Multi-messenger light curves from gamma-ray bursts

1409.2874, 1606.02325

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8th Huntsville Gamma-Ray Burst Symposium
Huntstville — October 24, 2016
Why are GRBs natural $\nu$ source candidates?

1. They are bright
   - $10^{52} - 10^{53}$ erg in gamma rays (Sun: $10^{40}$ erg in 1 yr; SN: $10^{42}$ erg)
   - Photons up to $\sim 100$ GeV

   Implies possible acceleration of protons to high energies

2. They have fast time-variability
   - Features at 0.01 s scale
   - Compact emission regions

   Implies high proton and photon number densities ($p\gamma \rightarrow \nu$)

Natural expectation:
GRBs produce copious high-energy neutrinos

(But they are far and relatively rare)
IceCube has not found neutrinos associated to GRBs

- 3 yr of showers (all flavors) + 4 yr of upgoing tracks with $> 1$ TeV
- Catalog of 807 bursts
- 6 coincident events (5 showers + 1 track) — not statistically significant

$\lesssim 1\%$ of the diffuse flux can be from prompt GRB emission

The elephant in the room

Why is it still interesting to look for GRB neutrinos?

1. **Best candidates for joint high-energy e.m.–neutrino emission**

2. **Potential sources of ultra-high-energy cosmic rays**

Also . . .

3. “Choked” bursts might contribute sizeably to the diffuse flux

   *e.g.*, [P. Mészáros, E. Waxman 2001] [N. Senno, K. Murase, P. Mészáros 2016] [I. Tamborra, S. Ando 2016]

4. **Neutrinos from GRB afterglows expected at \( \sim \) EeV**

   *e.g.*, [K. Murase 2007] [S. Razzque, L. Yang 2015]

So, every bit of insight into how GRBs make neutrinos is essential
GRBs – a zoo of light curves

Photon rate \( \left( 10^2 \text{ counts s}^{-1} \right) \)

**BATSE variability timescale** (width of pulses) \( \equiv t_v \approx 0.01 \text{ s} \)

Mauricio Bustamante (CCAPP OSU)  Multi-messenger GRB light curves
Which GRB is brighter in neutrinos?

Just from looking at these gamma-ray light curves,

![GRB920513](image1)

GRB920513
Trigger 1606

![GRB931008](image2)

GRB931008
Trigger 2571

Can we tell which GRB is likely bright in neutrinos?
Which GRB is brighter in neutrinos?

Just from looking at these gamma-ray light curves,

- GRB920513
  - Trigger 1606
  - Fast time variability

- GRB931008
  - Trigger 2571
  - Slow pulse + fast variability

Can we tell which GRB is likely bright in neutrinos?
Which GRB is brighter in neutrinos?

Just from looking at these gamma-ray light curves,

\begin{align*}
\text{GRB920513} & \quad \text{Trigger 1606} \\
\text{GRB931008} & \quad \text{Trigger 2571}
\end{align*}

\begin{align*}
\text{Photon rate}[10^3 \text{ counts s}^{-1}] & \\
\text{Time since trigger [s]} & \\
0 & \quad 20 & \quad 40 & \quad 60 & \quad 80 & \quad 100
\end{align*}

Fast time variability \quad Slow pulse + fast variability

can we tell which GRB is likely bright in neutrinos?

(Answer: yes, the one on the left)
The fireball model — internal collisions

1. Plasma shells propagate at different speeds
2. Two shells collide
3. The shells merge and particles are emitted

Mészáros, Reese, Goodman, Pachinsky, et al.

\[ p\gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+ \\ p\pi^0 \end{cases} \]
\[ \pi^+ \rightarrow \mu^+\nu_\mu \rightarrow \bar{\nu}_\mu e^+\nu_e\nu_\mu \]
\[ \pi^0 \rightarrow \gamma\gamma \]
\[ n \text{ (escapes)} \rightarrow pe^-\bar{\nu}_e \]

+ More \( \nu \) production modes
(\text{NeuCosmA, \textsc{Hummer}+ PRL 2012})

For each GRB,

\[ \text{energy in neutrinos} \propto \text{energy in gamma rays} \]
UHECR emission in a collision

UHECRs escape as

- **Protons** that leak out (not producing $\nu$’s)
- **Neutrons**, which decay into protons outside the source; or

\[ \tau_n < 1 \] optically thin to $n$ escape

$p$'s trapped in bulk by magnetic field

$p$'s can leak from borders

\[ \tau_n \geq 1 \] optically thick to $n$ escape

$p$'s trapped in bulk by $p\gamma$ and $n\gamma$ interactions

$p$, $n$'s can leak from borders

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


Multiple individual collisions

An evolving fireball:

- \( \sim 1000 \) expanding shells
- Different individual speeds
- Random initial speeds \((\Gamma)\) follow a distribution
- Many collision radii \((R_C)\)
- Falling \(\gamma, p\) densities

\[
\begin{align*}
\text{fraction of energy output} \\
\text{photosphere} \\
\text{neutrinos} \\
\text{UHECRs} \\
\text{\(\gamma\)-rays} \\
\text{direct escape} \\
\text{n escape}
\end{align*}
\]

\[
\log_{10}(R_C/\text{km})
\]


Synthetic light curves

Each collision emits a particle pulse – their superposition yields a synthetic light curve:

\[
\text{Log}_10 \left( \frac{F}{\text{GeV cm}^{-2} \text{s}^{-1}} \right)
\]

Gamma rays

Neutrinos (all flavors)

\[ t_{\text{obs}} \text{ [s]} \]

\[ t_{\text{obs}} \text{ [s]} \]

\[ \approx 59 \text{ s} \]

\[ E_{\text{iso}}^{\gamma, \text{tot}} = 10^{53} \text{ erg} \]

1000 initial shells \( \rightarrow \) 990 collisions

MB, P. Baerwald, K. Murase, W. Winter

Nature Commun. 6, 6783 (2015)
Synthetic light curves

Each collision emits a particle pulse – their superposition yields a **synthetic light curve**: 

**Energy in gamma-rays:** \( E_{\gamma,\text{tot}}^{\text{iso}} = 10^{53} \text{ erg} \)

![Graph showing synthetic light curves for Gamma rays and Neutrinos](image)

\( t_{\text{obs}} \text{ [s]} \)

\( T_{90} \approx 59 \text{ s} \)

1000 initial shells \( \rightarrow \) 990 collisions

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MB, P. BAERWALD, K. MURASE, W. WINTER
Nature Commun. 6, 6783 (2015)
Quasi-diffuse neutrino flux

Assuming 667 identical GRBs per year:

\[
\Gamma_0 = 500, \langle \Gamma \rangle = 369
\]

MB, P. BAERWALD, K. MURASE, W. WINTER
Nature Commun. 6, 6783 (2015)
Which GRB is brighter in neutrinos?

Back to our initial question:

Just from looking at these gamma-ray light curves,

can we tell which GRB is likely bright in neutrinos?

- **Fast time variability** (GRB920513)
- **Slow pulse + fast variability** (GRB931008)
What makes a GRB bright in neutrinos?

**Undisciplined GRB engine**
- Broad $\Gamma$ distribution
- *E.g.*, engine emits shells with log-normal $\Gamma$ distrib.

**Disciplined GRB engine**
- Narrow $\Gamma$ distribution
- *E.g.*, engine emits shells with oscillating $\Gamma$
Light curves

**Undisciplined GRB engine**
- Fast variability dominates
- No broad pulses

**Disciplined GRB engine**
- Broad pulses dominate
- Fast variability on top

---

**Gamma rays**

**Neutrinos (all flavors)**

---

**GRB 1**

**GRB 5**

---

MB, MURASE, WINTER, 1606.02325
How many optically thick collisions?

**Undisciplined GRB engine**
- Shells have very different speeds
- Collide quickly, close to center
- High $\rho$ and $\gamma$ densities
- $\sim 10$ collisions near photosphere are optically thick

**Disciplined GRB engine**
- Shells have similar speeds
- Collide far from center
- Low $\rho$ and $\gamma$ densities
- All (superphotospheric) collisions are optically thin
So which burst is neutrino-bright?

**Undisciplined GRB engine**
\[ \sim 10^{-11} \text{ GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \]

**Disciplined GRB engine**
\[ \sim 5 \cdot 10^{-13} \text{ GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \]

**MB, Murase, Winter, 1606.02325**
So which burst is neutrino-bright?

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So which burst is neutrino-bright?

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**Disciplined GRB engine**

\[ \sim 5 \cdot 10^{-13} \text{ GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \]

\[ E^2 J_{\nu,\mu} \quad [\text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

\[ E \quad [\text{GeV}] \]

\[ \vdots \quad \text{An undisciplined engine makes a GRB neutrino-bright} \]

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Using our new insight

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Multi-messenger GRB light curves

Using our new insight
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Multi-messenger GRB light curves

[Graphs showing the energy distribution of gamma rays and neutrinos for different GRBs, labeled 'Good $\nu$ emitter' or 'Poor $\nu$ emitter'.]
Neutrino-weak bursts show time delays in different energy bands —

\[ t_{\text{obs}} \text{ [s]} \]

\begin{align*}
10^{-6} – 10^{-2} \text{ GeV} & \quad \text{Fermi–GBM} \quad \text{GRB 5} \\
10^{-1} – 10^{2} \text{ GeV} & \quad \text{Fermi–LAT} \\
10^{2} – 10^{6} \text{ GeV} & \quad \text{CTA}
\end{align*}

MB, Murase, Winter, 1606.02325
See also: Bošnjak, Daigne, A&A 568, A45 (2014) [1404.4577]
Time delays in gamma-ray light curves

Neutrino-weak bursts show time delays in different energy bands —

![Graph showing time delays in gamma-ray light curves for different energy bands.](image)

MB, Murase, Winter, 1606.02325
See also: Bošnjak, Daigne, A&A 568, A45 (2014) [1404.4577]
The future

- GRBs could be the first resolved high-energy neutrino sources
- We have a new criterion to select promising GRBs
- We will add more emission models to our technique
- We need next-gen neutrino telescopes (IceCube-Gen2, KM3NeT)

Next step: ready our technique for application to data
Backup slides
What are the ingredients?

To calculate the $\nu$ flux from a GRB, we need:

- Its gamma-ray luminosity $L_{\gamma}^{\text{iso}}$ [erg s$^{-1}$] [measured]
- Its variability timescale $t_v$ [s], from the light curve [measured]
- Break energy of its photon spectrum $\epsilon_{\gamma,\text{break}}$ [MeV] [measured]
- Its redshift $z$ [(sometimes) measured]
- The bulk Lorentz factor of its jet $\Gamma$ [estimated]
- The energy in electrons, magnetic field, protons [estimated]

Now let us cook up the neutrinos
Normalizing neutrinos with observed gamma rays

For each GRB,

\[ \text{energy in neutrinos} \propto \text{energy in gamma rays} \]

\[ \int_{0}^{\infty} dE_{\nu} E_{\nu} F_{\nu}(E_{\nu}) = \frac{1}{8} \left[ 1 - (1 - \langle x_{p\rightarrow\pi} \rangle)^{\Delta R/\lambda_{p\gamma}} \right] \frac{1}{f_{e}} \int_{1 \text{ keV}}^{10 \text{ MeV}} d\epsilon_{\gamma} \epsilon_{\gamma} F_{\gamma}(\epsilon_{\gamma}) \]

\( \Delta R \): size of the emitting region
\( \lambda_{p\gamma} \): mean free path for \( p\gamma \) interactions
\( \langle x_{p\rightarrow\pi} \rangle \): avg. fraction of \( p \) energy transferred to a \( \pi \) in one interaction
\( f_{e}^{-1} \): ratio of energy in protons to energy in photons (“baryonic loading”)

Optical depth to \( p\gamma \) : 
\[ \frac{\Delta R}{\lambda_{p\gamma}} = \left( \frac{L_{\gamma}^{\text{iso}}}{10^{52} \text{ erg s}^{-1}} \right) \left( \frac{0.01}{t_{v}} \right) \left( \frac{10^{2.5}}{\Gamma} \right)^{4} \left( \frac{\text{MeV}}{\epsilon_{\gamma,\text{break}}} \right) \]
Cooking up the neutrinos

**Observed gamma-ray fluence [GeV$^{-1}$ cm$^{-2}$]**

\[
F_\gamma (\varepsilon_\gamma) \propto \begin{cases} 
(\varepsilon_\gamma / \varepsilon_{\gamma, br})^{-1} & , \varepsilon_\gamma < \varepsilon_{\gamma, br} = 1 \text{ MeV} \\
(\varepsilon_\gamma / \varepsilon_{\gamma, br})^{-2.2} & , \varepsilon_\gamma \geq \varepsilon_{\gamma, br}
\end{cases}
\]

\[E_{\nu, br}: \text{from photon spectrum} \quad + \quad E_{\nu, \mu}: \text{from } \mu \text{ synchrotron cooling}\]

**Assumed proton spectrum in the source**

\[N'_p(E_p) \propto E_p'^{-2}\]

**Neutrinos from } p\gamma, \text{ via } \Delta \text{ resonance**}

\[
F_{\nu}(E_\nu) \propto \begin{cases} 
\left( \frac{E_\nu}{E_{\nu, br}} \right)^{-\alpha_\nu} & , E_{\nu} < E_{\nu, br} \\
\left( \frac{E_\nu}{E_{\nu, br}} \right)^{-\beta_\nu} & , E_{\nu, br} \leq E_{\nu} < E_{\nu, \mu} \\
\left( \frac{E_\nu}{E_{\nu, br}} \right)^{-\beta_\nu} \left( \frac{E_\nu}{E_{\nu, \mu}} \right)^{-2} & , E_{\nu} \geq E_{\nu, \mu}
\end{cases}
\]

\[E_{\nu, br} \text{: from photon spectrum} \quad E_{\nu, \mu} \text{: from } \mu \text{ synchrotron cooling} \]

---

Refining the neutrino spectrum — NeuCosmA

More production channels, more complete particle-physics treatment

For example, GRB080603A:

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

2. Change due to full numerical calculation

Neutrino spectra (at Earth)

Electron neutrino spectrum

Muon neutrino spectrum

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Multi-messenger GRB light curves
Diffuse fluxes at Earth

Neutron model vs. two-component model: prompt and cosmogenic $\nu$’s

UHECRs

Neutrinos

$E^3 J_{CR}[\text{GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$\alpha_p = 2.0$

$E/J_{CR}[\text{GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$\alpha_p = 2.0$

$E^2 J_{\nu}[\text{GeV} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$E [\text{GeV}]$

$E [\text{GeV}]$

$\chi^2$/d.o.f. = 3.31

CR (neutron dominated (#1)) $f_e^{-1} \approx 41$

$\chi^2$/d.o.f. = 5.95

CR (leakage dominated (#2)) $f_e^{-1} \approx 62$

NeuCosmA 2014

IC (2010–12) diffuse UHE $\nu_\mu$ flavor limit

IC40+59 stacking GRB limit


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A simplifying assumption: identical collisions

All internal collisions are identical and occur at the same radius —

\[ l' = \Gamma c t_v (1+z) \sim 9 \times 10^4 (1+z) \text{ km} \]

\[ R_C = 2c\Gamma^2 t_v / (1+z) \sim 5 \times 10^7 / (1+z) \text{ km} \]

\[ N_{\text{coll}} \approx T_{90} / t_v \sim 100-1000 \text{ identical collisions} \]

- Calculate particle emission spectra once
- Then multiply by \( N_{\text{coll}} \)
- \( \Gamma \) is the average speed of shells

Typical values:
\( \Gamma = 300 \)
\( T_{90} = 10 \text{ s} \)
\( t_v = 10^{-3} \text{ s} \)
Initial distribution of shell speeds

Distribution of initial shell speeds (Lorentz factors):

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

\(x\) 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
Anatomy of an internal collision

1 Propagation

- Fast shell
  - $m_f$
  - $l_f$
  - $\Gamma_f$
- Slow shell
  - $m_s$
  - $l_s$
  - $\Gamma_s$

2 Collision

- Reverse shock
- Forward shock

3 Radiation

- Merged shell
- $m_m \approx m_f + m_s$
- $l_m < l_f, l_s$
- $\Gamma_m \approx \sqrt{\Gamma_f \Gamma_s}$

Part of the initial kinetic energy radiated as $\gamma$’s, $\nu$’s, $p$’s, and $n$’s:

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

- $1/12 \epsilon_e E_{\text{coll}}^{\text{iso}}$
  - Energy in photons
- $1/12 \epsilon_B E_{\text{coll}}^{\text{iso}}$
  - Energy in magnetic fields
- $5/6 \epsilon_p E_{\text{coll}}^{\text{iso}}$
  - Energy in baryons
Tracking each collision individually

Each collision occurs in a different emission regime –

Sub-photospheric: \( \tau_{e-\gamma} > 1 \)

\[ \nu_\mu + \bar{\nu}_\mu \text{ fluence} \]

neutrinos

maximum \( p \) energy

cosmic rays

Limited by \( \gamma + \gamma \rightarrow e^+ + e^- \)

maximum \( \gamma \) energy

gamma–rays

\( E^2E_\mu \text{ GeV cm}^{-2} \)

\( E_{p,\text{max}} \text{ GeV} \)

\( E_{\gamma,\text{max}} \text{ GeV} \)

(observer’s frame)

(source frame)

NeuCosmA: (revised) GRB particle emission – I

Two ingredients:

\[ N'_p \left( E'_p \right) \]  \hspace{1cm} \text{proton density at the source [GeV}^{-1} \text{ cm}^{-3}] \]

\[ N'_\gamma \left( E'_\gamma \right) \]  \hspace{1cm} \text{photon density at the source} \]

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

▶ Photons (same shape as observed at Earth):

\[ N'_\gamma \left( E'_\gamma \right) = \begin{cases} 
\left( E'_\gamma / E'_{\gamma, \text{break}} \right)^{-1}, & E'_\gamma, \text{min} = 0.2 \text{ eV} \leq E'_\gamma < E'_\gamma, \text{break} = 1 \text{ keV} \\
\left( E'_\gamma / E'_{\gamma, \text{break}} \right)^{-2.2}, & E'_\gamma \geq E'_\gamma, \text{break} \\
0, & \text{otherwise}
\end{cases} \]

▶ Protons: \[ N'_p \left( E'_p \right) \propto E'_p^{-\alpha_p} e^{-E'_p/E'_{p, \text{max}}} \] \hspace{1cm} (\alpha_p \gtrsim 2)
NeuCosmA: (revised) GRB particle emission – I

Two ingredients:

\[
\begin{align*}
N'_p (E'_p) & \quad \text{proton density at the source [GeV}^{-1} \text{ cm}^{-3}] \\
N'_\gamma (E'_\gamma) & \quad \text{photon density at the source} \\
\end{align*}
\]

\[
\begin{align*}
\text{=} & \quad Q'_\nu (E'_\nu) \\
& \quad \text{emitted neutrino spectrum [GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}] \\
\end{align*}
\]

▶ Photons (same shape as observed at Earth):

\[
N'_\gamma (E'_\gamma) = \begin{cases} 
(\frac{E'_\gamma}{E'_{\gamma,\text{break}}} - 1)^{-1} & , \quad E'_\gamma,\text{min} = 0.2 \text{ eV} \leq E'_\gamma < E'_\gamma,\text{break} = 1 \text{ keV} \\
(\frac{E'_\gamma}{E'_{\gamma,\text{break}}} - 2.2) & , \quad E'_\gamma \geq E'_\gamma,\text{break} \\
0 & , \quad \text{otherwise} 
\end{cases}
\]

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

▶ Protons: \[N'_p (E'_p) \propto E'_p^{-\alpha_p} e^{-E'_p/E'_{p,\text{max}}} \quad (\alpha_p \gtrsim 2) \]
Normalize the particle densities at the source —

► Photons:

\[
\int E'_\gamma N'_\gamma(E'_\gamma) \, dE'_\gamma
\]

\[
\text{photon energy density per collision} = \frac{E_{\gamma,\text{tot}}^{\text{iso},',}}{N_{\text{coll}} \cdot V_{\text{iso}}}
\]

\[
E_{\gamma,\text{tot}}^{\text{iso},'} \sim 10^{53} \text{ erg (from observed fluence)}
\]

► Protons:

\[
\int E'_p N'_p(E'_p) \, dE'_p
\]

\[
\text{proton energy density per collision} = \frac{1}{f_{\text{e}}} \cdot \text{photon energy density per collision}
\]

\[
\text{baryonic loading (energy in p's / energy in e's + \gamma's), e.g., 10}
\]
NeuCosmA: (revised) GRB particle emission – III

Injected/ejected spectrum of secondaries ($\pi$, $K$, $n$, $\nu$, etc.):

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

where

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

$R$ contains cross sections, multiplicities for different channels

What does NeuCosmA include?

- $p\gamma \rightarrow \Delta^+(1232) \rightarrow \pi^0, \pi^+, \ldots$
- extra $K$, $n$, $\pi^-$, multi-$\pi$ prod. modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum
- neutrino flavor transitions
NeuCosmA – the full photohadronic cross section

NeuCosmA 2010

$E^2 \phi_{\nu_\mu,\bar{\nu}_\mu} / (\text{GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2})$

$E/\text{GeV}$

$10^{-10}$

$10^{-9}$

$10^{-8}$

$10^{-7}$

$10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$

WB flux

WB $\Delta^+$ – approx.

Especially “Multi $\pi$” contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment
Contributions to \((\nu_\mu + \bar{\nu}_\mu)\) flux from \(\pi^\pm\) decay divided in:

- \(\Delta(1232)\)-resonance
Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

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

\[ E^2 \phi_{\nu_\mu + \bar{\nu}_\mu}/(\text{GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2}) \]

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

- \(\Delta(1232)\)-resonance
- Higher resonances
- \(t\)-channel (direct production)

\[
E^2 \phi_{\nu_\mu + \bar{\nu}_\mu}(\text{GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2})
\]

\(E\) in GeV

\(\Delta^+ \text{ only} \)

\(t\)-channel

WB flux

WB \(\Delta^+\) approx.

Higher resonances

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 \(\pi\))

Especially "Multi \(\pi\)" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment.

\[ E^2 \phi_{\nu_{\mu} + \bar{\nu}_{\mu}} / (\text{GeV} \text{s}^{-1} \text{sr}^{-1} \text{cm}^{-2}) \]

\(E / \text{GeV}\)

P. Baerwald, S. Hümmer, and W. Winter, 
NeuCosmA – further particle decays

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

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

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
NeuCosmA – further particle decays

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\mu^+ & \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu \\
\mu^- & \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\
K^+ & \rightarrow \mu^+ + \nu_\mu \\
n & \rightarrow p + e^- + \bar{\nu}_e
\end{align*}
\]

Resulting $\nu_e$ flux (at the observer)

\[
E^2\phi_{\nu_e}(E,\theta) \text{ (GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2})
\]

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 \( \nu_\mu \) flux (at the observer)

\[ E^2 \phi_{\nu_\mu} / (\text{GeV} \text{ sr}^{-1} \text{ s}^{-1} \text{ cm}^{-2}) \]

\[ \text{Total flux} \]

\[ \text{from } \mu \]

\[ \text{WB flux} \]

\[ \text{from } \pi \]

\[ \text{from } K \]

\[ P. \text{ Baerwald, S. Hümmer, and W. Winter, Phys. Rev. D83, 067303 (2011)} \]
Corrections to the analytical model:

- **shape revised:**
  - shift of first break (correction of photohadronic threshold)
  - different cooling breaks for $\mu$'s and $\pi$'s
  - $(1 + z)$ correction on the variability scale of the GRB

- **Correction $c_{f\pi}$ to $\pi$ prod. efficiency:**
  - $f_{C\gamma}$: full spectral shape of photons
  - $f_\approx = 0.69$: rounding error in analytical calculation
  - $f_\sigma \approx 2/3$: from neglecting the width of the $\Delta$-resonance

- **Correction $c_S$:**
  - energy losses of secondaries
  - energy dependence of the mean free path of protons
Neutron model of UHECR emission under tension?

In 2012, IceCube ruled this analytical version of the fireball model –

- assumed a fixed baryonic loading of 10
- extrapolated diffuse $\nu$ flux from 117–215 GRBs (“quasi-diffuse”)
- analytical calculation – in tension with upper bounds

---

**Graph:**

- **X-axis:** Neutrino Energy (GeV)
- **Y-axis:** $E^2 \Phi_\nu$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)

**Curves:**

- Waxman & Bahcall
- IC40 limit
- IC40 Guetta et al.
- IC40+59 Combined limit
- IC40+59 Guetta et al.

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**References:**

The new prediction of the quasi-diffuse GRB $\nu$ flux

Repeat the IceCube GRB neutrino analysis, with NeuCosmA —

- Same GRB sample and parameters
- Calculate $\nu$ fluence for each burst and stacked fluence $F_\nu (E_\nu)$
- Quasi-diffuse flux ($N_{GRB} = 117$):

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

Flux $\sim 1$ order of magnitude lower!

S. Hümmer, P. Baerwald, W. Winter, 
*PRL* 108, 231101 (2012)
Improved IceCube bounds (2014)

- Only upgoing $\nu_\mu$'s with $> 1$ TeV used
- Four years of data (IC-40, -59, -79, -86)
- Larger GRB catalogue (506 bursts)
- One coincident event found, with low statistical significance
- $\lesssim 1\%$ of the diffuse flux can be from prompt GRB emission

![Graph showing exclusion limits for neutrino break energy and photon index](image)

A two-component model of CR emission

Optical depth:

\[
\tau_n = \left. \frac{t_p^{-1}}{t_{\text{dyn}}^{-1}} \right|_{E_p, \text{max}} = \begin{cases} \lesssim 1, & \text{optically thin source} \\ > 1, & \text{optically thick source} \end{cases}
\]

Particles can escape from within a shell of thickness \( \lambda'_{\text{mfp}} \):

\[
\begin{align*}
\lambda'_{p, \text{mfp}} (E') &= \min \left[ \Delta r', R'_{L} (E'), ct'_{p\gamma} (E') \right] \\
\lambda'_{n, \text{mfp}} (E') &= \min \left[ \Delta r', ct'_{p\gamma} (E') \right]
\end{align*}
\]

\[
f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta r'}
\]

fraction of escaping particles
We *need* direct proton escape

Scan of the GRB emission parameter space –

acceleration efficiency \[ \eta = 0.1 \]

\[ \eta = 1.0 \]

we need high efficiencies \( \Rightarrow \) direct proton escape is required

A two-component model of UHECR emission

Sample neutrino fluences –

**Optically thin source**

- $L_{\gamma,\text{iso}} = 10^{50} \text{ erg s}^{-1}$
- $\tau_n = 3.04 \times 10^{-2}$

**Optically thick source**

- $L_{\gamma,\text{iso}} = 10^{52} \text{ erg s}^{-1}$
- $\tau_n = 3.37$

---

We have seen that protons interact with the cosmological photon fields (CMB, etc.), e.g.,

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n , \]

and neutrinos are created in the decays of the secondaries:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

These are called *cosmogenic neutrinos*.
Cosmogenic neutrinos

\[ E^2 J_\nu (\text{all flavours}) \, [\text{GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

IC (2012–12) diffuse UHE all–flavor limit

\[ E \, [\text{GeV}] \]

\( \nu ' s \) in the GRB internal shock model

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

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

Normalisation to the observed GRB photon flux \(F_\gamma\)

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

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

\[
\mathcal{F}^{\text{sh}} = t_v V'_\text{iso} \frac{(1 + z)^2}{4\pi d_L^2} Q'
\]
\( Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^\infty c d\varepsilon' N'_\gamma(\varepsilon') R(E', E'_p, \varepsilon') \)

- Photon density, shock rest frame (GeV\(^{-1}\) cm\(^{-3}\)):
  \[
  N'_{\gamma}(\varepsilon') \propto \begin{cases} 
  (\varepsilon')^{\alpha_\gamma}, & \varepsilon'_{\gamma,\text{min}} = 0.2 \text{ eV} \leq \varepsilon' \leq \varepsilon'_{\gamma,\text{break}} \\
  (\varepsilon')^{\beta_\gamma}, & \varepsilon'_{\gamma,\text{break}} \leq \varepsilon' \leq \varepsilon'_{\gamma,\text{max}} = 300 \times \varepsilon'_{\gamma,\text{min}} 
  \end{cases}
  \]
  \[
  \varepsilon'_{\gamma,\text{break}} \approx 300 \times \text{keV}, \alpha_\gamma \approx 1, \beta_\gamma \approx 2
  \]

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

  Maximum proton energy limited by energy losses:
  \[
  t'_{\text{acc}}(E'_{p,\text{max}}) = \min \left[ t'_{\text{dyn}}(E'_{p,\text{max}}), t'_{\text{syn}}(E'_{p,\text{max}}), t'_p(\gamma)(E'_{p,\text{max}}) \right]
  \]
\( \nu' \)'s in the GRB internal shock model

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

\[
Q' (E') = \int_{E'}^{\infty} \frac{dE_p'}{E_p'} N_p' (E'_p) \int_{0}^{\infty} c d\epsilon' N'_\gamma (\epsilon') R (E', E'_p, \epsilon')
\]

Normalisation to the observed GRB photon flux \( F_\gamma \)

\[
\int \epsilon' N'_\gamma (\epsilon') \, d\epsilon' = \frac{E_{\text{sh}}}{V_{\text{iso}}} \propto F_\gamma, \quad \int E'_p N_p' (E'_p) \, dE'_p = \frac{1}{f_e} \frac{E_{\text{sh}}}{V_{\text{iso}}} \propto \frac{F_\gamma}{f_e}
\]

Mauricio Bustamante (CCAPP OSU)
\(\nu's\) in the GRB internal shock model

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

\[
Q'(E') = \int_{E'}^{\infty} \frac{dE_p'}{E_p'} N_p'(E_p') \int_{0}^{\infty} c d\varepsilon' N_\gamma'(\varepsilon') R(E', E'_p, \varepsilon')
\]

Normalisation to the observed GRB photon flux \(F_\gamma\)

\[
\int \varepsilon' N_\gamma'(\varepsilon') d\varepsilon' = \frac{E_{iso}^{sh}}{V_{iso}'} \propto F_\gamma, \quad \int E'_p N_p'(E'_p) dE'_p = \frac{1}{f_e} \frac{E_{iso}^{sh}}{V_{iso}'} \propto \frac{F_\gamma}{f_e}
\]

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

\[
F_{iso}^{sh} = t_v V_{iso}' \left(1 + z\right)^2 \frac{1}{4\pi d_L^2} Q'
\]
A fast-rise-exponential-decay (FRED) gamma-ray pulse is emitted in every collision:

\[ L_{\gamma} \sim R_C^{-2} \]
The prediction is robust

Simulations show only weak dependence of the flux on the boost \( \Gamma \) . . .

\[ E^2 J_{\nu_\mu} / \text{GeV\cdotcm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1} \]

\[ \Gamma_0=300, \langle \Gamma \rangle=222 \]

\[ \Gamma_0=500, \langle \Gamma \rangle=369 \]

\[ \Gamma_0=1000, \langle \Gamma \rangle=779 \]

. . . and on the GRB engine variability time \( \delta t_{\text{eng}} \)

\[ E^2 J_{\nu_\mu} / \text{GeV\cdotcm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1} \]

\[ N_{\text{sh}}=1000, N_{\text{coll}}=794, \delta t_{\text{eng}}=0.1s, t_v=0.67s \]

\[ N_{\text{sh}}=1000, N_{\text{coll}}=85, \delta t_{\text{eng}}=1.0s, t_v=11.89 \]

\[ N_{\text{sh}}=100, N_{\text{coll}}=87–97, \delta t_{\text{eng}}=0.1s, t_v=0.53–0.66s \]
Accelerating iron

- Photodisintegration destroys nuclei close to the center (~ 10^8 km) e.g., ANCHORDOQUI et al., Astropart. Phys. 29, 1 (2008)
- However, they can survive at large radii:

\[ \Gamma_0 = 500, \langle \Gamma \rangle = 369 \]

\[ E_{Fe,\text{max}} / \text{GeV} \]

\[ R_C / \text{km} \]

MB, BAERWALD, MURASE, WINTER
Nature Commun. 6, 6783 (2015)
Contribution of GRBs to the diffuse $\nu$ flux

- **Three populations:** high-luminosity long GRBs (HL-GRB), low-luminosity long GRBs (LL-GRB), short GRBs (sGRB)
- **Sub-PeV:** GRBs contribute a few % to the IceCube diffuse flux
- **PeV:** contribution could be higher

Initialising the burst simulation

Initial number of plasma shells in the jet: \( \gtrsim 1000 \)

Initial values of shell parameters:

- Width of shells and separation between them: \( l = d = c \cdot \delta t_{\text{eng}} \)
- Equal kinetic energy for all shells \( (\sim 10^{52} \text{ erg}) \)
- Shell speeds \( \Gamma_{k,0} \) follow a distribution (log-normal or other)
Propagating and colliding the shells

During propagation:
- speeds, masses, widths do not change (only in collisions)
- 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 circumburst medium \((\gtrsim 6 \times 10^{11} \text{ km})\)

\[
\text{final number of collisions} \approx \text{number of initial shells (\(\gtrsim 1000\))}
\]

How is the new prediction different?

- The top-contributing collisions are at the photosphere.
- Pion production efficiency there is independent of $\Gamma$:

$$f_{\gamma}^{\mathrm{ph}} \sim 5 \cdot \frac{\varepsilon}{0.25} \cdot \frac{\epsilon_e}{0.1} \cdot \frac{1 \text{ keV}}{\epsilon'_{\gamma,\text{break}}}$$

$\varepsilon$: energy dissipation efficiency
$\epsilon_e$: fraction of dissipated energy as e.m. output (photons)

- ⇒ Time-integrated neutrino fluence dominated is independent of $\Gamma$:

$$\mathcal{F}_\nu \propto \frac{N_{\text{coll}} \left( f_{\gamma}^{\gamma} \gtrsim 1 \right)}{N_{\text{coll}}^{\text{tot}}} \times \min \left[ 1, f_{\gamma}^{\mathrm{ph}} \right] \times \frac{\epsilon_p}{\epsilon_e} \times E_{\gamma}^{\text{iso-tot}}$$

- Compare to standard predictions, which have a $\langle \Gamma \rangle^{-4}$ dependence.
- Raising $\epsilon_p$ automatically decreases $\epsilon_e$, so the photosphere grows, but still $\sim 10$ photospheric collisions dominate.
How is the new prediction different?

- The top-contributing collisions are at the photosphere
- Pion production efficiency there is independent of $\Gamma$:

$$f_{p\gamma}^{ph} \sim 5 \cdot \frac{\varepsilon}{0.25} \cdot \frac{\varepsilon_e}{0.1} \cdot \frac{1 \text{ keV}}{\varepsilon'_{\gamma,\text{break}}}$$

$\varepsilon$: energy dissipation efficiency
$\varepsilon_e$: fraction of dissipated energy as e.m. output (photons)

- $\Rightarrow$ Time-integrated neutrino fluence dominated is independent of $\Gamma$:

$$\mathcal{F}_\nu \propto \frac{N_{coll} (f_{p\gamma} \gtrsim 1)}{N_{coll}^{tot}} \times \min \left[ 1, f_{p\gamma}^{ph} \right] \times \frac{10}{\varepsilon_p / \varepsilon_e} \times 10^{53} \text{ erg}$$

- Compare to standard predictions, which have a $\langle \Gamma \rangle^{-4}$ dependence
- Raising $\varepsilon_p$ automatically decreases $\varepsilon_e$, so the photosphere grows, but still $\sim 10$ photospheric collisions dominate
What about low-luminosity and choked GRBs?

- Low-luminosity and choked GRBs might be in the same family as high-luminosity long GRBs
- Due to lower jet speeds ($\Gamma_b$), they do not break out
- They might explain the TeV region of the IceCube diffuse $\nu$ flux:

![Graph showing multi-messenger GRB light curves with different jet speeds and IceCube data points.](image.png)