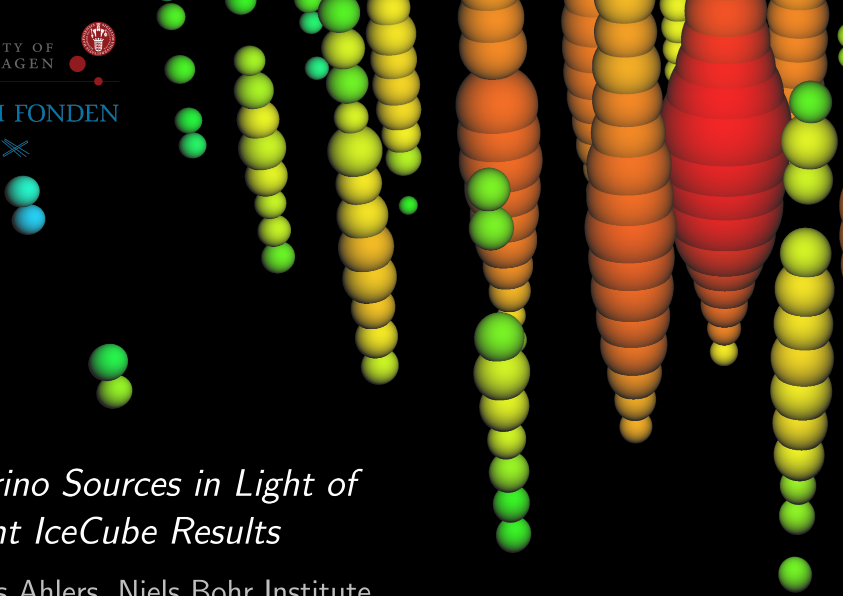
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



Neutrino Sources in Light of Recent IceCube Results

Markus Ahlers, Niels Bohr Institute

GSSI Seminar, February 20, 2019, L'Aquila

Multi-Messenger Astronomy

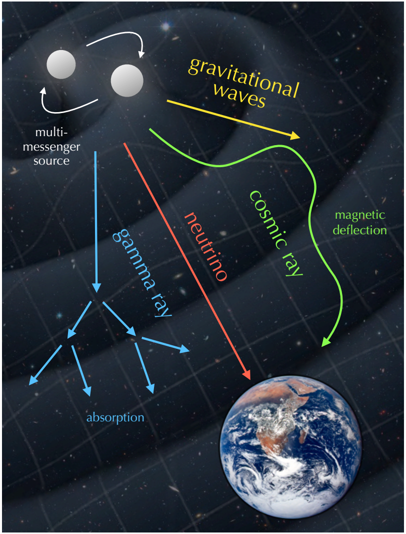
- **Cosmic ray (CR)** acceleration in the aftermath of cataclysmic events, sometimes seen in **gravitational waves**.

➜ 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



High-Energy Neutrino Detection

- High energy neutrino collisions with nuclei via **deep-inelastic charged and neutral current** interactions.

➜ Secondary charged particles can be detected by their **optical Cherenkov radiation** in transparent media.

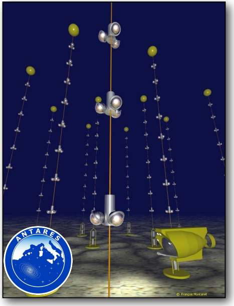
back-of-the-envelope ($E_\nu \sim 1\mathrm{PeV} = 10^{15}$ eV):

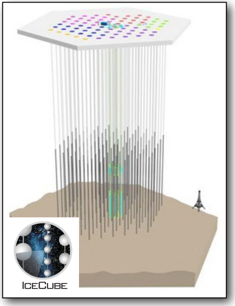
- **flux of neutrinos** : $\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5 \mathrm{yr}}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-8} \sigma_{pp} \sim 10^{-33} \mathrm{cm}^2$
- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

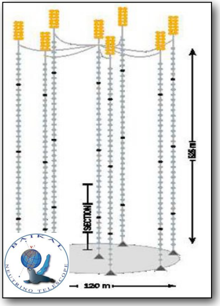
➜ **rate of events** :

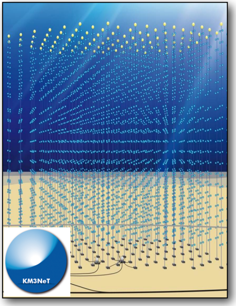
$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

Optical Cherenkov Observatories



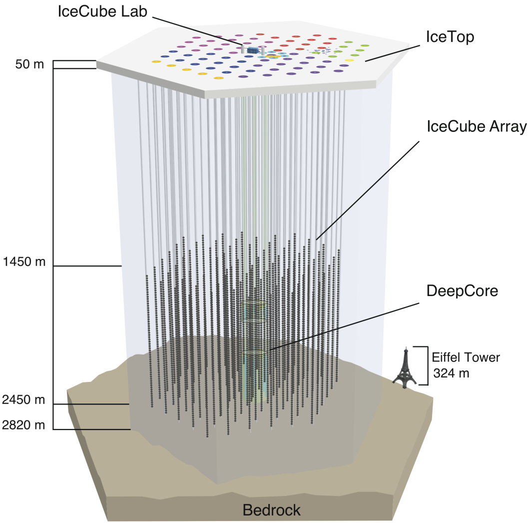






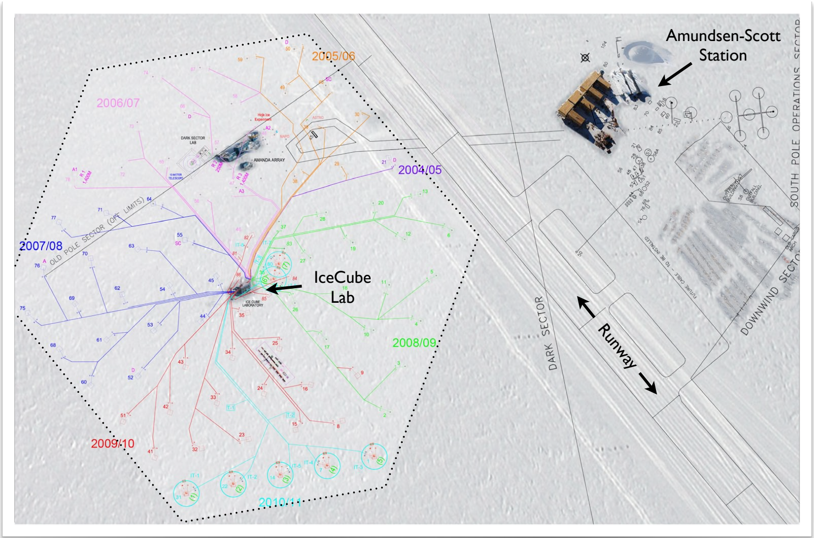
Antares	IceCube	Baikal-GVD	KM3NeT/ARCA
Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (3 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km^3	~1 km^3	~0.4 km^3 (Phase 1) ~1km^3	~0.1 km^3 (Phase 1) ~1 km^3
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

The IceCube Observatory



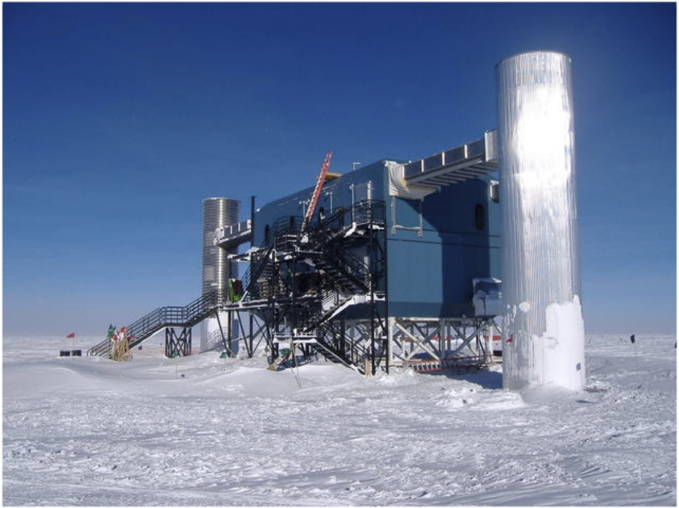
- Giga-ton **Cherenkov telescope** at the South Pole
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings** 125 m apart on triangular grid
- **8 DeepCore strings** DOMs in particularly clear ice
- **81 IceTop stations** two tanks per station, two DOMs per tank
- 7 year construction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

The IceCube Observatory



Area overview

The IceCube Observatory



IceCube Lab

The IceCube Observatory

Drilling with new IceTop tanks

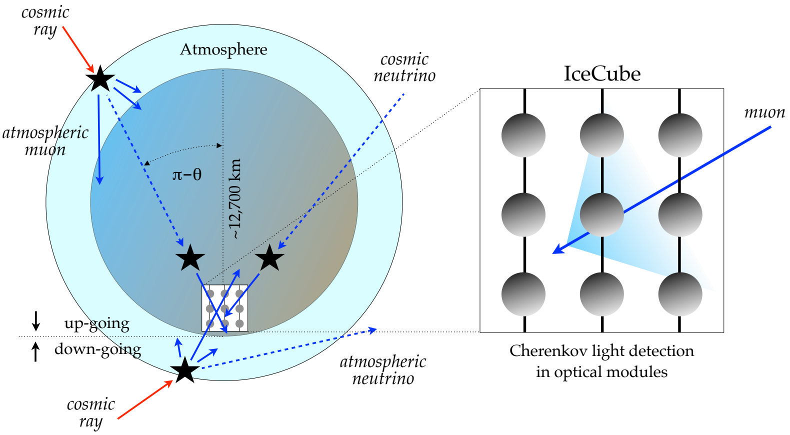
The IceCube Observatory

Firn & Ice Drilling

The IceCube Observatory

String & Optical Module

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

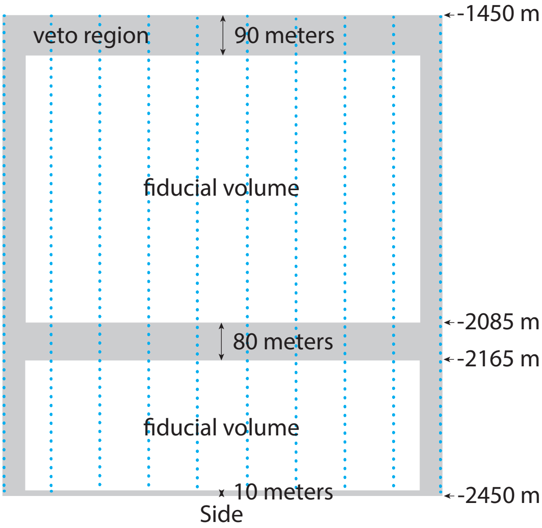
- Outer layer of optical modules can be used as a **veto region** (gray area):

✘ **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

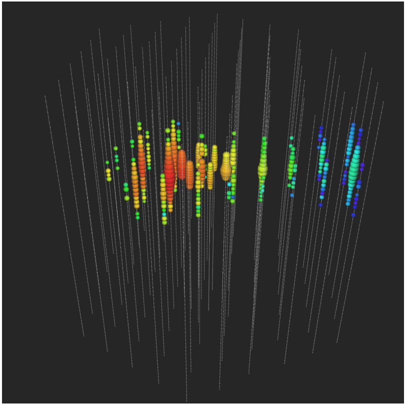


[IceCube Collaboration'13]

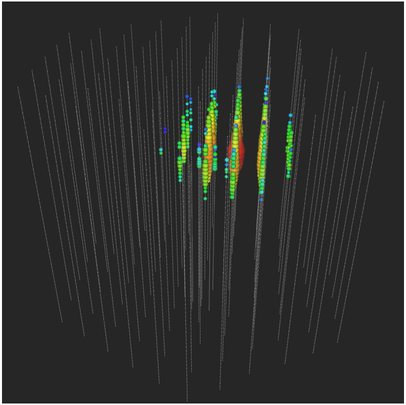
2013: A Milestone for Neutrino Astronomy

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering)



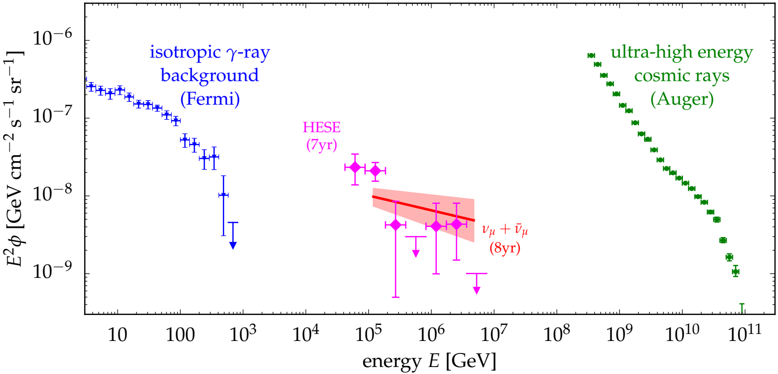
"cascade event" (from all flavours)



["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) (7yrs):** [Science 342 (2013); work in progress]
  - 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

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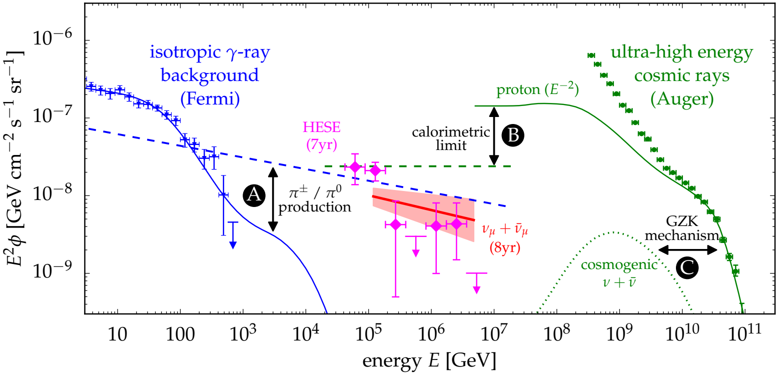


Ultra-Long Baseline Oscillations

- Limited energy resolution of detectors and large distance to neutrino source:

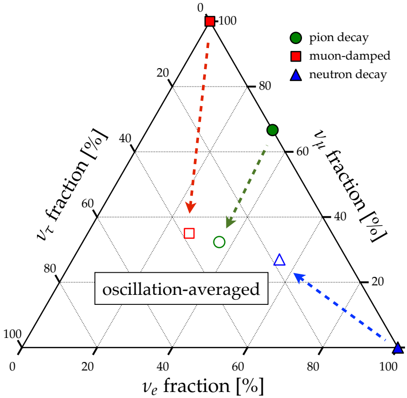
$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin^2\Delta_{ij}}_{\to 1/2} + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin 2\Delta_{ij}}_{\to 0}$$

➜ 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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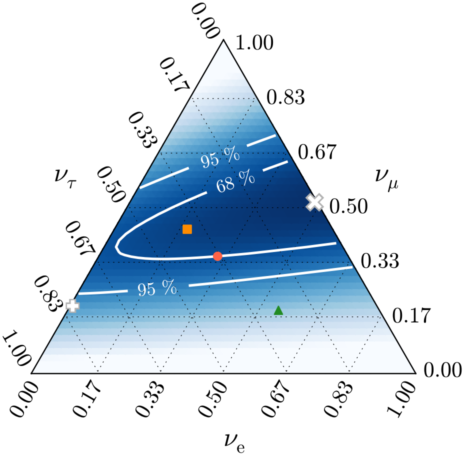
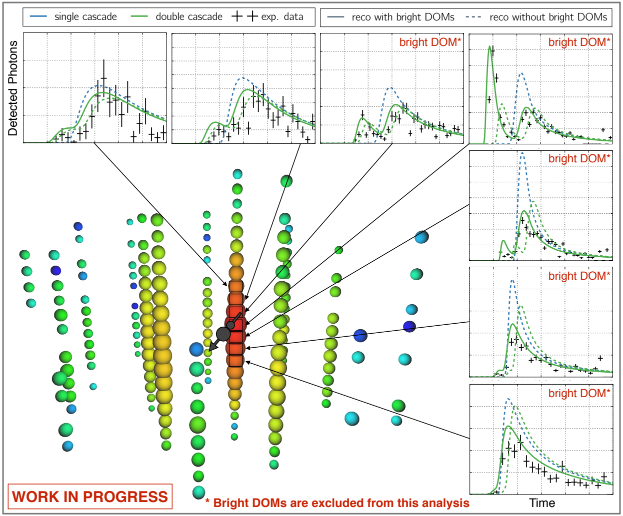


[**Astrophys.J.** 809 (2015) no.1, 98]

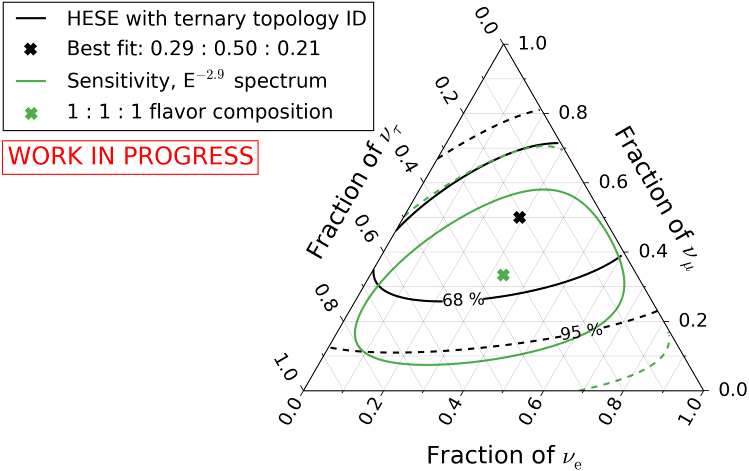
HESE 7-year Update (preliminary)



Double cascade event candidate. (Tau neutrino candidate)

The reconstructed double cascade positions are indicated as grey circles, the direction indicated with a grey arrow. The size of the circles illustrates the relative deposited energy of the two cascades.

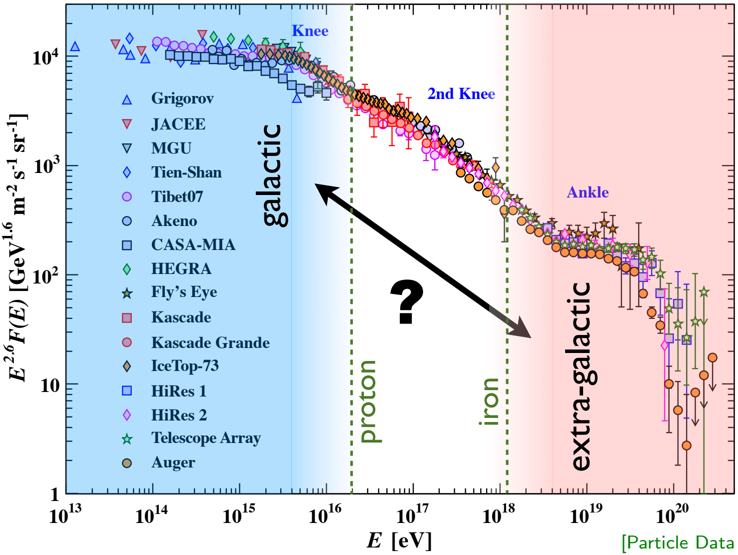
HESE 7-year Update (preliminary)



Measured flavor composition of IceCube HESE events and sensitivity at the best fit spectrum.

The Cosmic "Beam"

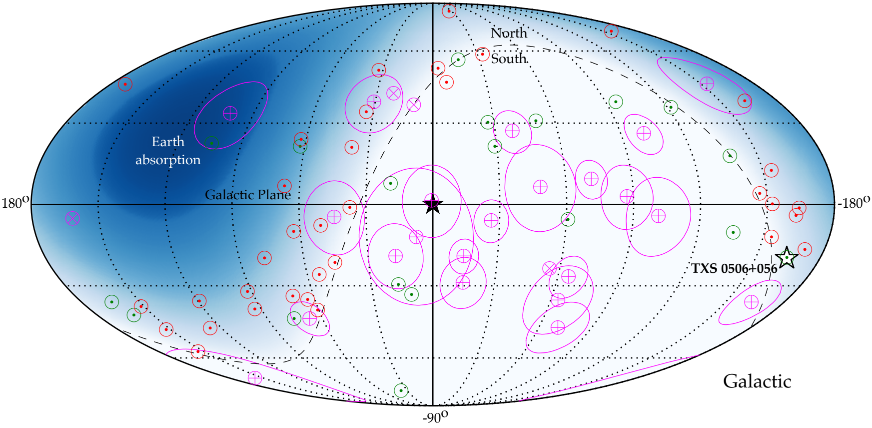
1 PeV neutrino ↔ 20-30 PeV cosmic ray nucleon



[Particle Data Group'13]

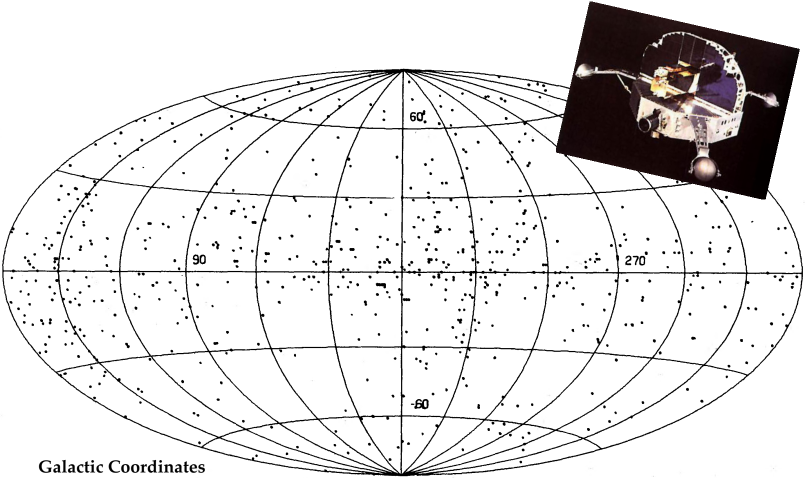
Arrival Directions of Cosmic Neutrinos

Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red) + public alerts (green))



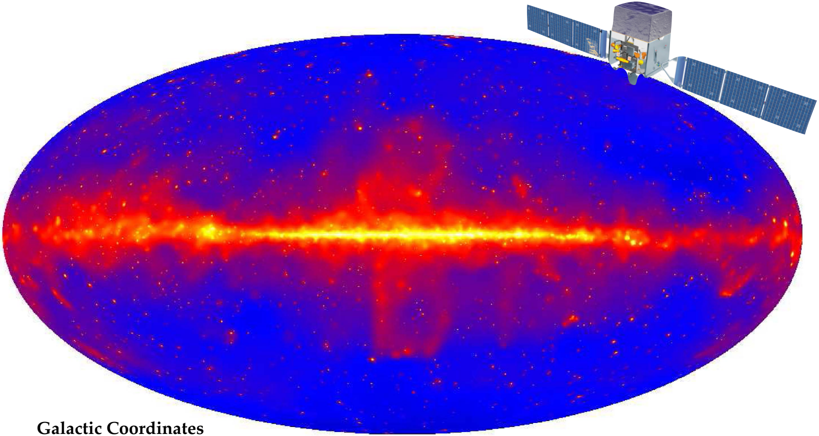
No significant correlation of diffuse flux with known sources, except TXS 0506+056.

Gamma-Ray Sky in **1967**



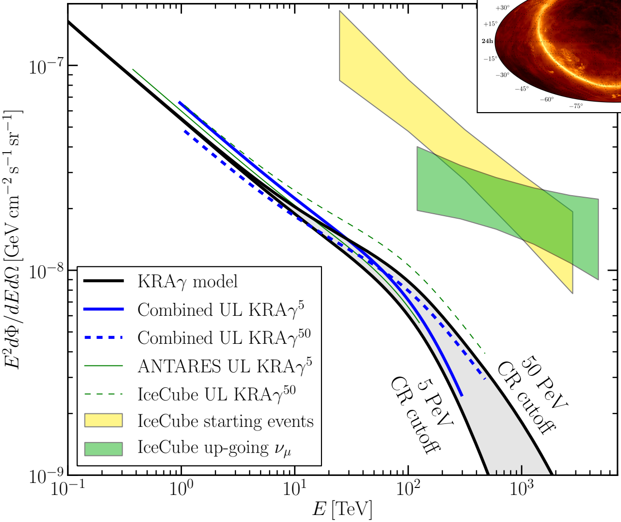
First γ-ray map with the Orbiting Solar Observatory (OSO-3)

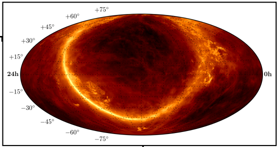
Gamma-Ray Sky in **2017**



Recent γ-ray map collected by the Fermi satellite.

Galactic Diffuse Limits





[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

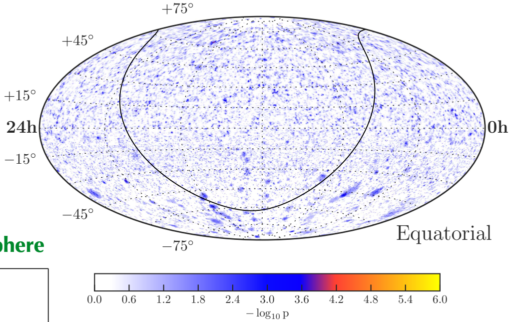
Galactic diffuse emission is subdominant compared to isotropic flux.

Neutrino Point-Source Limits

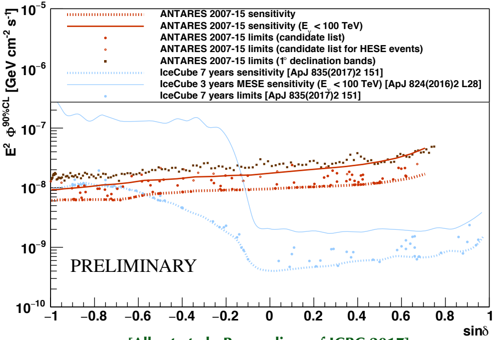
IceCube and ANTARES/KM3NeT with complementary field of views.

ICECUBE

Southern Hemisphere | Northern Hemisphere



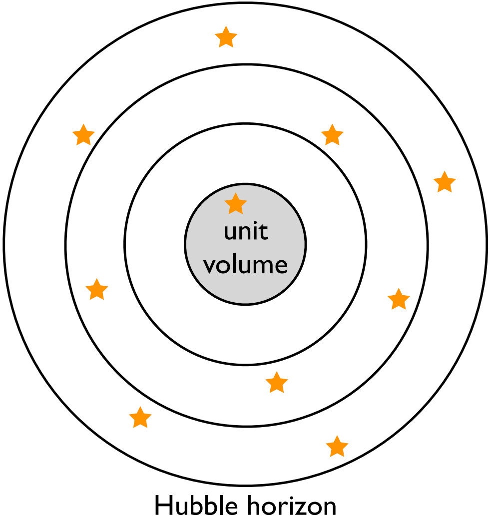
[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]



[Albert et al., Proceedings of ICRC 2017]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

Diffuse vs. Point-Source



- Low neutrino absorption in the Universe allows to observe distant sources.

➜ Quasi-diffuse flux observed by IceCube is composed of **many individual sources**.

- Can they be identified?

lower density (ρ)

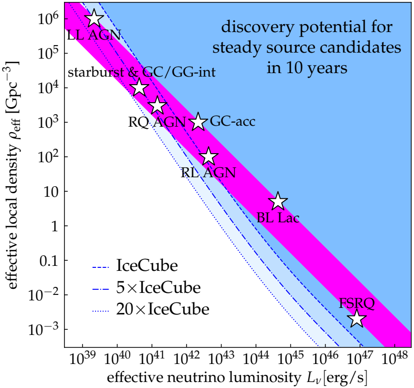
$\Downarrow$

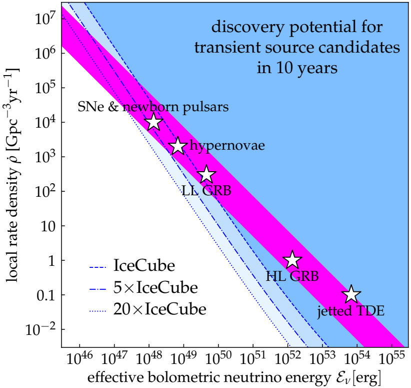
higher luminosity (L)

$\Downarrow$

brighter sources (ϕ)

Constraints from Point-Source Limits





[effective local density from Murase & Waxman'16; local rate density from Murase & Takami'08]

- **Left:** time-integrated discovery potential (Nothern Hemisphere; 10 years)

$$E^2\phi_{\nu_\mu+\bar\nu_\mu} \simeq 10^{-12}\ \mathrm{TeV/cm^2/s}$$

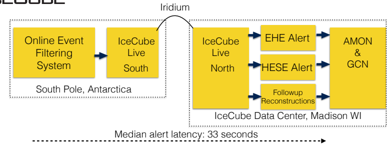
- **Right:** time-dependent discovery potential (Nothern Hemisphere; 10 years)

$$E^2F_{\nu_\mu+\bar\nu_\mu} \simeq 0.1\ \mathrm{GeV/cm^2}$$

Realtime Alerts

ICECUBE

IceCube and ANTARES issue realtime neutrino alerts to multi-messenger partners for rapid follow-up.



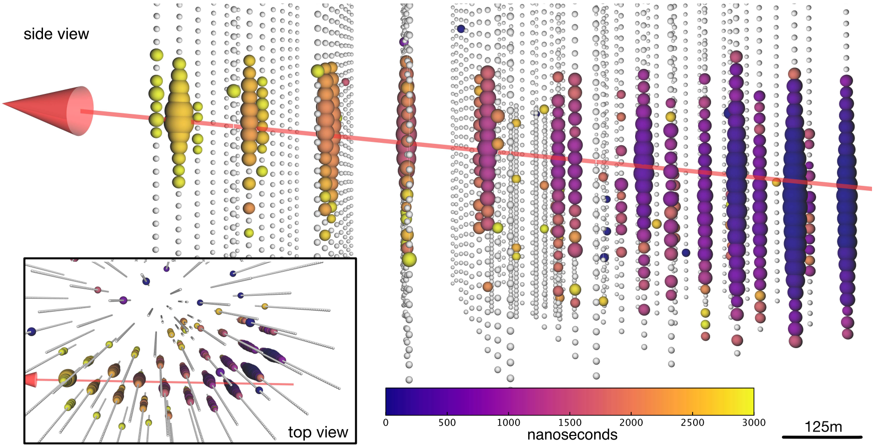
- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- **high-energy starting tracks** (>60TeV)
  - 4.8 alerts/year (1.1 signal/year)
- **through-going muons** (>100TeV)
  - 4-5 alerts/year (2.5-4 signal/year)

[Blaufuss et al., Proceedings of ICRC 2017]

- time to issue alert: 5s
- median angular resolution 0.5deg
- **neutrino doublets**
  - 0.04 alerts/year
- **neutrinos from local galaxies** (>1TeV)
  - 10 alerts/year
- **high-energy neutrinos** (>5TeV)
  - 20 alerts/year
- **very high-energy neutrinos** (>30TeV)
  - 3-4 alerts/year

[Dornic et al., Proceedings of ICRC 2017]

IceCube 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.

First Multi-Messenger Blazar: TXS 0506+056

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*†

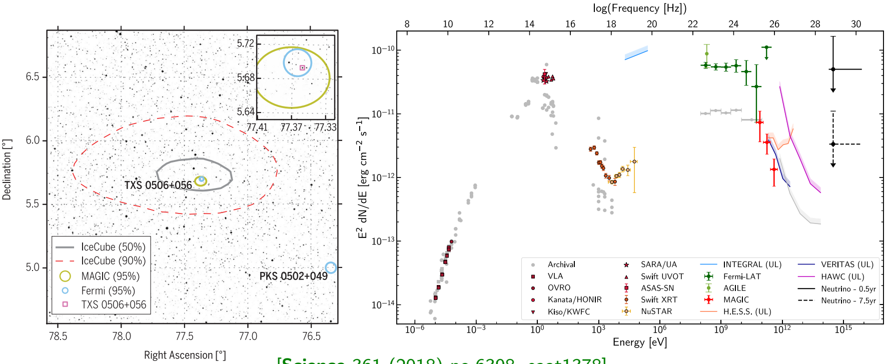
[**Science** 361 (2018) no.6398, eaat1378]

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

IceCube Collaboration*†

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

Multi-Messenger Observations of TXS 0506+056

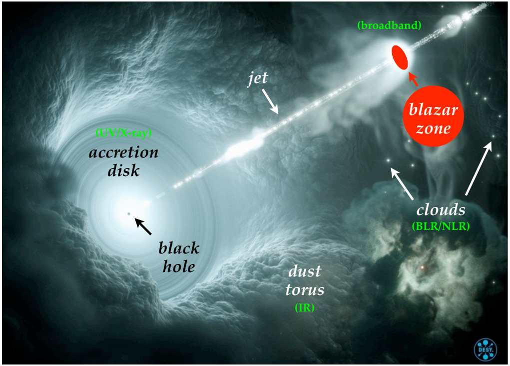


[**Science** 361 (2018) no.6398, eaat1378]

- Coincident with Fermi flare; **chance correlation can be rejected at the 3σ-level.**
- TXS 0506+056 is among the 3% brightest Fermi-LAT blazars.
- One of the most luminous BL Lacs (2.8×10^{46} erg/s).

Blazars as Neutrino Factories

- **Blazars:** *active galaxies powered by accretion onto a supermassive black hole expel relativistic jets pointing into our line of sight.*
- Cosmic ray acceleration and $p\gamma$ interaction in blazar zone leads to neutrino beam. [Stecker *et al.*'91] [Mannheim'96; Halzen & Zas'97]
- **Non-power-law neutrino spectra due to diverse photon spectra.**
- Typically, deficit of sub-PeV and excess of EeV neutrinos.



[credit: DESY, Zeuthen]

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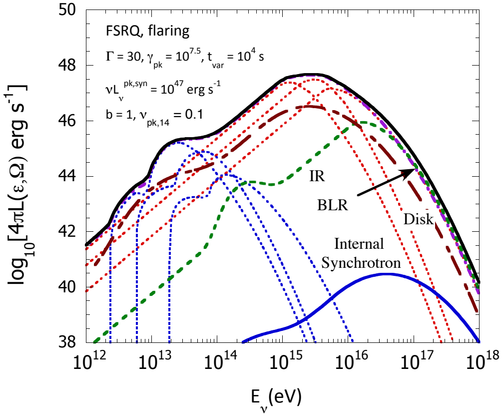
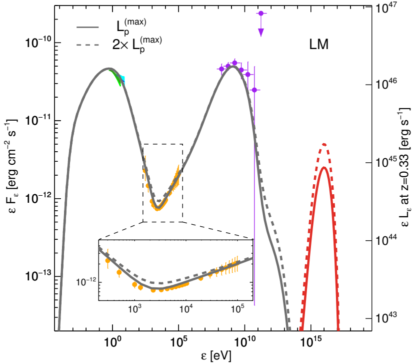
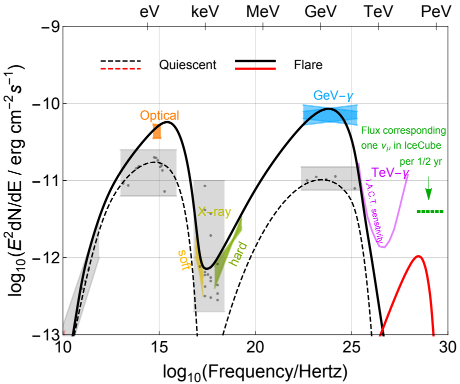


[Dermer, Murase & Inoue'14]

Neutrino Flux Predictions

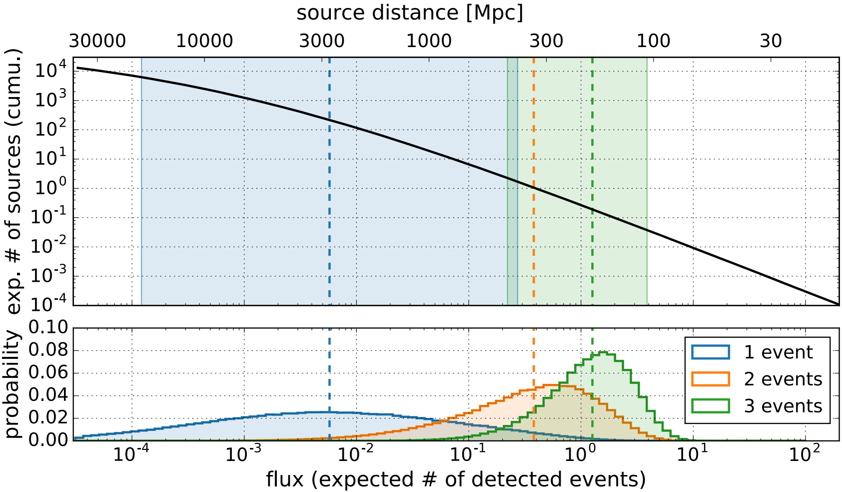




[Keivani *et al.*, arXiv:1807.04537] [Gao *et al.*, arXiv:1807.04275]

- Photon SED can be modelled with **lepto-hadronic** or **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 of 2017 flare limited to **less than one event** by theoretically feasible proton luminosity and X-ray data. [Murase, Oikonomou & Petropoulou, arXiv:1807.04748]

Source Lottery (Eddington Bias)

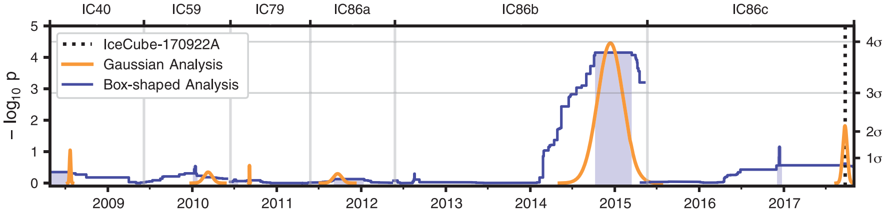


[Strotjohann, Kowalski & Franckowiak'18]

- Median expected number of events from BL Lac observed by one event:

$$0.006 - 0.03$$

Neutrino Outburst in 2014/15



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

- **Previous** 3.5σ **neutrino flare** $(13 \pm 5$ events) between Sept. 2014 and March 2015.

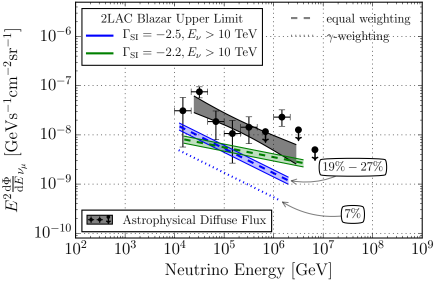
! Second-warmest TS in Northern sky in IC86-II–IV time-dependent analysis

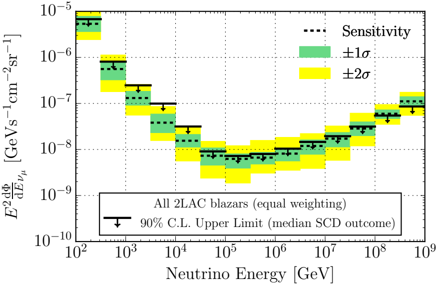
- Implies neutrino luminosity of 1.2×10^{47} erg/s over 158 days $(\simeq 4 \times L_{\rm Fermi})$.
- No flaring state in Fermi-LAT, but **maybe hard spectrum**?

[Padovani *et al.*, arXiv:1807.04461; IceCube'19]

- About **1000 times brighter** than 2017 outburst!

Limits on Diffuse Blazar Flux



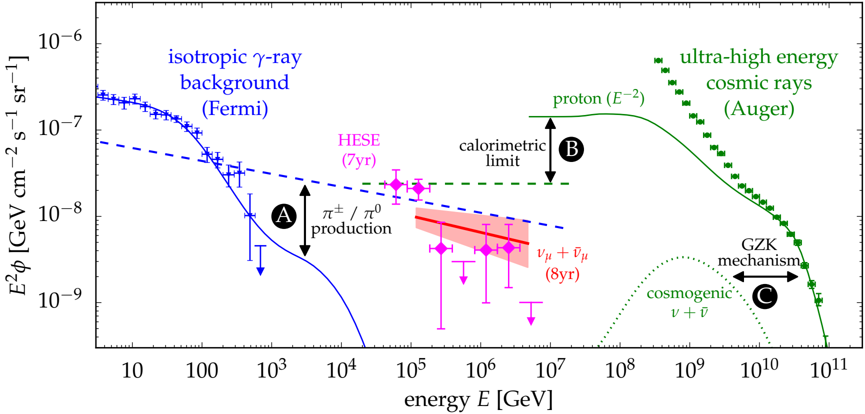


- **Blazar stacking limits** derived from Fermi-LAT AGN catalogue (2LAC).

  [**Astrophys.J.** 835 (2017) no.1, 45]

- Upper limit on the diffuse flux at the level of 30% assuming all blazar classes contribute.
- Energy of IC-170922A in the region of strongest differential upper limit.

Multi-Messenger Interfaces



A Joined **production of charged pions and neutral pions** in cosmic-ray interactions leads to the emission of neutrinos (dashed blue) and gamma-rays (solid blue), respectively.

Hadronic Gamma-Ray Emission

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

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

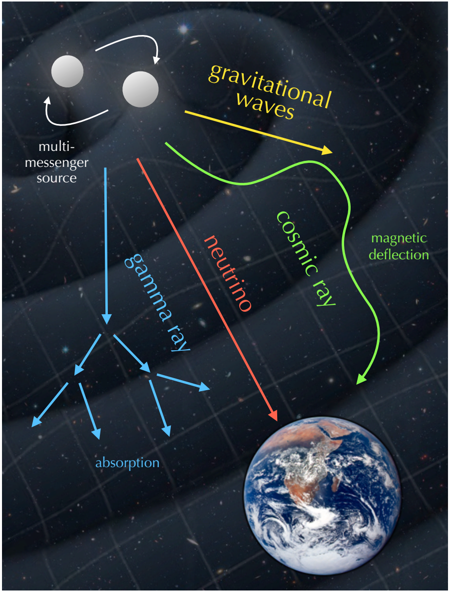
$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

- relative production rates comparable

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

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

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



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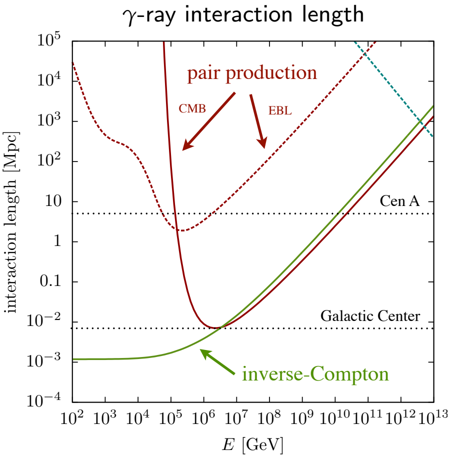


Isotropic Diffuse Gamma-Ray Background (IGRB)

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

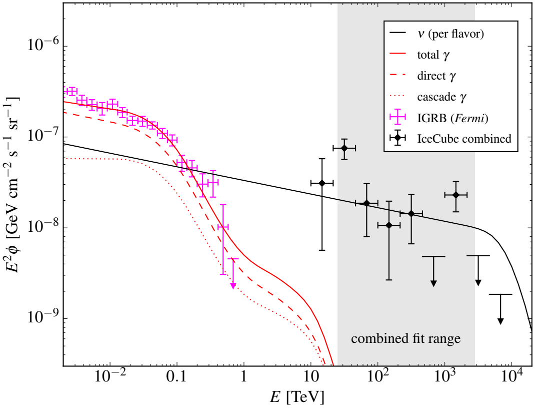
✘ Cosmic ray spectral index **strongly constrained** by the isotropic diffuse gamma-ray background (IGRB)

[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]
[Palladino, Fedynitch, Rasmussen & Taylor'19]

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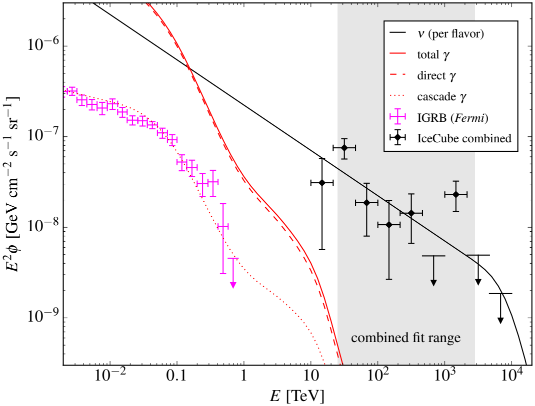

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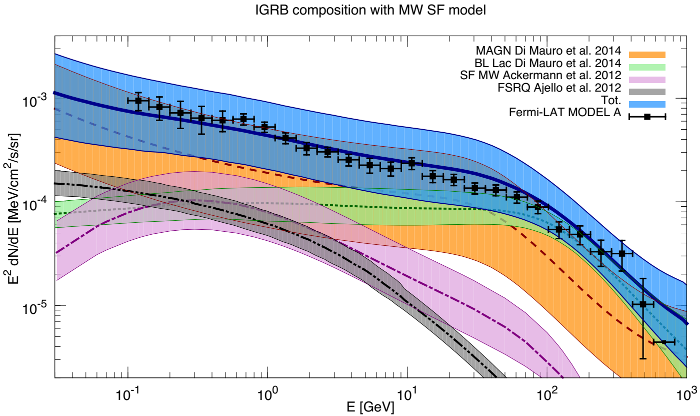
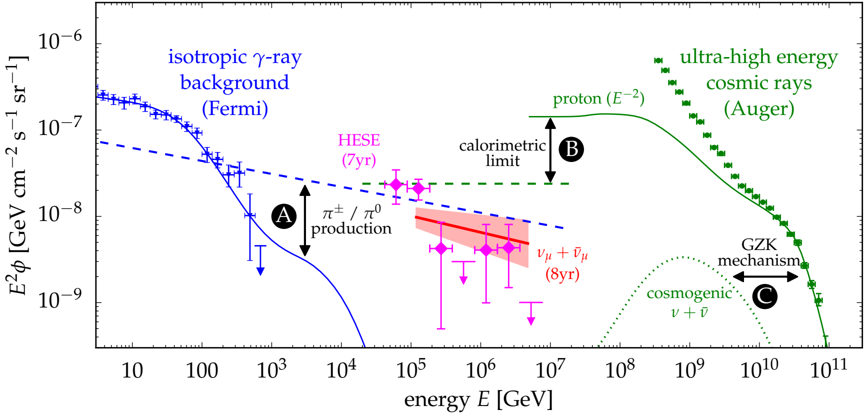


[Di Mauro & Donato'15]

- **IGRB** : extragalactic γ-ray background consisting of unidentified point-like sources and diffuse contributions
- extrapolation of identified (bright) γ-ray sources allows to model the emission
- large contribution ($\gtrsim 50\%$) from unidentified blazars (BL Lac) at $E > 50$ GeV

Multi-Messenger Interfaces



B/C	The most energetic cosmic rays (solid green) imply a maximal flux (**calorimetric limit**) of neutrinos from the same sources (green dashed) and **cosmogenic neutrinos** (dotted line).

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]

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

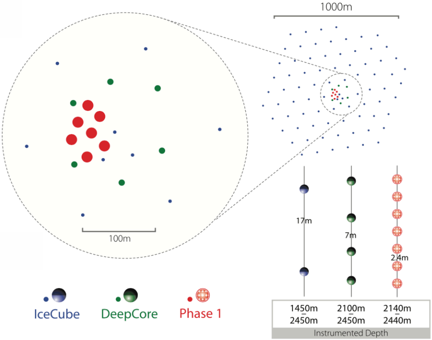
✘ **But**, how to reach $E_{\max} \simeq 10^{20}$ eV in environments of high energy loss ($f_\pi \simeq 1$)?

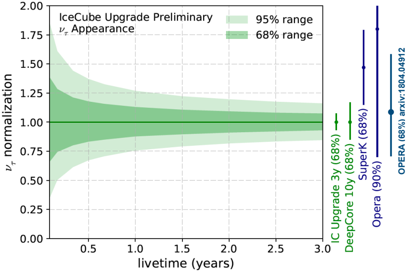
➜ two-zone models: acceleration + CR "calorimeter"?

- starburst galaxies [Loeb & Waxman'06]
- galaxy clusters [Berezinsky, Blasi & Ptuskin'96; Beacom & Murase'13]

Outlook: IceCube Upgrade

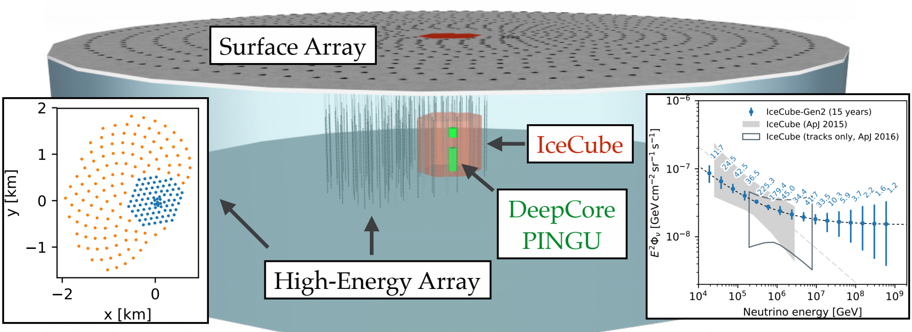
- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.
- **Precision measurement** of atmospheric neutrino oscillation.
- Midscale NSF project with an estimated total cost of $23M.
- deployment in 2022/23
- **October 1, 2018: first $1M increment**
- additional $9M in capital equipment alone from partners





Vision: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger).
- In-ice **high-energy Cherenkov array** with 6-10 km^3 volume.
- **Under investigation:** Surface arrays for in-ice radio Askaryan and cosmic ray veto (air Cherenkov and/or scintillator panels).



[Aartsen et al., Proceedings of ICRC 2017]

Summary

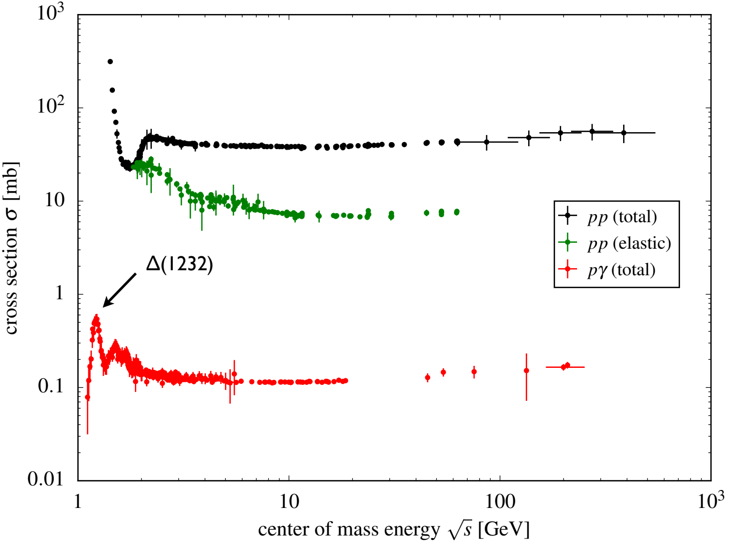
- IceCube has identified a **diffuse flux of astrophysical neutrinos** in the TeV-PeV energy range of **unknown origin**.
- Galactic and Extragalactic Sources are candidate sources, but **absence of anisotropies** favours the latter.
- **No compelling scenario** for the TeV-PeV energy range.
- **High 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`)]

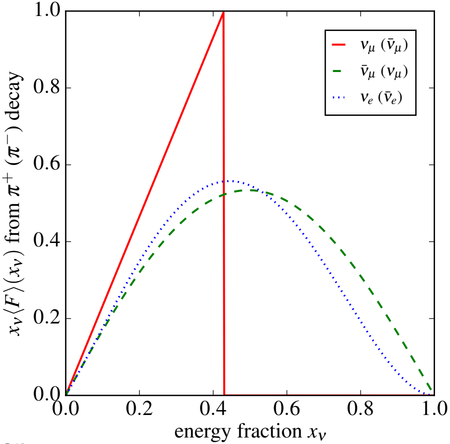
Neutrinos from Pion Decay

- 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 ($r_\pi \equiv m_\mu^2/m_\pi^2 \simeq 0.57$):

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



- 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 : $\kappa_\pi = \kappa / \langle N_{\mathrm{all}\ \pi} \rangle \simeq 0.17 - 0.2$
- "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

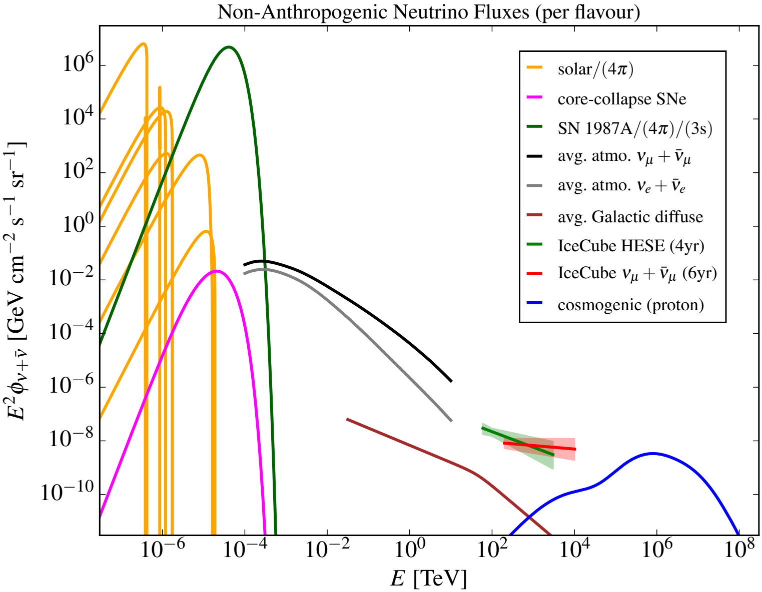
$$\frac{1}{3}\sum_{\alpha} E_\nu Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{2} \frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle} [E_\gamma Q_\gamma(E_\gamma)]_{E_\gamma = 2E_\nu}$$

- 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

Non-Anthropogenic Neutrino Fluxes



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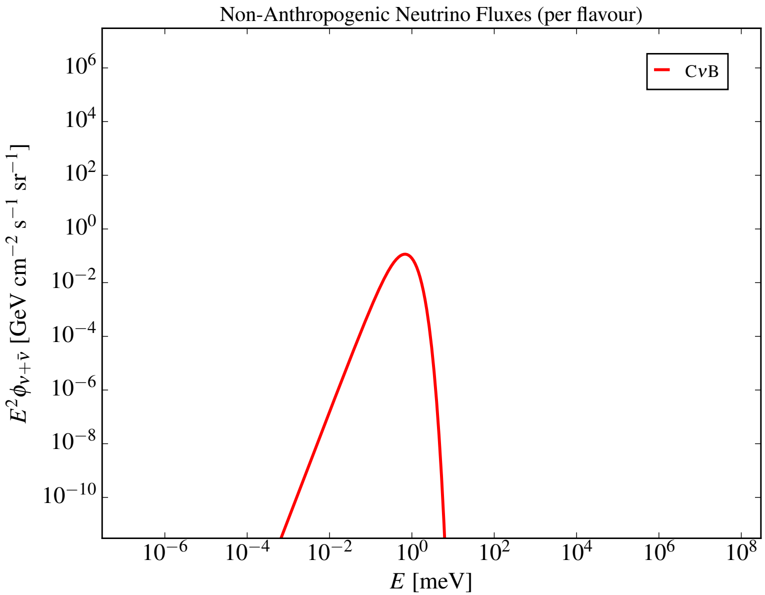
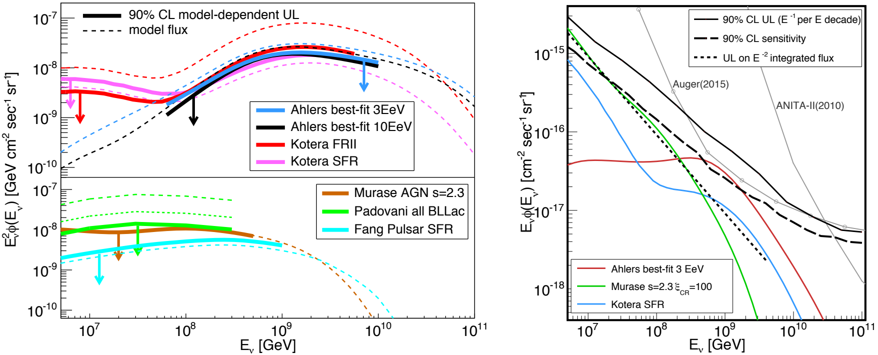


Cosmogenic ("GZK") Neutrinos

- 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



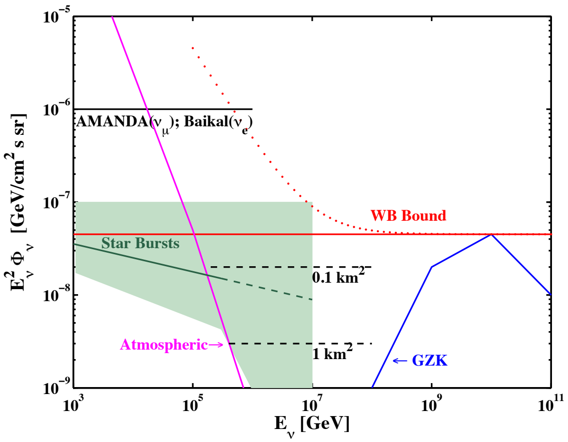
[**Phys.Rev.Lett.** 117 (2016) 241101]

- 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

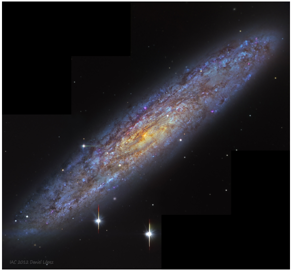
Messier 82 ($\delta \simeq 69^\circ$)

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

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

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

NGC 253 ($\delta \simeq -25^\circ$)



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

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

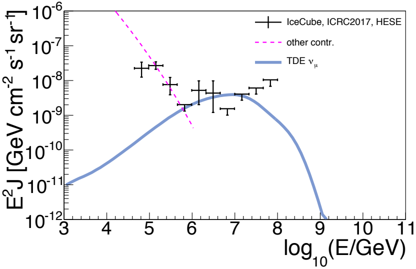
- Stars torn apart by tidal forces in the vicinity of a supermassive black hole can launch jet-like outflows.

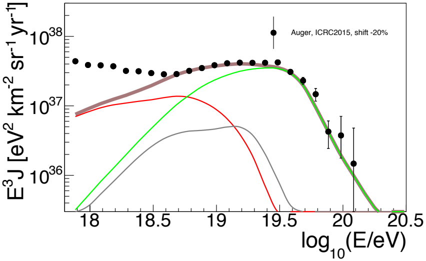
➜ good candidate sources of UHE CRs [Farrar & Gruzinov'09; Farrar & Piran'14]

- 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]

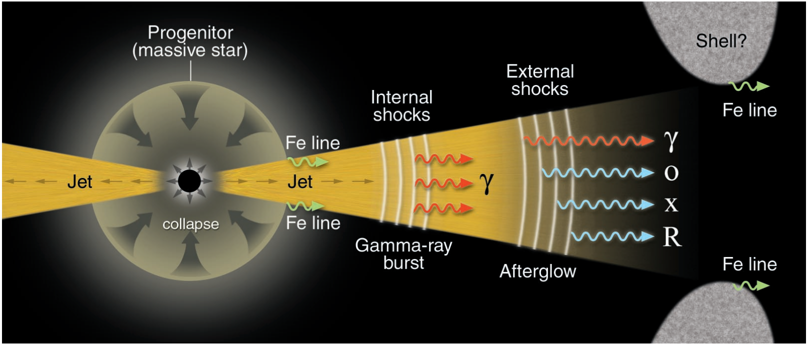




[*e.g.* Biehl, Boncioli, Lunardini & Winter'17]

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]

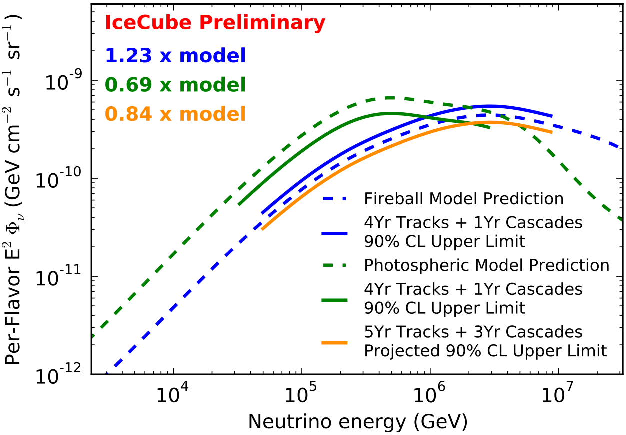


[Meszaros'01]

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.

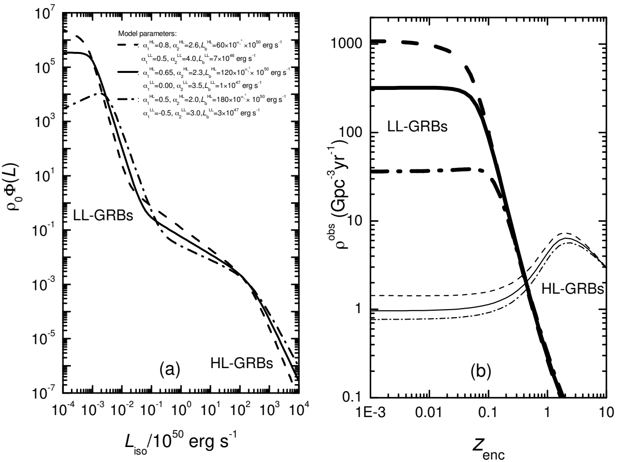


[IceCube'16]

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]

Power-Law Fits

- power-law fit (per flavour):

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

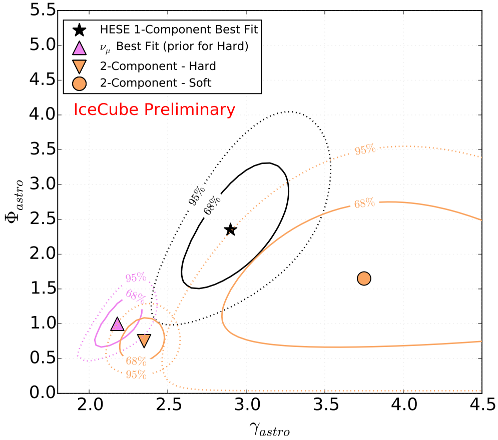
- HESE (6yr) fit range:

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

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

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

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



[IceCube; ICRC 2017]

Model Variations

✘ BL Lacs less favorable neutrino emitters due to **weak external radiation**.

⋆ Cosmic ray interaction with external photons from **sheath**?

[Ansoldi *et al.*, arXiv:1807.04300]

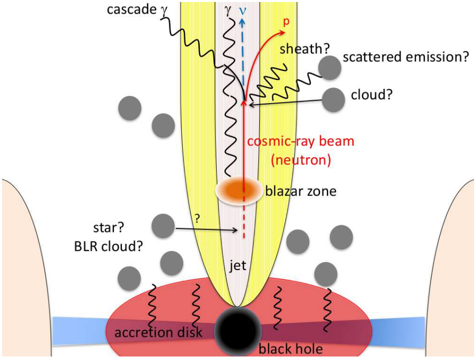
⋆ Thick disks from **radiatively inefficient accretion flow**?

[Righi, Tavecchio & Inoue, arXiv:1807.10506]

⋆ **Clouds or stars** entering the jet?

[see also Liu *et al.*, arXiv:1807.05113]

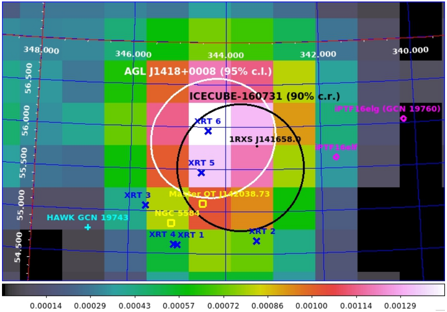
[Wang *et al.*, arXiv:1809.00601]



[Murase, Oikonomou & Petropoulou; arXiv:1807.04748]

More Neutrino Flares?

- We need more observations like TXS to identify the emission process and to establish blazars as neutrino emitters.
- Maybe we have already witnessed these sources:
  - ⋆ PKS B1424-418 & “Big Bird”
    [Kadler *et al.*’16]
  - ⋆ PKS 0723-008 & “Dr. Strangepork”
    [Kun, Biermann & Gergely’16]
  - ⋆ AGL J1418+0008 & IC-160731A
    [Lucarelli *et al.*’17]
  - ⋆ GB6 J1040+0617 & IC-141209A
    [Garrappa *et al.*, in preparation]



[Lucarelli *et al.*’17]

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]

Non-Blazar Limits on Gamma-Ray Background

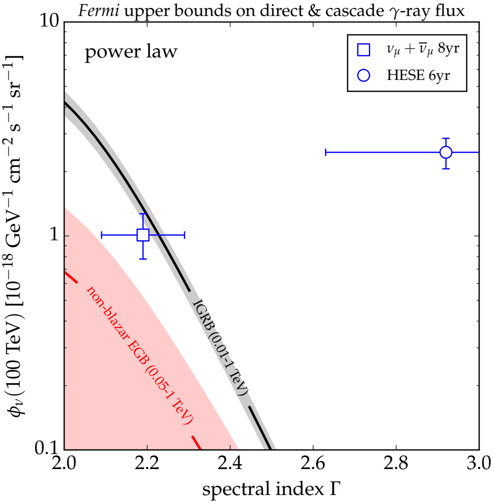
- Non-blazar contribution above 50 GeV: [based on Fermi'15]

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

✘ **strong tension** with IceCube observation ($E_\nu \lesssim 100$ TeV)

- Limits apply to generic **cosmic ray calorimeters**.

- **Crucial assumption:** free escape of γ-rays from source environment.



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

Diffuse vs. Point-Source

- (quasi-)diffuse flux approximated by effective luminosity and comoving density:

$$F_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\int {\rm d}L_\nu \frac{{\rm d}\rho}{{\rm d}L_\nu}\frac{L_\nu}{4\pi d_L^2(z)} \simeq \frac{1}{4\pi}\int {\rm d}z \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\rho_{\rm eff}(z) \underbrace{\frac{L_{\rm eff}}{4\pi d_L^2(z)}}_{\text{point-source flux}}$$

- Effective density accounts for model-dependent neutrino-photon luminosity relation. [Murase & Waxman'16]

- Redshift distribution of brightest (closest) source: [MA& Halzen'14]

$$p(z) \simeq \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\rho_{\rm eff}(z)\exp\left(-\int_0^z {\rm d}z' \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\rho_{\rm eff}(z')\right)$$

➜ Comparison with IceCube's point-source discovery potential:

$$\langle F_{\rm PS}\rangle \equiv \int {\rm d}z\, p(z)\frac{L_{\rm eff}}{4\pi d_L^2(z)} \leq F_{5\sigma}$$

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:

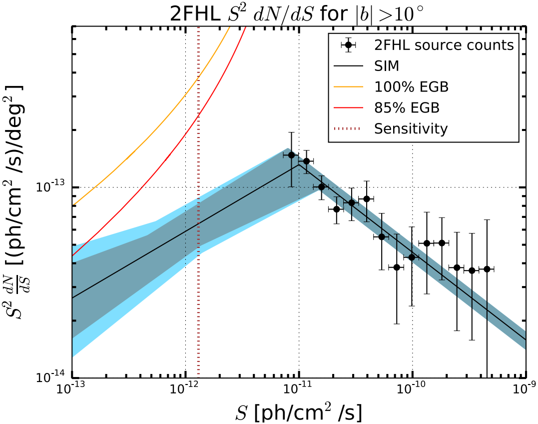
    $86^{+16}_{-14}\%$ of EGB

  - Lisanti *et al.*'16:

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

  - Zechlin *et al.*'16

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



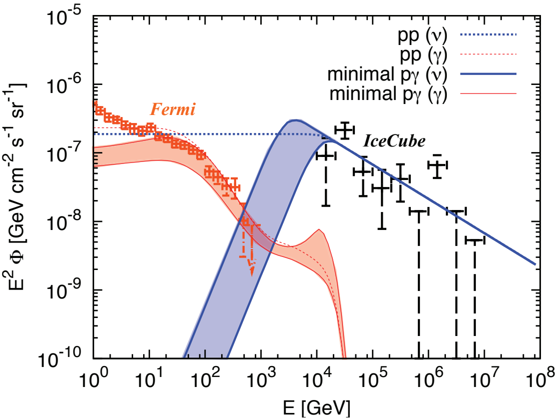
[Fermi'15]

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:

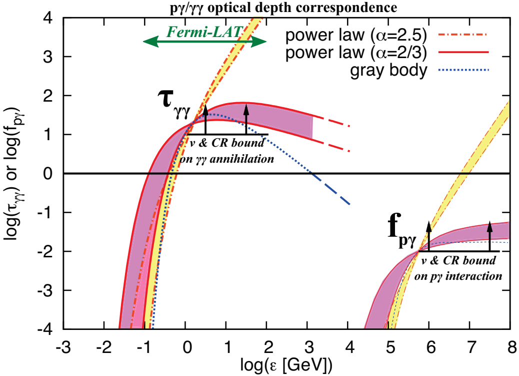
$$\varepsilon_t \sim 200\,\text{keV} \left(\frac{\Gamma}{10}\right)^2 \left(\frac{E_\nu}{3\ \text{TeV}}\right)^{-1}$$

- **opacity relation**:

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

➜ strong internal γ-absorption:

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



[Murase, Guetta & MA'15]