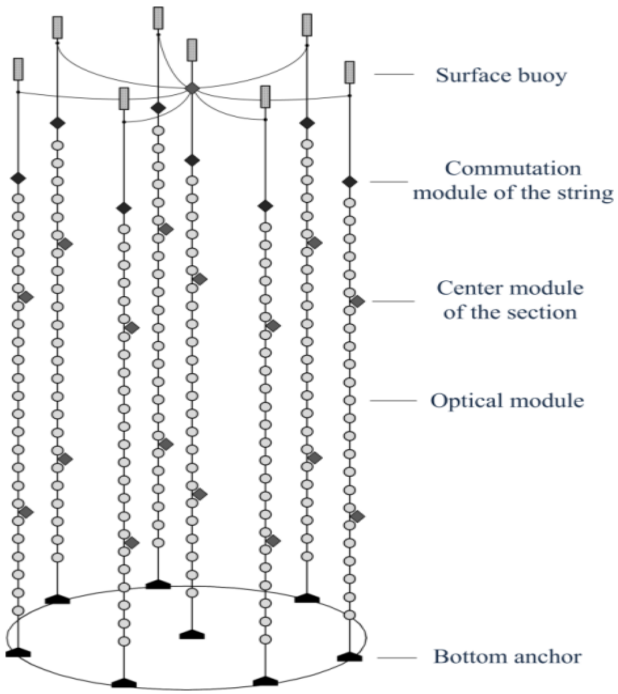
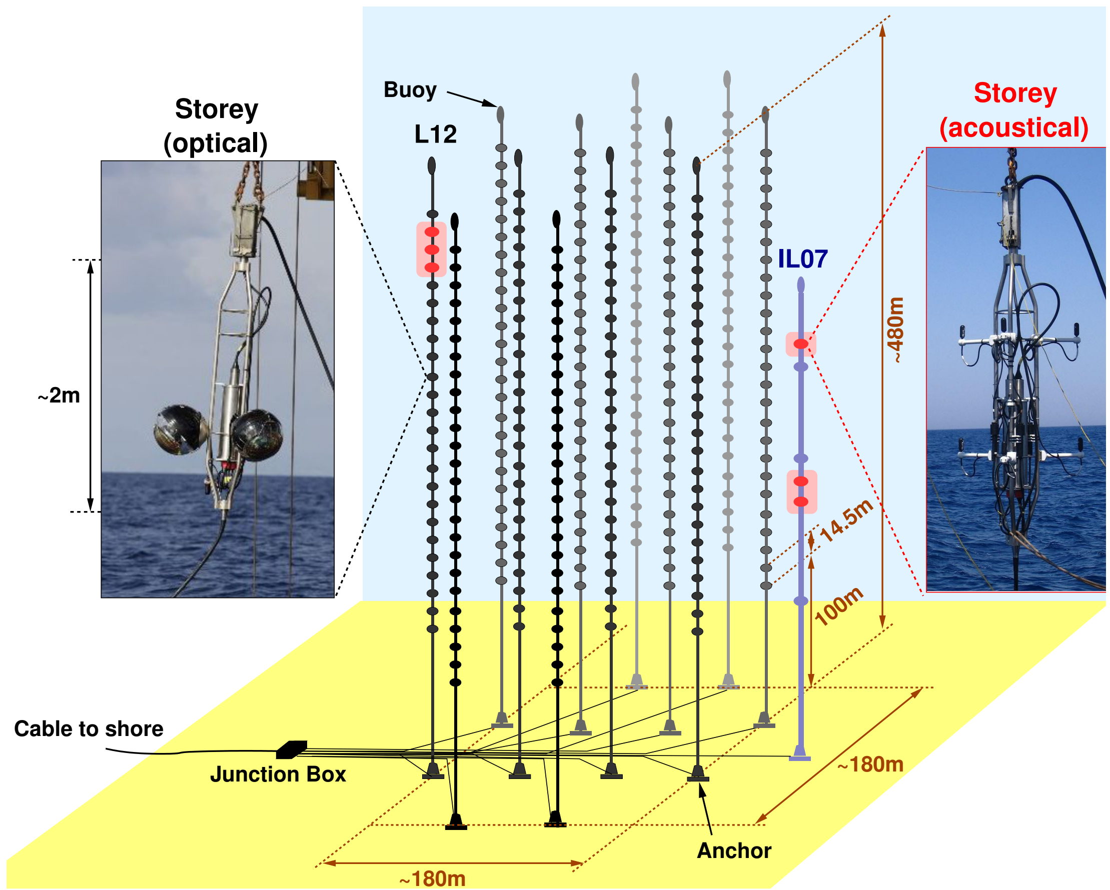
# Neutrino astronomy

and atmospheric neutrinos

# Present detectors




First cluster of Baikal-GVD




ANTARES has now run for 10 years. See presentation of Antoine Kouchner this session.

# IceCube

Carlos Arguelles, next talk

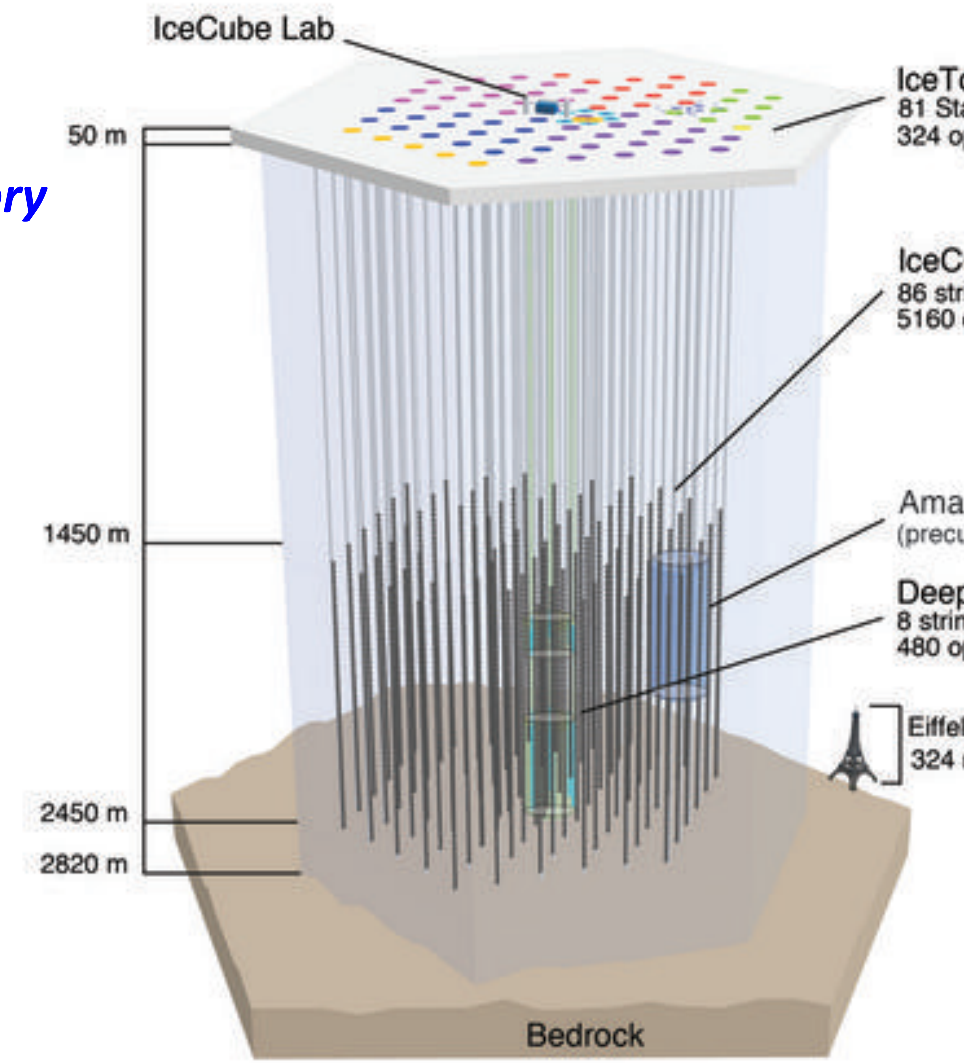
***Deployment history***

**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

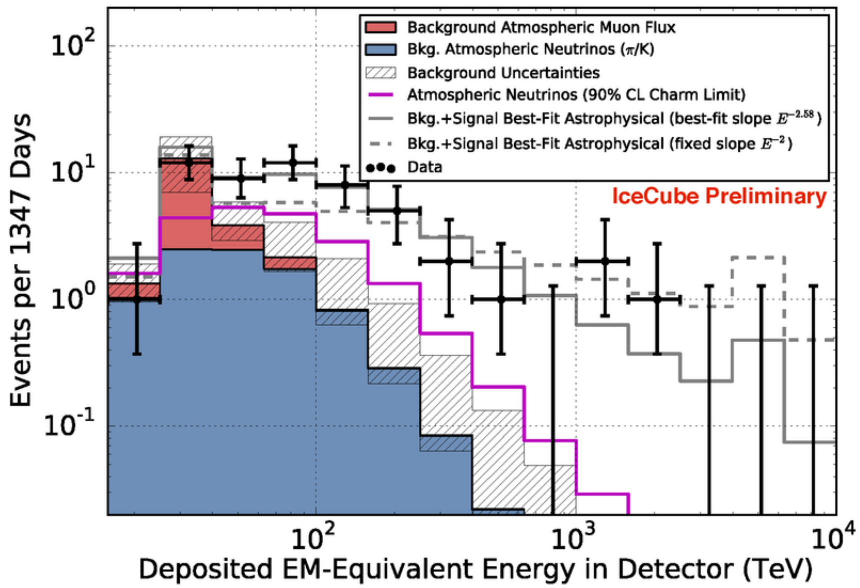
Surface stations

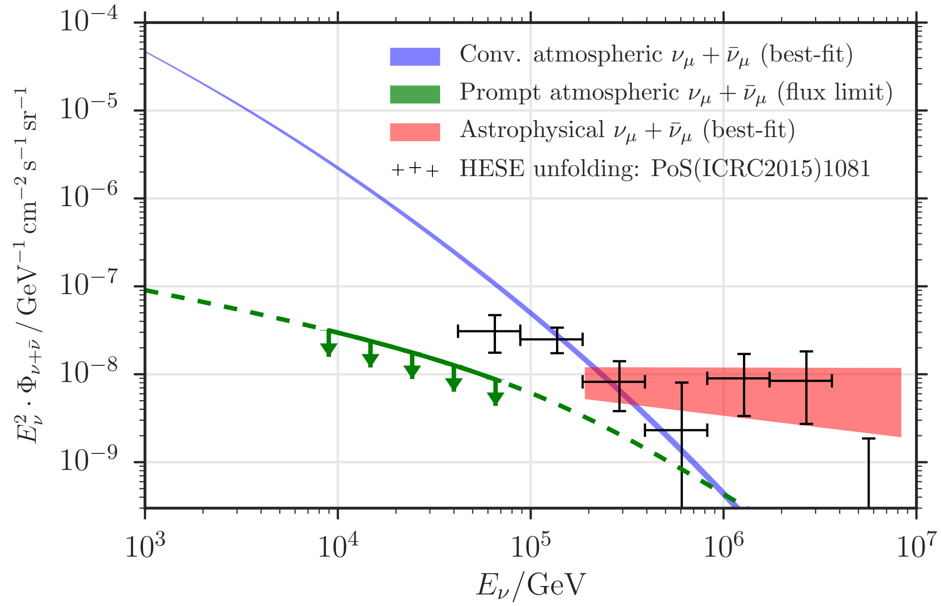



> 5400 Digital Optical Modules

# IceCube Construction: 2004-2011

# Astrophysical neutrinos



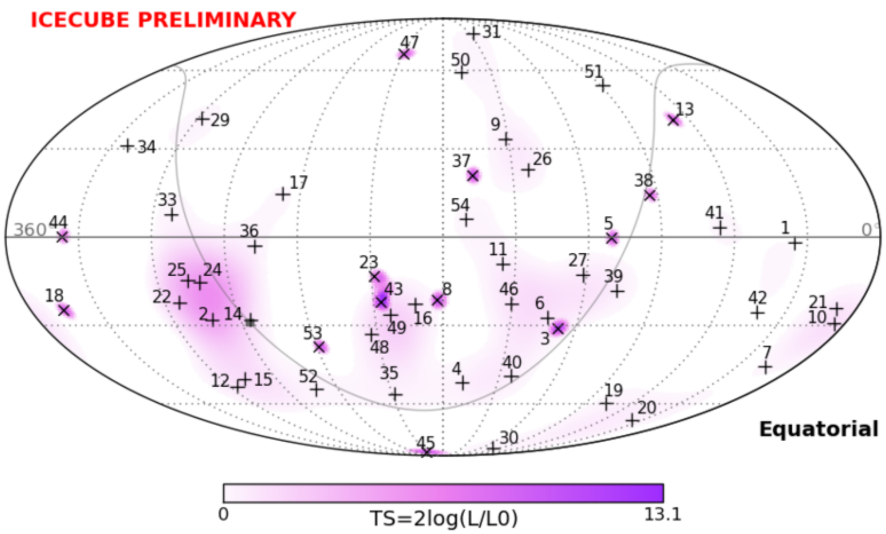

IceCube *4 year* HESE analysis
( HESE = High Energy Starting Event )
ICRC 2015 arXiv:1510.05223

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

**Note upper limits on prompt atmospherics**

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

# Sky maps of high-energy events




IceCube HESE 4 year
ICRC 2015 arXiv:1510.05223

IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
arXiv:1607.08006 (accepted for ApJ)

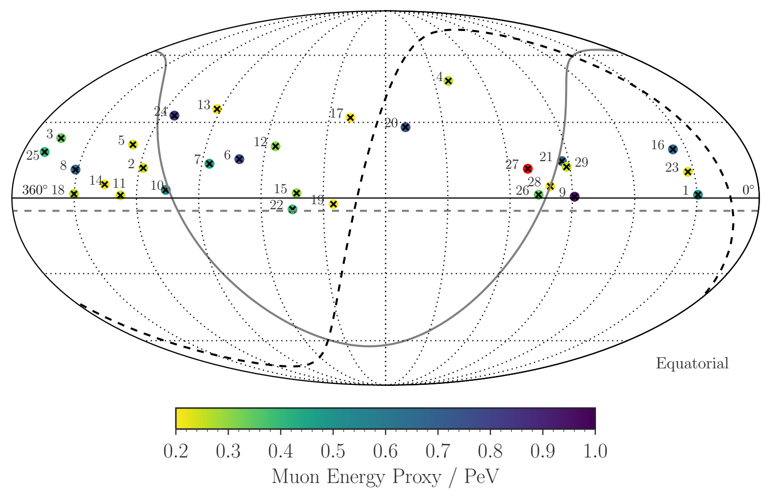



**Figure 16**. Arrival directions of events with a muon energy proxy above 200TeV. Given the best-fit spectrum the ratio of astrophysical to atmospheric events is about two to one. The horizontal dashed gray line shows the applied zenith angle cut of 85°. The curved gray line indicates the galactic plane 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 point source is identified yet*

# High-energy astrophysical neutrinos

*Cosmic-ray – gamma-ray – Neutrino connection*

Galactic | Extragalactic

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

## Galactic

**Diffuse**

C.R. + gas → ν

Stecker, 1979
:
Gaggero et al, 2015

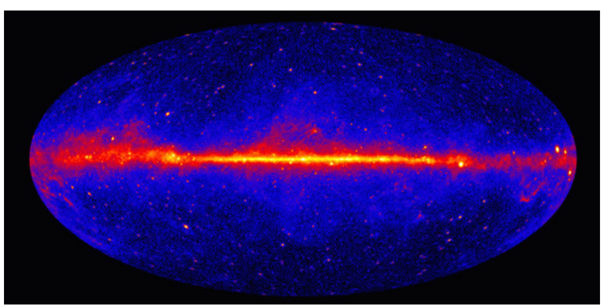
**Sources**

e.g. SNR near clouds

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

Ahlers et al., PR D93 (2016)

Analogous to $\gamma$ -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.

# Limits on neutrinos from Galactic plane

ANTARES, arXiv:1705.00497

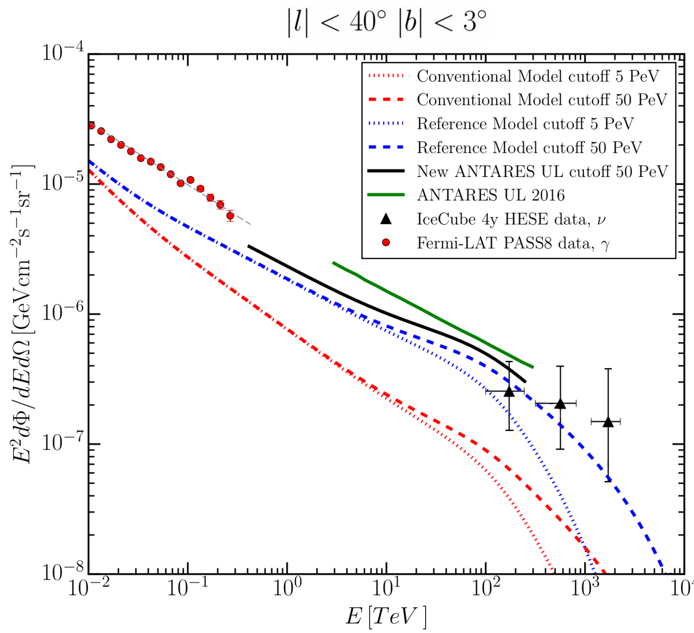
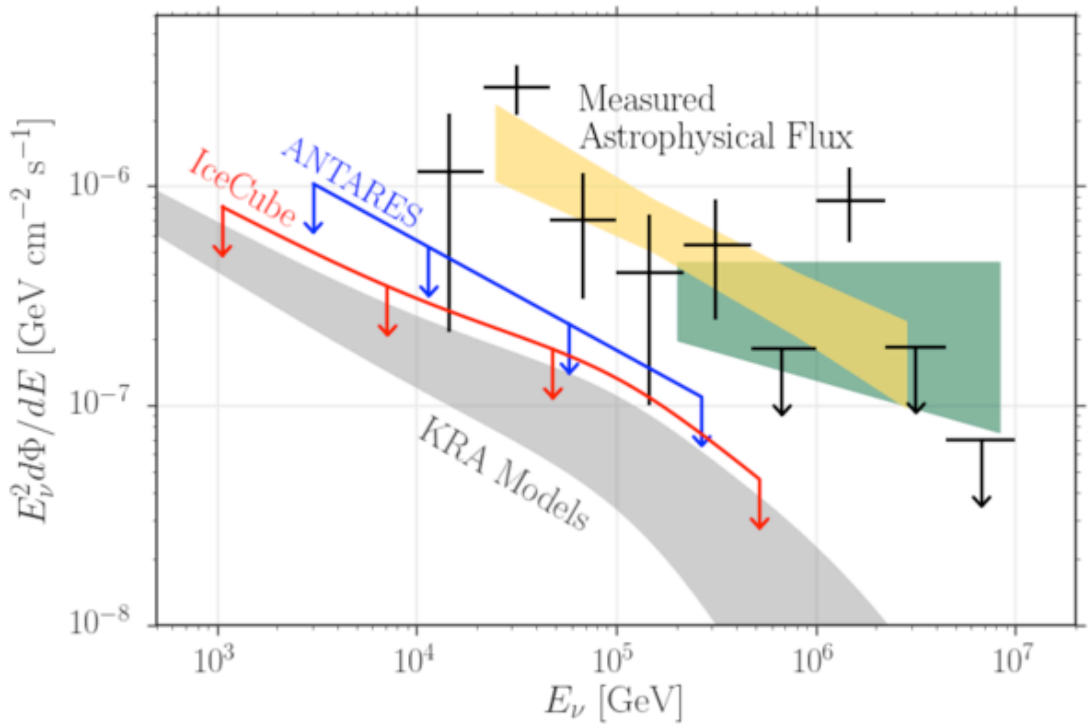



Figure 3: ANTARES upper limit at 90% confidence level on the three flavour neutrino flux (solid black line) on the reference model with a 50 PeV energy cut-off (blue dashed line). The neutrino fluxes according to the reference model with the 5 PeV energy cut-off (blue dotted line), the conventional model with the 50 PeV (red dashed line) and 5 PeV (red dotted line) cut-offs are shown for all neutrino flavours, as well as the previously published ANTARES upper limit (solid green line) and the 4 years of HESE reconstructed by IceCube (black triangles). The diffuse gamma ray spectral energy distribution derived from PASS8 Fermi-LAT data (red points) is also presented here.

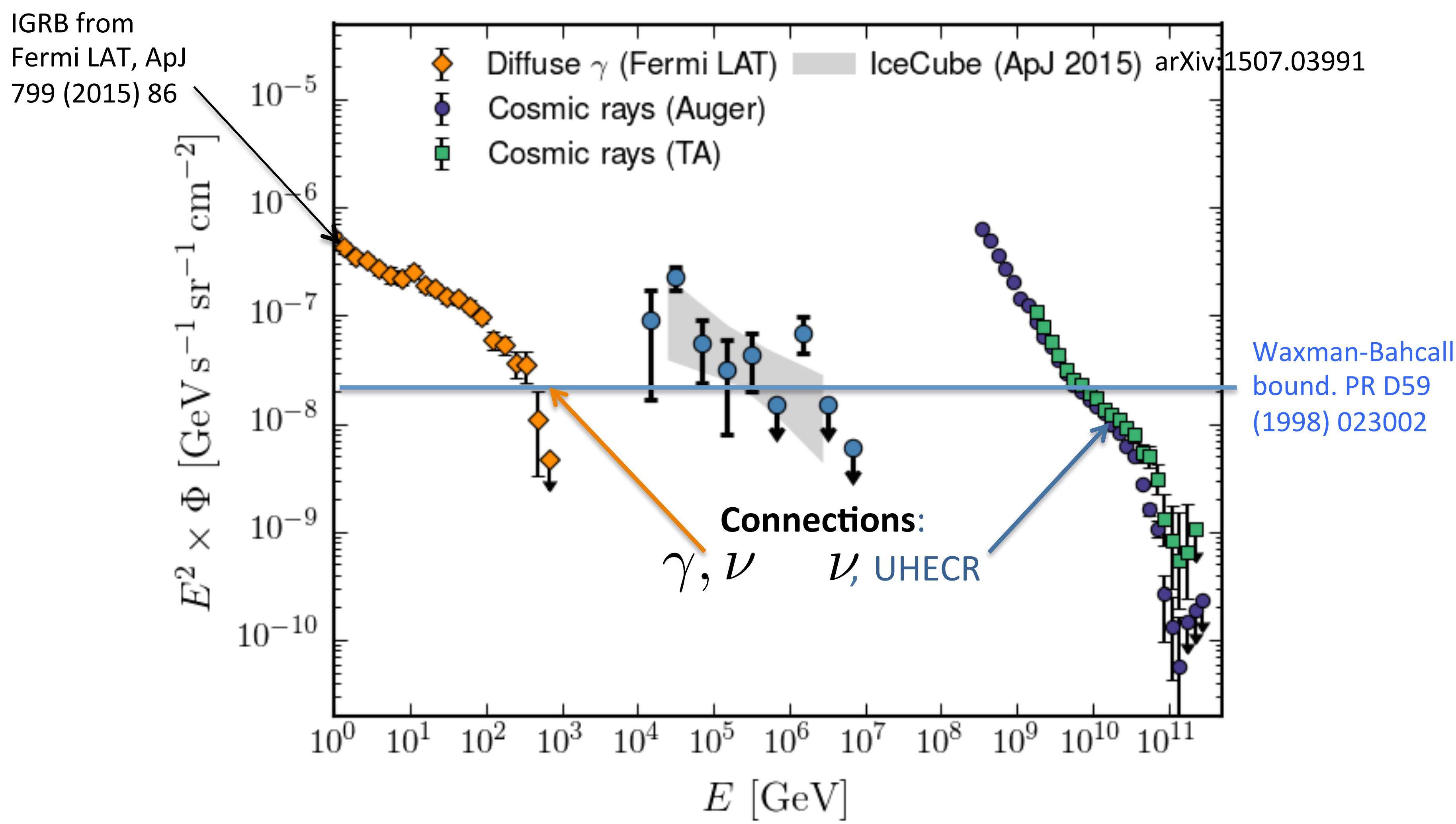



IceCube, ICRC 2017
Converted to all flavor, full sky for comparison with diffuse flux.

# Galactic fraction

- Of order 10%
- It is a guaranteed source
- Limits are close to predictions
- Galactic plane will be resolved, if not by Antares and IceCube, then by KM3NeT and IceCube Gen2
- Galactic point sources not yet seen

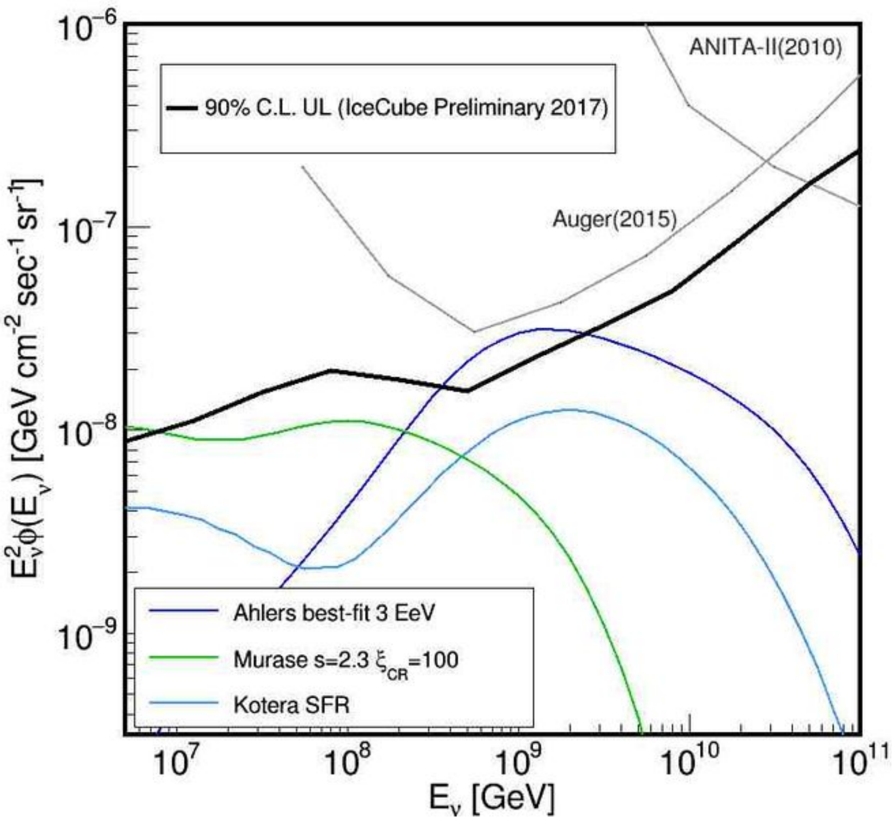
# Extragalactic neutrinos
# The multi-messenger landscape

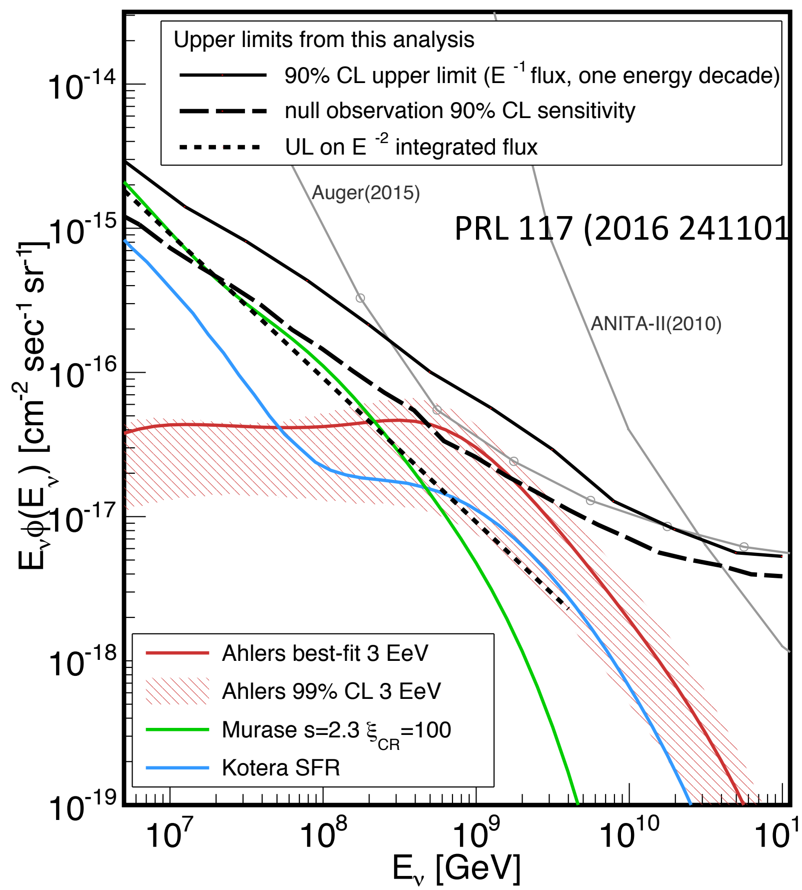


# UHECR & Cosmogenic neutrinos

- IceCube limits compared to models

PRL 7 years data



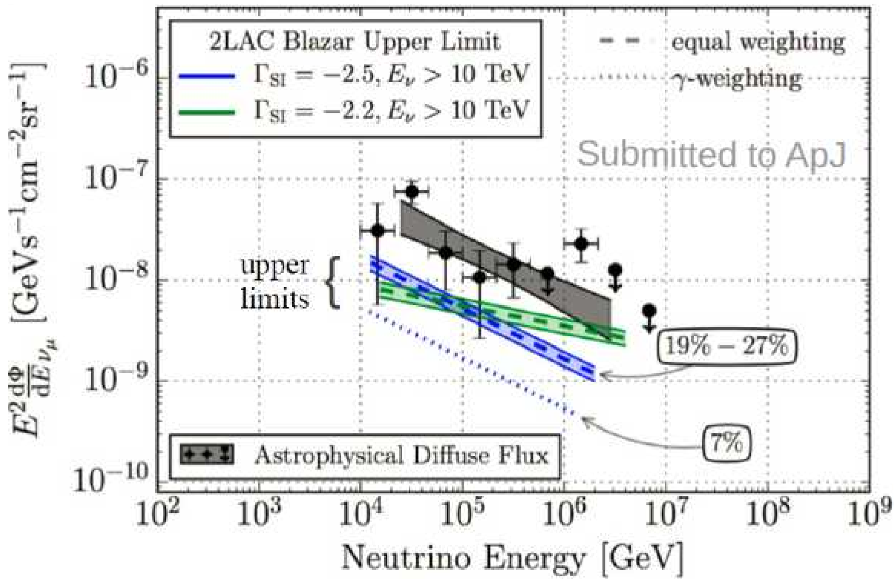

ICRC 2017, 9 years data

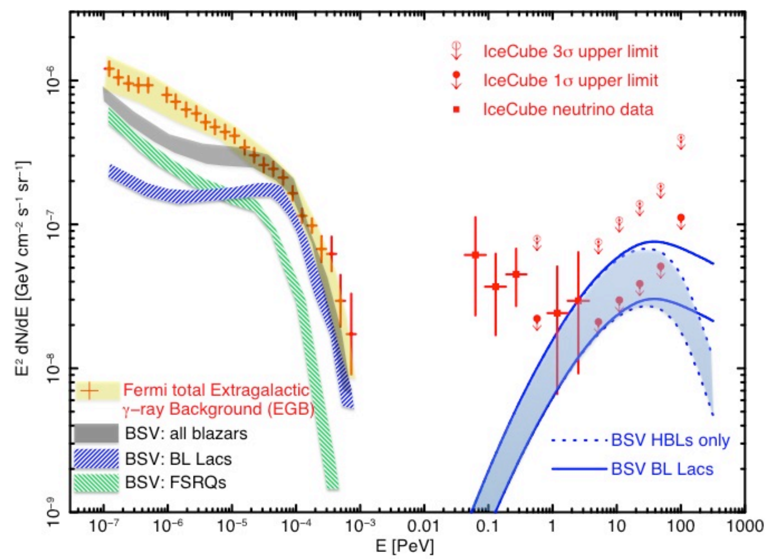
# Implications of EHE limits

- Models of UHECR source with strong evolution dominated by protons are disfavored
  - Auger* composition result suggests $R_{max} \sim 3x10^{18}$ V so the highest energy cosmic rays may be nuclei

    *PR D90 (2014) 12206
- The absence of neutrinos of 10 PeV and higher limits models in which neutrinos are produced *inside* the same sources that produce UHECR (whether they are protons or nuclei)
- Such inferences are possible because the Universe is transparent to neutrinos

# Blazars, AGN, GRB




- IceCube Upper limit: blazars < 20% of observed astrophysical flux,
  Ap.J. 835 (2017) 45

- GRB limits are even stronger:
  IceCube, arXiv:1702.06868

Padovani et al., MNRAS 457 (2016) 3582

Blazars may contribute with hard spectrum at high energy but not account for all the flux.

# Two extremes for acceleration of UHECR by active galaxies

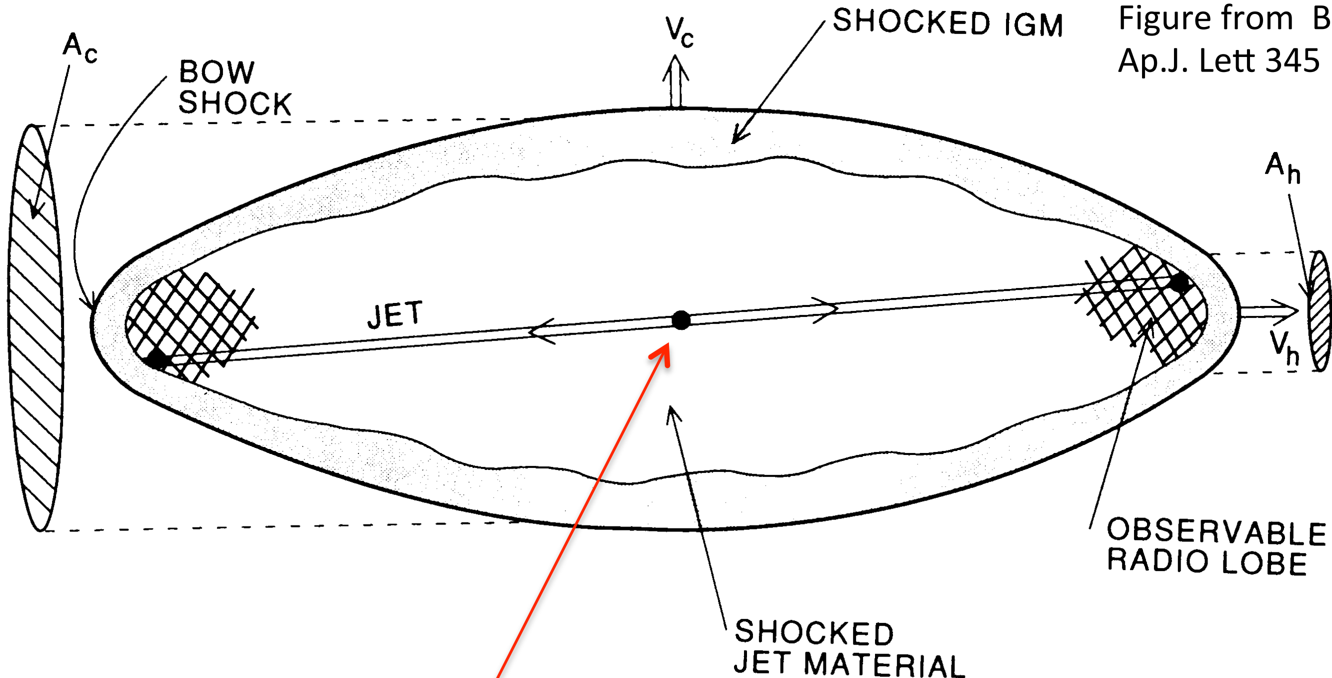



Figure from Begalman & Cioffi, Ap.J. Lett 345 (1989) L21-24

- Inside jets in the nucleus (with abundant neutrino production)
  Murase et al., PR D90 (2014) 023007, Padovani et al., MNRAS 452 (2015) 1877, many others
- At the termination shock (far out with little neutrino production)
  E.G. Berezhko, Ap.J.Lett. 684 (2008) L69-L71 (See also “Radio galaxy lobes” in the Hillas plot)

# Power needed to produce the diffuse (extra-galactic) IceCube signal

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

where the Hubble radius is $R_H = \frac{c}{H_0} \approx 4000 Mpc$

The cosmological factor is $\xi = \int_0^\infty \frac{H_0}{H(z)} \frac{\rho(z)}{\rho_0} \frac{\mathrm{d}z}{1+z} \sim 3$

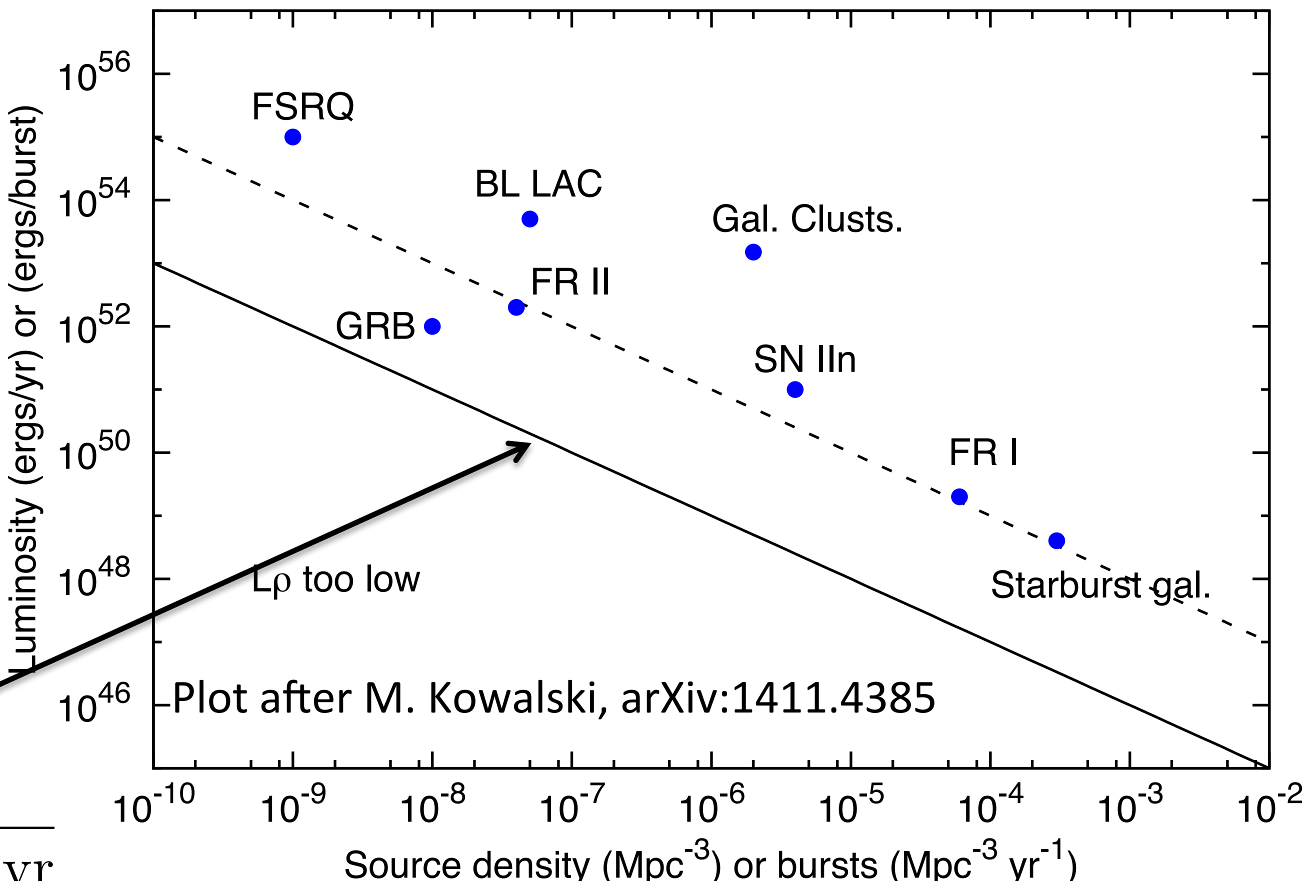
Assume $E^{-2}$ spectrum and equate the Flux to the observed IceCube signal:

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

and find the implied source power density

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

# Kowalski plot shows luminosity vs source density




$$\rho L_\nu = 10^{43} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

Dashed line assumes 1% efficiency for production of neutrinos

# Implications of point source limits

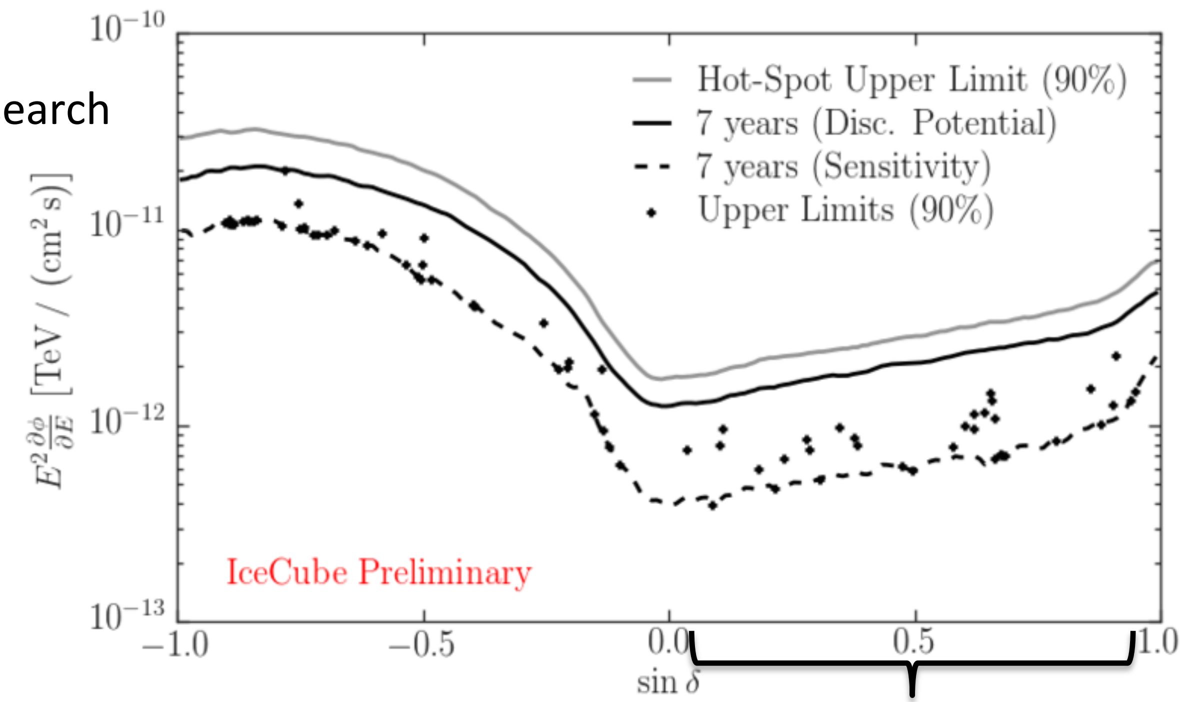
*Relation between flux from whole sky and number/intensity of individual sources*

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

Murase & Waxman, PR D94 (2016) 103006

IceCube 7 yr pt src search

Ap. J. 835 (2017) 151




Northern hemisphere, good pointing with $\nu_\mu$-induced μ, limits

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

# Minimum density of sources

For a distribution of sources each with $L_\nu$ and density ρ, estimate the distance to a nearby source: $d \sim (4\pi\rho)^{-1/3}$

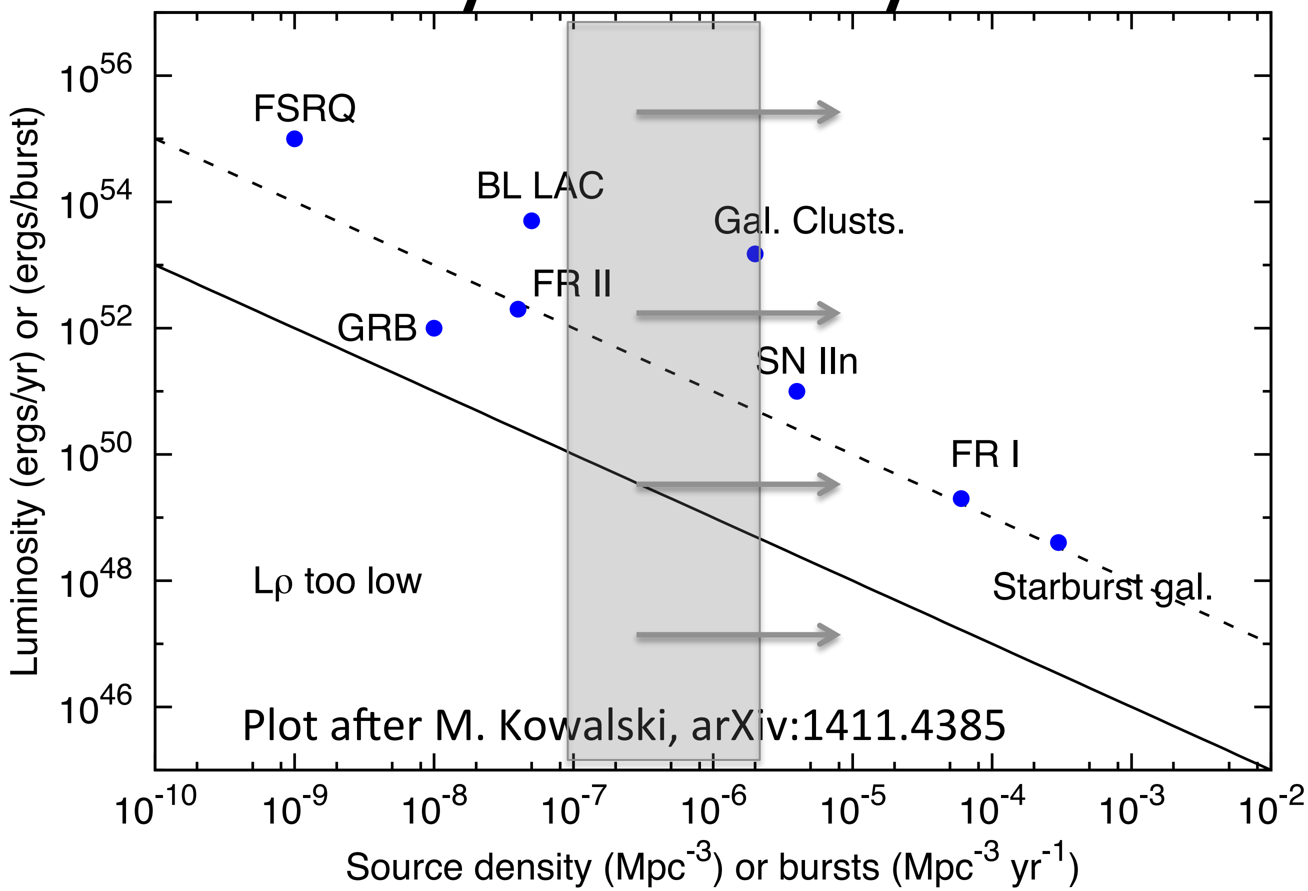
Then the flux from a nearby source is $F_\nu \approx \frac{L_\nu}{4\pi d^2} = \frac{L_\nu d}{4\pi d^3} = L_\nu \rho d.$

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 steady sources




Dashed line assumes 1% efficiency for production of neutrinos

# Star forming galaxies and SNIIn

- Both have attractive features:
  - High density, so point source limits are ok
  - Acceleration by SN shocks so $E_{max}$ is consistent with absence of $\geq$ 10 PeV neutrinos
- Both must avoid exceeding the Fermi limit on non-blazar diffuse gamma-rays
  - Many papers on this problem for starburst galaxies
  - Spectral index must be harder than 2.2

    Murase, Ahlers & Lacki, PR D88 (2013) 121301
  - and even that may not be enough

    Bechtol et al., Ap.J. 836 (2017) 47

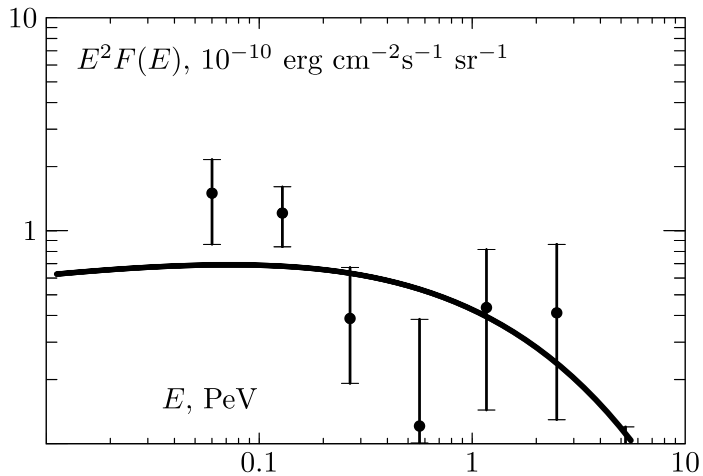
# Type IIn Supernova explosions

Murase et al., PR D84 (2011) 043003

Explosion into dense wind of progenitor star

Acceleration to $10^{17}$ eV; ν to > PeV with cutoff; Δ < 30 yrs

Zirakashvili & Ptuskin, Astropart. Phys. 78 (2016) 28.




Zirakashvili & Ptuskin, Astropart. Phys. 78 (2016) 28.
Integrated flux from all Type Iin SNR could account for high-energy part of IceCube signal with a cutoff

Zirakashvili and Ptuskin note two possible coincidences:

- SN 2005bx at z=0.03 is 1.35$^{o}$ from HESE #47 track
- SN 2005jq at z=0.23 is 0.3$^{o}$ from track event #11 in upward $\nu_\mu$ sample

# 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: $$\frac{\text{nearby}}{\text{all sky}} \sim \frac{d}{\xi R_H} \approx \frac{1}{\xi (4\pi\rho)^{1/3} R_H}$$

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.

# Near real-time alerts now in operation at IceCube

TITLE: GCN/AMON NOTICE
NOTICE_DATE: Mon 01 Aug 16 02:35:38 UT
NOTICE_TYPE: AMON ICECUBE HESE
RUN_NUM: 128290
EVENT_NUM: 6888376
SRC_RA: 214.5440d {+14h 18m 11s} (J2000),
214.7568d {+14h 19m 02s} (current),
213.9029d {+14h 15m 37s} (1950)
SRC_DEC: -0.3347d {-00d 20' 04"} (J2000),
-0.4106d {-00d 24' 37"} (current),
-0.1045d {-00d 06' 15"} (1950)
SRC_ERROR: 45.00 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50: 20.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE: 17600 TJD; 213 DOY; 16/07/31 (yy/mm/dd)
DISCOVERY_TIME: 6904 SOD {01:55:04.00} UT
REVISION: 1
N_EVENTS: 1 [number of neutrinos]
STREAM: 1
DELTA_T: 0.0000 [sec]
SIGMA_T: 0.0000 [sec]
FALSE_POS: 0.0000e+00 [s^-1 sr^-1]
PVALUE: 0.0000e+00 [dn]
CHARGE: 15814.74 [pe]
SIGNAL_TRACKNESS: 0.91 [dn]
SUN_POSTN: 131.73d {+08h 46m 54s} +17.93d {+17d 55' 43"}
SUN_DIST: 83.50 [deg] Sun_angle= -5.5 [hr] (East of Sun)
MOON_POSTN: 107.82d {+07h 11m 18s} +18.14d {+18d 08' 20"}
MOON_DIST: 106.20 [deg]
GAL_COORDS: 343.68, 55.52 [deg] galactic lon,lat of the event
ECL_COORDS: 212.39, 12.72 [deg] ecliptic lon,lat of the event
COMMENTS: AMON_ICECUBE_HESE.

Astropart. Phys., 92, 30 (2017)

Optical follow-up
Gamma follow-up
HESE near real-time alerts
EHE near real-time alerts

An event on 01 August 2016 passed both HESE and EHE alert thresholds

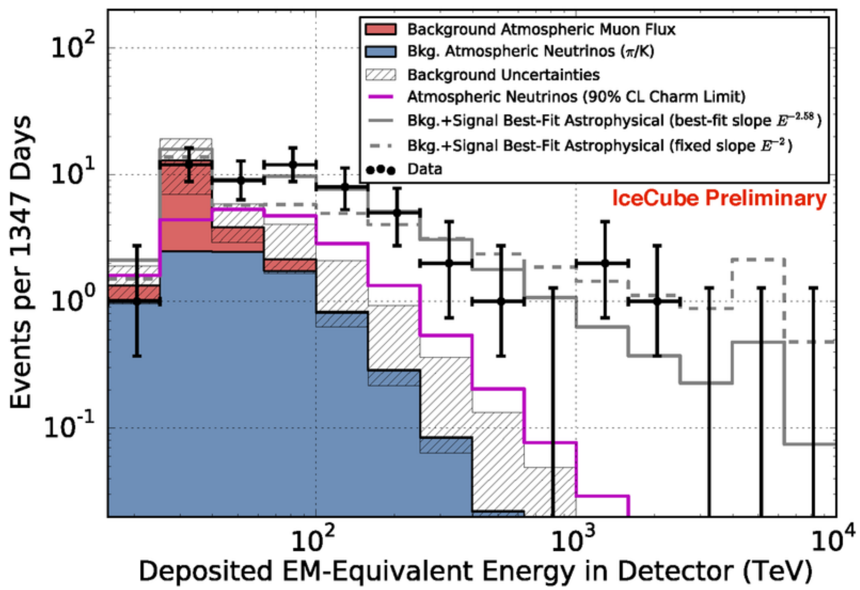
8 alerts in past year

# Prompt neutrinos in IceCube?

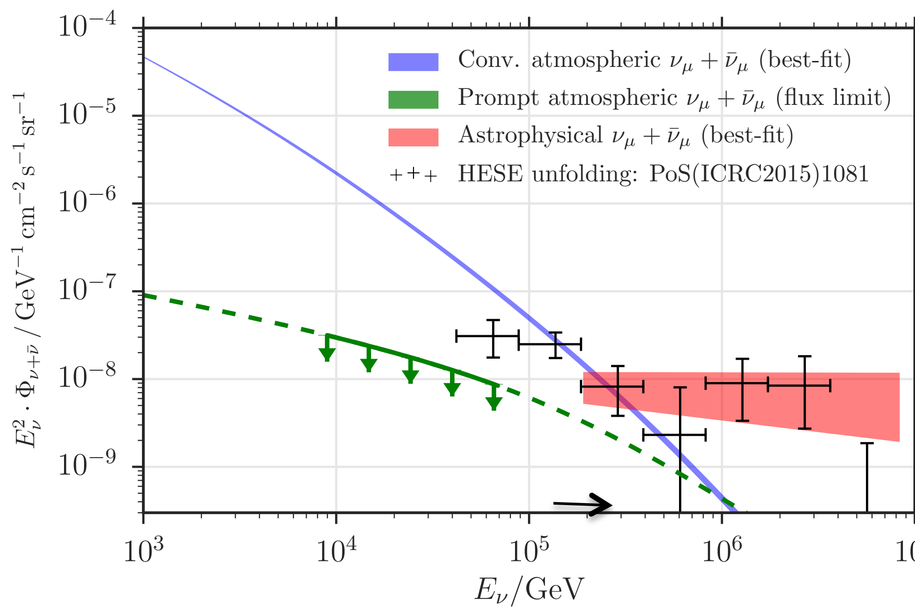
- Charm hadrons with $E < 10$ PeV rarely re-interact
  - $\mu$ and $\nu$ from decay of charm are isotropic and
  - have the same spectrum as the primary cosmic rays
- *Conventional* neutrinos from decay of $\pi^{\pm}$, K have
  - Angular dependence proportional to $\sec(\theta)$
  - Energy spectrum steeper than primary cosmic rays
- Prompt neutrinos from decay of charm
  - exceed atmospheric neutrinos at very high energy
  - but are obscured by astrophysical neutrinos

# Astrophysical neutrinos

IceCube *4 year* HESE analysis
( HESE = High Energy Starting Event )
ICRC 2015 arXiv:1510.05223



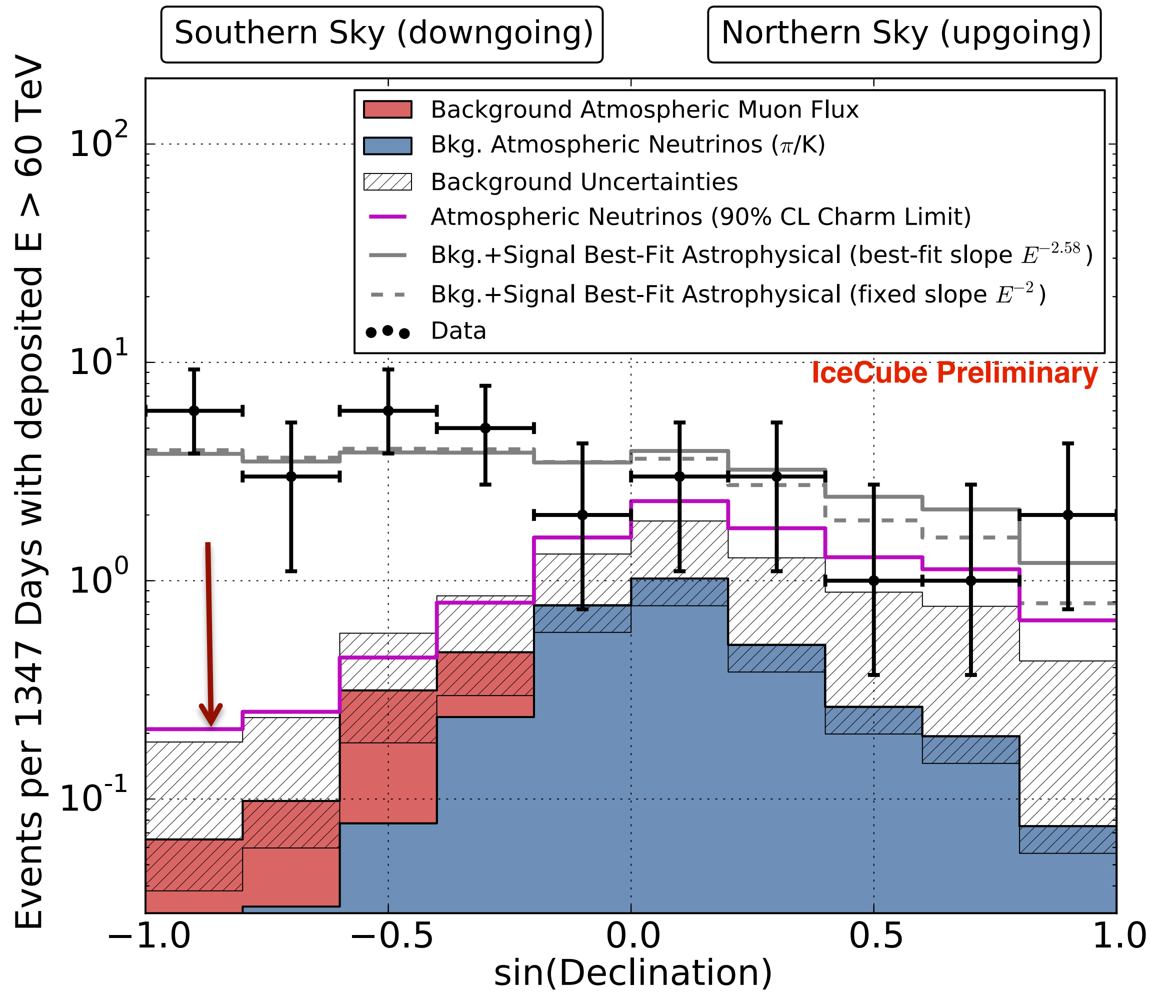

IceCube 6 year $\nu_\mu$ μ analysis
Ap.J. 833 (2016) 3




*Note upper limits on prompt atmospheric neutrinos*

# Angular distribution (E> 60 TeV)

Effect of atmospheric ν self-veto



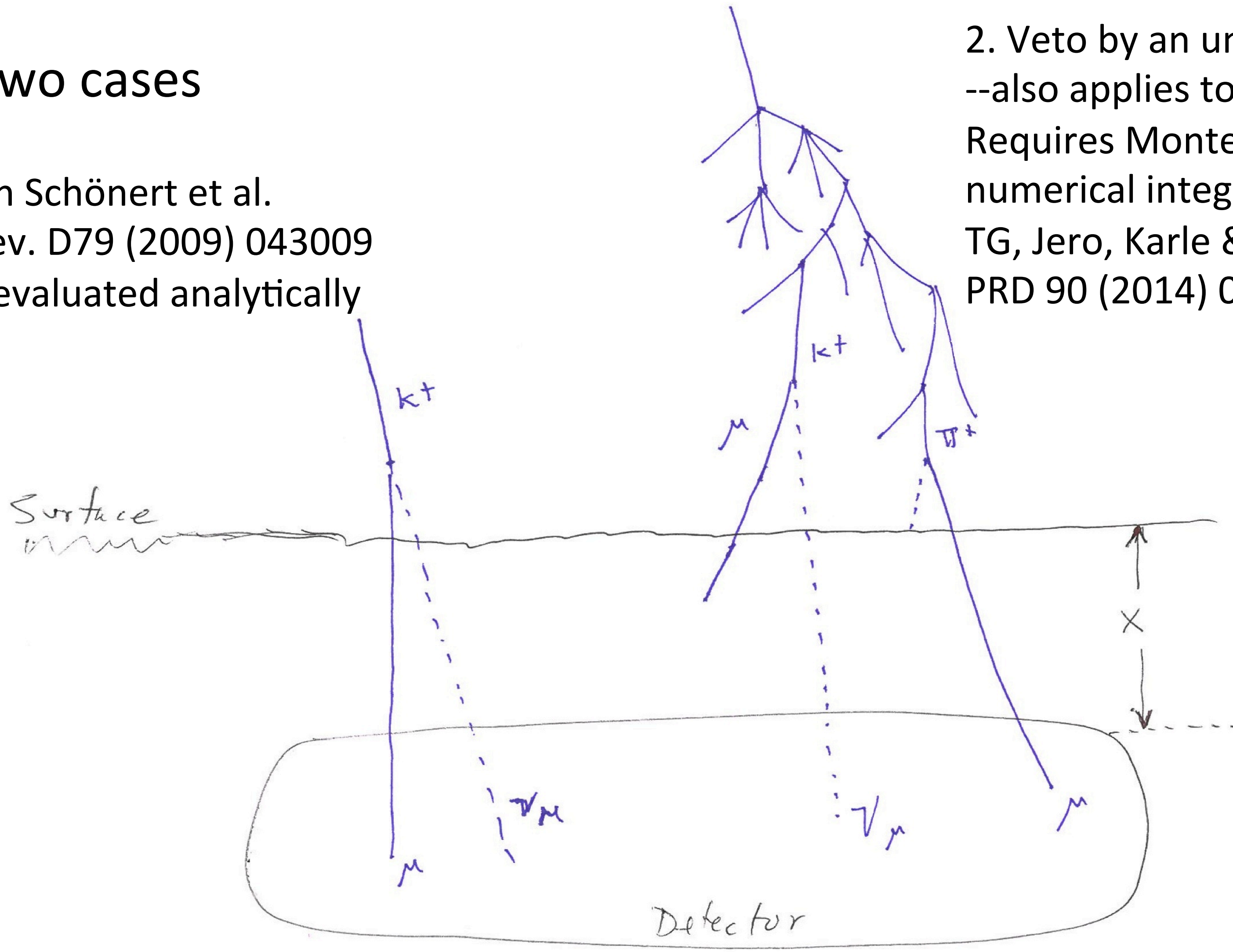

Select E > 60 TeV to get above atmospheric μ background.
Note shape of atmospheric ν backgrounds.

# Atmospheric neutrino self veto

Two cases

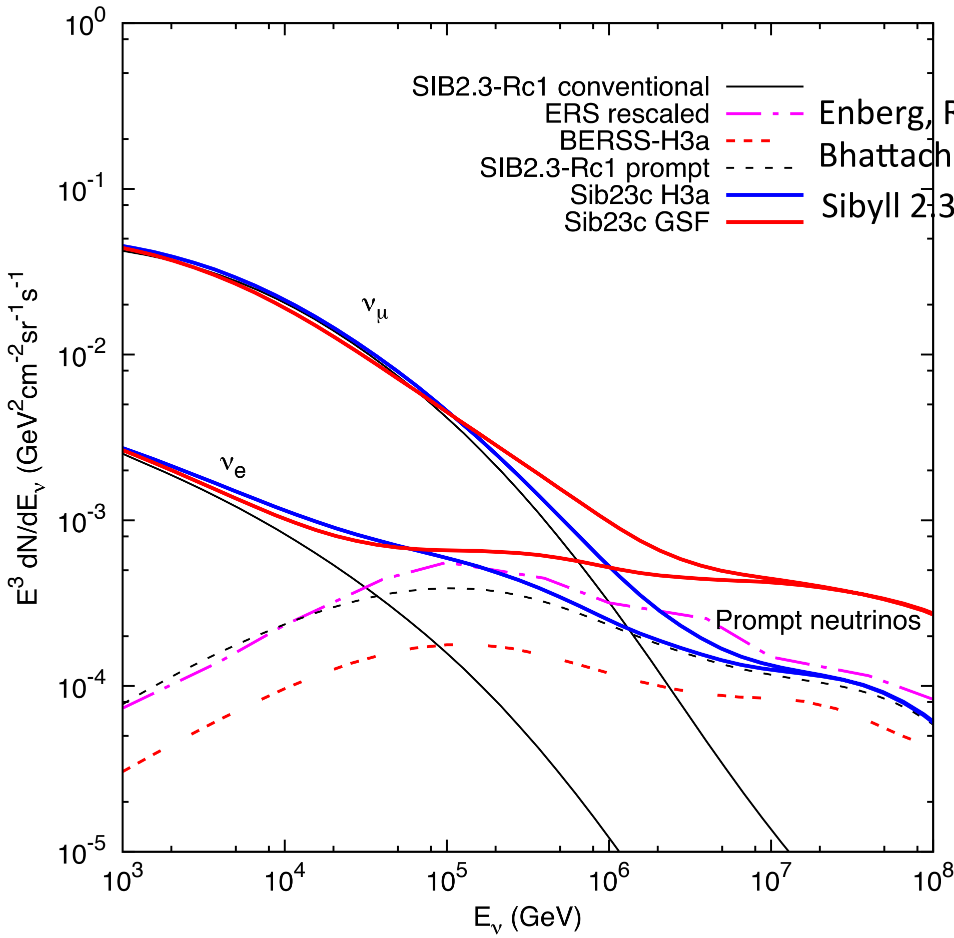
1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

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



# Prompt ν

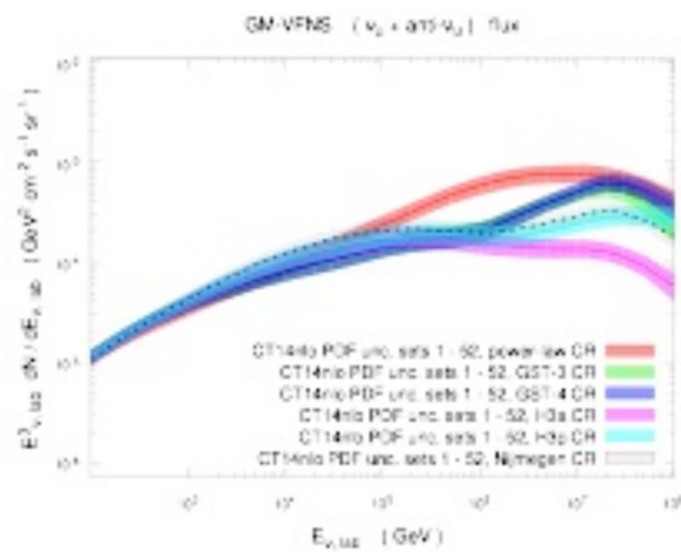
One of the topics at Viet nus




Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Bhattacharya, Enberg, Reno, Sarcevic, Stasto, JHEP 06 (2015) 110

Sibyll 2.3: F. Riehn et al., ICRC 2017



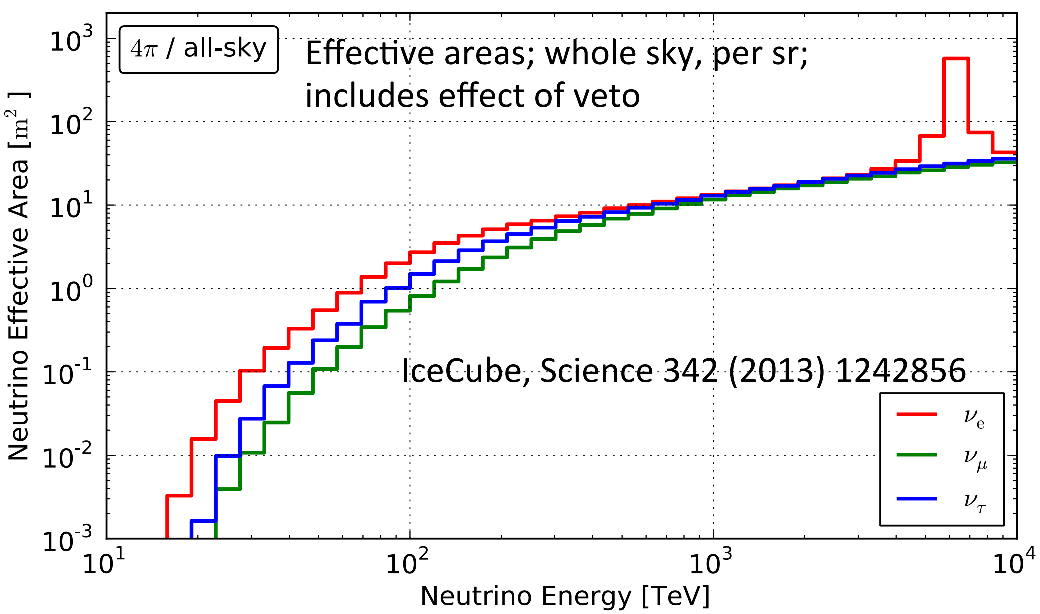
Note lower crossover for electron neutrinos

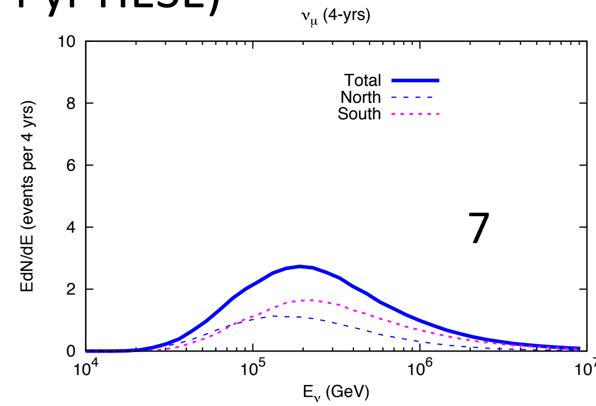
Benzke Garzelli, et al., arXiv: 1705.10386

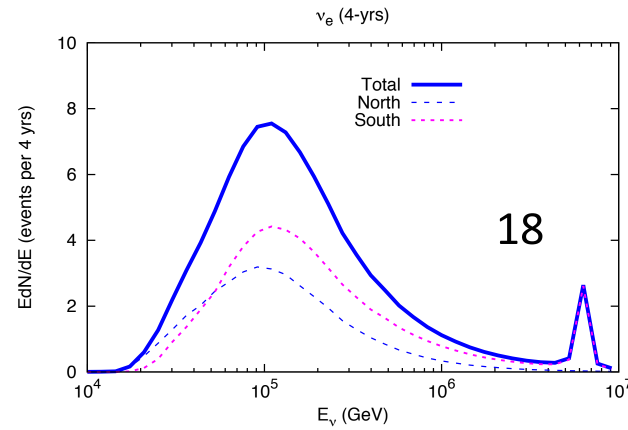
Effective area × Astro flux ⟶ Astro rates ( 4 yr HESE)

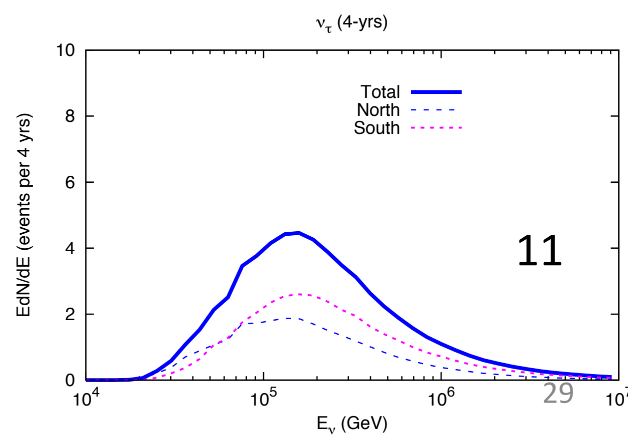
$$E_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = 2.2 \times 10^{-8} \left( \frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-0.58} \frac{\mathrm{GeV}}{\mathrm{cm^2 s\, sr}}$$

per flavor

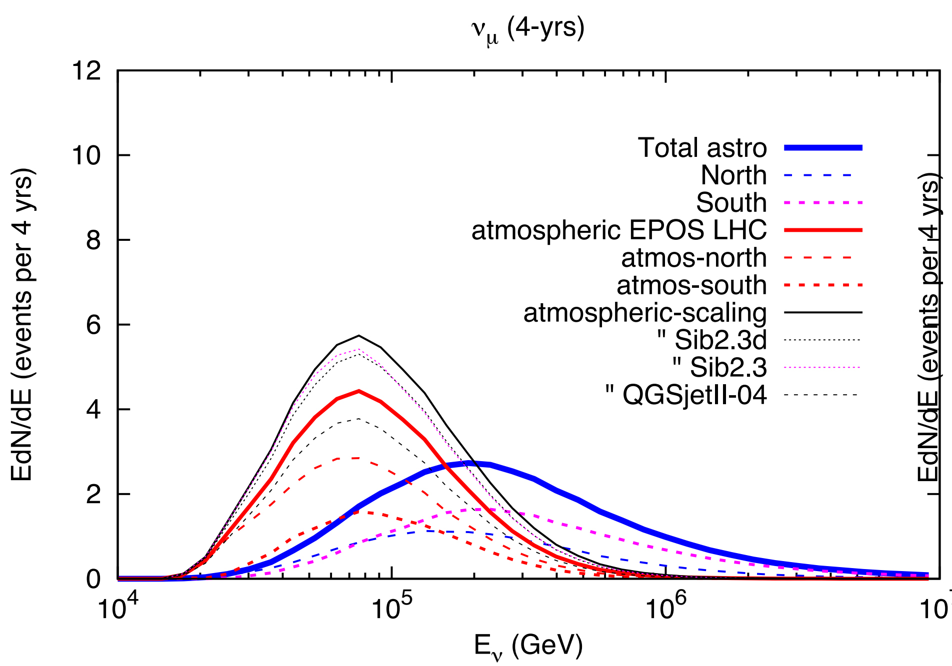


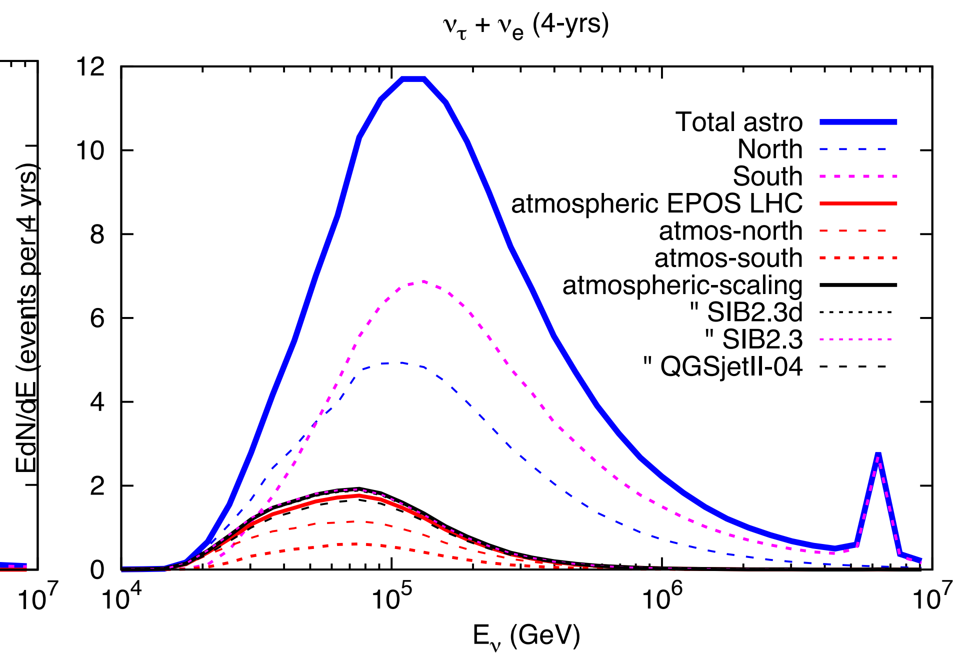



# Astro rates (4 yrs) compared to calculated atmospheric neutrino rates (including prompt) after veto




Note: these calculations show events as a function of true neutrino energy, not deposited energy in the detector--especially important for $\nu_\mu$ (and $\nu_\tau$ )

# Summary of calculated events (4 yrs)

TABLE VI. Accounting for fifty-four events ($E^{-2.58}$ spectrum, 4 yrs.)

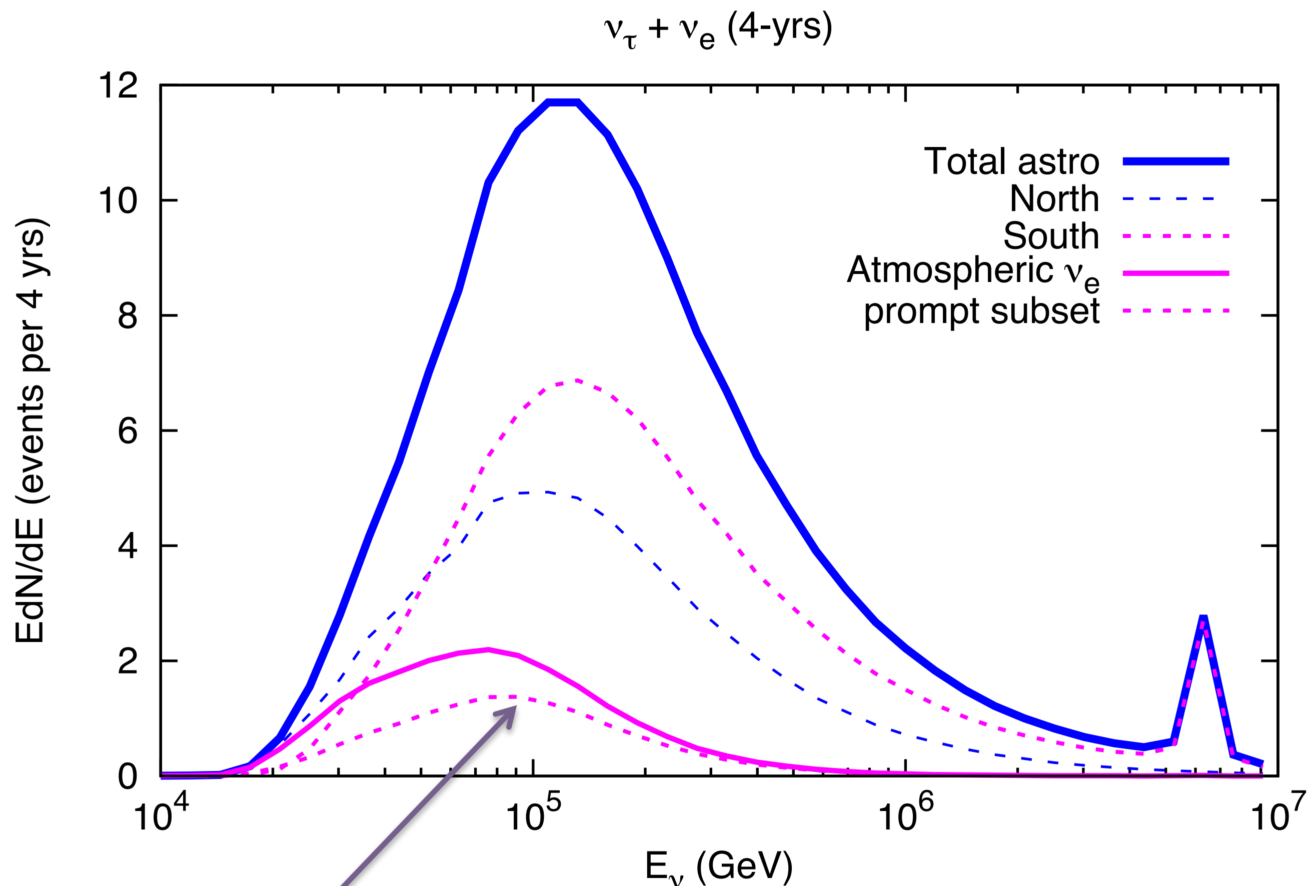
| | South | (before selfveto) | North | Total |
|---|---|---|---|---|
| Astro $\nu_e$ | 10.51 | N/A | 7.15 | 17.66 |
| Astro $\nu_\tau$ | 6.21 | N/A | 4.55 | 10.76 |
| Astro $\nu_\mu$ | 4.22 | N/A | 2.85 | 7.07 |
| Total Astro | 20.9 | N/A | 14.6 | 35.5 |
| Conventional $\nu_e$ | 0.71 | (0.92) | 0.92 | 1.63 |
| Conventional $\nu_\mu$ | 3.15 | (5.68) | 5.85 | 9.0 |
| Charm (ERS) $\nu_e$ | 0.99 | (1.91) | 1.53 | 2.52 |
| Charm (ERS) $\nu_\mu$ | 0.14 | (0.62) | 0.50 | 0.64 |
| Total atmospheric | 4.99 | (9.14) | 8.80 | 13.8 |
| Total neutrinos | 25.9 | (30.0) | 23.4 | 49 |
| Atmospheric $\mu$ (by subtraction) | $\approx 5$ | N/A | 0 | $\approx 5$ |

Astrophysical ν:
~ 26 shower events
~ 9 tracks

Atmospheric ν:
~ 4 shower events
~ 10 tracks

Even with ERS prompt flux, only 3 prompt expected (2.5 $\nu_e$ , 0.5 $\nu_\mu$)

# Prompt atmospheric in HESE




SIB 2.3, H3a primary folded with HESE 4 yr $A_{eff}$
2 or 3 prompt nue, 30 – 300 TeV

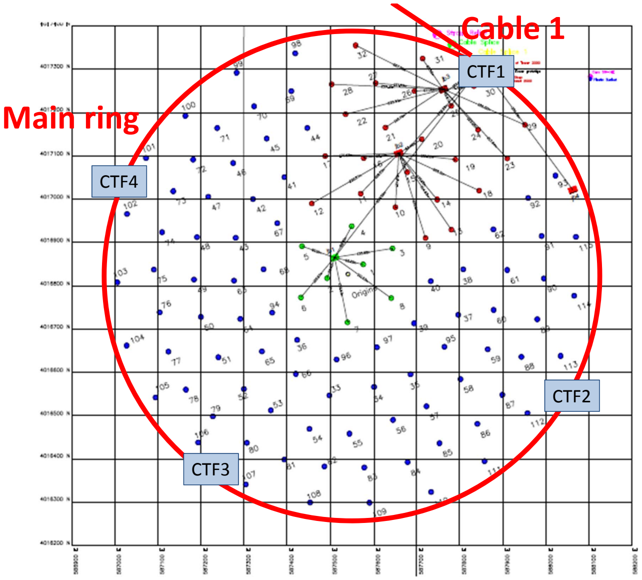
# Summary: prompt leptons

- IceCube typically finds a result in which the preferred level of prompt neutrinos is zero
  - But upper limit allows something like ~ ERS
- Compare the cascade channel at lower energy
  - The prompt component is relatively more important for atmospheric electron neutrinos
- There are suggestions of a significant prompt component in atmospheric muons in IceCube
  - Complications:
    - Events are muon bundles rather than single muons
    - There is a prompt component from $\rho^0 \rightarrow \mu^+\mu^-$ (and others) that is not present for neutrinos

# Future neutrino telescopes

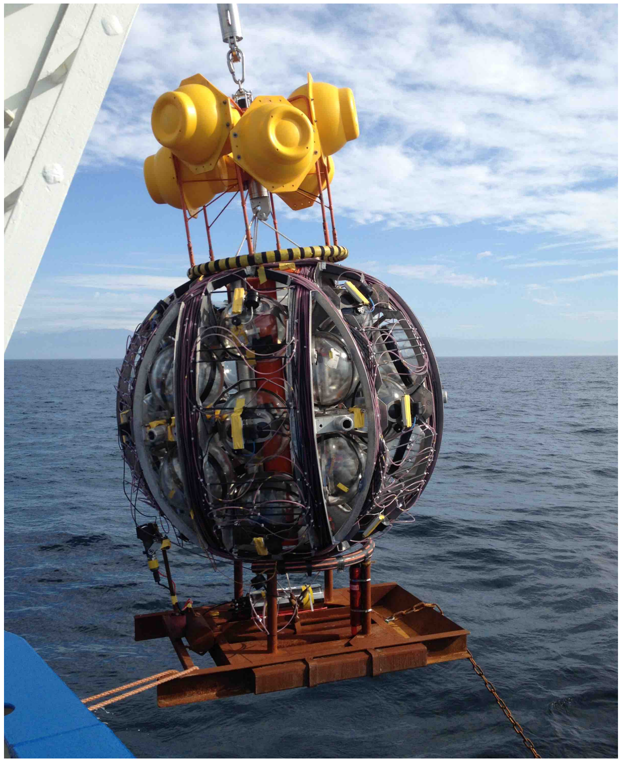
- KM3NeT (L.O.I. – arXiv:1601.07457)
  - ORCA for neutrino physics (Antoine Kouchner)
  - ARCA for high energy (Joao Coelho)
- GVD, km$^3$ detector at Baikal
- IceCube Gen2
  - PINGU for neutrino physics
    - Talks by Ty DeYoung,
  - HEA for high energy
    - arXiv:1412.5106 and 1510.05228
- Radio detection of neutrinos: ARA, ARIANNA…

# KM3NeT/ARCA from LOI




ARCA building block:
115 strings, 18 DOMs/string
500 Mton volume;
Two ARCA building blocks = Gton

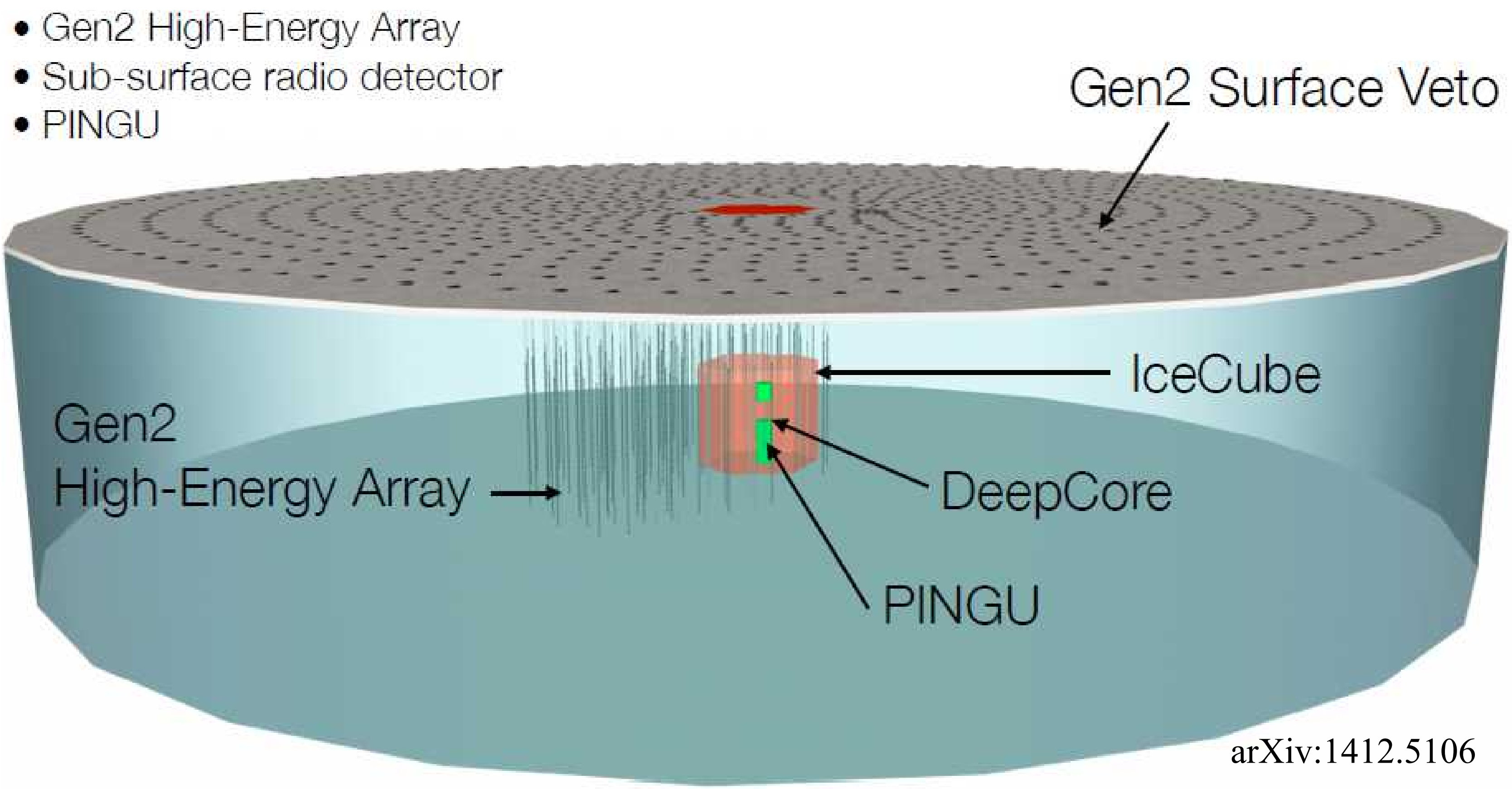
31 PMTs per DOM



One string on a launch vehicle

Test string 2014-15; Two strings of ARCA deployed at the Italian site running now; funding for 24 mare is available.

# IceCube Gen2 HEA

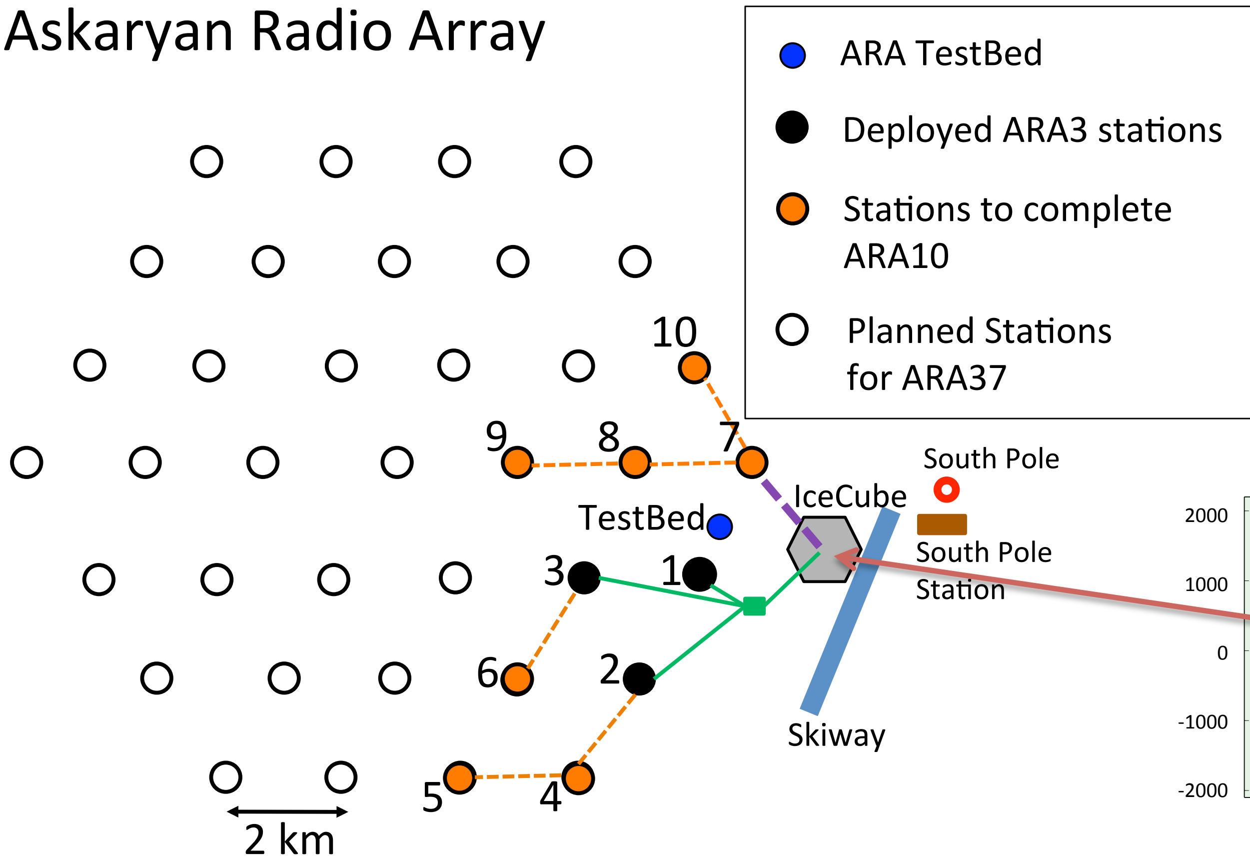


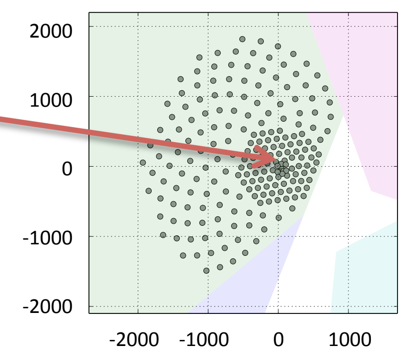

An extended surface array with a much larger footprint could expand the veto

# ARA next to IceCube

Askaryan Radio Array

arXiv:1404.5285




IceCube Gen2 to scale

# Event 45