

A dynamical GRB fireball model: new gamma-ray, cosmic-ray, and neutrino predictions

Mauricio Bustamante

Collaborators: Philipp Baerwald, Kohta Murase, and Walter Winter

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

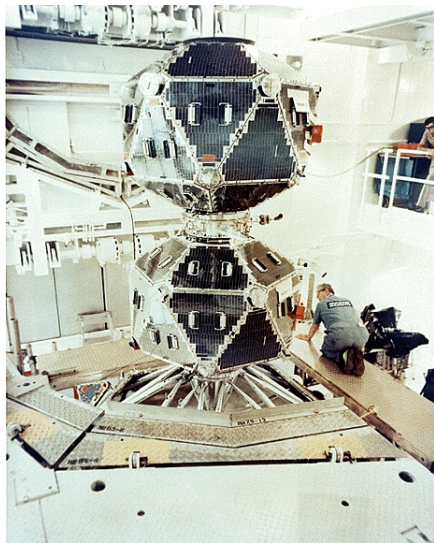
Recent results in astroparticle physics
DESY Zeuthen, July 15, 2014





After the 1963 Nuclear Test Ban Treaty, the U.S. launched six pairs of *Vela* satellites:

- ▶ They carried X-ray, gamma-ray, and neutron detectors
- ▶ *Vela* 5a-b had enough spatial resolution to pinpoint the direction of events
- ▶ Intense gamma-ray emission from a nuclear explosion lasts $\lesssim 10^{-6}$ s ...
- ▶ ... however, longer-lasting emissions were detected



VELA 5A/B SATELLITES (NASA)

THE ASTROPHYSICAL JOURNAL, **182**:L85–L88, 1973 June 1

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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

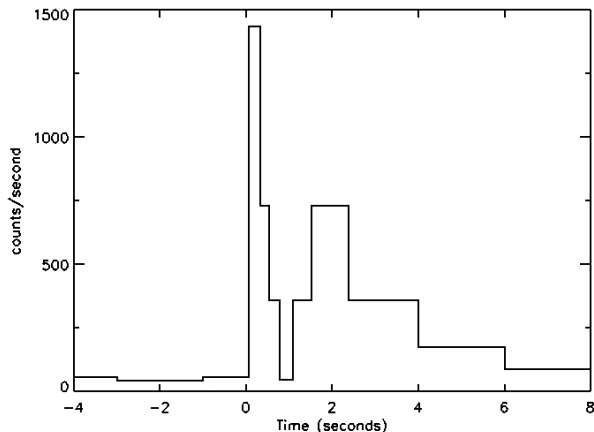
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~ 30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

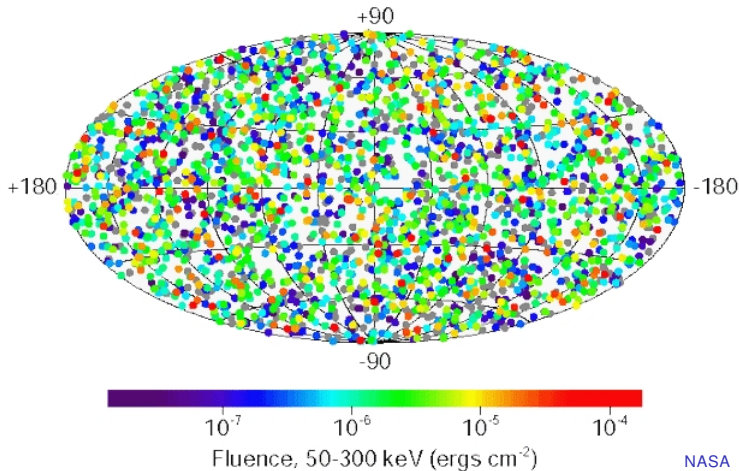
Subject headings: gamma rays — X-rays — variable stars

First GRB detected: July 2, 1967, 14:19 UTC

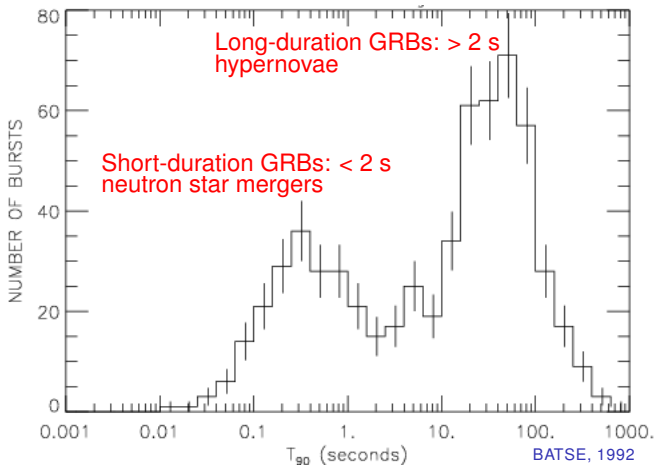


Detected by *Vela* 3, 4a, 4b (found on archival data)

Dedicated missions were flown – *e.g.*, BATSE detected 2704 GRBs between 1991 and 2000

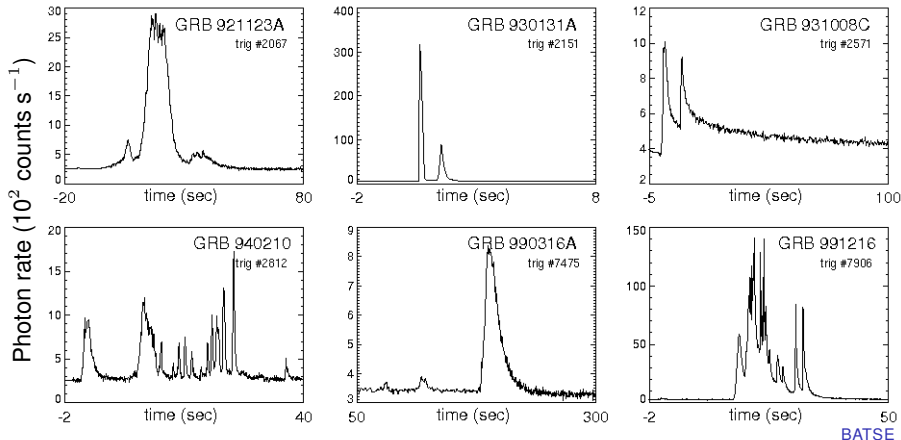


Two populations of GRBs:



T_{90} : time during which 90% of gamma-ray energy is recorded

GRB light curves come in different shapes:



variability timescale (width of pulses) $\equiv t_v \approx 1 \text{ ms}$

1962: discovery of UHECRs (ultra-high energy cosmic rays) at the Park Ranch Experiment, New Mexico



$> 10^{18}$ eV – most energetic particles in known Universe

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
- ▶ plus: low backgrounds (for ν 's) due to small time window

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

Solution: we need to build more realistic models!

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

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

10^{20} erg	H bomb
10^{26} erg	killer asteroid
10^{40} erg	Death Star
10^{33} erg s $^{-1}$	Sun
10^{41} erg s $^{-1}$	supernova
10^{45} erg s $^{-1}$	galaxy

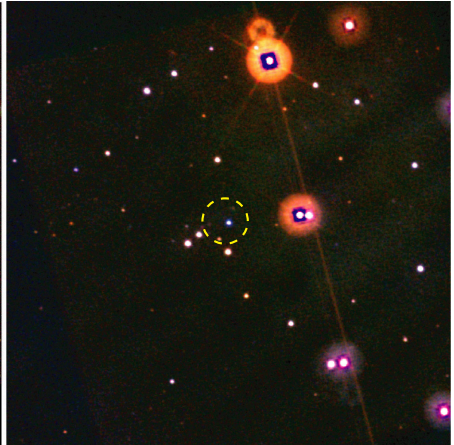
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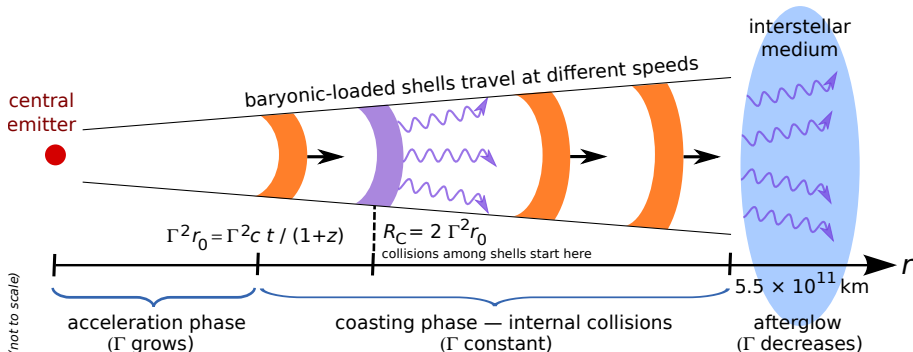
What does a GRB look like? *e.g.*, GRB060218 seen by *Swift*



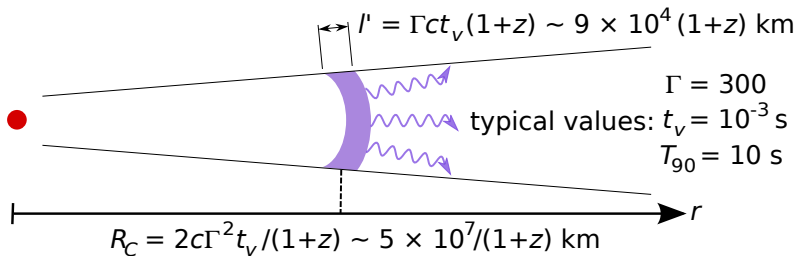
SDSS, SWIFT COLLAB., SLOAN FOUNDATION, NSF, NASA

Fireball model: our current paradigm of how a GRB works

- relativistically-expanding blobs of plasma collide with each other and, in the process, emit UHE particles



The **static** fireball picture: all collisions occur at the **same** radius



- ▶ Γ is inferred from afterglow observations
- ▶ t_v is measured from the light curve
- ▶ z is measured for the host galaxy

Static burst: made up of $T_{90}/t_v \sim 100 - 1000$ identical collisions

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

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

broken power law

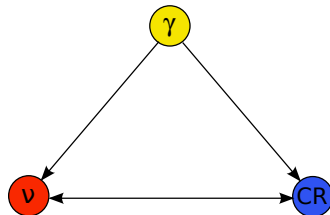
$$p \gamma \rightarrow \Delta^+ (1232) \rightarrow \begin{cases} n\pi^+, & \text{BR} = 1/3 \\ p\pi^0, & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



After propagation, with flavour mixing:

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

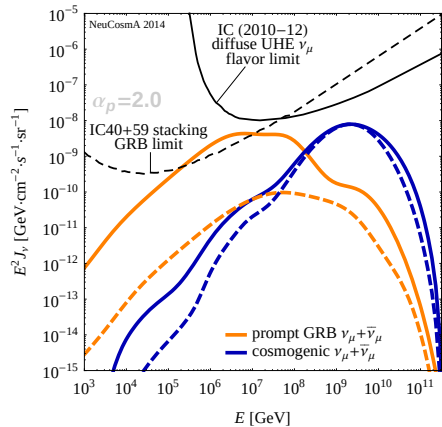
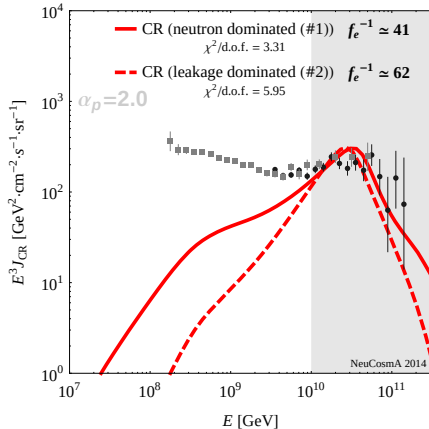
("one ν_μ per cosmic ray")

The *simplest* neutron model is now strongly disfavoured

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

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

However, we have improved UHECR and ν predictions, e.g.,



P. BAERWALD, MB, AND W. WINTER, ACCEPTED IN ASTROPART. PHYS. [ARXIV:1401.1820]

See also: H. HE *et al.*, *ApJ* **752**, 29 (2012)

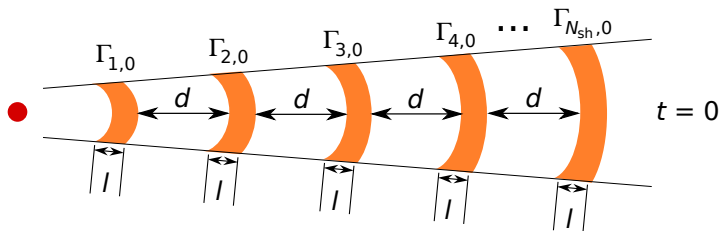
We have considered a dynamical fireball instead:

- ▶ the fireball expands with time
- ▶ shells propagate with different speeds
- ▶ they have different masses
- ▶ they collide at different radii (collisions no longer identical)

Why is this important?

The particle (γ , p) densities fall as the fireball expands – particle production conditions change with time/radius

Initial number of shells: $N_{\text{sh}} \gtrsim 1000$



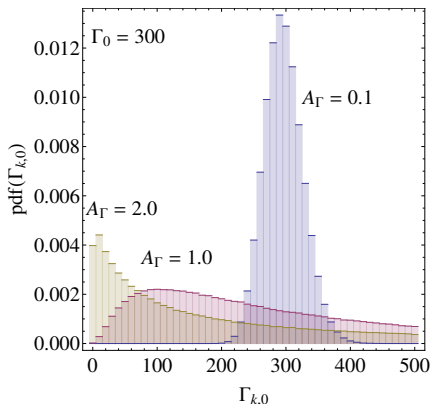
Initial values of shell parameters:

- ▶ Separation between shells: $d = l$
- ▶ Kinetic energy $E_{\text{kin},0}^{\text{iso}}$ equal for all collisions ($\sim 10^{52}$ erg)
- ▶ Speeds $\Gamma_{k,0}$ follow a distribution (see next slide)
- ▶ Masses: $m_{k,0} = E_{\text{kin},0}^{\text{iso}} / (\Gamma_{k,0}^2 c^2)$

Distribution of initial shell speeds (Lorentz factors):

$$\ln \left(\frac{\Gamma_{k,0} - 1}{\Gamma_0 - 1} \right) = A_{\Gamma} x$$

x follows a Gaussian distribution, $P(x) dx = dx e^{-x^2/2} / \sqrt{2\pi}$



$$A_{\Gamma} < 1$$

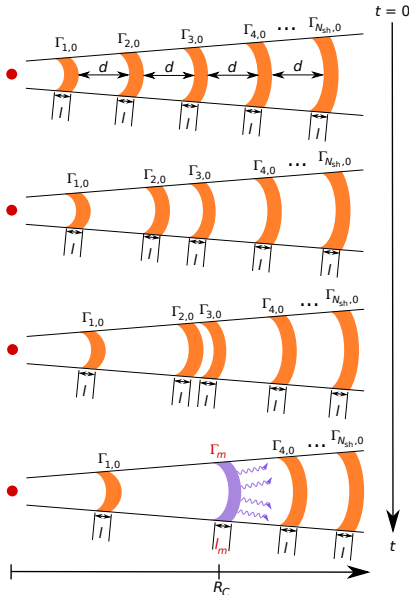
speeds too similar, collisions only at large radii

$$A_{\Gamma} \gg 1$$

spread too large, too many collisions at low radii

$$A_{\Gamma} \approx 1$$

just right, burst has high efficiency of conversion of kinetic to radiated energy



During propagation:

- ▶ speeds (Γ_k), masses (m_k), widths (l_k) **do not** change (only in collisions)
- ▶ shell volume: $V'_{iso,k} = 4\pi l'_k r_k^2$
- ▶ the new, merged shells continue propagating and can collide again

Evolution stops when either:

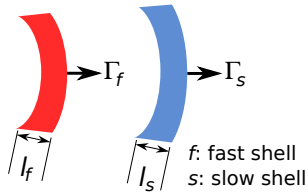
- ▶ a single shell is left; or
- ▶ all remaining shells have reached the interstellar medium ($\geq 5.5 \times 10^{11}$ km)

Final number of collisions:

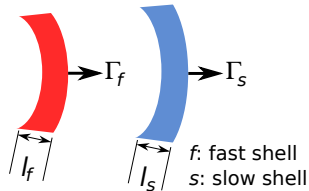
$$N_{\text{coll}} \approx N_{\text{sh}} \text{ if } A_{\Gamma} \gtrsim 1$$

S. KOBAYASHI, T. PIRAN, AND R. SARI, *ApJ* **490**, 92 (1997)
F. DAIGNE AND R. MOCHKOVITCH, *MNRAS* **296**, 275 (1998)

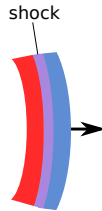
1 Propagation



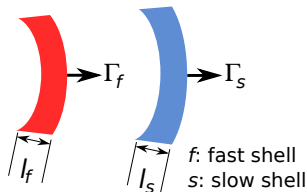
1 Propagation



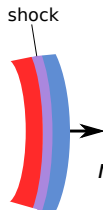
2 Collision



1 Propagation



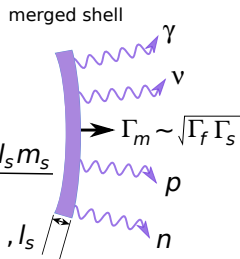
2 Collision



$$m_m = \frac{l_f m_f + l_s m_s}{l_m}$$

$$l_m < l_f, l_s$$

3 Radiation

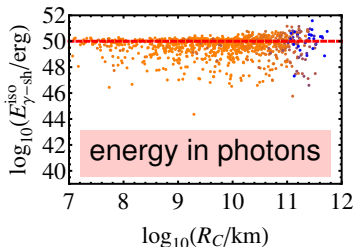
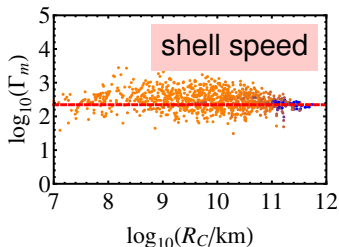
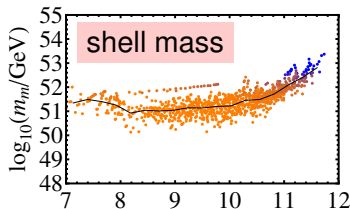
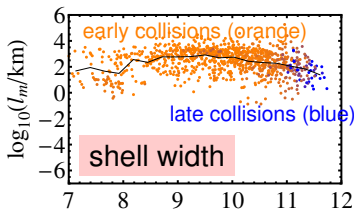


Part of the initial kinetic energy radiated as γ 's, ν 's, p 's, and n 's:

$$E_{\text{coll}}^{\text{iso}} = \left(E_{\text{kin},f}^{\text{iso}} - E_{\text{kin},m}^{\text{iso}} \right) + \left(E_{\text{kin},m}^{\text{iso}} - E_{\text{kin},s}^{\text{iso}} \right)$$

$$\underbrace{E_{\gamma\text{-sh}}^{\text{iso}} \stackrel{1/12}{\equiv} \epsilon_e E_{\text{coll}}^{\text{iso}}}_{\text{energy in photons}} \quad \underbrace{\epsilon_B E_{\text{coll}}^{\text{iso}} \stackrel{1/12}{\equiv}}_{\text{energy in magnetic fields}} \quad \underbrace{\epsilon_p E_{\text{coll}}^{\text{iso}} \stackrel{5/6}{\equiv}}_{\text{energy in baryons}}$$

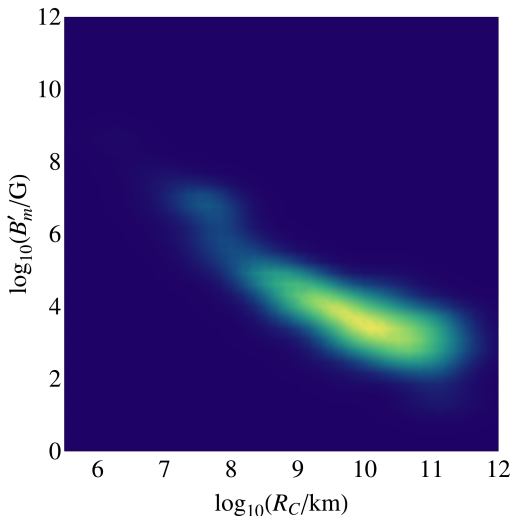
We keep track of collision parameters as the fireball expands:



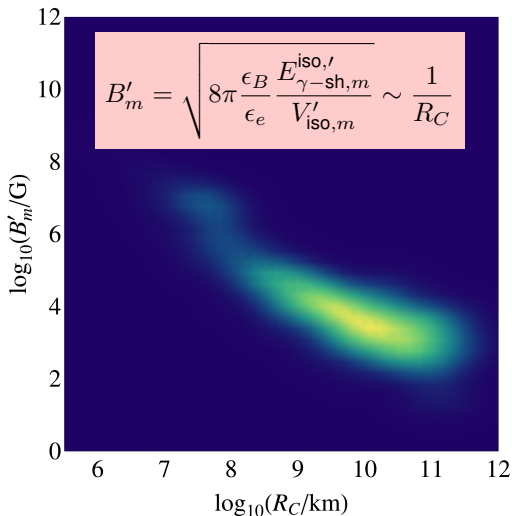
MB, P. BAERWALD, K. MURASE, AND W. WINTER, IN PREPARATION

(For this burst: $N_{\text{sh}} = 1000$, $N_{\text{coll}} = 990$, $\Gamma_0 = 300$, $A_\Gamma = 1$, $E_{\gamma\text{-tot}}^{\text{iso}} = 10^{53}$ erg)

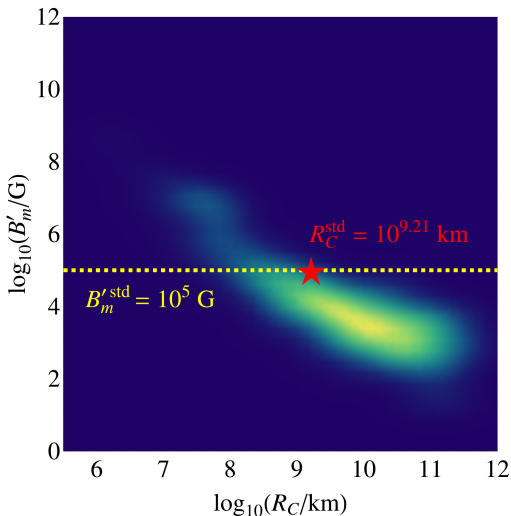
The magnetic field at emission falls with collision radius:



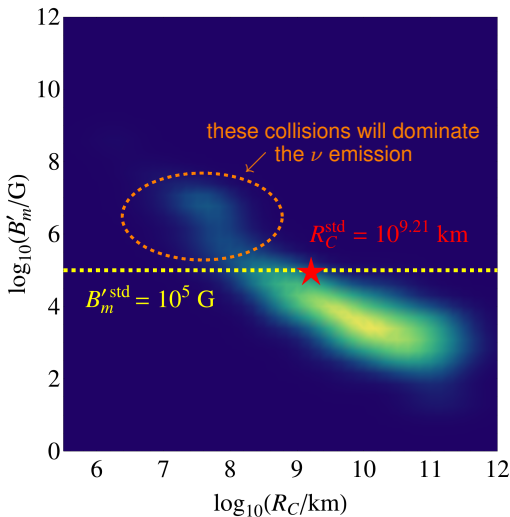
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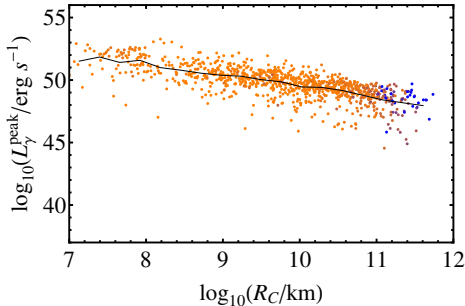
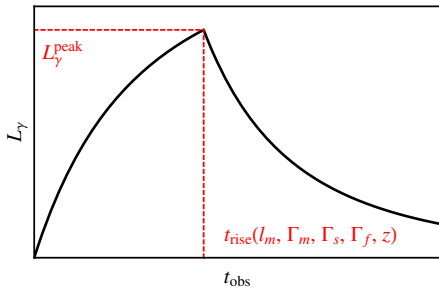
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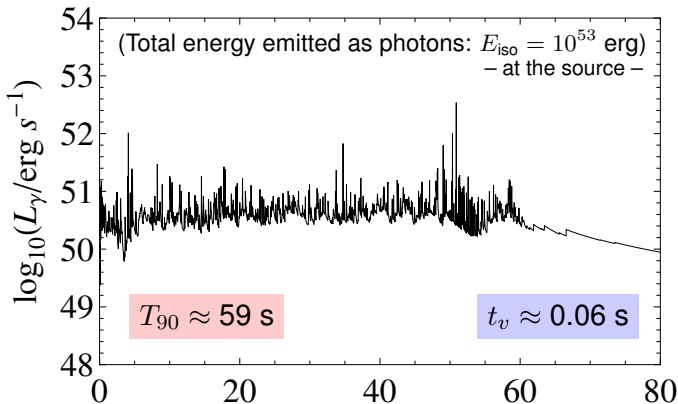


A fast-rise-exponential-decay (FRED) gamma-ray pulse is emitted in every collision:



$$L_\gamma^{\text{peak}} \sim R_C^{-2}$$

- A FRED pulse is assigned to each collision
– their superposition yields a **synthetic light curve**:



1000 initial shells $\mapsto$ 990 collisions

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

In a collision, UHE protons, photons, and neutrinos are emitted:

$$\underbrace{N'_p(E'_p)}_{\text{proton density at the source [GeV}^{-1} \text{ cm}^{-3}]} \quad \text{NeuCosmA} \quad \underbrace{N'_\gamma(E'_\gamma)}_{\text{photon density at the source}}$$

$$= \underbrace{Q'_\nu(E'_\nu)}_{\text{ejected neutrino spectrum [GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}]}$$

- From Fermi shock acceleration: $N'_p(E'_p) \propto E_p'^{-\alpha_p} e^{-E'_p/E'_{p,\max}}$
- Photon density at source has same shape as observed:

$$N'_\gamma(E'_\gamma) = \begin{cases} (E'_\gamma/E'_{\gamma,\text{break}})^{-\alpha_\gamma} & , E'_{\gamma,\min} \leq E'_\gamma < E'_{\gamma,\text{break}} \\ (E'_\gamma/E'_{\gamma,\text{break}})^{-\beta_\gamma} & , E'_\gamma \geq E'_{\gamma,\text{break}} \\ 0 & , \text{otherwise} \end{cases}$$

$$\alpha_\gamma = 1, \beta_\gamma = 2.2, E'_{\gamma,\min} = 0.2 \text{ eV}, E'_{\gamma,\text{break}} = 1 \text{ keV}$$

Normalise the densities at the source (for the k -th collision):

► Photons:

from the simulation

$$\underbrace{\int E'_\gamma N'_\gamma(E'_\gamma) dE'_\gamma}_{\text{total energy density in photons}} = \frac{E'^{\text{iso}}_{\gamma\text{-sh},k}}{V'_{\text{iso},k}} \propto \frac{1}{R_C^2}$$

► Protons:

baryonic loading (energy in p 's / energy in e 's + γ 's) = 10

$$\underbrace{\int E'_p N'_p(E'_p) dE'_p}_{\text{total energy density in protons}} = \frac{1}{f_e} \frac{E'^{\text{iso}}_{\gamma\text{-sh},k}}{V'_{\text{iso},k}} \propto \frac{1}{R_C^2}$$

Note: in our simulation, we make the total emitted energy match the observed energy of a burst,

$$E^{\text{iso}}_{\gamma\text{-tot}} \equiv \sum_{k=1}^{N_{\text{coll}}} E^{\text{iso}}_{\gamma\text{-sh},k} \simeq (1+z)^{-1} 10^{53} \text{ erg}$$

NeuCosmA calculates the injected/ejected spectrum of secondaries (π , K , n , ν , etc.):

$$x \equiv E'/E'_p$$

$$y \equiv E'_p E'_\gamma / (m_p c^2)$$

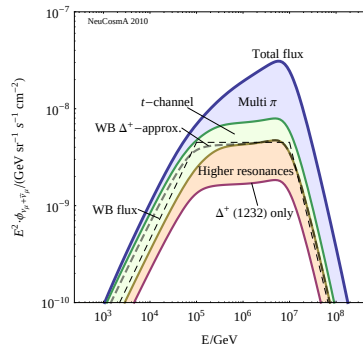
$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c dE'_\gamma N'_\gamma(E'_\gamma) R(x, y)$$

response function

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

- ▶ $p\gamma \rightarrow \Delta^+(1232) \rightarrow \pi^0, \pi^+, \dots$
- ▶ extra K , n , π^- , multi- π production modes
- ▶ synchrotron losses of secondaries
- ▶ adiabatic cooling
- ▶ full photon spectrum
- ▶ neutrino flavour transitions



Two important points:

- 1 $E'_{p,\max}$ is determined by energy-loss processes:

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

- 2 Photons can be trapped in the source by pair production:

$$\gamma + \gamma \rightarrow e^+ + e^-$$

Photosphere: radius where $\tau_{\gamma\gamma}(E'_\gamma) = 1$ for all E'_γ

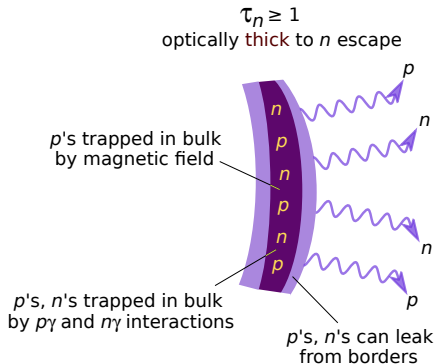
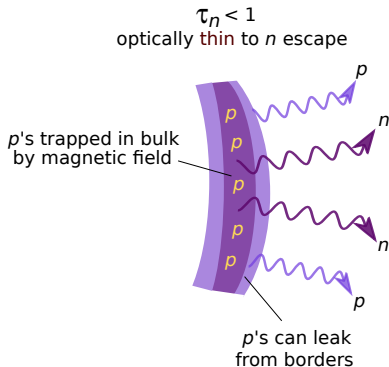
For each collision, $E'_{\gamma,\max}$ is determined by

$$\tau_{\gamma\gamma}(E'_{\gamma,\max}) = 1 .$$

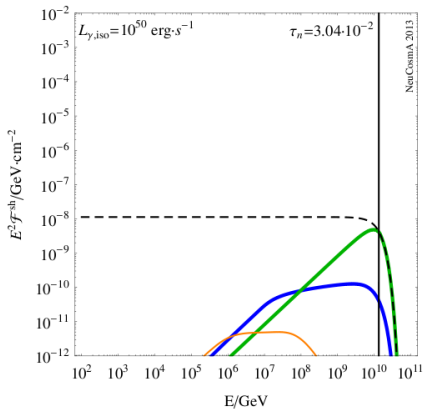
UHECRs escape as either:

- ▶ **neutrons**, which decay into protons outside the source; or
- ▶ **protons** that leak out without interacting inside the source

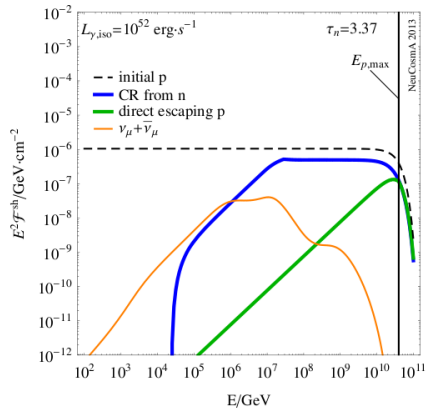
Relative contributions determined by $\tau_n \equiv \left(t_{p\gamma}^{-1} / t_{\text{dyn}}^{-1} \right) \Big|_{E'_{p,\text{max}}}$



Optically **thin** source:

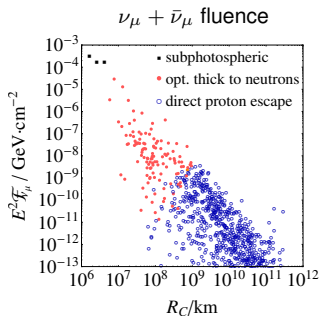


Optically **thick** source:

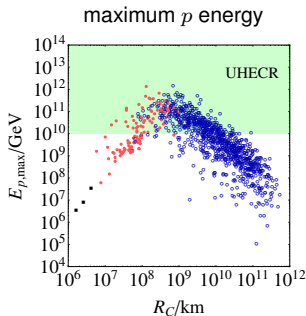


P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)

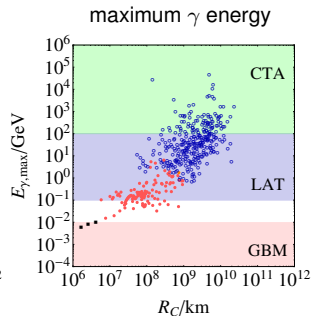
Each collision occurs in a different regime:



(observer's frame)

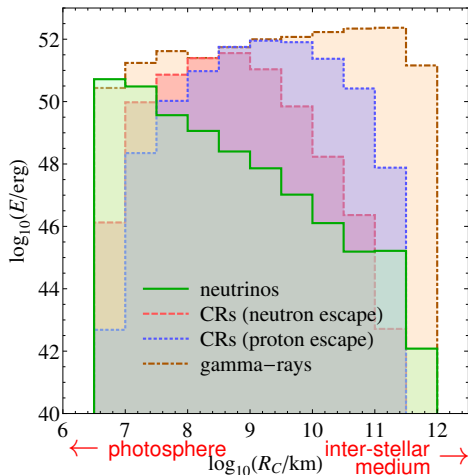


(source frame)



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 ...

Flux from a single simulated burst

- Flux at Earth [$\text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$] from the k -th collision:

$$J_{\nu,k} = \frac{1}{4\pi} V'_{\text{iso},k} \frac{(1+z)^2}{4\pi d_L^2} Q'_{\nu,k} \quad \begin{array}{l} \text{fluence from } k\text{-th collision} \\ [\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}] \end{array}$$

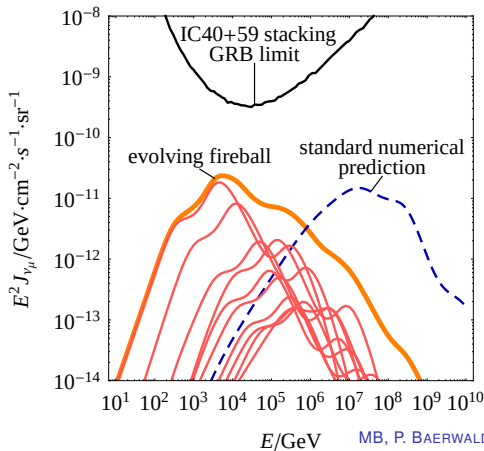
- Total flux from a single burst: $J_{\nu,\text{single}} = \sum_{k=1}^{N_{\text{coll}}} J_{\nu,k}$

Quasi-diffuse flux

If *all* of the long-duration GRBs behaved like this one simulated burst:

$$J_{\nu}(E) = J_{\nu,\text{single}}(E) \cdot (1 \text{ yr} \cdot 667 \text{ yr}^{-1})$$

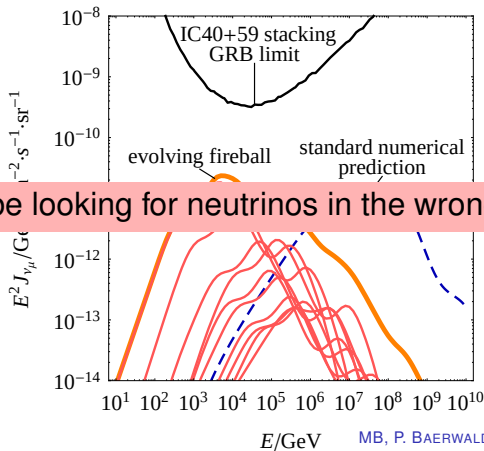
Quasi-diffuse flux:



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

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

Quasi-diffuse flux:



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

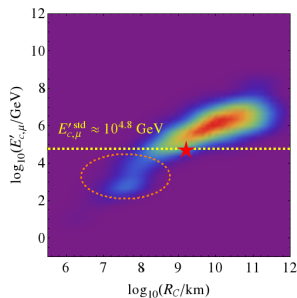
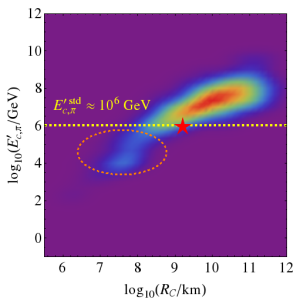
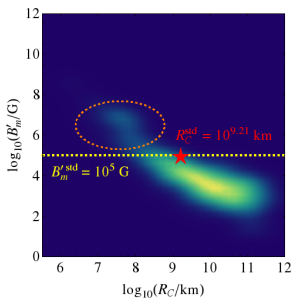
The prompt ν emission peaks at energies $\ll$ the typical $\sim$ PeV!

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

Why? Critical synchrotron energy for μ 's and π 's falls with B'_m ,

$$E'_{c,s} \approx 2.4 \cdot \sqrt{\frac{(m_s/\text{GeV})^5}{(\tau_s/\text{s}) (B'_m/\text{G})^2}} \text{ GeV} \quad (s = \pi, \mu)$$

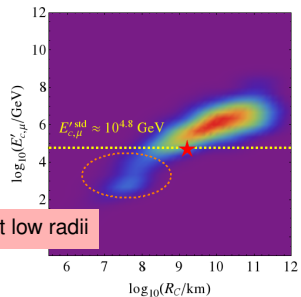
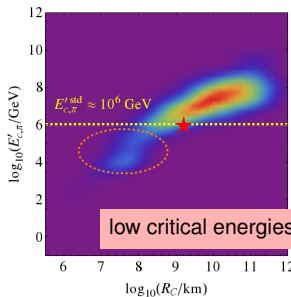
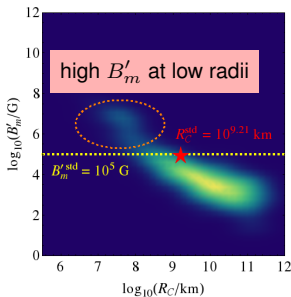
and we have seen that $B'_m \propto R_C^{-1}$



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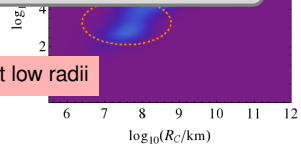
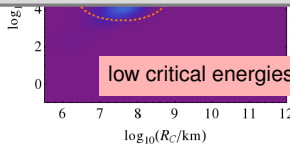
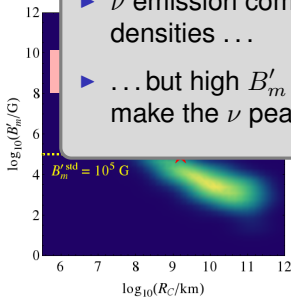


Why? Critical synchrotron energy for μ 's and π 's falls with B'_m ,

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and There is a trade-off at $B' \propto R_C^{-1}$

- ▶ ν emission comes mostly from low radii, due to the high p and γ densities ...
- ▶ ... but high B'_m there force intense synchrotron losses, which make the ν peak at lower energies



low critical energies at low radii

We have studied an evolving GRB fireball model where:

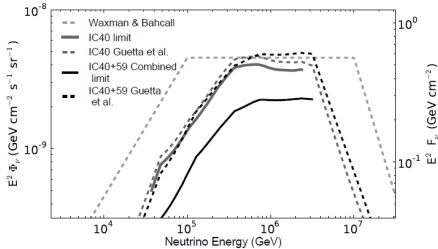
- ▶ baryonic-loaded shells propagate at different speeds
- ▶ collisions among shells are treated individually

As a result we have found that

- ▶ photon, proton, neutrino emissions peak at different radii
- ▶ quasi-diffuse ν flux peaks below typical energies ($\ll$ PeV)
- ▶ $\therefore$ we might be looking for neutrinos in the wrong energies
- ▶ the standard GRB estimators might not be adequate for CR and ν emission

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

Backup slides



IceCube Collaboration:

- ν flux normalised to GRB γ fluence:

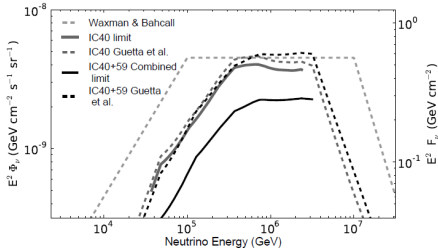
$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) \propto \int_{1 \text{ keV}}^{10 \text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma(\varepsilon_\gamma)$$

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

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

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

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



More detailed particle physics (NeuCosmA):

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

ν flux $\sim$ one order of magnitude lower

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

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

IceCube Collaboration:

- ▶ ν flux normalised to GRB γ fluence:

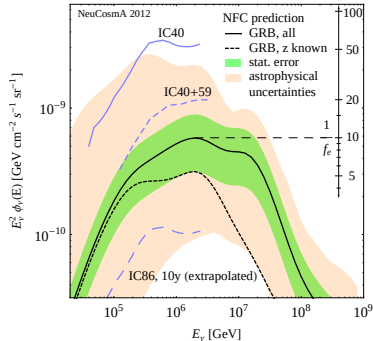
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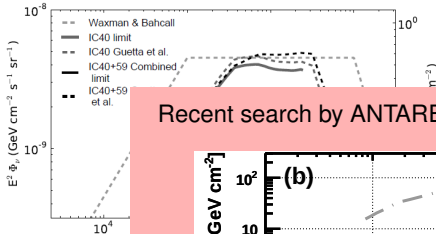
- ▶ quasi-diffuse ν flux from 117 GRBs
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ICECUBE COLL., *Nature* **484**, 351 (2012)

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

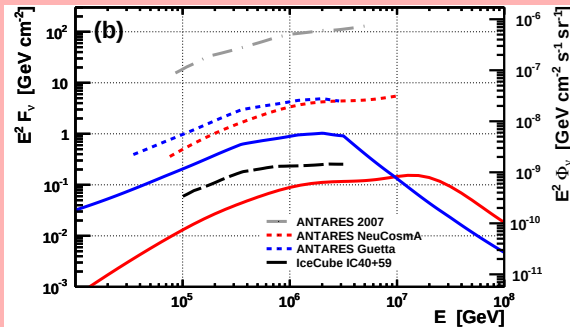




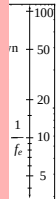
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- ▶ extra multi- π , K , n production modes
- ▶ synchrotron losses of secondaries

Recent search by ANTARES optimised for NeuCosmA:

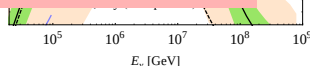


lower
1 (2012)



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

▶ IceCube is also revising its GRB predictions



IceCube Coll.

▶ ν flux

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

▶ quasi-c

▶ analyti

upper l

ICECUBE COLL.,

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

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

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

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)

Optical depth:

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

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

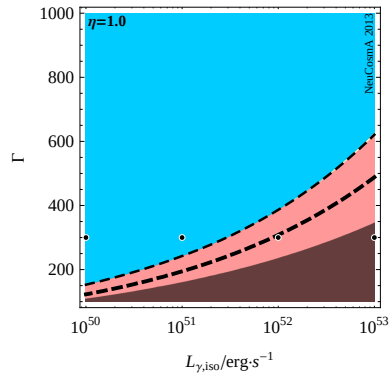
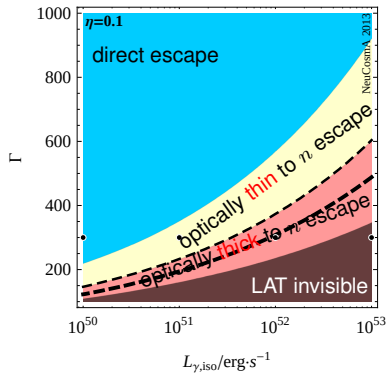
$$\left. \begin{aligned} \lambda'_{p,\text{mfp}}(E') &= \min [\Delta r', R'_L(E'), ct'_{p\gamma}(E')] \\ \lambda'_{n,\text{mfp}}(E') &= \min [\Delta r', ct'_{p\gamma}(E')] \end{aligned} \right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta r'}$$

fraction of escaping particles

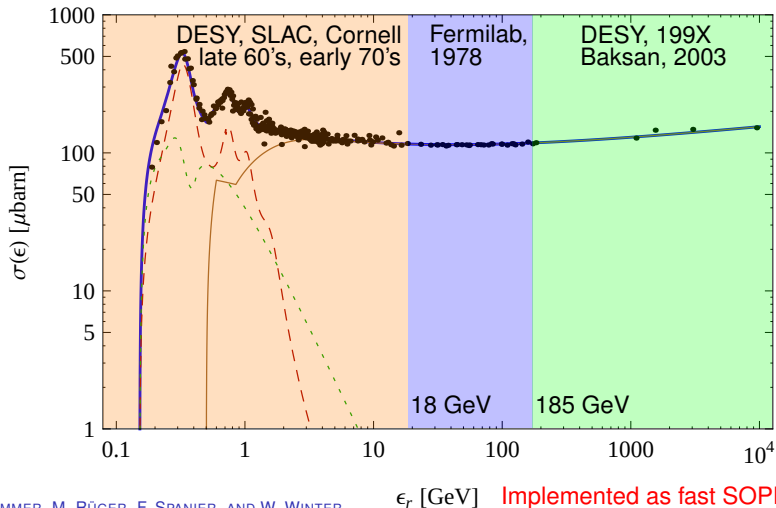
Scan of the GRB emission parameter space:

acceleration
efficiency $\longrightarrow \eta = 0.1$

$\eta = 1.0$



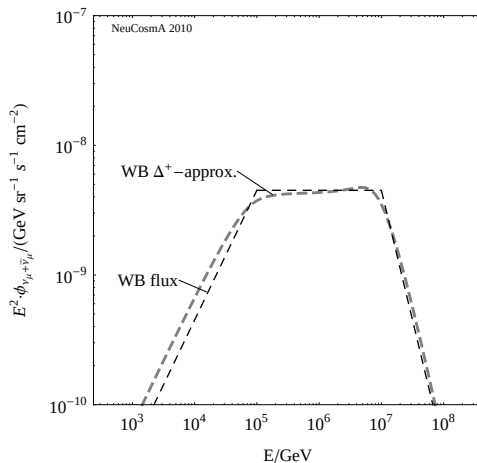
P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)



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

ϵ_r [GeV] Implemented as fast SOPHIA-based
parametrisation

- Contributions to the full photohadronic cross section

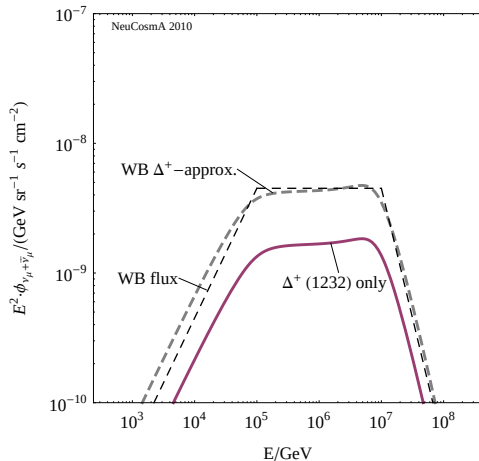


- Contributions to the full photohadronic cross section

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

- $\Delta(1232)$ -resonance

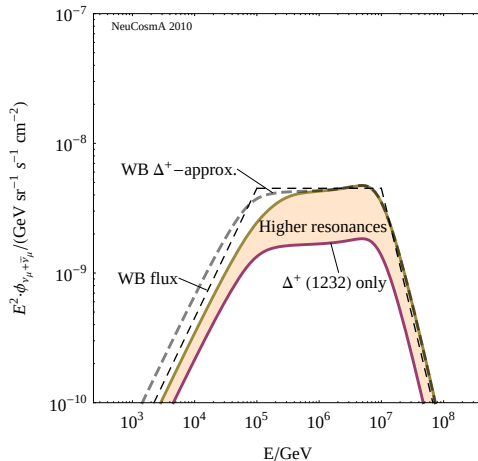
P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **D83**, 067303 (2011)



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

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

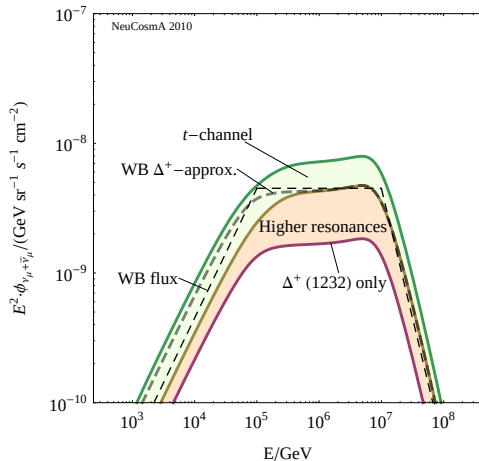
P. BAERWALD, S. HÜMMER, AND W. WINTER,
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Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux
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- ▶ $\Delta(1232)$ -resonance
- ▶ Higher resonances
- ▶ t -channel
(direct production)

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

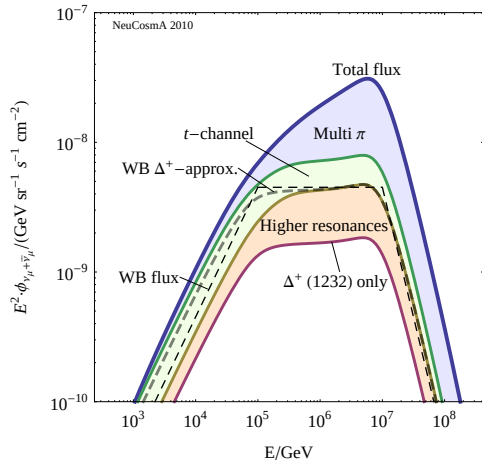


- Contributions to the full photohadronic cross section

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

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

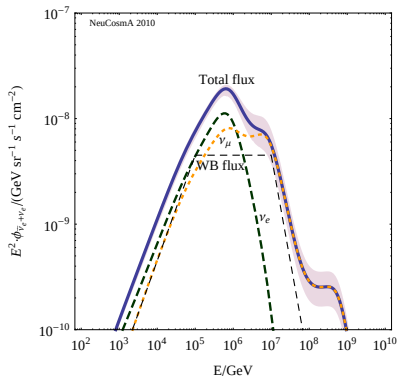
P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **83**, 067303 (2011)



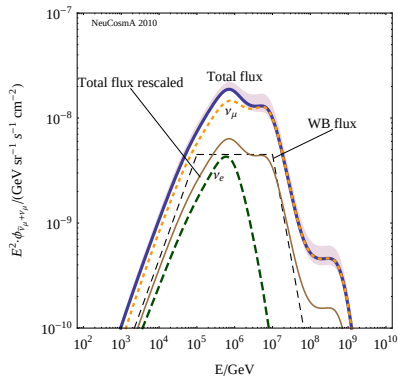
Especially "Multi π " contribution leads to **change of flux shape**; neutrino flux higher by up to a factor of 3 compared to WB treatment

- Neutrino spectra including flavour mixing

Electron neutrino spectrum



Muon neutrino spectrum



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

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

Corrections to the analytical model:

► **shape revised:**

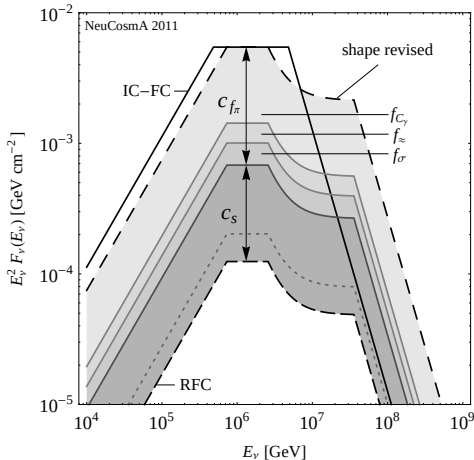
- shift of first break (correction of photohadronic threshold)
- different cooling breaks for μ 's and π 's
- $(1+z)$ correction on the variability scale of the GRB

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

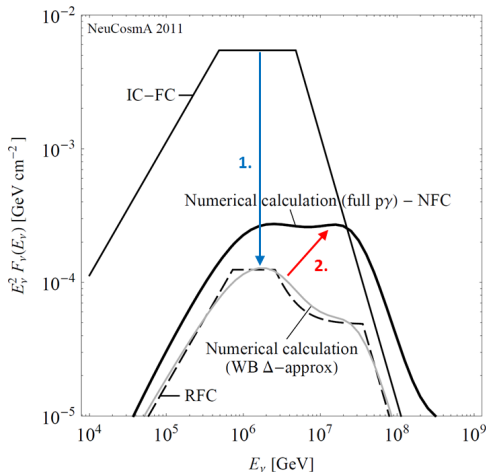
- f_{C_γ} : full spectral shape of photons
- $f_\approx = 0.69$: rounding error in analytical calculation
- $f_\sigma \simeq 2/3$: from neglecting the width of the Δ -resonance

► **Correction c_s :**

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



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



For example, GRB080603A:

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

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

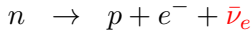
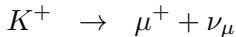
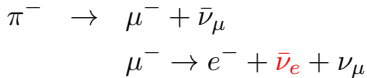
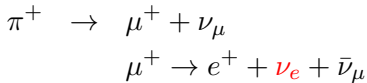
S. HÜMMER, P. BAERWALD, AND W. WINTER, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

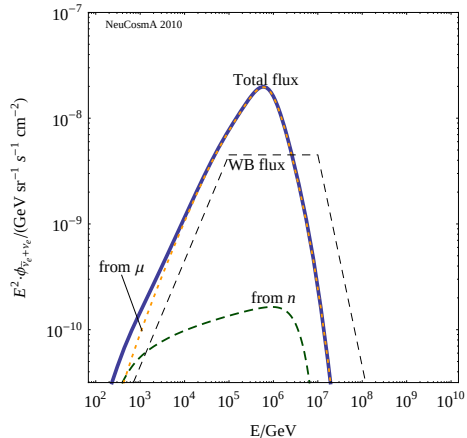
$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

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

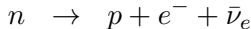
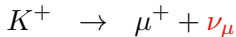
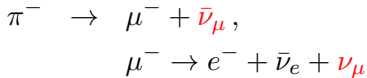
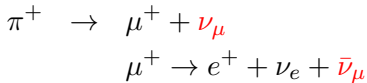
$$n \rightarrow p + e^- + \bar{\nu}_e$$



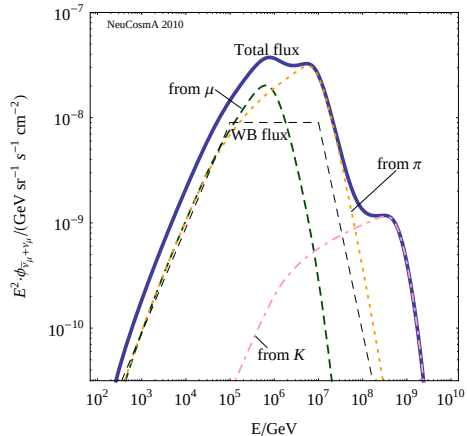
Resulting ν_e flux (at the observer)



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



Resulting ν_μ flux (at the observer)



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

- 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 $F_\nu(E_\nu)$

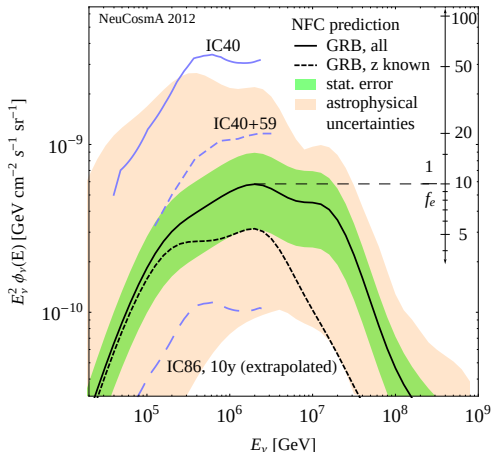
- ▶ Quasidiffuse flux:

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

- ▶ **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

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

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

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

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

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

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

► Proton density:

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

Maximum proton energy limited by energy losses:

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

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

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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 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