Ultra-high-energy cosmic rays and neutrinos from gamma-ray bursts: new predictions for a new era

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Introduction

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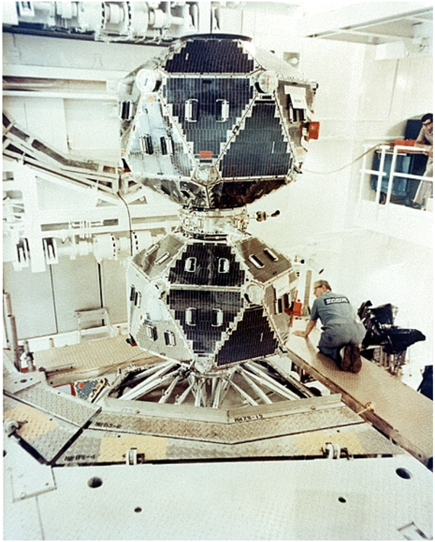
After the 1963 Nuclear Test Ban Treaty, the U.S. launched six pairs of *Vela* satellites:

- 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

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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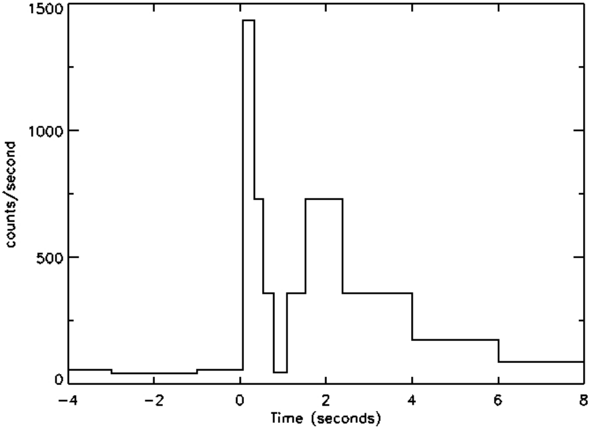
ABSTRACT

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 $\sim$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

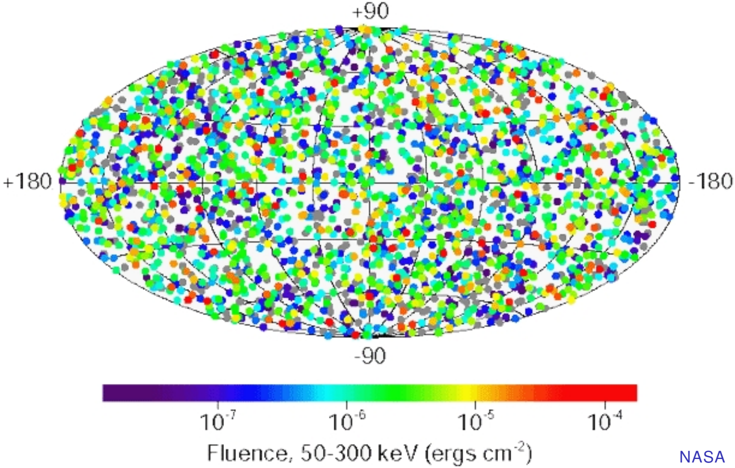
Introduction

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



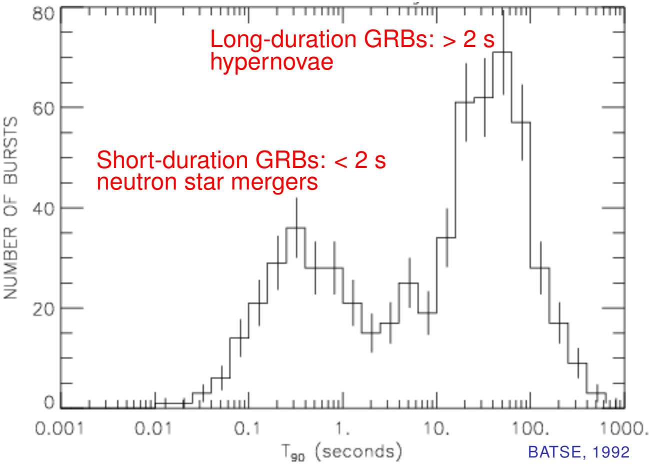
Detected by *Vela* 3, 4a, 4b (found on archival data)

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



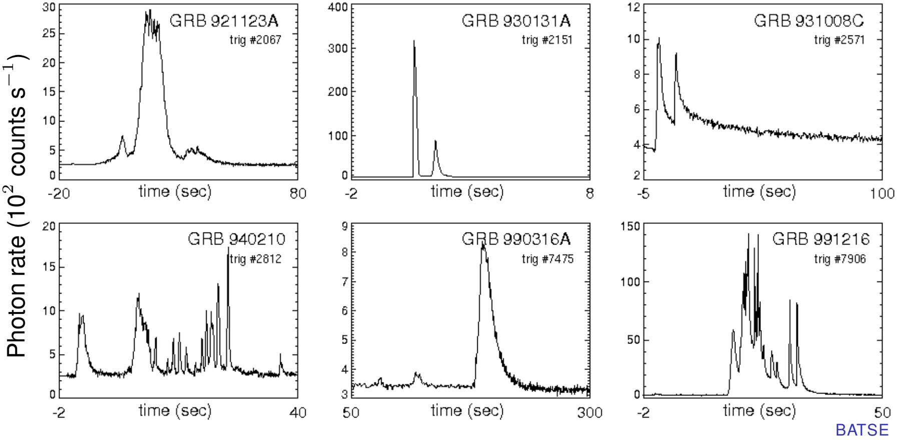
NASA

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 ms

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

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

Introduction

“Oh-my-God particle”: $\sim 3 \cdot 10^{20}$ eV $\equiv$ 50 J

(Fly’s Eye experiment, Utah, 1991)

This is equivalent to . . .

- a baseball (142 g) travelling at 94 km h^{-1}; or
- a football (410 g) travelling at 55 km h^{-1},

. . . but concentrated in a volume of radius 1 fm $\equiv 10^{-15}$ m

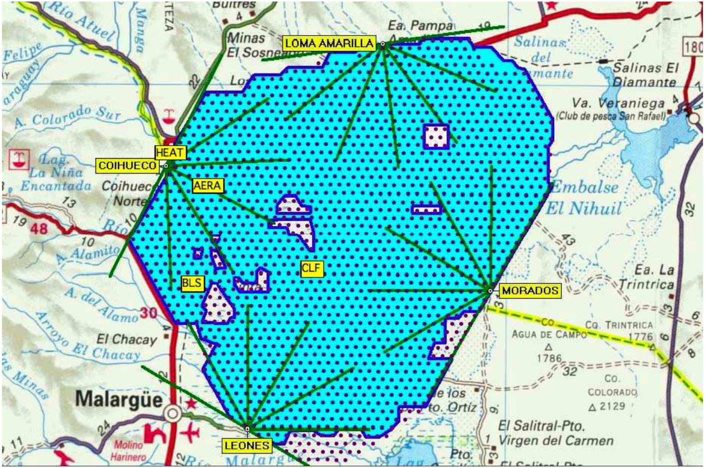
Approximate speed:

$$0.9999999999999999999999951c = (1 - 4.9 \cdot 10^{-24})c$$

$\sim$ 40 million times higher than a 7 TeV proton at the LHC

They are *very* rare: only a few dozen observed so far

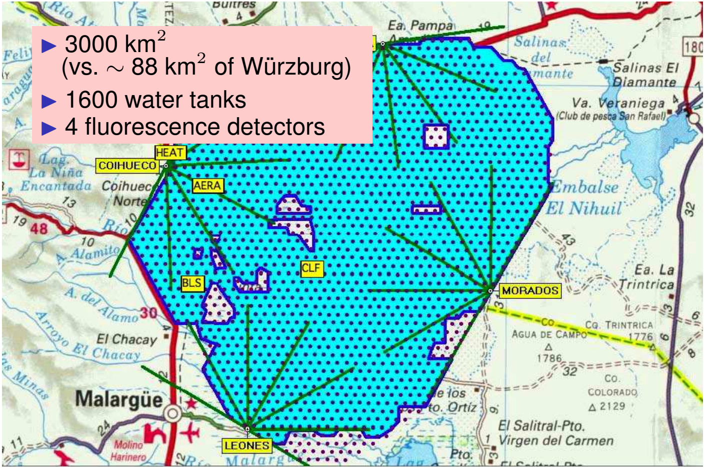
We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina



PIERRE AUGER COLLABORATION

We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina

- 3000 km^2 (vs. $\sim$ 88 km^2 of Würzburg)
- 1600 water tanks
- 4 fluorescence detectors



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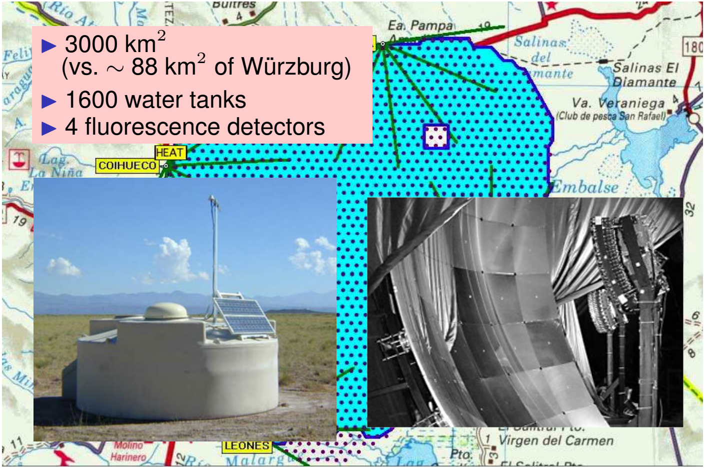
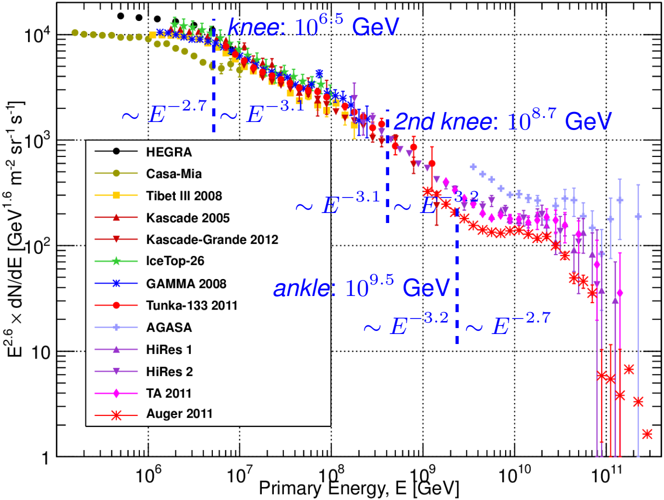


Pierre Auger Collaboration

After 102 years of the discovery of CRs, this is what we know:



GRBs as sources of UHE CRs and ν's

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!

GRBs as sources of UHE CRs and ν's

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- *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

GRBs are among the best candidate sour[ces]

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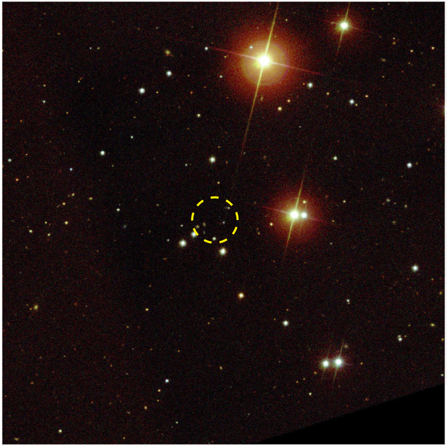
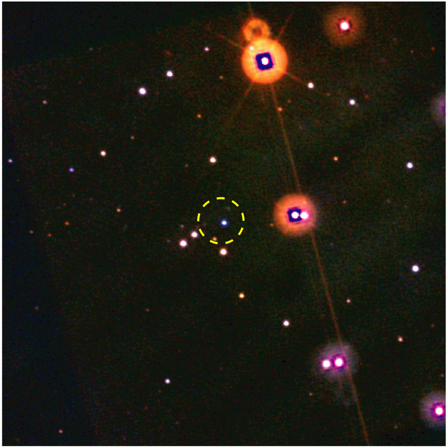
Solution: we need to build more realistic models!

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



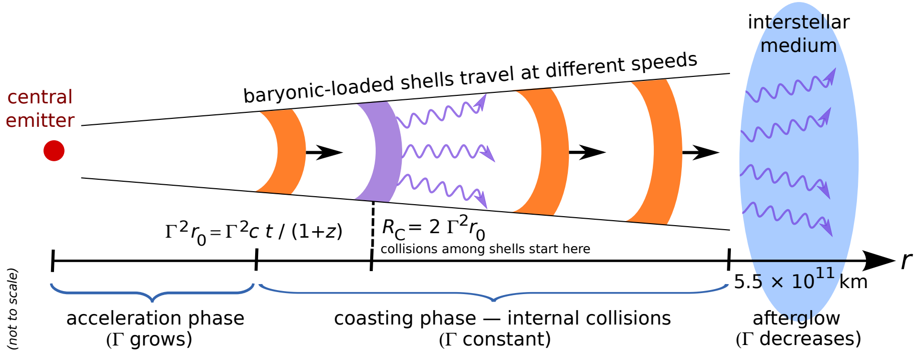


SDSS, Swift Collab., Sloan Foundation, NSF, NASA

The GRB fireball model

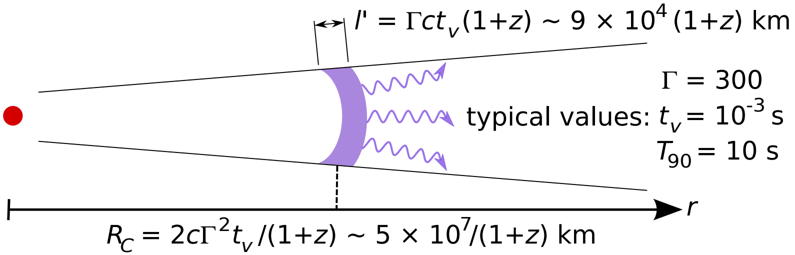
Fireball model: our current paradigm of how a GRB works

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



The static burst

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

A common origin for UHE particles

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

power law $\sim E^{-\alpha_p}$ — broken power law

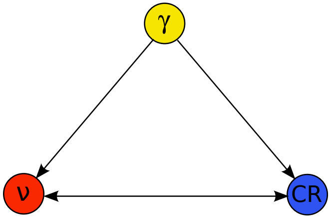
$$p\,\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \text{BR} = 1/3 \\ p\pi^0 , & \text{BR} = 2/3 \end{cases}$$

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

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

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

(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")

CR emission by n escape only is now strongly disfavoured

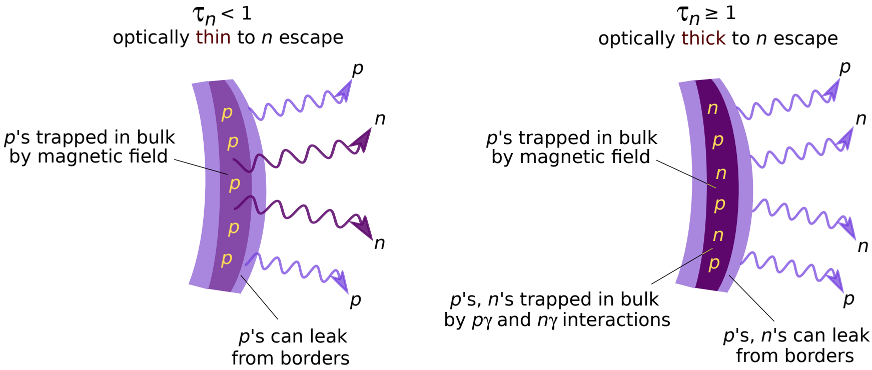
IceCube Coll., *Nature* **484**, 351 (2012)
Ahlers et al. *Astropart. Phys.* **35**, 87 (2011)

A two-component model of CR emission

We have improved the model – now UHECRs escape as either:

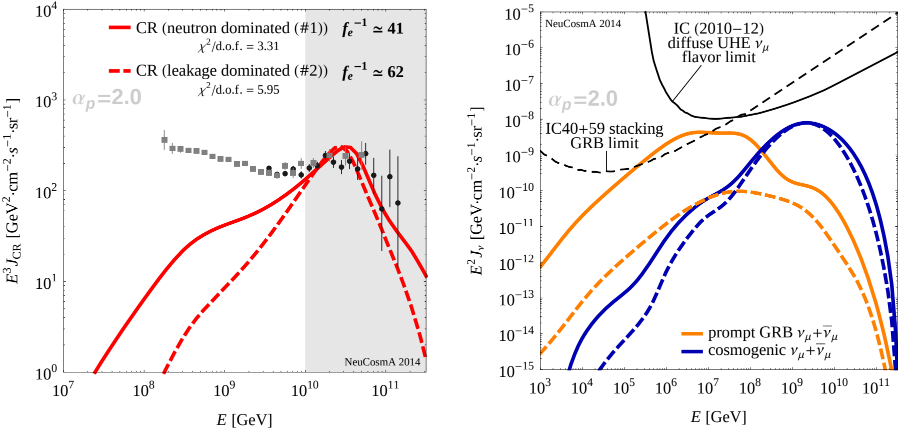
- neutrons, which decay into protons outside the source; or
- protons that leak out without interacting inside the source

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



A two-component model of CR emission

UHECR and neutrino predictions in this two-component model:



P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)
P. Baerwald, MB, and W. Winter, accepted in Astropart. Phys. [arXiv:1401.1820]
See also: H. He *et al.*, *ApJ* **752**, 29 (2012)

An evolving, dynamical burst

We have considered a dynamical fireball instead:

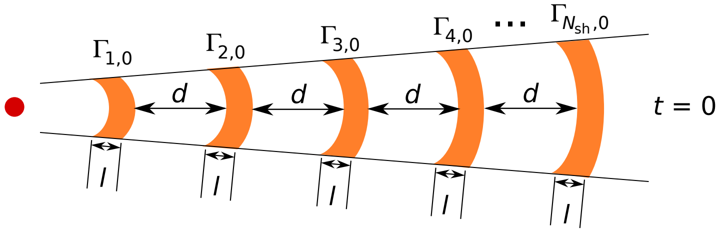
- the fireball expands with time
- shells propagate with different speeds
- they have different masses
- they collide at different radii (collisions no longer identical)

Why is this important?

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

Initialising the burst

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



Initial values of shell parameters:

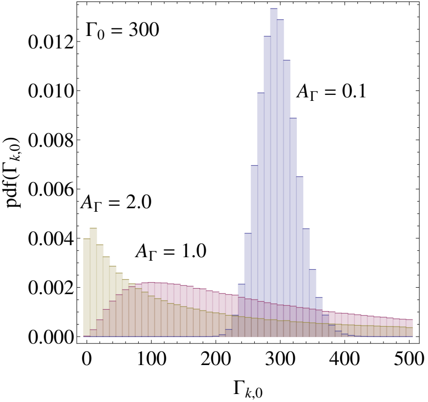
- Separation between shells: $d = l$
- Kinetic energy $E_{\text{kin},0}^{\text{iso}}$ equal for all collisions ($\sim 10^{52}$ erg)
- Speeds $\Gamma_{k,0}$ follow a distribution (see next slide)
- Masses: $m_{k,0} = E_{\text{kin},0}^{\text{iso}}/(\Gamma_{k,0}c^2)$

Initialising the burst

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

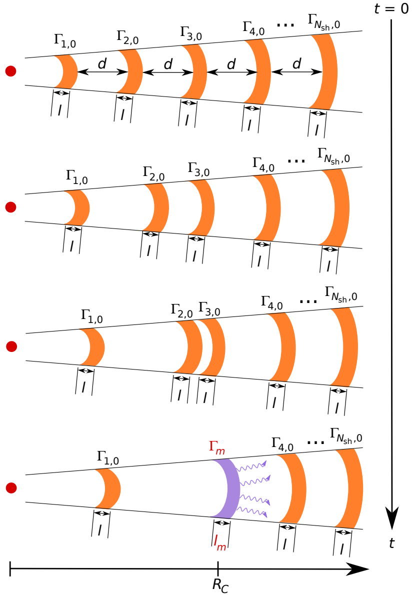
$A_\Gamma \gg 1$

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

Evolving the fireball



During propagation:

- speeds (Γ_k), masses (m_k), widths (l_k) do not change (only in collisions)
- shell volume: $V'_{\text{iso},k} = 4\pi l'_k r_k^2$
- 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)

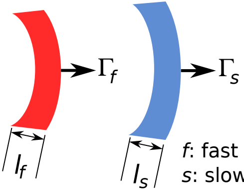
Final number of collisions:

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

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

Anatomy of an internal collision

1 Propagation

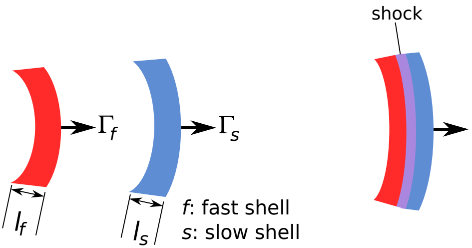


f: fast shell
s: slow shell

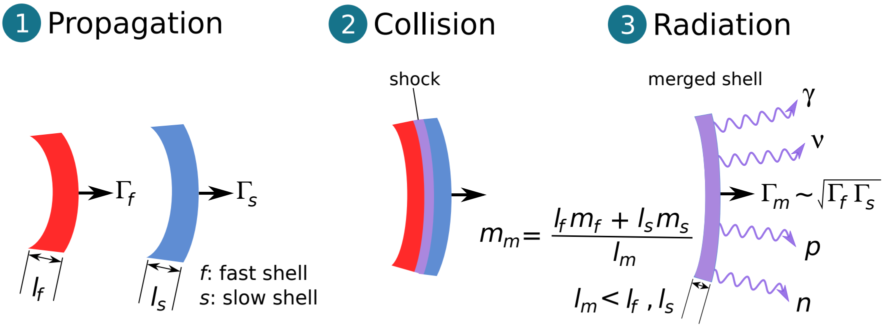
Anatomy of an internal collision

1 Propagation

2 Collision



Anatomy of an internal collision



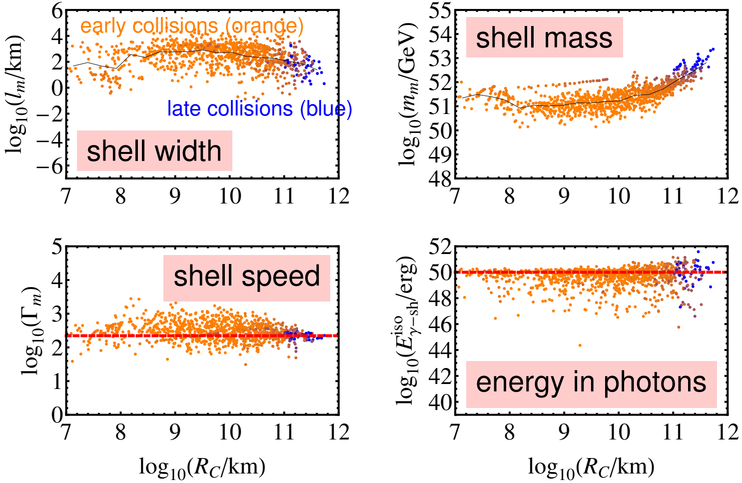
Part of the initial kinetic energy radiated as γ's, ν's, p's, and n's:

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

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

Evolution of parameters with collision radius

We keep track of collision parameters as the fireball expands:

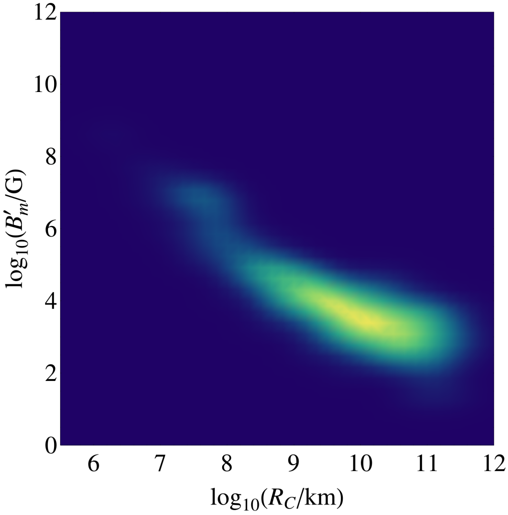


MB, P. BAERWALD, K. MURASE, AND W. WINTER, IN PREPARATION

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

Evolution of parameters with collision radius

The magnetic field at emission falls with collision radius:



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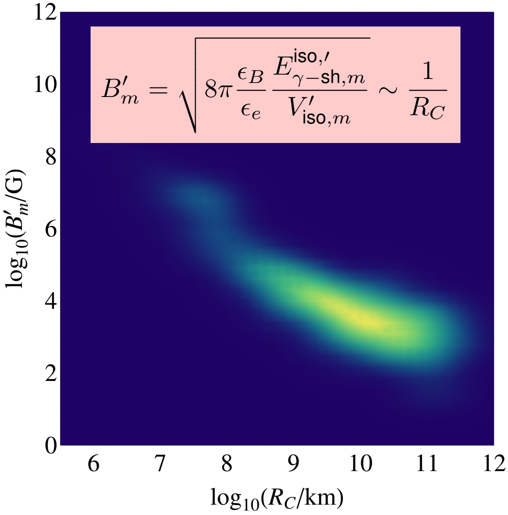

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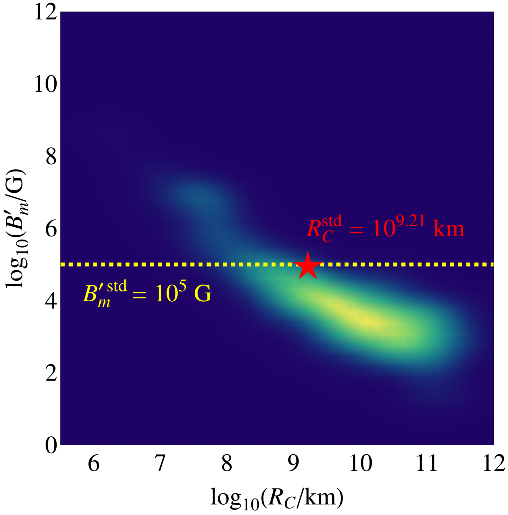

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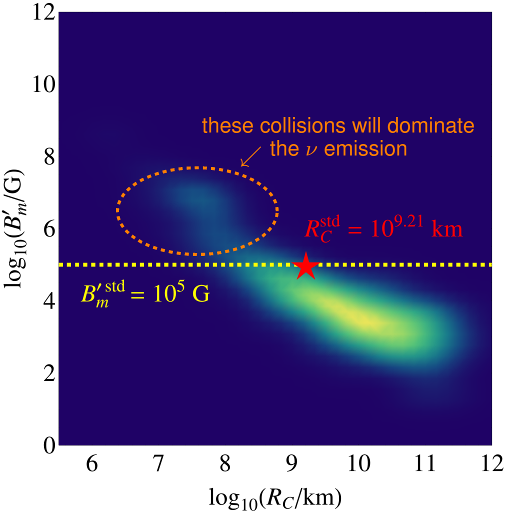
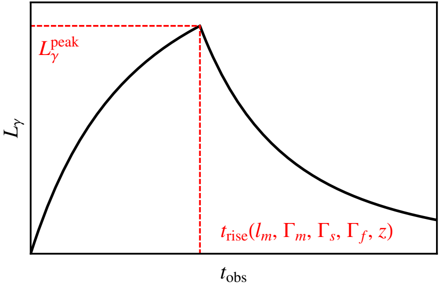
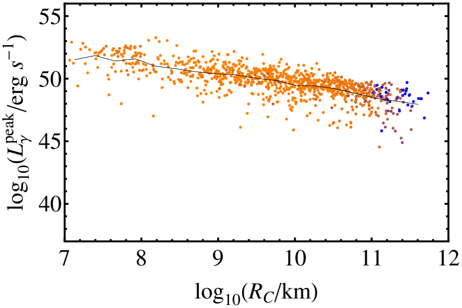


Synthetic light curves

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

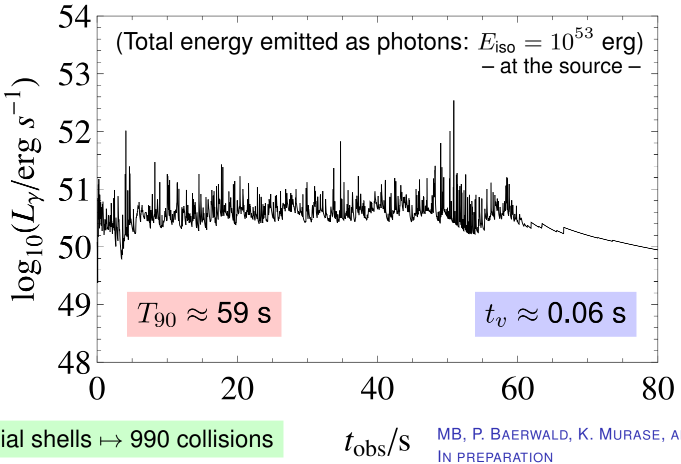




$$L_\gamma^{\text{peak}} \sim R_C^{-2}$$

Synthetic light curves

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

Particle emission from a collision

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

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

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

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

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

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

Particle emission from a collision

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

- Photons:

from the simulation

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

- Protons:

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

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

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

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

Particle emission from a collision

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

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

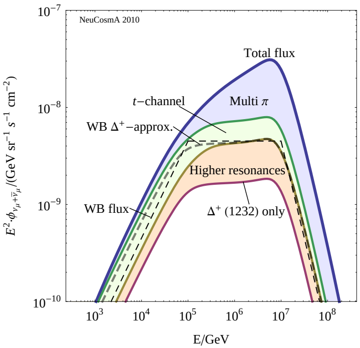
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

response function

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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



Particle emission from a collision

Two important points:

1. $E'_{p,\max}$ is determined by energy-loss processes:
$t'_{\text{acc}}\left(E'_{p,\max}\right) = \min\left[t'_{\text{dyn}}, t'_{\text{syn}}\left(E'_{p,\max}\right), t'_{p\gamma}\left(E'_{p,\max}\right)\right]$

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

$$\gamma + \gamma \to e^+ + e^-$$

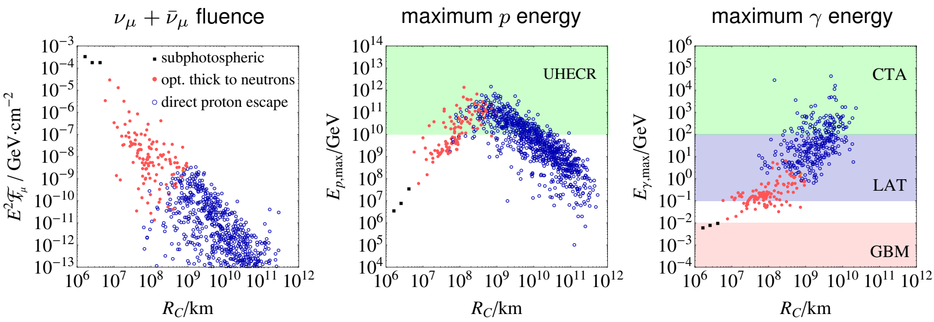
Photosphere: radius where $\tau_{\gamma\gamma}\left(E'_\gamma\right) = 1$ for all E'_γ

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

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

Particle emission from a dynamical fireball

Each collision occurs in a different regime:

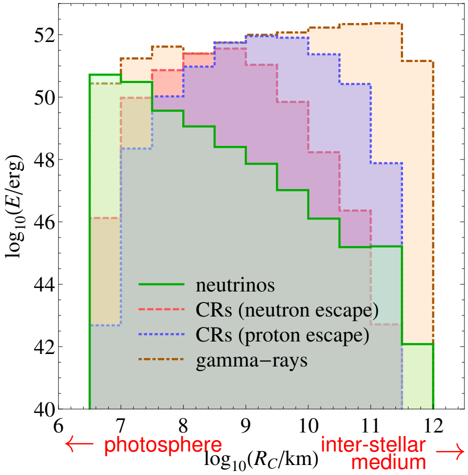


(observer's frame) (source frame)

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

Particle emission from a dynamical fireball

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

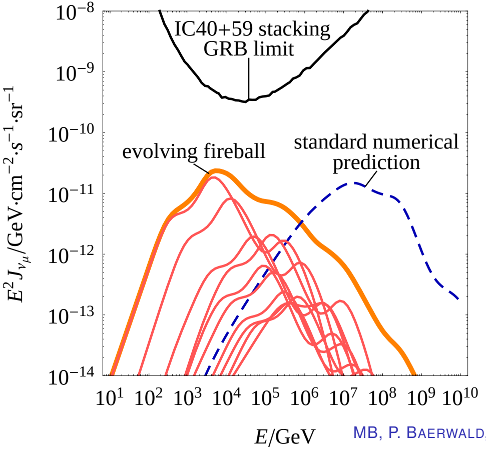
So what?

So the following happens . . .

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

A new GRB UHE neutrino prediction

Quasi-diffuse flux:

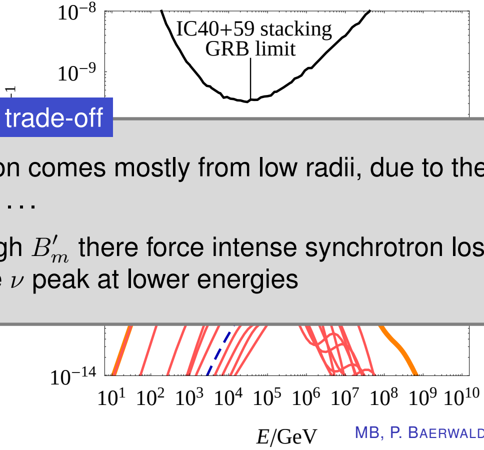


MB, P. Baerwald, K. Murase, and W. Winter, in preparation

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

A new GRB UHE neutrino prediction

Quasi-diffuse flux:



There is a trade-off

- 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

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

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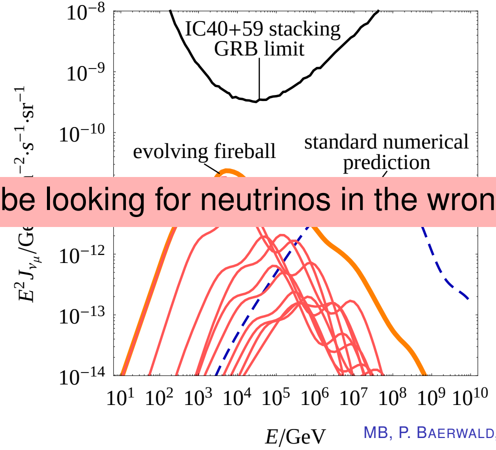


We might be looking for neutrinos in the wrong energies ...

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

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

Summary and conclusions

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

Outlook

Several ongoing projects, in different stages of progress:

- **Fireball evolution:** different GRB parameter sets, include nuclei

  P. Baerwald (Penn State), MB, K. Murase (IAS Princeton), W. Winter (DESY)

- **Seesaw and heavy neutrino decay detection in IceCube**

  MB, C. de los Heros (Uppsala Univ.), J. Jones (PUCP Lima), P. Ferrario (IFIC Valencia)

- **Lorentz invariance violation in cosmogenic neutrinos**

  MB, P. Mehta (Univ. Delhi), W. Winter (DESY)

- **Decay of UHE astrophysical neutrinos:** use the latest IceCube data to constrain the ν lifetime (based on *JCAP* **1210**, 020 (2012), P. Baerwald, MB, W. Winter)

  MB, K. Murase (IAS Princeton)

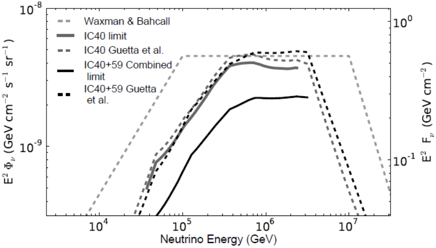
- **Prospects for correlations between UHECRs and neutrinos:** both in position and energy

  C. Argüelles (WIPAC Wisconsin), MB, J. Carpio (PUCP Lima), A. Gago (PUCP Lima), J. Salvadó (WIPAC Wisconsin)

Thanks to the professors and students of the GRK1147!

Backup slides

The neutron model under tension?



IceCube Collaboration:

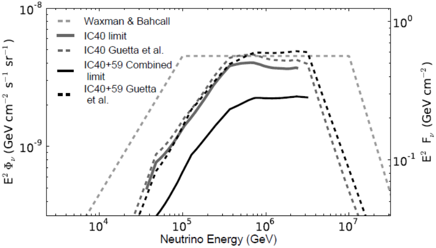
- ν flux normalised to GRB γ fluence:

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

- 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)

The neutron model under tension?



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:

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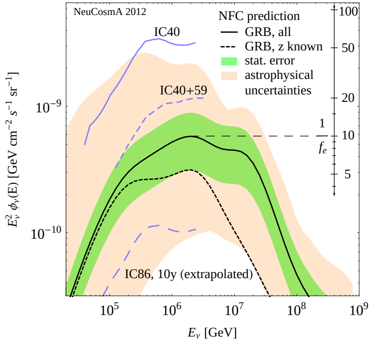

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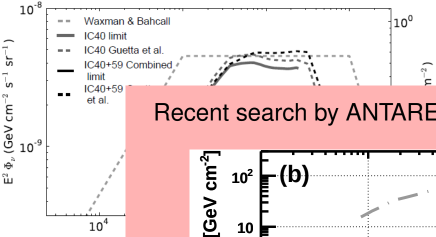


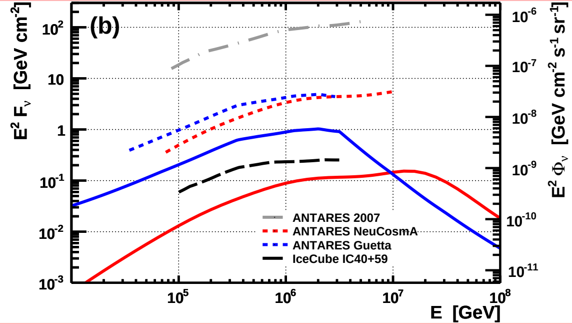
More detailed particle physics (NeuCosmA):

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

lower

1 (2012)

Recent search by ANTARES optimised for NeuCosmA:



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

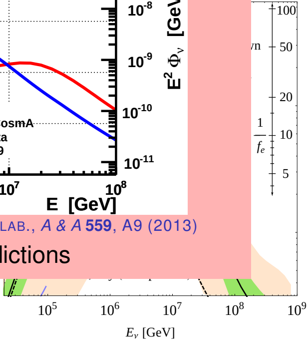
- IceCube is also revising its GRB predictions

IceCube Coll

- ν flux r

$\int_0^\infty dE_\nu$

- quasi-c
- analyti
upper l



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

Going beyond the neutron model

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:

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

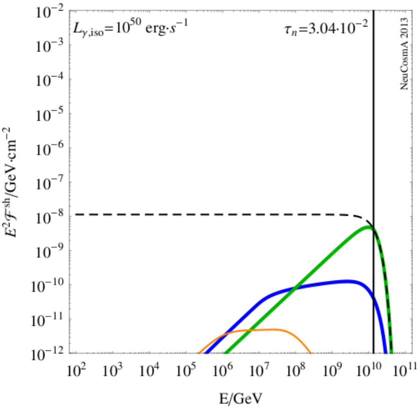
Particles can escape from within a shell of thickness λ'_{mfp}:

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

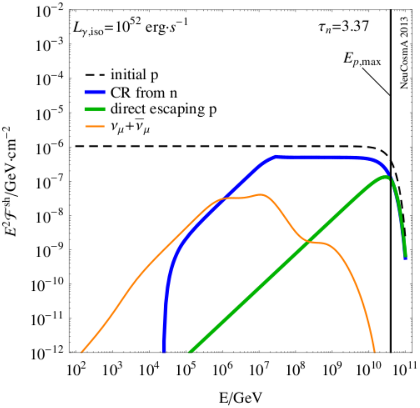
fraction of escaping particles

A two-component model of CR emission

Optically **thin** source:



Optically **thick** source:



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

A two-component model of CR emission

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

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

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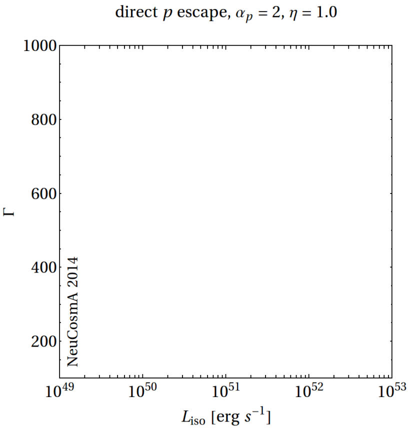

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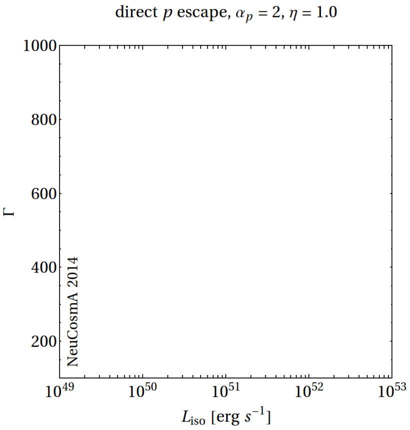

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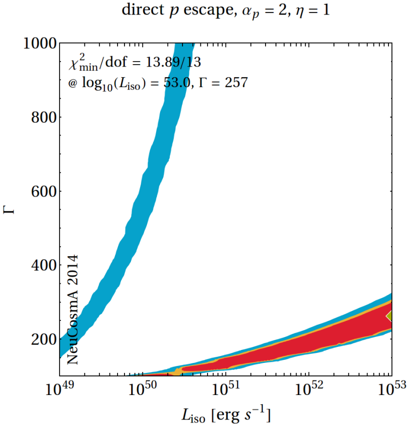

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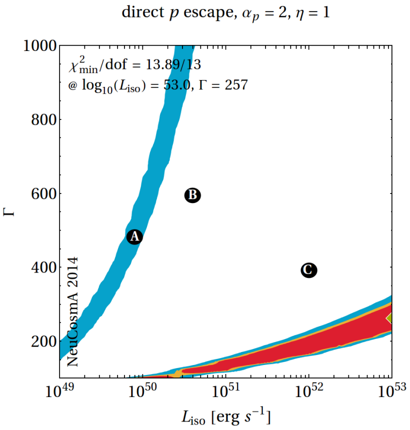

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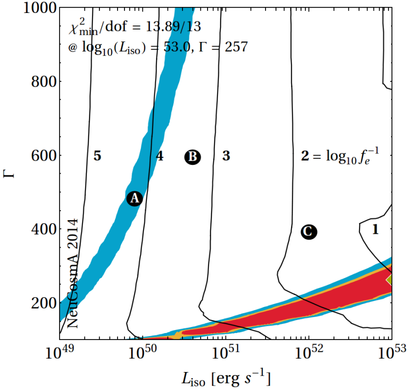

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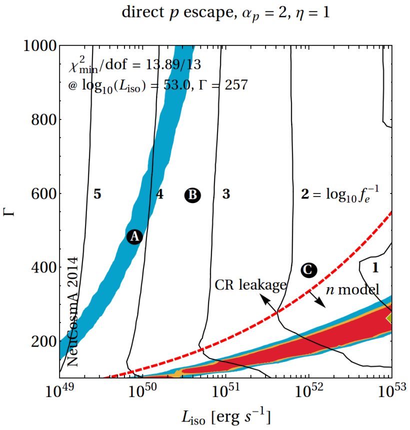

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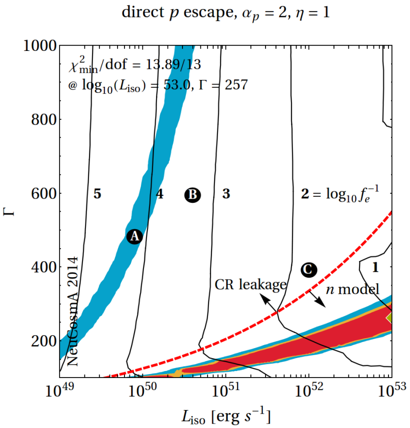

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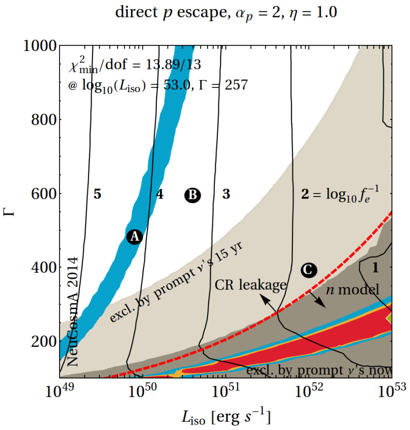
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



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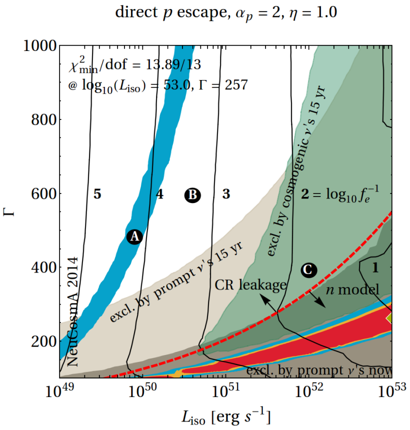
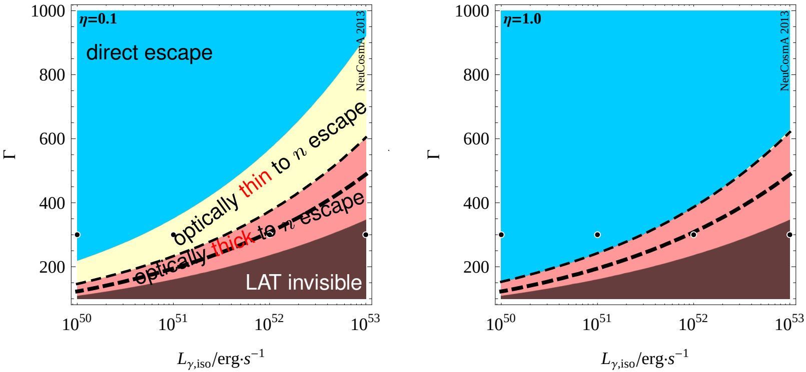


P. Baerwald, MB, and W. Winter, accepted on Astropart. Phys. [arXiv:1401.1820]

A two-component model of CR emission

Scan of the GRB emission parameter space:

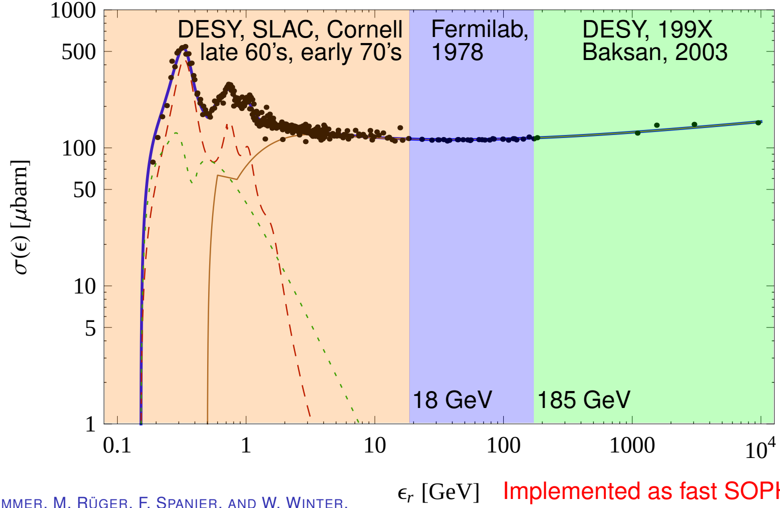
acceleration efficiency $\longrightarrow$ $\eta = 0.1$ $\eta = 1.0$



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

Revising the neutron model: NeuCosmA

• Detailed $p\gamma$ cross section

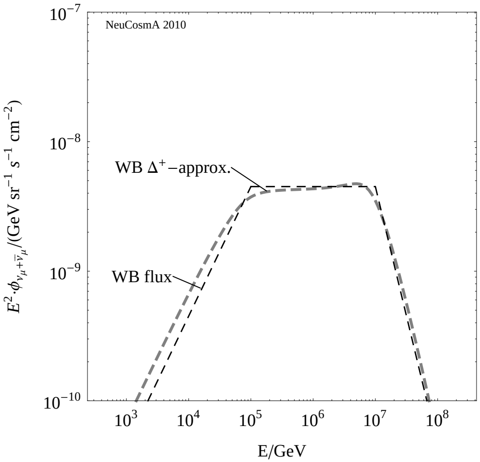


S. HÜMMER, M. RÜGER, F. SPANIER, AND W. WINTER, *Astrophys. J.* **721**, 630 (2010)

Implemented as fast SOPHIA-based parametrisation

Revising the neutron model: NeuCosmA

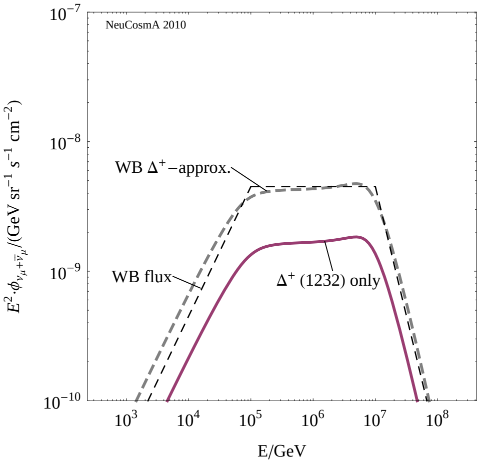
- Contributions to the full photohadronic cross section



Revising the neutron model: NeuCosmA

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

- $\Delta(1232)$-resonance



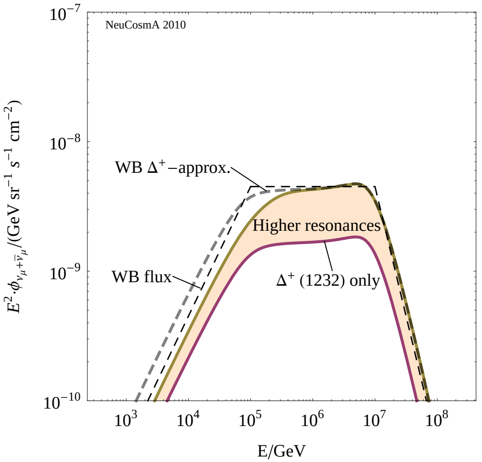
P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

Revising the neutron model: NeuCosmA

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, *Phys. Rev.* **D83**, 067303 (2011)



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● Contributions to the full photohadronic cross section

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

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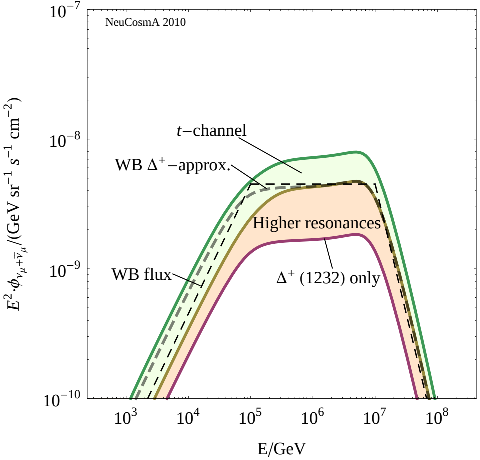
- t-channel (direct production)

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



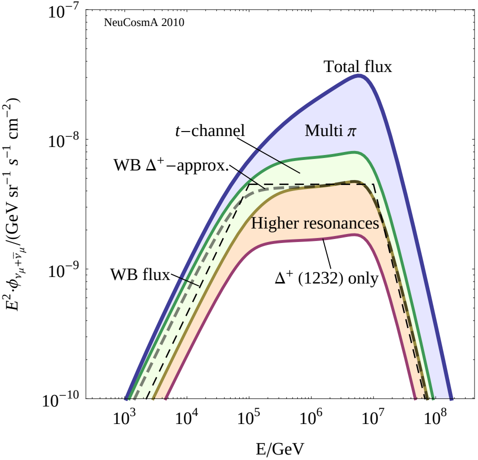
Revising the neutron model: NeuCosmA

• 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)

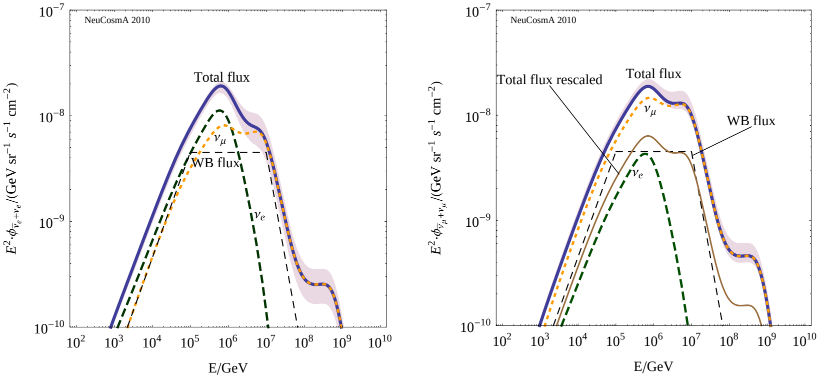


Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

Revising the neutron model: NeuCosmA

• Neutrino spectra including flavour mixing

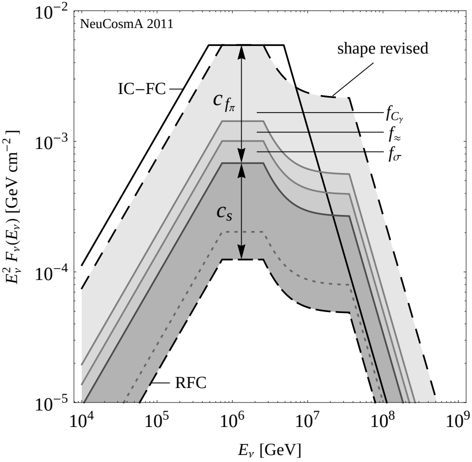
Electron neutrino spectrum — Muon neutrino spectrum



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

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

Revising the neutron model: NeuCosmA



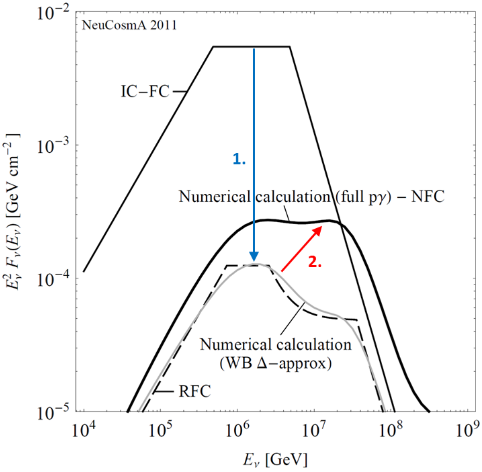
S. HÜMMER, P. BAERWALD, AND W. WINTER, *Phys. Rev. Lett.* **108**, 231101 (2012)

Corrections to the analytical model:

- shape revised:
  - shift of first break (correction of photohadronic threshold)
  - different cooling breaks for μ's and π's
  - $(1+z)$ correction on the variability scale of the GRB
- Correction $c f_\pi$ 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 → 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

• Further particle decays

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

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

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

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

Revising the neutron model: NeuCosmA

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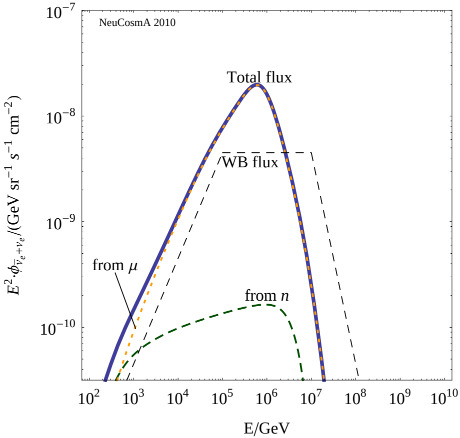
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

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

Resulting ν_e flux (at the observer)



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Revising the neutron model: NeuCosmA

• Further particle decays

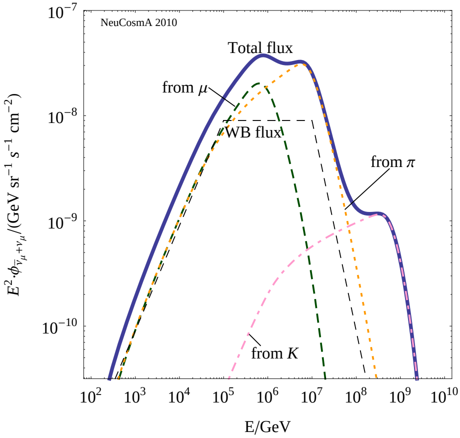
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

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

Resulting ν_μ flux (at the observer)



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

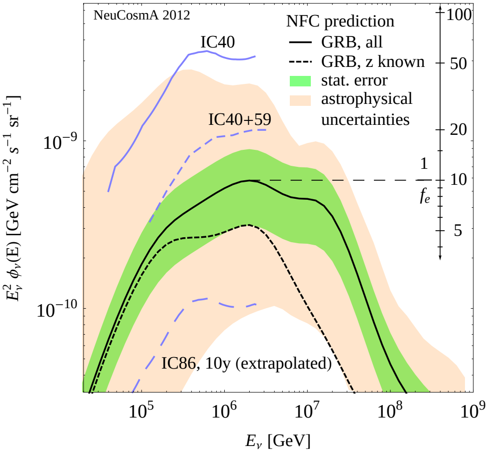
Revising the neutron model: NeuCosmA

• 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:
  - $0.001 \leq t_v$ [s] ≤ 0.1
  - $200 \leq \Gamma \leq 500$
  - $1.8 \leq \alpha_p \leq 2.2$
  - $0.1 \leq \epsilon_e/\epsilon_B \leq 10$



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

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

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

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

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

UHE ν's in the GRB internal shock model

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

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

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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

A new GRB UHE neutrino prediction

Flux from a single simulated burst

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

$$J_{\nu,k} = \frac{1}{4\pi} V'_{\text{iso},k} \frac{(1+z)^2}{4\pi d_L^2} Q'_{\nu,k}$$

fluence from k-th collision [GeV^{-1} cm^{-3} s^{-1}]

- 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:

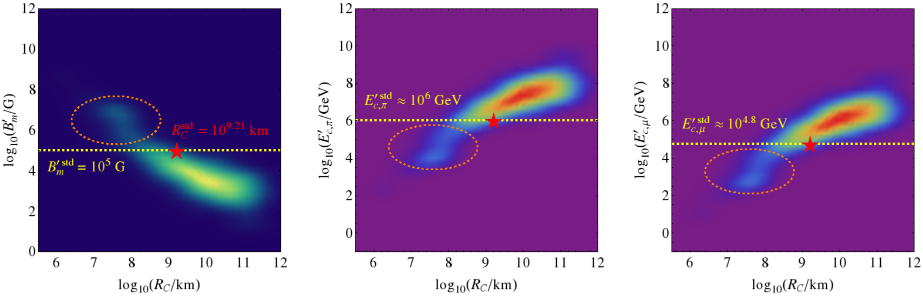
$$J_\nu(E) = J_{\nu,\text{single}}(E) \cdot \left(1 \text{ yr} \cdot 667 \text{ yr}^{-1}\right)$$

A new GRB UHE neutrino prediction

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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