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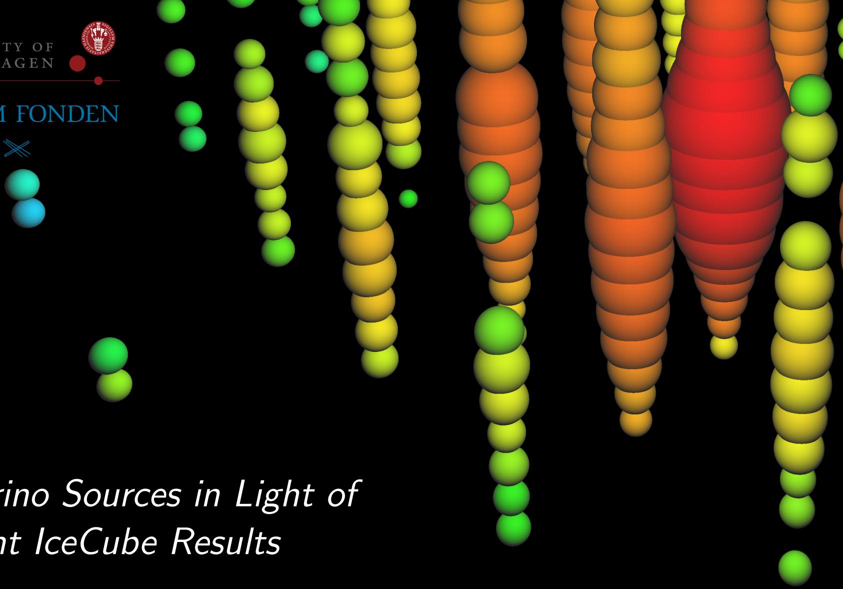
VILLUM FONDEN



Neutrino Sources in Light of Recent IceCube Results

Markus Ahlers, Niels Bohr Institute

RICAP 2018, September 5, Rome

Multi-Messenger Astronomy

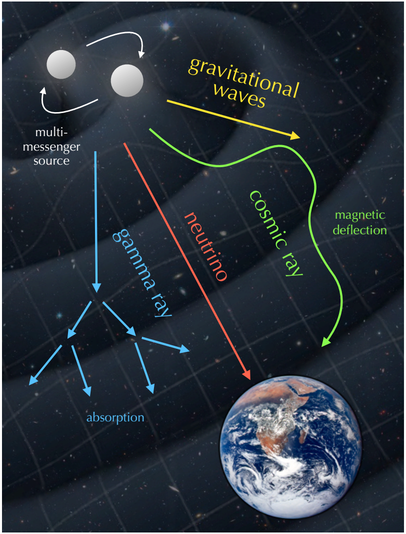
- **Cosmic ray (CR)** acceleration in the aftermath of cataclysmic events, sometimes seen in **gravitational waves**.

➜ Inelastic collisions with radiation or gas produce **γ-rays** and **neutrinos**, *e.g.*

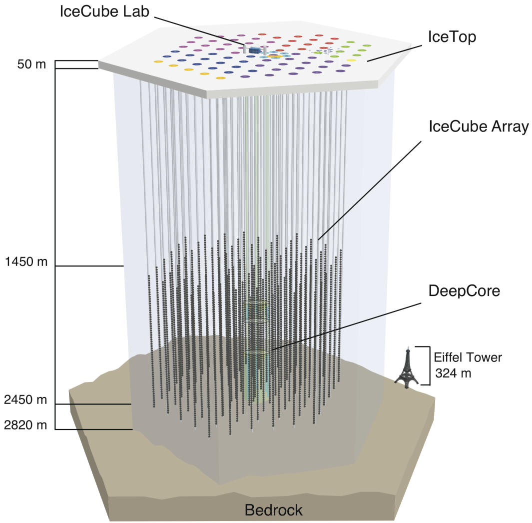
$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

- **Unique aspects of neutrino messengers**:
  - *identify* cosmic ray sources
  - *qualifies* γ-ray emission
  - *covers blind spot* of astronomy to the very-high-energy Universe

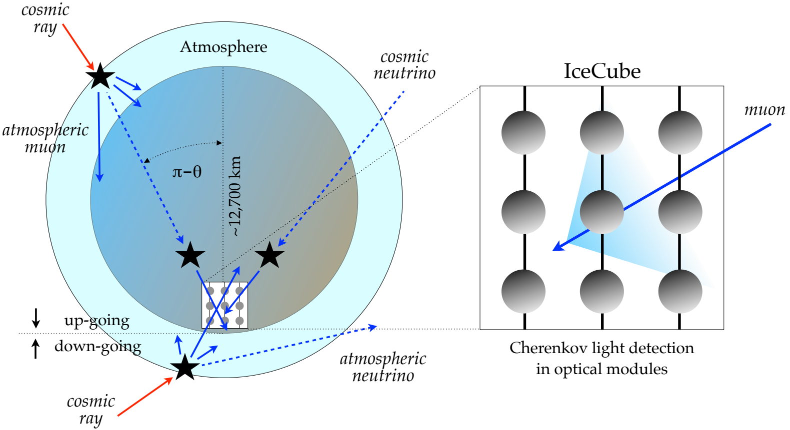


The IceCube Observatory



- Giga-ton **Cherenkov telescope** at the South Pole
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase (2004-2011)
- price tag: **€0.25 per ton**

Methods of Neutrino Detection I



➜ Selecting **up-going muon tracks** reduces atmospheric muon background:

$\underbrace{10,000,000,000}_{\text{atmospheric muons (from above)}} : \underbrace{100,000}_{\text{atmospheric neutrinos}} : \underbrace{10}_{\text{cosmic neutrinos}}$

Methods of Neutrino Detection II

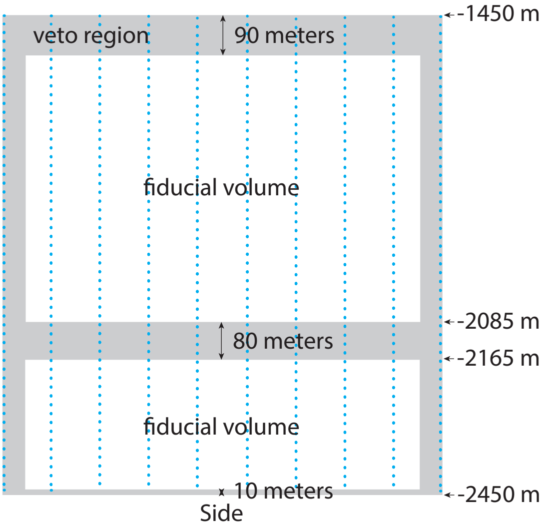
- Outer layer of optical modules can be used as a **veto region** (gray area):

✘ **Atmospheric muons** pass through veto from above.

✘ **Atmospheric neutrinos** are produced in coincidence with atmospheric muons.

✔ **Cosmic neutrino** events can **start inside the fiducial volume**.

➜ **High-Energy Starting Event** (HESE) analysis

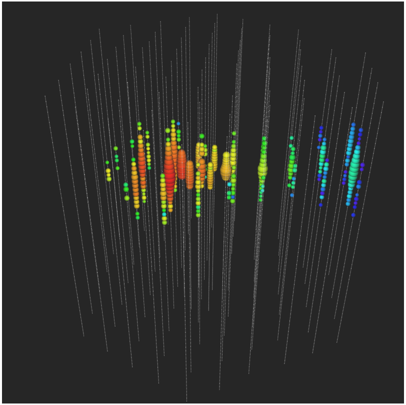


[IceCube Collaboration'13]

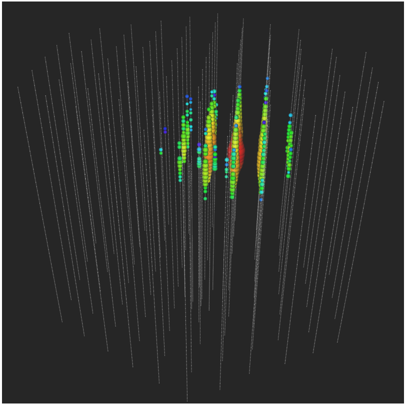
2013: A Milestone for Neutrino Astronomy

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering)



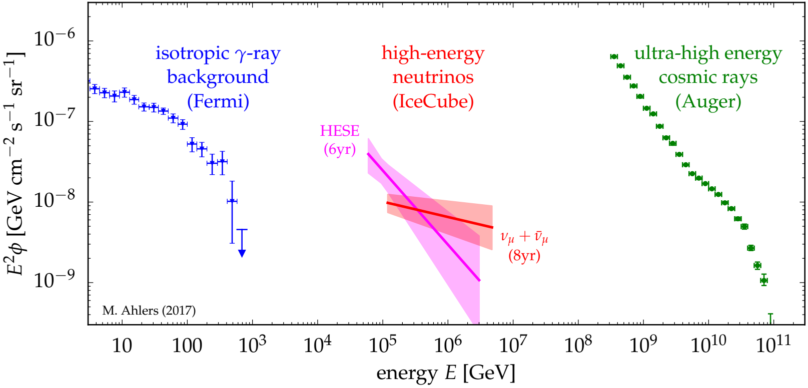
"cascade event" (from all flavours)



["Breakthrough of the Year" (Physics World), Science 2013]
(**time-dependent** neutrino signal: early to late light detection)

Cosmic TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (6yrs):** [Science 342 (2013); update ICRC 2017]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (8yrs):** [Astrophys.J. 833 (2016); update ICRC 2017]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption



Multi-Messenger Interfaces

- **High-Energy Starting Events (HESE) (6yrs):** [Science 342 (2013); update ICRC 2017]
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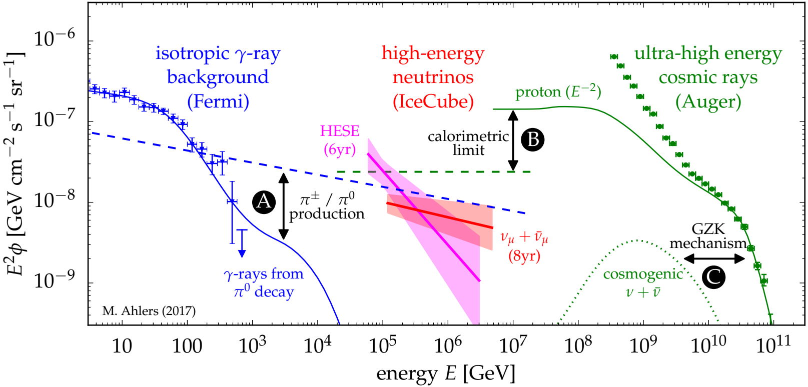


Power-Law Fits

- power-law fit (per flavour):

$$\phi(E) = \frac{\phi_{\rm astro} \times 10^{-8}}{\rm GeV\,cm^2\,s\,sr}\left[\frac{E}{100\,\rm TeV}\right]^{-\gamma_{\rm astro}}$$

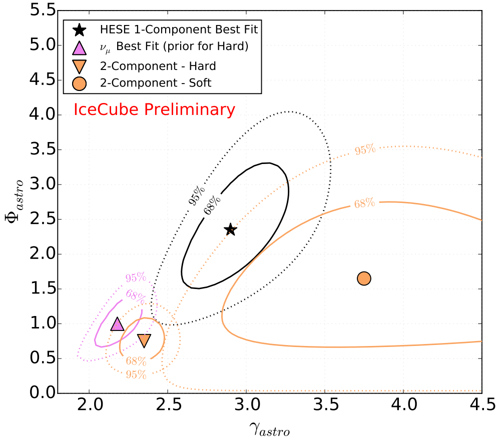
- HESE (6yr) fit range:

$$60\,{\rm TeV} \leq E \leq 3\,{\rm PeV}$$

- up-going $\nu_\mu + \overline{\nu}_\mu$ (8yr) fit range:

$$119\,{\rm TeV} \leq E \leq 4.8\,{\rm PeV}$$

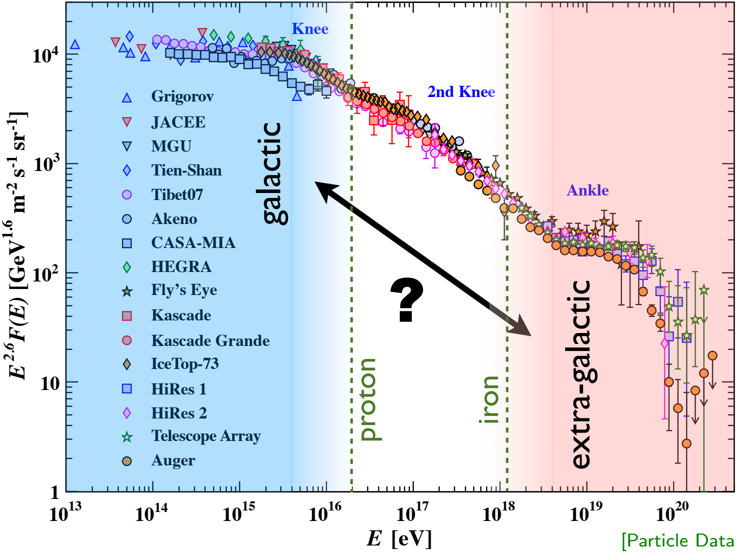
- **Hard spectrum of 2-component HESE fit consistent with $\nu_\mu + \overline{\nu}_\mu$ spectrum within 68% C.L.!**



[IceCube; ICRC 2017]

The Cosmic "Beam"

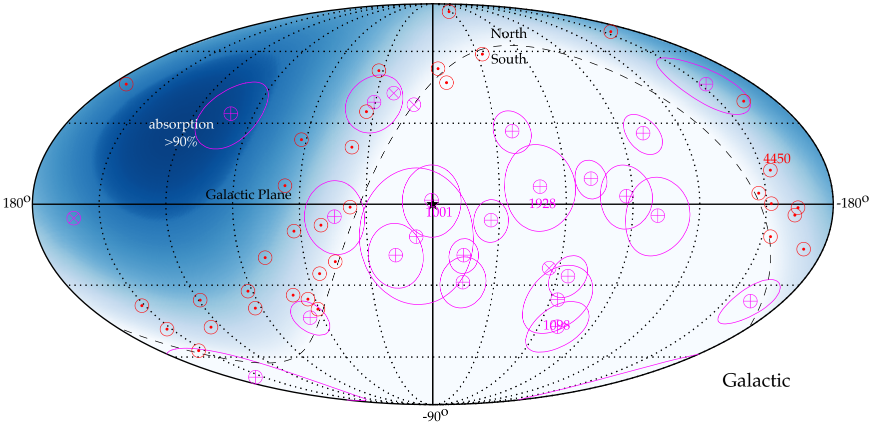
1 PeV neutrino ↔ 20-30 PeV cosmic ray nucleon



[Particle Data Group'13]

Arrival Directions of Cosmic Neutrinos

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))

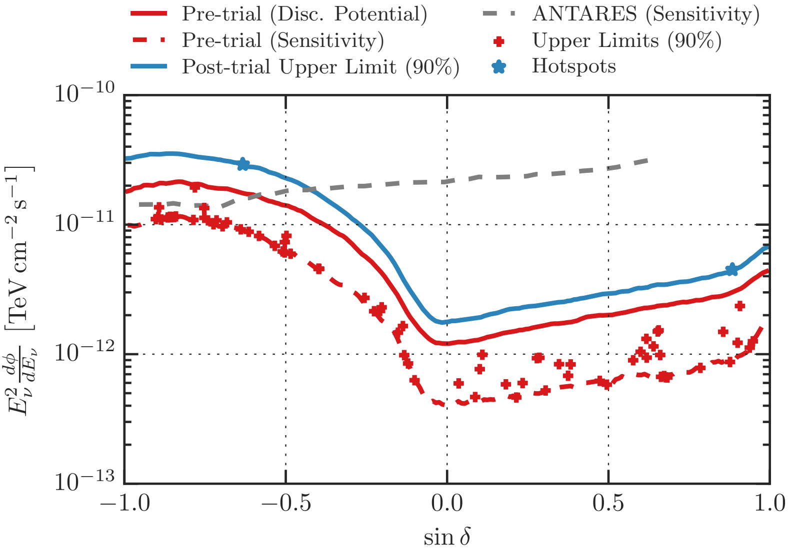


No significant correlation of diffuse flux with known Galactic or extragalactic sources.

Extragalactic Source Candidates

- association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
  [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
- association with diffuse γ-ray background [Murase, MA & Lacki'13]
  [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
  [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
  [Padovani & Resconi'14; Petropoulou *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16; Wang & Loeb'16]
- gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  [Senno, Murase & Meszaros'16; Denton & Tamborra'18; Boncioli, Biehl & Winter'18]
- galaxies with intense star-formation (*e.g.* starbursts)
  [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
  [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
  [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
  [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
- galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- tidal disruption events (TDE) [Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]
  [Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]

Neutrino Point-Source Limits



[IceCube, **Astrophys.J.** 835 (2017) no.2, 151]

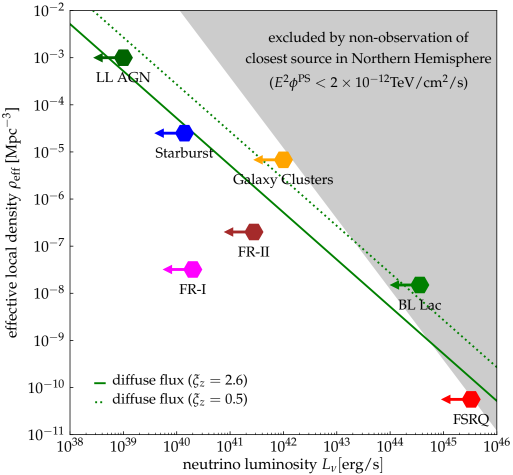
Constraints from Point-Source Limits

➜ **Populations with lower density require higher luminosity and predict brighter individual sources.** [Lipari'08; Kowalski'14] [MA & Halzen'14; Murase & Waxman'16] [Mertsch, Rameez & Tamborra'16]

- **non-observation** of individual neutrino sources constrain source populations, *e.g.*

  ✘ gamma-ray bursts ($\dot\rho_{\rm eff} \simeq {\rm Gpc}^{-3}{\rm yr}^{-1}$)

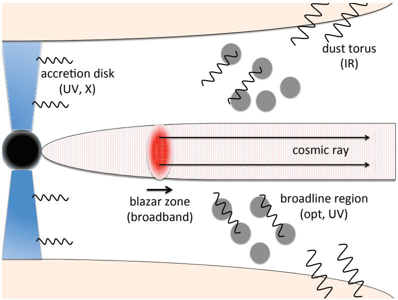
  ✘ BL Lacs / FSRQ ($\rho_{\rm eff} \simeq 0.1 - 10\ {\rm Gpc}^{-3}$)

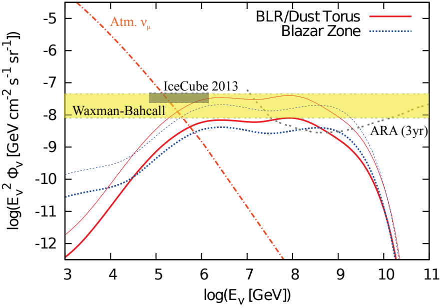


[MA & Halzen'18]

Active Galactic Nuclei / Blazars

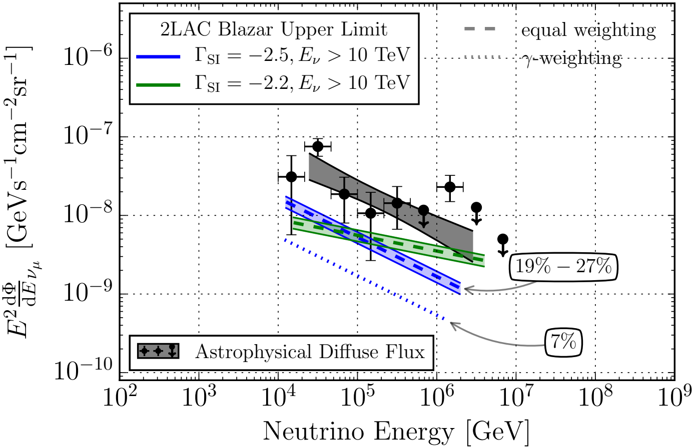
- neutrinos from $p\gamma$ interactions in AGN [Stecker *et al.*'91; Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





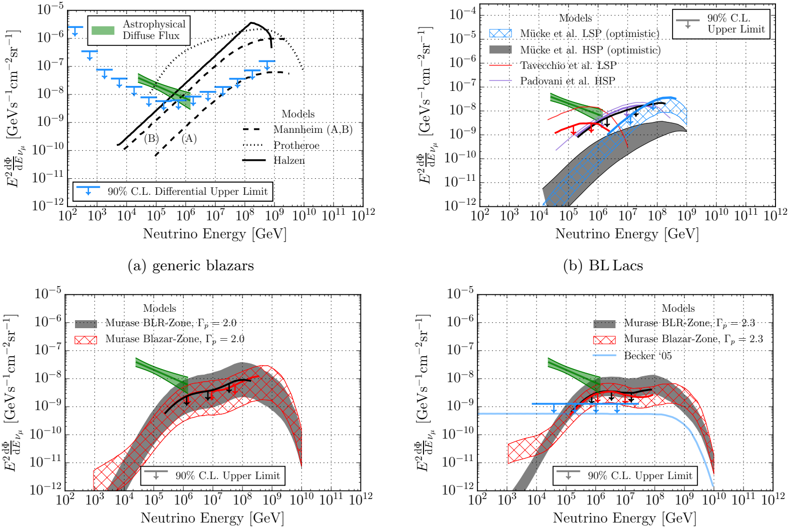
[Murase, Inoue & Dermer'14]

TeV Gamma-Ray Blazars



Blazar stacking limits derived from Fermi-LAT AGN catalogue (2LAC) [IceCube'16]

TeV Gamma-Ray Blazars



(a) generic blazars

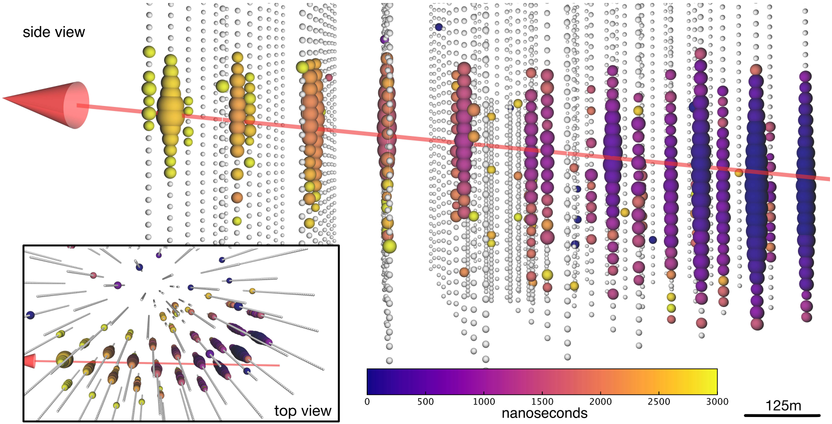
(b) BL Lacs

(c) FSRQs - 1

(d) FSRQs - 2

Blazar stacking limits derived from Fermi-LAT AGN catalogue (2LAC) [IceCube'16]

IceCube Alert IC-170922A



IceCube EHE ("extremely-high energy") alert IC-170922A
Up-going muon track (5.7° below horizon) observed on September 22, 2017.
The best-fit neutrino energy for an E^{-2}-spectrum is 311 TeV.

Breaking News (July 12, 2018)

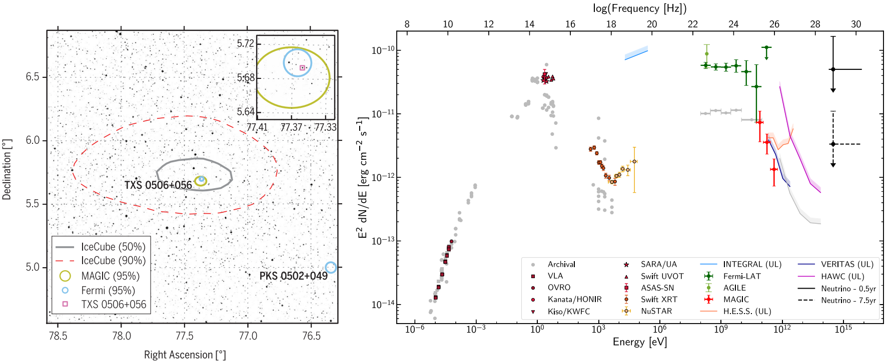
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

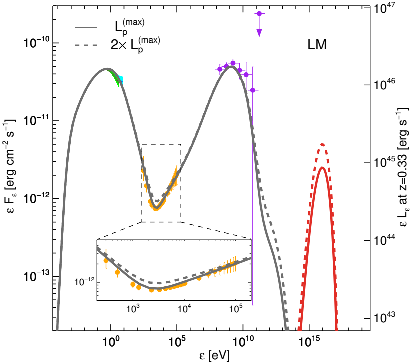
Multi-Messenger Observations of TXS 0506+056

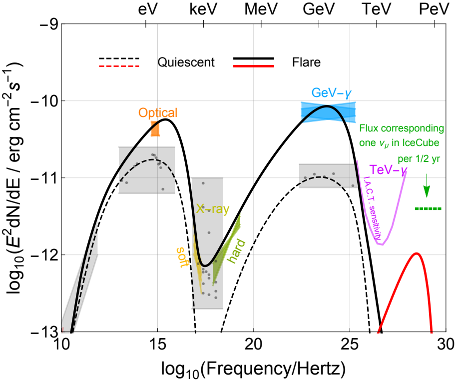


[**Science** 361 (2018) no.6398, eaat1378]

- IC-170922A observed in coincident with flaring blazar TXS 0506+056.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the 3% brightest Fermi-LAT blazars and one of the most luminous BL Lacs (2.8×10^{46} erg/s).

Fits of Multi-Messenger SED





[Keivani *et al.*, arXiv:1807.04537]

[Gao *et al.*, arXiv:1807.04275]

- Photon SED can be modelled with lepto-hadronic and proton-synchrotron models.

  [see also Cerruti *et al.* arXiv:1807.04335; Zhang, Fang & Li, arXiv:1807.11069]

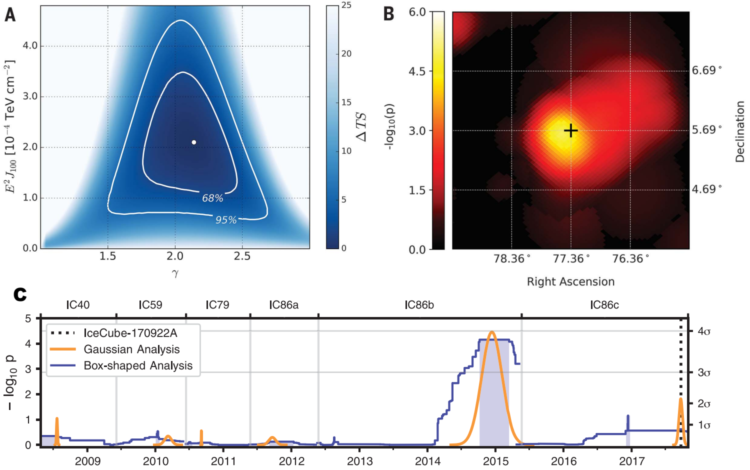
  [Gokus *et al.* arXiv:1808.05540; Sahakyan, arXiv:1807.05651]

- Neutrino flux limited by theoretically feasible proton luminosity and X-ray data.

  [see, however, Righi, Tavecchio & Inoue, arXiv:1807.11069]

  [Murase, Oikonomou & Petropoulou, arXiv:1807.04748; Liu *et al.*, arXiv:1807.05113]

Neutrino Flare in 2014/15 from TXS 0506+056



[**Science** 361 (2018) no.6398, 147-151]

- Previous 3.5σ neutrino flare (13 ± 5 events) between Sept. 2014 and March 2015.
- Implies neutrino luminosity of 1.2×10^{47} erg/s over 158 days ($\simeq 4 \times L_{\rm Fermi}$).

Hadronic Gamma-Ray Emission

➜ Inelastic collisions of **cosmic rays (CR)** with radiation or gas produce γ-rays and **neutrinos** via pion decay:

$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

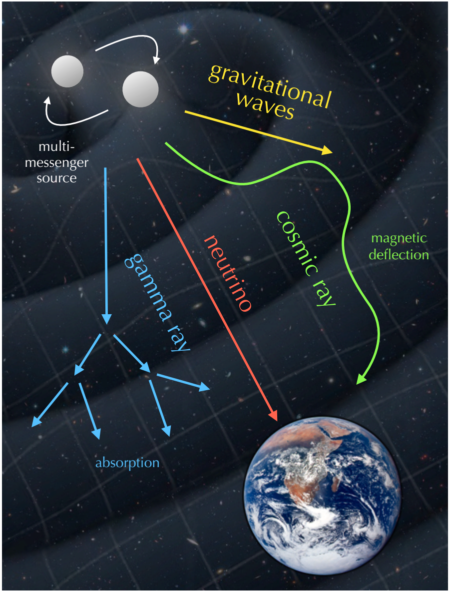
- relative production rates:

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

✘ TeV γ-rays scatter in cosmic microwave background (CMB) and initiate electromagnetic cascades:

$$\gamma + \gamma_{\rm CMB} \to e^+ + e^-$$

$$e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma$$



Isotropic Diffuse Gamma-Ray Background (IGRB)

- Gamma-ray emission from electromagnetic cascades ends up in the sub-TeV range observed with Fermi satellite.

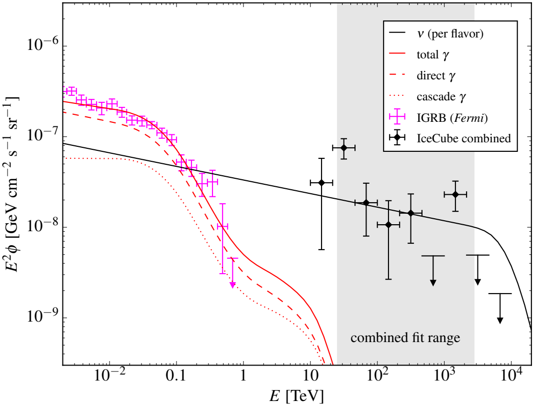
✘ Cosmic ray spectral index **strongly constrained** by the isotropic diffuse gamma-ray background (IGRB)

[Murase, MA & Lacki'13]

$$\Gamma \lesssim 2.15 - 2.2$$

✘ IceCube best-fit: [IceCube'15]

$$\Gamma \simeq 2.4 - 2.6$$



[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]
[Ando, Tamborra & Zandanel'15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

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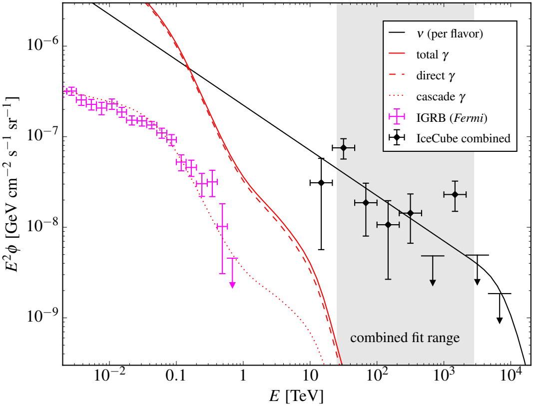

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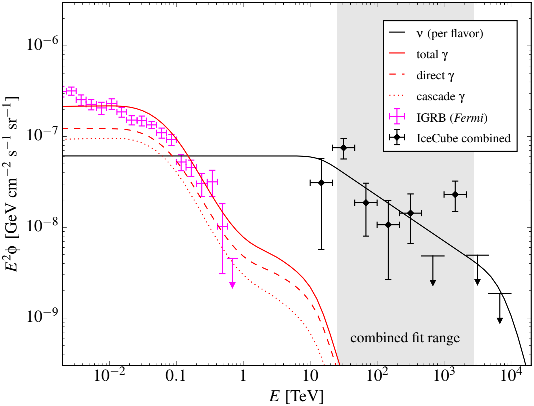

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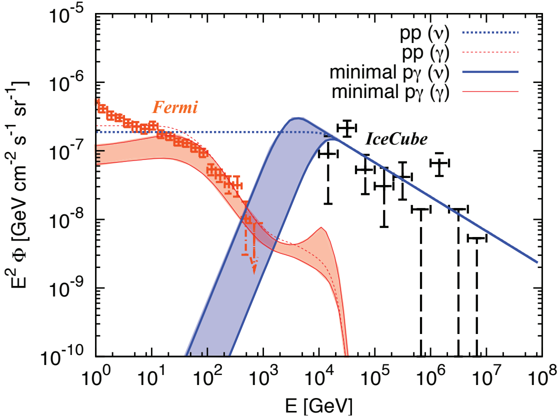
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Fermi Bounds for $p\gamma$ Sources

- Fermi constraints less severe for $p\gamma$ scenarios:
  1. **no power-law extrapolation** to Fermi energy range
  2. **high pion production efficiency** implies strong γ-absorption in sources
- source candidates:
  - AGN cores [Stecker'91;'13] [Kimura, Murase & Toma'14]
  - choked GRB jets [Mészáros & Waxman'01] [Senno, Murase & Mészáros'16]



[Murase, Guetta & MA'15]

Corresponding Opacities

- required cosmic ray energy:

$$E_{\rm CR} \sim 20 E_\nu$$

- required target photon energy:

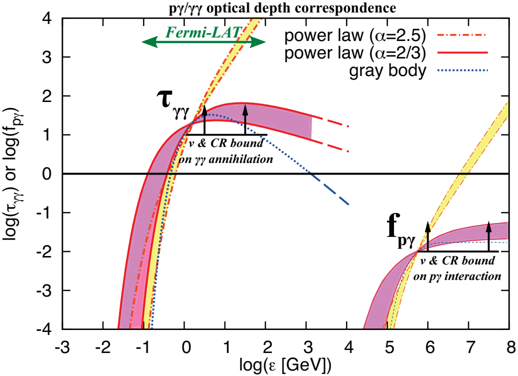
$$\varepsilon_t \sim 200\,{\rm keV}\left(\frac{\Gamma}{10}\right)^2\left(\frac{E_\nu}{3\ {\rm TeV}}\right)^{-1}$$

- **opacity relation**:

$$\tau_{\gamma\gamma}(E_\gamma) \sim 1000\, f_{p\gamma}(E_p)$$

➜ strong internal γ-absorption:

$$E_\gamma \gtrsim 100\,{\rm MeV}\left(\frac{E_\nu}{3\ {\rm TeV}}\right)$$



[Murase, Guetta & MA'15]

UHE CR association?

- UHE CR proton emission rate density: [e.g. MA & Halzen'12]

$$[E_p^2 Q_p(E_p)]_{10^{19.5}\mathrm{eV}} \simeq 8 \times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- corresponding per flavor neutrino flux ($\xi_z \simeq 0.5 - 2.4$ and $K_\pi \simeq 1 - 2$):

$$E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1 + K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}}_{\sim\ \text{IceCube diffuse}}$$

- **Waxman-Bahcall bound:** $f_\pi \leq 1$ [Waxman & Bahcall'98]

- **similar** UHE nucleon emission rate density (local minimum at $\Gamma \simeq 2.04$) [Auger'16]

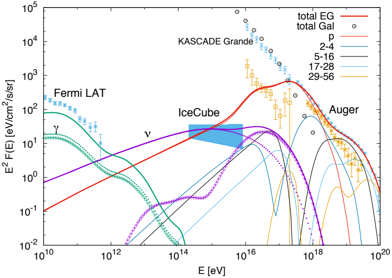
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

✘ **But**, how to reach $E_{\rm max} \simeq 10^{20}$ eV in environments of high energy loss ($f_\pi \simeq 1$)?

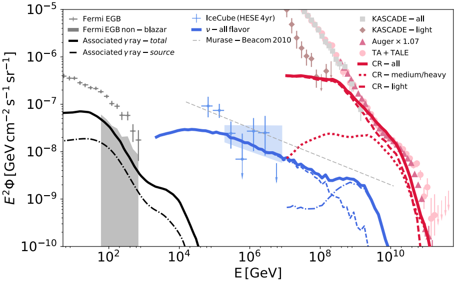
UHE CR association?

➜ **two-zone models**: CR accelerator + CR “calorimeter”?

- starburst galaxies [Loeb & Waxman’06]
- galaxy clusters [Berezinsky, Blasi & Ptuskin’96; Beacom & Murase’13]
- “unified” sources (UHE CRs, γ-ray & neutrinos):



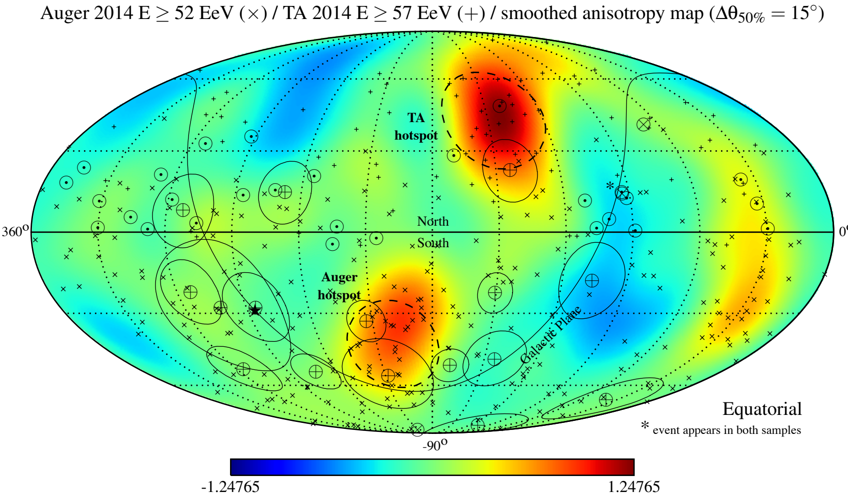
[Kachelriess, Kalashev, Ostapchenko & Semikoz’17]



[Fang & Murase’17]

✘ **However,** $E_\nu < 100$ TeV neutrino data remains a challenge!

Correlation with UHE CRs?



- $\theta_{\rm rms} \simeq 1^\circ\,(D/\lambda_{\rm coh})^{1/2}(E/55{\rm EeV})^{-1}(\lambda_{\rm coh}/1{\rm Mpc})\,(B/1{\rm nG})$ [Waxman & Miralda-Escude'96]
- "hot spots" (dashed), but no significant auto-correlation in Auger and Telescope Array data

Summary

- IceCube has identified a **diffuse flux of astrophysical neutrinos** in the TeV-PeV energy range of **unknown origin**.

- Galactic and Extragalactic Sources are candidate sources, but **absence of anisotropies** favours the latter.

- **No compelling scenario** for the TeV-PeV energy range.

- **High intensity** of the emission is comparable to that of ultrahigh-energy cosmic rays and γ-ray backgrounds.

➜ Excellent conditions for **multi-messenger studies**:

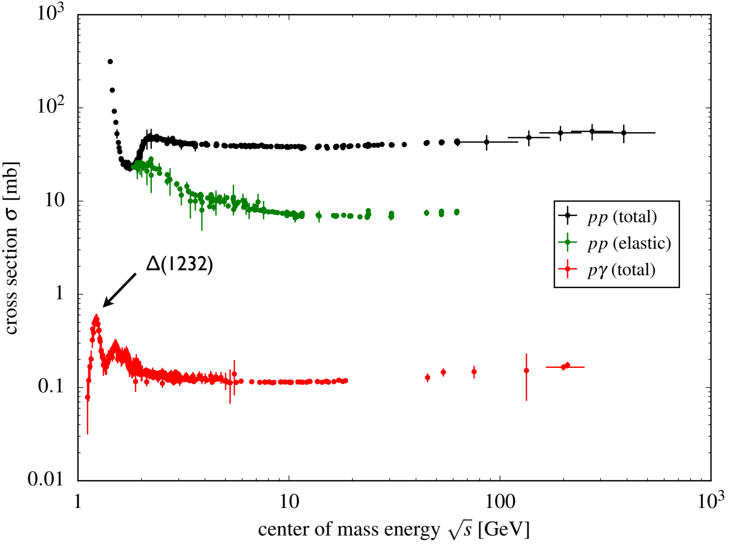
  - Large neutrino flux in the $1-10$ TeV range is challenged by constraints set by the **extragalactic γ-ray background** observed by Fermi.

  - New candidate sources **TXS 0506+056** for neutrino/γ-ray emission.

  - Saturation of calorimetric bounds of **UHE CR sources** might indicate common origin.

Appendix

Cosmic Ray Interactions



[data from PDG (http://pdg.lbl.gov)]

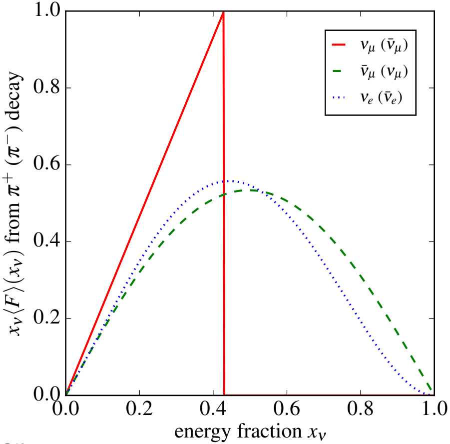
Neutrinos from Pion Decay

- Neutrinos from pion and muon decay:

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

- average energy fraction from relativistic pions ($r_\pi \equiv m_\mu^2/m_\pi^2 \simeq 0.57$):

$$\langle x \rangle_{\pi^+ \to \nu_\mu} = \frac{1 - r_\pi}{2} \simeq 21\%$$
$$\langle x \rangle_{\pi^+ \to \nu_\mu} = \frac{3 + 4 r_\pi}{20} \simeq 26\%$$
$$\langle x \rangle_{\pi^+ \to \nu_e} = \frac{2 + r_\pi}{10} \simeq 26\%$$



- In practice, we often use the **approximation**:

$$\langle x \rangle_{\nu_x} \simeq \langle x \rangle_{\bar{\nu}_x} \simeq \frac{1}{4} \quad \& \quad \kappa_\pi \simeq \frac{1}{5} \quad \to \quad \frac{\langle E_\nu \rangle}{E_N} \simeq \frac{1}{20}$$

Galactic Source Candidates

- diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess and Ostapchenko'14; Neronov, Semikoz & Tchernin'13; Neronov & Semikoz'14,'16] [Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15; Neronov, Kachelriess & Semikoz'18]
- unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
- *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
- supernova remnants [Mandelartz & Tjus'14]
- pulsars [Padovani & Resconi'14]
- microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
- Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15,'16]
- Galactic Halo [Taylor, Gabici & Aharonian'14]
- heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14] [Murase, Laha, Ando, MA'15; Boucenna *et al.*'15 ; Chianese, Miele, Morisi & Vitagliano'16]

Pion Production Efficiency

- pion production depend on target opacity $\tau = \ell\sigma n$
- "bolometric" pion production efficiency (inelasticity κ):

$$f_\pi = 1 - \exp(-\kappa\tau)$$

- inelasticity per pion : $\kappa_\pi = \kappa / \langle N_{\text{all }\pi} \rangle \simeq 0.17 - 0.2$
- "bolometric" relation of the production rates Q:

$$E_\pi^2 Q_{\pi^\pm}(E_\pi) \simeq \frac{\langle N_{\pi^+} \rangle + \langle N_{\pi^-} \rangle}{\langle N_{\pi^0} \rangle + \langle N_{\pi^+} \rangle + \langle N_{\pi^-} \rangle} \left[f_\pi E_N^2 Q_N(E_N) \right]_{E_N = E_\pi/\kappa_\pi}$$

- charged-to-neutral pion ratio:

$$K_\pi \equiv \frac{\langle N_{\pi^+} \rangle + \langle N_{\pi^-} \rangle}{\langle N_{\pi^0} \rangle} \simeq \begin{cases} 2 & pp \\ 1 & p\gamma \end{cases}$$

- or in more compact form with K_π:

$$E_\pi^2 Q_{\pi^\pm}(E_\pi) \simeq f_\pi \frac{K_\pi}{1 + K_\pi} \left[E_N^2 Q_N(E_N) \right]_{E_N = E_\pi/\kappa_\pi}$$

Neutrino and Gamma-Ray Emission

- neutrino emission from pion decay

$$\frac{1}{3}\sum_\alpha E_\nu Q_{\nu_\alpha}(E_\nu) \simeq [E_\pi Q_{\pi^\pm}(E_\pi)]_{E_\pi \simeq 4E_\nu} \simeq \frac{1}{4} f_\pi \frac{K_\pi}{1+K_\pi} \left[E_N^2 Q_N(E_N)\right]_{E_N = 4E_\nu/\kappa_\pi}$$

- neutrino and γ-ray emission are related as

$$\frac{1}{3}\sum_\alpha E_\nu Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{2} \frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle} [E_\gamma Q_\gamma(E_\gamma)]_{E_\gamma = 2E_\nu}$$

- again, a more compact form with K_π:

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4} \left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

- γ-ray emission is attenuated in sources and, in particular, in the extragalactic radiation background

Ultra-Long Baseline Oscillations

- Energy resolution of detectors is limited and size of cosmic neutrino source is large.

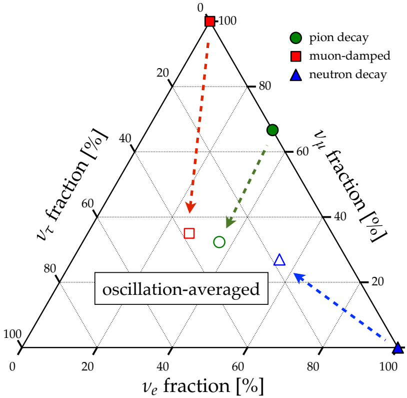
$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin^2\Delta_{ij}}_{\to 1/2} + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin 2\Delta_{ij}}_{\to 0}$$

➜ oscillation-averaged probability:

$$P_{\nu_\alpha\to\nu_\beta} \simeq \sum_i |U_{\alpha i}|^2|U_{\beta i}|^2$$

- initial composition: $\nu_e : \nu_\mu : \nu_\tau$

pion & muon decay:	$1:2:0$
muon-damped decay:	$0:1:0$
neutron decay:	$1:0:0$



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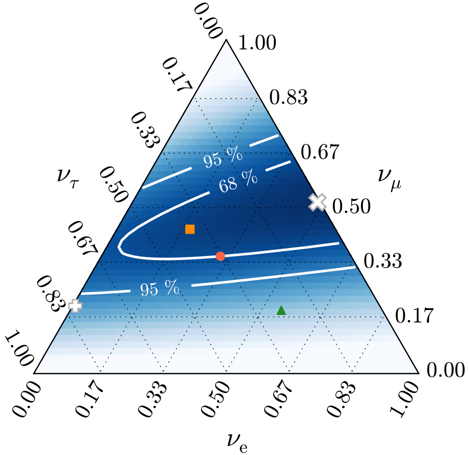
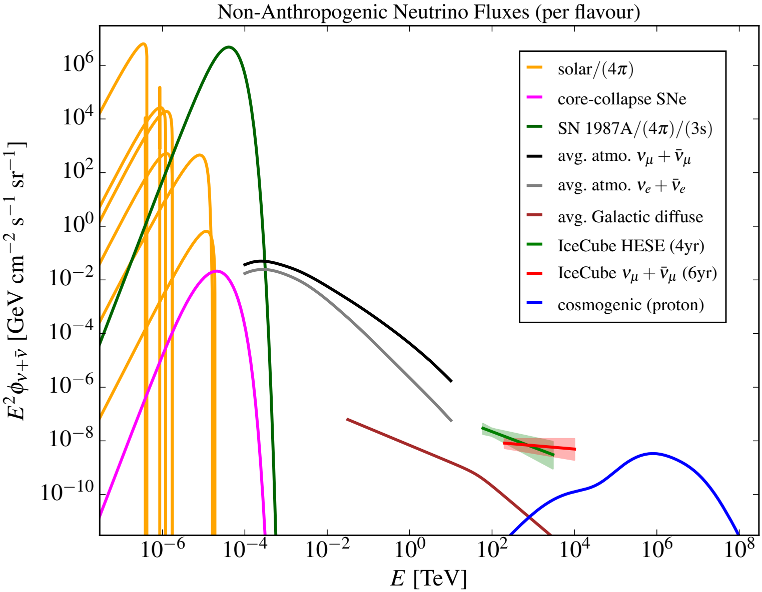


[**Astrophys.J.** 809 (2015) no.1, 98]

Non-Anthropogenic Neutrino Fluxes



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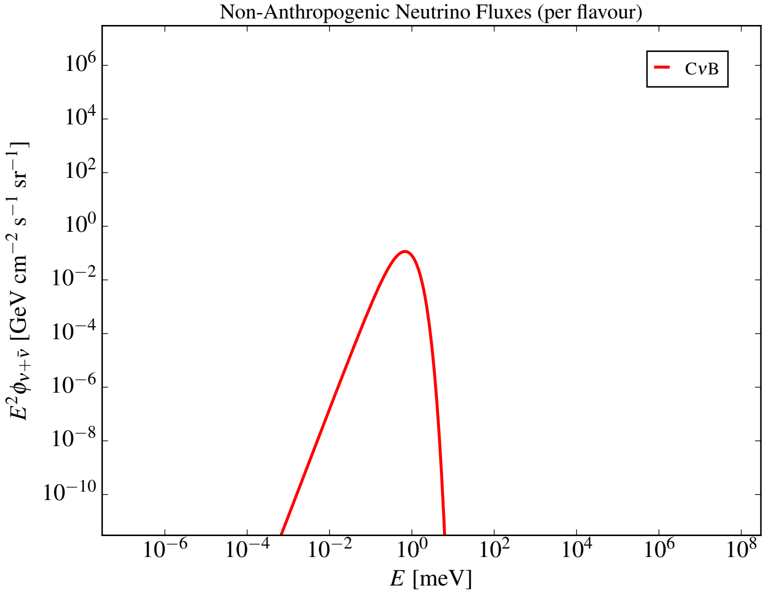
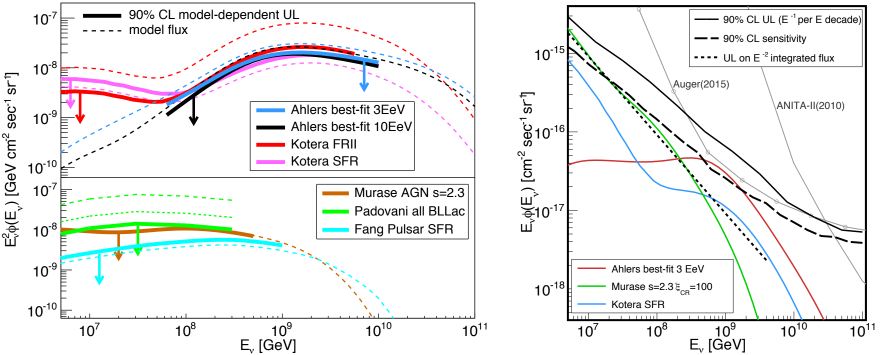


Cosmogenic ("GZK") Neutrinos

- Observation of UHE CRs and extragalactic radiation backgrounds "guarantee" a flux of high-energy neutrinos, in particular via resonant production in CMB.
  [Berezinsky & Zatsepin'69]

- "Guaranteed", but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**
    [Berezinsky & Zatsepin'69; Yoshida & Teshima'93; Protheroe & Johnson'96; Engel, Seckel & Stanev'01; Fodor, Katz, Ringwald &Tu'03; Barger, Huber & Marfatia'06; Yuksel & Kistler'07; Takami, Murase, Nagataki & Sato'09, MA, Anchordoqui & Sarkar'09, Heinz, Boncioli, Bustamante & Winter'15]
  - **+ mixed compositions**
    [Hooper, Taylor & Sarkar'05; Ave, Busca, Olinto, Watson & Yamamoto'05; Allard, Ave, Busca, Malkan, Olinto, Parizot, Stecker & Yamamoto'06; Anchordoqui, Goldberg, Hooper, Sarkar & Taylor'07; Kotera, Allard & Olinto'10; Decerprit & Allard'11; MA & Halzen'12]
  - **+ extragalactic γ-ray background limits**
    [Berezinsky & Smirnov'75; Mannheim, Protheroe & Rachen'01; Keshet, Waxman, & Loeb'03; Berezinsky, Gazizov, Kachelriess & Ostapchenko'10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar'10; MA & Salvado'11; Gelmini, Kalashev & Semikoz'12]

Limits on Cosmogenic Neutrinos



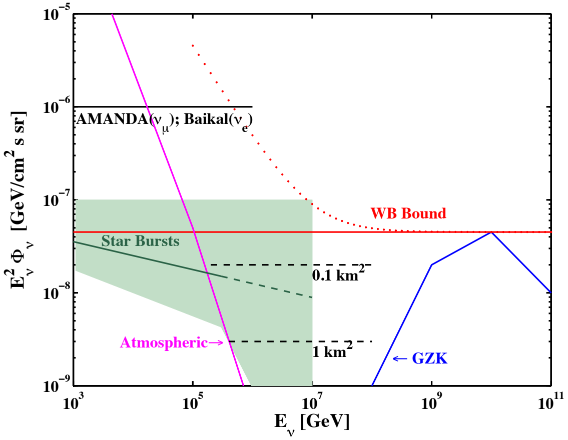
[**Phys.Rev.Lett.** 117 (2016) 241101]

- Upper limits on cosmogenic (top left) and astrophysical (bottom left) neutrino emission models.
- Differential upper limits (right) in comparison with Auger and ANITA.

➜ **Proton-dominated cosmogenic neutrino models are disfavoured.**

Starburst Galaxies

- **Increased star formation** enhances cosmic ray production.
- **Dense environment and strong magnetic fields** enhance CR containment and interaction.
- Expect spectral break at $(0.1-1)$ PeV from CR leakage ("CR knee").
- Plot shows muon neutrinos on production (3/2 of total neutrino flux).



[Loeb & Waxman'06]

TeV Starburst Galaxies

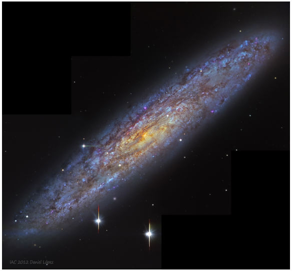
Messier 82 ($\delta \simeq 69°$)

$$E^2\phi_\gamma(E) \simeq 3.3 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-0.5} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

$$E^2\phi_\nu(E) \lesssim 1.09 \times 10^{-12} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

[IceCube 7yr $\nu_\mu + \overline{\nu}_\mu$]

NGC 253 ($\delta \simeq -25°$)



$$E^2\phi_\gamma(E) \simeq 9.6 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-0.14} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

no neutrino limit

expected from CR-gas interactions: $E_\nu^2\phi_{\nu_\mu}(E_\nu) \simeq \frac{1}{2}E_\gamma^2\phi_\gamma(E_\gamma)$

Tidal Disruption Events

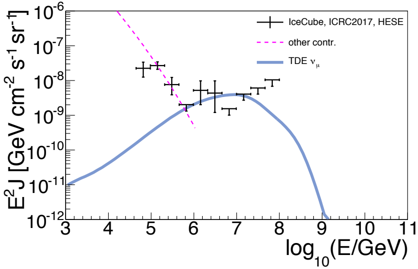
- Stars torn apart by tidal forces in the vicinity of a supermassive black hole can launch jet-like outflows.

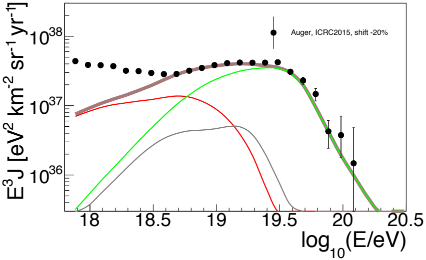
➜ good candidate sources of UHE CRs [Farrar & Gruzinov'09; Farrar & Piran'14]

- associate neutrino production via $p\gamma$ interactions:

[Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]

[Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]

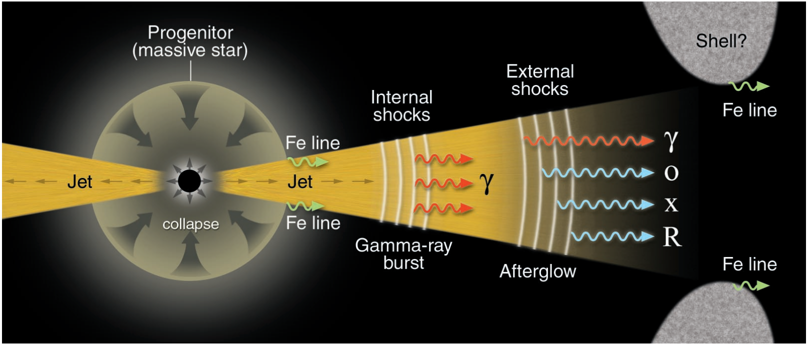




[*e.g.* Biehl, Boncioli, Lunardini & Winter'17]

Gamma-Ray Bursts

- Neutrino production at various stages of a gamma-ray burst (GRB).
  - ➜ **precursor** pp and $p\gamma$ interactions in stellar envelope; also possible for "failed" GRBs [Razzaque,Meszaros&Waxman'03]
  - ➜ **burst** $p\gamma$ interactions in internal shocks [Waxman&Bahcall'97]
  - ➜ **afterglow** $p\gamma$ interactions in reverse external shocks [Waxman&Bahcall'00;Murase&Nagataki'06;Murase'07]

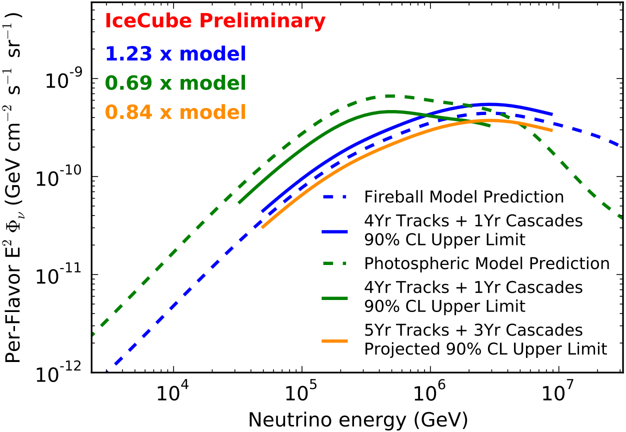


[Meszaros'01]

Gamma-Ray Bursts

- strong limits on neutrino emission associated with "fireball" model [Abbasi *et al.*'12]

➜ PeV neutrino flux exceeds GRB limit by one order of magnitude.



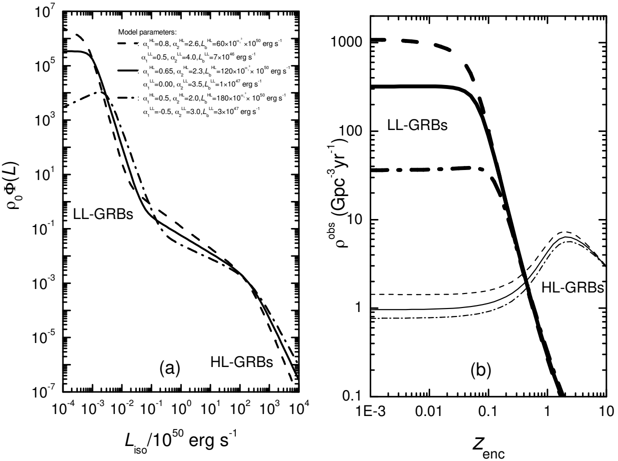
[IceCube'16]

Low-Luminosity Gamma-ray Bursts

- *loop-hole:* undetected low-luminosity γ-ray bursts (GRB)

  [Murase & Ioka'13; Senno, Murase & Mészáros'16; Boncioli, Biehl & Winter'18]

- *claim:* distinct population of LL-GRB more abundant in the local ($z \ll 1$) Universe



[Liang, Zhang, Virgili & Dai'06]

Non-Blazar Limits on Gamma-Ray Background

- **Photon fluctuation analyses** of Fermi data allow to constrain the source count distribution of blazars **below** the source detection threshold.
- inferred blazar contribution above 50 GeV:
  - Fermi Collaboration'15:

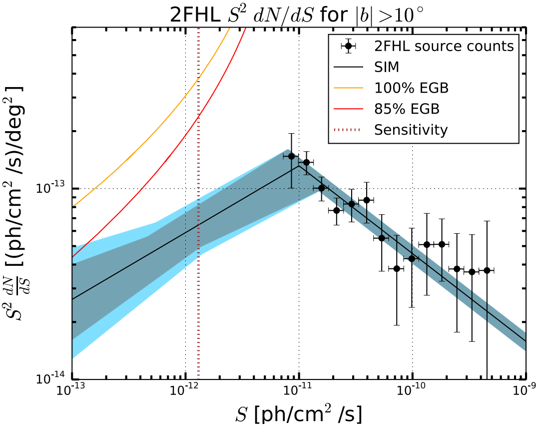
    $86^{+16}_{-14}\%$ of EGB

  - Lisanti *et al.*'16:

    $68^{+9}_{-8}(\pm 10)_{\rm sys}\%$ of EGB

  - Zechlin *et al.*'16

    $81^{+52}_{-19}\%$ of EGB



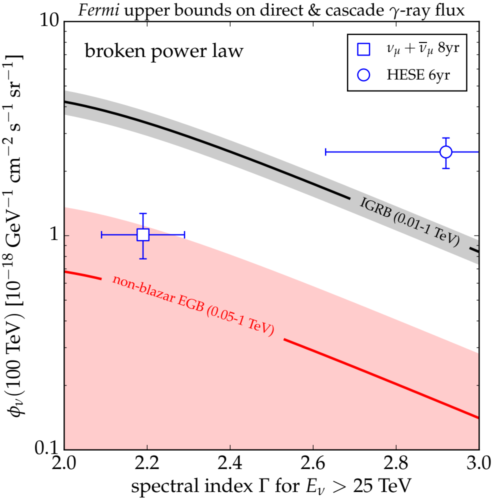
[Fermi'15]

Non-Blazar Limits on Gamma-Ray Background

- non-blazar contribution above 50 GeV: [Fermi'15]

  $14^{+14}_{-14}\%$ of EGB

- ✘ **strong tension** with IceCube observation ($E_\nu \lesssim 100$ TeV)
- limits apply to generic **cosmic ray calorimeters**
- *possible loop-holes*:
  - γ-absorption in source? [Chang & Wang'14]
  - suppression of γ-ray cascades? [Broderick, Chang & Pfrommer'12]



[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]