

# Revisiting the cosmic ray-neutrino connection in gamma-ray bursts

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IFIC, Valencia  
April 30, 2014



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

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

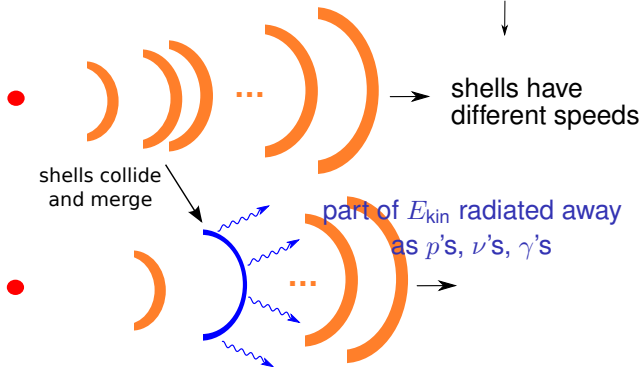
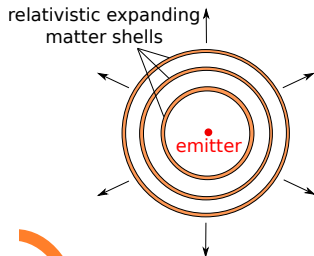
GRBs are among the best candidate sources:

- ▶ 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 ( $\geq 2$  s):**  
a compact object ( $\sim 10^3$  km)  
emits relativistically expanding  
**baryonic-loaded** matter ejecta



Joint production of UHECRs,  $\nu$ 's, and  $\gamma$ 's:

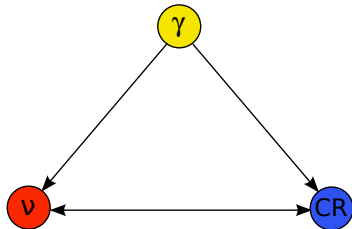
$$p\gamma \rightarrow \Delta^+ (1232) \rightarrow \begin{cases} n\pi^+, & \text{BR} = 1/3 \\ p\pi^0, & \text{BR} = 2/3 \end{cases}$$

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

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

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

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

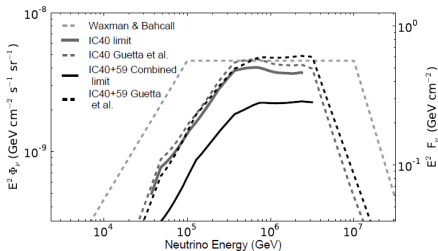


After propagation, with flavour mixing:

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

(“one  $\nu_\mu$  per cosmic ray”)

The *simplest* neutron model is now strongly disfavoured ►



## IceCube Collaboration:

- $\nu$  flux normalised to GRB  $\gamma$  fluence:

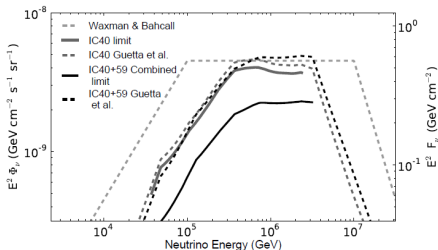
$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) \propto \int_{1 \text{ keV}}^{10 \text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma(\varepsilon_\gamma)$$

- quasi-diffuse  $\nu$  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- $\pi$ ,  $K$ ,  $n$  production modes
- ▶ synchrotron losses of secondaries
- ▶ adiabatic cooling
- ▶ full photon spectrum, etc.

$\nu$  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:

- ▶  $\nu$  flux normalised to GRB  $\gamma$  fluence:

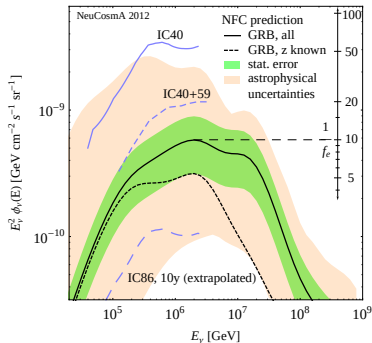
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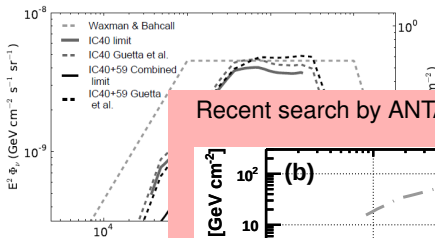
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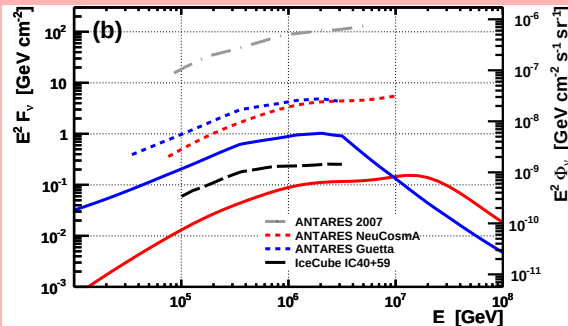




More detailed particle physics (NeuCosmA):

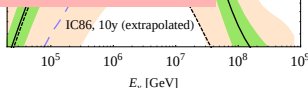
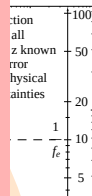
- ▶ extra multi- $\pi$ ,  $K$ ,  $n$  production modes
- ▶ synchrotron losses of secondaries

Recent search by ANTARES optimised for NeuCosmA:



ANTARES Collab., 1307.0304

side lower  
31101 (2012)  
12)



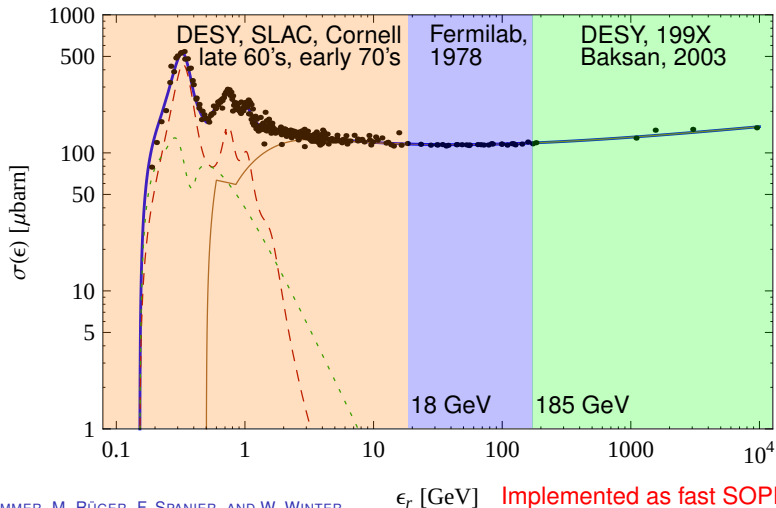
IceCube Collabor

- ▶  $\nu$  flux norm

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

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

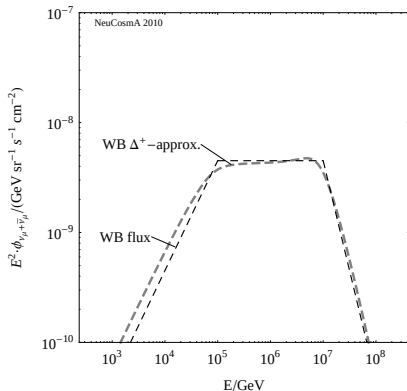
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 GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)



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

Implemented as fast SOPHIA-based  
parametrisation

- Contributions to the full photohadronic cross section



“WB flux”:

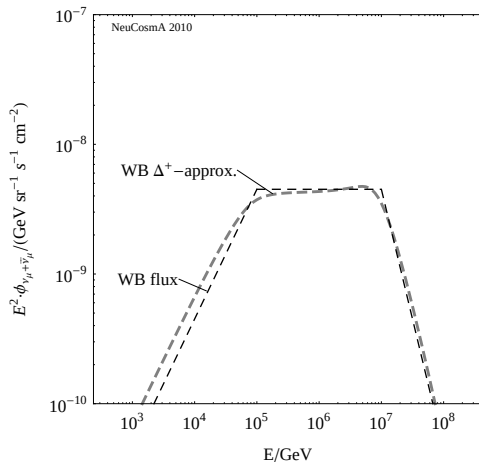
traditional, analytical  
Waxman-Bahcall prediction

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

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

“WB  $\Delta^+$ –approx.”: explicit  
synchrotron cooling of pions

- Contributions to the full photohadronic cross section

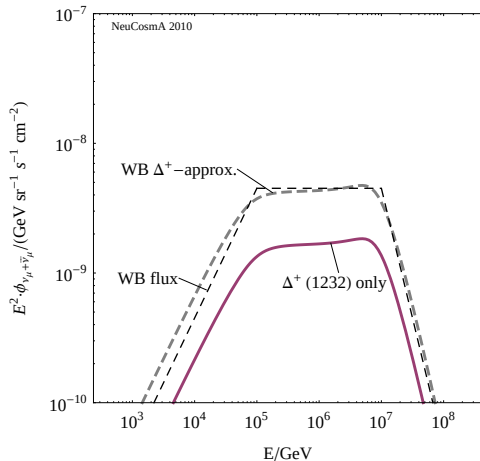


- Contributions to the full photohadronic cross section

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

- $\Delta(1232)$ -resonance

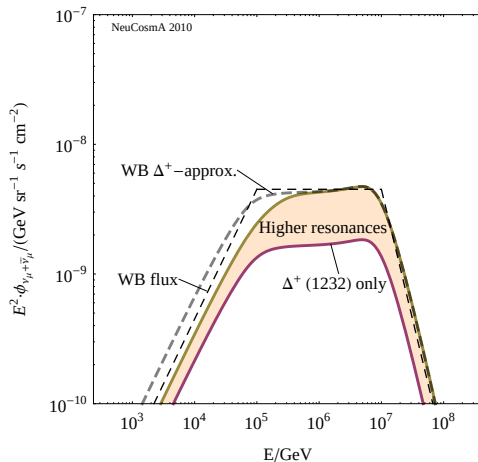
P. BAERWALD, S. HÜMMER, AND W. WINTER,  
*Phys. Rev. D* **D83**, 067303 (2011)



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

- ▶  $\Delta(1232)$ -resonance
- ▶ Higher resonances

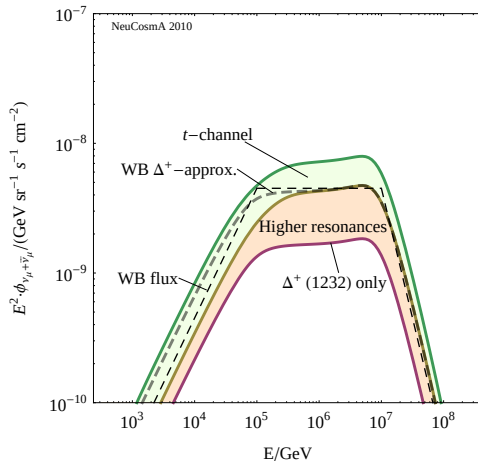
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Contributions to  $(\nu_\mu + \bar{\nu}_\mu)$  flux  
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- ▶  $\Delta(1232)$ -resonance
- ▶ Higher resonances
- ▶  $t$ -channel  
(direct production)

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

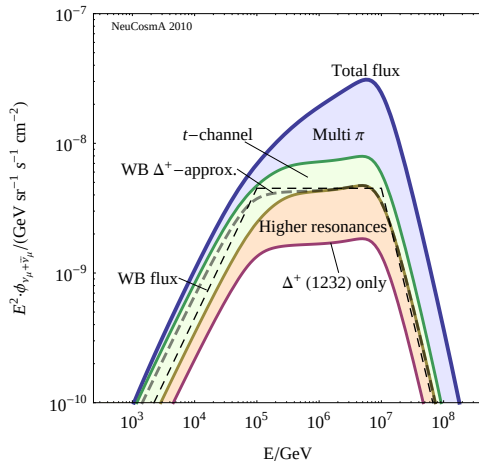


- Contributions to the full photohadronic cross section

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  $\pi$ )

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



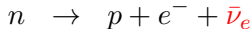
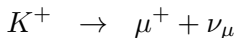
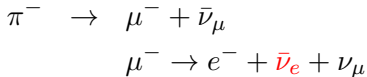
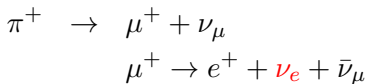
Especially "Multi  $\pi$ " contribution leads to **change of flux shape**; neutrino flux higher by up to a factor of 3 compared to WB treatment

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

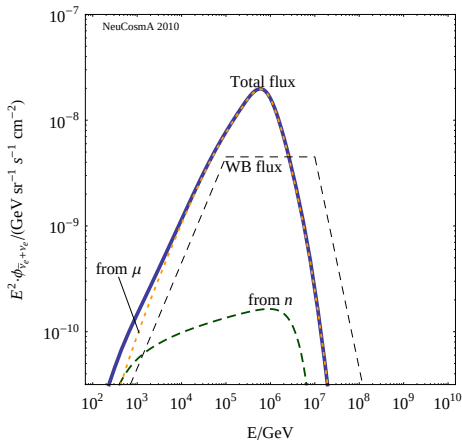
$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

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

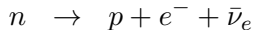
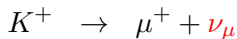
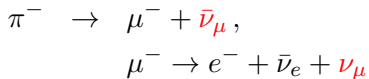
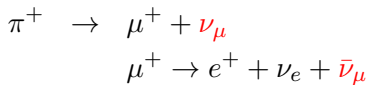
$$n \rightarrow p + e^- + \bar{\nu}_e$$



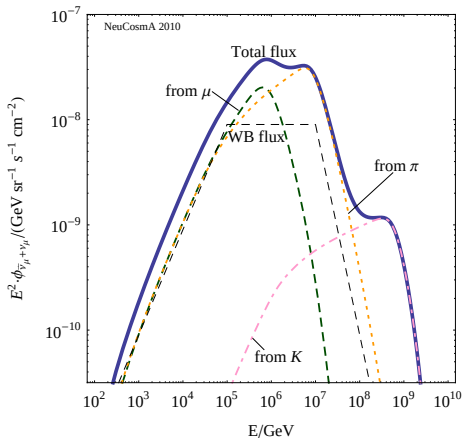
Resulting  $\nu_e$  flux (at the observer)



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



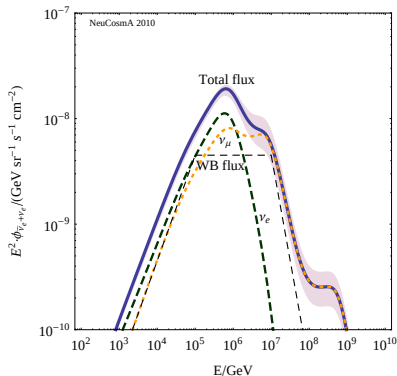
Resulting  $\nu_\mu$  flux (at the observer)



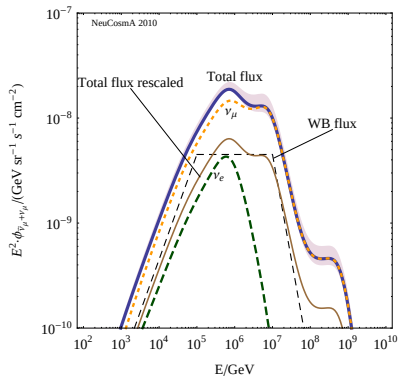
P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

- 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  $\mu$  and  $\pi$  decay in both flavours, additional peak from  $K^+$  decay at  $10^8$  to  $10^9$  GeV

Corrections to the analytical model:

► **shape revised:**

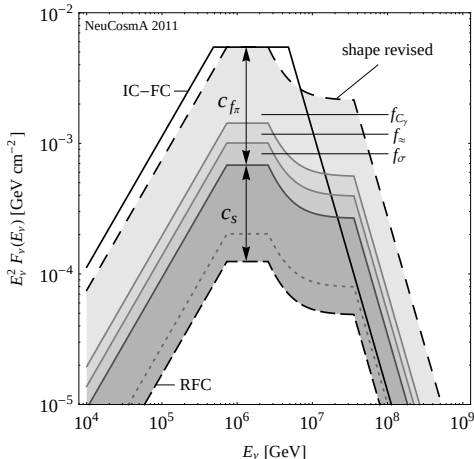
- shift of first break (correction of photohadronic threshold)
- different cooling breaks for  $\mu$ 's and  $\pi$ 's
- $(1+z)$  correction on the variability scale of the GRB

► **Correction  $cf_\pi$  to  $\pi$  prod. efficiency:**

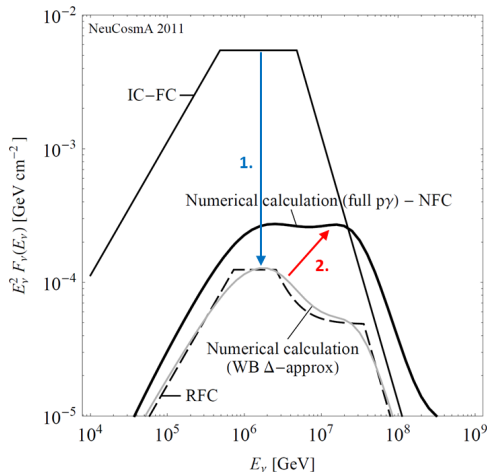
- $f_{C_\gamma}$ : full spectral shape of photons
- $f_\approx = 0.69$ : rounding error in analytical calculation
- $f_\sigma \simeq 2/3$ : from neglecting the width of the  $\Delta$ -resonance

► **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  $\nu$  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  $F_\nu(E_\nu)$

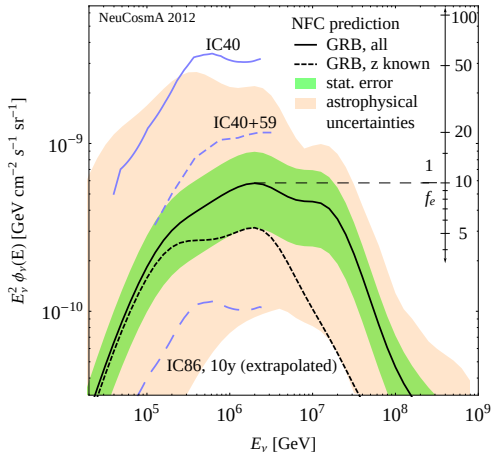
- ▶ Quasidiffuse flux:

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

- ▶ **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  $\nu_\mu$  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)  $\nu$  production
- ▶ multiple  $p$  interactions enhance the  $\nu$  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,  $\eta$ :  $t'_{\text{acc}}(E'_p) = \frac{E'_p}{\eta c e B'}$

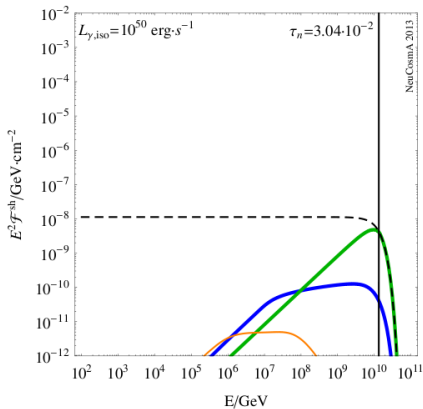
Particles can escape from within a shell of thickness  $\lambda'_{\text{mfp}}$ :

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

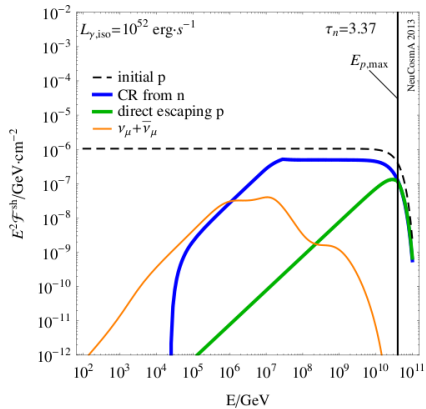
fraction of escaping particles

# A two-component model of CR emission

Optically **thin** source:



Optically **thick** source:

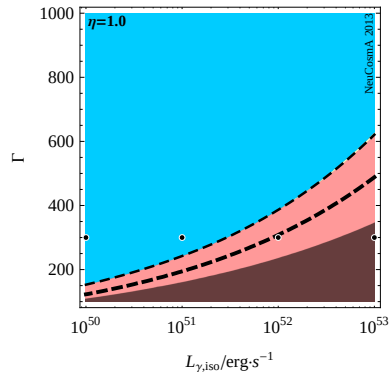
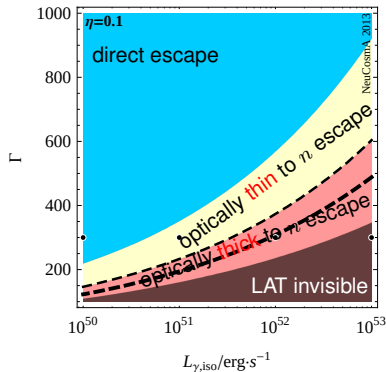


P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

## 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 ( $\text{GeV}^{-1} \text{ cm}^{-3}$ ):

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

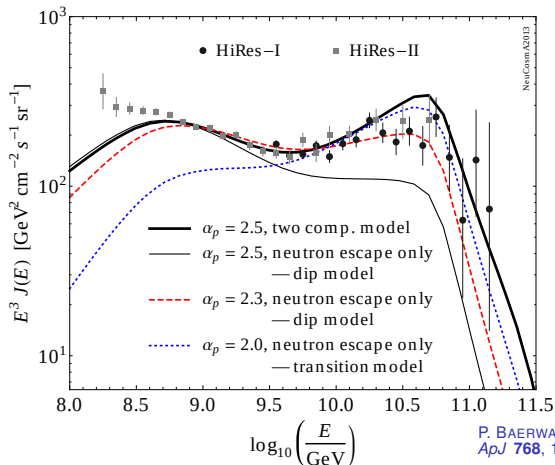
with  $n_p$  the real number density

- ▶ Transport equation (comoving source frame):

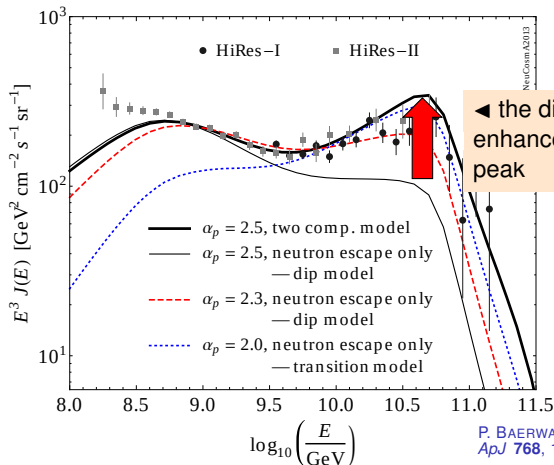
$$\dot{Y}_p = \underbrace{\partial_E (H E Y_p)}_{\text{adiabatic losses}} + \underbrace{\partial_E (b_{e^+e^-} Y_p)}_{\text{pair production losses}} + \underbrace{\partial_E (b_{p\gamma} Y_p)}_{\text{photohadronic losses}} + \underbrace{\mathcal{L}_{\text{CR}}}_{\text{CR injection from sources}}$$

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

## UHECR flux at Earth from $n$ and direct $p$ escape:

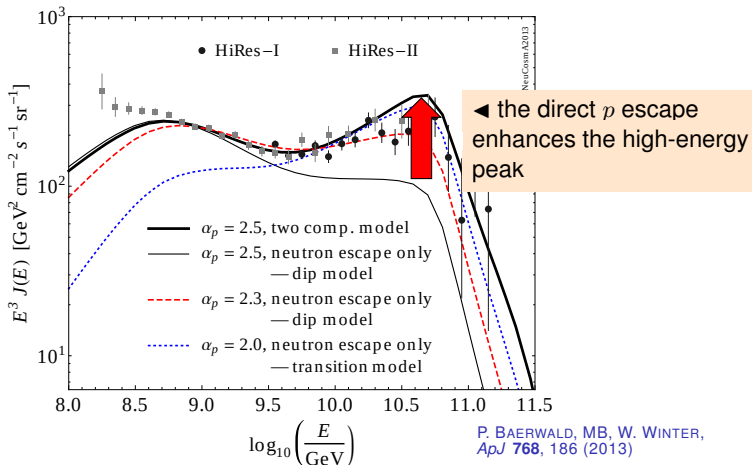


## UHECR flux at Earth from $n$ and direct $p$ escape:



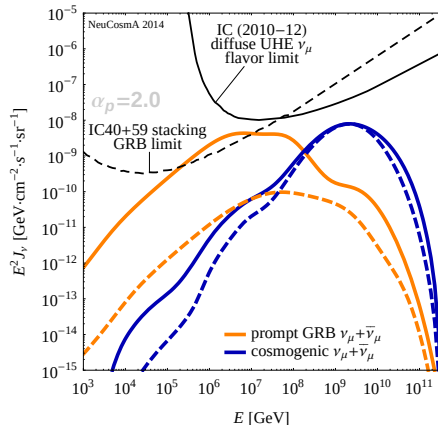
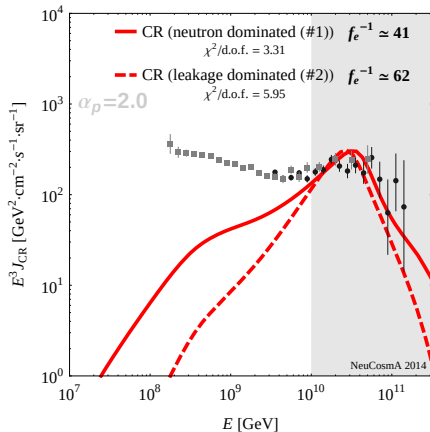
P. BAERWALD, MB, W. WINTER,  
*ApJ* **768**, 186 (2013)

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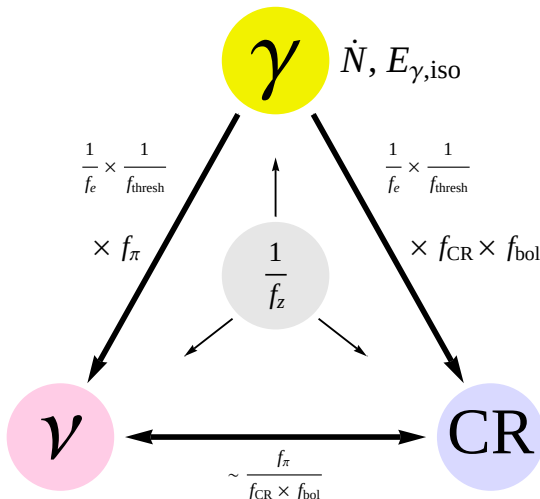
Our two-component model *is* able to fit the UHECR data

neutron model vs. two-component model:  
prompt and cosmogenic  $\nu$ 's



P. BAERWALD, MB, W. WINTER, ARXIV:1401.1820

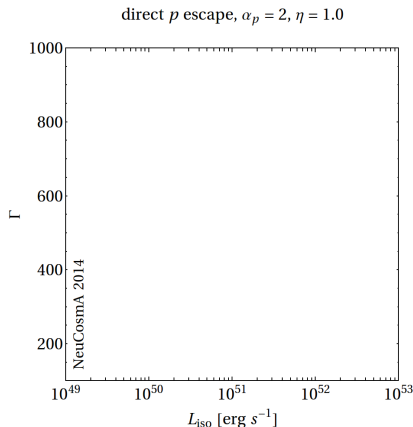
The big (multi-messenger) picture:



We can already limit the parameter space by using the UHECR observations and  $\nu$  upper bounds:

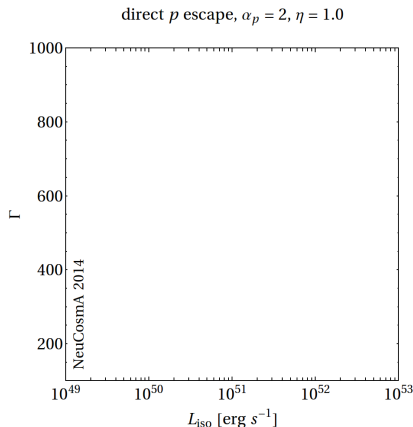
We can already limit the parameter space by using the UHECR observations and  $\nu$  upper bounds:

- 1 Generate the UHECR spectrum at every point in parameter space (e.g., in  $\Gamma$  vs.  $L_{\text{iso}}$ )



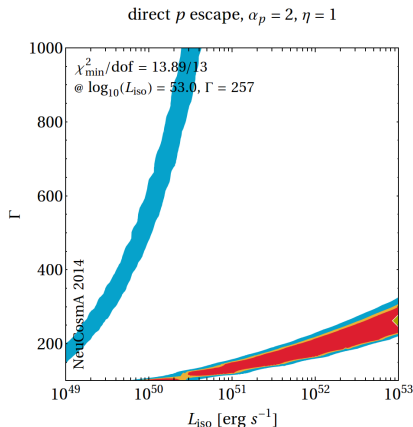
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- 1 Generate the UHECR spectrum at every point in parameter space (e.g., in  $\Gamma$  vs.  $L_{\text{iso}}$ )
- 2 Fit each spectrum to the HiRes data



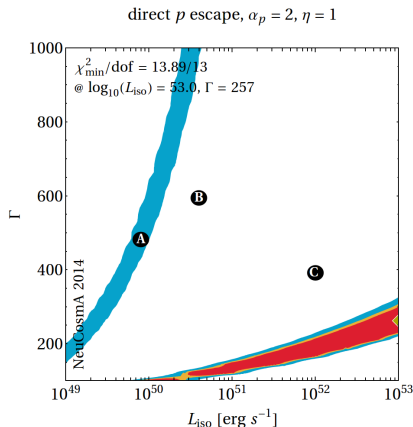
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- 1 Generate the UHECR spectrum at every point in parameter space (e.g., in  $\Gamma$  vs.  $L_{\text{iso}}$ )
- 2 Fit each spectrum to the HiRes data
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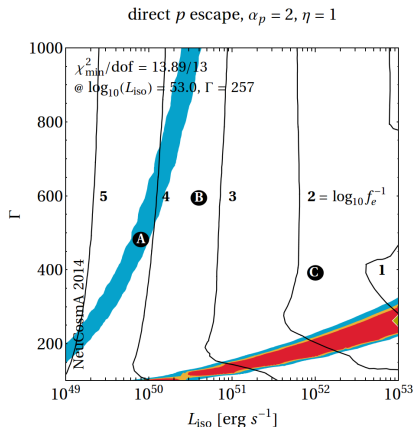
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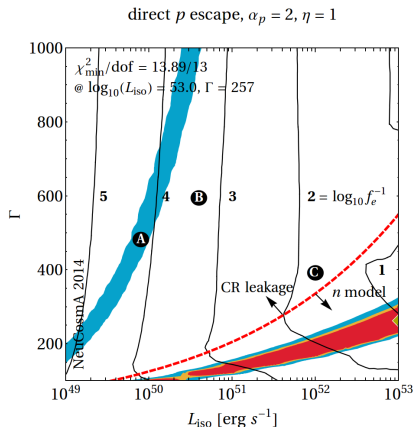
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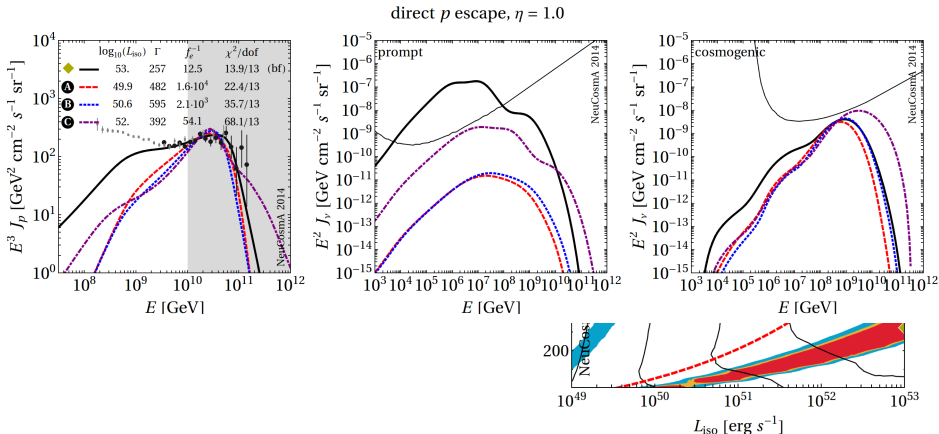


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- 5 Identify the region corresponding to pure  $n$  escape and to  $n$  escape + CR leakage



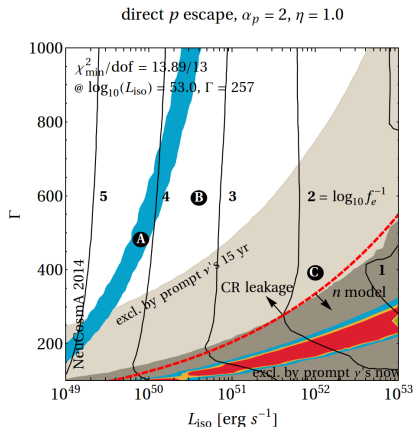
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P. BAERWALD, MB, W. WINTER, ARXIV:1401.1820

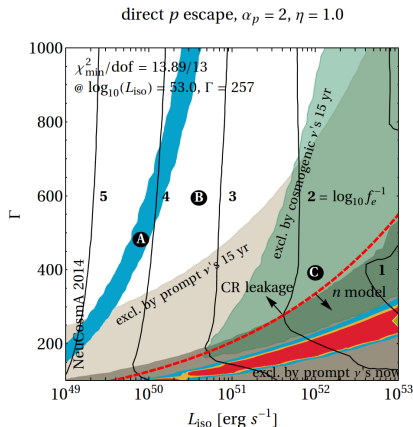
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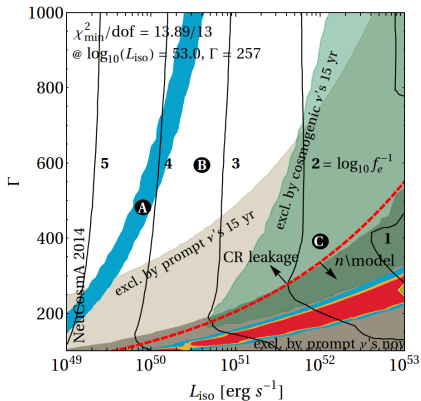
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- 7 After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



## Where to now? Constraining the connection

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

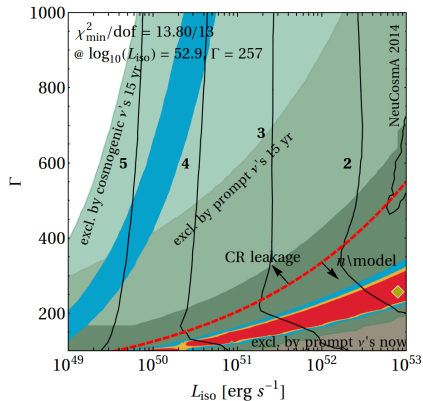
direct  $p$  escape,  $\eta = 1.0$



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

(star formation rate)

direct  $p$  escape,  $\eta = 1.0$



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

- ▶ We have revised the GRB  $n$  model of  $\nu$  emission:
  - ▶ corrected, full numerical calculation with detailed particle physics
  - ▶ yields a quasi-diffuse flux  $\sim 1$  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  $\nu$  flux,
  - ▶ but not (much) the cosmogenic flux

By clarifying the UHE  $\gamma$ –CR– $\nu$  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  $F_\gamma$

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

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 ( $\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$ )

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► 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 ( $\text{GeV}^{-1} \text{cm}^{-3} \text{s}^{-1}$ )

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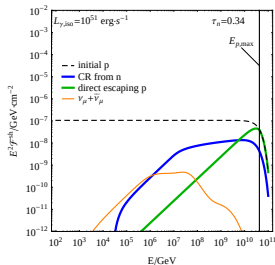
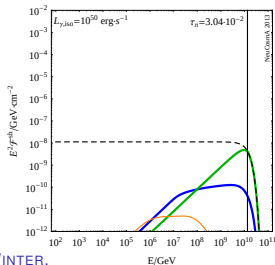
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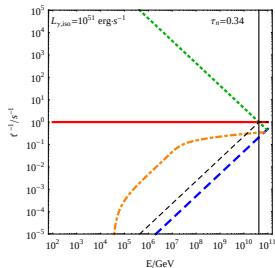
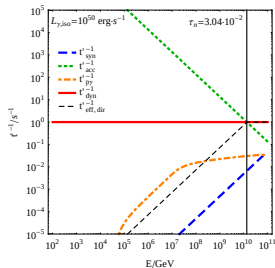
Fluence per shell, at Earth ( $\text{GeV}^{-1} \text{cm}^{-2}$ )

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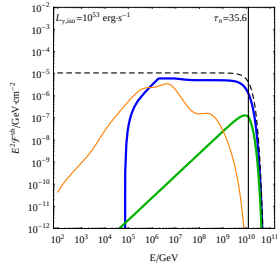
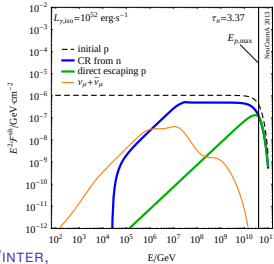
Optically **thin** sources ( $\tau_n < 1$ ):



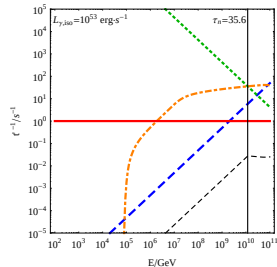
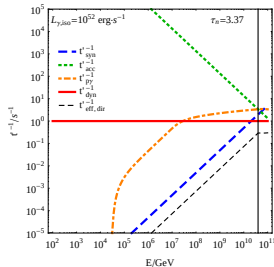
P. BAERWALD, MB, W. WINTER,  
*ApJ* **768**, 186 (2013)



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  $\nu$ '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  $\nu_\mu$  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
- ▶  $\nu$  production enhanced

- ▶ Energy loss rate ( $\text{GeV s}^{-1}$ ):

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

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

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

- ▶  $n_\gamma$ : isotropic photon background ( $\text{GeV}^{-1} \text{ cm}^{-3}$ )
- ▶  $\xi$ : 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 ( $\text{s}^{-1}$  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

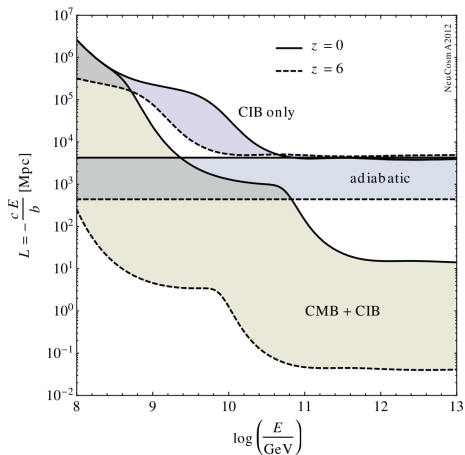
$$t_{p\gamma}^{-1} (E, z) = \sum_i^{\text{all channels}} \Gamma_{p \rightarrow p}^i (E, z) K^i ,$$

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]

Comoving source density:  $\dot{\rho}_{\text{CR}}(z)$  [ $\text{Mpc}^{-3} \text{yr}^{-1}$ ]

$\mathcal{H}$ : normalised to the local rate, *i.e.*,  $\mathcal{H}(z) \equiv \dot{\rho}_{\text{CR}}(z) / \dot{\rho}_{\text{CR}}(0)$

$$\mathcal{H}_{\text{SFR}}(z) = \begin{cases} (1+z)^{3.4} & , \quad z < 1, \\ N_1 (1+z)^{-0.3} & , \quad 1 \leq z < 4 \\ N_1 N_4 (1+z)^{-3.5} & , \quad z \geq 4 \end{cases} \quad , \quad \mathcal{H}_{\text{GRB}}(z) = (1+z)^\alpha \mathcal{H}_{\text{SFR}}(z)$$

