Astroparticle Physics with the IceCube Neutrino Observatory and its High-Energy Extension

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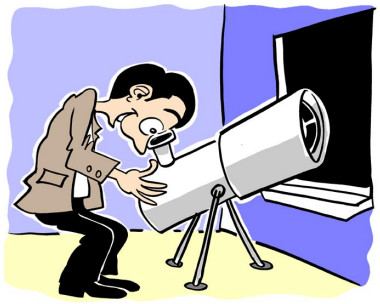
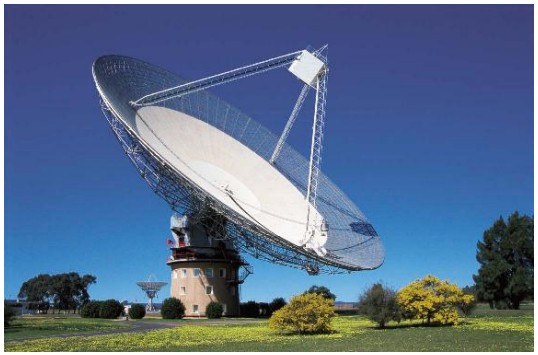
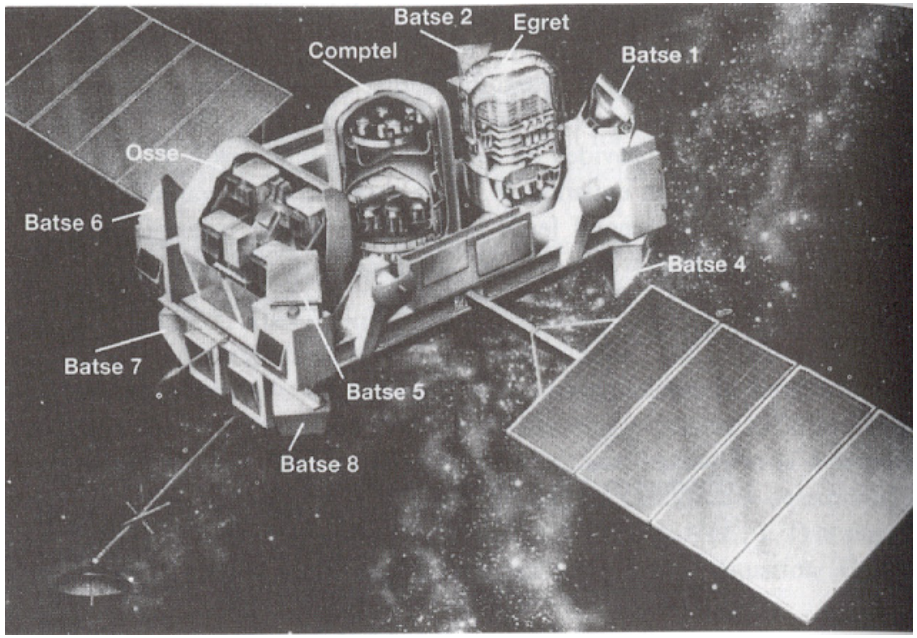
Overview

Investigating the Universe with electromagnetic radiation





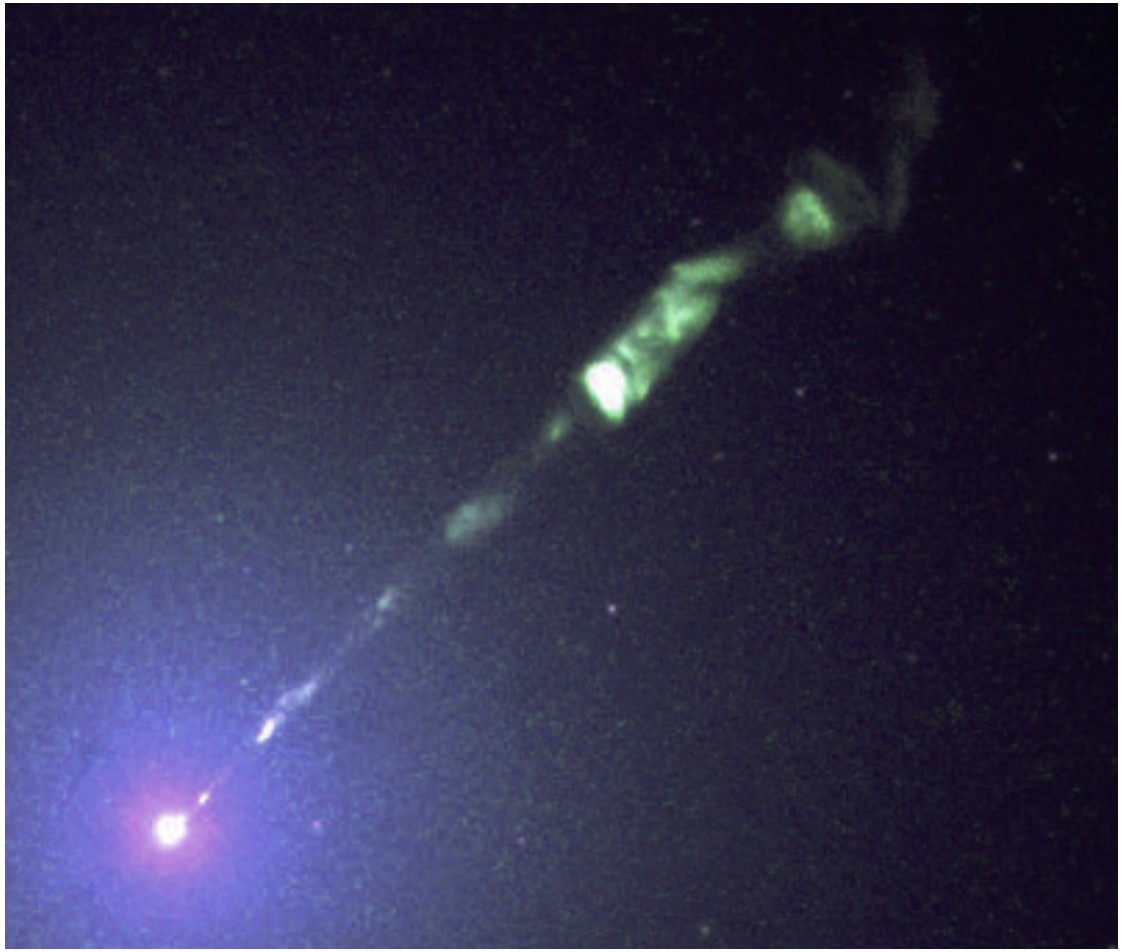


[Credit NASA]

Observations at different wavelengths

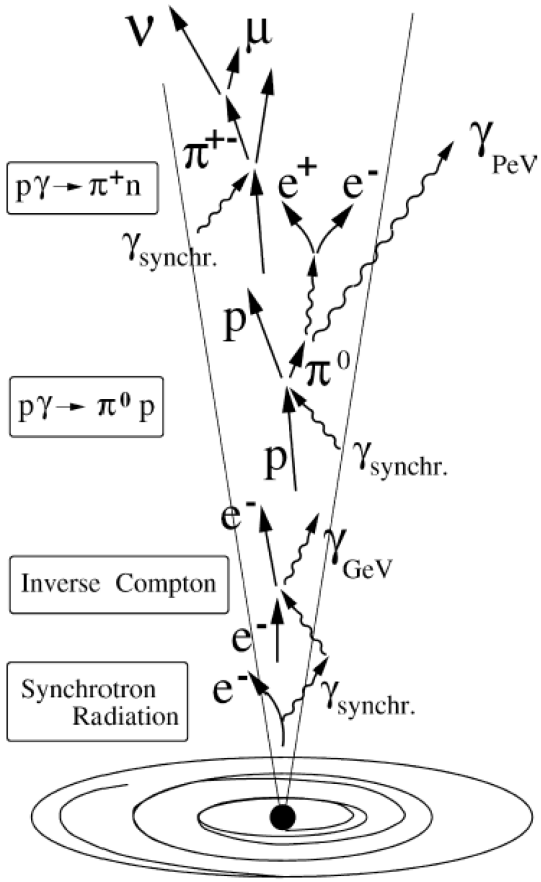
- Various new discoveries (pulsars)
- Better insight in (astro)physical processes
- Rather complete view on the large picture of the Universe

Observed jet signature (M87)



[Credit NASA]

Processes in the jet

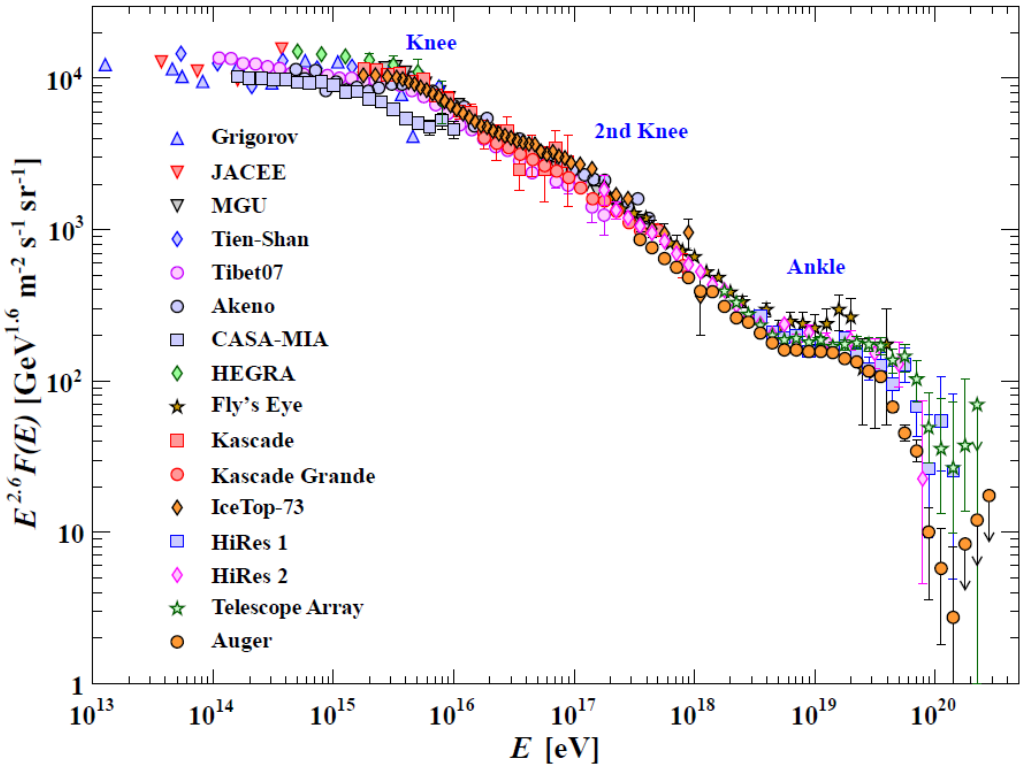


[Credit C. Spiering]

Acceleration in shock waves

High-energy γ, nuclei and ν

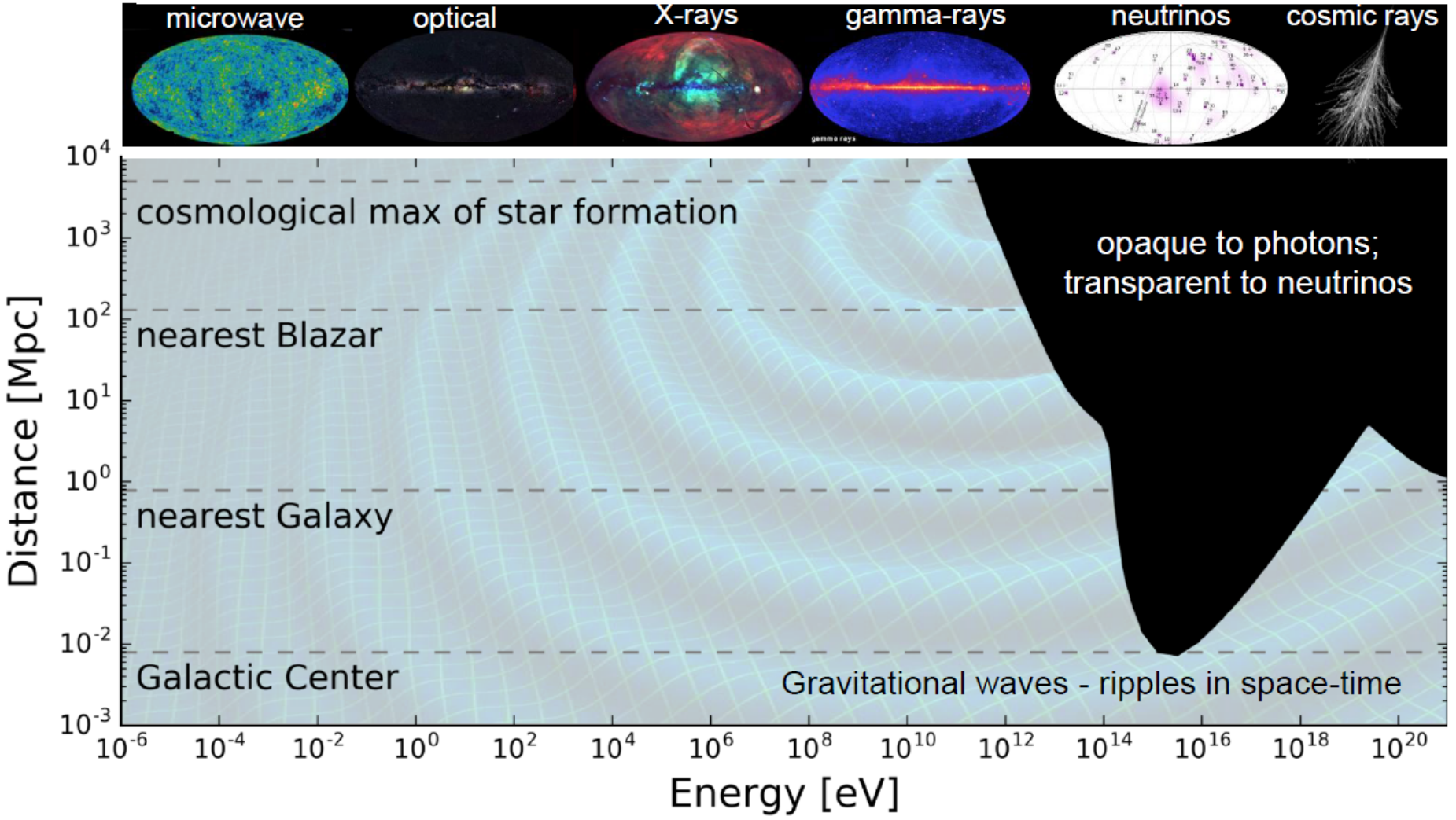
The $E^{2.6}$ scaled Cosmic Ray flux



[Credit PDG 2014]

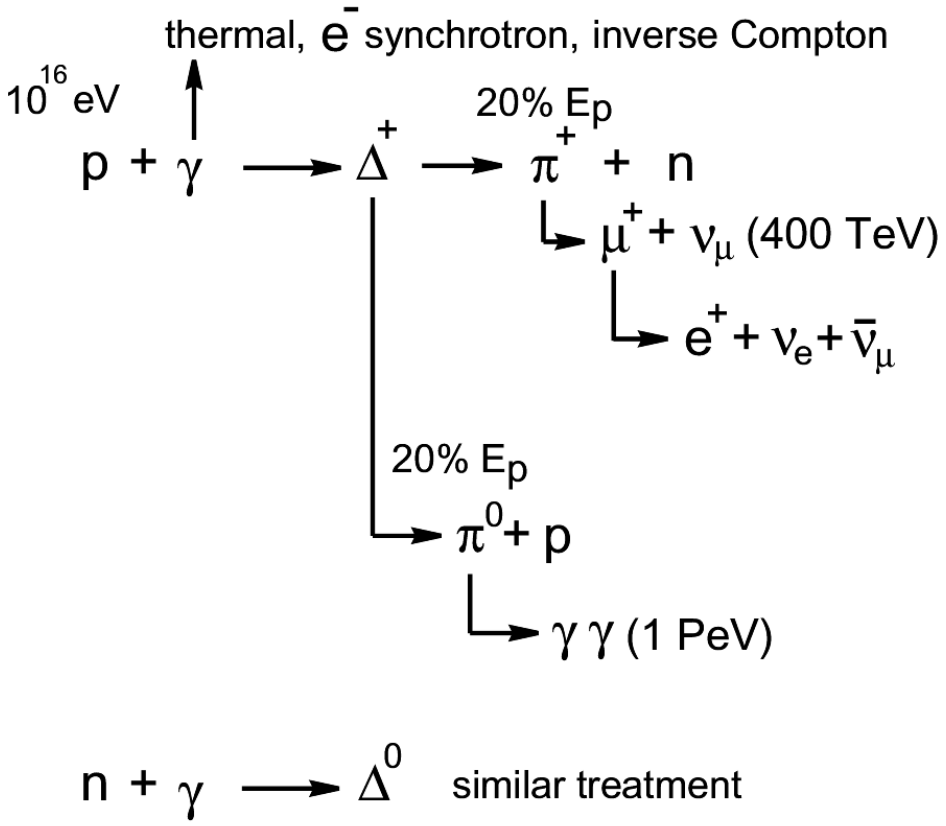
- Spectral features (knee, ankle)
  E limits of cosmic accelerators ?
  Onset of extra-galactic component ?
  Do we observe the GZK cut-off ?
- Sources ? (SNe, GRBs, AGN, ...)

Beware of the observable Universe: $\gamma + \gamma_{EBL} \rightarrow e^+e^-$ $N + \gamma_{CMB} \rightarrow \Delta$



[Credit Marek Kowalski]

Neutrino production mechanism



- Δ prod. threshold : $E_\gamma \geq 10$ eV (UV photons)

- **Waxmann-Bahcall** [PRL 78 (1997) 2292]

  High-E p diffuse out of the shocks

  Observed CR $\longrightarrow$ lower limit on p flux

  Fraction of p used for ν production ?

- **M. Ahlers et al.** [APP 35 (2011) 87]

  Protons trapped, neutrons escape

  CR observations provide the n flux

  Direct relation CR $\leftrightarrow$ ν flux

- **Generic broken powerlaw ν spectrum**

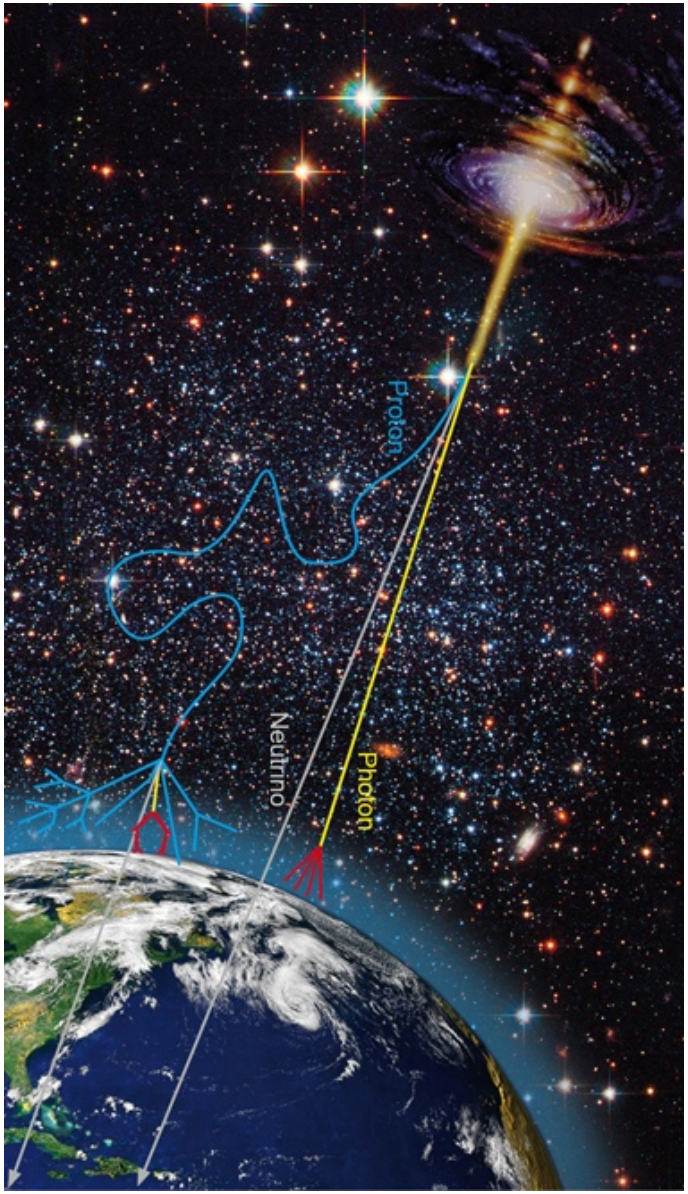
$$E^{-1}\epsilon_b^{-1} \quad (E < \epsilon_b)$$

$$\Phi_\nu(E) \sim E^{-2} \quad (\epsilon_b \leq E \leq 10\epsilon_b)$$

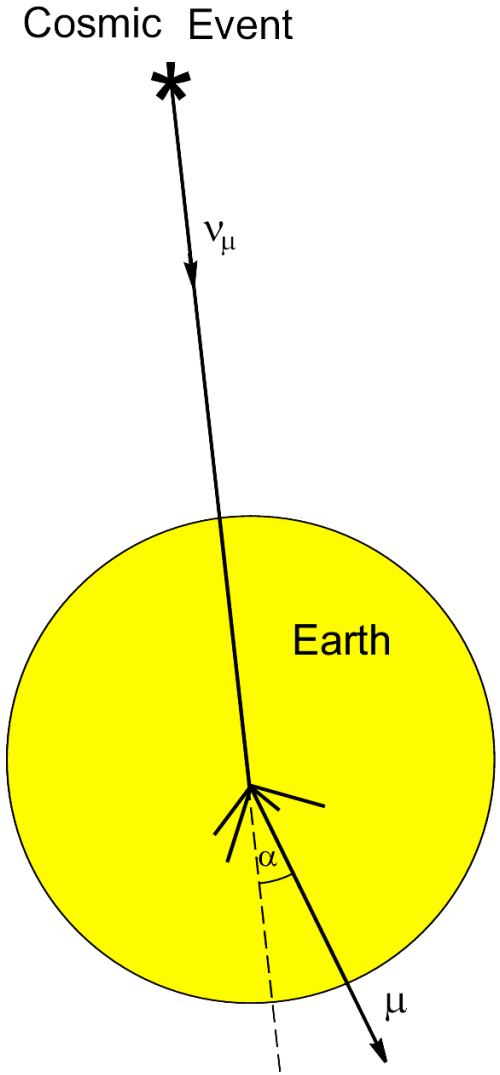
$$E^{-4}(10\epsilon_b)^2 \quad (E > 10\epsilon_b)$$

  with $\epsilon_b \approx 1$ PeV [JCAP 0903 (2009) 020]

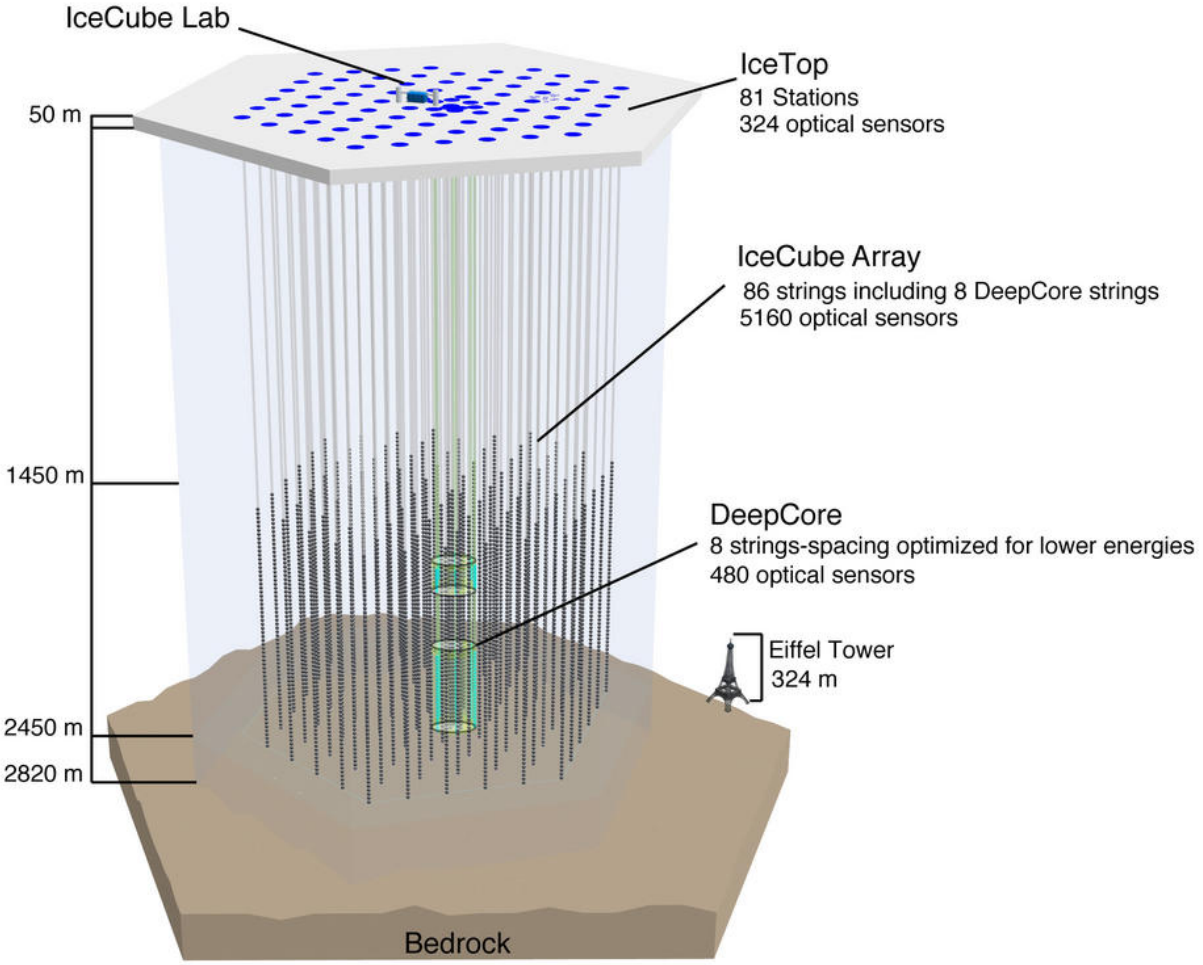
* Let's search for cosmic high-E ν



Neutrino detection principle

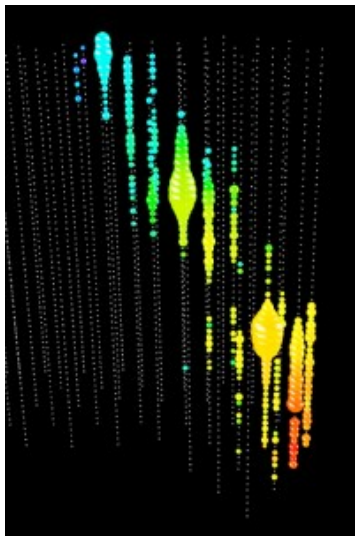


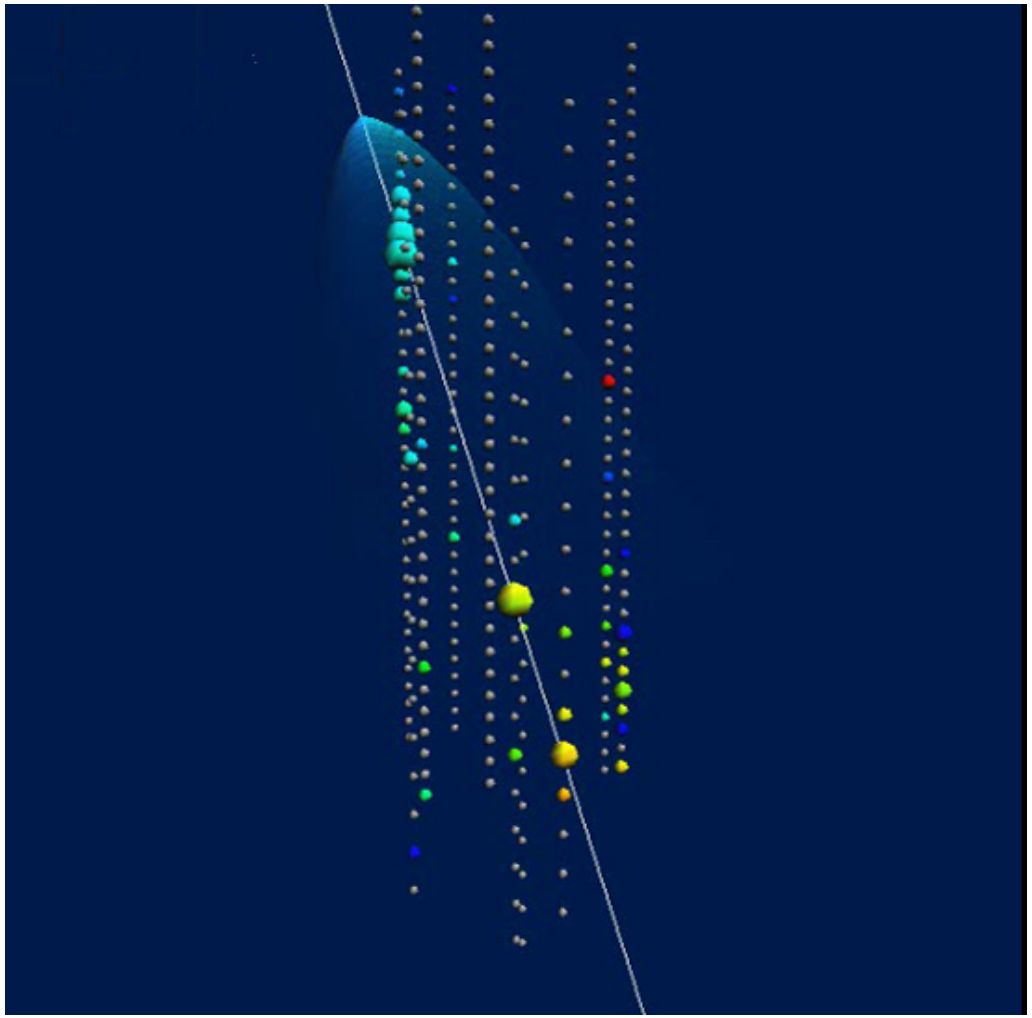
The IceCube Neutrino Observatory at the South Pole



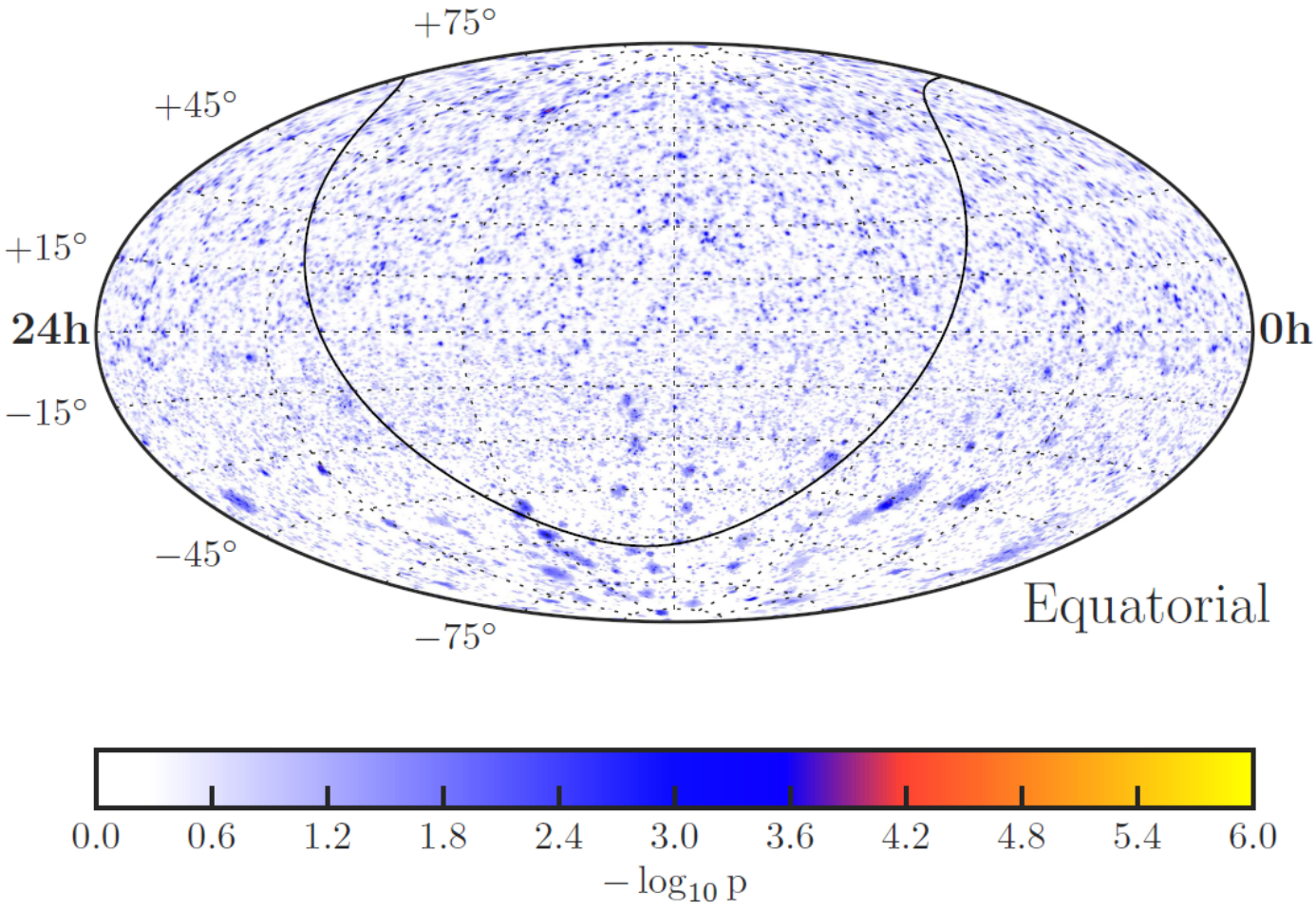
86 strings, 5160 optical sensors, instrumented volume $\sim 1\ \mathrm{km}^3$

The InIce detection principle



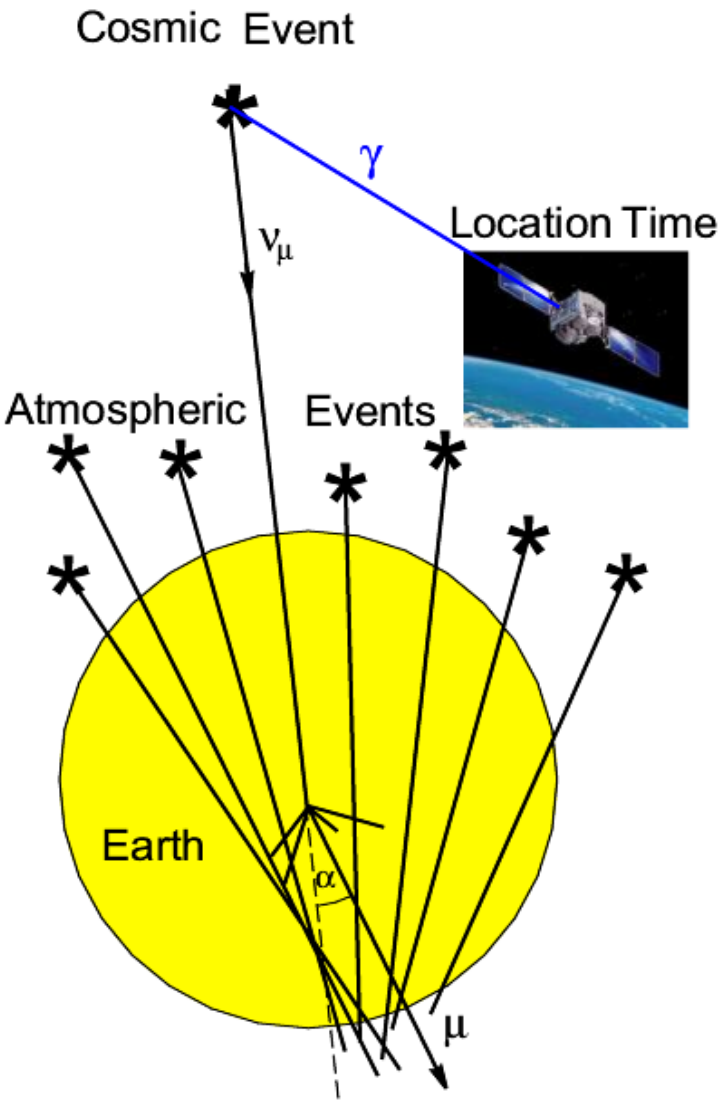


IceCube 7-years skymap (∼700'000 events) [ApJ 835 (2017) 151]



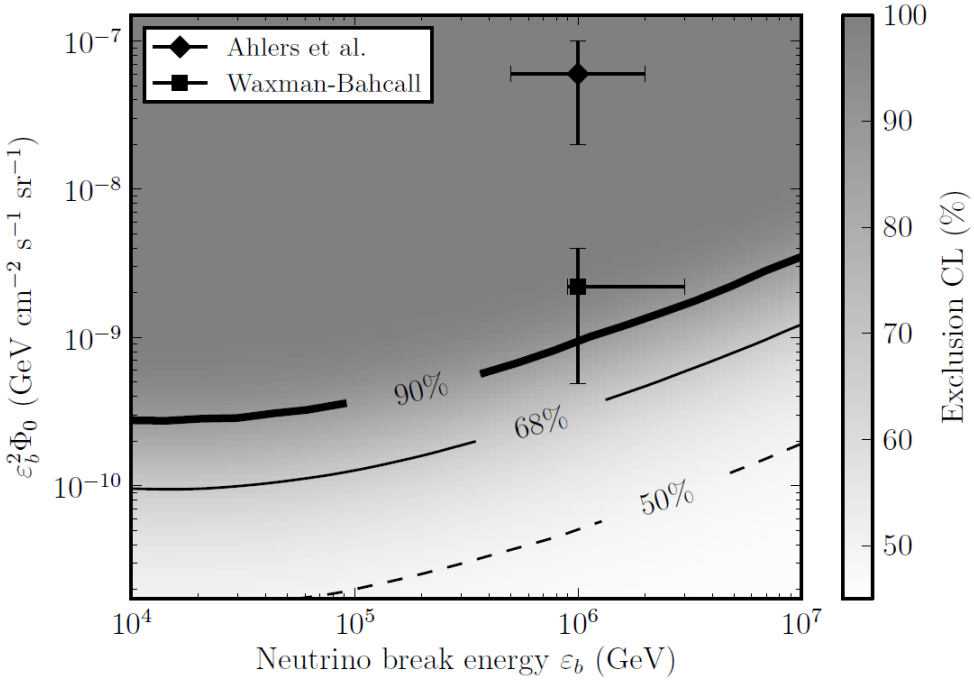
No evidence for point sources (yet)

Hunting for Cosmic Neutrinos



IceCube GRB prompt ν flux limit

[ApJ Let. 805 (2015) L5]



GRBs not the (only) UHECR sources

Or : ν prod. lower than expected

Or : ν prod. outside prompt phase

Hunting for Cosmic Neutrinos

- Many point sources : diffuse ν flux

  Expected flux $\sim E^{-2}$

  (Fermi shock acceleration)

  Observed in TeV photons
- CR primaries : flux $\sim E^{-2.7}$

  $\longrightarrow$ Calculate atm. ν E-spectrum
- ν det. observe atm. ν spectrum

  Validate calculated spectrum

$*$ PDF for atm. ν E-spectrum

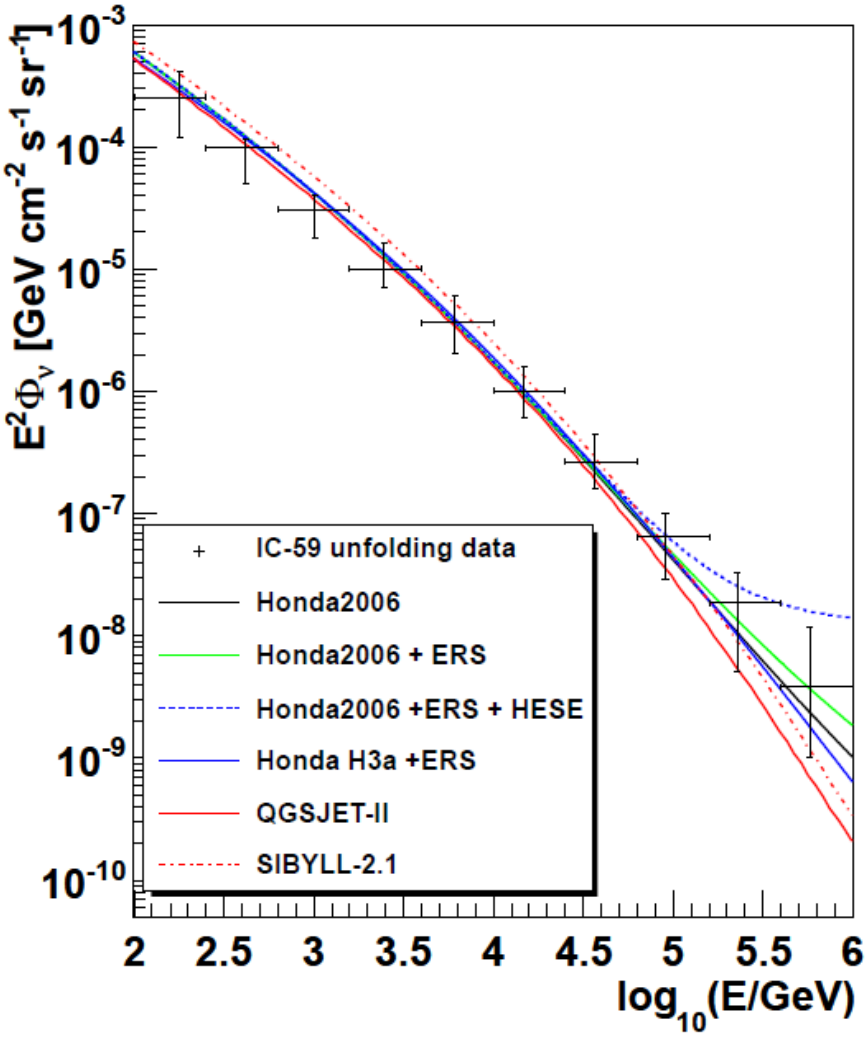
- Very high E : Nearly atm. bkg free

  0.1 atm. ν km^{-3} year^{-1} at 1 PeV

VHE events might prove cosmic ν

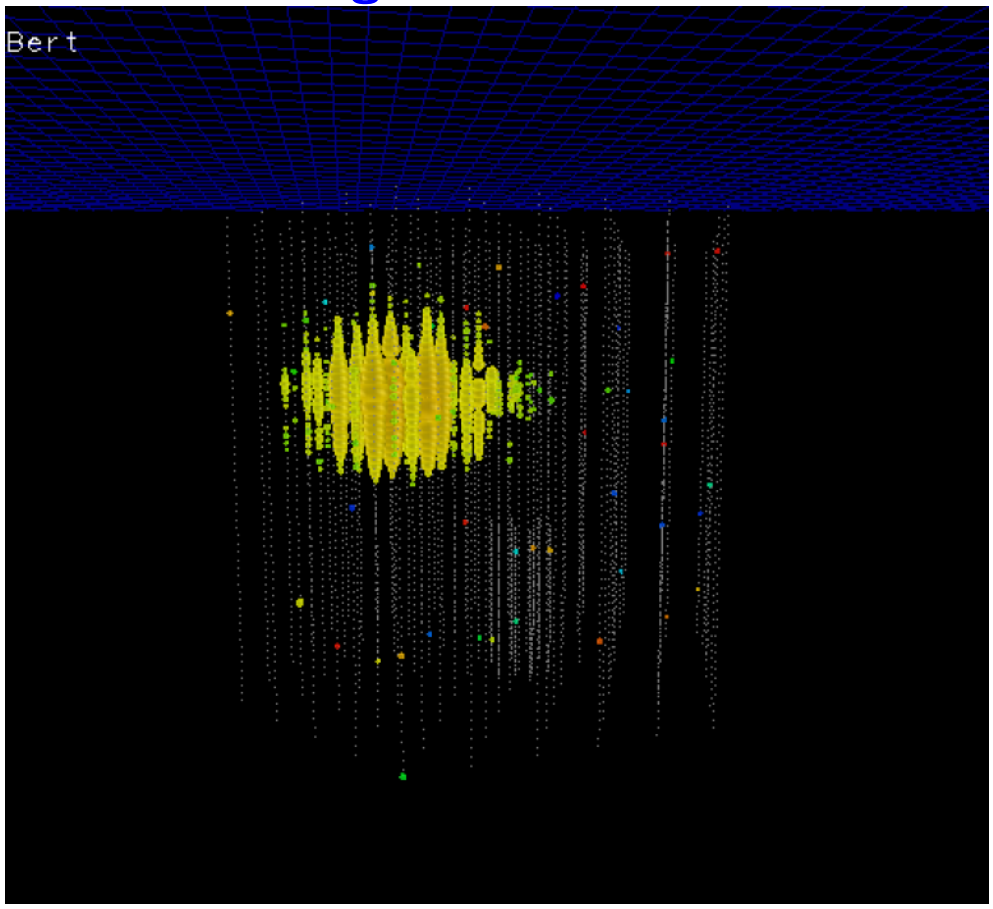
IceCube atmospheric ν spectrum

[Eur. Phys. J. C75 (2015) 116]



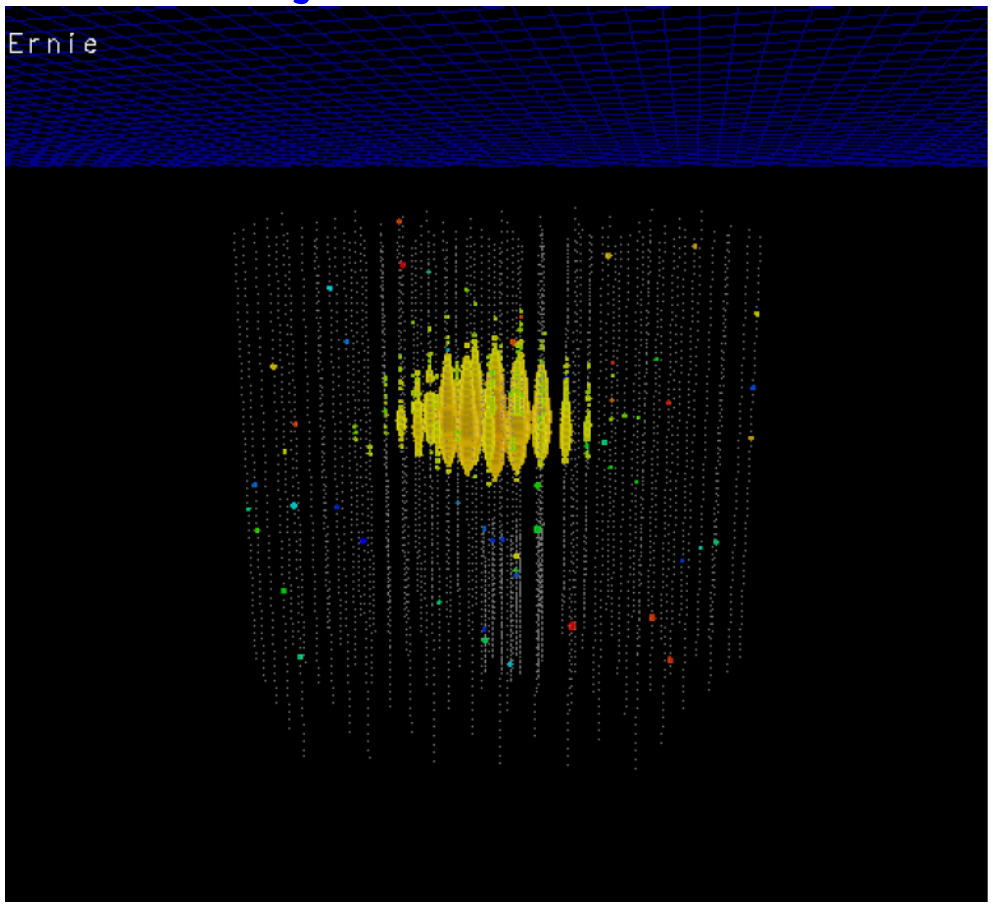
Hunting for Cosmic Neutrinos

Tue 09-aug-2011 07:23:18 UTC



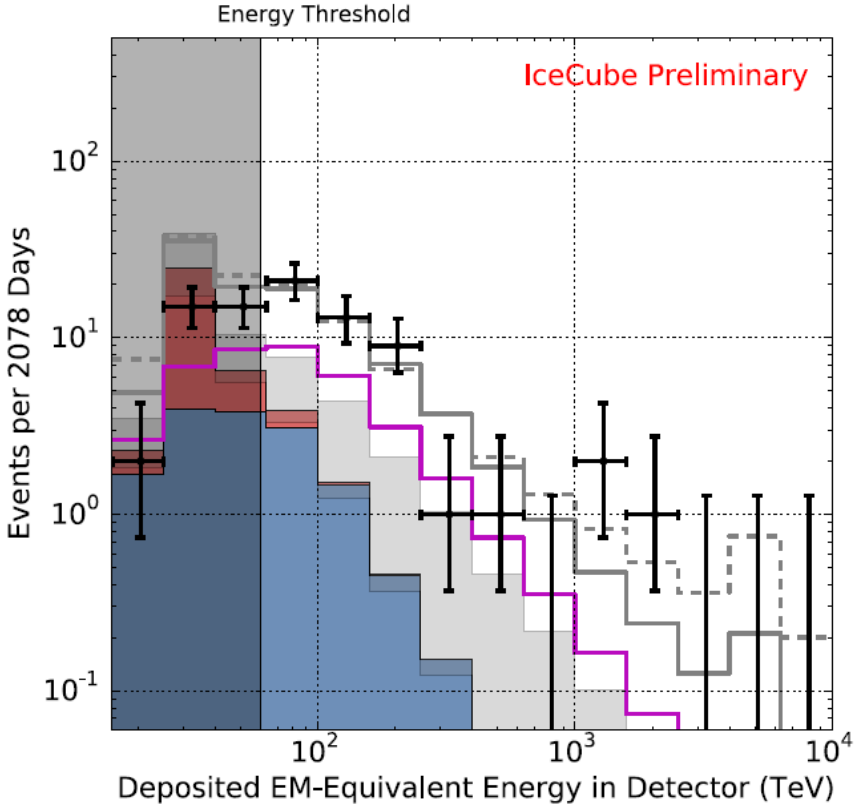
1.04 ± 0.14 **PeV**
(IceCube HESE event no. 14)

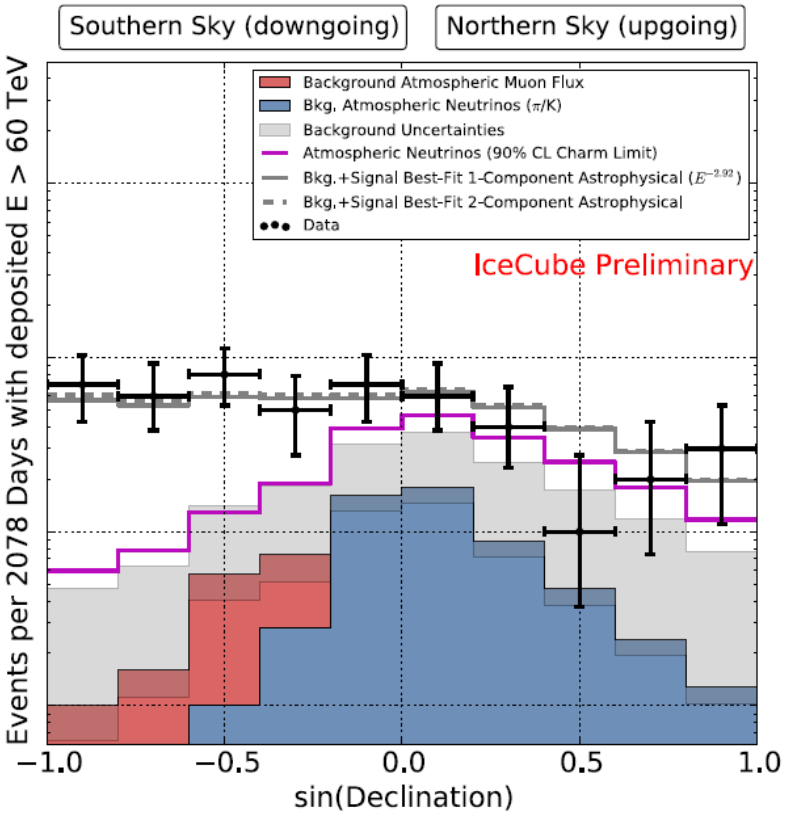
Tue 03-jan-2012 03:34:01 UTC



1.14 ± 0.14 **PeV**
(IceCube HESE event no. 20)

82 observed Icecube High-Energy Starting Events (HESE) [C. Kopper, ICRC2017]

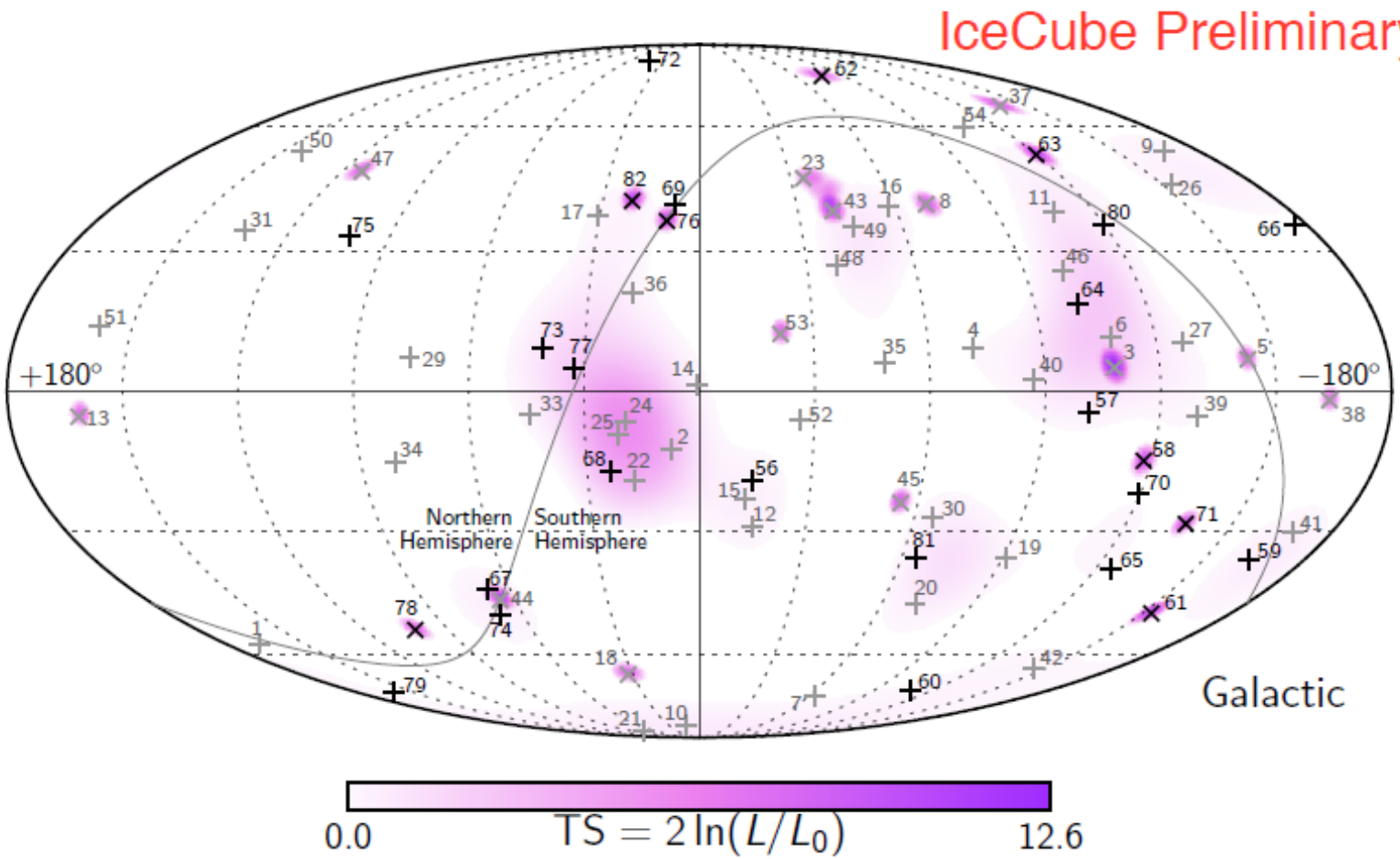




Evidence ($> 7\sigma$) for cosmic high-energy neutrinos

What are the sources ?
Where are the multi-PeV events ?

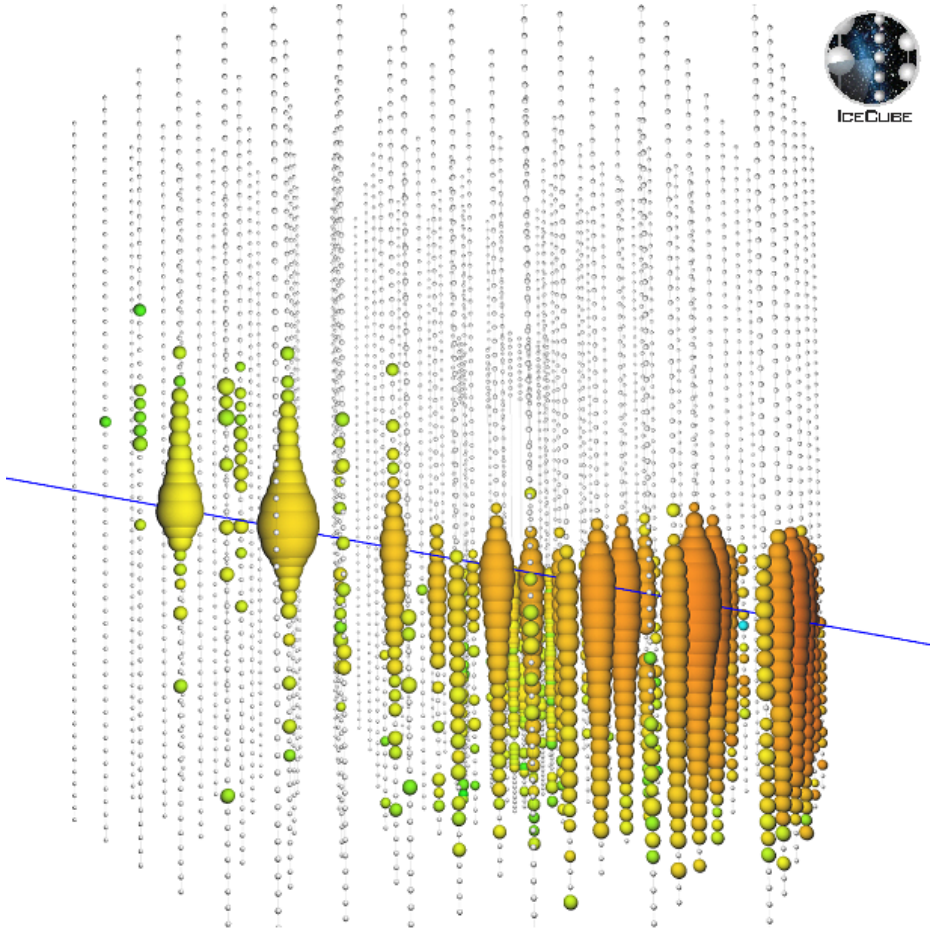
Source directions of the HESE events



No evidence for point sources (yet)

IceCube observation (11-jun-2014) of a very energetic through-going muon

α : 7h 21m 22s δ : 11.5° [ApJ 833 (2016) 3]



Deposited energy 2.6 ± 0.3 PeV $\rightarrow$ $E_\mu = 4 - 5$ PeV $\rightarrow$ $E_\nu > 5$ PeV

More neutrino data needed at multi-PeV energies

Radio signals of ν showers

- Long (km-scale) attenuation length

  Cover large ($\sim$200 km^2) area
- Detect events $> 10^{17}$ eV
- GZK ν : Proof of GZK effect

  or : Insight in UHECR composition
- $p + \gamma \rightarrow \Delta \rightarrow \nu \quad (E_\nu \approx 4\% \; E_p)$

  $p + \gamma_{EBL}$: Low-E bump

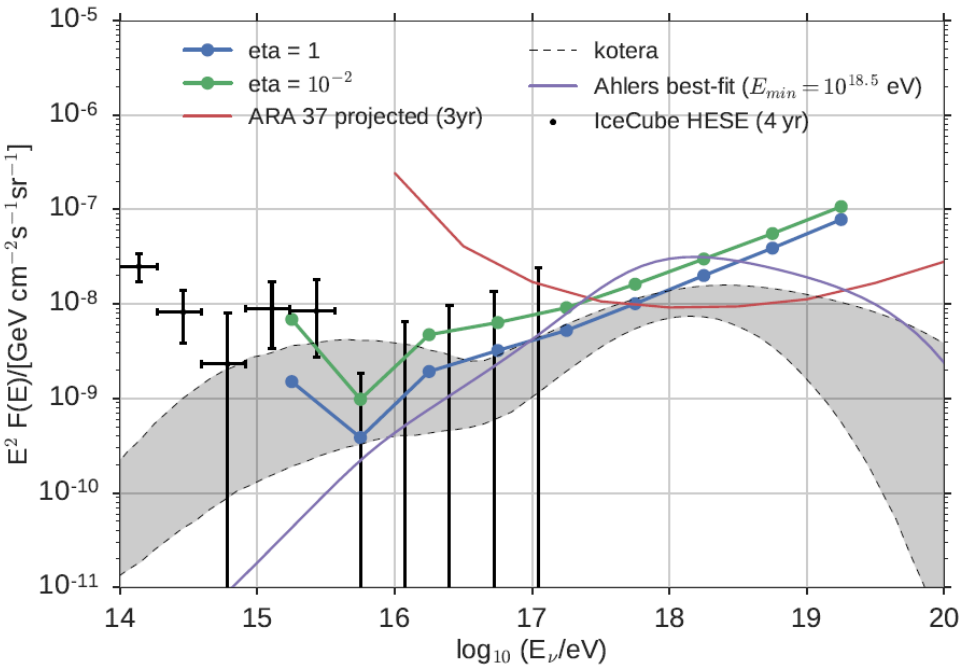
  $p + \gamma_{CMB}$: High-E bump
- Iron: lower E/A and dissociation

  $\rightarrow$ Higher E threshold and lower flux
- IceCube-Radio energy gap

  Currently not covered

The multi-PeV neutrino landscape

[arXiv:1802.05543]

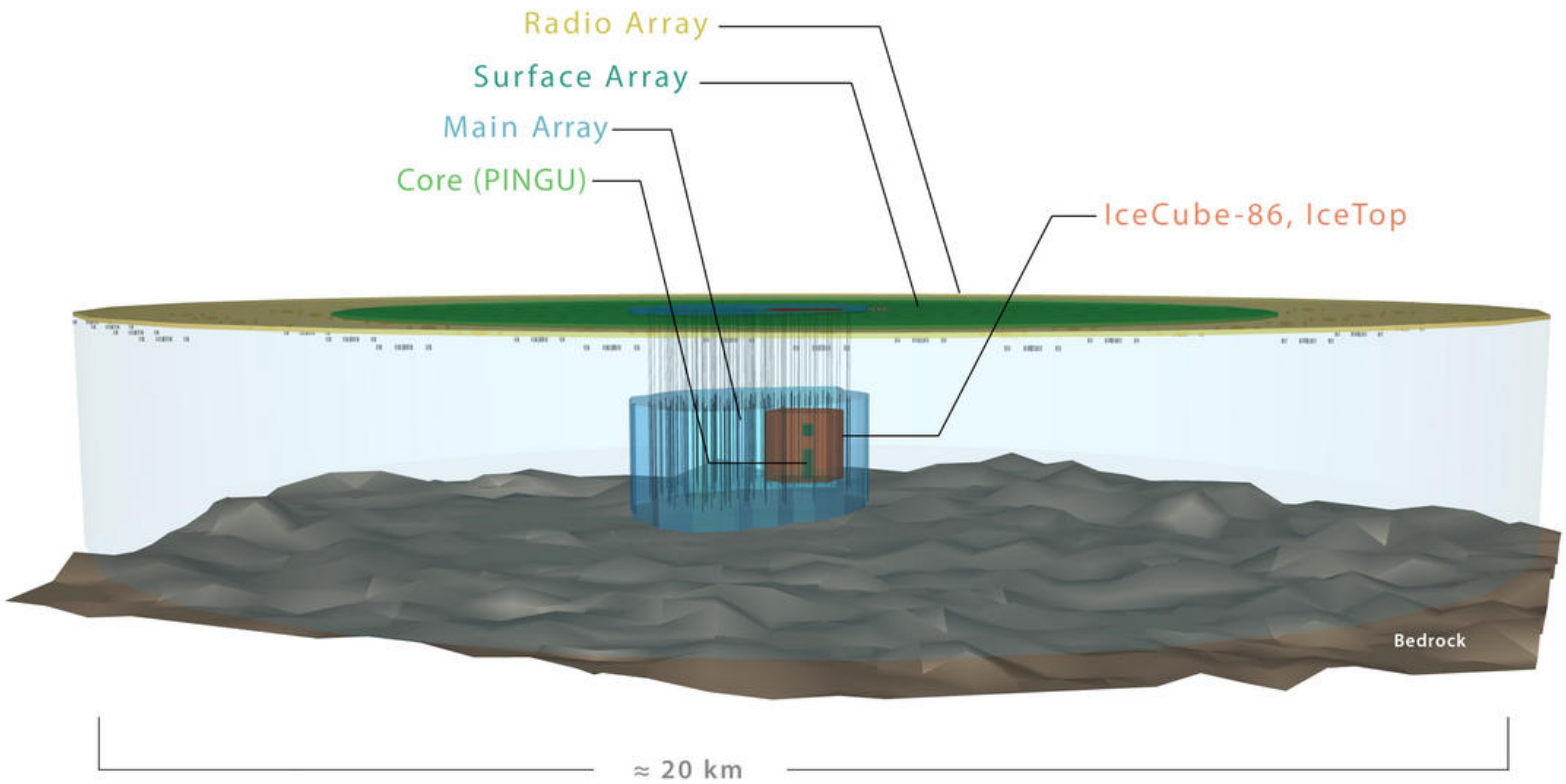


Radar reflections from shower plasma

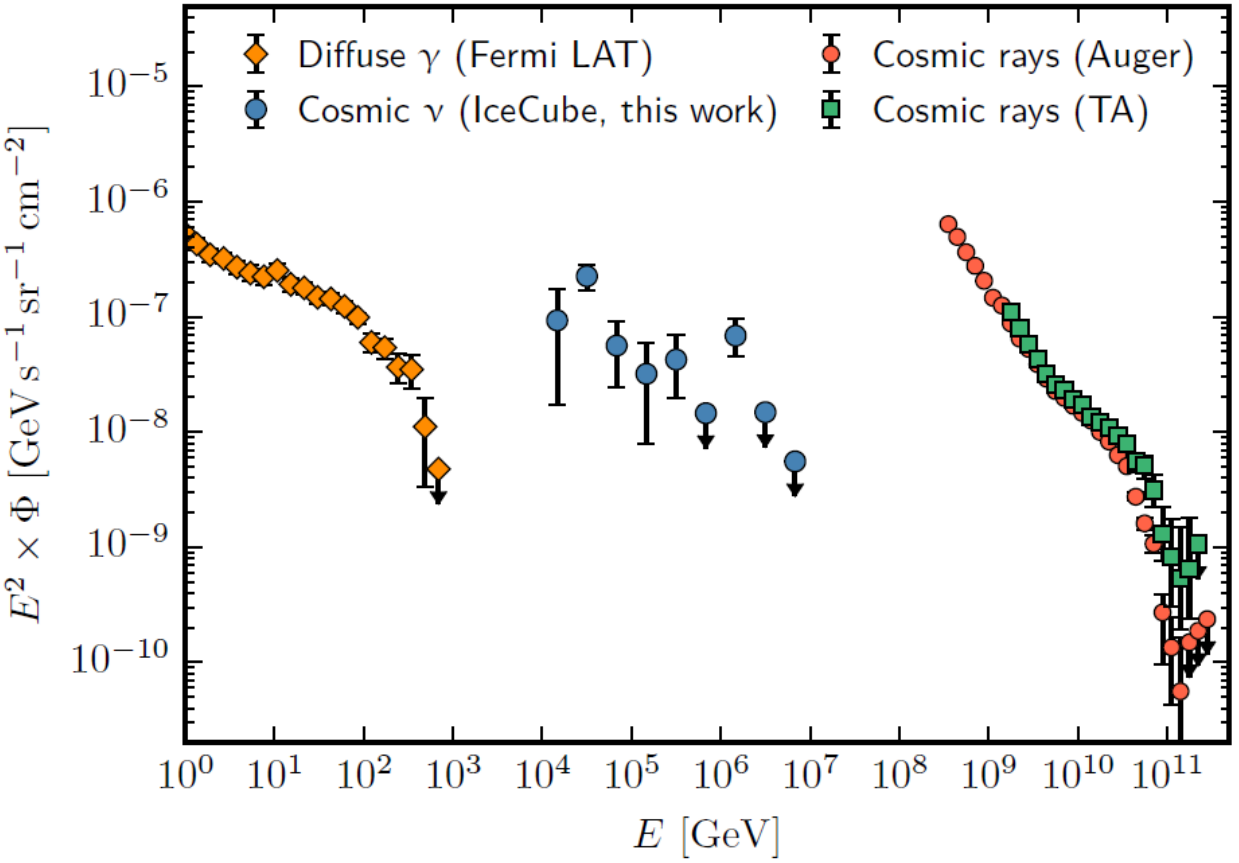
New idea (VUB) for $E < 10^{17}$ eV

Fill IceCube-Radio E gap

The IceCube Gen2 Facility



The Neutrino-Gamma connection



[Lars Mohrmann, PhD 2015, Humboldt University Berlin]

Common astrophysical sources ?

$N + \gamma \rightarrow \Delta \rightarrow \pi + N$ **(CR)** $\quad \pi^0 \rightarrow \gamma\gamma$ **(Fermi)** $\quad \pi^{\pm} \rightarrow \nu, \bar{\nu}$ **(IceCube)**

The Neutrino-Gamma connection

- Fermi EGB observations

  ∼85% of diffuse γ's from Blazars

- IceCube observations [ApJ 835 (2017) 45]

  Cosmic ν's NOT from Fermi Blazars

- Take EGB NON-Blazar component

  $\longrightarrow$ Prediction for ν flux

* ν flux underestimated

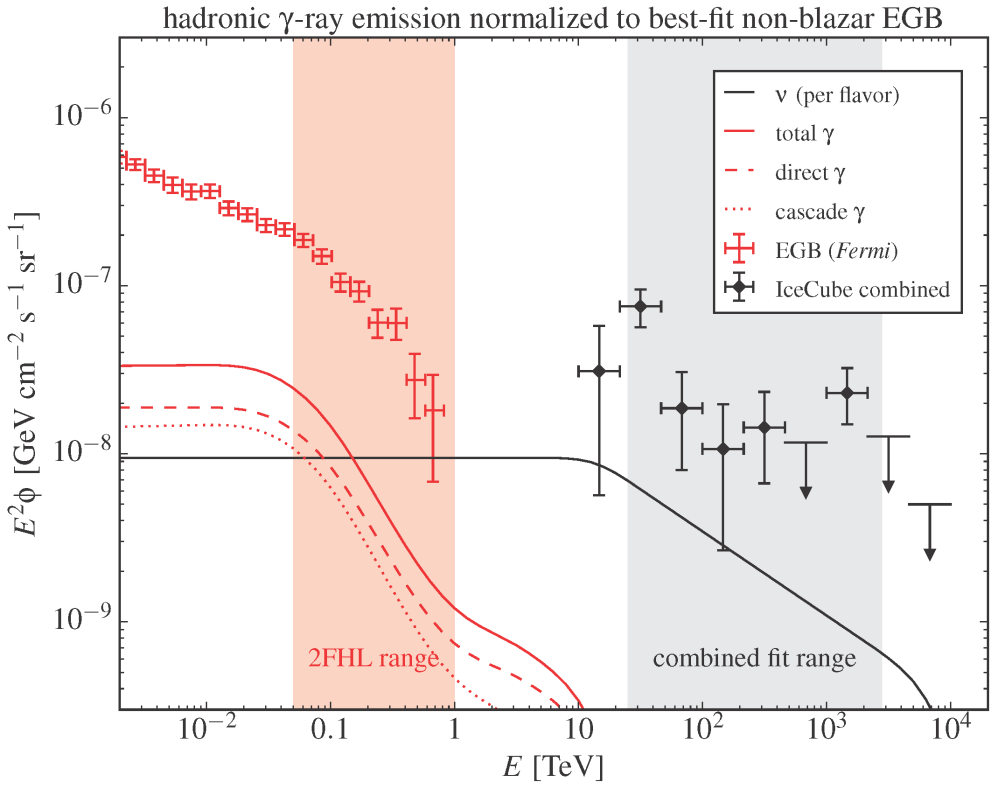
Fermi and IceCube data tension

- Cosmic ν's from obscured sources ?

  [PRD 94 (2016) 103007]

- Dust may provide a "CR beam dump"

  $\longrightarrow$ Neutrino factory



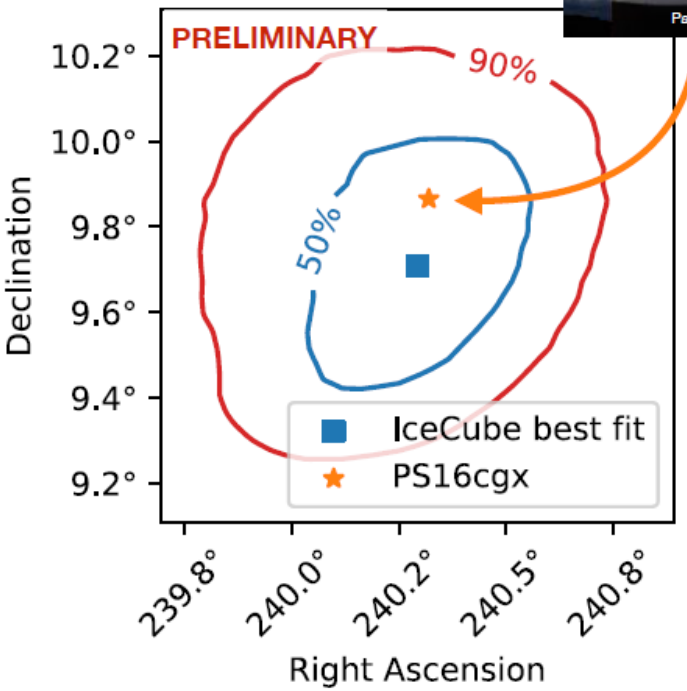
[arXiv:1511.00688]

(2FHL: 2nd Fermi Hard Source List)

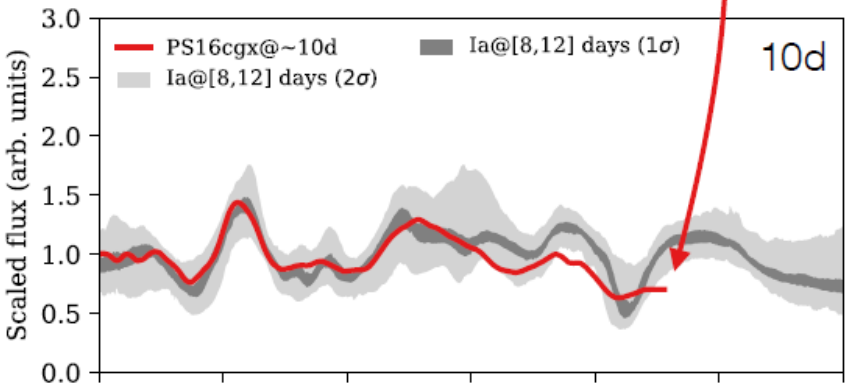
Follow up for transients on neutrino alerts

PanStarrs follow up of IceCube alert on 2016-04-27 and found a young supernova at z=0.3:

Light curve consistent with explosion days before neutrino alert



Optical spectroscopy 10, 20 days post-peak



Features atypical for SNIa, but not sufficient to exclude

Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

[Credit M. Kowalski SuGAR2018]

nature physics

ARTICLES

PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1]*, F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]

individual objects are too low to make an unambiguous source association. Here, we report that a major outburst of the blazar PKS B1424–418 occurred in temporal and positional coincidence with a third petaelectronvolt-energy neutrino event (HESE-35) detected by IceCube. On the basis of an analysis of the full sample of γ-ray blazars in the HESE-35 field, we

There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ~5% for a chance coincidence. Our model reproduces the

[Credit M. Ahlers SuGAR2018]

IceCube: Track with $E_{dep} \sim 20$TeV and $\sim 1^\circ$ error observed $\rightarrow$ EHE alert

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

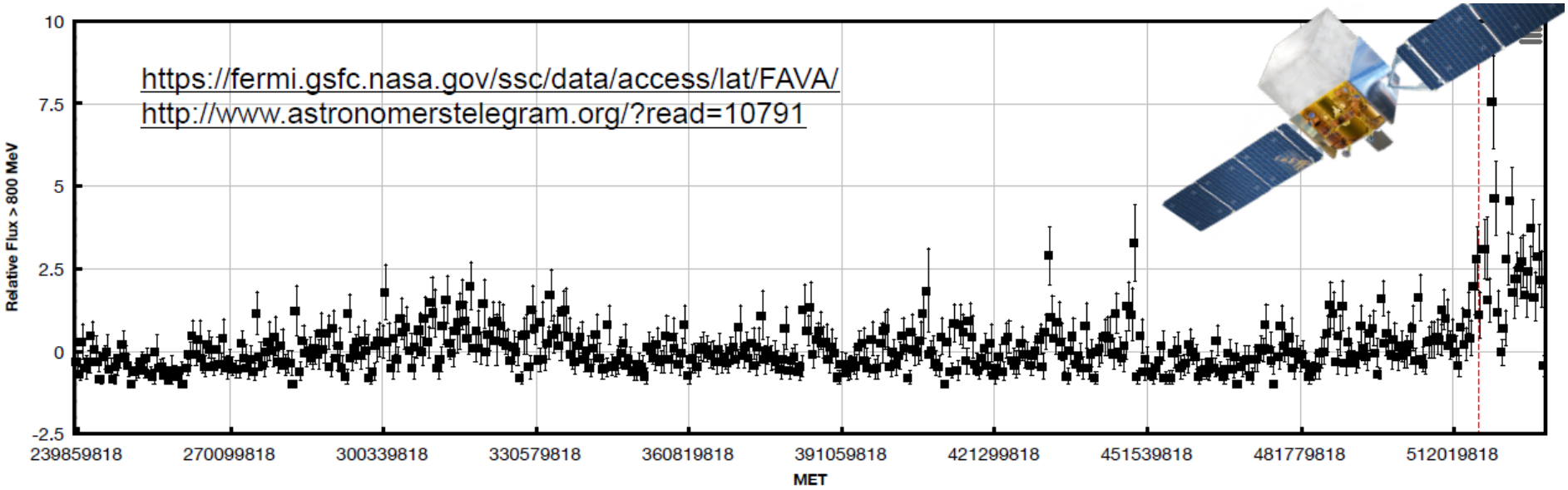
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Fermi lightcurve for IC170922A



[Credit M. Kowalski SuGAR2018]

More information coming soon STAY TUNED !