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Restrictions on cosmogenic neutrinos and UHECR from Fermi 3 years data

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arXiv:1107.1672 (submitted to JCAP)

Restrictions on cosmogenic neutrinos and UHECR from Fermi 3 years data

Overview

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

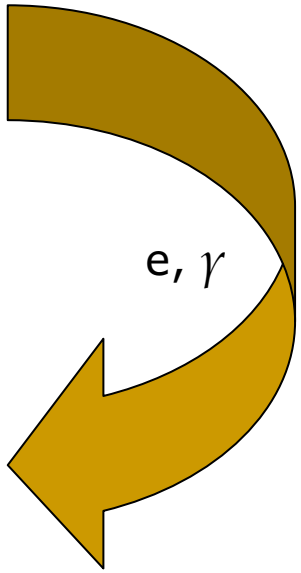
Interactions

- Protons ,neutrons and nuclei

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

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

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



- Electron-photon cascade

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

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

Simulations of cosmic rays propagation

- Monte Carlo based simulations
  - Random extragalactic magnetic field is taken into account
  - Describes random nature of interactions more precisely
- 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

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

Fitting UHECR energy spectrum

- 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 (P-value) 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
- χ^2 test:

$$P(\chi^2, N_{df}) = 1 - \frac{\gamma(N_{df}/2, \chi^2/2)}{\Gamma(N_{df}/2)}$$

γ - lower incomplete gamma function

Phenomenological source model:

$F(E, z) = \Phi(E)\, S(z)$

$\Phi(E) = f\, E^{-\alpha} \exp(-E/E_{max}) \exp(-E_{min}/E)$

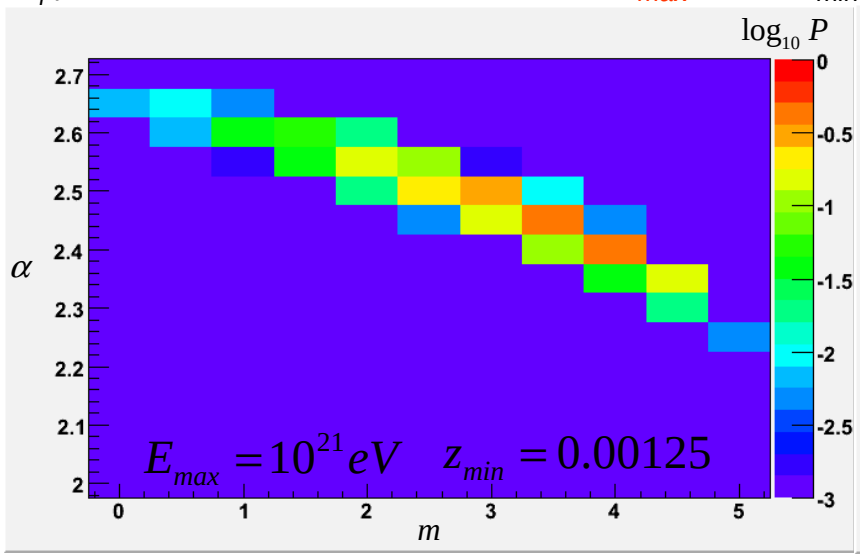
$S(z) = (1+z)^m \Theta(z-z_{min})\, \Theta(z_{max}-z)$

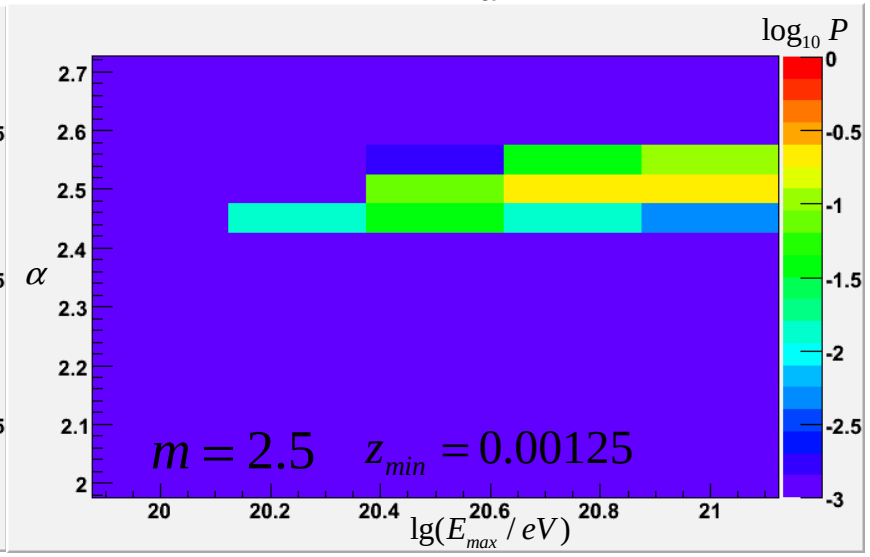
z – red shift, $\Theta(x)$-step function

Parameter	Name	Typical Values
Power of the Injection Spectrum, $E^{-\alpha}$	α	$2 \le \alpha \le 2.7$
End point of the Energy Spectrum	E_{max}	$10^{20} \le E_{max}/eV \le 10^{21}$
Evolution factor: $(1+z)^{3+m}$	m	$0 \le m \le 5$
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}, 10^{18}, 10^{19} eV

Goodness of fit plots HiRes Spectrum (dip model)

$E_{fit} > 10^{18} eV$ $F(E, z) \sim E^{-\alpha} \exp(-E/E_{max}) \exp(-E_{min}/E) \ (1+z)^{m} \Theta(z-z_{min}) \ \Theta(z_{max}-z)$





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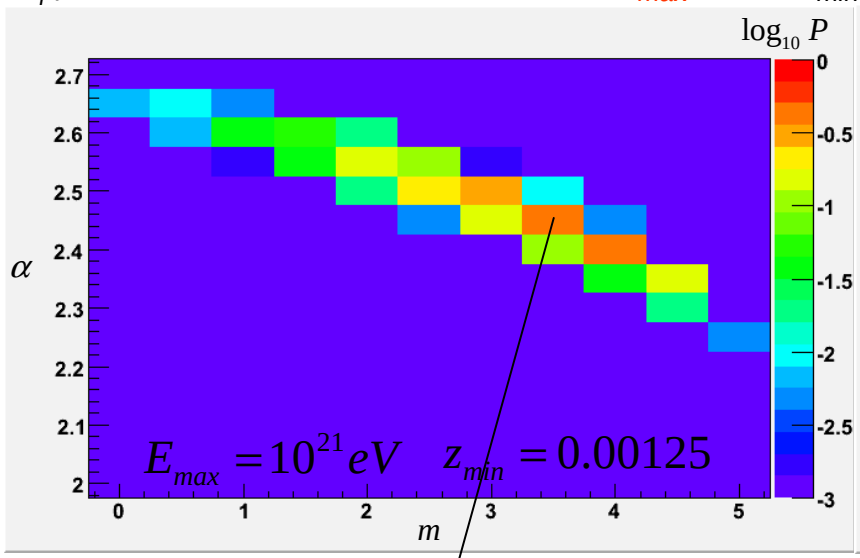

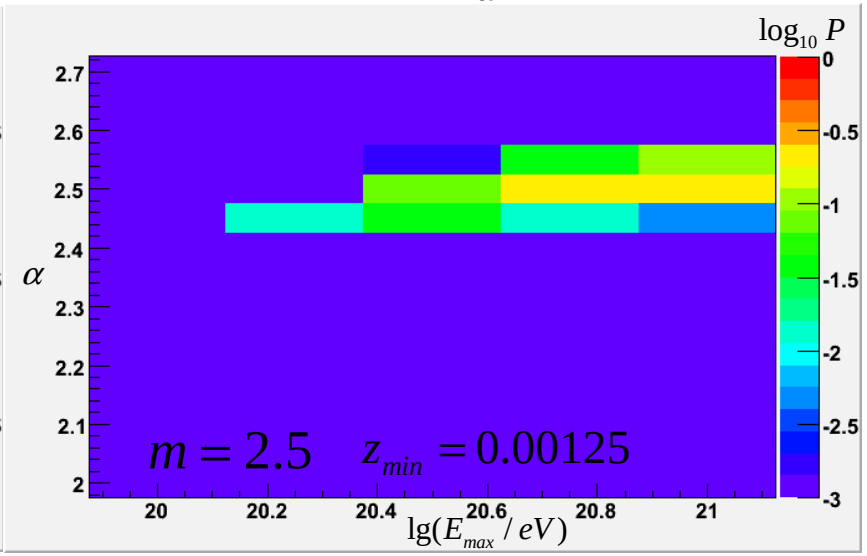

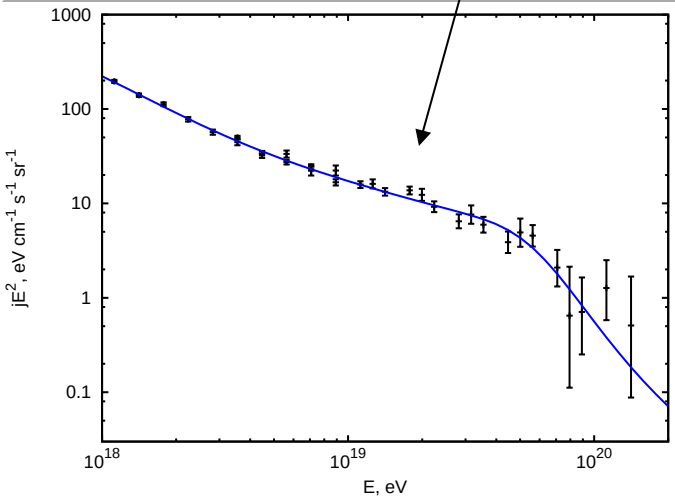

$\alpha = 2.45$

$m = 3.5$

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

$E_{min} = 10^{17} eV$

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

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)*

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

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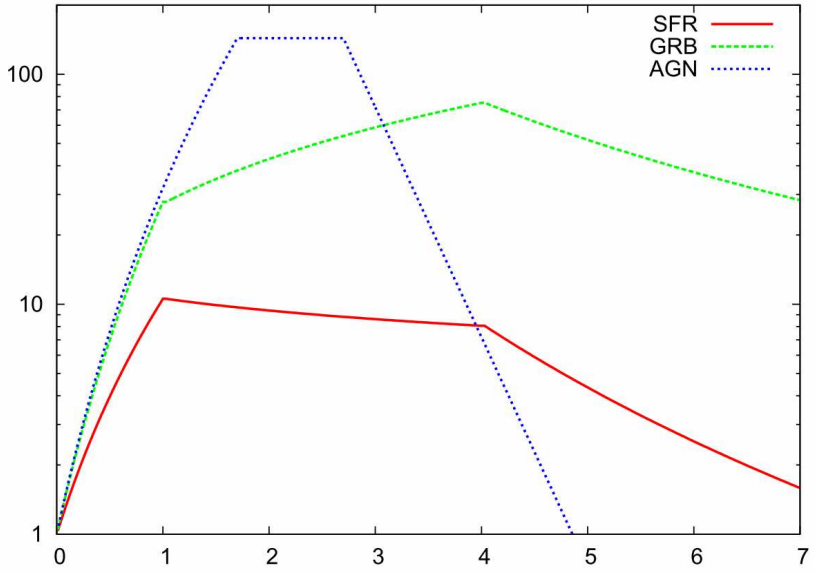
$$S_{\rm AGN}(z) \propto \begin{cases} (1+z)^{5.0}, & z < 1.7 \\ \text{constant}, & 1.7 < z < 2.7 \\ 10^{(2.7-z)}. & z > 2.7 \end{cases}$$



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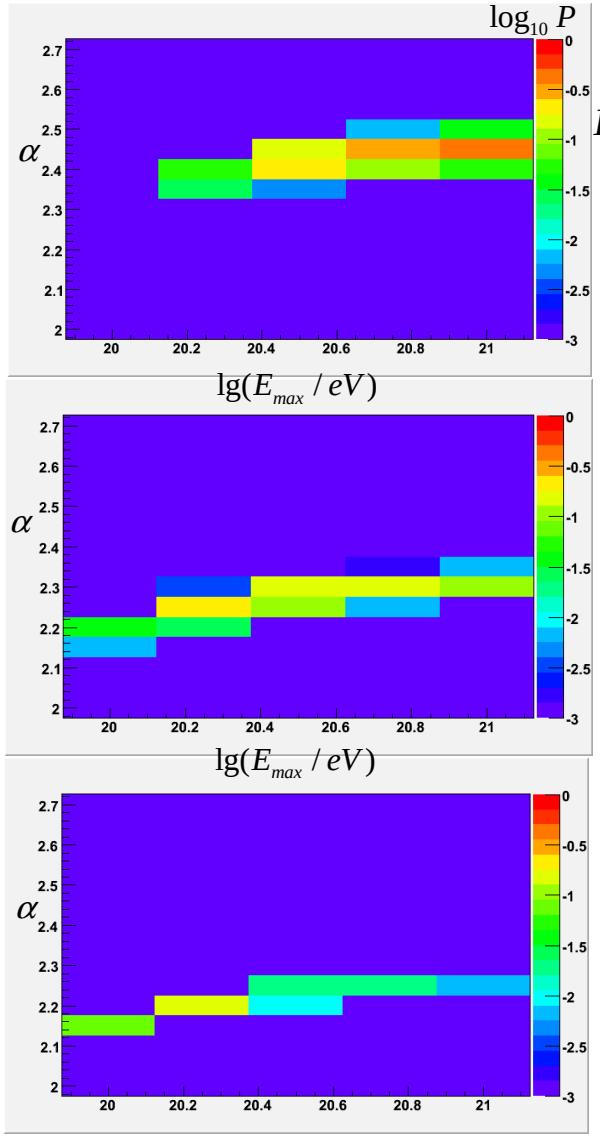


Fermi Gamma-ray Space Telescope

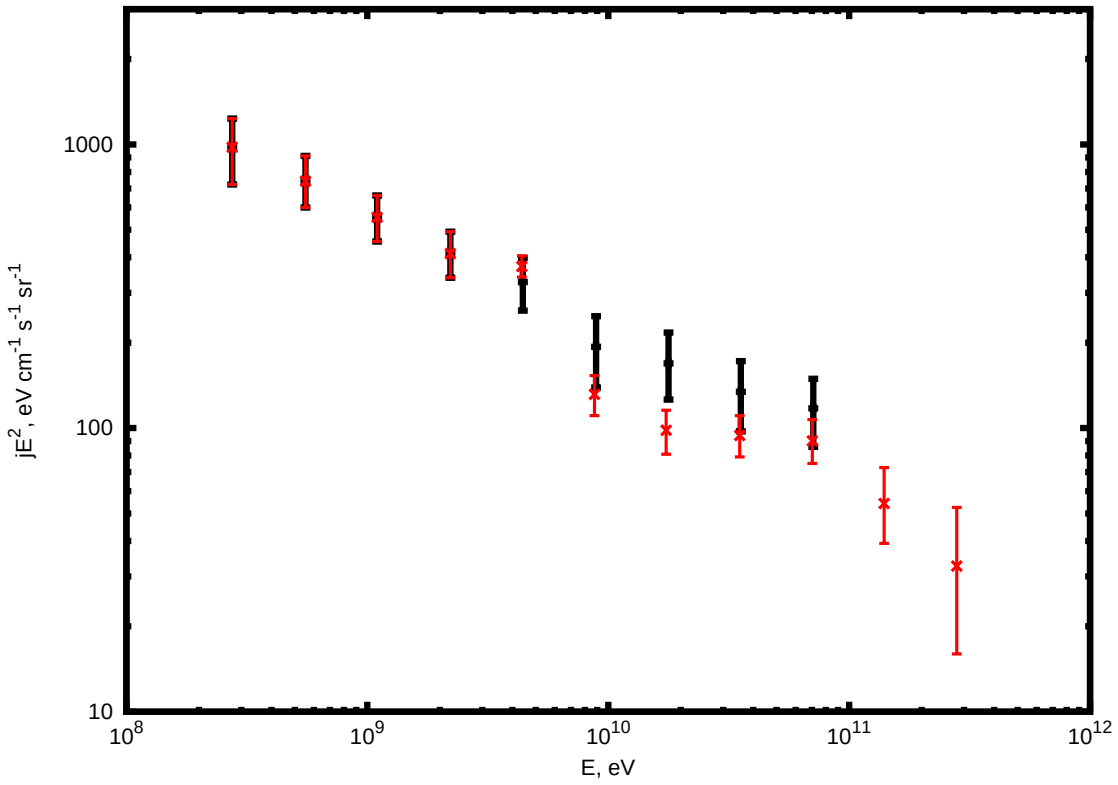
Energy range (LAT): 20 MeV - 300 GeV

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

Launched from Cape Canaveral Air Station 11 June 2008

Fermi Gamma-ray Space Telescope

The Spectrum of the Isotropic Diffuse Gamma-Ray Emission

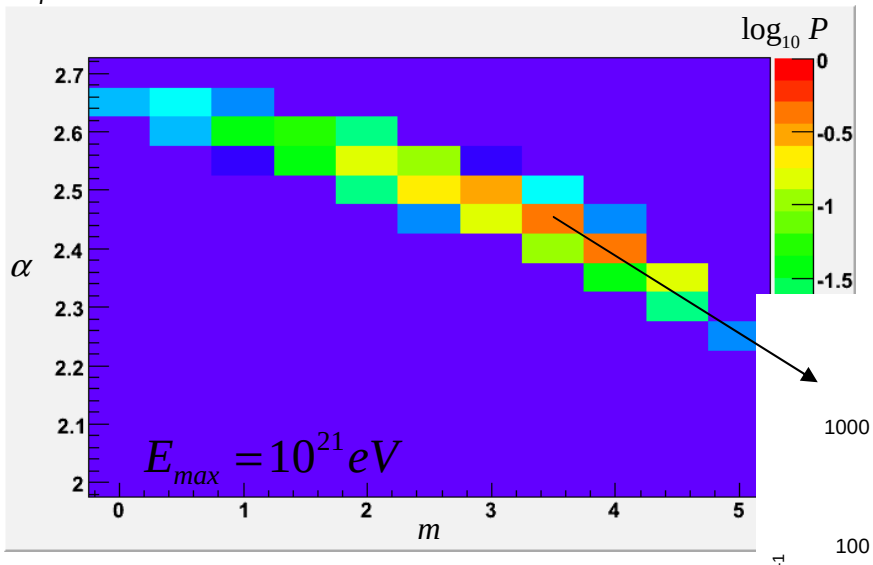


—— 1 year data based estimate:
Fermi collaboration
Phys.Rev.Lett.104:101101,2010

—— 2.5 years data based estimate:
A.Neronov, D.V.Semikoz
astro-ph 1103.3484

Previous example fit with interaction products included

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



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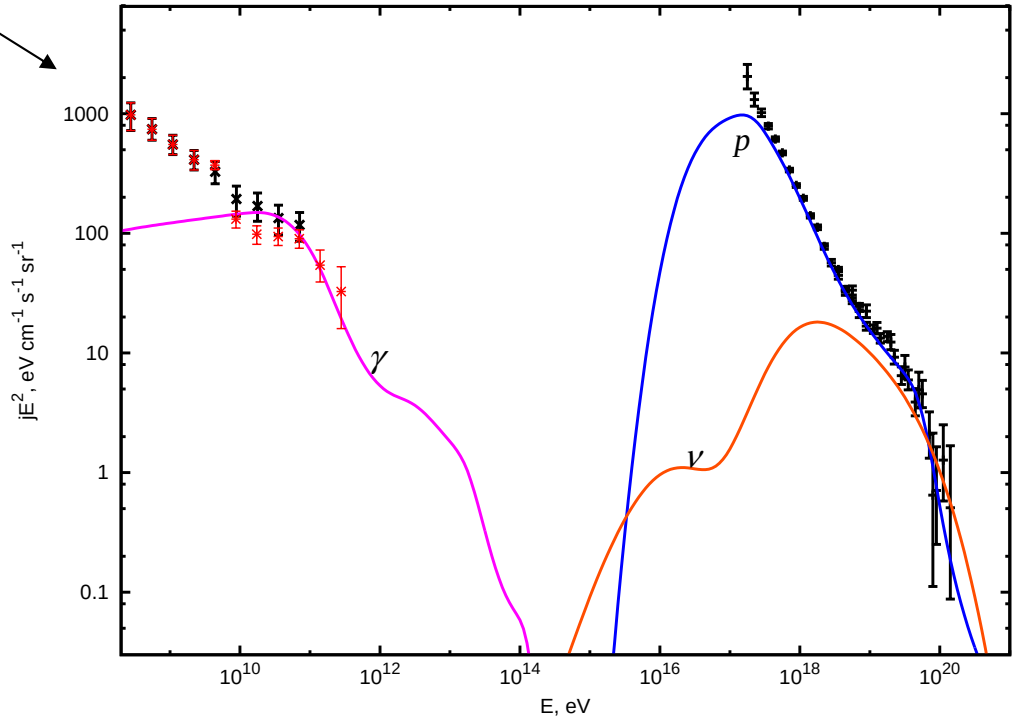


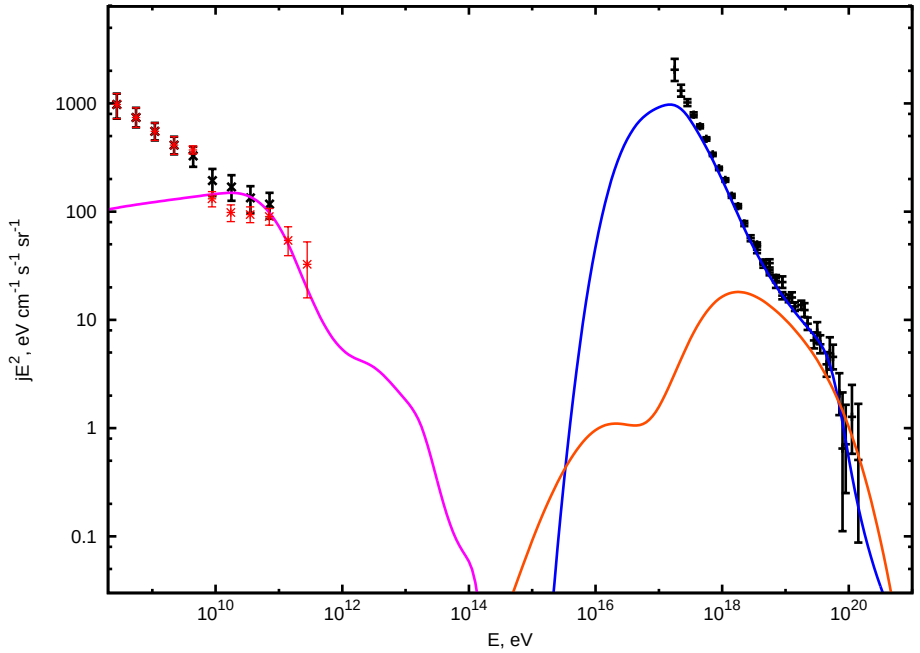
Fitting of the UHECR spectrum with Fermi bound imposed on secondary photon flux

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

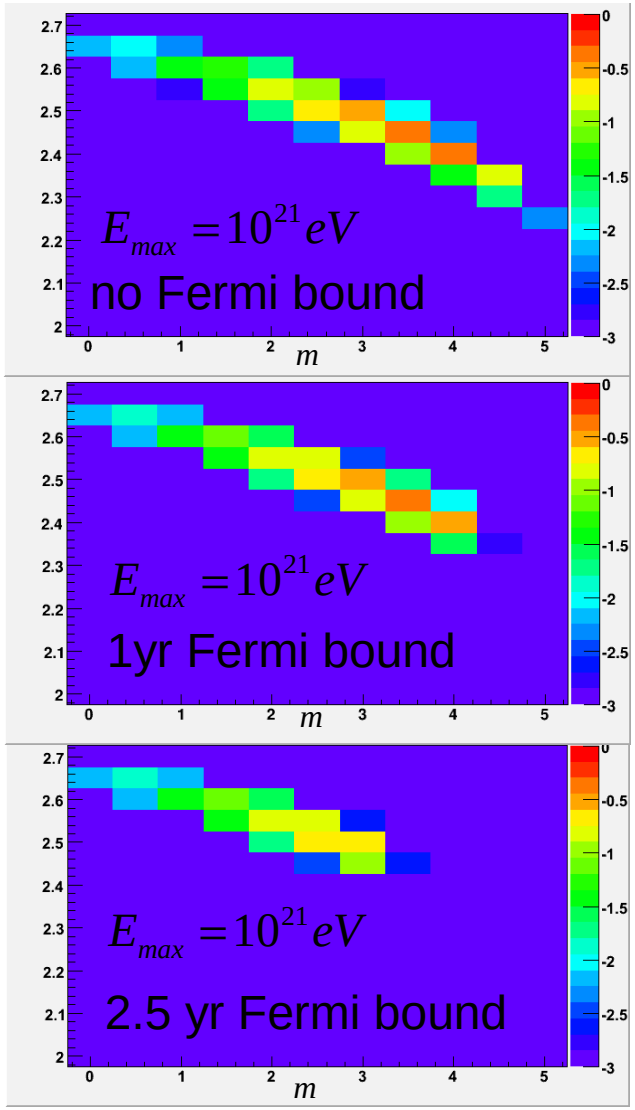
Bins with small number of events are combined into larger bins

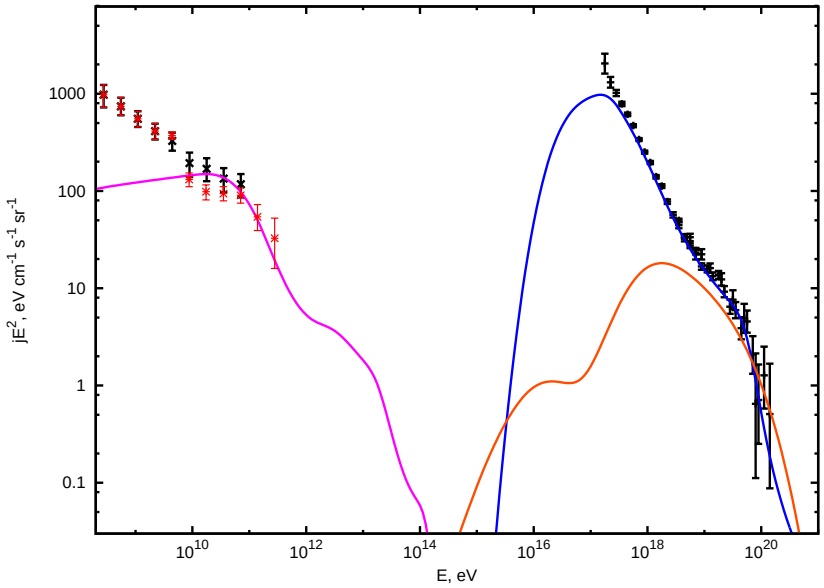
For Fermi bound only bins with photon flux exceeding bound are included in χ^2

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



Goodness of fit plots (dip model)





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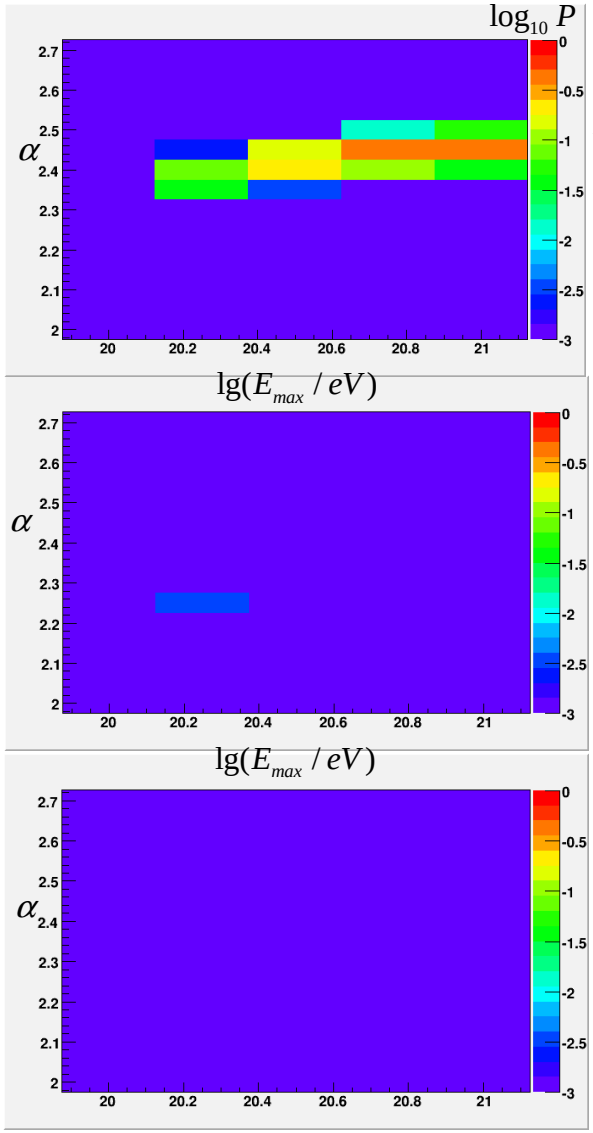
1 yr Fermi bound imposed



$z_{min} = 0$

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

Energy scale shift as attempt to solve problem

Extra parameter: Δ-energy scale shift for UHECR data

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

Dip Model Fits

1 yr Fermi

2.5 yr Fermi

SFR

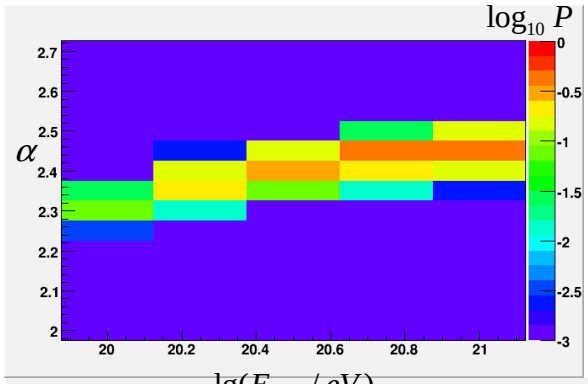
GRB

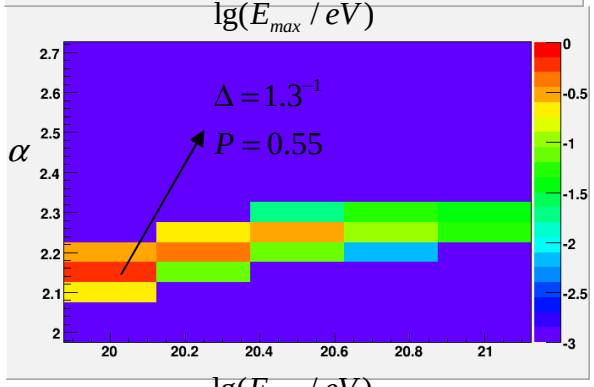
AGN

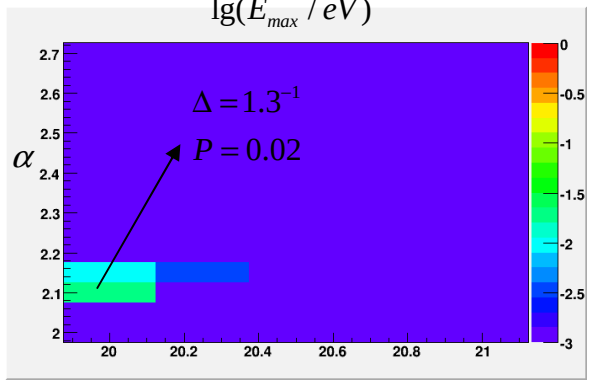
$E_{fit} > 10^{18} eV$

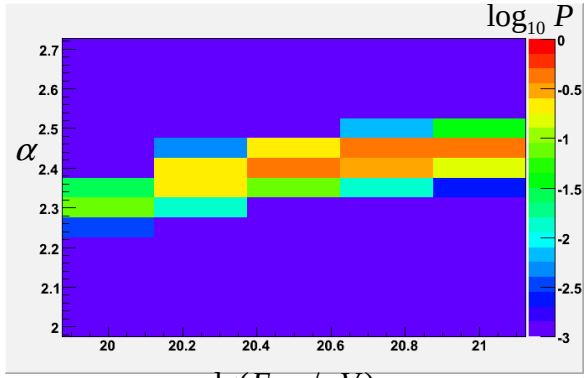
$E \to E\Delta$

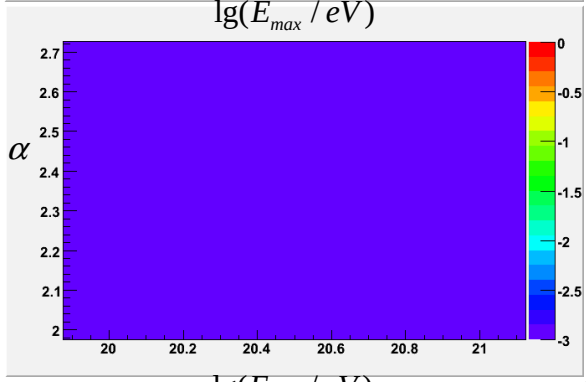
$1.3^{-1} \le \Delta \le 1.3$

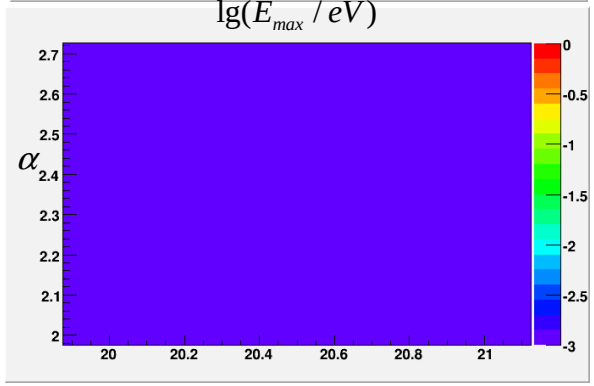




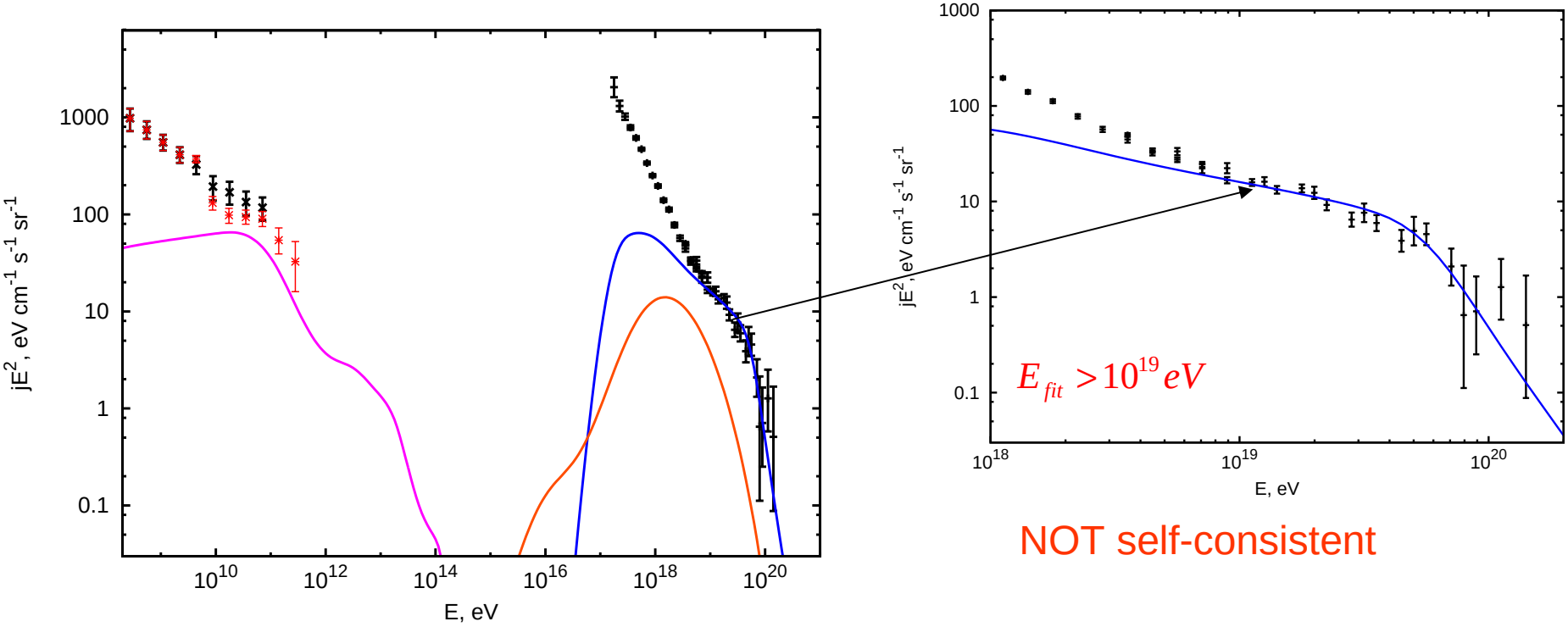








Ankle Model Fits



NOT self-consistent

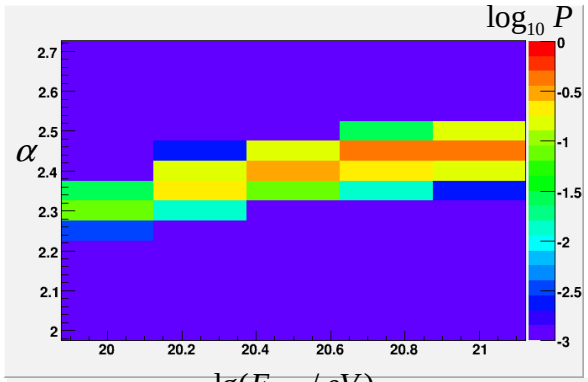
Another component needed below $E<10^{19}$ eV:

- EG protons – additional contribution to GeV gamma flux
- Nuclei – contradict composition measurements
- Galactic protons - anisotropy

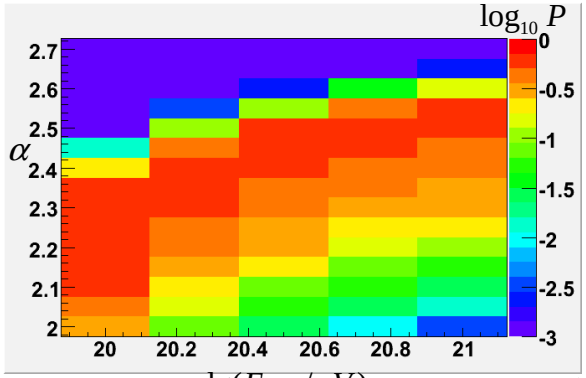
$E_{fit} > 10^{18} eV \quad E_{min} = 10^{17} eV$

1yr Fermi bound imposed

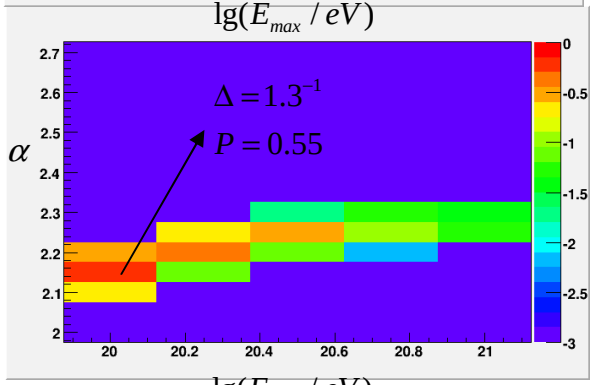
$E_{fit} > 10^{19} eV \quad E_{min} = 10^{18} eV$



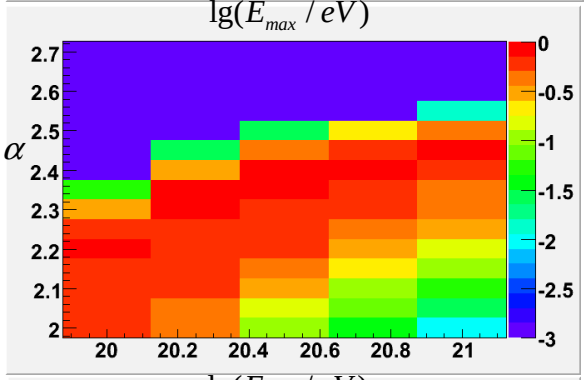
SFR



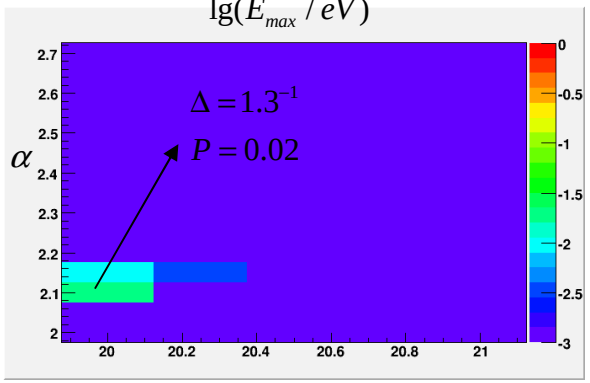
DIP



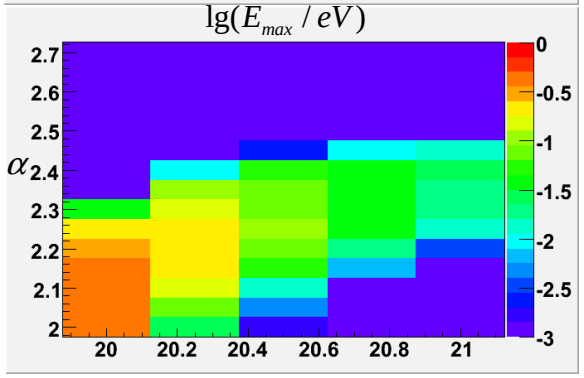
GRB



ANKLE



AGN

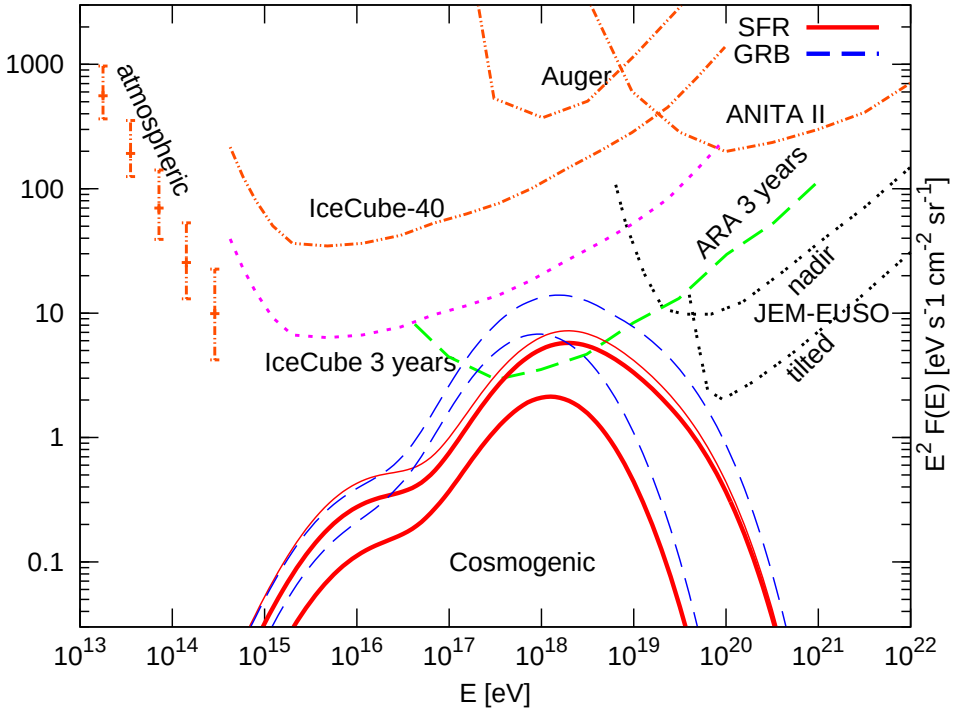


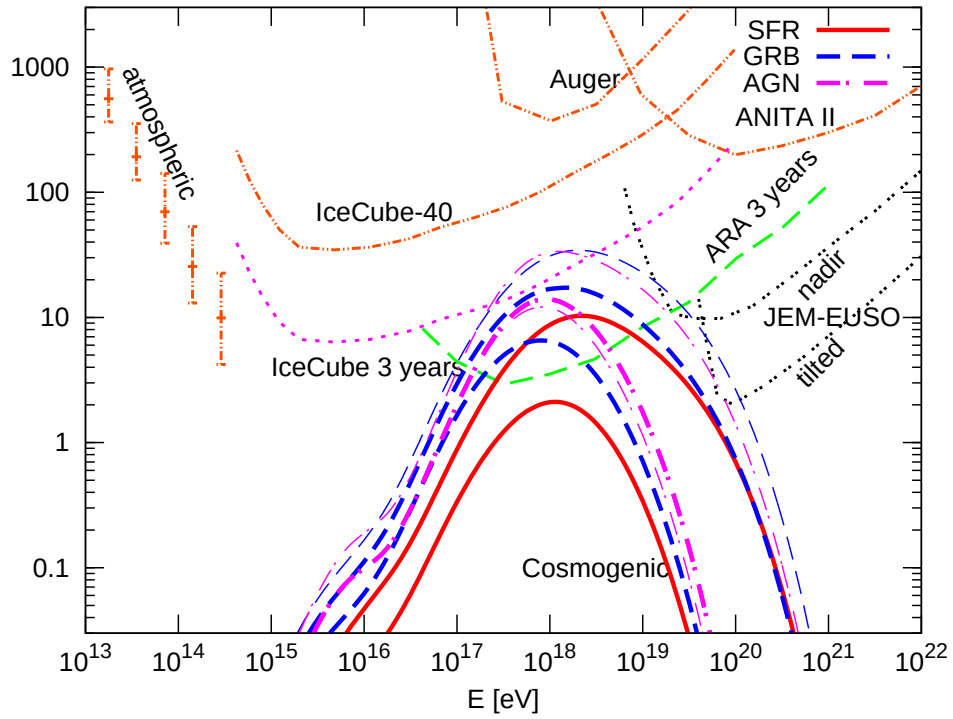
Restrictions on cosmogenic neutrinos and UHECR from Fermi 3 years data

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





Dip models (E_{fit}>10^{18}eV)

2.5 yr

1yr

Ankle models (E_{fit}>10^{19}eV)

Restrictions on cosmogenic neutrinos and UHECR from Fermi 3 years data

Conclusions

- Fermi LAT diffuse gamma ray flux limits become to constrain possible set of allowed UHECR source models and cosmogenic neutrino fluxes
- Pure proton sources with strong evolution are disfavored in the dip scenario.
- The largest fluxes predicted in the dip model would be detectable by IceCube in about 10 years of observation and are within the reach of a few years of observation with the ARA project

Appendix

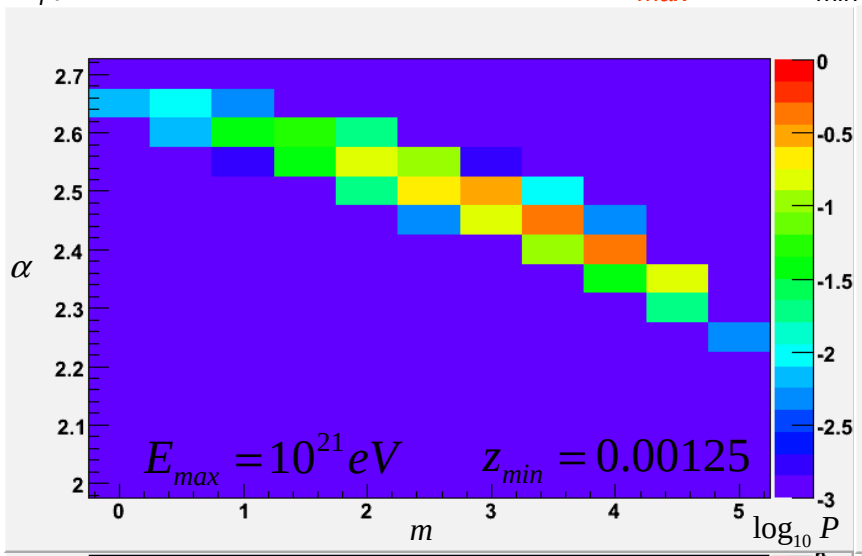
Restricting cosmogenic neutrino fluxes

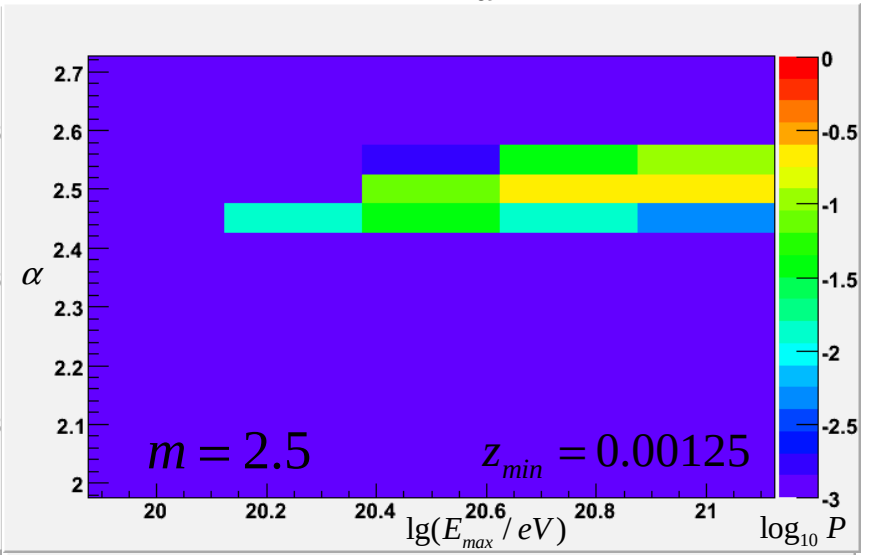
Some works on the subject:

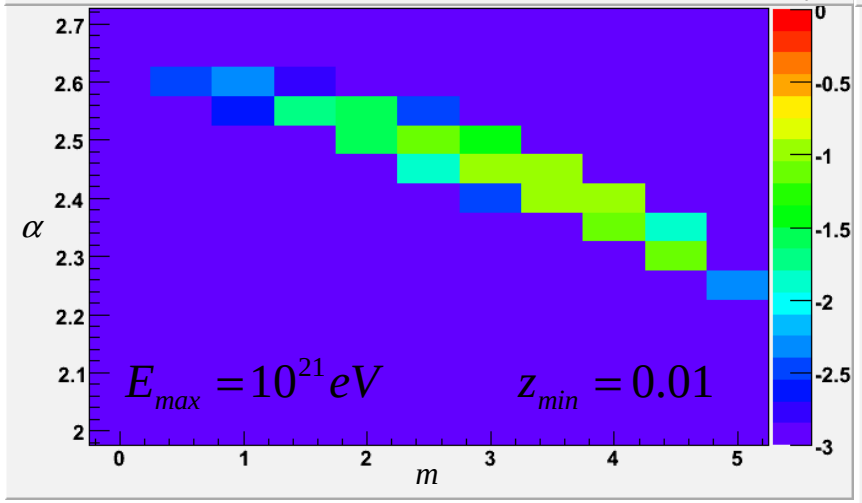
- V. S. Berezinsky and A. Yu. Smirnov, Astrophys. Sp. Sci. 32 461 (1975)
- M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen and S. Sarkar, Astropart. Phys. 34, 106 (2010) [arXiv:1005.2620 [astro-ph.HE]]
- V. Berezinsky, A. Gazizov, M. Kachelriess and S. Ostapchenko, Phys. Lett. B 695, 13 (2011) [arXiv:1003.1496 [astro-ph.HE]]
- X. Wang, R. Liu, F. Aharonian, arXiv:1103.3574 [astro-ph.HE]
- Guillaume Decerprit, Denis Allard, arXiv:1107.3722 [astro-ph.HE]

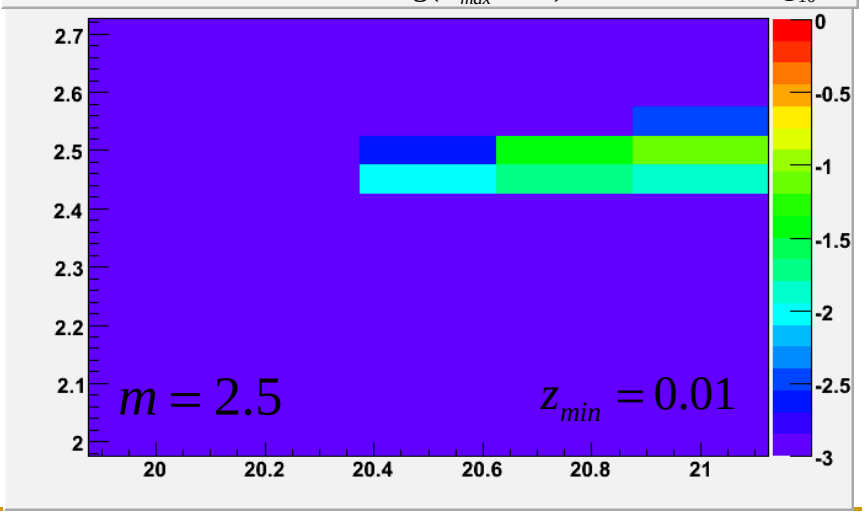
Goodness of fit plots HiRes Spectrum (dip model)

$E_{fit} > 10^{18} eV$ $F(E, z) \sim E^{-\alpha} \exp(-E/E_{max}) \exp(-E_{min}/E) (1+z)^{m} \Theta(z-z_{min}) \Theta(z_{max}-z)$

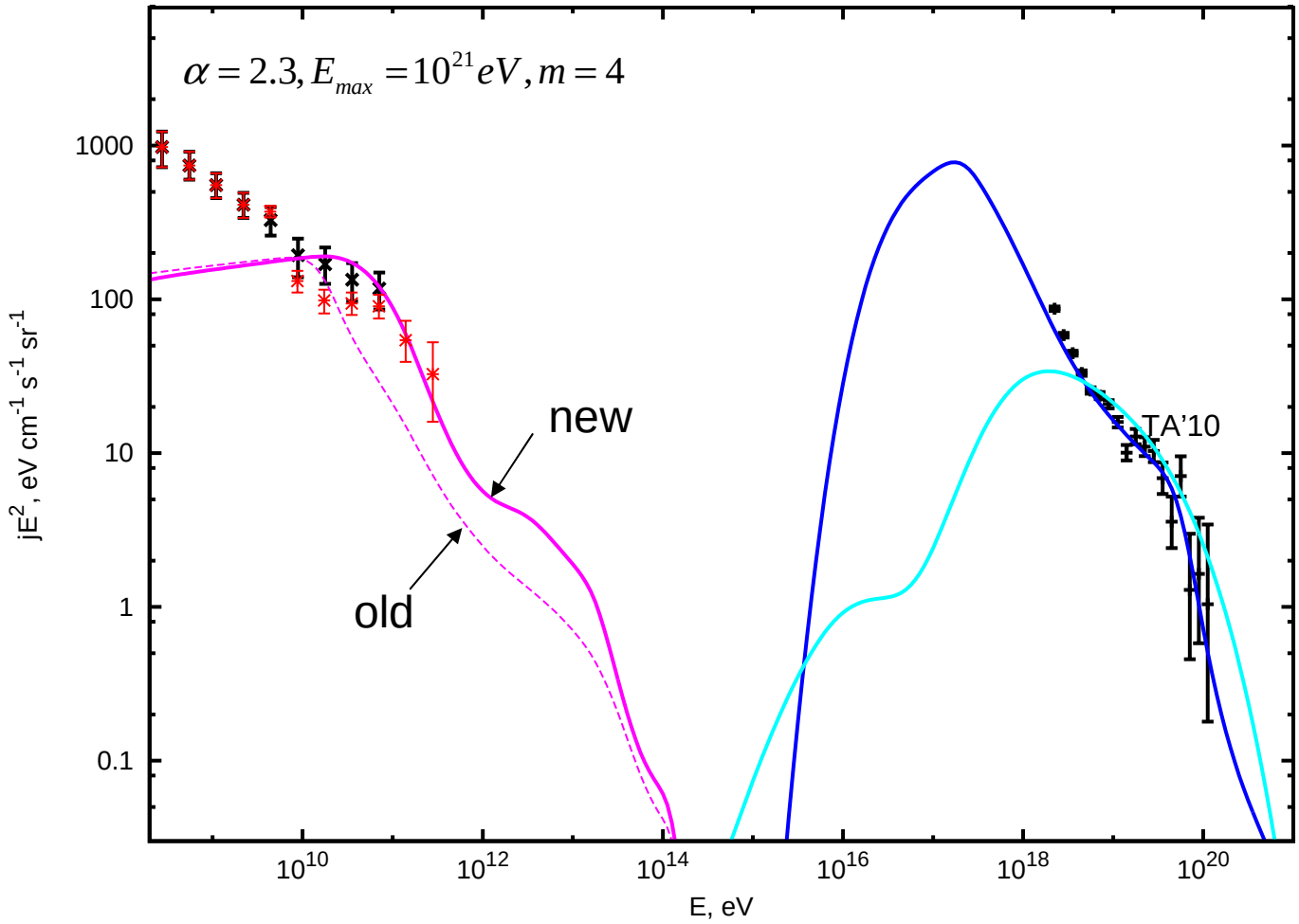






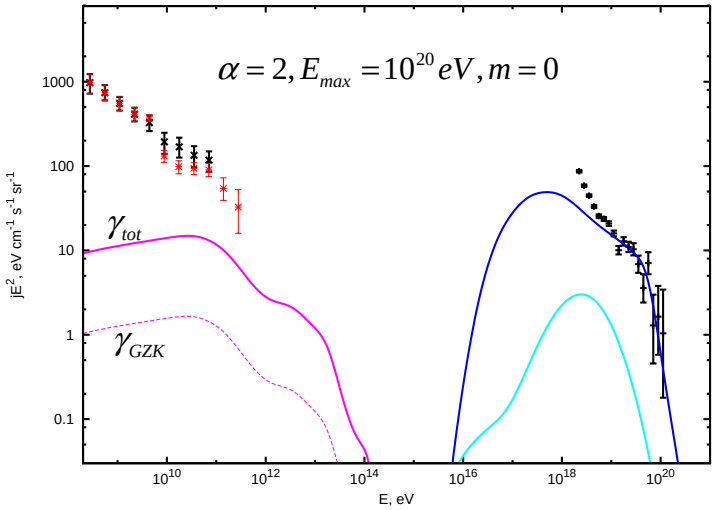


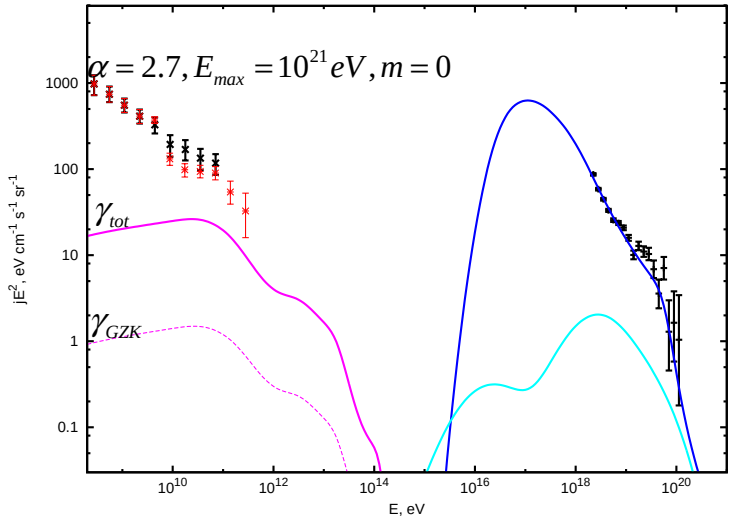
Photon diffuse flux dependence on EBL

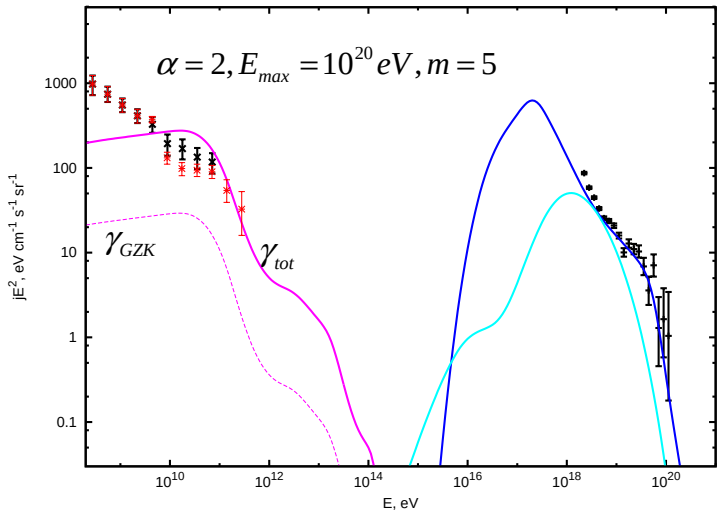


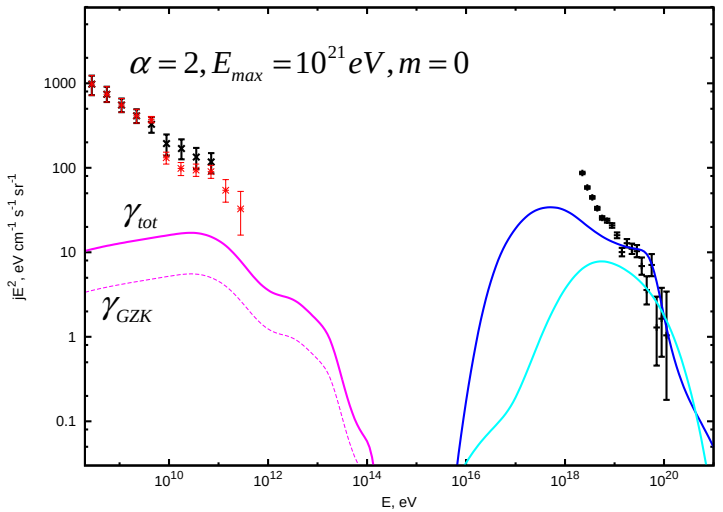
IR/Optic background models used here:
Old: F.Stecker et al. astro-ph/0510449
New: Kneiske et al. astro-ph/1001.2132v1

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



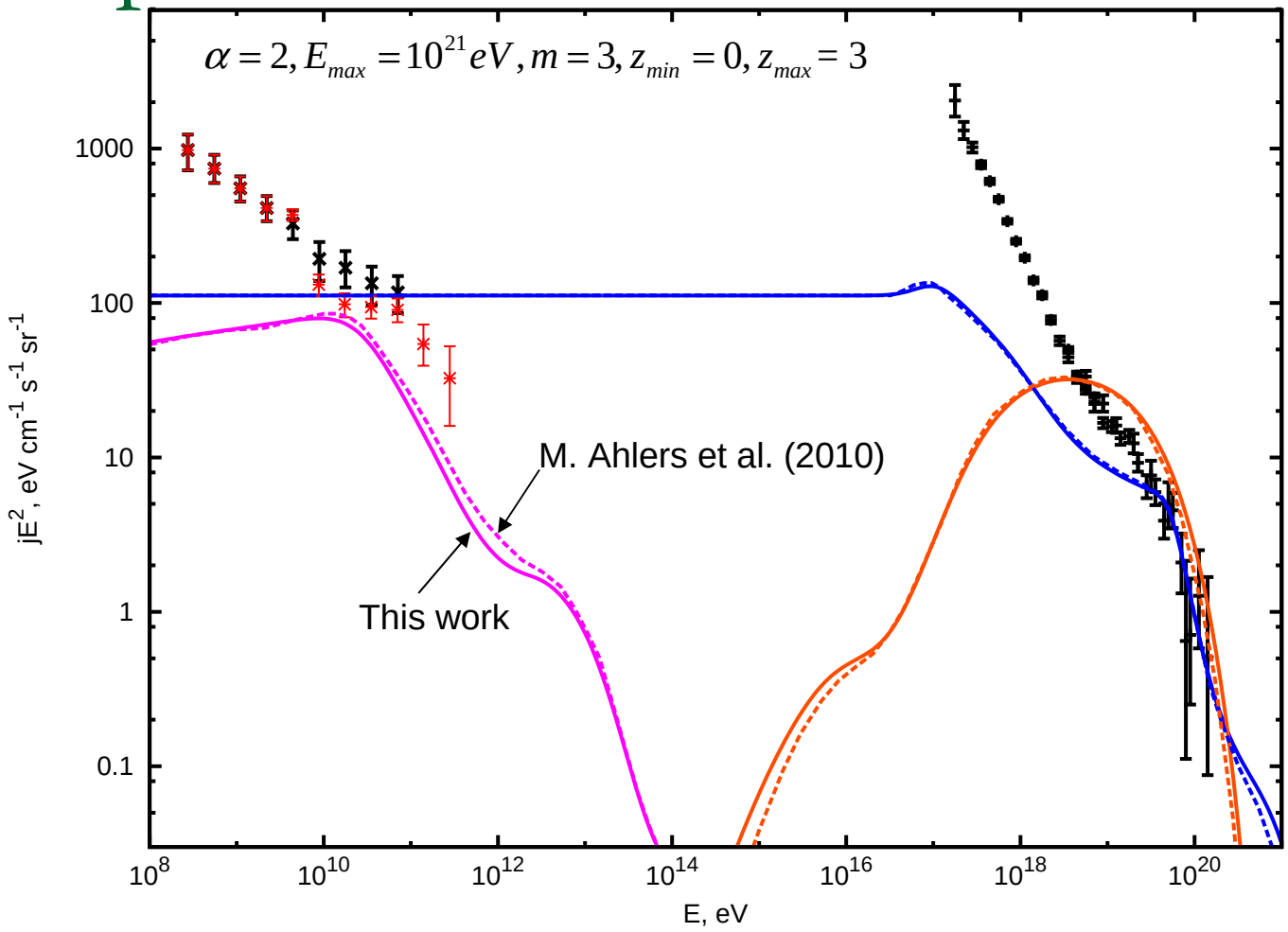






Restrictions on cosmogenic neutrinos and UHECR from Fermi 3 years data

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

Simulations of cosmic rays propagation

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

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

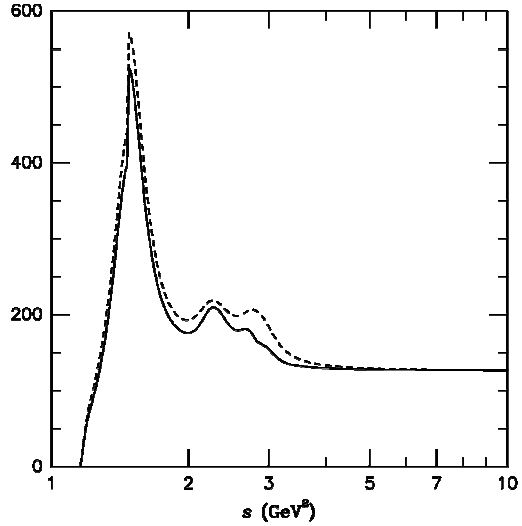
Interactions

- Protons and neutrons

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

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

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



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

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

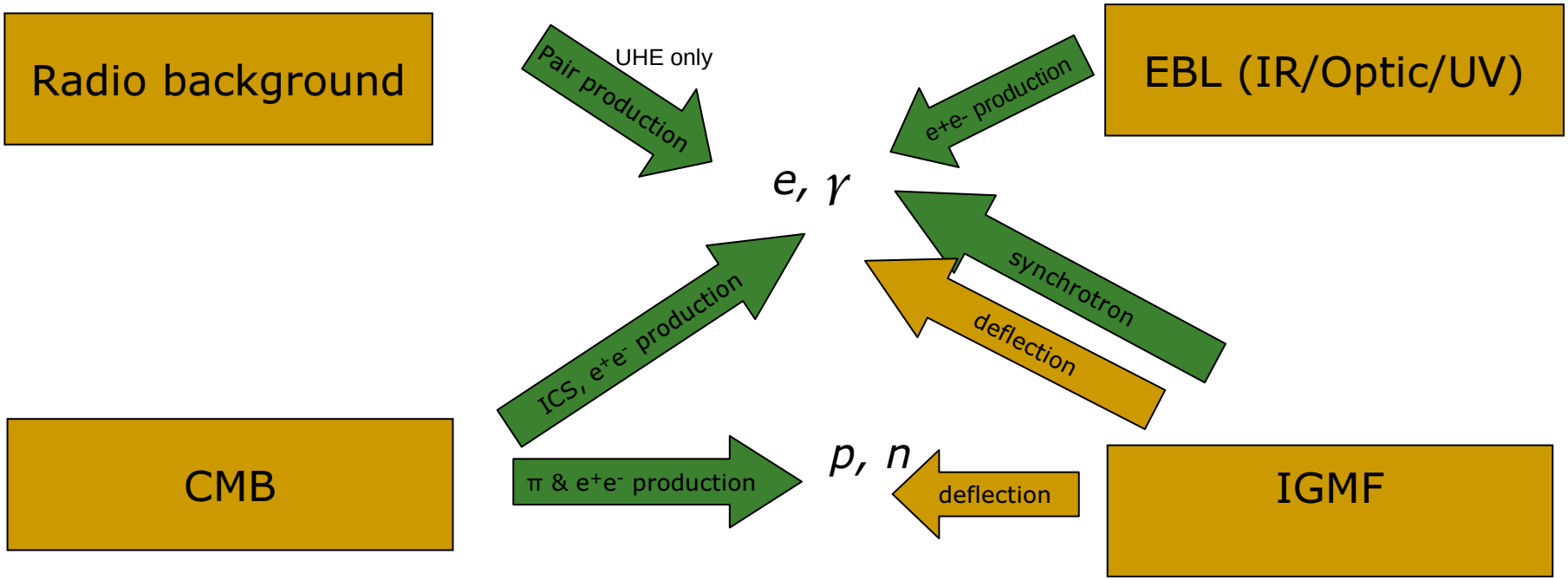
$$E_{th} = \frac{m_e(m_A + m_e)}{\epsilon} \simeq 5 \times 10^{14} \left(\frac{\epsilon}{eV}\right)^{-1} eV$$

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)

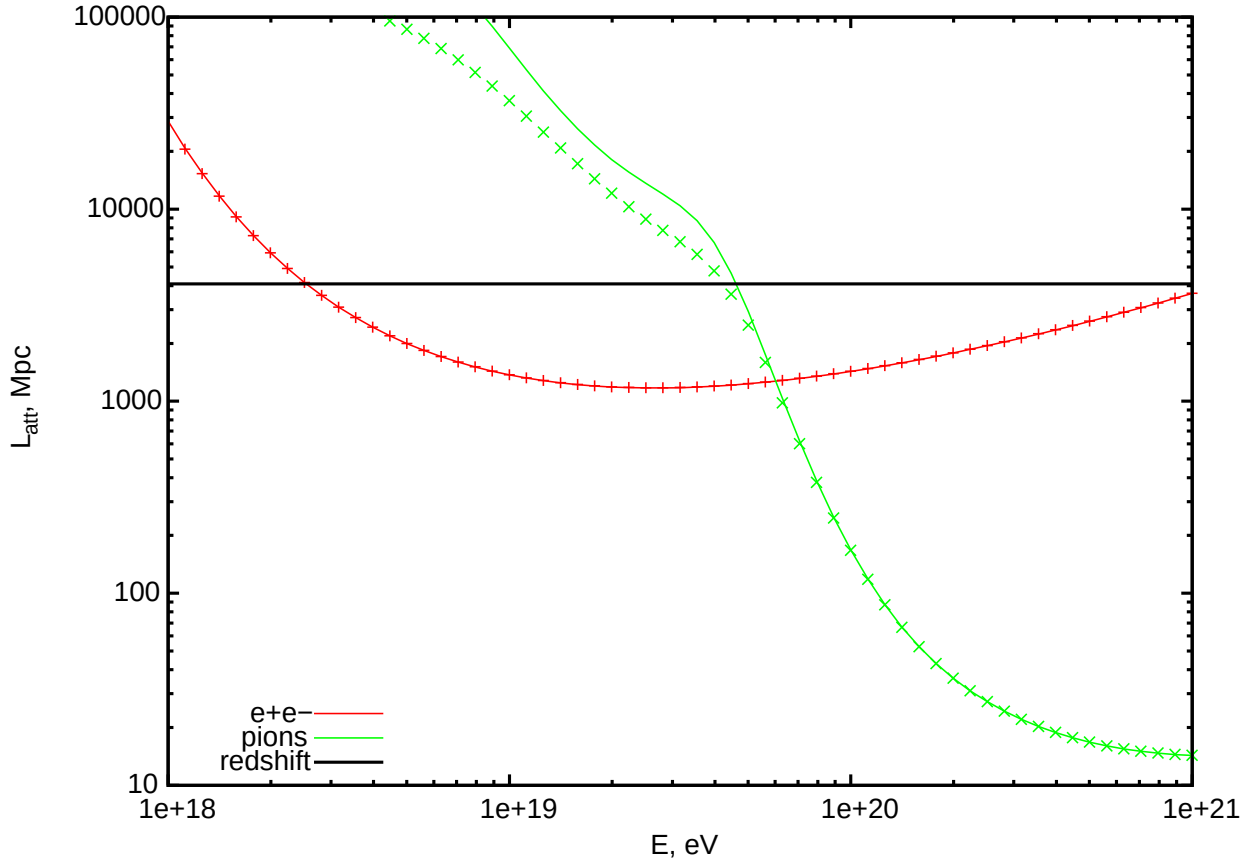
neutron β-decay $n \to pe^-\bar{\nu}_e \qquad \tau = 900s$

Main Factors influencing UHECR and γ-ray propagation



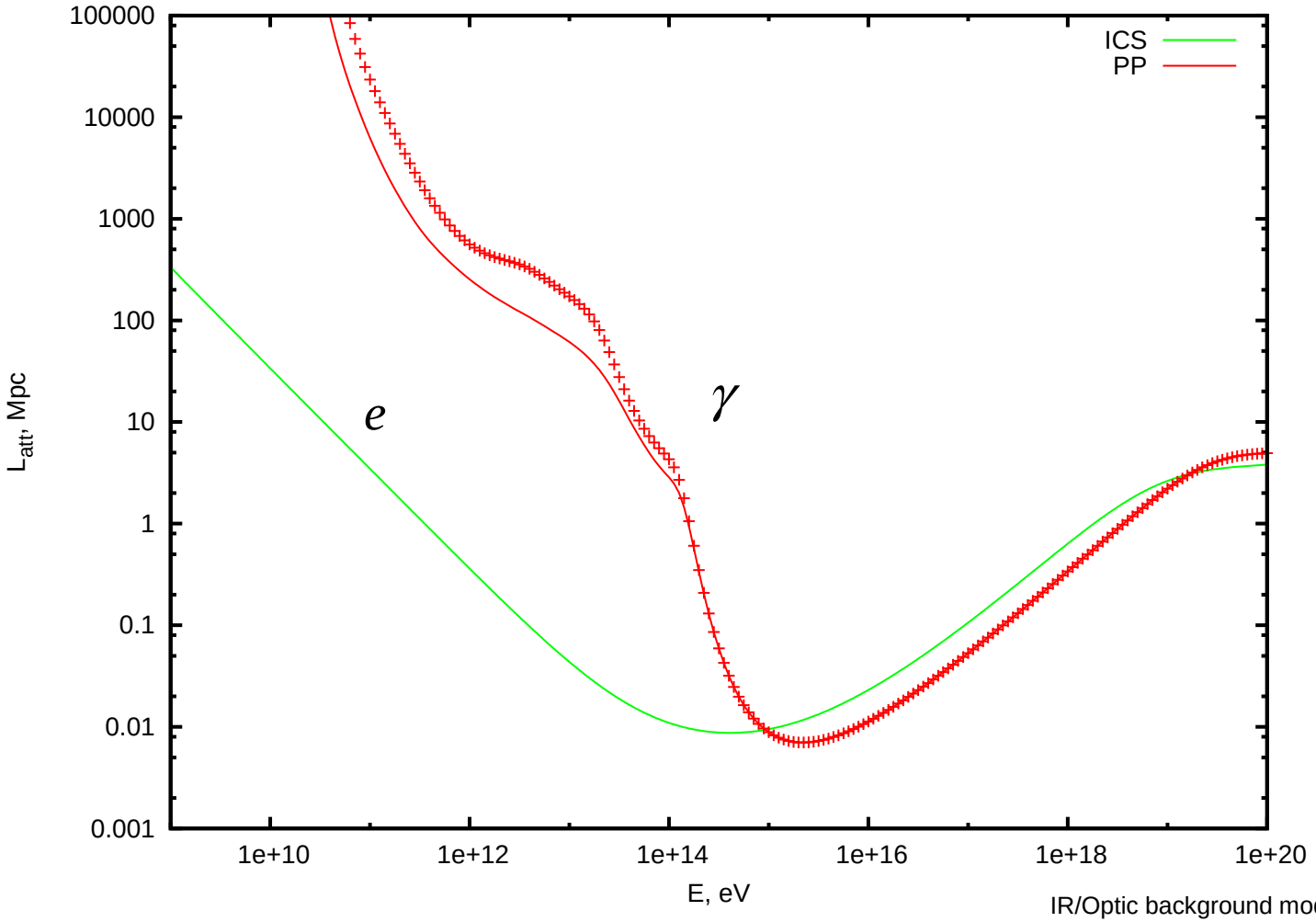
Proton attenuation length

p



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

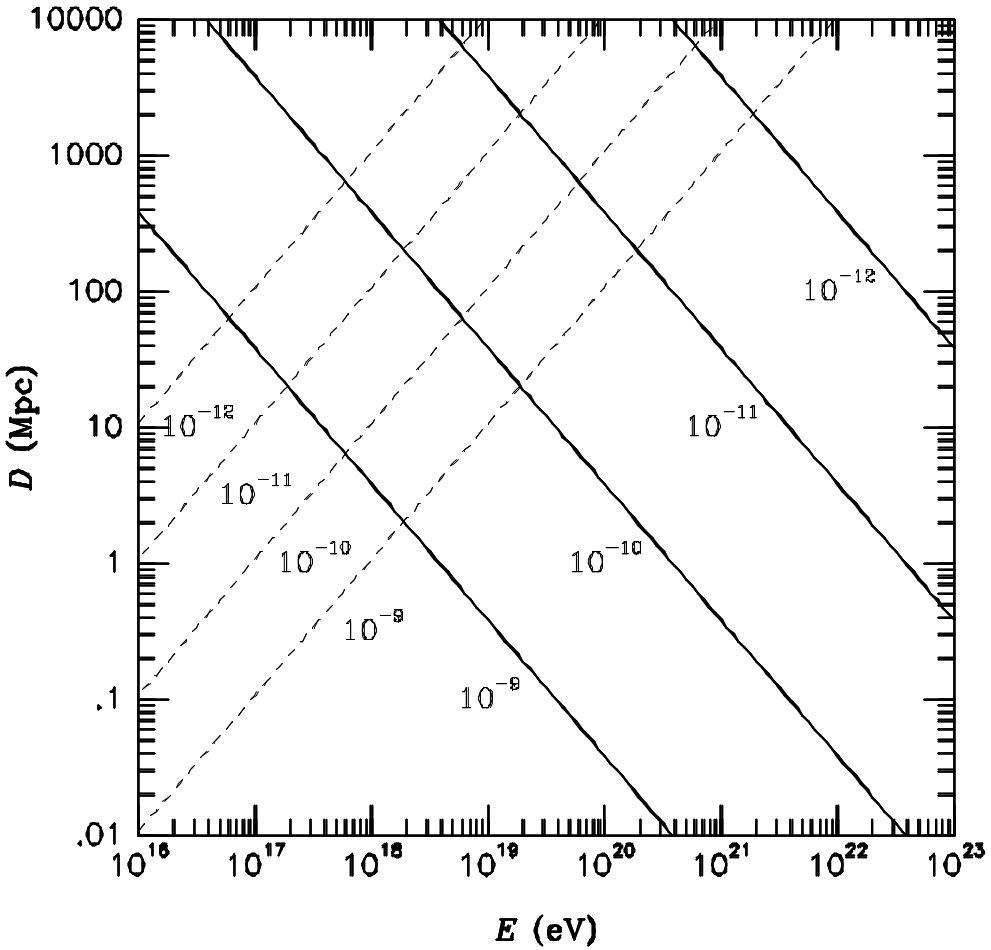
Attenuation lengths (EM cascade)



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

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

EGMF estimates

$B<10^{-9}$ 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)*

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

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- RFBR grant 11-02-09584-моб_з