Abstract

IceCube has recently detected high energy astrophysical neutrinos for the first time. While many known astrophysical processes are anticipated to create high energy neutrinos, the origin of the observed neutrinos remains unclear. In this talk I will first present evidence disfavoring the Milky Way as the primary origin of the flux based on event-by-event anisotropy arguments. I will also consider a promising extragalactic source of high energy astrophysical neutrinos – gamma ray bursts. I will present a detailed description of the expected neutrino flux from GRBs and then use the measured IceCube flux to constrain several unknown GRB properties.

What We Can Tell About the Sources of IceCube's Neutrinos, and What IceCube Can Tell Us About Gamma Ray Bursts

Peter B. Denton

Fermilab Astrophysics Seminar

August 14, 2017

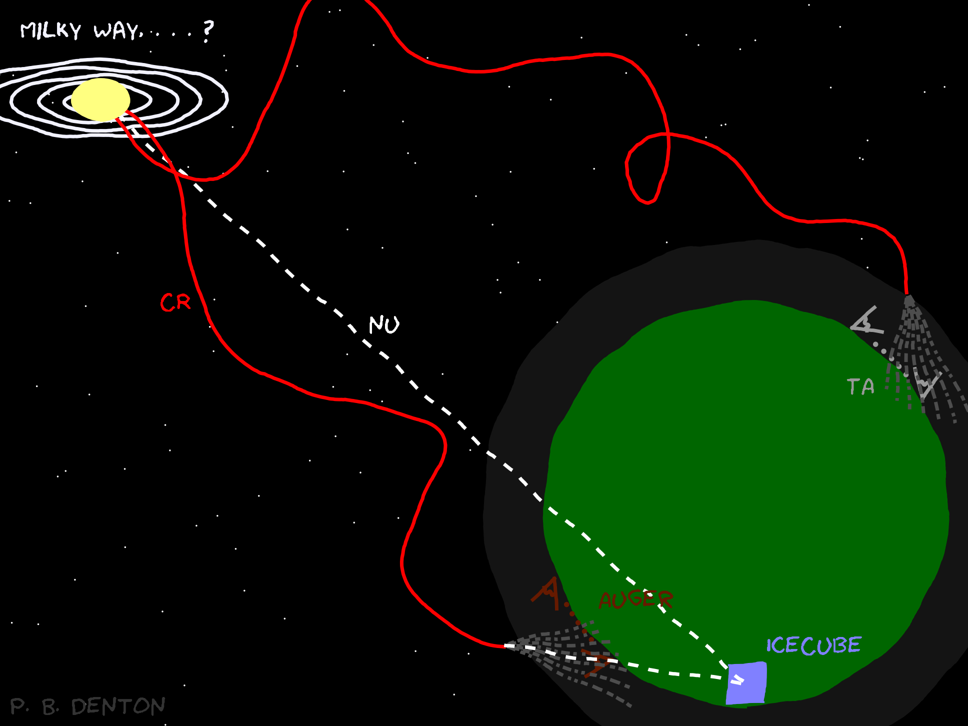
1703.09721 JCAP (as of Tuesday)
with Tom Weiler and Danny Marfatia

and

in preparation
with Irene Tamborra

The Niels Bohr International Academy

VILLUM FONDEN


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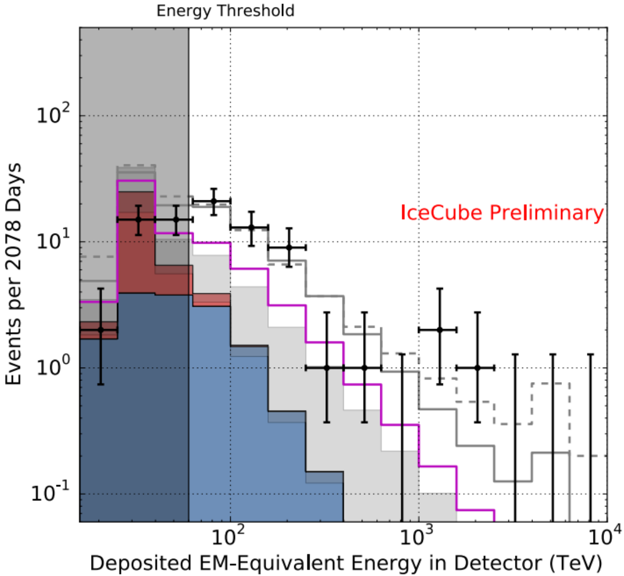
P. B. DENTON

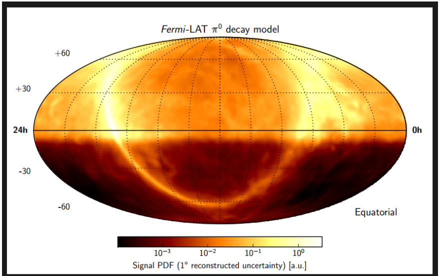
IceCube Detects Astrophysical Neutrinos

IC's 6 yr HESE: ICRC 2017

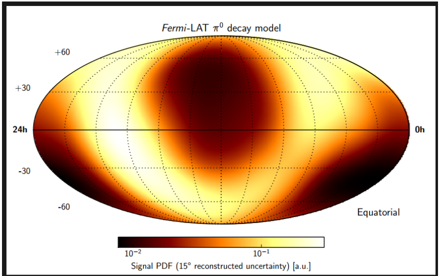


HESE vs. Track ⇒ Galactic Center vs. Galactic Plane

IceCube finds better sensitivity with cascades than with tracks:
2.5×10^{-11} vs. 3×10^{-11} TeV cm^{-2} s^{-1} (IC preliminary)



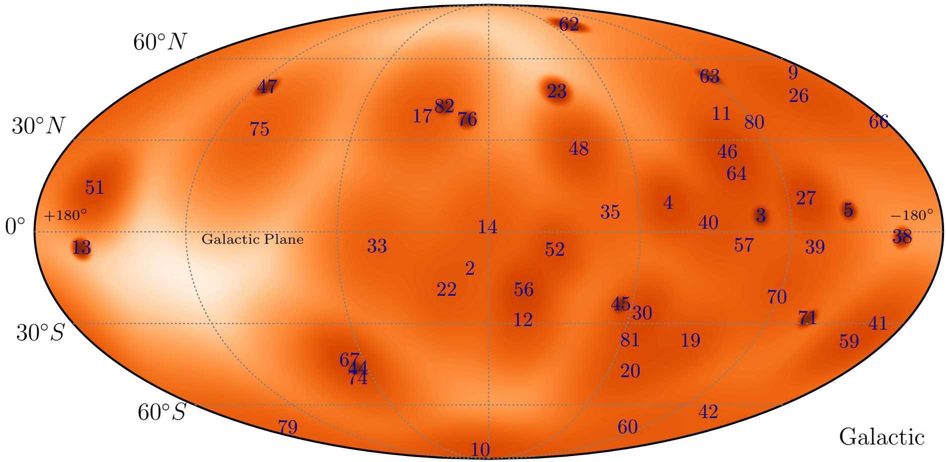
as viewed with throughgoing tracks



as viewed with cascades

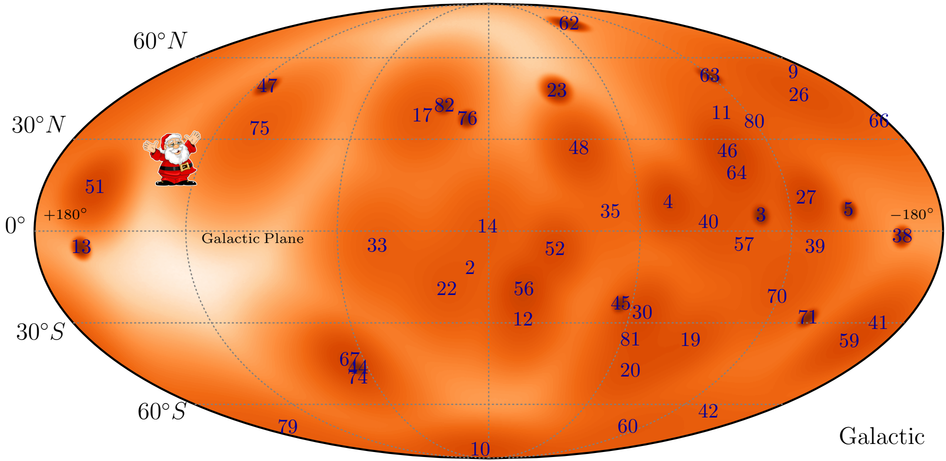
Mike Richman's talk at TeVPA

IceCube Detects Astrophysical Neutrinos



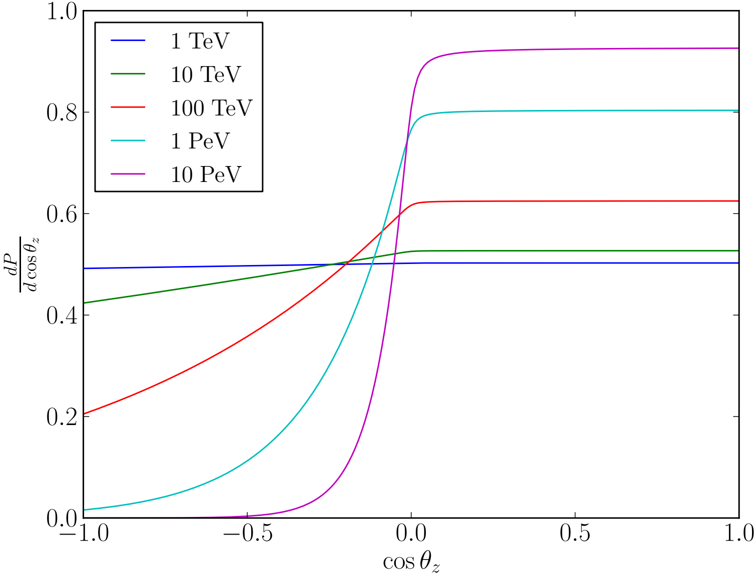
50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

IceCube Detects Astrophysical Neutrinos

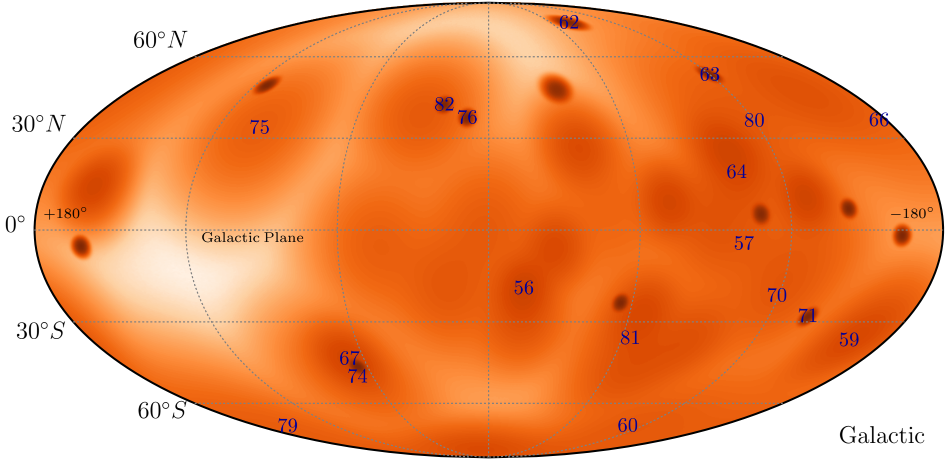


50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

High energy neutrinos are absorbed by the Earth



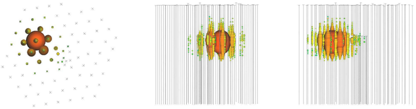
IceCube Detects Astrophysical Neutrinos

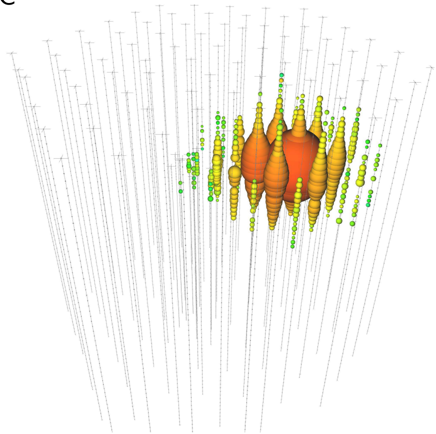


The 18 new events from the two latest years

IceCube Detects Astrophysical Neutrinos

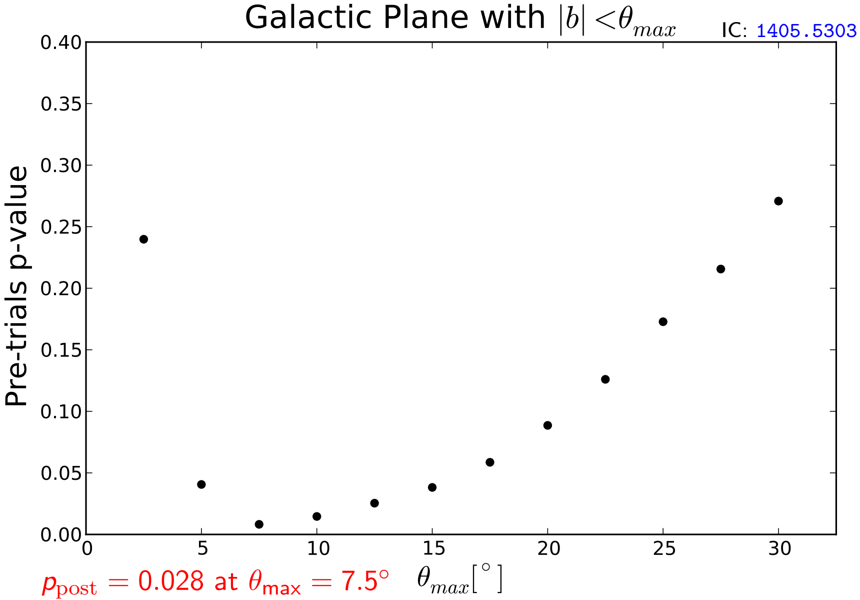
Event 14
$E = 1$ PeV
1.2° from the GC
$\alpha_{50\%} = 13.2^\circ$





IC: 1311.5238

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, γ-ray correlations, GC, misc. Galactic catalogs, ...

  IC: 1406.6757 + 1707.03416

  Ahlers, et. al.: 1505.03156

  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

A More General Approach

- Treat the extragalactic flux as isotropic, $\Phi_{\rm exgal}(\Omega) = \frac{1}{4\pi}$.
- Scale the galactic flux with the matter distribution $\rho_{\rm gal}$,

McMillan: 1102.4340

$$\Phi_{\rm gal}(\Omega) = \frac{\int ds\, \rho_{\rm gal}(s,\Omega)}{\int ds d\Omega'\, \rho_{\rm gal}(s,\Omega')}\,.$$

- Cross checked results with SNR and PWN distributions.

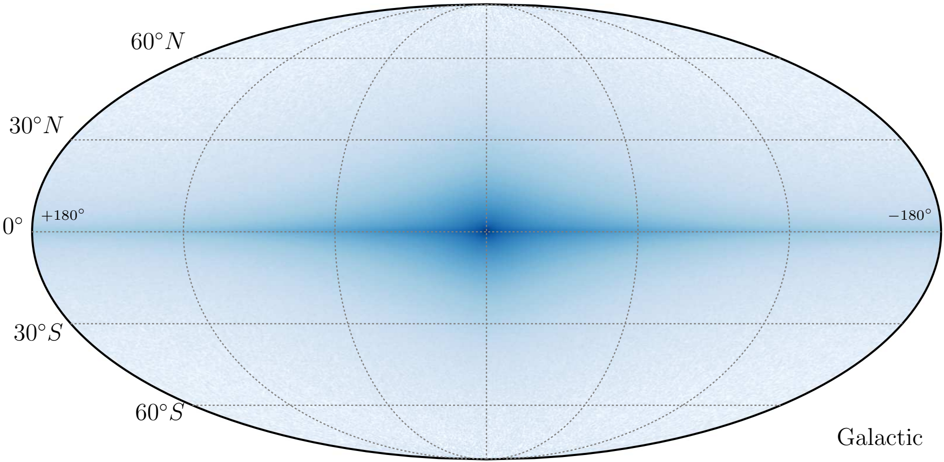
Case, Bhattacharya: astro-ph/9807162

Lorimer, et. al.: astro-ph/0607640

- $f_{\rm gal}$ is the fraction of the astrophysical flux from the Galaxy,

$$\Phi_{\rm astro}(\Omega, f_{\rm gal}) = f_{\rm gal}\Phi_{\rm gal}(\Omega) + (1-f_{\rm gal})\Phi_{\rm exgal}(\Omega)\,.$$

Expected Distribution From the Galaxy



Galactic or Extragalactic?

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

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

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

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

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

and the total likelihood is the product,

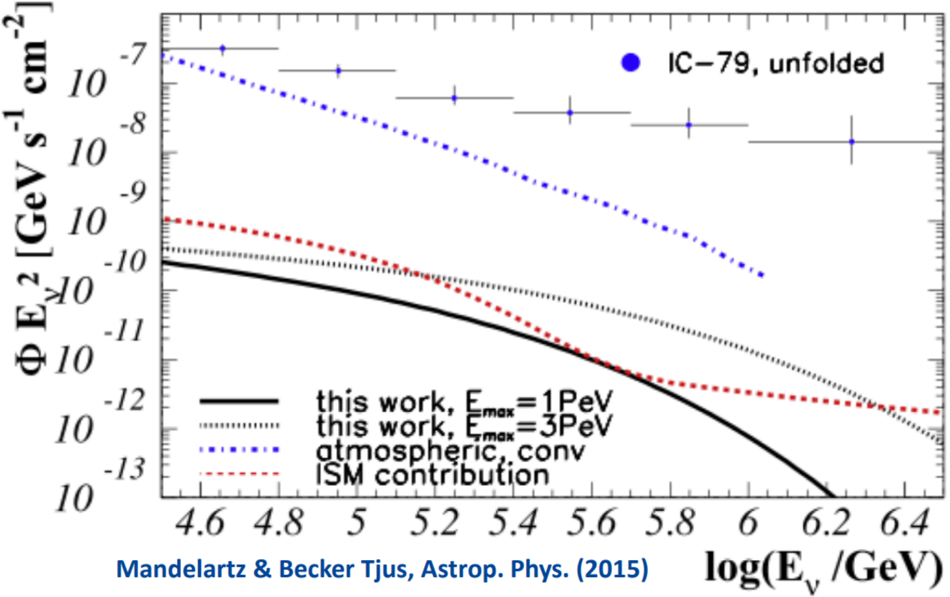
$$\mathcal{L}(f_{\mathrm{gal}}) = \prod_i \mathcal{L}_i(f_{\mathrm{gal}})\,.$$

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

  IC: 1405.5303

- Results independent of spectral fit, use data directly.

Galactic contribution to the flux

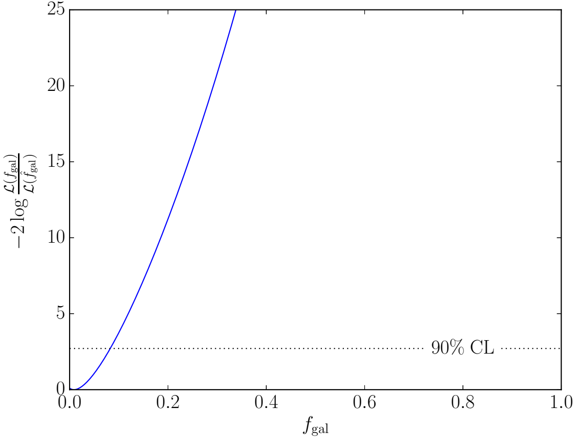


Mandelartz & Becker Tjus, Astrop. Phys. (2015)

Julia Tjus's talk at TeVPA

Results

Updated with 6 years of HESE data.



$\hat{f}_{\rm gal} = 0.044 \to 0.013$

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

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

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_{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

Possible extragalactic sources

- Cosmogenics from UHECR energy loss: wrong energy, flux.

  Berezinsky, Zatsepin: PLB '69

- Point source searches: nothing found.

  IC: 1406.6757

- Catalog correlations: nothing (significant) found.

  Moharana, Britto, Razzaque: 1602.03694

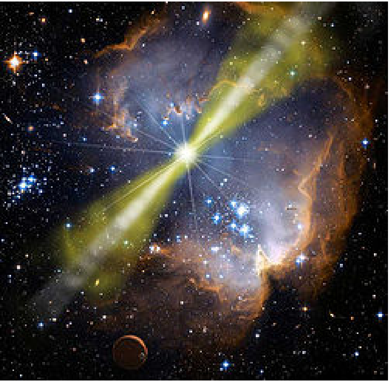
- UHECR correlation: nothing (significant) found.

  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?

GRB model: initial conditions

- Protons accelerated by the central engine at E_p^{-2}.
- Photons given by non-thermal Band spectrum, $E_\gamma^{-1} \to E_\gamma^{-2}$.
- Magnetic fields, $\epsilon_B = 0.1$.
- Variability time $\tilde{t}_v = 0.1$ s $\to$ sets the internal shock radius.
- Jets parameterized by opening angle θ_j.
  - More on this later.

Notation note:
X – Earth, $\tilde{X}$ – GRB, X' – jet
$\tilde{E} = (1+z)E$, $E' = \frac{1}{\Gamma}\tilde{E}$, ...

Jet properties

Jet time

If $\tau'_T \gtrsim 1$, efficient proton acceleration is impossible.

Murase, Ioka: 1306.2274

Require $\tilde{t}_j$ long enough such that $\tau'_T \leq 1$.

Otherwise scale jet time with observations,

$$\tilde{t}_j = \frac{3 \times 10^3 \text{ s}}{\Gamma} .$$

Photon break energy

$$E'_{\gamma,\mathrm{b}} = \frac{(1+z)\epsilon_{e,-1}^{3/2}\epsilon_{B,-1}^{1/2}\tilde{L}_{\mathrm{iso},52}^{1/6}}{\Gamma t_{v,-2}^{2/3}} \text{ MeV} ,$$

Tamborra, Ando: 1512.01559

Waxman: astro-ph/0303517

which is modified to reproduce the empirical Amati relation.

Amati, et. al.: astro-ph/0205230

Uncooled neutrino spectra

We consider contributions from both $p\gamma$ and pp.

$$\left.\frac{dN_\nu^*}{dE_\nu'}\right|_{i,a,\mathrm{unc}} = E_\nu'^{-2}\int dE_\gamma' \,\frac{dN_\gamma^\dagger}{dE_\gamma'}\tau_{pa}'(E_p',E_\gamma')\,,$$

where $E_\nu' = a_i E_p'$. For pp this integral reduces to,

$$\left.\frac{dN_\nu^*}{dE_\nu'}\right|_{i,a=p,\mathrm{unc}} = E_\nu'^{-2}\tau_{pp}'(E_p')\,.$$

τ is the mean number of interactions within the interaction region.

Proton cooling

Mean acceleration time:

$$t'_{p,\mathrm{acc}} = \frac{E'_p}{B' ec} \, .$$

Cooling processes:

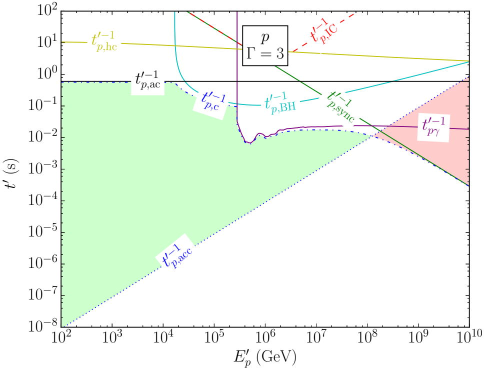
$$t'_{p,\mathrm{sync}} = \frac{3 m_p^4 c^3 8\pi}{4\sigma_T m_e^2 E'_p B'^2} \, ,$$

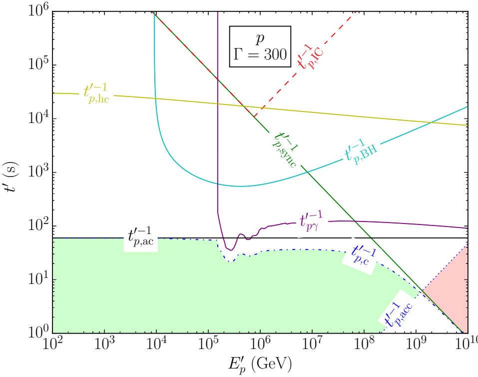
$$t'_{p,\mathrm{IC}} = \begin{cases} \frac{3 m_p^4 c^3}{4\sigma_T m_e^2 E'_p E'_\gamma n'_\gamma} & E'_p E'_\gamma < m_p^2 c^4 \\ \frac{3 E'_p E'_\gamma}{4\sigma_T m_e^2 c^5 n'_\gamma} & E'_p E'_\gamma > m_p^2 c^4 \end{cases} \, .$$

$$t'_{p,\mathrm{BH}} = \frac{E'_p \sqrt{m_p^2 c^4 + 2 E'_p E'_\gamma}}{2 n'_\gamma \sigma_{\mathrm{BH}} m_e c^3 (E'_p + E'_\gamma)} \, ,$$

$$t'_{p,p\gamma} = \frac{E'_p}{c \sigma_{p\gamma} n'_\gamma \Delta E'_p} \, , \qquad t'_{p,\mathrm{hc}} = \frac{E'_p}{c \sigma_{pp} n'_p \Delta E'_p} \, , \qquad t'_{p,\mathrm{ac}} = \frac{\tilde{r}_j}{c \Gamma} \, .$$

Proton cooling





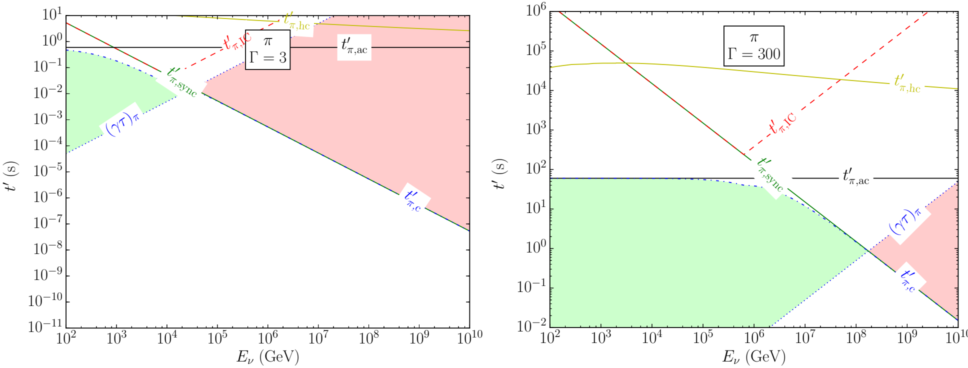
Particle production

$$\left.\begin{array}{c} p+p \\ p+\gamma \end{array}\right\} \rightarrow \left.\begin{array}{c} \pi \\ K \end{array}\right\} \rightarrow \begin{array}{ccc} \mu & \rightarrow & \nu \\ \nu & & \end{array}$$

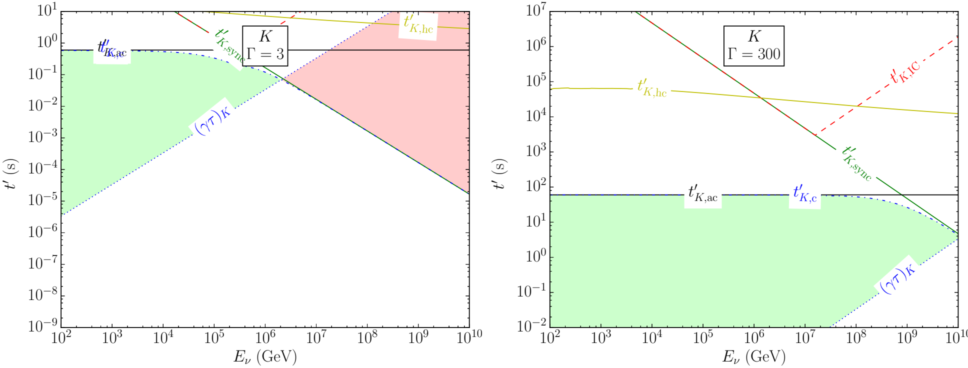
Pions, kaons, muons: decay or cool?

Same cooling processes as protons without Bethe-Heitler, $a+\gamma$, and hadronic cooling is negligible for muons.

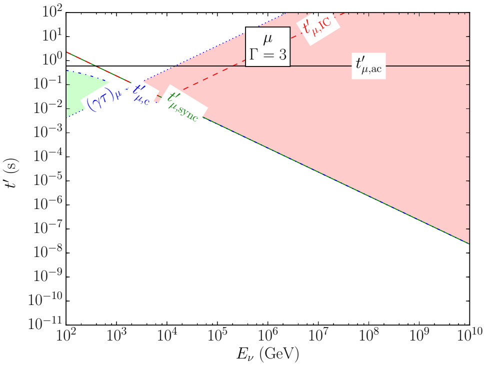
Pion cooling

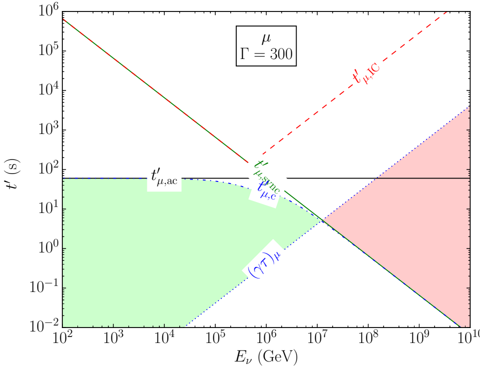


Kaon cooling



Muon cooling





Cooled spectra

The spectrum is modified by a factor of,

$$\left.\frac{dN_\nu}{dE'_\nu}\right|_{i,\mathrm{c}} = \left.\frac{dN_\nu}{dE'_\nu}\right|_{i,\mathrm{unc}} \left[1 - \exp\left(-\frac{1}{\eta_\mu^{-1} + \eta_{\pi(K)}^{-1} + \eta_p^{-1}}\right)\right],$$

where,

$$\eta_i = \frac{t'_{i,\mathrm{c}} m_i}{E'_i \tau_i}, \qquad \eta_p = \frac{t'_{p,\mathrm{c}}}{t'_{p,\mathrm{acc}}},$$

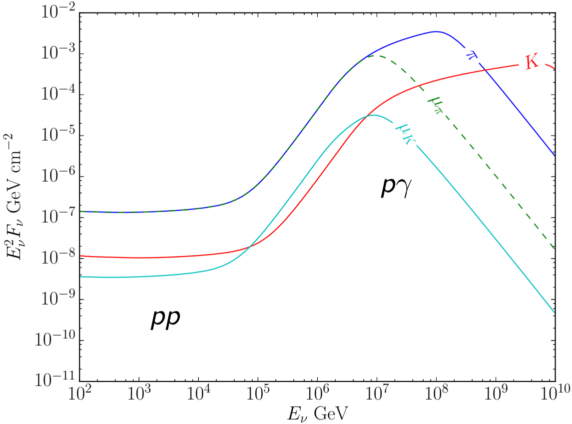
and the total cooling time is given by,

$$t'^{-1}_{p,\mathrm{c}} = \sum_i t'^{-1}_{p,i}.$$

Spectra → flux

$$F_{\nu,i,a}(E_\nu) = \frac{(1+z)^3}{\Omega_j \Gamma d_L^2} E'_j N_a f_p \left[1 - (1-\chi_{pa})^{\tau'_{pa}}\right] \left.\frac{dN_\nu}{dE'_\nu}\right|_{i,a,\mathrm{c}} ,$$

$$F_{\nu,i} = \frac{F_{\nu,i,p}\tau'_{pp} + F_{\nu,i,\gamma}\tau'_{p\gamma}}{\tau'_{pp} + \tau'_{p\gamma}} , \quad f_p = \frac{\int dE'_\nu\, E'_\nu \left.\frac{dN_\nu}{dE'_\nu}\right|_{\mathrm{c},pp+p\gamma}}{\int dE'_\nu\, E'_\nu \left.\frac{dN_\nu}{dE'_\nu}\right|_{\mathrm{pc},pp+p\gamma}} .$$



Neutrino production

$$F_{\nu_e,\mathrm{unosc}} = F_{\nu,\mu_\pi} + F_{\nu,\mu_K} \,,$$
$$F_{\nu_\mu,\mathrm{unosc}} = F_{\nu,\pi} + F_{\nu,\mu_\pi} + F_{\nu,K} + F_{\nu,\mu_K} \,.$$

Neutrinos oscillate.

Everyone

Oscillation averaged probabilities*:

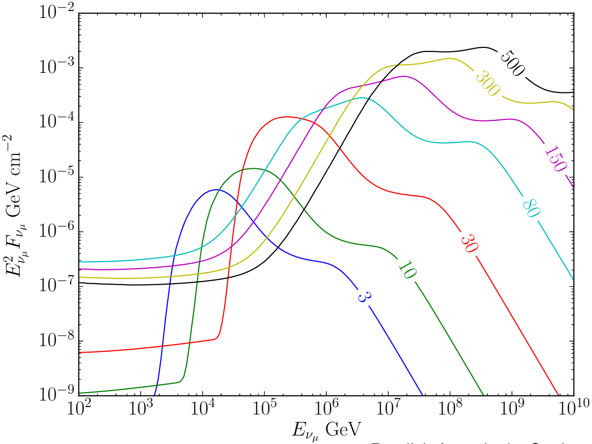
$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta_{12}$$
$$P(\nu_e \leftrightarrow \nu_\mu) = P(\nu_e \leftrightarrow \nu_\tau) = \frac{1}{4}\sin^2 2\theta_{12}$$
$$P(\nu_\mu \to \nu_\mu) = P(\nu_\tau \to \tau) = P(\nu_\mu \leftrightarrow \nu_\tau) = \frac{1}{8}\left(4 - \sin^2 2\theta_{12}\right)$$

Anchordoqui, et. al.: 1312.6587

*For $\theta_{23} = 45^\circ, \theta_{13} = 0$ which is a fine approximation.

Oscillated one flavor flux

Flux at earth for GRBs with different Γ's.
High Γ jets peak at high energies.



Distribution of jets: model 1

Each jet has one Γ value sampled from a power law* distribution,

$$\xi(\Gamma) = \mathcal{N}\Gamma^{\alpha_\Gamma}\,,$$

where $\alpha_\Gamma \sim [-1, -3]$.

*Other functional forms possible,
but a linear function doesn't work.

We normalize with the SN and HL-GRB rates,

$$\int_1^{1000} d\Gamma\,\mathcal{N}\Gamma^{\alpha_\Gamma} = R_{\rm SN}(0)\zeta_{\rm SN}\frac{\langle\Omega_j\rangle}{4\pi}\,,$$

$$\int_{200}^{1000} d\Gamma\,\mathcal{N}\Gamma^{\alpha_\Gamma} = \rho_{0,\rm HL-GRB}\,,$$

where $\zeta_{\rm SN}$ is the fraction of CC-SN that form jets.

θ_j vs. Γ

We consider general relationships between jet angles and boosts,

$$\theta_j^m \Gamma = c\,,$$

parameterized as (m, c).

- $(1, 1)$ is the oft used canonical expectation.

  Razzaque, Meszaros, Waxman: astro-ph/0407064

- $(1, 10)$ or $(2.5, 0.025)$ are empirical fits to data.

  Tchekhovskoy, McKinney, Narayan: 0901.4776

  Ghirlanda, et. al.: 1210.1215

- Constant jet size: $\theta_j = 5^\circ$.

  Tamborra, Ando: 1512.01559

Rate $\rightarrow$ diffuse intensity

Take the SN rate to be similar to the SFR:

$$R(z) \propto \left[(1+z)^{p_1 k} + \left(\frac{1+z}{5000}\right)^{p_2 k} + \left(\frac{1+z}{9}\right)^{p_3 k}\right]^{1/k},$$

Yuksel, Kistler, Beacom, Hopkins: 0804.4008

$$I_\nu(E_\nu) = \int d\Gamma \int dz\, d_L^2 (1+z)^3 \frac{c}{H_0} \frac{1}{E(z)} R(z) \mathcal{N} \Gamma^{\alpha_\Gamma} F_\nu(E_\nu)$$

Distribution of jets: model 2

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,

$$\xi(\Gamma_{\rm max}) = \mathcal{N}\Gamma_{\rm max}^{\alpha_\Gamma}\,,$$

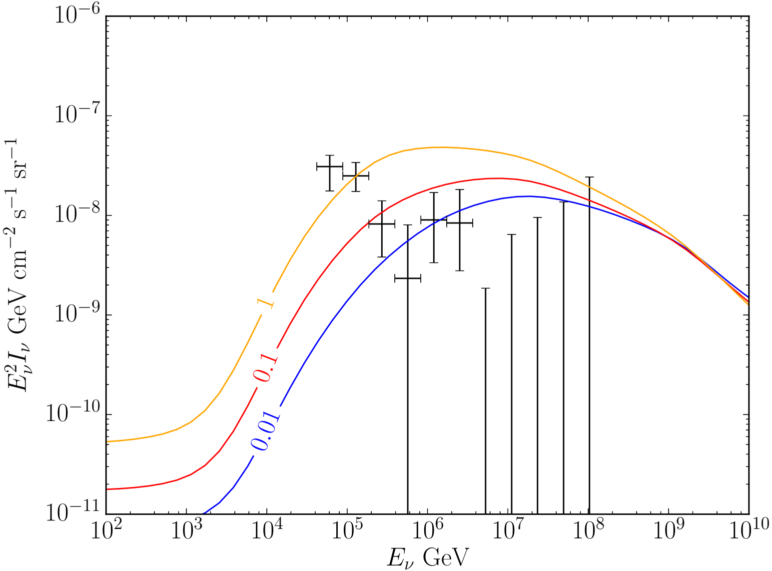
$$\Gamma = \Gamma_{\rm max} e^{\theta^2/2\sigma_\Gamma^2}\,,$$

with total jet opening angle wide enough to contain down to $\Gamma = 1$.

- Intensity integral now includes an angle integral.

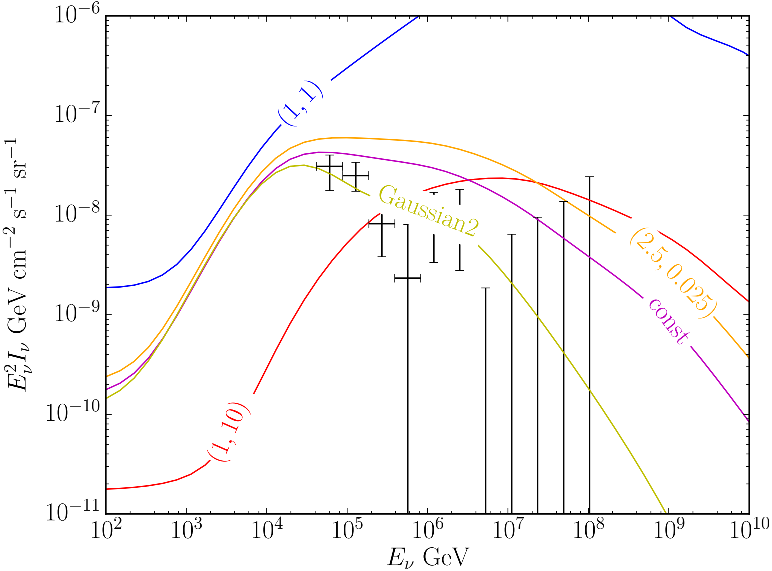
Diffuse intensities

For the $(1, 10)$ scaling and with $\tilde{E}_j = 3 \times 10^{51}$ erg.

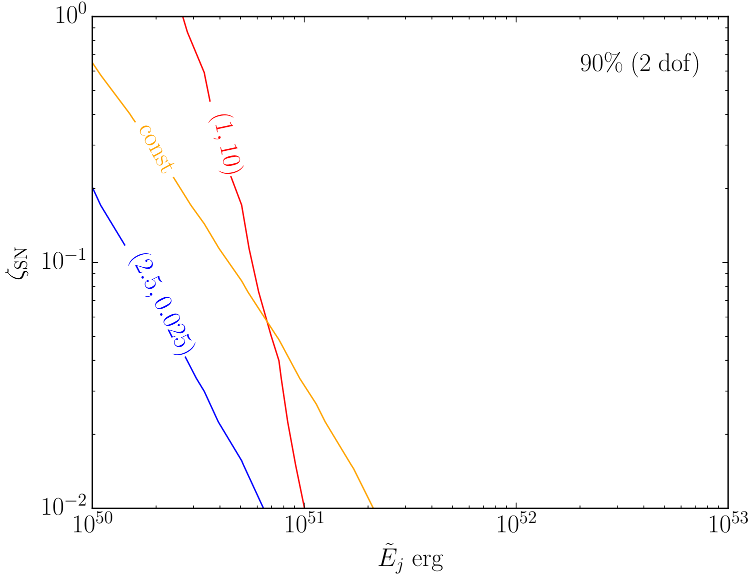


Diffuse intensities

At $\zeta_{\rm SN} = 0.1$ and $\tilde{E}_j = 3 \times 10^{51}$ erg.

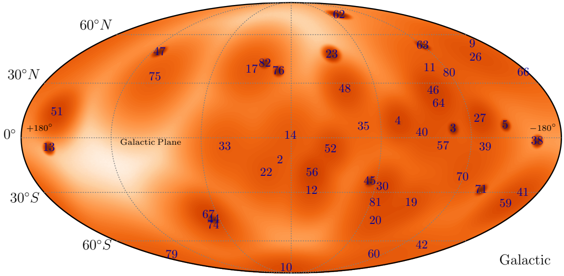


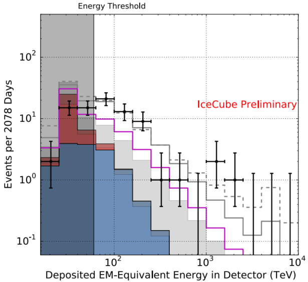
Source parameter exclusion limits



Conclusions

- IceCube has measured the astrophysical neutrino flux.
- 50 events with $E_{\rm dep} > 60$ TeV in the clean HESE data set.
- The astrophysical neutrino flux is largely extragalactic.
  - A subleading galactic component $< 10\%$ (90% CL) is allowed.
  - Consistent with models: galactic component $< 10\%$.
- Independent of details of galactic distribution and spectrum shape.
- GRBs naturally lead to a high neutrino flux.
- Some canonical GRB models are inconsistent with IceCube's measurements.





Backups

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 $\ell_{\max} = 1$ km,
  we can relate the deposited and neutrino energies by,

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

  which is valid in the region of interest.

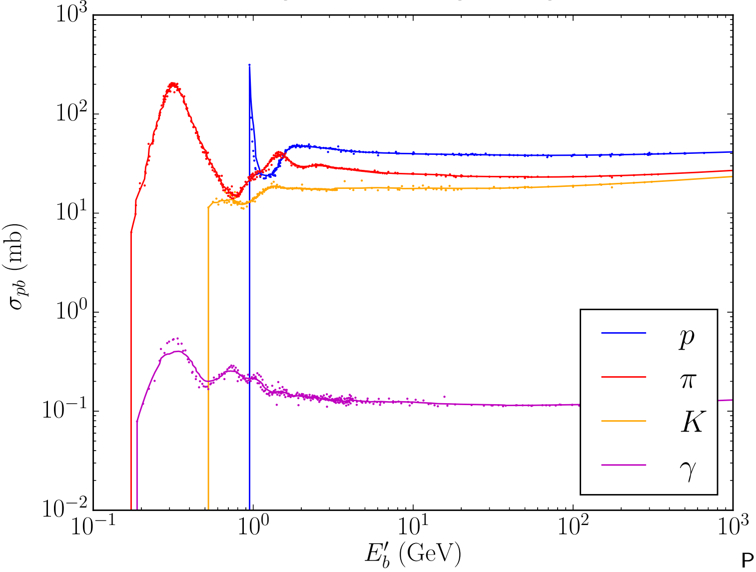
  Anchordoqui, Weiler, et. al.: 1611.07905

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

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

Cross sections

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



PDG