Searching for Astrophysical Neutrinos Coincident with Gamma-Ray Bursts with the IceCube Detector

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Motivation for Neutrino-GRB Study

Study two mysteries in particle astrophysics:

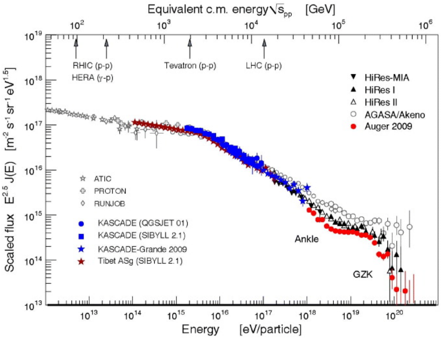
- Source of ultra-high energy cosmic rays (UHECRs)
- Source of IceCube's astrophysical neutrino flux

Gamma-ray bursts (GRBs) are highly energetic

- Right conditions to produce neutrinos
- Neutrinos suggest hadronic acceleration of UHECRs

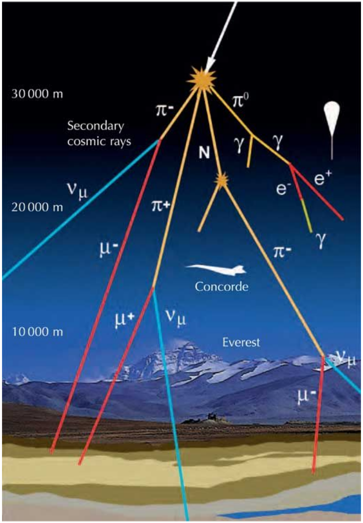
Mystery #1: Cosmic Rays

- Cosmic ray spectrum from satellites and ground-based detectors
- Above 10^{18} eV (the "ankle")
  - GRBs fit energy requirements



Cosmic Ray Showers (Background)

- ν, μ, and more produced in shower
  - "Atmospheric neutrinos"
- Large source of background in detector
  - ν_{astro} : ν_{atm} : μ
  - 1 : 10^3 : 10^9



Mystery #2: Astrophysical Neutrinos (Signal)

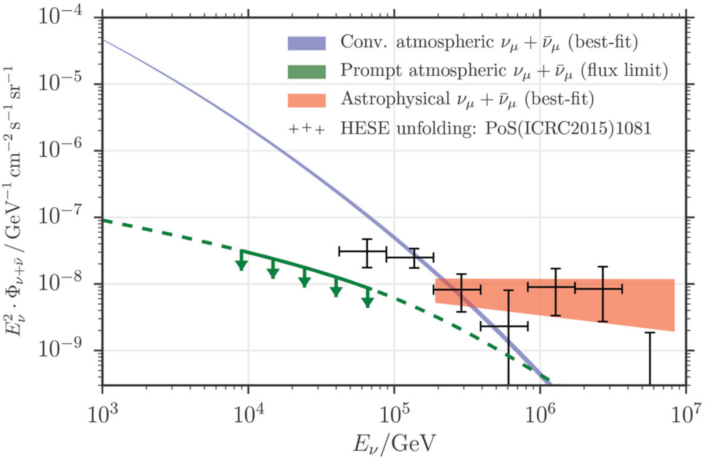
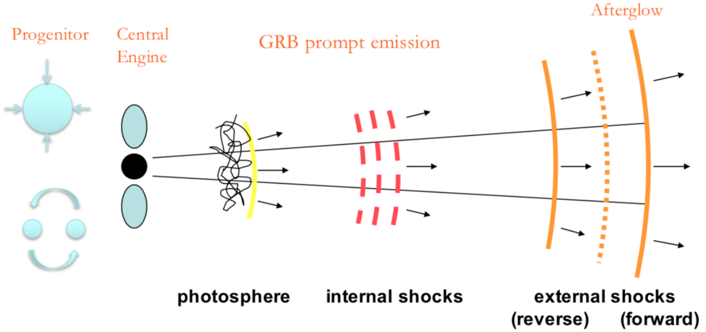


Figure: Astrophysical neutrino flux detected by IceCube.

GRBs: The Fireball Model

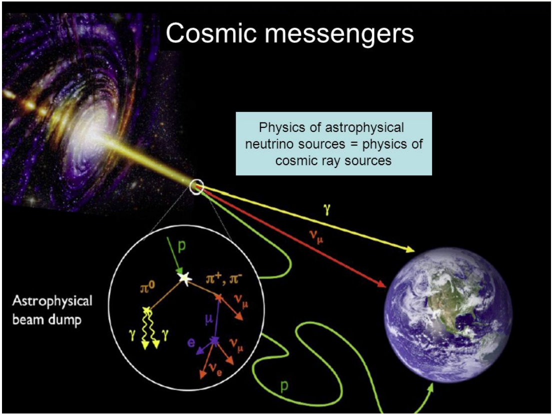


- Some of most energetic events in universe
- Brief transients: milliseconds to thousands of seconds
- Expect ∼300 GRBs per year

GRBs	$\sim 10^{51}$ ergs/s
Supernova	$10^{50} - 10^{51}$ ergs
AGN	$10^{42} - 10^{46}$ ergs/s
Stars	$10^{33} - 10^{35}$ ergs

https://jsi.astro.umd.edu/images/stories/PDF/2017Workshop/BingZhangJSI17.pdf

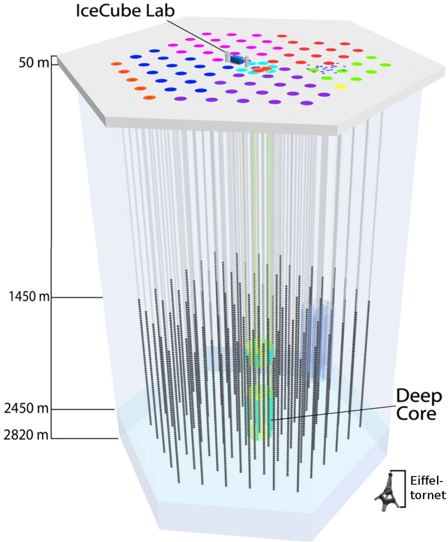
Photo-Hadronic Neutrino Production



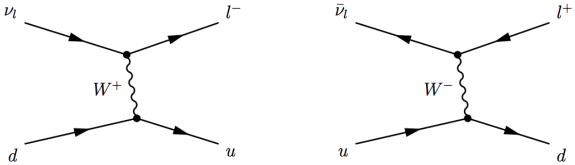
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \implies \gamma - rays \\ \pi^+ + n \implies neutrino \end{cases}$$

The IceCube Neutrino Detector

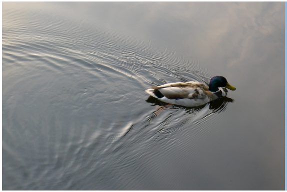
- Digital Optical Module (DOM) can detect single photon
- 60 DOMs on a string
- 86 strings

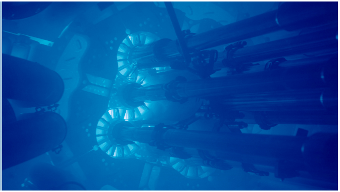


Neutrino Interactions in Ice



Charged Current





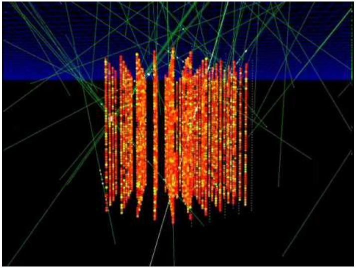
Duck: Wake

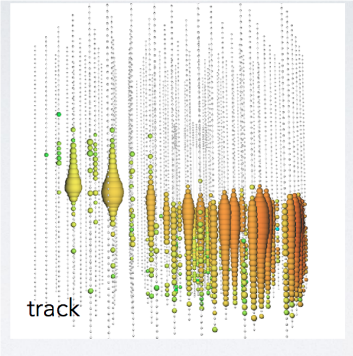
Plane: Sonic Boom

Charged Particle: Cherenkov Radiation

All-Sky Track Search

- Search for ν_μ in northern and southern sky
  - $< 1^\circ$ angular resolution
- $\sim$3,000 background events every second
  - Atmospheric ν_μ and μ are primary background
- Separate signal from background
  - Log likelihood method
  - Compare ν time and spatial coordinates to GRB

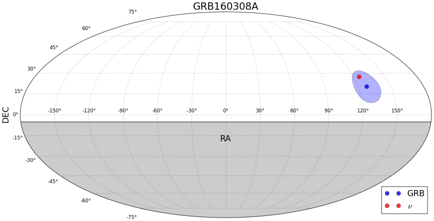


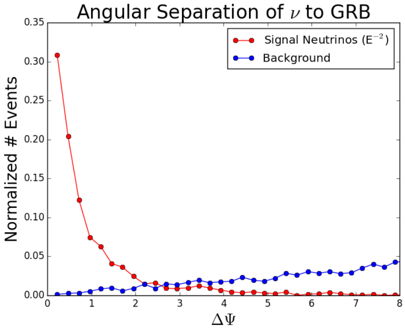


Log Likelihood Method

- Probability density function (PDF) of energy, time, and space
- Ratio of signal PDFs, $S(x)$, to background PDFs, $B(x)$
- Test statistic tells "signal-like" or "background-like"

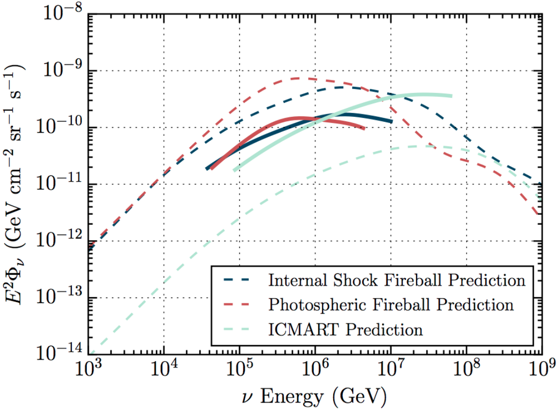
$$TS \propto \sum_{i=1}^{N} ln\left[\frac{\hat{n}_s S(x_i)}{\langle n_b \rangle B(x_i)}\right]$$





Fireball Model Constraints

- No significant ν-GRB correlation (most recent IceCube study)
- Dashed lines: ν production models
- Solid lines: 90% confidence limits



https://arxiv.org/abs/1702.06868

Analysis in Real-Time

- Search triggered by GRB alerts
- Send IceCube alert if neutrino appears coincident with GRB
- Allow time for other experiments to follow up

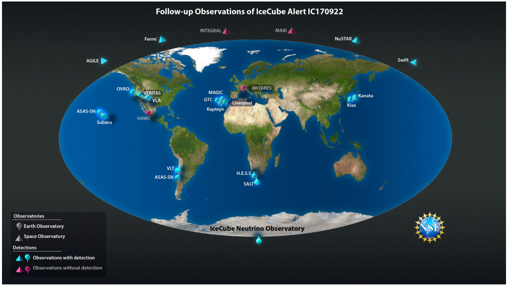
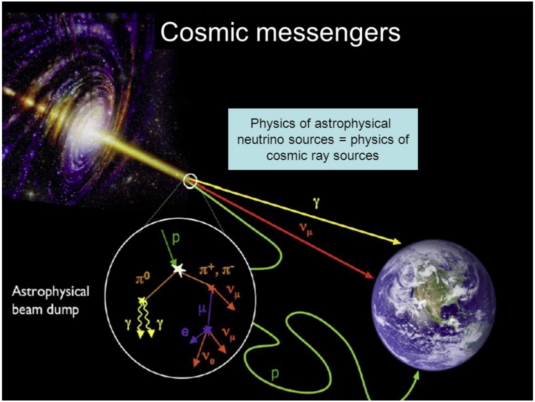


Figure: Over 20 observatories around the world followed up IceCube's neutrino alert (IC170922)

Thank You

Back-Up Slides

Photo-Hadronic Neutrino Production



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

$$\pi^0 + p \to p + 2\gamma$$

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

Gamma-Ray Burst Discovery

- 1967: Vela satellites launched
  - Looking for γ-rays from nuclear tests
  - Found γ-rays that did not match nuclear signature
- 1991: Burst Transient Source Experiment (BATSE) confirmed GRBs
  - Isotropic
  - Extragalactic

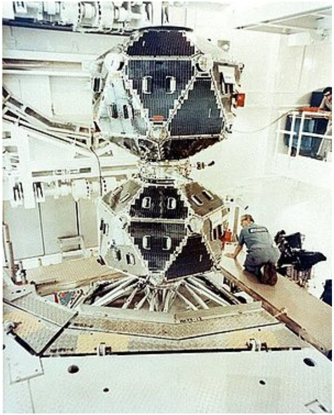


Figure: Vela-5A/B satellite in clean room

https://heasarc.gsfc.nasa.gov/docs/vela5b/vela5b_images.html

Modern GRB Detection

- Swift and Fermi measure more than 90% of GRBs
- Send alerts to Gamma-ray Coordinates Network (GCN)
- AGILE, INTEGRAL, Konus-Wind, and more also measure GRBs and send GCN alerts

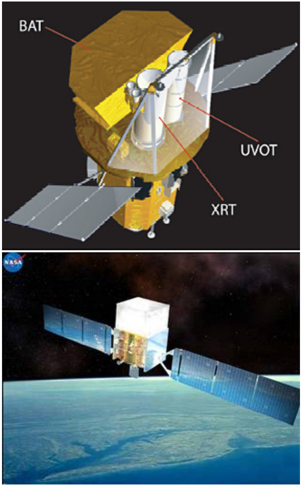
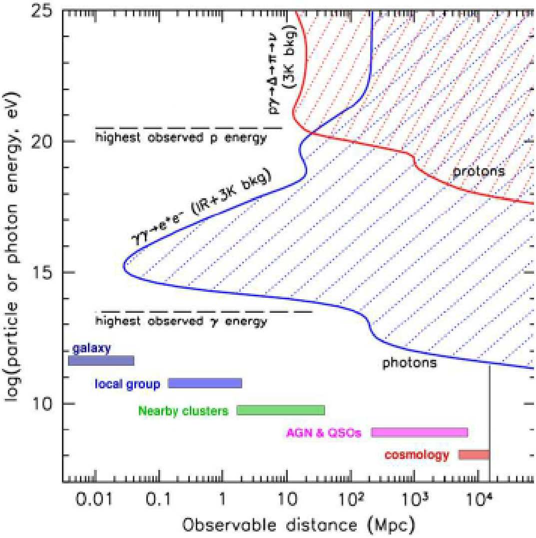


Figure: The Swift and Fermi satellites.

Universe Becomes Opaque in Photons

- Photons annihilate and pair produce at high energies
- Protons interact with CMB photons



Ultra High Energy Cosmic Rays

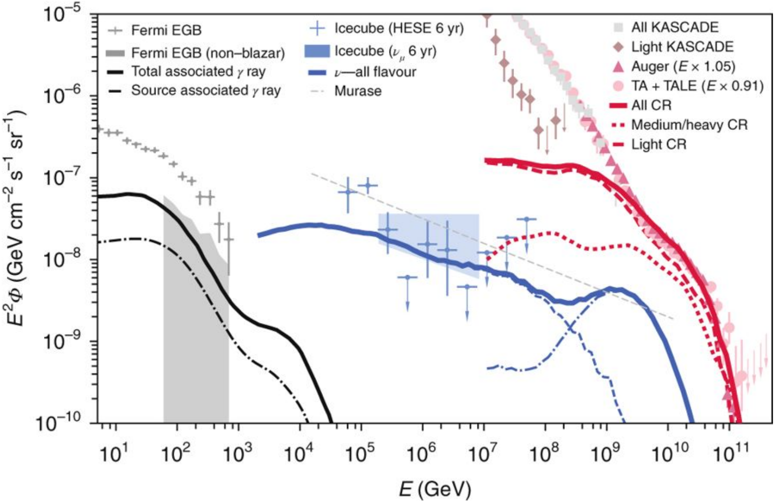
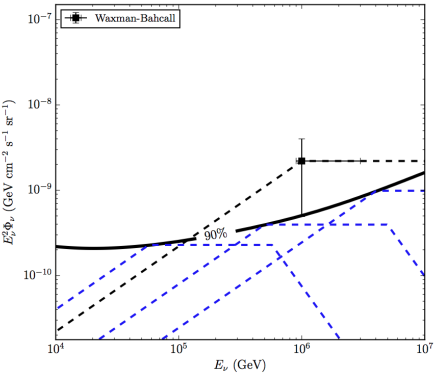


Figure: The balancing act of a source producing γ-rays, neutrinos, and cosmic rays.

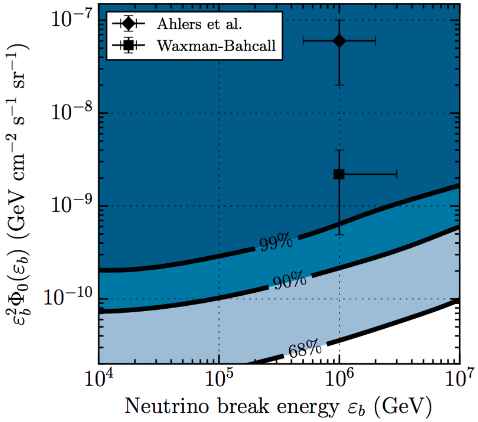
Waxman-Bahcall Limit

- Double broken power law
  - First break energy, ε_b
  - Flux normalization, ϕ_b
  - $\varepsilon_b^2 \phi_0 \approx 6 \times 10^{-8}$ GeV cm^{-2} sr^{-1}
- Upper bound on neutrino flux
  - Assumes GRBs produce all cosmic rays
  - Assumes all cosmic rays are protons

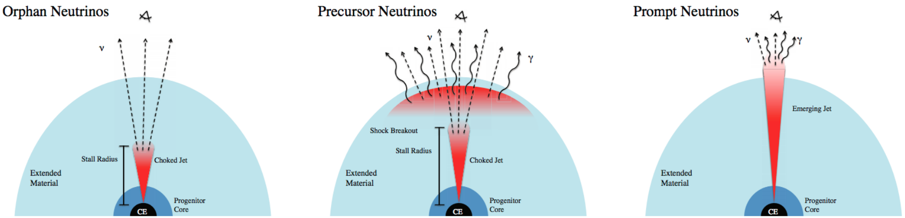


Generic Double Broken Power Law Limits

- Generic double broken power law constraints
- Breaking energy, ε_b and flux normalization, ϕ_0
- Waxman-Bahcall limit strongly ruled out



GRBs Models: Choked Jet



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Likelihood Method

$$L(n_s|n_b, x_i) = P_N \prod_{i=1}^{N} [p_s S(x_i) + p_b B(x_i)]$$

- n_s and n_b are the number of expected signal and background counts
- The log of the likelihood is maximized with respect to n_s to find the test statistic
- $\hat{n}_s$ indicates the maximum n_s for the test statistic
- Probabilities are $p_s = \frac{n_s}{n_s+n_b}$ and $p_b = \frac{n_b}{n_s+n_b}$
- P_N is the Poisson probability of the total observed event count:

$$P_N = \frac{(n_s + n_b)^N e^{-(n_s+n_b)}}{N!}$$

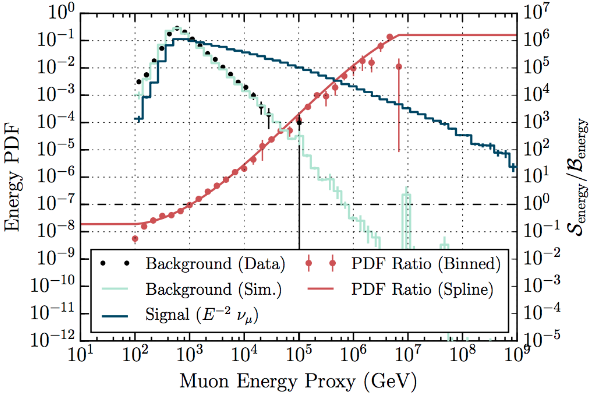
Probability Density Functions (PDFs)

- Describe expected values for atmospheric ν (background) and astrophysical ν (signal)
- Space, time, and energy PDFs
- Ratio of signal to background is used throughout likelihood calculations

$$S(x) = S_{space}(\vec{x}) \times S_{time}(t) \times S_{energy}(E)$$
$$B(x) = B_{space}(\vec{x}) \times B_{time}(t) \times B_{energy}(E)$$

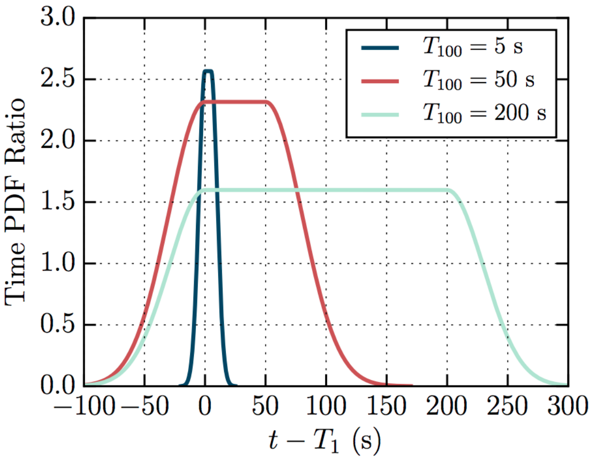
Energy PDF

- Background and signal PDFs shown in blue
- Background data shown as black dots (atmospheric ν)
- Ratio of signal to background shown in red



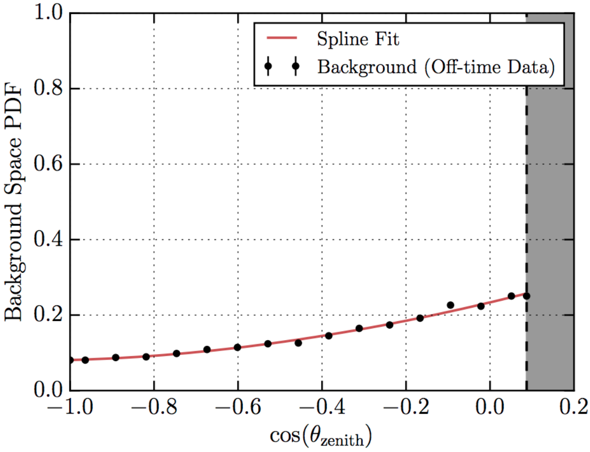
Background Time PDF

- PDF is flat during GRB T_{100}
- Gaussian tails go out to 4σ before T_0 and after T_{100}
- Different length GRBs to demonstrate Gaussian tails
- Signal time PDF is flat for entire time window



Background Space PDF (Northern Sky)

- Space PDF (spline fit) is based on simulation
- Events are most probable at the horizon (cos(θ)=0)
- Signal space PDF is a Kent distribution normalized on the unit sphere



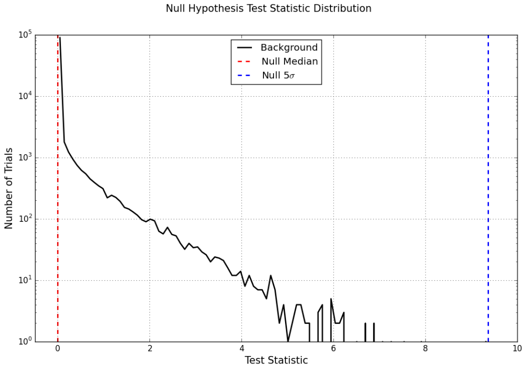
Test Statistic

- All six PDFs combined into ratio
- Likelihood is maximized with respect to number of signal events, n_s
- Test Statistic (TS) indicates if event is signal-like or background-like
- In a real time search, each ν gets a test statistic

$$TS = ln\left[\frac{L(\hat{n}_s)}{L(n_s = 0)}\right] = -\hat{n}_s + \sum_{i=1}^{N} ln\left[\frac{\hat{n}_s S(x_i)}{\langle n_b \rangle B(x_i)} + 1\right]$$

Test Statistic Distribution

- Using background (atmospheric ν), simulate millions of events/TS
- Assume no signal (no astrophysical ν)
- This gives test statistic distribution for the background ("Null Hypothesis")



Discovery Potential

- Simulate signal (astrophysical ν)
- Create new test statistic distribution
- Compare to 5σ TS of null
- TS where 50% of trials are above 5σ indicates discovery potential