## 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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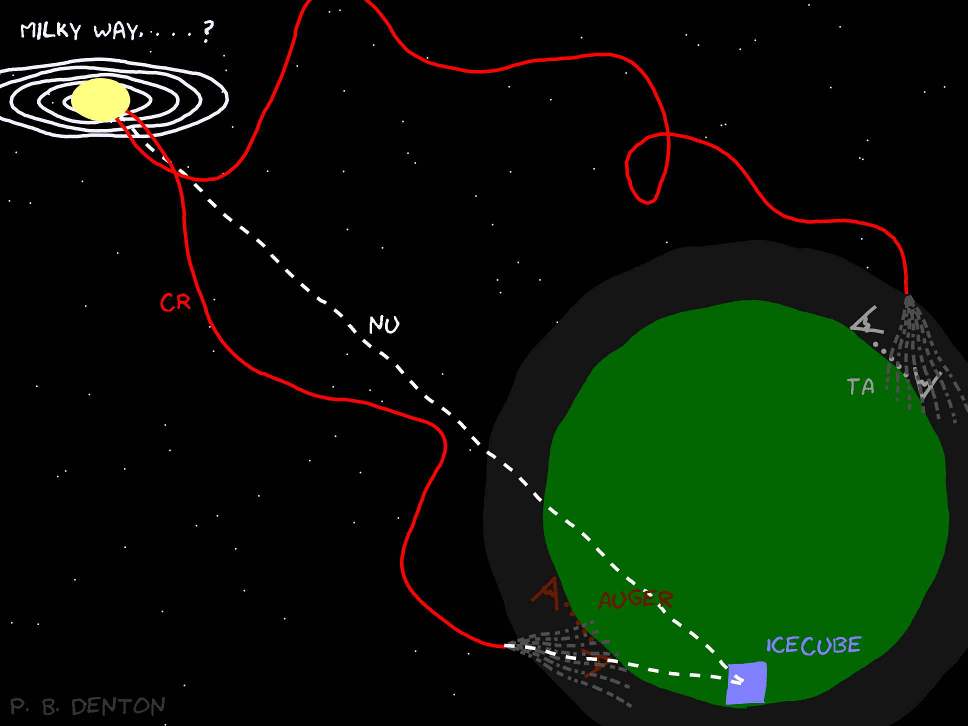
January 12, 2018

1703.09721 with Danny Marfatia and Tom Weiler
1711.00470 with Irene Tamborra

The Niels Bohr International Academy

VILLUM FONDEN


MILKY WAY. . . . ?
CR
NU
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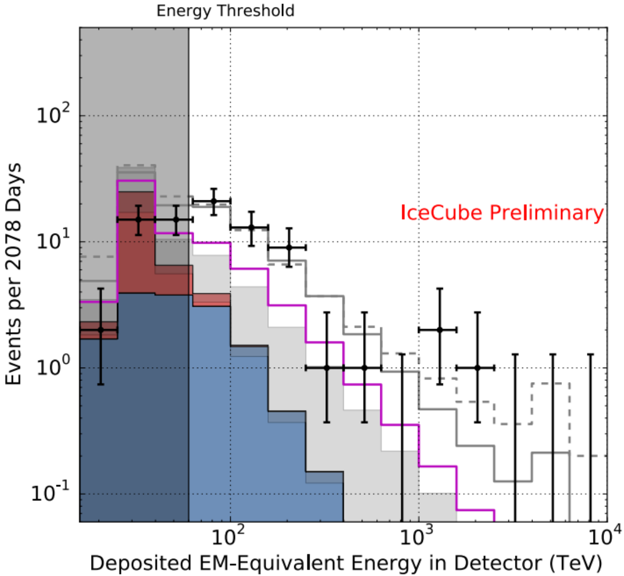
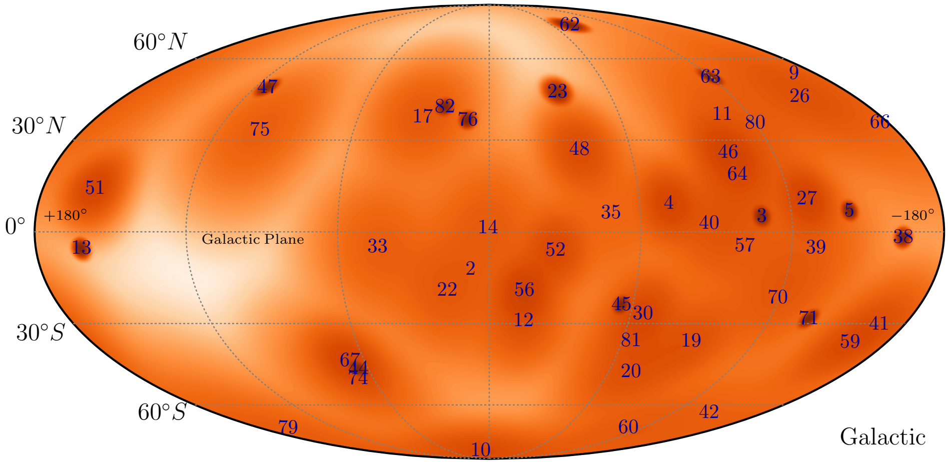
AUGER
ICECUBE
P. B. DENTON

# IceCube detects astrophysical neutrinos

IC's 6 yr HESE: ICRC 2017

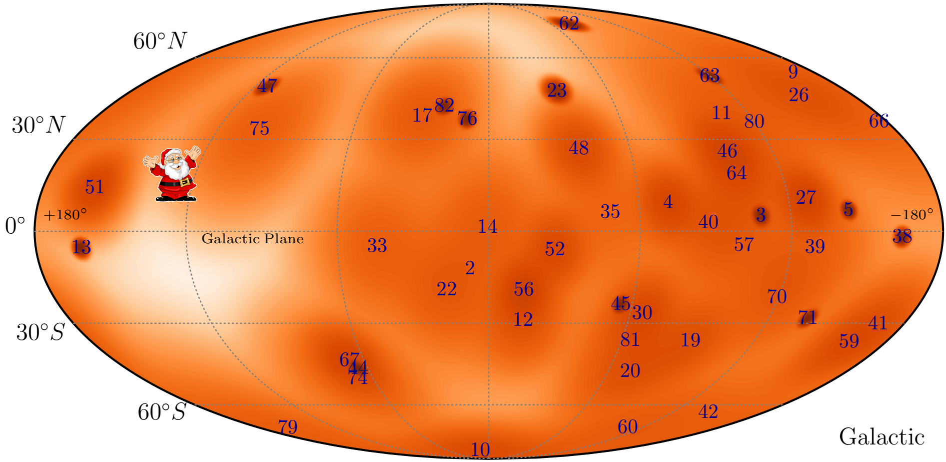


# IceCube detects isotropic flux of astrophysical neutrinos



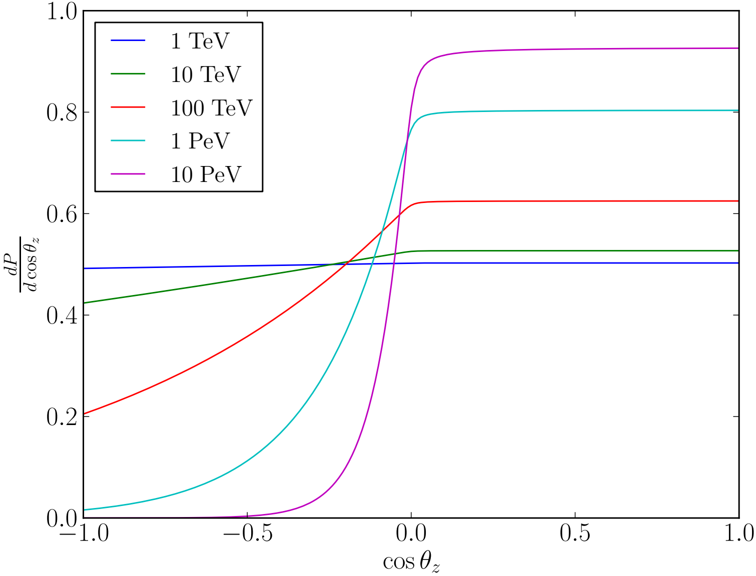

50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

# IceCube detects isotropic flux of astrophysical neutrinos

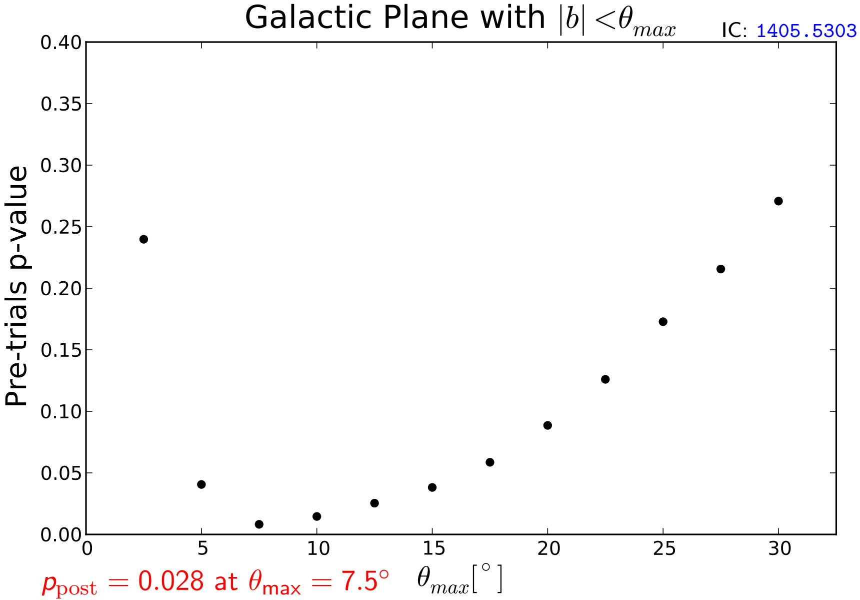



50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

# High energy neutrinos are absorbed by the Earth



# Significance of the galaxy as the source




$p_{\rm post} = 0.028$ at $\theta_{\rm max} = 7.5^\circ$

# 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, Vissani: 1601.06678

- Known Galactic sources:
  CRs, $\gamma$-ray correlations, GC, Fermi bubbles, misc. Galactic catalogs, ...

IC: 1406.6757 + 1707.03416

Lunardini, Razzaque, Yang: 1504.07033

Troitsky: 1511.01708

Celli, Palladino, Vissani: 1604.08791

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

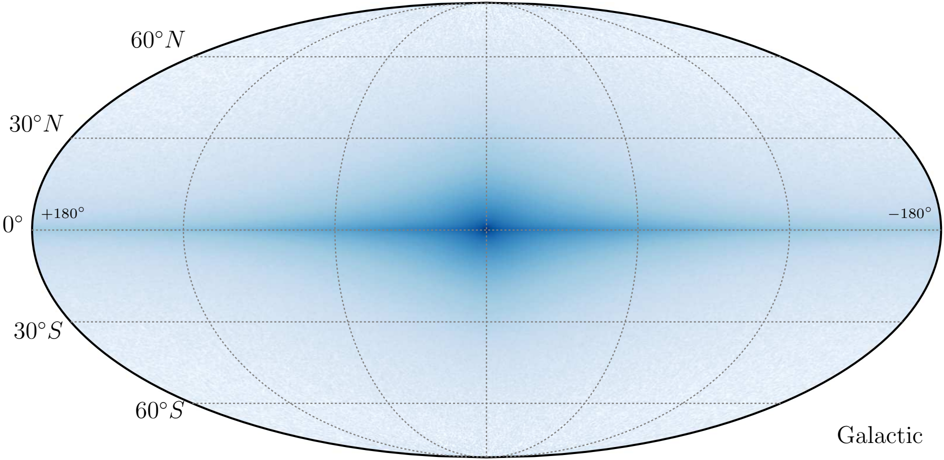
Bechtol, et al.: 1511.00688

Murase: 1511.01590

IC: 1601.06484

Padovani, et al.: 1601.06550

# 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,

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

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

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

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

and the total likelihood is the product,

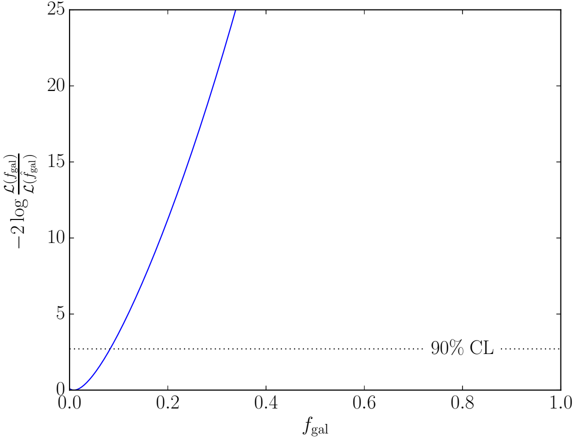
$$\mathcal{L}(f_{\mathrm{gal}}) = \prod_i \mathcal{L}_i(f_{\mathrm{gal}})\,.$$

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

IC: 1405.5303

- Results independent of spectral fit, use data directly.

# Galactic fraction: results




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

| CL | $f_{\rm gal}$ |
|---|---|
| $1\sigma$ | $< 0.057$ |
| 90% | $< 0.095$ |
| $3\sigma$ | $< 0.2$ |

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.

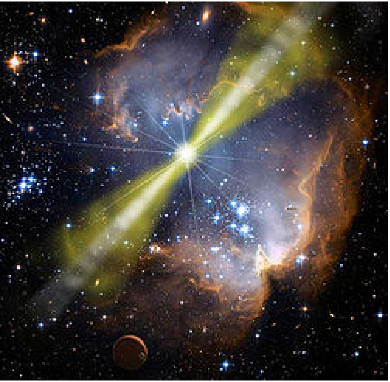
IC, Auger, TA: 1511.09408

Seem to be running out of source catalogs to check.

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

# Gamma ray bursts

GRBs are potential UHECR and HE$\nu$ sources.



- Have observed $\sim$ 1000 GRBs.
- Most luminous events observed.
- Photon measurements $\Rightarrow$ high $\Gamma$ 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

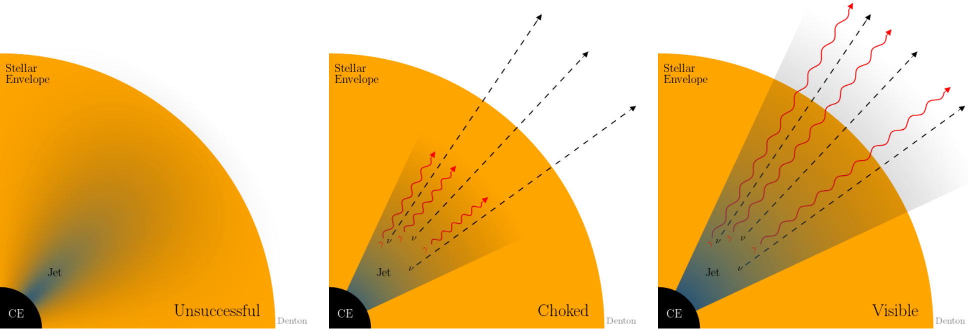
Margutti, et al.: 1402.6344

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 $\gamma$'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 $\zeta_{\rm SN}$: 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 $\Gamma$: $\sim 100$ s for small $\Gamma$ down to $\sim 0.001$ s for $\Gamma \sim 1000$.

Sonbas, et al.: 1408.3042

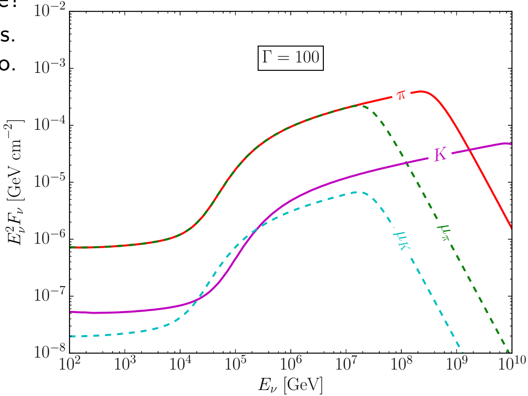
Campana, et al.: astro-ph/0603279

Gupta, Zhang: astro-ph/0606744

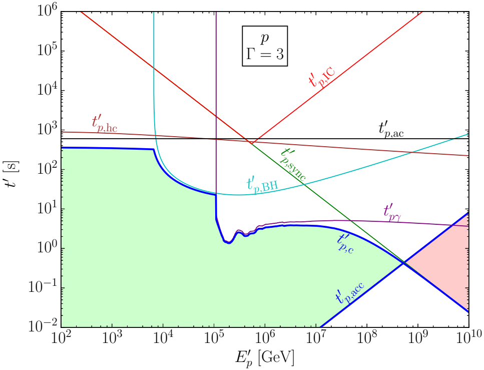
- The shock radius of acceleration follows the internal shock model and is $r_{\rm IS} \propto t_v$.

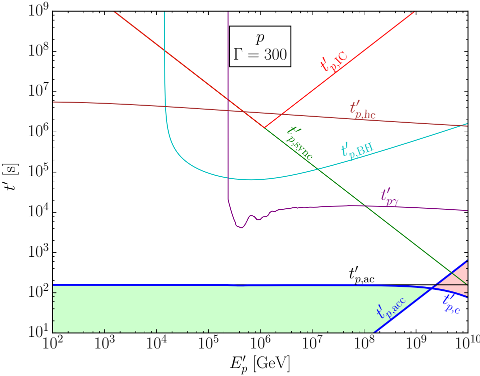
# Particle physics in jets

- $p\gamma$ 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 $\pi$'s, $\mu$'s, and $K$'s.

# Distribution of jets: the Simple model

Each jet has one $\Gamma$ 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 $\zeta_{\rm SN}$ 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.

Yuksel, et al.: 0804.4008

# Structured jets: the Advanced model

As a particle is shocked multiple times, its angle will follow a random walk with more boosted particles in the middle of the jet.

Consider a distribution of jets given instead by a power law $\propto \Gamma_{\rm max}^{\alpha_{\Gamma_{\rm max}}}$.
In each jet:

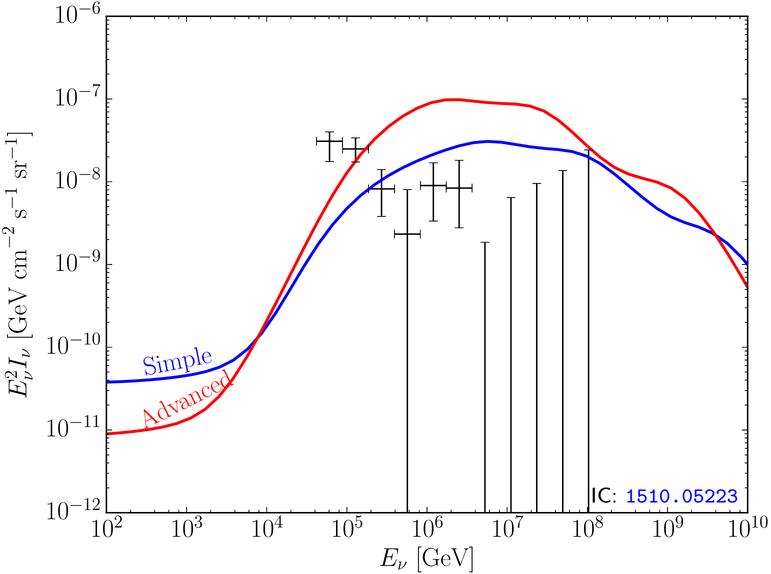
- $\Gamma = \Gamma_{\rm max}$ along the jet axis.
- $\Gamma$ falls off as the angle increases with characteristic width $\sigma = 1/\sqrt{\Gamma_{\rm max}}$.
- The total jet opening angle wide enough to contain down to $\Gamma = 1$.

The observed distribution in $\Gamma$'s comes from both

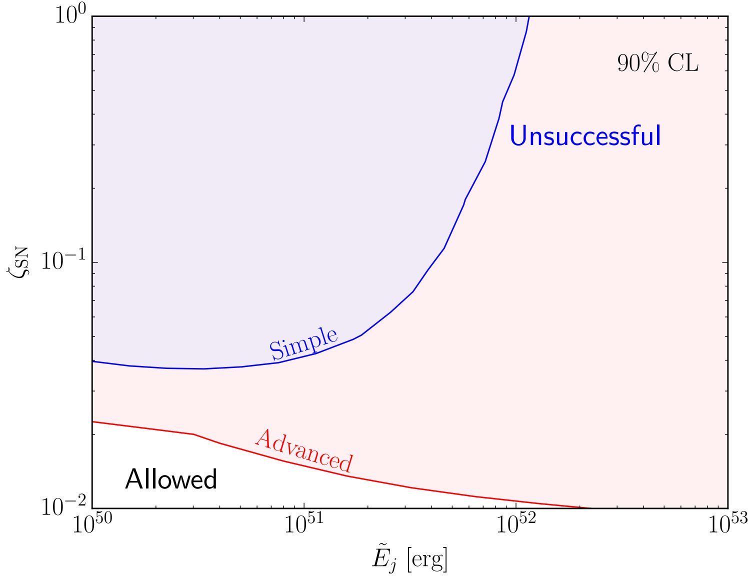
- Distribution of jets: power law in $\Gamma_{\rm max}$, and
- Angle of the jets relative to the Earth.

# Diffuse intensities

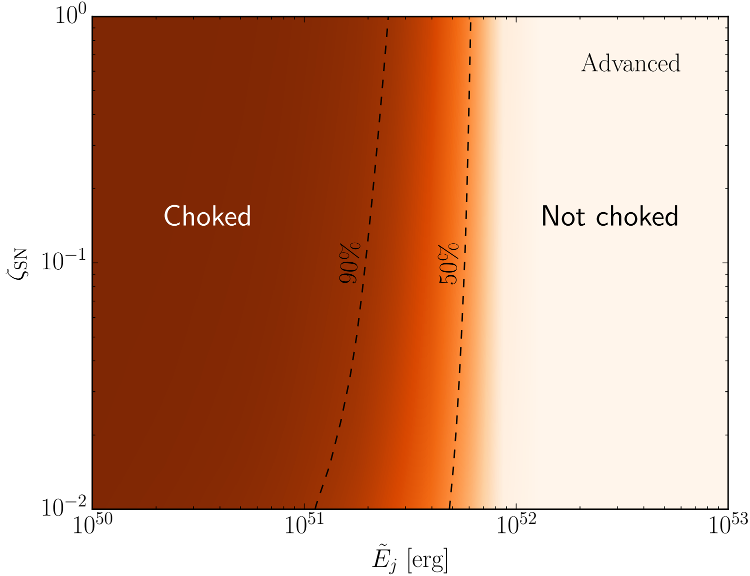
At $\zeta_{\rm SN} = 0.1$ and $\tilde{E}_j = 10^{51}$ erg.



# 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

- $R_{\rm GRB}(0)/R_{\rm Ibc}(0) \sim 0.1 - 1\%$, 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 $90^\circ$ from observer, $\tilde{E}_j = 5 \times 10^{50}$ erg.

Totani: astro-ph/0303621

# Conclusions

- IceCube has measured the 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

# Other projects

- Choked GRBs for IceCube and ANTARES's low energy excess?
  with Irene Tamborra
- UHECR isotropy, local anisotropy, and composition.
  with M. Rameez and Markus Ahlers
- Non standard neutrino interactions, LMA-Dark, COHERENT, and light mediators.
  with Ian Shoemaker, Yasaman Farzan, and John Cherry

# Likelihoods to Probabilities

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

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

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

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

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

| $E$ | id | $p_{\mathrm{gal}}$ | $p_{\mathrm{exgal}}$ | $p_{\mathrm{bkg}}$ |
|---|---|---|---|---|
| 2003 | 35 | 0.0096 | 0.99 | 0 |
| 1140 | 20 | 2e-5 | 1 | 0 |
| 1040 | 14 | 0.36 | 0.64 | 0 |
| 885 | 45 | 1.2e-4 | 1 | 0 |
| 512 | 13 | 1.8e-4 | 1 | 8.6e-4 |
| 404 | 38 | 3.8e-4 | 0.87 | 0.13 |
| 384 | 33 | 0.012 | 0.98 | 0.0045 |
| 318 | 82 | 2.7e-5 | 0.56 | 0.44 |
| 249 | 76 | 6.8e-5 | 0.7 | 0.3 |
| 219 | 22 | 0.046 | 0.93 | 0.021 |
| 210 | 26 | 0 | 0.88 | 0.12 |
| 199 | 17 | 1.9e-4 | 0.84 | 0.16 |
| 190 | 63 | 1.1e-5 | 0.75 | 0.25 |
| 165 | 67 | 0 | 0.47 | 0.53 |
| 165 | 4 | 0.0017 | 1 | 0 |
| 164 | 44 | 1.4e-5 | 0.84 | 0.16 |
| 164 | 75 | 4.2e-5 | 1 | 0 |
| 159 | 23 | 2.8e-5 | 0.94 | 0.06 |
| 158 | 79 | 0 | 0.81 | 0.19 |
| 158 | 52 | 0.043 | 0.96 | 0 |
| 158 | 46 | 4.2e-5 | 0.94 | 0.057 |
| 157 | 40 | 0.0014 | 1 | 0 |
| 152 | 3 | 4.7e-4 | 0.95 | 0.046 |
| 151 | 81 | 1.2e-4 | 1 | 0 |
| 146 | 62 | 0 | 0.89 | 0.11 |

| $E$ | id | $p_{\mathrm{gal}}$ | $p_{\mathrm{exgal}}$ | $p_{\mathrm{bkg}}$ |
|---|---|---|---|---|
| 143 | 47 | 0 | 0.96 | 0.041 |
| 141 | 71 | 1.6e-5 | 0.92 | 0.079 |
| 137 | 5 | 1.3e-4 | 0.81 | 0.19 |
| 132 | 57 | 6.9e-4 | 1 | 0 |
| 128 | 30 | 1e-4 | 1 | 0 |
| 124 | 59 | 0 | 0.81 | 0.19 |
| 117 | 2 | 0.12 | 0.87 | 9.5e-4 |
| 104 | 48 | 3.2e-4 | 1 | 0.0032 |
| 104 | 56 | 0.0046 | 1 | 0 |
| 104 | 12 | 0.002 | 1 | 0 |
| 101 | 39 | 2.8e-4 | 0.96 | 0.04 |
| 98 | 70 | 9.9e-5 | 0.99 | 0.0064 |
| 97 | 10 | 0 | 0.99 | 0.0074 |
| 93 | 60 | 0 | 1 | 0 |
| 88 | 11 | 3.9e-5 | 0.9 | 0.095 |
| 87 | 41 | 1.4e-5 | 0.78 | 0.22 |
| 85 | 80 | 3.5e-5 | 0.91 | 0.091 |
| 84 | 66 | 2.5e-5 | 0.95 | 0.054 |
| 76 | 42 | 0 | 0.98 | 0.017 |
| 71 | 19 | 2.6e-5 | 1 | 0 |
| 71 | 74 | 1.6e-5 | 0.77 | 0.23 |
| 70 | 64 | 1.9e-4 | 0.98 | 0.016 |
| 66 | 51 | 6.3e-5 | 0.96 | 0.044 |
| 63 | 9 | 0 | 0.91 | 0.092 |
| 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 $y \equiv E_{\rm had}/E_\nu$.
- 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.

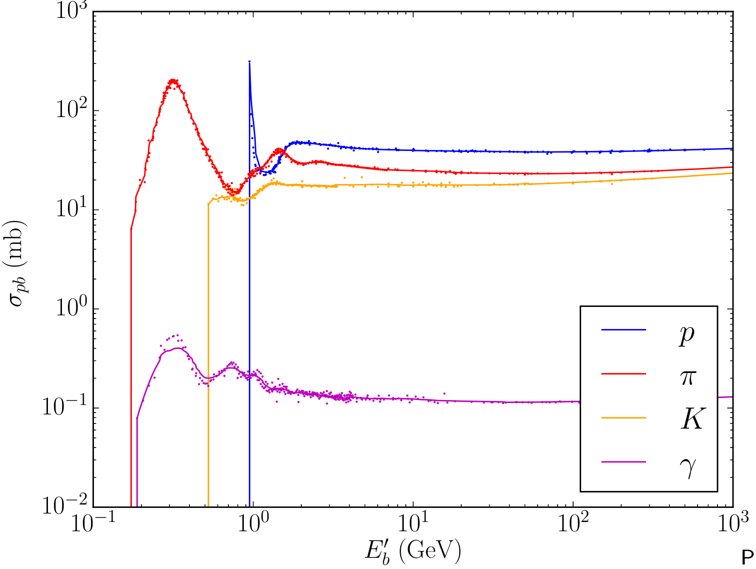
  Anchordoqui, Weiler, et al.: 1611.07905

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

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

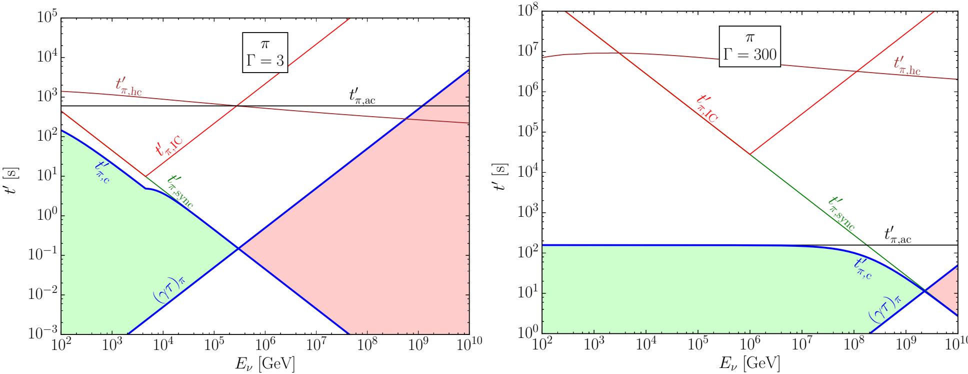
# Cross sections

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

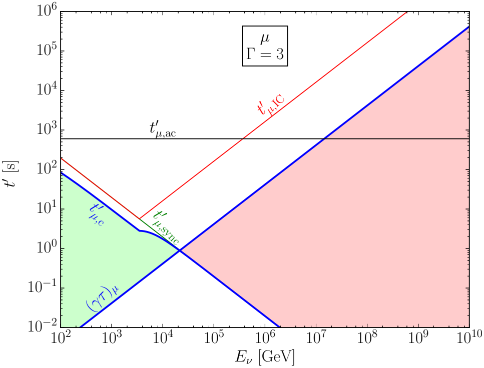


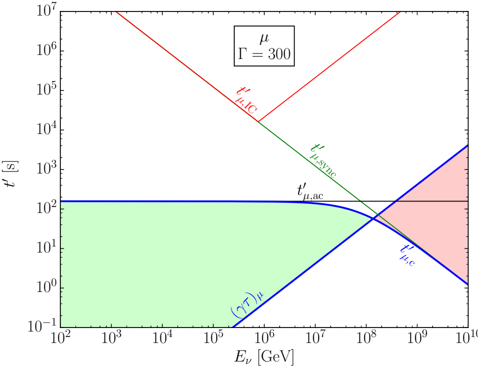

PDG

# Pion cooling



# Muon cooling



# Kaon cooling