Ultra-high energy cosmic rays and neutrinos from GRBs: revising the predictions and clarifying the connection

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Introduction

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:

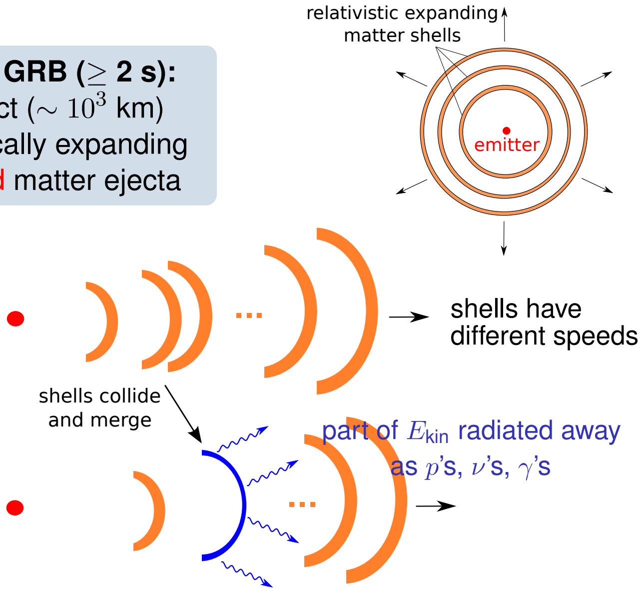
- radiated energy of $\sim 10^{52} - 10^{53}$ erg
- intense magnetic fields of $\sim 10^5$ G
- magnetically-confined p's shock-accelerated to $\sim 10^{12}$ GeV

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

Solution: we need to build more realistic models!

Internal shocks in the fireball model

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



The standard "neutron model" of emission

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

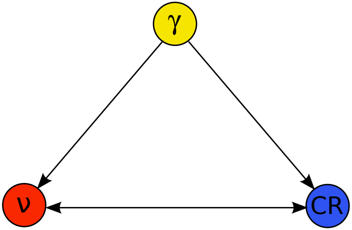
$$p\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \text{BR} = 1/3 \\ p\pi^0 , & \text{BR} = 2/3 \end{cases}$$

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

$$\pi^0 \to \gamma\gamma$$

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

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



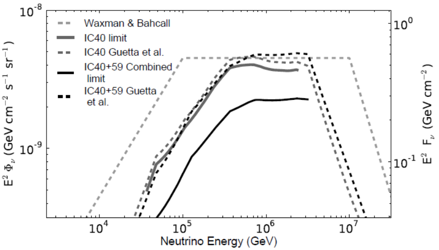
After propagation, with flavour mixing:

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

("one ν_μ per cosmic ray")

The *simplest* neutron model is now strongly disfavoured ▶

The neutron model under tension?



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)

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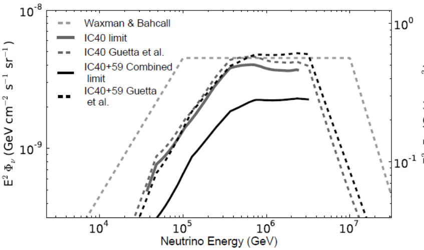

More detailed particle physics (NeuCosmA):

- 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)

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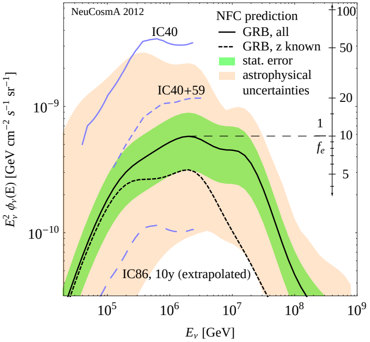

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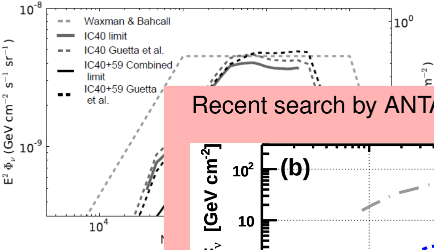

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- extra multi-π, K, n production modes
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...31101 (2012)

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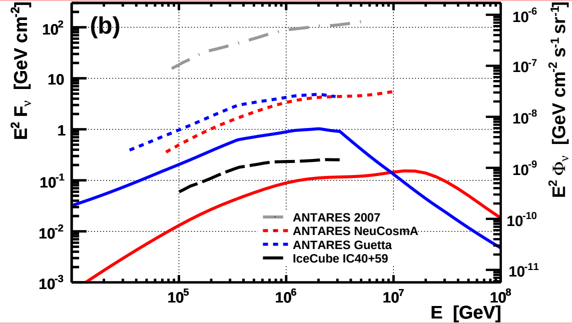
Recent search by ANTARES optimised for NeuCosmA:



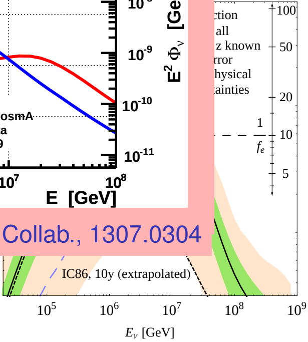
ANTARES Collab., 1307.0304

IceCube Collabo...

- ν flux norm...

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

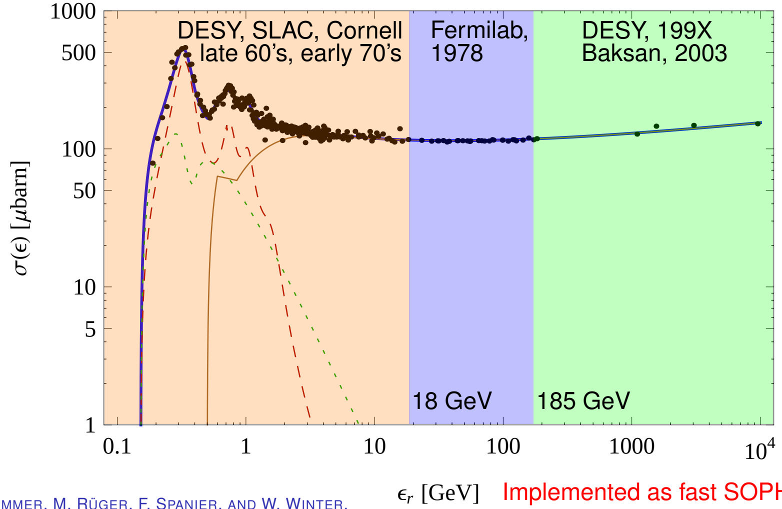
- quasi-diffus...
- analytical c... upper bour...



ICECUBE COLL., *Nature* **484**, 351 (2012)
AHLERS ET AL. *Astropart. Phys.* **35**, 87 (2011)
GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)

Revising the neutron model: NeuCosmA

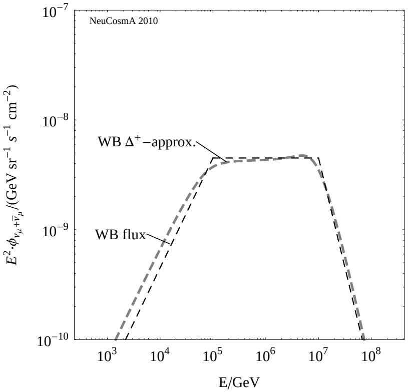
• Detailed $p\gamma$ cross section



S. Hümmer, M. Rüger, F. Spanier, and W. Winter, *Astrophys. J.* **721**, 630 (2010)

Implemented as fast SOPHIA-based parametrisation

Revising the neutron model: NeuCosmA



"WB flux":
traditional, analytical
Waxman-Bahcall prediction

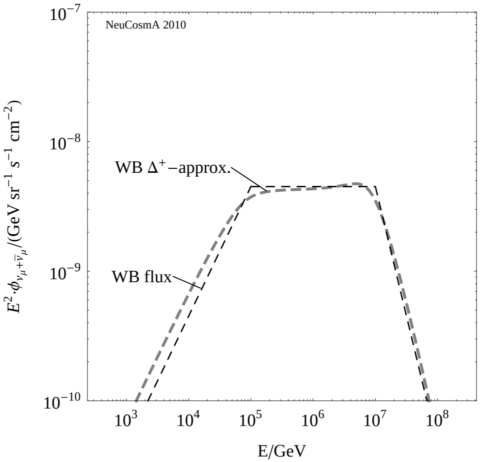
$$E_\nu^2 \phi_\nu = 0.45 \times 10^{-8} \frac{f_\pi}{0.2}$$

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

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

Revising the neutron model: NeuCosmA

• Contributions to the full photohadronic cross section



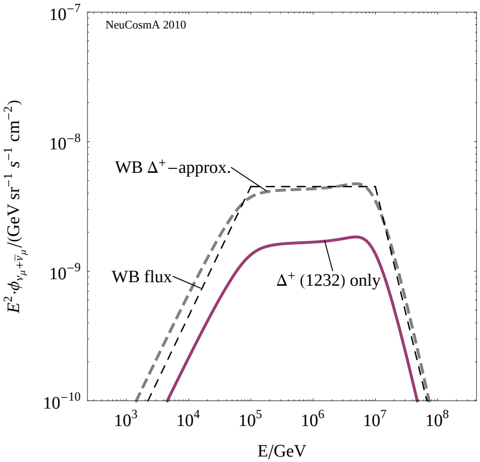
Revising the neutron model: NeuCosmA

• 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.* **D83**, 067303 (2011)



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

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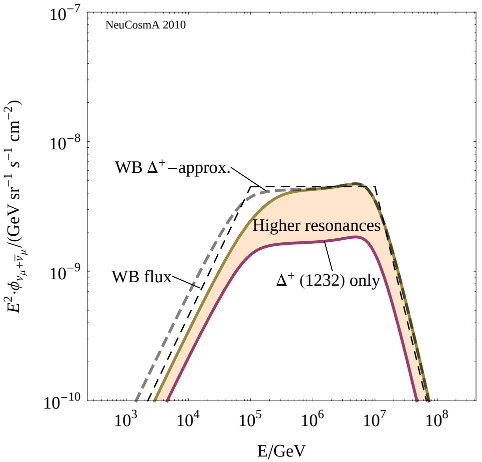

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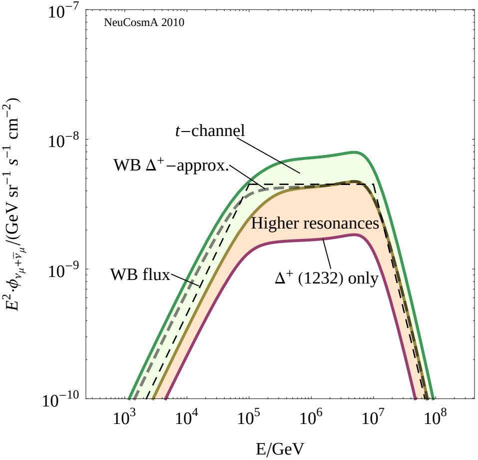
P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)



Revising the neutron model: NeuCosmA

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)

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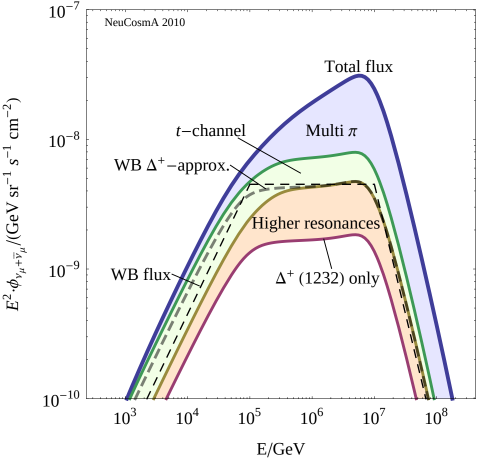

Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

Revising the neutron model: NeuCosmA

• Further particle decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

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

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

Revising the neutron model: NeuCosmA

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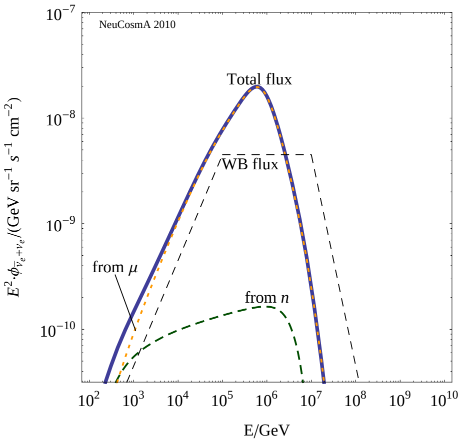
Resulting ν_e flux (at the observer)



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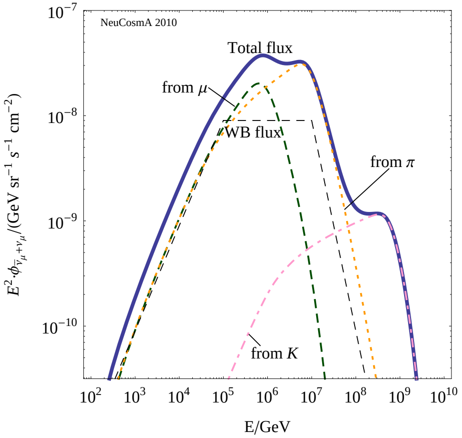
Resulting ν_μ flux (at the observer)

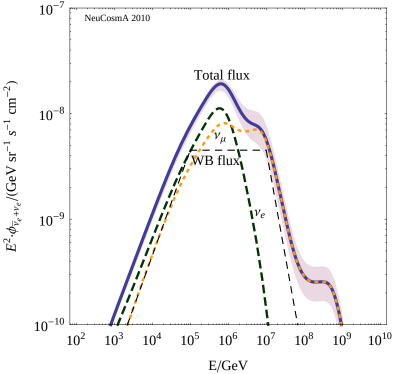


P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

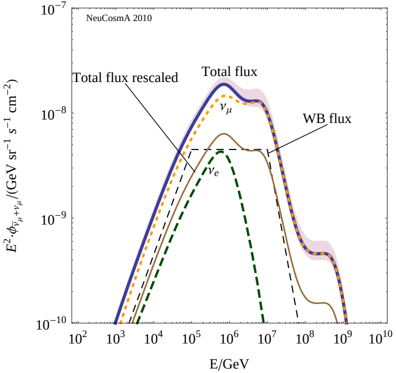
Revising the neutron model: NeuCosmA

• Neutrino spectra including flavour mixing

Electron neutrino spectrum



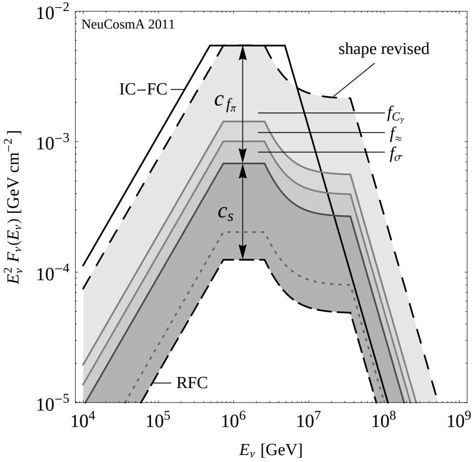
Muon neutrino spectrum



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

Revising the neutron model: NeuCosmA



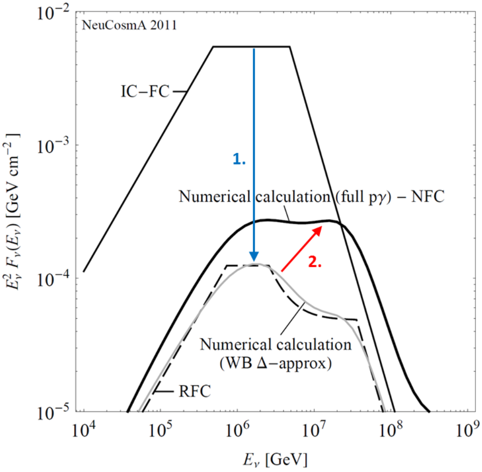
S. Hümmer, P. Baerwald, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

Revising the neutron model: NeuCosmA

• How the spectrum changes ... (cont.)



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)

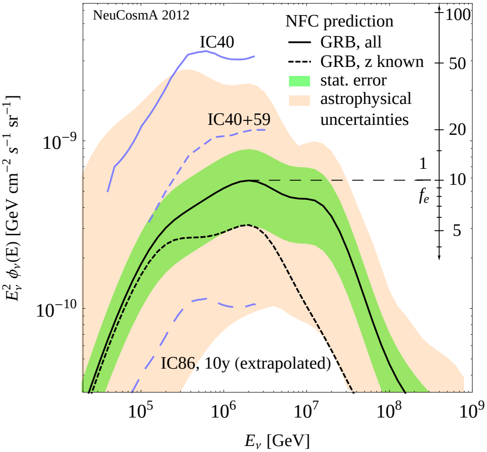
Revising the neutron model: NeuCosmA

• 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 $F_\nu\left(E_\nu\right)$
- Quasidiffuse flux:

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

- Statistical uncertainty: extrapolation of a few bursts to a quasidiffuse flux
- Astrophysical uncertainty:
  - $0.001 \leq t_v$ [s] ≤ 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)

Further revisions: direct proton escape

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)

A two-component model of CR emission

Optical depth:

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

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

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

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

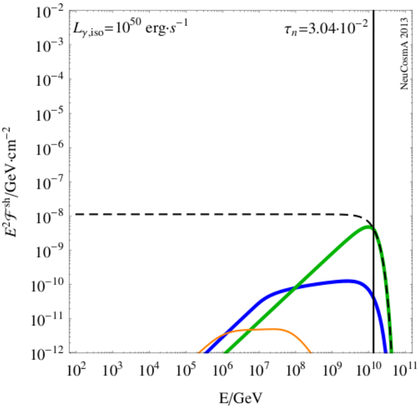
Particles can escape from within a shell of thickness λ'_{mfp}:

$$\left.\begin{aligned} \lambda'_{p,\text{mfp}}\left(E'\right) &= \min\left[\Delta r', R'_L\left(E'\right), c t'_{p\gamma}\left(E'\right)\right] \\ \lambda'_{n,\text{mfp}}\left(E'\right) &= \min\left[\Delta r', c t'_{p\gamma}\left(E'\right)\right] \end{aligned}\right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta r'}$$

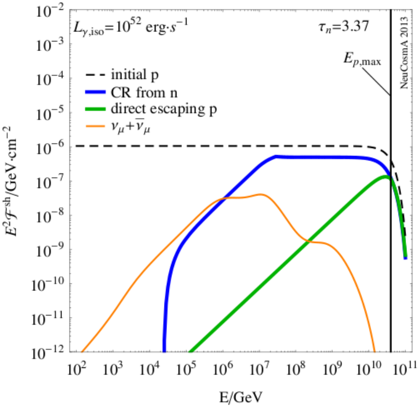
fraction of escaping particles

A two-component model of CR emission

Optically **thin** source:



Optically **thick** source:

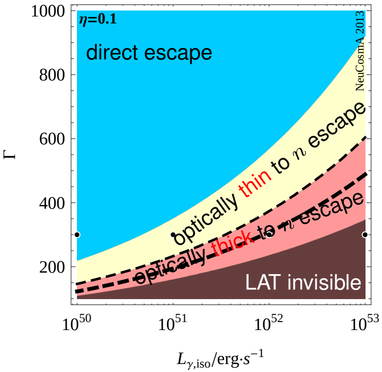


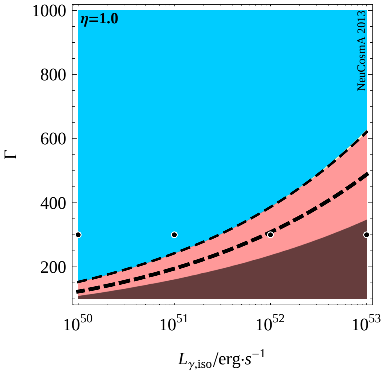
P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

A two-component model of CR emission

Scan of the GRB emission parameter space:

acceleration efficiency $\longrightarrow$ $\eta = 0.1$ $\eta = 1.0$





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

The UHECR and UHE ν fluxes at Earth

We use a Boltzmann equation to transport protons to Earth:

- Comoving number density of protons (GeV^{-1} 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):

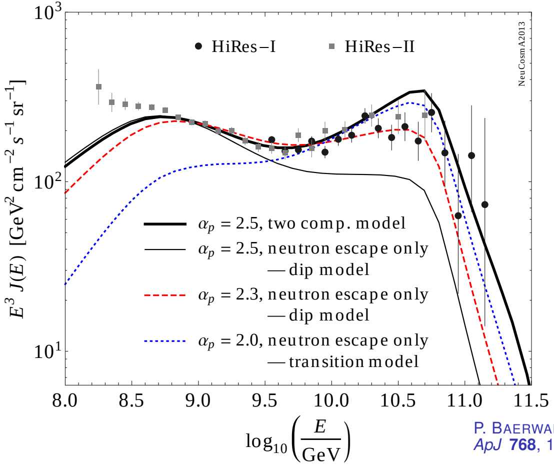
$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\rm CR}$$

  - $\partial_E(HEY_p)$: adiabatic losses
  - $\partial_E(b_{e^+e^-}Y_p)$: pair production losses
  - $\partial_E(b_{p\gamma}Y_p)$: photohadronic losses
  - $\mathcal{L}_{\rm CR}$: CR injection from sources

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

The UHECR and UHE ν fluxes at Earth

UHECR flux at Earth from n and direct p escape:



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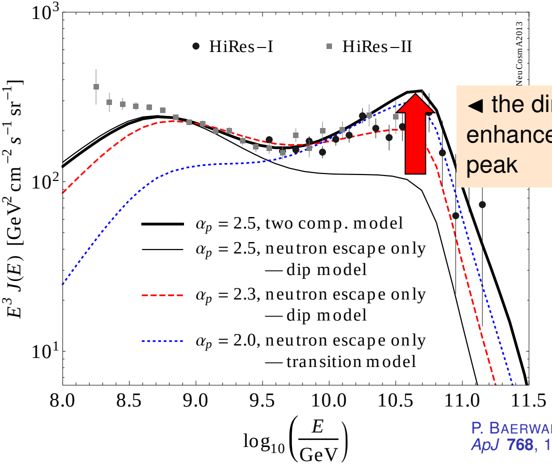

◄ the direct p escape enhances the high-energy peak

P. Baerwald, MB, W. Winter, *ApJ* **768**, 186 (2013)

The UHECR and UHE ν fluxes at Earth

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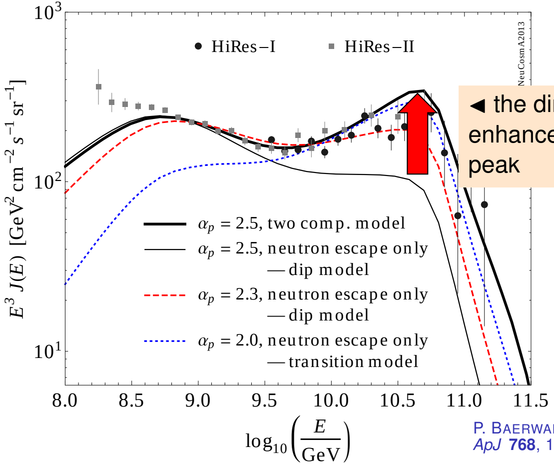

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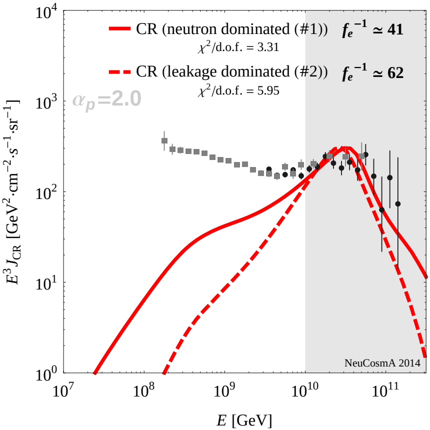
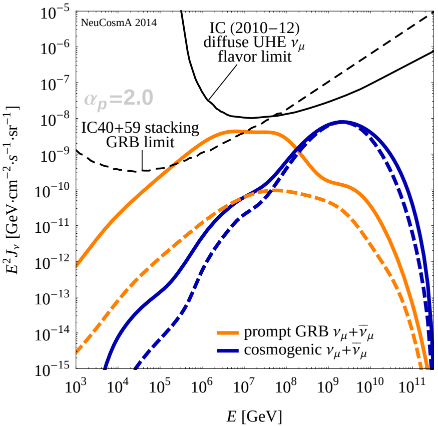
P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

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

The UHECR and UHE ν fluxes at Earth

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

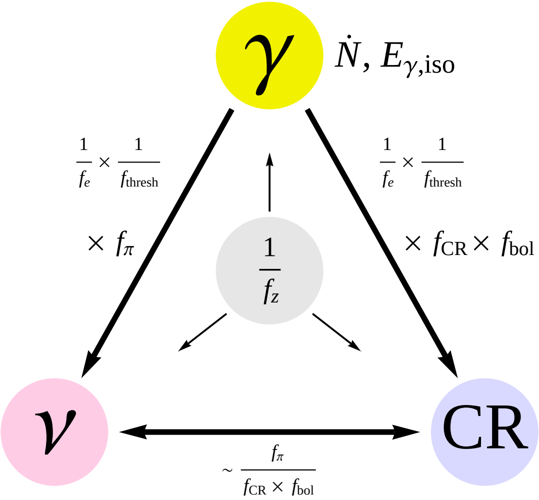




P. BAERWALD, MB, W. WINTER, ARXIV:1401.1820

Where to now? Constraining the connection

The big (multi-messenger) picture:



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

P. Baerwald, MB, W. Winter, arXiv:1401.1820

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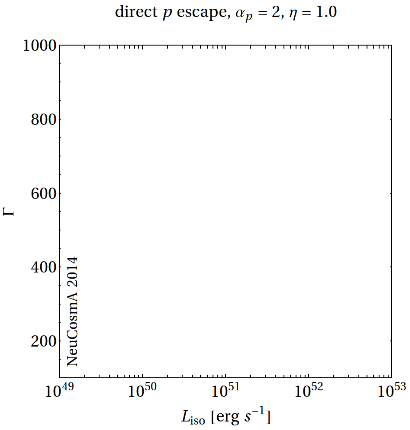
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

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



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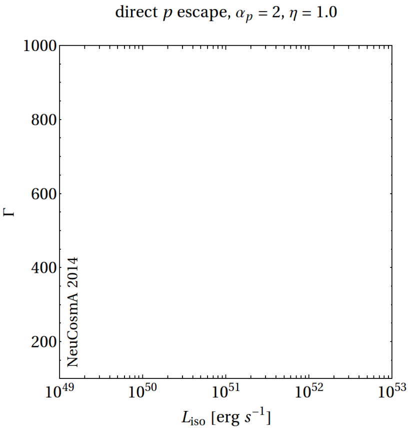
1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. L_{iso})
2. Fit each spectrum to the HiRes data



P. Baerwald, MB, W. Winter, arXiv:1401.1820

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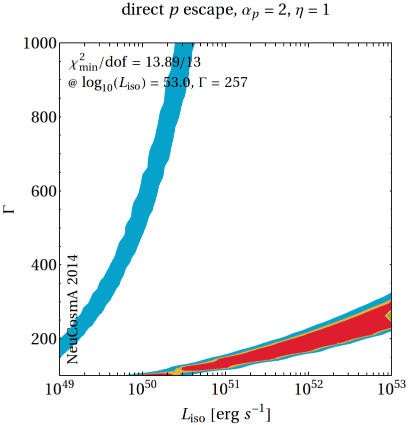
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

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



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

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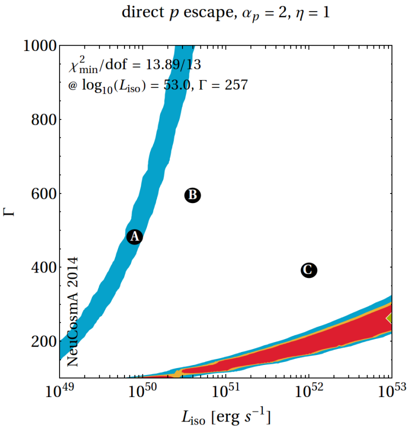

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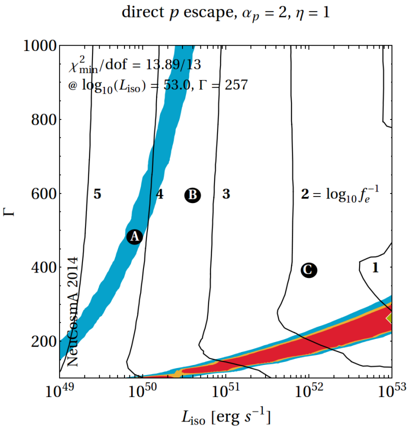

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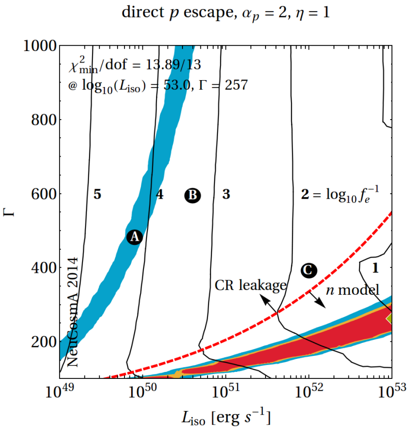

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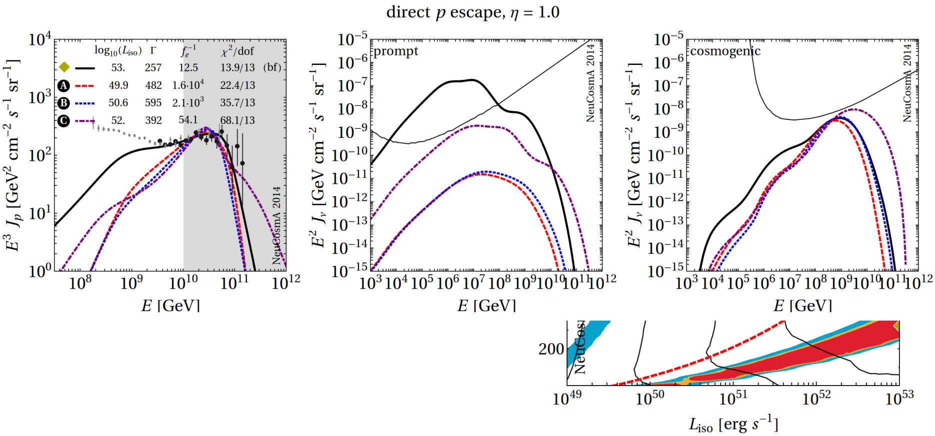

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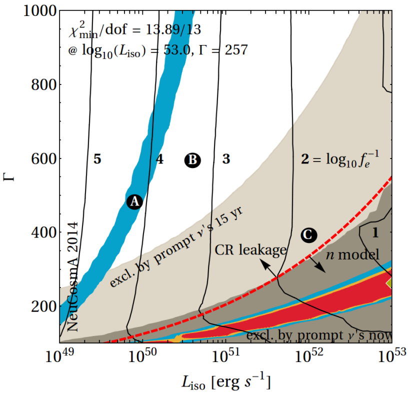
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.

direct p escape, $\alpha_p = 2$, $\eta = 1.0$



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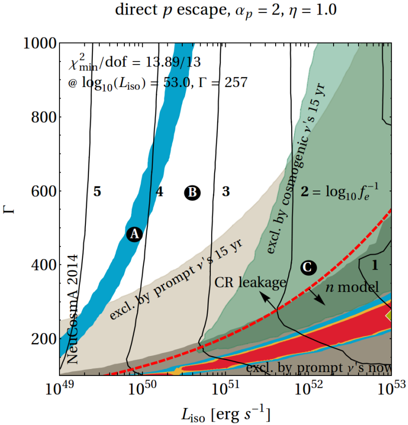
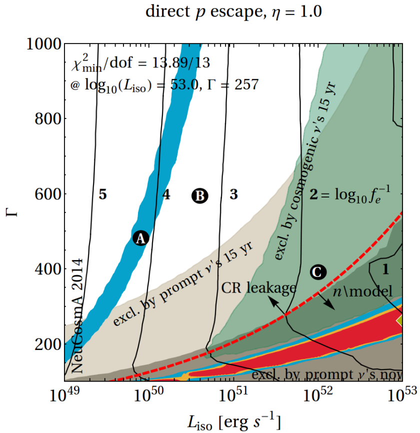
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



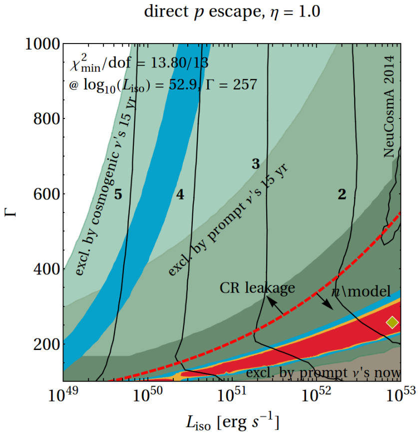
P. Baerwald, MB, W. Winter, arXiv:1401.1820

Where to now? Constraining the connection

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



$n_{\mathrm{GRB}}(z) \propto \rho_{\mathrm{SFR}}(z)$
(star formation rate)



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

Summary

- We have revised the GRB n model of ν 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 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

UHE ν's in the GRB internal shock model

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

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

Normalisation to the observed GRB photon flux F_γ

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

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

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

UHE ν's in the GRB internal shock model

Secondary injection of neutrons, neutrinos (GeV^{-1} cm^{-3} 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 (GeV^{-1} cm^{-3}):

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

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Normalisation to the observed GRB photon flux F_γ

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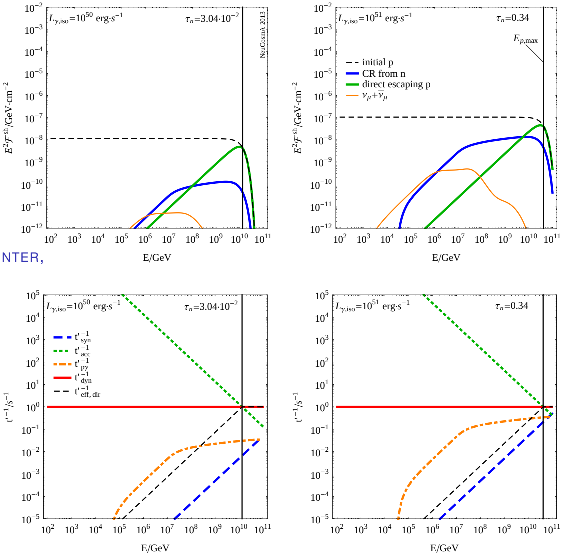
Fluence per shell, at Earth (GeV^{-1} cm^{-2})

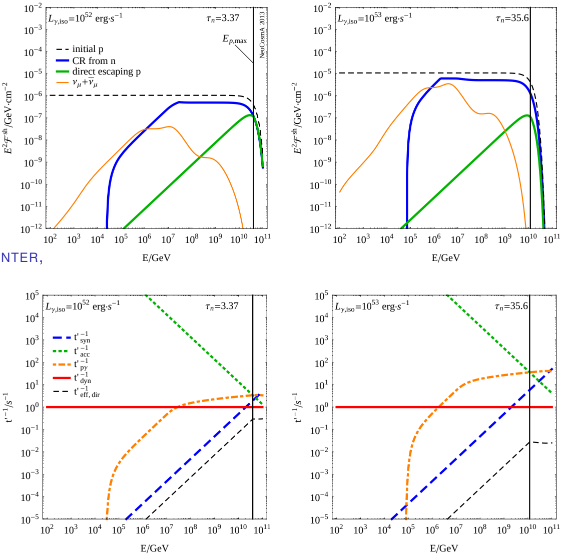
$$\mathcal{F}^{\text{sh}} = t_v V'_{\text{iso}} \frac{\left(1+z\right)^2}{4\pi d_L^2} Q'$$

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)

Three emission regimes

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

Interaction with the photon backgrounds

- Energy loss rate (GeV s^{-1}):

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

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

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

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

Interaction with the photon backgrounds

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

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

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

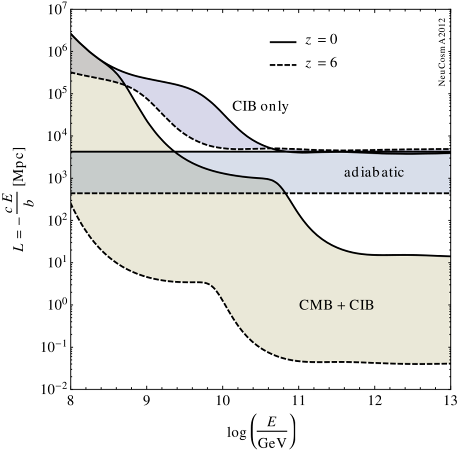
$$t_{p\gamma}^{-1}(E,z) = \sum_i^{\text{all channels}} \Gamma_{p\to p}^i(E,z)\, K^i ,$$

   with $K^i E$ the loss of energy per interaction
2. From this, we calculate back $b_{p\gamma}$ (GeV s^{-1}) ...
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]

Interaction lengths

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]

Source evolution with redshift

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

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

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