Search for transient neutrinos sources with IceCube

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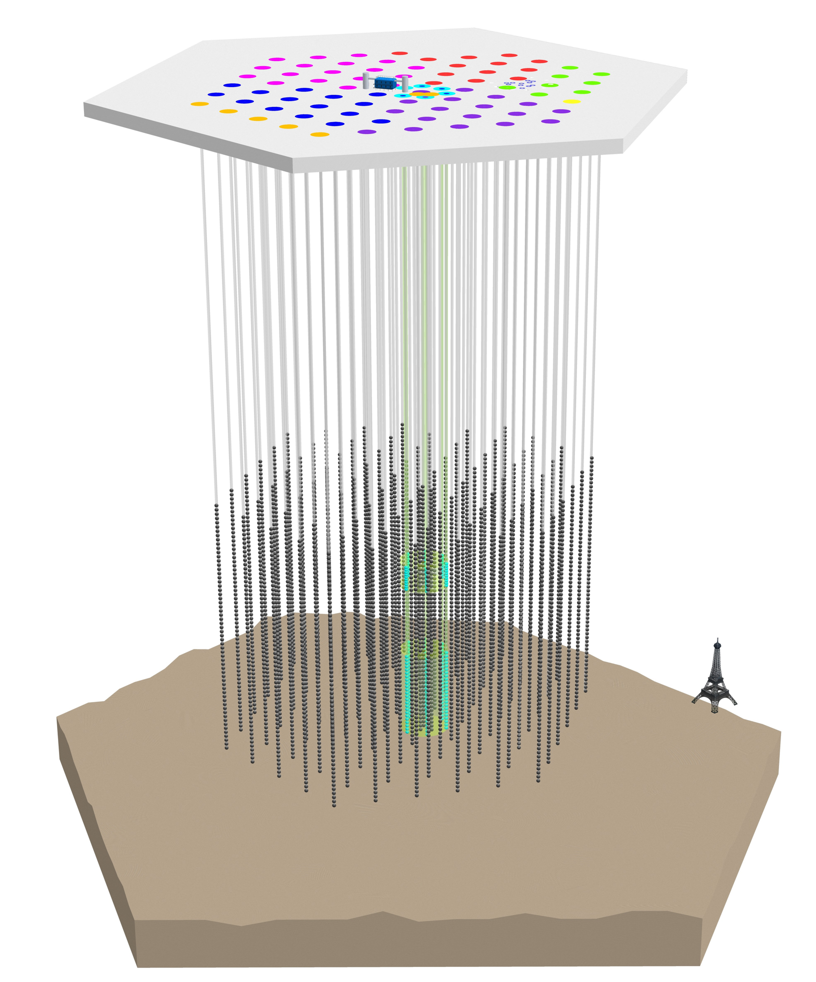
The IceCube Detector

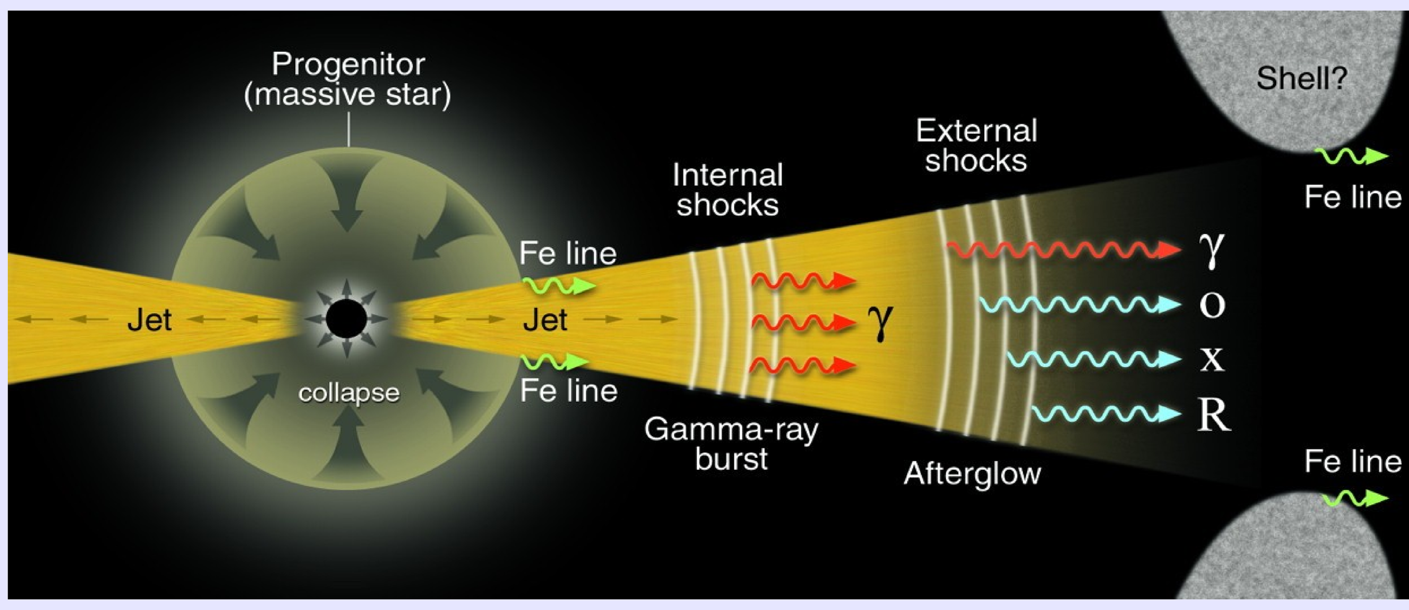


IceCube detector with its low energy extension DeepCore (green) [1].

Location	Antarctic ice under the geographic South Pole
Detector	86 strings, each with 60 digital optical sensors, instrumenting 1 km³ at depth of 1450-2450 m
Sensors	Photomultiplier tubes operating with custom signal digitization electronics in pressure-resistant glass housings
Detection Principle	High-energy ν_μ interacting in the ice or the underlying rock produce muons in neutrino-nucleon interactions. The μ travels co-linear to the ν_μ direction and emits Cherenkov light.
Performance	Energy threshold: E_ν = 100GeV Resolution <1°
Aim	Probing the universe for violent astrophysical sources such as AGNs and GRBs

Neutrinos escape astrophysical acceleration regions and propagate through space basically unaffected, while protons are deflected in magnetic fields and do not point back to their source. Unlike gamma-rays neutrinos are solely produced in hadronic processes and could therefore reveal the sources of the highest energy charged cosmic rays.

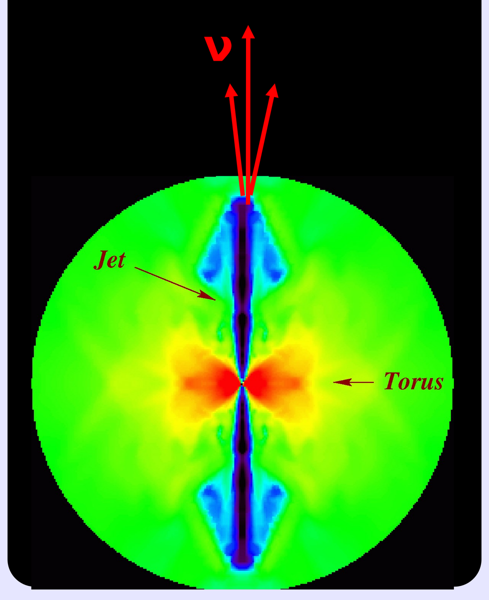
High energy neutrinos from GRBs and SNe



Fireball shock model[2]

Matter is ejected in a relativistic jet. Internal and external shocks accelerate charged particles producing electromagnetic emission at various wavelength in synchroton and inverse Compton processes.

Simulation of a choked fireball by MacFadyen (2000)



GRB-SN Connection[3] → core-collapse SN might produce soft relativistic jets:

- Jets cannot penetrate the stellar surface → choked jet
- No electromagnetic jet signature
- High-energy neutrinos can espace the stellar interior ([5],[6]) and their detection would prove the internal jet production
- SN Neutrino flux depends on the jet energy E_{jet}, the rate ρ of SN with jets and the jet boost factor Γ

GRBs are one of the leading candidates for the source of the highest energy cosmic rays. Protons accelerated in GRB or choked SN jets interact with the ambient photon field producing delta resonances. Neutrinos are products along the decay chain of the Δ particle.

$$p+\gamma\rightarrow\Delta^+\rightarrow n+\pi^+ \qquad \pi^+\rightarrow\mu^++\nu_\mu\rightarrow e^++\nu_e+\overline{\nu}_\mu+\nu_\mu$$

Offline: GRB Neutrino Search

Search for neutrinos in temporal and angular correlation with prompt GRB emission triggered by GCN notices

Method

- Data sample reduced to irreducible background of upward going atmospheric neutrinos
- Unbinned maximum likelihood method taking into consideration the event direction, arrival time relative to the GRB trigger time and reconstructed energy
- Background obtained from non-GCN-alert periods

Dataset

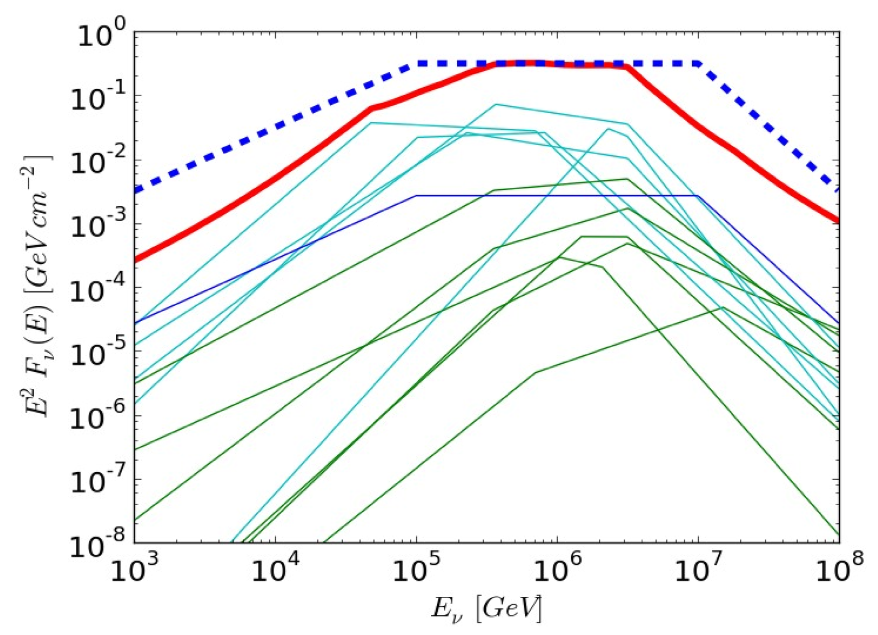
- Neutrino data collected with 40-string configuration (Apr. 5, 2008 to May 20, 2009) and 59 string configuration (May 20, 2009 to May 25, 2010)
- 117 and 98 GCN Northern hemisphere bursts from all GRB satellites[6]

Expectation

- Predicted events by Guetta et al. modeling of the fireball model[7] (all GRBs stacked):
  IceCube-40: 3.0
  IceCube-59: 5.8

Results

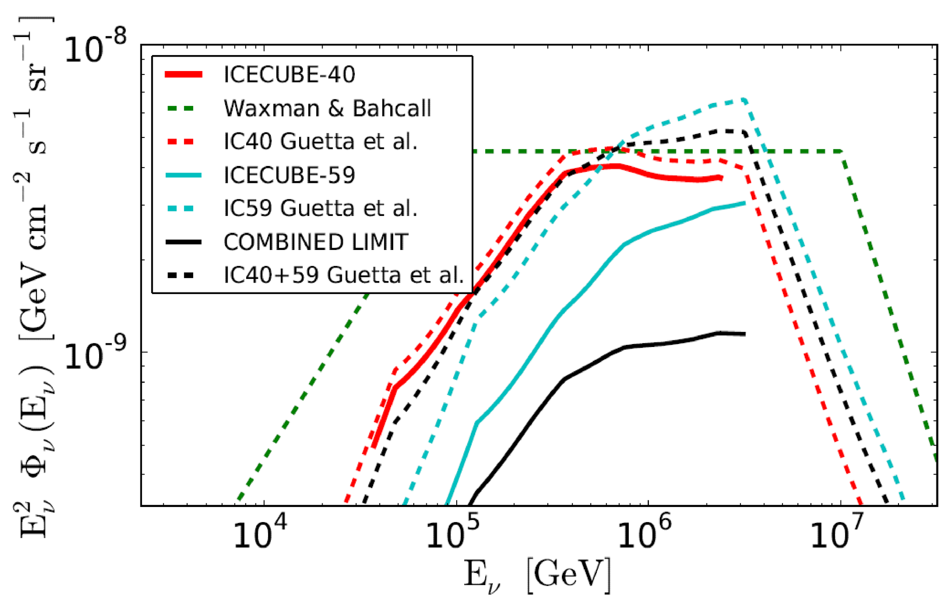
- No neutrino event found in temporal and angular correlation with reported GRB



Predicted GRB neutrino spectra (IceCube-40)[8]
Cyan: Five brightest GRBs. Green: Eight randomly selected bursts. Blue: Single burst with Waxman-Bahcall average flux. Red: Sum of all 117 individual bursts. Blue: Sum of average Waxman-Bahcall bursts.

Average model parameters

- bulk Lorentz factor = 316
- Fraction of energy transferred to electrons = 0.1
- Variability in γ-light curve = 10ms (long bursts), 1ms (short bursts)



90% CL Neyman upper limit (including systematics)
IceCube-40: 0.82 below prediction[8]
IceCube-59: 0.44 below prediction
Combined: 0.22 below prediction PRELIMINARY

No significant excess is found and the upper limit is 0.22 times below the predictions of the fireball model, Hence the current model is strongly disfavored. However, enough uncertainty remains in these models to prevent ruling out GRB fireballs as the source of the highest energy cosmic rays. If future observations with the growing IceCube detector continue to find no neutrinos in coincidence with GRBs, the acceleration of protons to ultra-high energies in GRB will be constrained.

Online: Optical Follow-up Program

Triggered by a burst of neutrinos telescopes search the corresponding region in the sky for an electromagnetic counterpart.

Method - IceCube

- First online analysis of high energy neutrinos at South Pole
- Background reduced by 6 orders of magnitude to mainly atmospheric neutrinos
- Multiplet selection: at least two events arriving within 100s and an angular difference of less than 4° → random triggers reduced to ~25 per year[9,10]
- Alerts forwarded to telescopes with a delay of initially 6h (now 5 min)

Method - Optical

- Image subtraction to find optical SN counterpart correlated with the neutrino emission.
- Automated source candidate selection, final candidates scanned by eye

Dataset

- Dec. 16, 2008 to Dec. 31, 2009, 40 and 59 string configuration
- 17 alerts observed by ROTSE

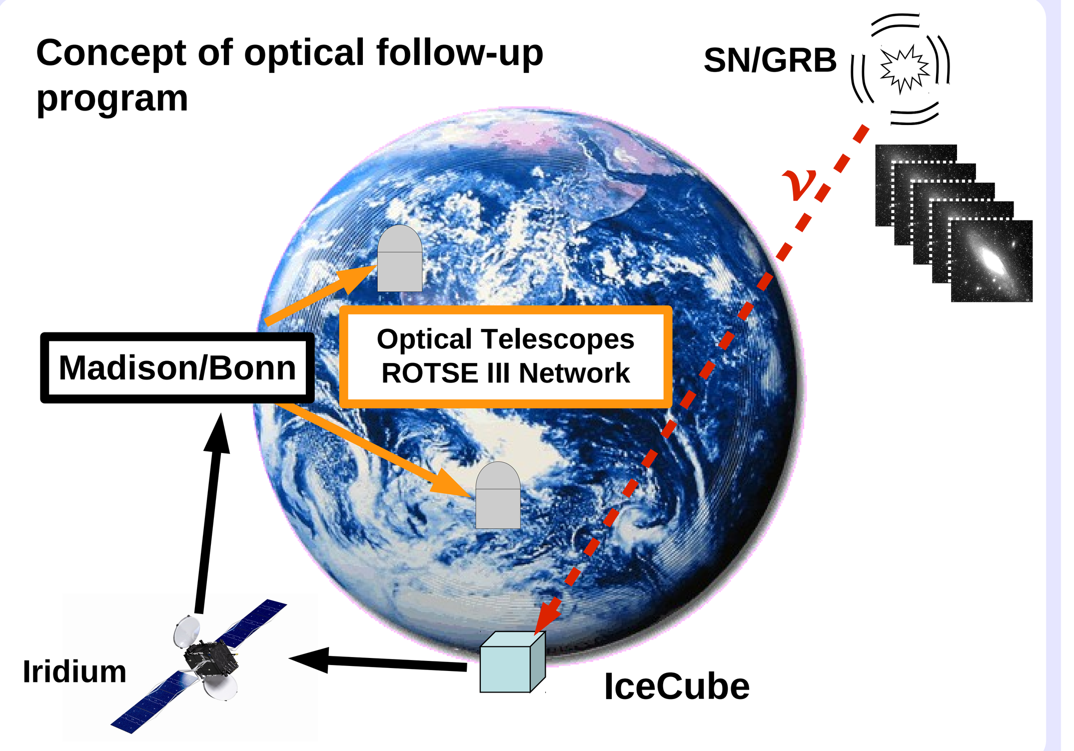
Expectation

- 24.2 background doublets
- 0.04 background optical SN

Results

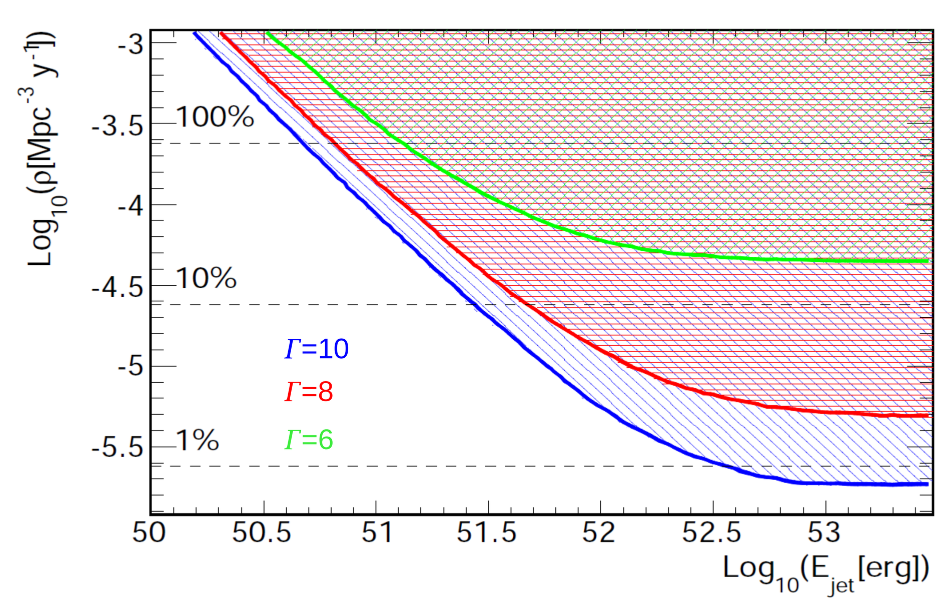
- 34 doublets (non-significant upward fluctuation)
- no optical SN found

Concept of optical follow-up program



Telescope	FoV	Triggered since
ROTSE [11]	1.85°x1.85°	Dec. 2008
PTF [12]	3.5°x2.31°	Jul. 2010
Swift XRT	Diameter: 0.4°	Feb. 2011

Limit on CCSN jet model (90% confidence level) depending on the jet energy E_{jet}, the Lorentz boost factor of the SN jet Γ and the rate of core-collapse SN hosting a jet ρ.



No significant excess of neutrino multiplets and no optical counterpart have been observed. First limits to the hadronic jet production in core-collapse SNe jet could be derived. Especially in cases of high boost Lorentz factors of Γ=10 stringent limits to the soft jet SN model are obtained. Less than 7.8% of all SNe have a jet with Γ=10 and a typical jet energy of $E_{jet}=3\cdot10^{51}$erg.

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