Abstract

IceCube has provided the first measurements of the extragalactic high energy astrophysical neutrino flux. The sources of these neutrinos remains unknown. The most luminous events in the universe are Gamma ray bursts (GRBs) which are relativistic jetted outflows resulting from some supernovae (SNe). GRBs are a promising candidate of high energy cosmic rays and neutrinos despite no direct evidence of a correlation between events and known sources. Some GRBs may be electromagnetically choked emitting only neutrinos. To constrain the properties of GRBs, we assume that choked GRBs are a natural continuation of visible GRBs. This allows for constraints on GRB properties and the fraction of SNe that form jets from IceCube's data.

Gamma Ray Bursts, Supernovae, Neutrinos, and IceCube

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NBIA N-Talk

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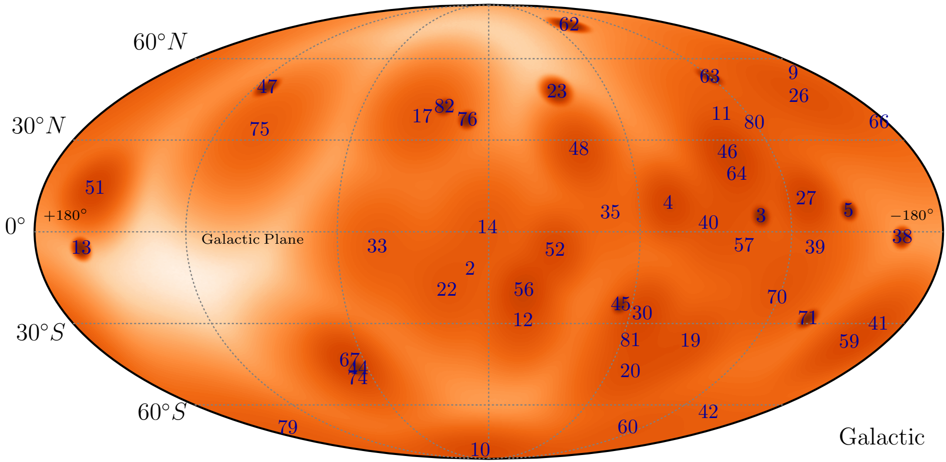
The Niels Bohr International Academy

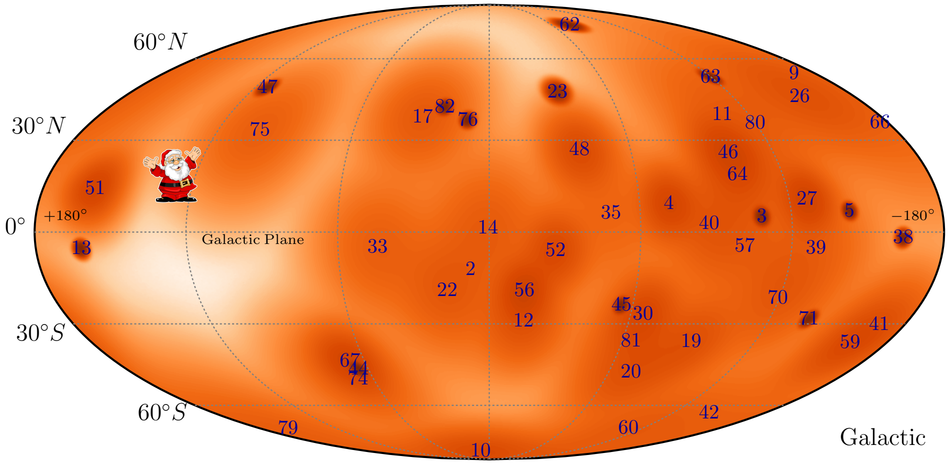
VILLUM FONDEN

IceCube detects isotropic flux of astrophysical neutrinos



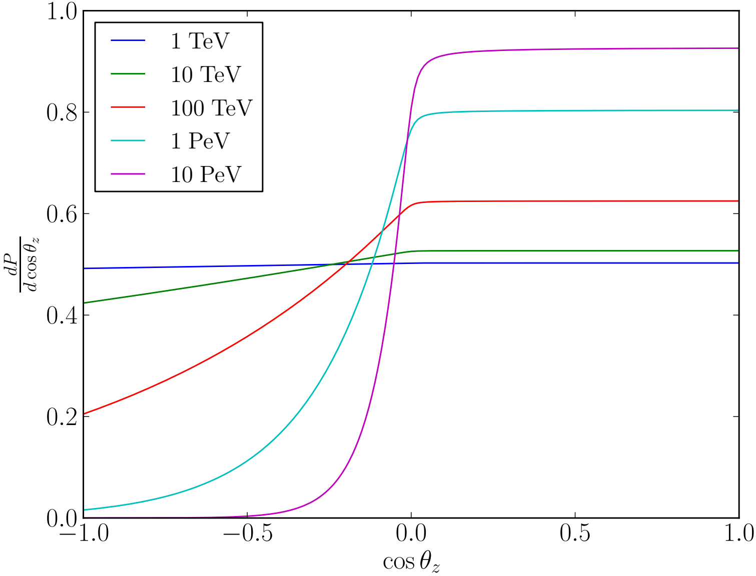
50 events with $E_{\mathrm{dep}} > 60$ TeV from IC 6 year HESE

IceCube detects isotropic flux of astrophysical neutrinos

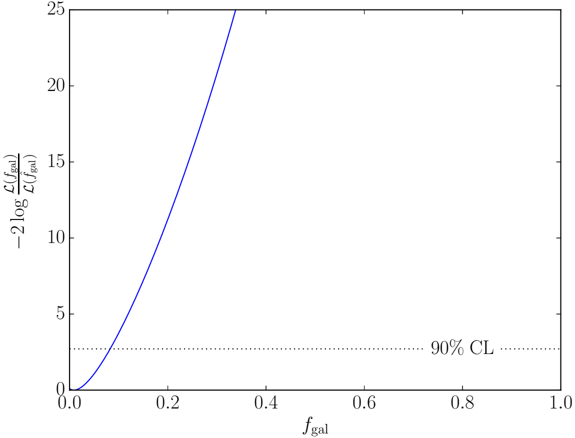


50 events with $E_{\mathrm{dep}} > 60$ TeV from IC 6 year HESE

High energy neutrinos are absorbed by the Earth



Galactic fraction



$\hat{f}_{\rm gal} = 0.013$
$f_{\rm gal} = 0$ consistent at $< 1\sigma$

CL	$f_{\rm gal}$
1σ	< 0.057
90%	< 0.095
2σ	< 0.12
3σ	< 0.2

PBD, D. Marfatia, Weiler: 1703.09721

Possible extragalactic sources

- Cosmogenics from UHECR energy loss: wrong energy.

  Berezinsky, Zatsepin: PLB '69
- Point source searches: nothing found.

  IC: 1406.6757
- Catalog correlations: nothing (significant) found.

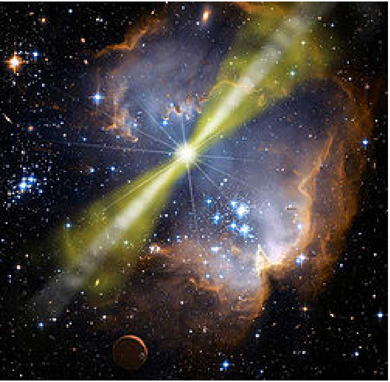
  Moharana, Britto, Razzaque: 1602.03694
- UHECR correlation: nothing (significant) found.

  IC, Auger, TA: 1511.09408

Seem to be running out of source catalogs to check.

$\therefore$ Move to diffuse backgrounds and use spectral information.

Gamma ray bursts



- Have observed ~ 1000 GRBs.
- Most luminous events observed (other than BH-BH mergers).
- Photon measurements $\Rightarrow$ high Γ outflow.
- Central engine?
  - CC-SN.
  - Binary mergers, ...?
- IceCube has strong constraints from spatial + timing correlations.

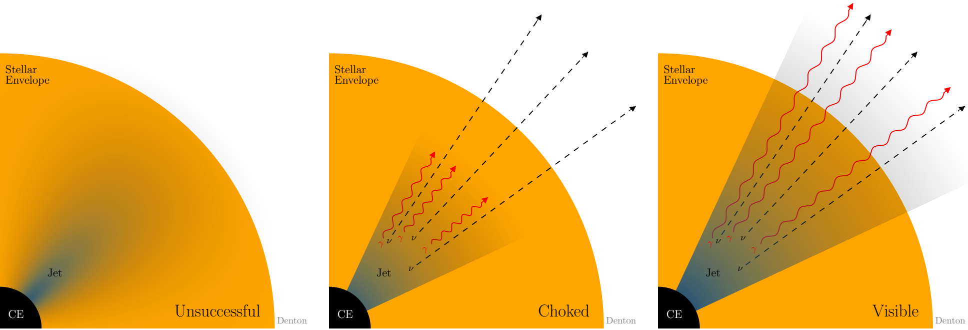
  IC: 1601.06484

  - Hidden sources, choked jets?

Three kinds of jets

The type of the jet determines the particle output:

- Unsuccessful $\Rightarrow \emptyset$.
- Successful but choked $\Rightarrow \nu$'s.
- Successful and visible $\Rightarrow \nu$'s and γ's.



Choked GRBs

- Without EM observations, it is possible to write down anything for a choked source.
- We assume that all jets are drawn from the same distribution.
- We match the high luminosity jets to observations.
- One extra parameter: fraction of SNe that become GRBs $\zeta_{\rm SN}$.

GRB model: properties

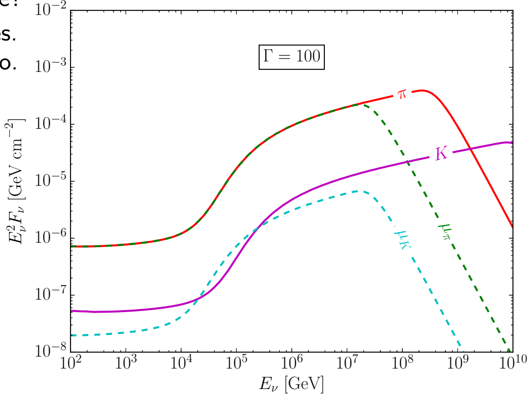
- Protons accelerated by the central engine following Fermi acceleration.
- Photons are measured to have a non-thermal spectrum.

  Band, et. al.: ApJ, 413, 281

  Amati, et. al.: astro-ph/0205230
- Magnetic fields carry $\sim 10\%$ of the total jet energy.
- Jet opening angle is related to the Lorentz boost factor $\theta_j = 1/\Gamma$.
- Variability time t_v scales with Γ:
  ~ 100 s for small Γ down to ~ 0.001 s for $\Gamma \sim 1000$.
- The shock radius of acceleration is $r \propto t_v$.

Particle physics in jets

- $p\gamma$ interactions lead to pions and kaons.
- Pions and kaons quickly decay to muons and neutrinos.
- Muons decay to more neutrinos.
- Protons, pions, kaons, and muons lose energy in the jet,
  - Do they decay in time?
    - Low energy $\Rightarrow$ yes.
    - High energy $\Rightarrow$ no.



Distribution of jets: “simple”

Each jet has one Γ value sampled from a power law in Γ.

We normalize with the SN and HL-GRB rates,

- All jets are equal to the fraction of SNe $\zeta_{\rm SN}$ that form jets and point at us.
- Relativistic jets ($\Gamma > 200$) forms the observed HL-GRB data set.

This leads to exponents $\alpha_\Gamma \sim [-1, -3]$ depending on $\zeta_{\rm SN}$.

Then the redshift evolution follows that of star formation rate not that of GRBs.

Distribution of jets: “advanced”

We consider multiple shocks leading to a random walk with more boosted particles in the middle of the jet.

The observed distribution in Γ's comes from,

- Distribution in jets, $\Gamma_{\rm max}$ and
- Angle of the jets relative to the Earth.

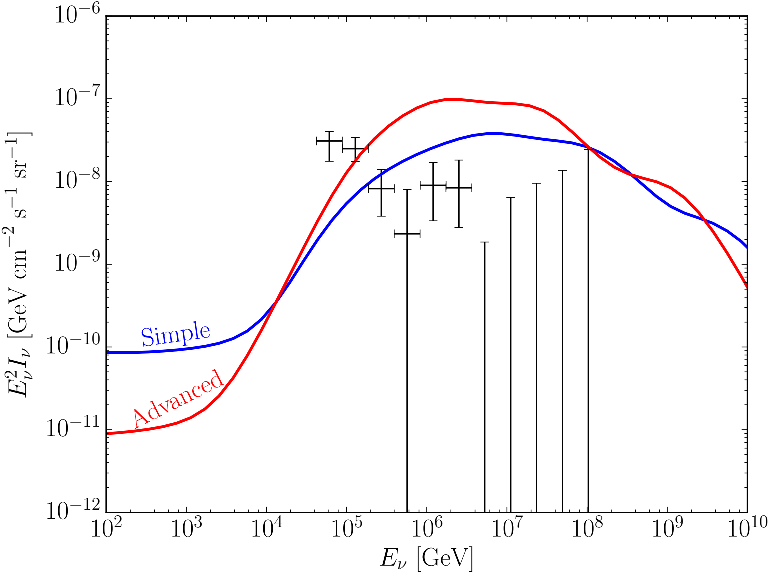
Consider a distribution of jets given instead by a power law in $\Gamma_{\rm max}$:

- $\Gamma = \Gamma_{\rm max}$ along the jet axis.
- Γ falls off as the angle increases with characteristic width $\sigma = 1/\sqrt{\Gamma_{\rm max}}$.
- The total jet opening angle wide enough to contain down to $\Gamma = 1$.

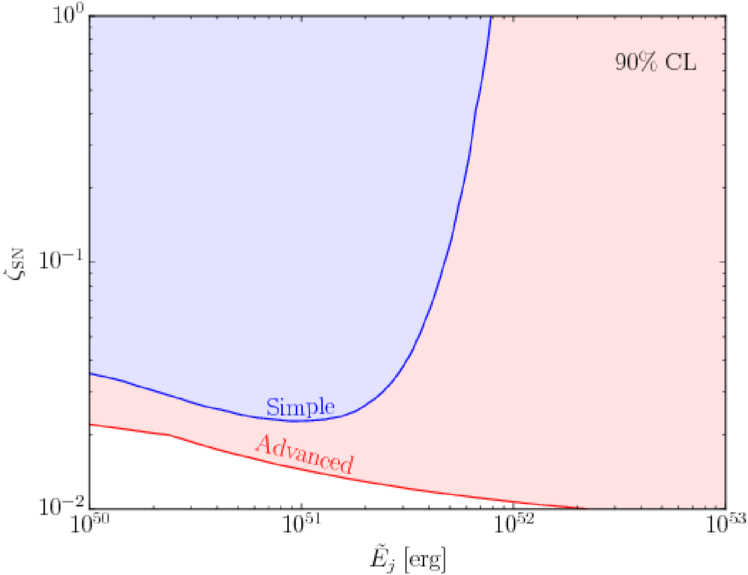
Normalize to GRB and SNe rates in the same way.

Diffuse intensities

At $\zeta_{\rm SN} = 0.1$ and $\tilde{E}_j = 10^{51}$ erg.



Source parameter exclusion limits

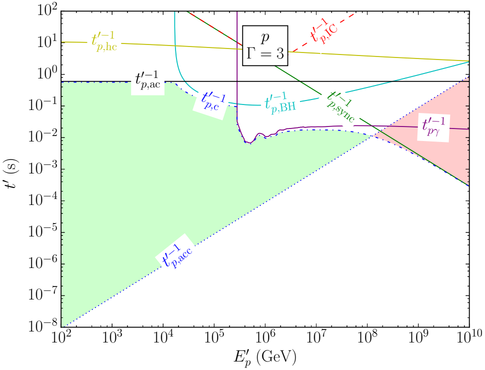


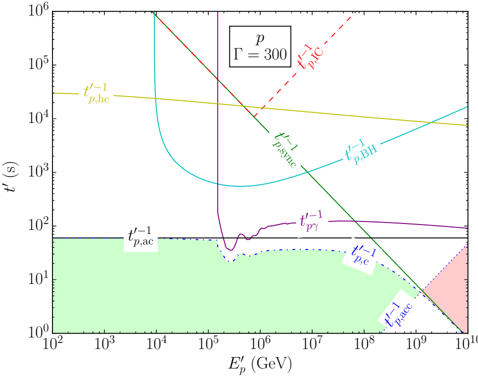
Conclusions

- IceCube has measured the astrophysical neutrino flux.
- The astrophysical neutrino flux is largely extragalactic.
- GRBs naturally lead to a high neutrino flux.
- Need to consider different classes of jets.
- SNe-GRB connection allows for physical constraints on choked GRBs.
- $\lesssim 1\%$ of SNe form jets, the majority of which will be choked.

Backups

Proton cooling





Muon energy correction

The energy deposited in tracks is not the true neutrino energy because the muon carries some of the energy out of the detector.

- Muon energy loss rate: $\frac{dE_\mu}{d\ell} = -(a + bE_\mu)$.
- Inelasticity parameter $y \equiv E_{\rm had}/E_\nu$.
- For a finite sized detector $\ell_{\sf max} = 1$ km,
  we can relate the deposited and neutrino energies by,

$$\frac{E_{\rm dep}}{E_\nu} \approx \langle y \rangle + (1 - \langle y \rangle) b\ell_{\sf max}\,,$$

  which is valid in the region of interest.

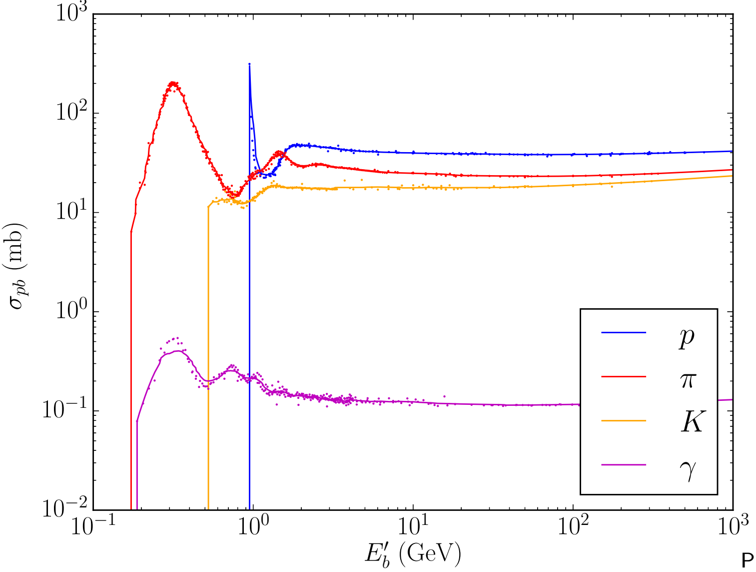
  Anchordoqui, Weiler, et. al.: 1611.07905

- $\langle y \rangle \in [0.25, 0.55]$ for relevant energies.

  Gandhi, Quigg, Reno, Sarcevic: hep-ph/9512364

Cross sections

Use the data for low energies, fits for high energies.



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