

Abstract

IceCube has provided the first measurements of the extragalactic high energy astrophysical neutrino flux. The sources of these neutrinos remains unknown. I will first discuss the possibility that they are of galactic origin and show that they are dominantly extragalactic. 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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DESY-Zeuthen

January 29, 2018

1703.09721 with Danny Marfatia and Tom Weiler

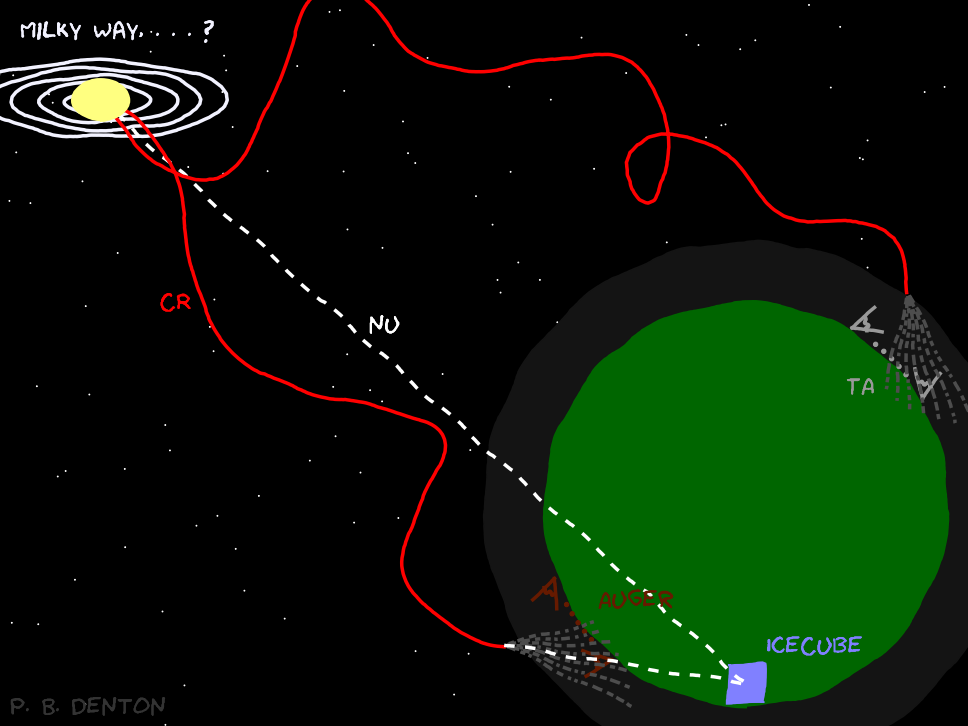
1711.00470 with Irene Tamborra



The Niels Bohr
International Academy

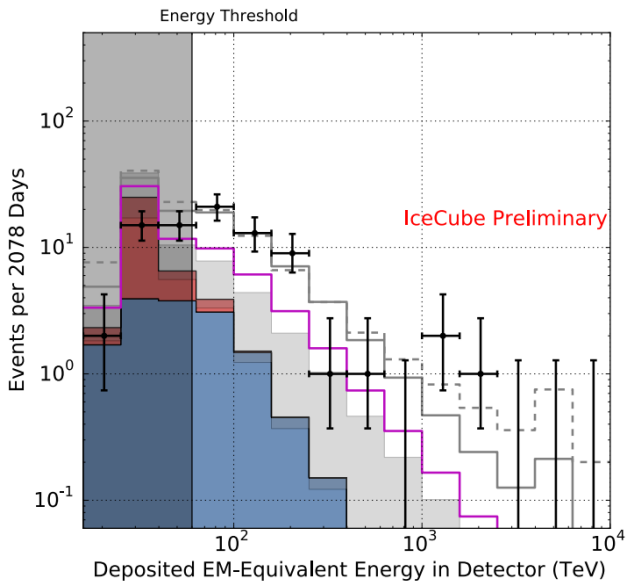
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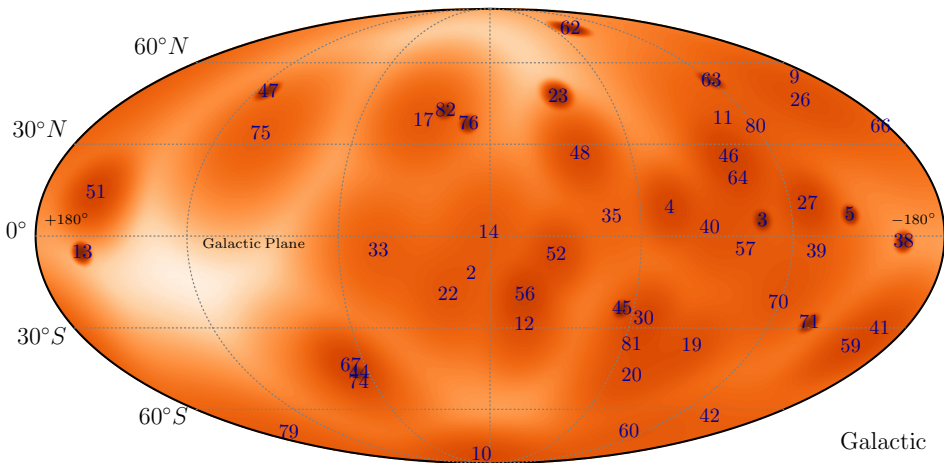


IceCube detects astrophysical neutrinos

IC's 6 yr HESE: ICRC 2017

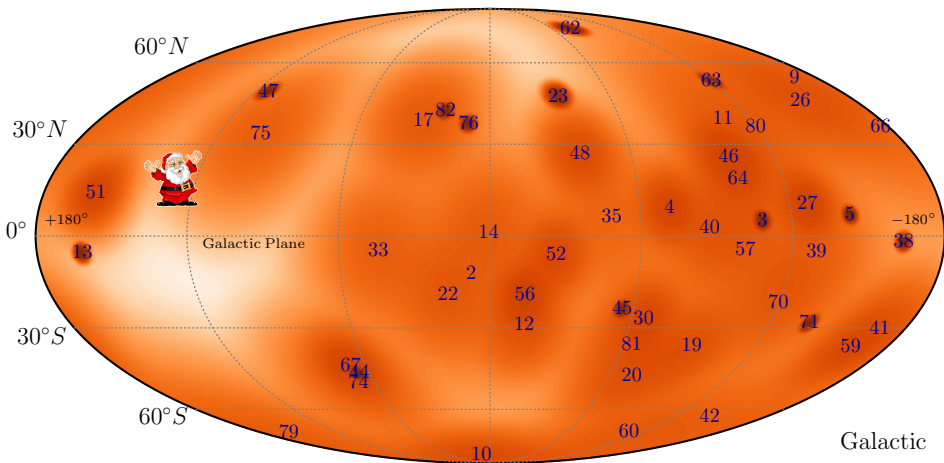


IceCube detects isotropic flux of astrophysical neutrinos



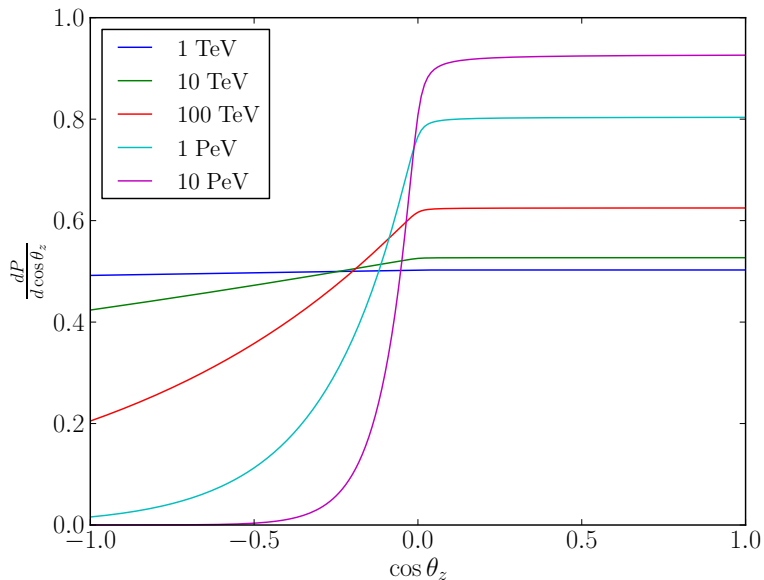
50 events with $E_{\text{dep}} > 60$ TeV from IC 6 year HESE

IceCube detects isotropic flux of astrophysical neutrinos



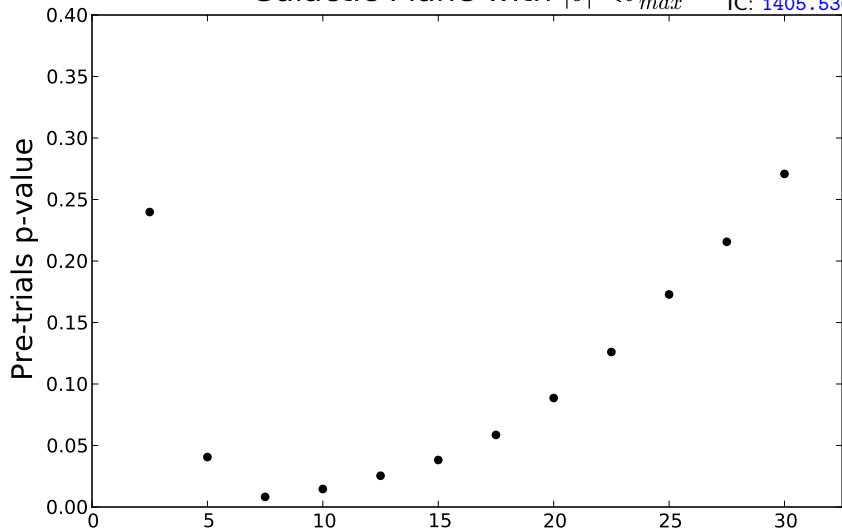
50 events with $E_{\text{dep}} > 60$ TeV from IC 6 year HESE

High energy neutrinos are absorbed by the Earth



Significance of the galaxy as the source

Galactic Plane with $|b| < \theta_{max}$ IC: 1405.5303



$p_{\text{post}} = 0.028$ at $\theta_{\text{max}} = 7.5^\circ$ $\theta_{\text{max}} [^\circ]$

Galactic or extragalactic?

Various methods to search for anisotropies:

- ▶ Windowed search around the Galactic center/plane.

IC: [1311.5238](#), [1405.5303](#)

Ahlers, Murase: [1309.4077](#)

Anchordoqui, et al.: [1410.0348](#)

Palladino, Winter: [1801.07277](#)

- ▶ Known Galactic sources:

CRs, γ -ray correlations, GC, Fermi bubbles, misc. Galactic catalogs, ...

IC: [1406.6757](#) + [1707.03416](#)

Ahlers, et al.: [1505.03156](#)

Celli, Palladino, Vissani: [1604.08791](#)

- ▶ Known extragalactic sources: AGNs, blazars, SFGs, GRBs, ...

Bechtol, et al.: [1511.00688](#)

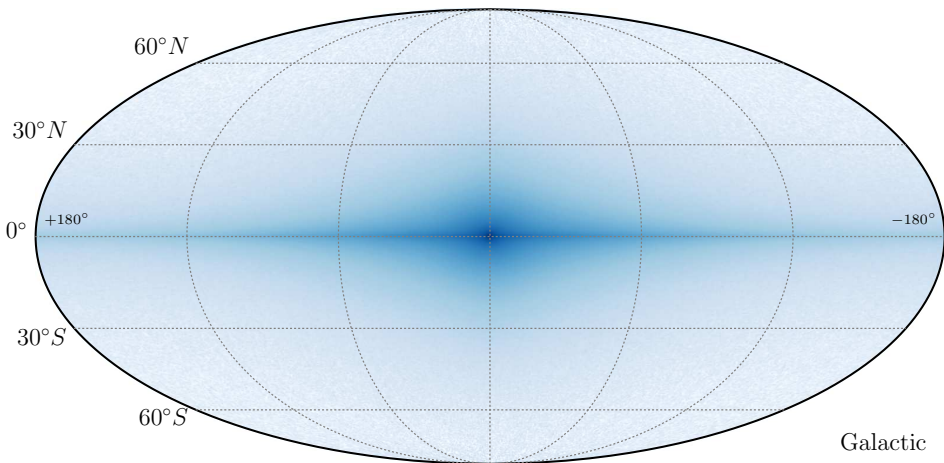
IC: [1601.06484](#)

Padovani, et al.: [1601.06550](#)

Lunardini, Winter: [1612.03160](#)

Biehl, et al.: [1711.03555](#), [1705.08909](#)

Expected distribution from the galaxy



Mass distribution in MW

McMillan: [1102.4340](#)

Galactic or extragalactic?

Given that an event is astrophysical, the conditional likelihoods are,

$$\mathcal{L}_{\text{gal}|\text{astro},i}(f_{\text{gal}}) = f_{\text{gal}} \int d\Omega \Phi_{\text{gal}}(\Omega) f_{\text{vMF}}(\theta, \kappa_i), \quad \leftarrow \text{IC's psf}$$

$$\mathcal{L}_{\text{exgal}|\text{astro},i}(f_{\text{gal}}) = (1 - f_{\text{gal}}) \frac{1}{4\pi}.$$

The likelihood that event i is described by this model is,

$$\mathcal{L}_i(f_{\text{gal}}) = \mathcal{L}_{\text{bkg},i} \frac{1}{4\pi} + \mathcal{L}_{\text{astro},i} [\mathcal{L}_{\text{gal}|\text{astro},i}(f_{\text{gal}}) + \mathcal{L}_{\text{exgal}|\text{astro},i}(f_{\text{gal}})],$$

and the total likelihood is the product,

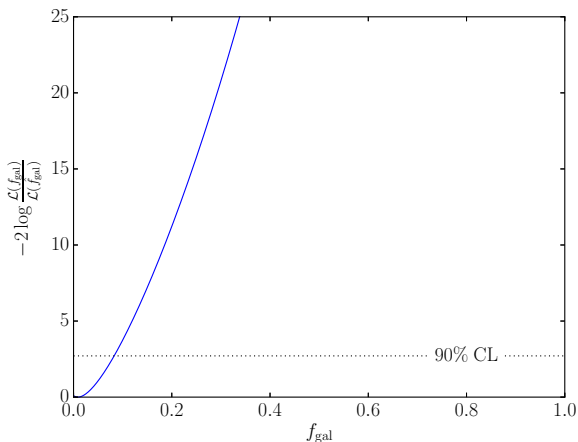
$$\mathcal{L}(f_{\text{gal}}) = \prod_i \mathcal{L}_i(f_{\text{gal}}).$$

- ▶ For $E_{\text{dep}} > 60$ TeV, we expect < 6 events from backgrounds.

IC: [1405.5303](#)

- ▶ Results independent of spectral fit, use data directly.

Galactic fraction: results



$$\hat{f}_{\text{gal}} = 0.013$$

$f_{\text{gal}} = 0$ consistent at $< 1\sigma$

CL	f_{gal}
1σ	< 0.057
90%	< 0.095
3σ	< 0.2

PBD, D. Marfatia, Weiler: [1703.09721](#)

Other possible sources

- ▶ Other galactic sources such as the Crab, Fermi bubbles:
nothing found.

IC: [1106.3484](#)

Ahlers, Murase: [1309.4077](#)

Ahlers, et al.: [1505.03156](#)

- ▶ 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.

∴ Move to diffuse backgrounds and use spectral information.

Gamma ray bursts

GRBs are potential UHECR and $\text{HE}\nu$ sources.



- ▶ Have observed ~ 1000 GRBs.
- ▶ Most luminous events observed.
- ▶ Photon measurements \Rightarrow high Γ outflow.
- ▶ Central engine?
 - ▶ CCSN.
 - ▶ Binary mergers, ...?
- ▶ IceCube has strong constraints from spatial + timing correlations.

IC: [1601.06484](#)

CCSN–GRB connection

Mounting evidence that some or all long duration GRBs are associated with CCSNe.

- ▶ Theoretical:

Lazzati, Morsony, Blackwell, Begelman: [1111.0970](#)

Sobacchi, Granot, Bromberg, Sormani: [1705.00281](#)

- ▶ Observational:

Paczyński: [astro-ph/9710086](#)

Hjorth, Bloom: [1104.2274](#)

Modjaz: [1105.5297](#)

Hjorth: [1304.7736](#)

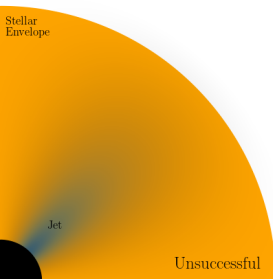
Margutti, et al.: [1402.6344](#)

CCSN + (rotation, B field) \Rightarrow jet.

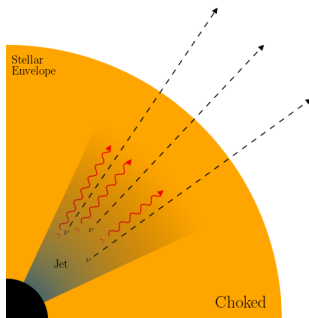
Three kinds of jets

The type of the jet determines the particle output:

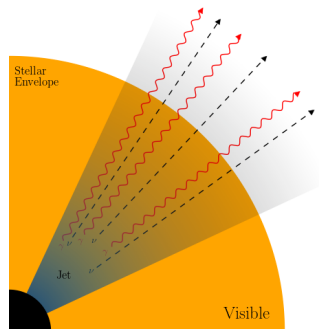
- ▶ Unsuccessful $\Rightarrow \emptyset$.
- ▶ Successful but choked $\Rightarrow \nu$'s.
- ▶ Successful and visible $\Rightarrow \nu$'s and γ 's.



Peter B. Denton (NBIA)



1703.09721, 1711.00470



DESY-Zeuthen: January 29, 2018 14/25

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 ζ_{SN} : fraction of CCSNe that harbor jets.

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:
 $\theta_j = 1/\Gamma$ for $\Gamma \leq 100$, $\theta_j = 30/\Gamma$ else.

Goldstein, et al.: [1512.04464](#)

- ▶ Variability time t_v scales with Γ :
 ~ 100 s for small Γ down to ~ 0.001 s for $\Gamma \sim 1000$.

Sonbas, et al.: [1408.3042](#)

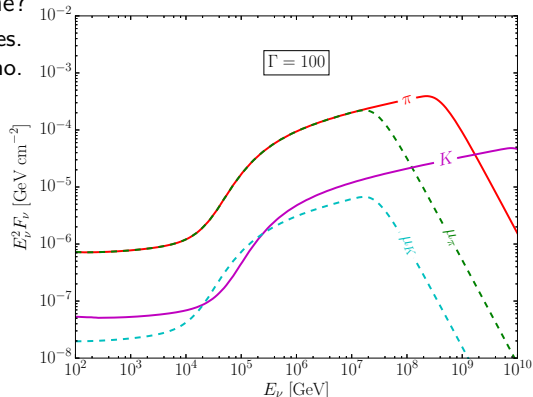
Campana, et al.: [astro-ph/0603279](#)

Gupta, Zhang: [astro-ph/0606744](#)

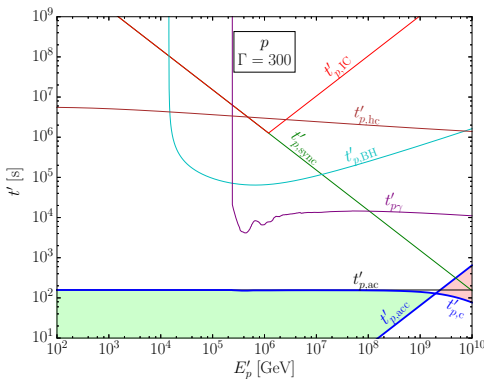
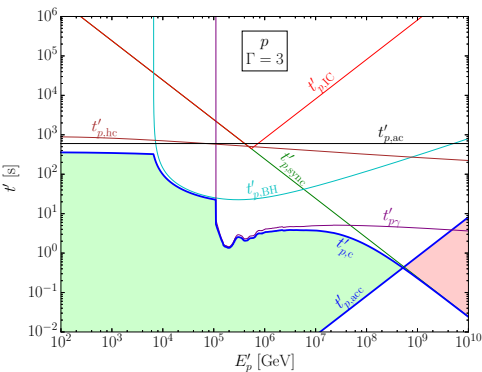
- ▶ The shock radius of acceleration follows the internal shock model and is $r_{IS} \propto t_v$.

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.



Proton cooling



Similarly for π 's, μ 's, and K 's.

Distribution of jets: the Simple model

Each jet has one Γ value sampled from a power law $\propto \Gamma^{\alpha_\Gamma}$.

We normalize with the SN and HL-GRB rates,

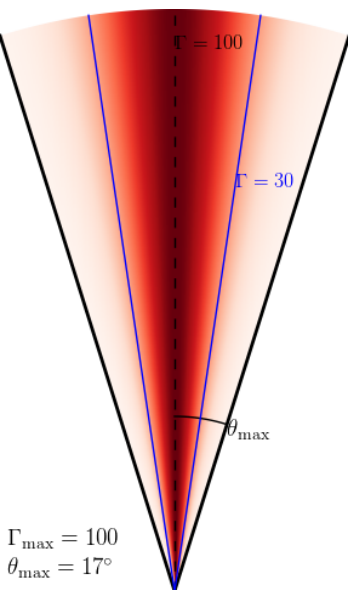
- ▶ All jets are equal to the fraction of SNe ζ_{SN} that form jets and point at us.
- ▶ Relativistic jets ($\Gamma > 200$) forms the observed HL-GRB data set.

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

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

Yuksel, et al.: [0804.4008](#)

Structured jets: the Advanced model



Multiple shocks \rightarrow random walk.

Distribution of jets drawn from a power law.
In each jet:

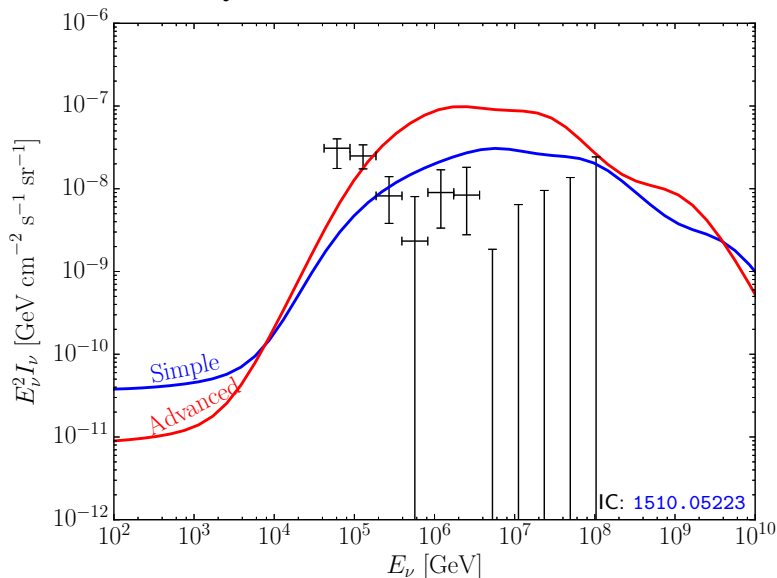
- ▶ $\Gamma = \Gamma_{\max}$ along the jet axis.
- ▶ Γ falls off as the angle increases with characteristic width $\sigma = 1/\sqrt{\Gamma_{\max}}$.
- ▶ The total jet opening angle contains all $\Gamma > 1$.

The observed distribution in Γ 's comes from both:

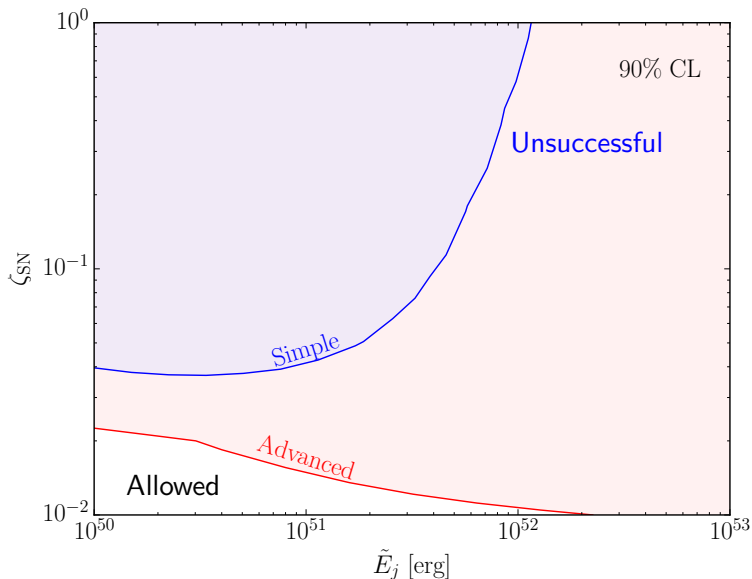
- ▶ Distribution of jets: power law in Γ_{\max} , and
- ▶ Angle of the jets relative to the Earth.

Diffuse intensities

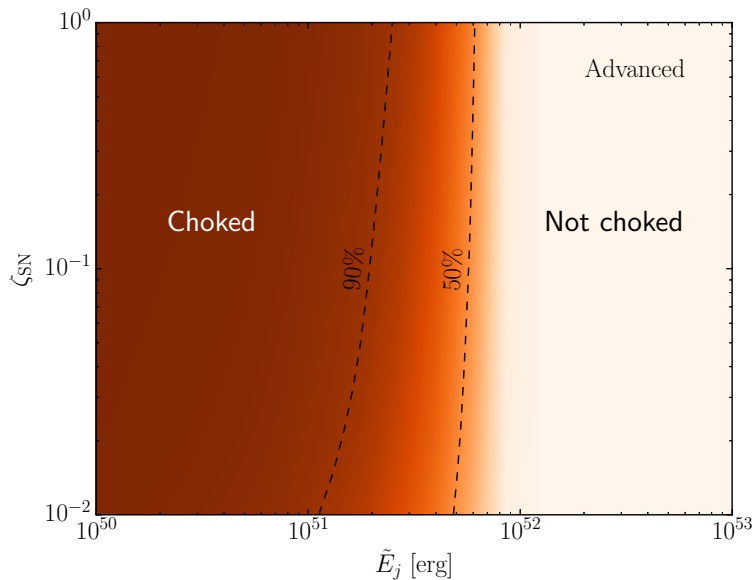
At $\zeta_{\text{SN}} = 0.1$ and $\tilde{E}_j = 10^{51}$ erg.



Source parameter exclusion limits



Choked fraction



GRB–Supernovae in the literature

- ▶ If all Ibc's form a jet, $\lesssim 10\%$ are visible.

Soderberg, Frail, Wieringa: [astro-ph/0402163](#)

Soderberg, Nakar, Kulkarni: [astro-ph/0507147](#)

Sobacchi, Granot, Bromberg, Sormani: [1705.00281](#)

- ▶ $R_{\text{GRB}}(0)/R_{\text{Ibc}}(0) \sim 0.1 - 1\%$, and Ibc's are $\sim 10\%$ of all CCSNe.

Grieco, et al.: [1204.2417](#)

- ▶ The subclass broadlined CCSNe linked to GRBs sans gamma rays.

Podsiadlowski, et al.: [astro-ph/0403399](#)

Mazzali, et al.: [astro-ph/0505199](#)

Soderberg, Nakar, Kulkarni: [astro-ph/0507147](#)

Soderberg: [astro-ph/0601693](#)

- ▶ Example: SN2002ap (Ic) had a jet 90° from observer,
 $\tilde{E}_j = 5 \times 10^{50}$ erg.

Totani: [astro-ph/0303621](#)

Conclusions

- ▶ IceCube has measured the HE astrophysical neutrino flux.
- ▶ The astrophysical neutrino flux is extragalactic and isotropic.
- ▶ GRBs naturally lead to a high neutrino flux.
- ▶ Need to consider different classes of jets.
- ▶ CCSNe-GRB connection allows for physical constraints on choked GRBs.
- ▶ $\lesssim 1\%$ of CCSNe form jets, the majority of which will be choked.
- ▶ These could be type Ibc SNe forming jets: unsuccessful, choked, off/on-axis.

Backups

Likelihoods to Probabilities

$$p_{\text{gal},i} = \frac{\mathcal{L}_{\text{gal}|\text{astro},i}(\hat{f}_{\text{gal}})\mathcal{L}_{\text{astro},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})},$$

$$p_{\text{exgal},i} = \frac{\mathcal{L}_{\text{exgal}|\text{astro},i}(\hat{f}_{\text{gal}})\mathcal{L}_{\text{astro},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})},$$

$$p_{\text{bkg},i} = \frac{\frac{1}{4\pi}\mathcal{L}_{\text{bkg},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})}.$$

$$\sum_i p_{\text{gal},i} = 0.6, \quad \sum_i p_{\text{exgal},i} = 45.3, \quad \sum_i p_{\text{bkg},i} = 4.1.$$

50 Event-By-Event Probabilities at $\hat{f}_{\text{gal}} = 0.013$

E	id	p_{gal}	p_{exgal}	p_{bkg}	E	id	p_{gal}	p_{exgal}	p_{bkg}
2003	35	0.0096	0.99	0	143	47	0	0.96	0.041
1140	20	2e-5	1	0	141	71	1.6e-5	0.92	0.079
1040	14	0.36	0.64	0	137	5	1.3e-4	0.81	0.19
885	45	1.2e-4	1	0	132	57	6.9e-4	1	0
512	13	1.8e-4	1	8.6e-4	128	30	1e-4	1	0
404	38	3.8e-4	0.87	0.13	124	59	0	0.81	0.19
384	33	0.012	0.98	0.0045	117	2	0.12	0.87	9.5e-4
318	82	2.7e-5	0.56	0.44	104	48	3.2e-4	1	0.0032
249	76	6.8e-5	0.7	0.3	104	56	0.0046	1	0
219	22	0.046	0.93	0.021	104	12	0.002	1	0
210	26	0	0.88	0.12	101	39	2.8e-4	0.96	0.04
199	17	1.9e-4	0.84	0.16	98	70	9.9e-5	0.99	0.0064
190	63	1.1e-5	0.75	0.25	97	10	0	0.99	0.0074
165	67	0	0.47	0.53	93	60	0	1	0
165	4	0.0017	1	0	88	11	3.9e-5	0.9	0.095
164	44	1.4e-5	0.84	0.16	87	41	1.4e-5	0.78	0.22
164	75	4.2e-5	1	0	85	80	3.5e-5	0.91	0.091
159	23	2.8e-5	0.94	0.06	84	66	2.5e-5	0.95	0.054
158	79	0	0.81	0.19	76	42	0	0.98	0.017
158	52	0.043	0.96	0	71	19	2.6e-5	1	0
158	46	4.2e-5	0.94	0.057	71	74	1.6e-5	0.77	0.23
157	40	0.0014	1	0	70	64	1.9e-4	0.98	0.016
152	3	4.7e-4	0.95	0.046	66	51	6.3e-5	0.96	0.044
151	81	1.2e-4	1	0	63	9	0	0.91	0.092
146	62	0	0.89	0.11	60	27	1.8e-4	0.89	0.11

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 $y \equiv E_{\text{had}}/E_\nu$.
- ▶ For a finite sized detector $\ell_{\text{max}} = 1 \text{ km}$, we can relate the deposited and neutrino energies by,

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

which is valid in the region of interest.

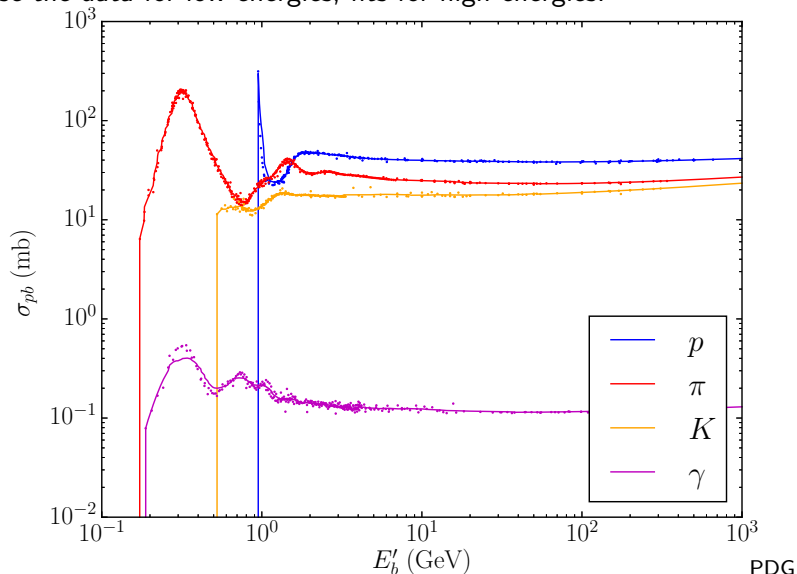
Anchordoqui, Weiler, et al.: [1611.07905](#)

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

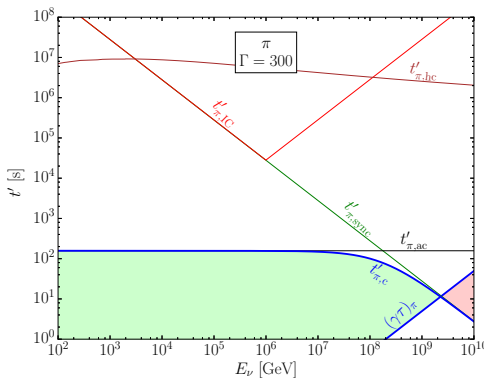
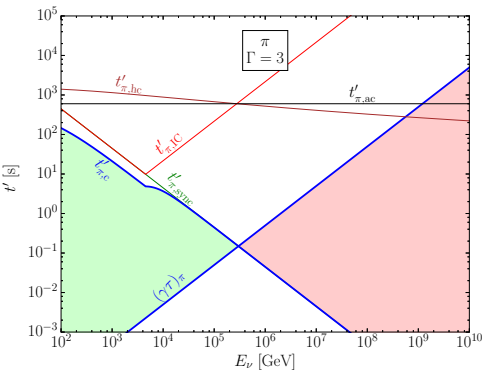
Gandhi, Quigg, Reno, Sarcevic: [hep-ph/9512364](#)

Cross sections

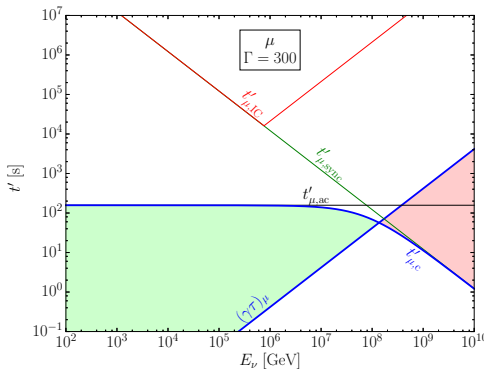
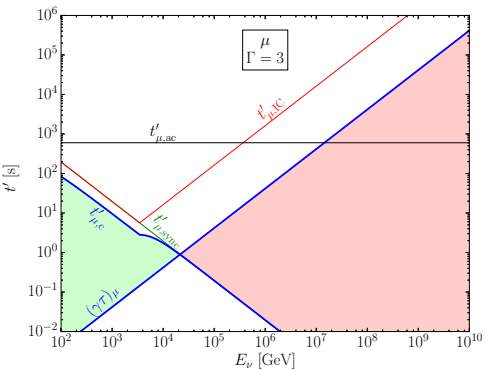
Use the data for low energies, fits for high energies.



Pion cooling



Muon cooling



Kaon cooling

