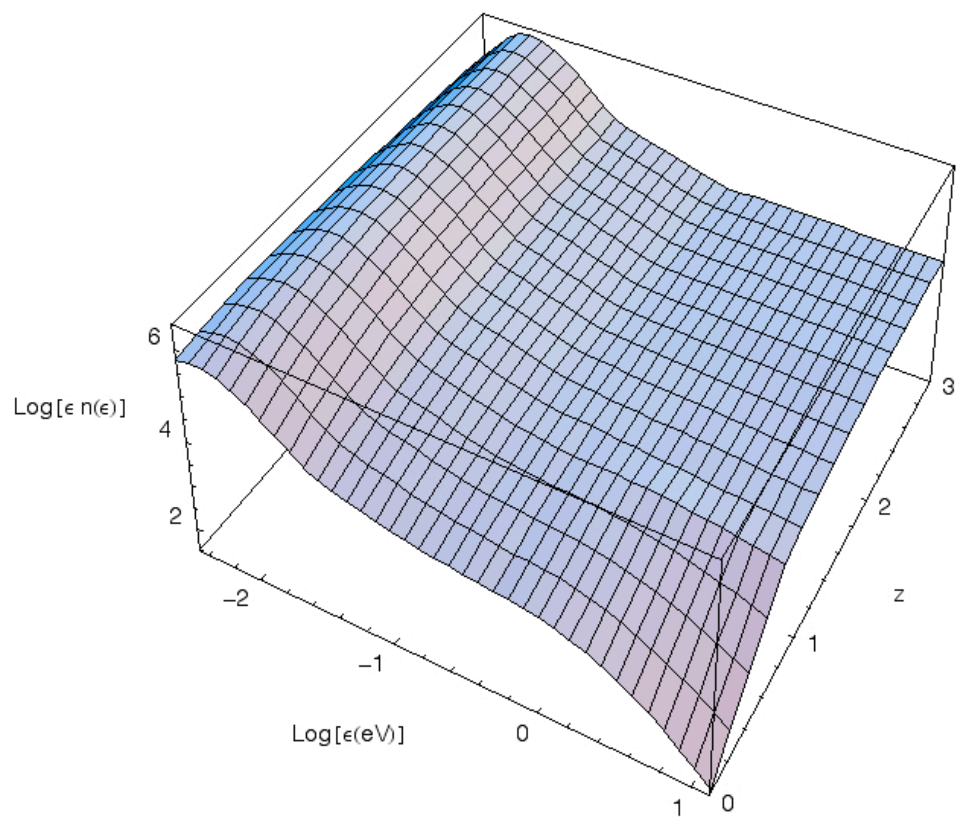
Intergalactic IR-UV Photon Densities



IR-UV photon density



Intergalactic IR-UV Photon Densities



$$\tau(E_\gamma, z) = \int_0^{z_{Source}} dz \frac{dl}{dz} \int_0^2 dx \frac{x}{2} \int_{\frac{2m_e^2c^4}{E_\gamma x(1+z)}}^{\infty} d\varepsilon \; n(\varepsilon, z)\sigma(s)$$

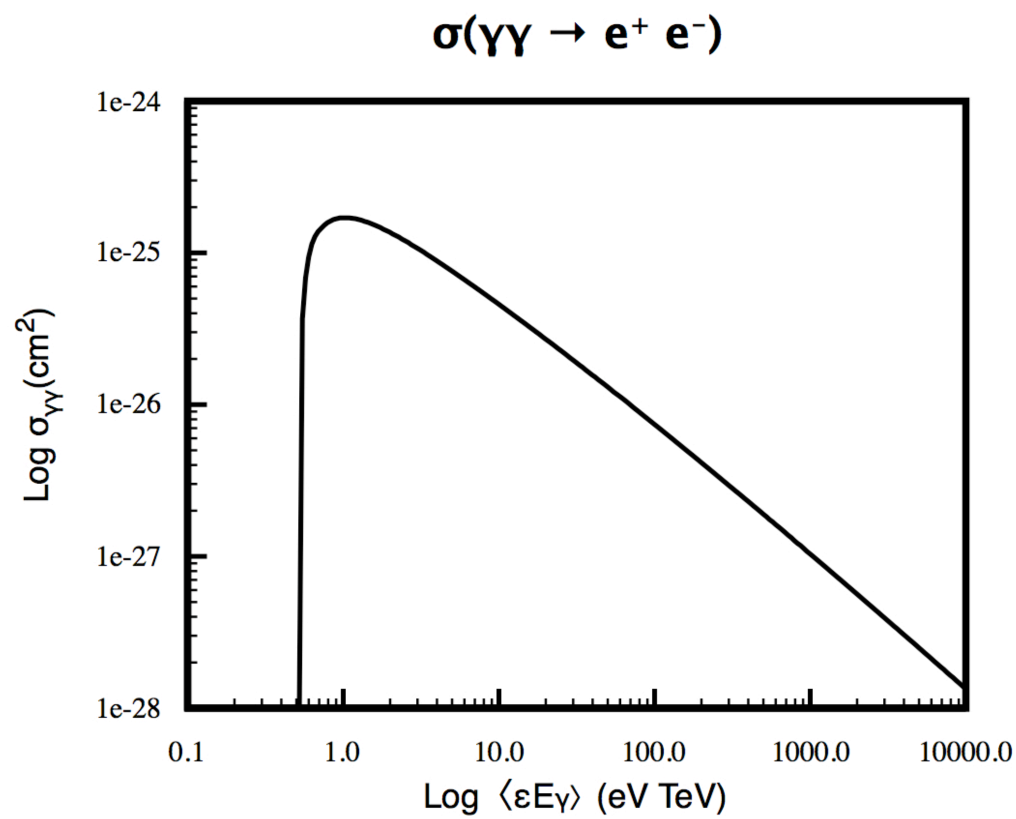
$$s = 2xE_\gamma \varepsilon(1+z) \qquad E_\gamma = E_\gamma(z=0)$$

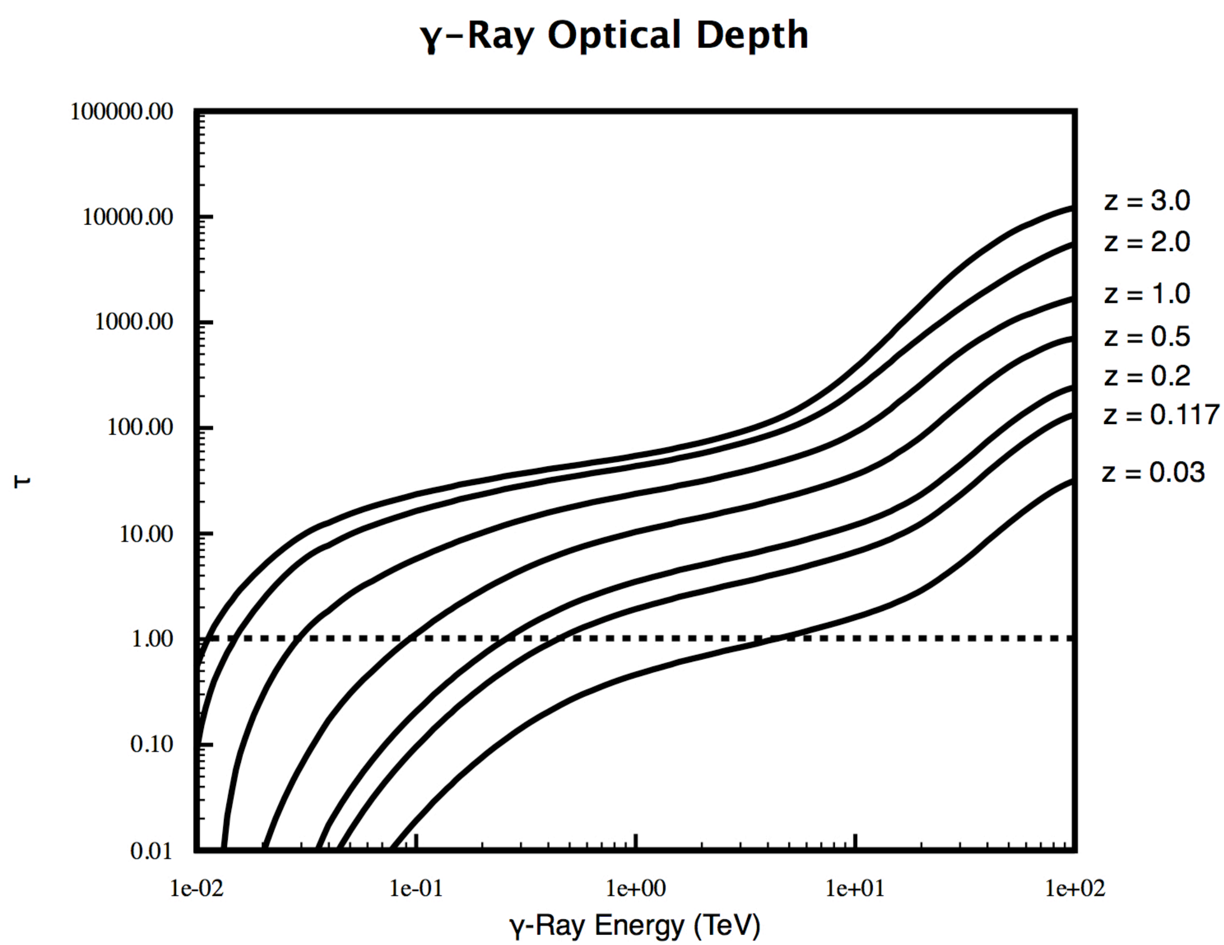
$$x = 1 - \cos\theta \qquad \varepsilon = \varepsilon(z)$$

$$\sigma(s) = \sigma_0(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

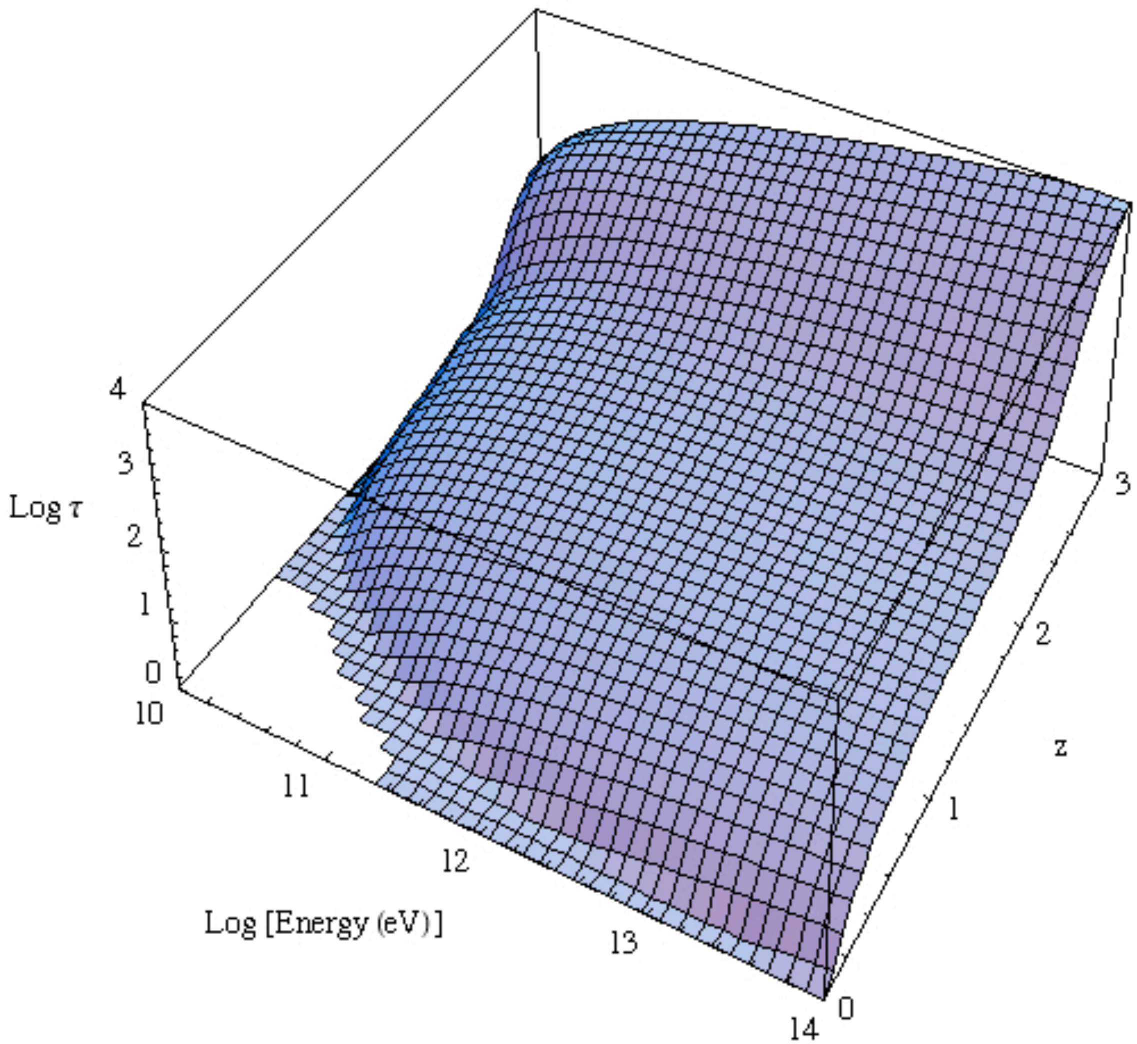
$$\frac{dl}{dz} = \frac{c}{H_0}(1+z)^{-1}\left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{-1/2}$$

Pair Production Cross Section

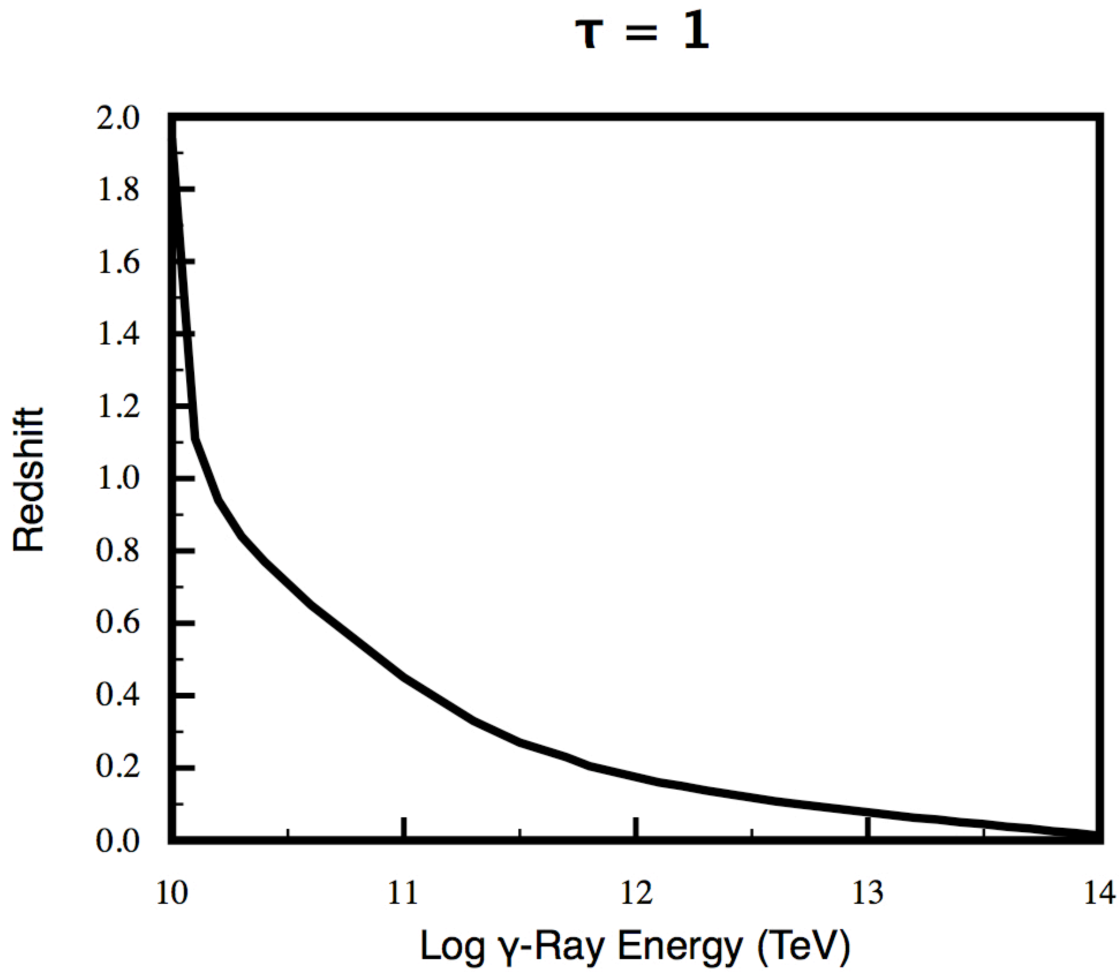



γ-Ray Optical Depth
100000.00
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
τ
1e-02
1e-01
1e+00
1e+01
1e+02
γ-Ray Energy (TeV)
z = 3.0
z = 2.0
z = 1.0
z = 0.5
z = 0.2
z = 0.117
z = 0.03

τ = 1 Baseline Curve



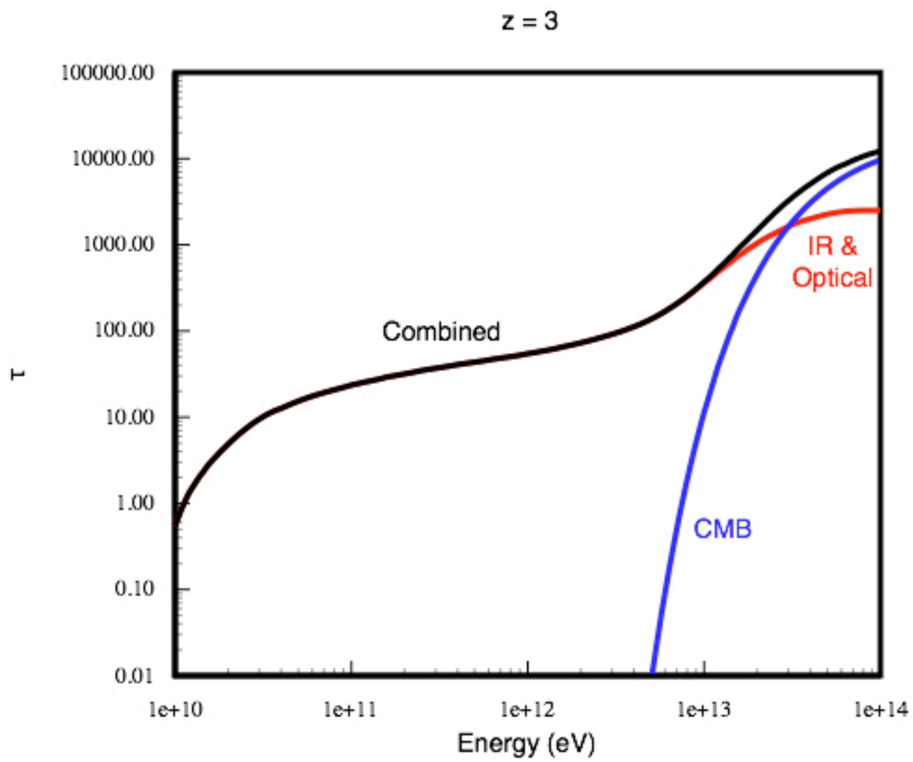
Critical γ-Ray Energy for $\tau = 1$



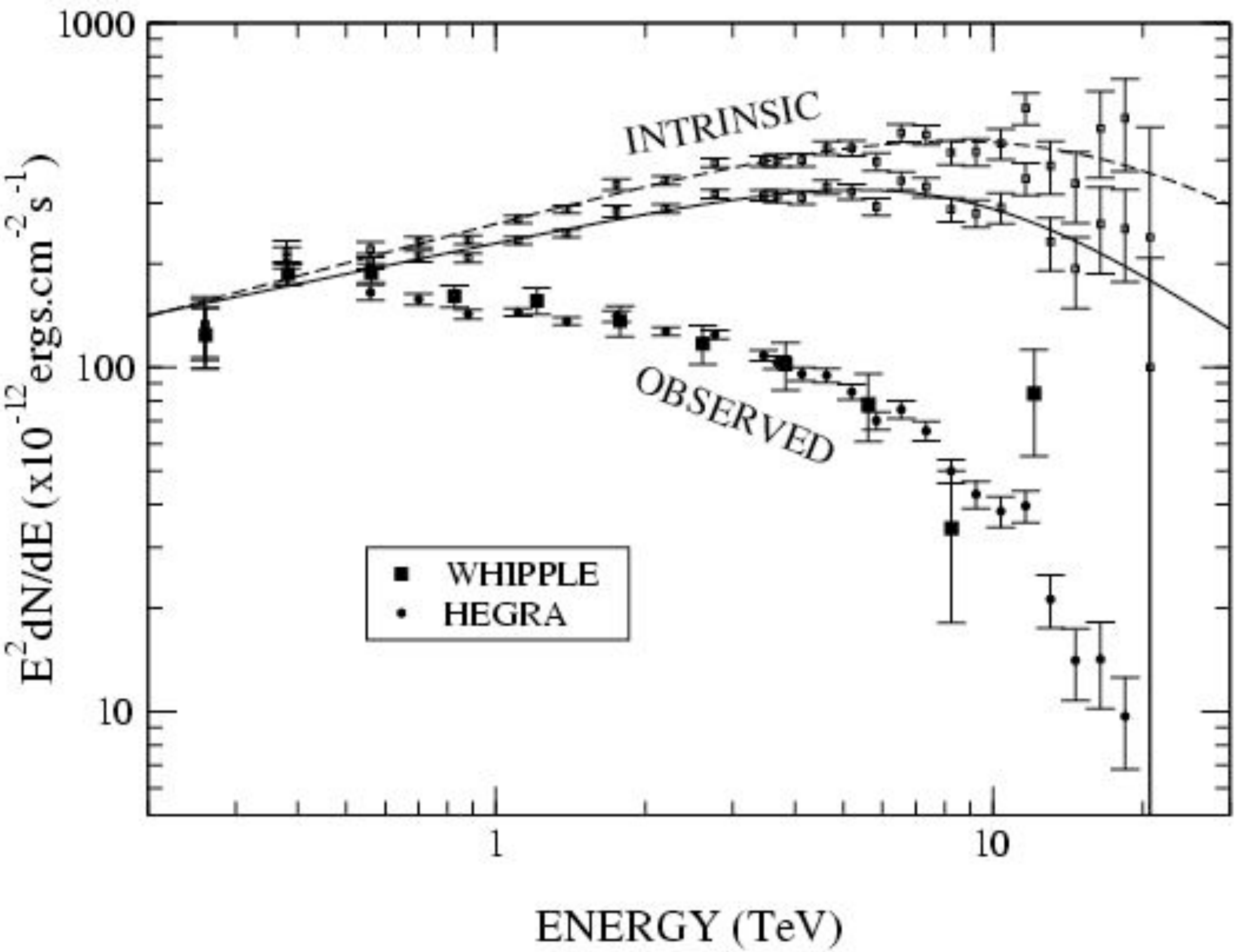
Opacity of CMB for E_γ << 1 PeV (see Stecker 1969, ApJ **157**, 507)

$$\tau_{\mathrm{CMB}} = 5.00 \times 10^5 \left(\frac{1.11\ \mathrm{PeV}}{\mathrm{E}_\gamma} \right)^{1/2} \int_0^z dz \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}\ e^{\frac{-1.11\ \mathrm{PeV}}{(1+z)^2 \mathrm{E}_\gamma}}$$

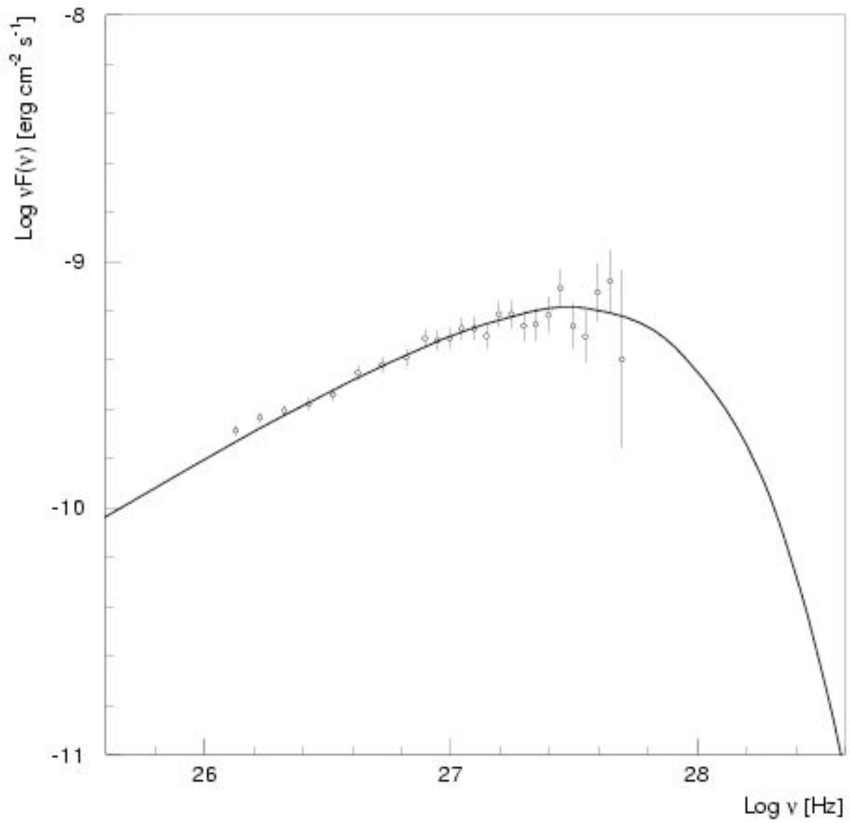
Contribution of CBR at z = 3



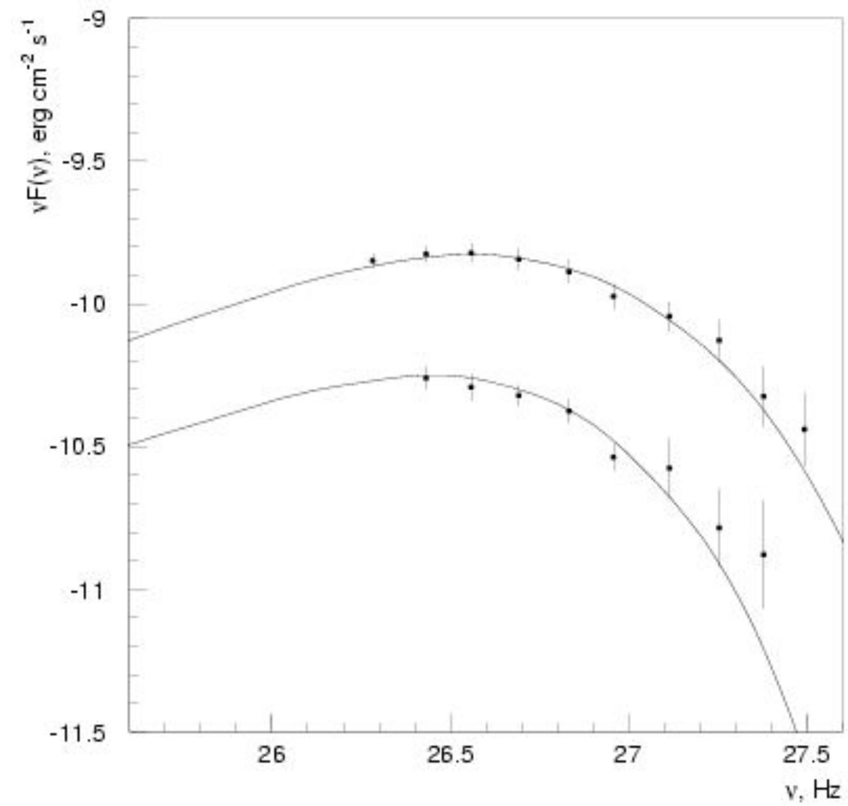
Mkn 501 Spectrum (SD98)



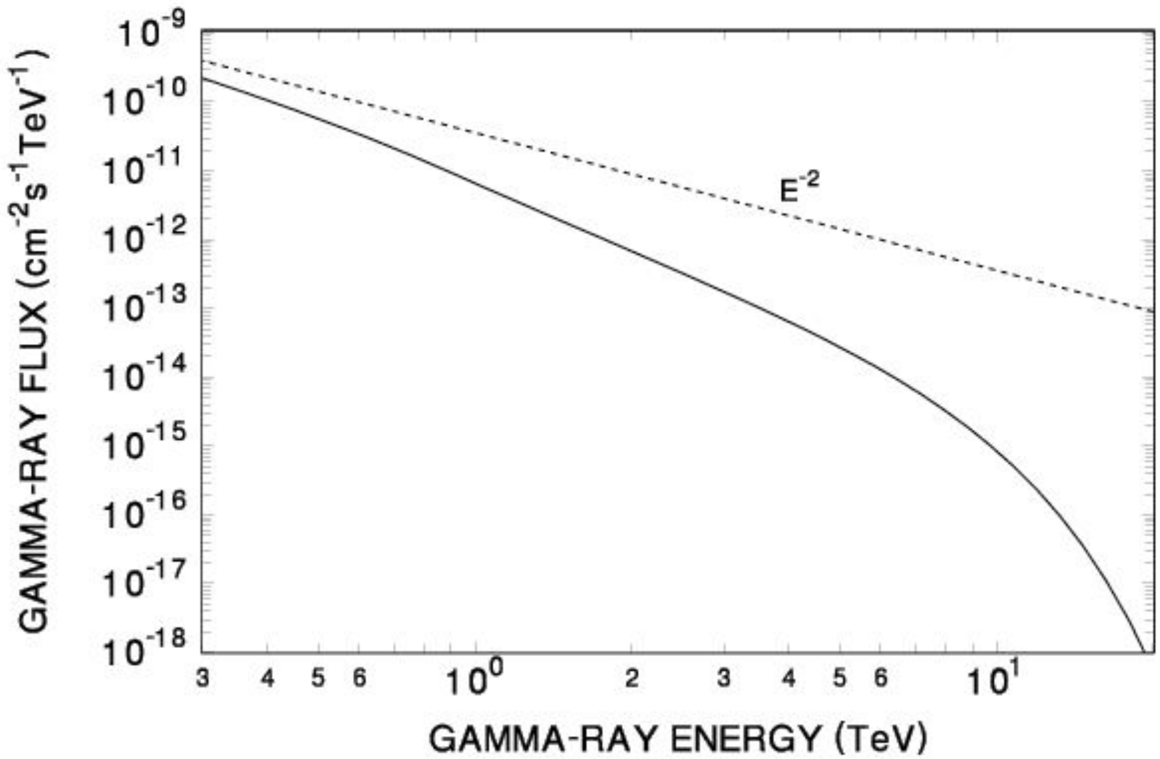
Mkn 501 Intrinsic with SSC Fit Using X-ray Data (KMKDS03)



Mkn421 Intrinsic Spectrum SSC Fits (Flare & Quiescent) (KMKDS03)



Prediction of Absorbed Spectrum for PKS2155 (Stecker 1999)



Beyond Einstein (?)

- Group of Lorentz boosts is open to the Planck scale – possible modifications by quantum gravity, extra dimensions, string theory, etc.
- The cosmic background radiation is only isotropic in one *preferred* frame.

Limit on Lorentz Invariance Violation from Blazar Absorption Features

Let us characterize Lorentz invariance violation by the parameter δ such that

$$c_e \equiv c_\gamma (1 + \delta)$$

(Coleman & Glashow 1999). If $\delta > 0$, the γ-ray photon propagator in the case of pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$

is changed by the quantity

$$\varepsilon p_\gamma^2 = -2E_\gamma^2 \delta$$

so that the threshold energy condition is now given by

$$2\varepsilon E_\gamma^2 (1 - \cos\theta) > 4m_e^2 + 2E_\gamma^2 \delta.$$

Limit on Lorentz Invariance Violation from Blazar Absorption Features

Thus, the pair production threshold is raised significantly if

$$\delta > \frac{2m_e^2}{E_\gamma^2}.$$

The existence of electron-positron pair production for γ-ray energies up to ~20 TeV in the spectrum of Mkn 501 therefore gives an upper limit on δ at this energy scale of

$$\delta < 1.3 \times 10^{-15}$$

(Stecker & Glashow 2001).

Limit on the Quantum Gravity Scale

For pair production, $\gamma + \gamma \to e^+ + e^-$ the electron (& positron) energy $E_e \sim E_\gamma / 2$. For a third order QG term in the dispersion relation, we find

$$\delta = \frac{E_\gamma}{2M_{QG}} - \frac{2m^2}{E_\gamma^2},$$

And the threshold energy from Stecker and Glashow (2001)

$$\frac{E_\gamma^2 \delta}{2} \leq \frac{m^2}{E_\gamma}$$

reduces to

$$M_{QG} \geq \frac{E_\gamma^3}{8m^2}$$

Limit on Lorentz Invariance Violation from Blazar Absorption Features

Since pair production occurs for energies of at least E_γ = 20 TeV, we then find the numerical constraint on the quantum gravity scale

$$M_{QG} \geq 0.3 M_{Planck},$$

Arguing against some TeV scale quantum gravity models involving extra dimensions!

Previous constraints on M_{QG} from limits on an energy dependent velocity dispersion of γ-rays from a TeV flare in Mkn 412 (Biller, *et al.* 1999) and γ-ray bursts (Schaefer 1999) were of order

$$M_{QG} \geq (5-7) \times 10^{-3} M_{Planck}.$$

Shutting off Interactions with LIV

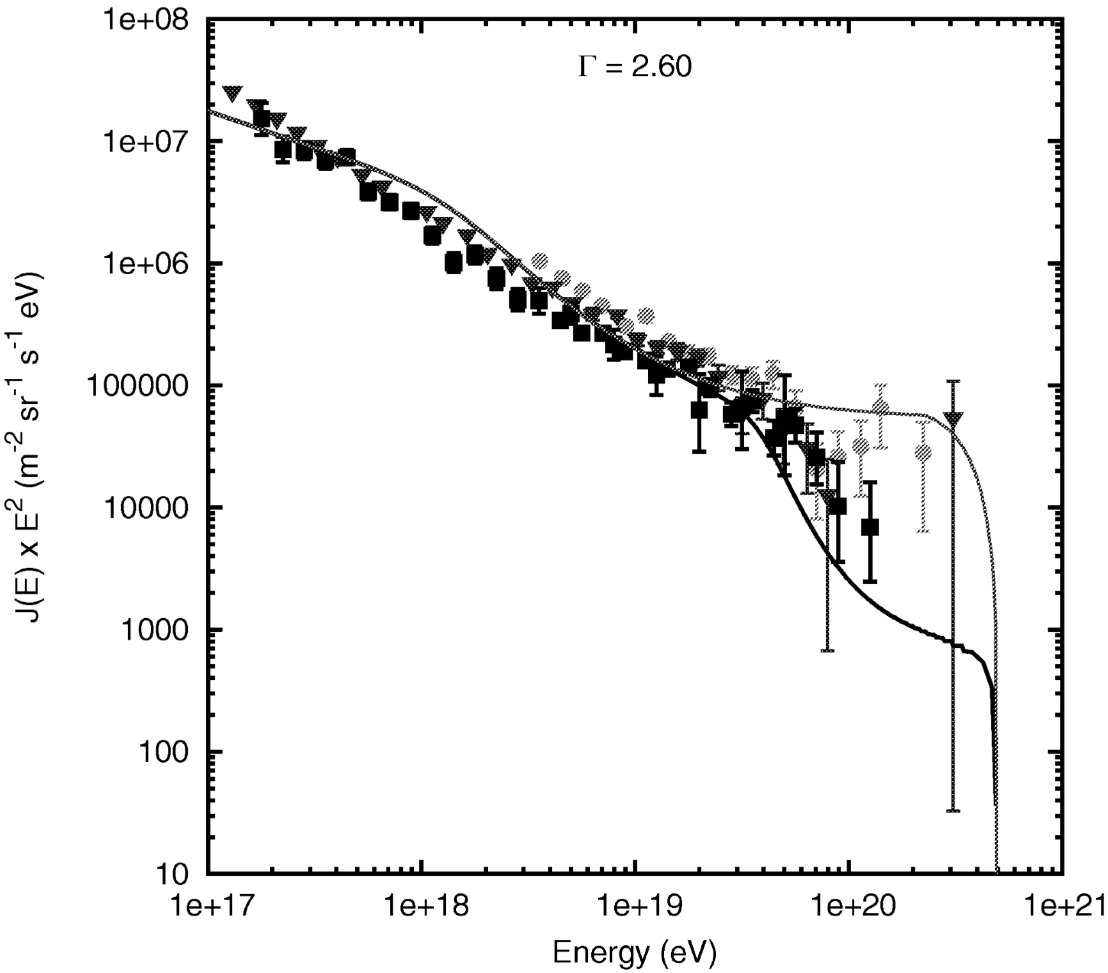
- With LIV, different particles, *i*, can have different maximum attainable velcities c_i.
- Photomeson production interactions of ultrahigh energy cosmic rays are disallowed if $c_p - c_\pi > 5 \, x \, 10^{-24}(\varepsilon/T_{CBR})^2$
- Electron-positron pair production interactions of ultrahigh energy cosmic rays can be suppressed if $c_e - c_p > [(m_p + m_e)m_p]/E_p^2$

Theoretical Spectra Shown with Data for the Following Assumptions

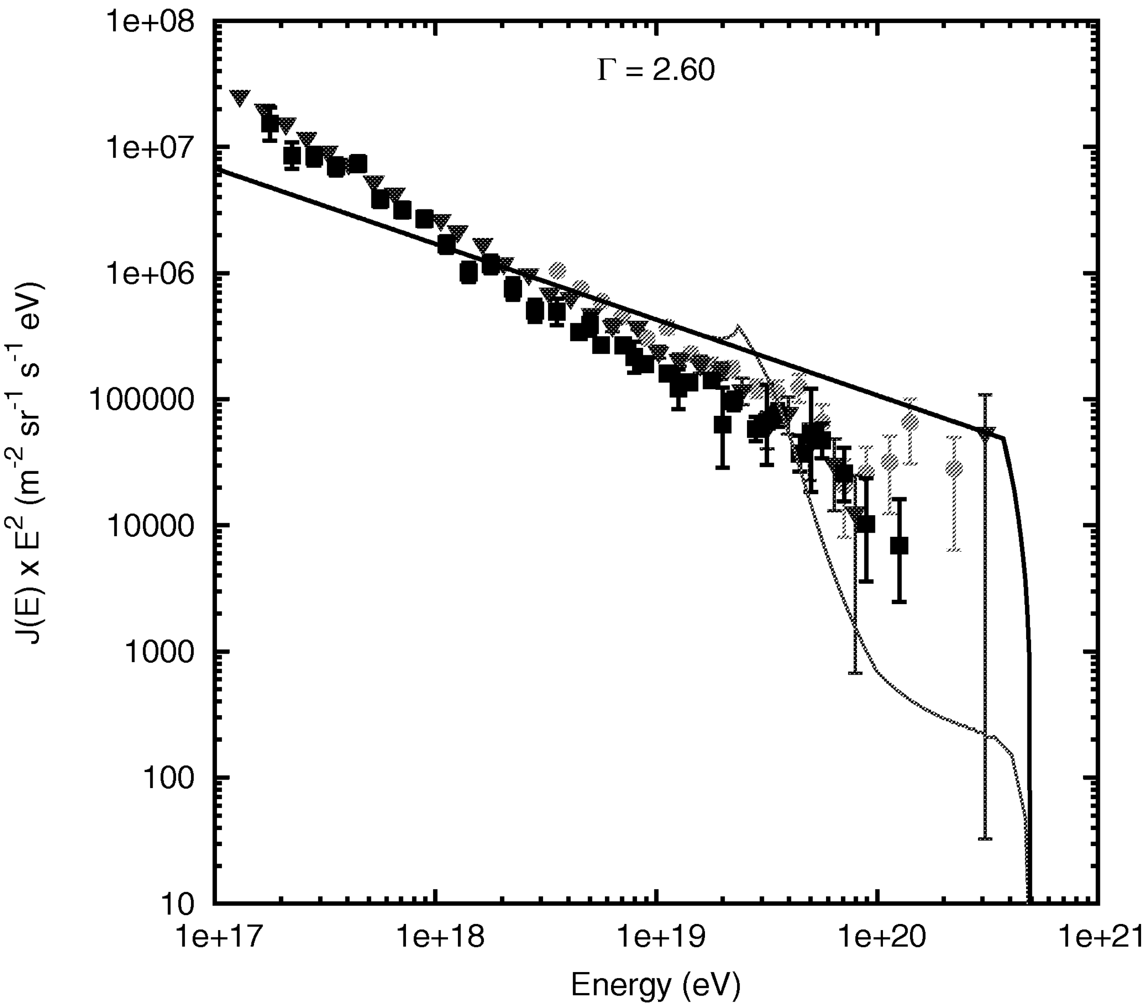
- The Source Spectrum is of the form $K(z)E^{-2.6}$ up to a maximum energy $E_{max} = 500$ EeV, where z is the redshift and $K(z)$ evolves proportional to the star formation rate.

The final spectrum is normalized to the data at 3 EeV, above which energy the UHECR are assumed to be extragalactic.

UHECR Spectra with Photomeson Production Both On (Dark) and Turned off by LIV (Light)



UHECR Spectra with Pair Production Turned Off and with Photomeson Production both On (Light) and Off (Dark)



Minimum Source Spectrum Local Power Density Requirements in W Mpc^{-3} for $E > 3$ EeV

- With source evolution and including pair production energy losses: 1.5×10^{31}
- With source evolution and no pair production energy losses: 1.2×10^{30}
- With no source evolution and including pair production energy losses: 2.2×10^{31}
- With no source evolution and no pair production energy losses: 7.7×10^{30}

High Energy Astrophysics Tests of Lorentz Invariance Violation

- Energy dependent time delay of γ-rays from GRBs & AGN (Amelino-Camelia *et al.* 1997; Biller *et al* 1999).
- Cosmic γ-ray decay constraints (Coleman & Glashow 1999, Stecker & Glashow 2001).
- Cosmic ray vacuum Cherenkov effect constraints (Coleman & Glashow 1999; Stecker & Glashow 2001).
- Shifted pair production threshold constraints from AGN γ-rays (Stecker & Glashow 2001).
- Long baseline vacuum birefringence constraints from GRBs (Jacobson, Liberati, Mattingly & Stecker 2004).
- Electron velocity constraints from the Crab Nebula γ-ray spectrum (Jacobson, Liberati & Mattingly 2003).
- Ultrahigh energy cosmic ray spectrum GZK effect (Coleman & Glashow 1999; Stecker & Scully 2005).