



A revised view of the ultra-high energy cosmic ray-neutrino connection: the case of gamma-ray bursts

Mauricio Bustamante

Collaborators: Philipp Baerwald, Kohta Murase, and Walter Winter

Inst. für Theoretische Physik und Astrophysik, Uni. Würzburg &
Deutsches Elektronen-Synchrotron DESY, Zeuthen

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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 for CRs *and* ν 's:

- ▶ 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 joint emission models

Solution: we need to build more realistic models!



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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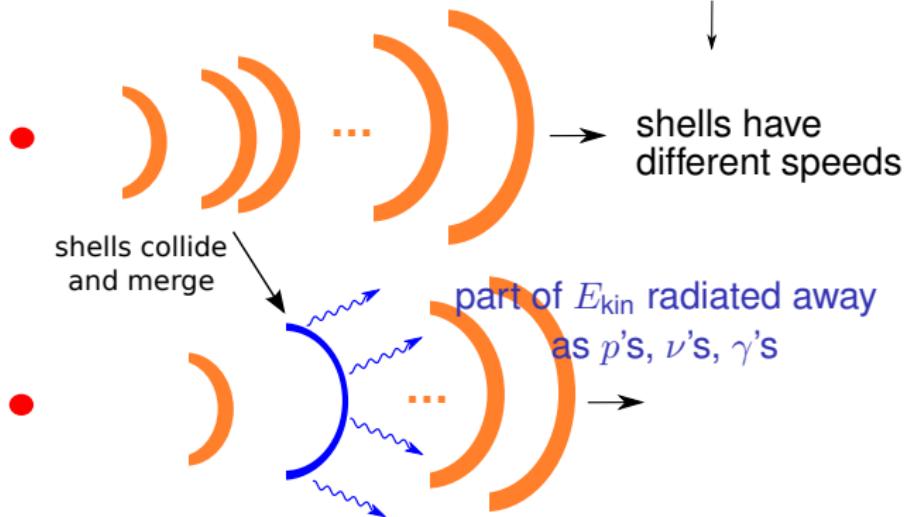
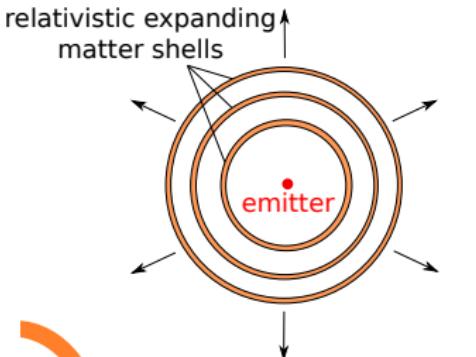
Go beyond the simplest UHECR-neutrino connection

Step 3

Treat the fireball dynamically (neutrino “light curves”)

Internal collisions in the fireball model

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:

power law $\sim E^{-\alpha p}$

Band function

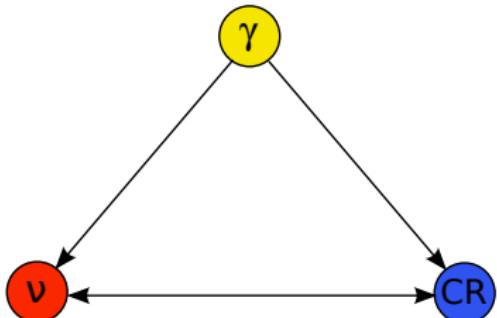
$$p + \gamma \rightarrow \Delta^+ (1232) \rightarrow \begin{cases} n\pi^+, & \text{BR} = 1/3 \\ p\pi^0, & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



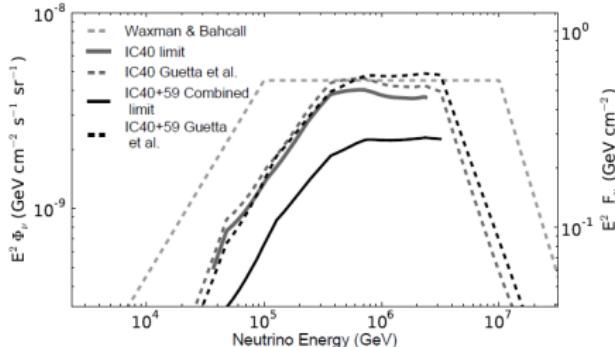
After propagation, with flavour mixing:

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

(“one ν_μ per cosmic ray”)

The *simplest* neutron model is now strongly disfavoured ►

The neutron model under tension?



IceCube Collaboration:

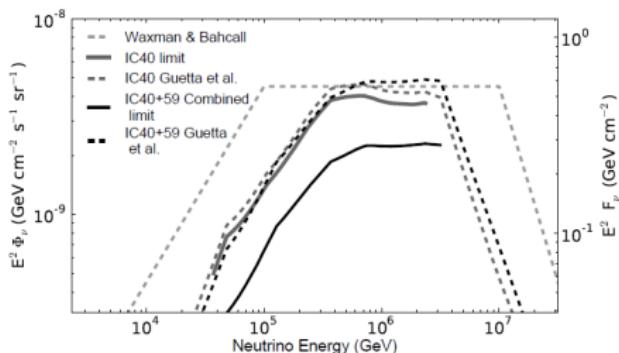
- ▶ ν flux normalised to GRB γ fluence:
$$\int_0^\infty dE_\nu E_\nu F_\nu (E_\nu) \propto \int_{1 \text{ keV}}^{10 \text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma (\varepsilon_\gamma)$$
- ▶ quasi-diffuse ν flux from 117 GRBs
- ▶ **analytical calculation** – in tension with upper bounds

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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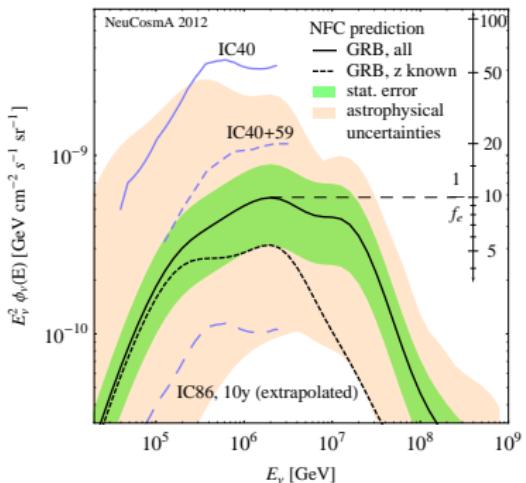
More detailed particle physics (NeuCosmA):

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

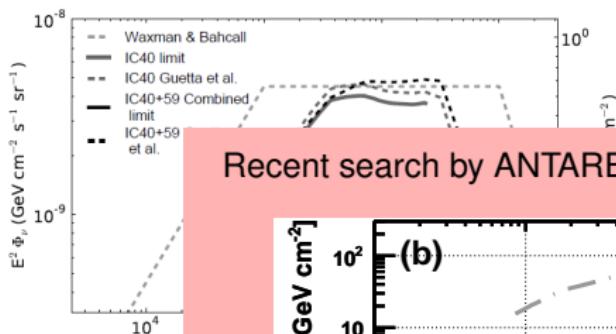
ν flux \sim one order of magnitude lower

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

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



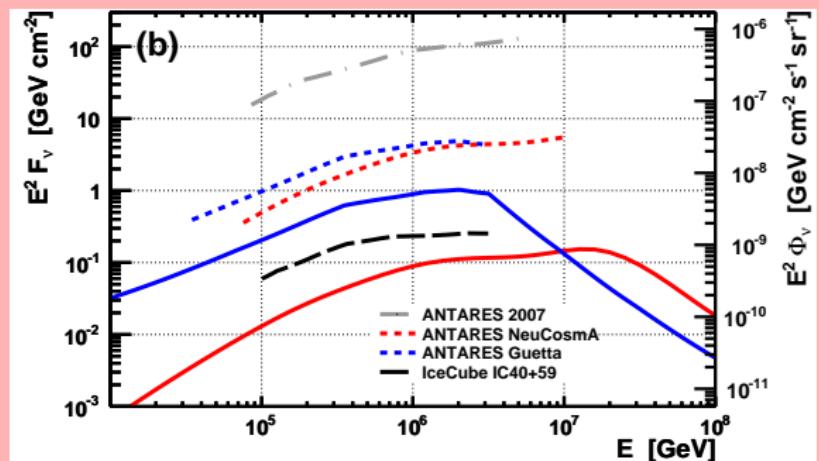
The neutron model under tension?



More detailed particle physics (NeuCosmA):

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- ▶ synchrotron losses of secondaries

Recent search by ANTARES optimised for NeuCosmA:



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

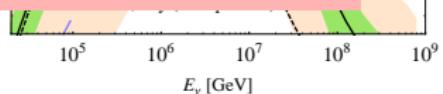
IceCube Coll.

- ▶ ν flux ratio
- $\int_0^\infty dE \nu$
- ▶ quasi-d
- ▶ analytic upper l

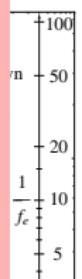
ICECUBE COLL.

AHLERS ET AL. Astropart. Phys. 35, 87 (2011)
GUETTA ET AL. Astropart. Phys. 20, 429 (2004)

- ▶ IceCube is also revising its GRB predictions

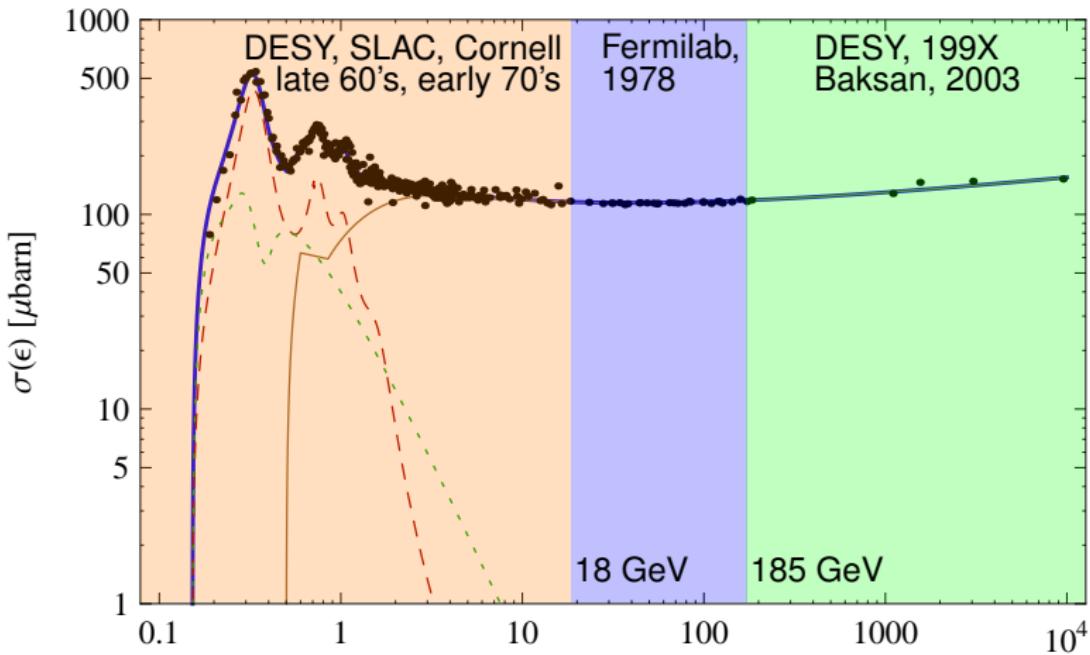


lower
1 (2012)



Revising the neutron model: NeuCosmA

- Detailed $p\gamma$ cross section

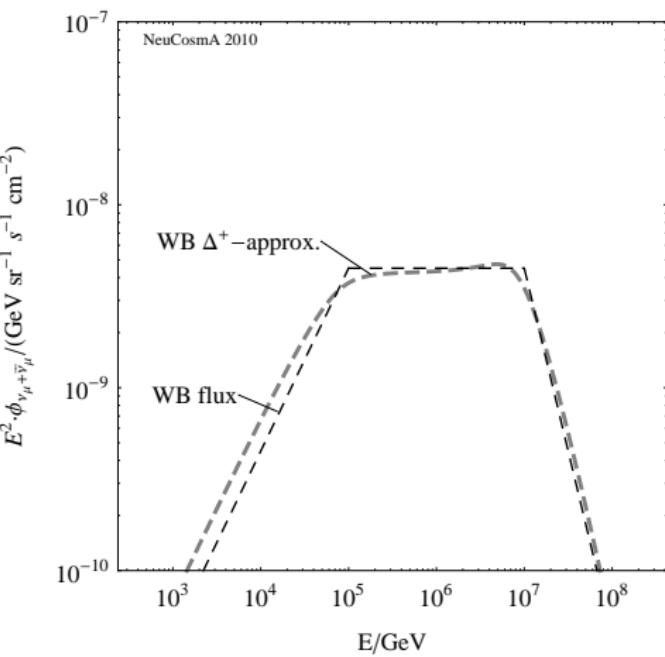


S. HÜMMER, M. RÜGER, F. SPANIER, AND W. WINTER,
Astrophys. J. **721**, 630 (2010)

$\epsilon_r [\text{GeV}]$ Implemented as fast SOPHIA-based parametrisation

Revising the neutron model: NeuCosmA

- Contributions to the full photohadronic cross section

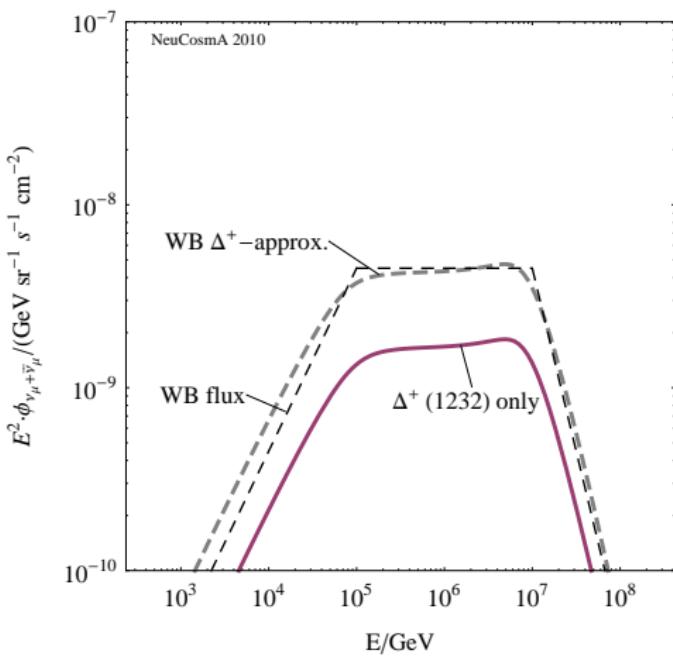


Revising the neutron model: NeuCosmA

- Contributions to the full photohadronic cross section

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

- ▶ $\Delta(1232)$ -resonance



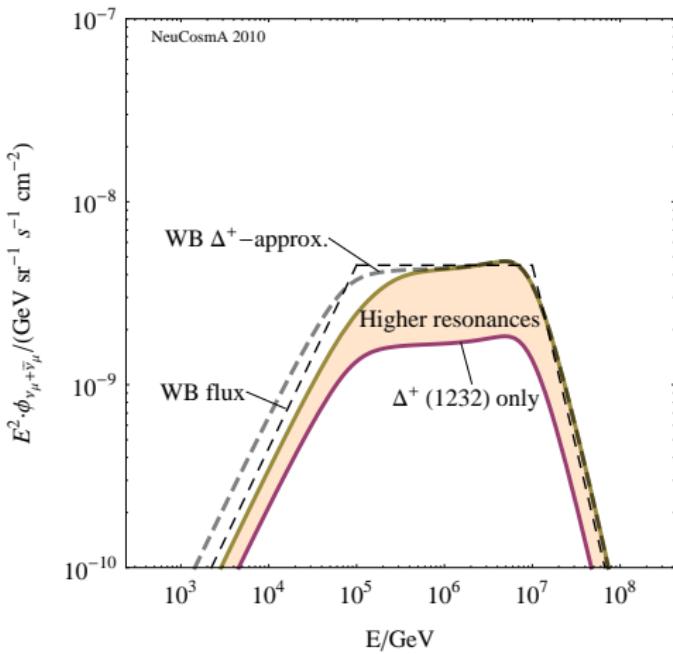
P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D83, 067303 (2011)

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- ▶ Higher resonances



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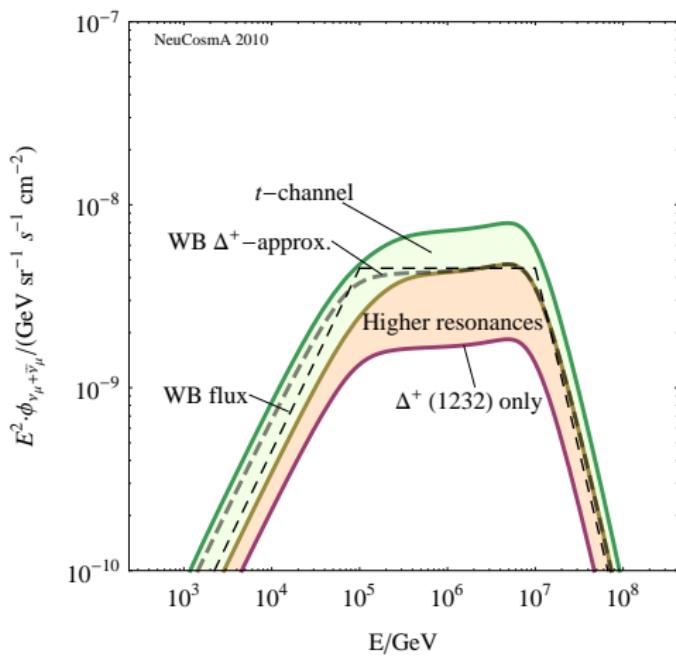
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- ▶ t -channel
(direct production)

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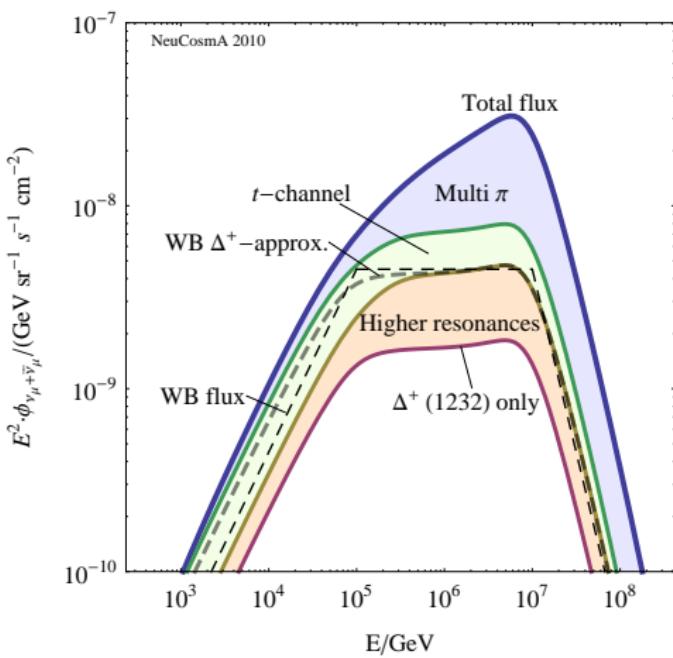
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- ▶ Higher resonances
- ▶ t -channel
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- ▶ High energy processes
(multiple π)

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

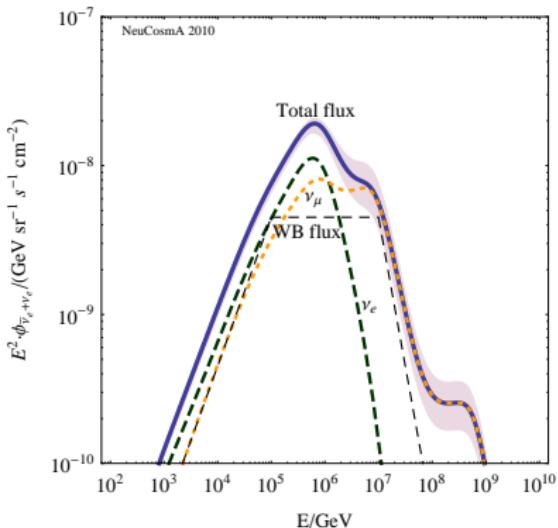


Especially "Multi π " contribution leads to **change of flux shape**; neutrino flux higher by up to a factor of 3 compared to WB treatment

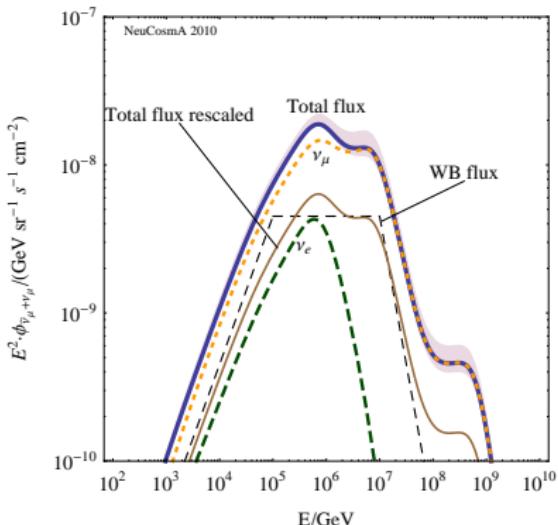
Revising the neutron model: NeuCosmA

- 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...

Corrections to the analytical model:

► shape revised:

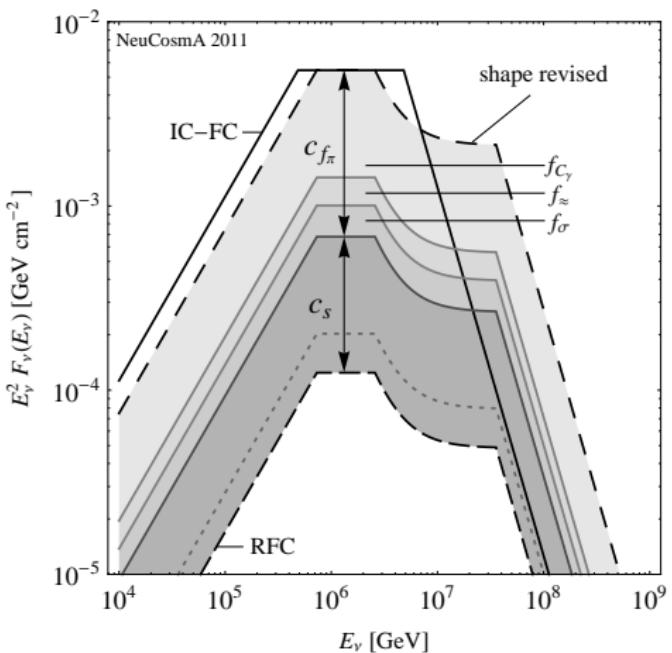
- ▶ shift of first break (correction of photohadronic threshold)
- ▶ different cooling breaks for μ 's and π 's
- ▶ $(1+z)$ correction on the variability scale of the GRB

► Correction cf_π to π prod. efficiency:

- ▶ $f_{C\gamma}$: 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 Δ -resonance

► Correction c_s :

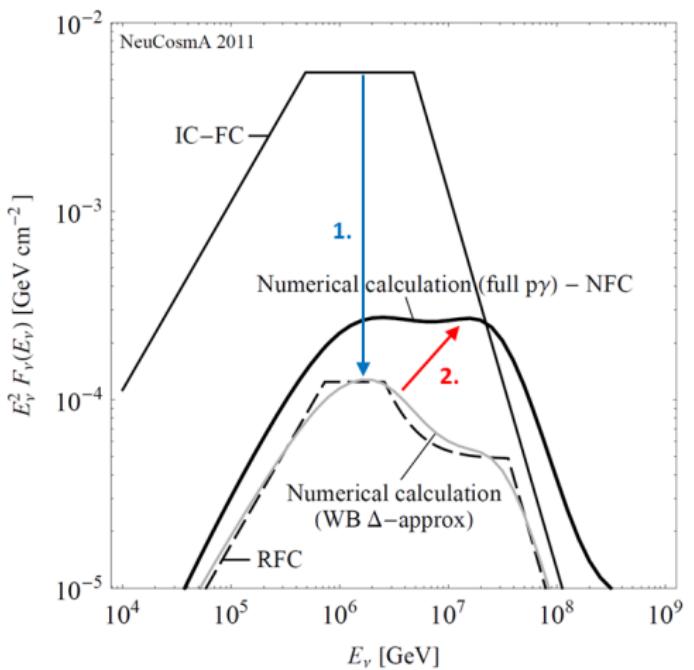
- ▶ energy losses of secondaries
- ▶ energy dependence of the mean free path of protons



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

Revising the neutron model: NeuCosmA

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



For example, GRB080603A:

1. Correction to analytical model ($\text{IC-FC} \rightarrow \text{RFC}$)
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)



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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:

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

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

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

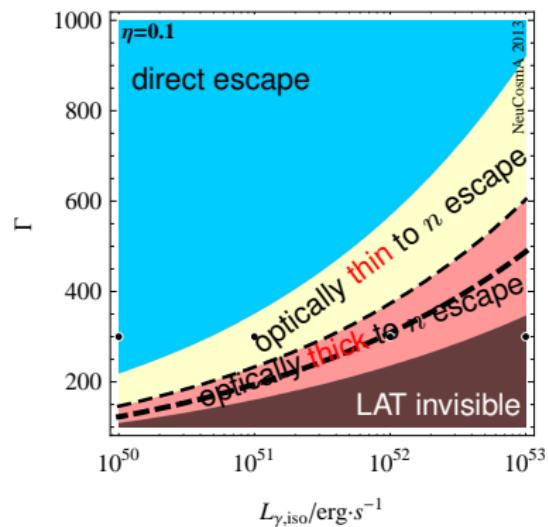
fraction of escaping particles

A two-component model of CR emission

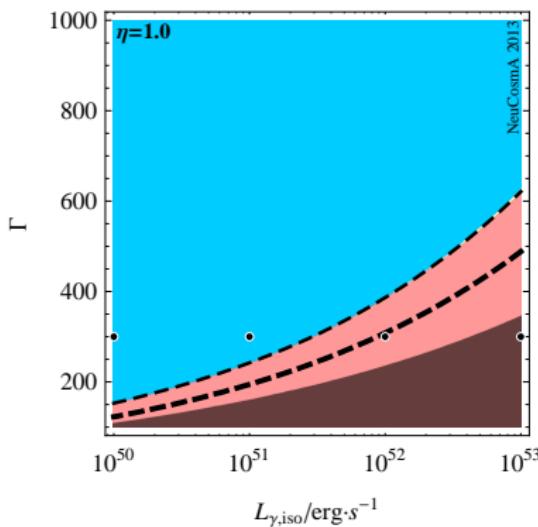
Scan of the GRB emission parameter space:

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

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

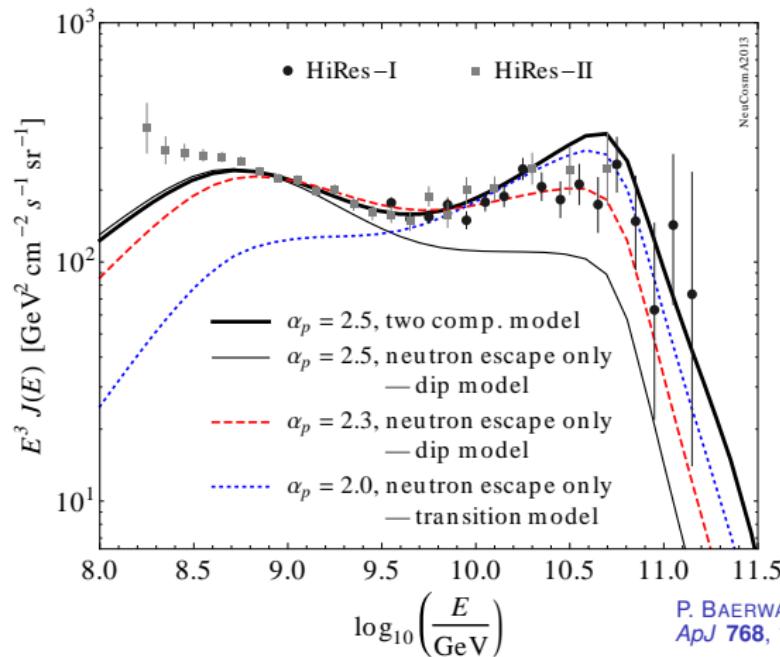
with n_p the real number density

- ▶ Transport equation (comoving source frame):

$$\dot{Y}_p = \partial_E (H E Y_p) + \partial_E (b_{e^+ e^-} Y_p) + \partial_E (b_{p\gamma} Y_p) + \mathcal{L}_{\text{CR}}$$
$$Q_{\text{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\max}}$$

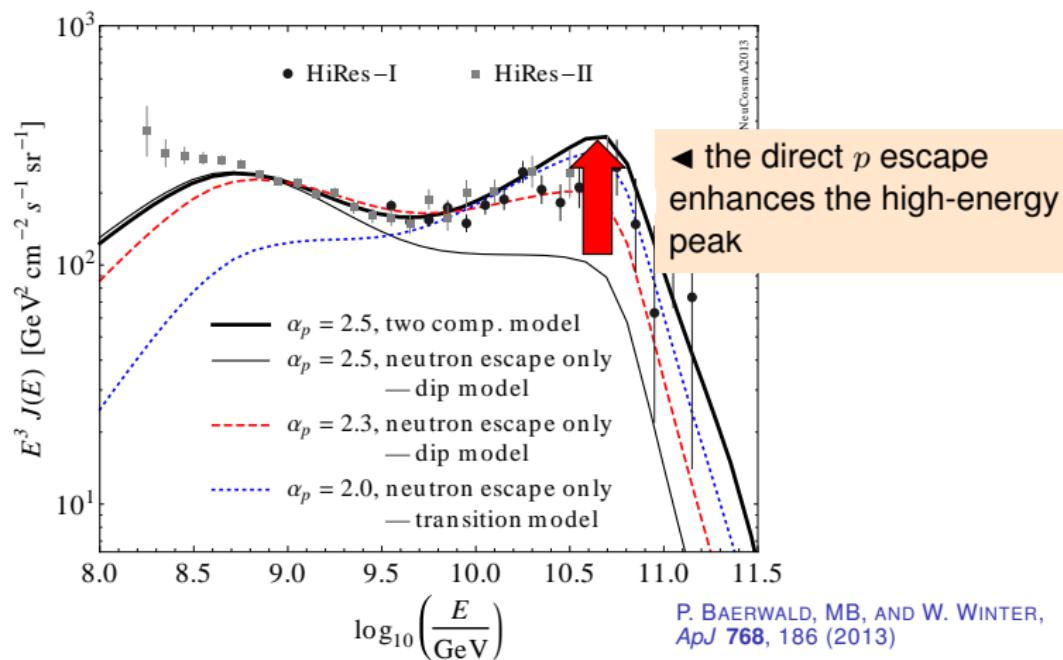
The UHECR and UHE ν fluxes at Earth

UHECR flux at Earth from n and direct p escape:



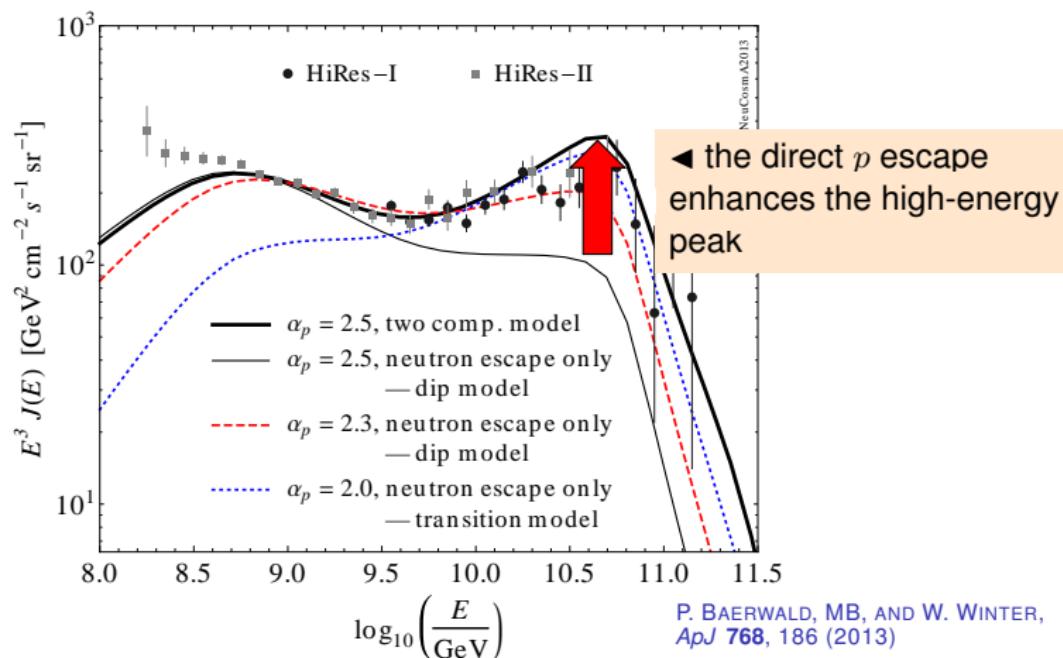
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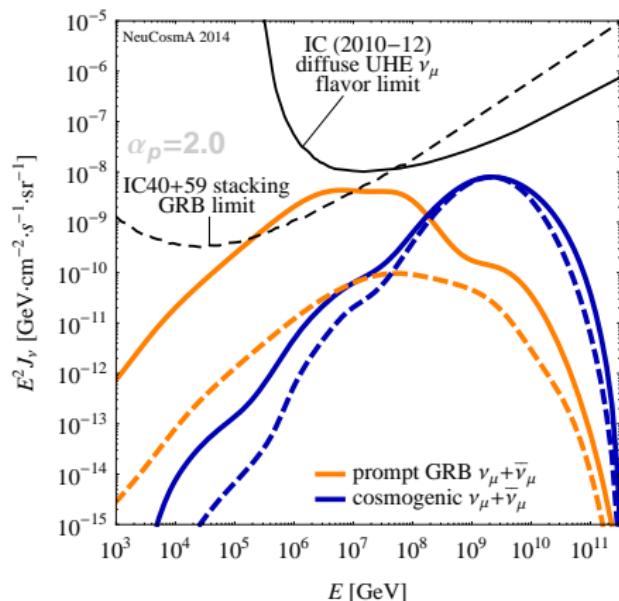
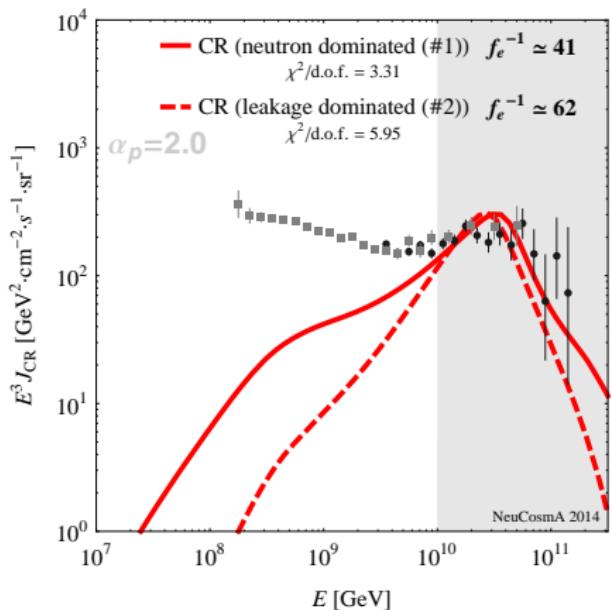
UHECR flux at Earth from n and direct p escape:



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

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

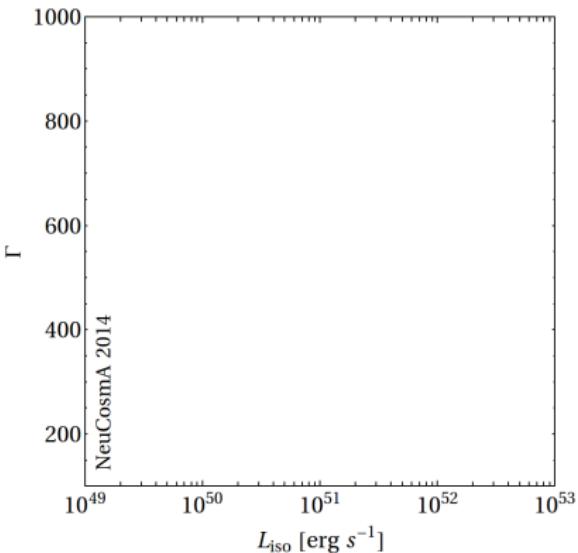
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Constraining the GRB parameter space

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

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



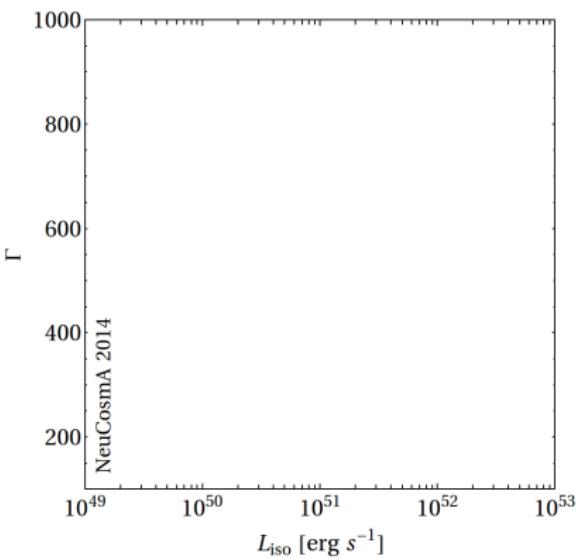
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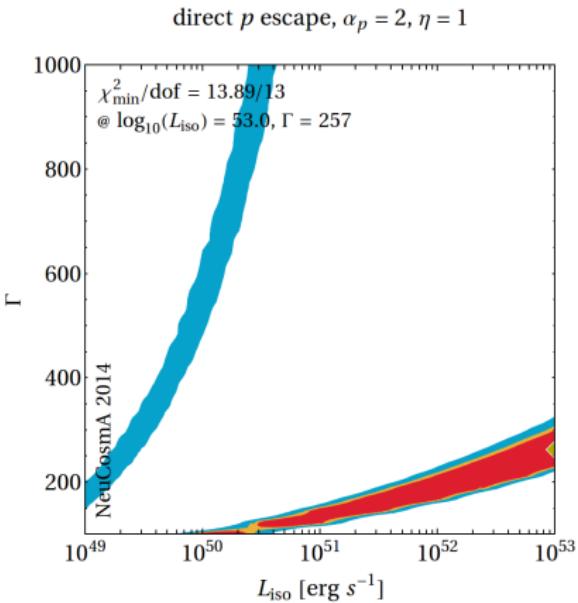
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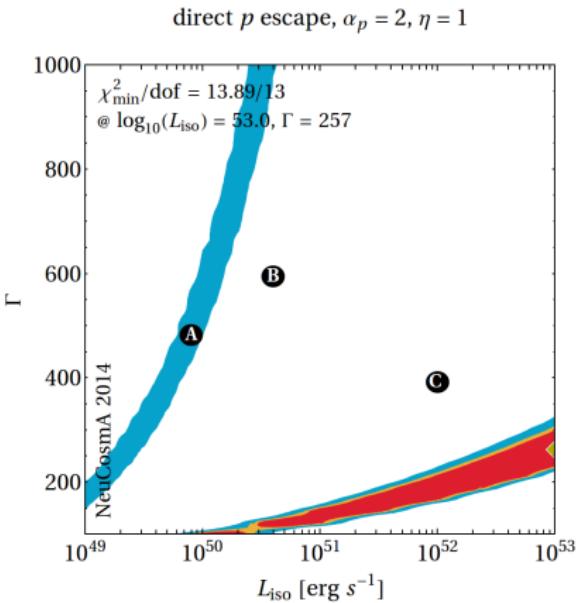
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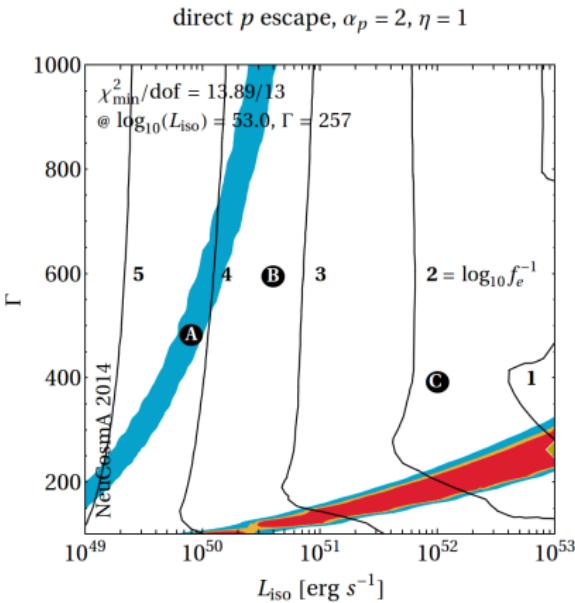
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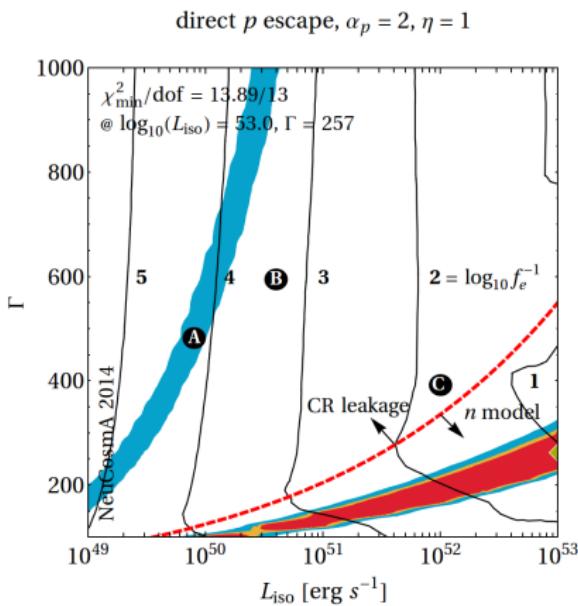
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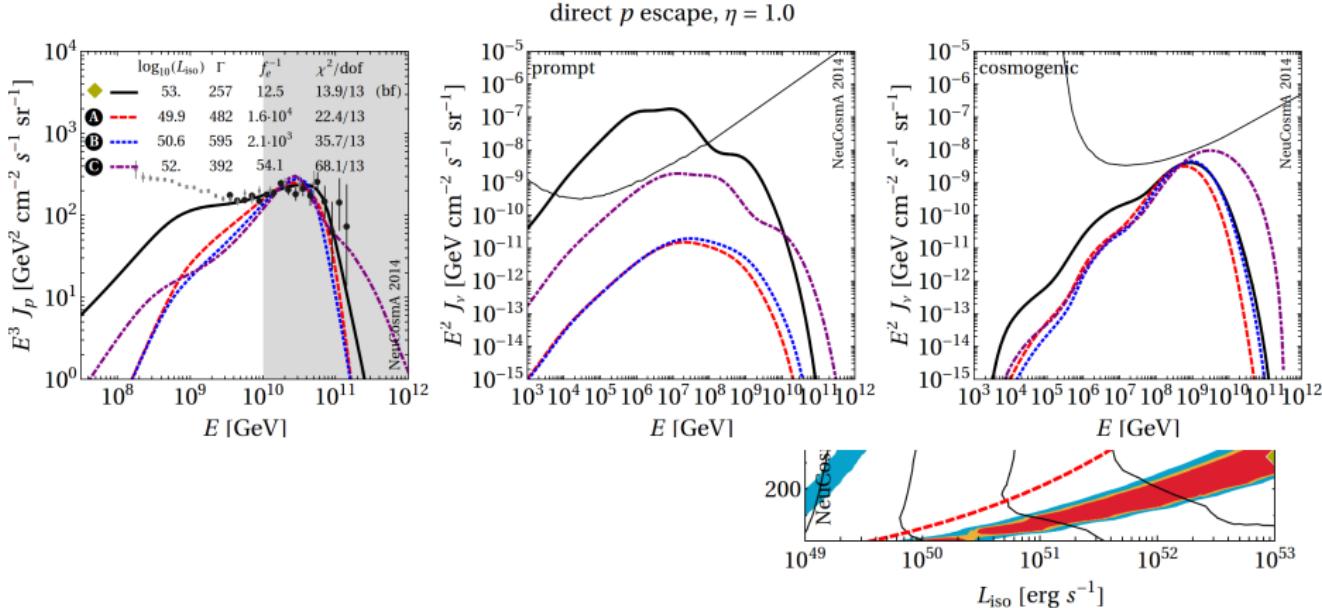
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- 5 Identify the region corresponding to pure n escape and to n escape + CR leakage



Constraining the GRB parameter space

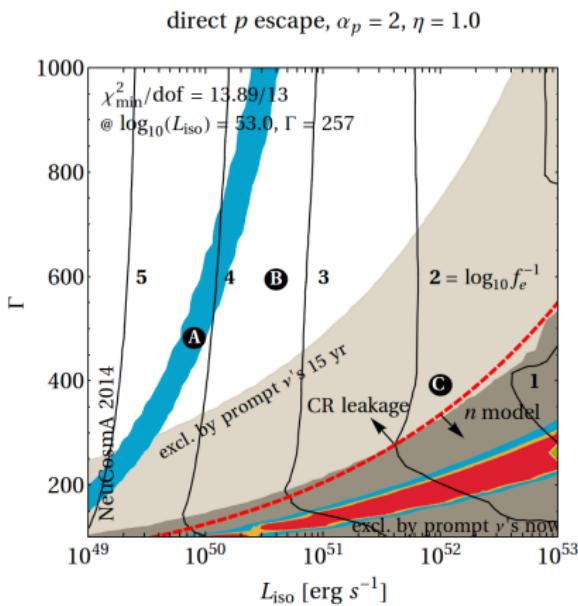
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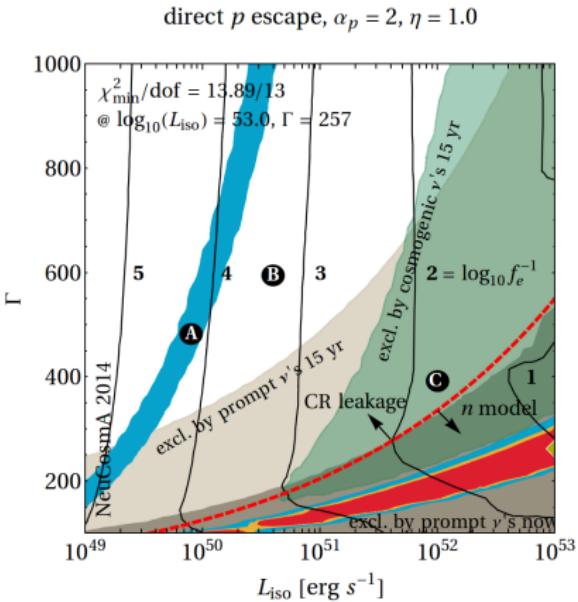
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- 7 After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



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



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Step 3 (preliminary)

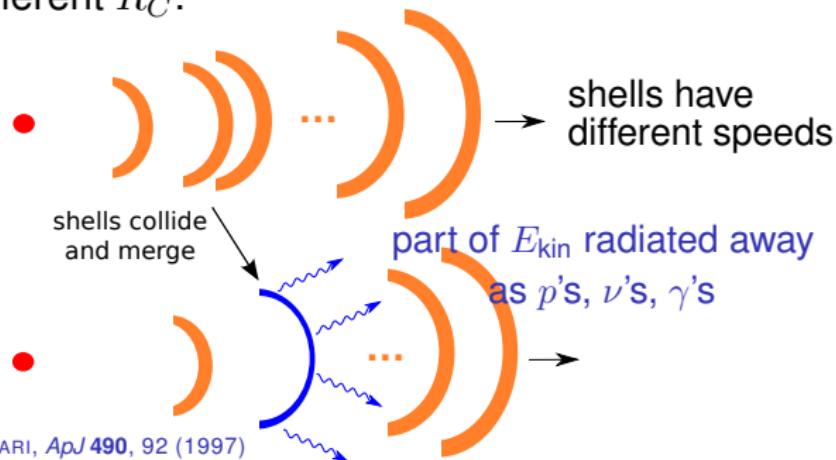
Treat the fireball dynamically (neutrino “light curves”)

Up to now, **all** of the collisions in the burst have been identical – they have occurred at the same radius,

$$R_C = 2 \Gamma^2 c t_v / (1 + z) ,$$

where Γ and t_v are inferred from gamma-ray observations

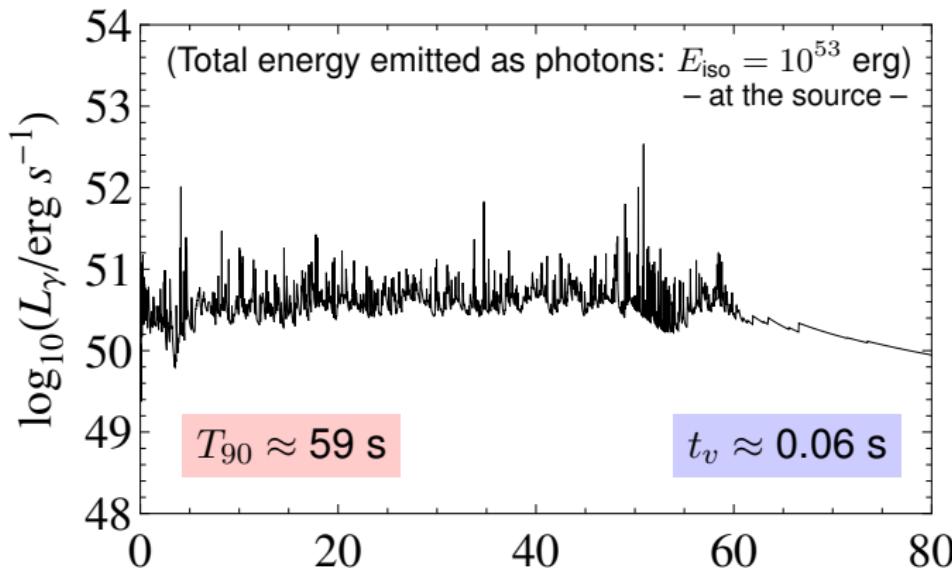
Now: treat the expanding fireball dynamically, with each collision at a different R_C :



S. KOBAYASHI, T. PIRAN, AND R. SARI, *ApJ* 490, 92 (1997)

F. DAINNE AND R. MOCHKOVITCH, *MNRAS* 296, 275 (1998)

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

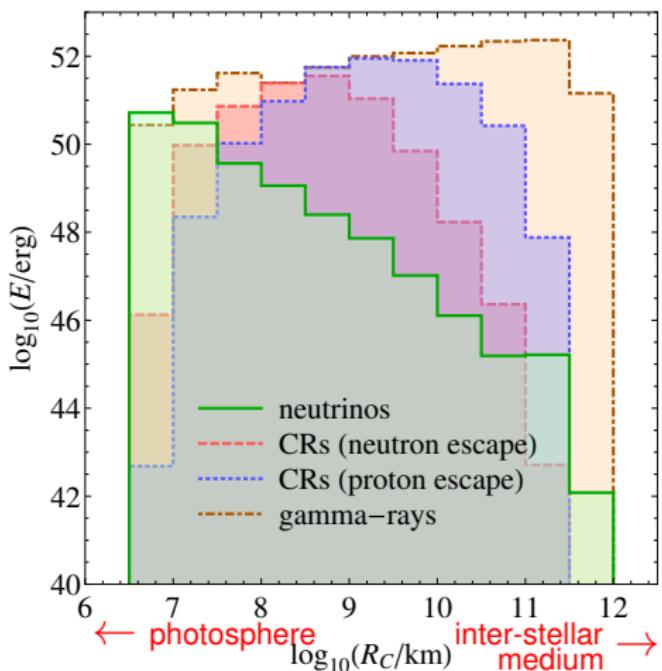


1000 initial shells \mapsto 990 collisions

t_{obs}/s

MB, P. BAERWALD, K. MURASE, AND W. WINTER,
IN PREPARATION

Emission of different species peaks at different collision radii:



Why?

As the fireball expands, photon and proton densities fall

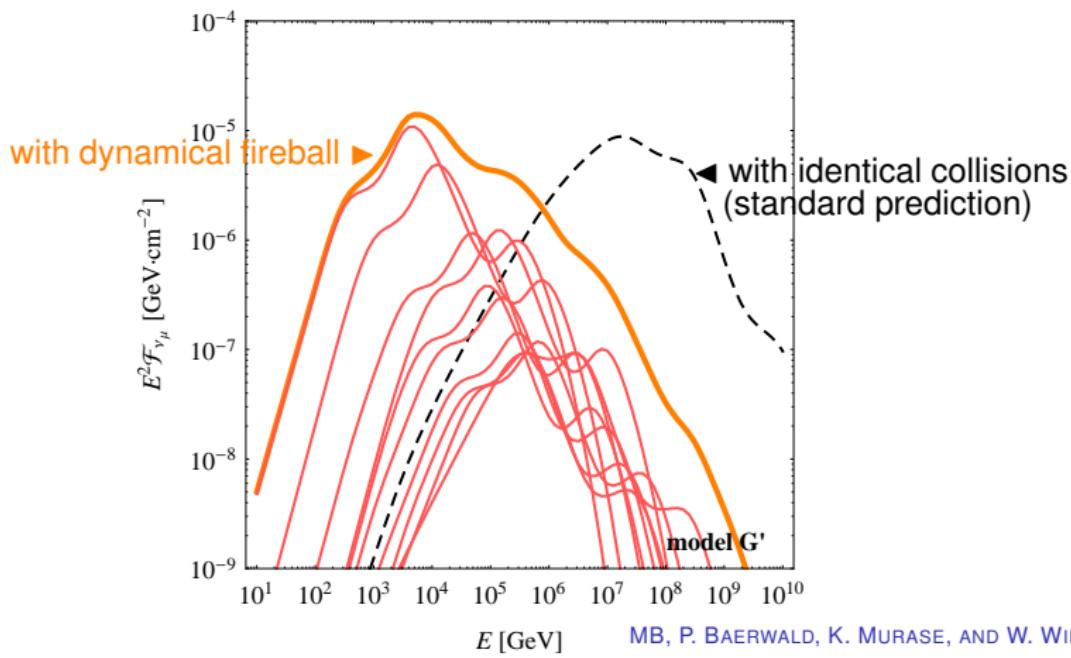
Why does it matter?

GRB parameters derived from gamma-ray observations might not be adequate to describe ν and UHECR emission

So what?

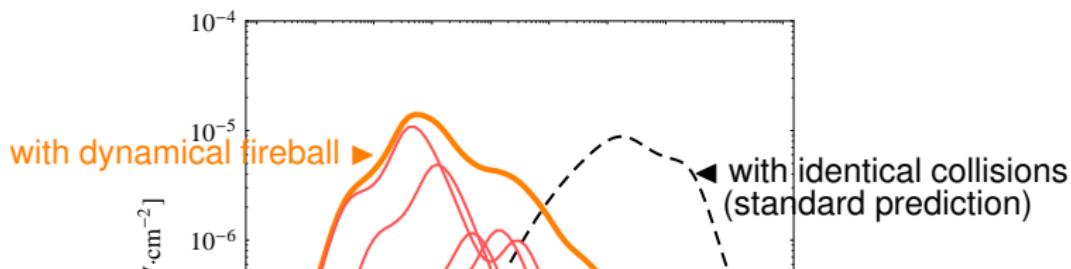
So the following happens ...

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

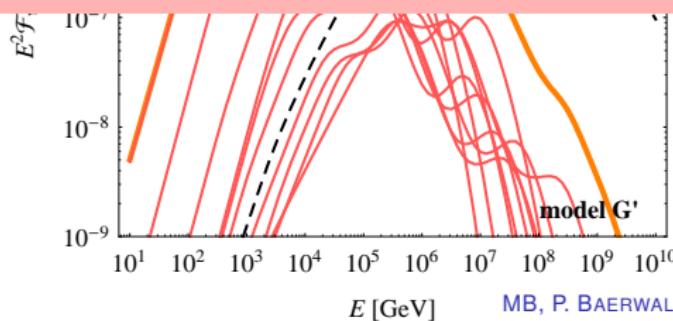


The prompt ν emission peaks at energies \ll the typical \sim PeV!

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



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



E [GeV]

MB, P. BAERWALD, K. MURASE, AND W. WINTER,
IN PREPARATION

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



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 ~ 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 component
 - ▶ fits to UHECR observations yield values of baryonic loading
 - ▶ IceCube ν upper bounds exclude large parts of parameter space
- 3 Dynamical fireball model
 - ▶ 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

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

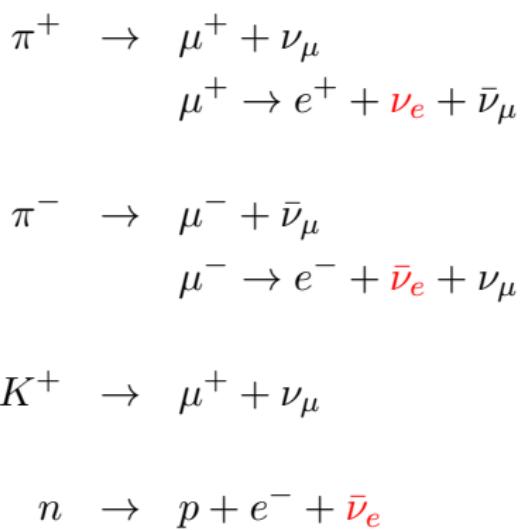
$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

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

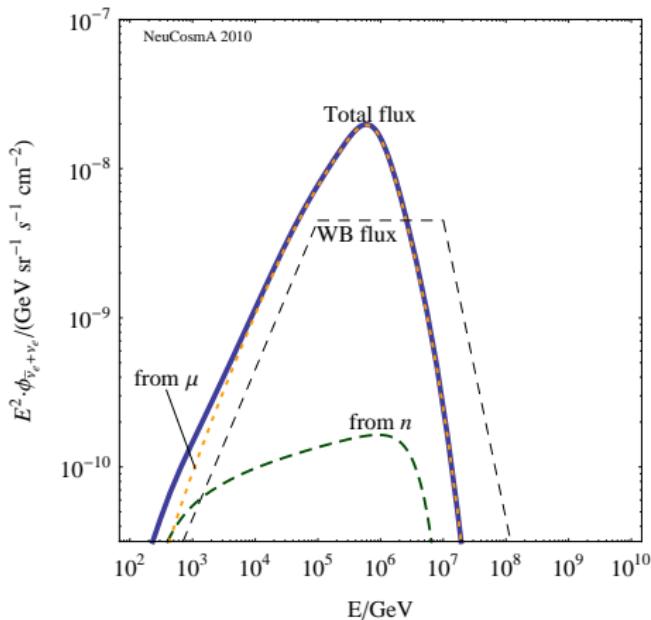
$$n \rightarrow p + e^- + \bar{\nu}_e$$

UHE ν 's in the GRB internal shock model

- Further particle decays



Resulting ν_e flux (at the observer)



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

UHE ν 's in the GRB internal shock model

- Further particle decays

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

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

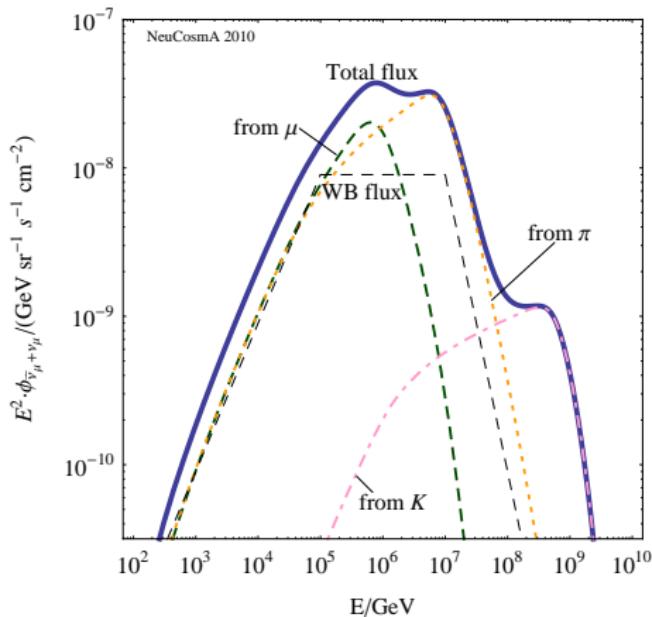
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

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

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

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

Resulting ν_μ flux (at the observer)



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

UHE ν 's in the GRB internal shock model

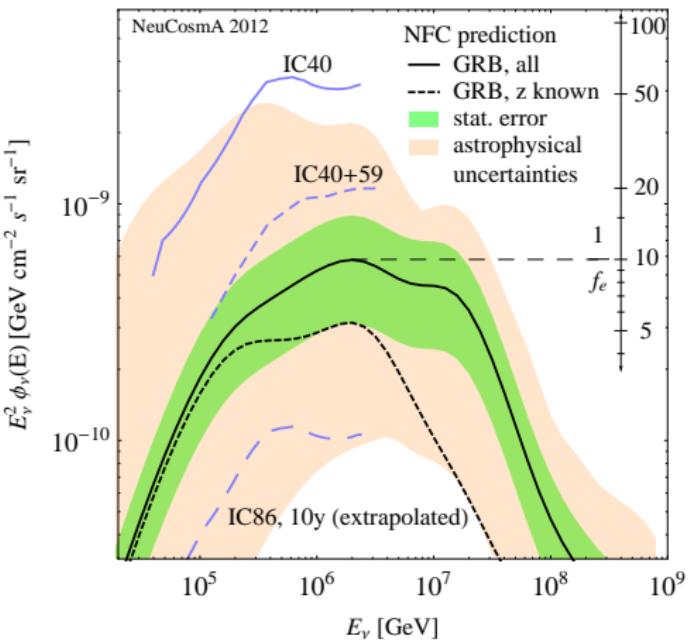
- The new prediction of the quasi-diffuse GRB ν flux

- ▶ 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)

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}

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

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

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

► 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:

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

Maximum proton energy limited by energy losses:

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

UHE ν 's in the GRB internal shock model

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

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

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UHE ν 's in the GRB internal shock model

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

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Normalisation to the observed GRB photon flux F_{γ}

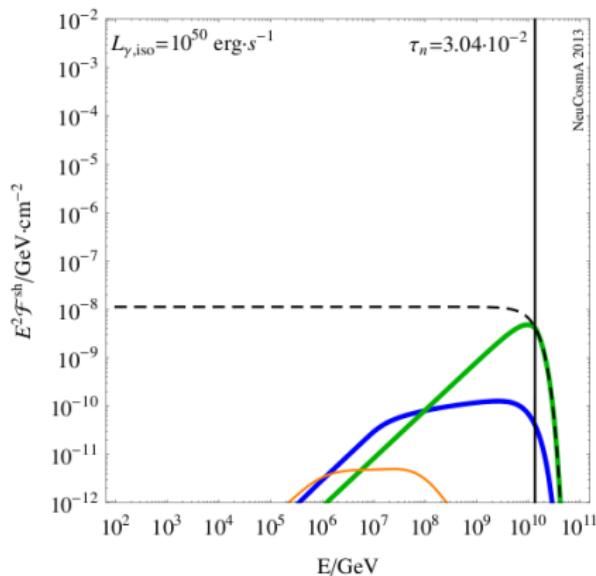
$$\int \varepsilon' N'_{\gamma} (\varepsilon') d\varepsilon' = \frac{E'_{\text{iso}}^{\text{sh}}}{V'_{\text{iso}}} \propto F_{\gamma}, \quad \int E'_p N'_p (E'_p) dE'_p = \frac{1}{f_e} \frac{E'_{\text{iso}}^{\text{sh}}}{V'_{\text{iso}}} \propto \frac{F_{\gamma}}{f_e}$$

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

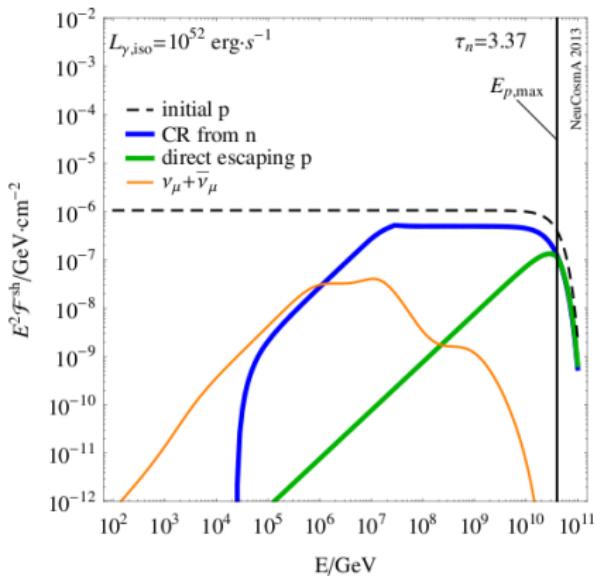
$$\mathcal{F}^{\text{sh}} = t_v V'_{\text{iso}} \frac{(1+z)^2}{4\pi d_L^2} Q'$$

Optically thin vs. thick sources

Optically **thin** source:



Optically **thick** source:



P. BAERWALD, MB, AND 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 $p\gamma \rightarrow pe^+e^-$:

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

- ▶ 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)

Interaction with the photon backgrounds

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

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

- 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

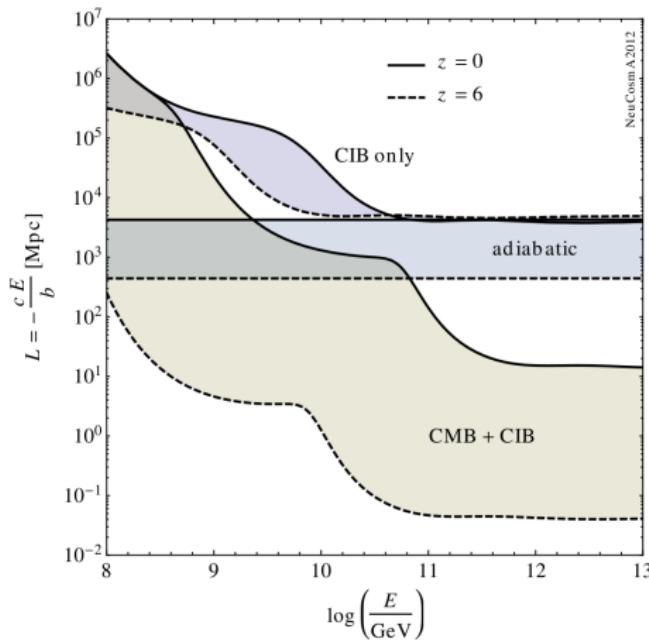
$$t_{p\gamma}^{-1}(E, z) = \sum_i^{\text{all channels}} \Gamma_{p \rightarrow p}^i(E, z) K^i,$$

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

- From this, we calculate back $b_{p\gamma} (\text{GeV s}^{-1}) \dots$
- \dots 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 $L_{\text{CIB}} \gg L_{\text{CMB}}$:

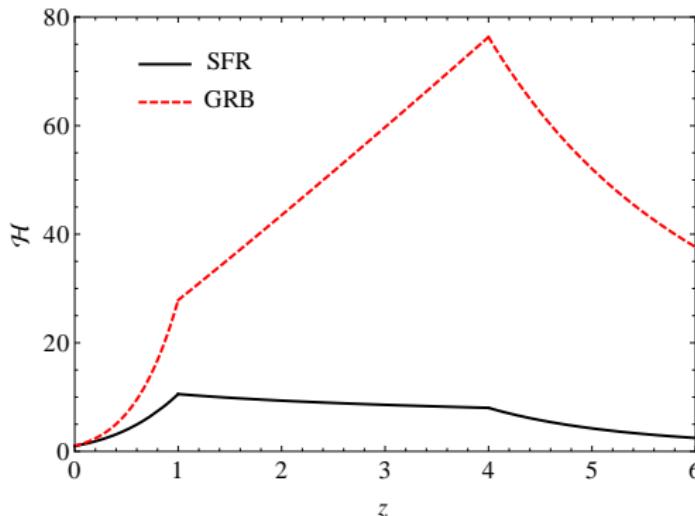


Matches, e.g., H. TAKAMI, K. MURASE, S. NAGATAKI, K. SATO, *Astropart. Phys.* **31**, 201 (2009) [0704.0979]

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

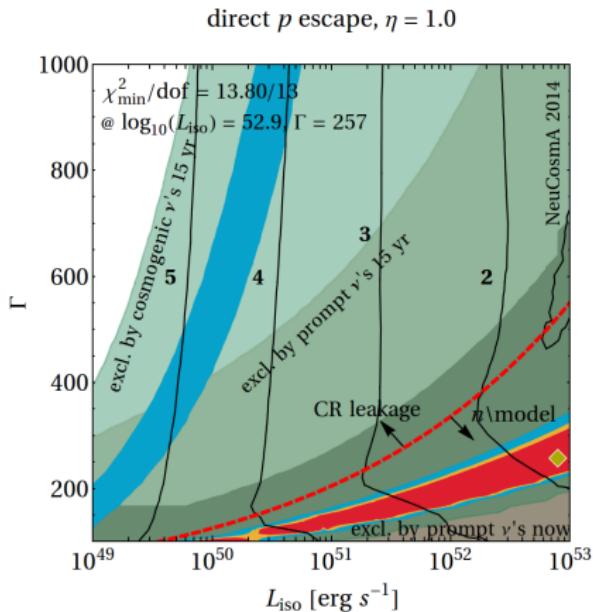
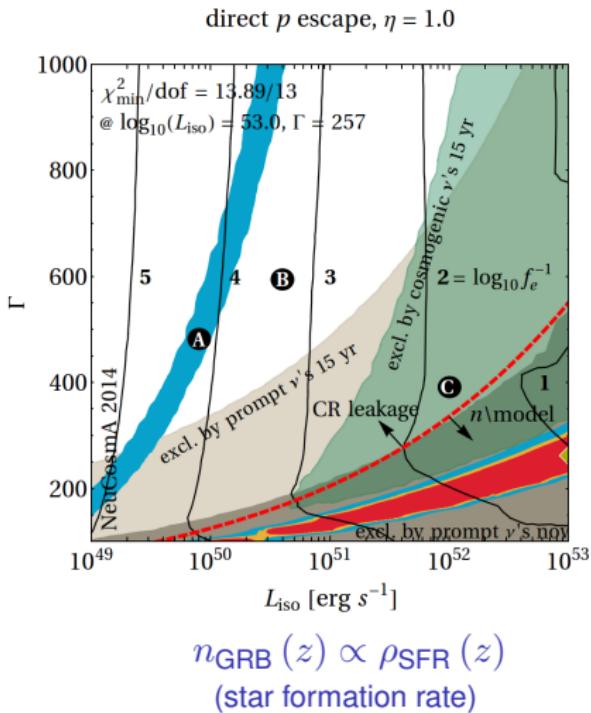
\mathcal{H} : normalised to the local rate, i.e., $\mathcal{H}(z) \equiv \dot{\rho}_{\text{CR}}(z) / \dot{\rho}_{\text{CR}}(0)$

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



Constraints: SFR vs. GRB redshift evolution

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

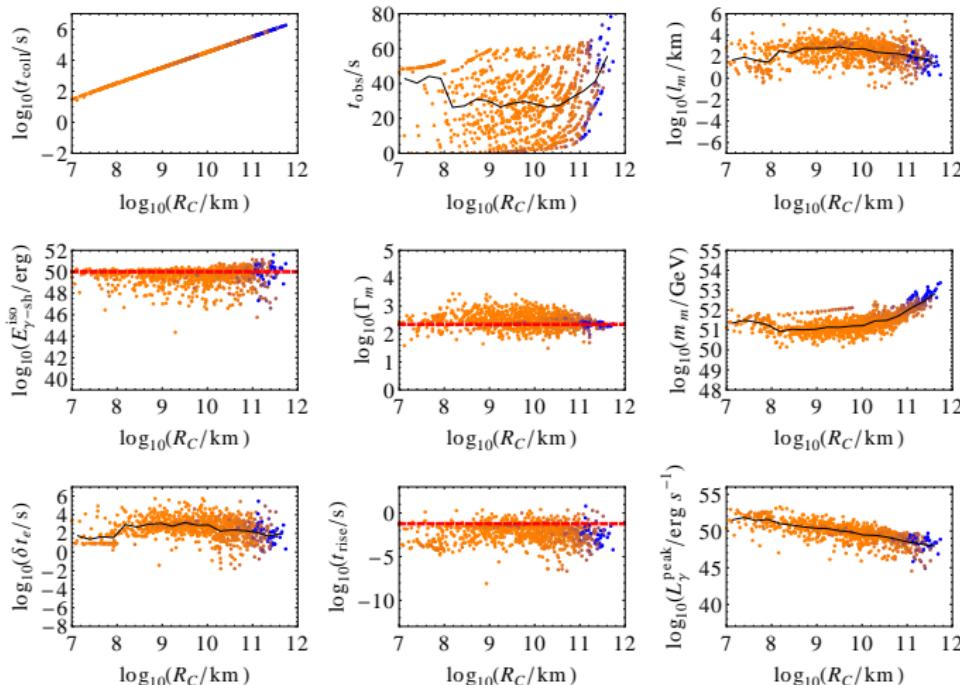


$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z) \times (1+z)^{1.2}$$

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

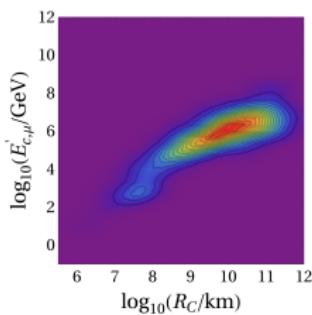
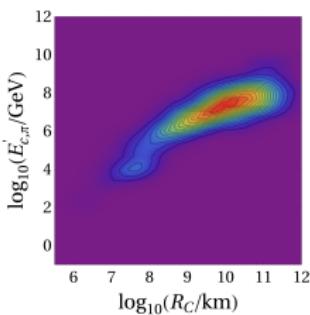
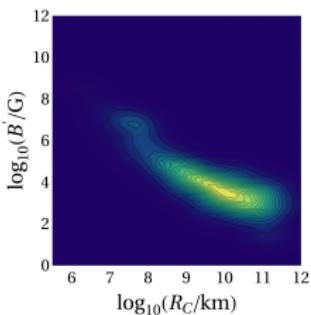
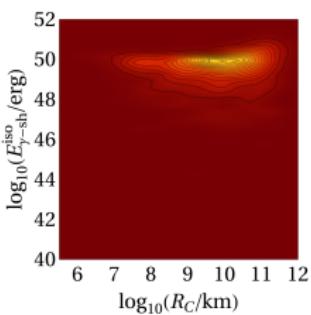
Parameter evolution in the dynamical fireball

We can track how the parameters change with collision radius:



MB, P. BAERWALD, K. MURASE, AND W. WINTER, IN PREPARATION

Energy emitted as photons ($E_{\gamma-\text{sh}}^{\text{iso}}$, source frame), magnetic field (B' , SRF), critical energy for synchrotron losses of pions ($E'_{c,\pi}$) and muons ($E'_{c,\mu}$):



MB, P. BAERWALD, K. MURASE, AND W. WINTER, IN PREPARATION