Gamma-ray attenuation by extragalactic background radiation

Martin Raue & Daniel Mazin (2007)
High Energy Phenomena in Relativistic Outflows
September 24-28, 2007, Dublin, Ireland [arXiv:0802.0129]
http://www.desy.de/~mraue/ebl/

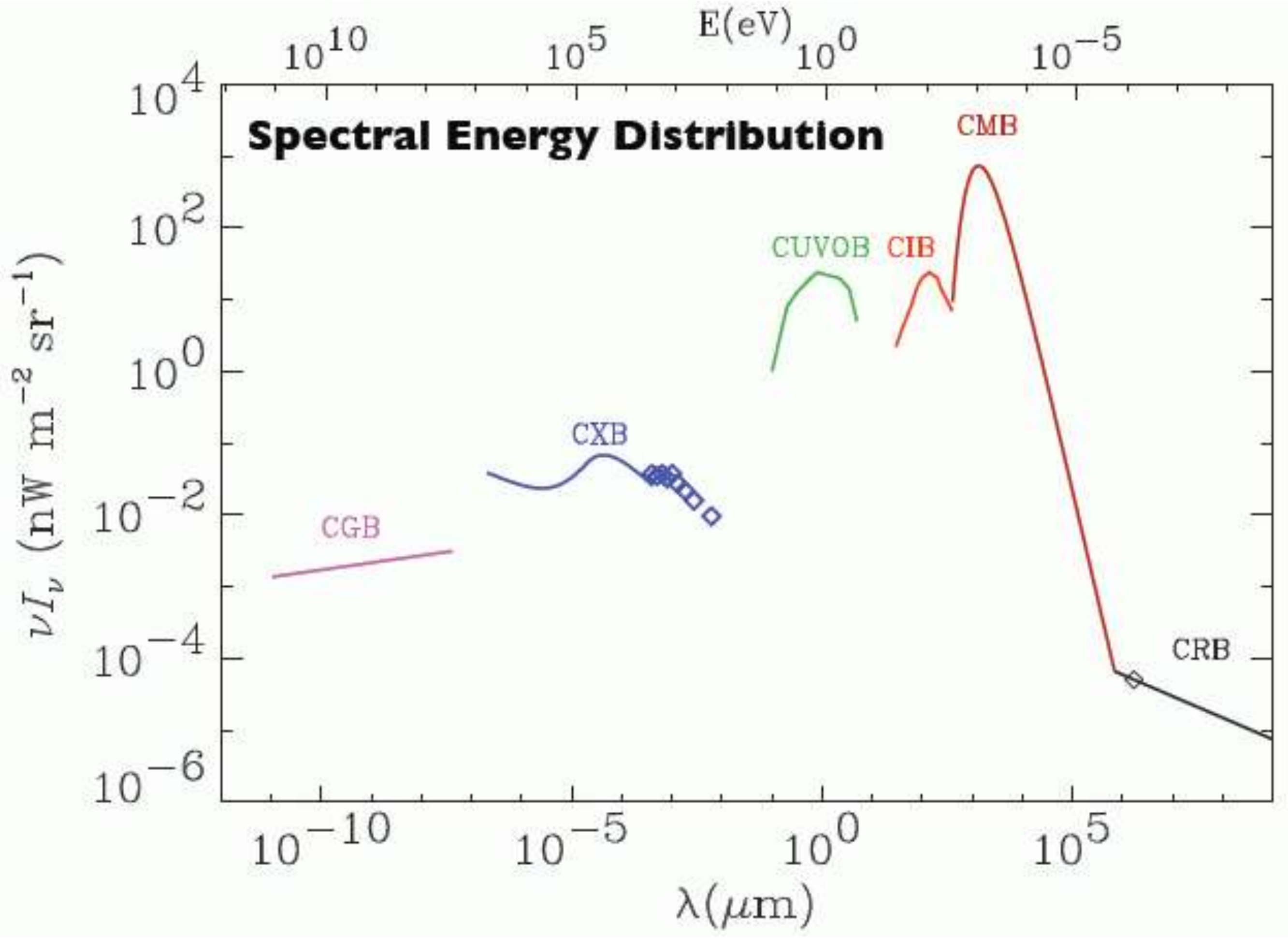
Masaki Mori

ICRR CANGAROO group internal seminar, February 28, 2008

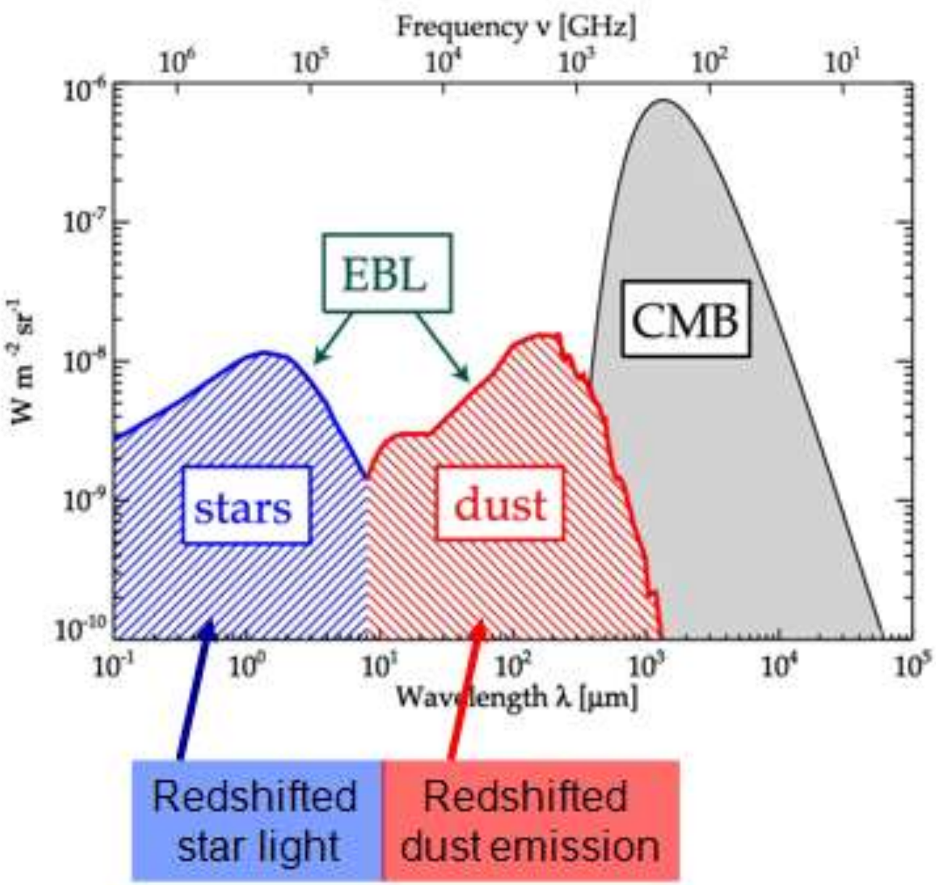
Presented on May 8, 2008

Extragalactic background light

(Residual after subtracting any foreground sources)



Extragalactic background light



- Unique imprint of the history of the universe
- Test of star formation and galaxy evolution models
- Cosmological evolution models have to explain current EBL
- Opacity source for GeV-TeV photons

TeV gamma-ray attenuation by pair creation

観測されるスペクトルには銀河間空間での伝播効果がかかる！

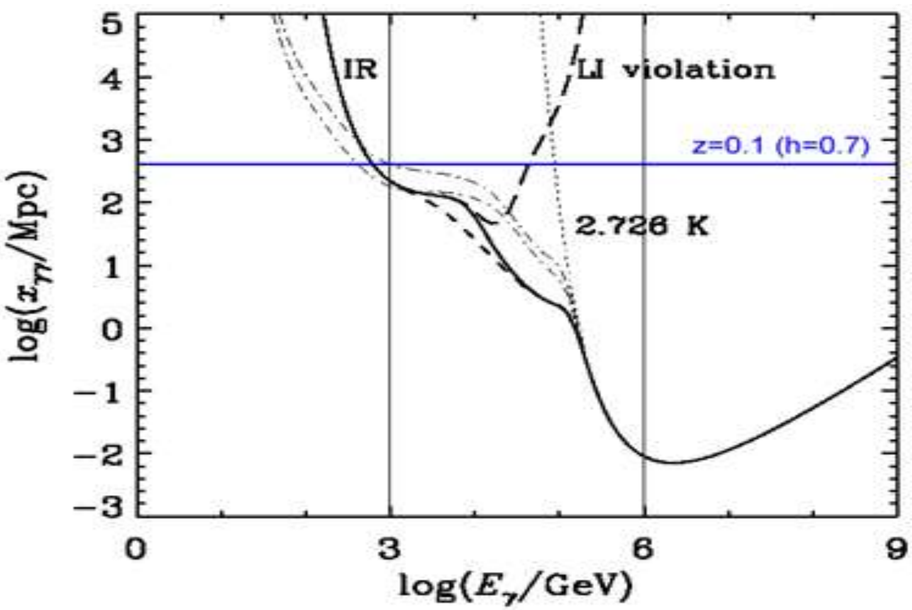
$$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^-$$

$$s = E_{TeV} E_{IR} (1 - \cos\theta) \geq (2 m_e c^2)^2$$

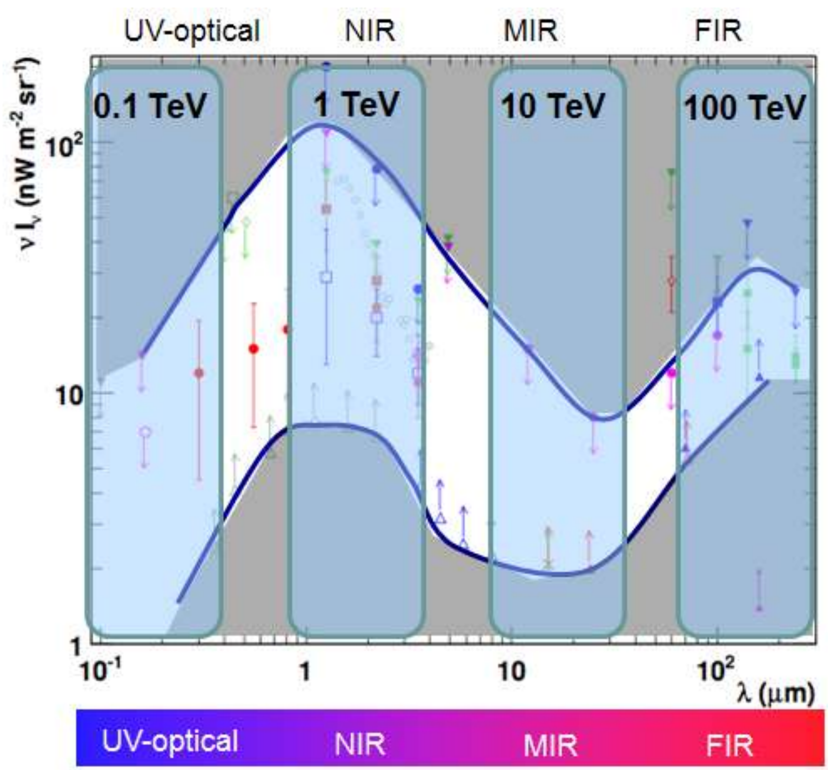
$$\therefore E_{TeV} \geq (2 m_e c^2)^2 / E_{IR}$$

$$\therefore E_{TeV}(\mathrm{TeV}) \geq 0.8 \lambda_{IR}(\mu \mathrm{m})$$

Mean free path for e^+e^- pair production



Protheroe & Meyer, Phys.Lett. B493 (2000) 1



EBL model by Stecker et al. (1992)

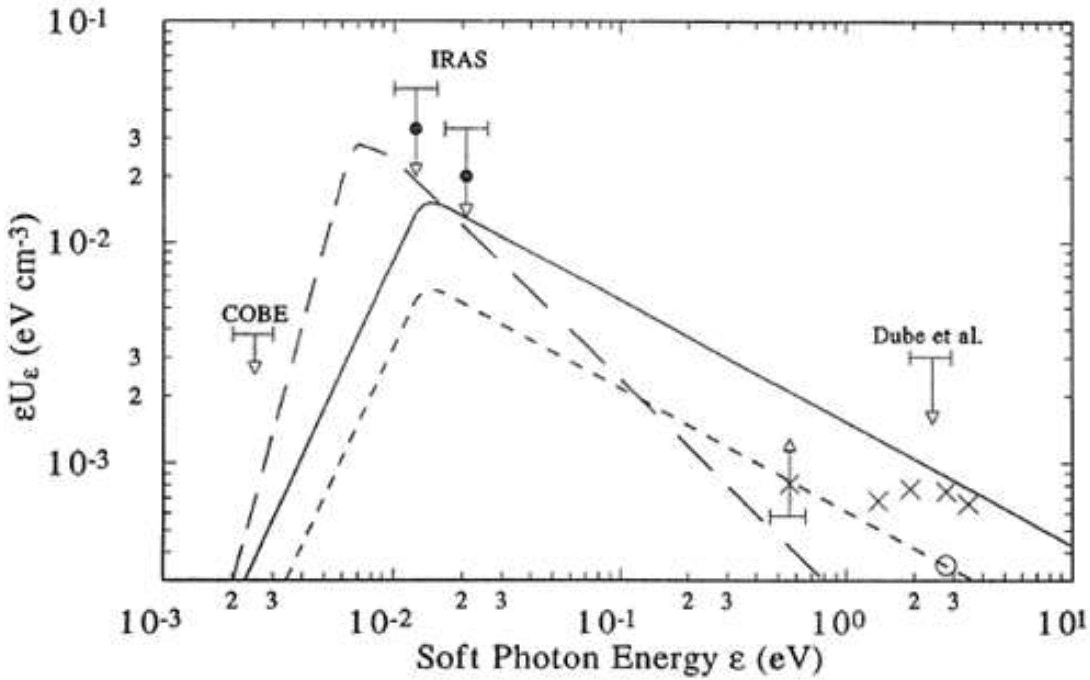


FIG. 1.—Extragalactic infrared background photon spectrum derived from evolving galaxies, Seyfert galaxies, and quasars is shown as a long-dashed line. The spectrum $n_{UL}(\epsilon)$ corresponding to the maximum contribution from normal galaxies is shown as a solid line, whereas the corresponding minimum contribution $n_{LL}(\epsilon)$ is shown as a short dashed line. The observed upper limits in the optical by Dube et al. (1979), and far infrared from *IRAS* (Boulanger & Perault 1988) and *COBE* (Mather et al. 1990) are also shown. The model estimates by Tyson (1990) are shown as crosses and that of Yoshii & Takahara (1988) by an open circle.

Stecker, De Jager & Salamon, ApJ 390, L49(1992)

EBL absorption by Stecker et al. (1992)

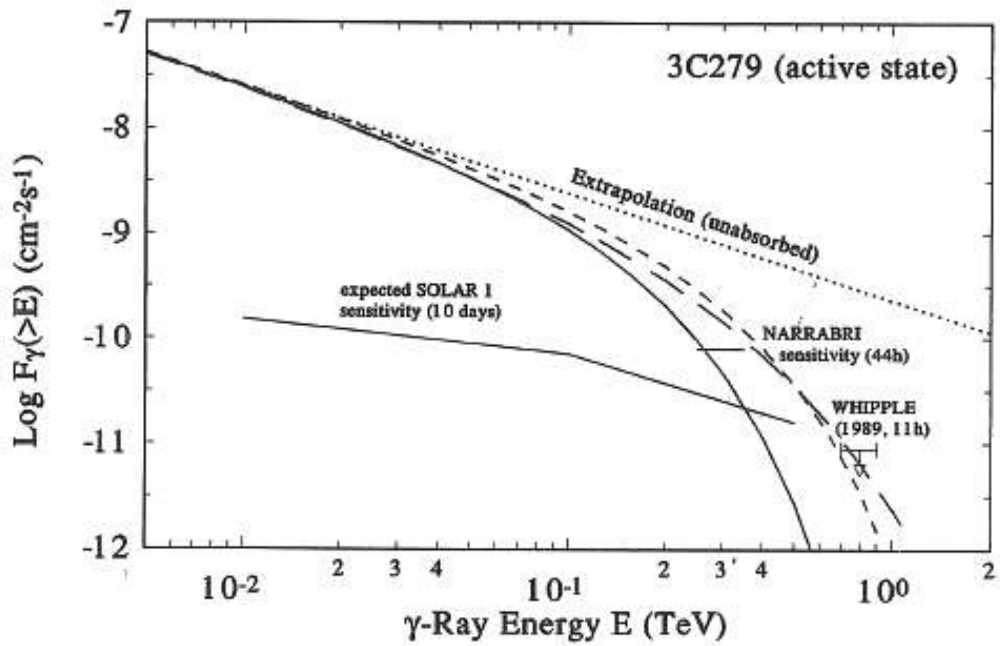
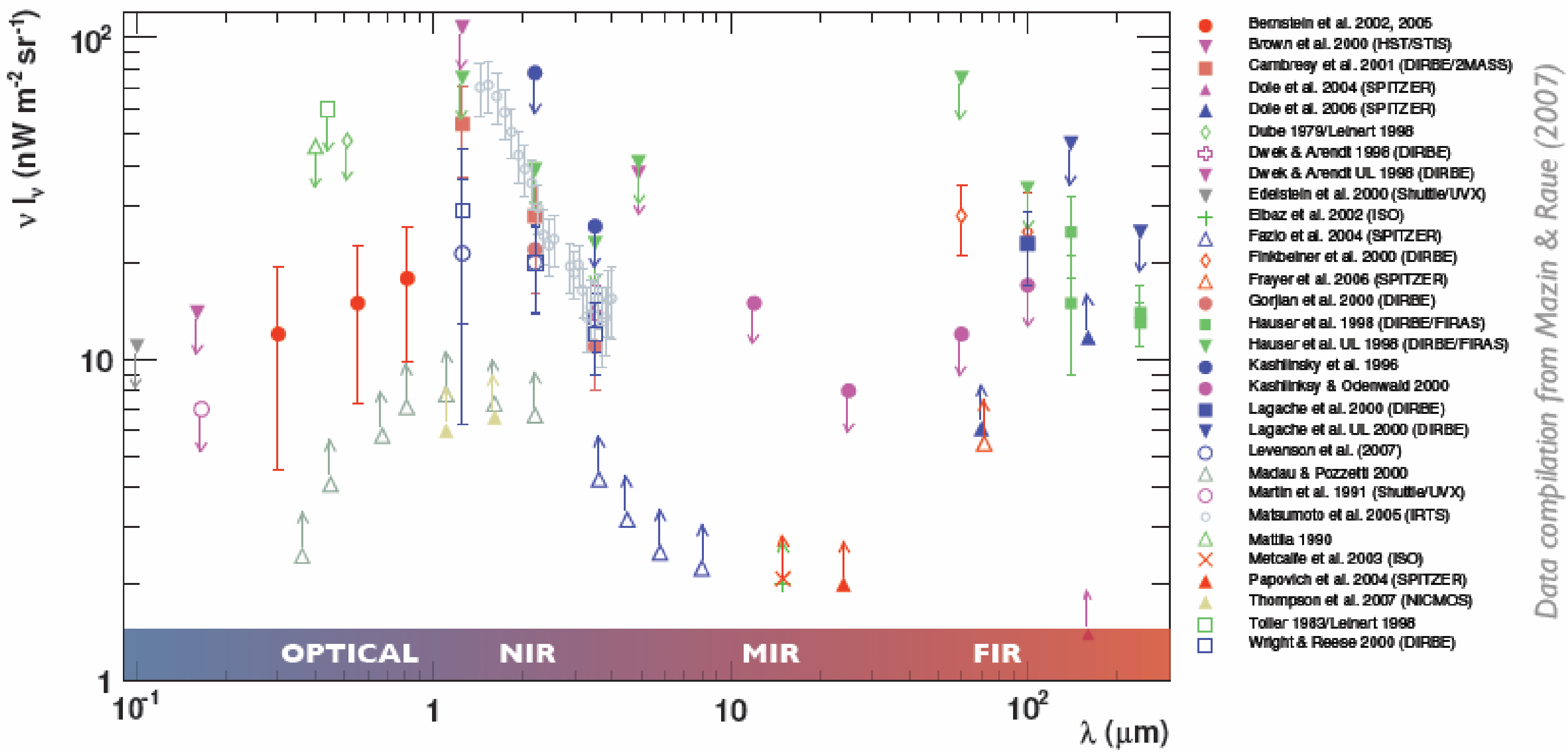


FIG. 2.—Extrapolated γ-ray spectrum of 3C 279 from the EGRET detection of 1991 June, but corrected for photon-photon absorption on the extragalactic background infrared radiation field described by eq. (7) (*solid line*) and eq. (8) (*short-dashed line*). The long-dashed line is for the energy independent value of $\epsilon U_\epsilon = 8 \times 10^{-4}$ eV cm^{-3} based on Tyson (1990) (see text). The short horizontal solid line represents the expected 3 σ sensitivity for 44 hr observation by the Narrabri detector at 300 GeV (Carramiñana et al. 1990). The Whipple upper limit (Vacanti et al. 1990) represents actual measurements of 3C 279 above 700 GeV during 1989. The expected sensitivity for a 10 day observation (raw data) by the proposed Solar One array (Tümer et al. 1991) is also shown.

Stecker, De Jager & Salamon, ApJ 390, L49(1992)

The Extragalactic Background Light (EBL)



- **Direct measurements difficult** especially in the MIR (dominant foregrounds)
- **Direct limits** from **source counts** (lower limits; LL) and fluctuation/direct measurements (upper limits; UL)
- Indirect measurements/limits through **attenuation imprint** on VHE γ-ray spectra

Stecker et al. 1992, review: Hauser & Dwek 2001, Dwek & Krennrich 2005, Aharonian et al. 2006 ... 3

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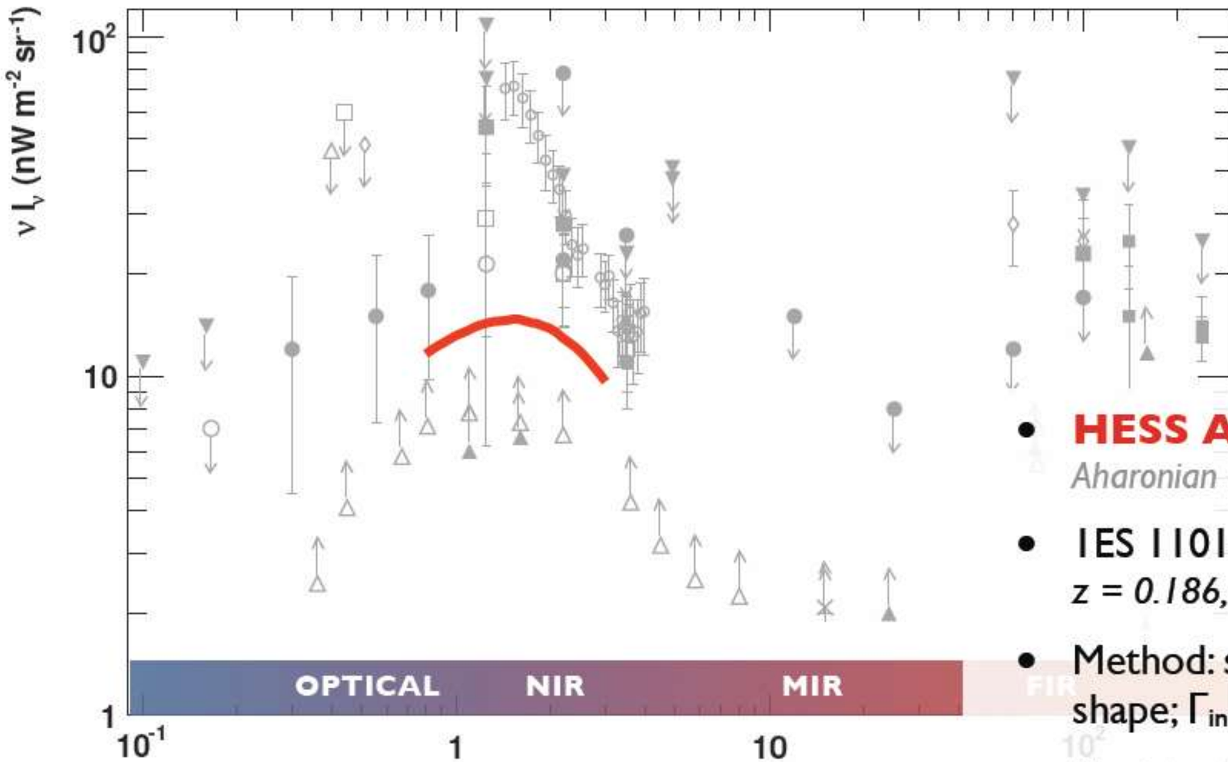
TeV gamma-ray limit: HESS A



- **HESS A**
  Aharonian et al. (2006)
- 1ES 1101-232
  $z = 0.186$, $dN/dE \sim E^{-\Gamma}$, $\Gamma \sim 3$, ~0.2-3 TeV
- Method: scaling of fixed EBL shape; $\Gamma_{intr} < 1.5$ ($dN/dE \sim E^{-\Gamma}$)
- Strongest limit in the NIR
  Excluding claimed NIR excess from Matsumoto et al. (2005)
- Confirmed by 1ES 0347-121
  Aharonian et al. (2007)

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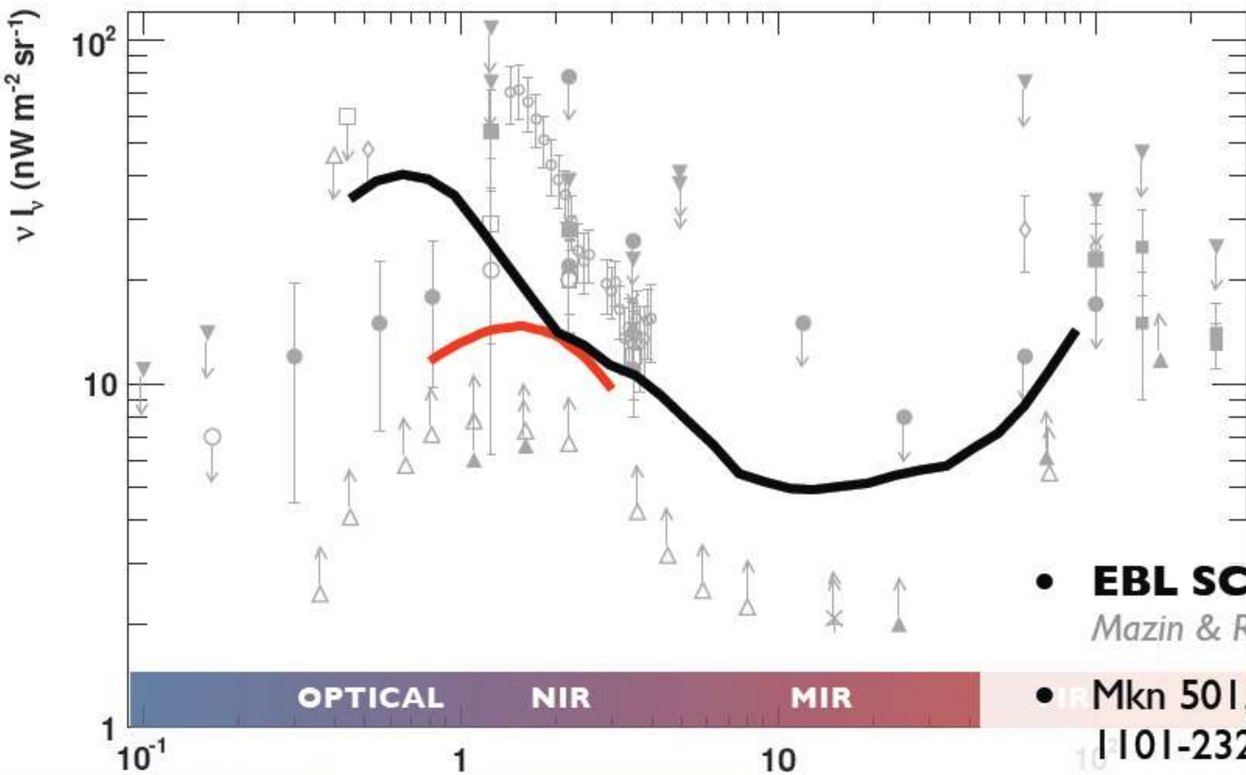
TeV gamma-ray limit: EBL scan



- **EBL SCAN**
  Mazin & Raue (2007)
- Mkn 501, H1426+428, 1ES 1101-232, ...
- Generic EBL shapes; $\Gamma_{intr} > 1.5$ + no exponential rise
- Limit over a wide EBL range
  NIR to FIR

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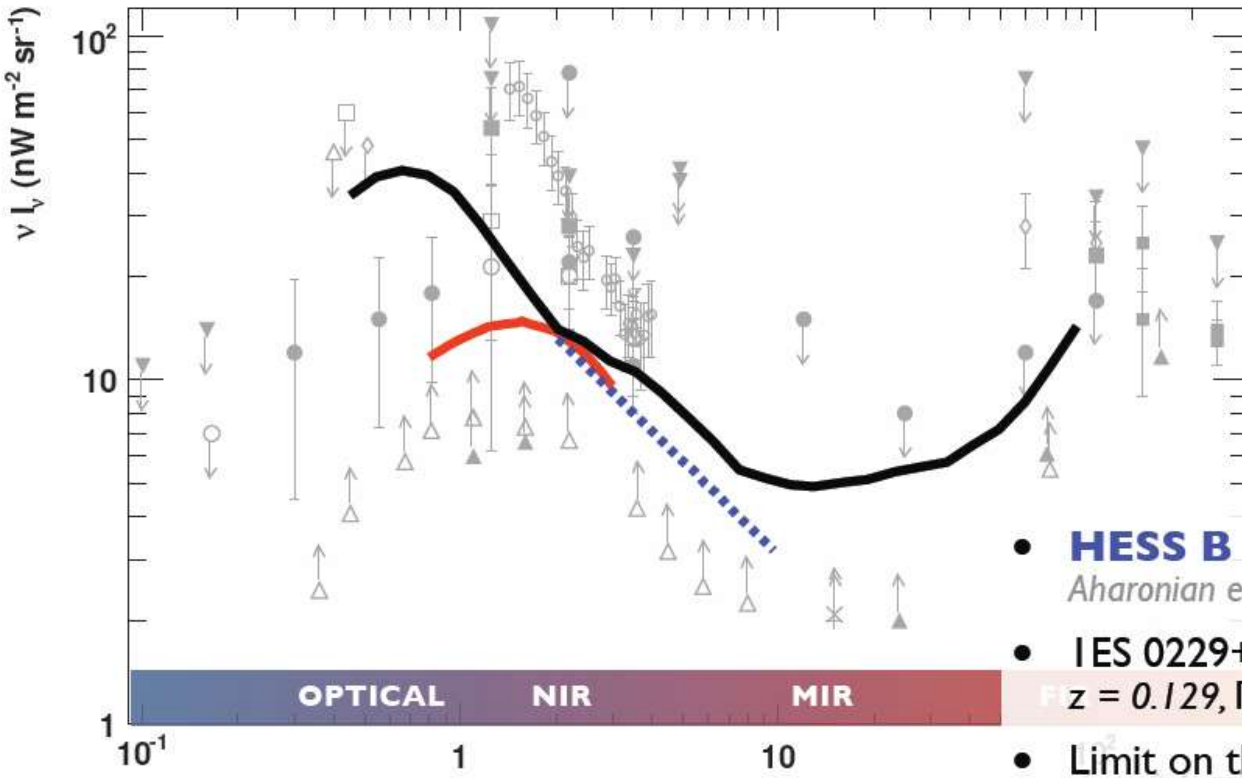
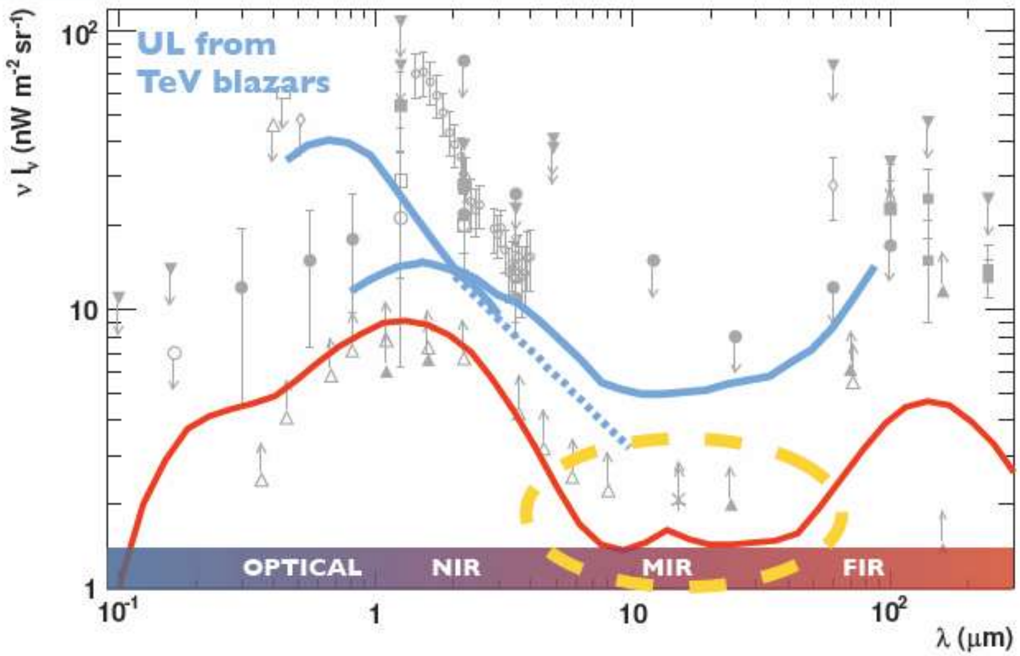
TeV gamma-ray limit: HESS B



- **HESS B**
  Aharonian et al. (2007), A&A submitted
- 1ES 0229+200 *(also H1426+428)*
  $z = 0.129, \Gamma \sim 2.5$, *~0.6 - 11 TeV*
- Limit on the **EBL slope** in the NIR-MIR, $\alpha > 1.1 \pm 0.25$ ($\nu I_\nu \sim \lambda^{-\alpha}$)
- Together with **HESS A**: EBL close source counts in the NIR-MIR

EBL model by Primack

EBL Models - Primack



- **PRIMACK**
  Primack et al. (2001,2004)
- **UL:** Ok. ✔
- **LL:** below source counts in the MIR/FIR ✘

7

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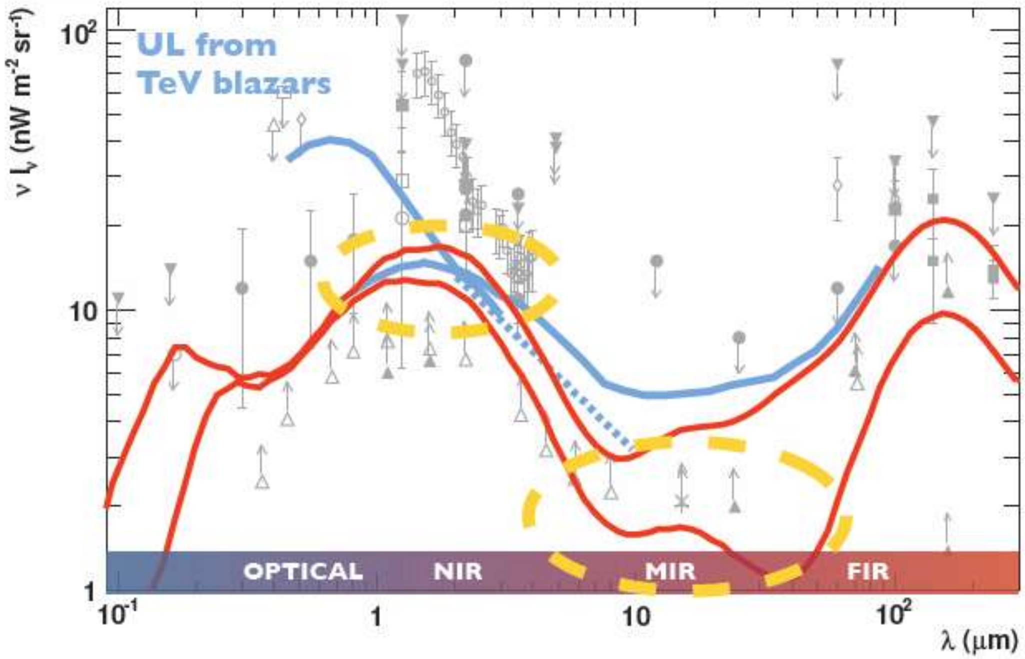
EBL model by Kneiske

EBL Models - Kneiske



- **KNEISKE**
  Kneiske et al. (2002,2004)
- high / low model
- **UL:** above VHE blazar UL ✗ / Ok. ✔
- **LL:** Ok. ✔ / below source counts in the MIR ✗

8

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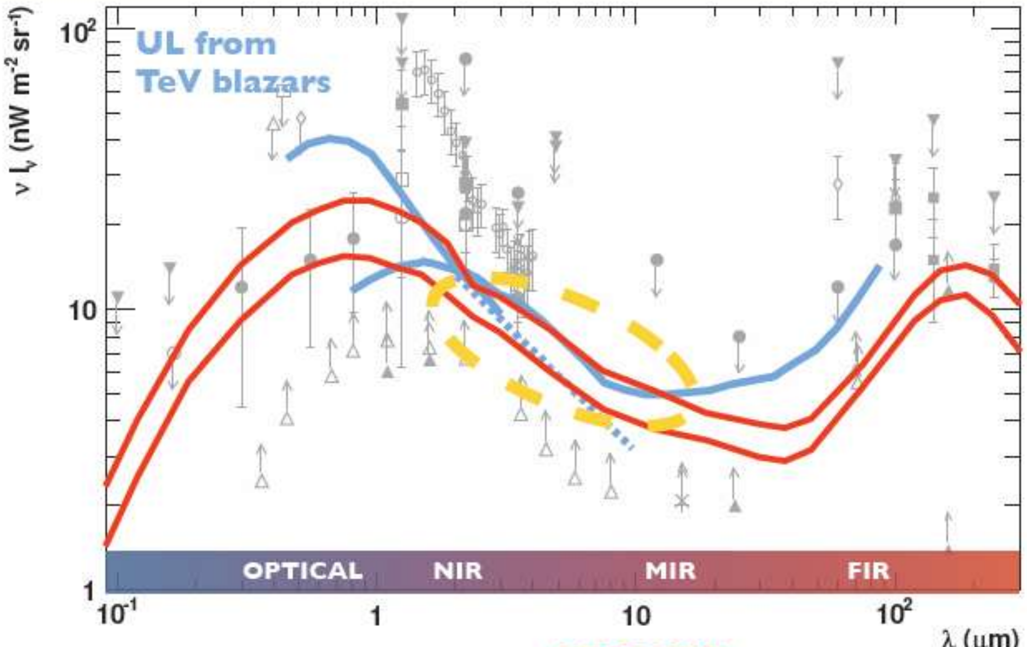
EBL model by Stecker

EBL Models - Stecker



- **STECKER**
  Stecker et al. (2006)
- fast evolution / baseline model
- UL: (marginal above TeV blazar UL ✗) / Ok. ✔
  BUT: NIR-MIR slope in conflict with HESS B UL ✗ ✗
- LL: Ok. ✔ / Ok. ✔

9

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Comparison of EBL models

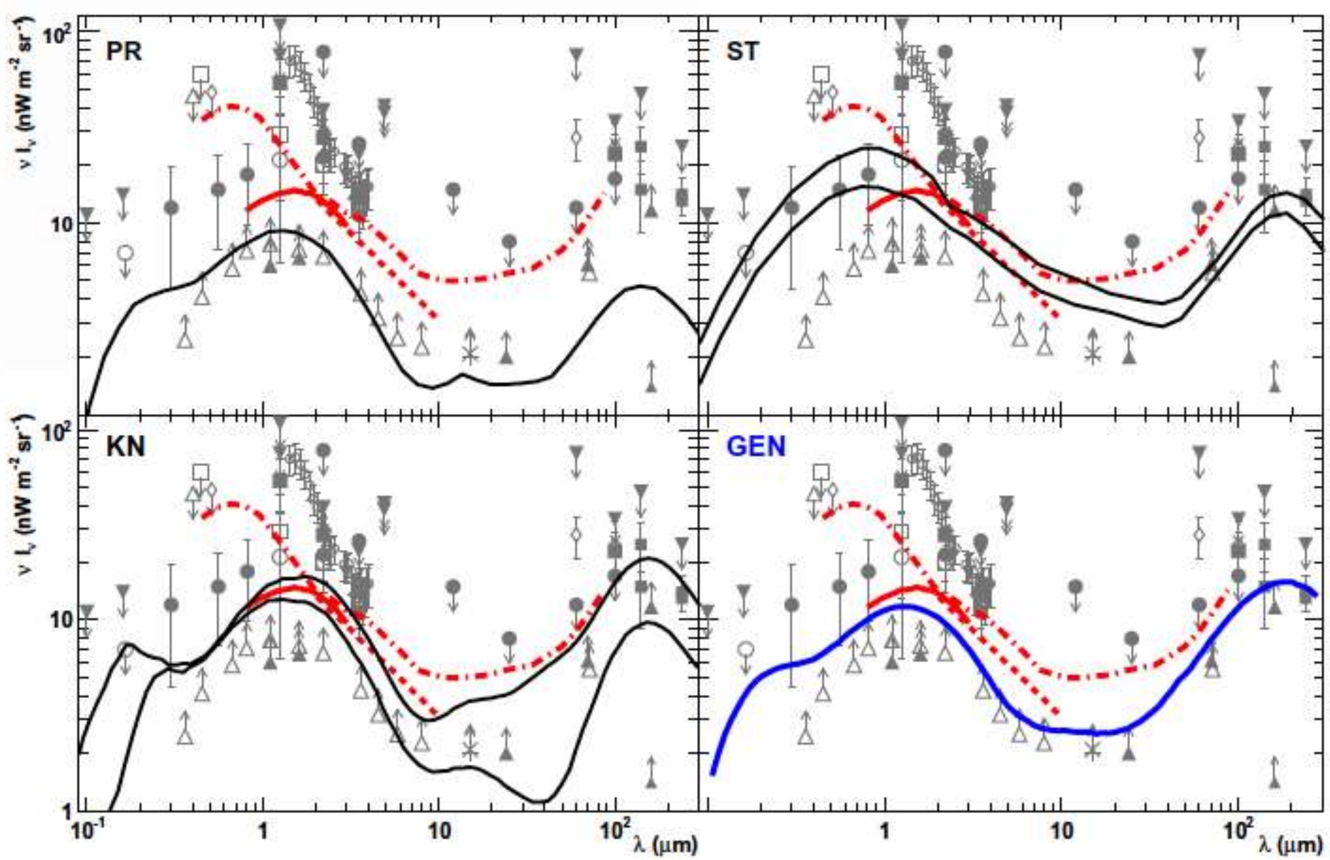

Fig. 1. EBL models versus EBL limits. Black solid curves show different EBL models for $z = 0$. Grey markers are measurements and limits from direct measurements, fluctuation analysis and from source counts (data compilation from [9]). Red curves are upper limits derived from VHE γ-ray spectra (solid [7], dashed [8], dashed-dotted [9]). *Upper-Right:* EBL model from [10]. *Upper-Left:* Fast evolution and baseline models from [11]. *Lower-Left:* Updated high and low models from [12]. *Lower-Right:* Generic EBL proposed in this paper (blue curve).

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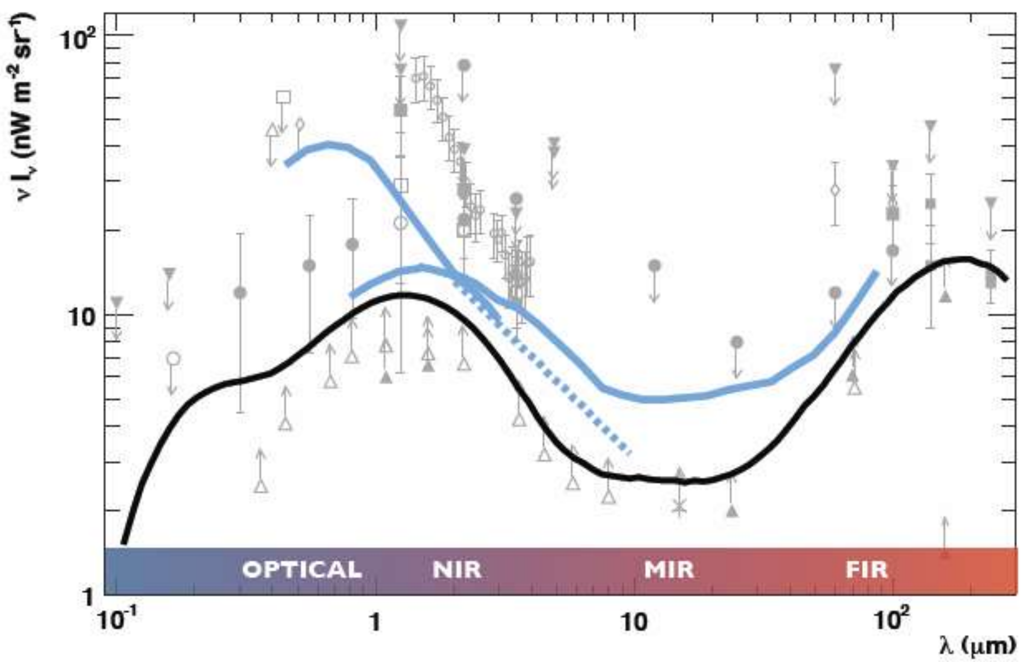
"Generic" EBL

Generic EBL Shape

- Many current EBL models in contradiction with UL or/and LL
- New **generic EBL shape** (at z=0) in compliance with limits (close to LL)
- EBL evolution? ⇒ Generic EBL evolution (next slide)



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10

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Cross section

The cross section for the $\gamma+\gamma \rightarrow e^{+}+e^{-}$ interaction of a γ-ray photon of energy E_γ emitted from a source at redshift z with a background photon of energy ϵ is given by (e.g., Jauch & Rohrlich 1955)

$$\sigma_{\gamma\gamma}(E_\gamma,\ \epsilon,\ \mu) = \frac{3\sigma_T}{16}(1-\beta^2) \times \left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right],$$

$$\beta \equiv \sqrt{1-\frac{\epsilon_{th}}{\epsilon}},$$

$$\epsilon_{th}(E_\gamma,\ \mu) = \frac{2\,(m_e c^2)^2}{E_\gamma\,(1-\mu)}, \qquad (1)$$

where $\sigma_T = 6.65\times10^{-25}$ cm^2 is the Thompson cross section, ϵ_{th} the threshold energy of the interaction, and $\mu \equiv \cos\theta$, where θ is the angle between the incident photons. The γ-γ cross section for the interaction with an isotropic distribution of background photons has a peak value of 1.70×10^{-25} cm^2 for $\beta = 0.70$, which corresponds to energies for which the product $E_\gamma\epsilon \approx 4\,(m_e c^2)^2 \approx 1$ MeV^2, or $\lambda_\epsilon\,(\mu\text{m}) \approx 1.24 E_\gamma\,(\text{TeV})$, where λ_ϵ is the wavelength of the background photon.

Dwek & Krennrick, ApJ 618, 657 (2005)

Approximation by Aharonian (2004)

$$\sigma_{\gamma\gamma} = \frac{3\sigma_T}{2s_0^2}\left[\left(s_0+\frac{1}{2}\ln s_0-\frac{1}{6}+\frac{1}{2s_0}\right)\ln(\sqrt{s_0}+\sqrt{s_0-1}) - \left(s_0+\frac{4}{9}-\frac{1}{9s_0}\right)\sqrt{1-\frac{1}{s_0}}\right].$$

$$s_0 = \varepsilon_\gamma\omega_0$$

Optical depth

The optical depth traversed by a photon observed at energy E_γ that was emitted by a source at redshift z is given by

$$\tau_\gamma(E_\gamma, z) = \int_0^z \left(\frac{dl}{dz'}\right) dz' \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{th}}^{\infty} d\epsilon' n_\epsilon(\epsilon', z') \sigma_{\gamma\gamma}(E'_\gamma, \epsilon', \mu), \quad (2)$$

where $n_\epsilon(\epsilon', z')d\epsilon'$ is the comoving number density of EBL photons with energies between ϵ' and $\epsilon' + d\epsilon'$ at redshift z', $\epsilon'_{th} = \epsilon_{th}(E'_\gamma, \mu)$, $E'_\gamma = E_\gamma(1+z')$, and where dl/dz is given by (e.g., Peacock 1999)

$$\left(\frac{dl}{dz}\right) = c\left(\frac{dt}{dz}\right) = \frac{R_H}{(1+z)E(z)}$$

$$E(z) \equiv \{(1+z)^2(\Omega_m z + 1) + z(2+z)[(1+z)^2\Omega_r - \Omega_\Lambda]\}^{1/2},$$

where Ω_m and Ω_r are, respectively, the matter and radiation energy density normalized to the critical density, $\Omega_\Lambda = \Lambda/3H_0^2$ is the dimensionless cosmological constant ($\Omega_m + \Omega_r + \Omega_\Lambda = 1$ in a flat universe), $R_H \equiv c/H_0$ is the Hubble radius, c is the speed of light, and H_0 is the Hubble constant, taken here to be 70 km s^{-1} Mpc^{-1}. The comoving number density of EBL photons of energy ϵ at redshift z is given by

$$\epsilon^2 n_\epsilon(\epsilon, z) = \left(\frac{4\pi}{c}\right)\nu I_\nu(\nu, z) = \int_z^\infty \nu' L_\nu(\nu', z') \left|\frac{dt}{dz'}\right| \frac{dz'}{1+z'}, \quad (4)$$

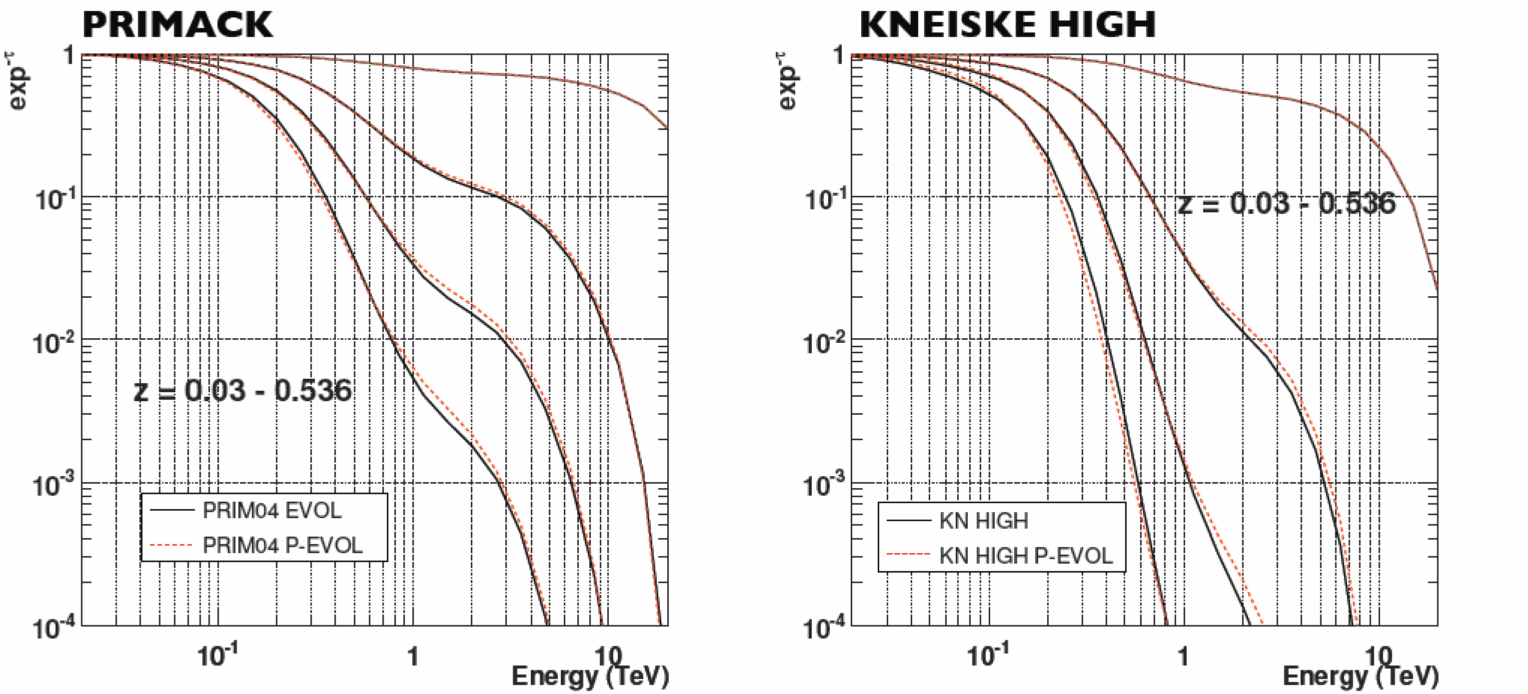
where $\epsilon = h\nu$, $\nu' = \nu(1+z')$, and $L_\nu(\nu', z')$ is the specific comoving luminosity density at frequency ν' and redshift z'.

If z<<1, $\int_0^z dl(z') = \int_0^z \frac{R_H}{1+z'} dz = R_H \log(1+z)$

Dwek & Krennrick, ApJ 618, 657 (2005)

EBL evolution

- Photon number density scales cosmologically $(1 + z)^n$ with n = 3
- Use $n = (3 - f_{EVO})$ with e.g. $f_{EVO} = 1.2$ *(L. Costamante priv. com.)*
- Model EBL evolution / generic EBL evolution



$z = \{0.03, 0.199, 0.34, 0.536\}$

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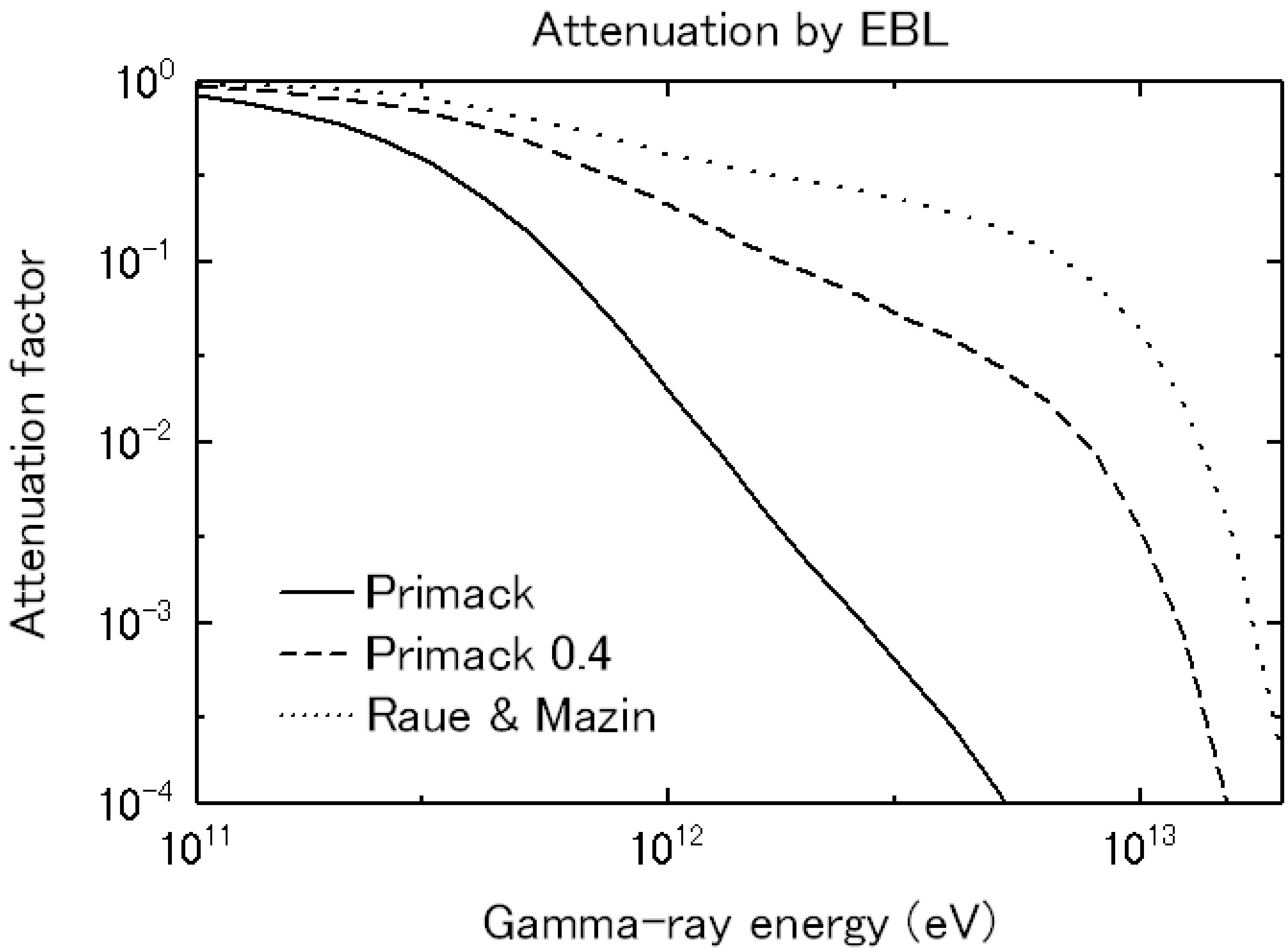
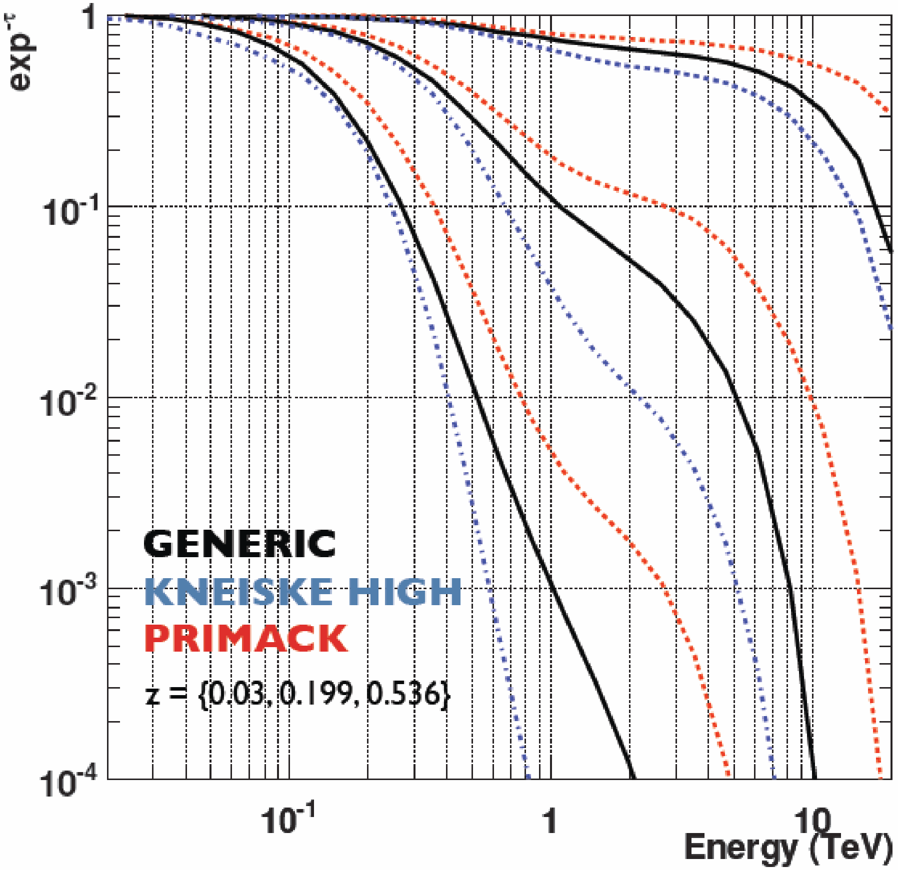
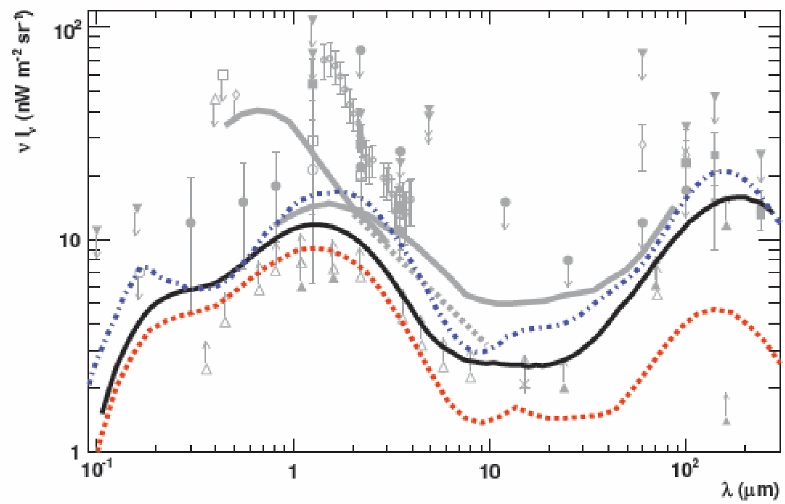
Calculation

$$F_{abs}(E) = F_{int}(E)\, e^{-\tau_\gamma(E)}$$



Attenuation: comparison of models

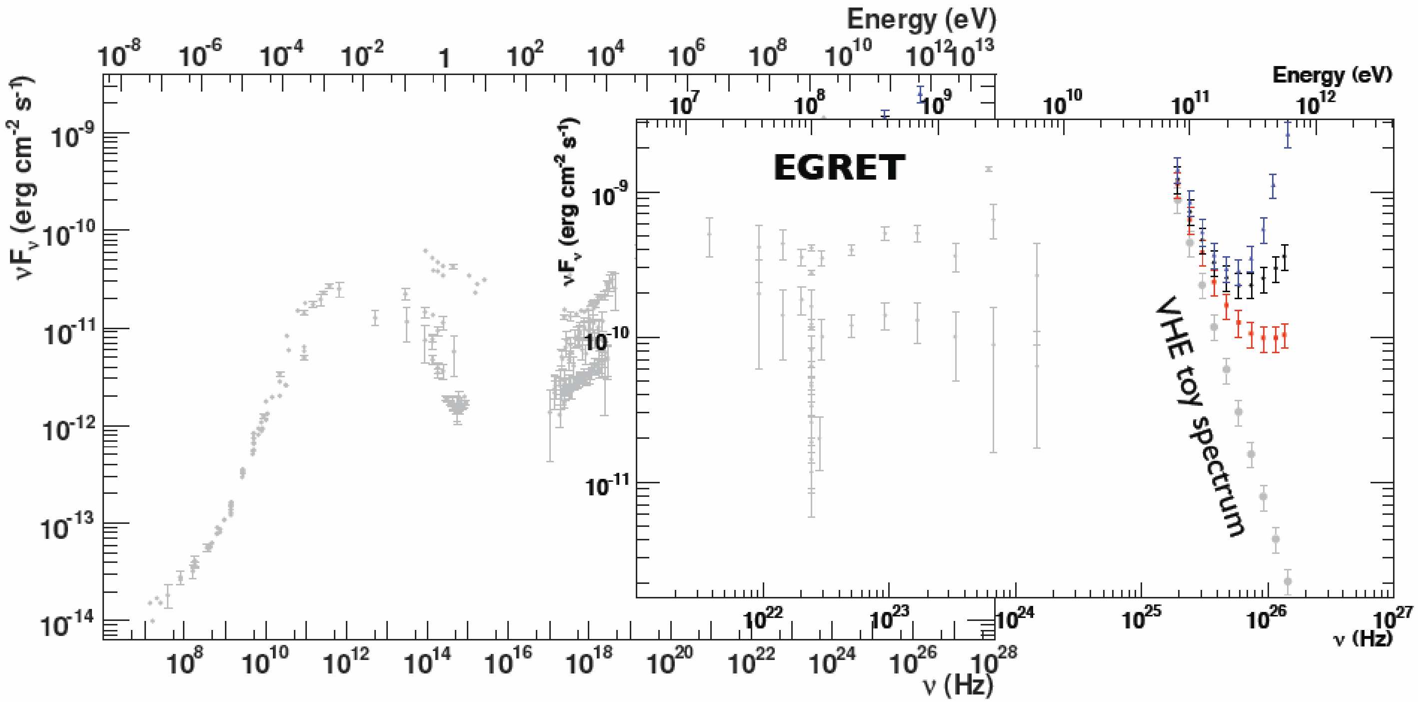




- Attenuation tables for different redshifts and energy ranges (soon): http://www.desy.de/~mraue/ebl/
- Use to calculate source fluxes / spectra /modeling ...
- Other generic EBL shapes (double hump in the MIR ...)

The case of 3C279 (z=0.536)

- MAGIC claimed VHE detection (80-600 GeV) during flare in one night Feb 22, 2006
  Teshima et al., ICRC (2007)
- Very distant source (z=0.536)! Plausible? → Toy VHE spectrum
  F(E>200GeV) = 15% Crab, 0.08-0.6 TeV, assume: E ~ $E^{-\Gamma}$, Γ=5



Detection plausible with EBL at lower limits

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Conclusion

- **EBL limits from VHE γ-ray spectra**
  - Recent discoveries of distant source of VHE γ-rays with hard spectra (1ES 1101-121, 1ES 0347-121, 1ES 0229+200)
  - Strong upper limits (UL) on the EBL in the NIR to MIR
  - (new/different blazar physics)
- **EBL models vs limits**
  - Current popular models have problems either with UL from VHE γ-ray data
    or with lower limits from source counts
  - New models needed?
    → for now: **generic EBL shape with generic EBL evolution**
    http://www.desy.de/~mraue/ebl/
- **• 3C 279 (z =0.536)**
  - VHE detection claimed by MAGIC (~80-600 GeV) during one night in 2006
  - Seems possible with soft spectra (Γ~4-5) and EBL at lower limits.

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