ICECUBE PRESENT AND FUTURE

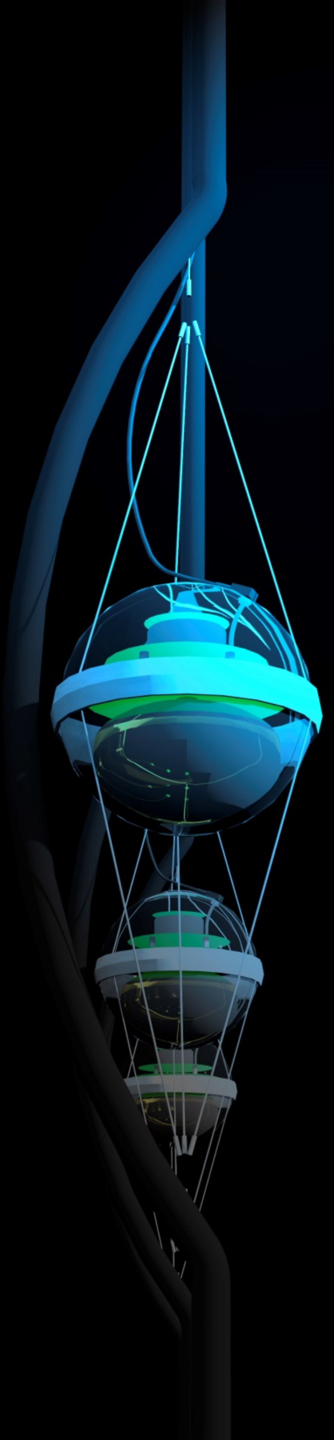
Photo: Sven Lidström

OLGA BOTNER, UPPSALA

IN MEMORIAM

Per Olof Hulth

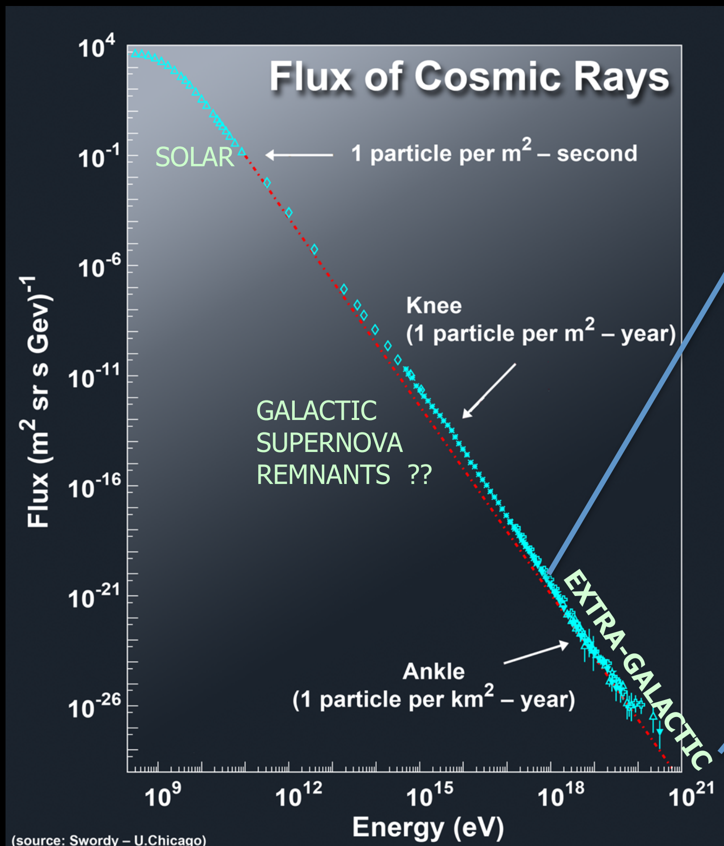
1943 - 2015

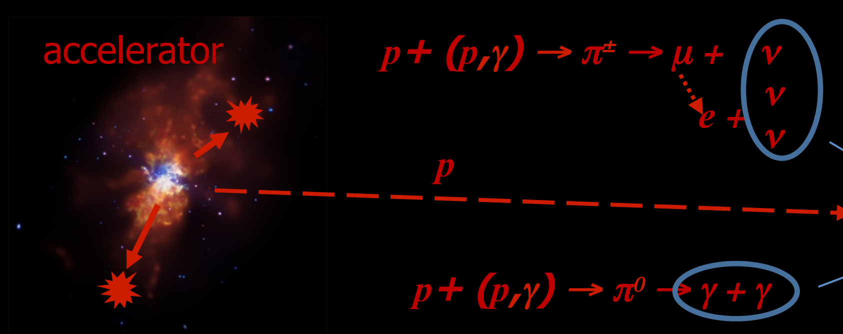


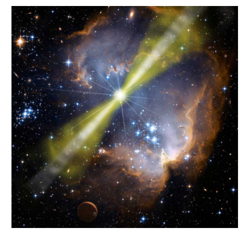
OUTLINE

- A CUBIC KILOMETER DETECTOR
- LOOKING FOR A NEEDLE IN A HAYSTACK
- SELECTED RESULTS
- WHAT NEXT?
- CONCLUSIONS

RATIONALE FOR NEUTRINO ASTRONOMY







- detection of ν's clarifies CR acceleration processes

ν's
- point back to source
- trace hadronic interactions

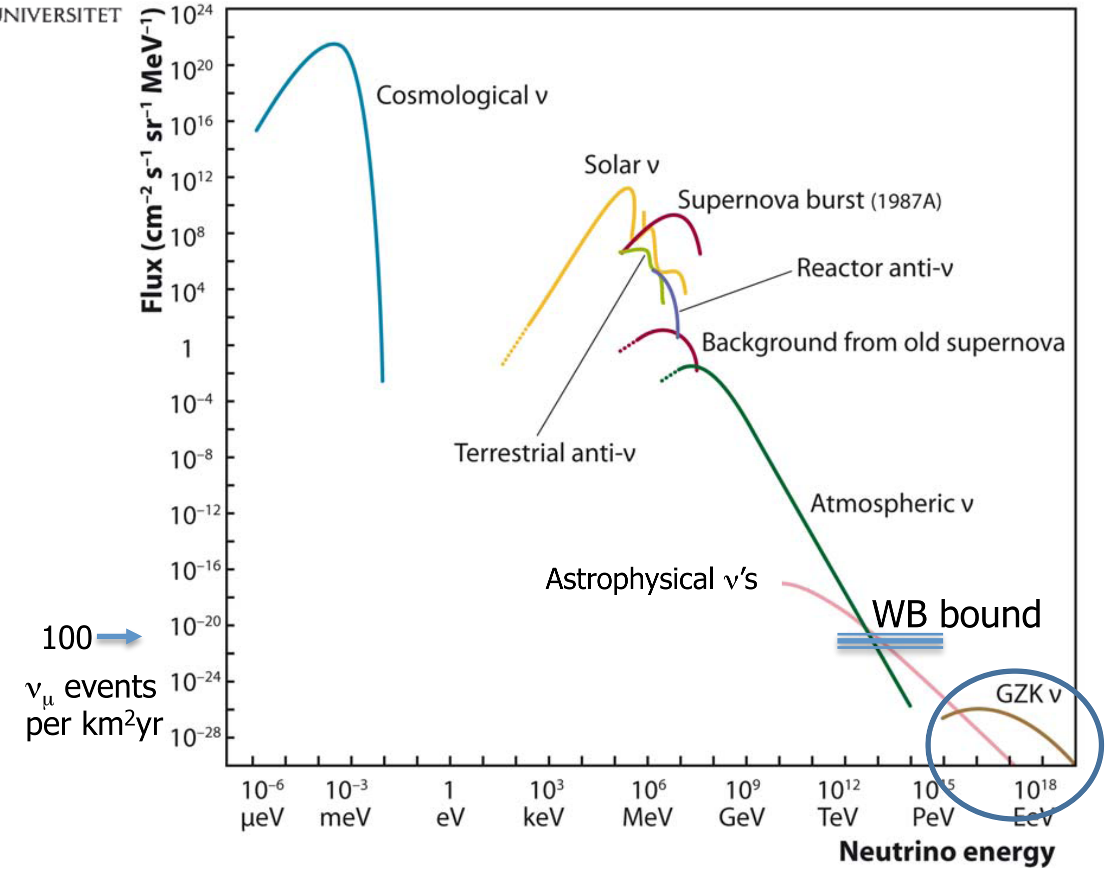
$\nu_e : \nu_\mu : \nu_\tau =$ 1:2:0 at source

↓

1:1:1 at Earth

CR – ν – γ connection

THE ν SPECTRUM



- atmospheric ν's dominate < 100 TeV
- astrophysical ν's (perhaps) > 100 TeV

"guaranteed" flux

Greisen-Zatsepin-Kuzmin cosmogenic ν's

$$p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{array}{l} n\pi^+ \rightarrow n\mu\nu \\ p\pi^0 \rightarrow \gamma\,\gamma \end{array}$$

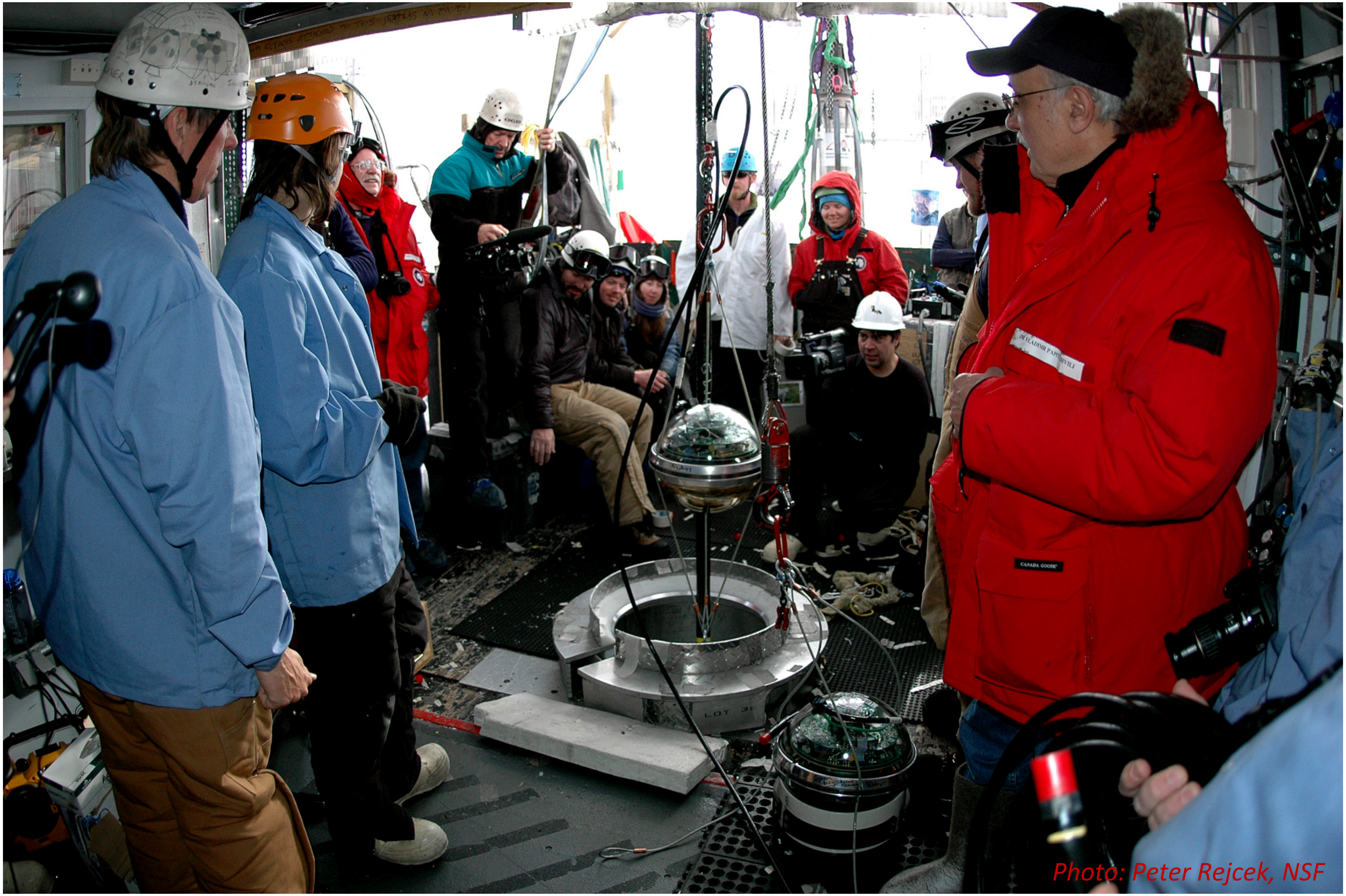
- produced < 100 Mpc from source
- carry information on
  - location
  - cosmological evolution of the UHE CR sources

➢ many model uncertainties and constraints

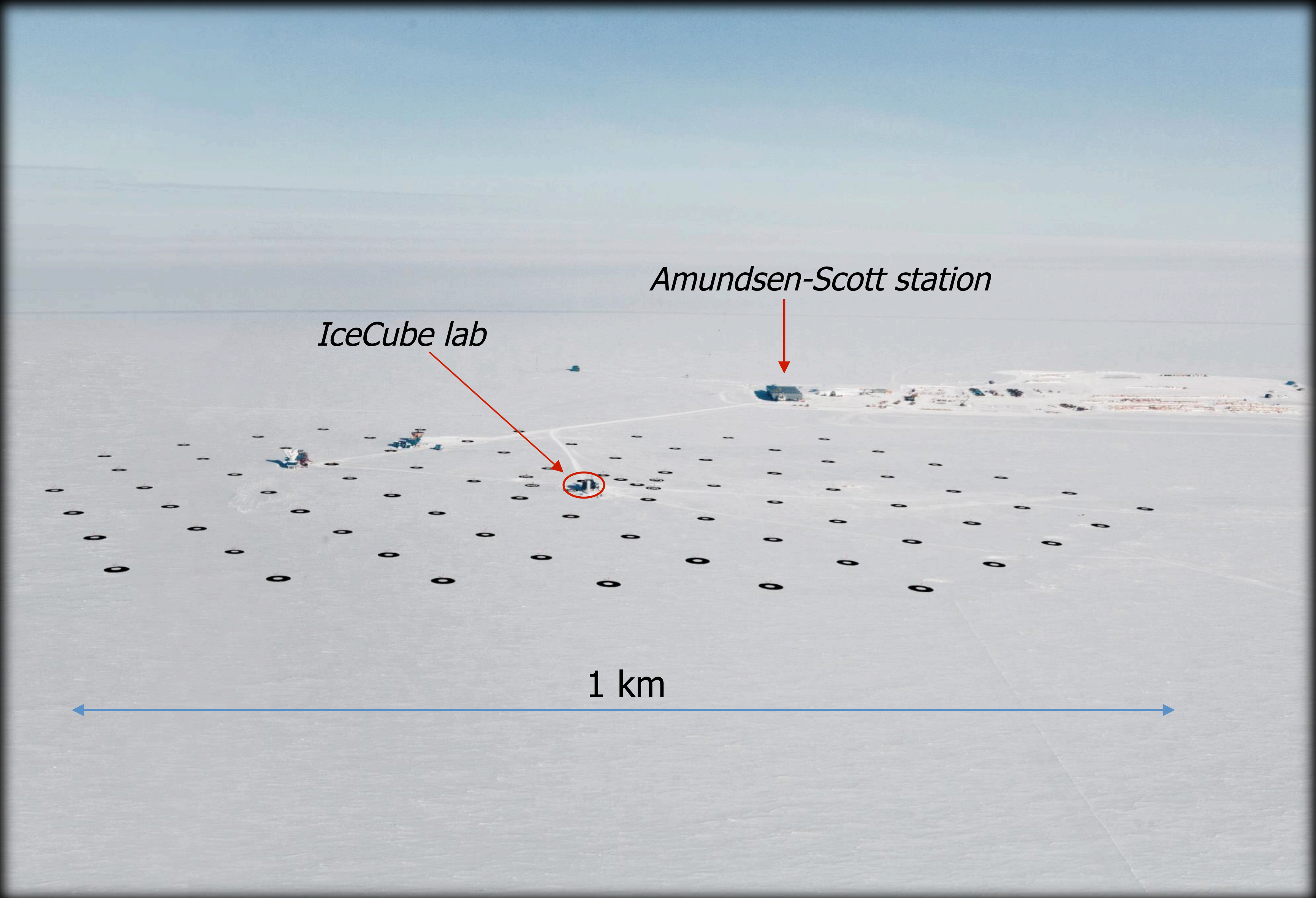
THE ICECUBE NEUTRINO OBSERVATORY

5 megawatt hot water drilling system
IceTop tanks
drill tower
CONSTRUCTION 2004 - 2010

DEPLOYMENT OF FINAL STRING on Dec 18, 2010



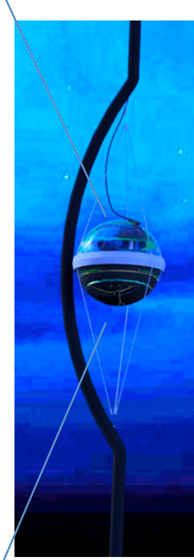
LOCATIONS OF DEPLOYED STRINGS

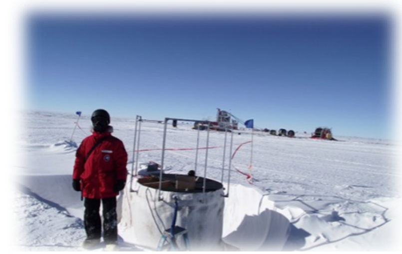


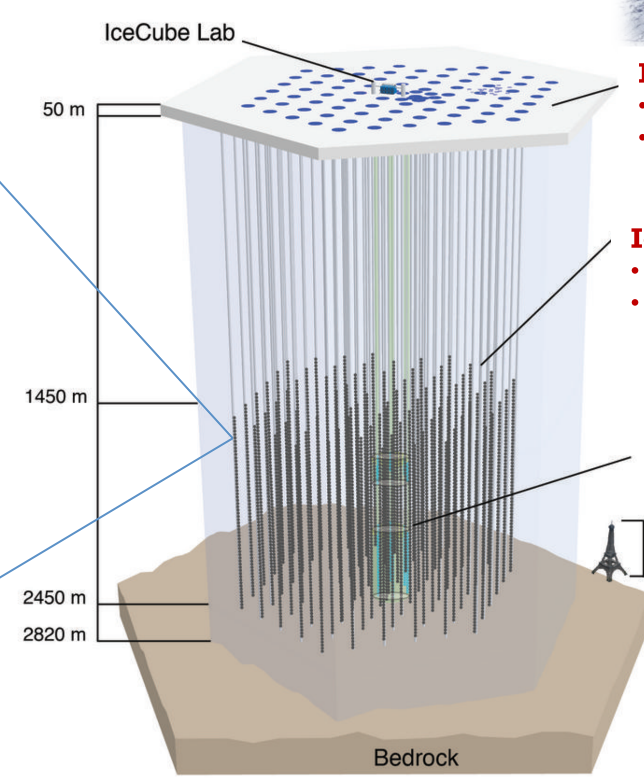
ICECUBE – THE WORLD'S LARGEST NEUTRINO OBSERVATORY

- 5160 Digital Optical Modules in deep ice
- 86 "strings"
- ~ 125 m between strings
- 60 DOMs per string, 17 m between DOMs

DIGITAL OPTICAL MODULE







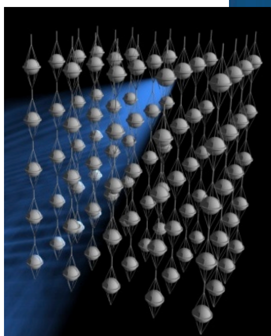
IceTop
- **162 frozen water tanks**
- **1 km^2 air shower surface array**

IceCube Array (1 Gt instr. volume)
- **86 strings (incl. 8 DC strings)**
- **1 km^3 deep ice array**

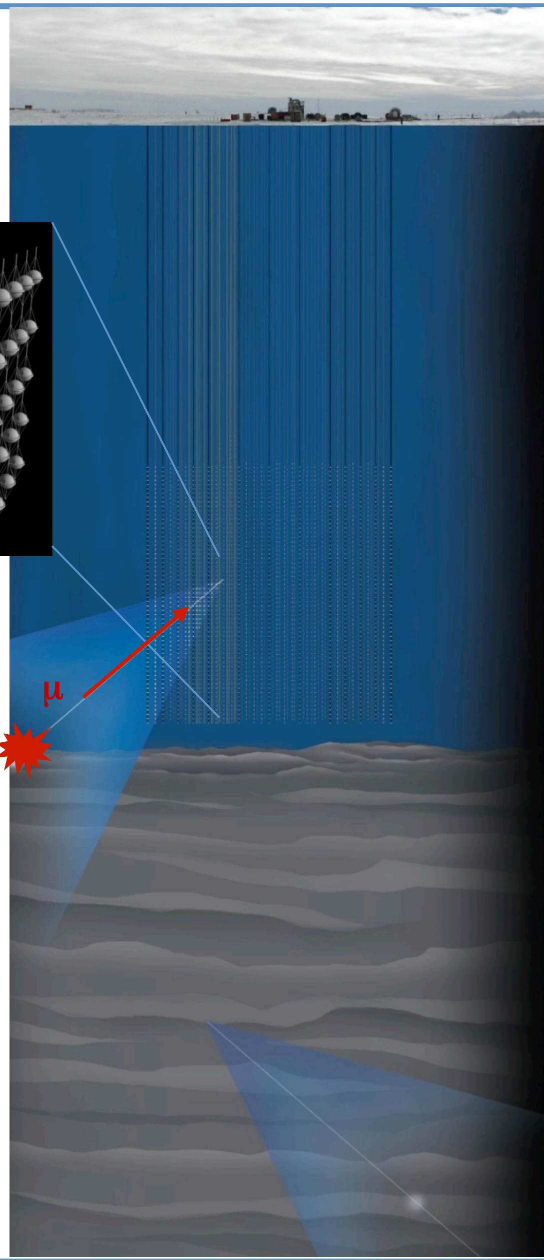
DeepCore (20 Mt)
- **low-energy extension**
- **threshold: 10 GeV**

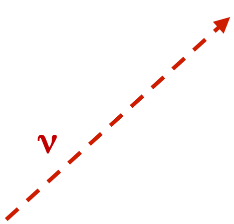
ν DETECTION

CHERENKOV RADIATION

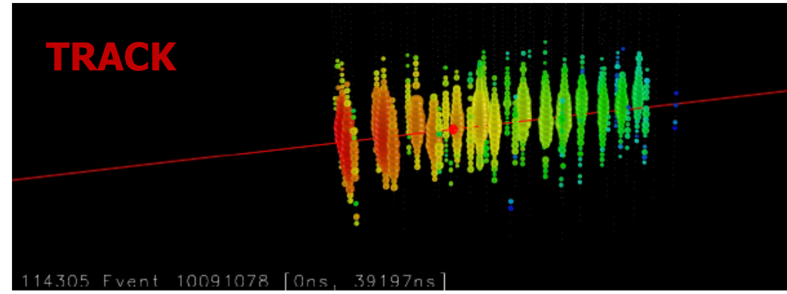


DETECTED BY A 3D ARRAY OF DOMS

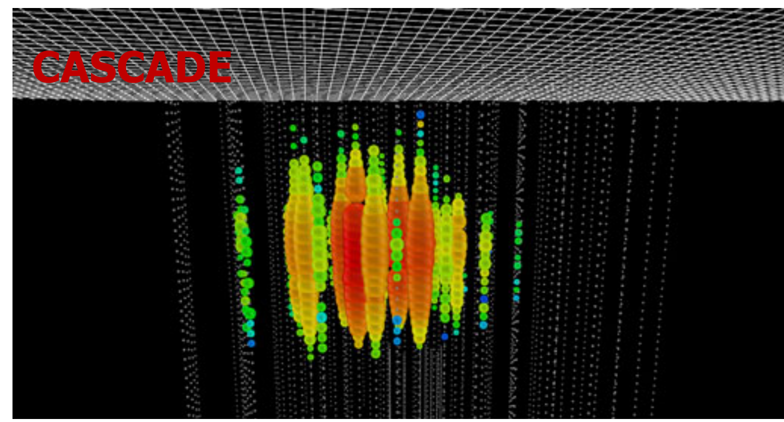




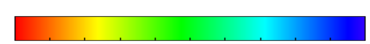
POSITION, TIME, AMPLITUDE ⇢ ν ENERGY, DIR.



- no direct E_ν measurement
- good pointing resolution 0.2 – 1°



- good E_ν measurement, resol^n ~ 15%
- decent pointing resol^n ~ 10 – 15°

early  late

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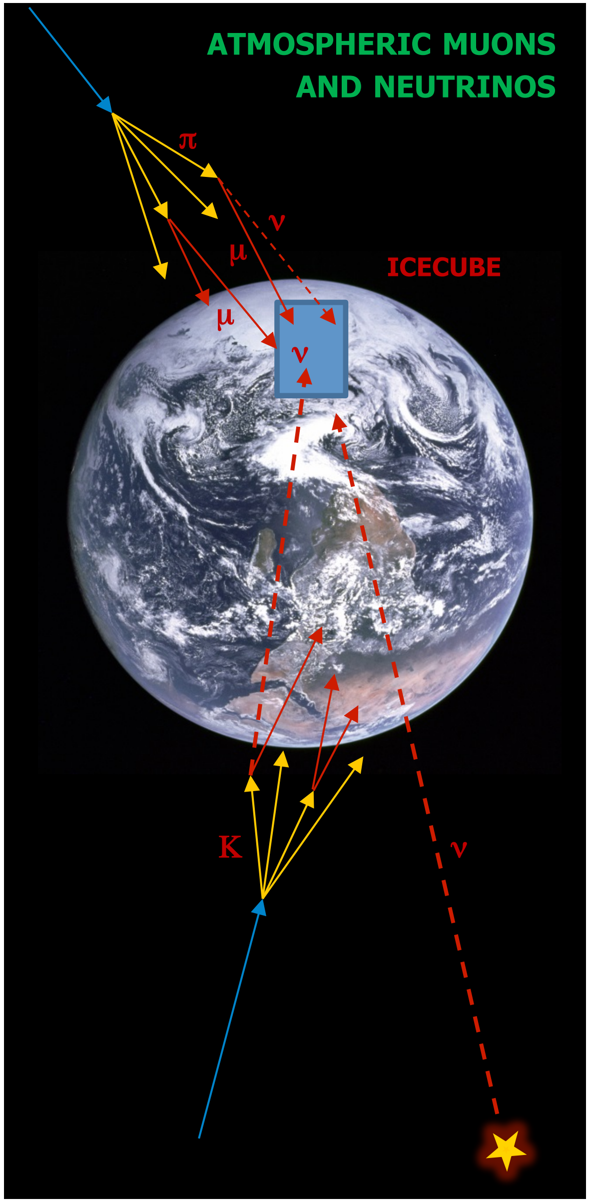
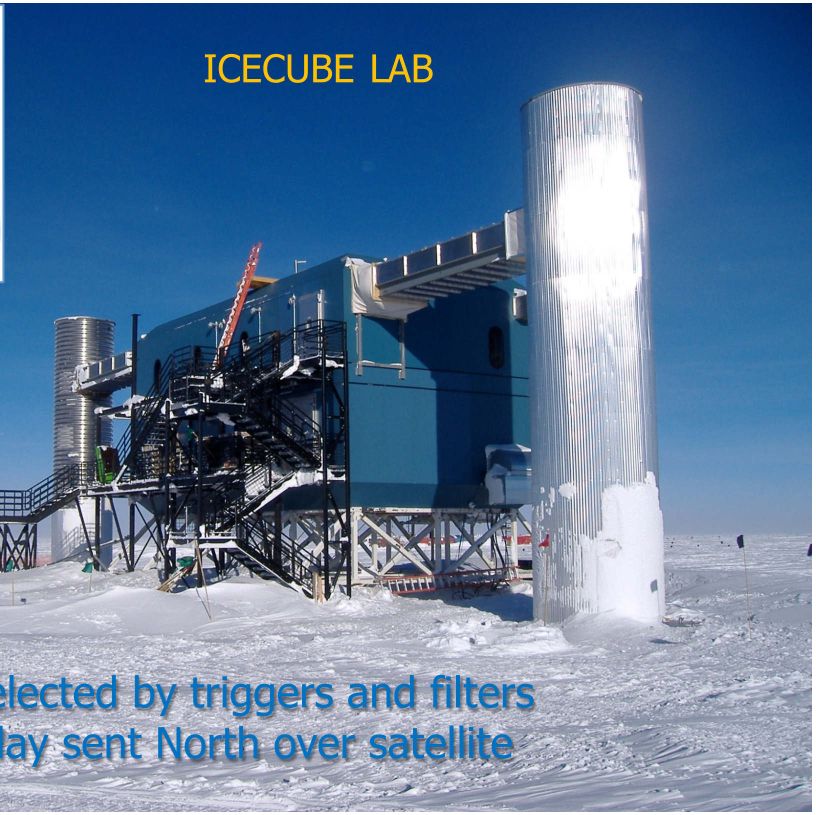
WHY ν ASTRONOMY IS NOT SIMPLE …

ICECUBE



- atmospheric μ rate ~ 10^3 Hz (from above)
- atmospheric ν rate ~ 10^{-3} Hz (isotropical)
- ASTROPHYSICAL ν rate ~ 10^{-6} Hz (isotropical)



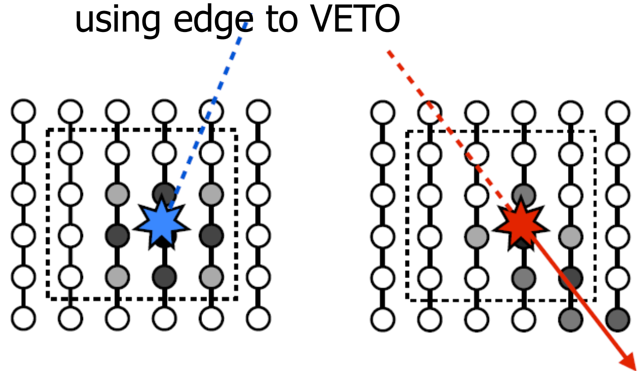
- events selected by triggers and filters
- 100 GB/day sent North over satellite

BACKGROUND SUPPRESSION STRATEGIES

suppress atm. μ background

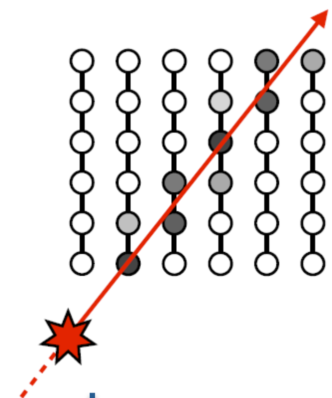
"starting" events

using edge to VETO



upgoing tracks

using Earth as filter



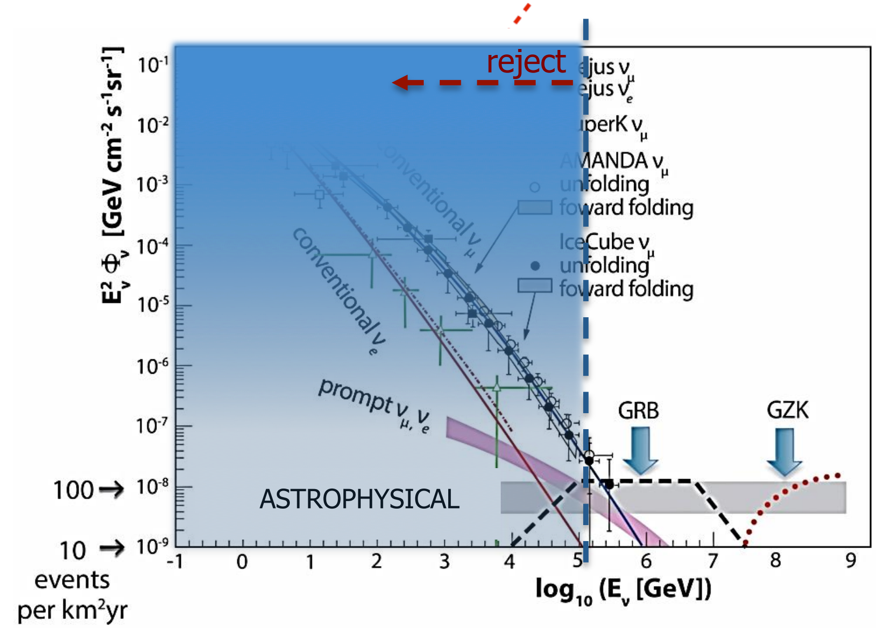
suppress atm. ν background

using ENERGY

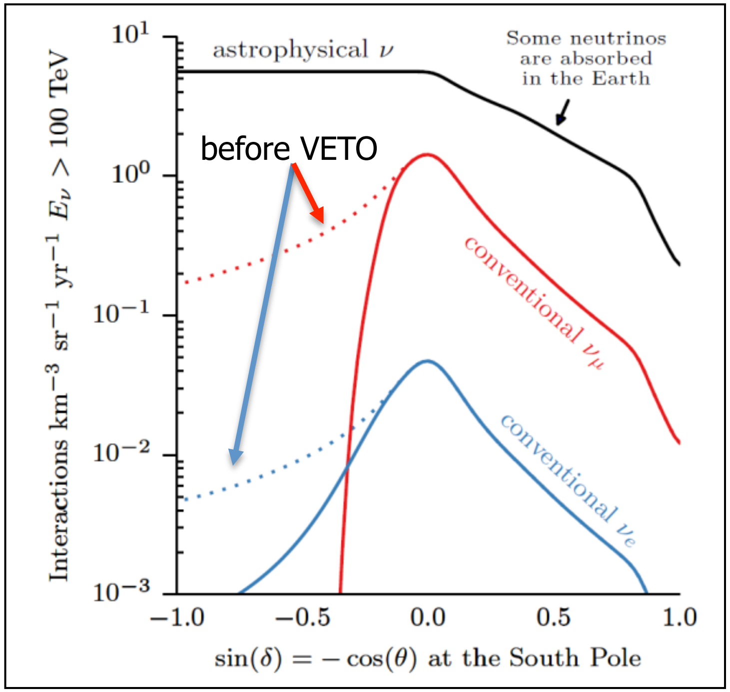
diffuse searches

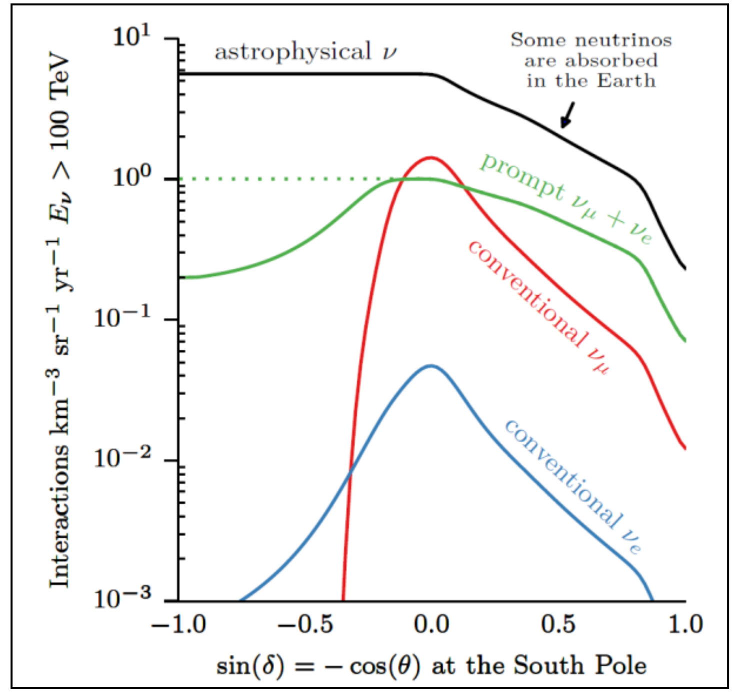
SPATIAL TEMPORAL CORRELATIONS

point sources



BACKGROUND SUPPRESSION STRATEGY



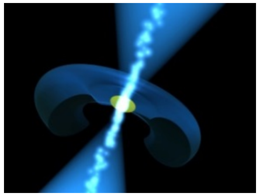
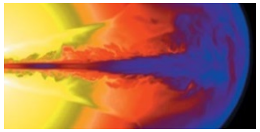


- the μ VETO also removes atm. CONVENTIONAL and PROMPT ν's

[*Schönert, Gaisser, Resconi, Schultz, Phys.Rev.D79:043009 (2009)*]
[*Gaisser, Jero, Karle, Van Santen, Phys.Rev.D90:023009 (2014)*]

ICECUBE SCIENCE

- **ASTROPHYSICS**
  - point sources of ν's (SNR, AGN …), extended sources
  - transients (GRB, AGN flares …)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- **COSMIC RAY PHYSICS**
  - energy spectrum around "knee", composition, anisotropy
- **DARK MATTER**
  - indirect searches (Earth, Sun, galactic center/halo)
- **EXOTIC SOURCES OF ν'S**
  - magnetic monopoles
- **PARTICLE PHYSICS**
  - ν oscillations, sterile ν's
  - charm in CR interactions
  - violation of Lorentz invariance
- **SNe** (galactic/LMC)
- **GLACIOLOGY**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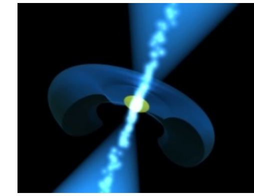
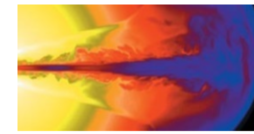
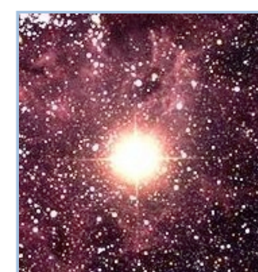
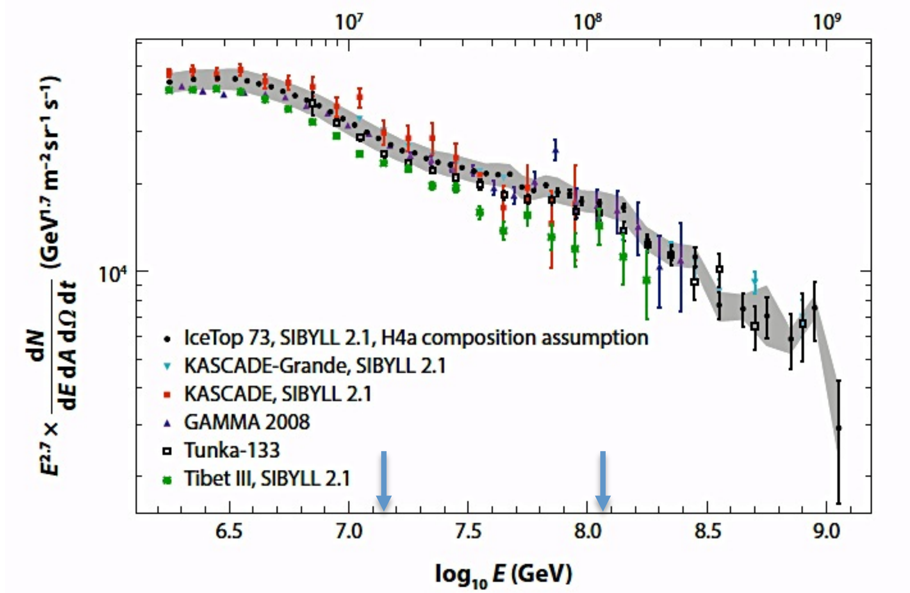






Where is the transition galactic/extra-galactic CRs?

- investigate energy spectrum between knee and ankle

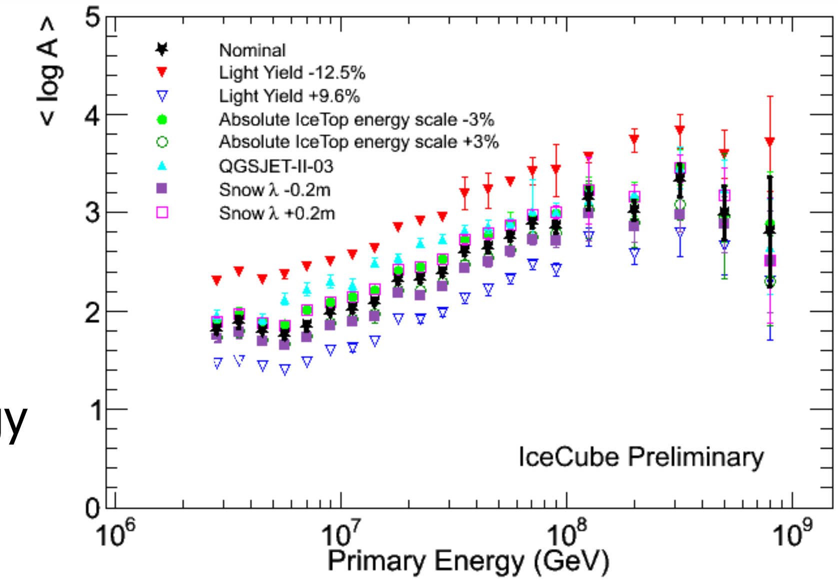


- NOT a single power law
- spectral hardening at ~ 20 PeV
- steepening at ~130 PeV

- measurement close to shower max – minimizes fluctuations
- energy from particle density 125m from shower core; mixed composition assumed (H4a)

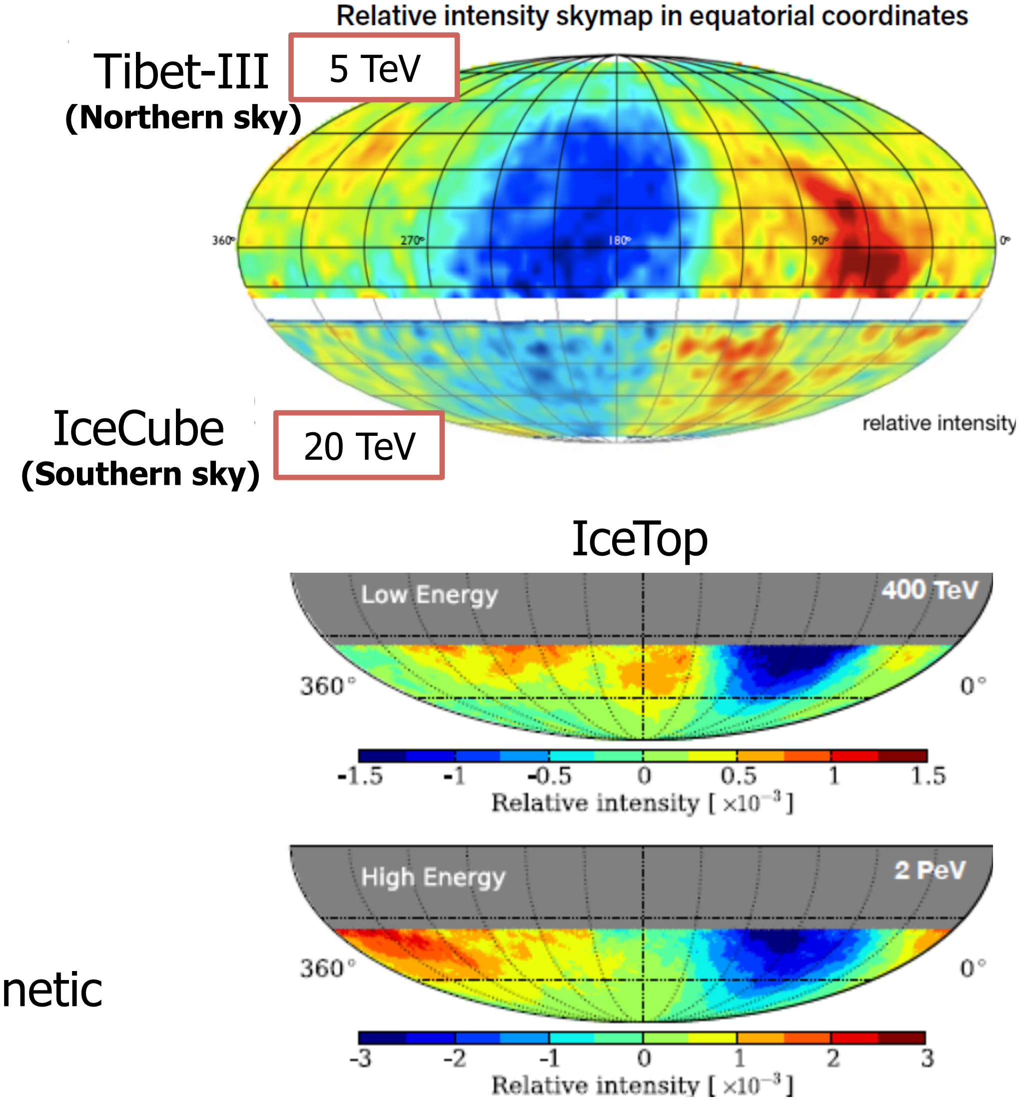
[*Gaisser, Astropart.Phys. 35, 801 (2012)*]
[*IceCube, Phys.Rev.D88:042004 (2013)*]
[*Gaisser, Halzen, Ann.Rev.Nucl.Part.Sci. 64:101 (2014)*]

- mass composition as function of energy – light nuclei component?



COSMIC RAY ANISOTROPIES – ICETOP

- CR arrival dir. probe distr. of galactic sources & propagation in the magnetized galactic medium
- scrambled over history of galaxy
- OBSERVE ANISOTROPIES AT ‰ LEVEL
- cont. structure observ. in the North
- studies at various angular scales
- CHANGE OF TOPOLOGY AT ~100 TEV
- AMPLITUDE INCREASES WITH ENERGY
- ORIGIN OF THE ANISOTROPY UNKNOWN
- signature of a few nearby SNR?
- effects of turbulent interstellar magnetic fields within few pc
- interplay with heliosphere



[IceCube, ApJ 765:55 (2013)]

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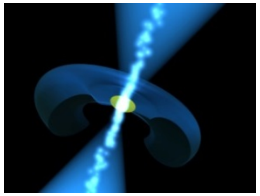
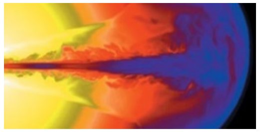




POINT SOURCE SEARCHES

- 4 years data 2008 – 2012
- livetime 1373 days
- well-reconstructed muon tracks

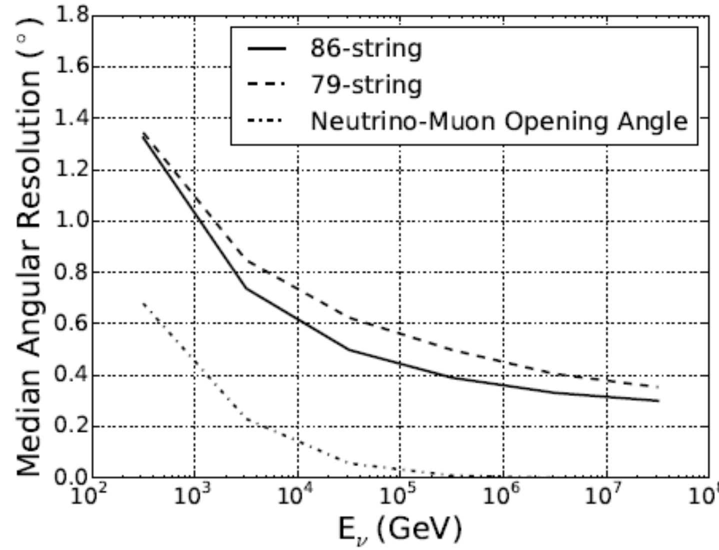
178k up-going ν_μ's
216k (mostly) down-going μ's

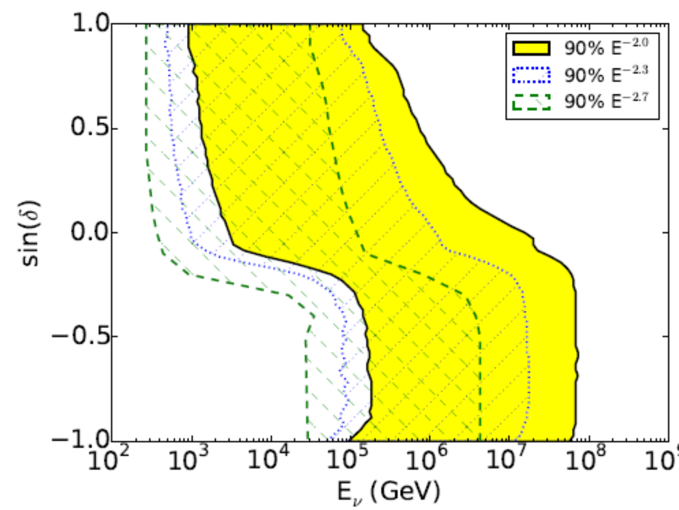
- all-sky point source search
- extended source scan
- pre-defined catalog of potential sources
- stacking searches
- time dependent searches

in all cases

- data compatible with background only
- limits on ν_μ flux reported

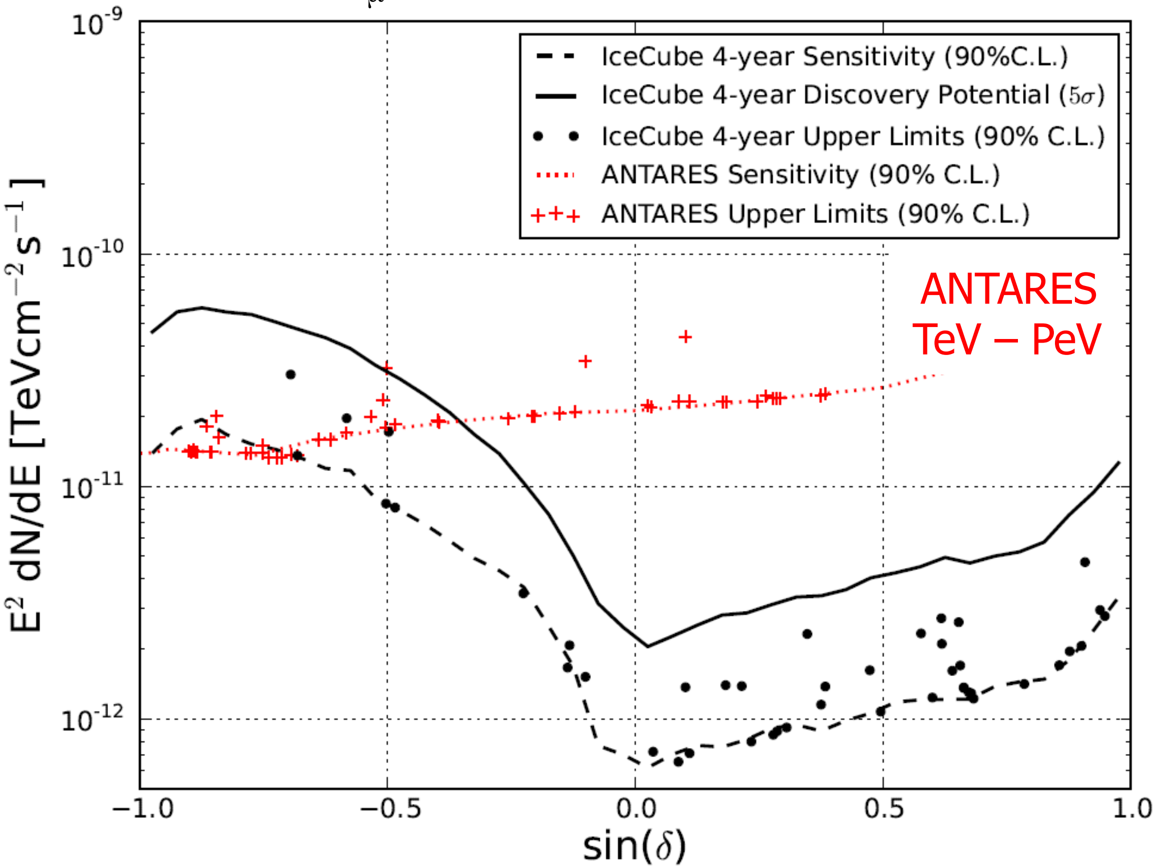
[*IceCube, Astrophys.J.796 (2014) 109*]





POINT SOURCE SEARCHES

ν_μ upper limits for 44 sources



median sensitivity (90% C.L.)

~ 10^{-12} TeV^{-1}cm^{-2}s^{-1}

Northern sky sensitive to TeV - PeV

~ 10^{-11} TeV^{-1}cm^{-2}s^{-1}

Southern sky sensitive mainly > PeV

[*IceCube, Astrophys.J.796 (2014) 109*]
[*IceCube, arXiv:1503.0098*]

- several IceCube analyses aiming to lower energy threshold in the South
- joint analysis IceCube/Antares improves limits in Southern hemisphere

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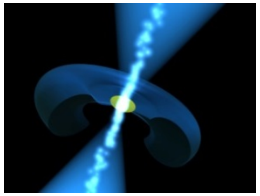
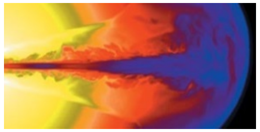
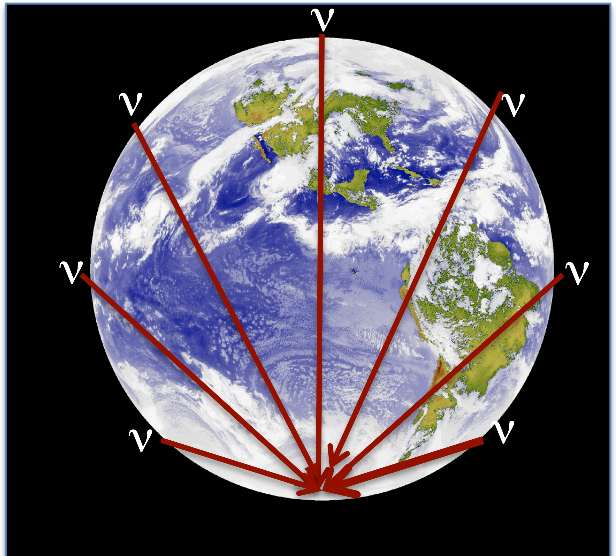
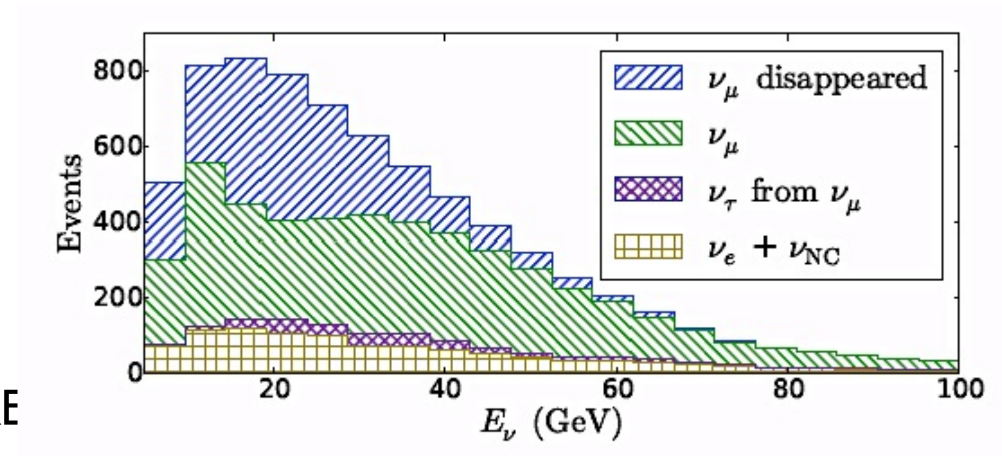
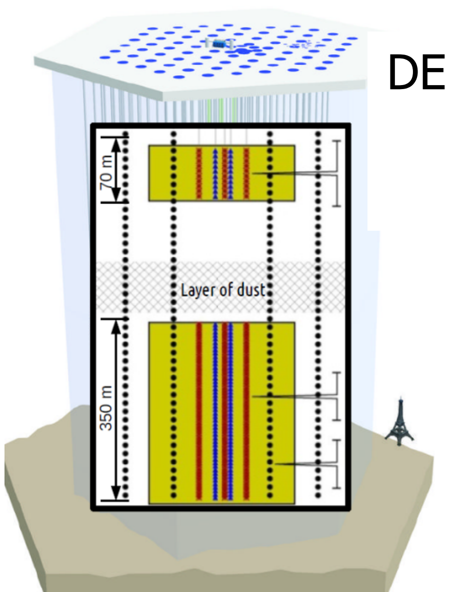



> 10^5 atm. ν's per yr allows sensitive measurement of ν_μ dissappearance

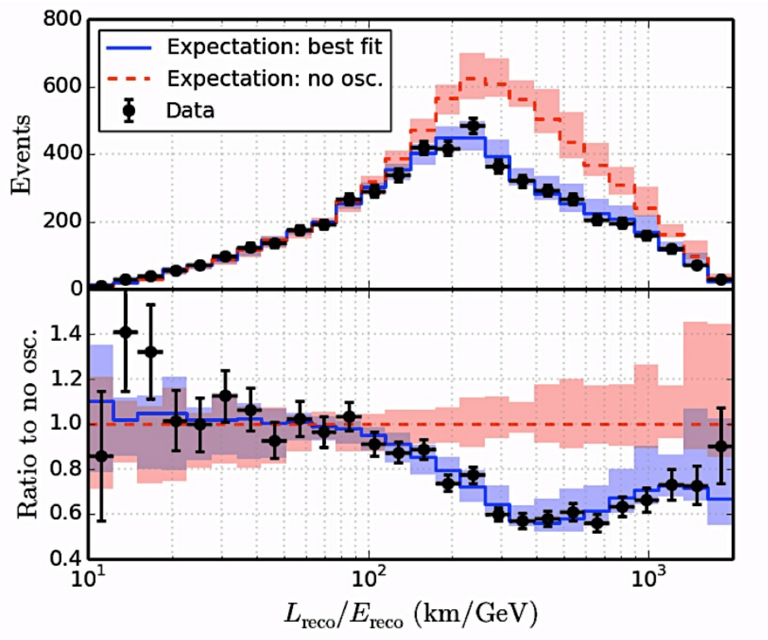




DEEPCORE

- at 2 – 2.5 km depth
- 0.02 km^3 volume
- denser instrumentation
- ν threshold 10 GeV
- IceCube helps veto atm. μ bckg

NEUTRINO OSCILLATIONS

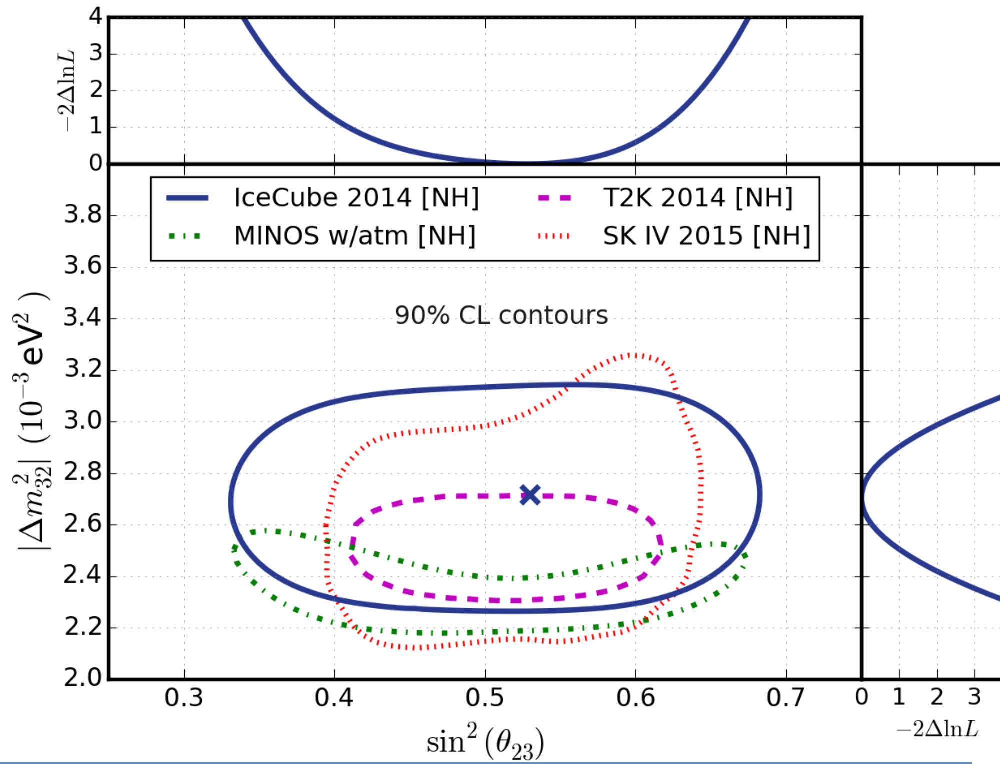


[*IceCube, Phys.Rev.D91:072004 (2015)*]

- competitive result (3 years)
- will improve further

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

- select
  - starting events
  - clear μ tracks
  - rely on direct photons
- 5174 events observed cf. 6830 expected if no oscillation
- perform 2D fit in *E* and *cos(θ)*



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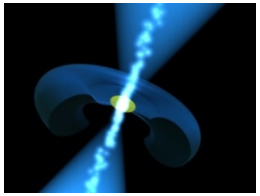

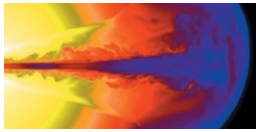

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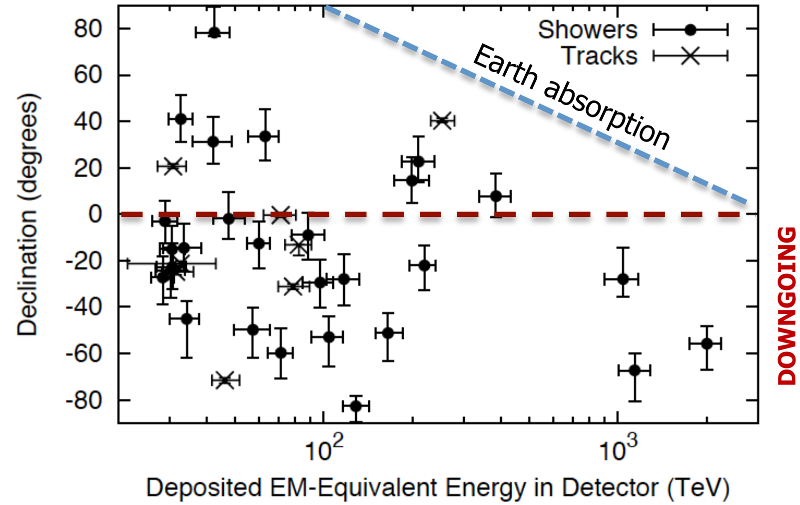
ASTROPHYSICAL NEUTRINOS

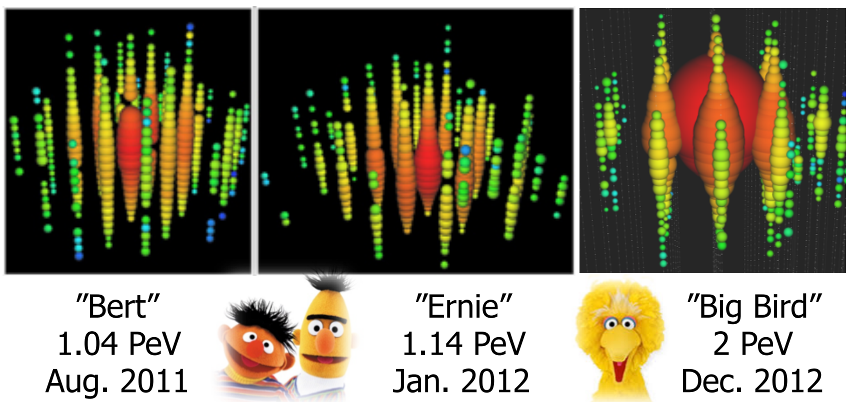
- first evidence for an extra-terrestrial flux shown at IPA2013 [IceCube, Science 342 (2013)]

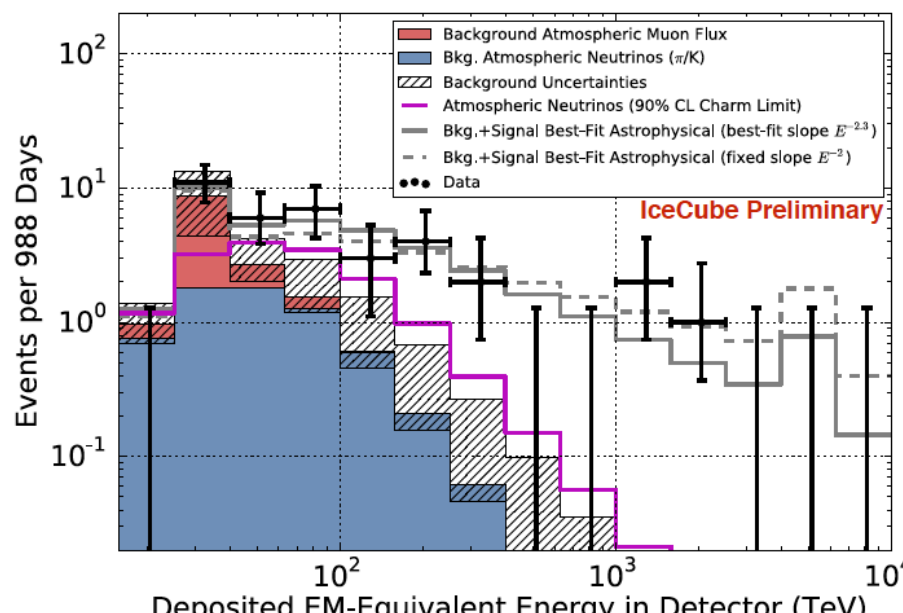


[IceCube, Phys.Rev.Lett. 113:101101 (2014)]

- 3 yrs: 37 events in 988 days $\boxed{5.7\sigma}$
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 ν

- mostly ν_e CC and NC cascades





- zenith distribution consistent with isotropic astrophysical flux

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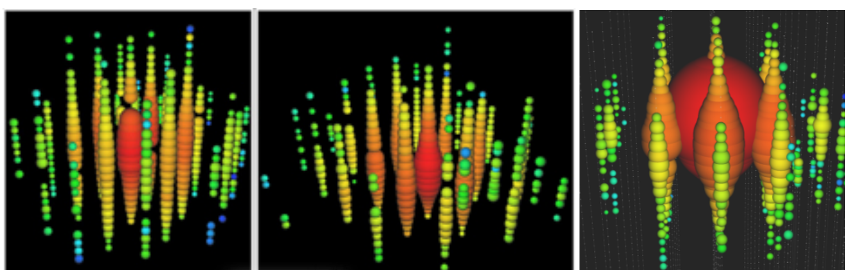
- 3 yrs: 37 events in 988 days **5.7σ**
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 ν

- 4 yrs: 54 events **~ 7 σ**

- mostly ν_e CC and NC cascades

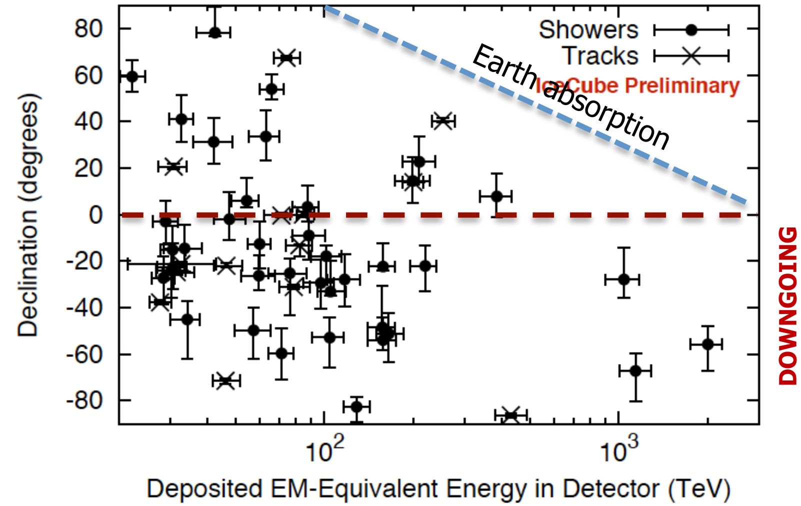


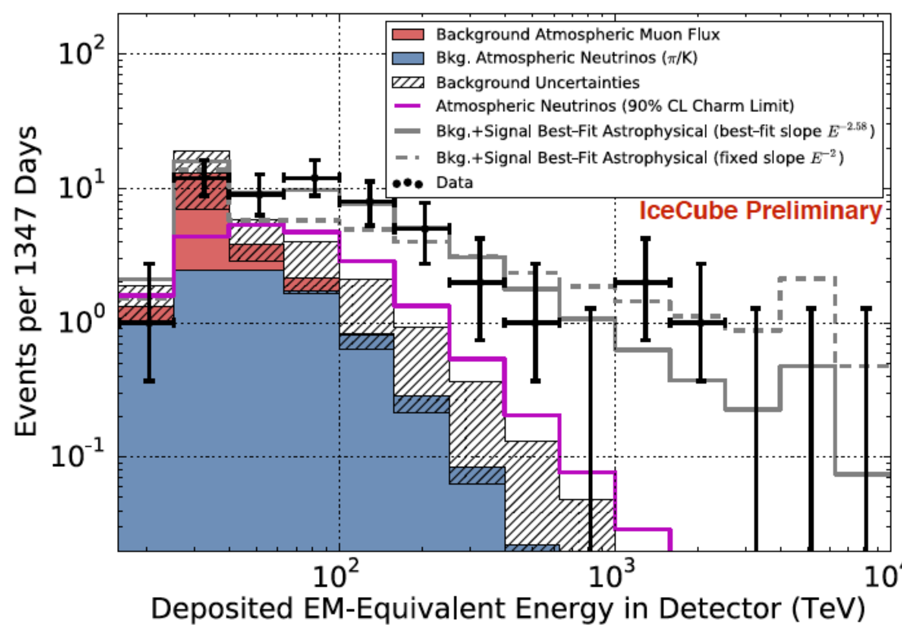
"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

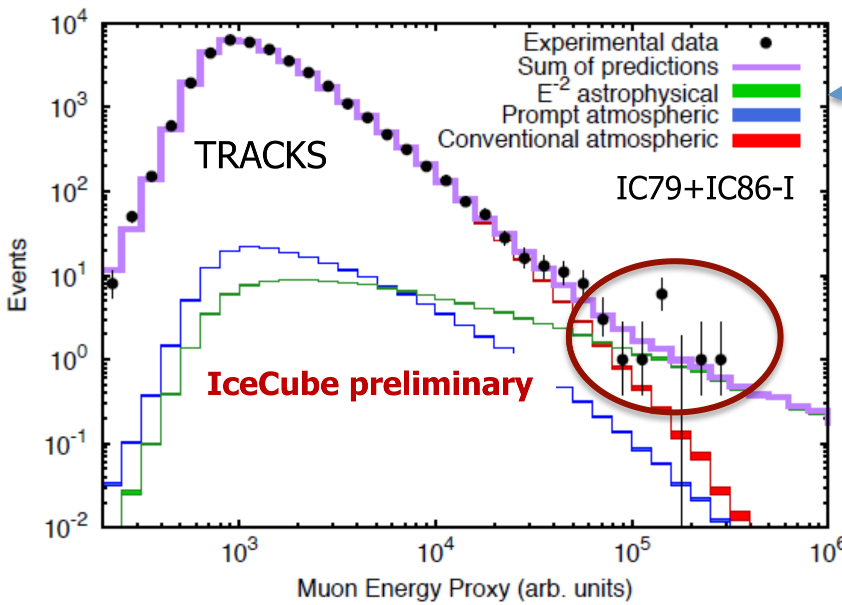
- zenith distribution consistent with isotropic astrophysical flux

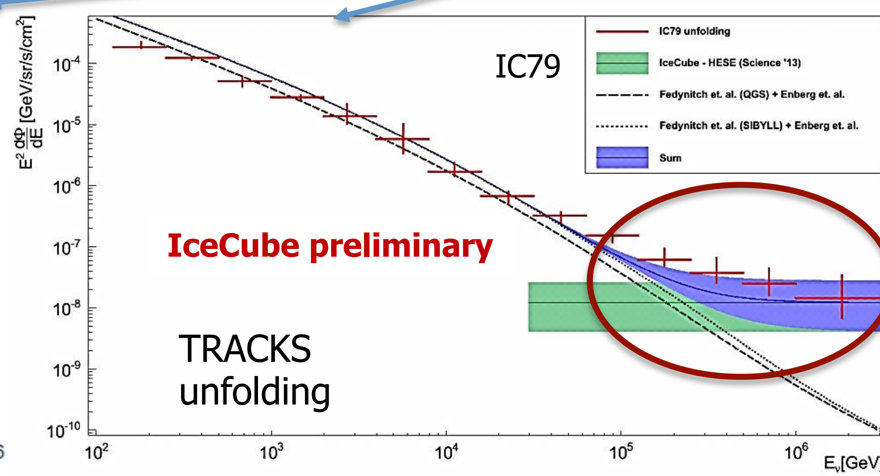


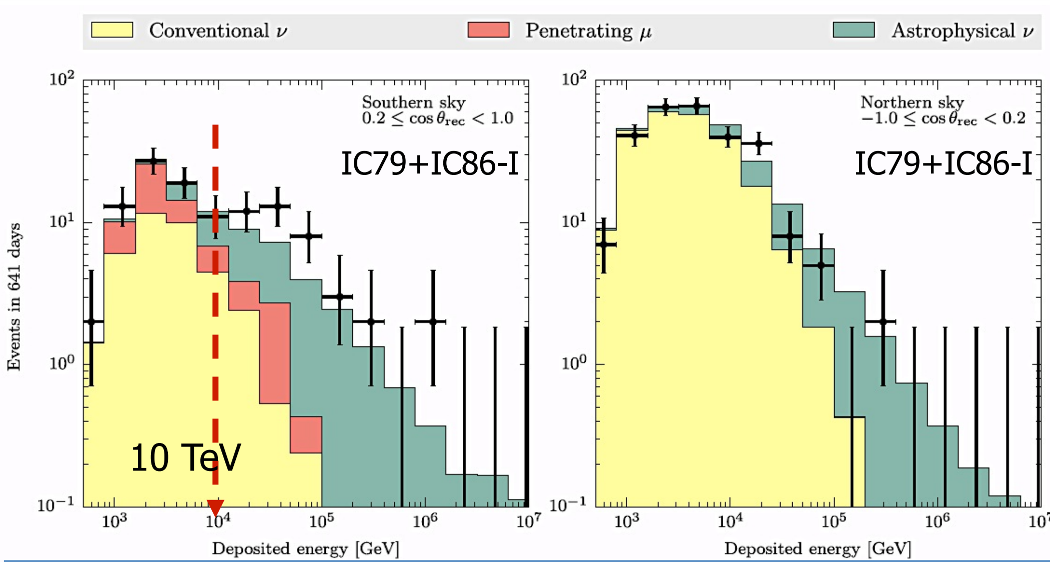


ASTROPHYSICAL NEUTRINOS

through-going tracks from ν_μ CC







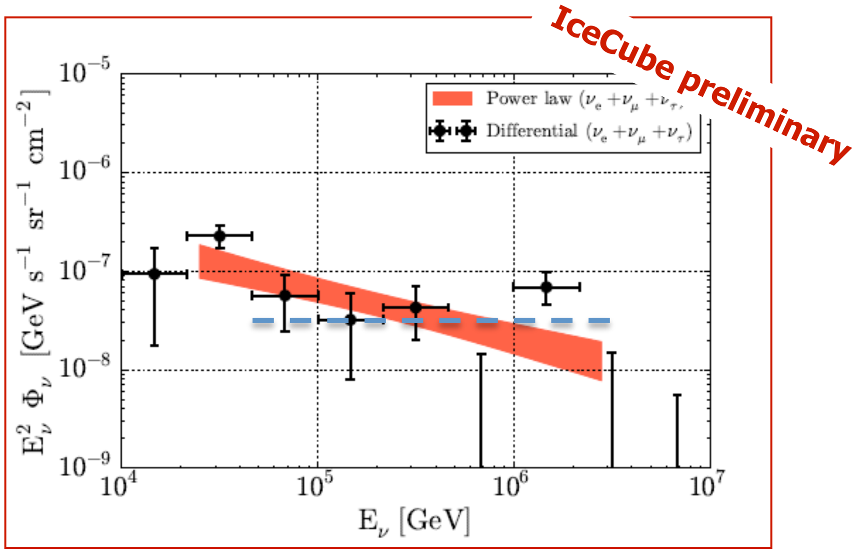
starting events
lower energies

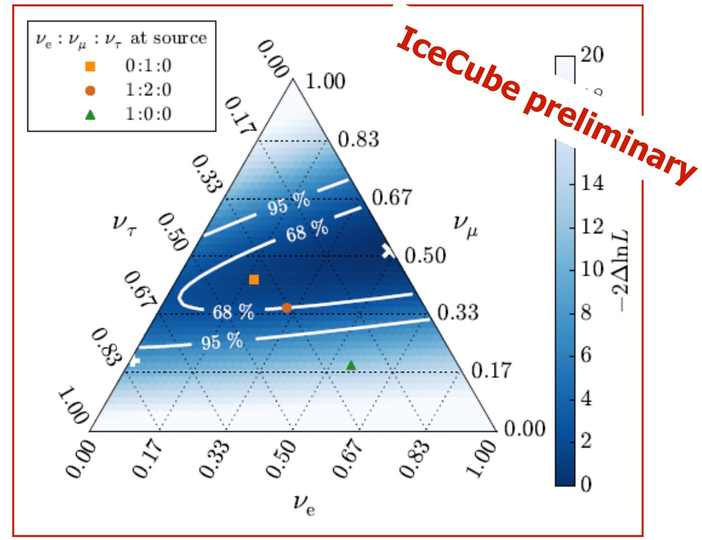
[IceCube, Phys.Rev.D91:022001 (2015)]

the astrophysical flux extends to lower energies

COMBINED MAX-LIKELIHOOD ANALYSIS OF THE ASTROPHYSICAL FLUX

- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events

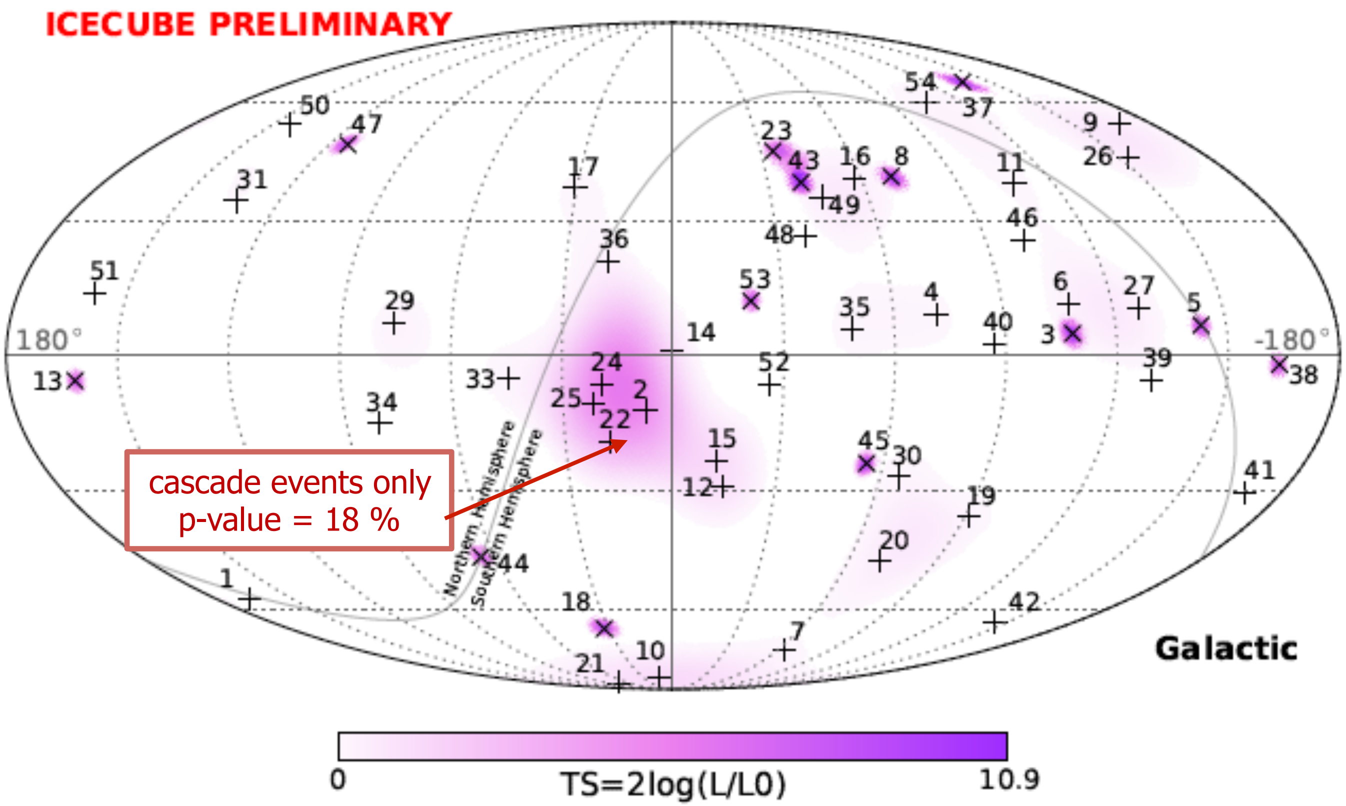




assuming isotropic astrophysical flux and $\nu_e{:}\nu_\mu{:}\nu_\tau$ = 1:1:1 at Earth →

unbroken power-law between 25 TeV and 2.8 PeV
spectral index – 2.5 ± 0.09 (-2 disfavored at 3.8 σ)
flux at 100 TeV $(6.7 \pm 1.2)\times10^{-18}$ (GeV · cm^2 · s · sr)$^{-1}$

the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

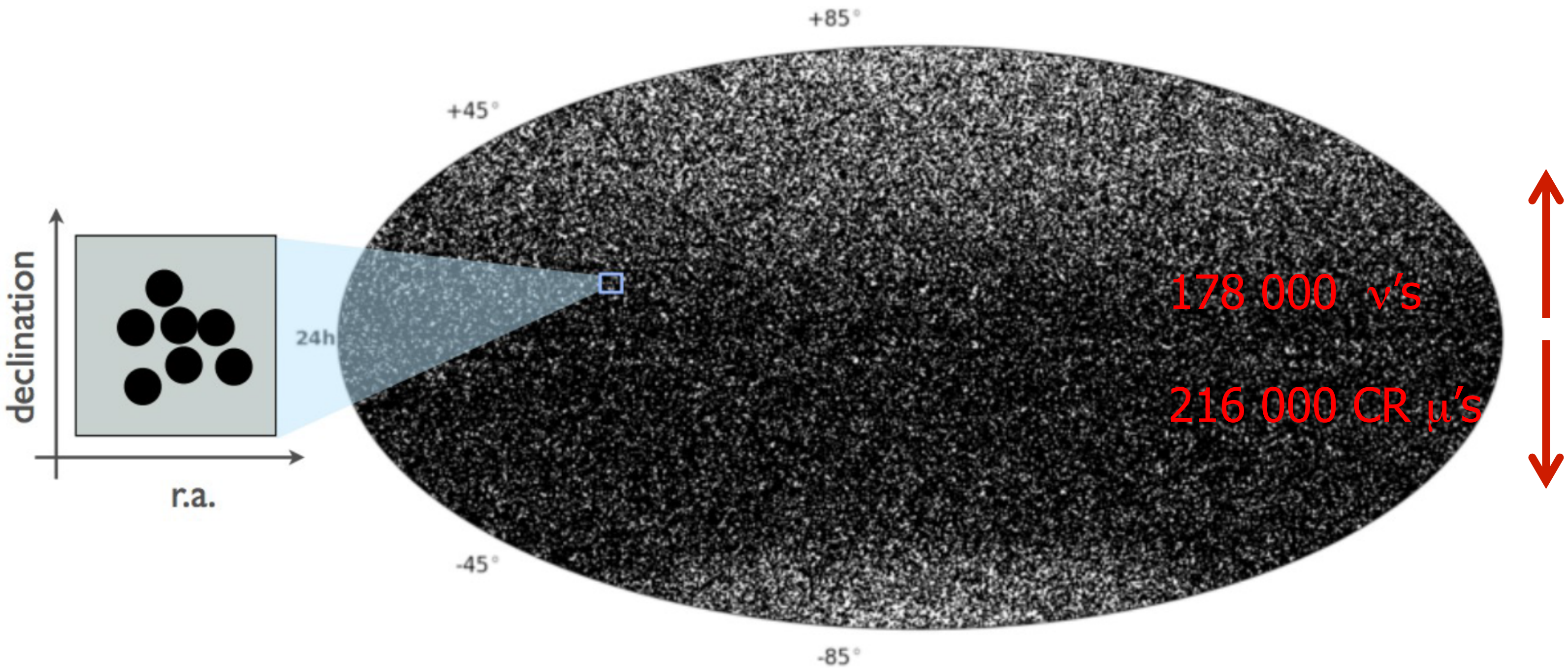


no significant correlations – spatial or temporal

- too few events to identify sources

POINT SOURCE SAMPLE

- looser optimization
- background estimated off source at similar declination
- unbinned maximum likelihood test for a fine grid of potential sources

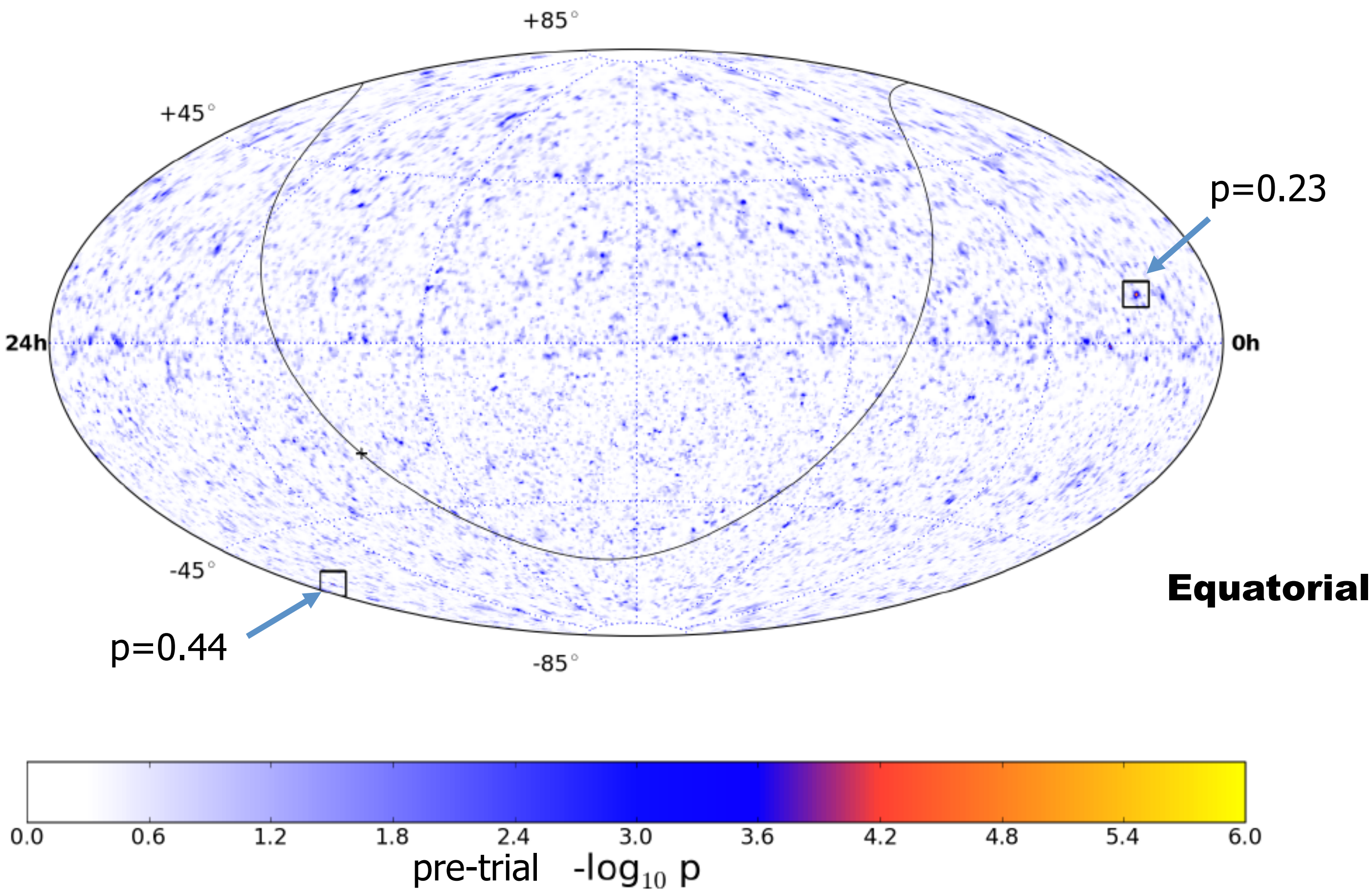


search for significant clustering of events above random background

POINT SOURCES – SIGNIFICANCE MAP

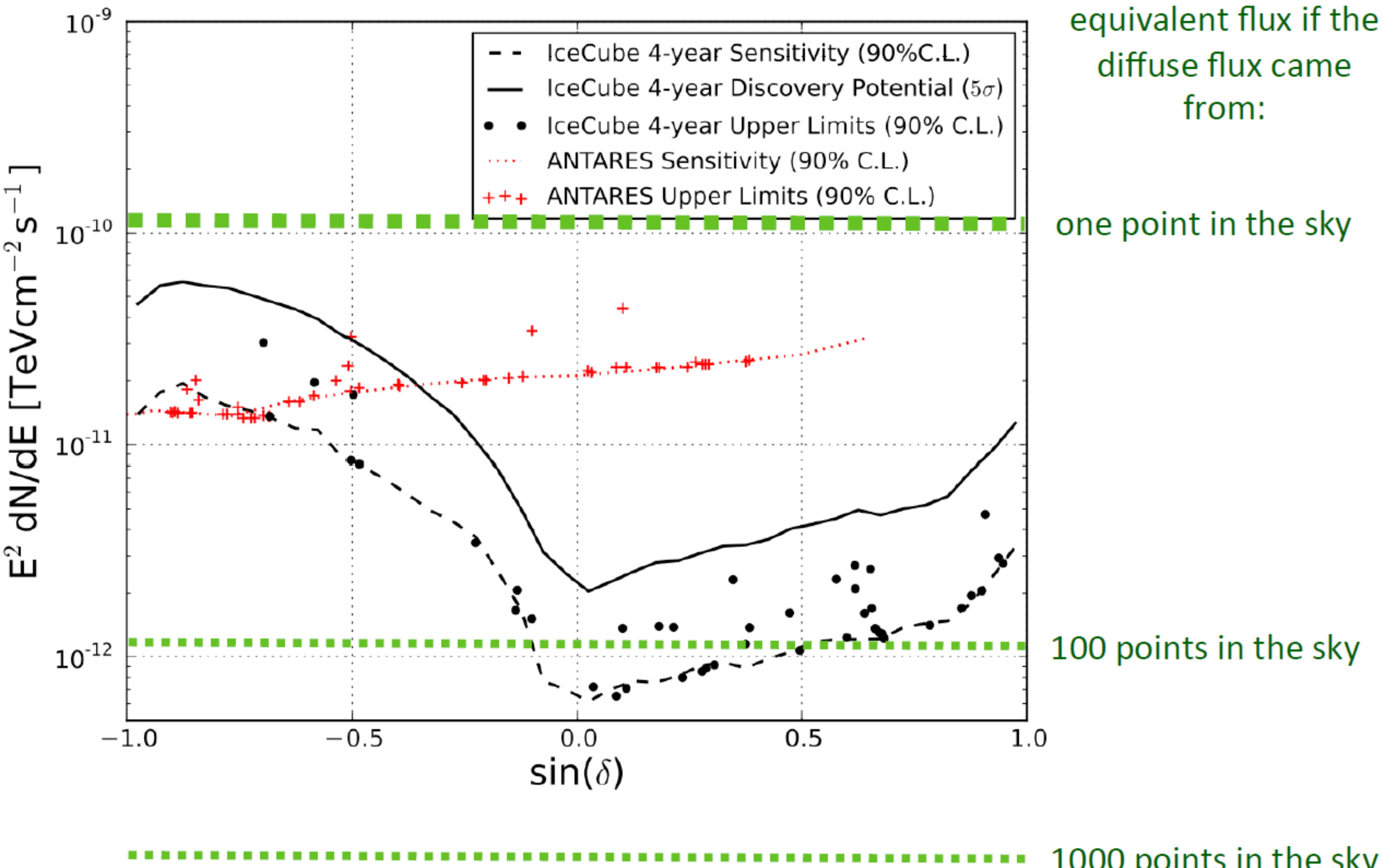
[*IceCube, Astrophys.J. 796:109 (2014)*]

- no significant clustering found



POINT SOURCE LIMITS

[*IceCube, Astrophys.J. 796:109 (2014)*]



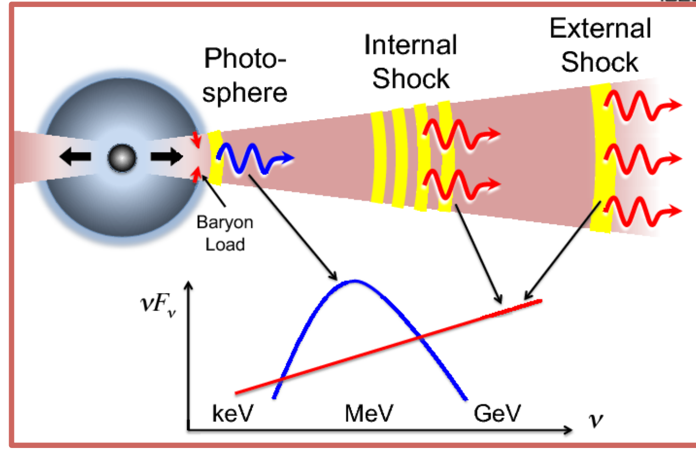
Point-source equivalent flux if the diffuse flux came from:

Slide from Chad Finley, RICAP 2014

GAMMA RAY BURSTS?

- energetically probable sources of UHE CRs
- data from Swift and Fermi
- good information on location and time
  ⇨ very low background

- predicted ν production in $p\gamma$ interactions
  - precursor
  - photosphere
  - shocks



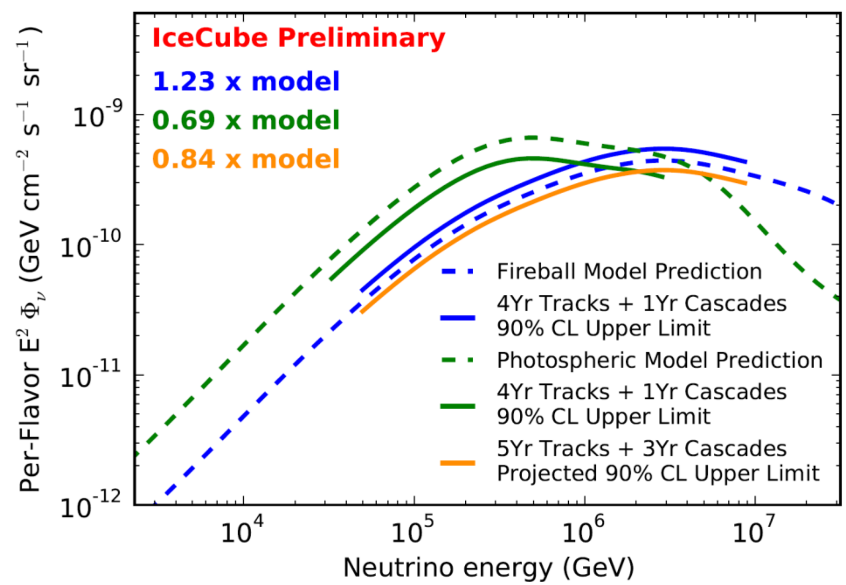
https://inspirehep.net/record/868436/plots

IceCube, Nature 484 (2012) 351 significantly constrains GRBs as dominant sources of UHECRs

- upgoing ν_μ track search – 506 bursts (4 years)
- all-flavor cascade search – 257 bursts (1 year)

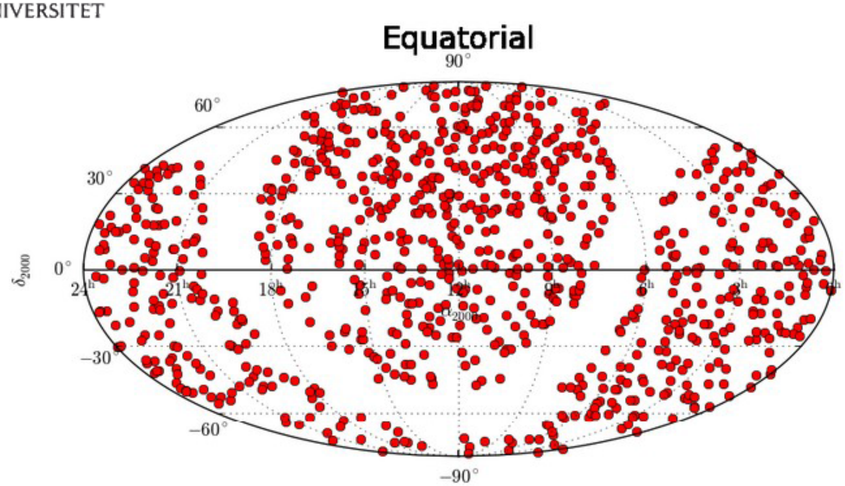
limits on the ν flux disfavor much of the parameter space for the latest models

ONLY ~1% OF THE ASTROPHYSICAL ν FLUX CAN COME FROM GRBs



[IceCube, arXiv:1412.6510]

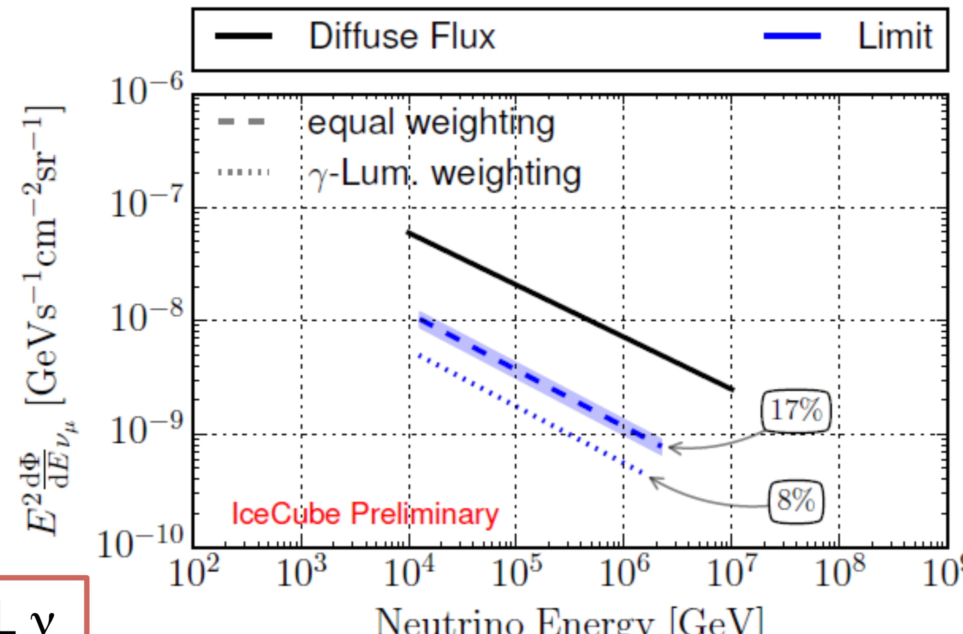
BLAZARS?



- blazars could be a prominent source of astrophysical neutrinos

862 blazars from the 2nd Fermi AGN catalog

- as few assumptions as possible
- tracks 2009 – 2011
- estimate of max. signal from the entire population
- compare with $E^{-2.5}$ energy spectrum



[*T. Glüsenkamp, RICAP 2014, proceedings*]

ONLY ~20% OF THE ASTROPHYSICAL ν FLUX CAN COME FROM BLAZARS

PROPOSED SOURCE CANDIDATES

- **Galactic:** (full or partial contribution)
  - diffuse or unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [MA & Murase'13; Neronov, Semikoz & Tchernin'13;Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - extended Galactic emission [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11] [Lunardini & Razzaque'12;MA & Murase'13; Razzaque'13; Lunardini *et al.*'13] [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico '13; Bai, Lu & Salvado'13]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - active galactic nuclei (AGN) [Stecker'91,'13;Kalashev, Kusenko & Essey'13] [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14;Kalashev, Semikoz & Tkachev'14]
  - gamma-ray bursts (GRB) [Murase & Ioka'13]
  - starburst galaxies [Loeb & Waxman'06; He *et al.*'13;Yoast-Hull, Gallagher, Zweibel & Everett'13] [Murase, MA & Lacki'13; Anchordoqui *et al.*'14; Chang & Wang'14]
  - hypernovae in star-forming galaxies [Liu *et al.*'13]
  - galaxy clusters/groups [Murase, MA & Lacki'13;Zandanel *et al.*'14]
  - . . .

Slide from M. Ahlers, NeuTel 2015

CONNECTIONS?

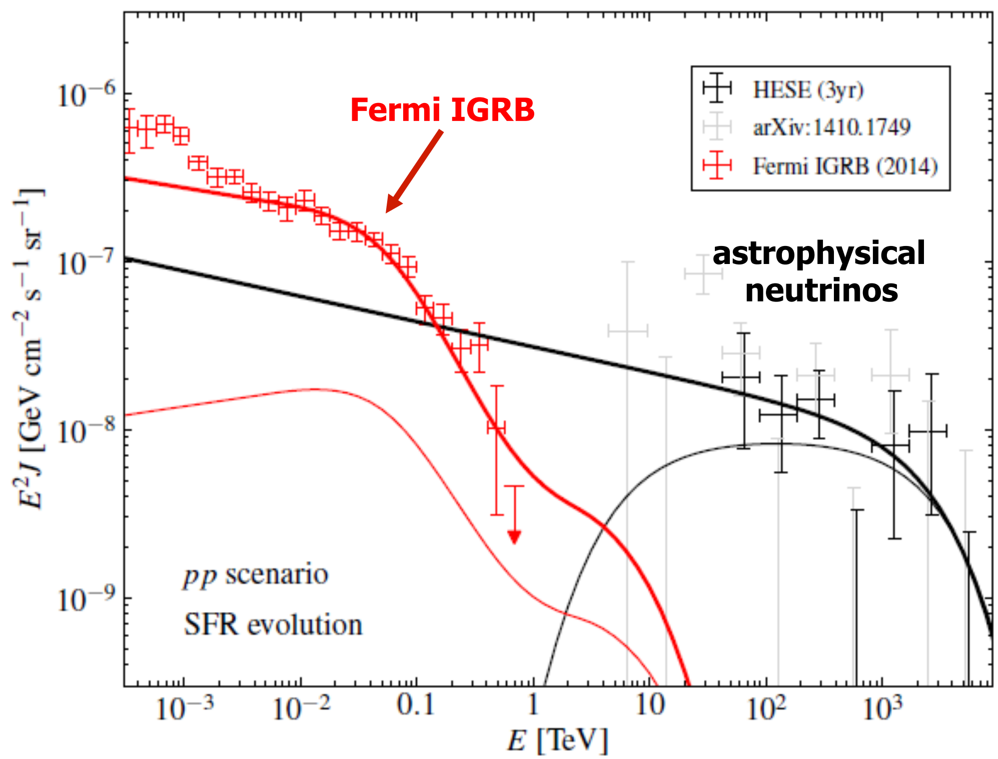
- the measured ν flux E>60 TeV is $E^2\Phi \sim 10^{-8}$ GeVcm^{-2}s^{-1}sr^{-1} i.e. comparable to the Waxman-Bahcall bound

- charged π decay ⇨ IceCube UHE ν flux

- neutral π decay ⇨ UHE γ's ⇨ cascading down to < TeV

- level compatible with IGRB measured by Fermi

[M. Ahlers, arXiv:, updated for IceCube-Gen2 arXiv:1412.5106]



observations compatible with the conjecture that cosmic accelerators are hadronic and radiate comparable energy in γ's and ν's

IceCube in its full configuration works exceedingly well

★ performance – superior to expectation

✶ has discovered the hypothesized flux of high-energy cosmic ν's

★ key to neutrino astronomy, imagined in the 1960's

✶ has demonstrated that an ice-based detector can pursue physics related to ν mass

But …

✘ the rate of astrophysical ν's is modest

✘ no sources identified yet

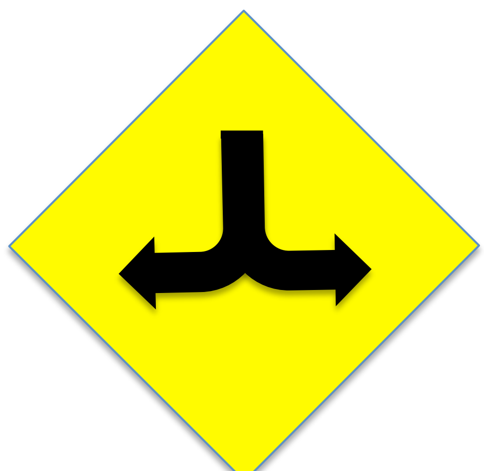
✘ poor sensitivity to ν mass ordering

wait and see …

~1 evt/y @ E>1 PeV

~10 evts/y @ E>60 TeV

- sensitivity to point sources increases with time
- so does sensitivity to ν oscillations



- enhance IceCube for future astrophysical and particle physics discoveries

FUTURE – ICECUBE-GEN2

- capitalize on the success – enhance the sensitivity of the existing detector

LOW ENERGIES

- dense in-fill subarray
- inside DeepCore

exploit the large flux of atm. ν's
for

- precise measurement of ν osc. param.
- determination of the ν mass ordering

also
– indirect searches for WIMP DM
at low energies

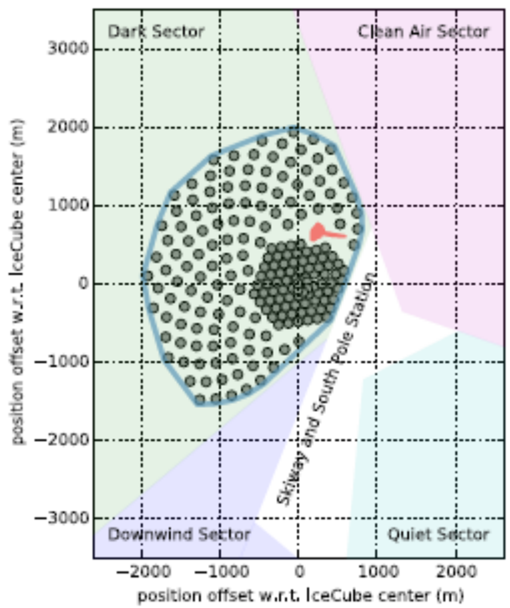
HIGH ENERGIES

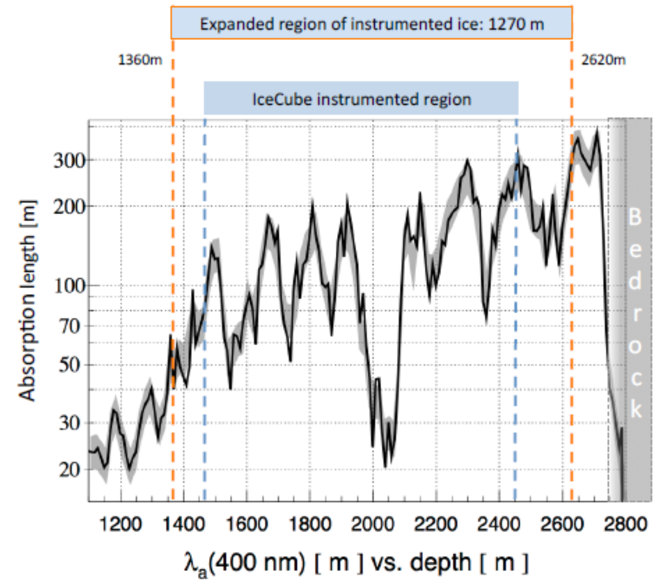
- widely spaced additional strings
- a large-area surface veto array

explore the unknown universe

- characterize the flux of the high-energy astrophysical ν's
- spectrum
- flavor composition
- identify cosmic sources

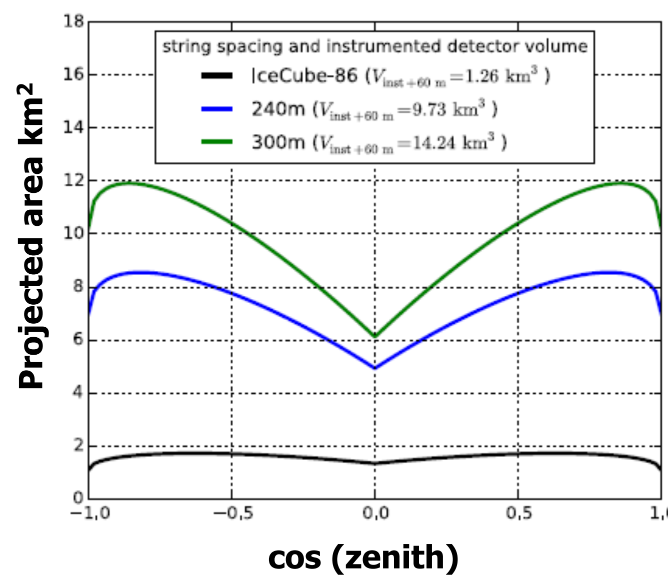
FUTURE –ICECUBE-GEN2 – HIGH-ENERGY





STRAWMAN DETECTOR

- 120 additional strings
- length 1.3 km
- average spacing 240 m
- volume 9.7 km^3

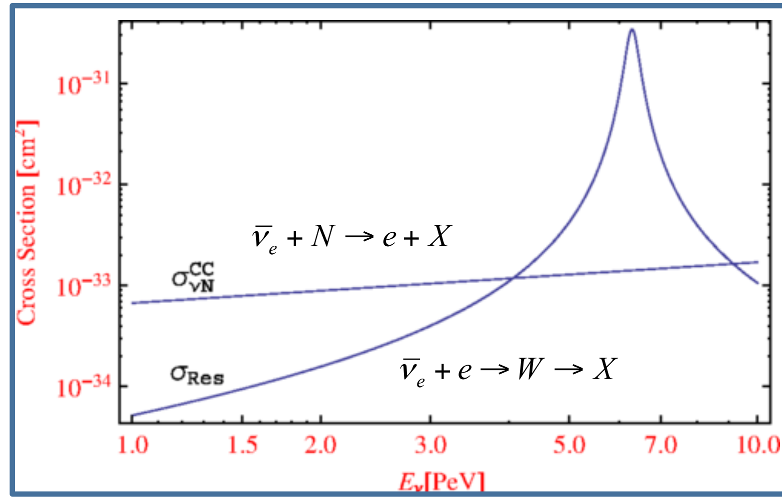


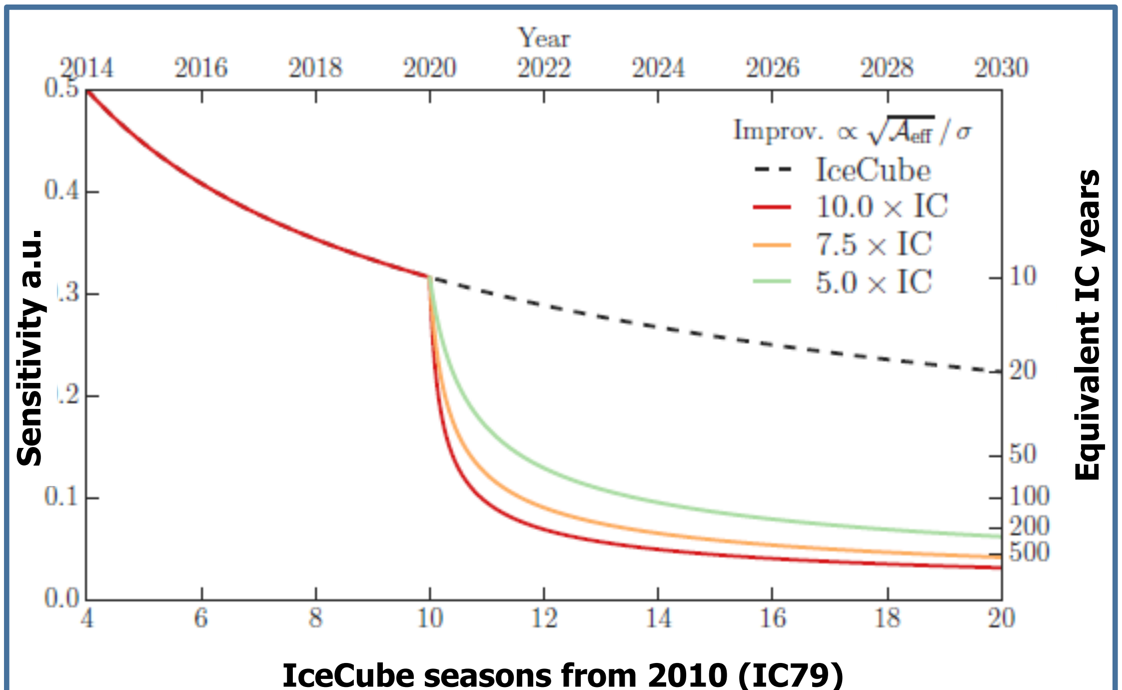
INCREASE IN VOLUME AND PROJECTED AREA

Sensitivity @ Glashow resonance

For an electron in the rest frame the neutrino must have an energy of 6.3 PeV.

Φ_{ν_e} $[\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}]$	interaction type	pp source IC-86	pp source 240m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2
	DIS	0.09	0.8



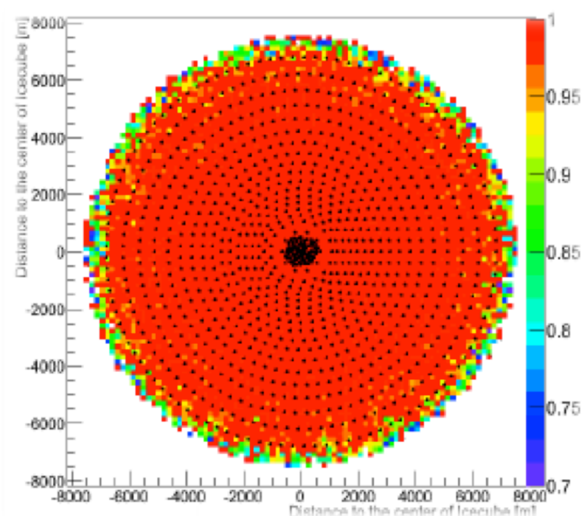


Point source sensitivity

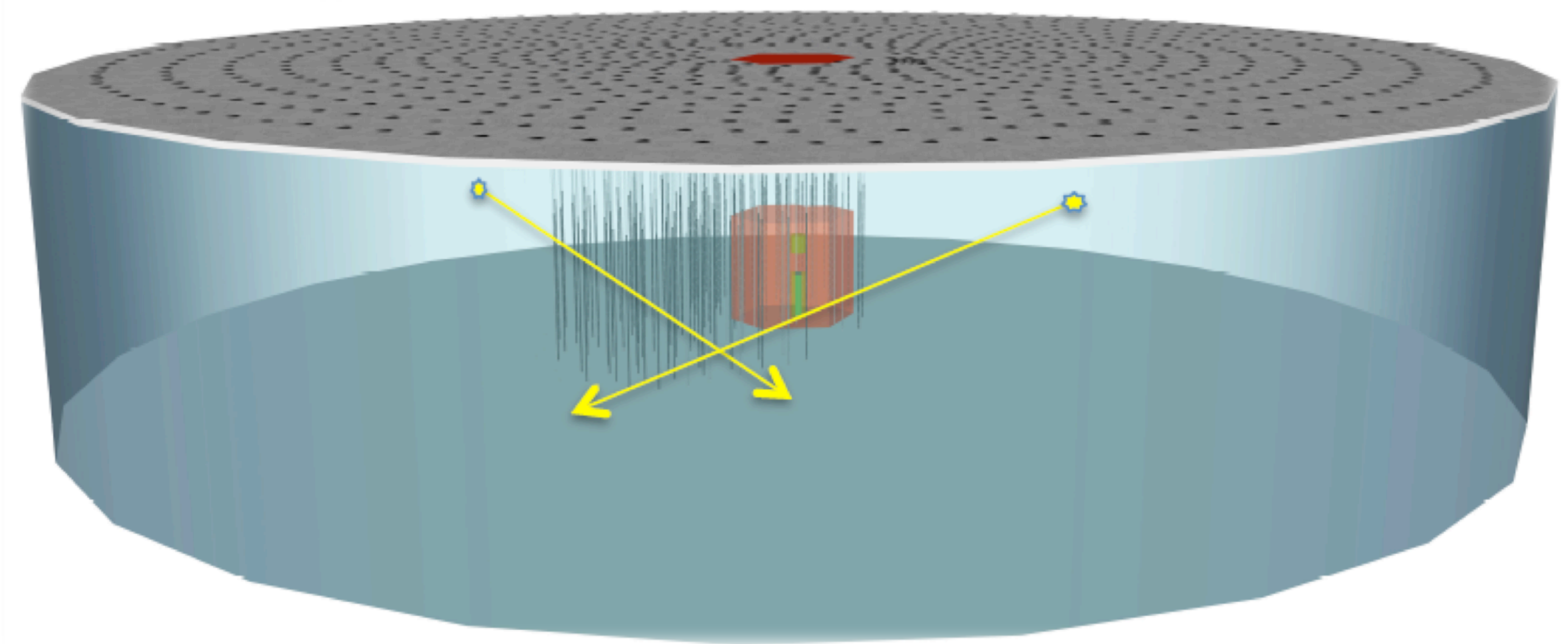
- in the presence of bckg assumed to scale as √*A*

Expect better resolution σ

- longer lever arm
- larger effective area – more strings

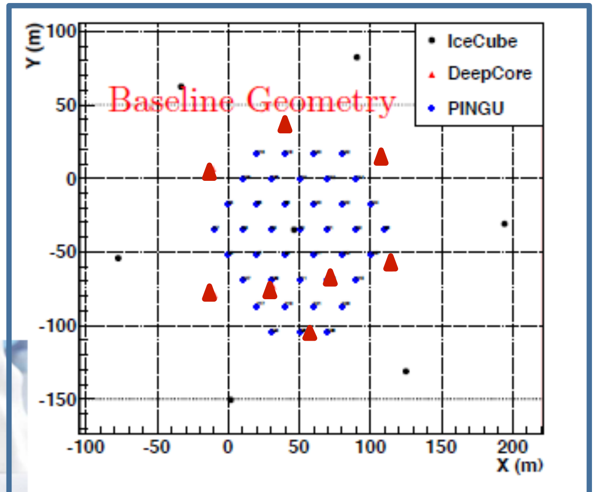


Opening the Southern sky with a surface veto!

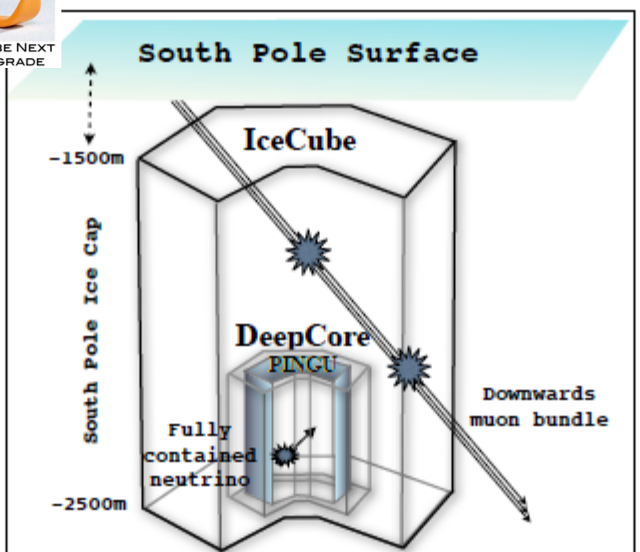


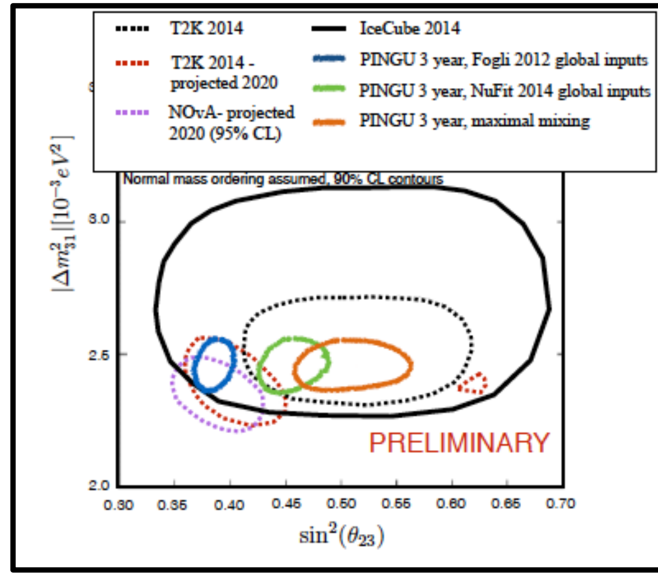
FUTURE – ICECUBE-GEN2 – LOW ENERGY

40 strings, 60 (→ 96) DOMs/string,
~5 m spacing, ~25 m between strings

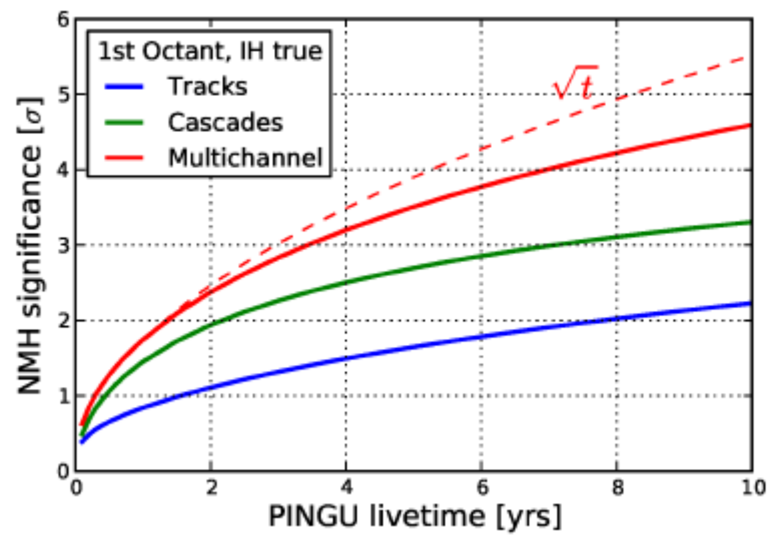


PRECISION ICECUBE NEXT GENERATION UPGRADE





Predicted sensitivity to ν osc. after 3 yrs (96 DOMs /string)

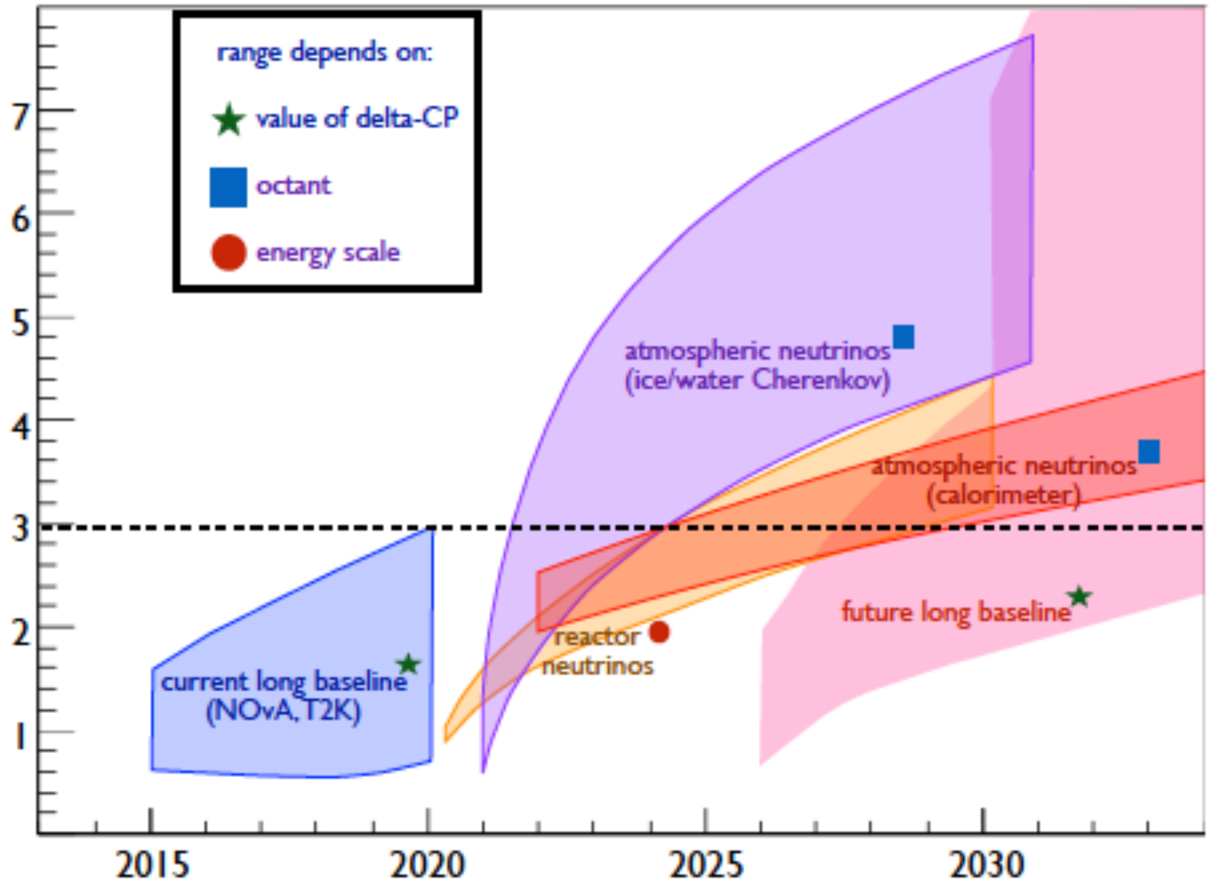


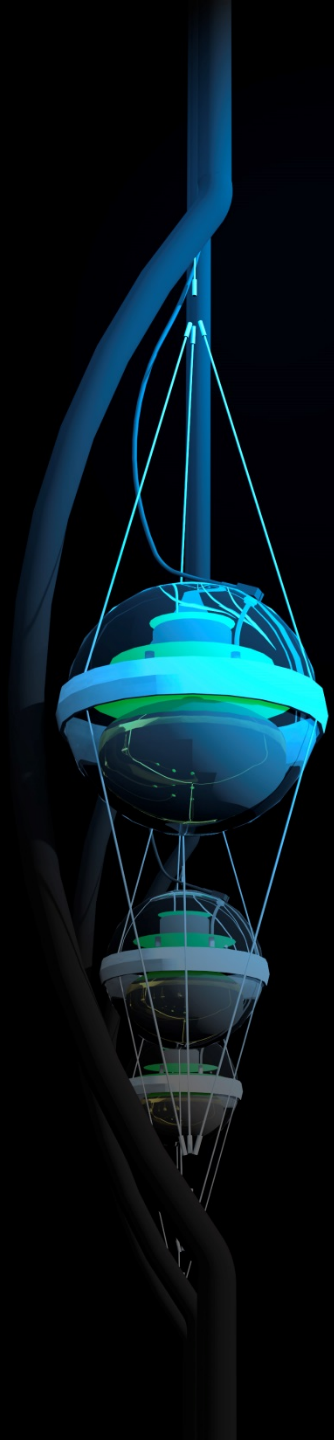
Significance of the ν mass hierarchy determination

FUTURE –ICECUBE-GEN2 – LOW ENERGY

- several current or planned experiments will have sensitivity to the neutrino mass ordering in the next 10-15 years
  - NB! timelines may shift
  - NB! median expectations shown – large fluctuations possible

widths indicate main uncertainty

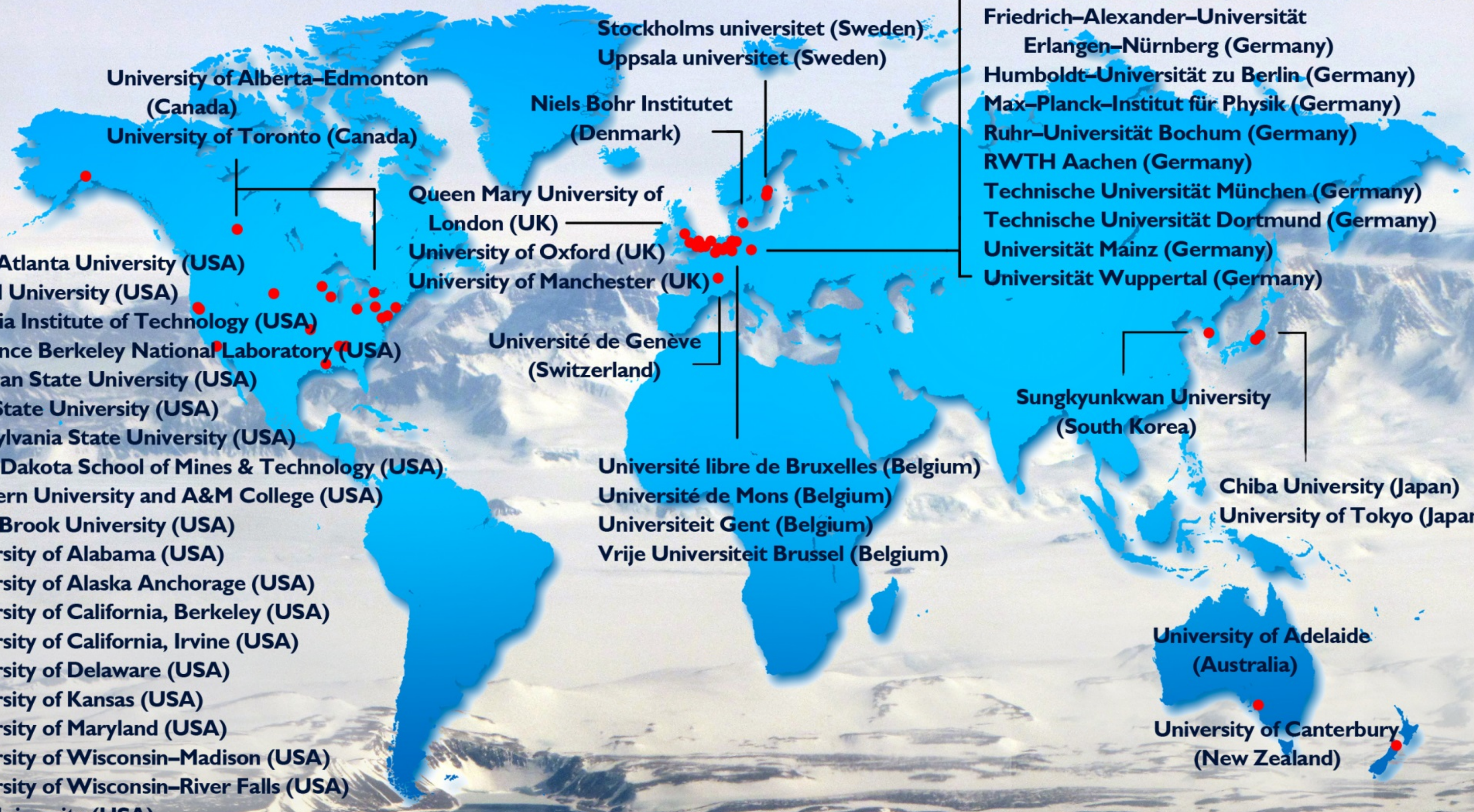




CONCLUSIONS

- Neutrinos are unique probes of the non-thermal Universe
- IceCube has shown that cosmic neutrinos are detectable
- But … what/where are the sources?
- What can we learn from spectrum and flavor composition?
- IceCube-Gen2 aims for extended ν physics reach at both high and low energies
- expect major improvements in sensitivity
- online correlation with optical/X-ray/γ-ray observatories enhances likely discoveries
- we hope that KM3NeT in the future will join the quest

The IceCube–PINGU Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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NSF–Physics Division
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The Swedish Research Council (VR)
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