Neutrinos from GRBs, and the connection to gamma-ray observations

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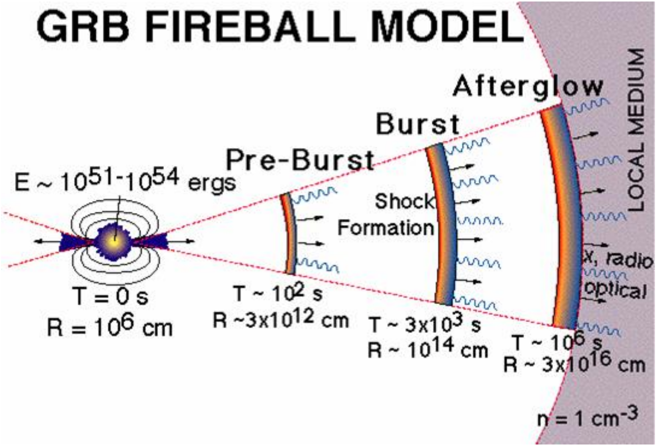
GRB Fireballs (What we assume)



from WWW.SWIFT.AC.UK

- Interactions of protons with photons can lead to the production of neutrinos

Photohadronic production of neutrinos

Basic approach by Waxman and Bahcall: approximation of $p\gamma$ interaction cross section using **Δ-resonance**

$$p + \gamma \to \Delta^+ \to \begin{cases} n + \pi^+ & \text{1/3 of all cases} \\ p + \pi^0 & \text{2/3 of all cases} \end{cases}$$

The π^+ **decay** producing ν_μ, $\bar{\nu}_\mu$ and ν_e in the process

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

Standard conclusion

ν result from interaction of p and γ in GRBs, with a ratio $(\nu_e : \nu_\mu : \nu_\tau)$ of $(1:2:0)$, or $(1:1:1)$ after flavor mixing.

See e.g. [Waxman and Bahcall, Phys. Rev. Lett. **78** (12), 2292 (1997)]

The normalization (IceCube approach)

$$\int_0^\infty \mathrm{d}E_\nu \, E_\nu F_\nu(E_\nu) = \overbrace{\frac{1}{8}}^{x_{\pi\to\nu} = \frac{1}{2}\cdot\frac{1}{4}} \underbrace{\left(1 - (1 - \langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right)}_{f_\pi} \overbrace{\frac{1}{f_e} \int_{1\,\mathrm{keV}}^{10\,\mathrm{MeV}} \mathrm{d}E_\gamma \, E_\gamma F_\gamma(E_\gamma)}^{\text{energy in protons}}$$

Fraction of energy f_π

with number of interactions

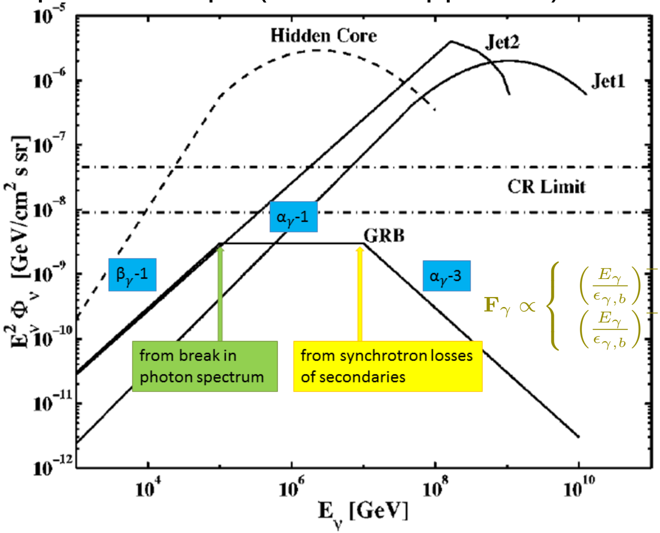
$$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right) \left(\frac{0.01\,\mathrm{s}}{t_{\mathrm{var}}}\right) \left(\frac{10^{2.5}}{\Gamma_{\mathrm{jet}}}\right)^4 \left(\frac{\mathrm{MeV}}{\epsilon_\gamma}\right)$$

and average energy lost to pions (per interaction)

$$\langle x_{p\to\pi}\rangle \simeq 0.2$$

from [Abbasi et al., Astrophys. J. **710**, 346 (2010)],
based on [Guetta et al., Astropart. Phys. **20**, 429 (2004)]

The spectral shape (IceCube approach)



$$\mathbf{F}_\gamma \propto \begin{cases} \left(\frac{E_\gamma}{\epsilon_{\gamma,b}}\right)^{-\alpha_\gamma} & \text{for } E_\gamma \leq \epsilon_{\gamma,b} \\ \left(\frac{E_\gamma}{\epsilon_{\gamma,b}}\right)^{-\beta_\gamma} & \text{for } E_\gamma > \epsilon_{\gamma,b} \end{cases}$$

from [Waxman and Bahcall, Phys. Rev. **D59**, 023002 (1998)]

GRB fireballs in trouble

LETTER

doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration*

Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} electronvolts. GRBs (γ-ray bursts) have been proposed as possible candidate sources[1–3]. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ-rays[4]. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux[5–7]. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions[4,8–10]. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} electronvolts or that the efficiency of neutrino production is much lower than has been predicted.

Neutrinos from GRBs are produced in the decay of charged pions produced in interactions between high-energy protons and the intense γ-ray background within the GRB fireball, for example in the Δ-resonance process $p+\gamma \to \Delta^+ \to n+\pi^+$ (p, proton; γ, photon (here γ-ray); Δ^+, delta baryon; n, neutron; π^+, pion). When these pions decay via $\pi^+ \to \mu^+ \nu_\mu$ and $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$, they produce a flux of high-

As in our previous study[7], we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ-ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ-ray spectra of individual GRBs[6,9]. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ±1 day, or with different spectra. Both analyses follow the methods used in our previous work[7], with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses, and were estimated by varying the simulated detector response and recomputing the limit, with the dominant factor being the efficiency of the detector's optical sensors.

In the 59-string portion of the model-dependent analysis, no events were found to be both on-source and on time (within 10° of a GRB and between $T_{\rm start}$ and $T_{\rm stop}$). From the individual burst spectra[6,9] with an

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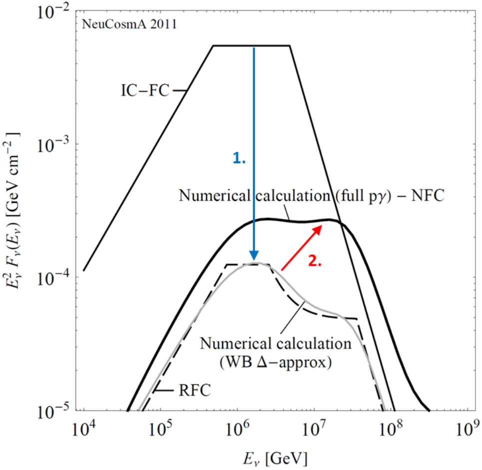
How the spectrum changes...



At example of GRB080603A:

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

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

from [Hümmer, PB, and Winter, arXiv:1112.1076, accepted for publication in Phys. Rev. Lett.]

Revised fireball model

Corrections to shape (c_s):

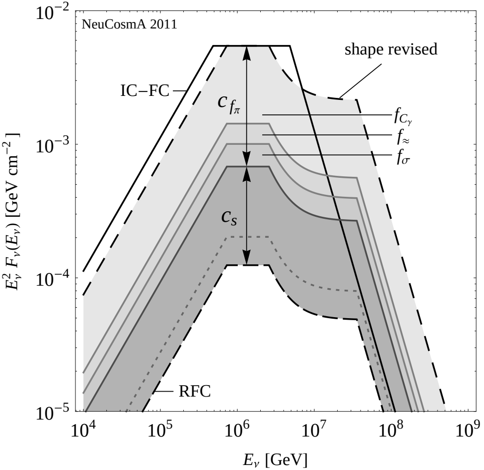
- Revised shape
- Correct energy losses of secondaries
- Full energy dependencies

See also [Li, Phys. Rev. **D85**, 027301 (2012)].

Corrections to f_π (c_{f_π}):

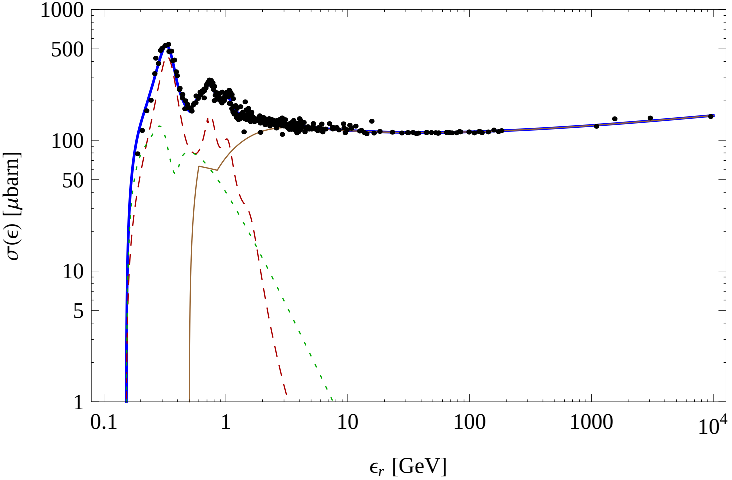
- Integral normalization of photon spectrum
- Rounding errors
- Width of Δ-resonance

Compare to [Guetta et al., Astropart. Phys. **20**, 429 (2004)].



from [Hümmer, PB, and Winter, arXiv:1112.1076, accepted for publication in Phys. Rev. Lett.]

The measured cross section



from [Hümmer, Rüger, Spanier, and Winter, Astrophys. J. **721**, 630 (2010)],
based on [Mücke, Engel, Protheroe, Rachen, and Stanev, Comp. Phys. Comm. **124**, 290 (2000)]

Further production modes

$$\begin{aligned}
\pi^+ &\rightarrow \mu^+ + \nu_\mu \, , \\
& \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \, , \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \, , \\
& \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \, , \\
K^+ &\rightarrow \mu^+ + \nu_\mu \, , \\
n &\rightarrow p + e^- + \bar{\nu}_e \, .
\end{aligned}$$

See also [Murase and Nagataki, Phys. Rev. **D73**, 063002 (2006)], [Kashti and Waxman, Phys. Rev. Lett. **95**, 181101 (2005)], [Asano and Nagataki, Astrophys. J. **640**, L9 (2006)], [Lipari, Lusignoli, and Meloni, Phys. Rev. **D75**, 123005 (2007)].

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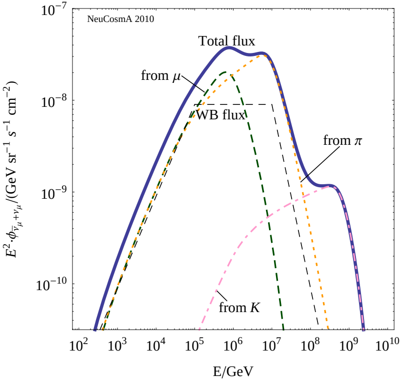
Resulting ν_μ flux (at the observer)



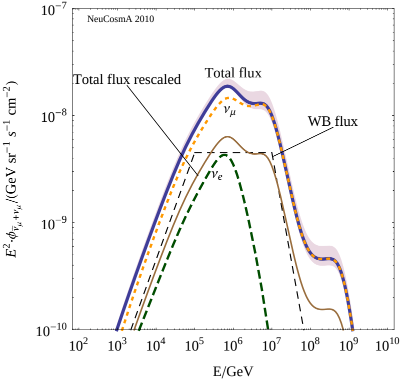
from [PB, Hümmer, and Winter, Phys. Rev. **D83**, 067303 (2011)]

Further production modes

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

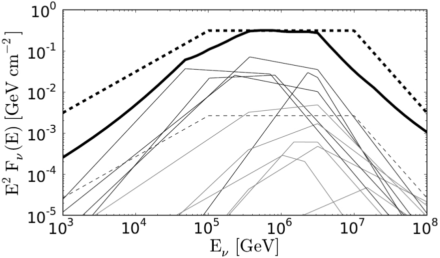
See also [Murase and Nagataki, Phys. Rev. **D73**, 063002 (2006)], [Kashti and Waxman, Phys. Rev. Lett. **95**, 181101 (2005)], [Asano and Nagataki, Astrophys. J. **640**, L9 (2006)], [Lipari, Lusignoli, and Meloni, Phys. Rev. **D75**, 123005 (2007)].

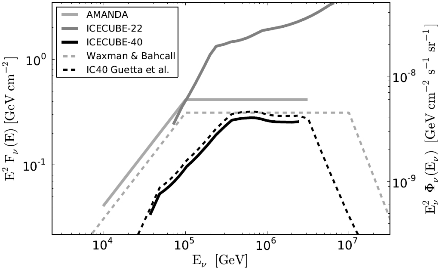
ν_μ flux after flavor mixing



from [PB, Hümmer, and Winter, Phys. Rev. **D83**, 067303 (2011)]

IceCube-40 GRB sample



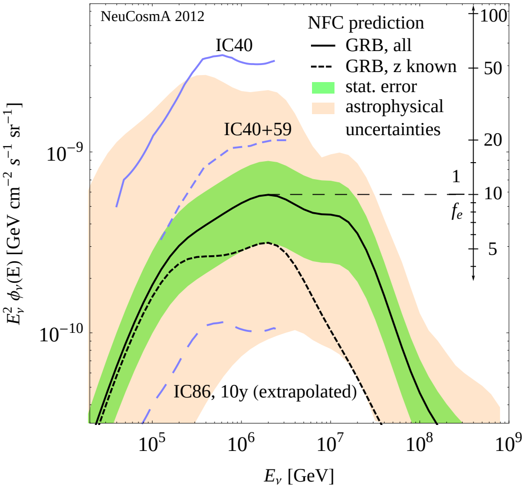


Experimental realization:

- 117 observed bursts, between April 2008 and May 2009
- Individual neutrino spectra stacked
- Parameters measured or standard value
- Diffuse limit for 667 bursts per year

from [Abbasi et al., Phys. Rev. Lett. **106**, 141101 (2011)]

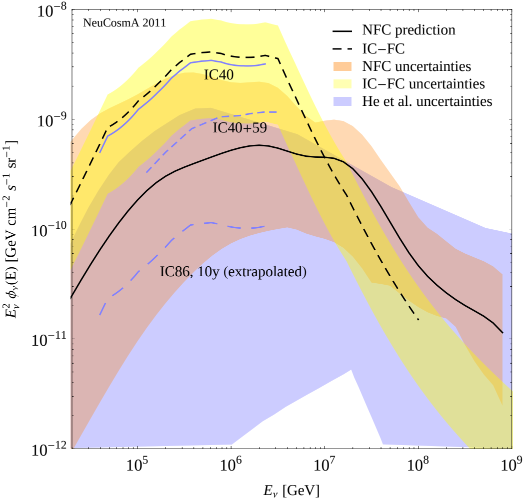
Result of re-computation



- Significantly reduced prediction
- Uncertainties of astrophysical parameters; tested ranges: $t_v = 0.001 - 0.1\,\text{s}$, $\Gamma = 200 - 500$, $\alpha_p = 1.8 - 2.2$, and $\epsilon_B/\epsilon_e = 0.1 - 10$
- Conservative bounds only with known parameters, here: known redshifts
- Additional uncertainty from statistics in stacking analysis

from [Hümmer, PB, and Winter, arXiv:1112.1076, accepted for publication in Phys. Rev. Lett.]

Uncertainties for different computations

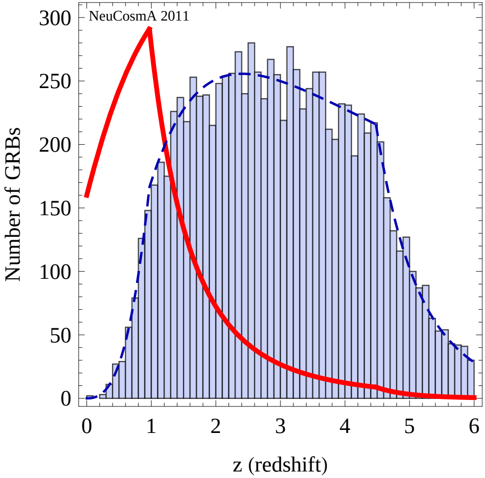


- **IceCube:** based on [Guetta, Spada, and Waxman, Astrophys. J. **559**, 101 (2001)]: origin of target photons fixed (synchrotron, IC scattering)
- **He et al.:** most general assumption with emission radius as free parameter; includes possibilities of other models (dissipative photosphere, magnetic reconnection...)
- **Hümmer et al.:** uncertainties of parameters in basic fireball model, target photon spectrum from observation

Data taken from [IceCube Collaboration, Nature **484**, 351 (2012)], [Hümmer, PB, and Winter, arXiv:1112.1076], and [He, Liu, Wang, Nagataki, Murase, and Dai, arXiv:1204.0857].

Aggregation of fluxes

- Diffuse flux = result of large number of (unresolved) individual sources
- GRB rate follows SFR
- z decoupled from other parameters
- General scaling: $F \propto d_L^{-2}$



from [PB, Hümmer, and Winter, Astropart. Phys. **35**, 508 (2012)]

Single burst detection probability estimate

Assumption: Diffuse flux from 10000 bursts is at the level of the WB flux ($1/10$ of WB), leading to a certain number of events in the full IceCube detector during 10 years of operation.

Question: How near would a single burst have to be to lead to at least 3 events?

Answer: Burst has to be at most at $z_{\mathsf{max}} = 0.14$ ($z_{\mathsf{max}} = 0.05$). The probability to have at least one such a close burst is about 40% (2%).

from [PB, Hümmer, and Winter, Astropart. Phys. **35**, 508 (2012)]

Summary

- Standard neutrino flux shape should be revised.
- Simulation of diffuse flux is model-dependent.
- Numerical re-analysis of IC40 GRB neutrino prediction is significantly lower than original prediction.
- Fireball model not ruled out yet.
- 10 years of IC86 data should give answer.

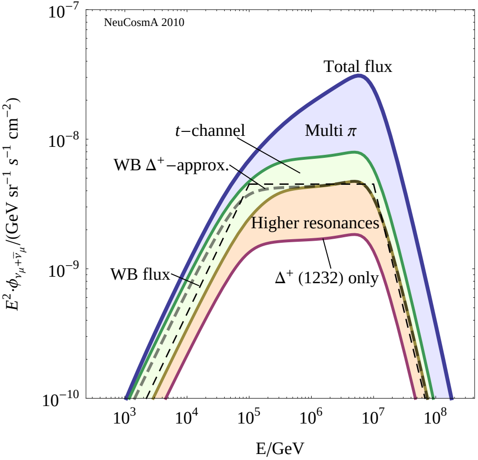
Back-up slides

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)

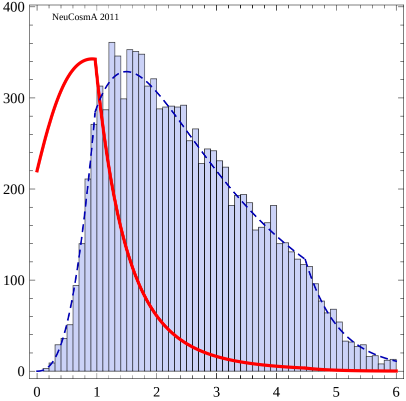
from [PB, S. Hümmer, and W. Winter, Phys. Rev. **D83**, 067303 (2011)]



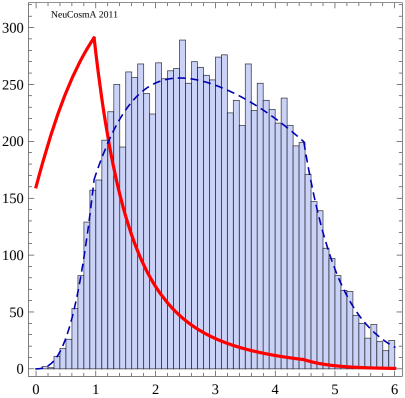
Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

Effect of minimal detectable flux

All L



$L > 10^{51}$ erg/s



Variations slightly higher compared to only redshift variation.

Used inputs

- Proton spectrum $N_p^{'}(E^{'}) \propto E^{'-2}$
- Photon spectrum resembling (simplified) Band function with parameters α, β, and $E_{\gamma,\text{break}}$
- Contributions to $\sigma_{p\gamma}$ from $\Delta(1232)$-resonance, higher resonances, t-channel (direct production), and high energy processes (multiple π)
- Decays of $\pi^{\pm}$, $\mu^{\pm}$, n, and K^{+} considered, in case of $\mu^{\pm}$ including helicity dependence

  [P. Lipari, M. Lusignoli, and D. Meloni, Phys. Rev. **D75**, 123005 (2007)]
- Simple neutrino mixing including three mass eigenstates and $\theta_{13} = 0$
- Normalization at the end matched to WB GRB ν_μ flux bound

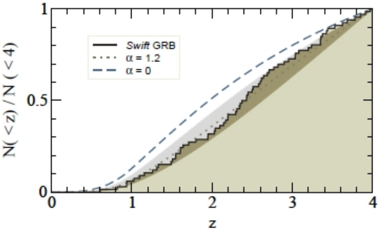
GRB rate from corrected SFR by Hopkins and Beacom

SFR by Hopkins and Beacom:

$$\dot{\rho}_* \propto \begin{cases} (1+z)^{3.44} & \text{for } 0 < z \leq 0.97 \\ 10^{1.09} \cdot (1+z)^{-0.26} & \text{for } 0.97 < z \leq 4.48 \\ 10^{6.66} \cdot (1+z)^{-7.8} & \text{for } 4.48 < z \end{cases}$$

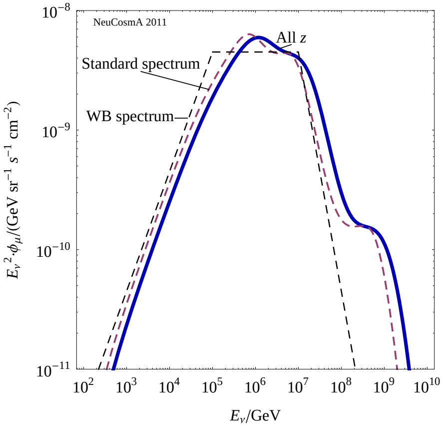
from [A. Hopkins, and J. Beacom, ApJ **651**, 142-154 (2006)]

Correction factor taken from [Kistler et al., ApJ **705**, L104-L108 (2009)]



$$\mathcal{E}(z) \propto (1+z)^{1.2}$$

Resulting aggregated flux



- Peak contribution from bursts at $z \lesssim 1$, few close bursts dominate
- Leads to shift to higher energies compared to single burst (with assumed $z = 2$)
- Characteristic features of single burst flux shape are preserved
- Analysis of other source parameters showed that only the magnetic field can wash out these features

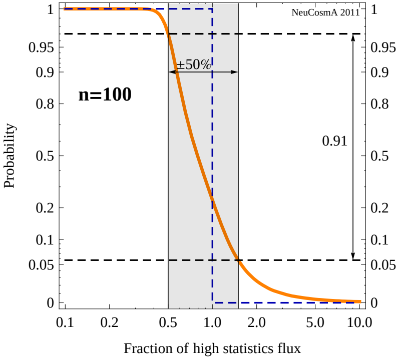
Result of statistical analysis

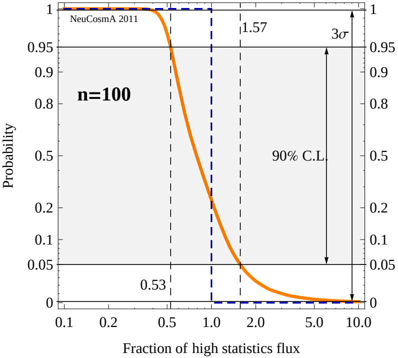
Simulated $100\,000$ samples of n bursts with different redshift, and extrapolated flux limits from stacked flux. Analysis of resulting limits gave the results:

n	Rel. error 90%	Rel. error 3σ
100	$0.53 - 1.57$	$0.39 - 8.78$
1000	$0.72 - 1.25$	$0.64 - 5.15$
10000	$0.83 - 1.08$	$0.78 - 2.62$

- Variation of extrapolated bound for 100 bursts (comparable with the 117 bursts from IceCube) still too high to rule out the (most basic) fireball model - due to statistics.
- For variation of multiple parameters effect gets even stronger.
- However, additional effects, such as bias through minimal observable flux when considering simultaneous variation of redshift and luminosity, reduce uncertainty compared to independent variation case.

Picked $100\,000$ samples with different redshifts according to redshift distribution shown earlier for each sample size.





n	$\pm 10\%$	$\pm 20\%$	$\pm 50\%$
100	0.17	0.37	0.91
1000	0.30	0.69	0.98
10000	0.48	0.97	0.99

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