Astrophysical and Dark Matter Origin of the IceCube High-energy Neutrino Events

BHUPAL DEV

Washington University in St. Louis

with Yicong Sui, arXiv:1804.04919 [hep-ph]

The Mitchell Conference on
Collider, Dark Matter, and Neutrino Physics 2018

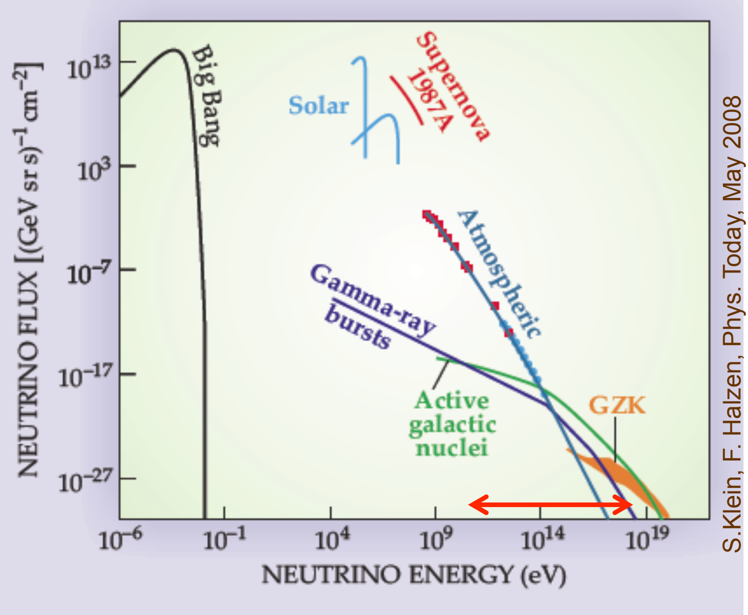
Texas A & M University, College Station

May 21, 2018

Outline

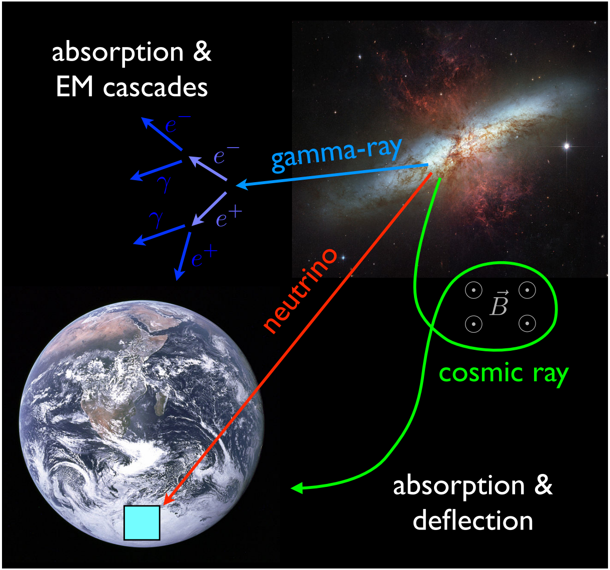
- Introduction: HESE vs. Throughgoing Events
- 1-comp vs. 2-comp Astrophysical Neutrinos
- Decaying Heavy Dark Matter ?
- Gamma-ray Constraints
- Conclusion

Ubiquitous Neutrino Flux

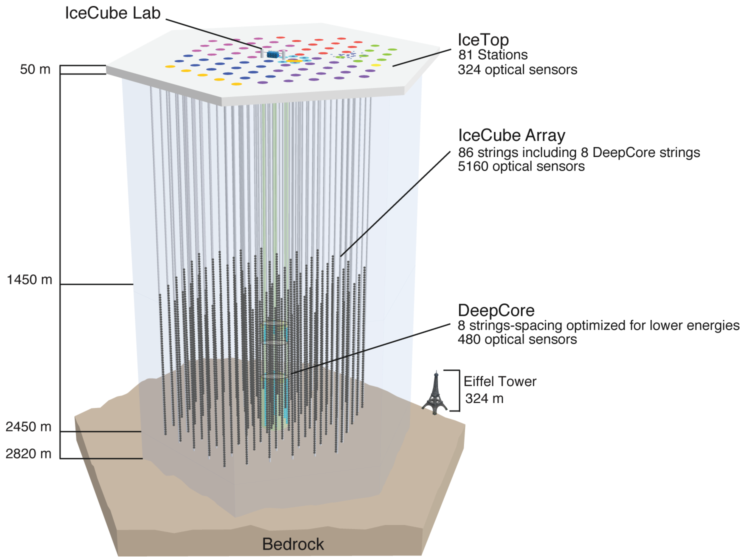


S.Klein, F. Halzen, Phys. Today, May 2008

High-energy Neutrinos: Astrophysical Messengers



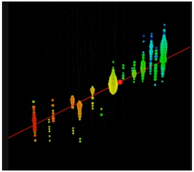
Need Very Large Detectors



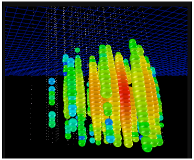
Neutrino Detection at IceCube

$$\nu_\ell + N \quad \rightarrow \quad \begin{cases} \ell + X & \text{(CC)} \\ \nu_\ell + X & \text{(NC)} \end{cases}$$

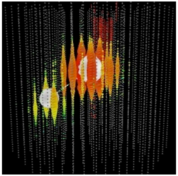
Events: Shower vs. Track; HESE vs. Throughgoing



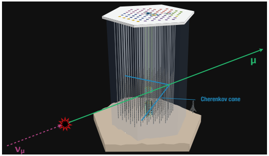
CC Muon
(track)



CC EM/NC all
(shower)



CC tau ‘double bang’
(simulation only)

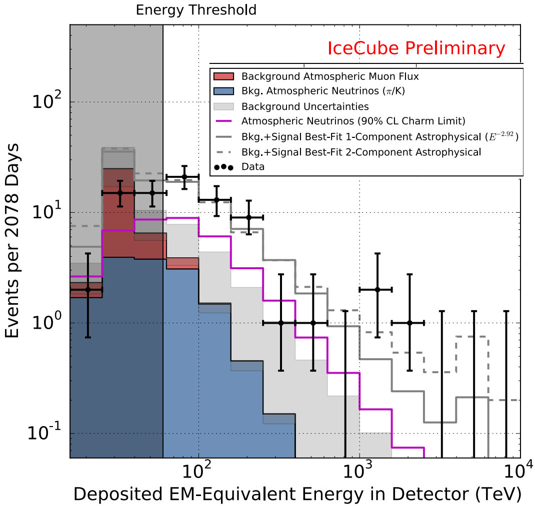


Throughgoing muon
(track only)

High Energy Starting Events (HESE)

[Picture courtesy: C. Kopper]

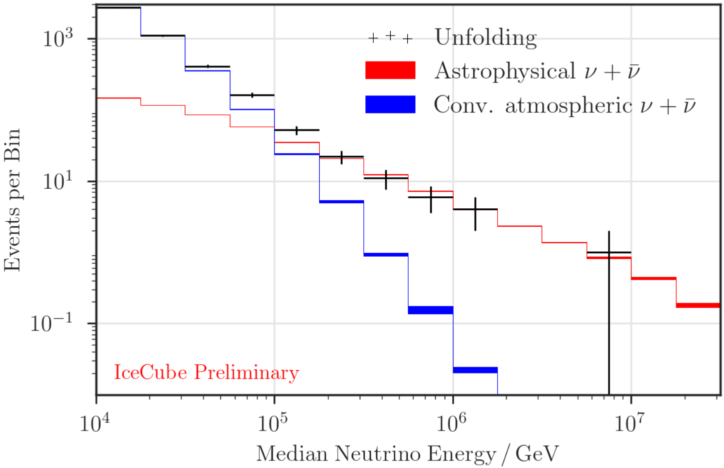
6-year HESE Dataset



82 events with $> 7\sigma$ excess over atmospheric background.

[ICRC Proceedings, 1710.01191]

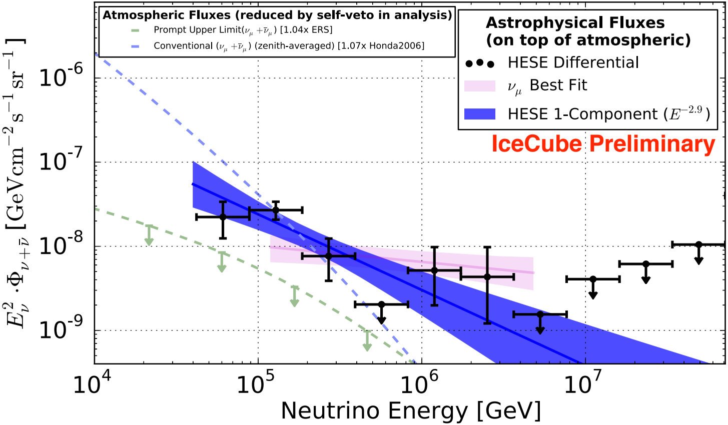
8-year TG Dataset



~ 1000 events with 6.7σ excess over atmospheric background.

[ICRC Proceedings, 1710.01191]

Comparison between HESE and TG Events



- For 1-comp power-law flux

$$\Phi_\nu = \Phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\gamma}, \quad \gamma = 2.9^{+0.33}_{-0.29} \text{ (HESE) vs } 2.19 \pm 0.10 \text{ (TG)}$$

- Theory expectation $\gamma \sim 2$.

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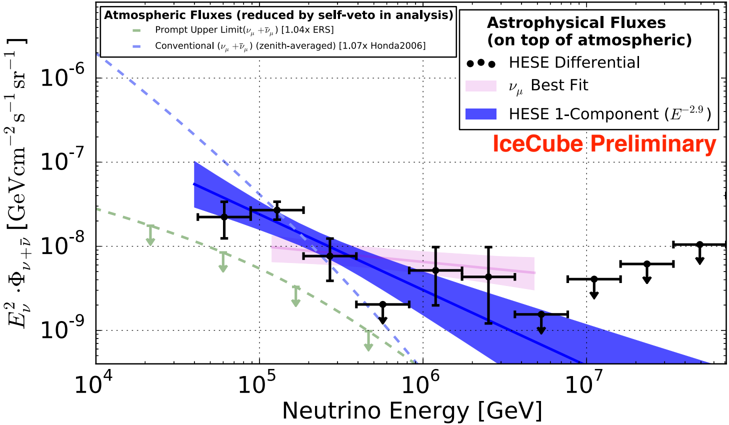

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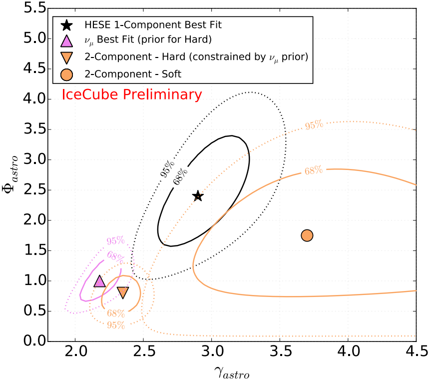
Two-component Solution

PHYSICAL REVIEW D **92,** 073001 (2015)

Two-component flux explanation for the high energy neutrino events at IceCube

Chien-Yi Chen,[1] P. S. Bhupal Dev,[2] and Amarjit Soni[1]
[1]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manches*
Manchester M13 9PL, United Kingdom
(Received 2 December 2014; published 1 October 2015)

$$\Phi_\nu = \Phi_1 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_1} e^{-E_\nu/E_c} + \Phi_2 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_2}$$



[ICRC Proceedings, 1710.01191]

- Break in the ν spectrum follows the break in the CR spectrum.
- Exponential cut-off could be due to a spectral resonance (e.g. Δ^+), or a dissipative source (e.g. GRB). [Murase, Ioka (PRL '13); Petropoulou, Giannios, Dimitrakoudis (MNRAS '14); Anchordoqui *et al.* (PRD '17)]

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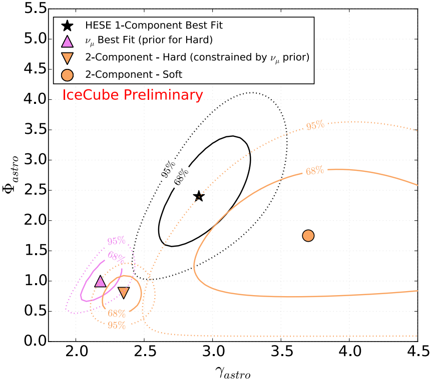

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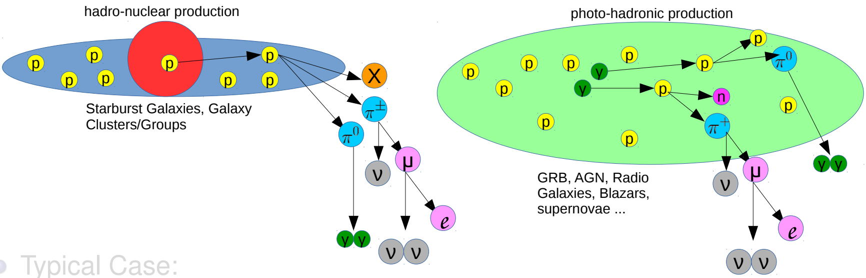
Flavor Composition



- Typical Case:

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau)_S = \begin{cases} \left(\frac{1}{6} : \frac{1}{3} : 0 : \frac{1}{6} : \frac{1}{3} : 0\right) & (pp) \\ \left(\frac{1}{3} : \frac{1}{3} : 0 : 0 : \frac{1}{3} : 0\right) & (p\gamma) \end{cases}$$

- Muon-damped case:

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau)_S = \begin{cases} \left(0 : \frac{1}{2} : 0 : 0 : \frac{1}{2} : 0\right) & (pp) \\ (0 : 1 : 0 : 0 : 0 : 0) & (p\gamma) \end{cases}$$

- Two possibilities for flavor composition at Earth (either pp or $p\gamma$):

$$(\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau) = \begin{cases} (1 : 1 : 1)_\oplus & \text{for } (1 : 2 : 0)_S \\ (4 : 7 : 7)_\oplus & \text{for } (0 : 1 : 0)_S \end{cases}$$

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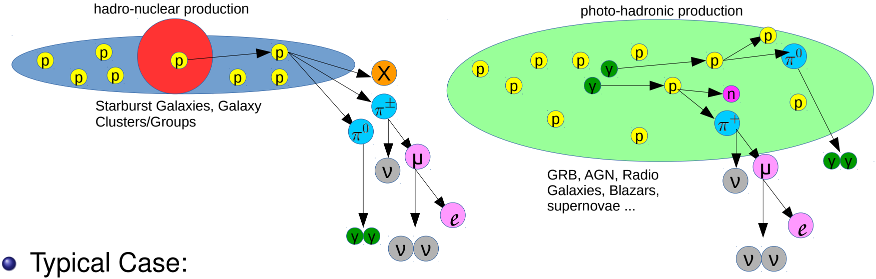

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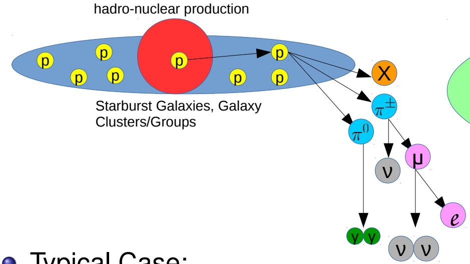

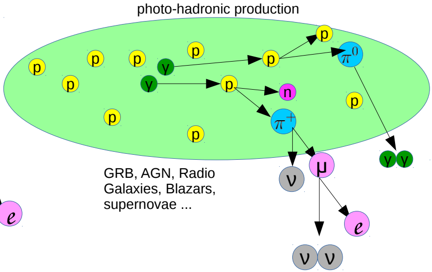

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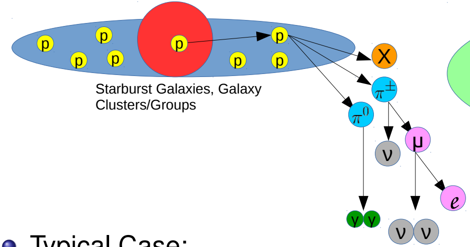

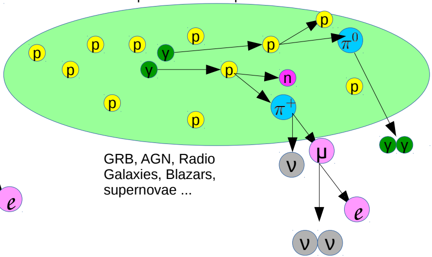

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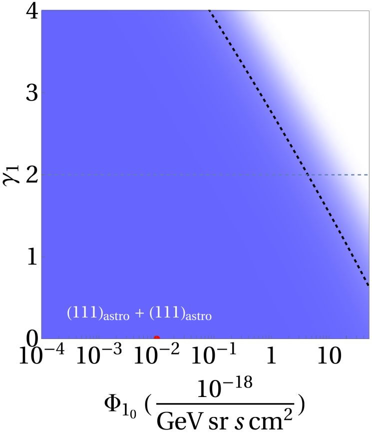
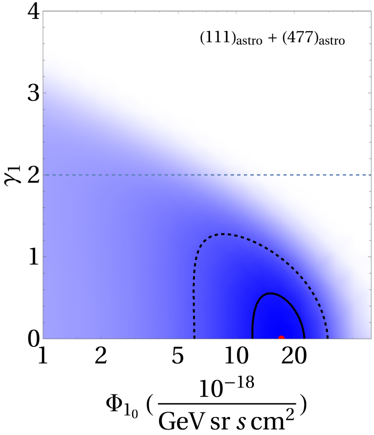
Fit Results

1st Comp.	2nd Comp.	Φ_{1_0}	Φ_{2_0}	γ_1	γ_2	$E_c/100$ TeV	TS/dof
$(1:1:1)$	$(1:1:1)$	0.01	2.21	1.47×10^{-4}	2.08	0.10	1.91
$(1:1:1)$	$(4:7:7)$	17.18	0.88	3.19×10^{-10}	1.83	0.50	1.48





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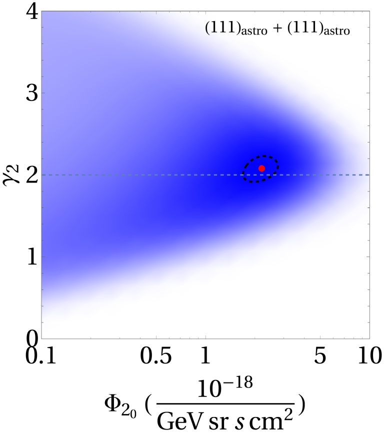
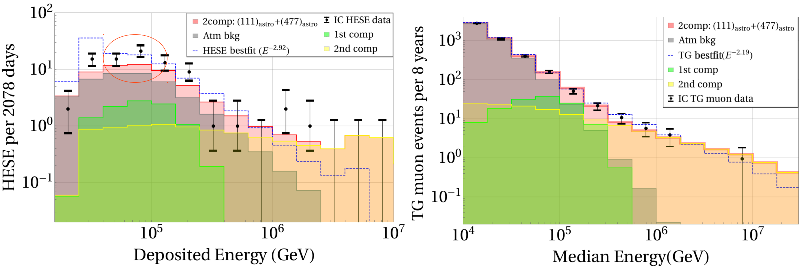


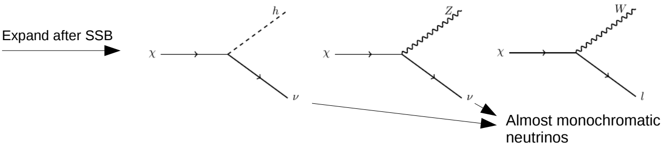
Event Spectrum



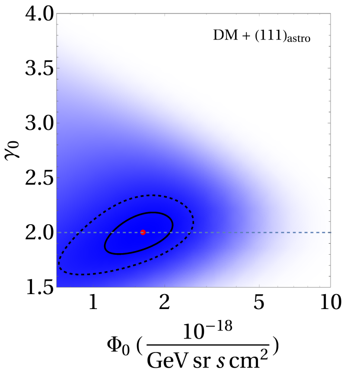
- $\sim 2\sigma$ excess around 100 TeV in the HESE data (consistent with [Chianese, Miele, Morisi (JCAP '17; PLB '17)])
- A possible explanation: Decaying Dark Matter (instead of the soft astrophysical component).
- Has been widely discussed in the context of PeV excess. [Esmaili, Serpico (JCAP '13); Bhattacharya, Reno, Sarcevic (JHEP '14); Rott, Kohri, Park (PRD '15); Bai, Lu, Salvado (JHEP '16); Bhattacharya, Esmaili, Palomares-Ruiz, Sarcevic (JCAP '17); ...]

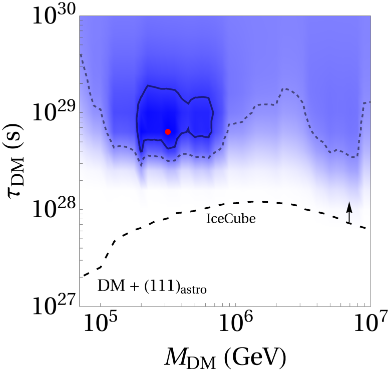
A Simple DM Model

$$-\mathcal{L}_{\rm Y} = y_i \bar{L}_i \tilde{\phi} \chi + {\rm H.c}$$



DM (1st comp.)	astro (2nd comp.)	Φ_0	γ_0	$M_{\rm DM}$ (TeV)	$\tau_{\rm DM}\,(10^{28}$ s)	TS/dof
$(1:1:1)$	$(1:1:1)$	1.62	2.00	316.23	6.31	1.38
$(1:1:1)$	$(4:7:7)$	1.39	1.97	316.23	6.31	1.37





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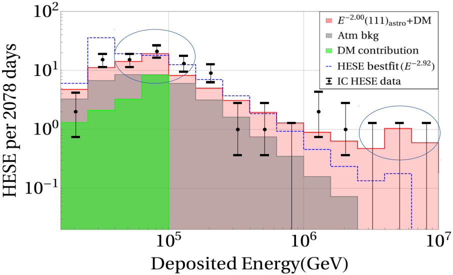
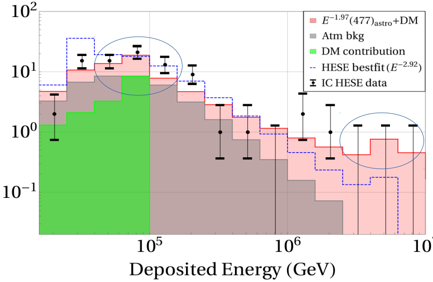
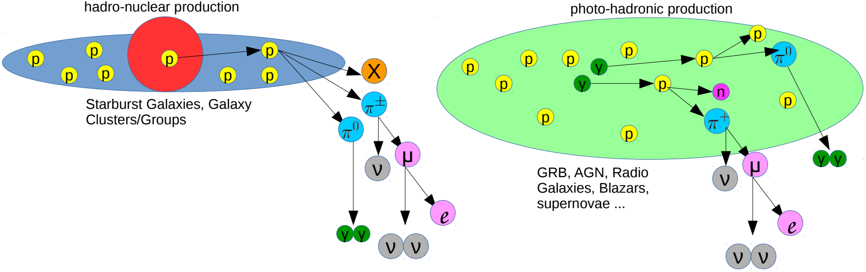




Gamma-ray Constraints

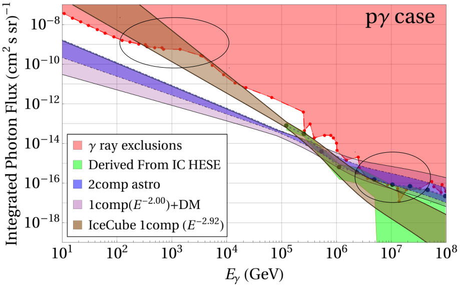


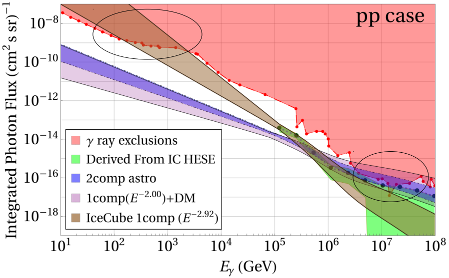
$$E_\gamma^2 \Phi_\gamma \simeq \frac{4}{K} E_\nu^2 \frac{\Phi_{(\nu+\bar{\nu})_{\rm tot}}}{3}\bigg|_{E_\nu = 0.5 E_\gamma} \qquad \text{with } K = 2\ (pp) \text{ or } 1\ (p\gamma)$$

[Waxman, Bahcall (PRL ’97); Murase, Laha, Ando, Ahlers (PRL ’15); Esmaili, Serpico (JCAP ’15); Cohen, Murase, Rodd, Safdi, Soreq (PRL ’17)]

We applied diffuse gamma-ray constraints from Fermi-LAT, HESS, VERITAS, HAWC, ARGO, MILARGO, GRAPES, KASCADE and CASA-MIA.

Gamma-ray Constraints





Single-component HESE bestfit ruled out

Two-component bestfit still consistent

DM+astro flux is (slightly) favored over the purely astro flux

Conclusion

- Understanding all aspects of the UHE neutrino events at IceCube is very important for both Astrophysics and Particle Physics ramifications.
- Single-component power-law fit to the HESE data is disfavored.
- Need (at least) two-component flux to simultaneously explain the HESE and throughgoing datasets.
- Could be either purely astrophysical or a combination of astro and particle physics origin.
- Considered a simple model of decaying fermionic dark matter.
- (Slightly) Favored by the data and gamma-ray constraints over a purely astro flux.
- More statistics and multi-messenger approach would be able to discriminate between the two solutions.

THANK YOU.

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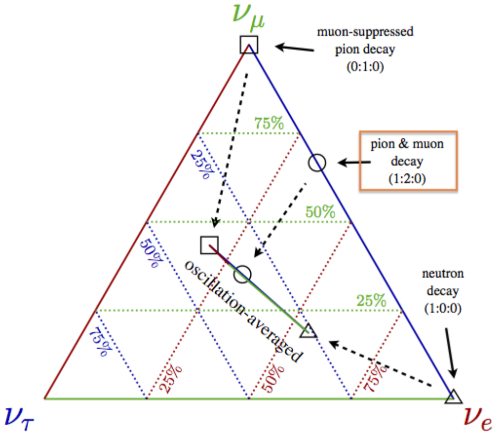
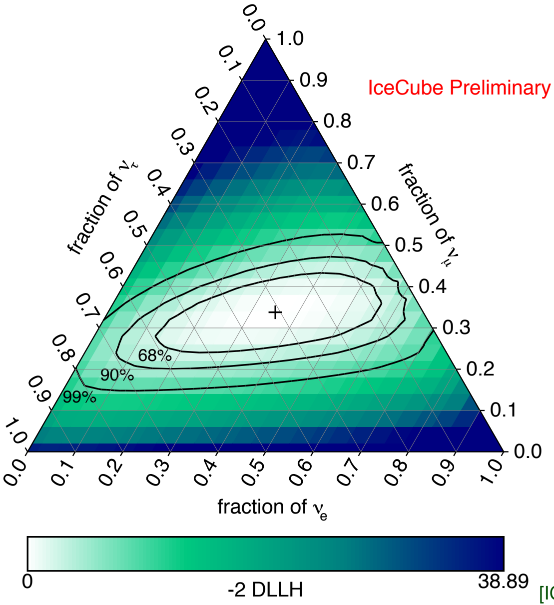
Physical Flavor Compositions



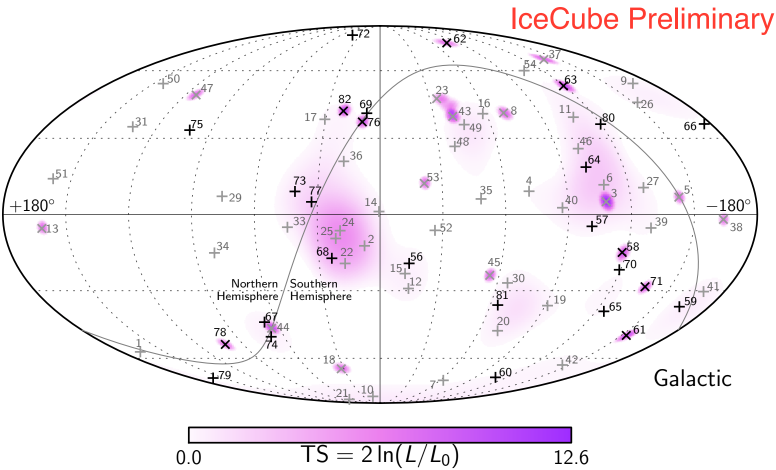
$$(1:2:0)_S \rightarrow (1:1:1)_\oplus$$
$$(0:1:0)_S \rightarrow (4:7:7)_\oplus$$
$$(1:1:0)_S \rightarrow (14:11:11)_\oplus$$
$$(1:0:0)_S \rightarrow (5:2:2)_\oplus$$

Flavor Composition from IceCube data



[ICRC Proceedings '17]

All-sky Event Distribution



[ICRC Proceedings '17]