

Gamma-ray bursts: revised predictions for ultra-high-energy neutrinos and cosmic rays

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Princeton cosmology lunch
October 14, 2013



The origin of UHE CRs ($\gtrsim 10^9$ GeV) and ν 's is still unknown:

- ▶ *how* are they produced?
- ▶ *where* are they produced?

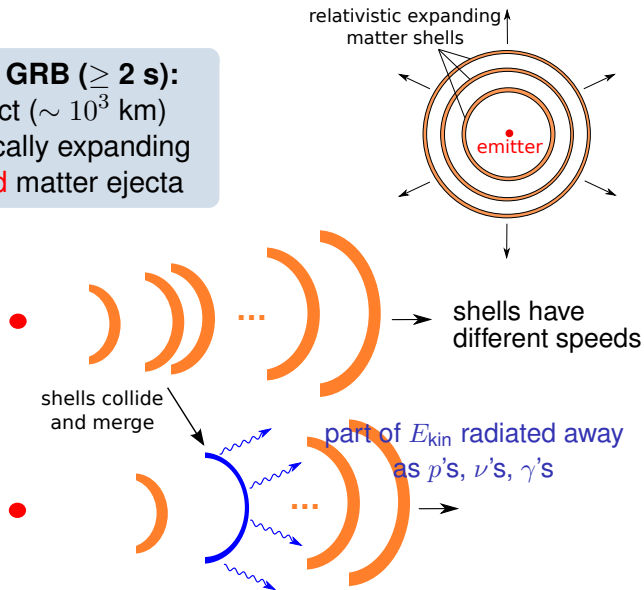
GRBs are among the best candidate sources:

- ▶ radiated energy of $\sim 10^{52} - 10^{53}$ erg
- ▶ intense magnetic fields of $\sim 10^5$ G
- ▶ magnetically-confined p 's shock-accelerated to $\sim 10^{12}$ GeV

Problem: experiments (IceCube, ANTARES) are starting to strongly constrain the simplest emission models

Solution: we need to build more realistic models!

Long-duration GRB (≥ 2 s):
a compact object ($\sim 10^3$ km)
emits relativistically expanding
baryonic-loaded matter ejecta



Joint production of UHECRs, ν 's, and γ 's:

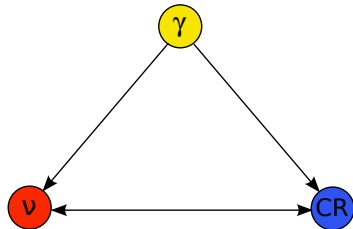
$$p\gamma \rightarrow \Delta^+ (1232) \rightarrow \begin{cases} n\pi^+, & \text{BR} = 1/3 \\ p\pi^0, & \text{BR} = 2/3 \end{cases}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$n \text{ (escapes)} \rightarrow p e^- \bar{\nu}_e$$

(Δ^+ : $\sim 50\%$ of all $p\gamma$ interactions)

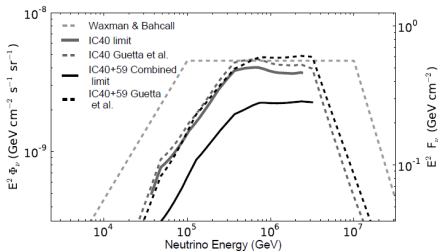


After propagation, with flavour mixing:

$$\nu_e : \nu_\mu : \nu_\tau : p = 1 : 1 : 1 : 1$$

(“one ν_μ per cosmic ray”)

The *simplest* neutron model is now strongly disfavoured ►



IceCube Collaboration:

- ▶ ν flux normalised to GRB γ fluence:

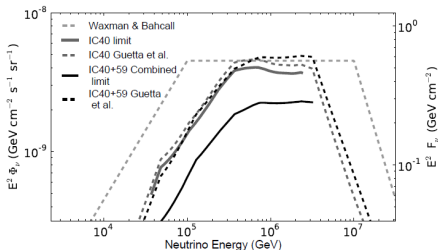
$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) \propto \int_{1 \text{ keV}}^{10 \text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma(\varepsilon_\gamma)$$

- ▶ quasi-diffuse ν flux from 117 GRBs
- ▶ **analytical calculation** – in tension with upper bounds

ICECUBE COLL., *Nature* **484**, 351 (2012)

AHLERS ET AL. *Astropart. Phys.* **35**, 87 (2011)

GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)



More detailed particle physics (NeuCosmA):

- ▶ extra multi- π , K , n production modes
- ▶ synchrotron losses of secondaries
- ▶ adiabatic cooling
- ▶ full photon spectrum, etc.

ν flux $\sim$ one order of magnitude lower

BAERWALD, HÜMMER, WINTER, *PRL* **108**, 231101 (2012)

See also: HE, LIU, WANG, *ApJ* **752**, 29 (2012)

IceCube Collaboration:

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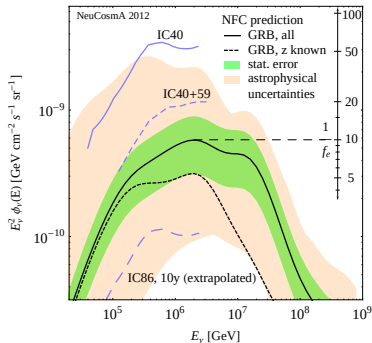
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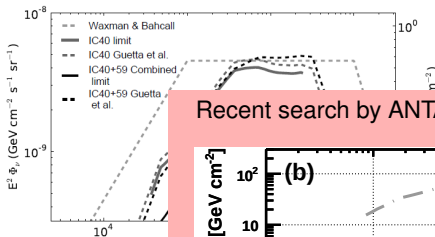
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GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)

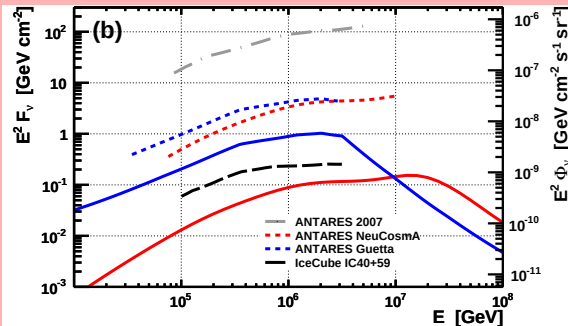




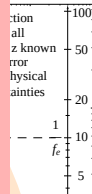
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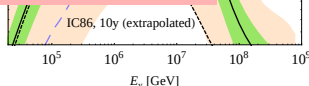
Recent search by ANTARES optimised for NeuCosmA:



side lower
31101 (2012)
12)



ANTARES Collab., 1307.0304



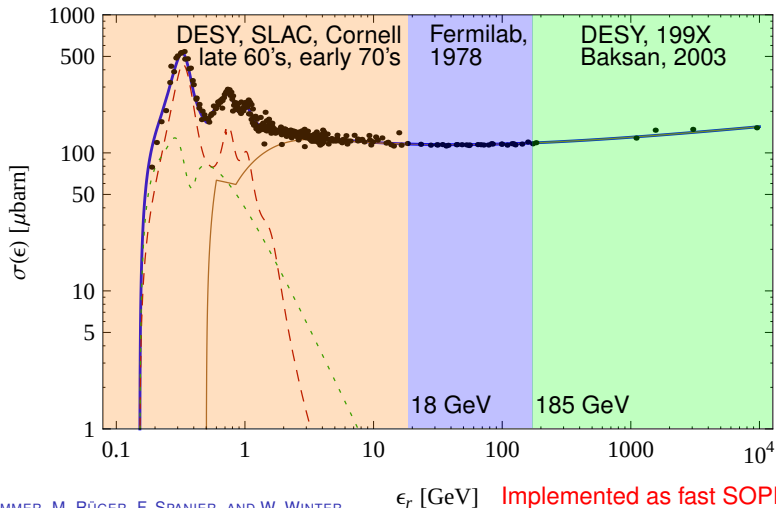
IceCube Collabor

- ▶ ν flux norm

$$\int_0^\infty dE_\nu E_\nu$$

- ▶ quasi-diffus
- ▶ analytical c
- ▶ upper bound

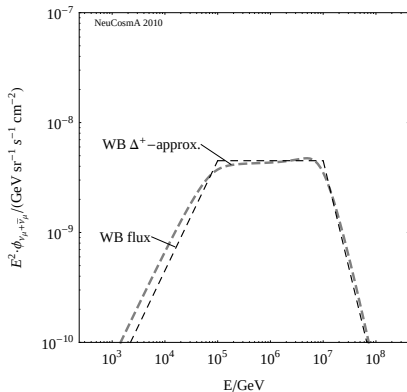
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S. HÜMMER, M. RÜGER, F. SPANIER, AND W. WINTER,
Astrophys. J. **721**, 630 (2010)

ϵ_r [GeV] Implemented as fast SOPHIA-based
parametrisation

- Contributions to the full photohadronic cross section



“WB flux”:

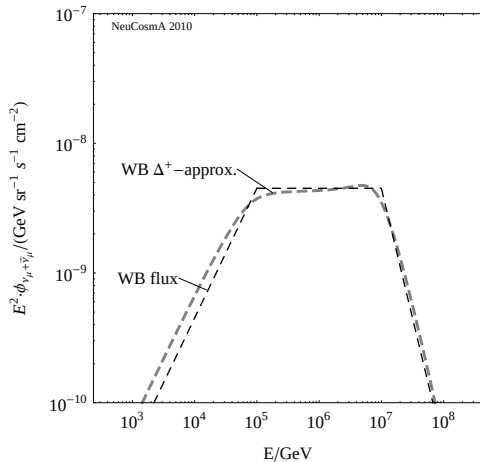
traditional, analytical
Waxman-Bahcall prediction

$$E_{\nu}^2 \phi_{\nu} = 0.45 \times 10^{-8} \frac{f_{\pi}}{0.2}$$

Use this to normalise the
proton and photon spectra –
and to study spectral changes

“WB Δ^+ –approx.”: explicit
synchrotron cooling of pions

- Contributions to the full photohadronic cross section

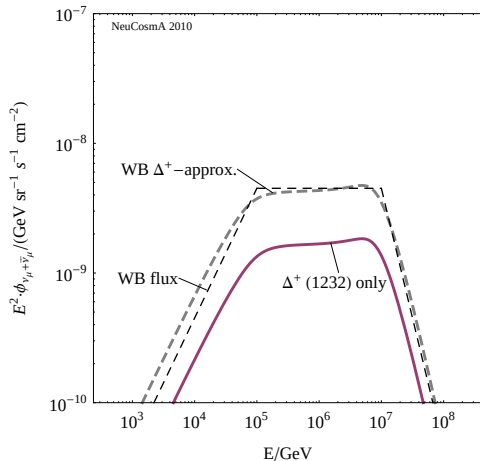


- Contributions to the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux
from $\pi^\pm$ decay divided in:

- $\Delta(1232)$ -resonance

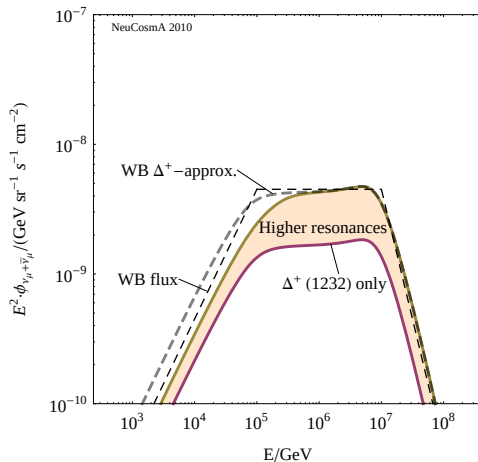
P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **D83**, 067303 (2011)



Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux
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- ▶ Higher resonances

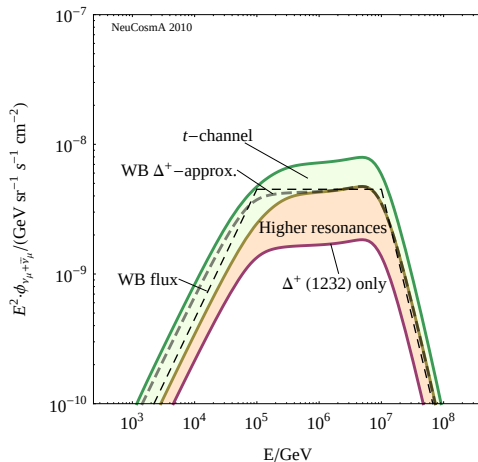
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- ▶ Higher resonances
- ▶ t -channel
(direct production)

P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **83**, 067303 (2011)

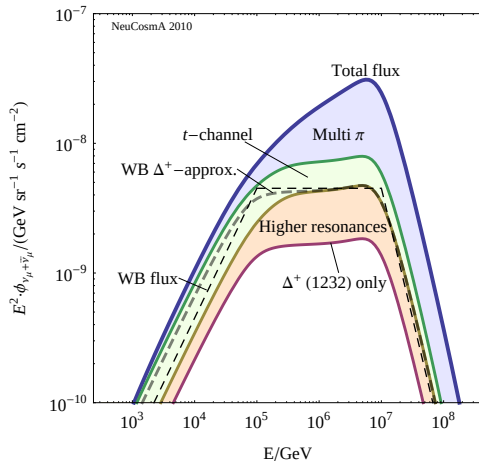


- Contributions to the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

- ▶ $\Delta(1232)$ -resonance
- ▶ Higher resonances
- ▶ t -channel (direct production)
- ▶ High energy processes (multiple π)

P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **83**, 067303 (2011)



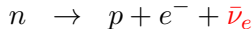
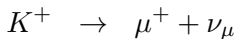
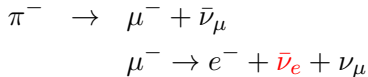
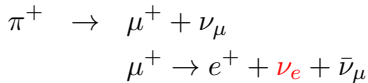
Especially "Multi π " contribution leads to **change of flux shape**; neutrino flux higher by up to a factor of 3 compared to WB treatment

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$

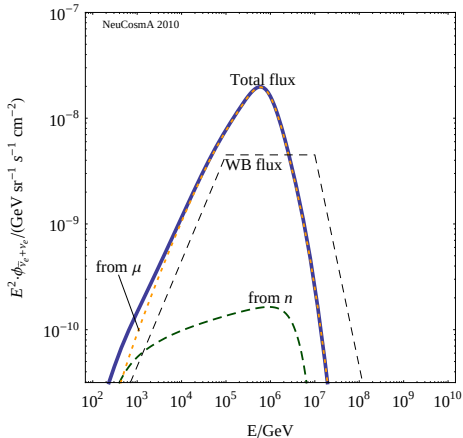
$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

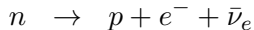
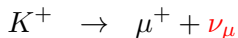
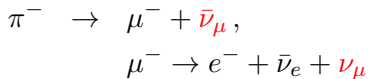
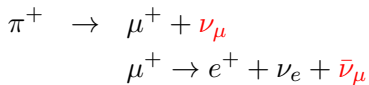
$$n \rightarrow p + e^- + \bar{\nu}_e$$



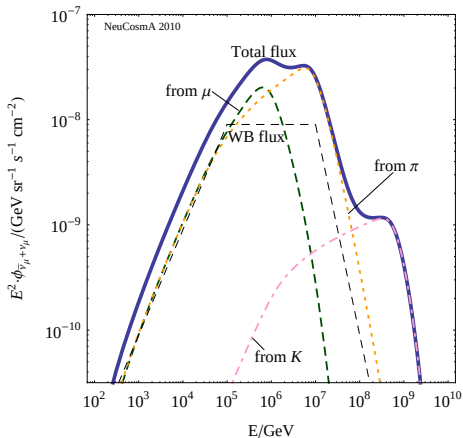
Resulting ν_e flux (at the observer)



P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)



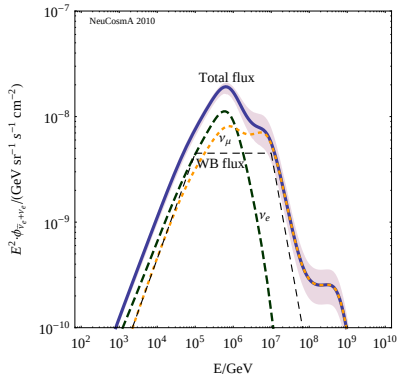
Resulting ν_μ flux (at the observer)



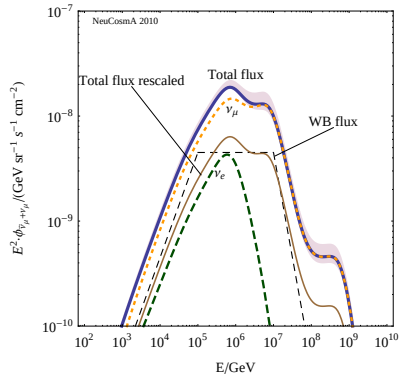
P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

- Neutrino spectra including flavour mixing

Electron neutrino spectrum



Muon neutrino spectrum



P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

Characteristic double peak structure from μ and π decay in both flavours, additional peak from K^+ decay at 10^8 to 10^9 GeV

Corrections to the analytical model:

► **shape revised:**

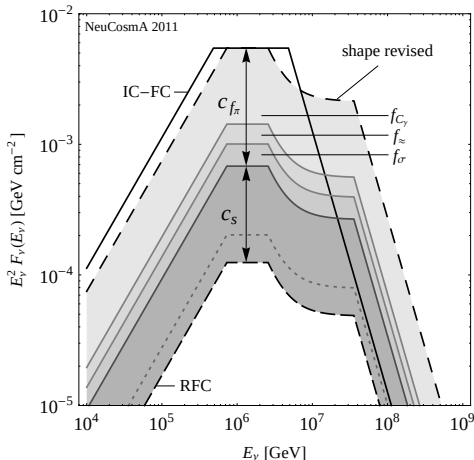
- shift of first break (correction of photohadronic threshold)
- different cooling breaks for μ 's and π 's
- $(1+z)$ correction on the variability scale of the GRB

► **Correction cf_π to π prod. efficiency:**

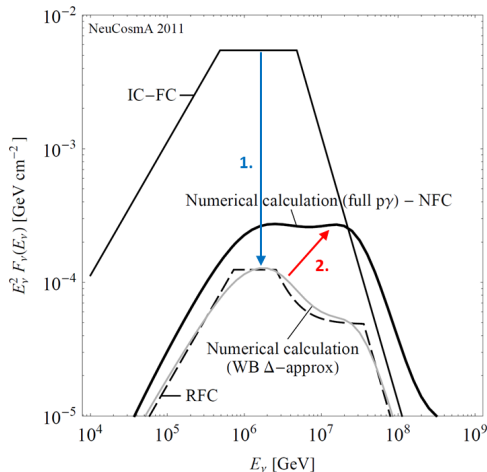
- f_{C_γ} : full spectral shape of photons
- $f_\approx = 0.69$: rounding error in analytical calculation
- $f_\sigma \simeq 2/3$: from neglecting the width of the Δ -resonance

► **Correction c_S :**

- energy losses of secondaries
- energy dependence of the mean free path of protons



S. HÜMMER, P. BAERWALD, AND W. WINTER,
Phys. Rev. Lett. **108**, 231101 (2012)



For example, GRB080603A:

1. Correction to analytical model (IC-FC $\rightarrow$ RFC)
2. Change due to full numerical calculation

IC-FC: IceCube-Fireball Calculation
RFC: Revised Fireball Calculation
NFC: Numerical Fireball Calculation

S. HÜMMER, P. BAERWALD, AND W. WINTER, *Phys. Rev. Lett.* **108**, 231101 (2012)

- The new prediction of the quasi-diffuse GRB ν flux

- ▶ Same $n = 117$ GRBs, effective area, and parameters as used by the IC-40 analysis

- ▶ Calculate the associated neutrino flux for each burst and the stacked flux $F_\nu(E_\nu)$

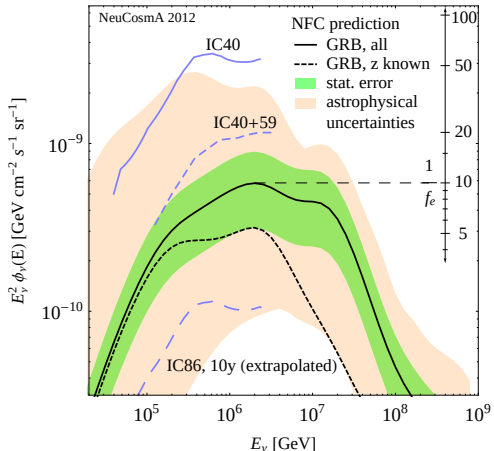
- ▶ Quasidiffuse flux:

$$\phi_\nu(E_\nu) = F_\nu(E_\nu) \frac{1}{4\pi} \frac{1}{n} \frac{667 \text{ bursts}}{\text{yr}}$$

- ▶ **Statistical uncertainty:**
extrapolation of a few bursts to a quasidiffuse flux

- ▶ **Astrophysical uncertainty:**

- ▶ $0.001 \leq t_v [\text{s}] \leq 0.1$
- ▶ $200 \leq \Gamma \leq 500$
- ▶ $1.8 \leq \alpha_p \leq 2.2$
- ▶ $0.1 \leq \epsilon_e/\epsilon_B \leq 10$



S. HÜMMER, P. BAERWALD, AND W. WINTER,
Phys. Rev. Lett. **108**, 231101 (2012)

The neutron model hinges on:

- 1 p 's magnetically confined, only n 's escape
- 2 p 's interact at most once, n 's do not (*optically thin source*)

However, under the “one ν_μ per CR” hypothesis, GRBs **are disfavoured** to be the sole source of UHECRs (**AHLERS et al.**).

M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

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What if ① and ② are violated?

- ▶ p 's “leak out”, not accompanied by (direct) ν production
- ▶ multiple p interactions enhance the ν flux
- ▶ in *optically thick sources*, only n 's at the borders escape

M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

Optical depth:

$$\tau_n = \frac{t_{p\gamma}^{-1}}{t_{\text{dyn}}^{-1}} \bigg|_{E_{p,\text{max}}} = \begin{cases} \lesssim 1, & \text{optically \textbf{thin} source} \\ > 1, & \text{optically \textbf{thick} source} \end{cases}$$

$E_{p,\text{max}}$ determined from a competition of processes:

$$t'_{\text{acc}}(E'_{p,\text{max}}) = \min [t'_{\text{dyn}}, t'_{\text{syn}}, t'_{p\gamma}(E'_{p,\text{max}})]$$

Acceleration efficiency, η : $t'_{\text{acc}}(E'_p) = \frac{E'_p}{\eta c e B'}$

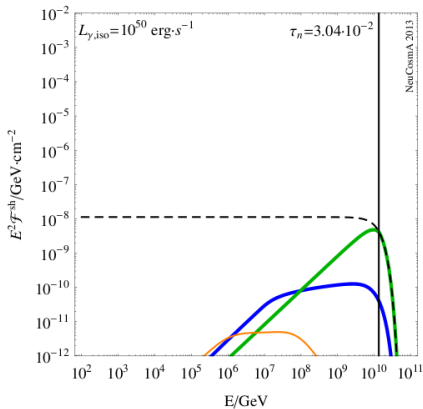
Particles can escape from within a shell of thickness λ'_{mfp} :

$$\left. \begin{aligned} \lambda'_{p,\text{mfp}}(E') &= \min [\Delta r', R'_L(E'), ct'_{p\gamma}(E')] \\ \lambda'_{n,\text{mfp}}(E') &= \min [\Delta r', ct'_{p\gamma}(E')] \end{aligned} \right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta r'}$$

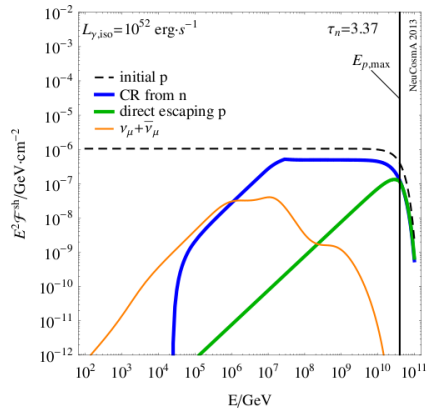
fraction of escaping particles

A two-component model of CR emission

Optically **thin** source:



Optically **thick** source:

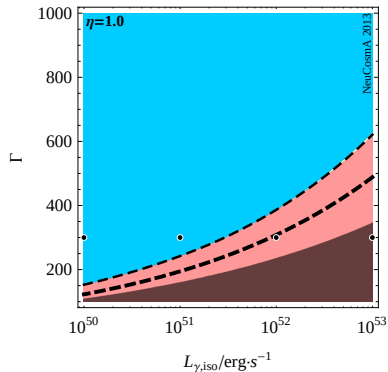
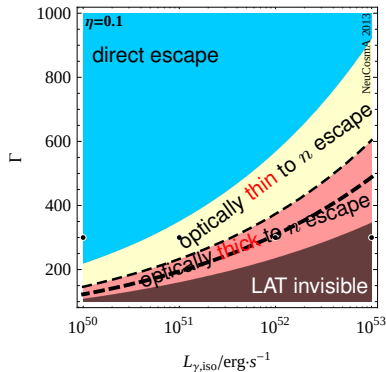


P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

Scan of the GRB emission parameter space:

acceleration
efficiency $\longrightarrow \eta = 0.1$

$\eta = 1.0$



We use a **Boltzmann equation** to transport protons to Earth:

- ▶ Comoving number density of protons ($\text{GeV}^{-1} \text{ cm}^{-3}$):

$$Y_p(E, z) = n_p(E, z) / (1 + z)^3 ,$$

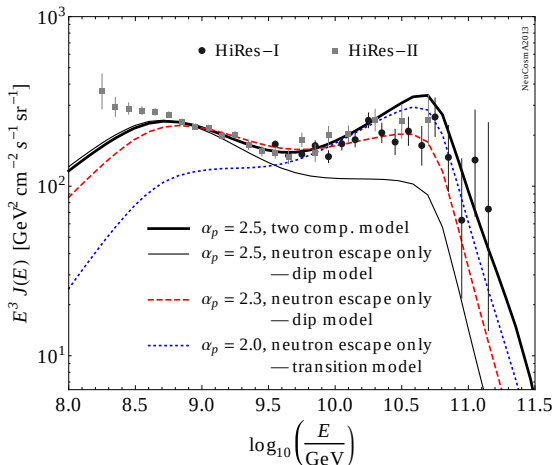
with n_p the real number density

- ▶ Transport equation (comoving source frame):

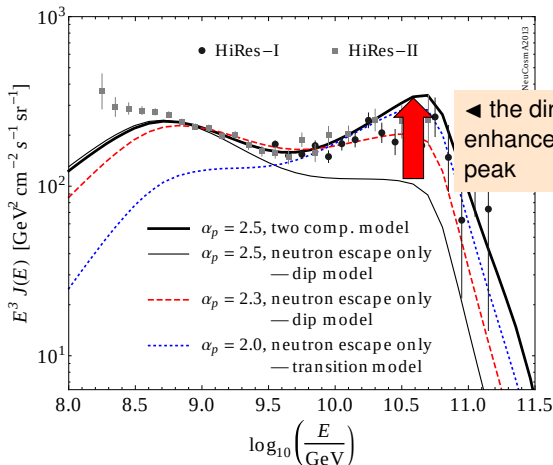
$$\dot{Y}_p = \underbrace{\partial_E (H E Y_p)}_{\text{adiabatic losses}} + \underbrace{\partial_E (b_{e^+e^-} Y_p)}_{\text{pair production losses}} + \underbrace{\partial_E (b_{p\gamma} Y_p)}_{\text{photohadronic losses}} + \underbrace{\mathcal{L}_{\text{CR}}}_{\text{CR injection from sources}}$$

$Q_{\text{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\text{max}}}$

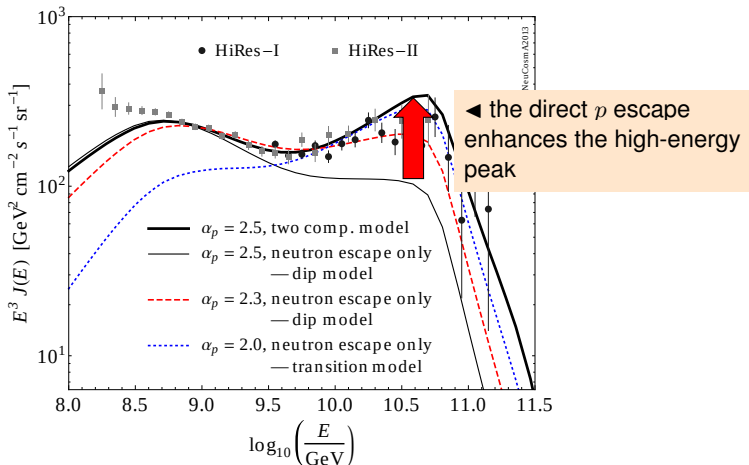
UHECR flux at Earth from n and direct p escape:



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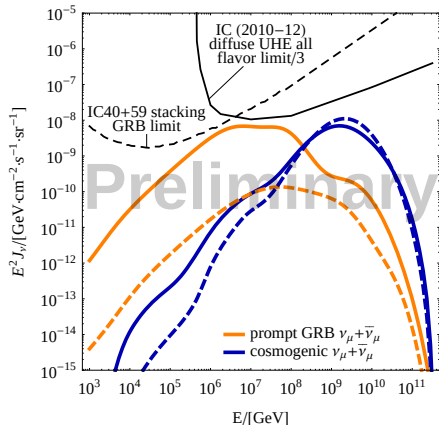
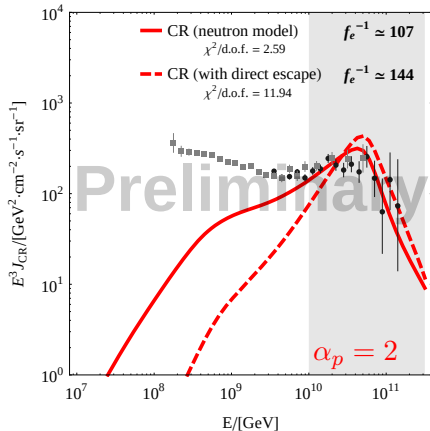


UHECR flux at Earth from n and direct p escape:

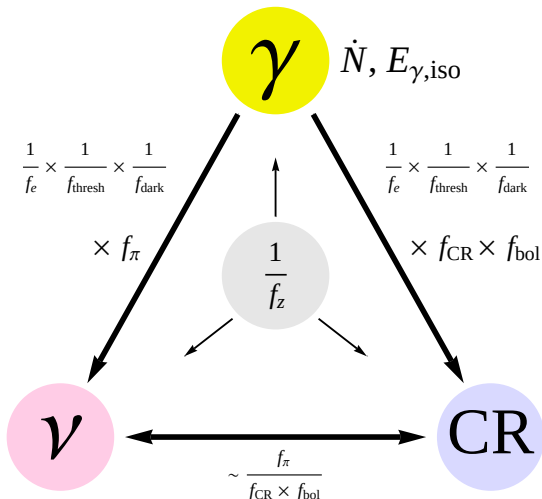


Our two-component model *is* able to fit the UHECR data

neutron model vs. two-component model:
prompt and cosmogenic ν 's



The big (multi-messenger) picture:



We can already limit the parameter space by using the UHECR observations and ν upper bounds:

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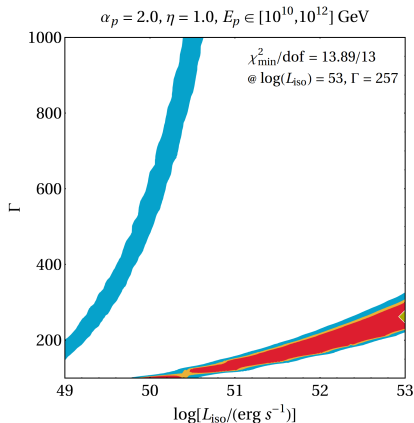
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- 2 Fit each spectrum to the HiRes data

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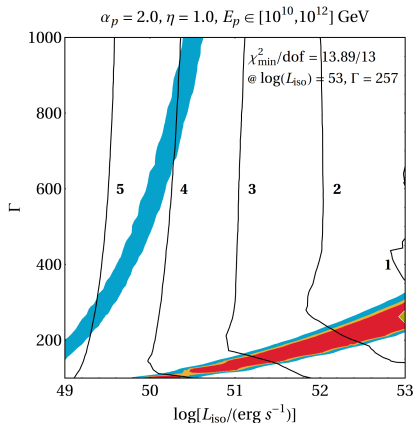
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- 3 Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions



M. AHLERS, P. BAERWALD, MB, F. HALZEN, N. WHITEHORN, W. WINTER, *In preparation*

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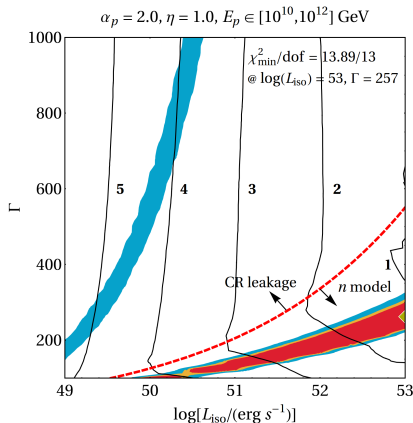
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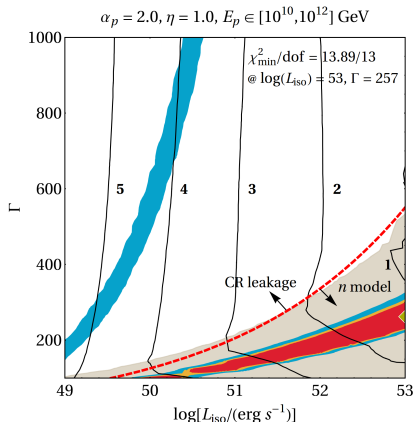
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- 4 Find the baryonic loading (i.e., relative energy of p 's to e 's) at each point
- 5 Identify the region corresponding to pure n escape and to n escape + CR leakage



M. AHLERS, P. BAERWALD, MB, F. HALZEN, N. WHITEHORN, W. WINTER, *In preparation*

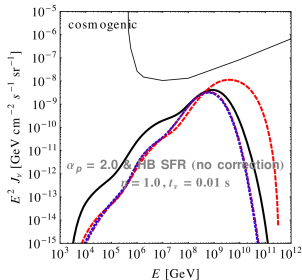
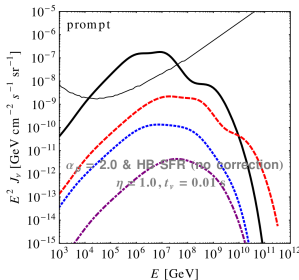
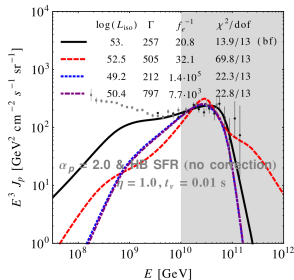
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

- 1 Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. L_{iso})
- 2 Fit each spectrum to the HiRes data
- 3 Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
- 4 Find the baryonic loading (*i.e.*, relative energy of p 's to e 's) at each point
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- 6 Find the region where the number of prompt ν_μ 's is > 2.44 , *i.e.*, the excluded region at 90% C.L.



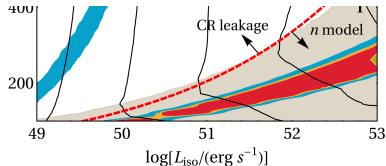
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escape and to n escape + CR leakage

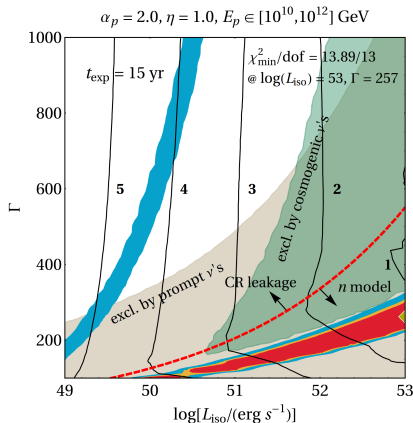
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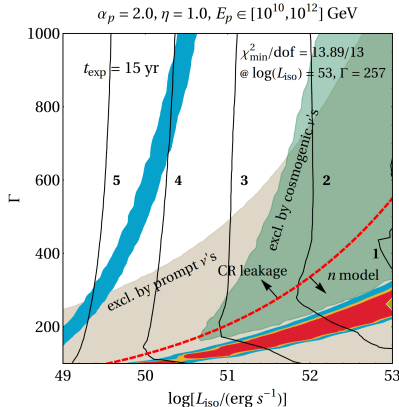
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- 7 After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



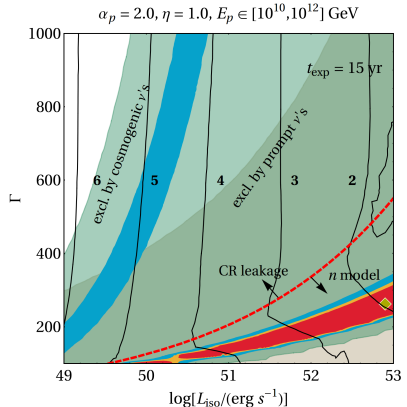
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The exclusion from cosmogenic ν 's grows if the number of GRBs evolves more strongly with redshift:



$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z)$$

(star formation rate)



$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z) \times (1+z)^{1.2}$$

- ▶ We have revised the GRB n model of ν emission:
 - ▶ corrected, full numerical calculation with detailed particle physics
 - ▶ yields a quasi-diffuse flux ~ 1 order magnitude below the analytical one by IceCube
- ▶ We have explored a GRB emission model with:
 - ▶ the standard n escape component, plus
 - ▶ **an explicit direct p escape component**
 - improves the fit to the UHECR observations
- ▶ The directly-escaping protons . . .
 - ▶ affect the prompt ν flux,
 - ▶ but not (much) the cosmogenic flux

By clarifying the UHE γ –CR– ν connection, we might rule out large regions of emission + propagation parameter space

Backup slides

Secondary injection of neutrons, neutrinos ($\text{GeV}^{-1} \text{cm}^{-3} \text{s}^{-1}$)

$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c d\varepsilon' N'_\gamma(\varepsilon') R(E', E'_p, \varepsilon')$$

Normalisation to the observed GRB photon flux F_γ

$$\int \varepsilon' N'_\gamma(\varepsilon') d\varepsilon' = \frac{E'_{\text{iso}}}{V'_{\text{iso}}} \propto F_\gamma, \quad \int E'_p N'_p(E'_p) dE'_p = \frac{1}{f_e} \frac{E'_{\text{iso}}}{V'_{\text{iso}}} \propto \frac{F_\gamma}{f_e}$$

Fluence per shell, at Earth ($\text{GeV}^{-1} \text{cm}^{-2}$)

$$\mathcal{F}^{\text{sh}} = t_v V'_{\text{iso}} \frac{(1+z)^2}{4\pi d_L^2} Q'$$

Secondary injection of neutrons, neutrinos ($\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$)

$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c d\varepsilon' N'_\gamma(\varepsilon') R(E', E'_p, \varepsilon')$$

► Photon density, shock rest frame ($\text{GeV}^{-1} \text{ cm}^{-3}$):

$$N'_\gamma(\varepsilon') \propto \begin{cases} (\varepsilon')^{-\alpha_\gamma}, & \varepsilon'_{\gamma,\min} = 0.2 \text{ eV} \leq \varepsilon' \leq \varepsilon'_{\gamma,\text{break}} \\ (\varepsilon')^{-\beta_\gamma}, & \varepsilon'_{\gamma,\text{break}} \leq \varepsilon' \leq \varepsilon'_{\gamma,\max} = 300 \times \varepsilon'_{\gamma,\min} \end{cases}$$

$$\varepsilon'_{\gamma,\text{break}} = \mathcal{O}(\text{keV}), \alpha_\gamma \approx 1, \beta_\gamma \approx 2$$

► Proton density:

$$N'_p(E'_p) \propto (E'_p)^{-\alpha_p} \times \exp \left[- (E'_p/E'_{p,\max})^2 \right] \quad (\alpha_p \approx 2)$$

Maximum proton energy limited by energy losses:

$$t'_{\text{acc}}(E'_{p,\max}) = \min [t'_{\text{dyn}}, t'_{\text{syn}}(E'_{p,\max}), t'_{p\gamma}(E'_{p,\max})]$$

Secondary injection of neutrons, neutrinos ($\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$)

$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c d\varepsilon' N'_\gamma(\varepsilon') R(E', E'_p, \varepsilon')$$

Normalisation to the observed GRB photon flux F_γ

$$\int \varepsilon' N'_\gamma(\varepsilon') d\varepsilon' = \frac{E'_{\text{iso}}}{V'_{\text{iso}}} \propto F_\gamma, \quad \int E'_p N'_p(E'_p) dE'_p = \frac{1}{f_e} \frac{E'_{\text{iso}}}{V'_{\text{iso}}} \propto \frac{F_\gamma}{f_e}$$

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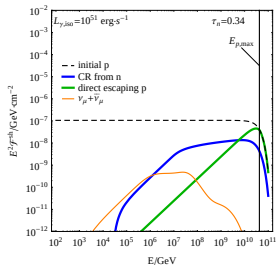
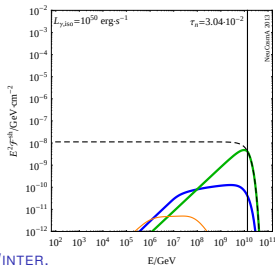
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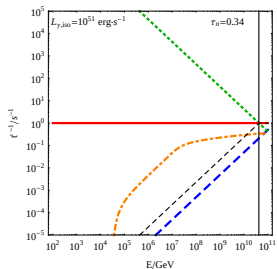
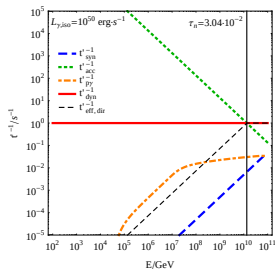
Fluence per shell, at Earth ($\text{GeV}^{-1} \text{ cm}^{-2}$)

$$\mathcal{F}^{\text{sh}} = t_v V'_{\text{iso}} \frac{(1+z)^2}{4\pi d_L^2} Q'$$

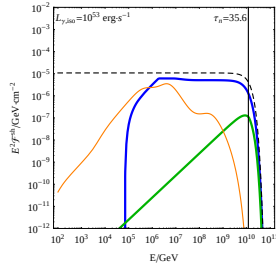
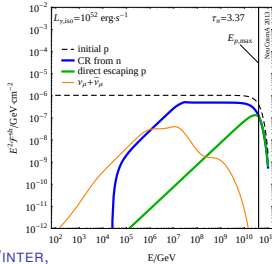
Optically **thin** sources ($\tau_n < 1$):



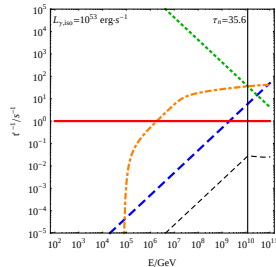
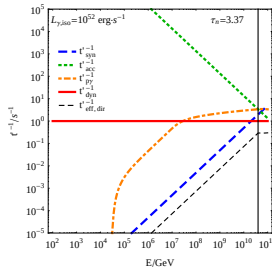
P. BAERWALD, MB, W. WINTER,
ApJ **768**, 186 (2013)



Optically **thick** sources ($\tau_n > 1$):



P. BAERWALD, MB, W. WINTER,
ApJ **768**, 186 (2013)



Optically thin to neutron escape regime

- ▶ the standard emission scenario
- ▶ p 's magnetically confined: n 's and ν 's from $p\gamma$ interactions
- ▶ n 's escape and decay to produce UHECRs

Direct escape regime

- ▶ directly-escaping p 's from the borders dominate
- ▶ subdominant n production
- ▶ more CRs emitted, so “one ν_μ per CR” no longer valid

Optically thick to neutron escape regime

- ▶ n 's and p 's in the bulk trapped by multiple $p\gamma$ interactions
- ▶ they only escape from the borders
- ▶ ν production enhanced

- ▶ Energy loss rate (GeV s^{-1}):

$$b(E) \equiv \frac{dE}{dt}$$

- ▶ For pair production $p\gamma \longrightarrow pe^+e^-$:

$$b_{e^+e^-}(E, z) = -\alpha r_0^2 (m_e c^2)^2 c \int_2^\infty d\xi n_\gamma \left(\frac{\xi m_e c^2}{2\gamma}, z \right) \frac{\phi(\xi)}{\xi^2}$$

- ▶ n_γ : isotropic photon background ($\text{GeV}^{-1} \text{cm}^{-3}$)
- ▶ ξ : photon energy in units of $m_e c^2$
- ▶ proton energy: $E = \gamma m_p c^2$ ($\gamma \gg 1$)
- ▶ $\phi(\xi)$: (tabulated) integral in energy of outgoing e^-

G. BLUMENTHAL, *Phys. Rev.* **D 1**, 1596 (1970)

H. BETHE, W. HEITLER, *Proc. Roy. Soc.* **A146**, 83 (1934)

Photohadronic interactions – $p\gamma$ interaction rate (s^{-1} per particle):

$$\Gamma_{p\gamma \rightarrow p'b} (E, z) = \frac{1}{2} \frac{m_p^2}{E^2} \int_{\frac{\epsilon_{\text{th}} m_p}{2E}}^{\infty} d\epsilon \frac{n_{\gamma}(\epsilon, z)}{\epsilon^2} \int_{\epsilon_{\text{th}}}^{2E\epsilon/m_p} d\epsilon_r \epsilon_r \sigma_{p\gamma \rightarrow p'b}^{\text{tot}}(\epsilon_r)$$

- 1 For given values of E and z , **NeuCosmA** calculates the cooling rate $t_{p\gamma}^{-1} \equiv -(1/E) b_{p\gamma} (\text{s}^{-1})$ as

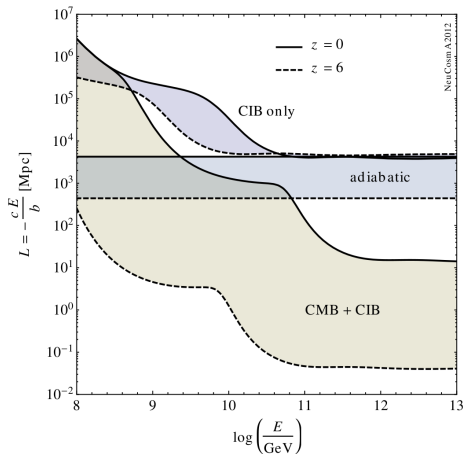
$$t_{p\gamma}^{-1} (E, z) = \sum_i^{\text{all channels}} \Gamma_{p \rightarrow p}^i (E, z) K^i ,$$

with $K^i E$ the loss of energy per interaction

- 2 From this, we calculate back $b_{p\gamma} (\text{GeV s}^{-1}) \dots$
- 3 ... and the corresponding energy-loss term in the transport equation, $\partial_E (b_{p\gamma} Y_p)$.

S. HÜMMER, M. RÜGER, F. SPANIER, W. WINTER, *Astrophys. J.* **721**, 630 (2010) [1002.1310]

Note that $L_{\text{CIB}} \gg L_{\text{CMB}}$:



Matches, e.g., H. TAKAMI, K. MURASE, S. NAGATAKI, K. SATO, *Astropart. Phys.* **31**, 201 (2009) [0704.0979]