Abstract

High energy neutrinos have been detected by IceCube, but their origin remains a mystery. Determining the sources of this flux is a crucial first step towards multi-messenger studies. In this work we systematically compare two classes of sources with the data: galactic and extragalactic. We build a likelihood function on an event by event basis including energy, event topology, absorption, and direction information. We present the probability that each high energy event with deposited energy $E_{\rm dep} > 60$ TeV in the HESE sample is galactic, extragalactic, or background. The galactic fraction of the astrophysical flux has a best fit value of 1.3% and is $< 9.5\%$ at 90% CL.

The Galactic Contribution to IceCube's Astrophysical Neutrino Flux

Peter B. Denton

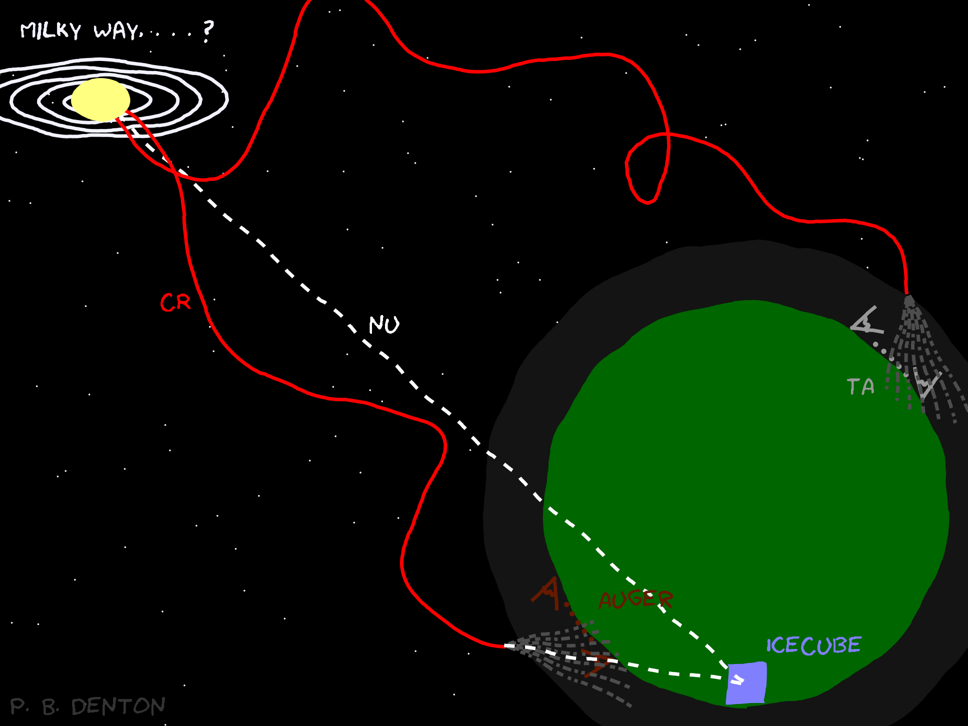
TeVPA 2017

August 10, 2017

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

The Niels Bohr International Academy

VILLUM FONDEN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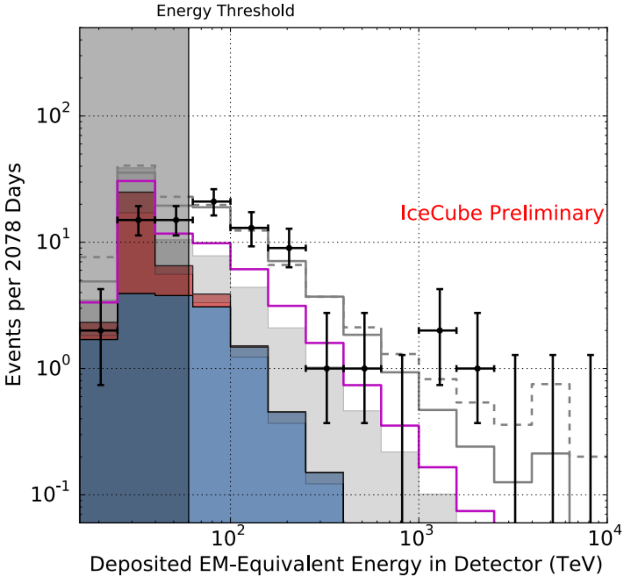
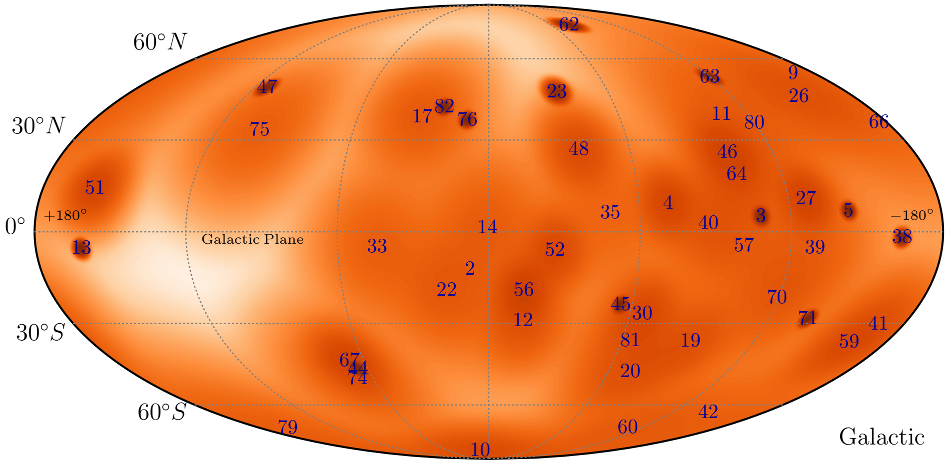
P. B. DENTON

IceCube Detects Astrophysical Neutrinos

IC's 6 yr HESE: ICRC 2017

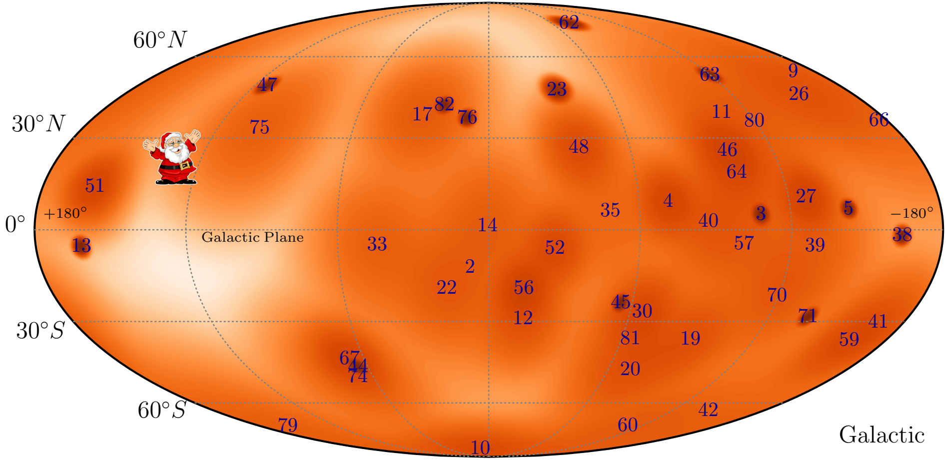


IceCube Detects Astrophysical Neutrinos



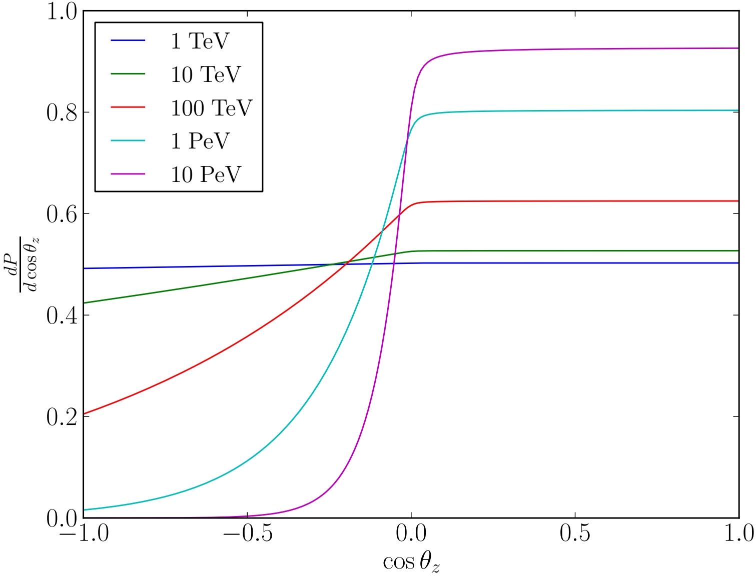
50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

IceCube Detects Astrophysical Neutrinos

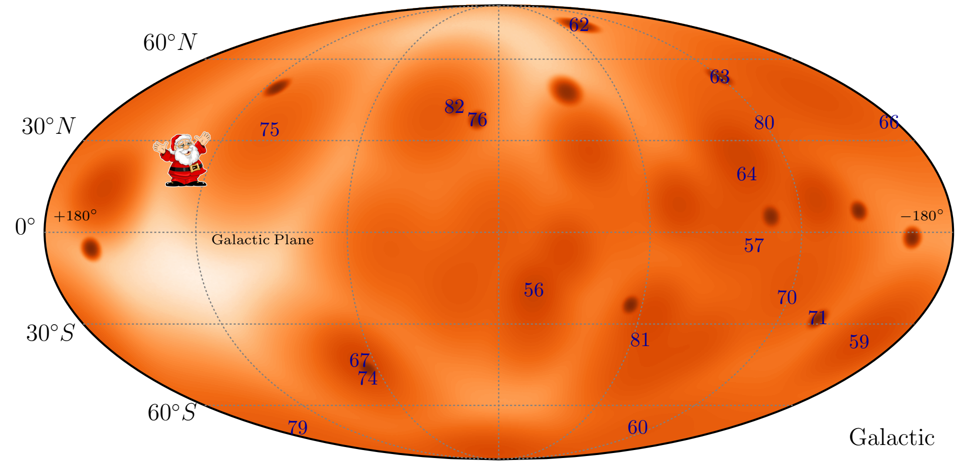


50 events with $E_{\rm dep} > 60$ TeV from IC 6 year HESE

High energy neutrinos are absorbed by the Earth

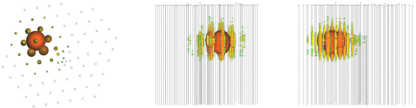


IceCube Detects Astrophysical Neutrinos

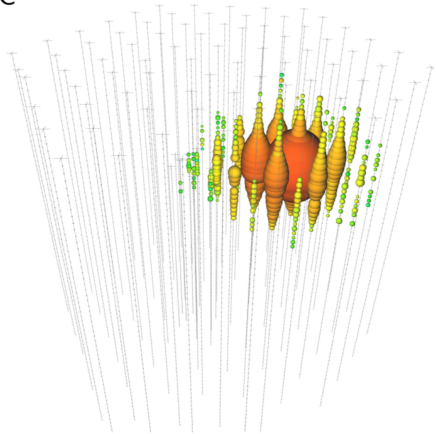


The 18 new events from the two latest years

IceCube Detects Astrophysical Neutrinos

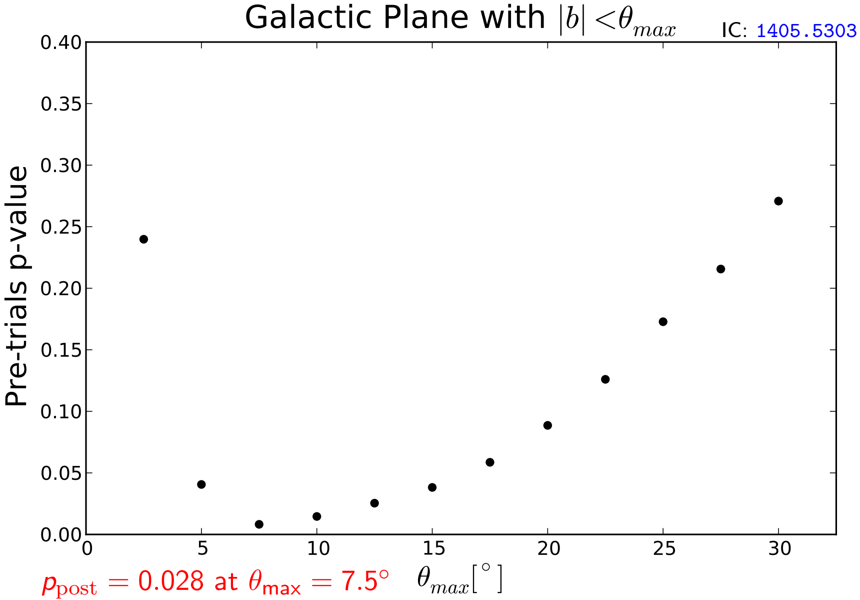


Event 14
$E = 1$ PeV
1.2° from the GC
$\alpha_{50\%} = 13.2^\circ$



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

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

- Cross checked results with SNR and PWN distributions.

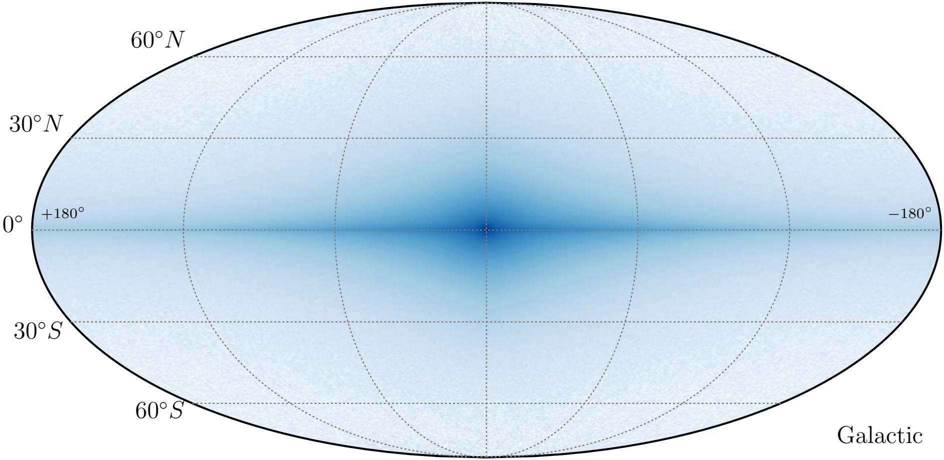
Case, Bhattacharya: astro-ph/9807162

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,

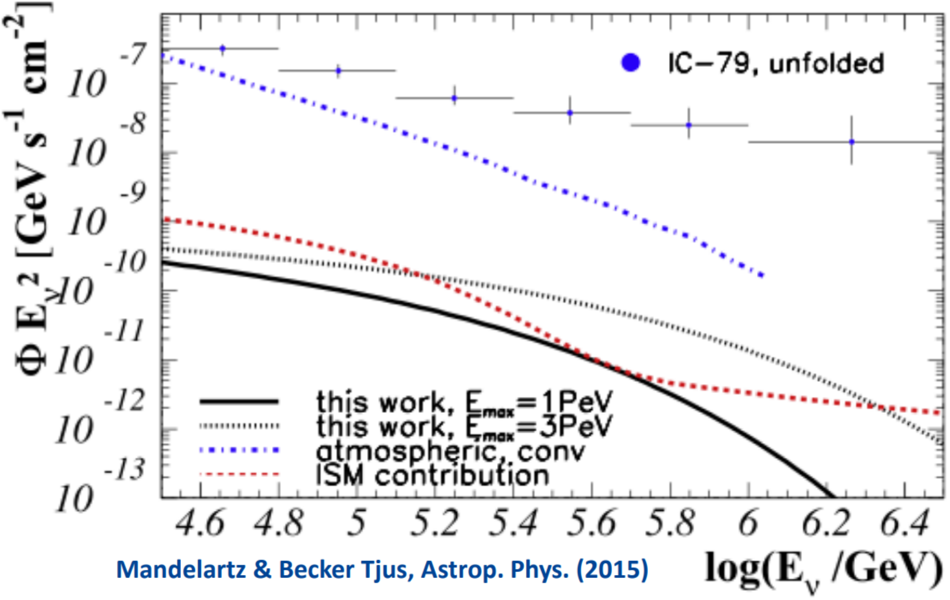
$$\mathcal{L}(f_{\mathrm{gal}}) = \prod_i \mathcal{L}_i(f_{\mathrm{gal}})\,.$$

- 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

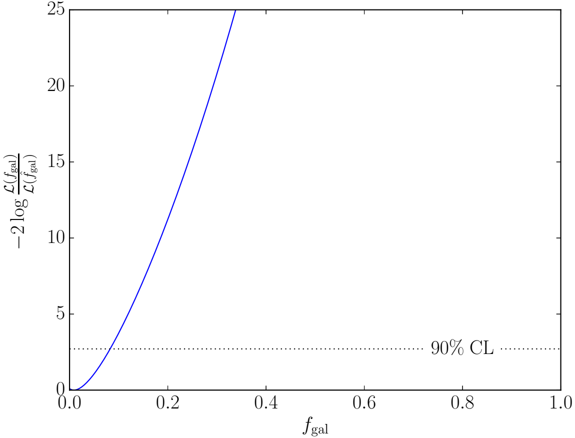


Mandelartz & Becker Tjus, Astrop. Phys. (2015)

Julia Tjus's Monday plenary.

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

E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$	E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$
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

Conclusions

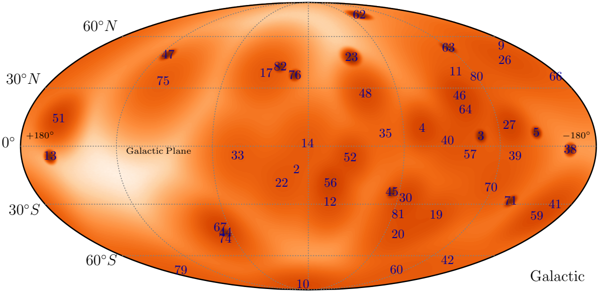
- IceCube has measured the astrophysical neutrino flux.
- 50 events with $E_{\rm dep} > 60$ TeV in the clean HESE data set.
- The astrophysical neutrino flux is largely extragalactic.
  - A subleading galactic component $< 10\%$ (90% CL) is allowed.
  - Consistent with models: galactic component $< 10\%$.

Julia Tjus's plenary on Monday.

Marek Kowalski's plenary on Tuesday.

Mike Richman's parallel on Tuesday.

- Independent of details of galactic distribution and spectrum shape.



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 $\ell_{\sf max} = 1$ 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.

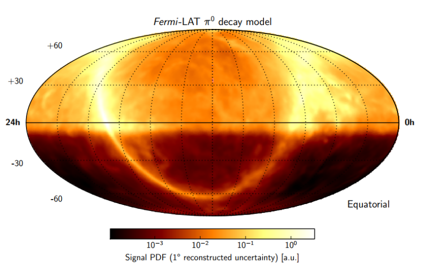
  Anchordoqui, Weiler, et. al. 1611.07905

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

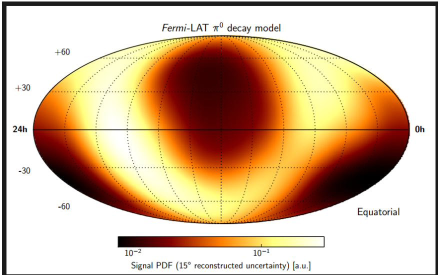
  Gandhi, Quigg, Reno, Sarcevic, hep-ph/9512364

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 Tuesday parallel