Atmospheric & Astrophysical Neutrinos with IceCube

IceCube

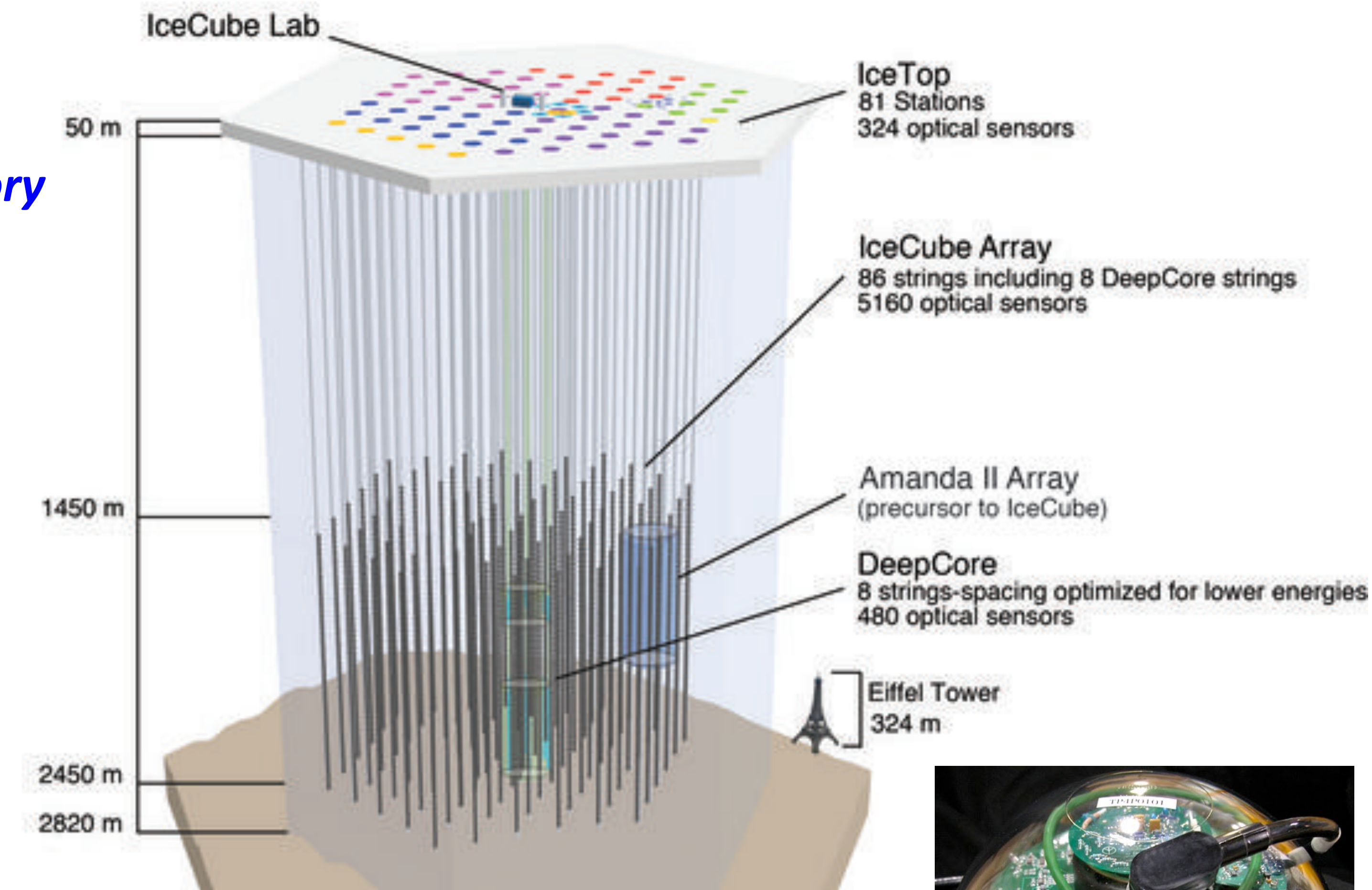
Deployment history

2002: proposal
2003-04 staging

2004-05	**1**	**4**
2005-06	**9**	**16**
2006-07	**22**	**26**
2007-08	**40**	**40**
2008-09	**59**	**59**
2009-10	**79**	**73**
2010-11	**86**	**81**

Deep strings

Surface stations

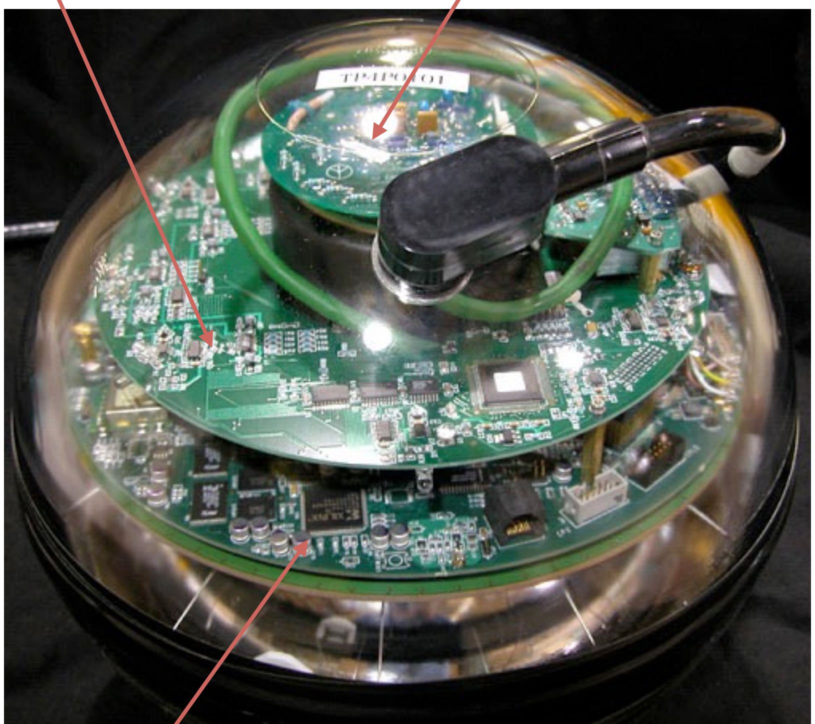


> 5400 Digital Optical Modules

IceCube Digital Optical Module and deployment

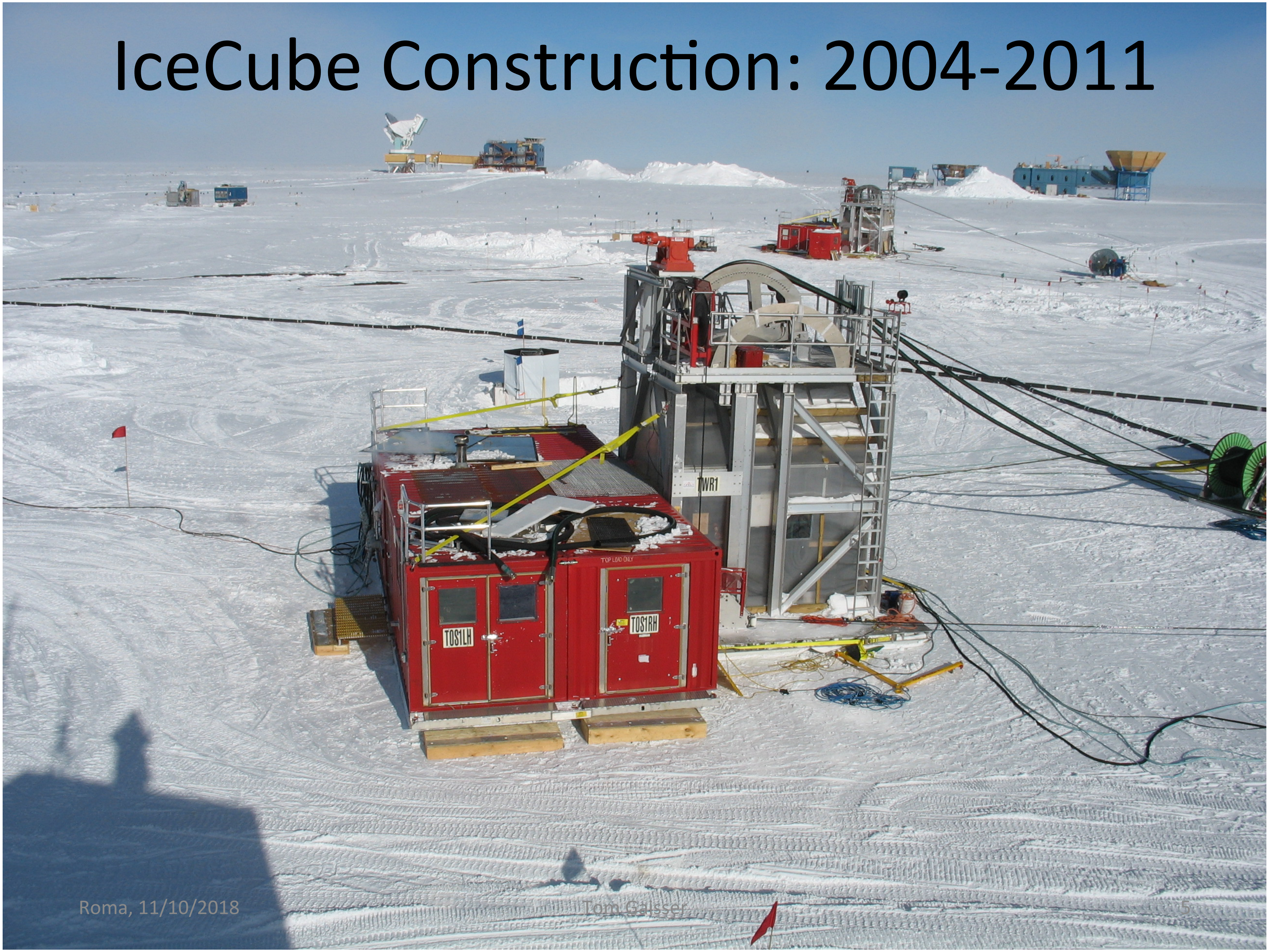
LED Flasher board

HV board



Main board for digitizing & time stamping

IceCube Construction: 2004-2011



Outline

- Phenomenology of atmospheric neutrinos
  - Importance of kaons for $E_\nu \geq$ TeV
  - Angular distributions
- Astrophysical neutrinos in IceCube
  - Signal from the whole sky
  - Multi-messenger astronomy
  - Discovery potential for extra-galactic ν sources
  - Future

Approximate solution to cascade equation for atmospheric ν_μ

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \simeq \frac{N_0(E_\nu)}{1-Z_{NN}} \left\{ \frac{Z_{N\pi}\, Z_{\pi\nu}}{1+\mathcal{B}_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + 0.635 \frac{Z_{NK}\, Z_{K\nu}}{1+\mathcal{B}_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \sum_i B_{D_i} \frac{Z_{ND}\, Z_{D\nu}}{1+\mathcal{B}_{D\nu}\cos\theta\, E_\nu/\epsilon_D} \right\}$$

Form for muons is same but different decay factors ($Z_{\pi\mu} >> Z_{\pi\nu}$)
Contribution from muon decay not included here

Table 1. Critical energies, ϵ_i (GeV)

μ	$\pi^\pm$	K$^\pm$	D$^\pm$	D^0
1.	115.	850.	3.9×10^7	9.9×10^7

$$E_{\text{critical}} = \epsilon_h / \cos\theta^*$$

Spectrum weighted moments

Production: $$Z_{Nh} = \int_0^1 (x_L)^\gamma \frac{\mathrm{d}n_h}{\mathrm{d}x_L}\mathrm{d}x_L \qquad \gamma \approx 1.7$$

Decay (E > $\varepsilon_{critical}$) :

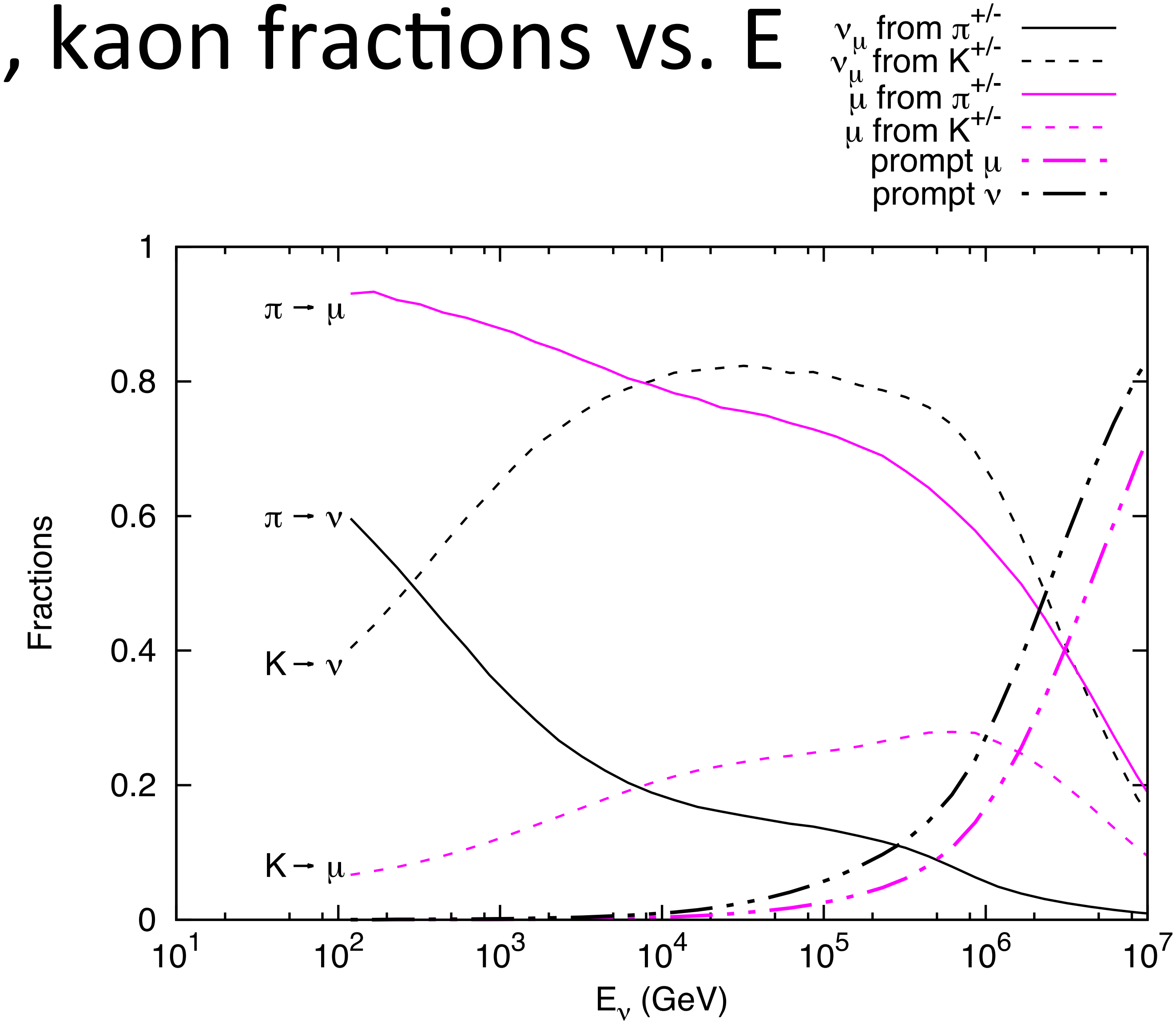
$$Z_{\pi\mu} = \frac{(1 - r_\pi^{\gamma+2})}{(\gamma+2)(1-r_\pi)} \quad \text{and} \quad Z_{\pi\nu_\mu} = \frac{(1-r_\pi)^{\gamma+2}}{(\gamma+2)(1-r_\pi)}$$

$$r_\pi = \frac{m_\mu^2}{m_\pi^2} \approx 0.573 \qquad r_K = \frac{m_\mu^2}{m_K^2} \approx 0.046$$

$$Z_{\pi\nu_\mu} << Z_{K\nu_\mu} \qquad Z_{\pi\mu} = 0.55 \quad Z_{K\mu} = 0.63$$

$$Z_{\pi\nu} = 0.027 \quad Z_{K\nu} = 0.53$$

Pion, kaon fractions vs. E



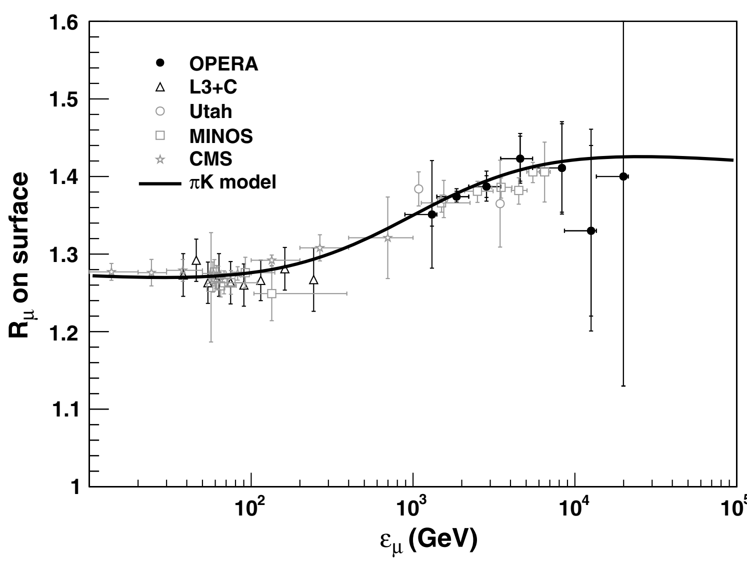
Muon charge ratio

Pions only (Frazer et al., PR D 5 (1972) 1653

$$\frac{\mu^+}{\mu^-} \approx \frac{1+\beta\delta_0\alpha_\pi}{1-\beta\delta_0\alpha_\pi} = \frac{f_{\pi^+}}{1-f_{\pi^+}},$$

$$\beta = \frac{1-Z_{pp}-Z_{pn}}{1-Z_{pp}+Z_{pn}} \approx 0.909;$$

$$\alpha_\pi = \frac{Z_{p\pi^+}-Z_{p\pi^-}}{Z_{p\pi^+}+Z_{p\pi^-}} \approx 0.165$$



Include K → $\mu + \nu_\mu$

TG Astropart. Phys. 35 (2012) 801

$$\frac{\mu^+}{\mu^-} = \left[\frac{f_{\pi^+}}{1+B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{\frac{1}{2}(1+\alpha_K\beta\delta_0)A_{K\mu}/A_{\pi\mu}}{1+B^+_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]$$
$$\times \left[\frac{(1-f_{\pi^+})}{1+B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK})A_{K\mu}/A_{\pi\mu}}{1+B_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]^-$$

$$\alpha_K = \frac{Z_{pK^+}-Z_{pK^-}}{Z_{pK^+}+Z_{pK^-}}$$

Rise in muon charge ratio reflects higher asymmetry in the charged kaon channel, which becomes more important when $E_\mu > \varepsilon_K \approx 850$ GeV.

The key parameter is $\alpha_K > \alpha_\pi$ due to associated production: p → ΛK^+

Implication: $\nu_\mu / \bar{\nu}_\mu$ rises to ≈ 2.5 @ 10 TeV

Fluxes for E_ν >> TeV

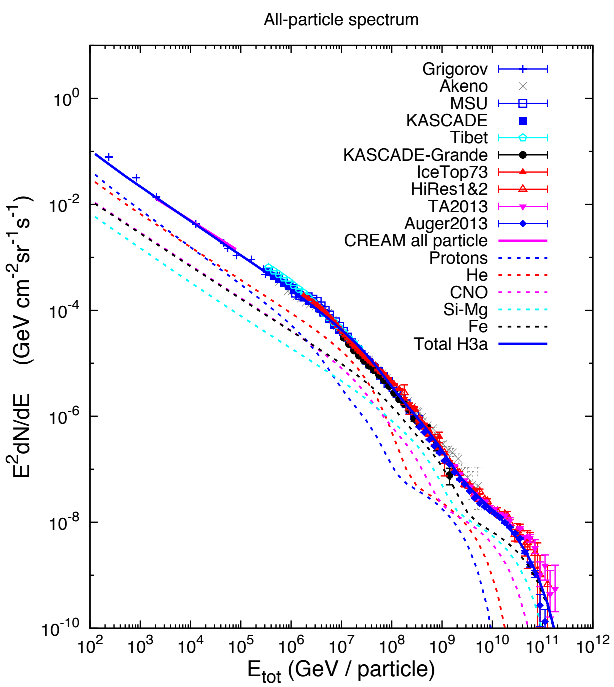


Fig. 12. All-particle spectrum showing' separately the contribution of five mass groups in a modified H3a model (see text).

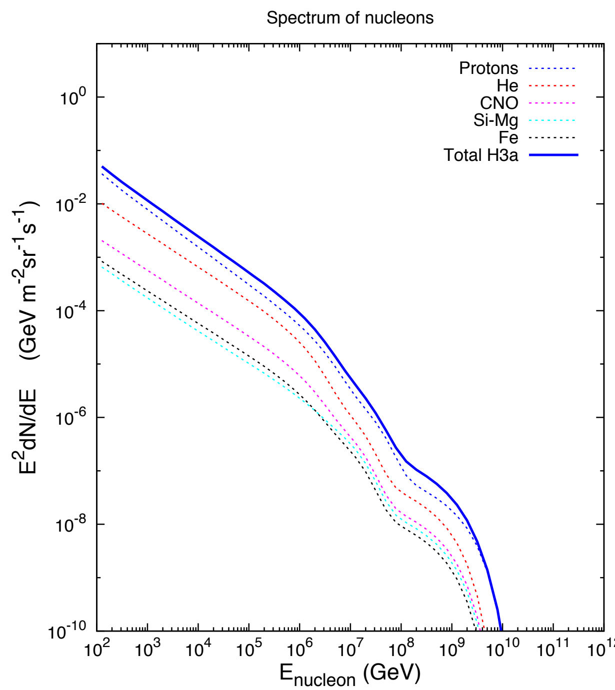


Fig. 13. Spectrum of nucleons corresponding to Fig. 12.

Need primary spectrum of nucleons to $E > E_{knee,1}$

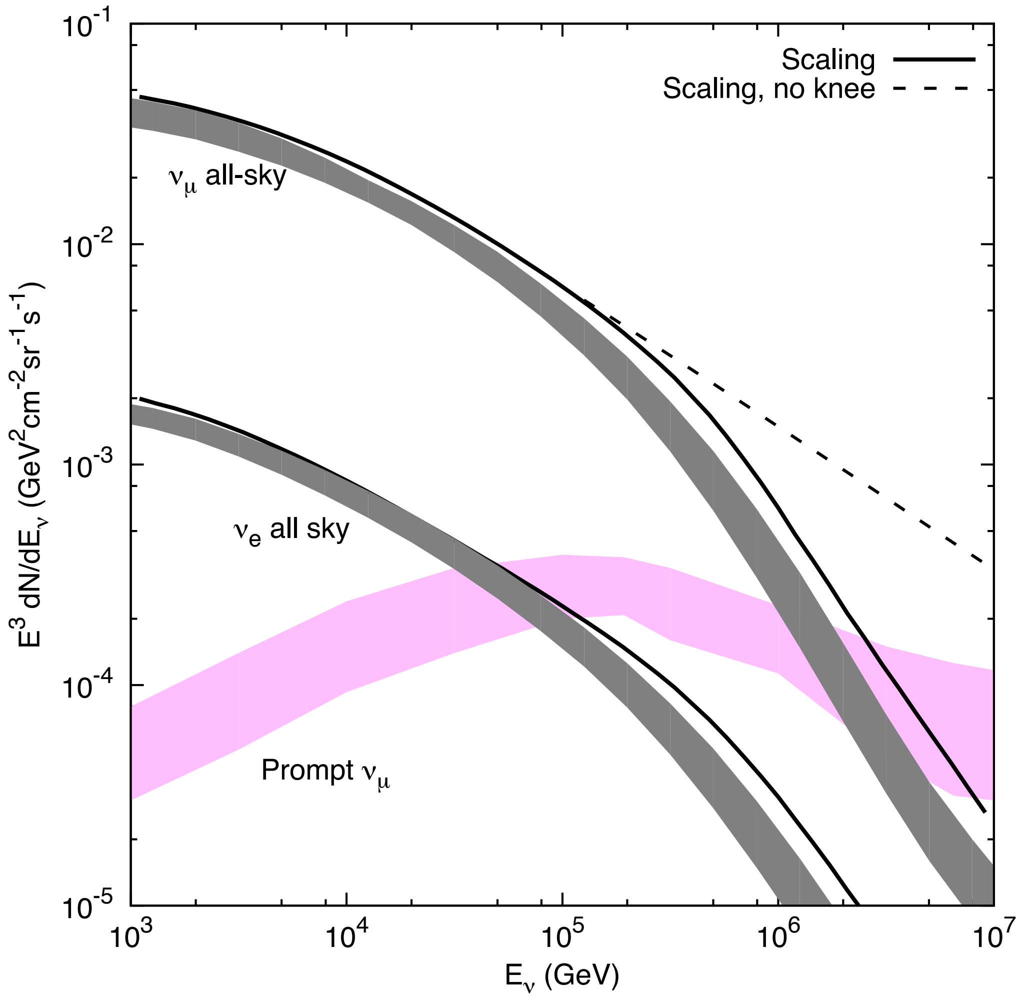
Energy-dependent Z-factors

Ref: P Gondolo, G. Ingelman, M Thunman, Astropart. Phys. 5 (1996) 309

Example: p + A → K^+ + X

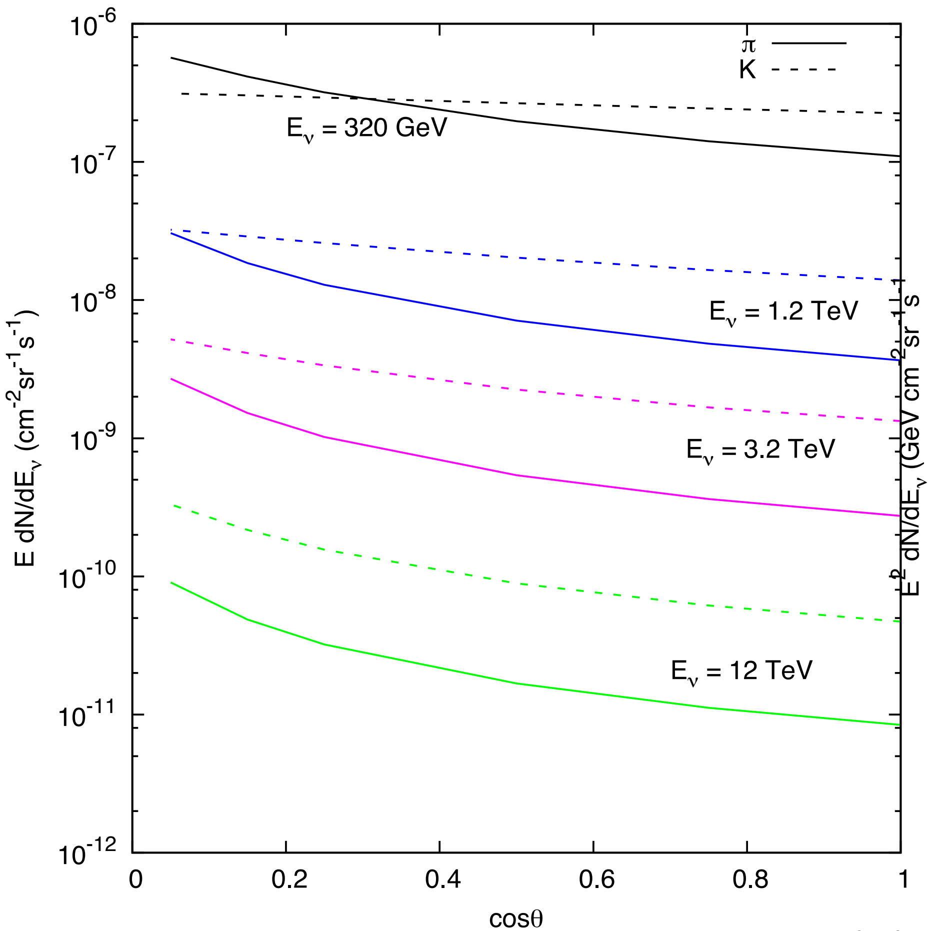
$$Z_{pK^+} = \int_0^1 x^\gamma \frac{\mathrm{d}n_{K^+}(x)}{\mathrm{d}x}$$

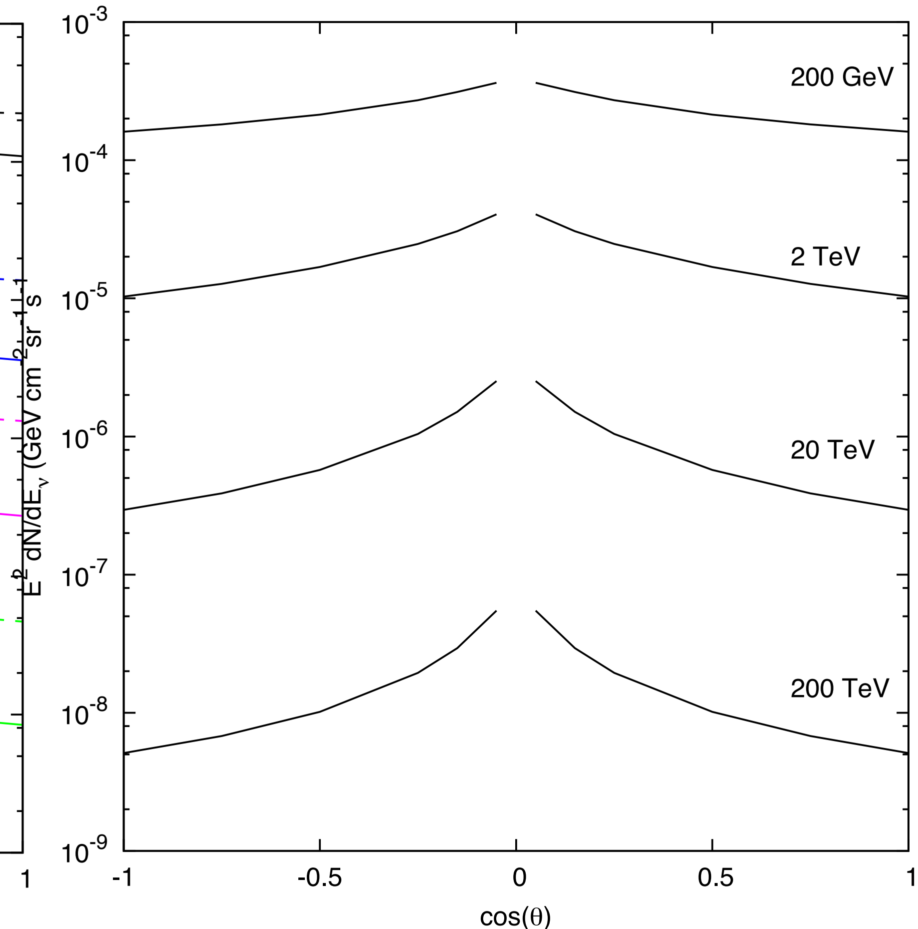
$$Z_{NK^+}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{K^+}(E', E)}{\mathrm{d}E}$$



Shaded bands for conventional span Sib2.3, Epos LHC, QGSjet II-04, prompt: PROSA, Sib2.3, GRRST, BERSS

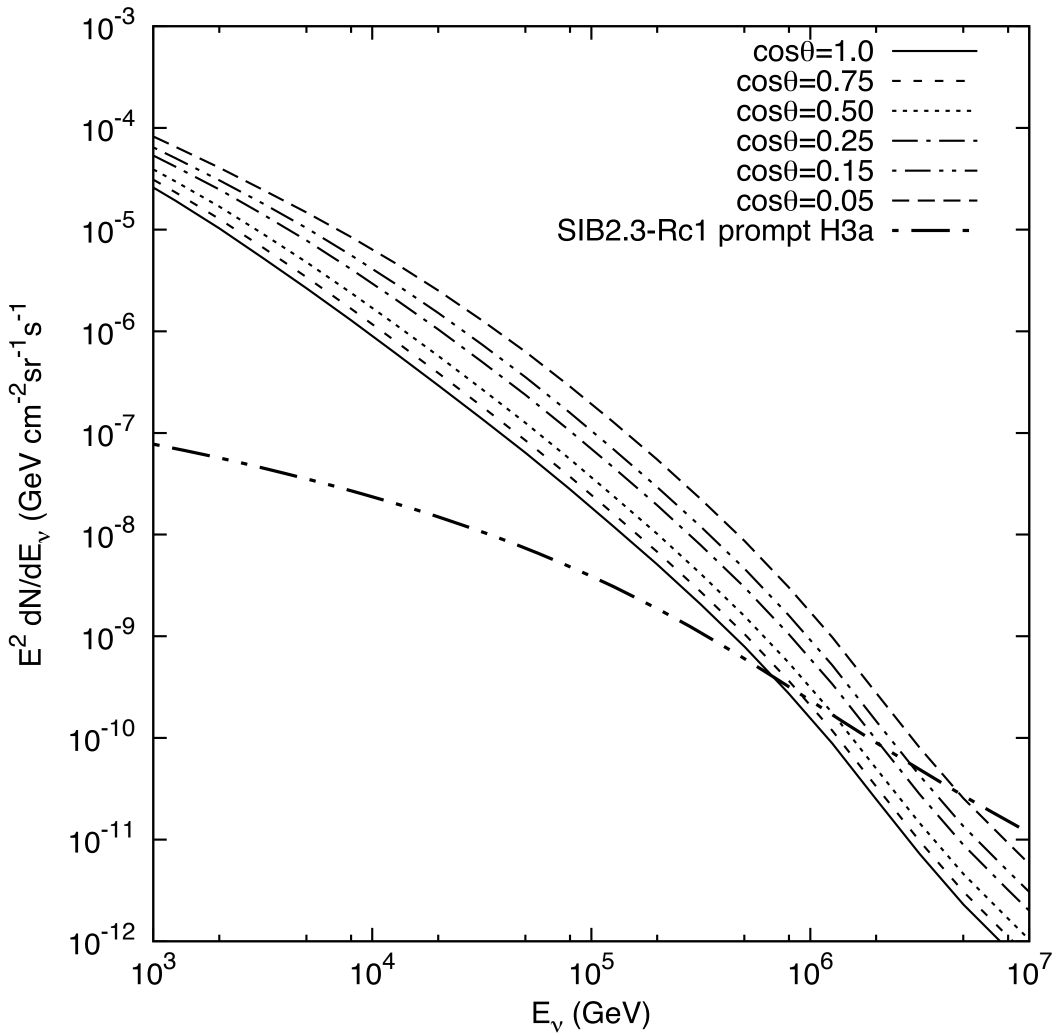
Evolution of angular distribution





For E ≈ TeV, pion component ≈ sec(θ), but kaon still almost isotropic

Flux of atmospheric ν_μ vs angle

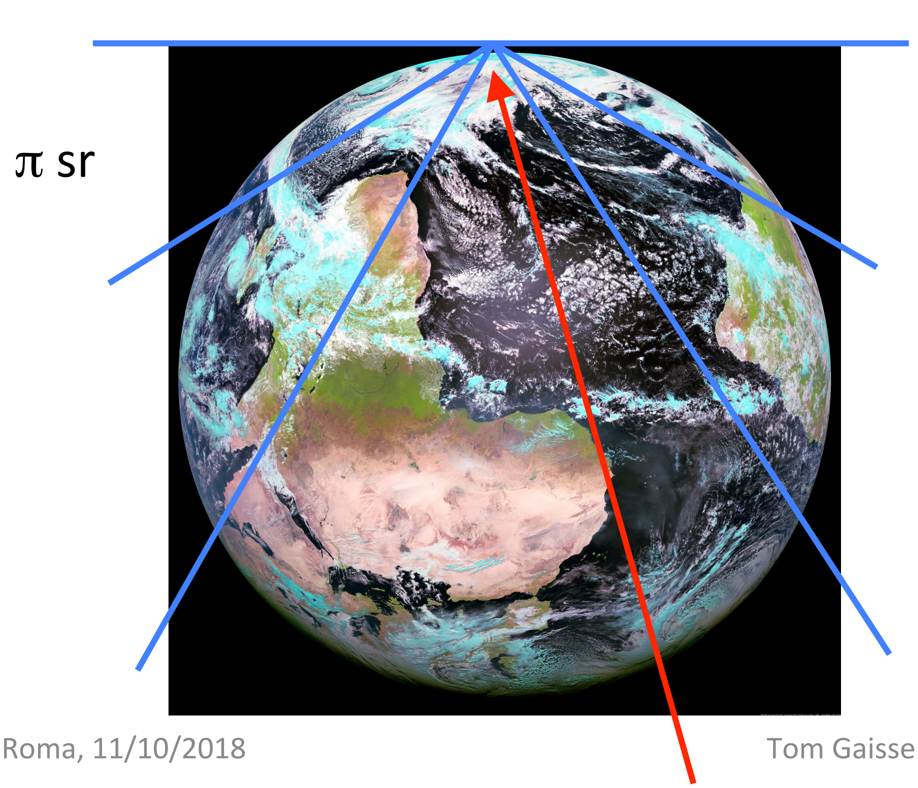


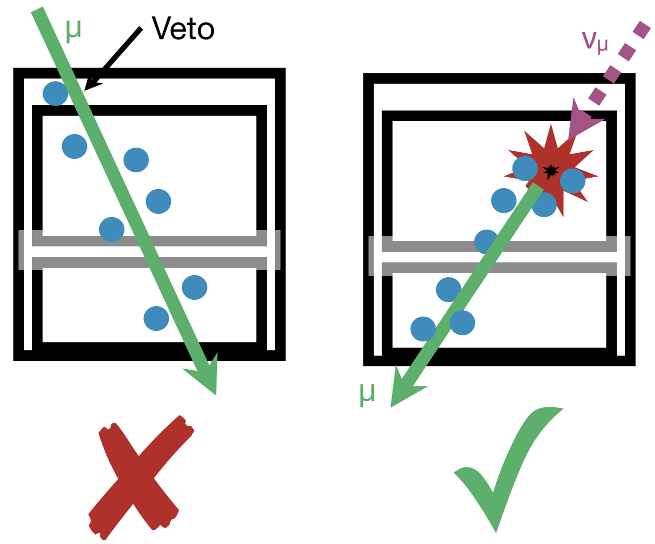
Note harder spectrum and higher flux at large zenith angles

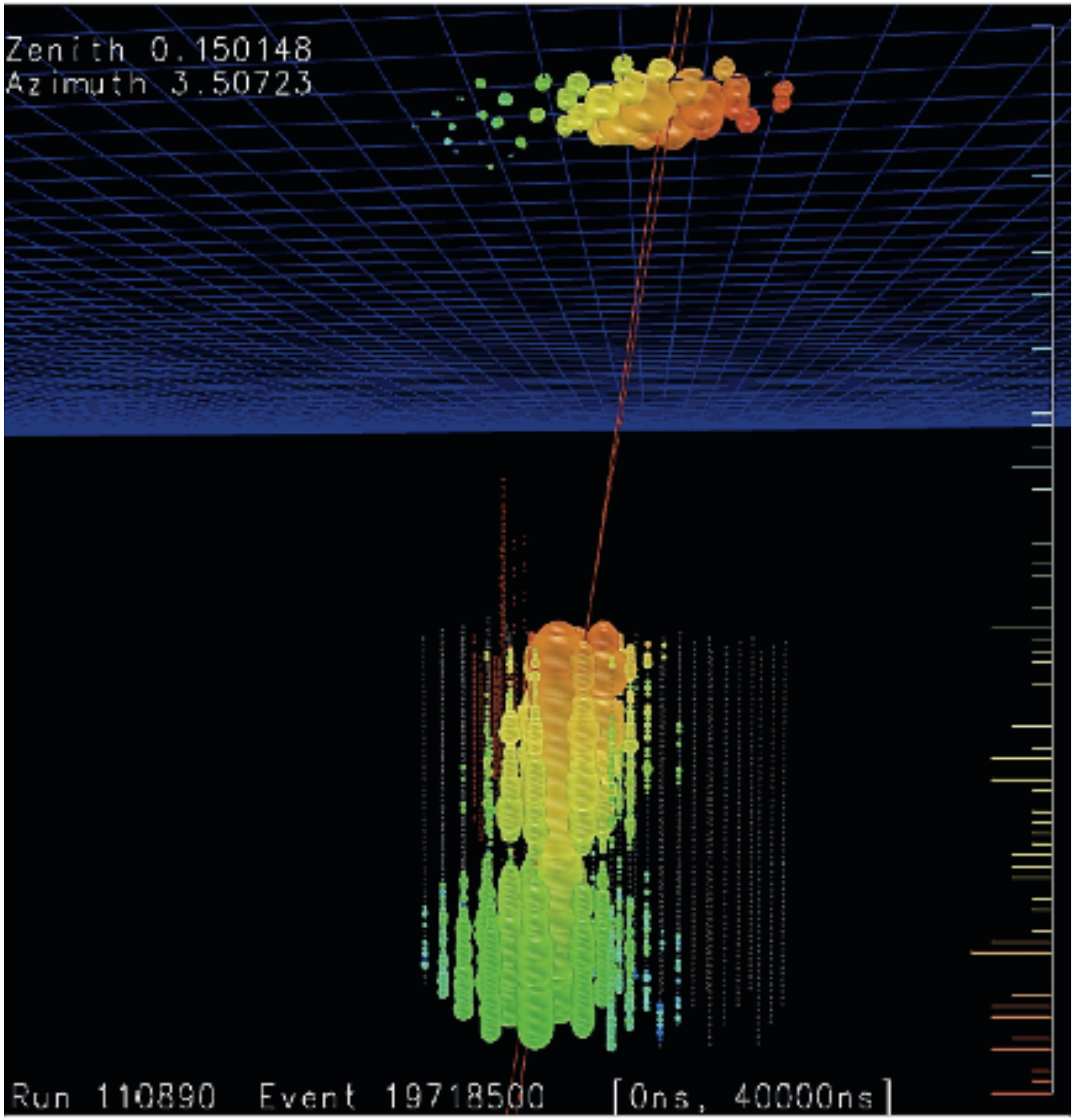
IceCube high-energy neutrinos

Two ways to identify neutrinos:

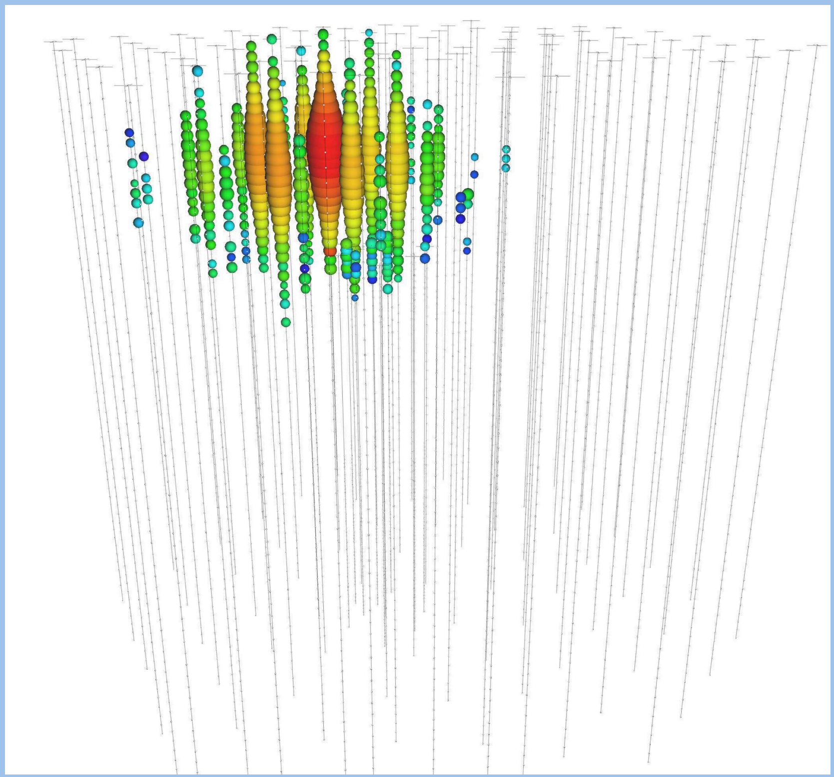
1. Upward using Earth as filter
2. Events start in detector

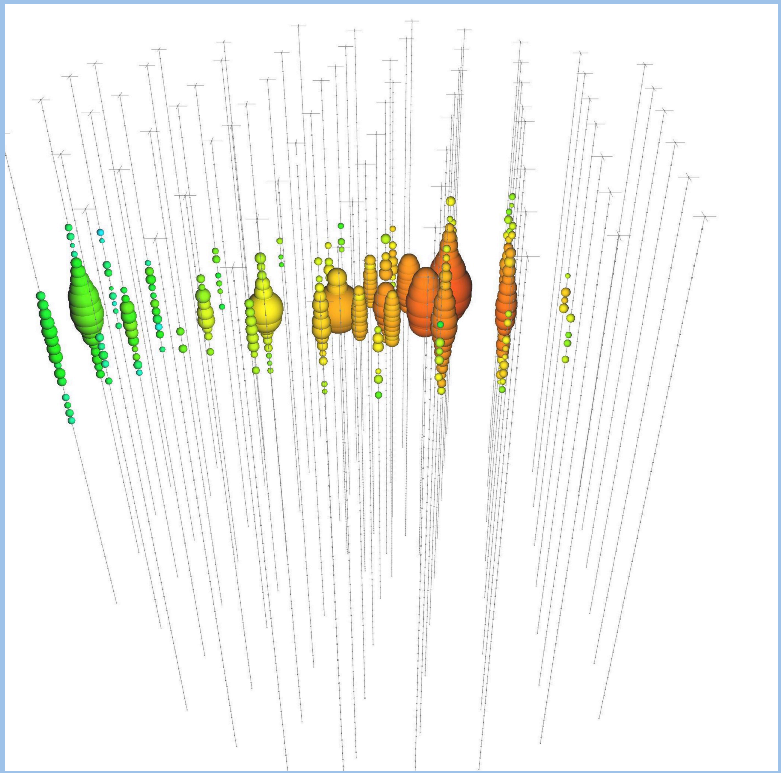





Zenith 0.150148
Azimuth 3.50723
Run 110890 Event 19718500 [0ns, 40000ns]

HESE event types in IceCube

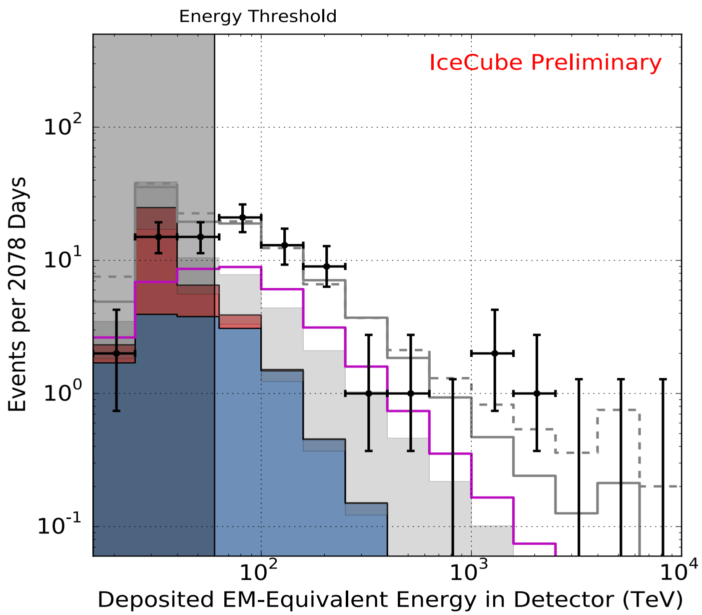




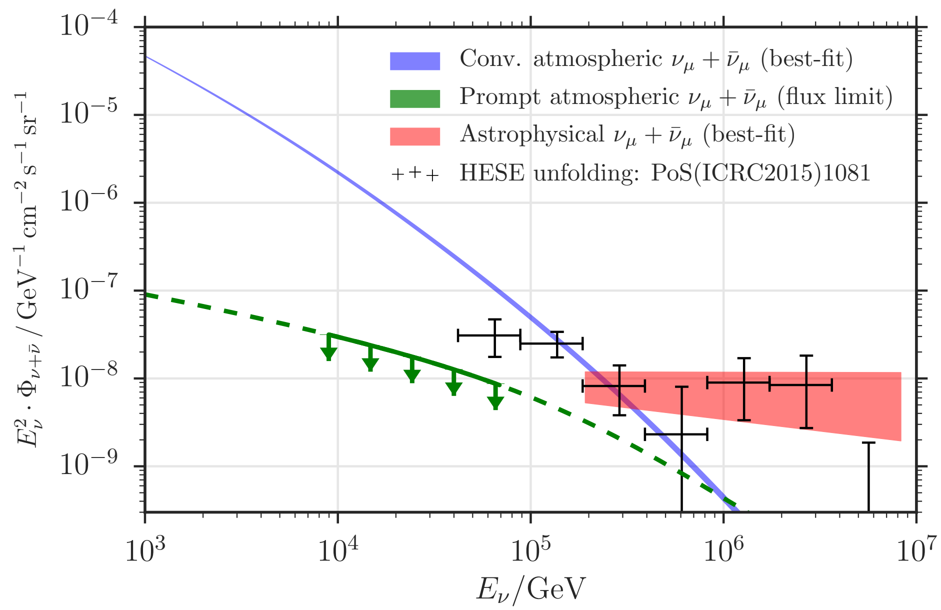
Cascade events:
CC interactions of ν_e and ν_τ
NC interactions of all flavors

Starting track: CC ν_μ
Note initial hadronic cascade

Astrophysical neutrinos



IceCube *6 year* HESE analysis
(HESE = High Energy Starting Event)
ICRC 2011 arXiv:1710.01191 (#981)

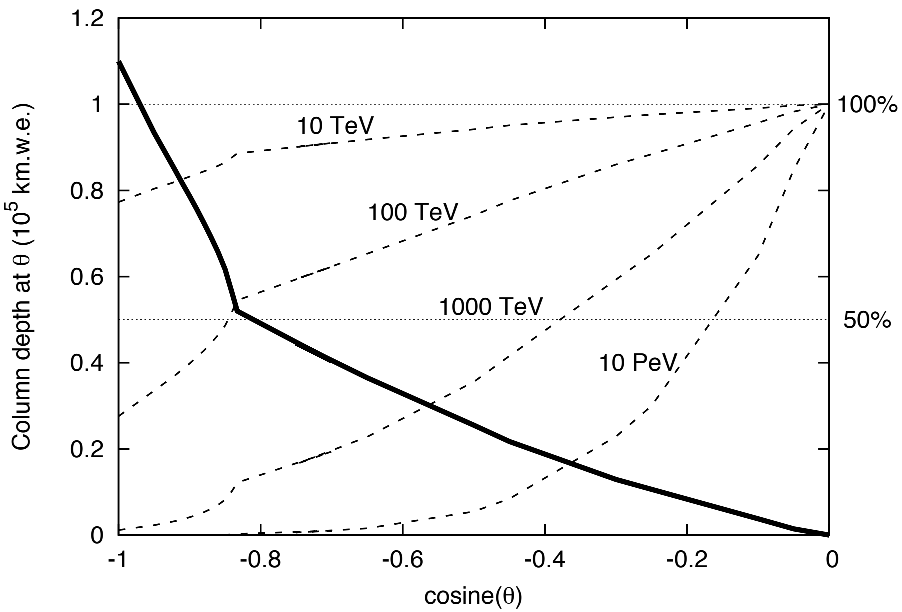


IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
arXiv:1607.08006, Ap.J. 833 (2016) 3

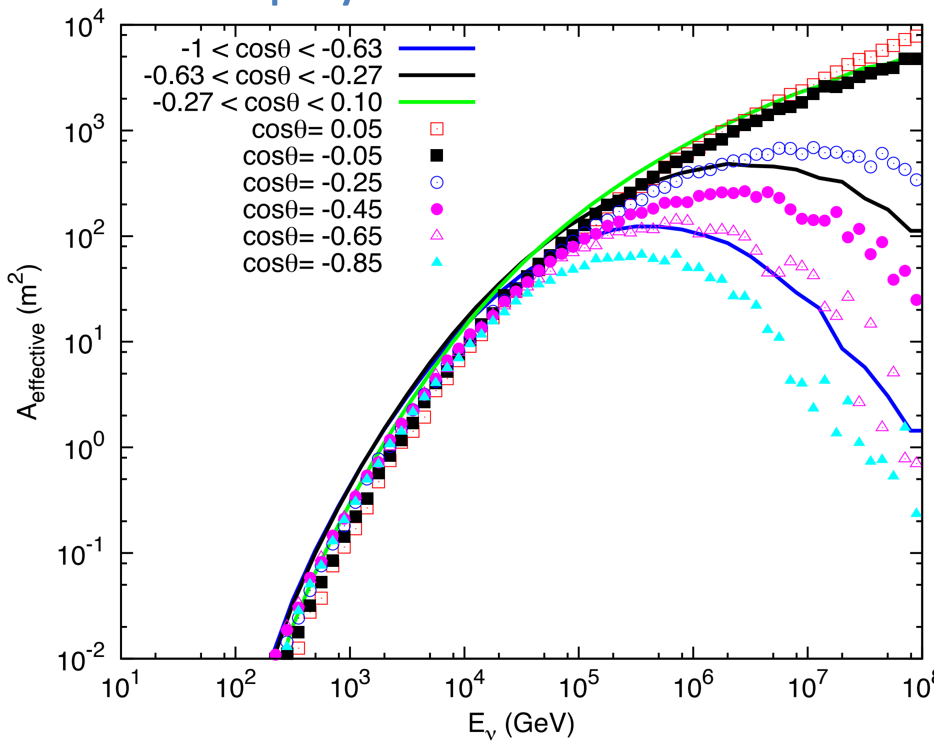
The astrophysical signal emerges above a steeply falling background of atmospheric neutrinos

Shadow of the Earth

Affects both atmospheric and astrophysical neutrinos



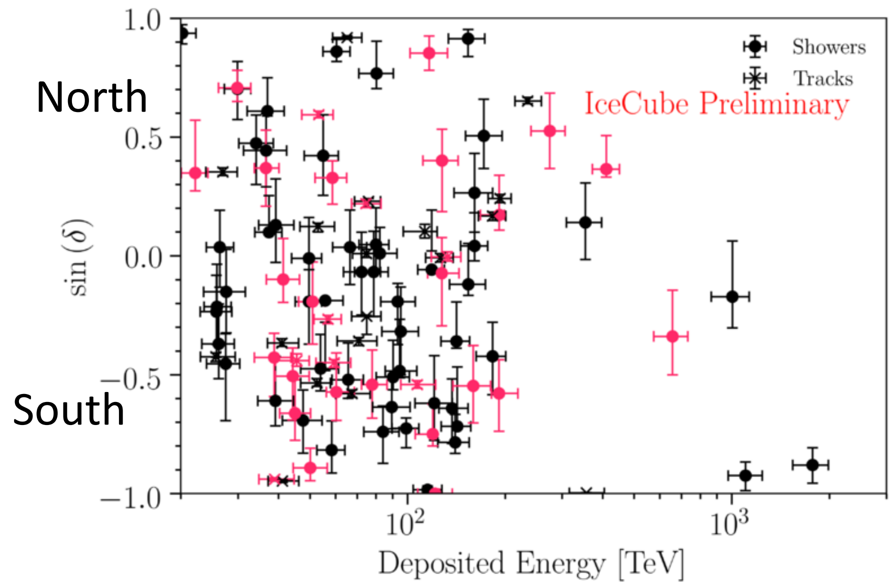
Transparency of the Earth for neutrinos. Dashed line show passing fractions at four neutrino energies.

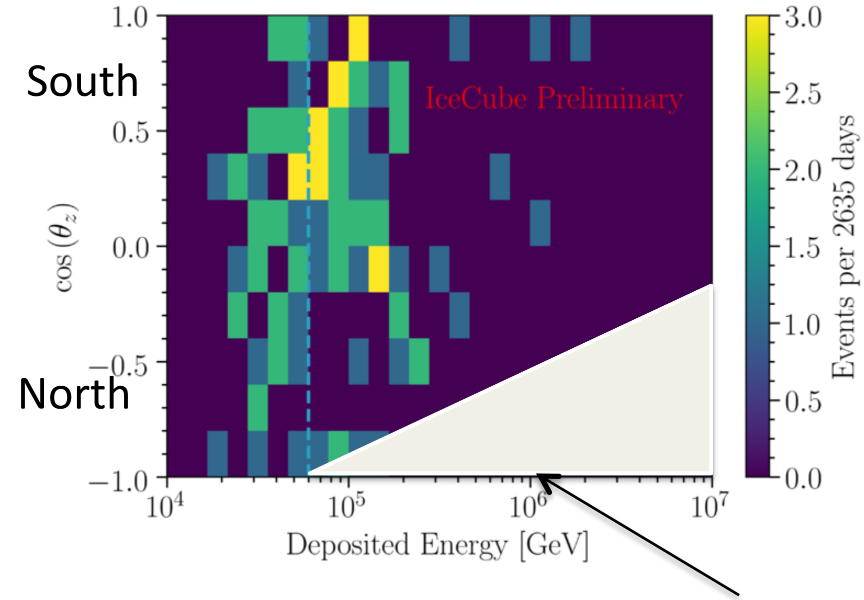


Effective areas for upward ν_μ in IceCube.
Solid: all-sky, Ap.J. 833 (2016) 3;
Points: Point source search: https://icecube.wisc.edu/science/data/ PS-IC86-2011.

HESE 7.5 yrs

New reconstructions for all years with IceCube Pass 2





Earth's shadow (>50%)

Note change in convention for direction: sin(δ) → cos(θ)

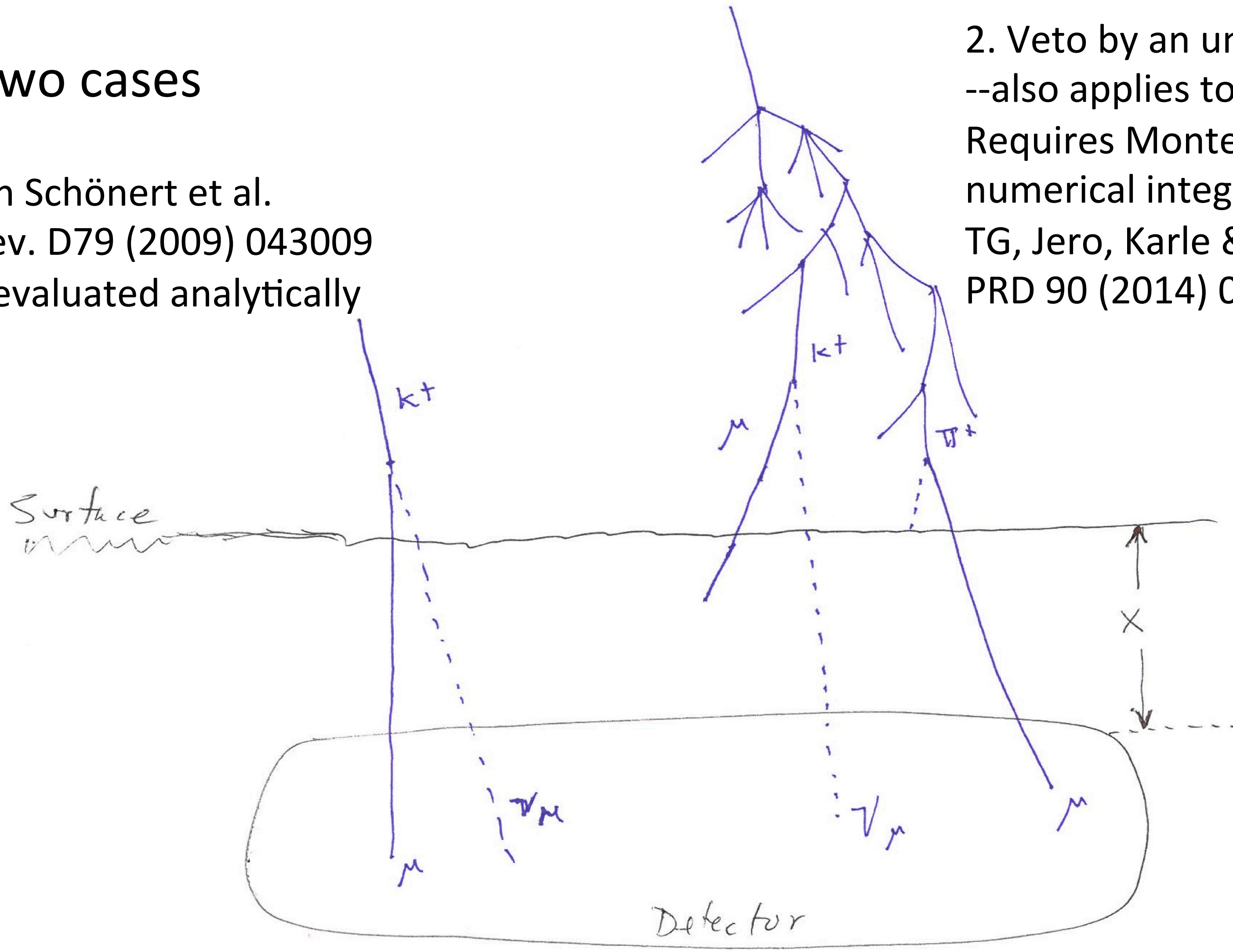
Work in progress reported at TeVPA 2018
(Austin Schneider for IceCube)

Atmospheric neutrino self veto

Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

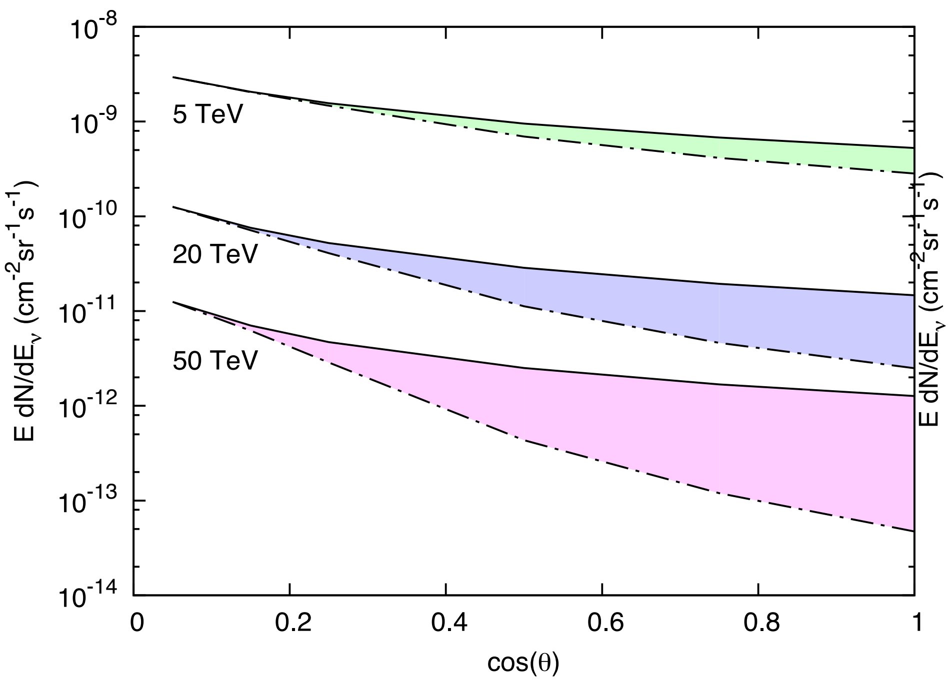
2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or
numerical integration
TG, Jero, Karle & van Santen,
PRD 90 (2014) 023009



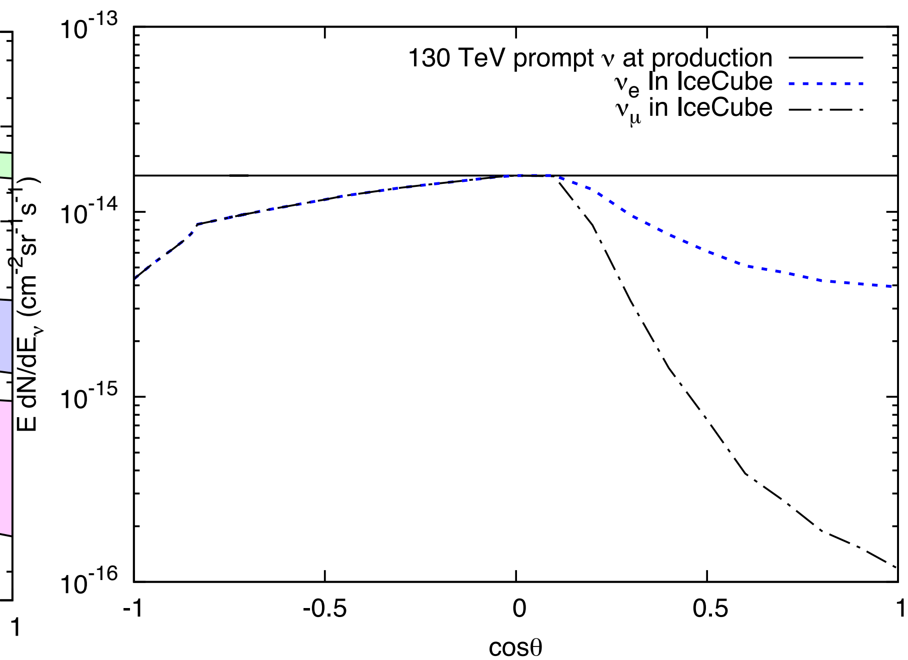
Neutrino self-veto

Applies only to atmospheric neutrinos from above

Conventional ν_μ from above



Prompt ν at 130 TeV

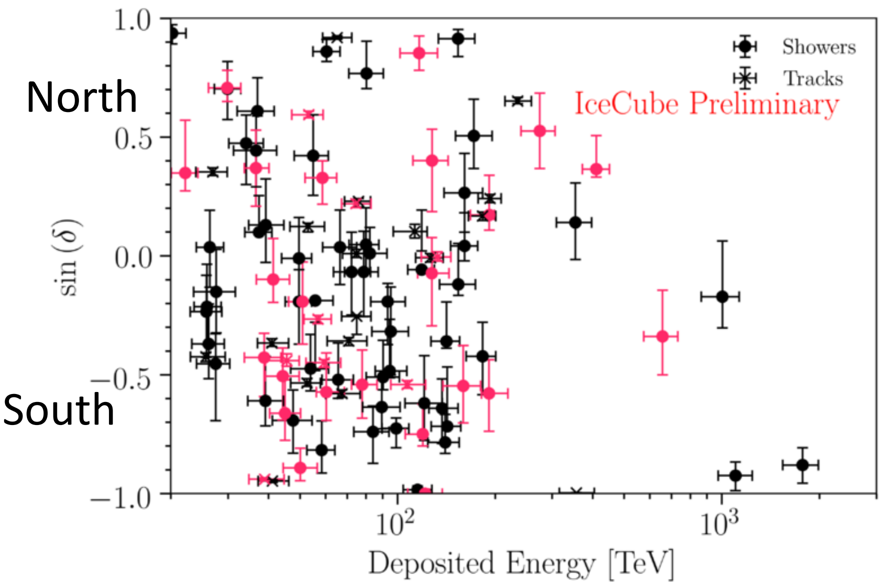


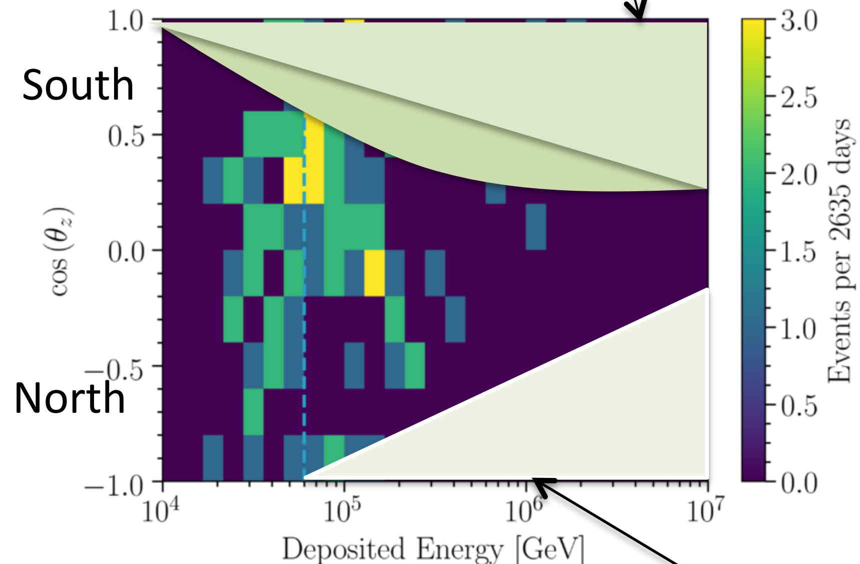
References: Schönert, TG, Resconi, Schulz, PRD 79 (2009) 043009
TG, Jero, Karle, van Santen PRD 90 (2014) 023009
→ Arguelles, Palomares-Ruiz, Schneider, Wille, Yuan /arxiv.org/abs/arXiv:1805.11003

HESE 7.5 yrs

New reconstructions for all years with IceCube Pass 2

Neutrino self-veto (>90%)

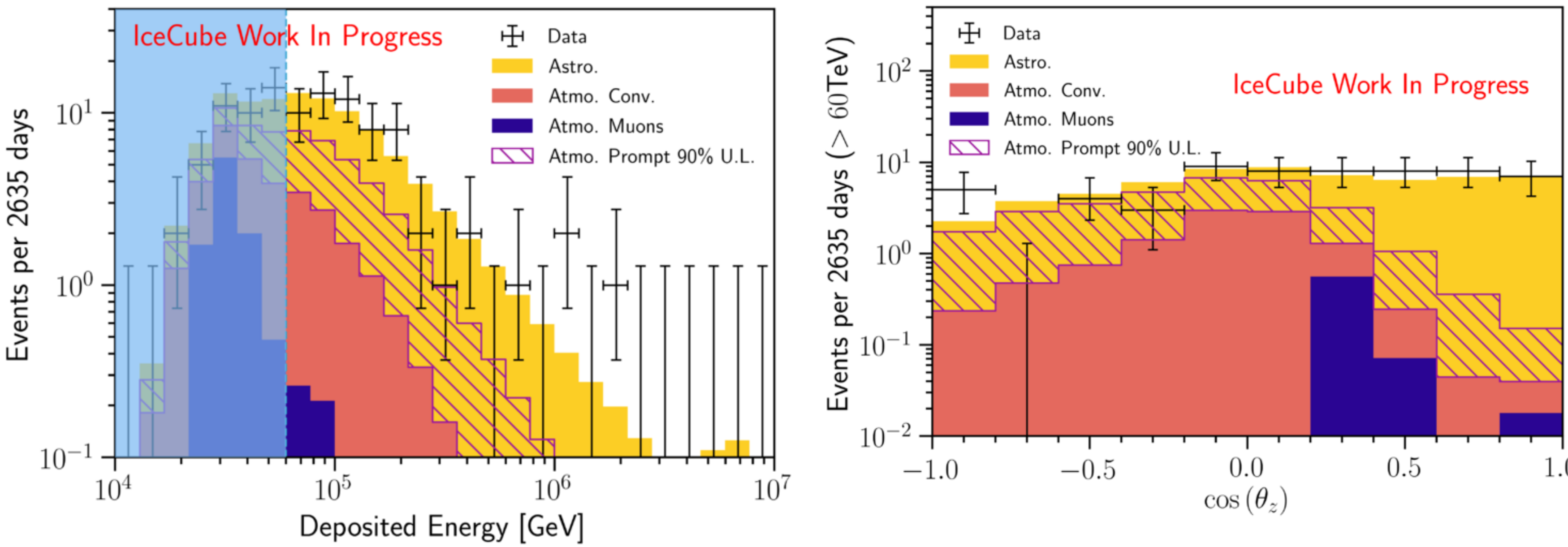




Earth's shadow

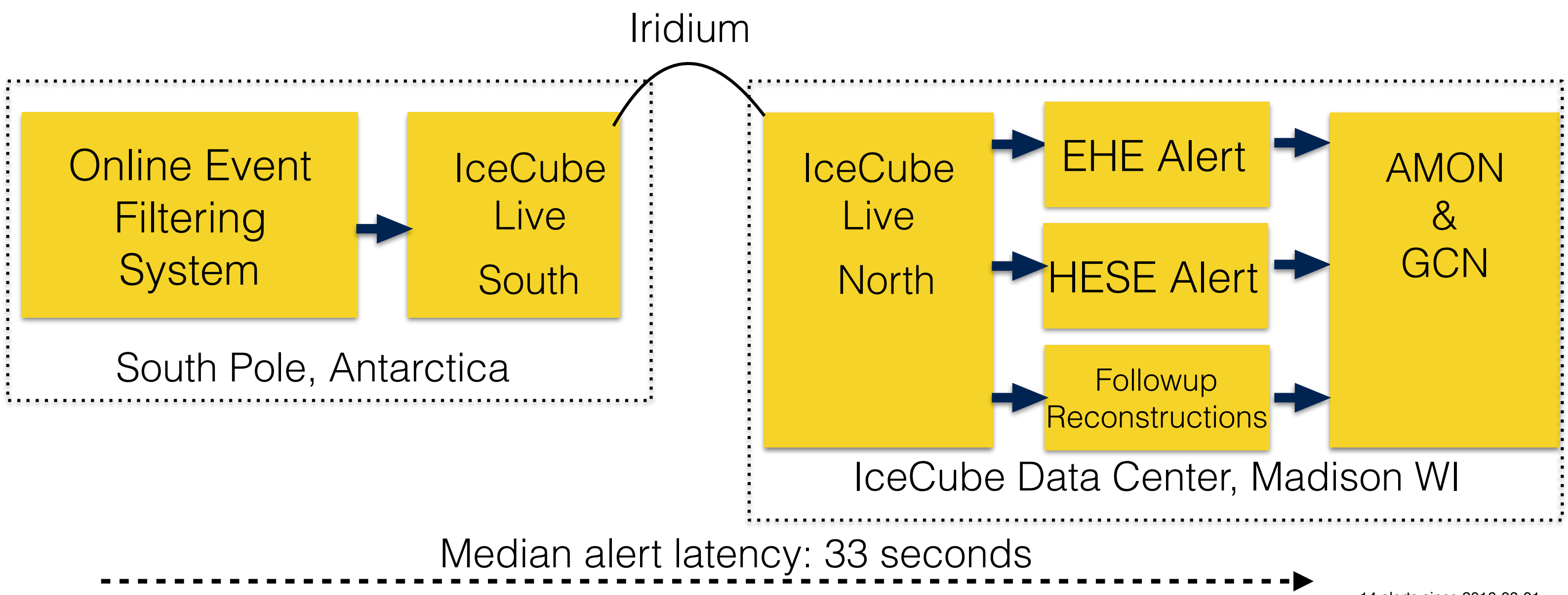
Note change in convention for direction: sin(δ) → cos(θ)

7.5 yr HESE: work in progress



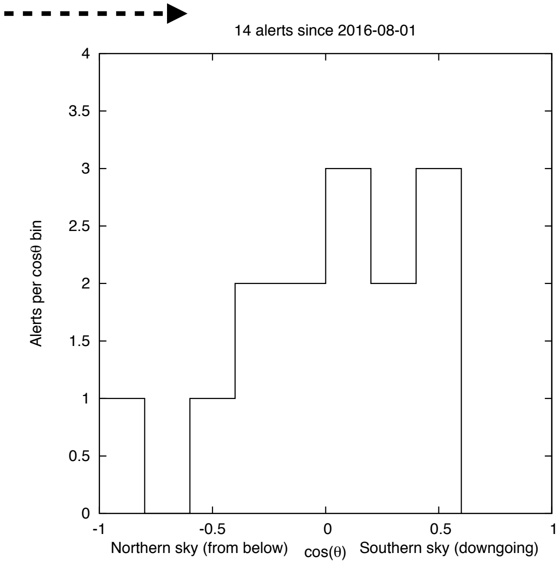
8 yr: IceCube (A. Schneider) TeVPA 2018, Berlin

IceCube Realtime Alert System



Erik Blaufuss and IceCube Realtime Oversight Committee

- HESE: high-energy starting tracks
- EHE: high-energy tracks
- 14 Alerts since April, 2016



IceCube 170922A

Initial notice

From Bacodine <vxw@capella2.gsfc.nasa.gov>
Subject [icecube-c] GCN/AMON_ICECUBE_EHE
To nl_169_email_none@capella2.gsfc.nasa.gov

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

Follow up GCN 4 hours later

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino
candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of
Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu
/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high
probability of being of astrophysical origin. The event was identified by the
Extremely High Energy (EHE) track event selection. The IceCube detector was in a
normal operating state. EHE events typically have a neutrino interaction vertex
that is outside the detector, produce a muon that traverses the detector volume,
and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon
/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the
direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a
possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating
at the geographic South Pole, Antarctica. The IceCube realtime alert point of
contact can be reached at roc@icecube.wisc.edu
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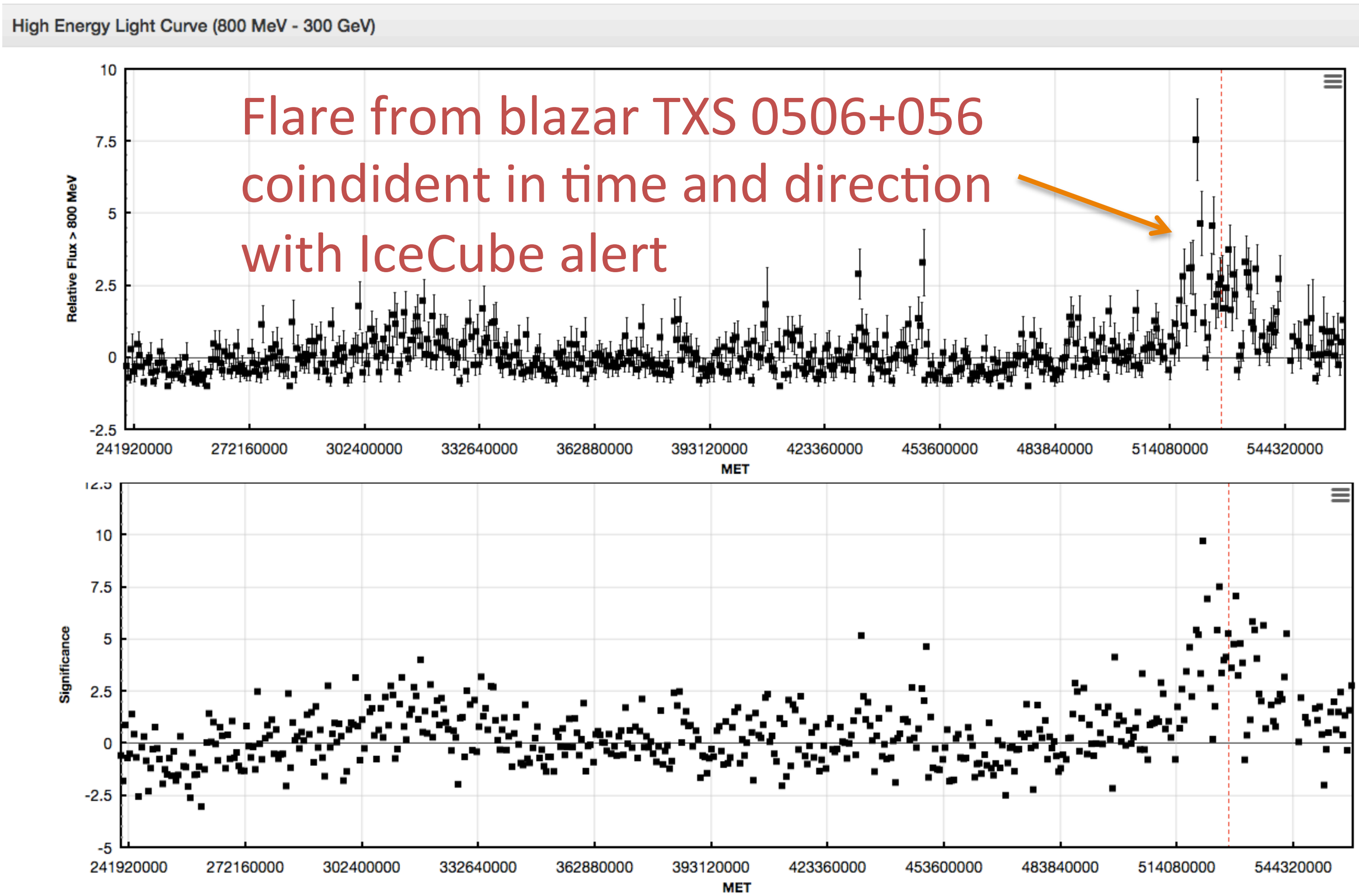
Throughgoing track with 24 TeV deposited energy

Fermi Atel 10791 (2017-09-28)

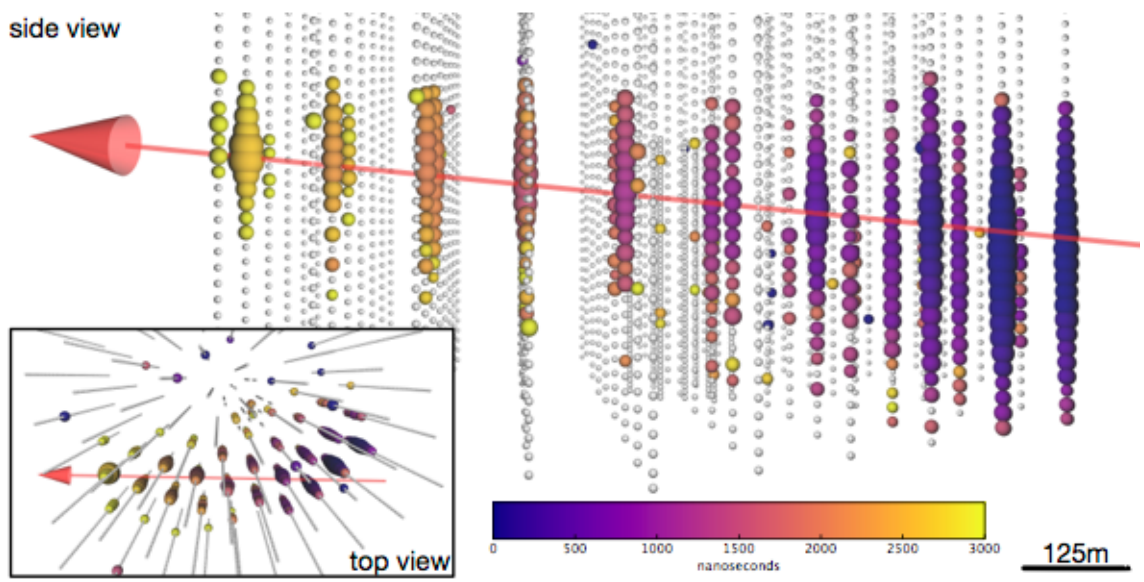


https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27

Publication in *Science,* 13 July 2018

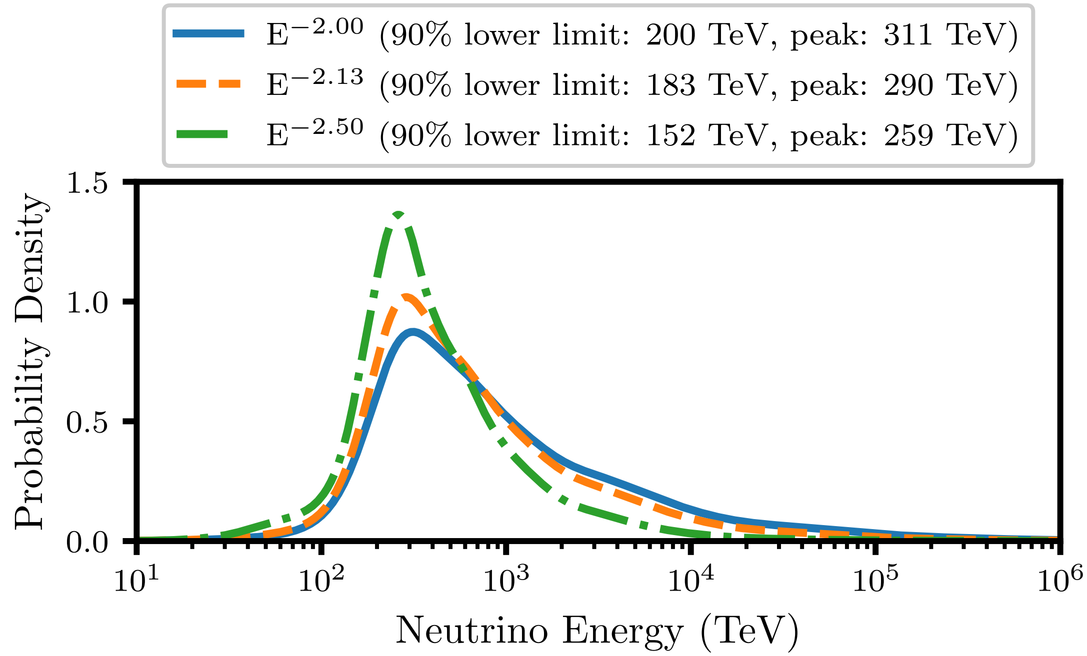
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

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*†



The IceCube Collaboration et al., Science 361, eaat1378 (2018) 13 July 2018

170922 neutrino energy ≈ 300 TeV



- Monte Carlo of ν_μ interaction, μ propagation
- Peak of distribution: 290 TeV with high energy tail
- 90% of area has E > 180 TeV

Likelihood that alert is not an atmospheric event

From Bacodine <vxw@capella2.gsfc.nasa.gov>
Subject **[icecube-c] GCN/AMON_ICECUBE_EHE**
To nl_169_email_none@capella2.gsfc.nasa.gov

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NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
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DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```
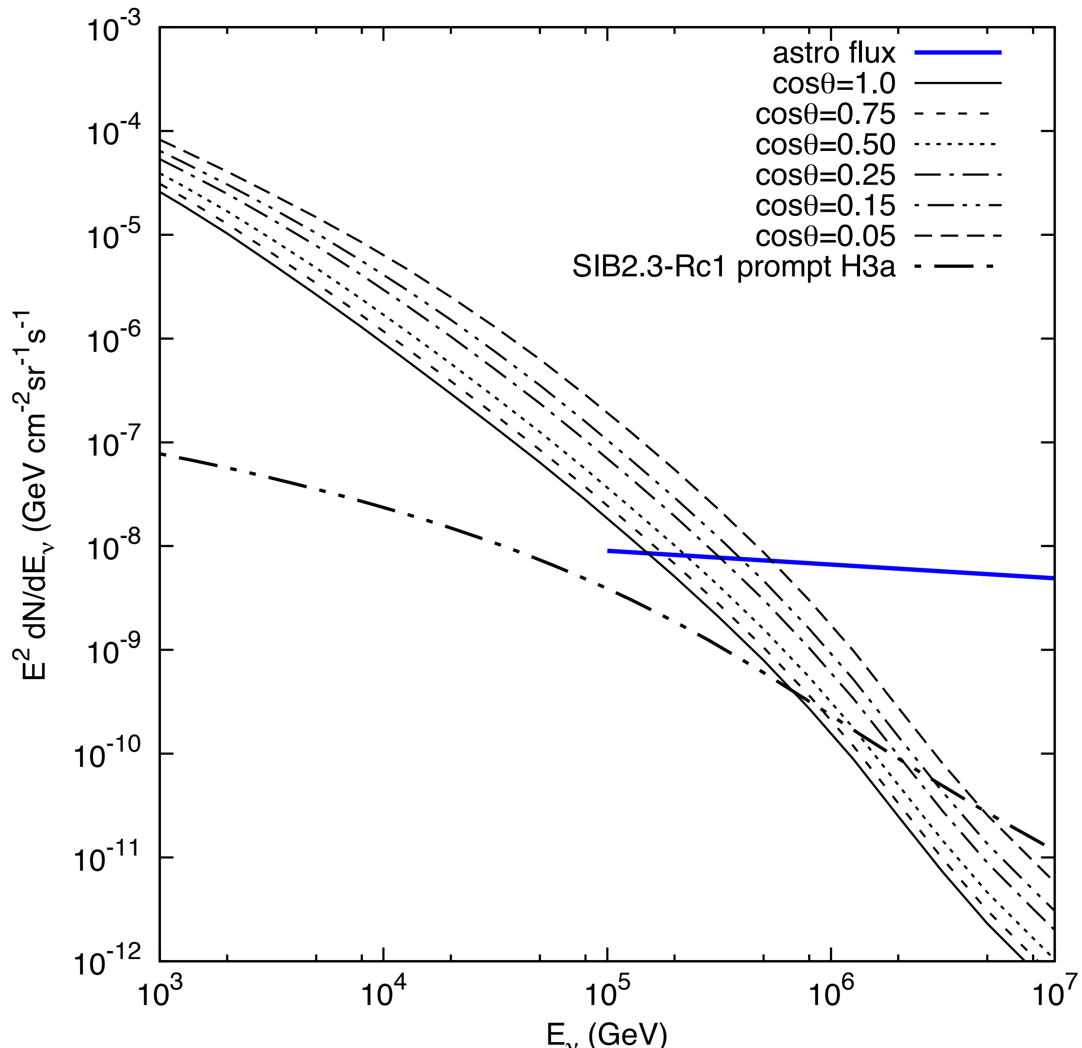

Signalness = 0.565

“Signalness” of 170922A

- Compare to the astrophysical spectrum of the upward ν_μ analysis (Ap.J. 833 (2016) 3):
  - At 100 TeV $E^2\phi_{\rm astro} \approx 0.9 \times 10^{-8}\, GeV\; cm^{-2} s^{-1} sr^{-1}$
  - Fitted differential spectral index = -2.13
- Compare to atmospheric flux accounting for direction of the event
  - Declination = 5.72°
  - Below horizon, so no atmospheric muons
  - Zenith angle = 95.72, cos(θ) ≈ -0.1, not absorbed by the Earth

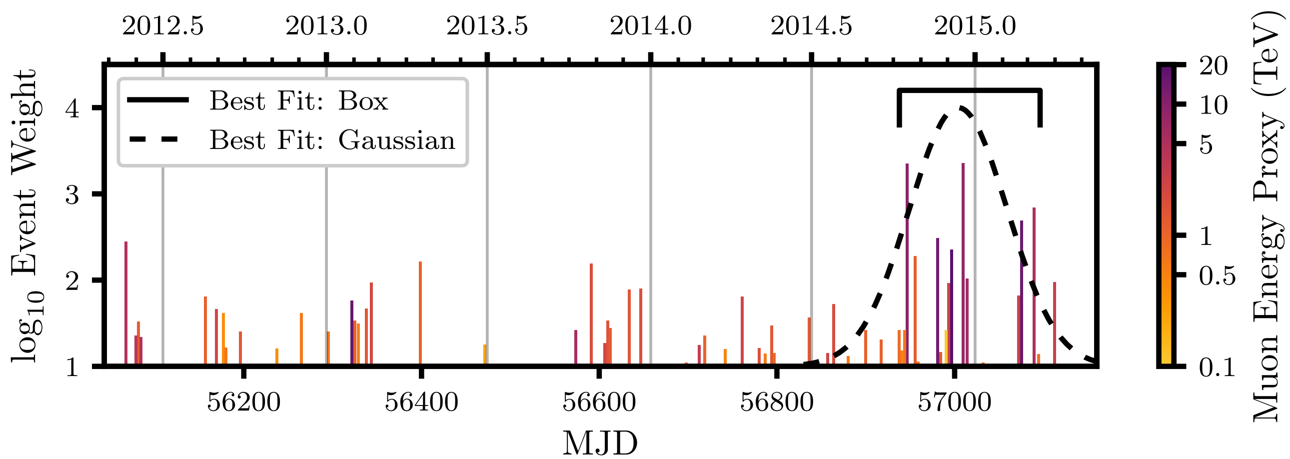
Flux of atmospheric ν_μ vs angle



Note: actual evaluation compares ν_μ –induced muon spectra rather than neutrino spectra.

Is 170922A from TXS 0506+056 ?

- Chance coincidence ruled out at > 3 sigma
- Consistent with upper limit on ν from blazars*
  ***IceCube, Ap.J. 835 (2017) 45**
- Archival data shows a 3.5 sigma excess of neutrinos from TXS 0506 in 2014/15
  – But no corresponding flare in gamma-rays (!!)



IceCube Collaboration, Science 361, 147–151 (2018) 13 July 2018

High-energy astrophysical neutrinos

Cosmic-ray – gamma-ray – Neutrino connection

Dark Matter
Talk of N. Rudd in ν-III session today

Galactic

Diffuse

C.R. + gas → ν

Stecker, 1979
:
Gaggero et al, 2015

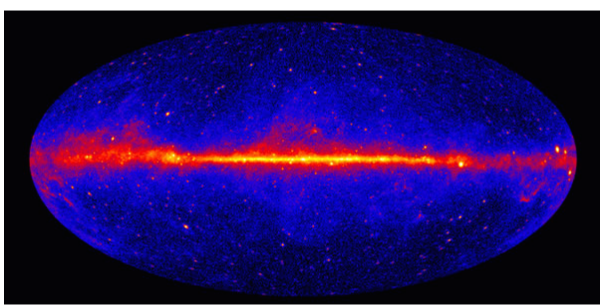
Sources

e.g. SNR near clouds

Unresolved at first,
≈ 0.1 of diffuse, but
harder spectrum

Ahlers et al., PR D93 (2016)

Analogous to γ -ray sky



Extragalactic

Diffuse

p + CMB → π
p + EBL → π

Sources*

Steady	Transient
SFG	GRB
AGN	AGN

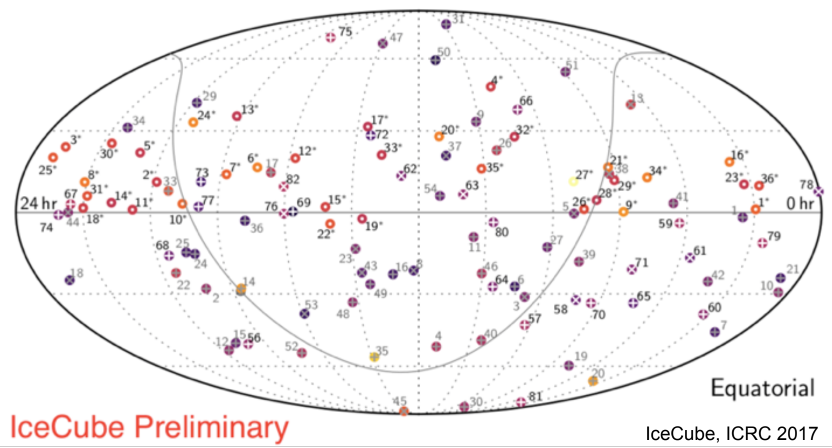
SNR

*Most sources are likely to be unresolved unless there are only a few bright sources

Enhance sensitivity by looking for coincidences with Fermi identified flares.

Sky maps of high-energy events

IceCube high-energy events > 30 TeV (2010 - 2016)



IceCube HESE 6 year
ICRC 2017 arXiv:1710.01191 #981

IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
arXiv:1607.08006 (E_μ > 200 TeV)

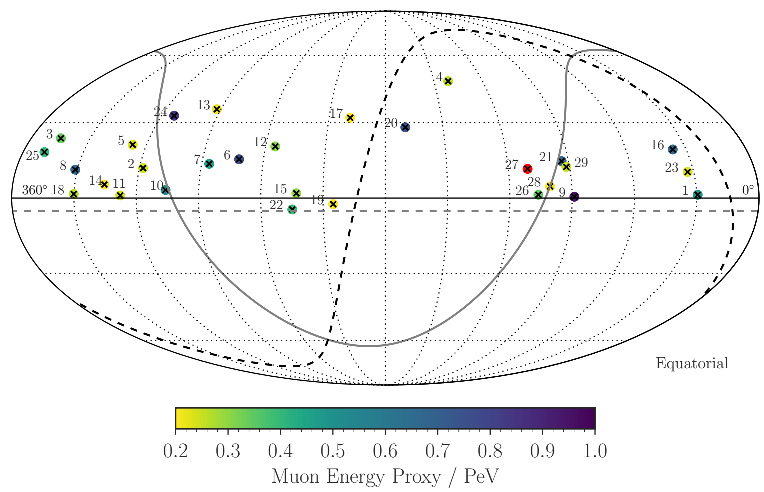


Figure 16. Arrival directions of events with a muon energy proxy above 200TeV. Given the best-fit spectrum the ratio of astrophysical to atmospheric events is about two to one. The horizontal dashed gray line shows the applied zenith angle cut of 85°. The curved gray line indicates the galactic plane and the dashed black line the supergalactic plane (Lahav et al. 2000). The multi-PeV track event is shown as a red dot and the energy proxy value listed in Tab. 4.

- *No steady point source is identified yet*
- *Isotropic distribution → mostly extragalactic*

Galactic fraction

- Of order 10%
- It is a guaranteed source
- Antares/IceCube limit is close to prediction (1808.03531)

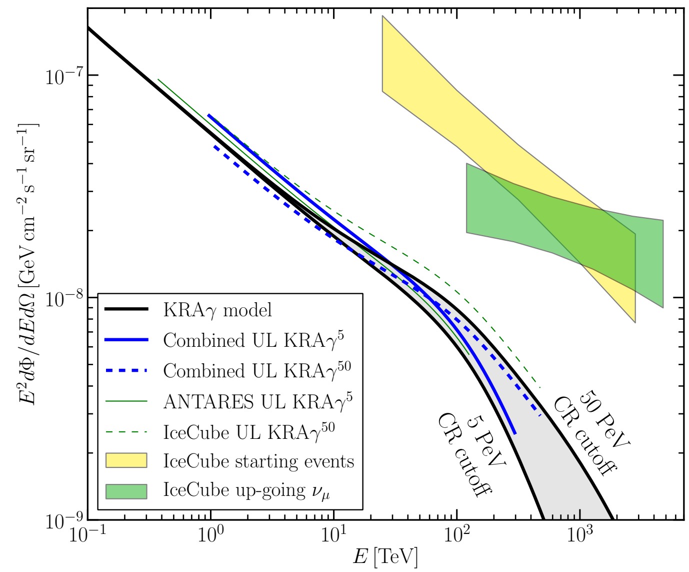
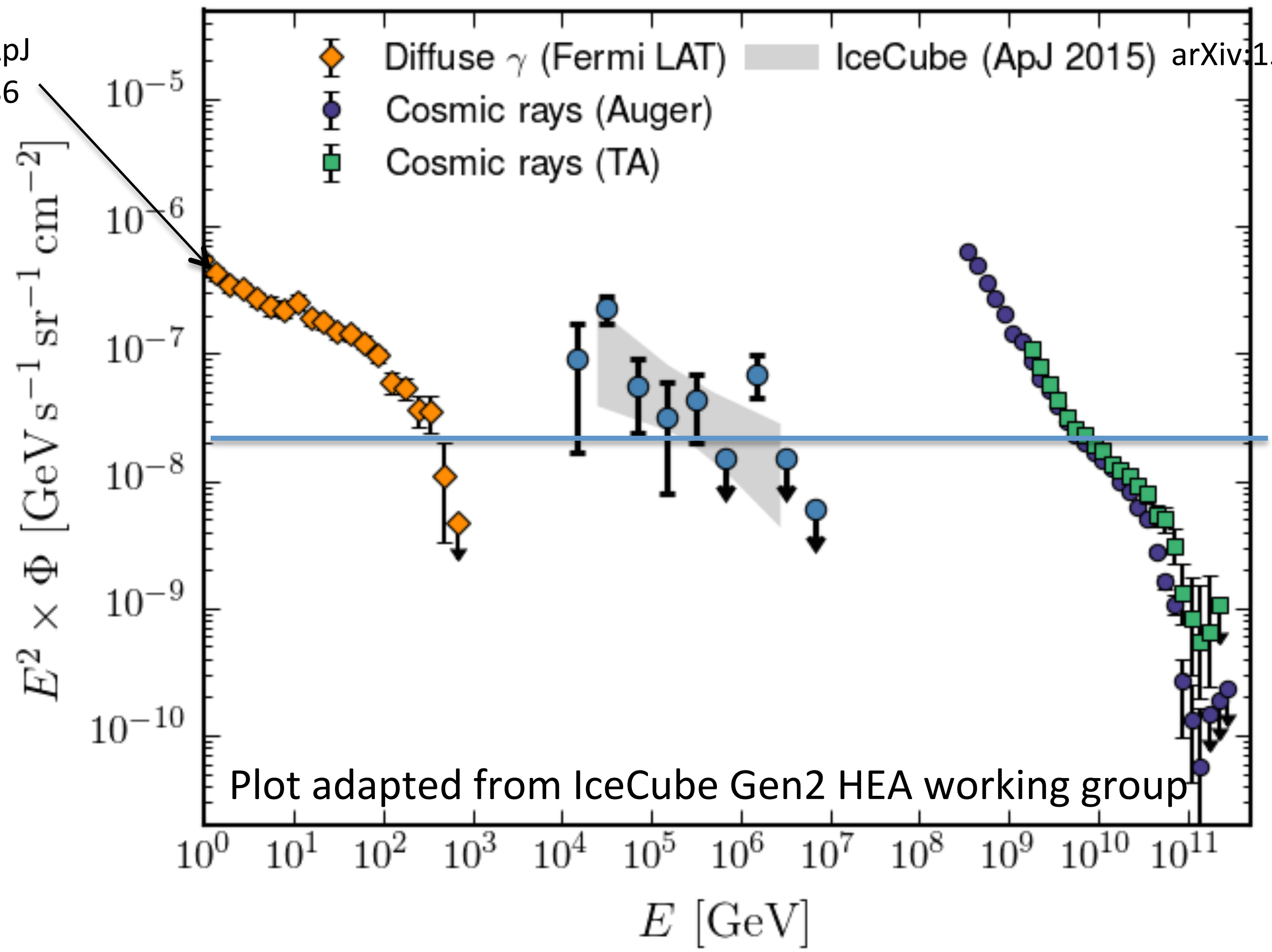


Figure 4. Combined upper limits (UL) at 90% confidence level (blue lines) on the three-flavor neutrino flux of the KRA$_\gamma$ model with the 5 and 50 PeV cutoffs (black lines). The boxes represent the diffuse astrophysical neutrino fluxes measured by IceCube using an isotropic flux template with starting events (yellow) and upgoing tracks (green).

Extragalactic neutrinos
The multi-messenger landscape

IGRB from Fermi LAT, ApJ 799 (2015) 86



arXiv:1507.03991

Waxman-Bahcall bound. PR D59 (1998) 023002

Correlation of HE neutrinos with UHECR ?

Comments:

- UHECR sources < 200 Mpc
- Neutrinos to $R_H \approx 4000$ Mpc
- No evidence yet for ν from UHECR
- AGN cores could give ν, with UHECR from termination shocks
- Remember the Hillas plot

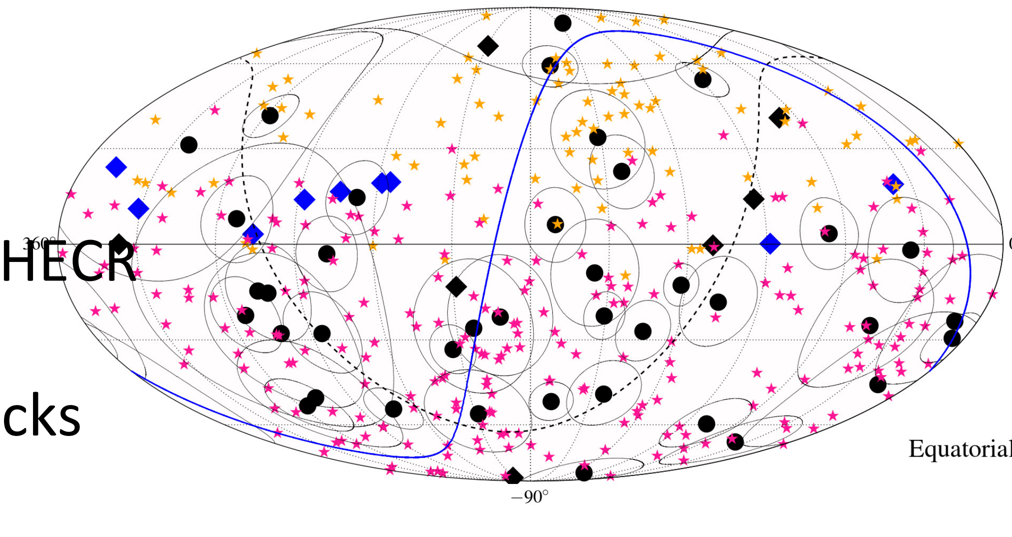
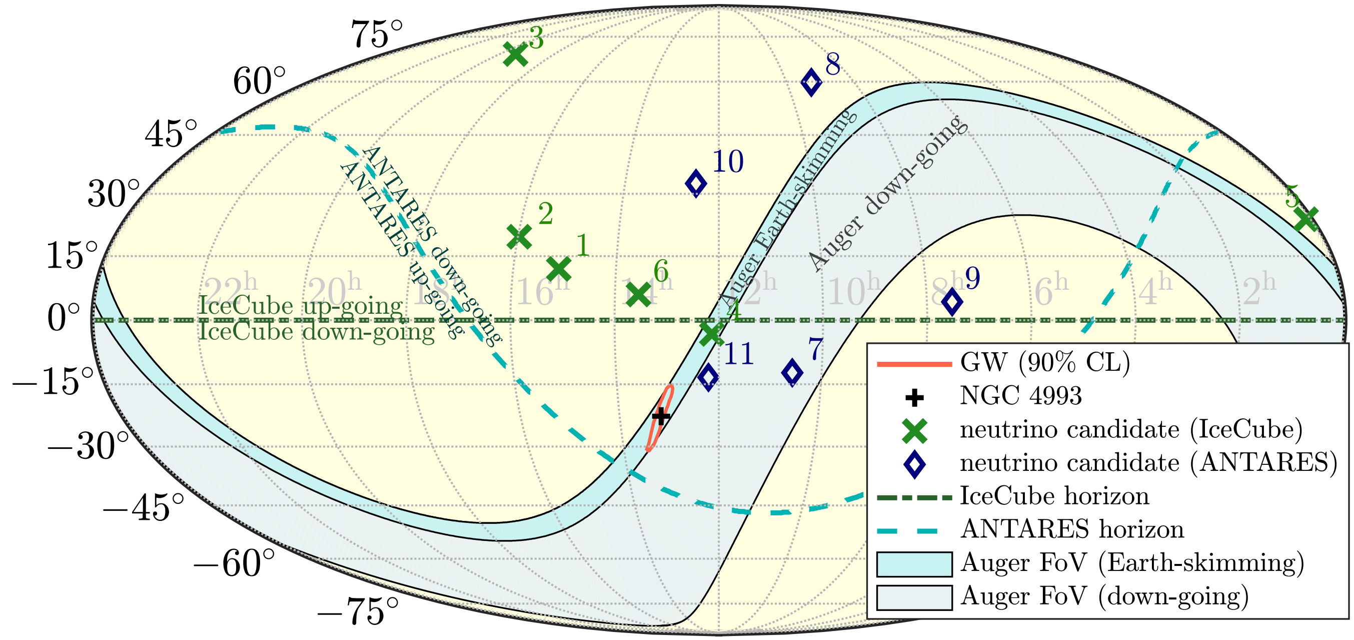


Figure 7. Maps in Equatorial and Galactic coordinates showing the arrival directions of the IceCube cascades (black dots) and tracks (diamonds), as well as those of the UHECRs detected by the Pierre Auger Observatory (magenta stars) and Telescope Array (orange stars). The circles around the showers indicate angular errors. The black diamonds are the HESE tracks while the blue diamonds stand for the tracks from the through-going muon sample. The blue curve indicates the Super-Galactic plane.

JCAP01 (2016) 037

Correlation of ν with GW from NS-NS merger ?

Search for neutrinos coincident with GW170817 by ANTARES, IceCube, Auger (arXiv:1710.05839v2, Ap.J. 850 (2017) L35)



Extragalactic neutrinos

$$F_\nu = \int L_\nu \rho \frac{\mathrm{d}^3 r}{4\pi r^2} = \frac{1}{4\pi}\int L_\nu \rho \,\mathrm{d}\Omega \mathrm{d}r \qquad \frac{\mathrm{d}F_\nu}{\mathrm{d}\Omega} = \xi \frac{L_\nu \rho R_H}{4\pi}, \;\; R_H = 4000\,\mathrm{Mpc}$$

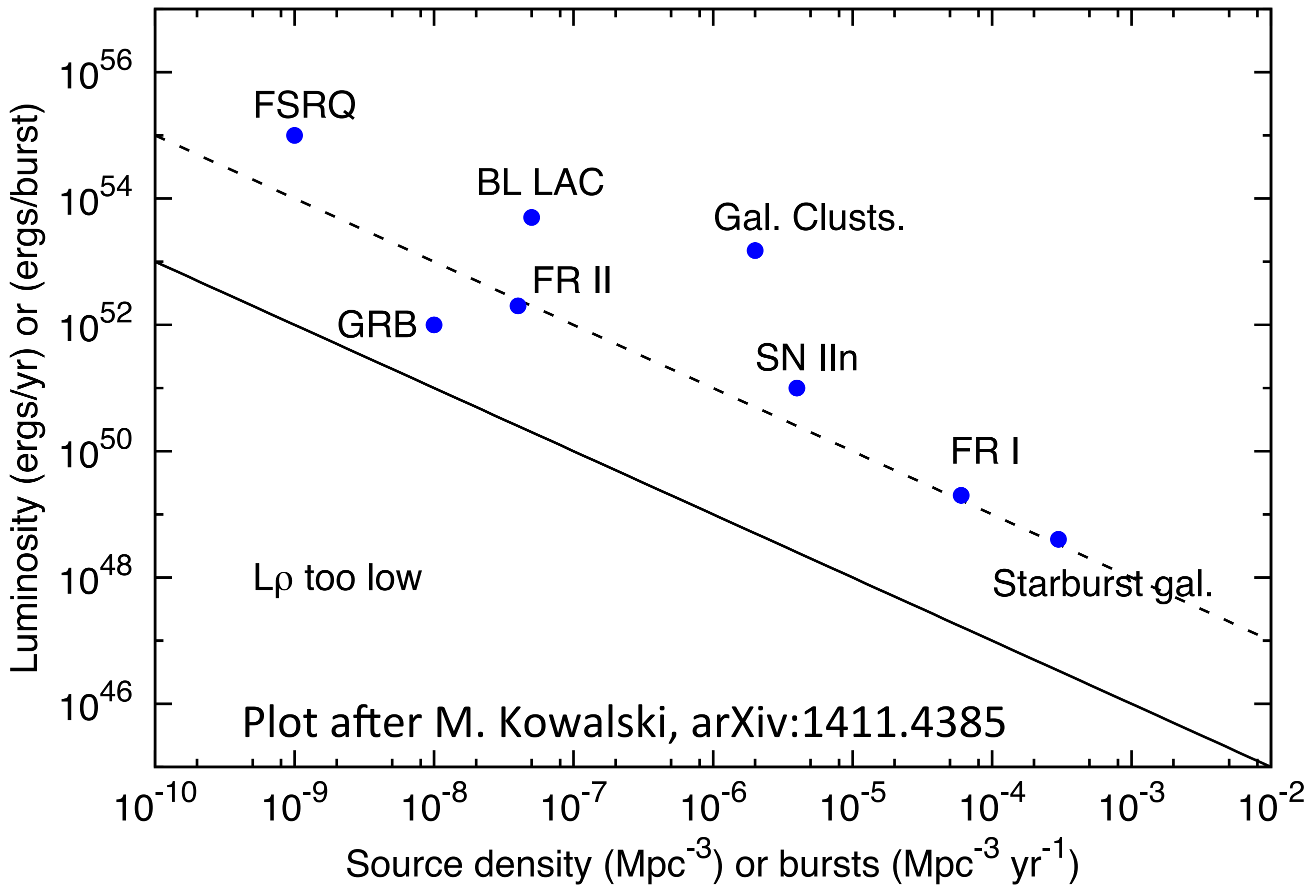
Equate F_ν to IceCube Flux and assume E^{-2} spectrum for illustration

$$\xi \frac{L_\nu \rho R_H}{4\pi} = \frac{E_\nu \mathrm{d}N_\nu}{\mathrm{d}\Omega\,\mathrm{d}\ln(E_\nu)} = 2.8\times 10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm}^2\mathrm{s\,sr}} = 1.3\times 10^{46}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^2\mathrm{yr\,sr}}$$

Invert to get minimum power density to produce the signal

$$\rho\, L_\nu = \frac{4\times 10^{43}}{\xi}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{yr}} \sim 10^{43}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{yr}}$$

Kowalski plot (L_ν vs ρ)



Dashed line assumes 1% efficiency for production of neutrinos

Point source limits

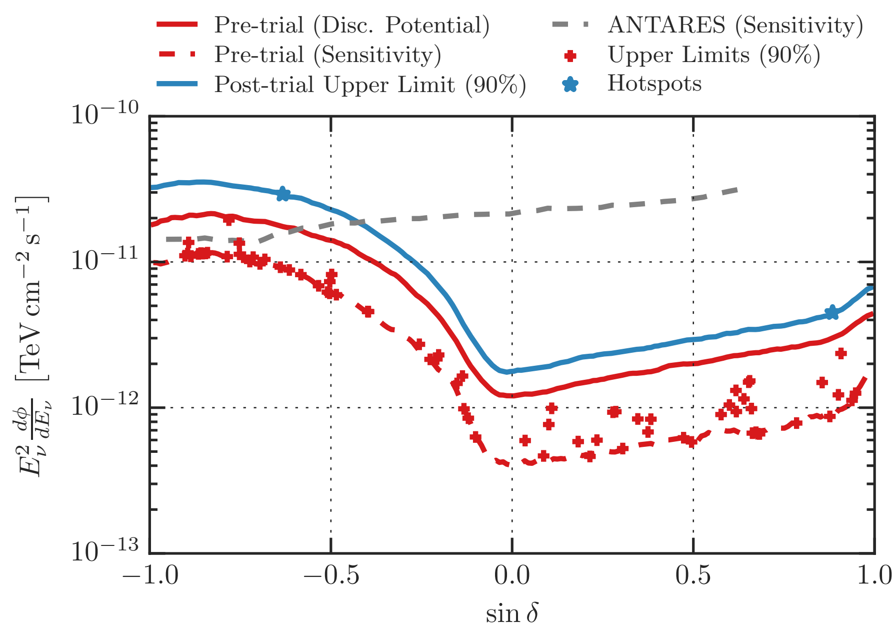
Relation between flux from whole sky and number/intensity of individual sources

P. Lipari, PR D78 (2008) 083001 … Ahlers & Halzen, PR D90 (2014) 043005 …

Murase & Waxman, PR D94 (2016) 103006; Ahlers & Halzen, arXiv:1805.11112

IceCube 7 yr pt src search

Ap.J. 835 (2017) 151



Northern hemisphere, good pointing with ν_μ-induced μ, limits

$$< 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1}}$$

Minimum density of sources

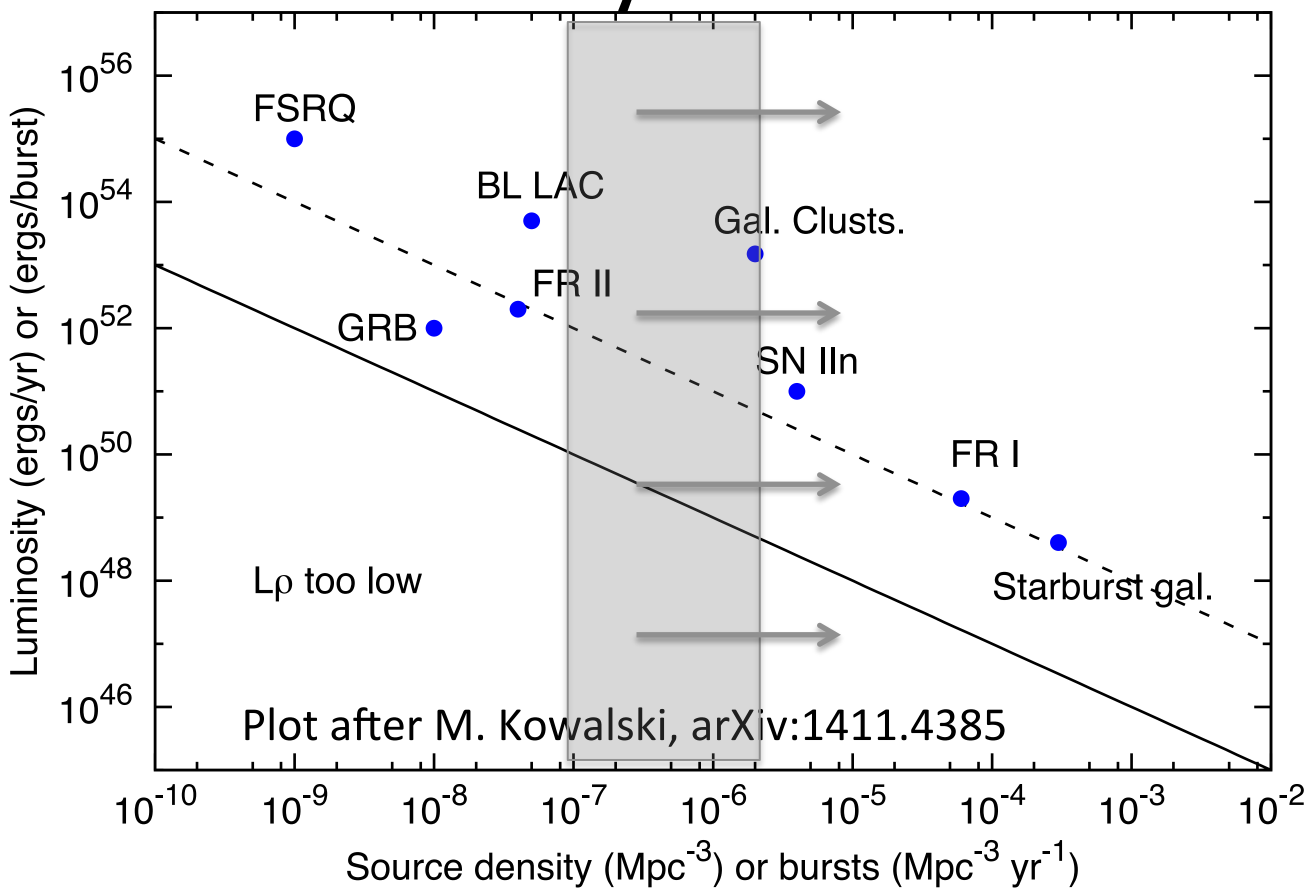
For a distribution of sources each with L_ν and density ρ, estimate the distance to a nearby source as $d=(4\pi\rho)^{-1/3}$.
Then the flux from a nearby source is $F_\nu \approx \frac{L_\nu}{4\pi d^2} = \frac{L_\nu d}{4\pi d^3} = L_\nu \rho d.$

Pt. src. Limits give $F_\nu < 2 \times 10^{-9}\ \mathrm{GeV\,cm^{-2}s^{-1}}$

So $d < \frac{2 \times 10^{-9}\ \mathrm{GeV\,cm^{-2}s^{-1}}}{L_\nu \rho}$. But $L_\nu \rho \sim \frac{4 \times 10^{43}}{\xi} \frac{\mathrm{erg}}{\mathrm{Mpc^3\,yr}}$

$$\text{Then } d < 100 \times \frac{\xi}{3} \text{ and } \rho > \frac{1}{4\pi d^3} \sim \frac{10^{-7}}{\mathrm{Mpc}^3} \left(\frac{3}{\xi}\right)^3$$

Implications of limits on point sources for density of sources



Dashed line assumes 1% efficiency for production of neutrinos

When will a point source emerge?

Events from a nearby source: $$\frac{L_\nu \otimes A_{eff}}{4\pi d^2} = \frac{\text{events}}{\text{cm}^2\text{s}}$$

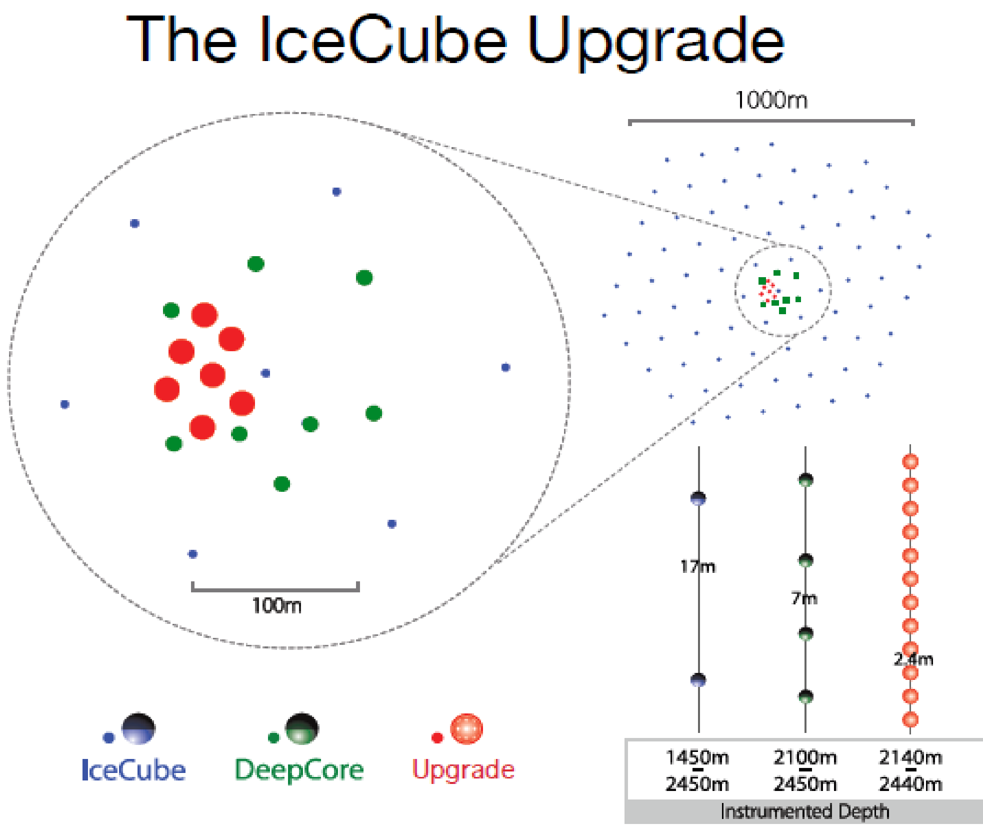
Events from whole sky: $$\xi \times L_\nu \rho R_H \otimes A_{eff}$$

Ratio: $$\frac{d}{\xi R_H} = \frac{1}{\xi (4\pi\rho)^{1/3} R_H}$$

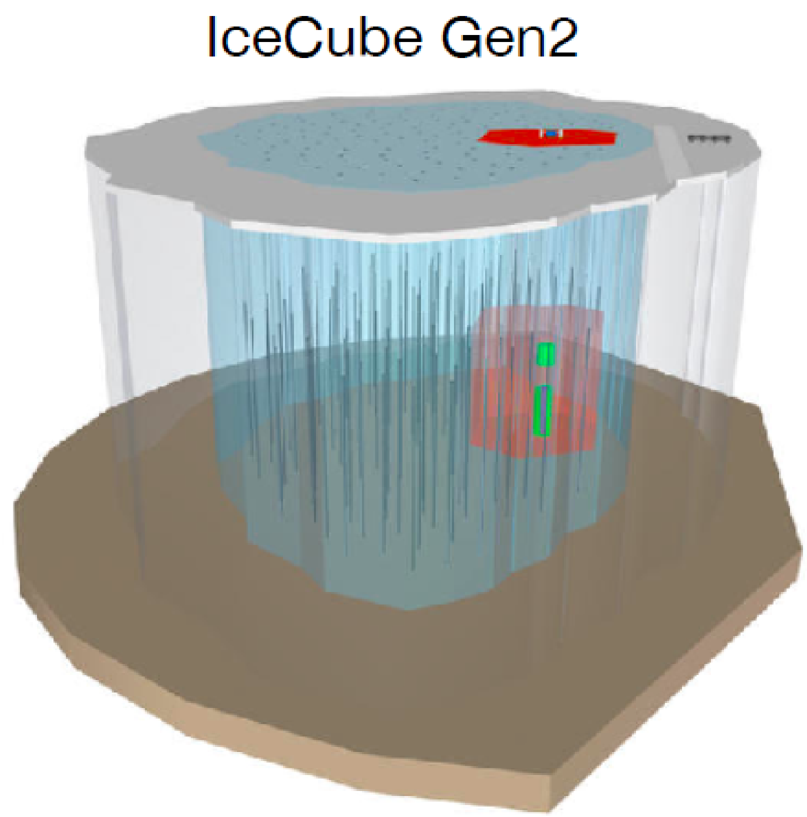
This ratio is small for high density of sources (e.g. 1/4000 for d = 2 Mpc) .
For d = 100 Mpc, $\rho = 10^{-7}$, the ratio is 1/100. In this case we should soon identify a source; hence the importance of the real-time alerts.

A plot of events vs distance (z) would show a few events from nearby sources and a scattering of events up to large z from unresolved sources

Future



- Funding for upgrade has started
- Neutrino physics with IceCube
- Calibration for HE neutrinos
- Planned deployment: 2022/23



- Expected to follow upgrade
- 8 times volume of IceCube
- In tandem with radio for EHE