GZK Neutrinos after Fermi-LAT

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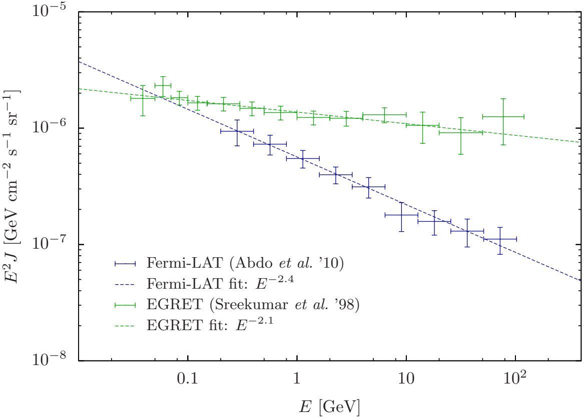
Fermi-LAT vs. EGRET

- New diffuse γ-ray background measured by Fermi-LAT is significantly softer than the former measurement by EGRET.
- *Reduced* energy density sets stronger limits on multi-messenger models, in particular UHE CRs and cosmogenic neutrinos.

[➜ talk by M.Kackelriess; see also Berezinsky/Gazizov/Kachelriess/Ostapchenko'10]



Cosmogenic Neutrinos and the γ-ray Background

- Photopion production of protons in cosmic background radiation (CMB) creates cosmogenic neutrinos. [Greisen'66;Zatsepin/Kuzmin'66;Berezinsky/Zatsepin'69]

$$
\begin{aligned}
p + \gamma_{\rm bgr} &\to \Delta(1232) \to \pi^+ + n \\
&\qquad\qquad\quad \hookrightarrow \mu^+ + \nu_\mu \\
&\qquad\qquad\qquad\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
p + \gamma_{\rm bgr} &\to \Delta(1232) \to \pi^0 + p \\
&\qquad\qquad\quad \hookrightarrow \gamma + \gamma
\end{aligned}
$$

- Simultaneous production of positrons and γ-rays with **comparable energy densities**:

$$\omega_{\rm EM} : \omega_\nu \sim 5 : 3$$

- Electromagnetic (EM) components **cascade** in background radiation via to Fermi-LAT energies (GeV-TeV).

➜ Diffuse γ-ray background limits the flux of cosmogenic neutrinos ("cascade limit"): [Mannheim/Protheroe/Rachen'98;Keshet/Waxman/Loeb'04]

$$E^2 J_\nu \lesssim \frac{c}{4\pi}\omega_{\rm cas} \log\frac{E_{\rm max}}{E_{\rm min}}$$

Bethe-Heitler Pair Production

- Additional contributions to the cascade by Bethe-Heitler (BH) pair production:

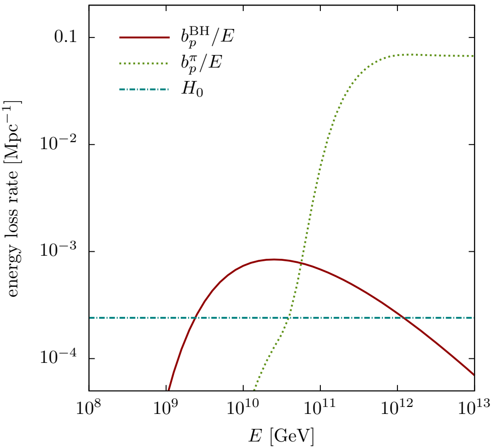
$$p + \gamma_{\rm bgr} \to p + e^+ + e^-$$

➜ BH is the dominant energy loss process for UHE CR protons at $\sim 2 \times 10^9 \div 2 \times 10^{10}$ GeV.

➜ *Decreases* the cascade limit on cosmogenic neutrinos.

[Kalashev/Semikoz/Sigl'09]

✘ **Challenge:**
Resulting limit on cosmogenic neutrinos depends on cosmic ray model.



UHE CR Model

- Most optimistic cosmogenic neutrino fluxes are obtained in UHE CR models assuming **all-proton spectra**.

  [*e.g.* Anchordoqui *et al.*'07]

- Candidates for the transition between galactic CRs and extra-galactic protons are the **"2nd knee"** or **"ankle"**.

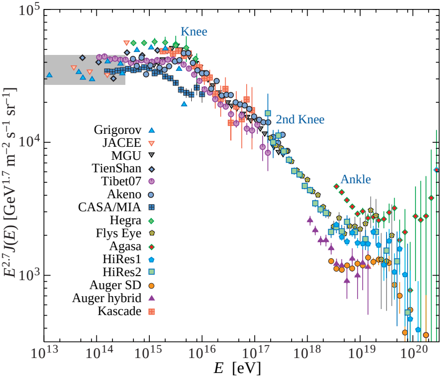
  [Berezinsky/Gazizov/Grigorieva'06]

- Relative energy densities $\omega^{\rm BH}_{\rm cas} \leftrightarrow \omega^{\pi}_{\rm cas}$ dependent on various assumptions, in particular:

  ➜ "cross-over" energy

  ➜ source spectrum and evolution

  ➜ systematic uncertainties of UHE CR measurements



[Amsler *et al.*'06]

UHE CR Model

- **spatially homogeneous and isotropic** distribution of sources
- Boltzmann equation of co-moving number density ($Y = n/(1+z)^3$):

$$\dot{Y}_i = \partial_E(HEY_i) + \partial_E(b_i Y_i) - \Gamma_i\, Y_i + \sum_j \int \mathrm{d}E_j\, \gamma_{ji} Y_j + \mathcal{L}_i\,,$$

- **power-law** proton emission rate:

$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \times \begin{cases} f_-(E/E_{\rm min}) & E < E_{\rm min}\,, \\ 1 & E_{\rm min} < E < E_{\rm max}\,, \\ f_+(E/E_{\rm max}) & E_{\rm max} < E\,. \end{cases}$$

- smooth **high and low energy cutoff**: $f_\pm(x) \equiv x^{\pm 2}\exp(1-x^{\pm 2})$
- **redshift evolution** $\mathcal{L}_p(z,E) = \mathcal{L}_p(0,E)(1+z)^n\Theta(z_{\rm max}-z)$.
- fixed in the following: $z_{\rm max} = 2$ and $E_{\rm max} = 10^{21}$ eV

➜ **free parameters** for goodness-of-fit test: γ, n, and $E_{\rm min}$

Energy Density of the Cascade

- **energy density** of the cascade per co-moving volume:

$$\omega_{\rm cas}(z) \equiv \int {\rm d}E\, E Y_{\rm cas}(z,E) = \int {\rm d}E\, E\left(Y_\gamma(z,E) + Y_{e^-}(z,E) + Y_{e^+}(z,E)\right)$$

- evolution equation:

$$\dot\omega_{\rm cas} + H\omega_{\rm cas} = \int {\rm d}E\, b(z,E) Y_p(z,E)$$

- solution at $z = 0$:

$$\omega_{\rm cas}(0) = \int {\rm d}t \int {\rm d}E \frac{b(z,E)Y_p(z,E)}{(1+z)}$$

- two CEL contributions, Bethe-Heitler ($b_{\rm BH}$) and photopion production:

$$b_\pi(z,E) \simeq \int {\rm d}E' E' \left[\gamma_{pe^-}(z,E,E') + \gamma_{pe^+}(z,E,E') + \gamma_{p\gamma}(z,E,E')\right]$$

- introduced as a **prior** on the CR normalization in the goodness-of-fit test:

[Berezinsky/Gazizov/Kachelriess/Ostapchenko'10]

$$\omega_{\rm cas} \leqslant \omega_{\rm Fermi} \simeq 5.8 \times 10^{-7}\ {\rm eV/cm}^3$$

Goodness of Fit Test

- Number of **expected events** depend on energy scale uncertainty (δ) and normalization ($\mathcal{N}$):

$$N_i(n,\gamma,\mathcal{N},\delta) = A_i \int_{E_i(1+\delta)-\Delta_i/2}^{E_i(1+\delta)+\Delta_i/2} \mathrm{d}E\, J^p_{\mathcal{N},n,\gamma}(E)$$

- **Probability distribution** $P_{\vec{k}}(n,\gamma,\mathcal{N},\delta)$ of replica experiments with events $\vec{k}$ is the product of the individual Poisson distributions.

- **Marginalization** with respect to δ and $\mathcal{N}$ using $\omega_{\rm cas} \leqslant \omega_{\rm Fermi}$ as a prior on $\mathcal{N}$:

$$P_{\rm exp}(n,\gamma) = \mathrm{Max}_{\delta,\mathcal{N}} P_{\vec{N}^{\rm exp}}(n,\gamma,\mathcal{N},\delta)$$

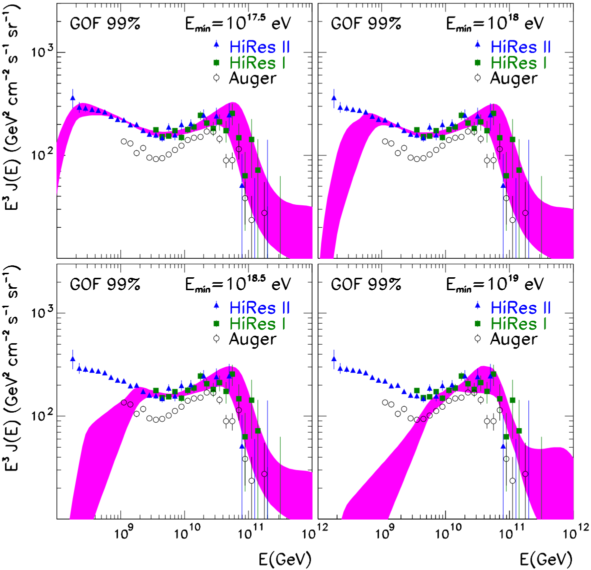
- Compatibility of a model with the experimental result at the confidence level "GOF" determined by:

$$\sum_{\vec{k}} P_{\vec{k}}(n,\gamma,\mathcal{N}_{\rm best},\delta_{\rm best})\Theta\left[P_{\vec{k}}(n,\gamma,\mathcal{N}_{\rm best},\delta_{\rm best}) - P_{\rm exp}(n,\gamma)\right] \leqslant \mathrm{GOF}$$

Goodness-of-Fit Test

- GoF based on Hires-I/II data ($\Delta E/E \simeq 25\%$)
- *fixed:*
  $E_{\rm max} = 10^{21}$ eV
  $z_{\rm min} = 0$ / $z_{\rm max} = 2$
- *priors:*
  $2.1 \leqslant \gamma \leqslant 2.9$
  $2 \leqslant n \leqslant 6$
  $\omega_{\rm cas} \leqslant \omega_{\rm Fermi}$
- *confidence levels:*
  68% (pink)
  95% **(blue)**
  99% **(magenta)**

➜ effect of $\omega_{\rm cas}$-prior shown as **black lines**



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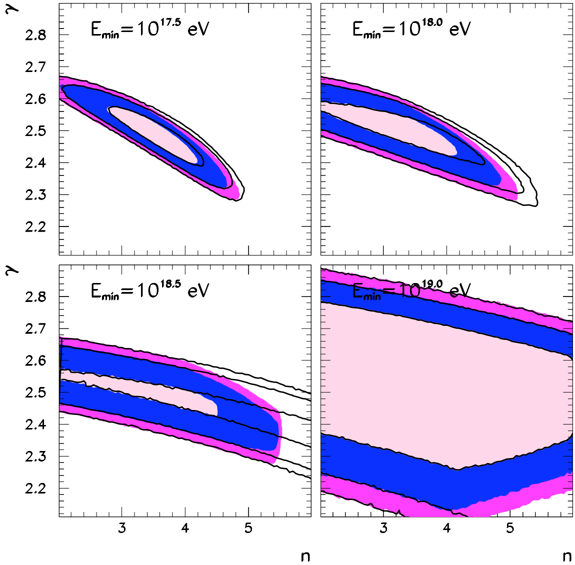
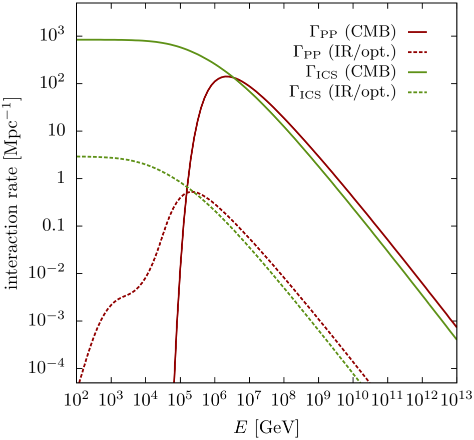


Explicit Calculation of γ-Ray Spectra

- ✔ CMB interactions **(solid lines)** dominate in casade:
  - inverse Compton scattering (ICS)
    $e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma$
  - pair production (PP)
    $\gamma + \gamma_{\rm CMB} \to e^+ + e^-$
- ✔ PP in IR/optical background **(red dashed line)** determines the "edge" of the spectrum:
- ✘ further contributions (negligible):
  - double pair production
    $\gamma + \gamma_{\rm bgr} \to e^+ + e^- + e^+ + e^-$
  - triple pair production
    $e^\pm + \gamma_{\rm bgr} \to e^\pm + e^+ + e^-$
  - synchrotron loss

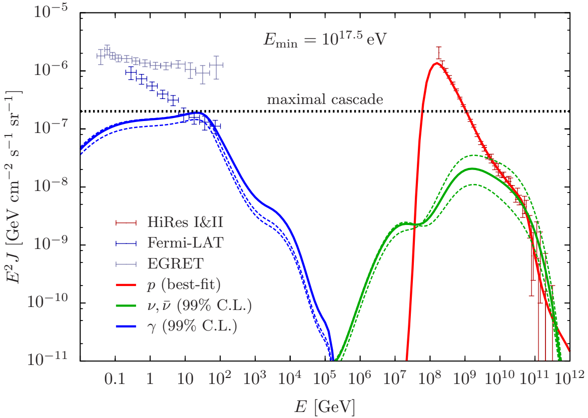


Explicit Calculation of γ-Ray Spectra

- ✔ Range of γ-ray spectra saturate the Fermi-LAT bound.
- ➜ Spectra at ~ 100 GeV depend on the IR/optical background.

[here: Franceschini *et al.* '08]

- "maximal cascade" : $E^2 J_{\rm cas} \lesssim \frac{c}{4\pi}\omega_{\rm Fermi}\log\left(\frac{\rm TeV}{\rm GeV}\right)$



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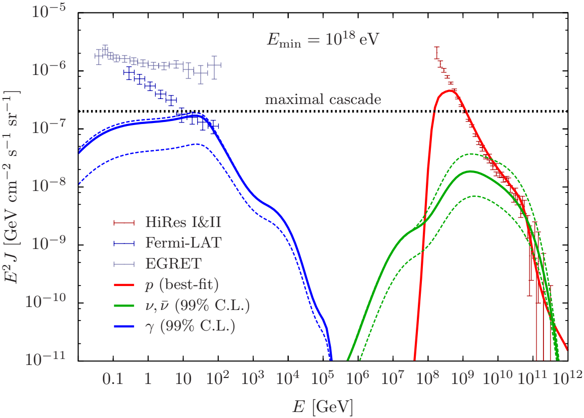

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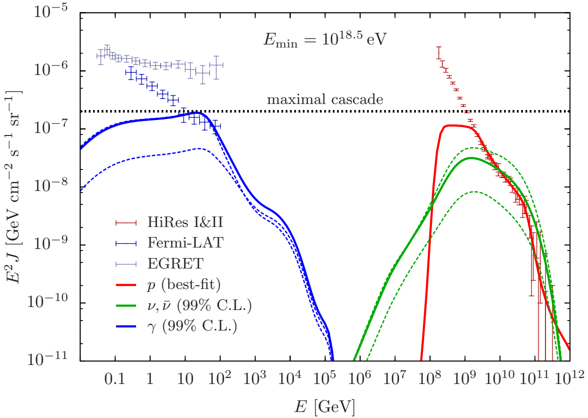

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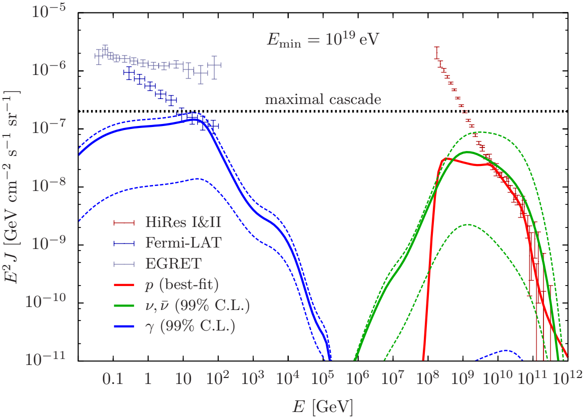
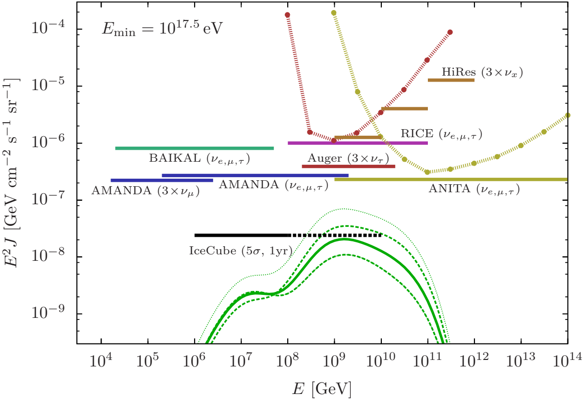


Cosmogenic Neutrinos

- For all cross-over energies considered, the range of models at the 99% C.L. **(dashed green lines)** is consistent with existing neutrino limits.
- Cascade bound, $\omega_{\rm cas} \leqslant \omega_{\rm Fermi}$, reduces the cosmogenic neutrino flux **(dotted green line)** by a factor 2-4.
- Range of cosmogenic neutrino fluxes increase along with the cross-over energy and lies *within reach of IceCube* **(black lines)**.



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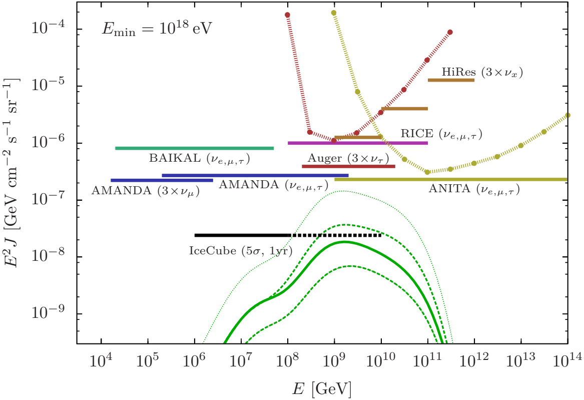

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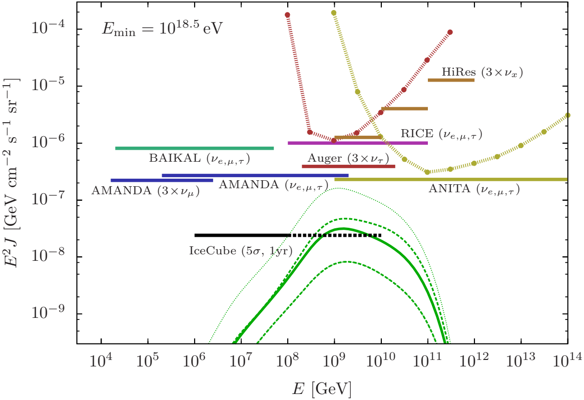

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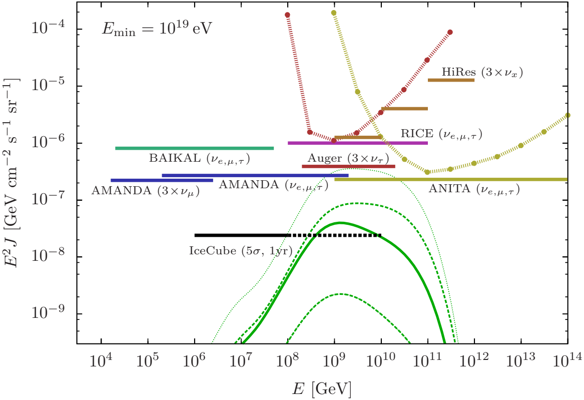


Summary

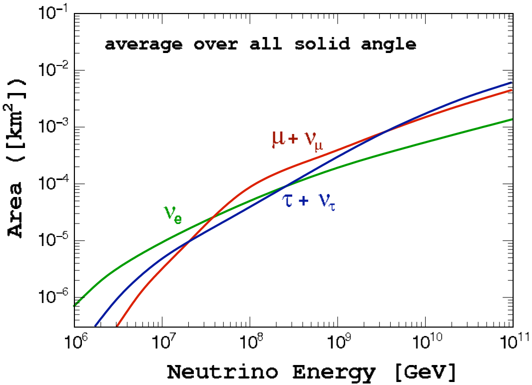
- The statistical impact of the cascade bound, $\omega_{\rm cas} \leqslant \omega_{\rm Fermi}$, depends on the energy uncertainty of UHE CR data.
  - A fit of an all-proton flux to HiRes data ($\Delta E/E \simeq 25$ %) predict maximal cosmogenic neutrino fluxes (99% C.L.) reduced by a factor 2-4.
  - **Ignoring** the energy scale uncertainty of HiRes rules out low cross-over models with strong source evolution ($n \gtrsim 3$). [Berezinsky *et al.*'10]
- For all cross-over energies considered, $10^{17.5}$eV-10^{19}eV, the range of models at the 99% C.L. is consistent with existing neutrino limits and lies within reach of future neutrino telescopes (IceCube).
- Best-fit cosmogenic neutrino fluxes increase along with the cross-over energy by a factor $\sim$2.

Appendix

Estimated EHEi-Sensitivity of IC80

- IceCube is also sensitive to EHE cosmic neutrinos, since atmospheric background dies off quickly.
- **Estimated (and preliminary!) IC80 sensitivity**: "$\Phi_{\rm IC80} \simeq (80/9)\Phi_{\rm IC9}$" ($5\sigma$, 1 yr):

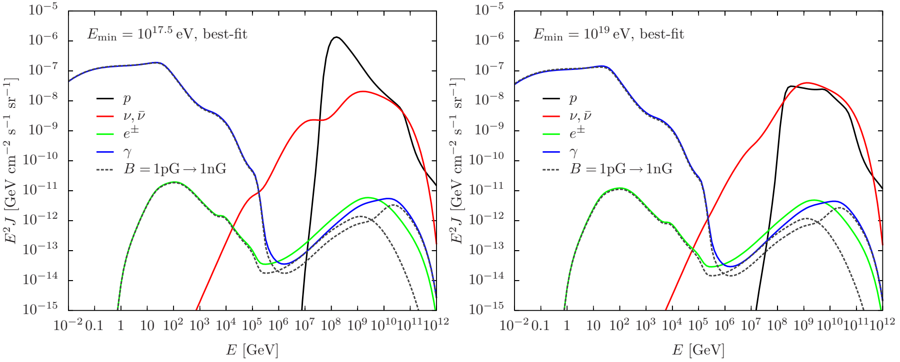
$$E^2\phi_{{\rm all}\,\nu} \simeq (3-4)\times 10^{-8}\,{\rm GeV\,cm^{-2}s^{-1}cr^{-1}} \quad (10^6\,{\rm GeV} < E_\nu < 10^{10}\,{\rm GeV})$$



[IC9 effective area, IceCube EHE group, ICRC'07]

Contribution of Strong Magnetic Fields

- Intergalactic magnetic fields in the range $B_{\rm IG} \simeq 10^{-16}$ G $\div$ 10^{-9} G.
  [Kronberg'93;Neronov/Vovk'10]
- Large-scale structure formation suggests $B_{\rm IG} = \mathcal{O}(10^{-12})$ G.
  [Dolag/Grasso/Springel/Tkachev'04]
- Effect of a strong magnetic field strength (10^{-9} G) as dashed lines:

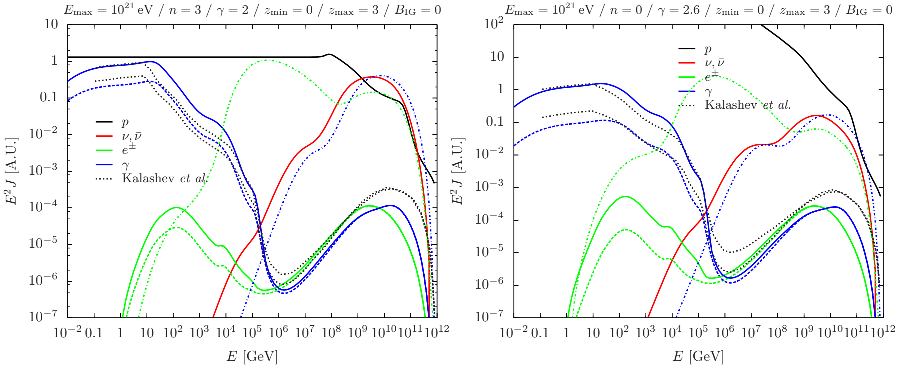


Comparison of the Cascade Spectra

- Comparison with γ-ray spectra derived by CRPropa.

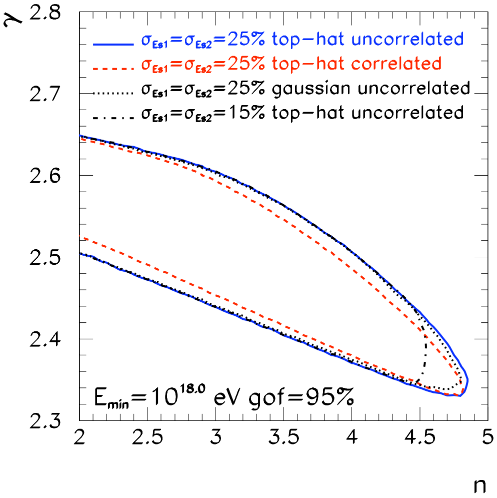
  [Armengaud/Beau/Sigl'07; γ-ray spectra from Kalashev/Semikoz/Sigl'07]

- Dashed lines: spectra **without BH**.
- Dot-dashed lines: spectra **without EM cascade**.



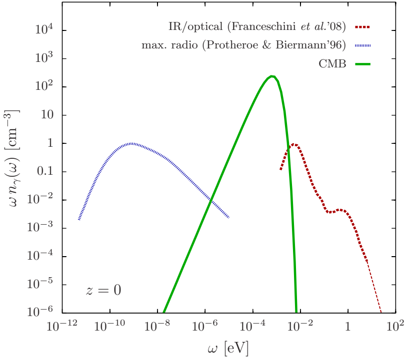
Effect of the CR Energy Resolution

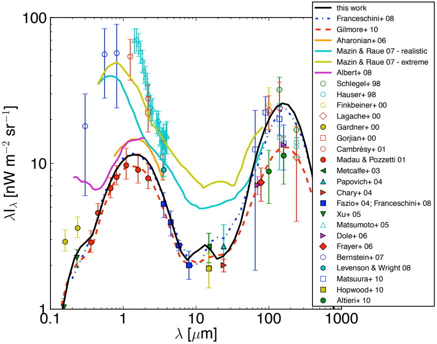
- Effect of the systematic uncertainties in the CR energy resolution.
- Variation of the method used in our analysis (blue):
  - correlated ↔ uncorrelated energy uncertainty between HiRes I and HiRes II
  - “top-hat” ↔ Gaussian
  - 15% width ↔ 25% width



Radiation Background

- **IR/optical** background from Franceschini/Rodighiero/Vaccari’08.
- **Radio** background (negligible) from Protheroe/Biermann’96.





[Dominguez *et al.*’10]