The Abdus Salam
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United Nations
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International Atomic Energy Agency

2246-16

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Restricting cosmogenic neutrino fluxes with Fermi 3 years data

Oleg KALASHEV
Institute for Nuclear Research
Moscow

NUSKY 11, Trieste June 22, 2011

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** e-mail: kalashev@ms2.inr.ac.ru*

Restricting cosmogenic neutrino fluxes

Some works on the subject:

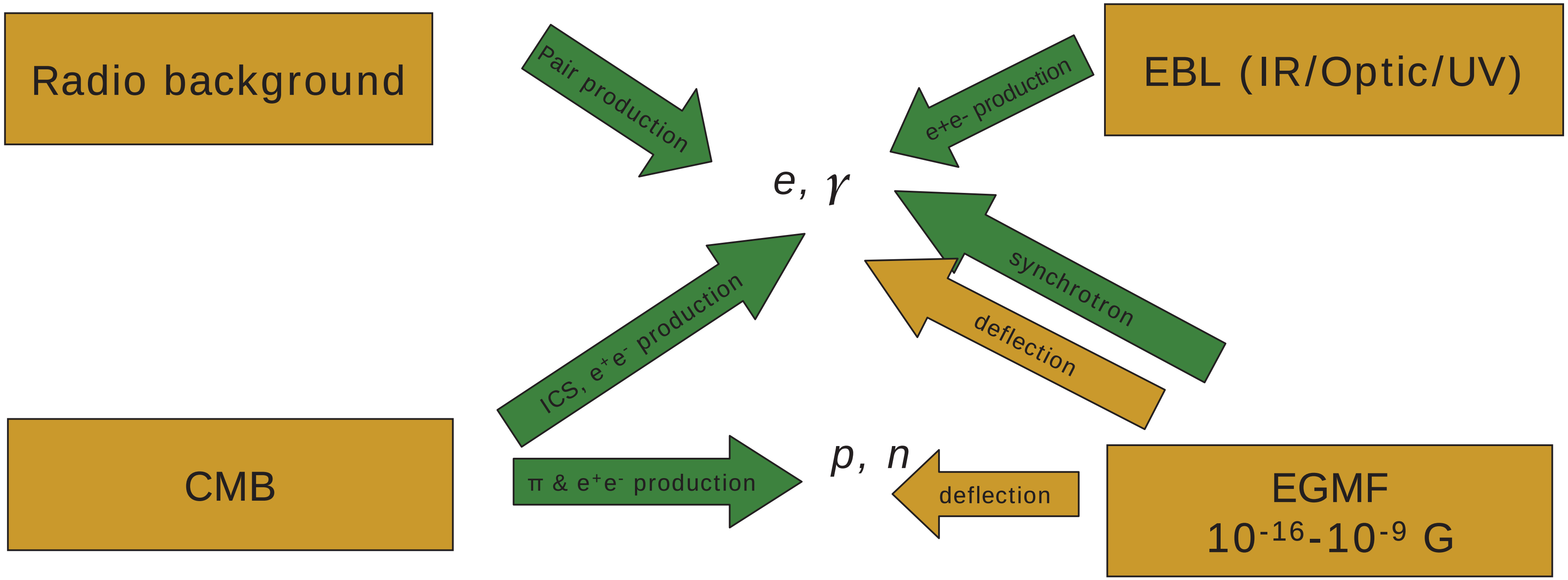
- V. S. Berezinsky and A. Yu. Smirnov, Astrophys. Sp. Sci. 32 461 (1975)
- M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen and S. Sarkar, Astropart. Phys. 34, 106 (2010) [arXiv:1005.2620 [astro-ph.HE]]
- V. Berezinsky, A. Gazizov, M. Kachelriess and S. Ostapchenko, Phys. Lett. B 695, 13 (2011) [arXiv:1003.1496 [astro-ph.HE]]
- X. Wang, R. Liu, F. Aharonian, arXiv:1103.3574 [astro-ph.HE]

Restricting cosmogenic neutrino fluxes with Fermi 2.5 years data

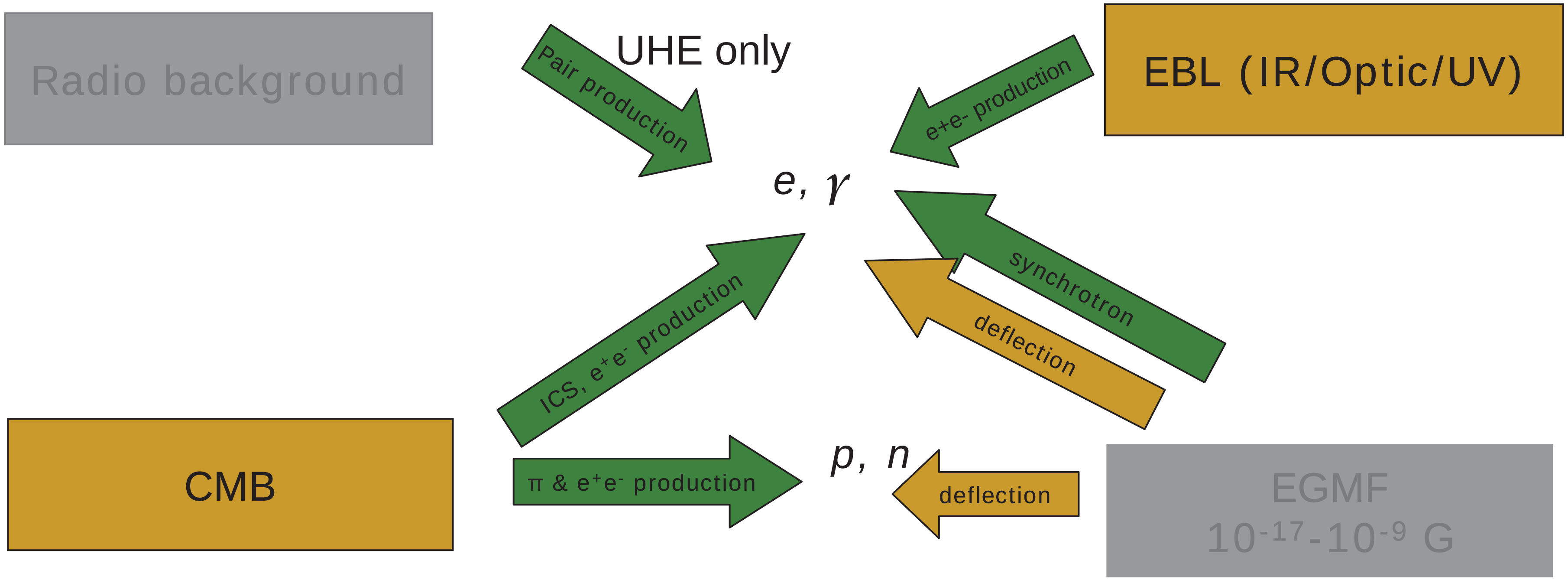
Overview

- Propagation of Ultra High Energy Cosmic Rays (UHECR)
- Fitting HiRes spectrum by models with proton primaries
- Secondary photons and limit on the diffuse gamma ray flux from FERMI LAT
- Secondary neutrino fluxes
- Conclusion

Main Factors influencing UHECR and γ-ray propagation

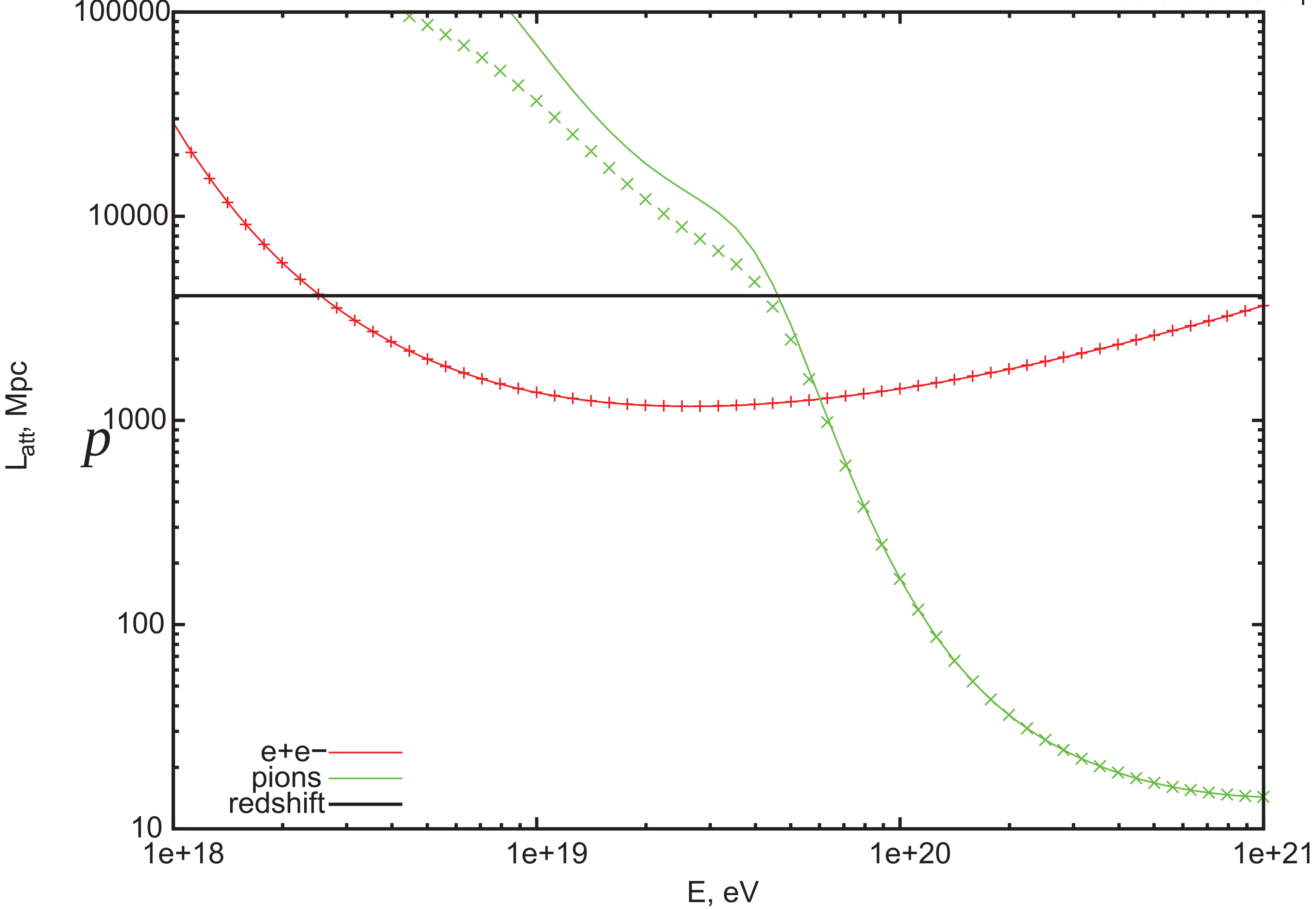


Main Factors influencing UHECR and γ-ray propagation



Attenuation lengths

IR/Optic background models used here:
F.Stecker et al. astro-ph/0510449 (solid line)
Kneiske et al. astro-ph/1001.2132v1 (dotted line)



Simulations of cosmic rays propagation

- Monte Carlo based simulations
  - Random extragalactic magnetic field is taken into account
- Transport equation approach (rectlinear propagation)
  - Fast calculation (good for parameter space scanning)
  - Gives reasonable result for homogeneous source distribution with density $n \geq 10^{-4} Mpc^{-3}$ for energies

$$E \geq 10^{18} eV \times Z \times \frac{B}{10^{-10} G}, \qquad L_{cor} = 1 Mpc$$

Fitting experimental data

- Energy spectrum j(E)
  - Binned maximum likelihood function is used
  - Poisson probability of the observed event set is maximized

$$L(\mathbf{n};\,\boldsymbol{\nu}) = \prod_{i}^{N} \frac{\nu_i^{n_i}}{n_i} e^{\nu_i}$$

  - Goodness of fit defined as fraction of hypothetical experiments which result in worse agreement with the theory than the real data having the same total number of events

Phenomenological source model:

$F(E, z) = \Phi(E)\, S(z)$; $\Phi(E) = f\, E^{-\alpha}\, Exp(-E/E_{max})\, Exp(-E_{min}/E)$

$S(z) = (1+z)^m \Theta(z-z_{min})\, \Theta(z_{max}-z)$

z – red shift, $\Theta(x)$-step function

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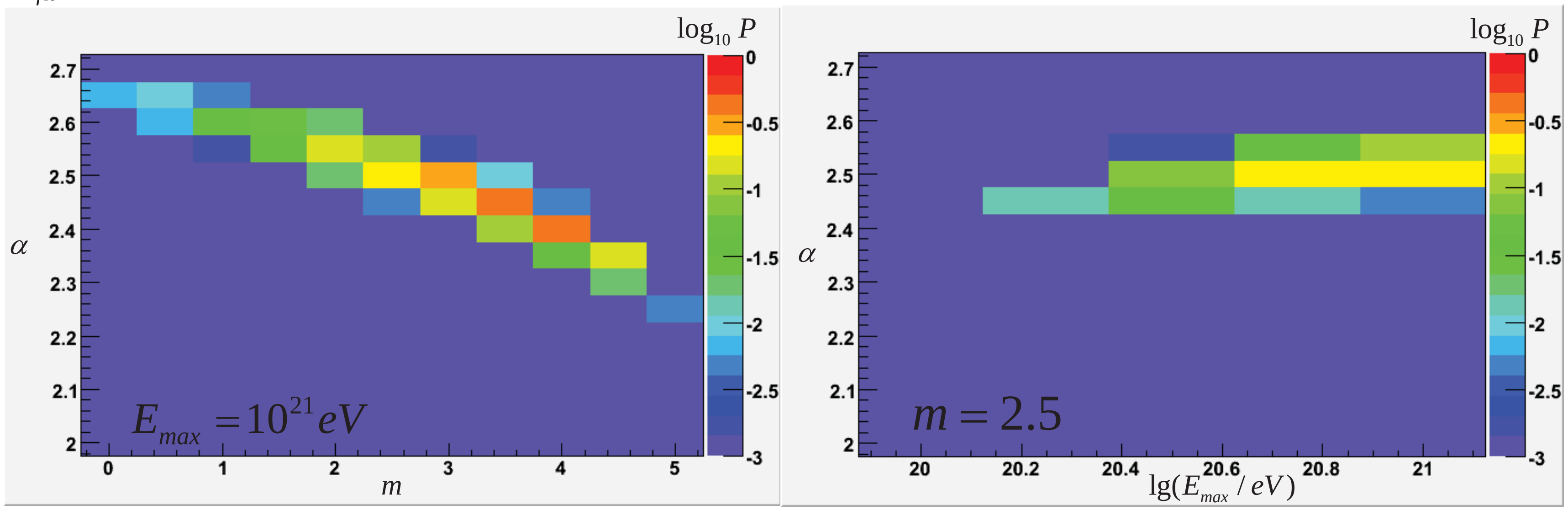
$S(z) = (1+z)^m \Theta(z-z_{min})\, \Theta(z_{max}-z)$

z – red shift, $\Theta(x)$-step function

Parameter	Name	Typical Values
Power of the Injection Spectrum, $E^{-\alpha}$	α	$2 \leq \alpha \leq 2.7$
End point of the Energy Spectrum	E_{max}	$10^{20} \leq E_{max}/eV \leq 10^{21}$
Evolution factor: $(1+z)^{3+m}$	m	$0 \leq m \leq 5$
Red shift of the nearest source	z_{min}	$0 < Z_{min} < 0.01$
Maximal source redshift	z_{max}	$Z_{max} = 2$
Minimal injection spectrum energy	E_{min}	10^{17}eV

Goodness of fit plots HiRes Spectrum

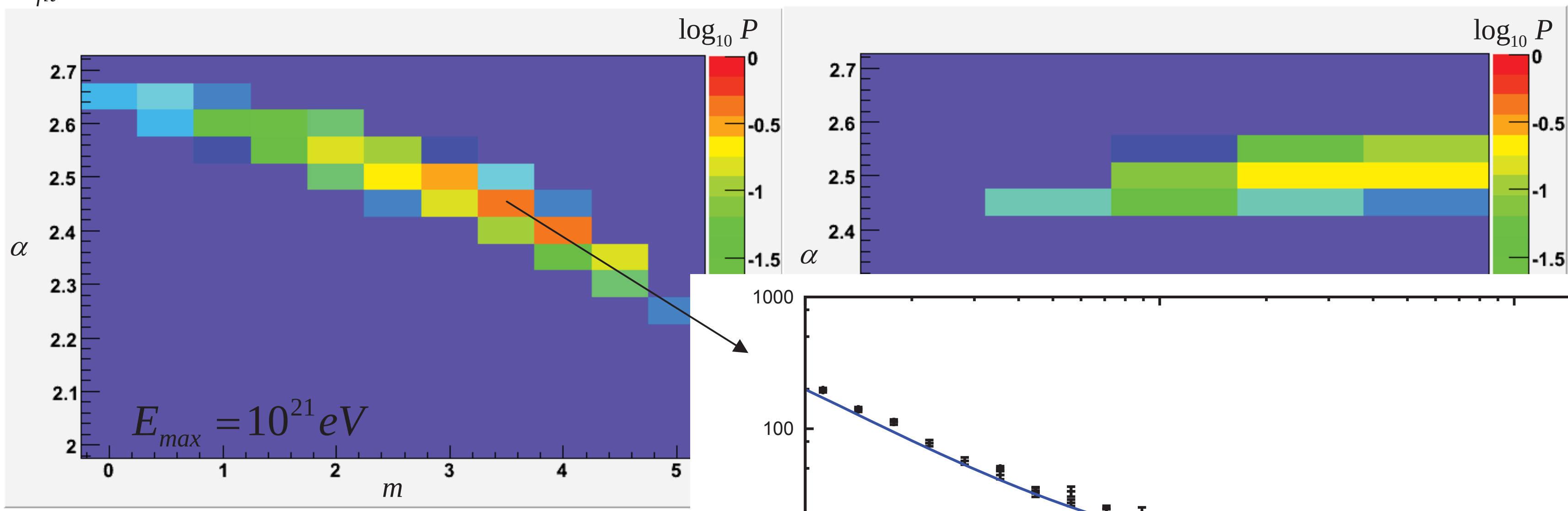
$E_{fit} > 10^{18} eV$

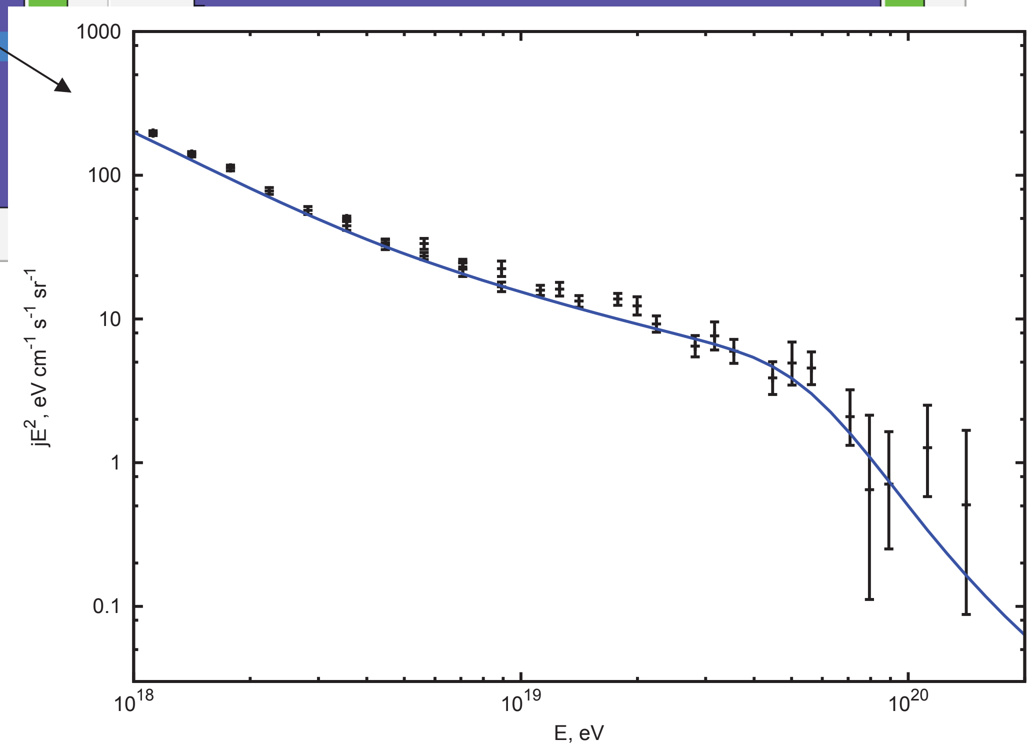


$z_{min} = 0.00125 \quad (\sim 5 Mpc)$

HiRes Spectrum fit example

$E_{fit} > 10^{18} eV$





$$\alpha = 2.45$$

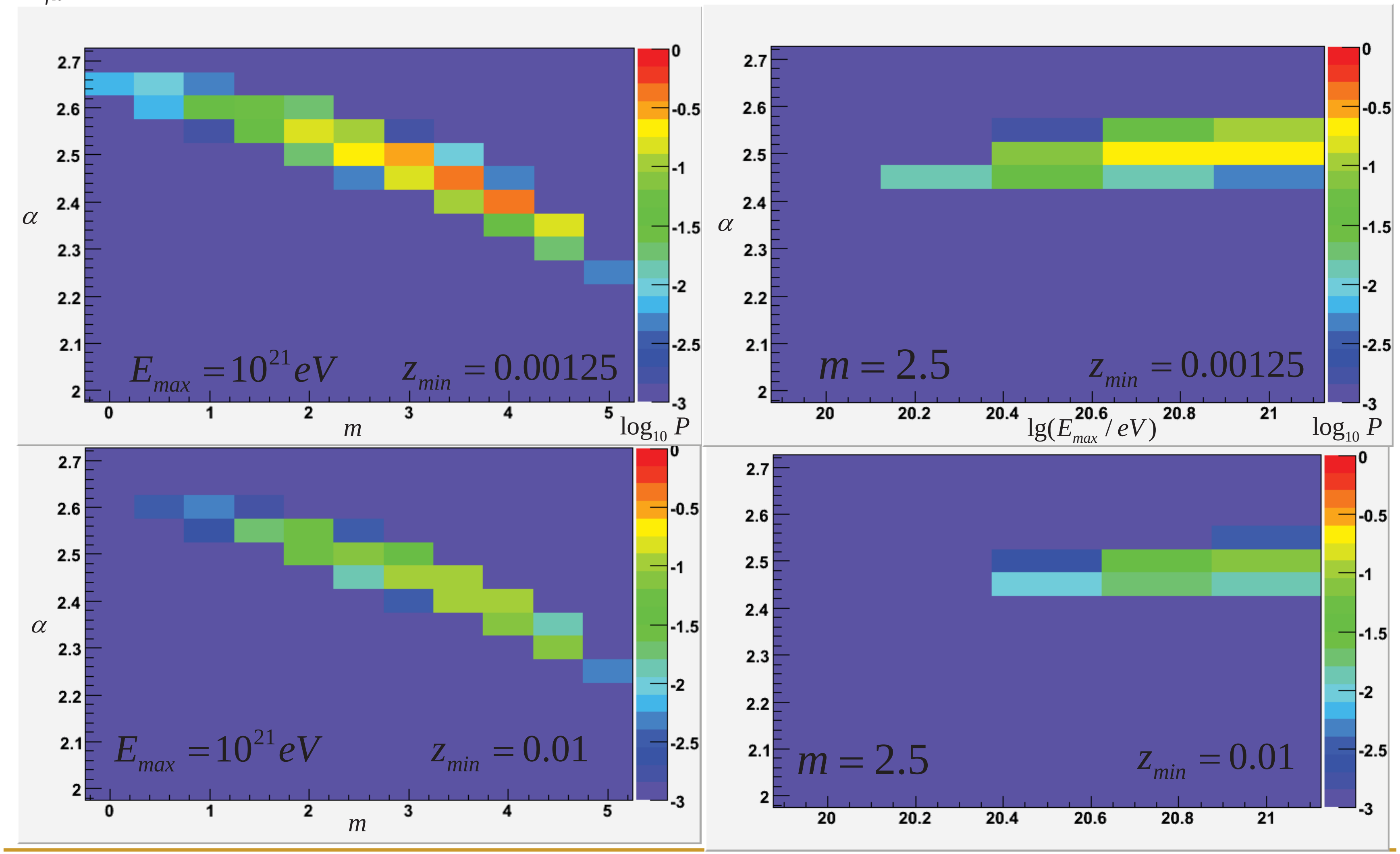
$$m = 3.5$$

$$E_{max} = 10^{21} eV$$

$$Z_{min} = 0.00125$$

Goodness of fit plots HiRes Spectrum

$E_{fit} > 10^{18} eV$



Sample source evolution models

Star Formation Rate: H. Yuksel, M. D. Kistler, J. F. Beacom and A. M. Hopkins, Ap. J. 638 L5 (2008)

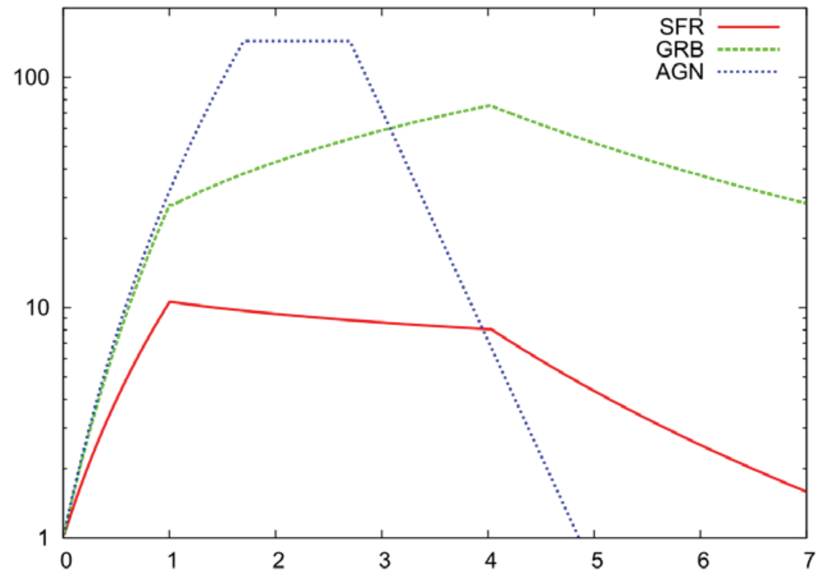
$$S_{SFR}(z) \propto \begin{cases} (1+z)^{3.4}, & z < 1 \\ (1+z)^{-0.3}, & 1 < z < 4 \\ (1+z)^{-3.5}. & z > 4 \end{cases}$$

GRB: H. Yuksel and M.D. Kistler Phys. Rev. D 75, 083004 (2007)

$$S_{\rm GRB}(z) \propto \begin{cases} (1+z)^{4.8}, & z < 1 \\ (1+z)^{1.1}, & 1 < z < 4 \\ (1+z)^{-2.1}. & z > 4 \end{cases}$$

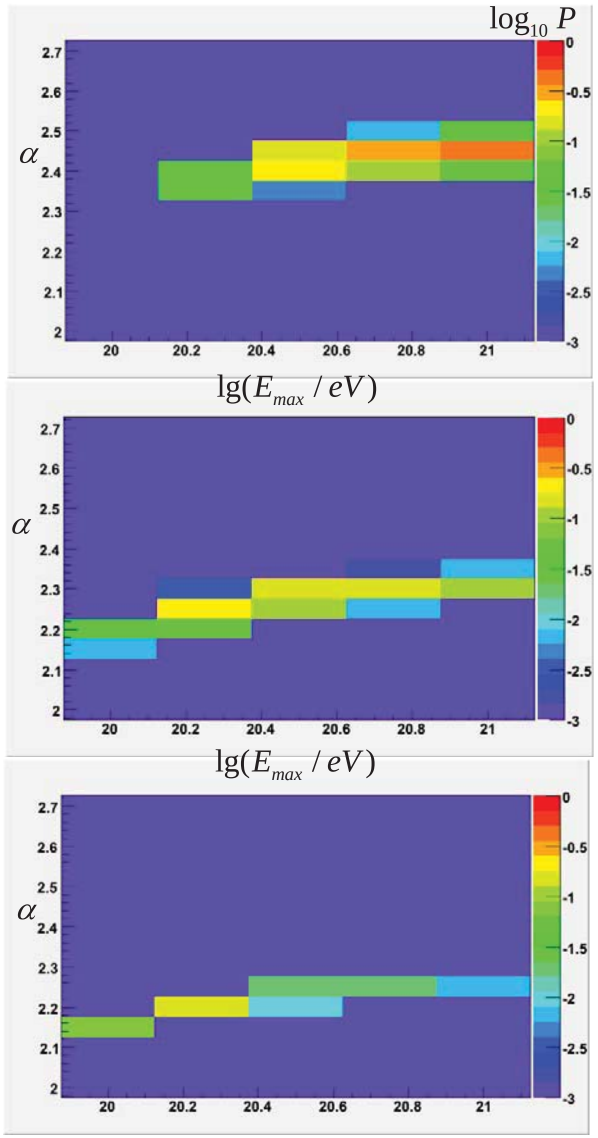
AGN: G. Hasinger, T. Miyaji, M. Schmidt, Astron. and Astroph. 441 417 (2005); M. Ahlers, L. A. Anchordoqui and S. Sarkar, Phys. Rev. D 79, 083009 (2009)

$$S_{\rm AGN}(z) \propto \begin{cases} (1+z)^{5.0}, & z < 1.7 \\ \text{constant}, & 1.7 < z < 2.7 \\ 10^{(2.7-z)}. & z > 2.7 \end{cases}$$



Sample source evolution models

$z_{min} = 0.00125$



Star Formation Rate: *H. Yuksel, M. D. Kistler, J. F. Beacom and A. M. Hopkins, Ap. J. 638 L5 (2008)*

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Fermi Gamma-ray Space Telescope

Energy range (LAT): 20 MeV - 300 GeV

Field of view: 20% of the sky at any instant; expose all parts of sky for ~30 minutes every 3 hours

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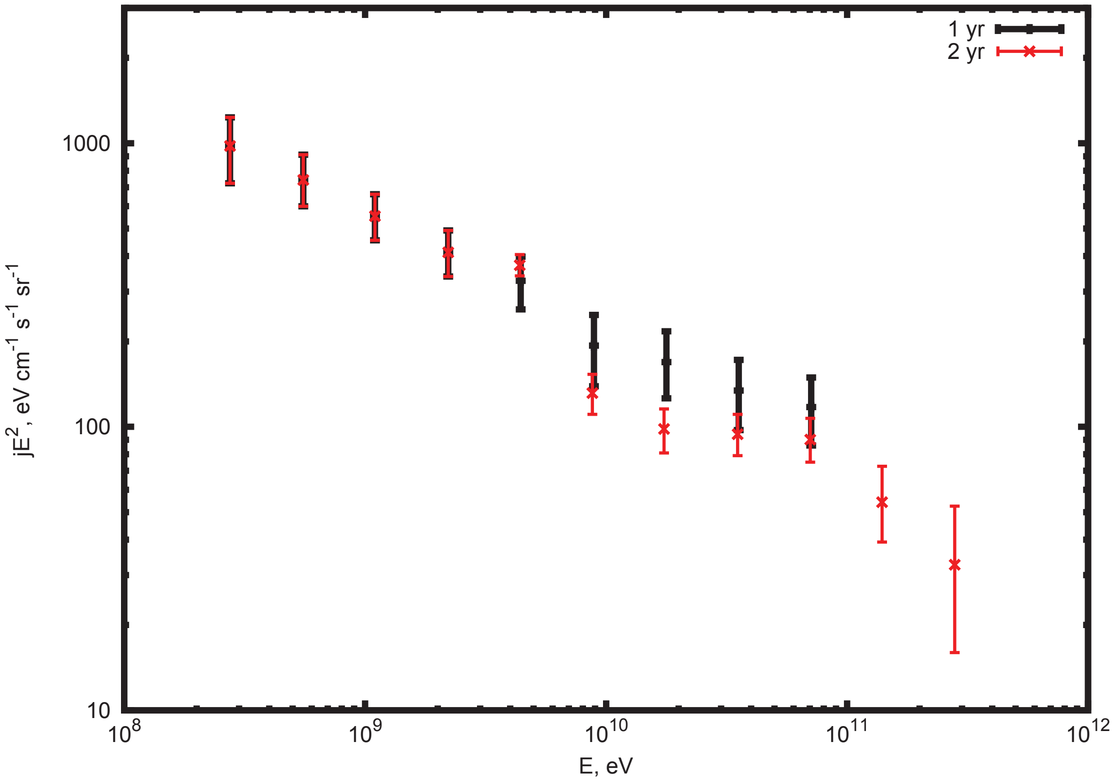
Launched from Cape Canaveral Air Station 11 June 2008

Fermi Gamma-ray Space Telescope

The Spectrum of the Isotropic Diffuse Gamma-Ray Emission



1 year data based bound:
Fermi collaboration
Phys.Rev.Lett.104:101101,2010

2.5 years data based bound:
A.Neronov, D.V.Semikoz 2011

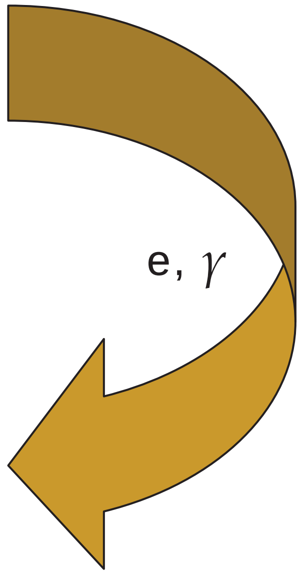
Interactions

- Protons ,neutrons and nuclei

Pion production $p\gamma_b \rightarrow p\pi\ldots$

$e^+ e^-$ pair production $p\,\gamma_b \rightarrow p\,e^+ e^-$

neutron β-decay $n \rightarrow p e^- \bar{\nu}_e$



- Electron-photon cascade

Inverse Compton $e\,\gamma_b \rightarrow e\,\gamma$

$e^+ e^-$ pair production $\gamma\,\gamma_b \rightarrow e^+ e^-$

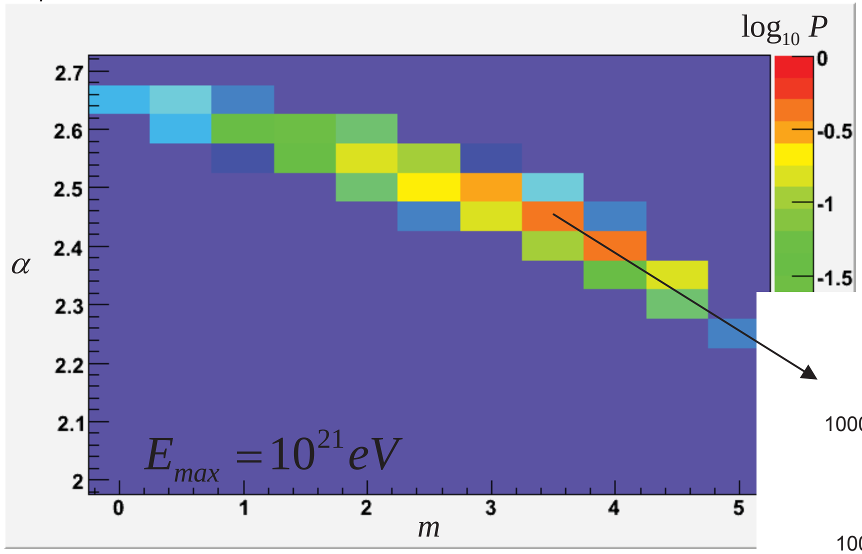
Synchrotron losses

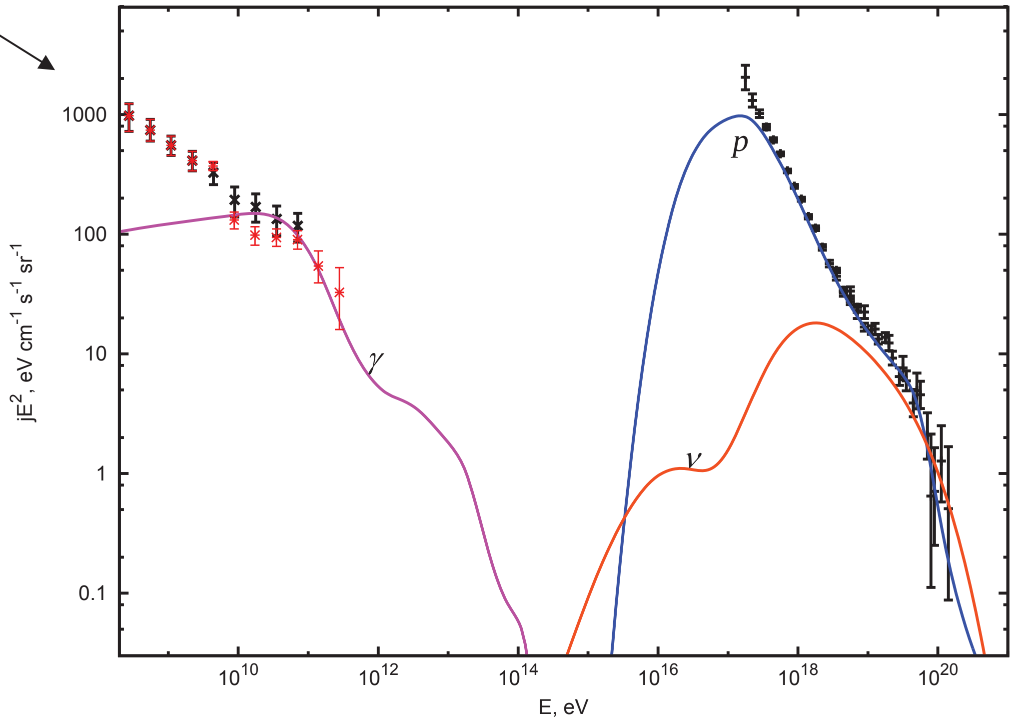
Double pair production $\gamma\,\gamma_b \rightarrow e^+ e^- e^+ e^-$

$e^+ e^-$ pair production by e $e\,\gamma_b \rightarrow e\,e^+ e^-$

Previous example fit with interaction products included

$E_{fit} > 10^{18} eV$





$$\alpha = 2.45$$

$$m = 3.5$$

$$E_{max} = 10^{21} eV$$

$$Z_{min} = 0.00125$$

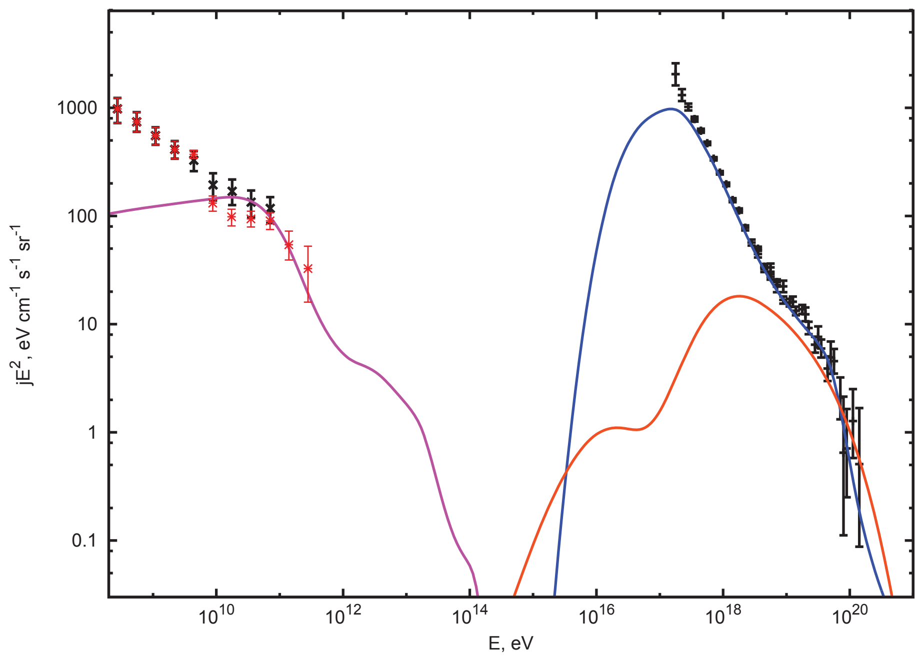
Fitting of the UHECR spectrum with Fermi bound imposed on secondary photon flux

χ^2 statistics is used to obtain goodness of joint fit

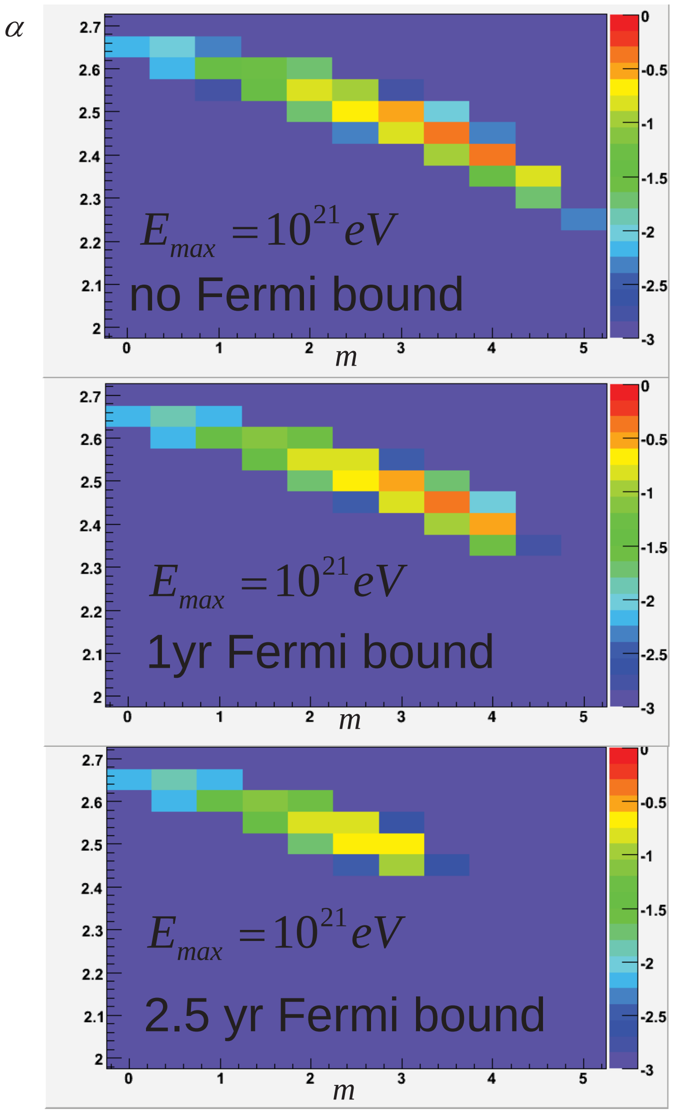
Bins with small number of events are combined into larger bins

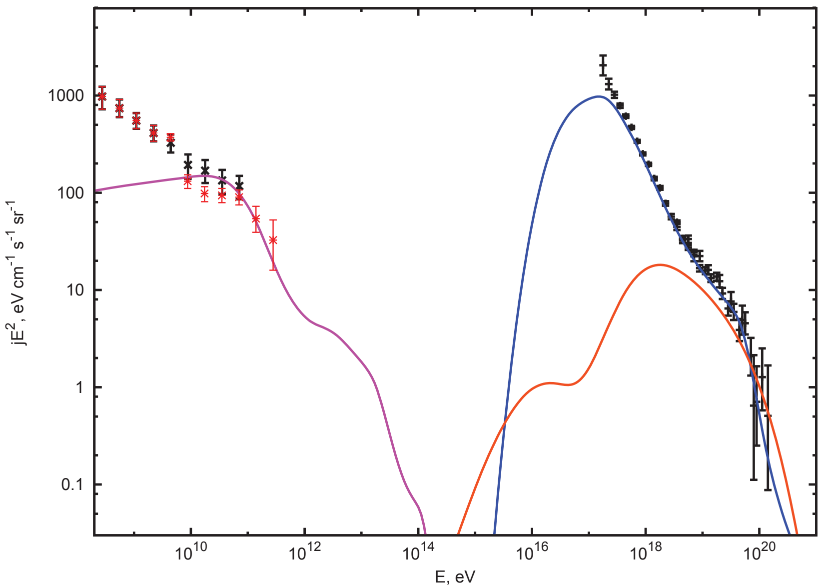
For Fermi bound only bins with photon flux exceeding bound are included in χ^2

Goodness of spectrum fit in the bins with small number of events is calculated separately on base of Poisson statistics



Goodness of joint fit plots





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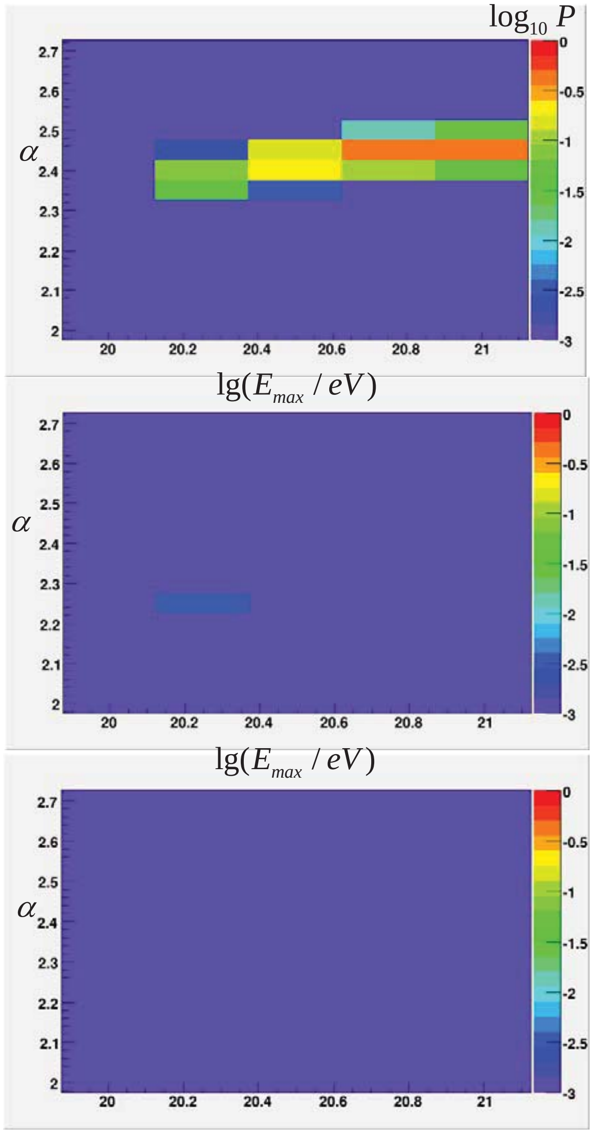
?

1 yr Fermi bound imposed

$z_{min} = 0$



Energy scale shift as attempt to solve problem

Extra parameter: Δ-energy scale shift for UHECR data

$$E \to E\Delta \qquad 1.3^{-1} \le \Delta \le 1.3$$

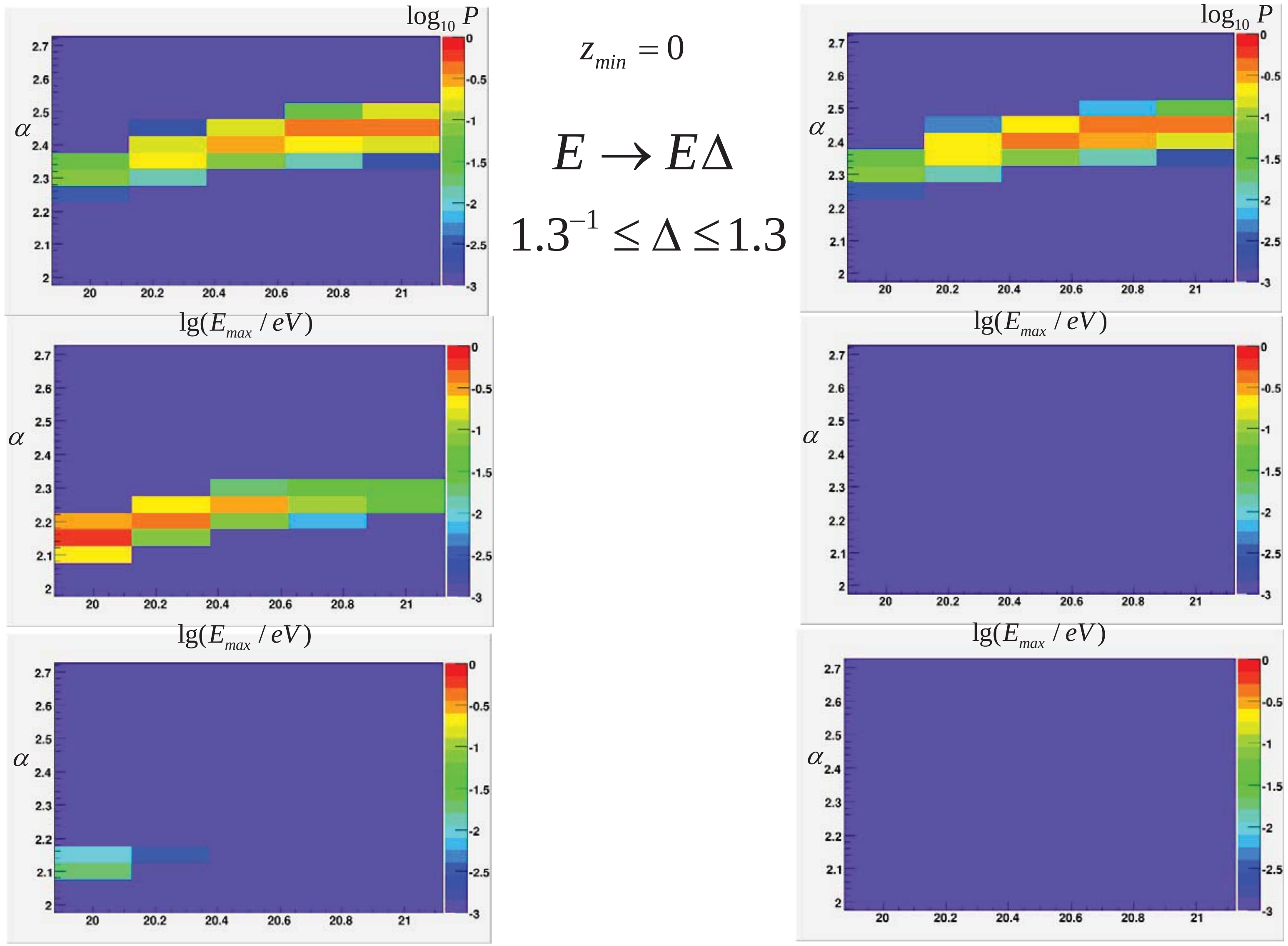
1 yr Fermi | 2.5 yr Fermi

SFR, GRB, AGN

$z_{min} = 0$

$$E \rightarrow E\Delta$$

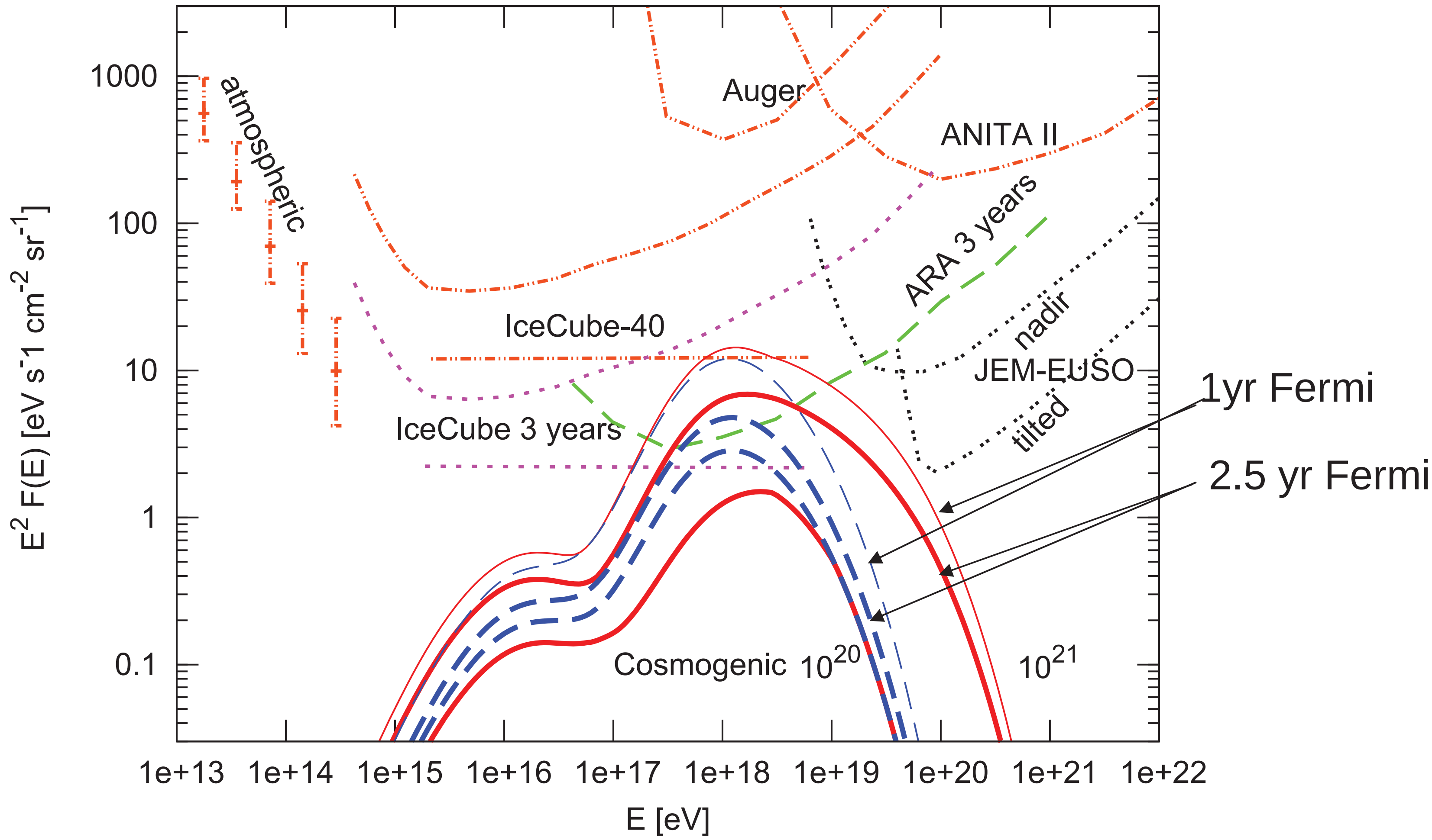
$$1.3^{-1} \leq \Delta \leq 1.3$$



95% CL secondary neutrino flux range calculation

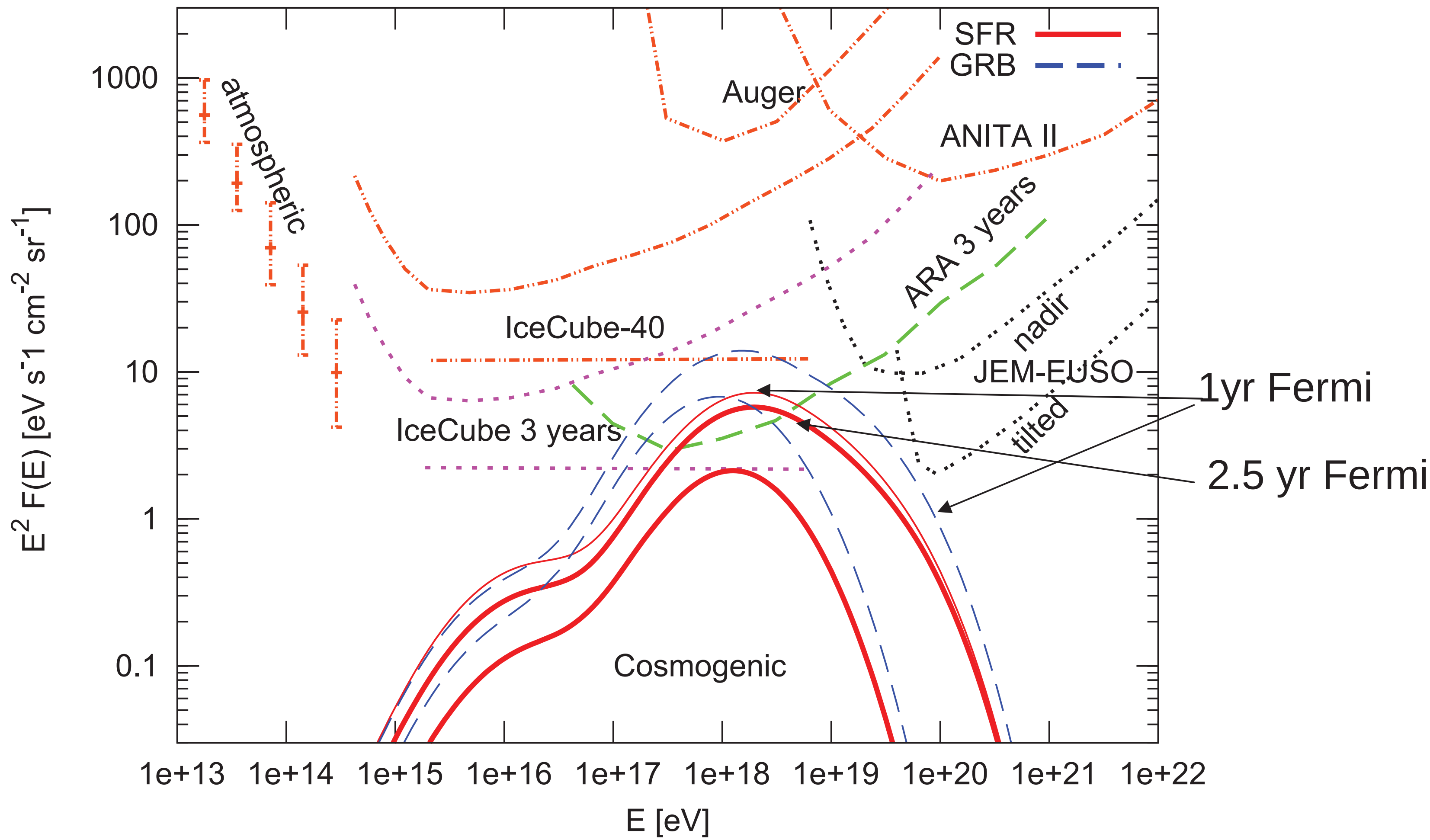
- Using only models with goodness of fit P>0.05
- For each energy bin we find model predicting highest/lowest neutrino flux

95% CL secondary neutrino flux range calculation



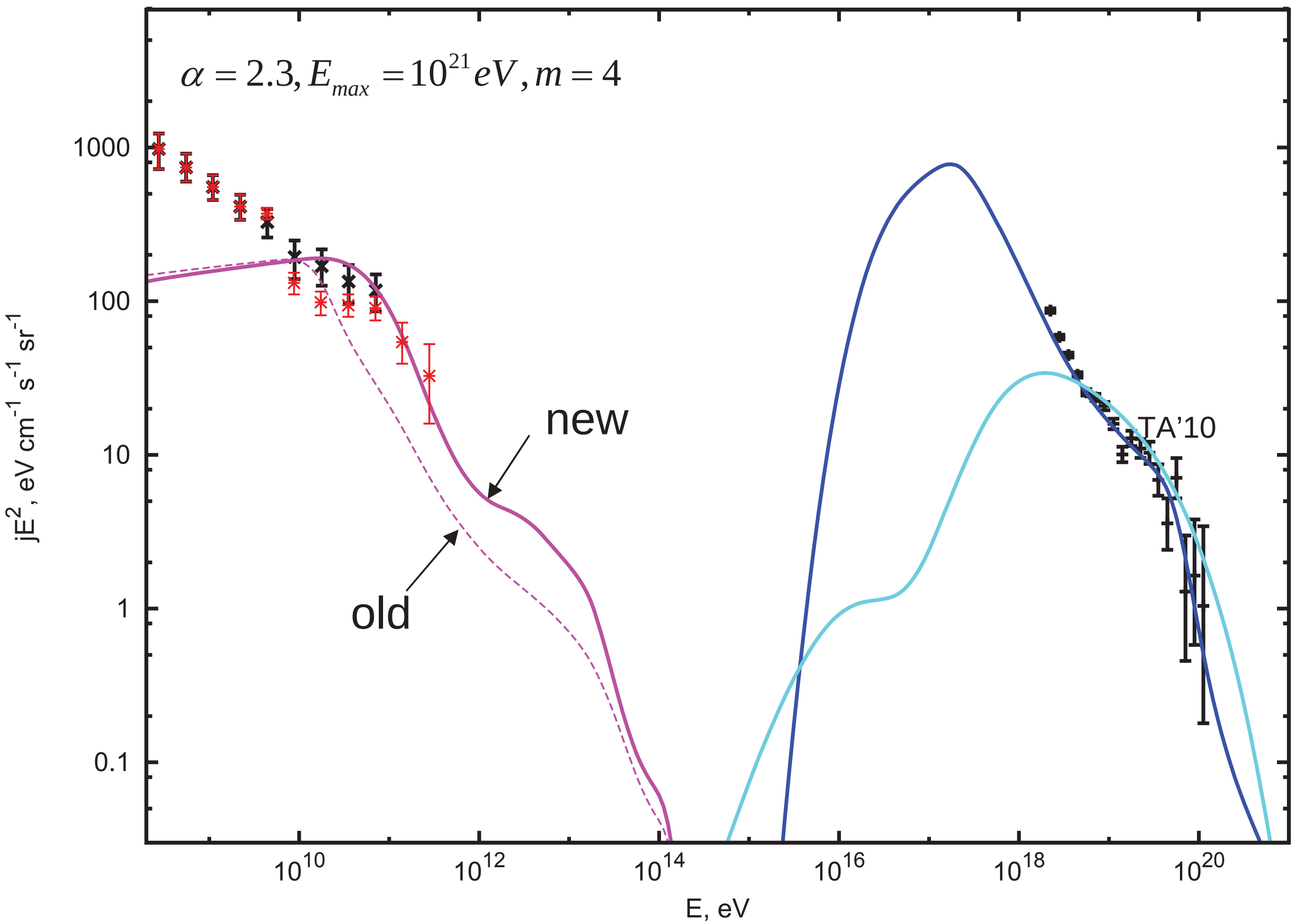
Dependence on E_{max} for models with evolution $S(z)=(1+z)^m$

95% CL secondary neutrino flux range calculation



SFR and GRB

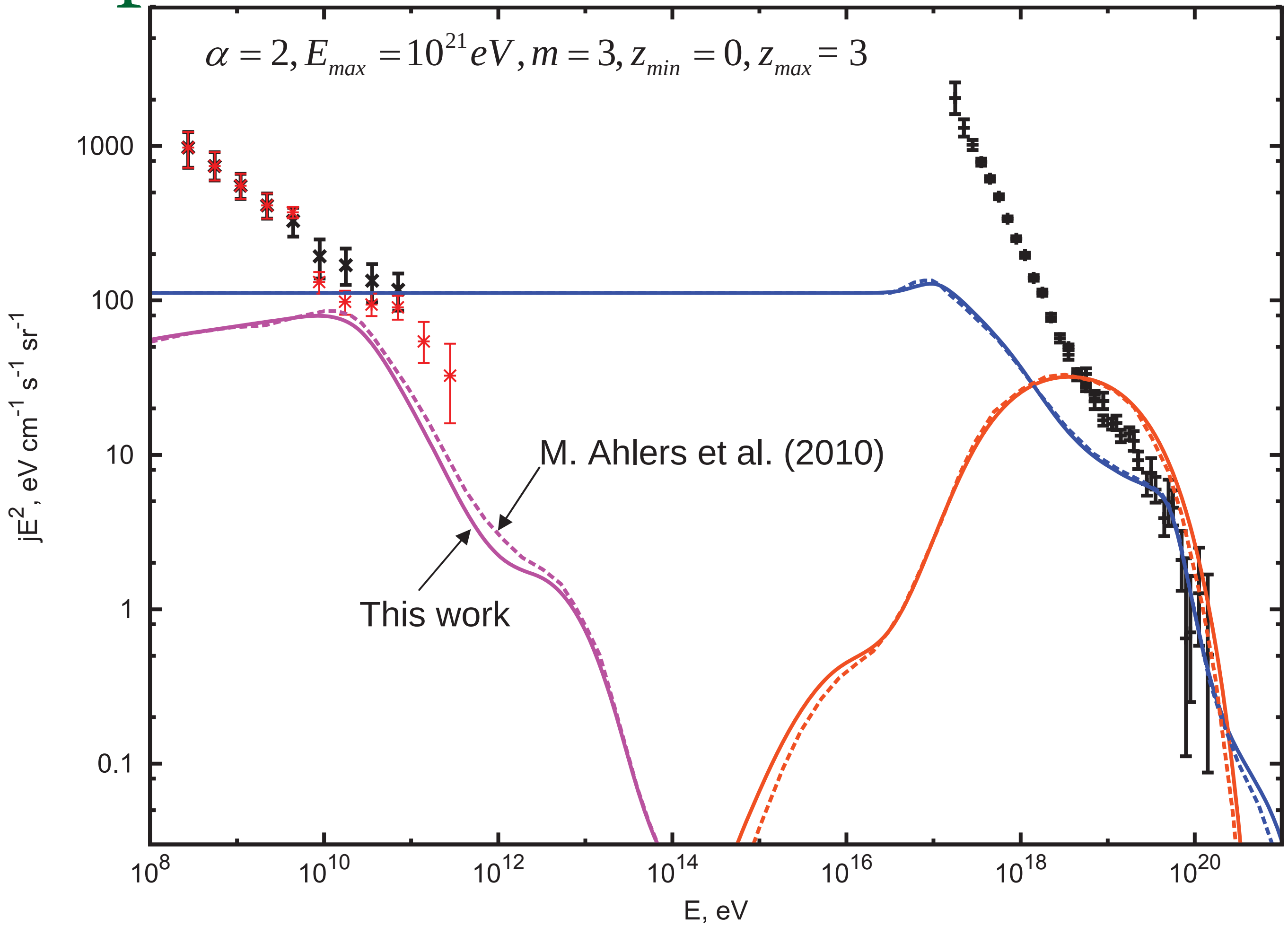
Photon diffuse flux dependence on EBL



IR/Optic background models used here:
Old: F.Stecker et al.   astro-ph/0510449
New: Kneiske et al. astro-ph/1001.2132v1

Theoretical modeling of TA energy spectrum

Comparison with other simulation



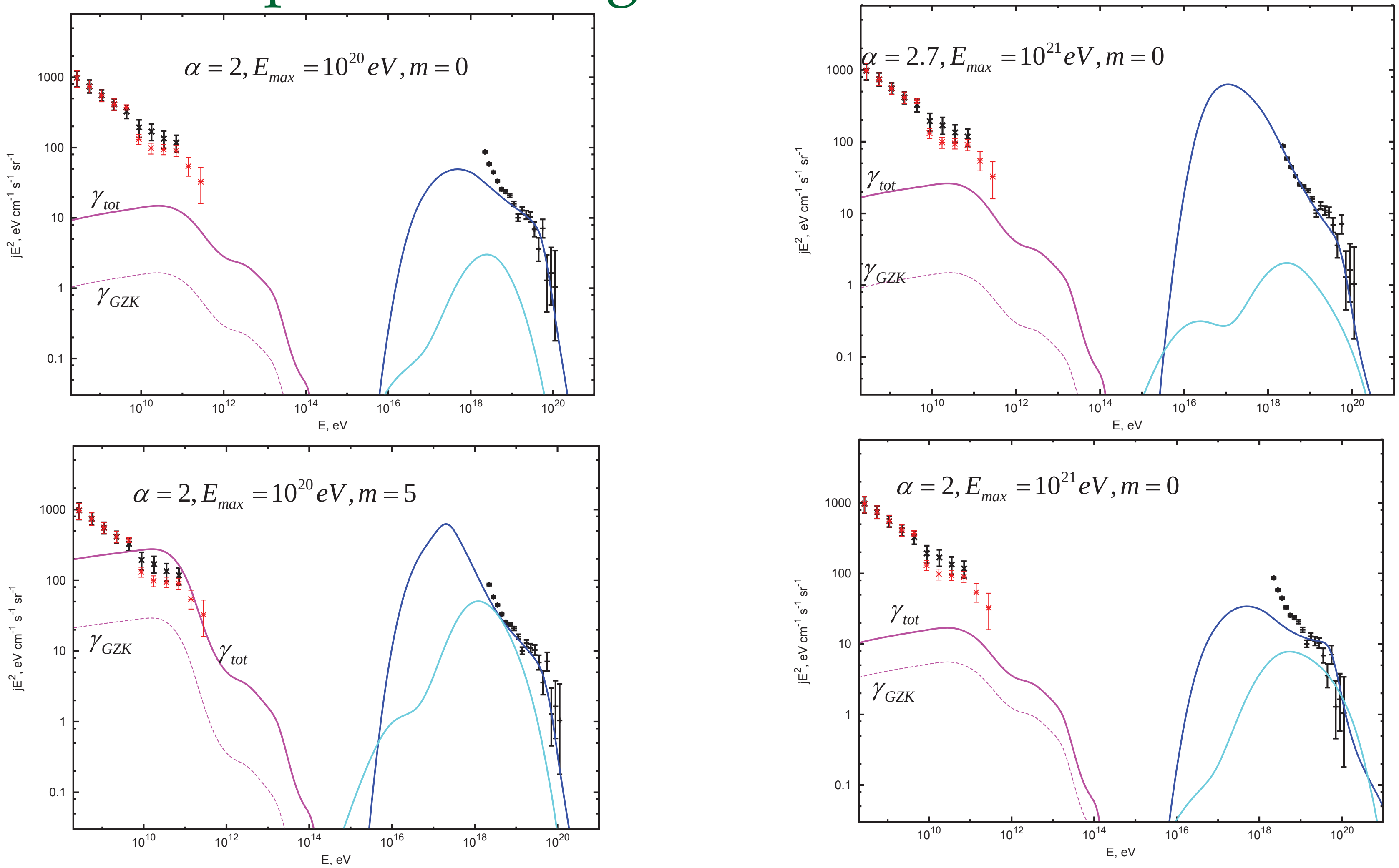
Reference:
M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen and S. Sarkar, Astropart. Phys. 34, 106 (2010)
Fig. B7

Conclusions

- Fermi LAT diffuse gamma ray flux limits become to constrain possible set of allowed UHECR source models and cosmogenic neutrino fluxes
- Pure proton source models with strong evolution are disfavored.
- Problems with strongly evolving sources can be avoided if one assumes nuclei primaries or local source overdensity

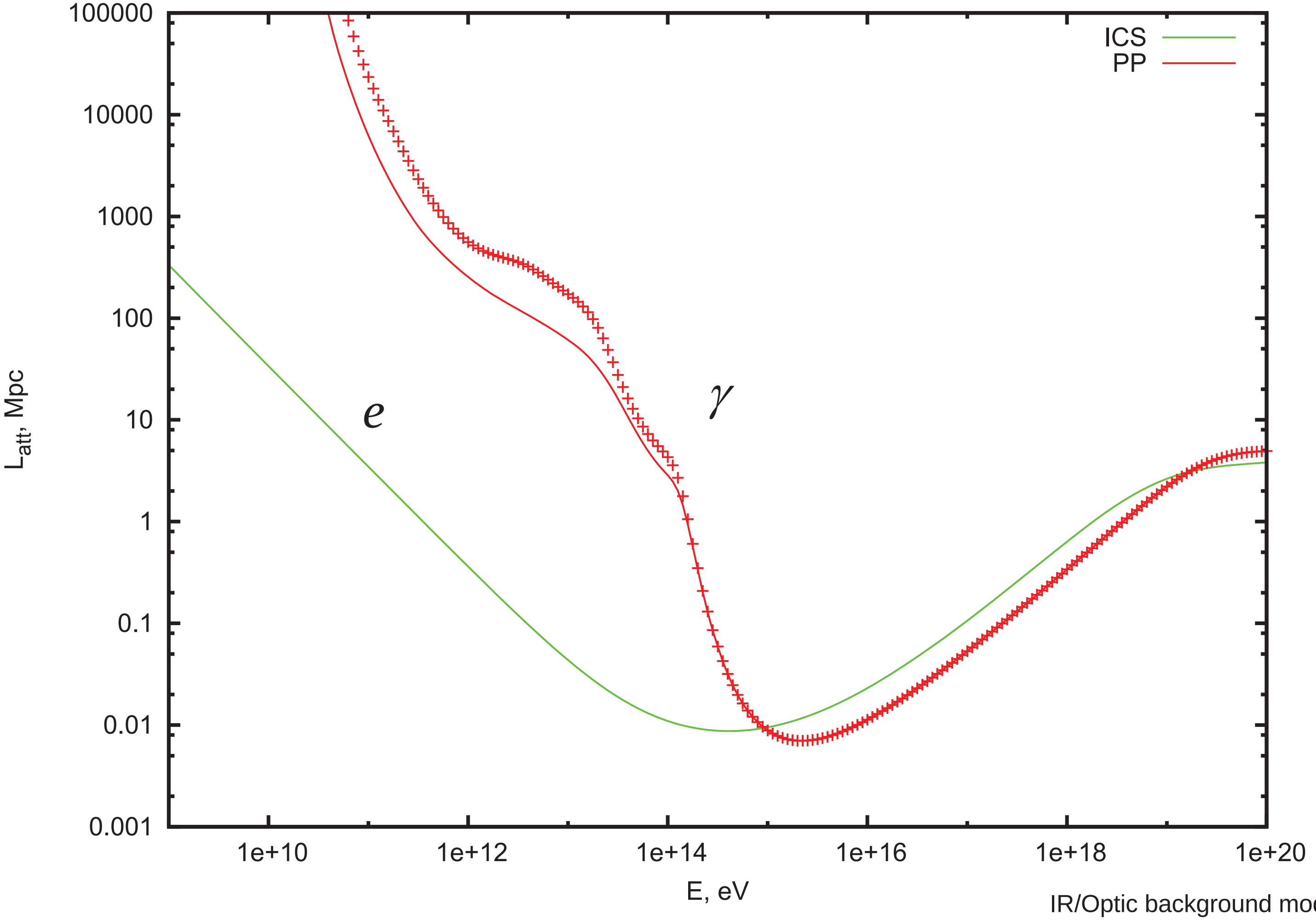
Appendix

e^+e^- pair production on p is the main source of diffuse photon background



Restricting cosmogenic neutrino fluxes with Fermi 2.5 years data

Attenuation lengths (EM cascade)



IR/Optic background models used here:
F.Stecker et al. astro-ph/0510449 (solid line)
Kneiske et al. astro-ph/1001.2132v1 (dotted line)

Simulations of cosmic rays propagation

Sample transport equation for electrons (includes only pair production PP and inverse Compton scattering ICS)

$$\begin{aligned}
\frac{d}{dt}N_e(E_e,t) \;&=\; -N_e(E_e,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta_e\mu}{2}\sigma_{\rm ICS}(E_e,\epsilon,\mu) + \\
&\int dE'_e N_e(E'_e,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta'_e\mu}{2}\frac{d\sigma_{\rm ICS}}{dE_e}(E_e;E'_e,\epsilon,\mu) + \\
&\int dE_\gamma N_\gamma(E_\gamma,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\mu}{2}\frac{d\sigma_{\rm PP}}{dE_e}(E_e;E_\gamma,\epsilon,\mu) + Q(E_e,t)
\end{aligned}$$

Interactions

- Protons and neutrons

Deflection by EGMF

$B<10^{-9}$ G P. Kronberg, Rept. Prog. Phys. 57, 325 (1994).

$B>10^{-17}$ G A. M. Taylor, I. Vovk, A. Neronov, Astronomy & Astrophysics, vol 529, 2011

$B\sim10^{-12}$ G K. *Dolag, D. Grasso, V. Springel and I. Tkachev, JCAP 0501, 009 (2005)*

Interactions

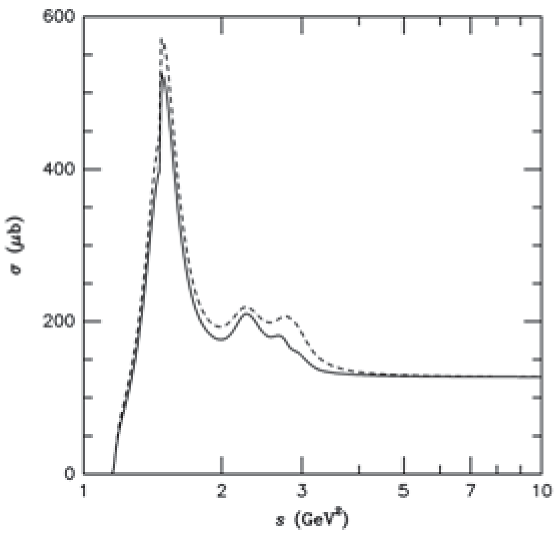
- Protons and neutrons

Pion production $N\gamma_b \rightarrow N'\pi...$

$$E_{th} = \frac{m_\pi(m_p+m_\pi/2)}{\epsilon} \simeq 7 \times 10^{16}(\frac{\epsilon}{eV})^{-1}eV$$

For MWB $(\epsilon \simeq 10^{-3}eV)$: $E_{th} \simeq 70EeV$

SOPHIA event generator
A.Mucke et al.,Comp.Phys.Comm.124,290(2000)



e^+e^- pair production $p\gamma_b \rightarrow pe^+e^-$

$$E_{th} = \frac{m_e(m_A+m_e)}{\epsilon} \simeq 5 \times 10^{14}(\frac{\epsilon}{eV})^{-1}eV$$

For MWB $(\epsilon \simeq 10^{-3}eV)$: $E_{th} \simeq 5 \times 10^{17}eV$

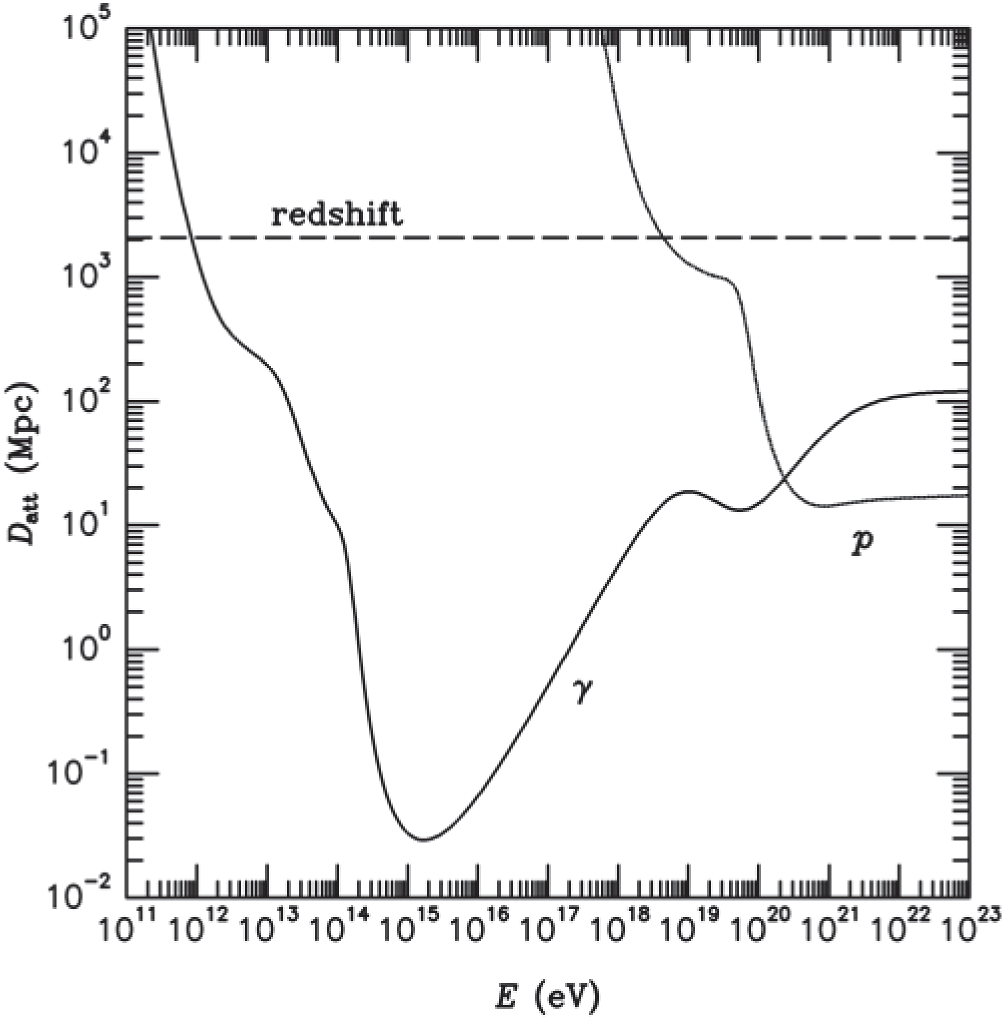
p energy loss rate:
M.J.Chodorowski et al. Astrophys.J.400,181(1992)

neutron β-decay $n \rightarrow pe^-\bar{\nu}_e$ $\tau = 900s$

Some references on UHECR propagation

π production	A.Mucke et al.,Comp.Phys.Comm.124,290(2000)
Photodisintegration	F.Stecker et al. Astrophys.J. 512 (1999) 521-526. E.Khan et al. Astropart.Phys. 23 (2005) 191-201
e^+e^- pair production	M.J.Chodorowski et al. Astrophys.J.400,181(1992)
Extragalactic magnetic field	K.Dolag et al., astro-ph/0410419
Infrared background	F.Stecker et al. astro-ph/0510449 Kneiske et al. astro-ph/1001.2132v1
Radio background	T.A. Clark, L.W. Brown, and J.K. Alexander, Nature 228, 847 R.J. Protheroe, P.L. Biermann, Astropart. Phys. 6, 45

Energy loss lengths



p and γ energy loss lengths
(minimal RB assumed)

Interactions

- Electron-photon cascade

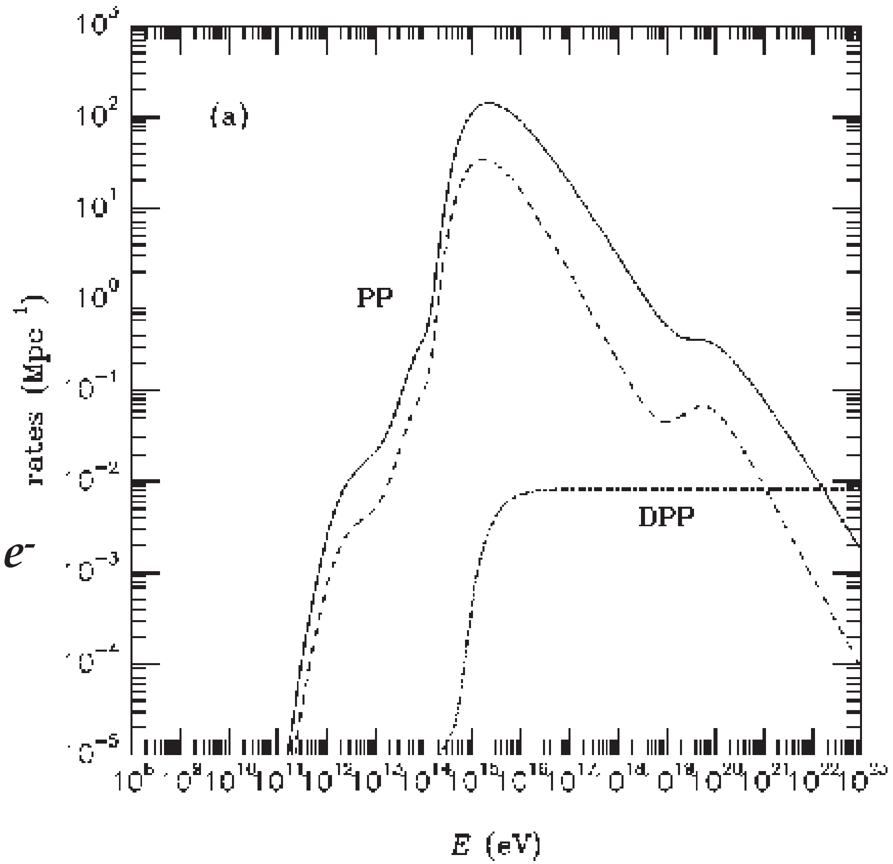
Inverse Compton $e\,\gamma_b \rightarrow e\,\gamma$

e+ e- pair production $\gamma\,\gamma_b \rightarrow e^+ e^-$

Synchrotron losses

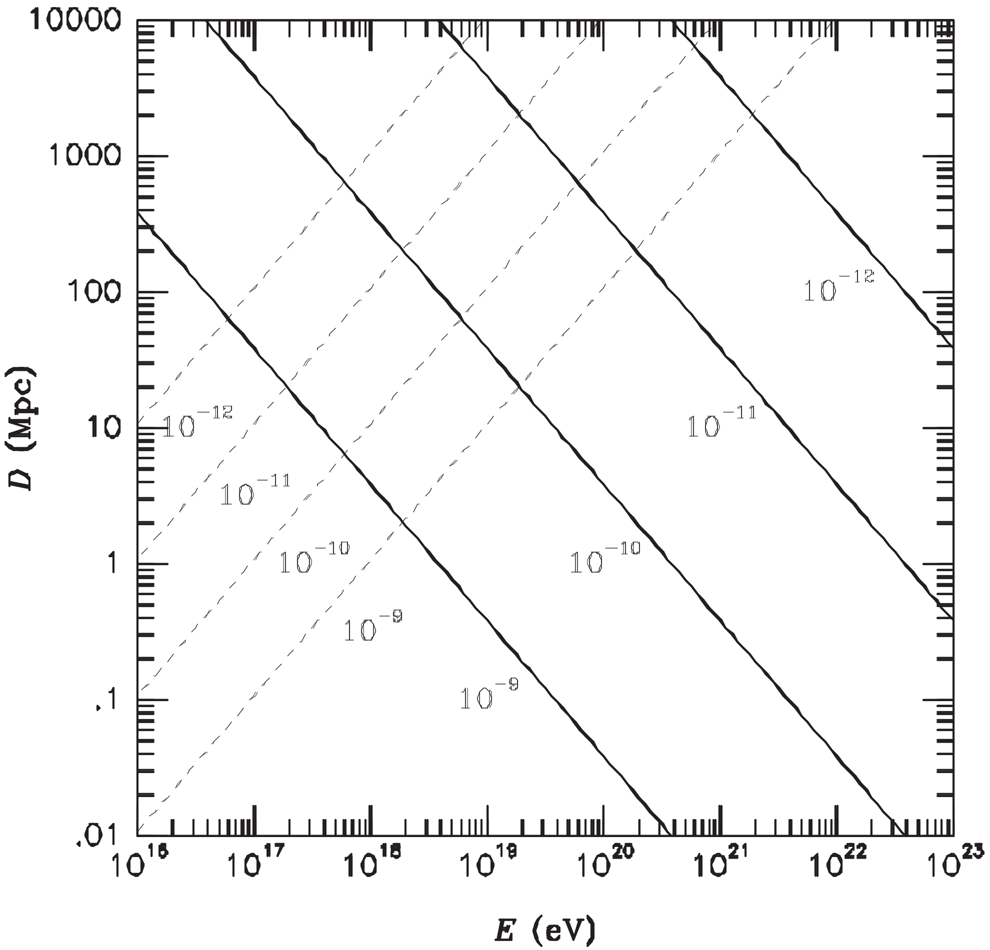
Double pair production $\gamma\,\gamma_b \rightarrow e^+ e^- e^+ e^-$

e+ e- pair production by e $e\,\gamma_b \rightarrow e\,e^+ e^-$



Deflection and synchrotron radiation

Gyroradius: $R_g = \frac{E}{qeB_\perp} \simeq 110 \times \frac{1}{Z}\left(\frac{E}{10^{19}\,\mathrm{eV}}\right)\left(\frac{B_\perp}{10^{-10}\mathrm{G}}\right)^{-1}\,\mathrm{Mpc}$



Synchrotron loss length:

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \frac{B^2}{8\pi}\left(\frac{qm_e}{m}\right)^4\left(\frac{E}{m_e}\right)^2$$

$$E_\gamma \simeq \frac{3eB}{2m_e}\left(\frac{E_e}{m_e}\right)^2 \simeq$$

$$2.2 \times 10^{14}\left(\frac{E_e}{10^{21}\,\mathrm{eV}}\right)^2\left(\frac{B}{10^{-9}\mathrm{G}}\right)\,\mathrm{eV}$$

The gyroradius and the synchrotron loss rates of electrons for various strengths of the EGMF

Observation of photons from distant blazars

HESS

1ES 1101−232 (z=0.186) $\Gamma = 2.88 \pm 0.17$

H2356−309 (z=0.165) $\Gamma = 3.06 \pm 0.21$

$$\frac{dN}{dE} \sim E^{-\Gamma}$$

Nature 440 (2006) 1018–1021

$$0.5 < E / TeV < 10$$

$$\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{sys}$$

VERITAS

3C66A (z = 0.444)

Astrophys. J. Lett. 693 (2009) L104–L108