Gamma-ray bursts as UHECR (and neutrino) sources

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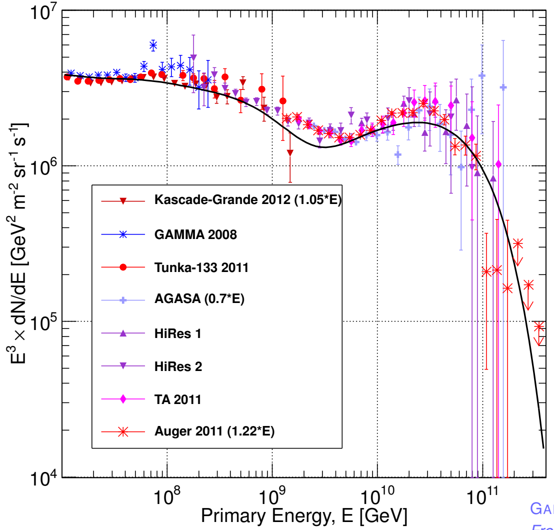
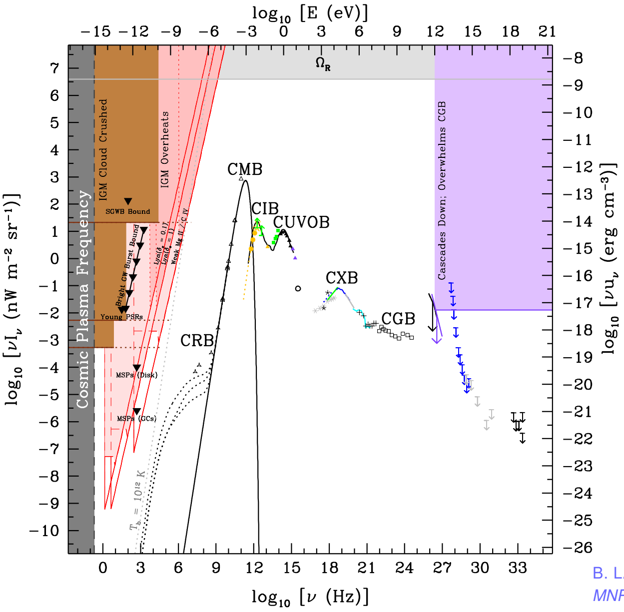
Ultra-high-energy cosmic rays

After 50+ years of UHECR measurements —



GAISSER, STANEV, TILAV, *Front. Phys. China* **8**, 748 (2013)

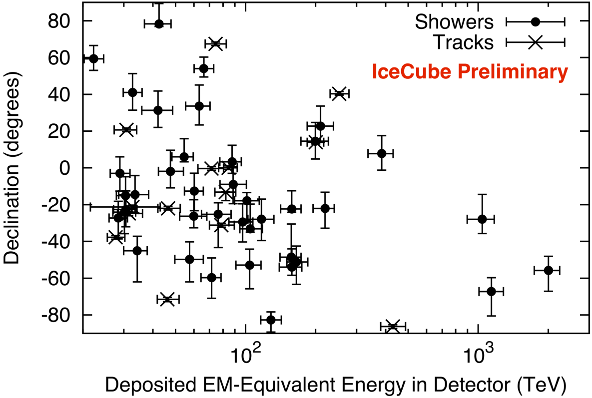
The electromagnetic sky



B. Lacki, *MNRAS* **406**, 863 (2010)

The high-energy neutrino sky

IceCube has reported 54 events with 30 TeV – 2 PeV in 4 years —



IceCube, ICRC2015

$9.0^{+8.0}_{-2.2}$ atmospheric neutrinos

12.6 ± 5.1 atmospheric muons

6.5σ detection

GRBs – good candidates for UHE CR & ν sources

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!

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

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3. Dark, "failed" GRBs might contribute an important part to the diffuse flux seen by IceCube

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   [I. Tamborra, S. Ando, *PRD* **93**, 053010 (2016)] [N. Senno, K. Murase, P. Mészáros, *PRD* **93**, 083003 (2016)]

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4. Neutrinos from GRB afterglows might be important at EeV energies (observable by radio neutrino detectors)

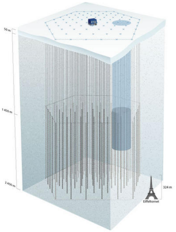
   [K. Murase, *PRD* **76**, 123001 (2007)] [S. Horiuchi, S. Ando, *PRD* **77**, 063007 (2008)]

   [S. Razzaque, L. Yang, *PRD* **91**, 043003 (2015)]

Why is *now* a good time to do this?

better, bigger detectors + loads of data + bright future

Neutrinos



- IceCube: diffuse flux of HE astrophysical ν's
- No point sources *yet*
- GRBs: low bg due to time and direction cuts
- IceCube-Gen2

GRBs

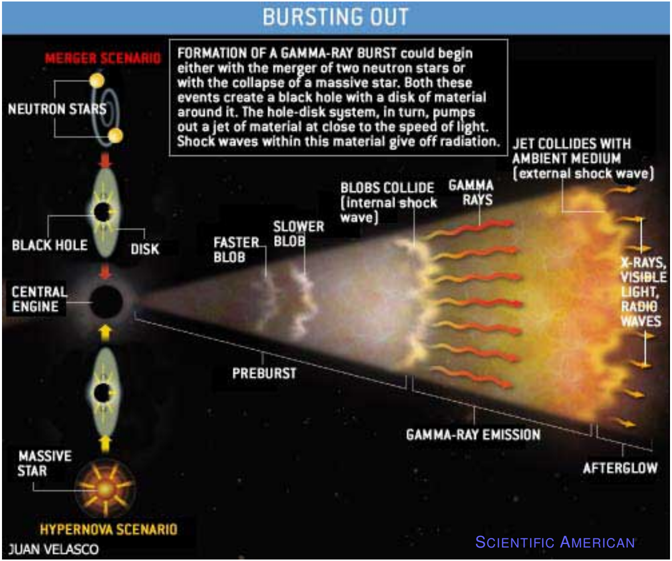
- *Fermi*: $\sim$ 250 GRBs yr^{-1} in 8 keV – 40 MeV
- $\sim$ 12 GRBs yr^{-1} in 20 MeV – 300 GeV
- different wavelengths: INTEGRAL, *Swift*
- 1000's GRBs detected so far

UHECRs

- Auger: 69 events > 57 EeV
- Telescope Array: 72 events
- surface + fluorescence
- future: LHAASO, JEM-EUSO

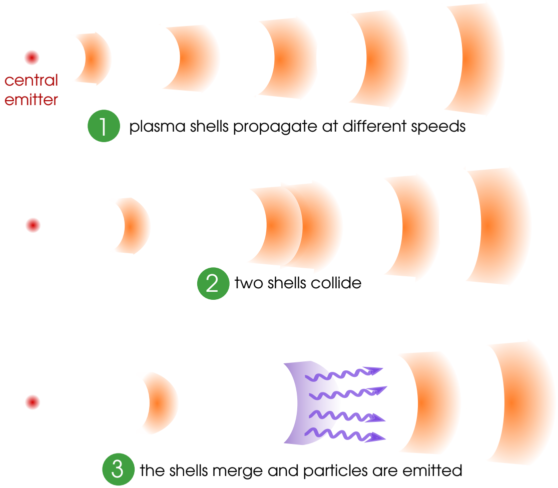
GRBs explained — the fireball model

Developed by Mészáros, Reese, Goodman, Pachinsky, *et al.* in the 1990s



Internal collisions

Relativistic expanding blobs of plasma collide with each other, merge, and emit UHE particles —



Producing the UHE ν's, CRs, γ rays – a first look

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

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

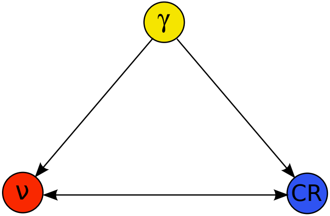
$$p\,\gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+ \,, & \text{BR} = 1/3 \\ p\pi^0 \,, & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



After propagation, with flavor mixing:

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

("one ν_μ per cosmic ray")

This neutron model of CR emission is now strongly disfavoured

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

What are the ingredients?

To calculate the ν flux from a GRB, we need:

- its gamma-ray luminosity L_γ^{iso} [erg s^{-1}] [measured]
- its variability timescale t_v [s], from the light curve [measured]
- the break energy of its photon spectrum $\epsilon_{\gamma,\text{break}}$ [MeV] [measured]
- the bulk Lorentz factor of its jet Γ [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,

energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8} \underbrace{\left[1 - (1 - \langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right]}_{f_\pi:\ \text{fraction of } p \text{ energy dumped to } \pi} \frac{1}{f_e} \int_{1\ \text{keV}}^{10\ \text{MeV}} d\epsilon_\gamma \epsilon_\gamma F_\gamma(\epsilon_\gamma)$$

ΔR: size of the emitting region
$\lambda_{p\gamma}$: mean free path for $p\gamma$ interactions
$\langle x_{p\to\pi}\rangle$: avg. fraction of p energy transferred to a π in one interaction
f_e^{-1}: ratio of energy in p's to energy in γ's/e's ("baryonic loading")

Optical depth to $p\gamma$:

$$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{0.01}{t_v}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\varepsilon_{\gamma,\mathrm{break}}}\right)$$

The original recipe: conventional fireball model

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

$$\mathcal{F}_\gamma(\varepsilon_\gamma) \propto \begin{cases} (\varepsilon_\gamma/\varepsilon_{\gamma,\text{break}})^{-1} & , \varepsilon_\gamma < \varepsilon_{\gamma,\text{break}} = 1 \text{ MeV} \\ (\varepsilon_\gamma/\varepsilon_{\gamma,\text{break}})^{-2.2} & , \varepsilon_\gamma \geq \varepsilon_{\gamma,\text{break}} \end{cases}$$

+

Assumed proton spectrum in the source

$$N'_p(E'_p) \propto E_p'^{-2} e^{-E'_p/E'_{p,\max}}$$

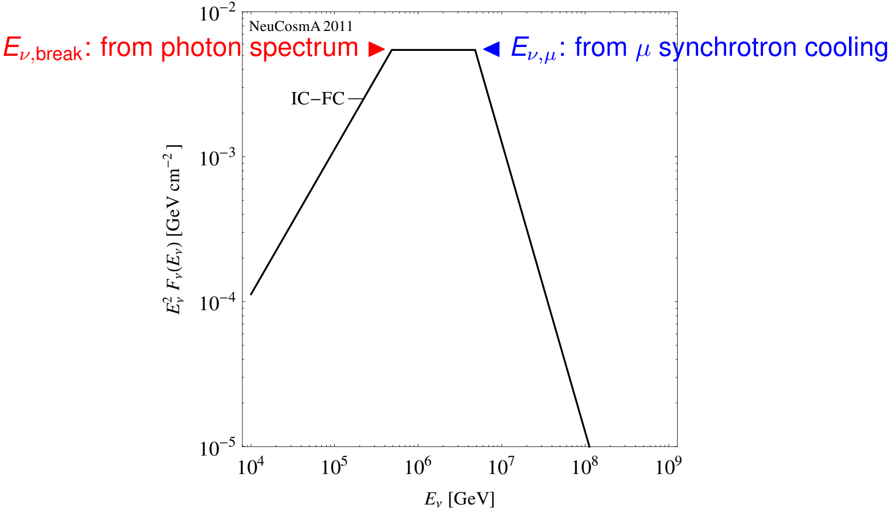
$$t'_{\text{acc}}(E'_{p,\max}) = \min\left[t'_{\text{dyn}}, t'_{\text{syn}}(E'_{p,\max}), t'_{p\gamma}(E'_{p,\max})\right]$$

=

Neutrino spectrum from $p\gamma$, via Δ resonance

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

Neutrino spectrum – conventional fireball

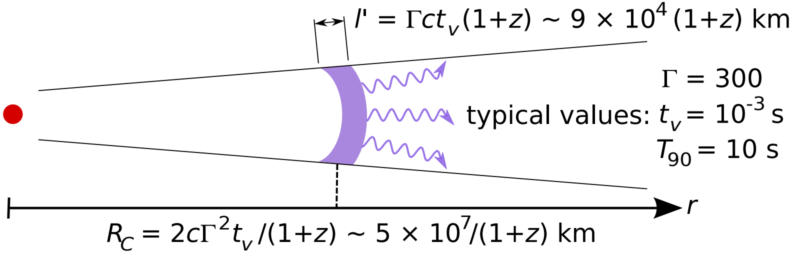


E. WAXMAN, J. N. BAHCALL, *PRL* **78**, 2292 (1997)

D. GUETTA *et al.*, *Astropart. Phys.* **20**, 429 (2004)

The one-zone approach

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

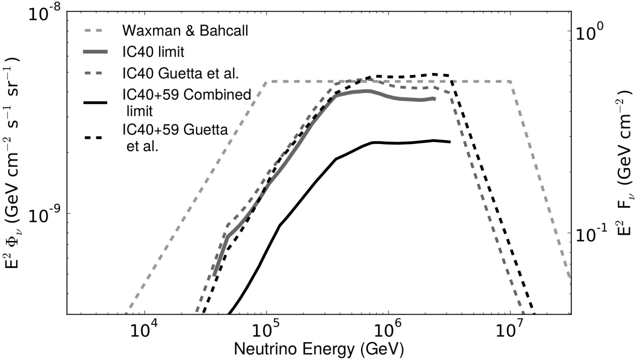


- Average speed Γ inferred from afterglow observations
- "Variability timescale" t_v measured from the light curve
- Redshift z measured for the host galaxy
- $N_{\rm coll} \approx T_{90}/t_v \sim$ 100–1000 identical collisions

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 ν flux from 117–215 GRBs ("quasi-diffuse")
- analytical calculation — in tension with upper bounds



IceCube, *Nature* **484**, 351 (2012)
M. Ahlers *et al. Astropart. Phys.* **35**, 87 (2011)
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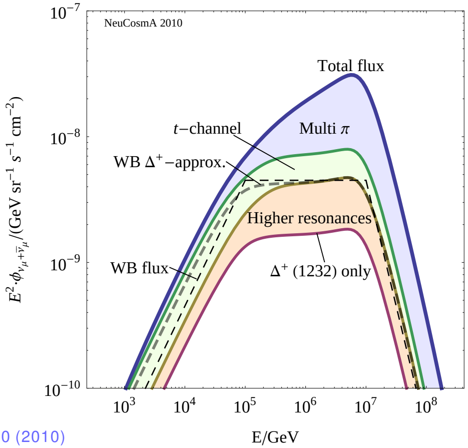
Revised GRB neutrino emission

NeuCosmA: numerical GRB neutrino emission —

What does it include?

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



S. Hümmer, M. Ruger, F. Spanier, W. Winter, *ApJ* **721**, 630 (2010)
S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)
Also: K. Murase, S. Nagataki, *PRD* **73**, 063002 (2006)

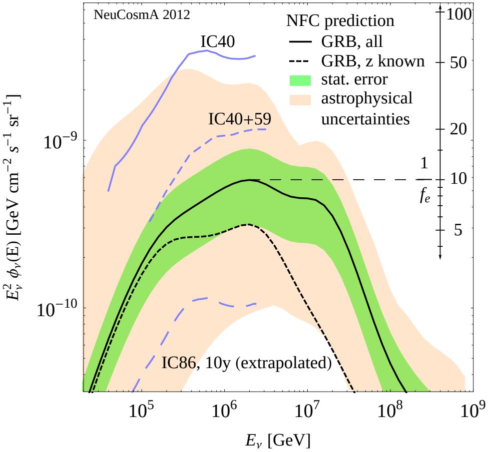
The new prediction of the quasi-diffuse GRB ν flux

Repeat the IceCube GRB neutrino analysis, with NeuCosmA —

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

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

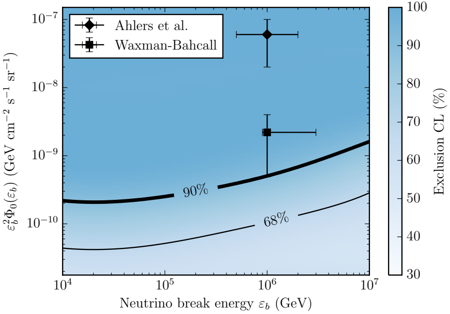
Flux $\sim$ 1 order of magnitude lower!

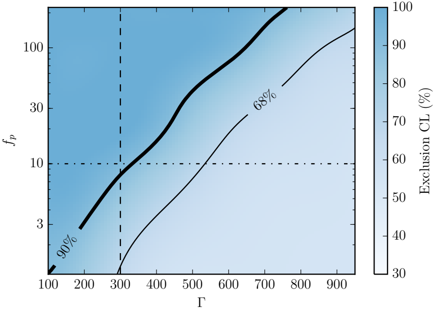


S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)

Improved IceCube limits (2016)

- 3 yr of showers (all flavors) + 4 yr of upgoing tracks with > 1 TeV
- Revised numerical GRB model (similar to NeuCosmA)
- 6 coincident events found (5 showers + 1 track) among 807 GRBs
- Low statistical significance
- $\lesssim$ 1% of the diffuse flux can be from prompt GRB emission





ICECUBE, 1601.06484

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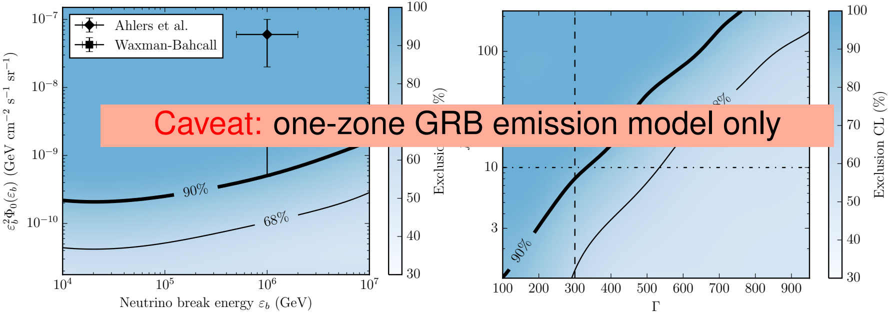

Caveat: one-zone GRB emission model only

IceCube, 1601.06484

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 disfavored as the sole sources of UHECRs (Ahlers *et al.*).

M. Ahlers, M. González-García, F. Halzen, *Astropart. Phys.* **35**, 87 (2011)

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What if 1 and 2 are violated?

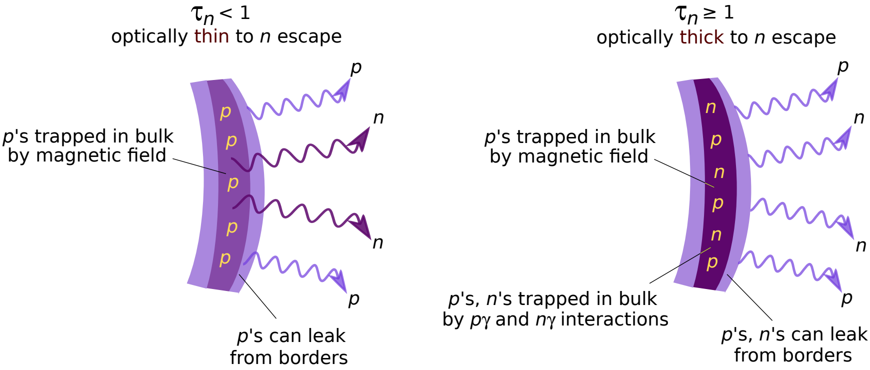
- *p*'s "leak out", not accompanied by (direct) ν production
- multiple *p* interactions enhance the ν flux
- in *optically thick sources*, only *n*'s at the borders escape

M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN, *Astropart. Phys.* **35**, 87 (2011)

Going beyond the neutron model

Now UHECRs escape as either

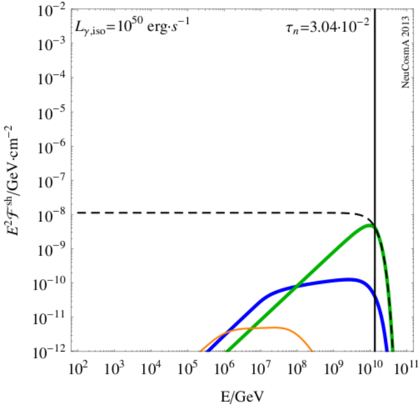
- neutrons, which decay into protons outside the source; or
- protons that leak out without interacting inside the source



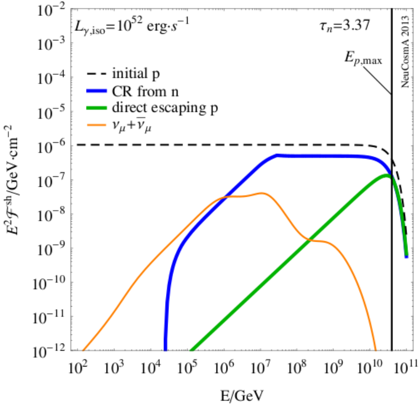
A two-component model of UHECR emission

Sample neutrino fluences –

Optically **thin** source



Optically **thick** source

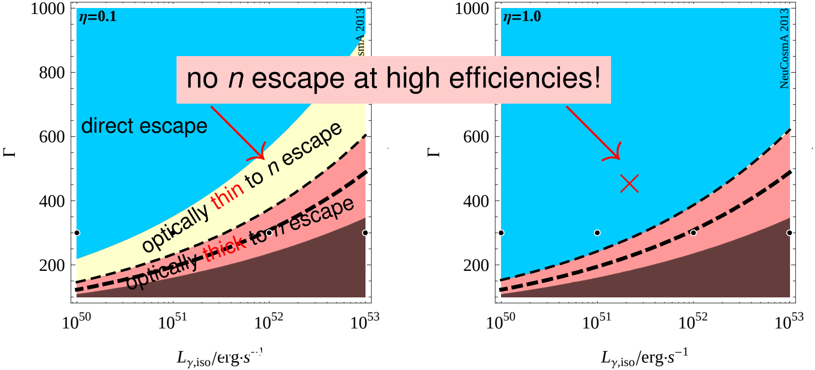


P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

We *need* direct proton escape

Scan of the GRB emission parameter space —

acceleration efficiency $\longrightarrow$ $\eta = 0.1$ $\quad t'_{\mathrm{acc}}\left(E'_p\right) = \dfrac{E'_p}{\eta c e B'}$ $\quad \eta = 1.0$

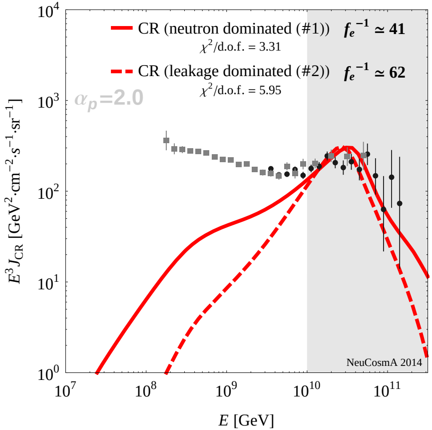


P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

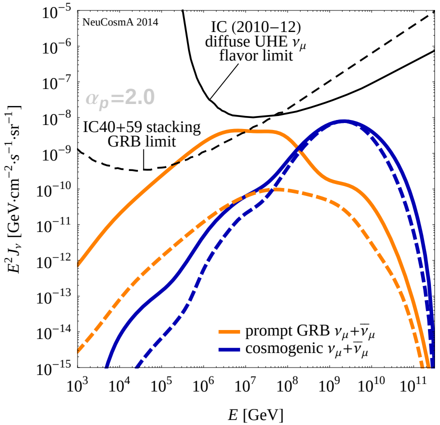
We need high efficiencies $\Rightarrow$ direct proton escape *is* required

Neutron model vs. two-component model: prompt and cosmogenic ν's

UHECRs



Neutrinos



P. Baerwald, MB, W. Winter, *ApJ* **768**, 186 (2013)
P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)
See also: H. He *et al.*, *ApJ* **752**, 29 (2012)

Using UHECR + neutrino constraints

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

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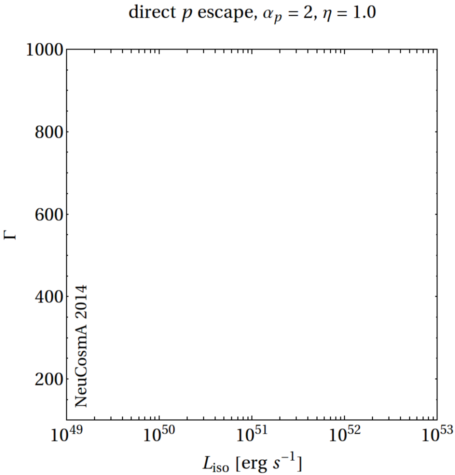

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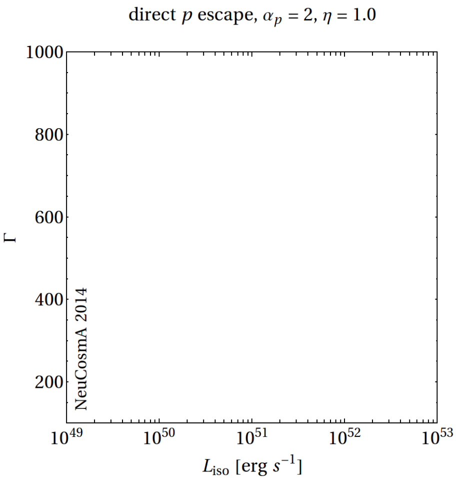

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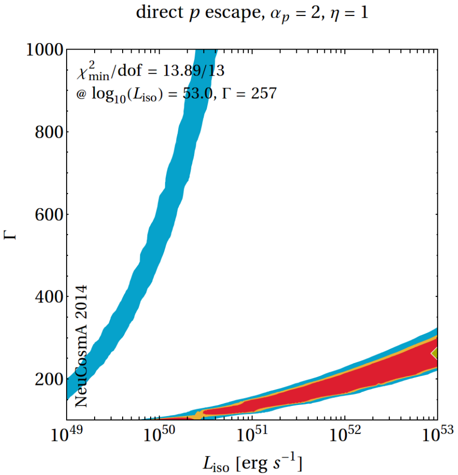

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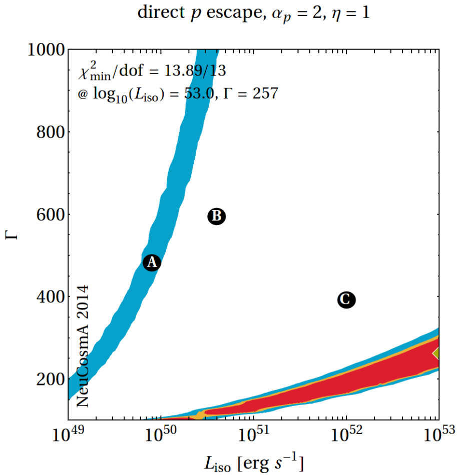

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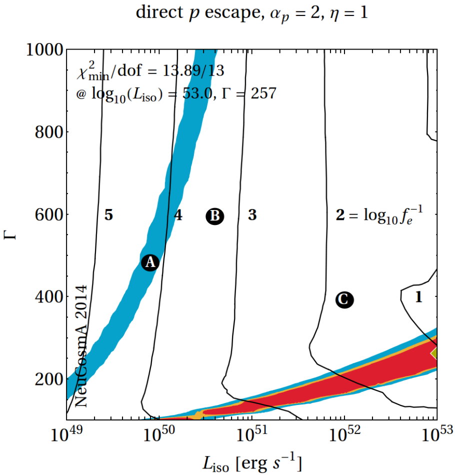

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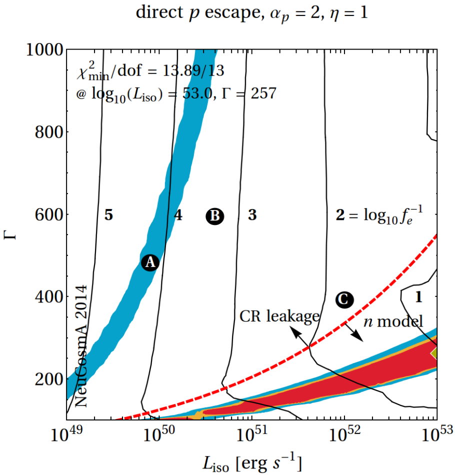
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage



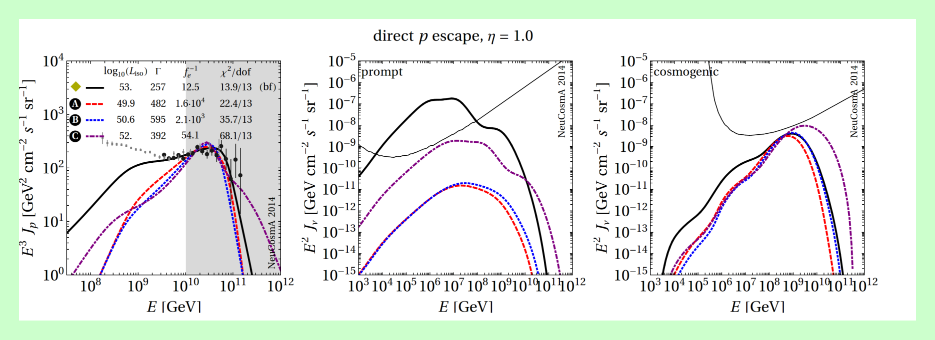
P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

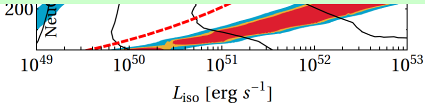
Using UHECR + neutrino constraints

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

1. Generate the UHECR spectrum at every

direct p escape, $\alpha_p = 2$, $\eta = 1$





P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

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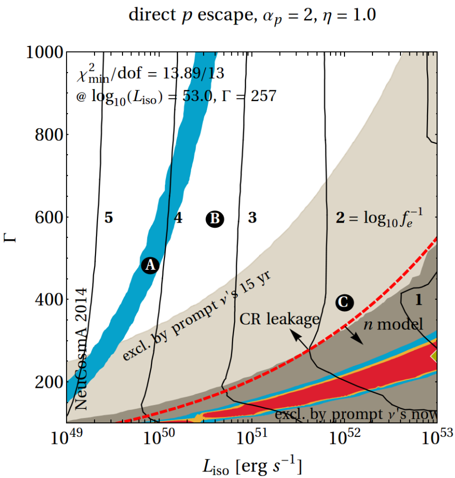
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to UHECR data (TA, PAO, HiRes)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
4. Find the baryonic loading (*i.e.*, relative energy of *p*'s to *e*'s) at each point
5. Identify the region corresponding to pure *n* escape and to *n* escape + CR leakage
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.



P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

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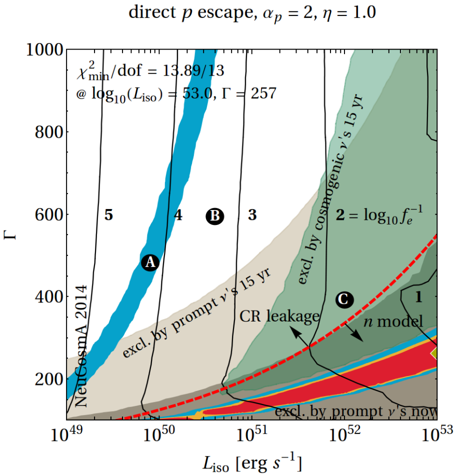
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude

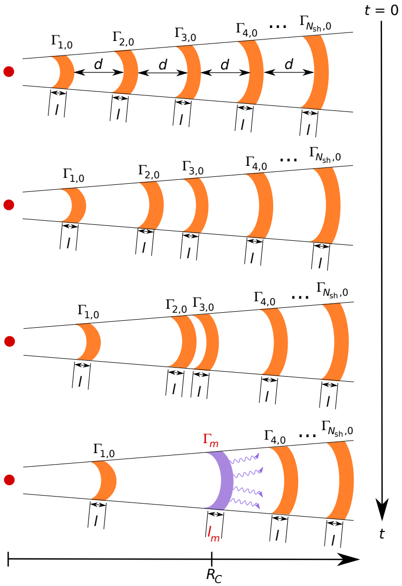


P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

Going further: an evolving burst

Consider an evolving fireball –

- the fireball expands with time
- $\sim$ 1000 shells propagate with different speeds
- they have different masses
- they collide at different radii (collisions no longer identical)



What is different?

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

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

Each collision occurs in a different emission regime –

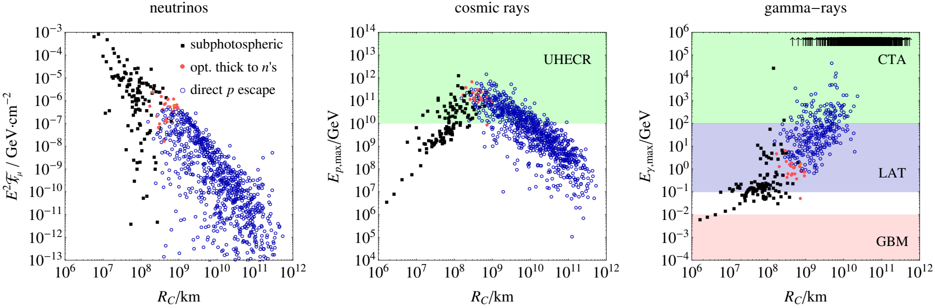
Sub-photospheric: $\tau_{e\gamma} > 1$

$\nu_\mu + \bar{\nu}_\mu$ fluence

maximum p energy

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

maximum γ energy

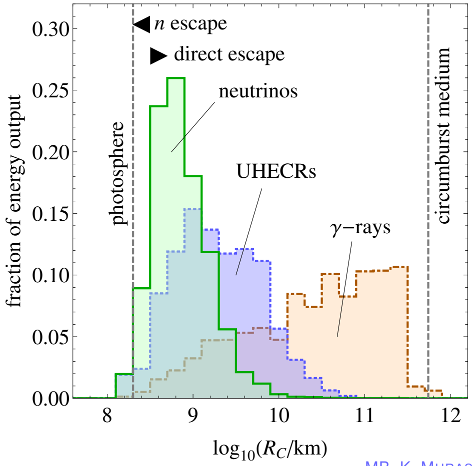


(observer's frame) (source frame)

MB, P. Baerwald, K. Murase, W. Winter, *Nat. Commun.* **6**, 6783 (2015)

Different particles come from different jet regions

Emission of different species peaks at different collision radii —



Why?

As the fireball expands, photon and proton densities fall

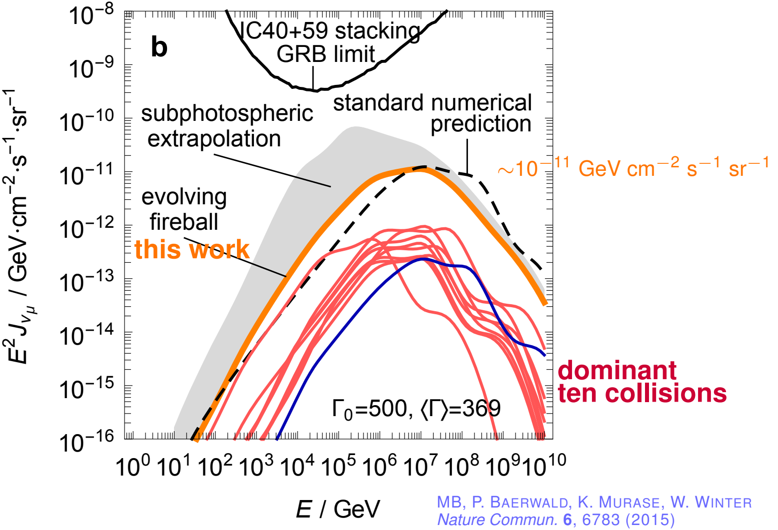
Why does it matter?

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

MB, K. MURASE, W. WINTER, 1606.02325
MB, P. BAERWALD, K. MURASE, W. WINTER, *Nat. Commun.* **6**, 6783 (2015)

A robust minimal diffuse ν flux from GRBs

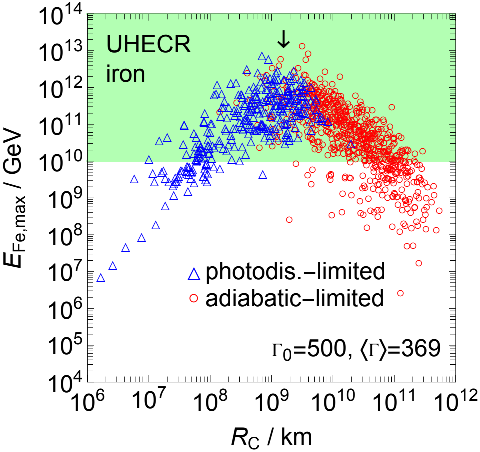
- Take the simulated burst as stereotypical
- Quasi-diffuse neutrino flux, assuming 667 identical GRBs per year:



MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

Accelerating iron

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



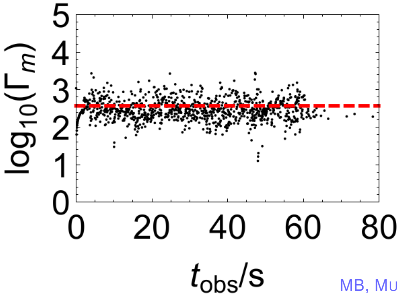
MB, BAERWALD, MURASE, WINTER

What makes a GRB bright in neutrinos?

- Goal: to use the morphology of the GRB gamma-ray light curve to assess whether the burst is neutrino-bright
- The central engine determines the features of the light curve

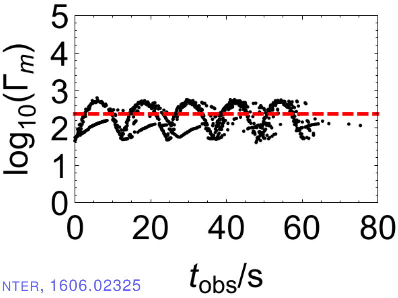
Undisciplined GRB engine

Engine emits shells with broad Γ distribution



Disciplined GRB engine

Engine emits shells with narrow Γ distribution



MB, Murase, Winter, 1606.02325

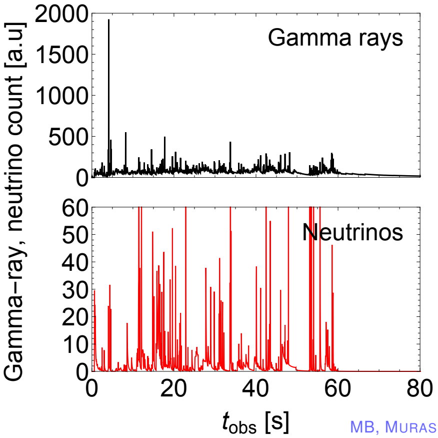
Light curves

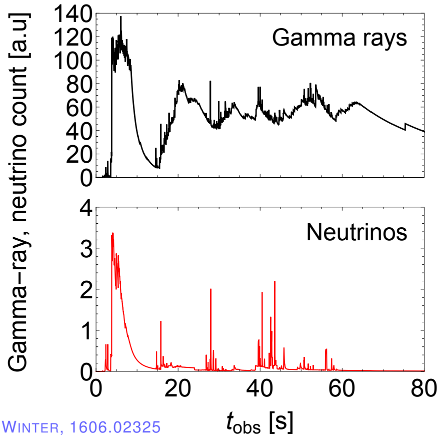
Undisciplined GRB engine

- Fast variability dominates
- No broad pulses

Disciplined GRB engine

- Broad pulses dominate
- Fast variability on top





MB, Murase, Winter, 1606.02325

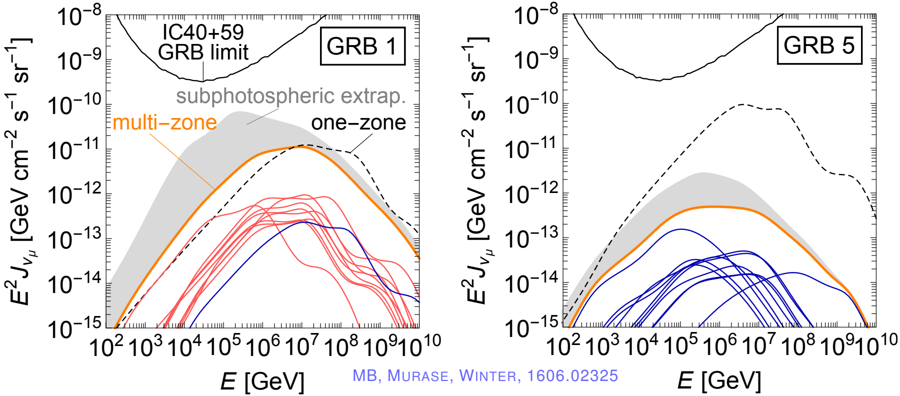
Compare the quasi-diffuse neutrino fluxes:

Undisciplined GRB engine

$\sim 10^{-11}$ GeV cm^{-1} s^{-1} sr^{-1}

Disciplined GRB engine

$\sim 5 \cdot 10^{-13}$ GeV cm^{-1} s^{-1} sr^{-1}



MB, Murase, Winter, 1606.02325

$\therefore$ An undisciplined engine makes a GRB neutrino-bright

Conclusions . . . and the future

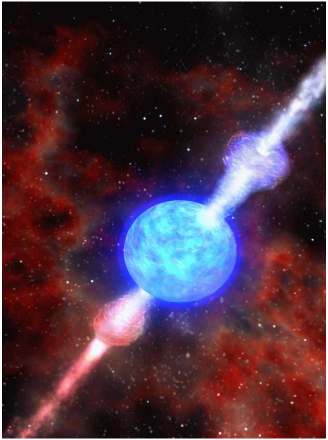
- GRBs *are* good UHECR and ν source candidates
- *But* the CR-ν-γ connection is trickier than originally thought
- Need next-gen neutrino telescopes (IceCube-Gen2, KM3NeT) . . .
- . . . while Auger, Telescope Array, CTA, *etc.* gather extensive UHECR statistics

Backup slides

GRBs – what are they?

GRBs: the most luminous explosions in the Universe

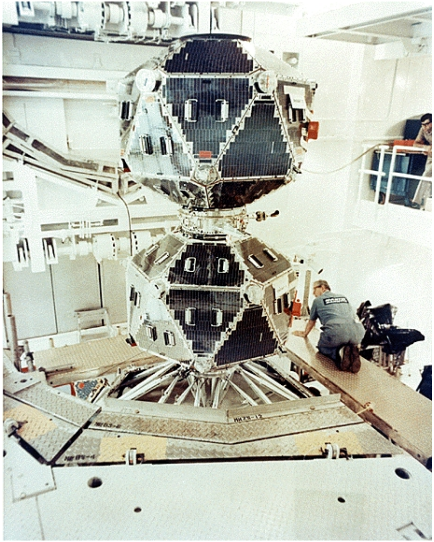
- **brief** flashes of gamma rays: from 0.1 s to few 100's s
- isotropically distributed in the sky
- they are **far**: most occur at ~ 1 Gpc from us ($z \approx 2$)
- they are **rare**: ~ 0.3 Gpc^{-3} yr^{-1}
- two populations:
  - **short-duration (< 2 s):** neutron star-neutron star or NS-black hole mergers
  - **long-duration (> 2 s):** associated to hypernovae
- powered by matter accretion onto a black hole



GRBs – an accidental discovery

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

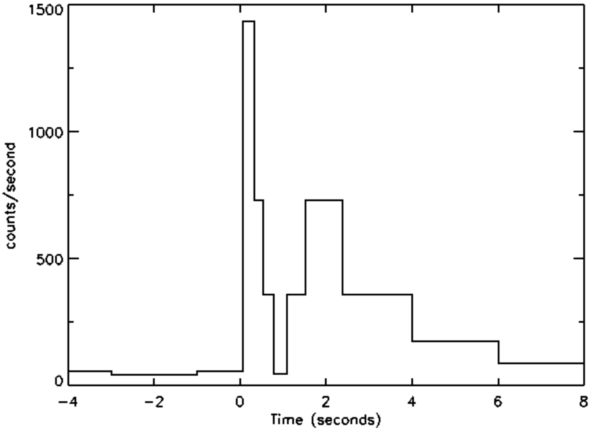
- They carried X-ray, gamma-ray, and neutron detectors
- *Vela* 5a-b had enough spatial resolution to pinpoint the direction of events
- Intense gamma-ray emission from a nuclear explosion lasts $\lesssim 10^{-6}$ s ...
- ... however, longer-lasting emissions were detected



VELA 5A/B SATELLITES (NASA)

GRBs – the first one detected

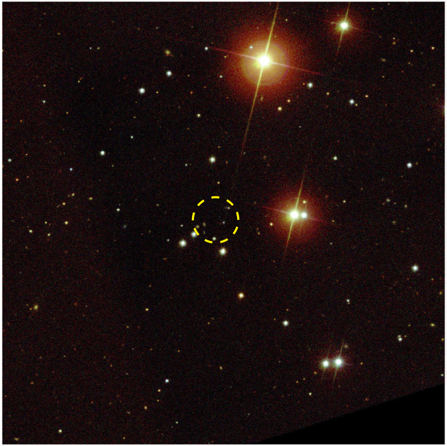
First GRB detected: July 2, 1967, 14:19 UTC

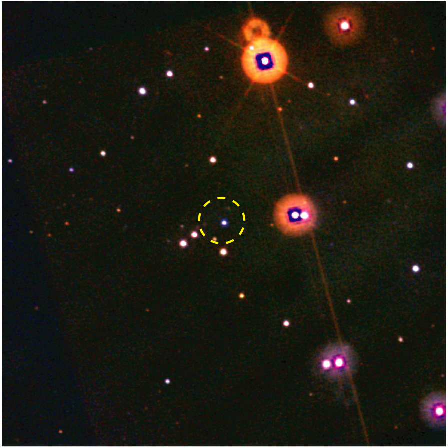


Detected by *Vela* 3, 4a, 4b (found on archival data)

What do they *look* like?

e.g., GRB060218 seen by *Swift*

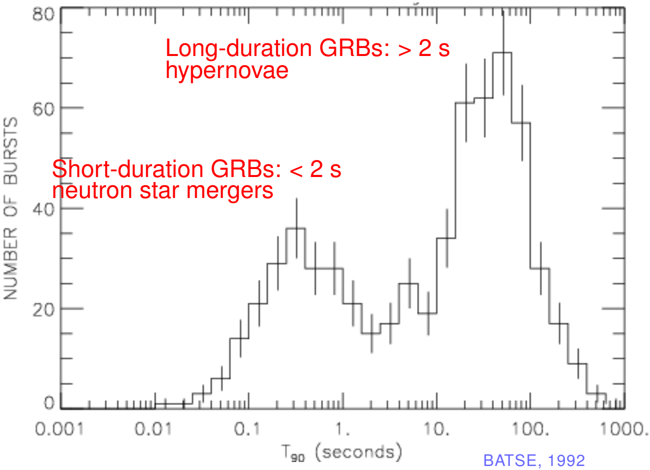




SDSS, SWIFT COLLAB., SLOAN FOUNDATION, NSF, NASA

GRBs – two populations

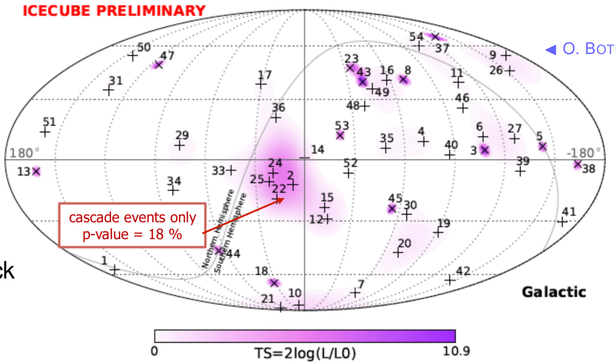
Two populations of GRBs:



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

What about the sources of HE neutrinos?

Arrival directions compatible with an isotropic distribution –



◀ O. BOTNER, IPA 2015

+: shower
×: muon track

No association with sources found yet

NeuCosmA: revised GRB particle emission – I

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

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

- 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: $N'_p\left(E'_p\right) \propto E_p'^{-\alpha_p} e^{-E'_p/E'_{p,\text{max}}} \quad (\alpha_p \gtrsim 2)$

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

- Protons: $N'_p\left(E'_p\right) \propto E'^{-\alpha_p}_p e^{-E'_p/E'_{p,\text{max}}} \quad (\alpha_p \gtrsim 2)$

NeuCosmA: revised GRB particle emission — II

Injected/ejected spectrum of secondaries (π, K, n, ν, etc.):

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

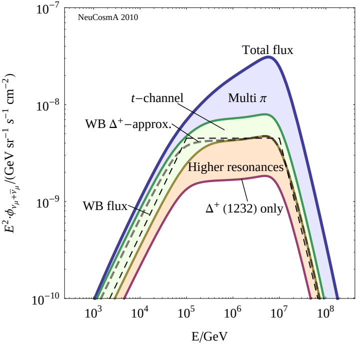
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

response function

R contains cross sections, multiplicities for different channels

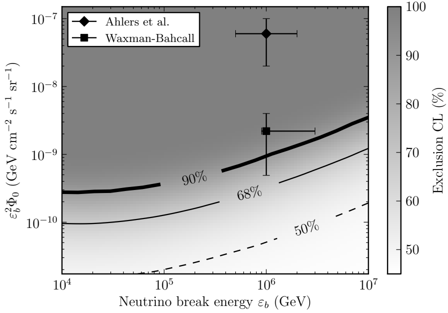
What does NeuCosmA include?

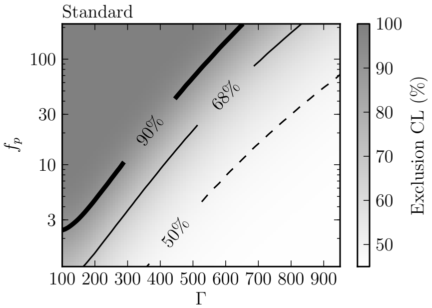
- $p\gamma \to \Delta^+(1232) \to \pi^0, \pi^+, \ldots$
- extra K, n, π^-, multi-π prod. modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum
- neutrino flavor transitions



Improved IceCube bounds (2014)

- Only upgoing ν_μ'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

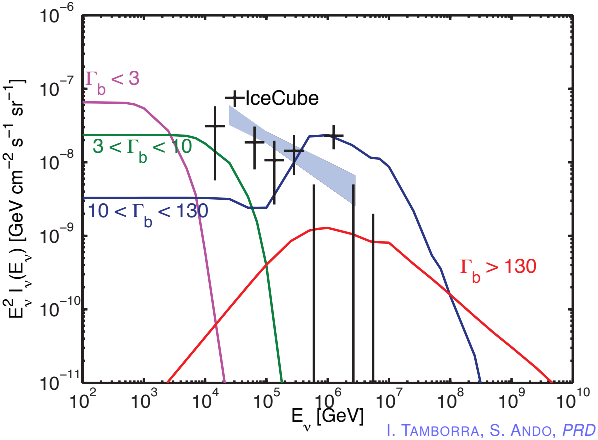




[IceCube, *ApJ* **805**, L5 (2015)]

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 (Γ_b), they do not break out
- They might explain the TeV region of the IceCube diffuse ν flux:



I. Tamborra, S. Ando, *PRD* **93**, 053010 (2016)

NeuCosmA: (revised) GRB particle emission – II

Normalize the particle densities at the source —

- Photons:

$$\underbrace{\text{photon energy density per collision}}_{\int E'_\gamma \ N'_\gamma\left(E'_\gamma\right) \ dE'_\gamma} = \frac{\overbrace{\text{total gamma-ray energy of burst}}^{E^{\text{iso},\prime}_{\gamma,\text{tot}} \sim 10^{53} \text{ erg (from observed fluence)}}}{\underbrace{\text{number of collisions}}_{N_{\text{coll}}} \cdot \underbrace{\text{volume of one collision}}_{V'_{\text{iso}}}}$$

- Protons:

baryonic loading (energy in p's / energy in e's + γ's), *e.g.*, 10

$$\underbrace{\text{proton energy density per collision}}_{\int E'_p \ N'_p\left(E'_p\right) \ dE'_p} = \boxed{\frac{1}{f_e}} \cdot \text{photon energy density per collision}$$

A two-component model of CR emission

Optical depth:

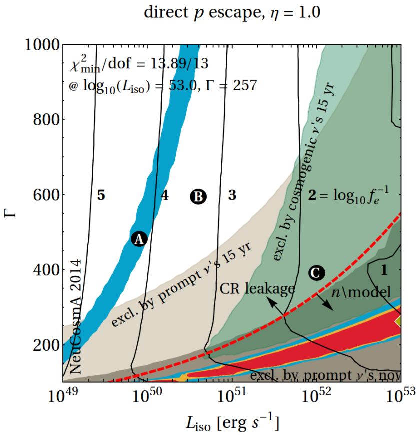
$$\tau_n = \left.\frac{t_{p\gamma}^{-1}}{t_{\text{dyn}}^{-1}}\right|_{E_{p,\max}} = \begin{cases} \lesssim 1\,, & \text{optically } \textbf{thin} \text{ source} \\ > 1\,, & \text{optically } \textbf{thick} \text{ source} \end{cases}$$

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

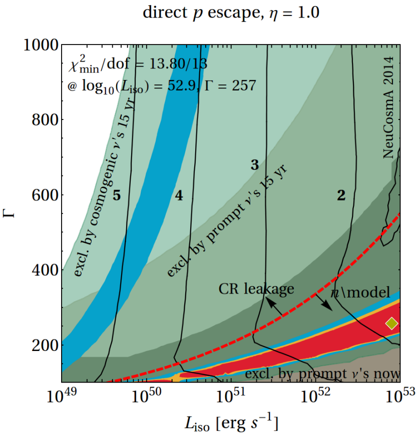
$$\left.\begin{array}{l} \lambda'_{p,\text{mfp}}\left(E'\right) = \min\left[\Delta r', R'_L\left(E'\right), ct'_{p\gamma}\left(E'\right)\right] \\ \lambda'_{n,\text{mfp}}\left(E'\right) = \min\left[\Delta r', ct'_{p\gamma}\left(E'\right)\right] \end{array}\right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta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

fraction of escaping particles

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

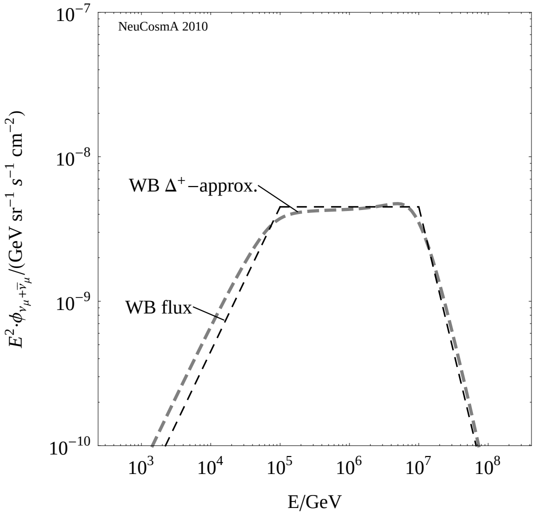


$n_{\rm GRB}(z) \propto \rho_{\rm SFR}(z)$
(star formation rate)



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

NeuCosmA – the full photohadronic cross section

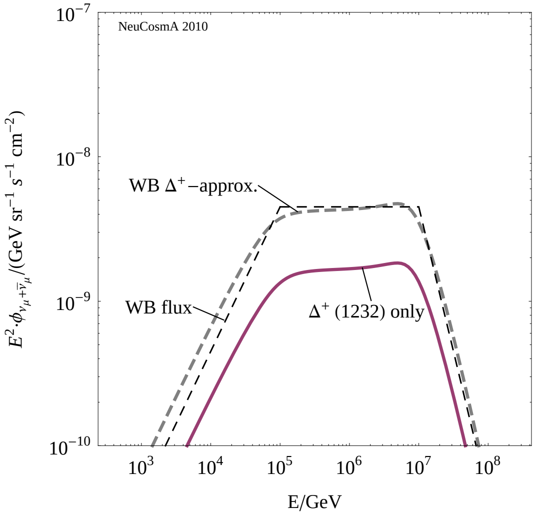


NeuCosmA – the full photohadronic cross section

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

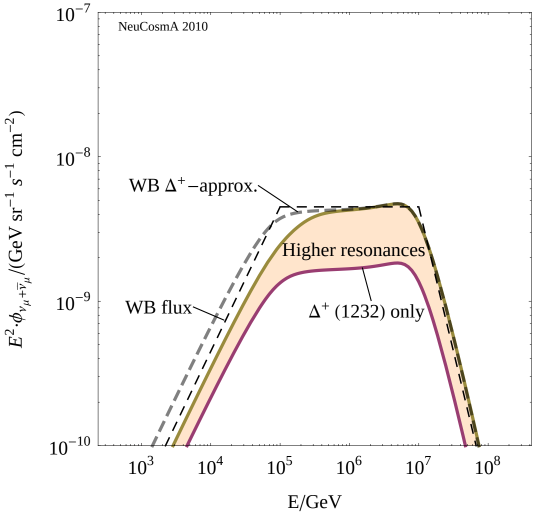


NeuCosmA – the full photohadronic cross section

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)



NeuCosmA – the full photohadronic cross section

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

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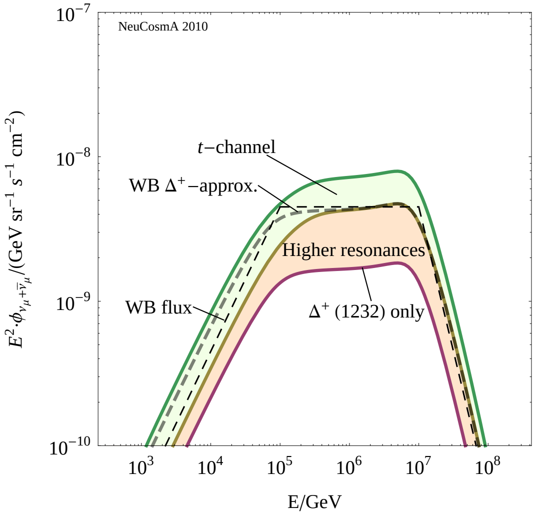
- *t*-channel (direct production)

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

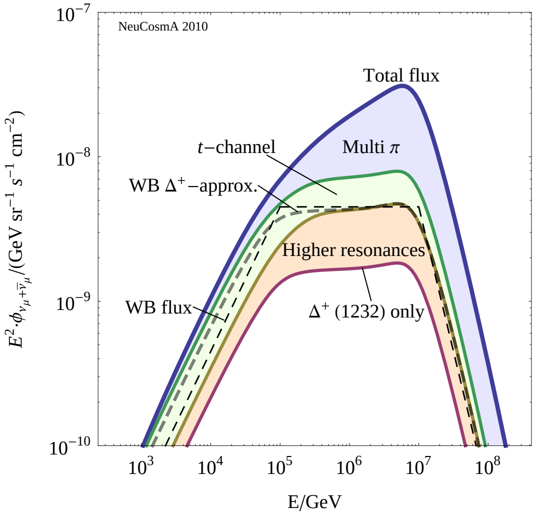


NeuCosmA – the full photohadronic cross section

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

NeuCosmA – further particle decays

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

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

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

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

NeuCosmA – further particle decays

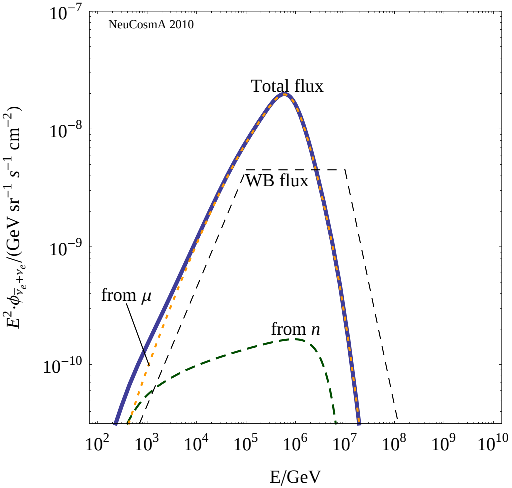
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

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

Resulting ν_e flux (at the observer)



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

NeuCosmA – further particle decays

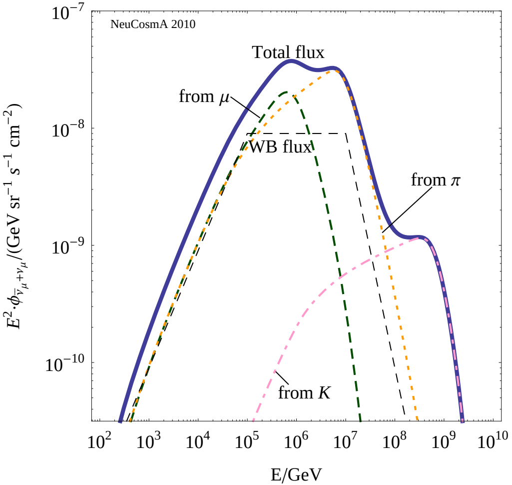
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

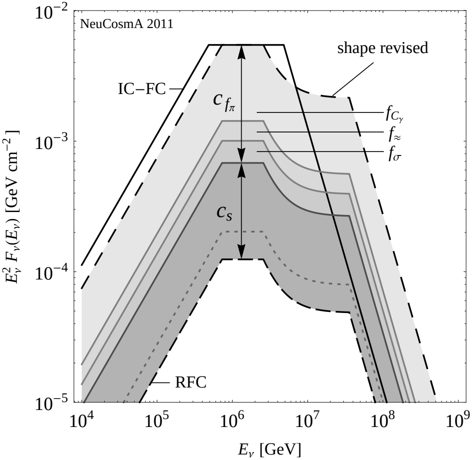
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Resulting ν_μ flux (at the observer)



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

NeuCosmA – how the neutrino spectrum changes – I

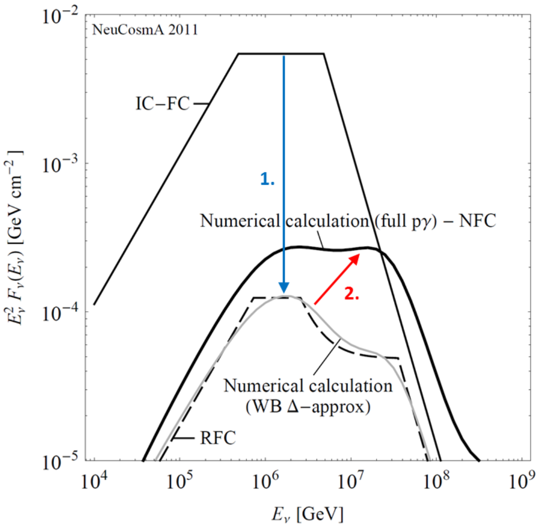


S. Hümmer, P. Baerwald, W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

Corrections to the analytical model:

- shape revised:
  - shift of first break (correction of photohadronic threshold)
  - different cooling breaks for μ's and π's
  - $(1+z)$ correction on the variability scale of the GRB
- Correction cf_π to π prod. efficiency:
  - f_{C_γ}: full spectral shape of photons
  - $f_\approx = 0.69$: rounding error in analytical calculation
  - $f_\sigma \simeq 2/3$: from neglecting the width of the Δ-resonance
- Correction c_S:
  - energy losses of secondaries
  - energy dependence of the mean free path of protons

NeuCosmA – how the neutrino spectrum changes – II



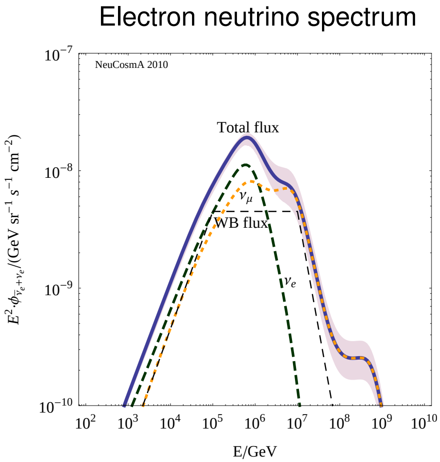
For example, GRB080603A:

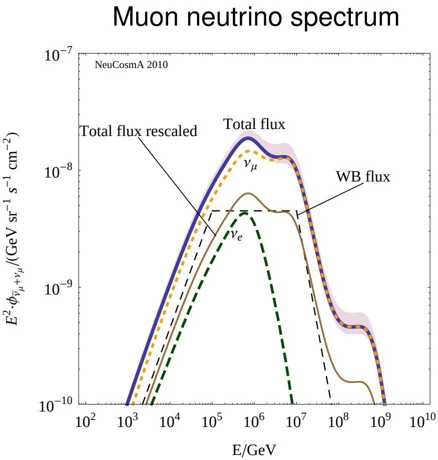
1. Correction to analytical model (IC-FC $\rightarrow$ RFC)
2. Change due to full numerical calculation

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

S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)

NeuCosmA – neutrino spectra including flavor mixing





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

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

The need for km-scale neutrino telescopes

Expected ν flux from cosmological accelerators (Waxman & Bahcall 1997 & 1998):

$$E^2\Phi_\nu \sim 10^{-8}\frac{f_\pi}{0.2}\left(\frac{\dot{\varepsilon}_{\rm CR}^{[10^{10},10^{12}]}}{10^{44}~\text{erg Mpc}^{-3}~\text{yr}^{-1}}\right)~\text{GeV cm}^{-2}~\text{s}^{-1}~\text{sr}^{-1}$$

Integrated flux above 1 PeV:

$$\Phi_\nu(>1~\text{PeV}) \sim \int_{1~\text{PeV}}^{\infty}\frac{10^{-8}}{E^2}\,dE \sim 10^{-20}~\text{cm}^{-2}~\text{s}^{-1}~\text{sr}^{-1}$$

Number of events from half of the sky (2π):

$$N_\nu \simeq 2\pi\cdot\Phi_\nu(>1~\text{PeV})\cdot 1~\text{yr}\cdot A_{\rm eff} \approx \left(2.4\times10^{-10}~\text{cm}^{-2}\right)A_{\rm eff}~,$$

where $A_{\rm eff}$ is the effective area of the detector

To detect $N_\nu > 1$ events per year, we need an area of

$$A_{\rm eff} \gtrsim 0.4~\text{km}^2$$

Therefore, we need km-scale detectors, like IceCube

Cosmogenic neutrinos

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

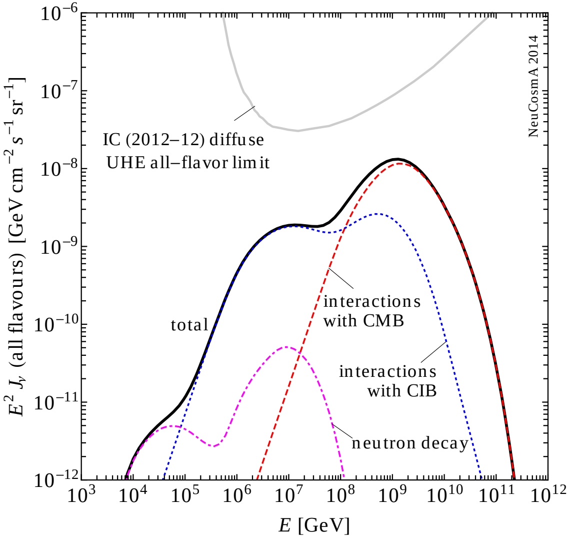
$$p + \gamma \to \Delta^+ \to \pi^+ + n \,,$$

and neutrinos are created in the decays of the secondaries:

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

These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Interaction with the photon backgrounds – I

- Energy loss rate (GeV s^{-1}):

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

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

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

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

G. BLUMENTHAL, *Phys. Rev.* **D 1**, 1596 (1970)
H. BETHE, W. HEITLER, *Proc. Roy. Soc.* **A146**, 83 (1934)

Interaction with the photon backgrounds – II

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

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

1. For given values of E and z, NeuCosmA calculates the cooling rate $t_{p\gamma}^{-1} \equiv -(1/E)\, b_{p\gamma}$ (s^{-1}) as

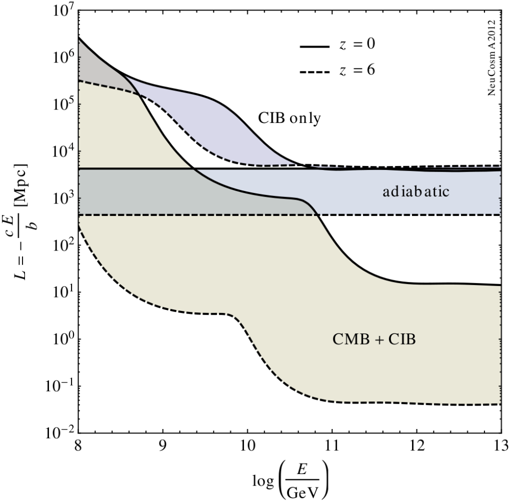
$$t_{p\gamma}^{-1}(E,z) = \sum_{i}^{\text{all channels}} \Gamma_{p\to p}^{i}(E,z)\, K^i \ ,$$

   with $K^i E$ the loss of energy per interaction
2. From this, we calculate back $b_{p\gamma}$ (GeV s^{-1}) ...
3. ...and the corresponding energy-loss term in the transport equation, $\partial_E(b_{p\gamma}Y_p)$.

S. Hümmer, M. Rüger, F. Spanier, W. Winter, *Astrophys. J.* **721**, 630 (2010) [1002.1310]

Interaction lengths

Note that $L_{\text{CIB}} \gg L_{\text{CMB}}$:



Matches, *e.g.*, H. Takami, K. Murase, S. Nagataki, K. Sato, *Astropart. Phys.* **31**, 201 (2009) [0704.0979]

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})

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

UHE ν's in the GRB internal shock model

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

UHE ν's in the GRB internal shock model

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

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

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UHE ν's in the GRB internal shock model

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

Normalisation to the observed GRB photon flux F_γ

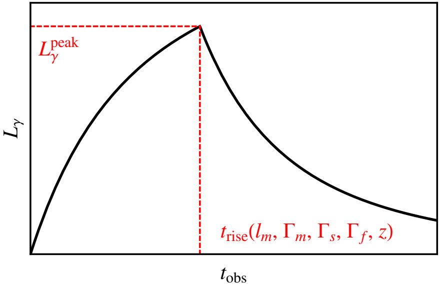
$$\int \varepsilon' N'_\gamma\left(\varepsilon'\right) d\varepsilon' = \frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto F_\gamma \ , \quad \int E'_p N'_p\left(E'_p\right) dE'_p = \frac{1}{f_e}\frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto \frac{F_\gamma}{f_e}$$

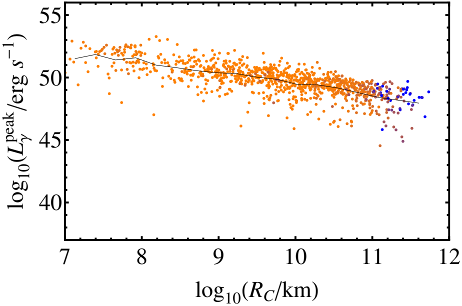
Fluence per shell, at Earth (GeV^{-1} cm^{-2})

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

Gamma-ray and neutrino pulses

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

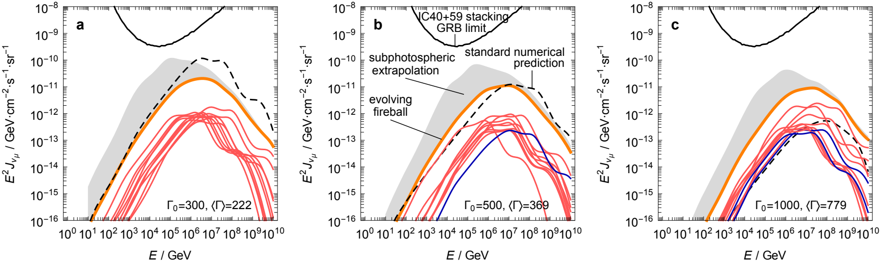




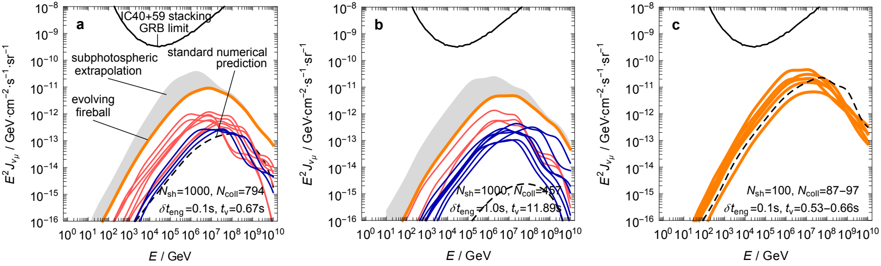
$$L_\gamma^{\rm peak} \sim R_C^{-2}$$

The prediction *is* robust

Simulations show only weak dependence of the **flux** on the boost Γ . . .



. . . and on the GRB engine variability time $\delta t_{\rm eng}$



Propagating the UHECRs to Earth

We use a Boltzmann equation to transport protons to Earth:

- Comoving number density of protons (GeV^{-1} cm^{-3}):

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

  with n_p the real number density

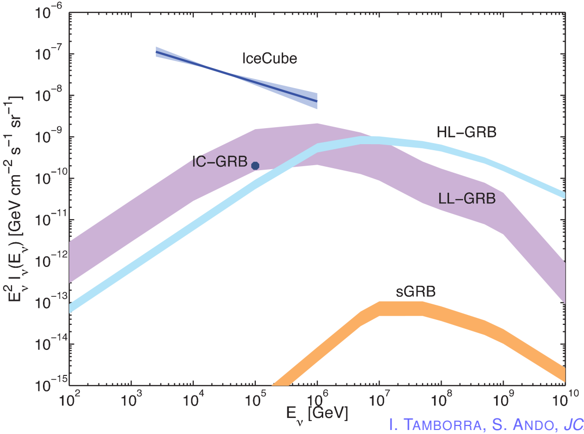
- Transport equation (comoving source frame):

$$\dot{Y}_p = \underbrace{\partial_E\left(HEY_p\right)}_{\text{adiabatic losses}} + \underbrace{\partial_E\left(b_{e^+e^-}Y_p\right)}_{\text{pair production losses}} + \underbrace{\partial_E\left(b_{p\gamma}Y_p\right)}_{\text{photohadronic losses}} + \underbrace{\mathcal{L}_{\rm CR}}_{\text{CR injection from sources}}$$

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

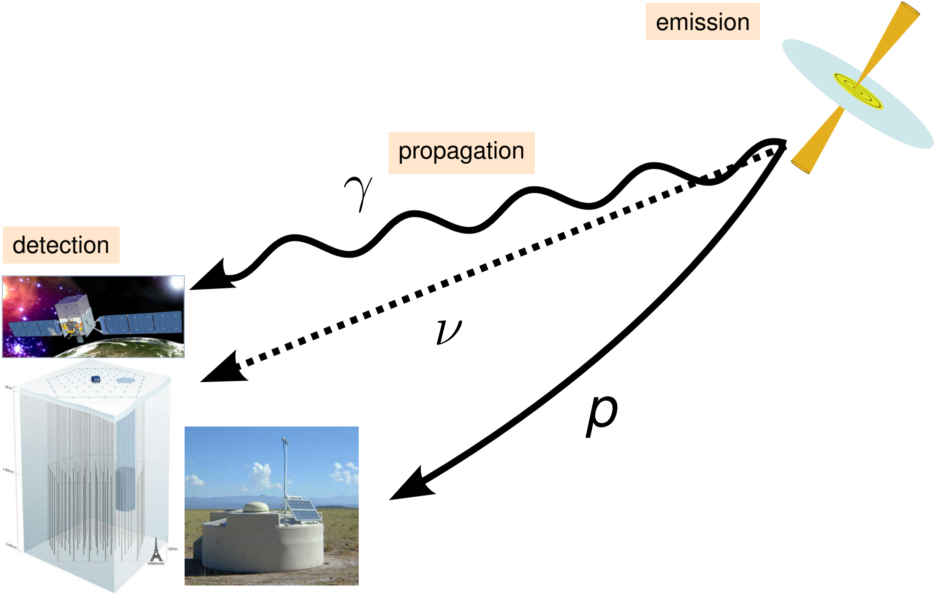
Contribution of GRBs to the diffuse ν flux

- 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

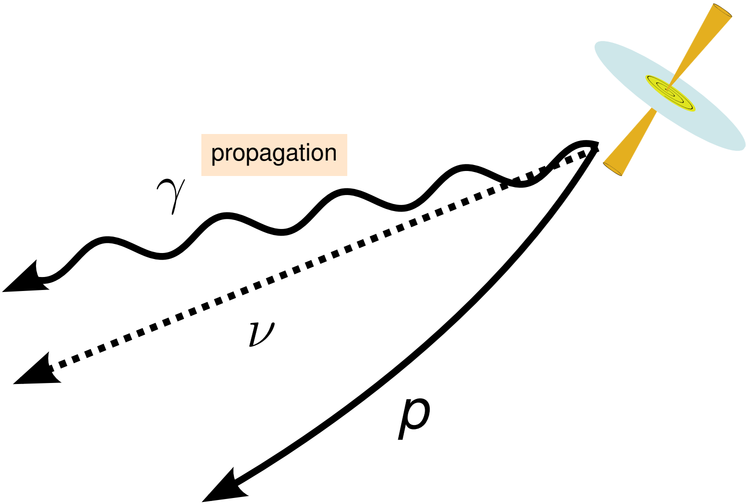


I. Tamborra, S. Ando, *JCAP* **1509**, 036 (2015)

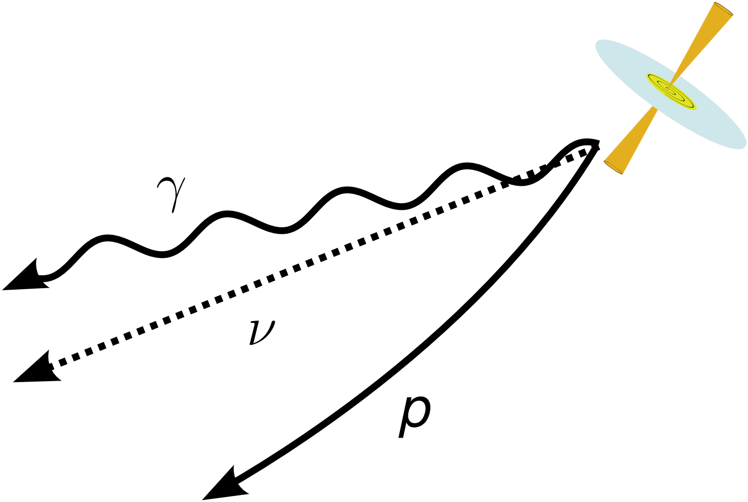
From the sources to us



From the sources to us



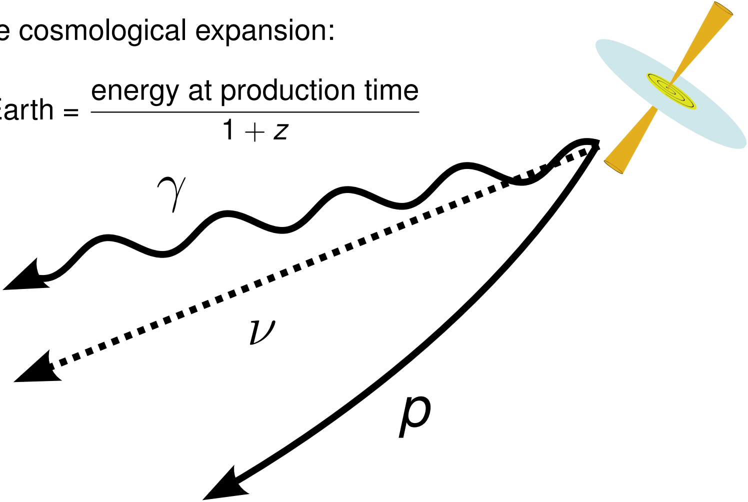
From the sources to us



From the sources to us

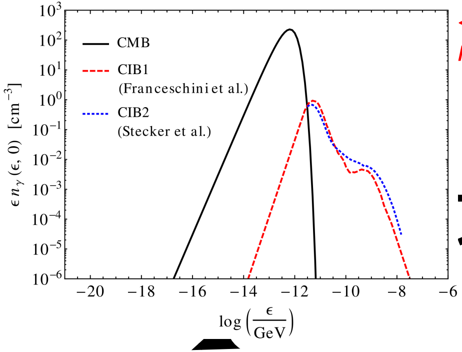
Because of the cosmological expansion:

$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$

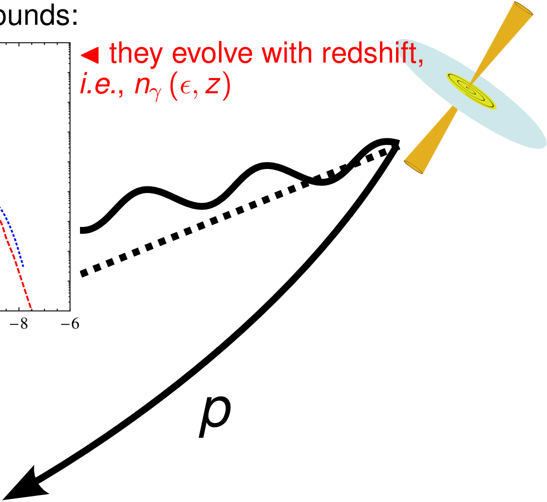


From the sources to us

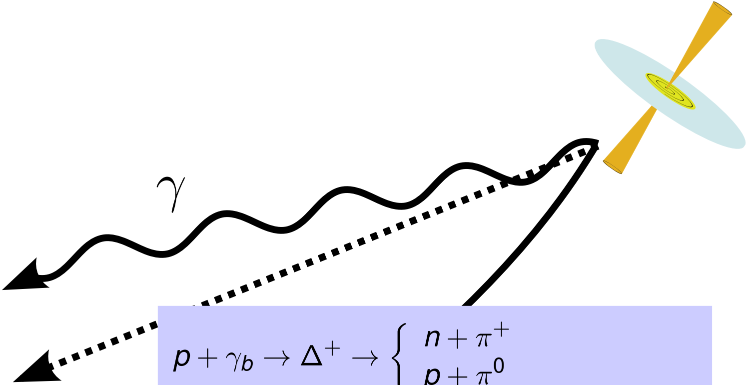
Cosmological photon backgrounds:



◀ they evolve with redshift, *i.e.*, $n_\gamma(\epsilon, z)$



From the sources to us



$$p + \gamma_b \to \Delta^+ \to \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

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

Cosmogenic ν's: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

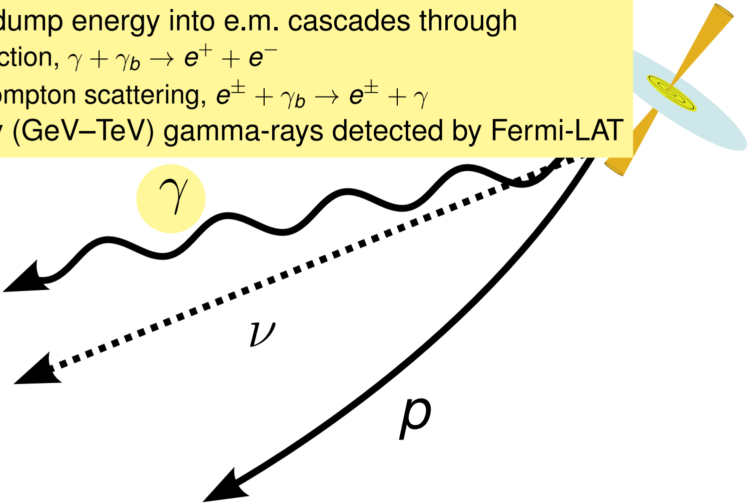
$n \to p + e^- + \bar{\nu}_e$

From the sources to us

γ's and $e^{\pm}$'s dump energy into e.m. cascades through

- pair production, $\gamma + \gamma_b \to e^+ + e^-$
- inverse Compton scattering, $e^{\pm} + \gamma_b \to e^{\pm} + \gamma$

Lower-energy (GeV–TeV) gamma-rays detected by Fermi-LAT



From the sources to us

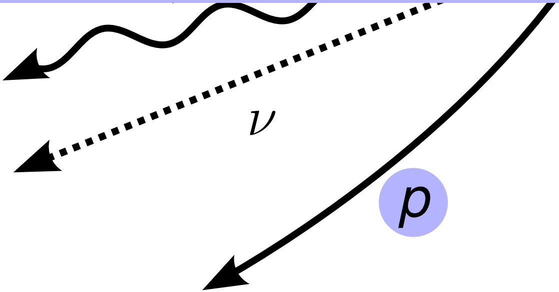
p's are deflected by extragalactic magnetic fields
$\Rightarrow$ except for the most energetic ones, they are **not** expected to point back to the sources

Pierre Auger found weak correlation with known AGN positions

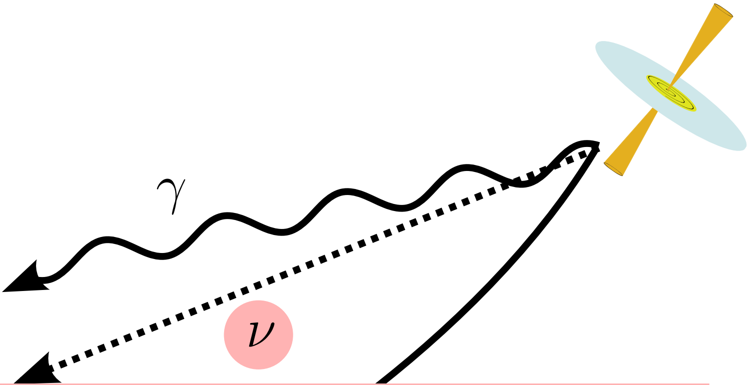
They lose energy through:

- pair production, $p + \gamma_b \rightarrow p + e^+ + e^-$
- photohadronic interactions, $p\gamma_b$

depend on the redshift evolution of the cosmological γ backgrounds



From the sources to us



Initial UHE ν flavor fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Probability of $\nu_\alpha \to \nu_\beta$ transition: $P_{\alpha\beta}\,(E_0, z)$

Flavor oscillations redistribute the fluxes

– at Earth: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ (might be changed by exotic physics!)

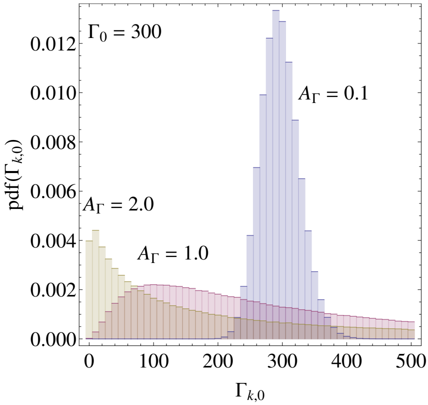
MB, Beacom, Winter, *PRL* **115**, 161302 (2015)

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

$A_\Gamma \gg 1$

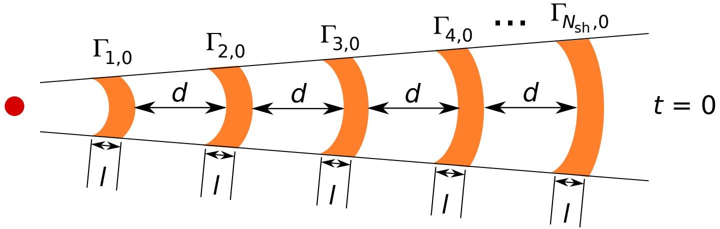
Spread too large, too many collisions at low radii

$A_\Gamma \approx 1$

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

Initialising the burst simulation

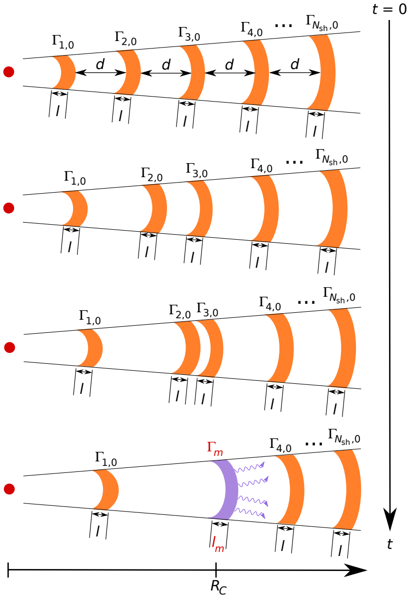
Initial number of plasma shells in the jet: $\gtrsim 1000$



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 ($\sim 10^{52}$ 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 ($\gtrsim 6 \times 10^{11}$ km)

final number of collisions

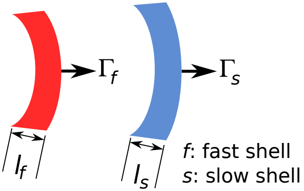
$\approx$

number of initial shells ($\gtrsim 1000$)

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

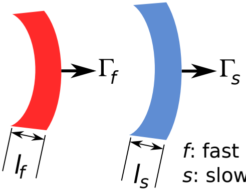
Anatomy of an internal collision

1. Propagation



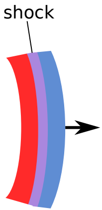
Anatomy of an internal collision

1 Propagation



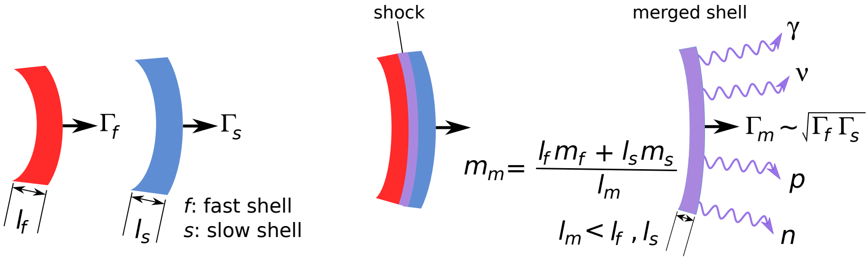
f: fast shell
s: slow shell

2 Collision



Anatomy of an internal collision

1 Propagation **2** Collision **3** Radiation



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

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

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

How is the new prediction different?

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

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

ε: energy dissipation efficiency
ϵ_e: fraction of dissipated energy as e.m. output (photons)

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

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

- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 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 Γ:

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

ε: energy dissipation efficiency
ϵ_e: fraction of dissipated energy as e.m. output (photons)

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

$$\mathcal{F}_\nu \propto \frac{\overset{\sim 10}{N_{\text{coll}}\left(f_{p\gamma} \gtrsim 1\right)}}{\underset{\sim 1000}{N_{\text{coll}}^{\text{tot}}}} \times \min\left[1, f_{p\gamma}^{\text{ph}}\right] \times \overset{10}{\frac{\epsilon_p}{\epsilon_e}} \times \overset{10^{53}\ \text{erg}}{E_{\gamma-\text{tot}}^{\text{iso}}}$$

- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 10 photospheric collisions dominate

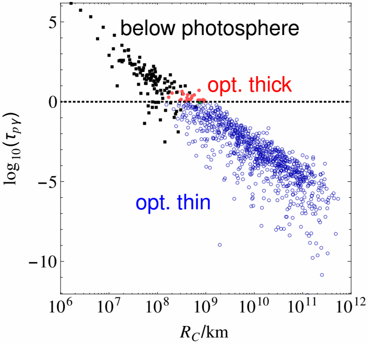
Why?

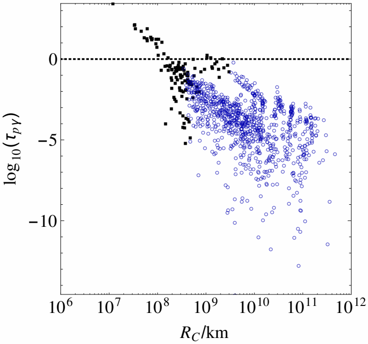
Undisciplined GRB engine

- Shells have very different speeds
- Collide quickly, close to engine
- High p and γ densities
- $\sim$ 10 optically-thick bursts near the photosphere

Disciplined GRB engine

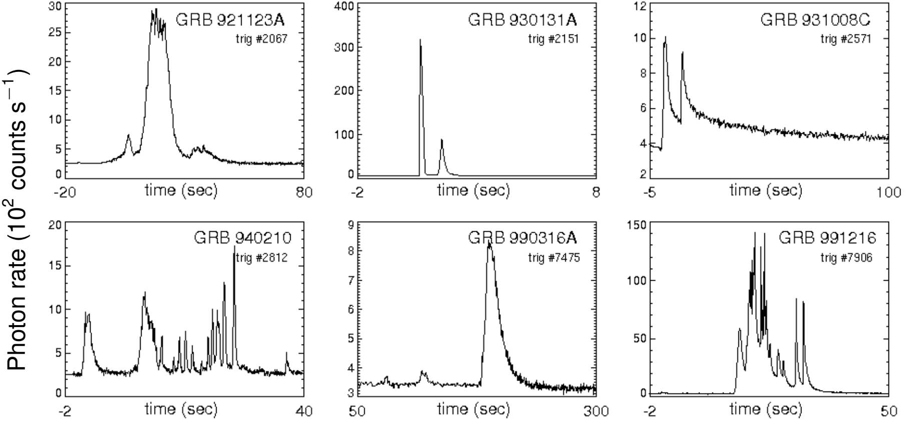
- Shells have similar speeds
- Collide far from engine
- Low p and γ densities
- All (superphotospheric) collisions are optically thin





GRBs – a zoo of light curves

GRB light curves come in different shapes:

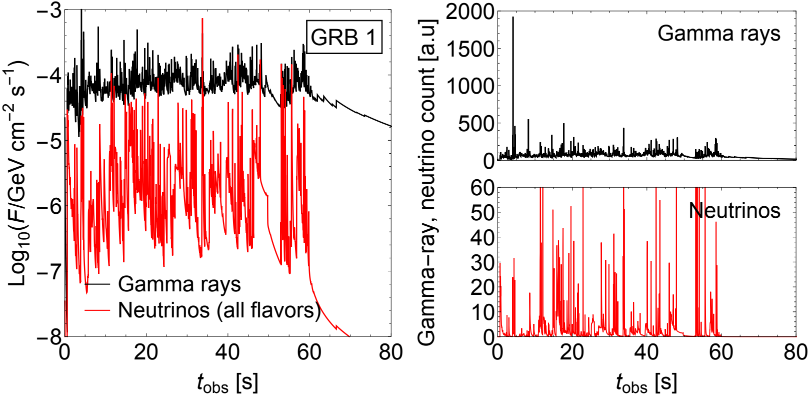


BATSE

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

Synthetic light curves

An emission pulse is assigned to each collision
– their superposition yields a synthetic light curve:

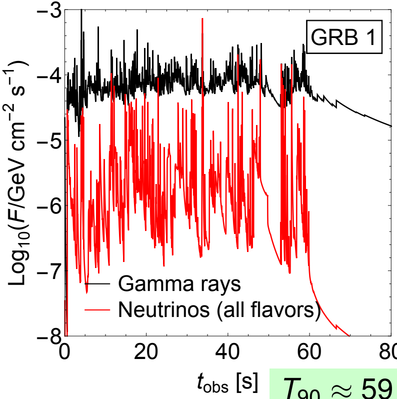


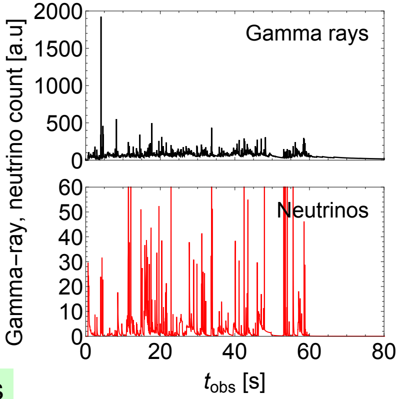
MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

Synthetic light curves

An emission pulse is assigned to each collision
– their superposition yields a synthetic light curve:

Energy in gamma-rays: $E_{\gamma,\mathrm{tot}}^{\mathrm{iso}} = 10^{53}$ erg





$T_{90} \approx 59$ s

1000 initial shells $\mapsto$ 990 collisions

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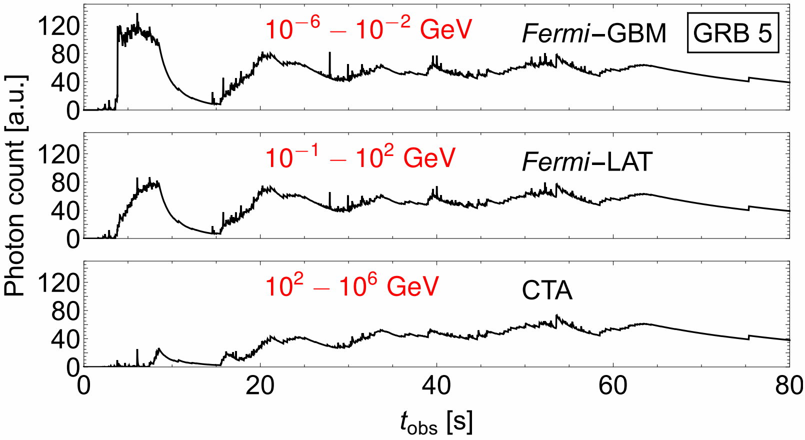
Time delays in gamma-ray light curves

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



MB, Murase, Winter, 1606.02325