Improved ultra-high-energy cosmic ray and neutrino predictions from gamma-ray bursts

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Gamma-ray bursts in the multi-messenger era
Paris, June 17, 2014

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!

Plan of attack

Three steps towards improving the GRB neutrino predictions:

Step 1

Refine the calculation of the neutrino yield
in $p\gamma$ interactions

Step 2

Go beyond the simplest UHECR-neutrino connection

Step 3

Treat the fireball dynamically (neutrino “light curves”)

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The standard “neutron model” of emission

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

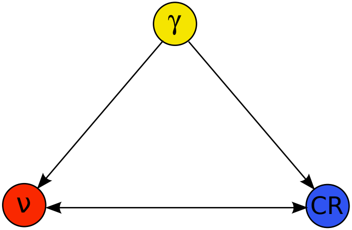
$$p\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \text{BR} = 1/3 \\ p\pi^0 , & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



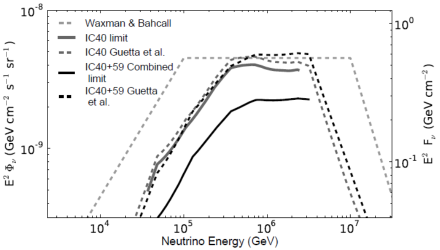
After propagation, with flavour mixing:

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

(“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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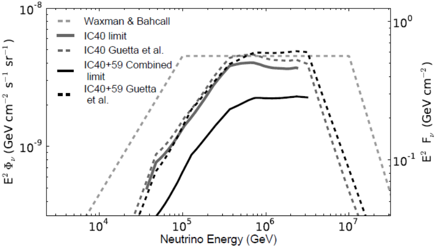

More detailed particle physics (NeuCosmA):

- 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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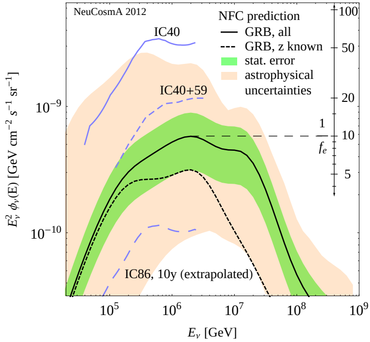

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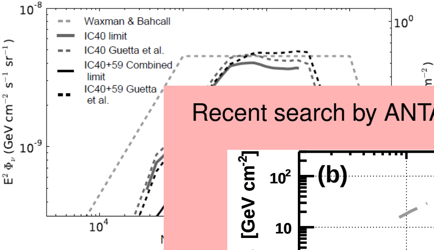

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IceCube Collabor

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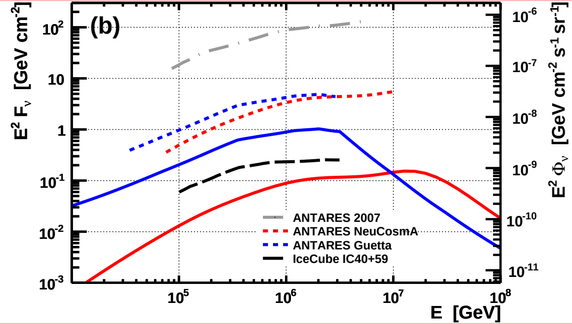
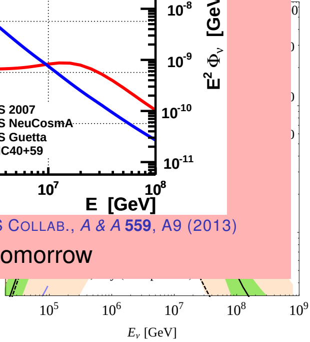
Recent search by ANTARES optimised for NeuCosmA:



ANTARES COLLAB., *A & A* **559**, A9 (2013)

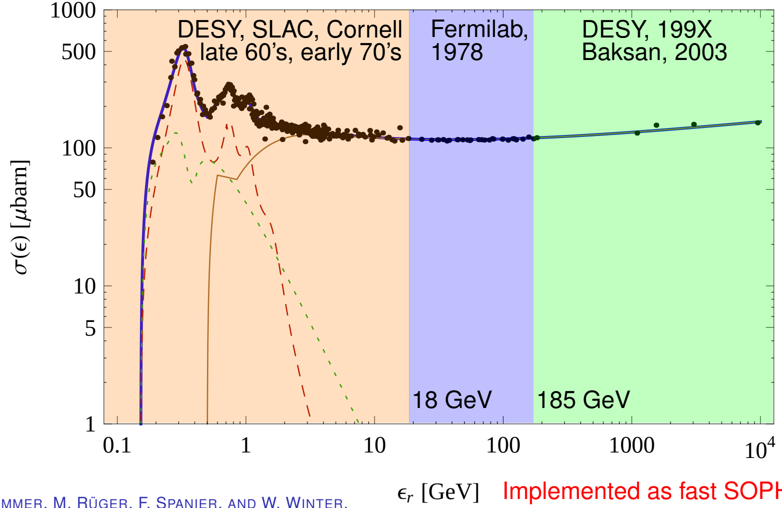
See talk by J. Schmid tomorrow



ICECUBE COLL., *Natu*
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

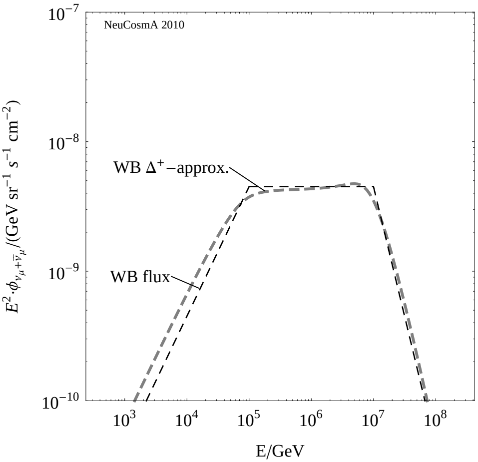


S. Hümmer, M. Rüger, F. Spanier, and W. Winter, *Astrophys. J.* **721**, 630 (2010)

Implemented as fast SOPHIA-based parametrisation

Revising the neutron model: NeuCosmA

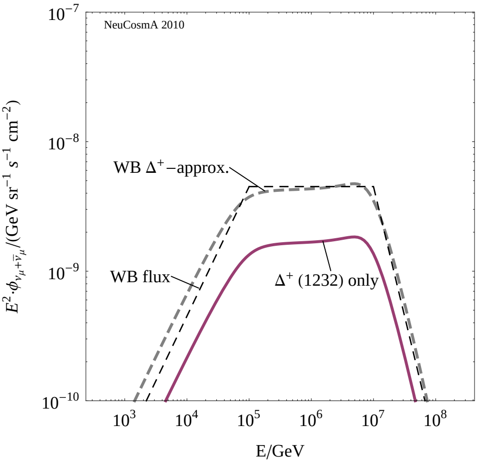
- Contributions to the full photohadronic cross section



Revising the neutron model: NeuCosmA

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 the full photohadronic cross section

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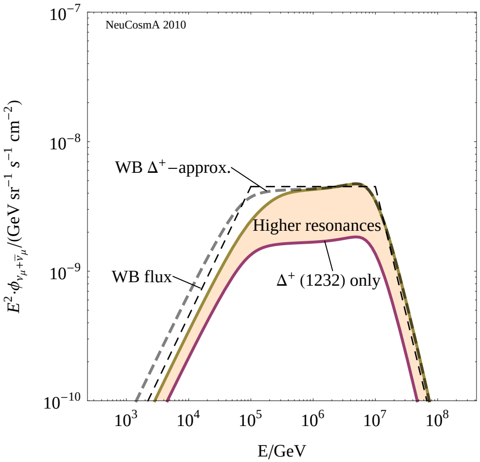

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- t-channel (direct production)

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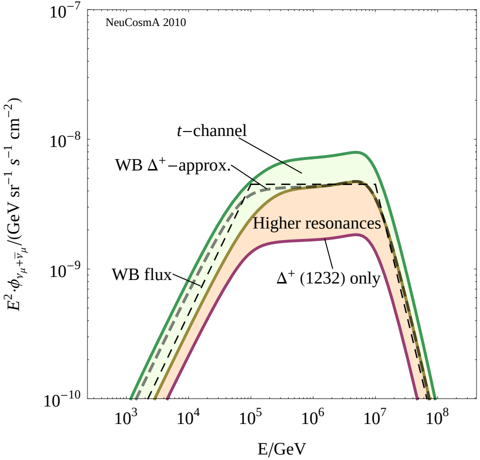


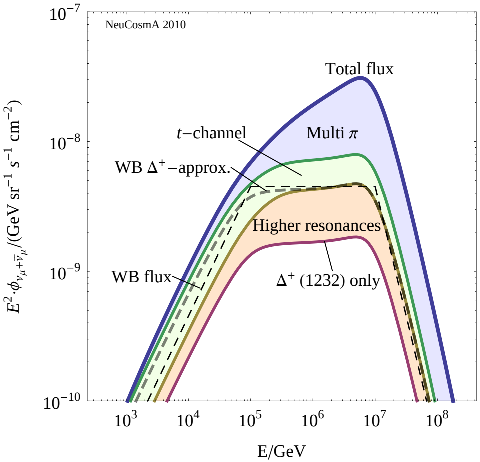
Revising the neutron model: NeuCosmA

• Contributions to the full photohadronic cross section

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

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

P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 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

Revising the neutron model: NeuCosmA

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

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

$$K^+ \to \mu^+ + \nu_\mu$$

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

Revising the neutron model: NeuCosmA

• Further particle decays

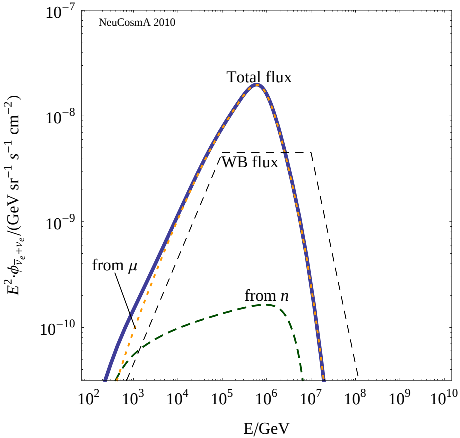
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

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

Resulting ν_e flux (at the observer)



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Revising the neutron model: NeuCosmA

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

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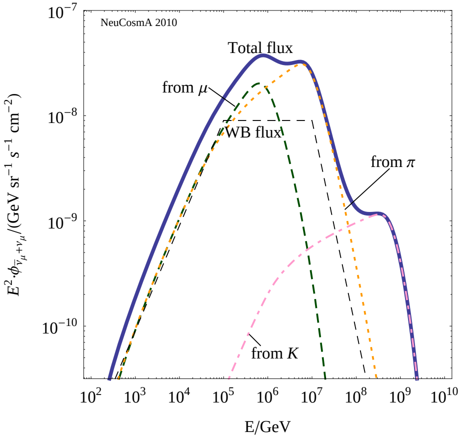
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Resulting ν_μ flux (at the observer)

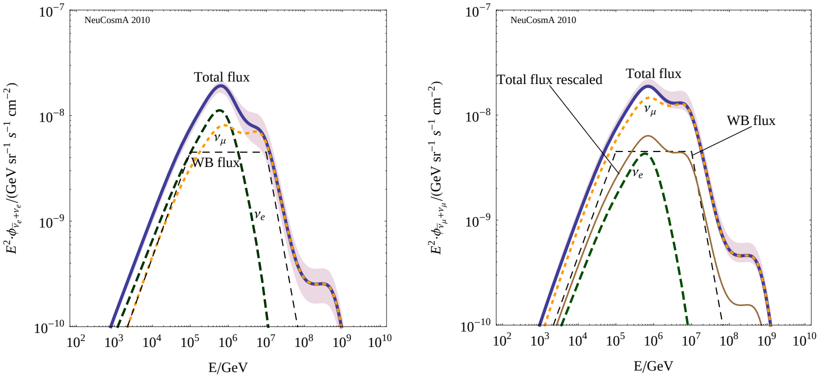


P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

Revising the neutron model: NeuCosmA

• Neutrino spectra including flavour mixing

Electron neutrino spectrum — Muon neutrino spectrum

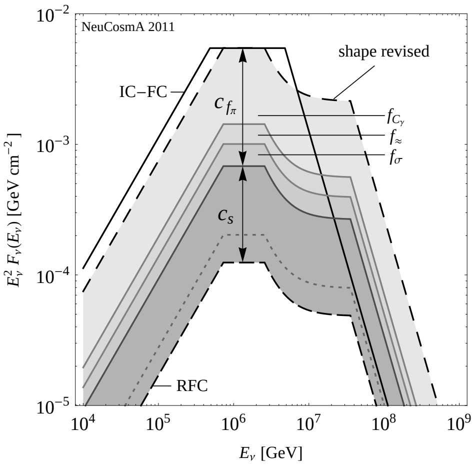


P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

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

• How the spectrum changes...



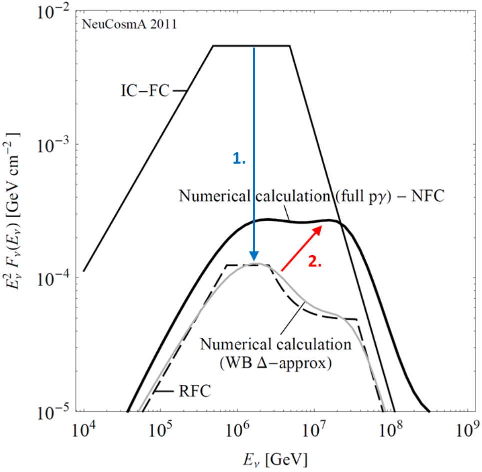
S. Hümmer, P. Baerwald, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

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)

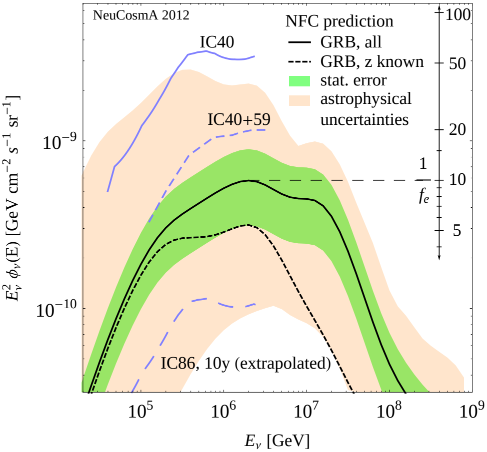
Revising the neutron model: NeuCosmA

• 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 $F_\nu(E_\nu)$
- 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:
  - $0.001 \leq t_v\,[\text{s}] \leq 0.1$
  - $200 \leq \Gamma \leq 500$
  - $1.8 \leq \alpha_p \leq 2.2$
  - $0.1 \leq \epsilon_e/\epsilon_B \leq 10$



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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, AND 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, AND F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

A two-component model of CR emission

Optical depth:

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

$E'_{p,\text{max}}$ 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: $\quad t'_{\text{acc}}\left(E'_p\right) = \frac{E'_p}{\eta c e B'}$

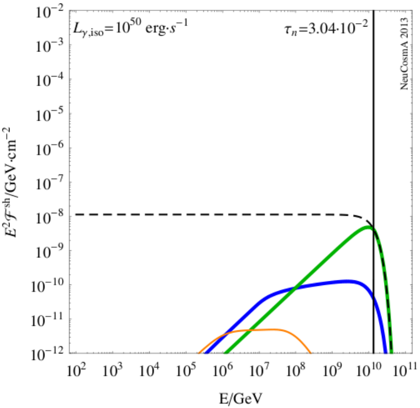
Particles can escape from within a shell of thickness λ'_{mfp}:

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

fraction of escaping particles

A two-component model of CR emission

Optically **thin** source:



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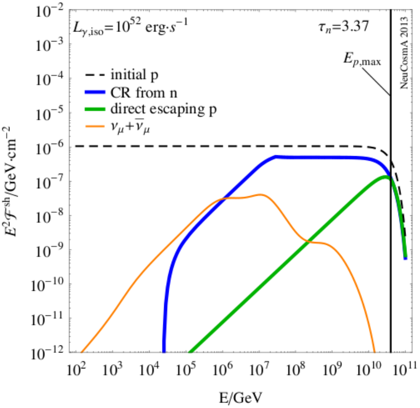
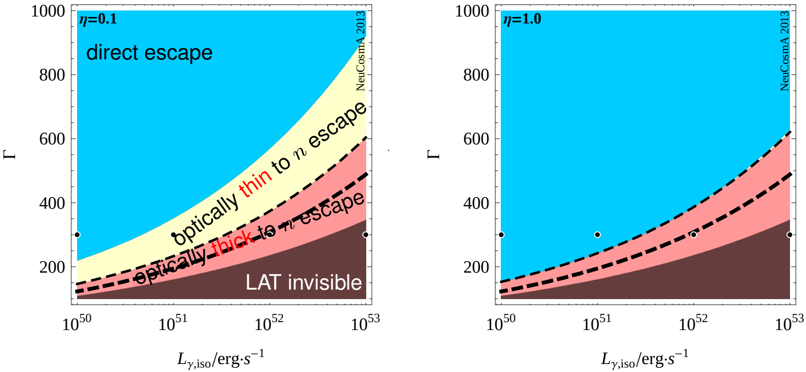


P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

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, and 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):

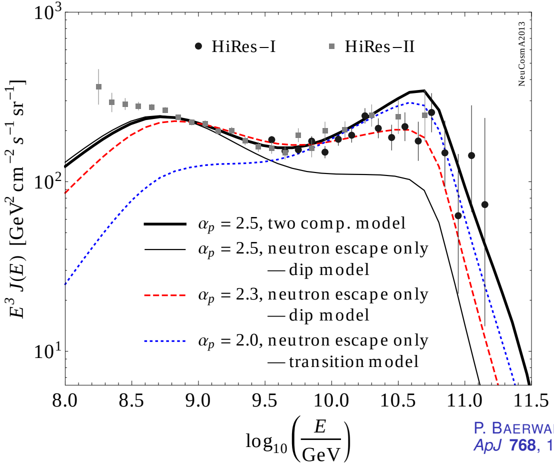
$$\dot{Y}_p = \partial_E (HEY_p) + \partial_E (b_{e^+e^-} Y_p) + \partial_E (b_{p\gamma} Y_p) + \mathcal{L}_{\text{CR}}$$

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

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

The UHECR and UHE ν fluxes at Earth

UHECR flux at Earth from n and direct p escape:



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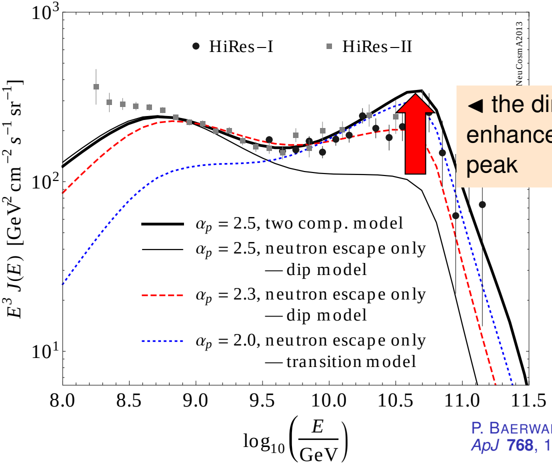

◀ the direct p escape enhances the high-energy peak

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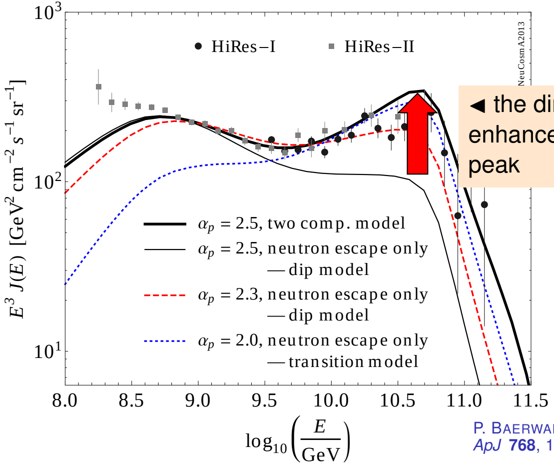


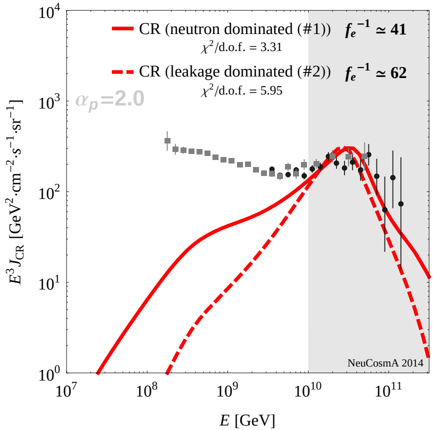
◀ the direct p escape enhances the high-energy peak

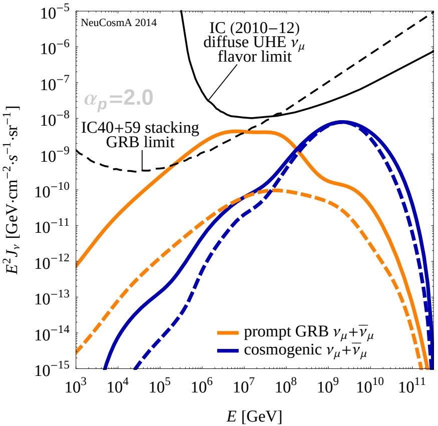
P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)

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, and W. Winter, arXiv:1401.1820

Where to now? Constraining the connection

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

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

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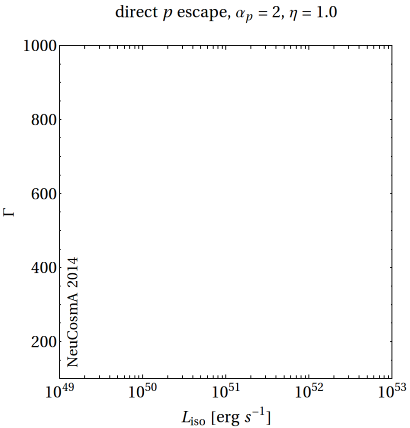
1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)



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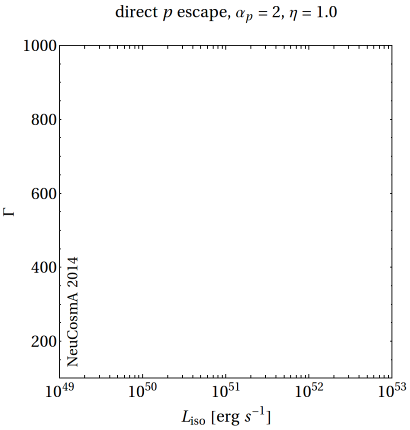

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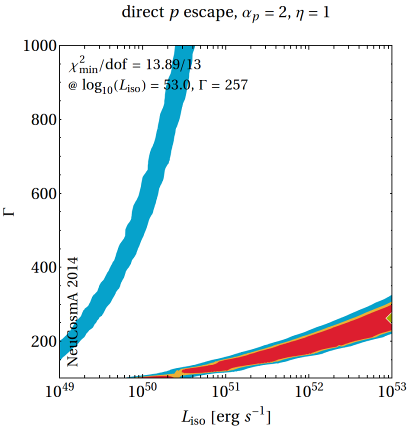

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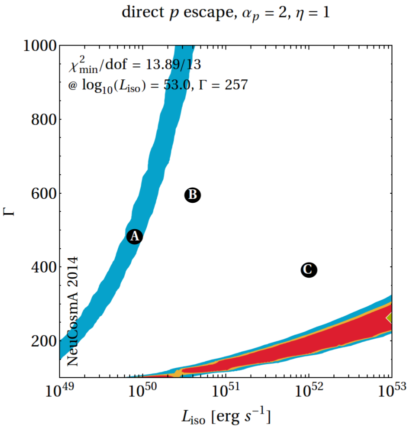

P. Baerwald, MB, and W. Winter, arXiv:1401.1820

Where to now? Constraining the connection

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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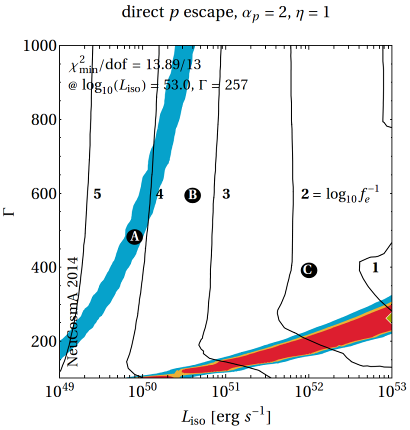

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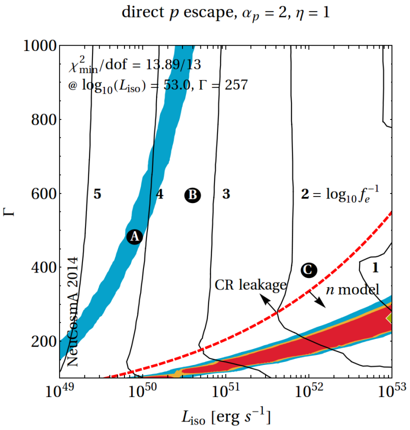

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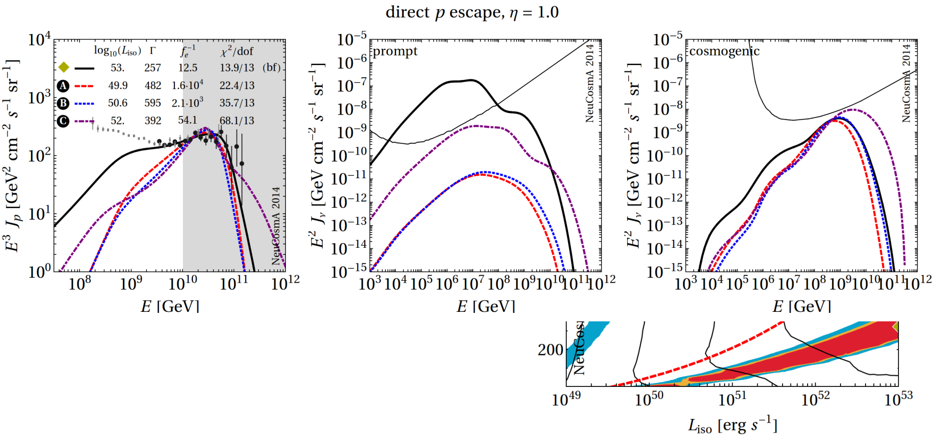

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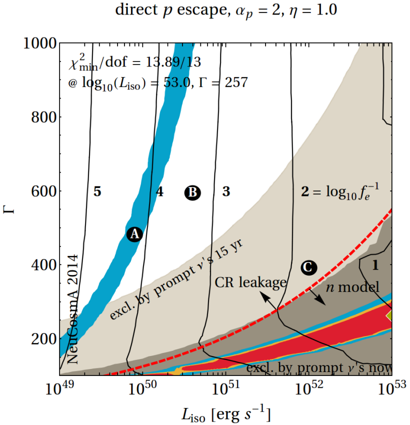
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.



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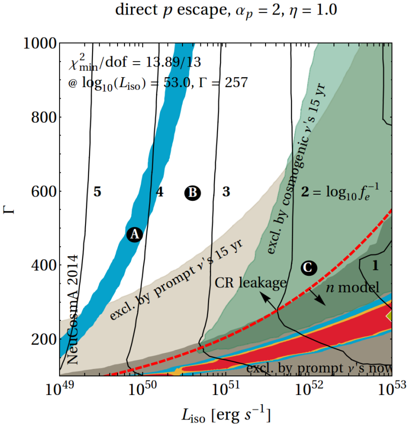
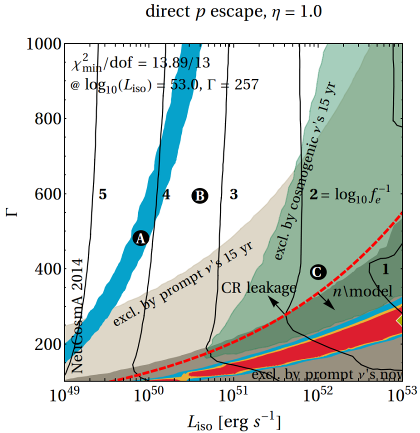
5. Identify the region corresponding to pure n escape and to n escape + CR leakage
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



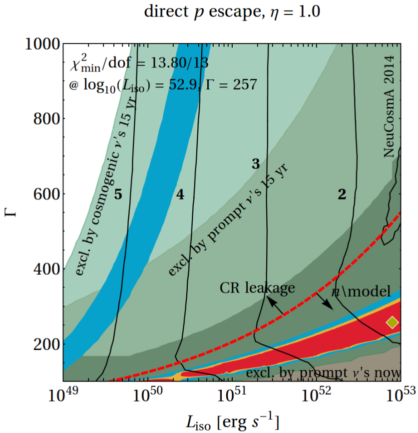
P. Baerwald, MB, and W. Winter, arXiv:1401.1820

Where to now? Constraining the connection

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



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



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

Plan of attack

Three steps towards improving the GRB neutrino predictions:

Step 1

Refine the calculation of the neutrino yield
in $p\gamma$ interactions

Step 2

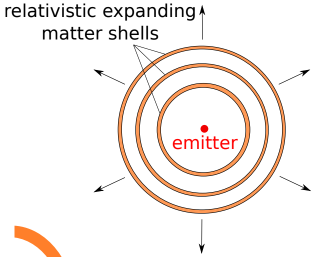
Go beyond the simplest UHECR-neutrino connection

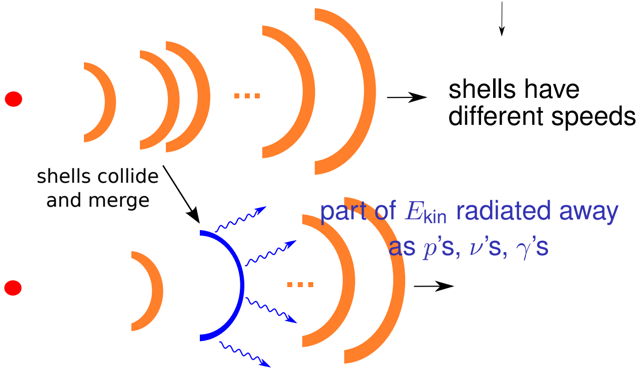
Step 3 (preliminary)

Treat the fireball dynamically (neutrino “light curves”)

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





Simulating a burst

Up to now, we have assumed that the burst is made up of T_{90}/t_v identical internal collisions.

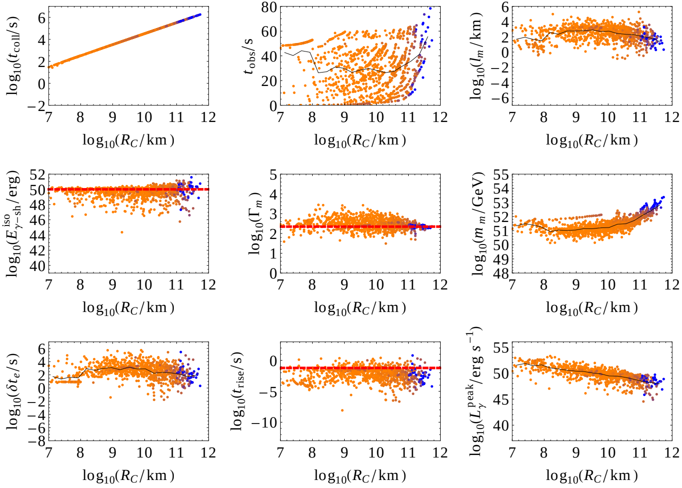
Let us go beyond that:

1. Start with $\sim$ 1000 initial baryon-loaded shells, each with a different speed Γ_i
2. Propagate them until an internal collision occurs
3. A new merged shell is created, with $\Gamma_m \simeq \sqrt{\Gamma_s \Gamma_f}$; it continues moving
4. Part of the kinetic energy of the former shells is radiated away as gamma-rays, protons, and neutrinos
5. Continue until there are no more shells left to collide, or the ISM is reached

S. Kobayashi, T. Piran, and R. Sari, *ApJ* **490**, 92 (1997)
F. Daigne and R. Mochkovitch, *MNRAS* **296**, 275 (1998)

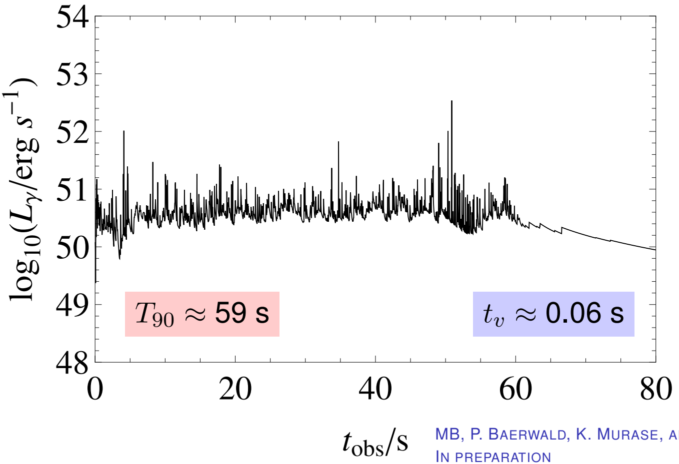
Loads of information

We can track how the parameters change with collision radius:



Synthetic light curves

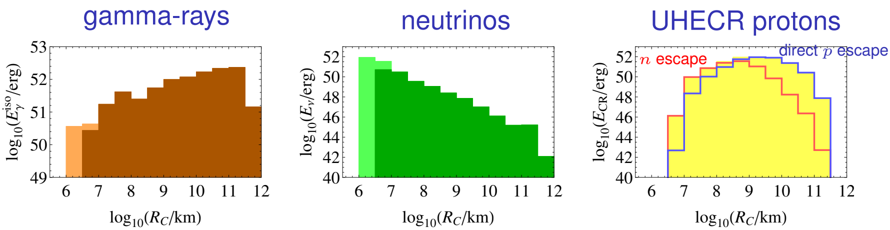
A fast-rise-exponential-decay (FRED) pulse is assigned to each collision; their superposition yields a synthetic light curve:



MB, P. Baerwald, K. Murase, and W. Winter, In preparation

Gamma-ray, neutrino, and proton emission

The gamma-ray, neutrino, and proton emission peak at different collision radii:



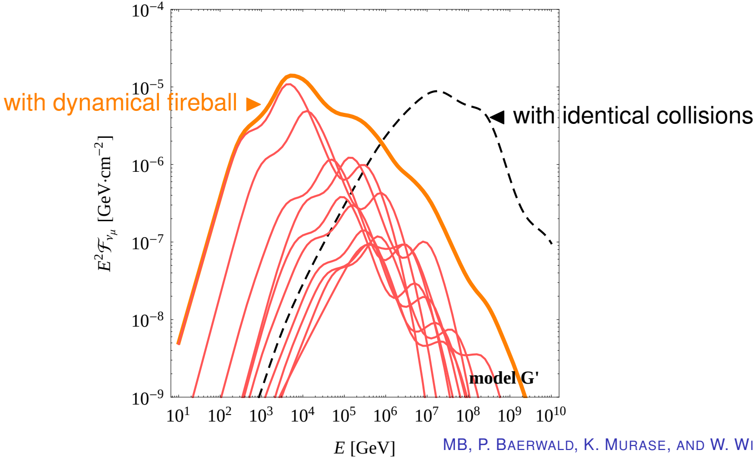
MB, P. Baerwald, K. Murase, and W. Winter, in preparation

- **Light colours:** sub-photospheric collisions
- Total gamma-ray emission normalised to $E_{\gamma-\rm tot}^{\rm iso} = 10^{53}$ erg

As the burst expands, the photon and proton densities fall, and this affects the relative emission of the different particle species

Synthetic neutrino spectra

Total ν fluence of the burst built up from the individual collisions:



MB, P. Baerwald, K. Murase, and W. Winter, In preparation

The prompt ν emission peaks at energies $\ll$ the typical $\sim$ PeV!

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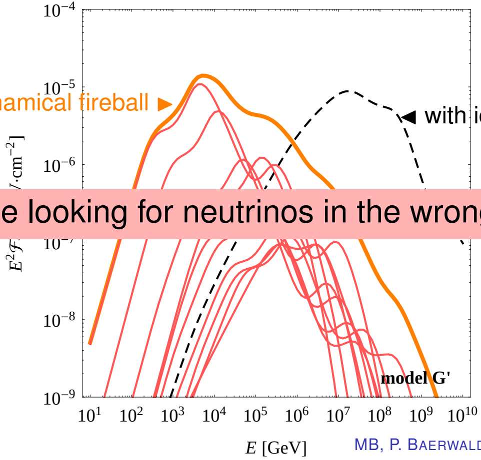

We might be looking for neutrinos in the wrong energies . . .

MB, P. Baerwald, K. Murase, and W. Winter, In preparation

The prompt ν emission peaks at energies $\ll$ the typical $\sim$ PeV!

Summary

We have revised the GRB neutrino predictions of ν emission:

1. Refine the ν yields from $p\gamma$ interactions
   - corrected, full numerical calculation with detailed particle physics
   - quasi-diffuse flux $\sim$ 1 order magnitude below analytical one by IceCube
2. Go beyond the neutron model of UHECR-neutrino production
   - the standard n escape component, plus a direct p escape componente
   - prompt ν flux affected; cosmogenic ν flux not much
   - fits to UHECR observations yield values of baryonic loading
   - IceCube bounds exclude large parts of parameter space
3. Dynamical fireball model
   - track burst parameters as the fireball expands
   - photon, proton, and neutrino emissions peak at different radii
   - total neutrino fluence peaks at lower energies ($\ll$ PeV)

The current (IceCube, ANTARES) and upcoming (KM3NeT, IceCube+) experiments force us to refine our predictions

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})

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

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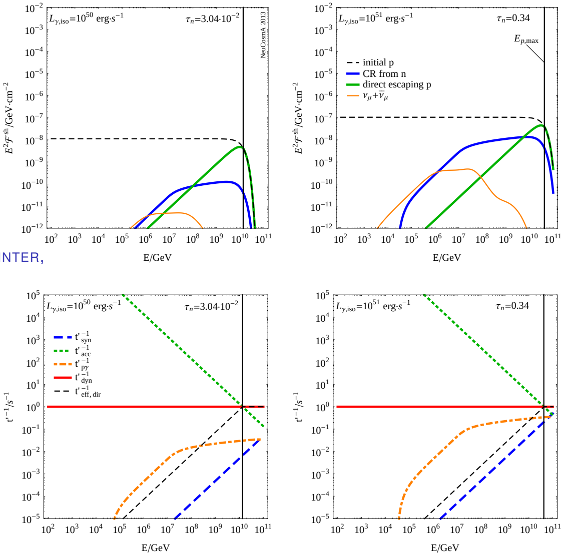
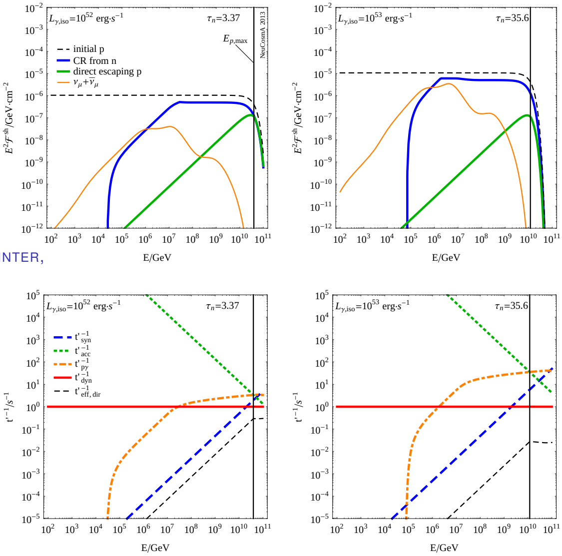
Optically **thin** sources ($\tau_n < 1$):



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

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



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

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}):

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

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

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

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

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

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

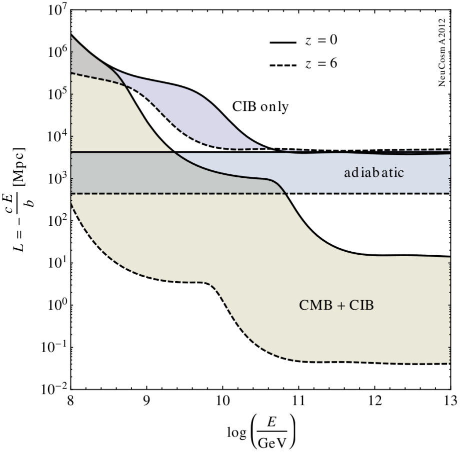
   with $K^i E$ the loss of energy per interaction

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

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

$$\mathcal{H}_{\rm SFR}(z) = \begin{cases} (1+z)^{3.4} & , \; z < 1, \\ N_1 (1+z)^{-0.3} & , \; 1 \le z < 4 \\ N_1 N_4 (1+z)^{-3.5} & , \; z \ge 4 \end{cases} \; , \; \mathcal{H}_{\rm GRB}(z) = (1+z)^{\alpha} \mathcal{H}_{\rm SFR}(z)$$