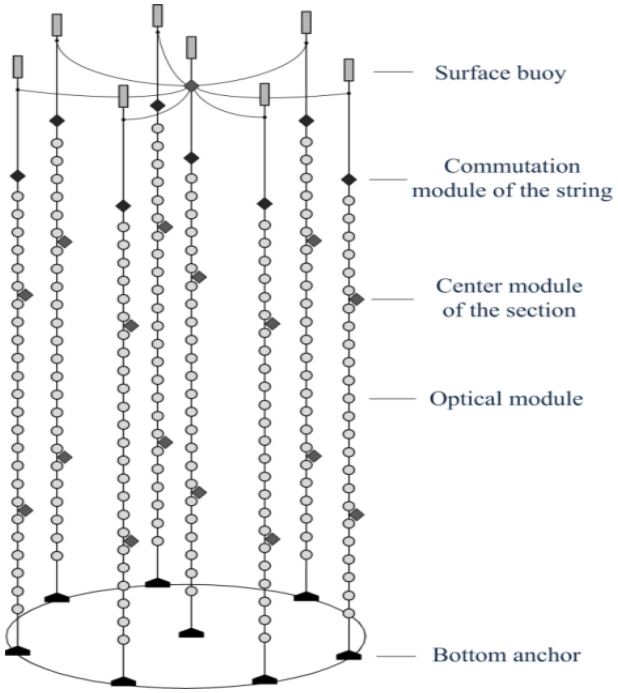
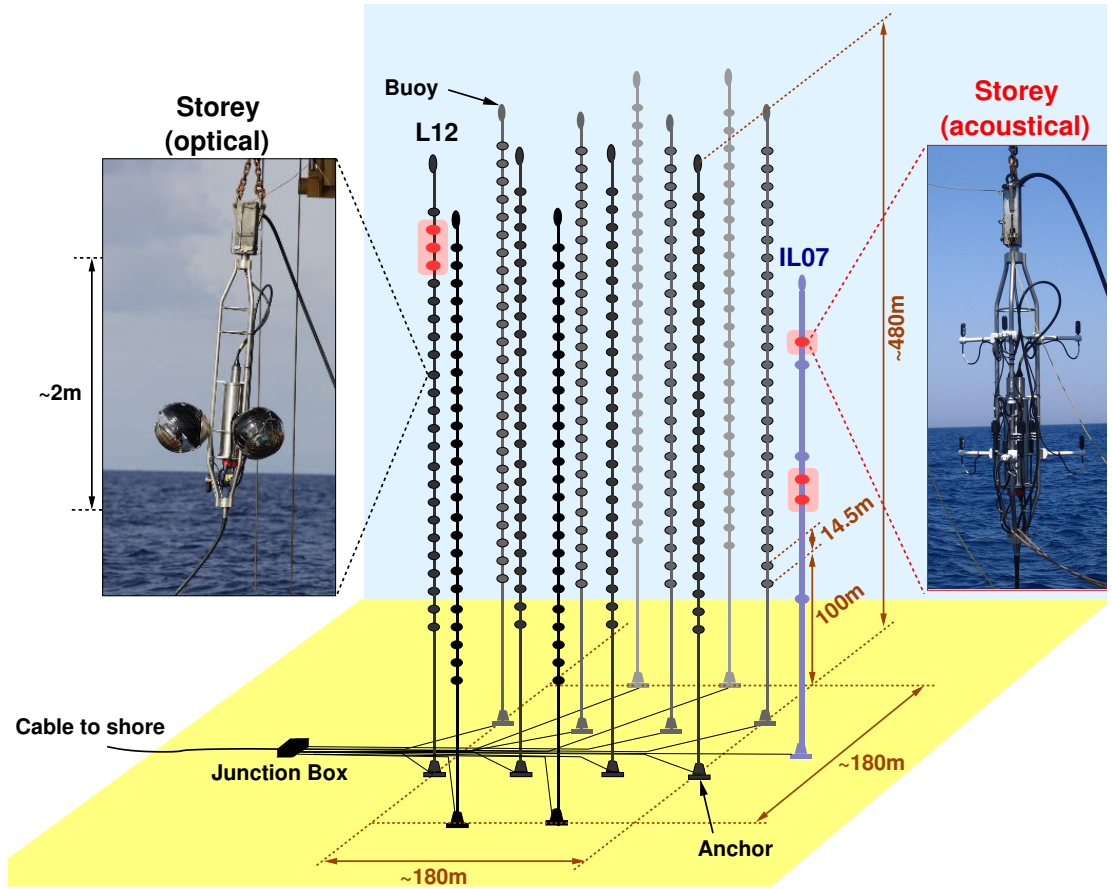
Neutrino particle astrophysics: status and outlook

TEVPA 2016

Present detectors



First cluster of Baikal-GVD



ANTARES has now run for 10 years. See presentation of Thierry Pradier yesterday.

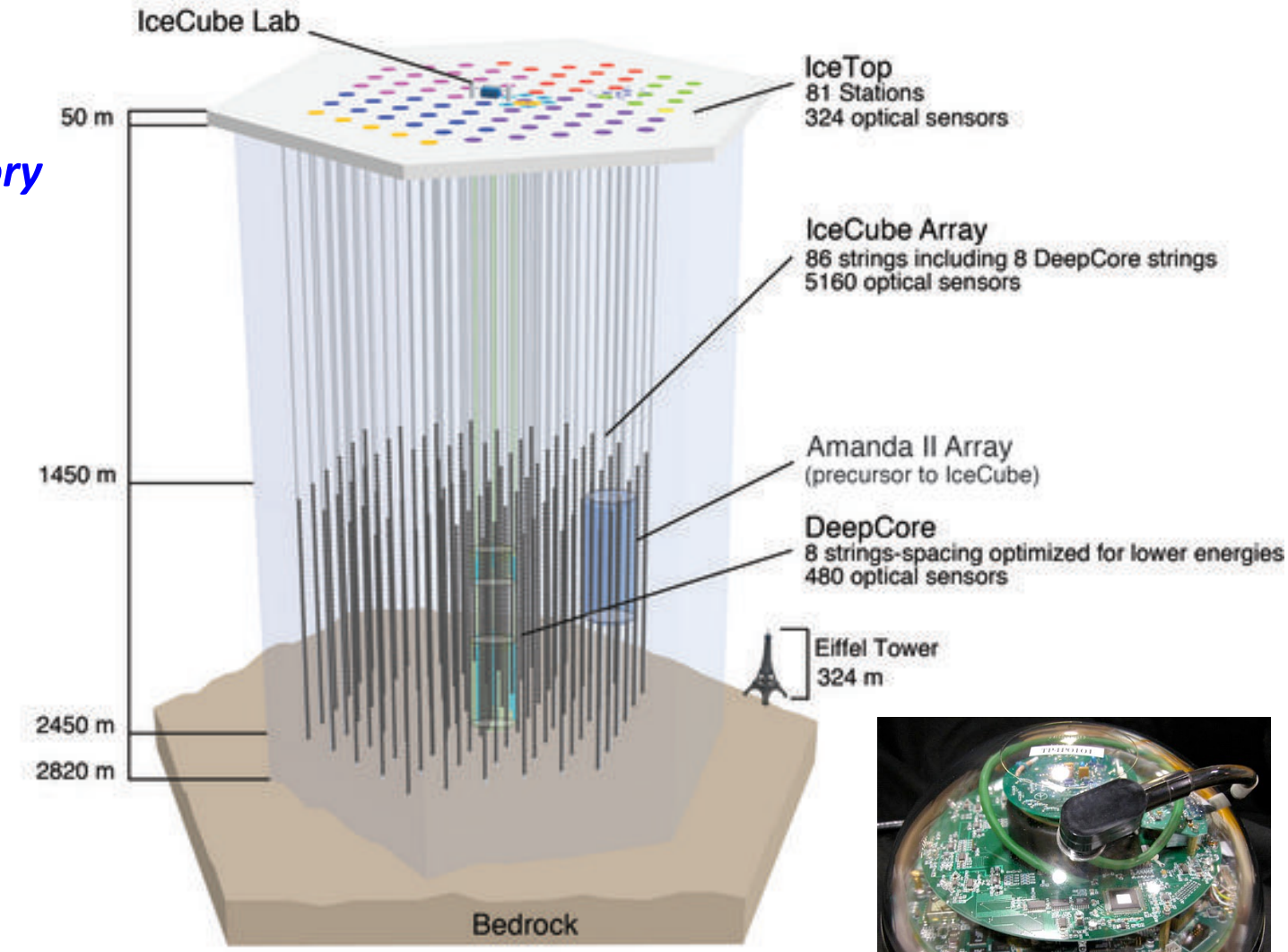
IceCube

Deployment history

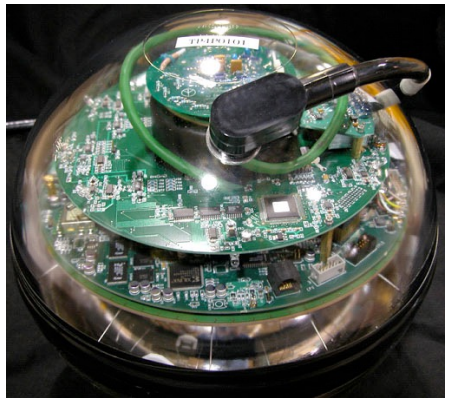
2002: proposal		
2003-04 staging		
2004-05	**1**	**4**
2005-06	**9**	**16**
2006-07	**22**	**26**
2007-08	**40**	**40**
2008-09	**59**	**59**
2009-10	**79**	**73**
2010-11	**86**	**81**

Deep strings

Surface stations

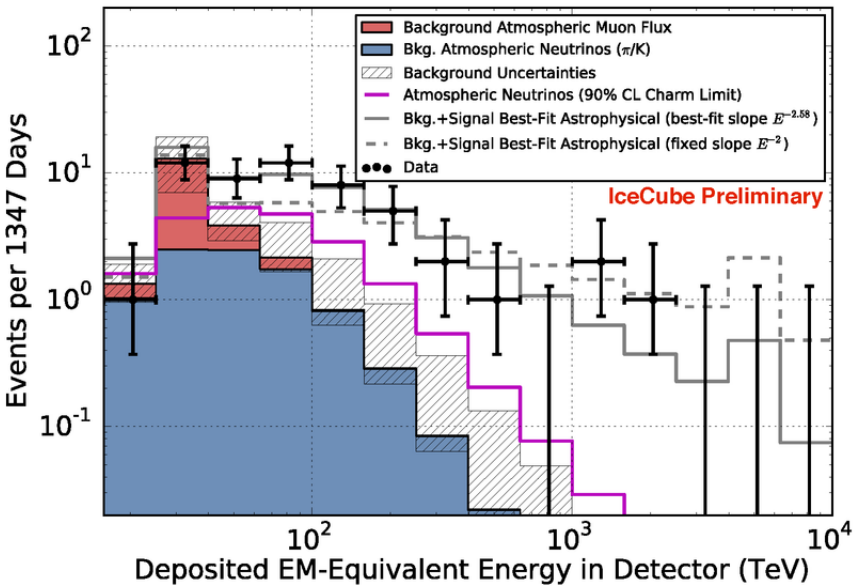


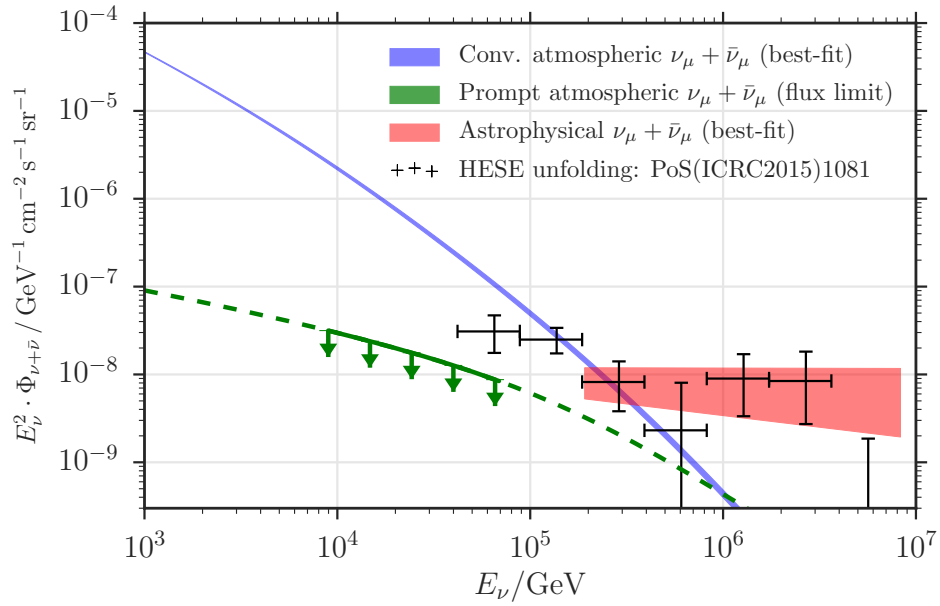
> 5400 Digital Optical Modules



IceCube Construction: 2004-2011

Astrophysical neutrinos



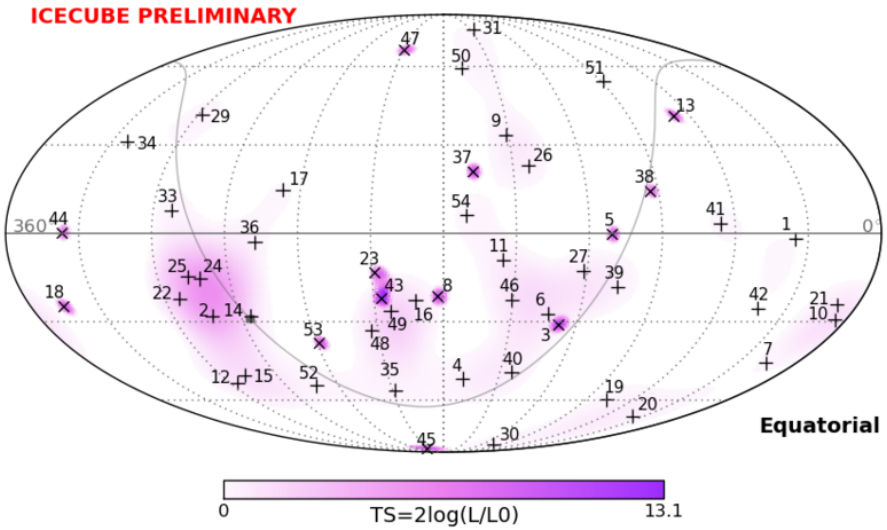


IceCube *4 year* HESE analysis
(HESE = High Energy Starting Event)
ICRC 2015 arXiv:1510.05223

IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
arXiv:1607.08006

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)

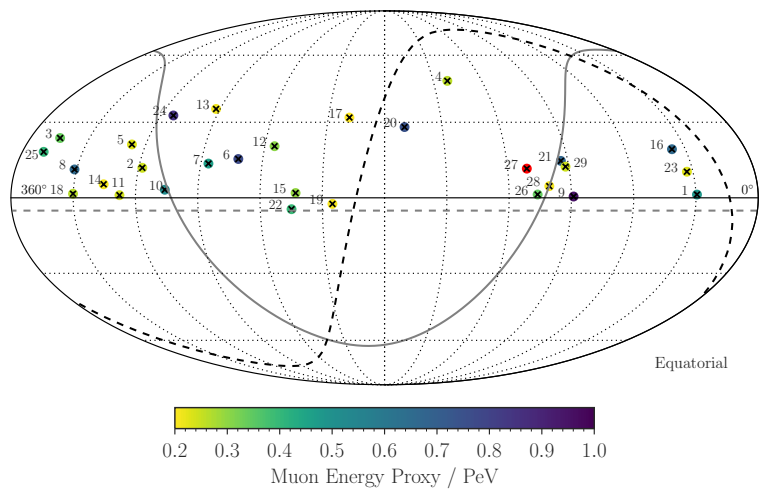


Figure 16. Arrival directions of events with a muon energy proxy above 200TeV. Given the best-fit spectrum the ratio of astrophysical to atmospheric events is about two to one. The horizontal dashed gray line shows the applied zenith angle cut of 85°. The curved gray line indicates the galactic plane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

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

Galactic

Diffuse

C.R. + gas → ν

Stecker, 1979
⋮
Gaggero et al, 2015

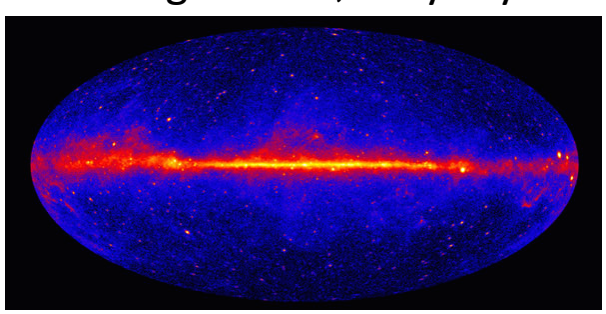
Sources

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

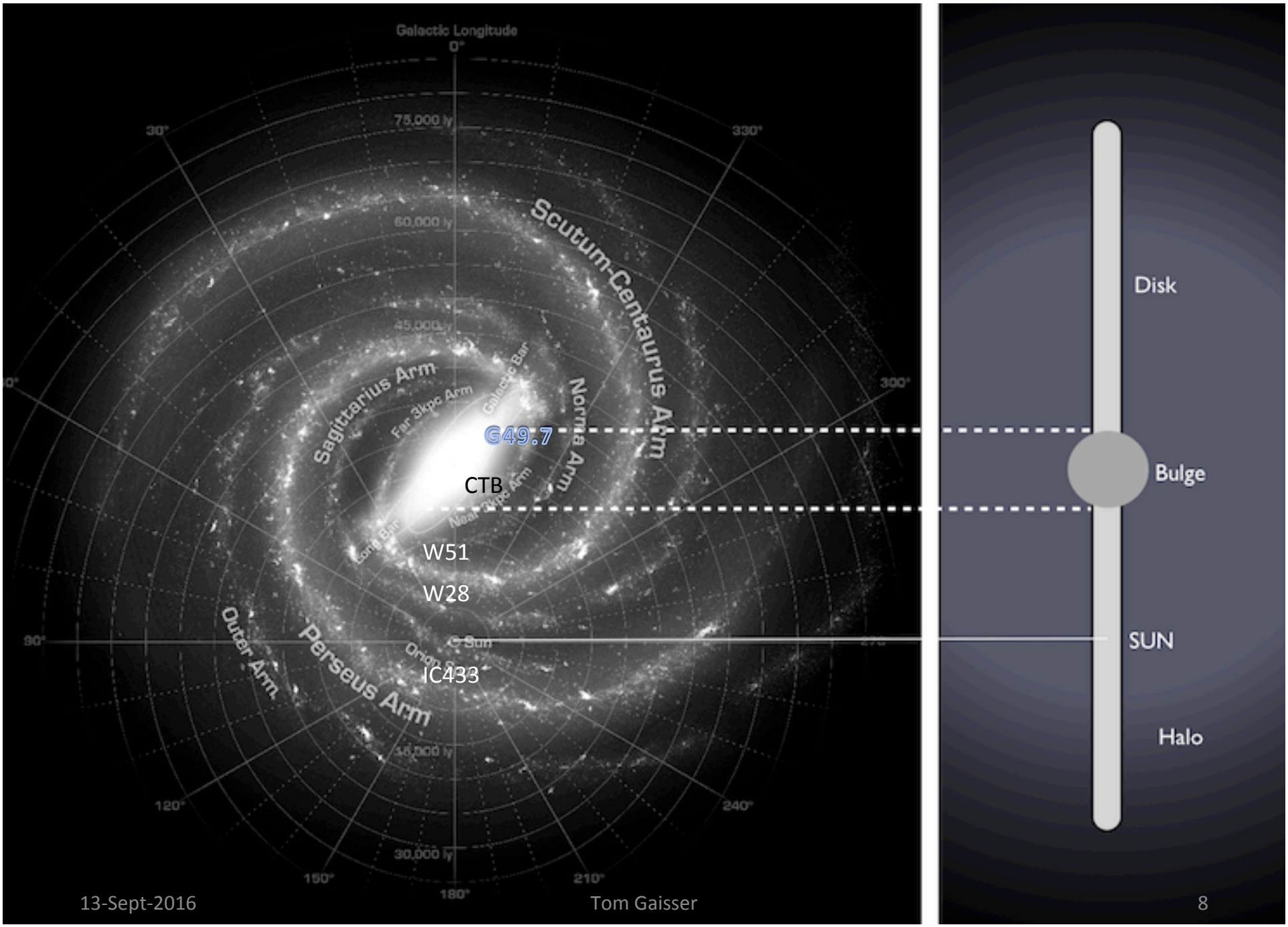
p + CMB→π
p + EBL→ π

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. Presentation by Asen Christov in ν-I session


Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
G49.7
CTB
W51
W28
IC433
Outer Arm
Perseus Arm
Orion Spur
Sun
90°
300°
240°
210°
180°
150°
120°
30,000 ly
Disk
Bulge
SUN
Halo

Example: The W28 complex

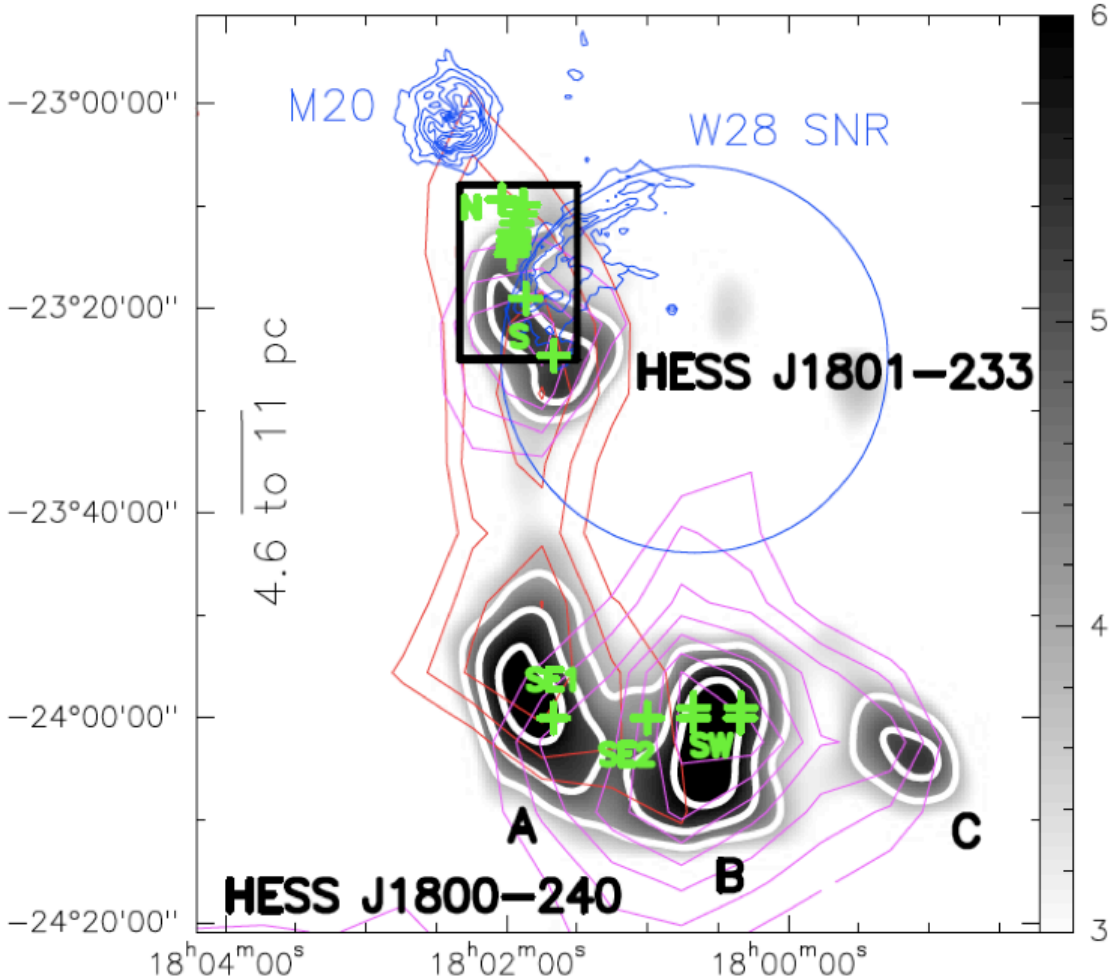


Figure from Vaupré et al., A&A 568 (2014) A50

Angular distribution of IceCube data relative to the Galactic plane

An excess from the Galactic plane would likely be a combination two components:

1. Diffuse neutrinos from cosmic-ray interactions with gas, and
2. Unresolved sources

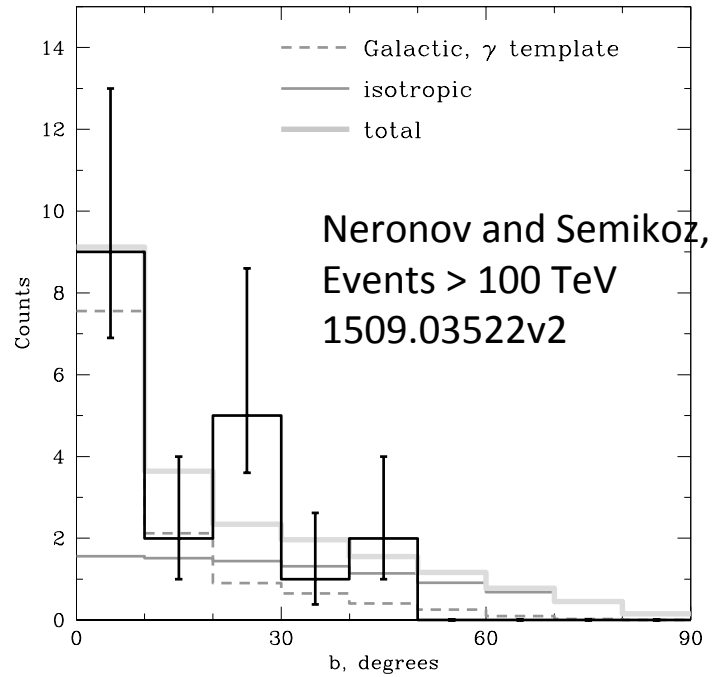
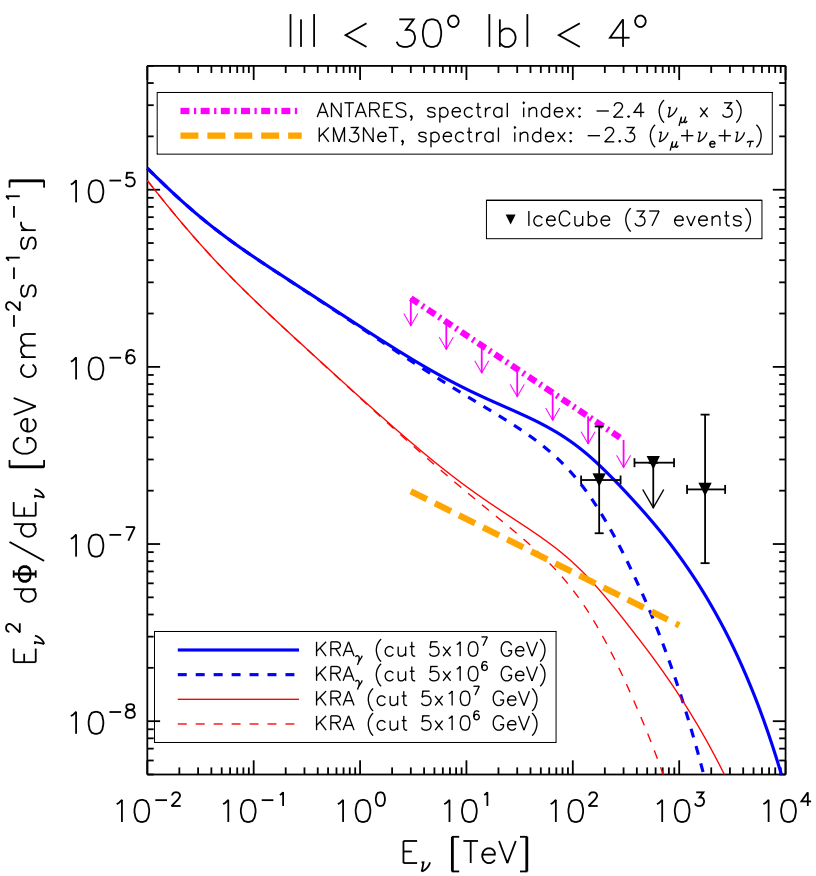
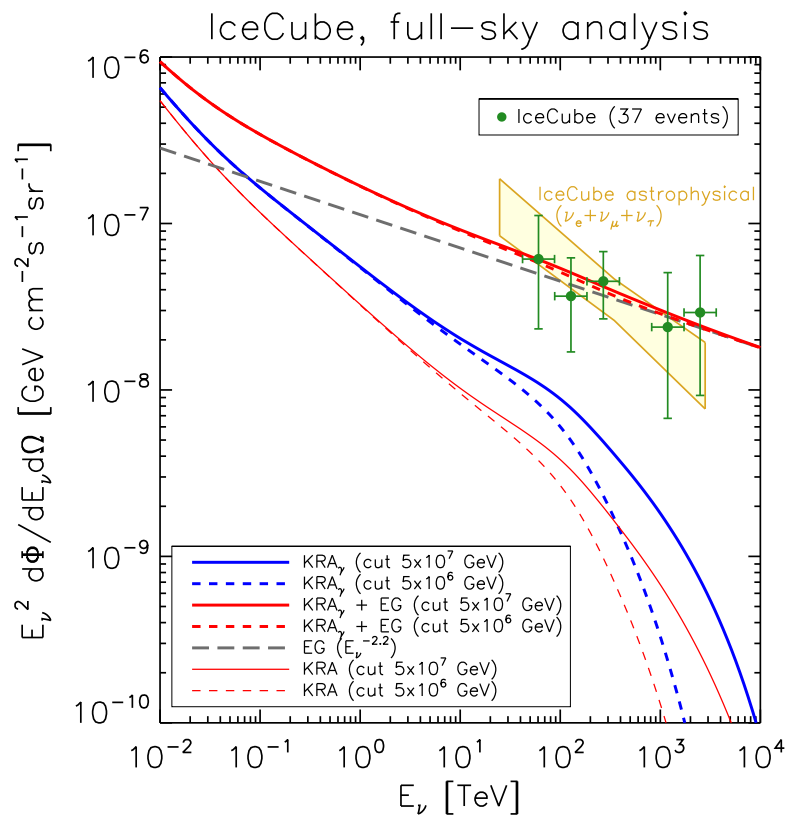


Figure 1: Galactic latitude profile of the $E > 100$ TeV IceCube neutrino signal. Dark grey solid histogram shows the expected profile of the isotropic neutrino signal. Dashed dark grey histogram shows the Galactic component profile. Thick light grey solid histogram shows the sum of the Galactic and extragalactic components.

Comparison of Galactic and extra-galactic

Gaggero et al., 1504.00227, Ap.J. Letters 815 (2015) L25



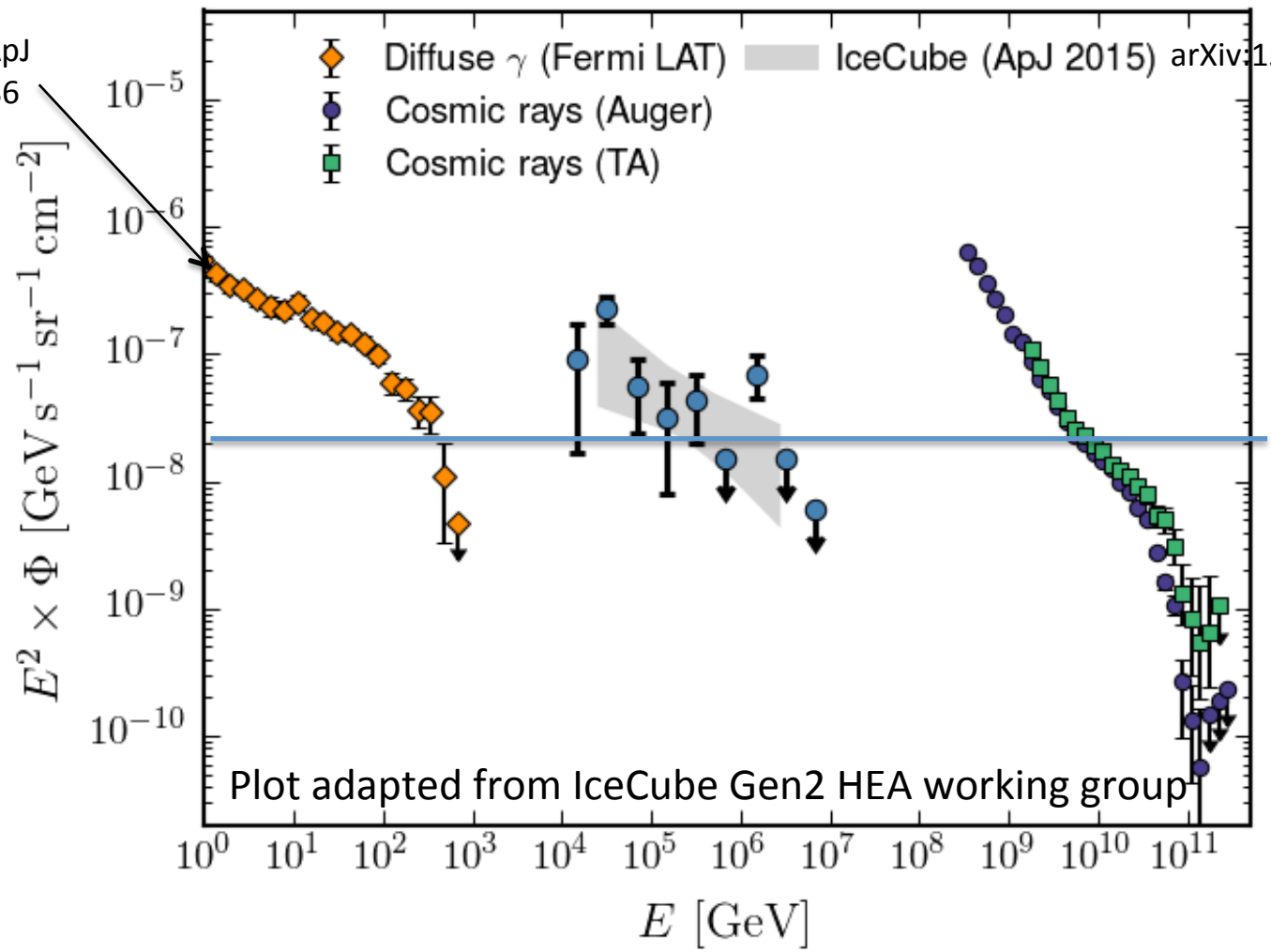


Galactic fraction

- Of order 10%
- It is a guaranteed source
- Antares limit is close to prediction
- Ongoing searches in IceCube using templates for the Galactic ridge based on Fermi-LAT
- Galactic plane will be resolved, if not by IceCube then by KM3NeT

Extragalactic neutrinos
The multi-messenger landscape

IGRB from Fermi LAT, ApJ 799 (2015) 86



arXiv:1507.03991

Waxman-Bahcall bound. PR D59 (1998) 023002

Extragalactic

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

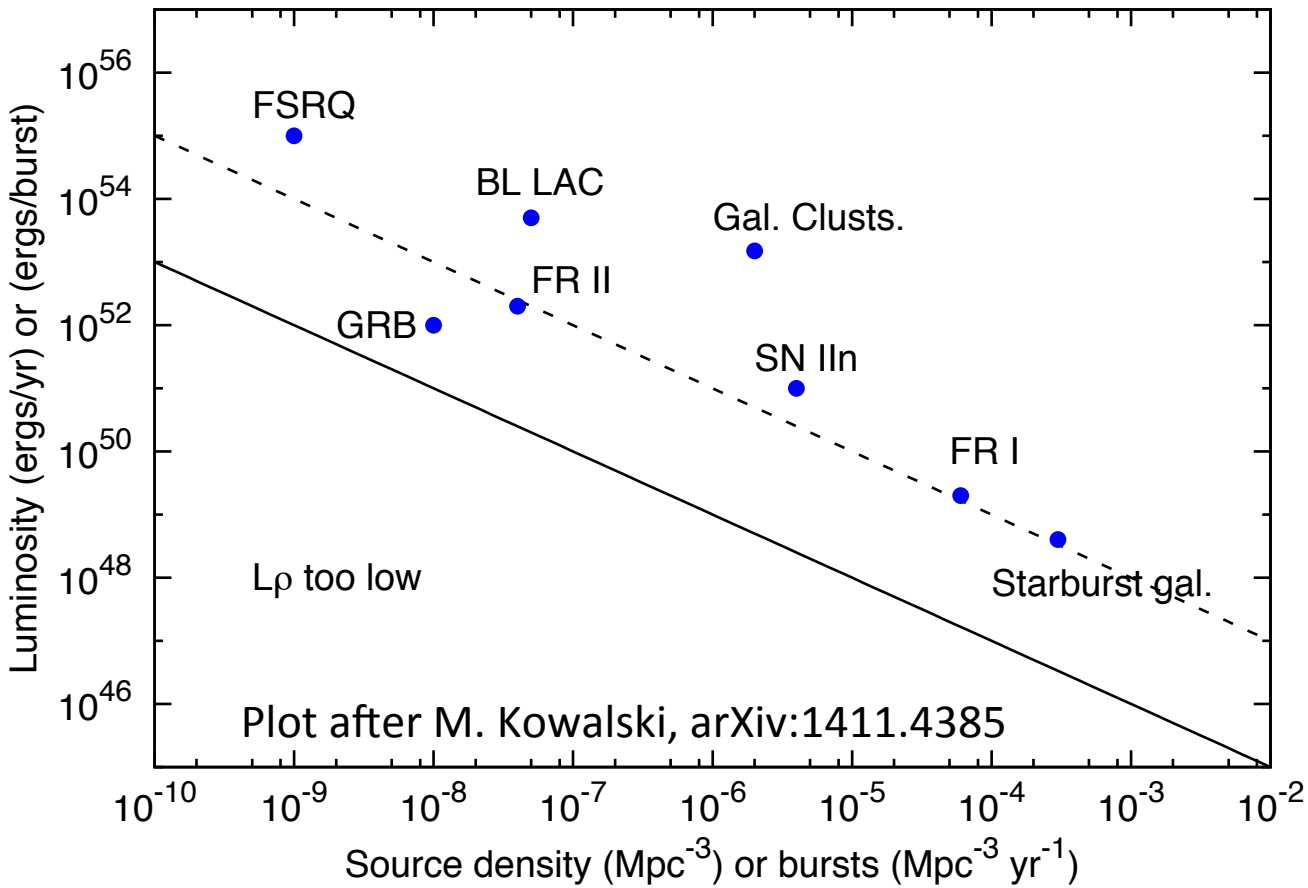
Equate F_ν to IceCube Flux and assume E^{-2} spectrum for illustration

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

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

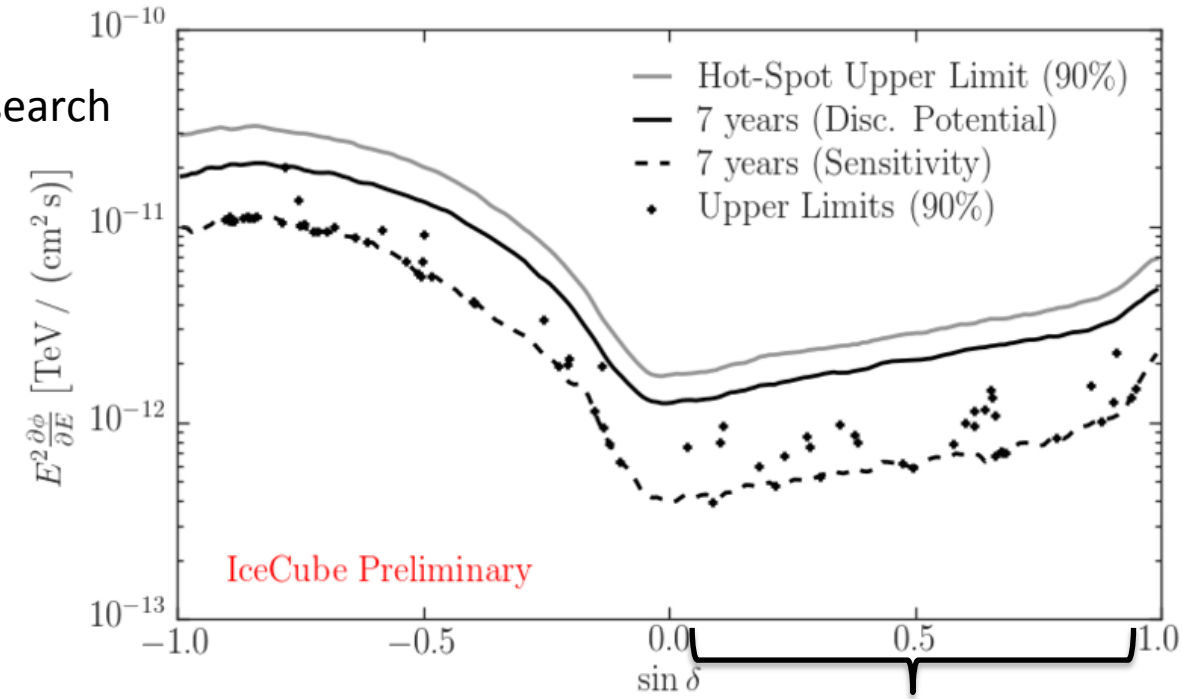


Dashed line assumes 1% efficiency for production of neutrinos

Point source limits

Relation between flux from whole sky and number/intensity of individual sources
P. Lipari, PR D78 (2008) 083001 ... Ahlers & Halzen, PR D90:043005 ...
Murase & Waxman, arXiv:1607.01601

IceCube 7 yr pt src search



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

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

Minimum density of sources

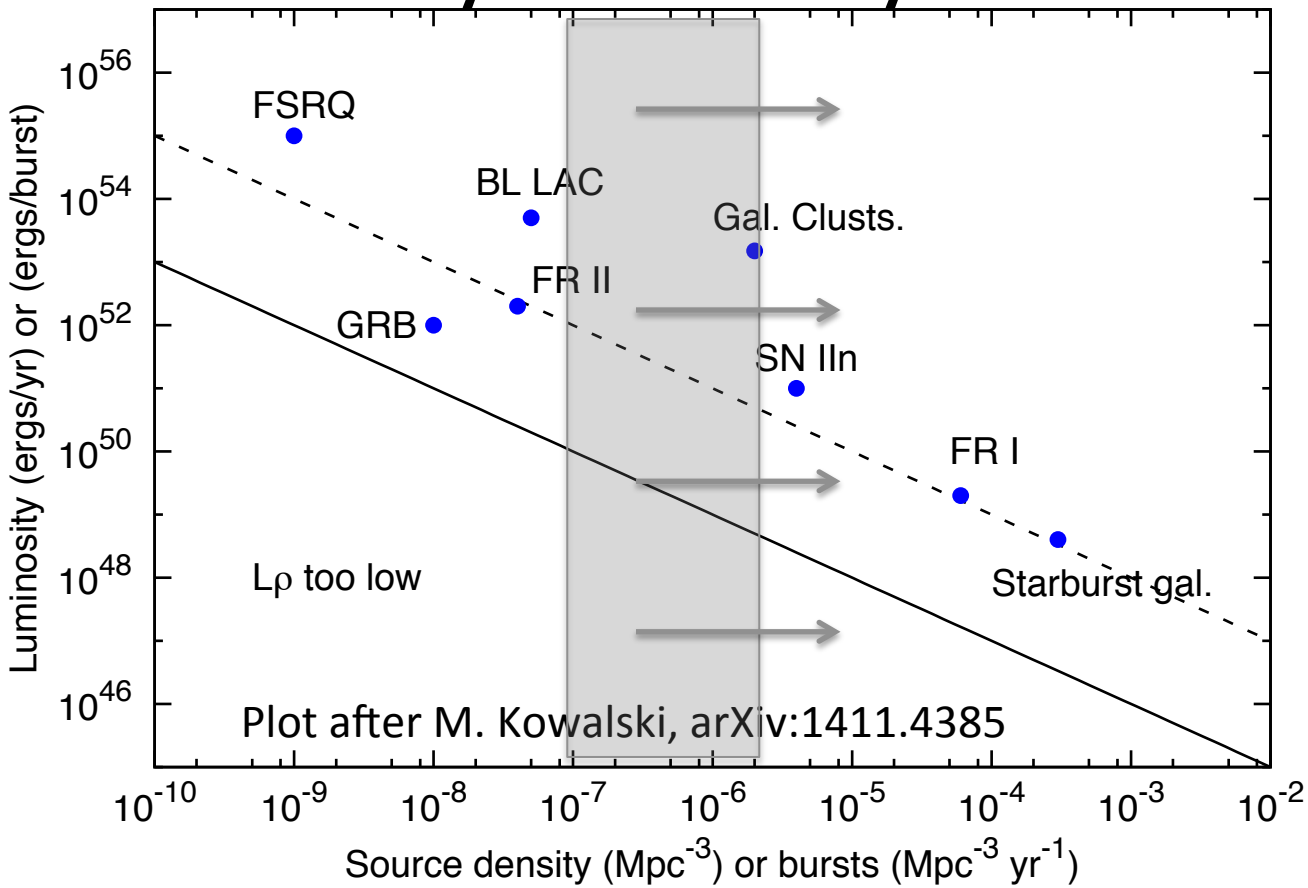
For a distribution of sources each with L_ν and density ρ, estimate the distance to a nearby source as $d=(4\pi\rho)^{-1/3}$.
Then the flux from a nearby source is $F_\nu \approx \frac{L_\nu}{4\pi d^2} = \frac{L_\nu d}{4\pi d^3} = L_\nu \rho d.$

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 steady 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

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.
```

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

Neutrinos from external galaxies

$$L_{\nu,\,\mathrm{MW}} \approx 10^{41} (E_{\mathrm{GeV}})^{-0.7}\,\mathrm{GeV/s}$$

For ξ = 1 and ρ = 0.1 (Mpc)$^{-3}$ then

$$F_\nu = \xi \frac{L_\nu \rho R_H}{4\pi} \approx 3 \times 10^{-7} (E_{\nu,\,\mathrm{GeV}})^{-0.7}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

$$F_\nu(_{100\,\mathrm{TeV}}) \approx 10^{-10}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

If spectrum is -2.5 instead of -2.7, then

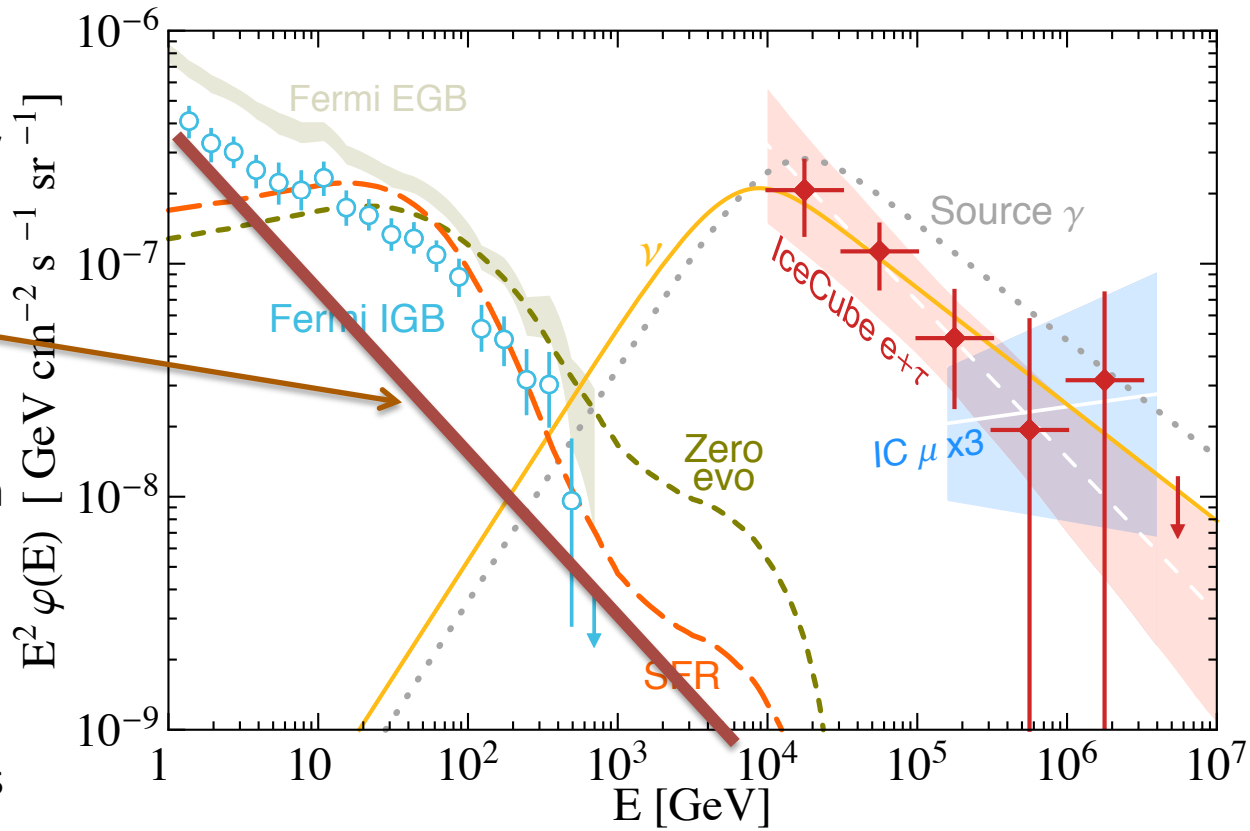
$$F_\nu(_{100\,\mathrm{TeV}}) \approx 10^{-9}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

Note: there will be a similar flux of photons produced with the neutrinos

Constraints from Fermi IGRB

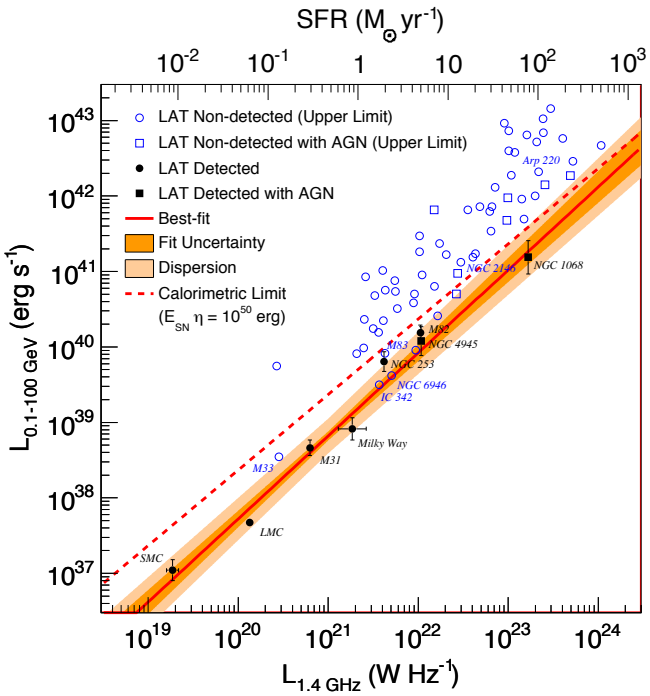
In this example, the photons that accompany the neutrinos at production are close to the Fermi IGB and way below the 100 TeV data.

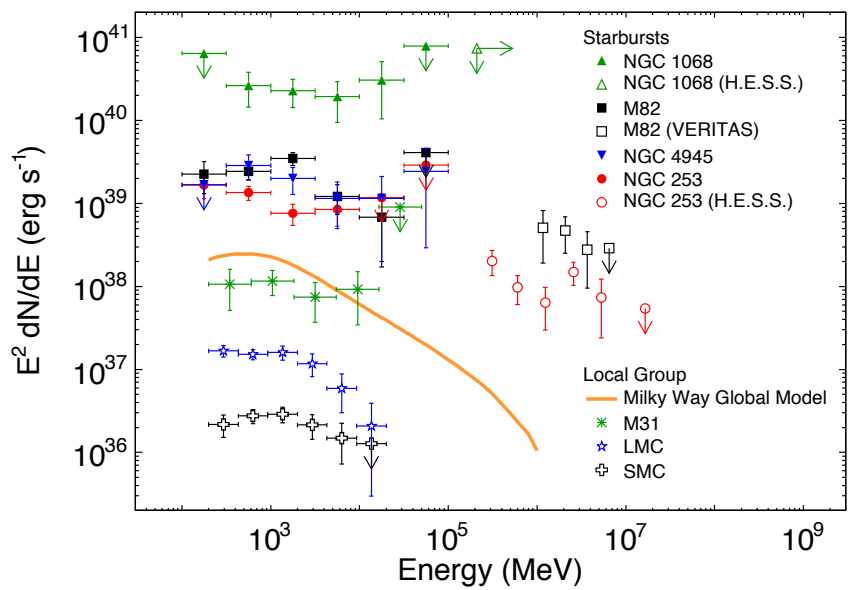
If production mechanism is photo-production. The neutrino spectrum does not continue to low energy. Even so, the ~2.5 IceCube spectrum is limited by the Fermi IGRB.



Plot from M. Kistler, arXiv:1511.01530

Star-forming Galaxies can produce more neutrinos (and photons!)





Plots from Fermi paper: "GeV Obs. Of Star-forming Galaxies", Ap.J. 755 (2012) 164

Note harder spectra for higher SFR galaxies.
Also, higher SFR galaxies are closer to the calorimetric limit, so greater L_ν (and L_γ)

Can SFG explain the IceCube signal?

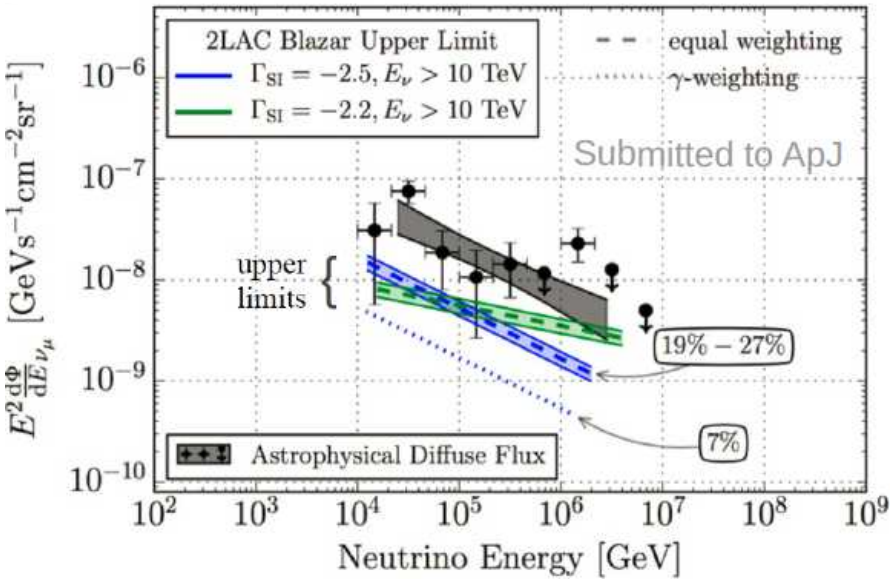
Proposed by Loeb & Waxman: "Cumulative background of High-Energy Neutrinos from Starburst Galaxies" JCAP 0605 (2006) 003
See also E. Waxman, arXiv:1511.00815

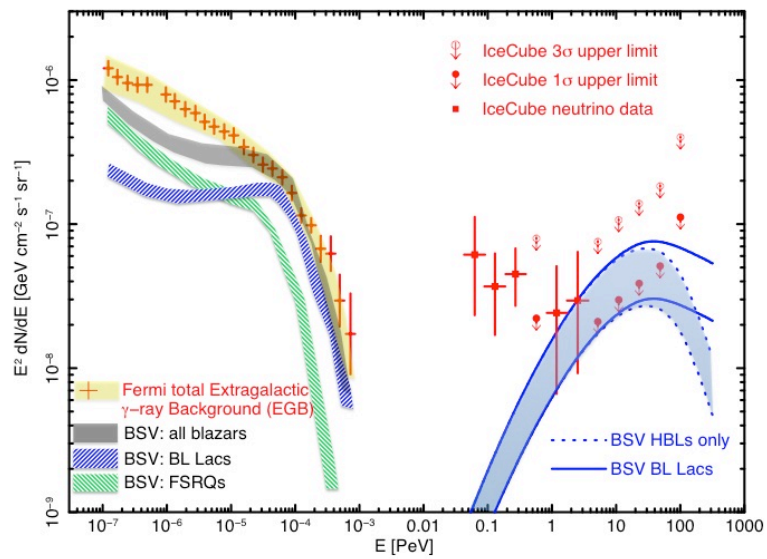
Many authors address the tension with the Fermi diffuse IGB.
At a minimum, the spectrum of CR in the sources must be quite hard, for example differential spectral index > -2.2 (e.g. Murase, Ahlers & Lacki, PR D88 (2013) 121301).
The paper of Ando, Tamborra & Zandanel (PRL 115 (2015) 221101) finds stringent requirements on hard spectrum and strong evolution.

The *observed* astrophysical neutrino spectrum is softer than -2.2, which suggests to me that multiple source classes are involved.

See talk by Keith Bechtol this afternoon at 16:50

Blazars and AGN





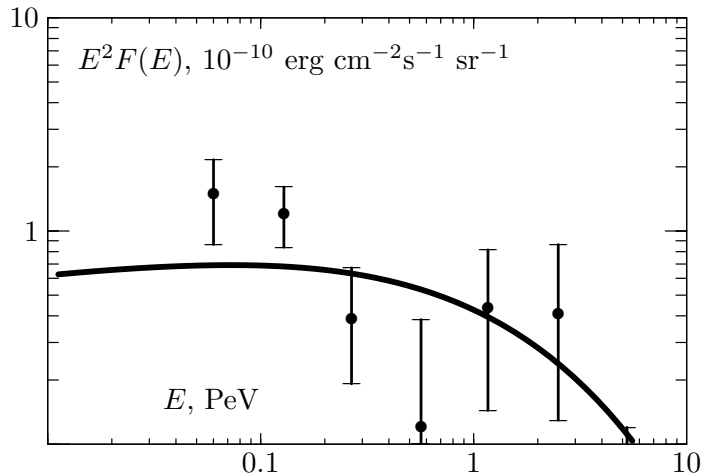
Padovani et al., MNRAS 457 (2016) 3582

IceCube Upper limit: blazars < 20% of observed astrophysical flux

Blazars may contribute with hard spectrum at high energy but not account for all the flux. *Talk by M. Petropoulou at 17:50 today*

Type IIn Supernova explosions

Explosion into dense wind of progenitor star
Acceleration to 10^{17} eV; ν to > PeV with cutoff
Murase et al., PR D84 (2011) 043003



Zirakashvili & Ptuskin arXiv:1510.08387
Integrated flux from all Type Iin SNR could account for high-energy part of IceCube signal with a cutoff

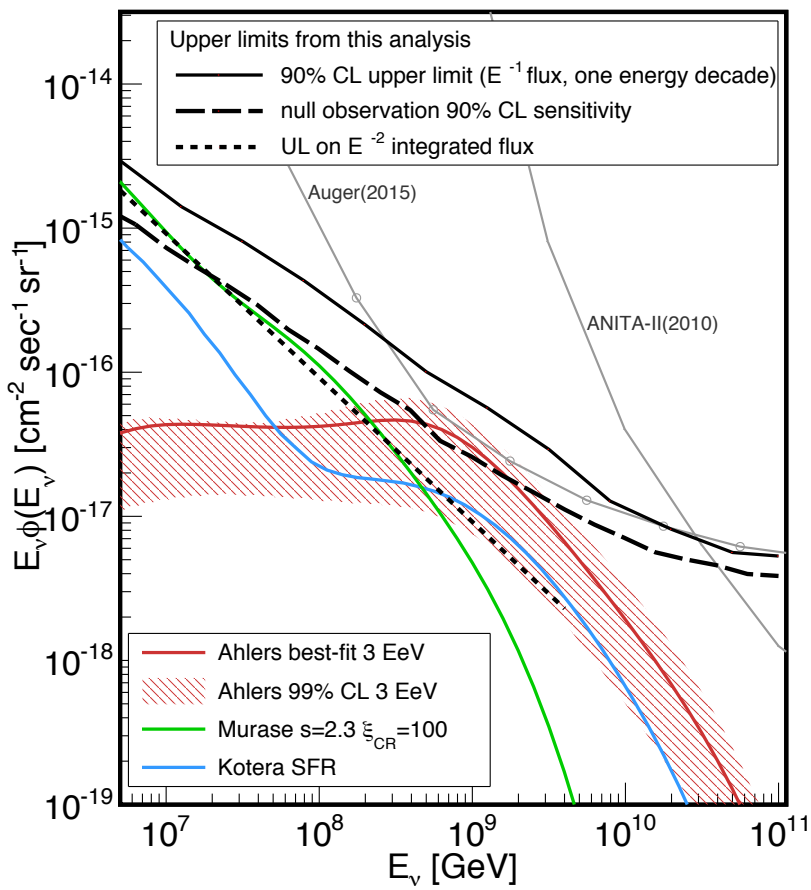
Zirakashvili and Ptuskin note two possible coincidences:

- SN 2005bx at z=0.03 is 1.35° from HESE #47 track
- SN 2005jq at z=0.23 is 0.3° from track event #11 in upward ν_μ sample

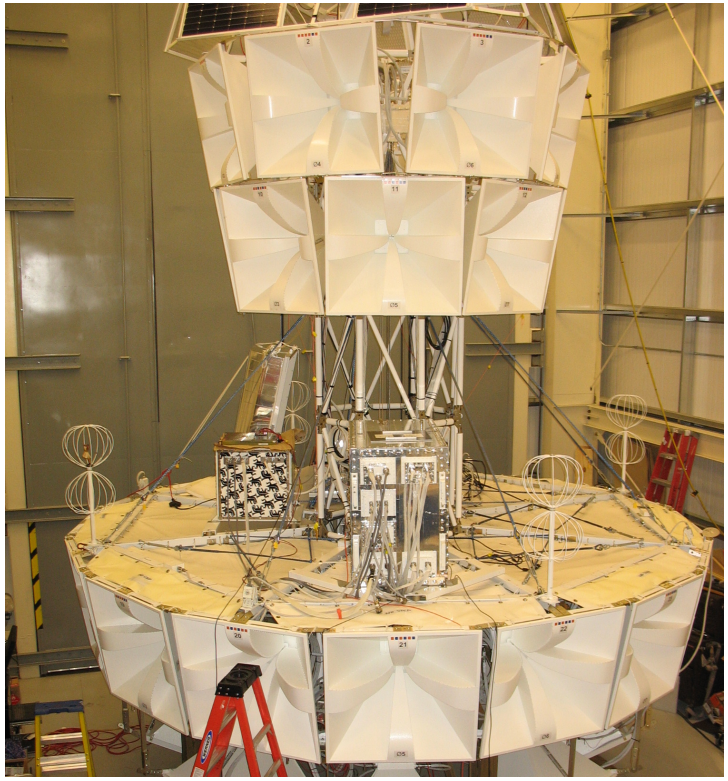
Cosmogenic neutrinos

- IceCube limit compared to models

IceCube, arXiv:1607.05886



Radio detectors for cosmogenic ν



ANITA: balloon borne detector
In preparation for 2008/09 flight

Power Tower

Station with mast
for communication

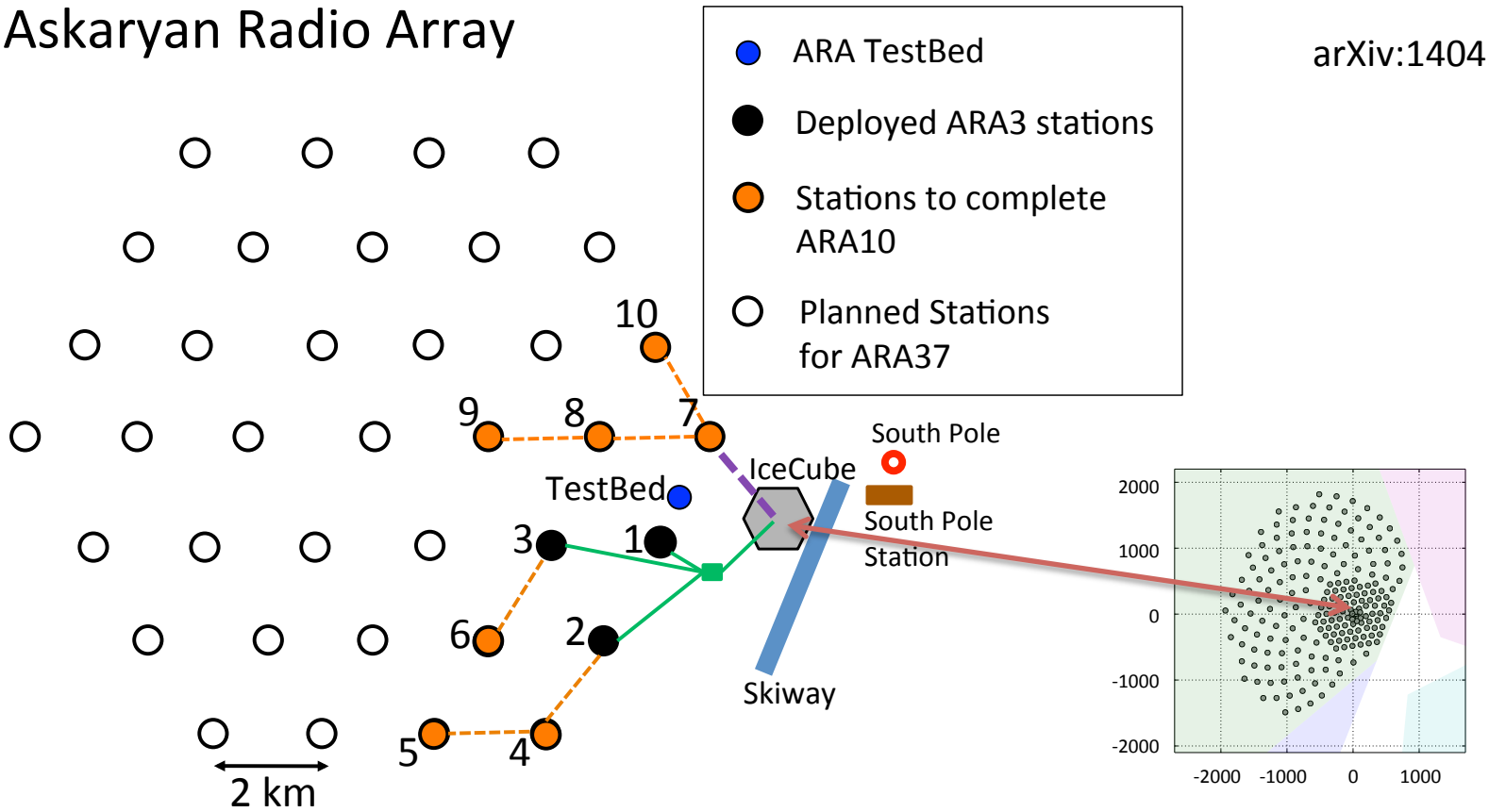
ARIANNA: antennas looking into the Ross Ice Shelf (arXiv: 1410.7369)

See talk by Jordan Hanson in Neutrino session yesterday

ARA next to IceCube

Askaryan Radio Array

arXiv:1404.5285

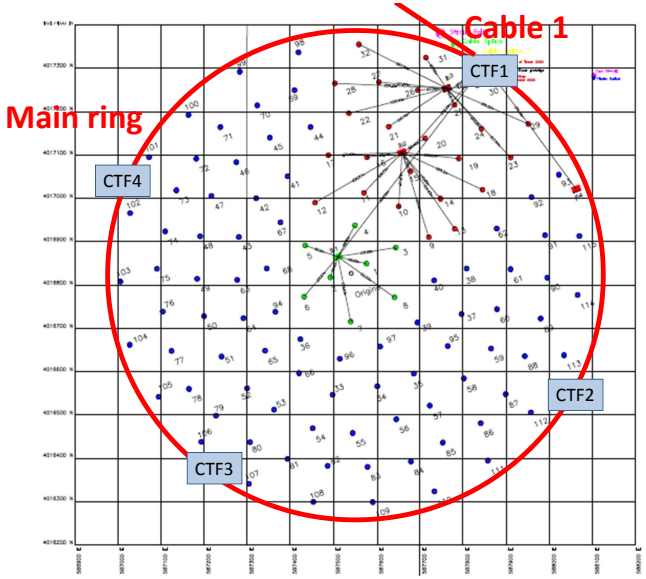


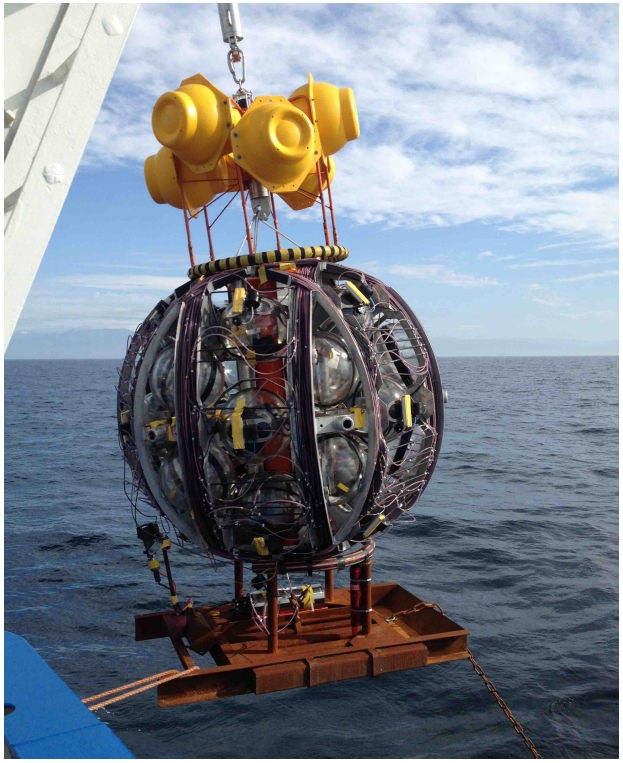
IceCube Gen2 to scale

Future neutrino telescopes

- KM3NeT (L.O.I. – arXiv:1601.07457)
  - ORCA for neutrino oscillations
  - ARCA for high energy
- GVD, km^3 detector at Baikal
- IceCube Gen2
  - PINGU for neutrino oscillations
    - Talk by Jason Koskinen in neutrino session yesterday
  - HEA for high energy
    - arXiv:1412.5106 and 1510.05228

KM3NeT/ARCA from LOI





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

31 PMTs per DOM

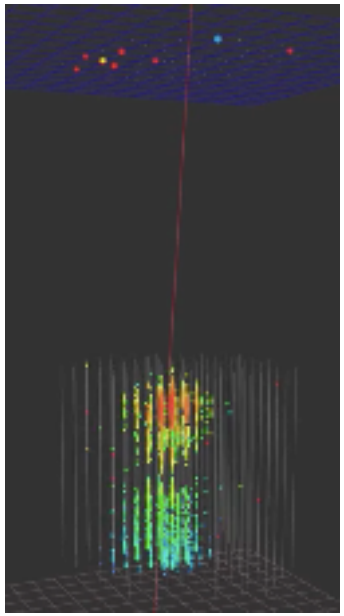
One string on a launch vehicle

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

See talk by Javier Barrios Martí in Neutrino session yesterday

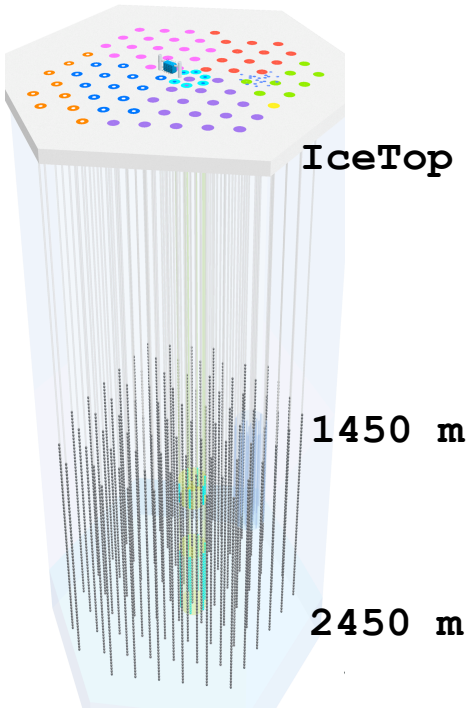
Importance of “neutrino self-veto”

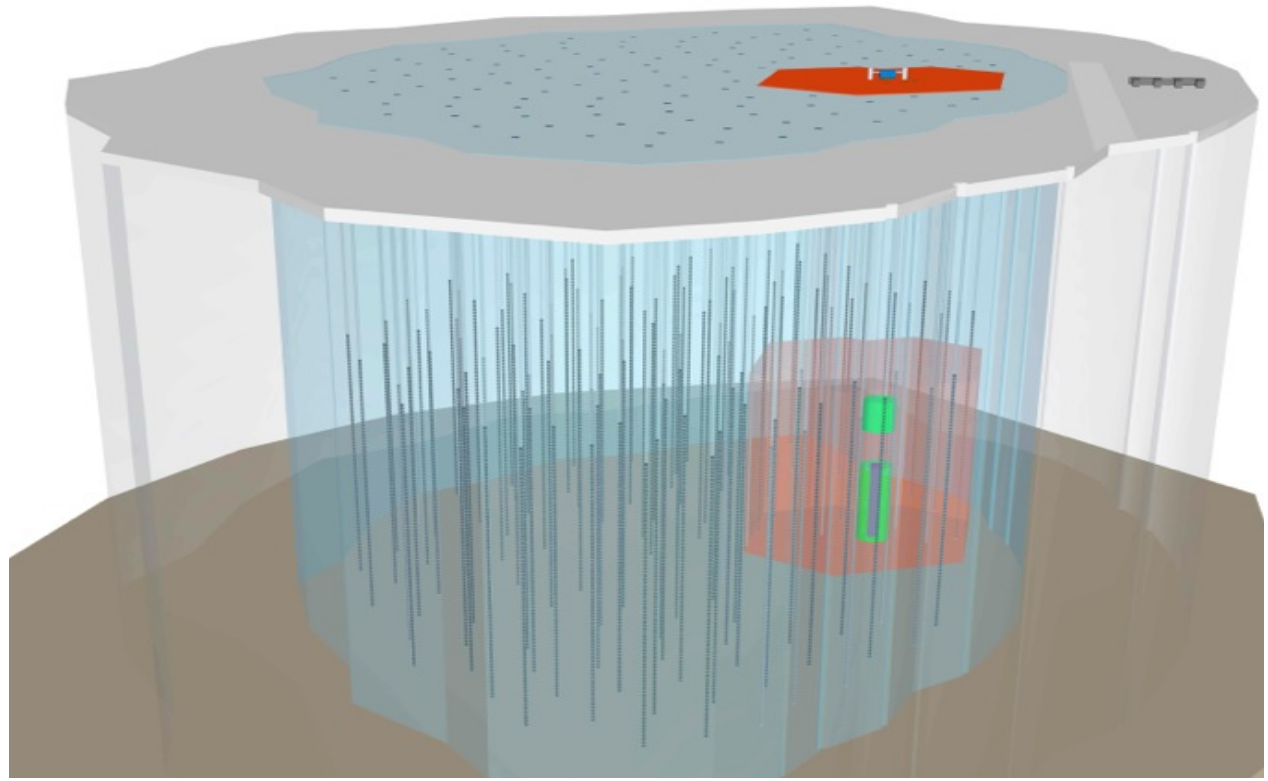
- Opens analysis to the sky above the detector
  - Southern hemisphere in the case of IceCube
  - Depends on depth and zenith angle
- Veto by a surface array would allow including events that start in the ice above the deep array
- HESE Event #45



Aperture for coincident events: ν, γ, cosmic rays

0.26 km^2 sr → ~ 10 km^2 sr

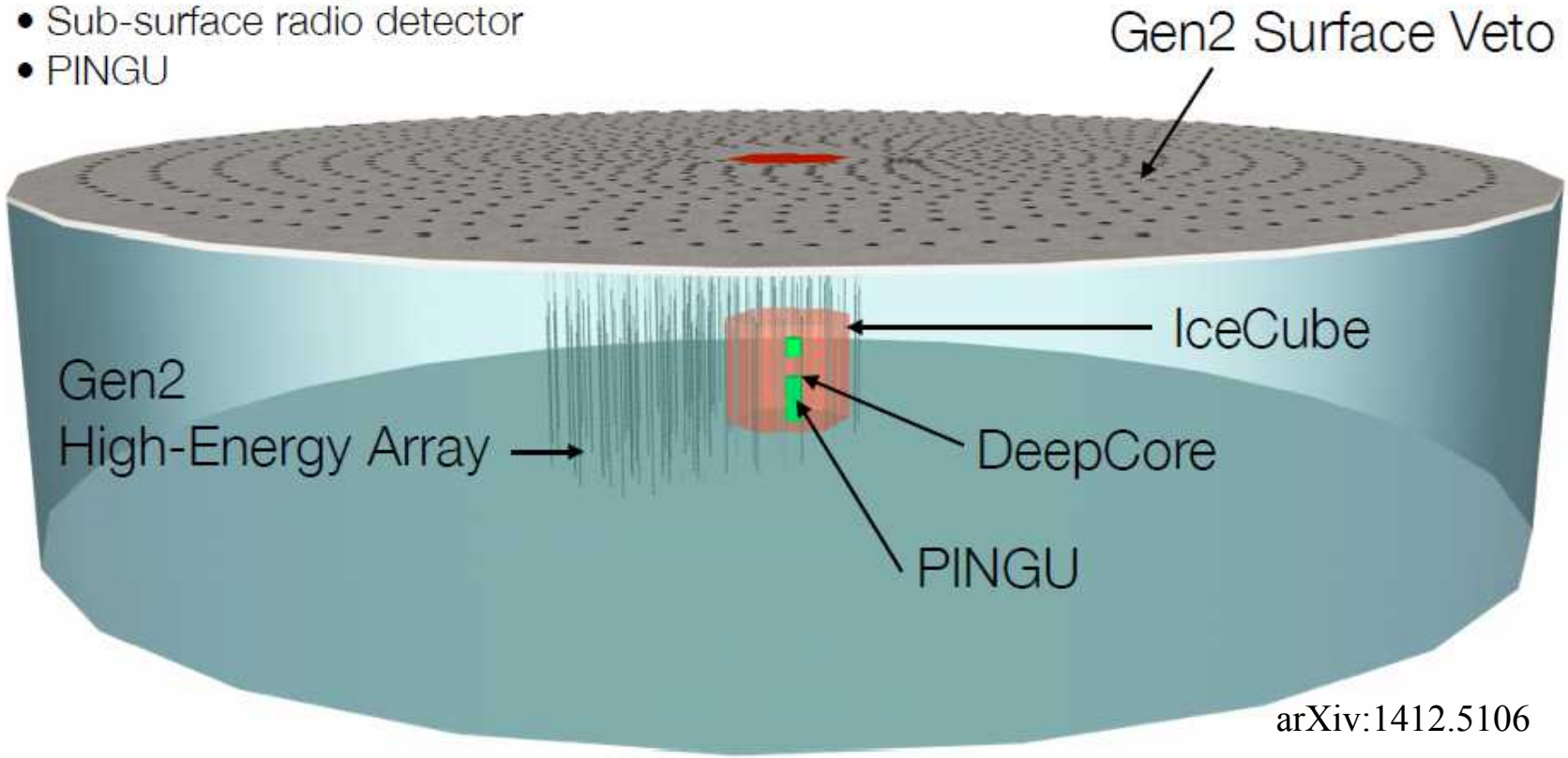




A surface array over Gen2 increases the acceptance for veto by a factor of 40

IceCube Gen2 HEA

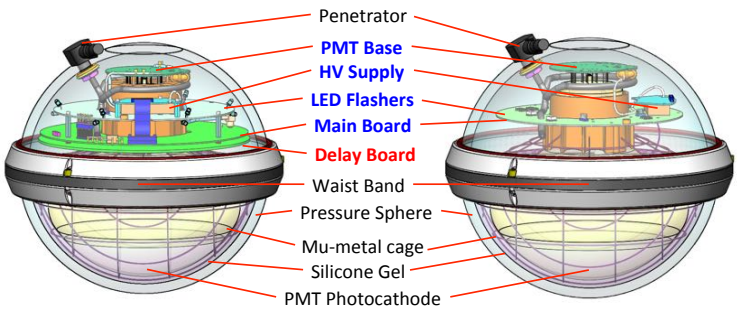
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



arXiv:1412.5106

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

IceCube Gen2 Detector concepts



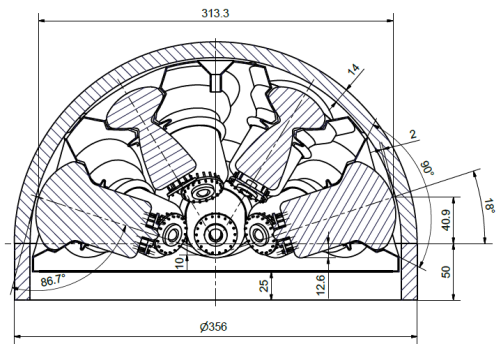
IceCube DOM

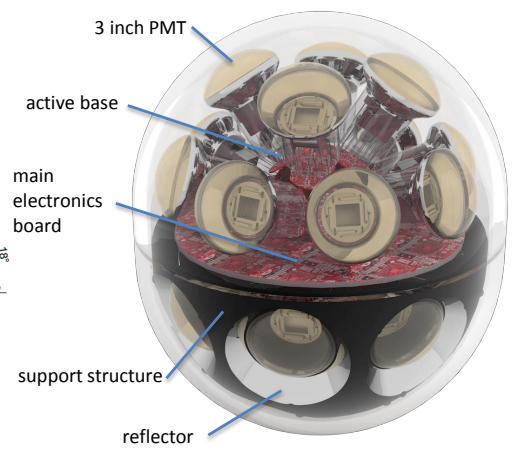
KEY:
Component identical
Component eliminated
Component redesigned

Gen2 DOM

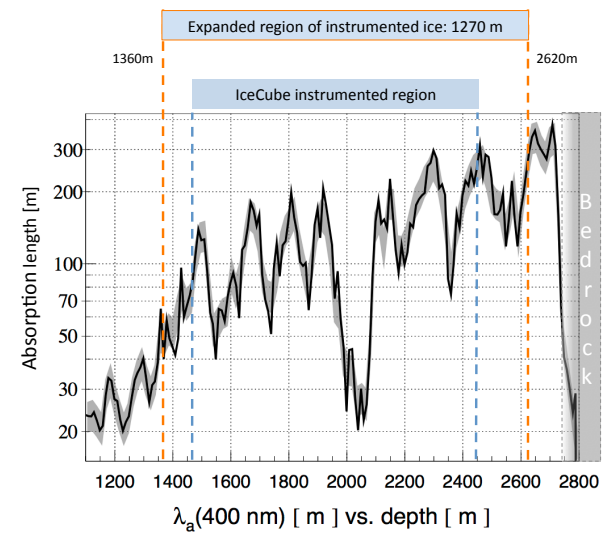
Streamlined IceCube DOM

D-Egg





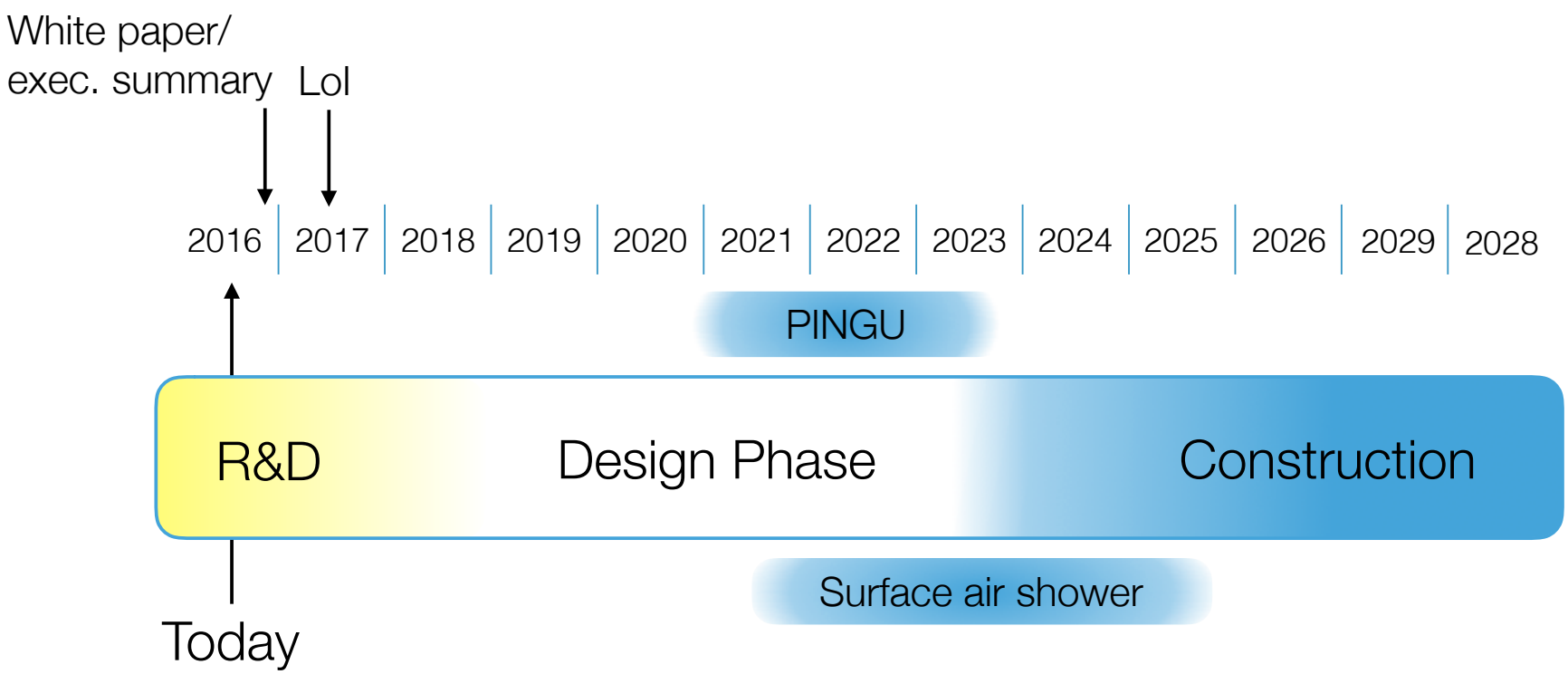
M-DOM with 24 PMTs



25% longer strings

IceCube Gen2 preliminary timeline

Preliminary timeline



Summary comments

- Several types of sources may be contributing
- Expect to see positive evidence for a contribution from the Galactic plane eventually (perhaps soon!)
- Most of the signal is probably extragalactic
- A census of the diffuse (extra-galactic) neutrino sky is needed
- Blazars produce most of the IGRB, so they are also still likely candidate sources despite IceCube limit (arXiv:1502.03104)
  - Talk by Maria Petropoulou at 17:50 this afternoon
- Some sources may absorb the gamma-rays before they emerge
  - Talk by M. Senno at 17:10 this afternoon.
- How the spectrum extends to low energy is important as well as how it extends higher energy
- Need to find ν_τ
- Future neutrino telescopes coming
  - Construction of KM3NeT has started (3 strings of ARCA off Sicily)

462 | NATURE | VOL 533 | 26 MAY 2016

An optical sensor begins its 2,500-metre journey down a borehole to become part of the IceCube neutrino detector in Antarctica.

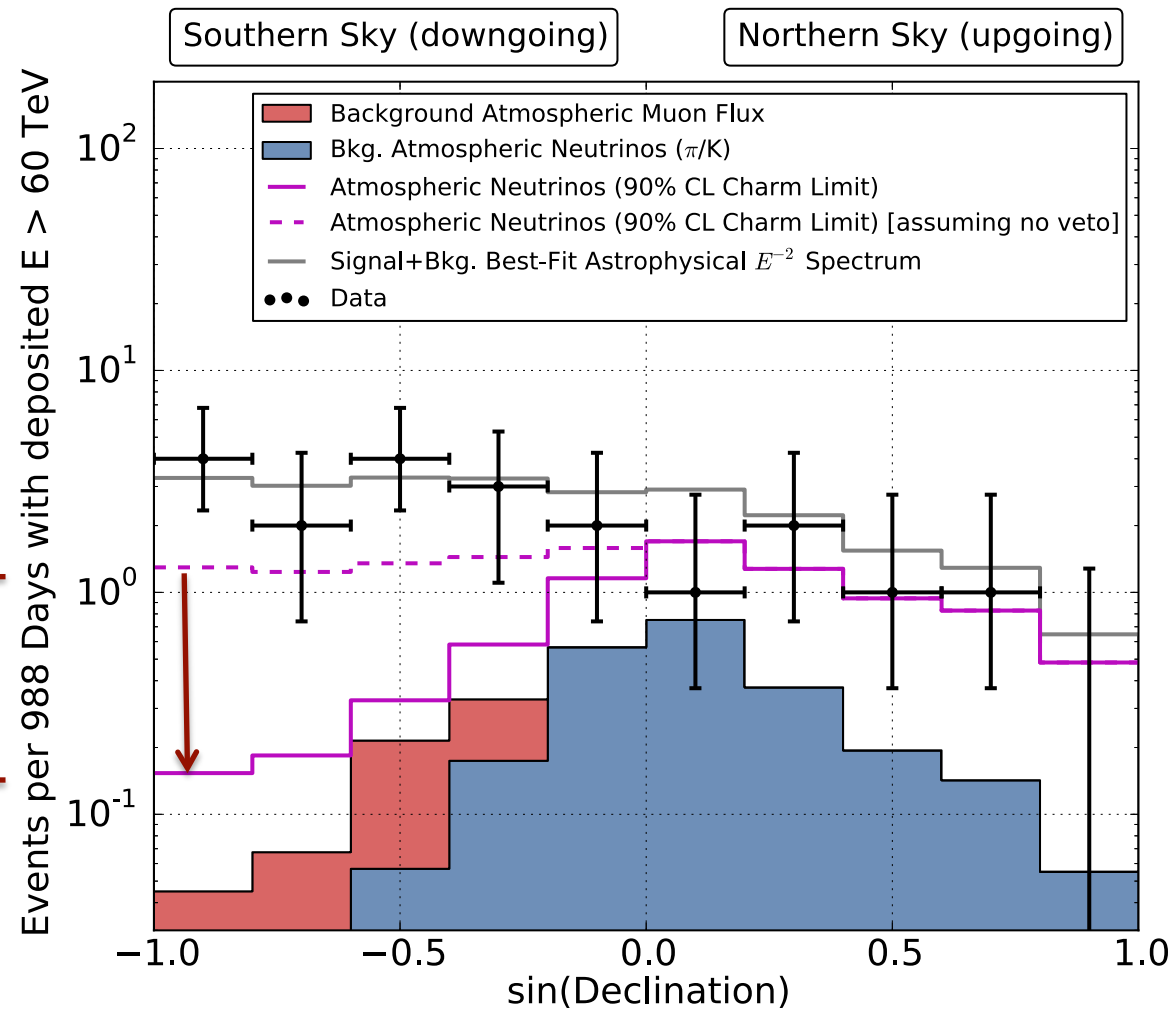
Invest in neutrino astronomy

Spencer Klein calls for bigger telescope arrays to catch particles from the most energetic places in the Universe.

Backup

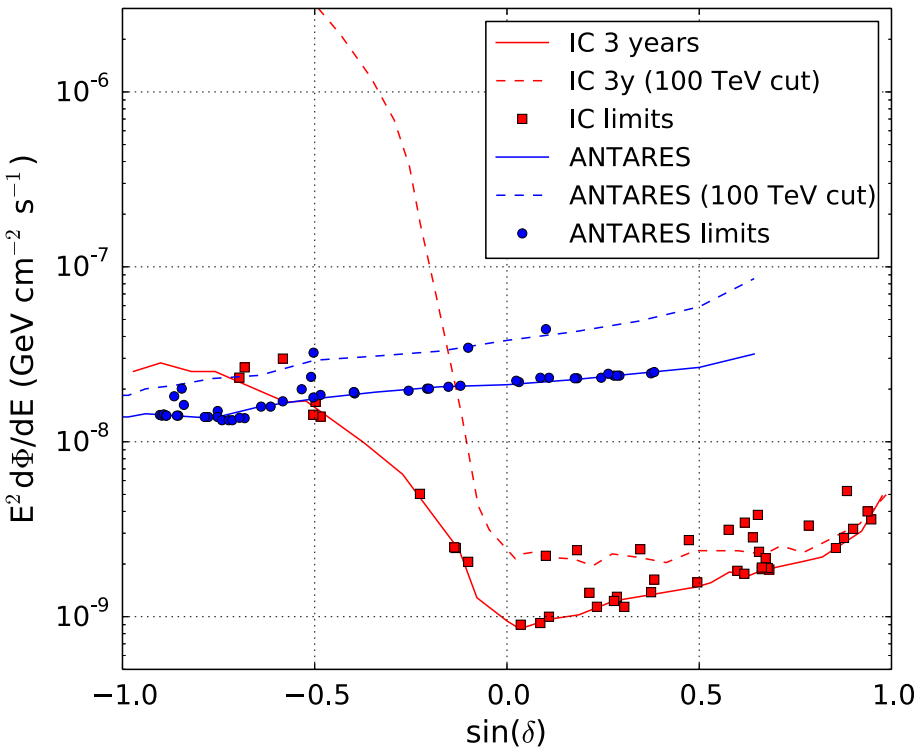
Angular distribution (E> 60 TeV)

Atmospheric ν veto



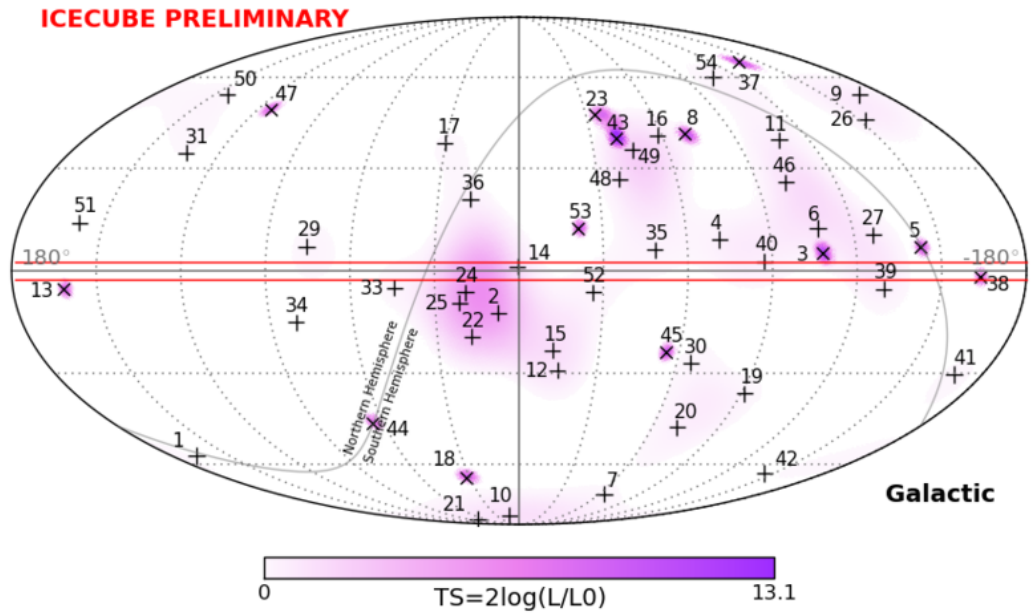
Select E > 60 TeV to get above atmospheric μ background.
Note shape of prompt atmospheric ν background.

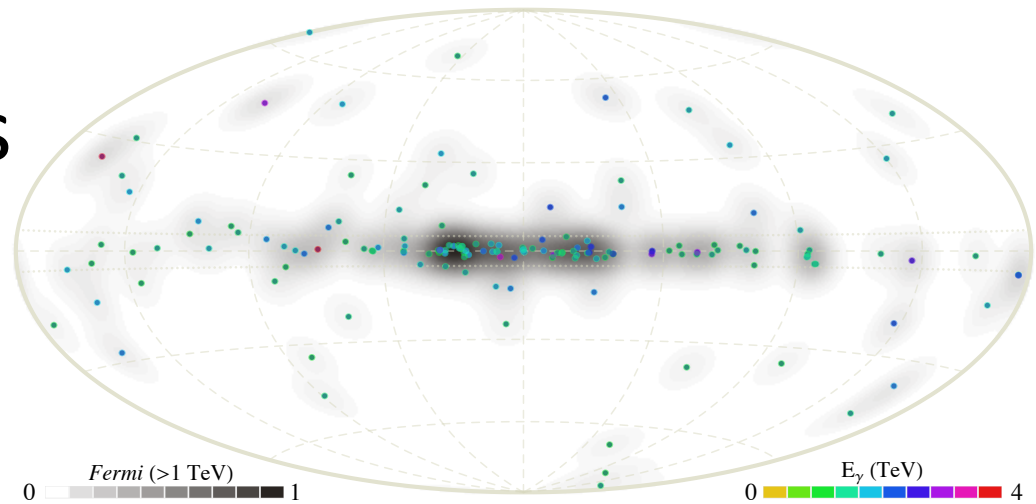
Southern Hemisphere Combined Search ANTARES-IceCube 3 years



Ap.J. 823 (2016) 65

Compare IceCube sky map, with TeV gamma-rays from Fermi-LAT using galactic coordinates





Analysis and diagram of Fermi TeV gamma-rays by Matt Kistler arXiv:1511.05188

Note that several of the IceCube events near the plane are in the outer Galaxy