IceCube-Gen2: the future extension of the IceCube neutrino observatory in Antartica

Fundamental Interactions and IAP meeting, Brussels19 June 2015

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Outline

- Cosmic Ray/Gamma-ray/Neutrino Connection
- The IceCube neutrino observatory
- The discovery of cosmic neutrinos
- The IceCube-Gen2 extension
- Conclusions

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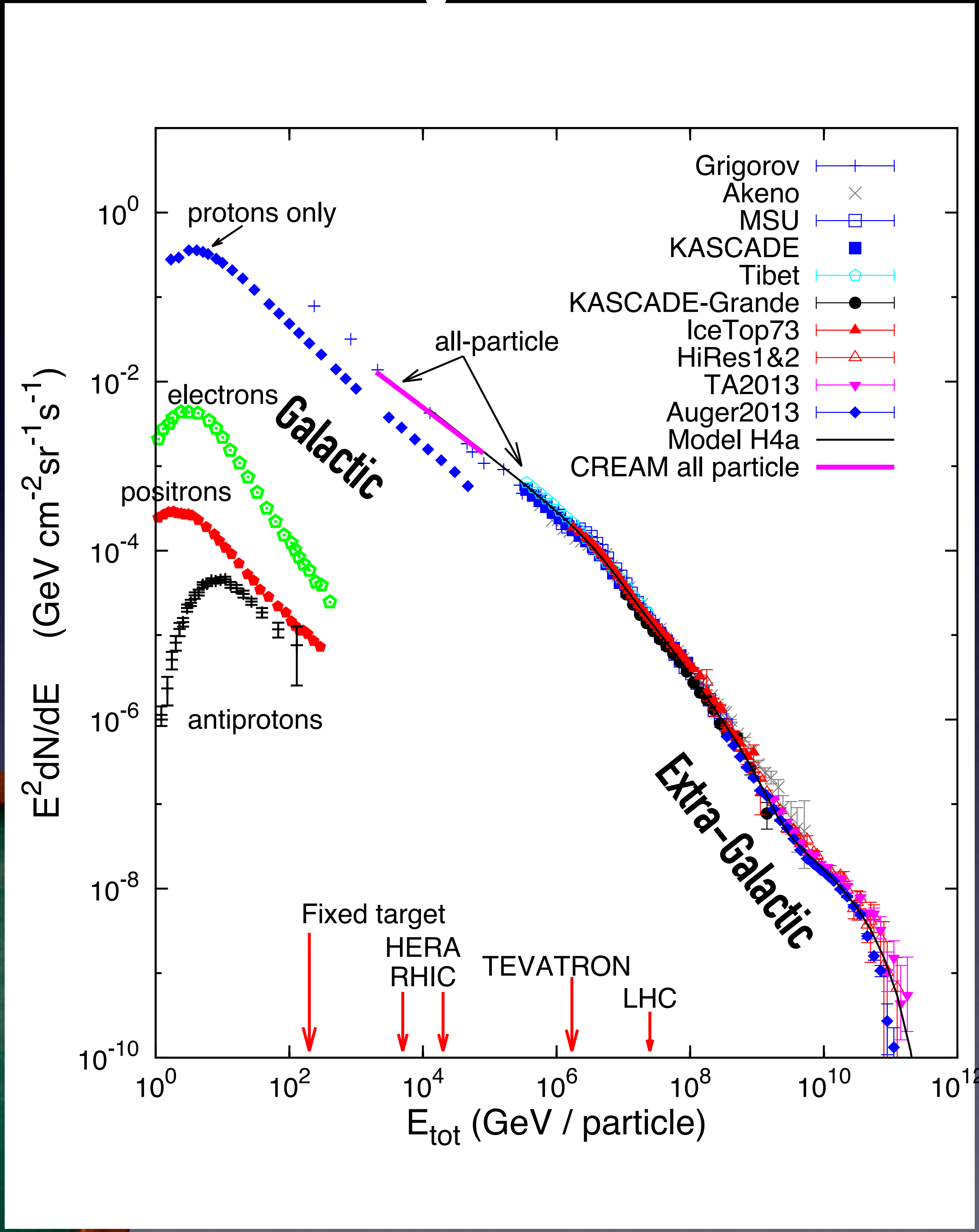
The CR-ν-γ connection

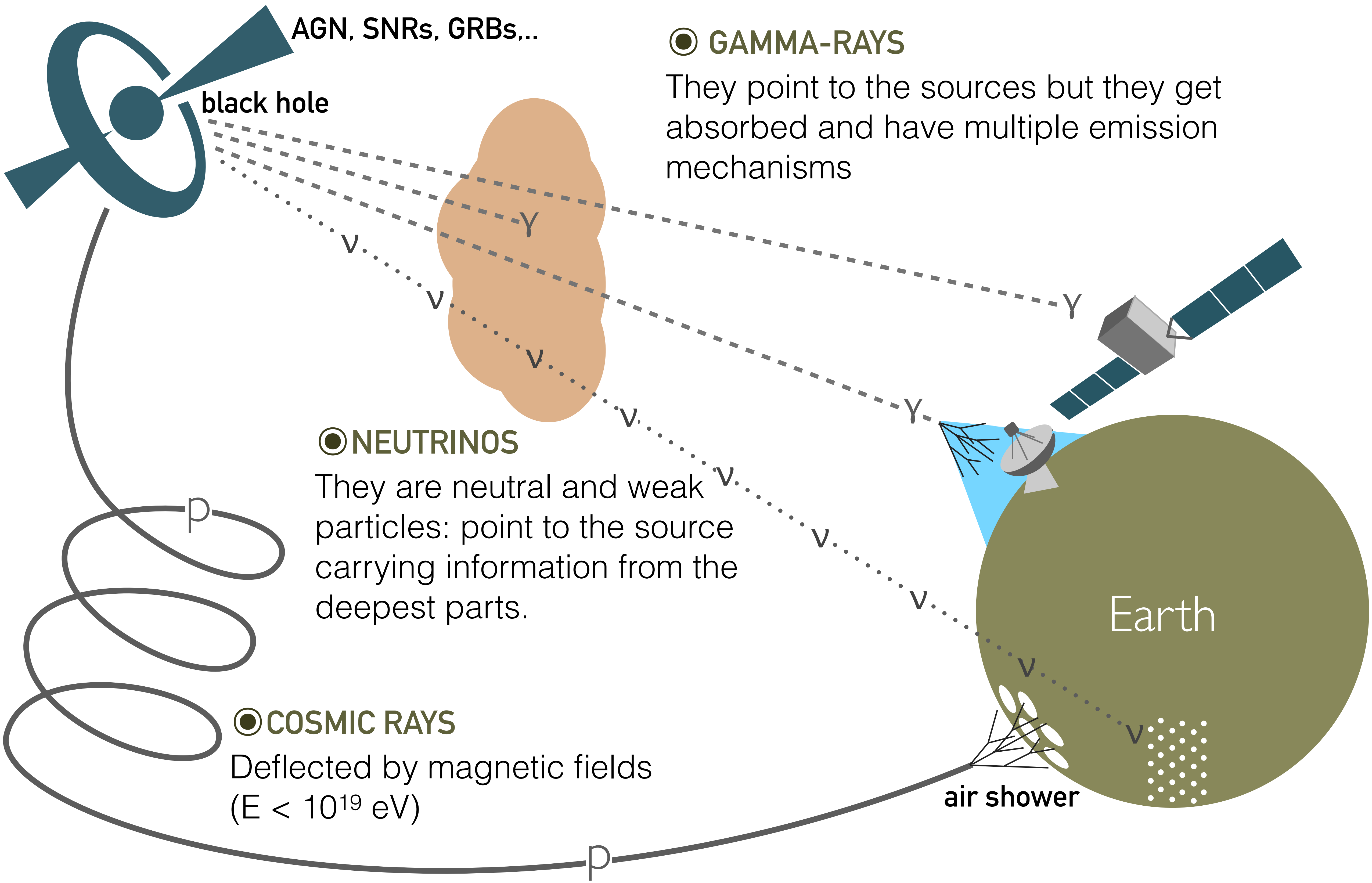
- Cosmic Rays discovered by Victor Hess in 1912
- Cosmic Ray spectrum spans over 10 decades in energies and nearly 30 orders of magnitude in flux.
- After more than a century origin is still unknown
  - Galactic CRs: Supernova remnants?
  - Extragalactic CR: AGNs, GRBs, Magnetars?



$$p + \gamma \rightarrow \pi^0 + p$$
$$\pi^0 \rightarrow \gamma\,\gamma$$

$$p + \gamma \rightarrow \pi^+ + n$$
$$\pi^+ \rightarrow \nu_\mu + \mu$$
$$\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

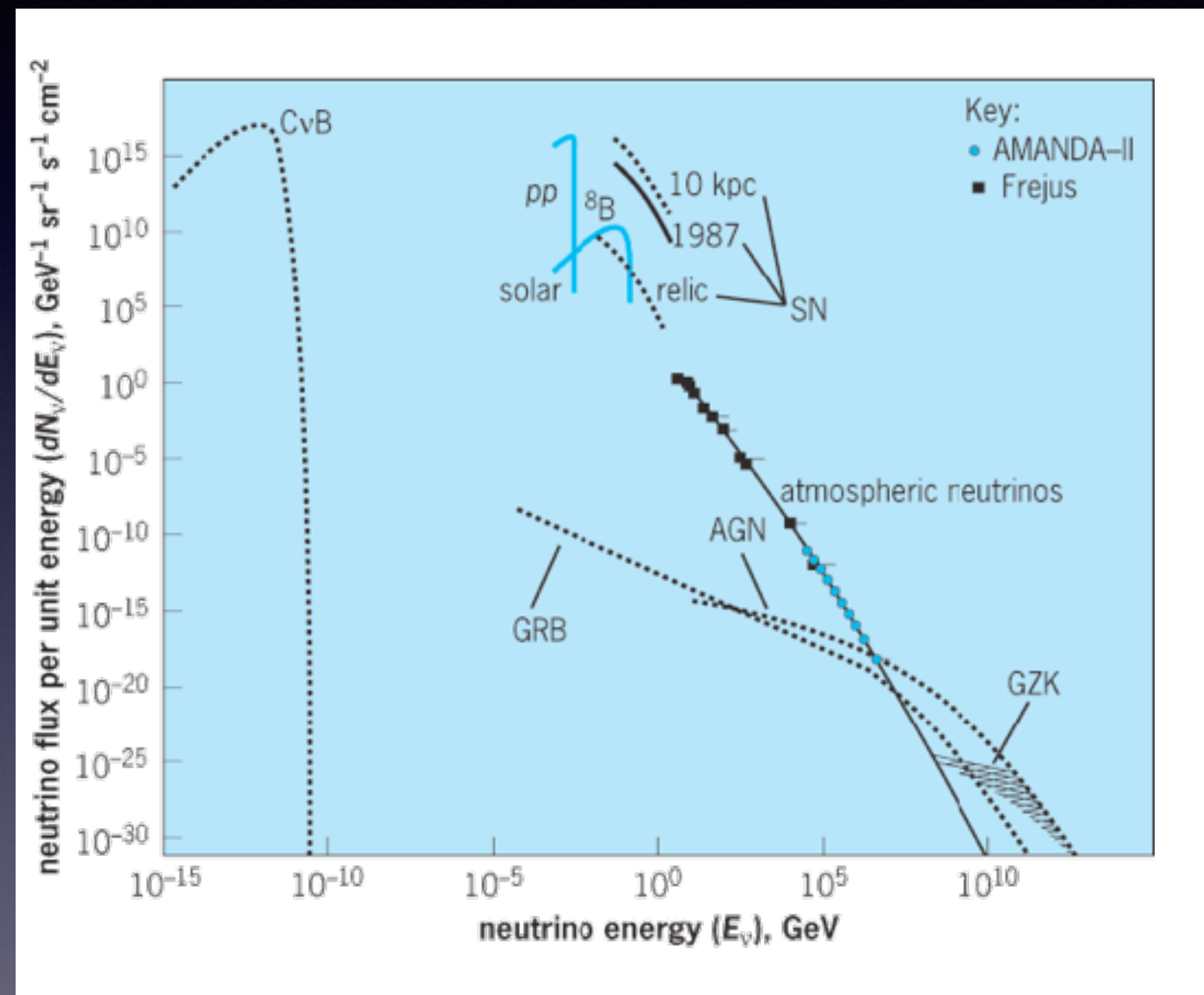
Why neutrinos?



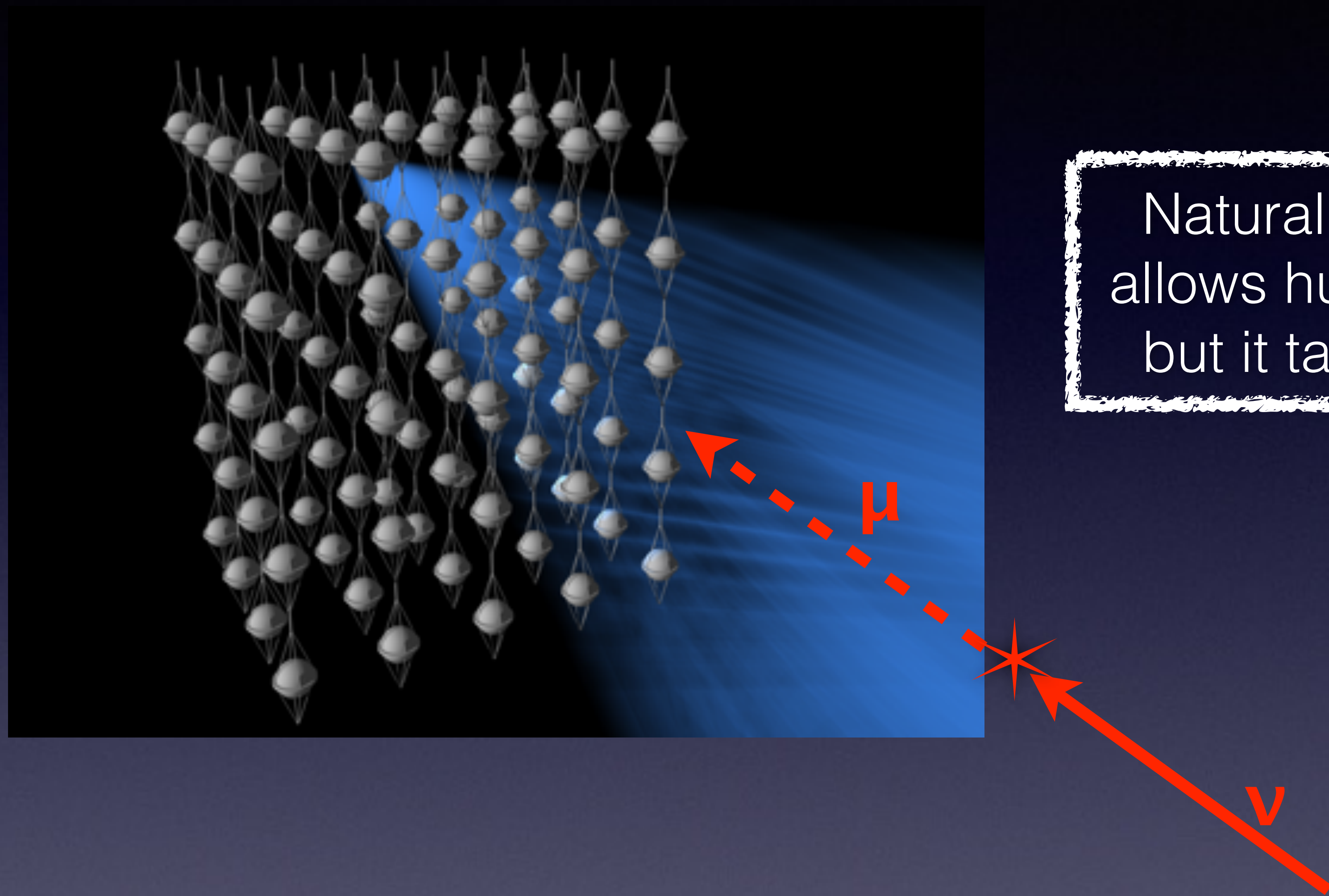
Slide from J. A. Aguilar, SuGAR 2015

The ν spectrum

- Atmospheric neutrinos (π/K)
  - dominant < 100 TeV
- Atmospheric neutrinos (charm)
  - "prompt" ~ 100 TeV
- Astrophysical neutrinos
  - maybe dominant > 100 TeV
- Cosmogenic neutrinos
  - > 10^6 TeV



Detection principle



Natural radiator is low cost and allows huge instrumented regions but it takes time to know it well!

Position, Time, Amplitude of the recorded signal in DOMs

ν Energy, direction

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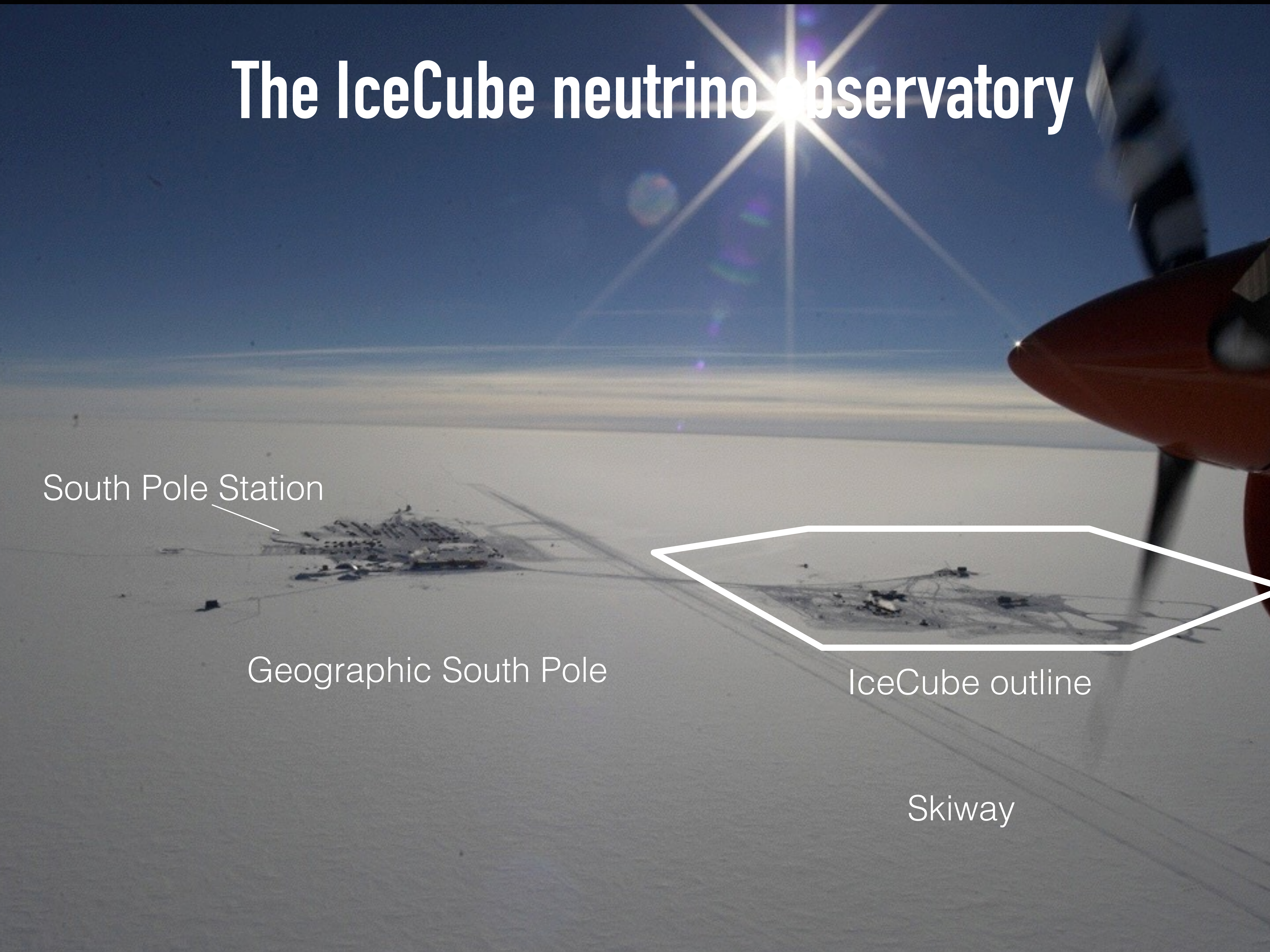
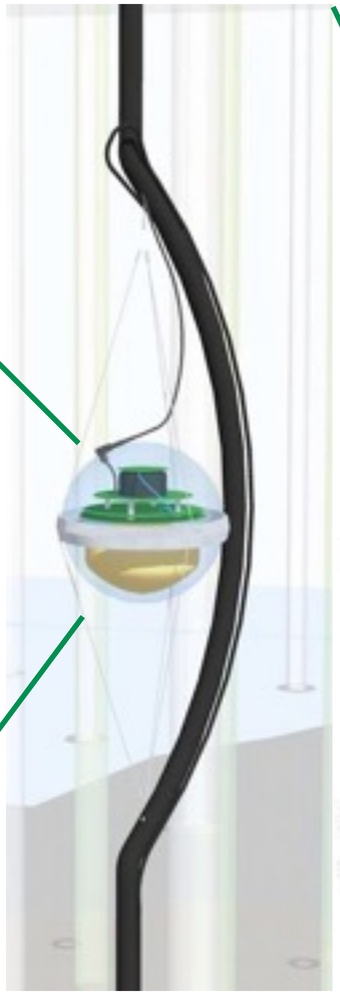
The IceCube neutrino observatory

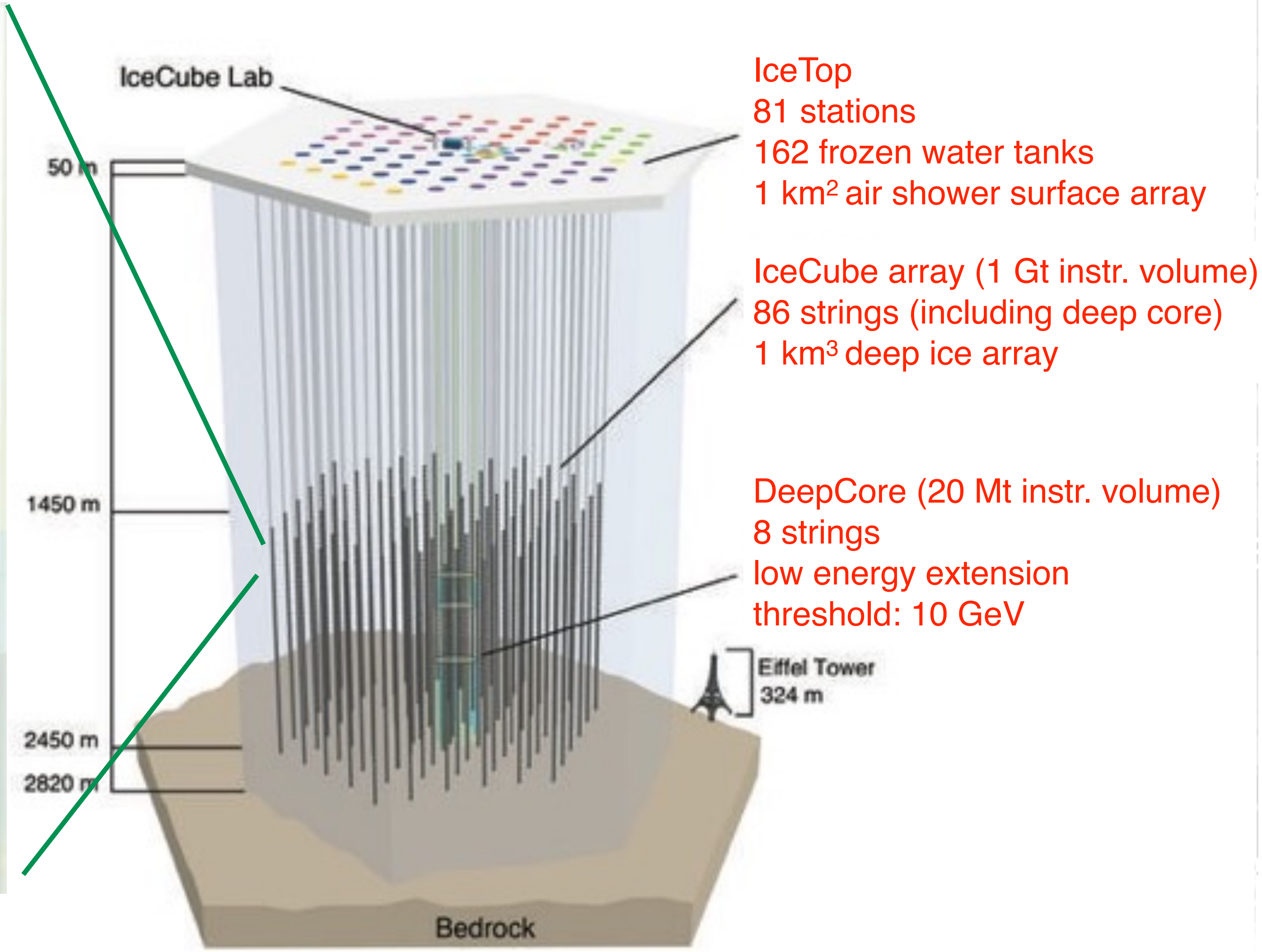


IceCube: the world's largest neutrino telescope

- 5186 Digital Optical Modules (DOMs) in deep ice
- 86 "strings"
- ~125 m between string
- 60 DOMs per string, 17 m between DOMs

Digital Optical Module



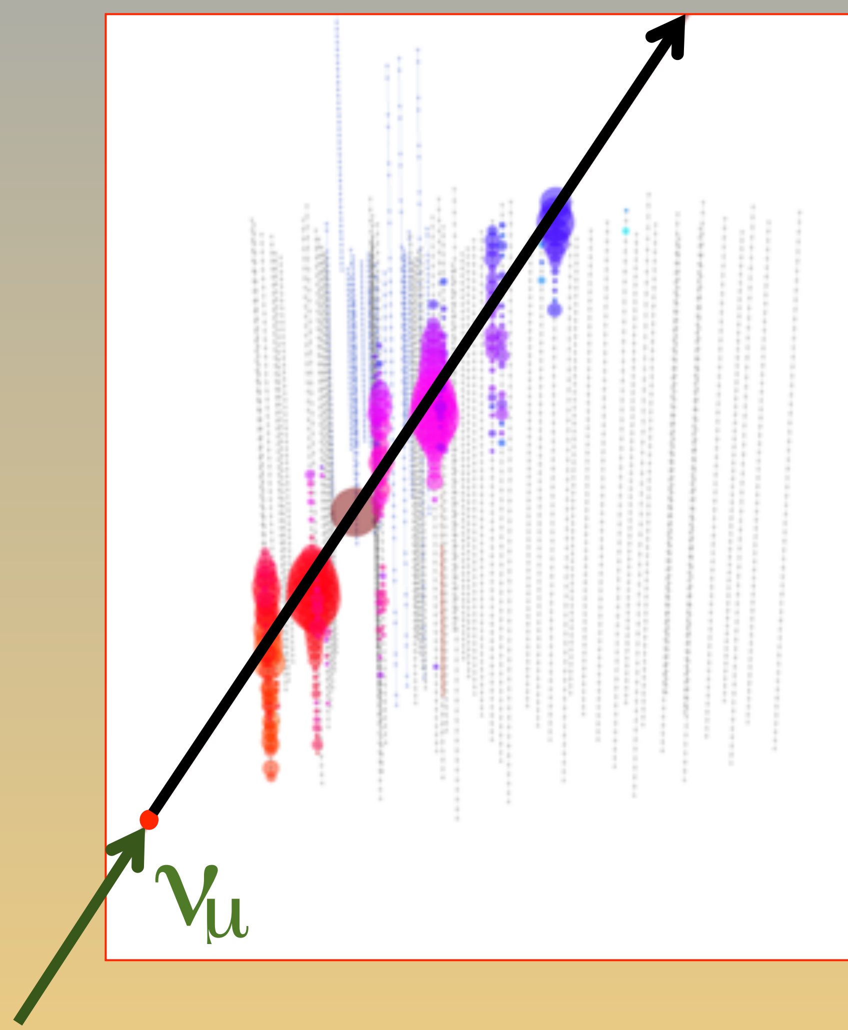



5 megawatt hot water drilling system
IceTop tanks
drill tower
CONSTRUCTION 2004 - 2010

Deployment of the final string – Dec 18 2010

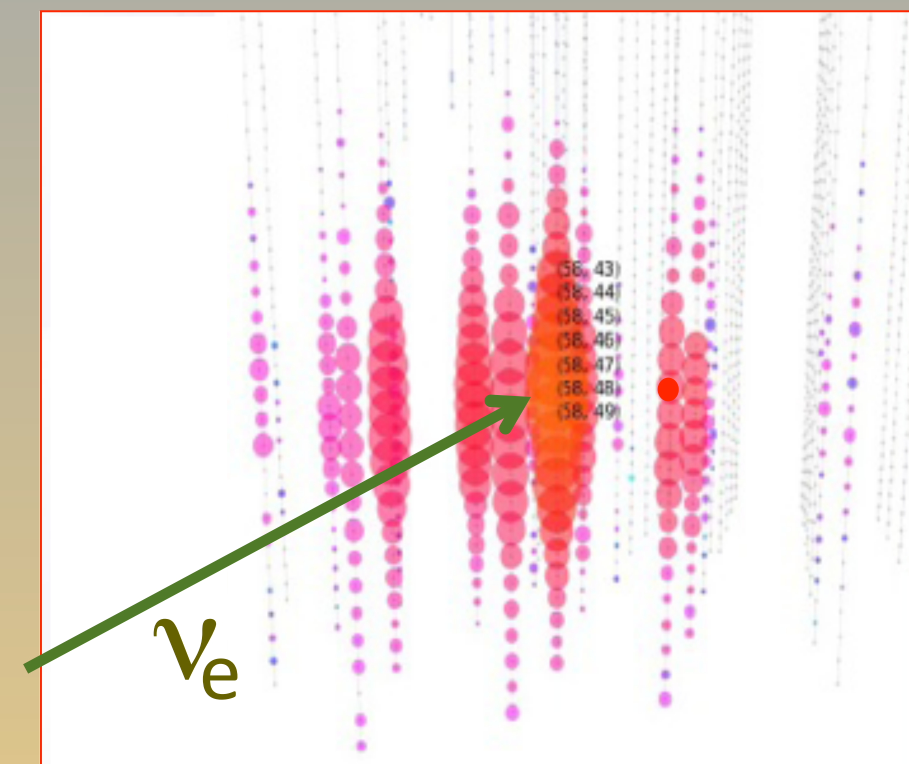
In-ice signature

through-going muons →



- **Good angular resolution:** 0.2°- 1°
- **Vertex can be outside detector:**
  - no E_ν direct measurement
  - increased effective volume.

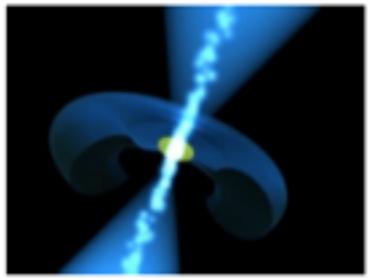
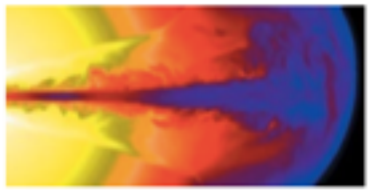
cascade → all flavors



- **ν_e, ν_τ and all flavour neutral current**
- Fully active calorimeter: **high energy resolution (~15%)**
- **Angular resolution not as good as for tracks.**

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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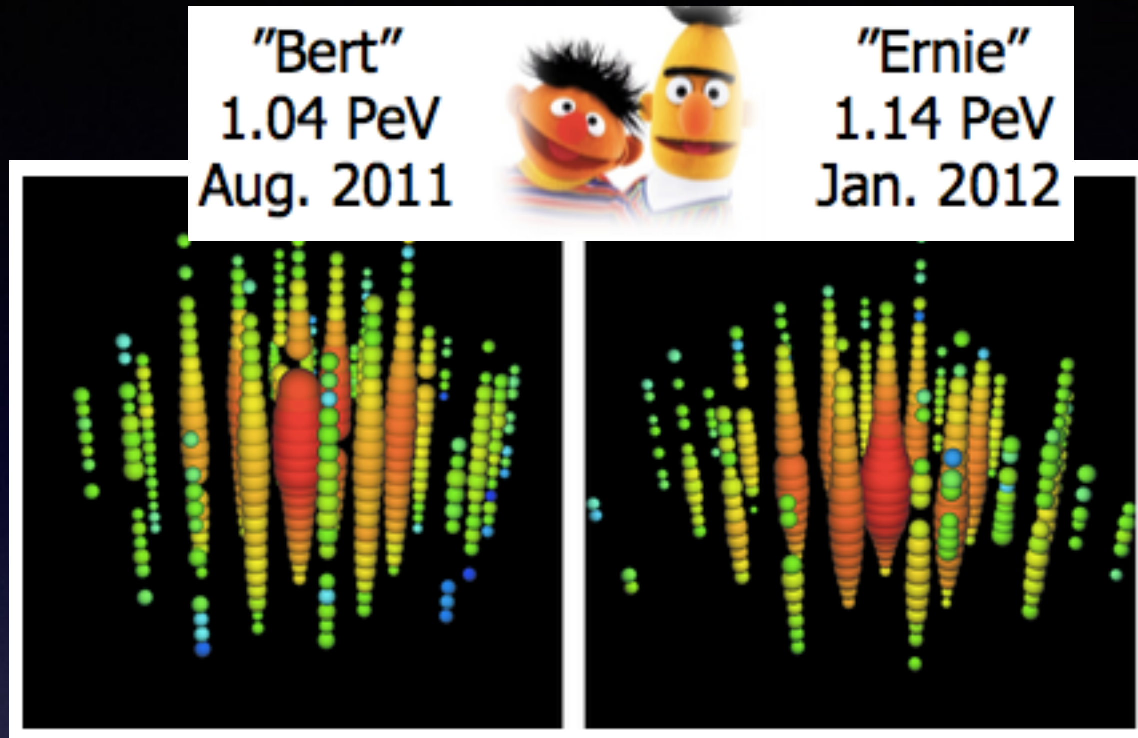
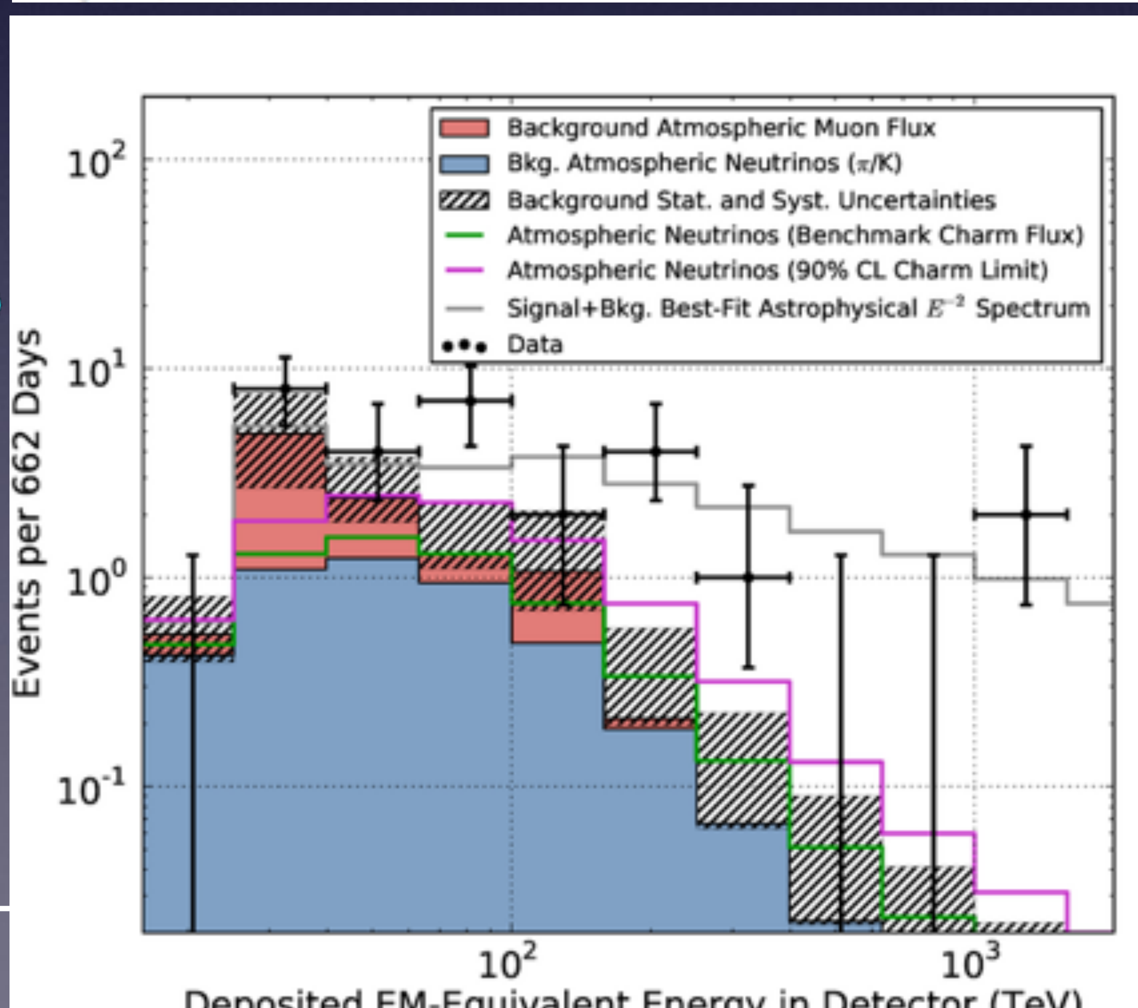
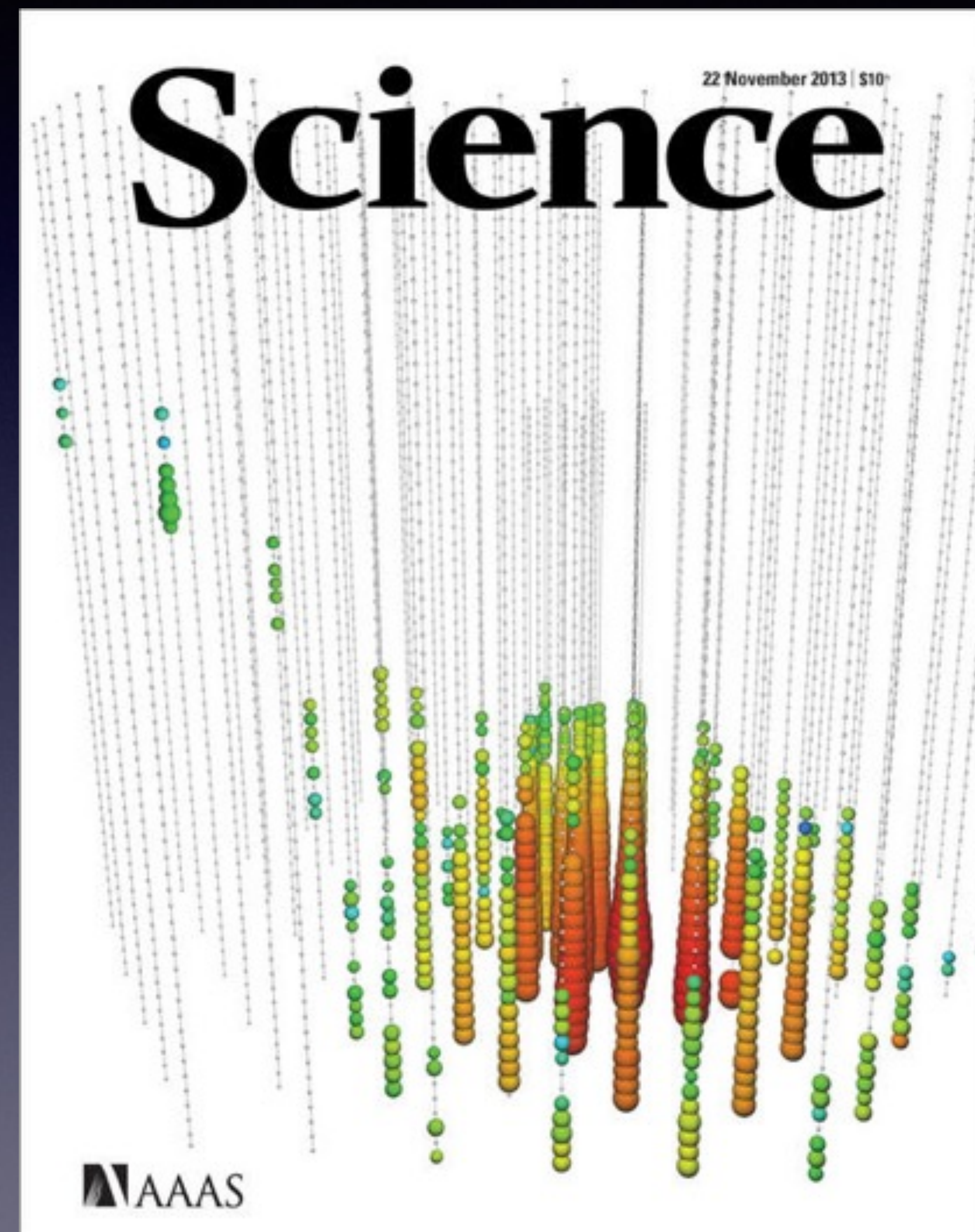
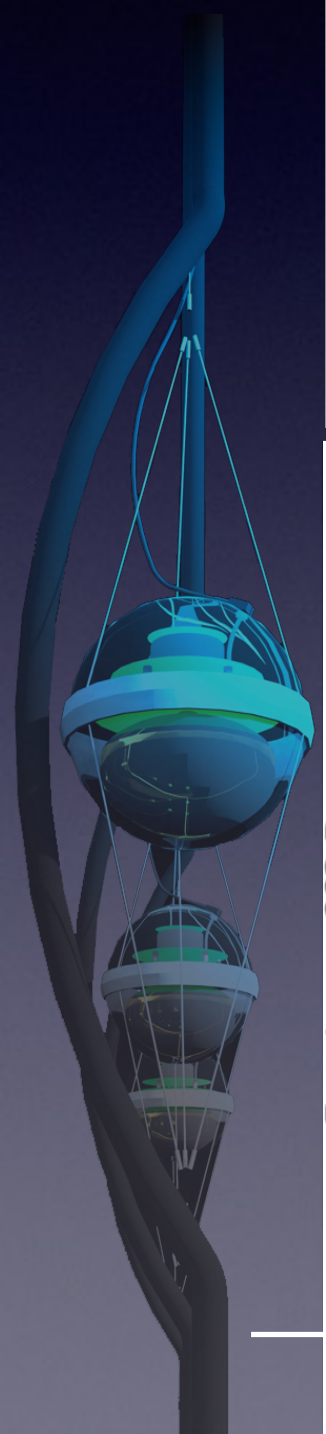
The birth of neutrino astronomy

First evidence of an extraterrestrial flux of neutrinos [*IceCube coll., Science 342 (2013)*]



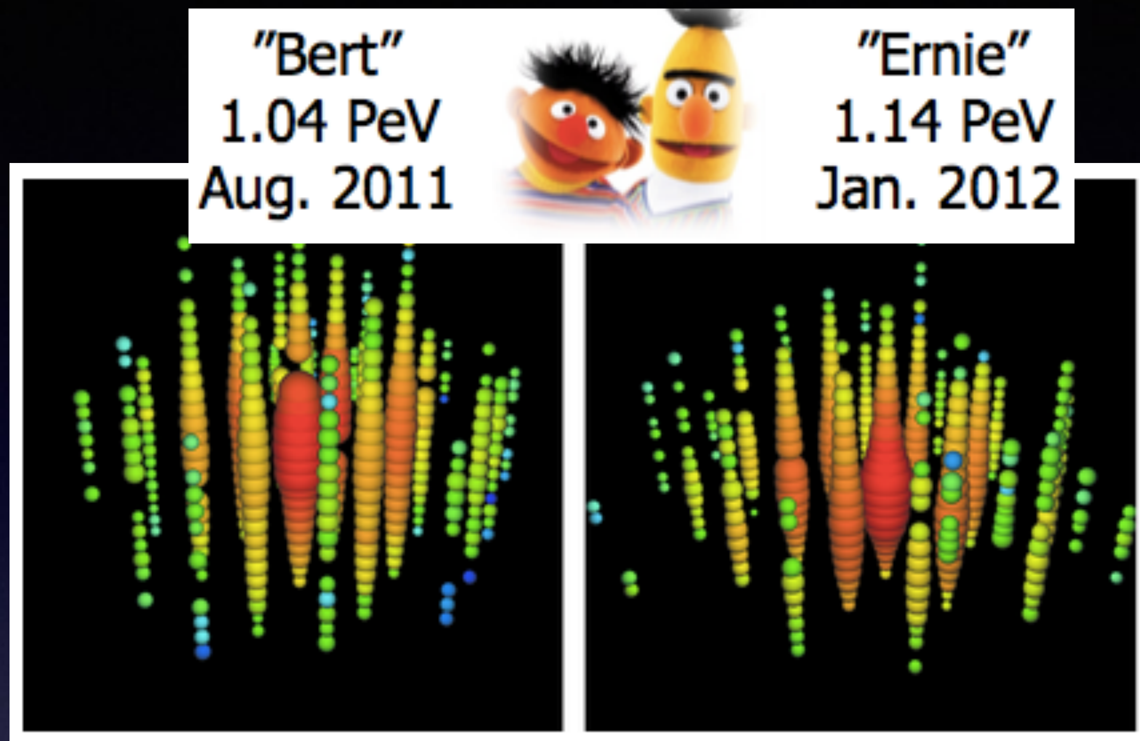


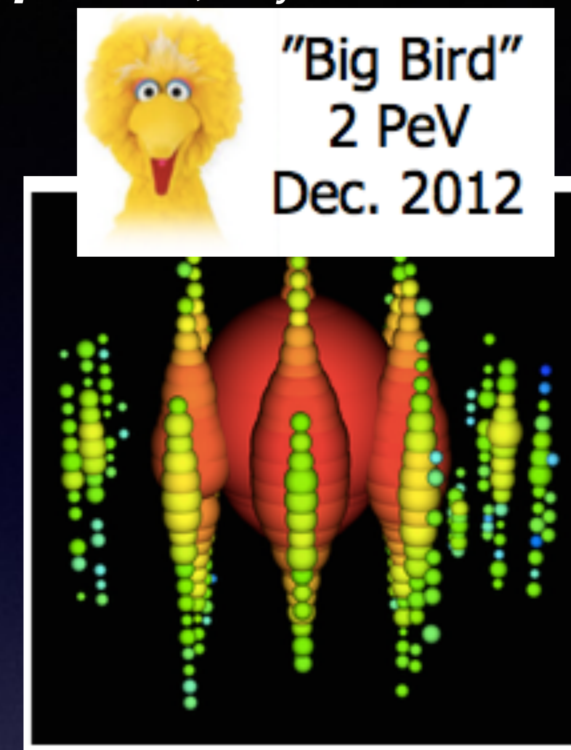




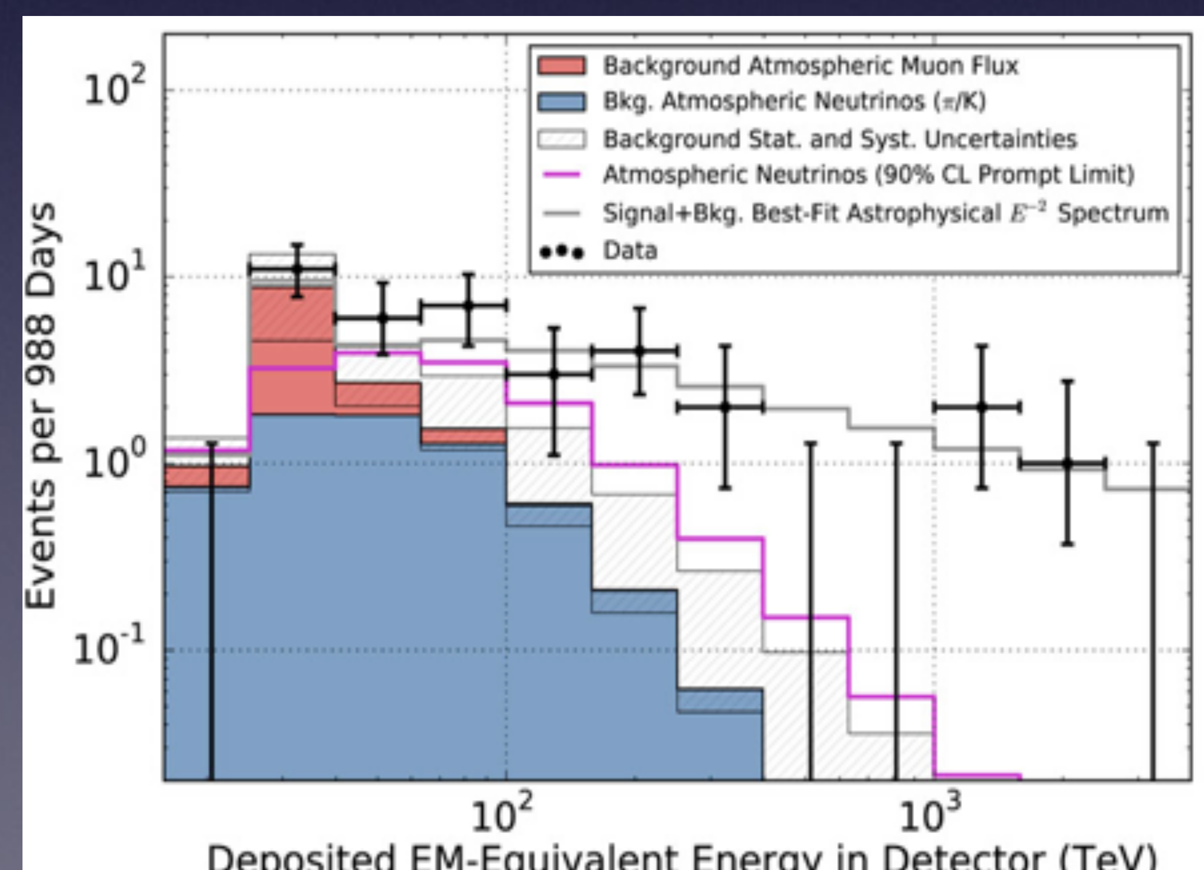
The birth of neutrino astronomy

Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data [IceCube, Phys.Rev.Lett. 113:101101 (2014)]





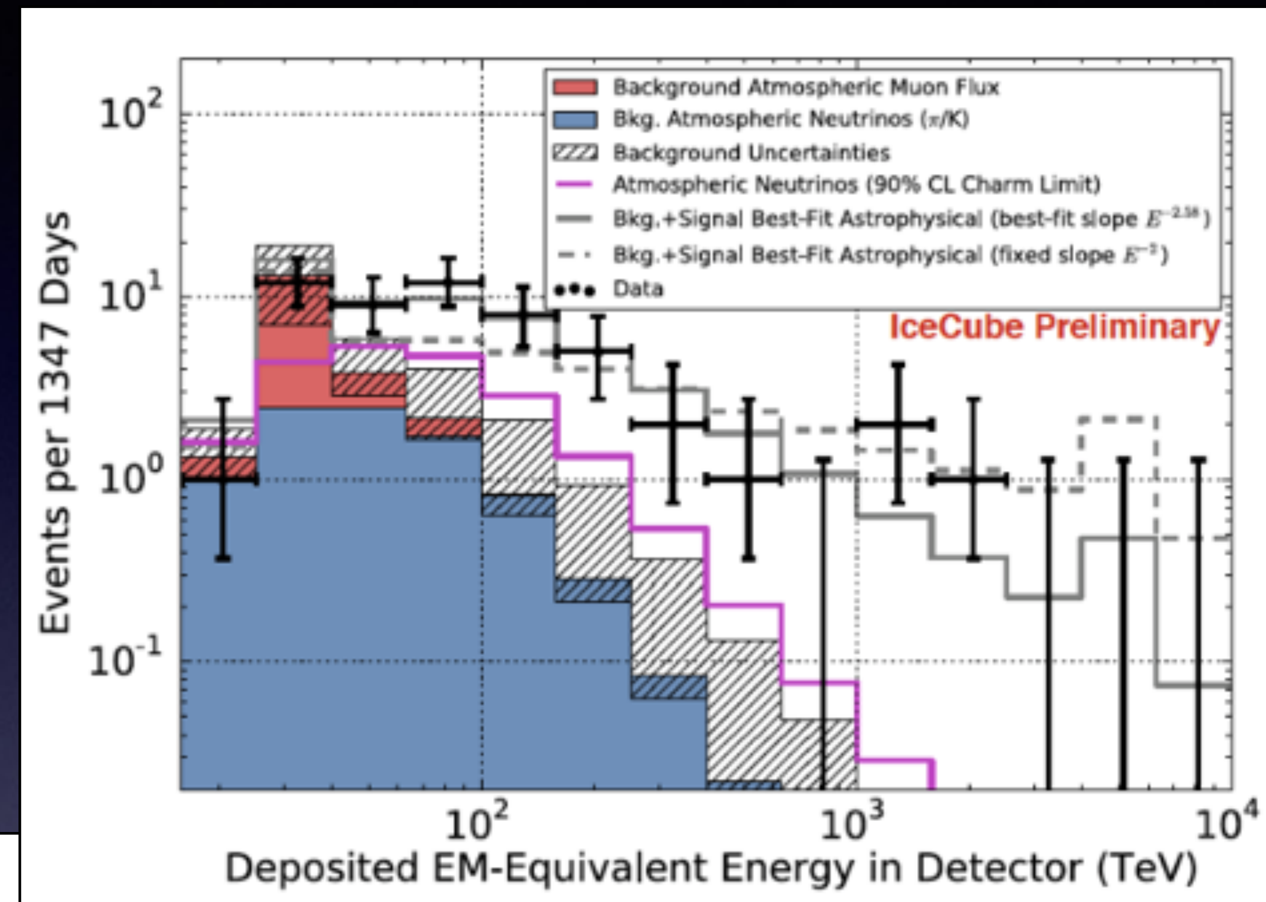
- **37** events allow for rejecting a purely atmospheric origin hypothesis at the **5.7 σ**.
- Observed flux consistent with an isotropic and equal flavour E^{-2} power-law spectrum, as expected for an astrophysical neutrino flux.
- Expected background: 8.4±4.2 atm. μ and 6.6+5.9 ν



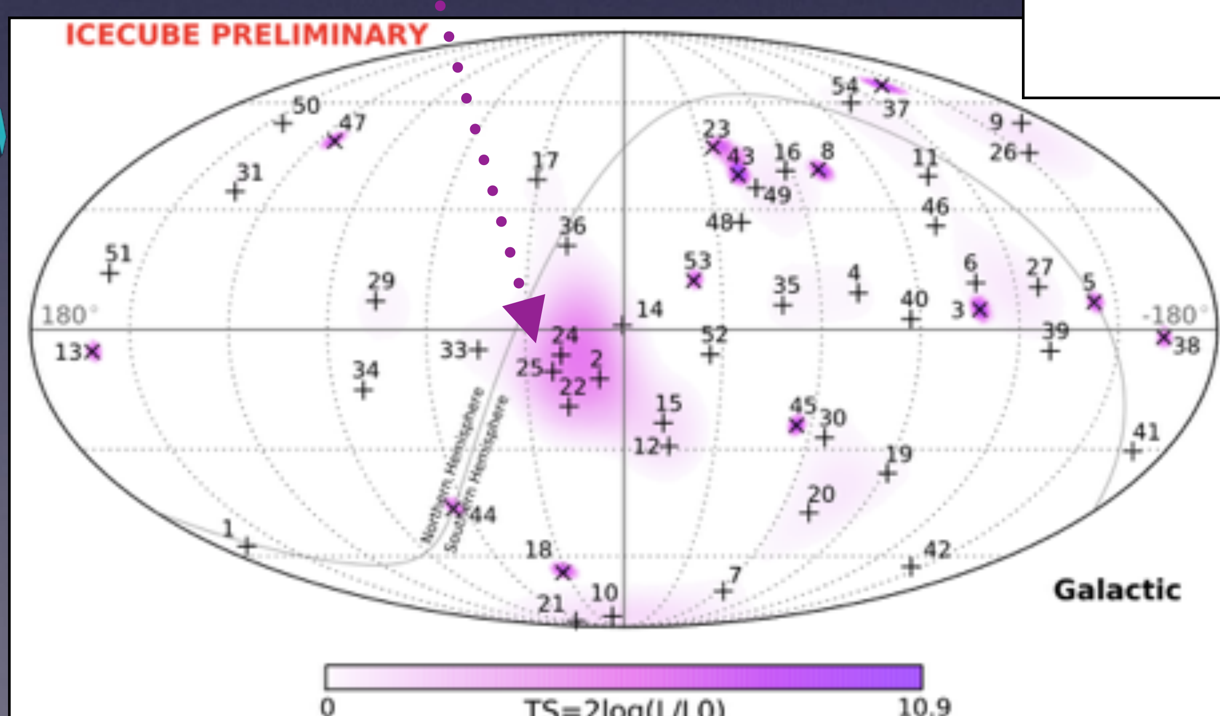
The birth of neutrino astronomy

IceCube preliminary analysis of 4 years of data (2010 - 2014)

- **54** events allow for rejecting a purely atmospheric origin hypothesis at the **7 σ**.



cascade events only
p-value = 18%



No significant spatial or temporal correlations

Too few events to identify sources

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

From discovery to astronomy

- IceCube has demonstrated the feasibility of the detection technique and proved the physics concepts

  ➡ **performance superior to expectations**

- IceCube has discovered the hypothesised flux of high-energy cosmic ν's.

  ➡ **neutrino astronomy is right behind the corner**

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

…We need more data to solve the mystery of the origin of cosmic neutrinos

From discovery to astronomy

…We need more data to solve the mystery of the origin of cosmic neutrinos

We wait for several years to increase statistics

(~tens of events in 4 years means we could not even reach the statistics we need during IceCube lifetime)

↔

Construct a bigger detector (10 km^3) to enhance our chances of new discoveries

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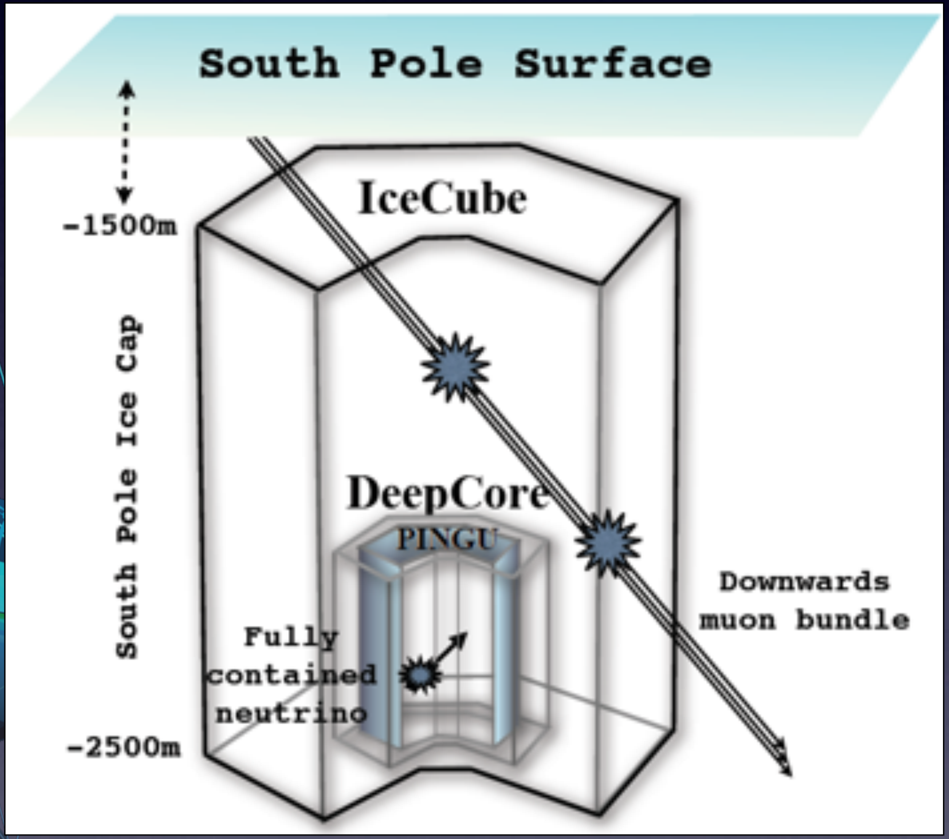
The Future: IceCube-Gen2

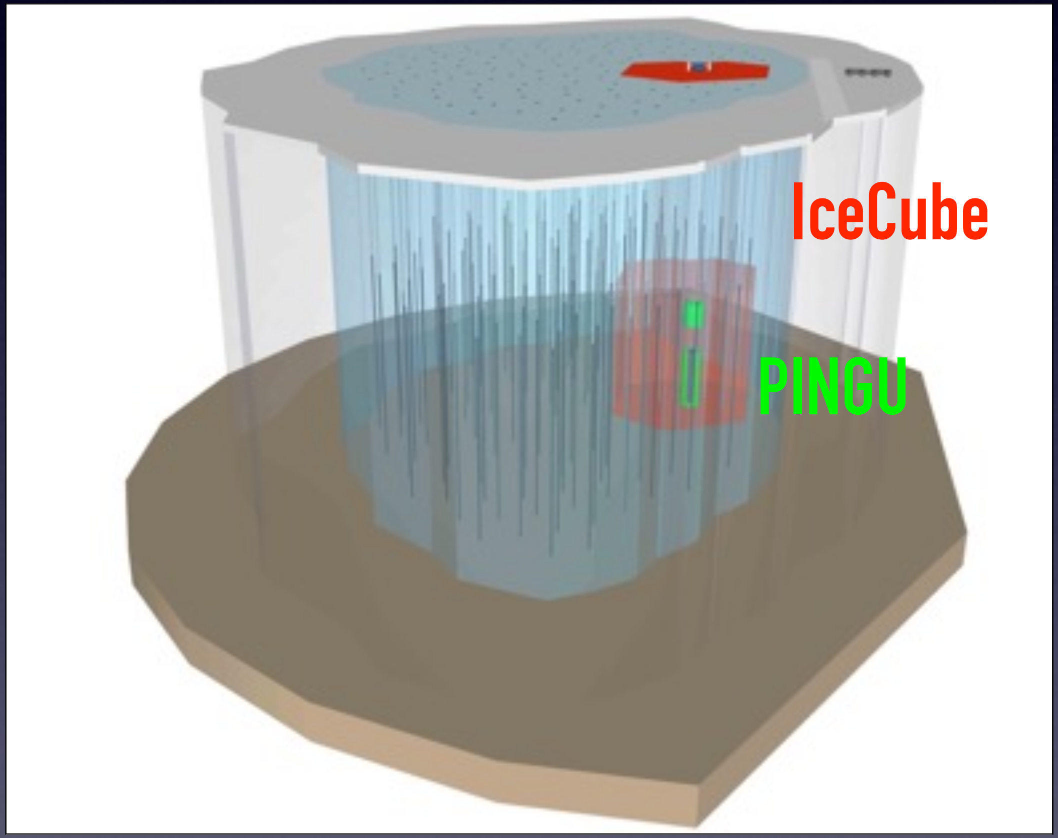
PINGU

Further in-fill of deep core.
Lower the energy threshold few GeV
Oscillations and Neutrino Mass Hierarchy

High Energy Extension

Extension of IceCube array
Look for high-energy events
GZK and **astrophysical neutrinos**





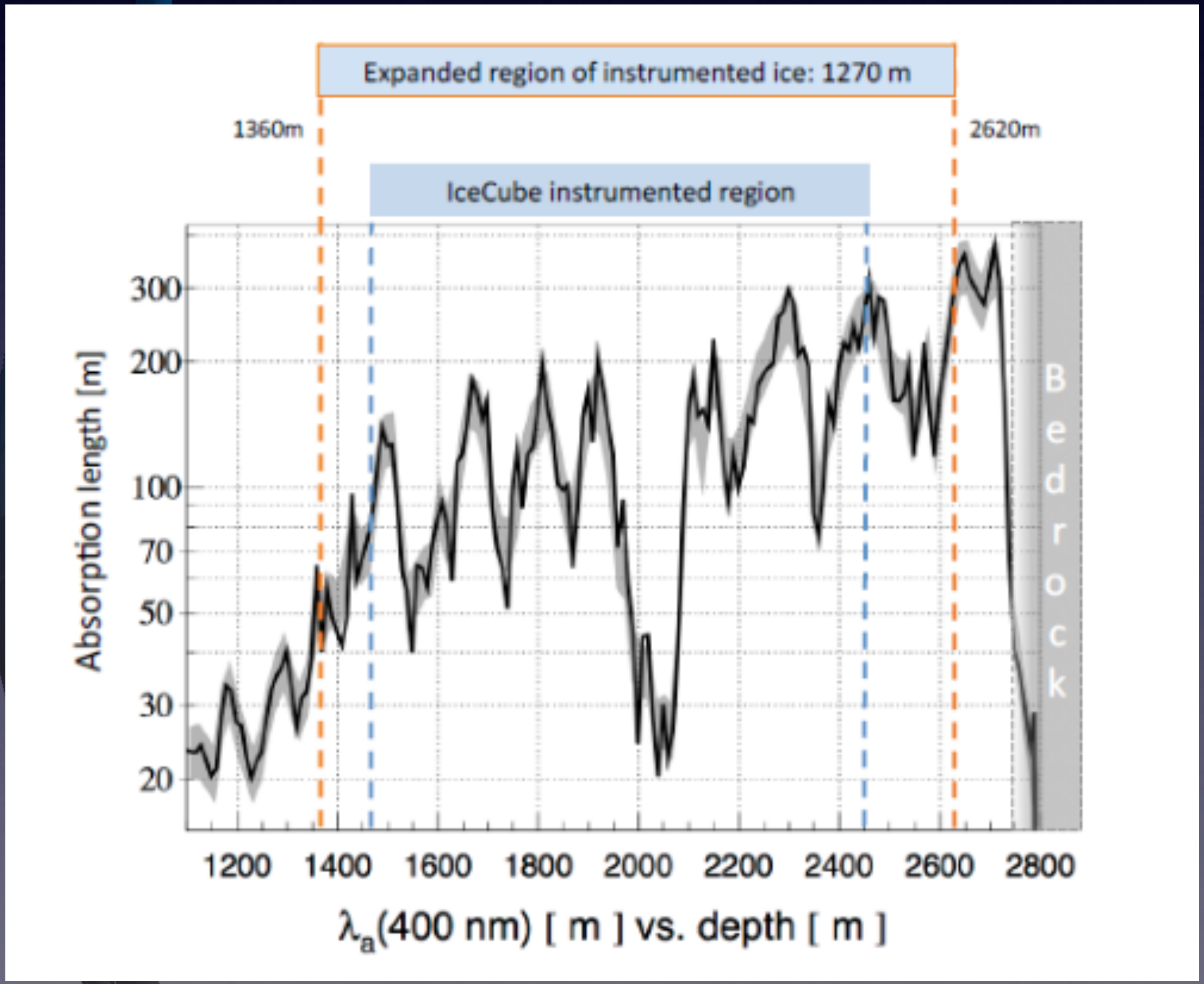
<u>Additional components</u>:

IceCube-Gen2 ***Cosmic Ray Veto Array***—a ~100-km^2 surface detector for veto for cosmic rays background

IceCube-Gen2 ***Radio Array*** —a 100 to ~300-km^2 scale detector for extremely high energy (≥ 10^{18} eV) cosmogenic neutrinos.

High-Energy In-Ice Component

Scale: O(100) strings, O (10 km^3)
Physics goals: identify the source of cosmic neutrinos and CRs, neutrino and particle physics
Surface component like IceTop



Thanks to the ice properties (long absorption length) we can instrument 10 times more volume with almost the same number of sensors used in IceCube.

More spacing/less dense detector: first study shows that we can work with that!

High-Energy In-Ice Component

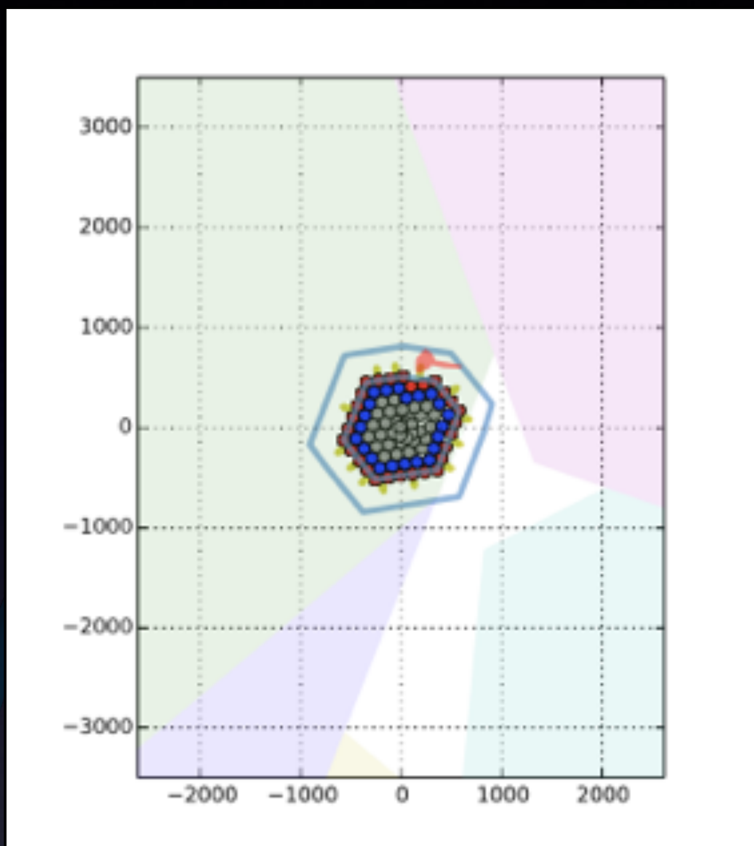
White paper:submitted in Dec. 2014 [arxiv.org:1412.5106]

18 Dec 2014

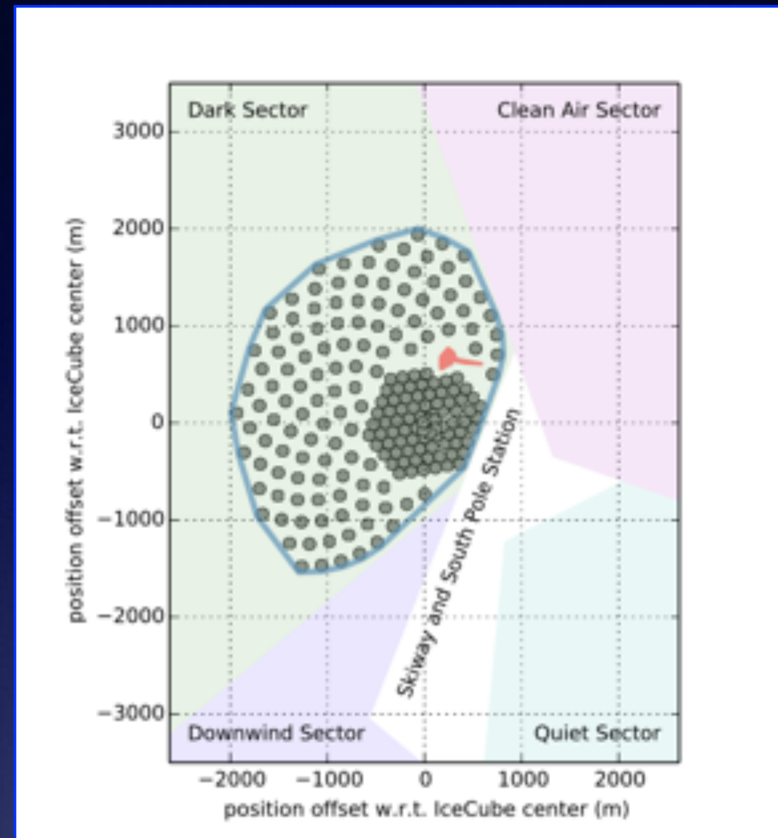
IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica

M. G. Aartsen,[2] M. Ackermann,[54] J. Adams,[16] J. A. Aguilar,[12] M. Ahlers,[31] M. Ahrens,[44] D. Altmann,[24] T. Anderson,[51] G. Anton,[24] C. Arguelles,[31] T. C. Arlen,[51] J. Auffenberg,[1] S. Axani,[23] X. Bai,[42] I. Bartos,[36] S. W. Barwick,[27] V. Baum,[32] R. Bay,[7] J. J. Beatty,[18,19] J. Becker Tjus,[10] K.-H. Becker,[53] S. BenZvi,[31] P. Berghaus,[54] D. Berley,[17] E. Bernardini,[54] A. Bernhard,[35] D. Z. Besson,[28] G. Binder,[8,7] D. Bindig,[53] M. Bissok,[1] E. Blaufuss,[17,*] J. Blumenthal,[1] D. J. Boersma,[52] C. Bohm,[44] F. Bos,[10] D. Bose,[46] S. Böser,[32] O. Botner,[52] L. Brayeur,[13] H.-P. Bretz,[54] A. M. Brown,[16] N. Buzinsky,[23] J. Casey,[5] M. Casier,[13] E. Cheung,[17] D. Chirkin,[31] A. Christov,[25] B. Christy,[17] K. Clark,[48] L. Classen,[24] F. Clevermann,[21] S. Coenders,[35] G. H. Collin,[14] J. M. Conrad,[14] D. F. Cowen,[51,50] A. H. Cruz Silva,[54] J. Daughhetee,[5] J. C. Davis,[18] M. Day,[31] J. P. A. M. de André,[22] C. De Clercq,[13] S. De Ridder,[26] P. Desiati,[31] K. D. de Vries,[13] M. de With,[9] T. DeYoung,[22] J. C. Díaz-Vélez,[31] M. Dunkman,[51] R. Eagan,[51] B. Eberhardt,[32] T. Ehrhardt,[32] B. Eichmann,[10] J. Eisch,[31] S. Euler,[52] J. J. Evans,[33] P. A. Evenson,[37] O. Fadiran,[31] A. R. Fazely,[6] A. Fedynitch,[10] J. Feintzeig,[31] J. Felde,[17] K. Filimonov,[7] C. Finley,[44] T. Fischer-Wasels,[53] S. Flis,[44] K. Frantzen,[21] T. Fuchs,[21] T. K. Gaisser,[37] R. Gaior,[15] J. Gallagher,[30] L. Gerhardt,[8,7] D. Gier,[1] L. Gladstone,[31] T. Glüsenkamp,[54] A. Goldschmidt,[8] G. Golup,[13] J. G. Gonzalez,[37] J. A. Goodman,[17] D. Góra,[54] D. Grant,[23] P. Gretskov,[1] J. C. Groh,[51] A. Groß,[35] C. Ha,[8,7] C. Haack,[1] A. Haj Ismail,[26] P. Hallen,[1] A. Hallgren,[52] F. Halzen,[31,*] K. Hanson,[31,†] J. Haugen,[31] D. Hebecker,[9] D. Heereman,[12] D. Heinen,[1] K. Helbing,[53] R. Hellauer,[17] D. Hellwig,[1] S. Hickford,[53] J. Hignight,[22] G. C. Hill,[2] K. D. Hoffman,[17] R. Hoffmann,[53] A. Homeier,[11] K. Hoshina,[47,31] F. Huang,[51] W. Huelsnitz,[17] P. O. Hulth,[44] K. Hultqvist,[44] A. Ishihara,[15] E. Jacobi,[54] J. Jacobsen,[31] G. S. Japaridze,[4] K. Jero,[31] O. Jlelati,[26] B. J. P. Jones,[14] M. Jurkovic,[35] O. Kalekin,[24] A. Kappes,[24] T. Karg,[54] A. Karle,[31] T. Katori,[29] U. F. Katz,[24] M. Kauer,[31,38]

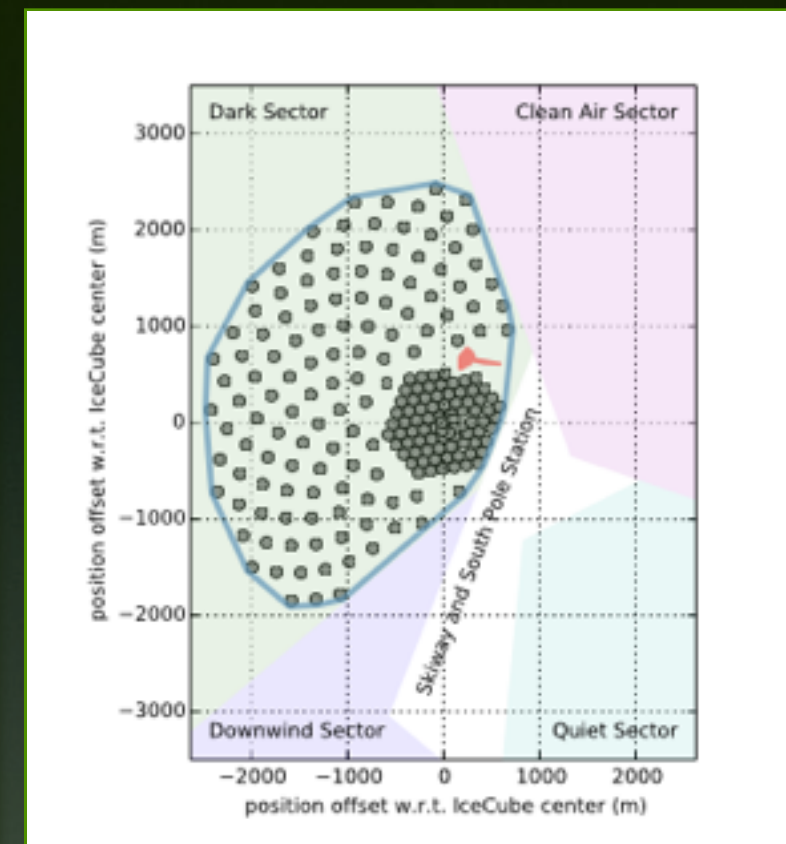
High-Energy In-Ice Component: “strawman" detector



top area(+60m border):
volume: 1.2 km3
strings: IceCube
spacing: ~125 m



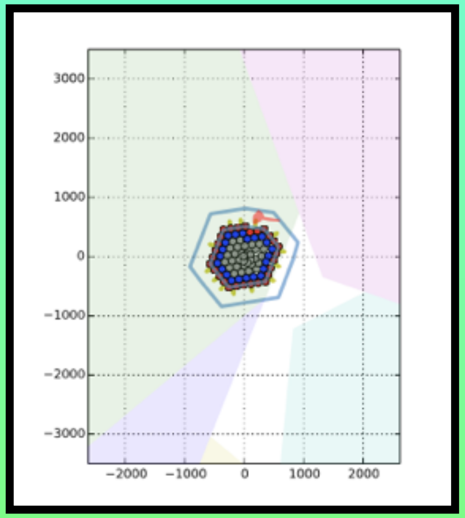
top area (+60m border)
volume: 9.7 km^3
strings: IceCube+120
spacing: ~240 m

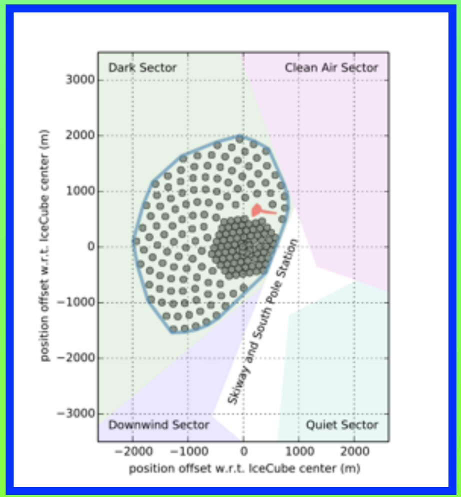


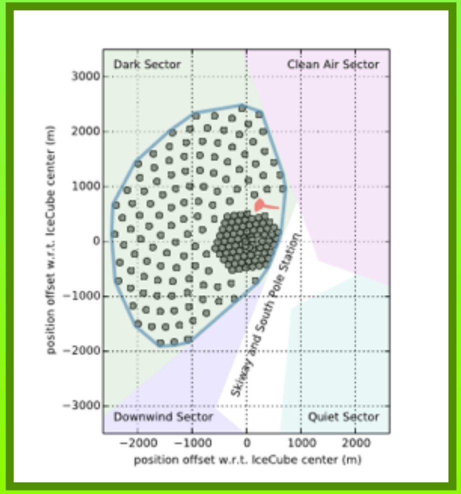
top area (+60m border)
volume: 14.2 km^3
strings: IceCube+120
spacing: ~300 m

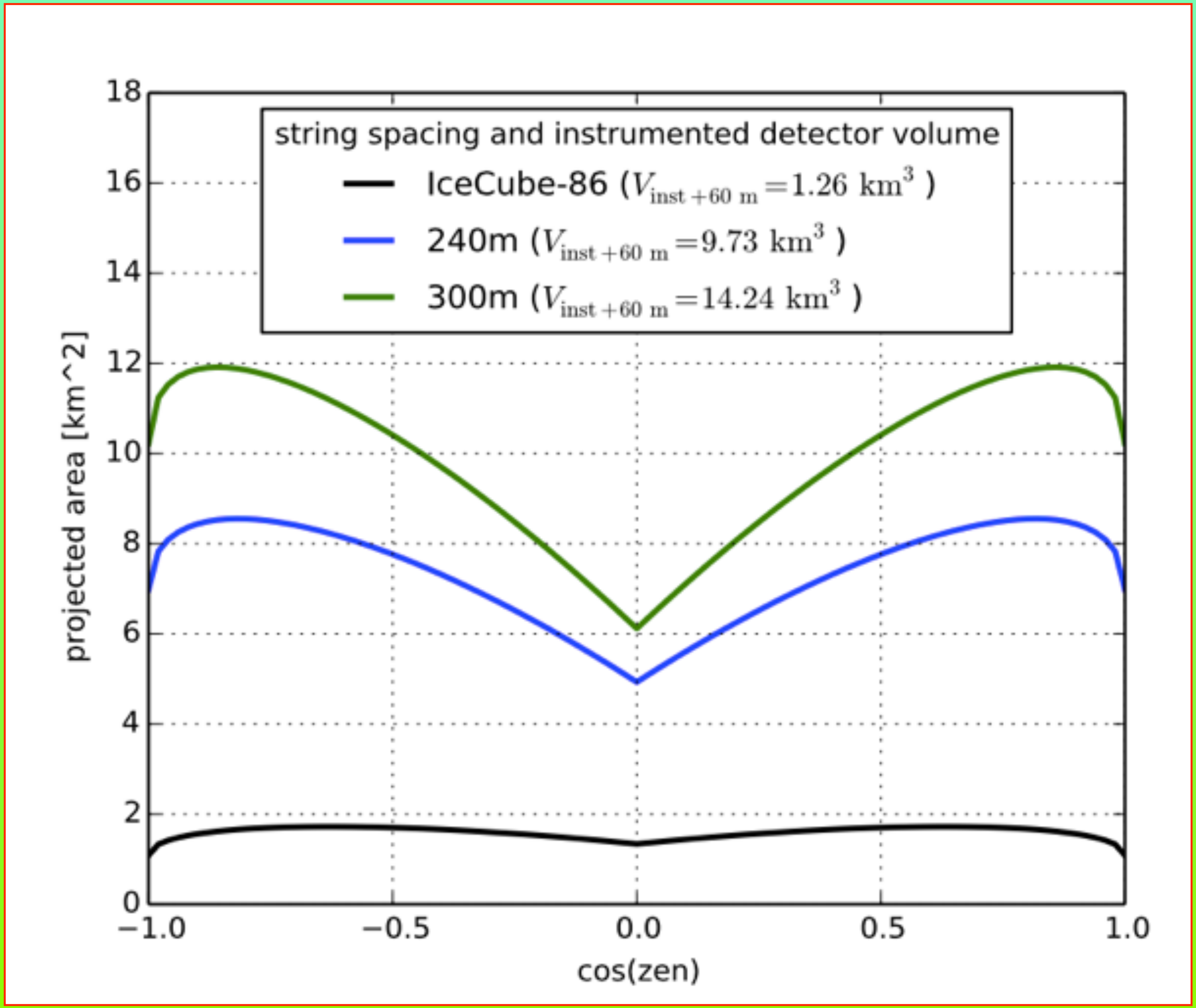
High-Energy In-Ice Component: “strawman" detector

Increase in volume and projected area (still optimisation to different analysis needed to fix the final design).

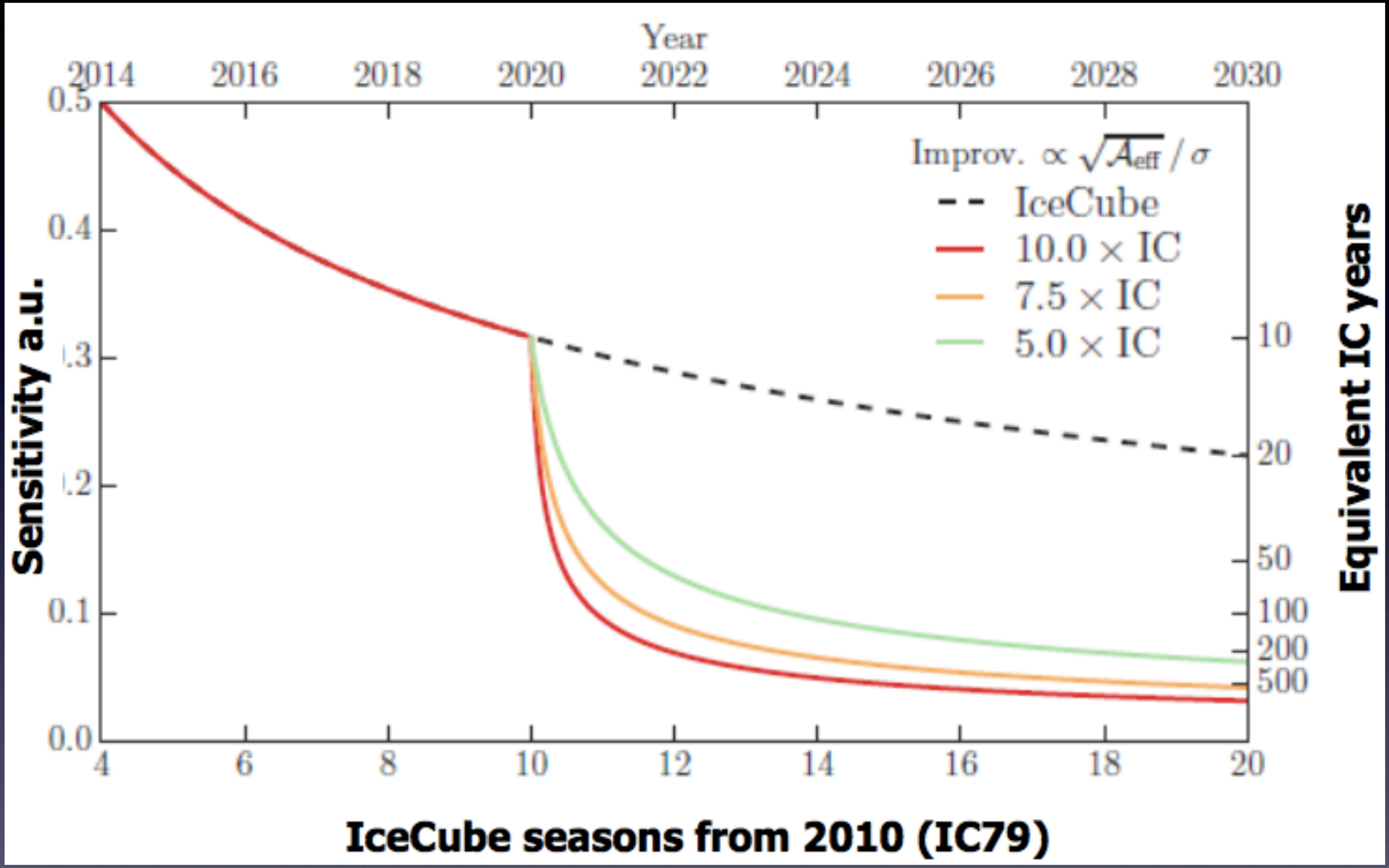








High-Energy In-Ice Component: point source sensitivity



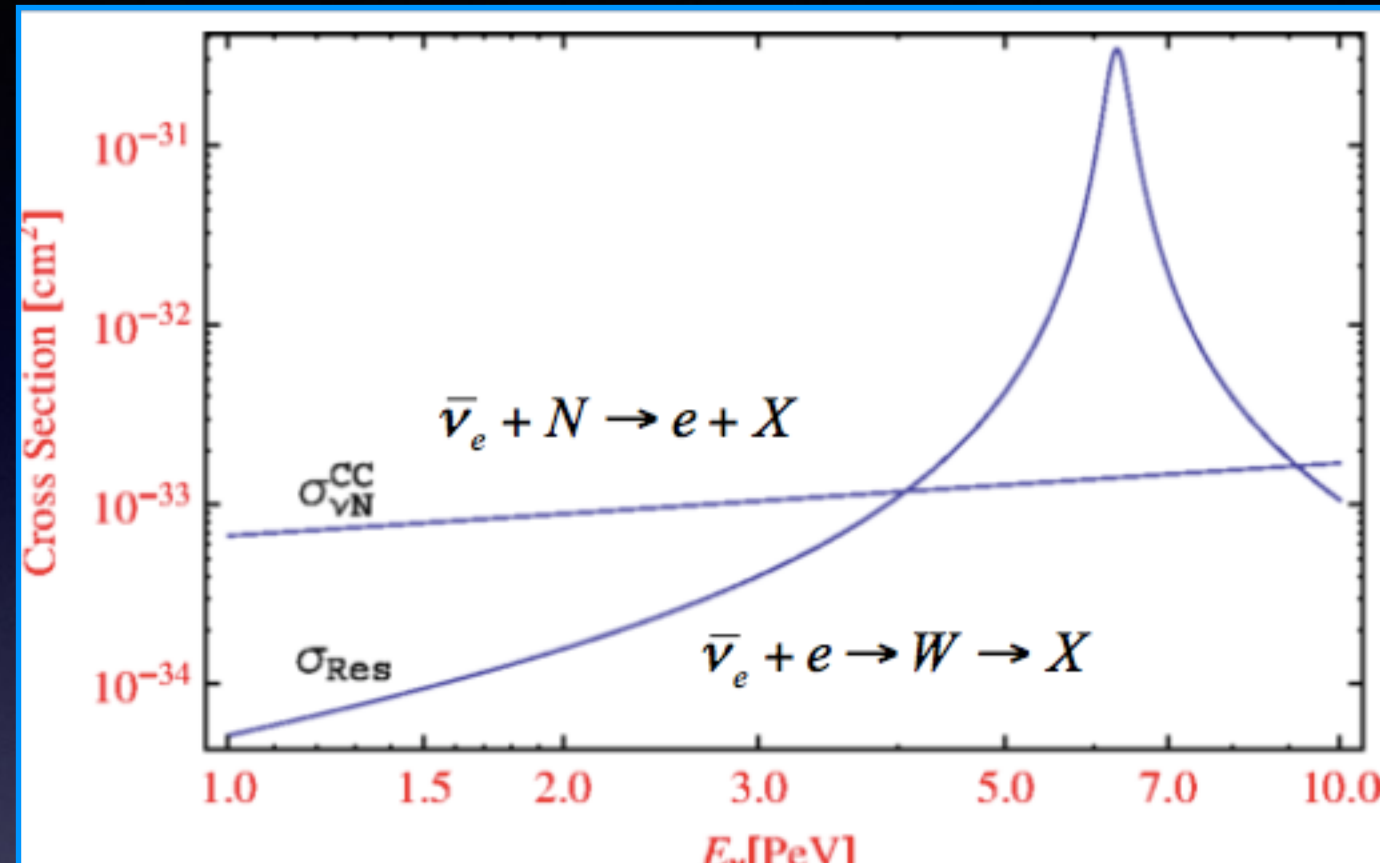
Sensitivity (in background dominated) assumed to scale as:
sqrt(Area*) / resolution**

* bigger Area due to larger instrumentation, ** better resolution due to longer lever arm

High-Energy In-Ice Component: Glashow resonance

Electron anti-neutrinos with an energy of E ~6.3 PeV have an enhanced probability to scatter off atomic electrons in the ice by forming a W-boson (Glashow resonance).

It is observable mostly as a peak in the cascade energy spectrum.



Larger volumes provide rates higher by an order of magnitude

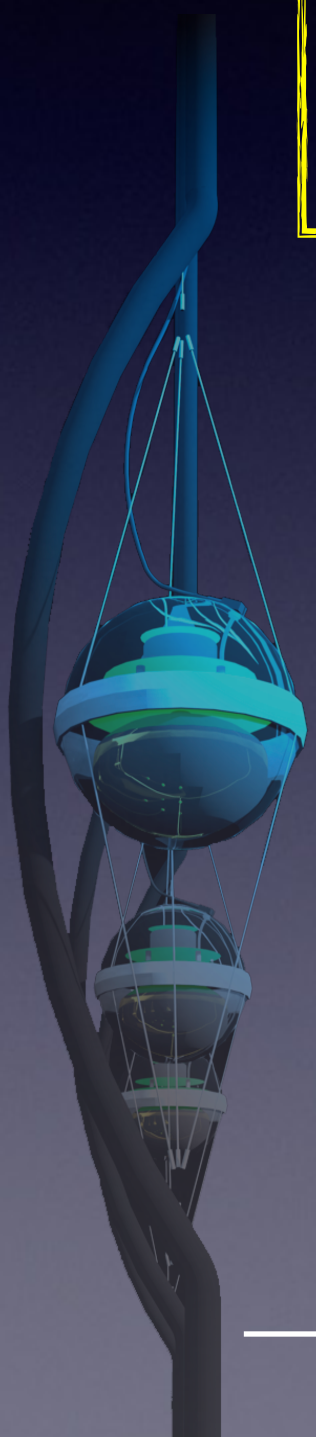
Φ_{ν_e} $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	interaction type	pp source IC-86	pp source 240m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2
	DIS	0.09	0.8

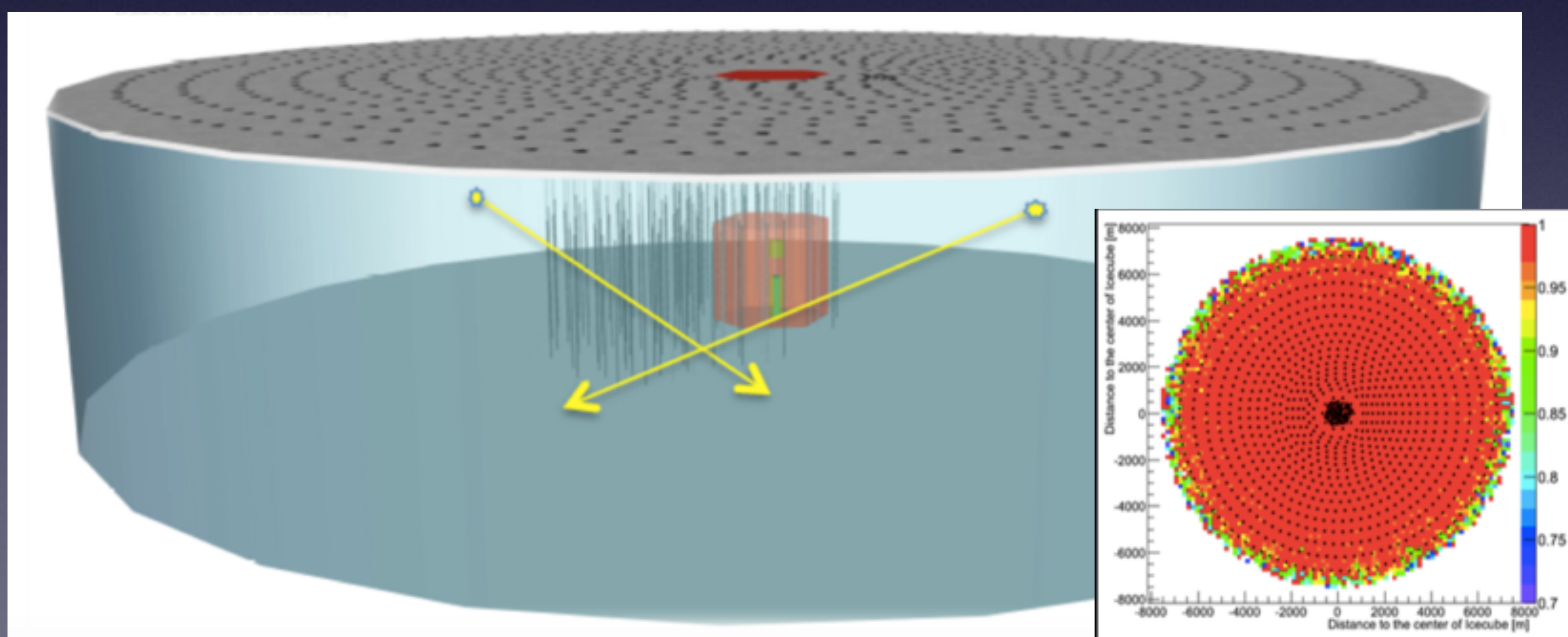
rate of contained cascades induced by electron anti-neutrinos with 5 PeV < E < 7 PeV

IceCube-Gen2 Cosmic Ray Surface Array

- Preliminary studies presume that the southern sky is inaccessible to the detector due to atmospheric μ's background.
- Background can be greatly suppressed by dedicating parts of the in-ice instrumentation in order to tag incoming muon tracks (HESE analysis).
- **Cosmic-ray showers can be directly vetoed on the ice surface (IceTop-like detector). Used for CR physics and veto the in-ice atmospheric μ's and ν's.**

Sensitivity to sources in the Southern sky greatly enhanced



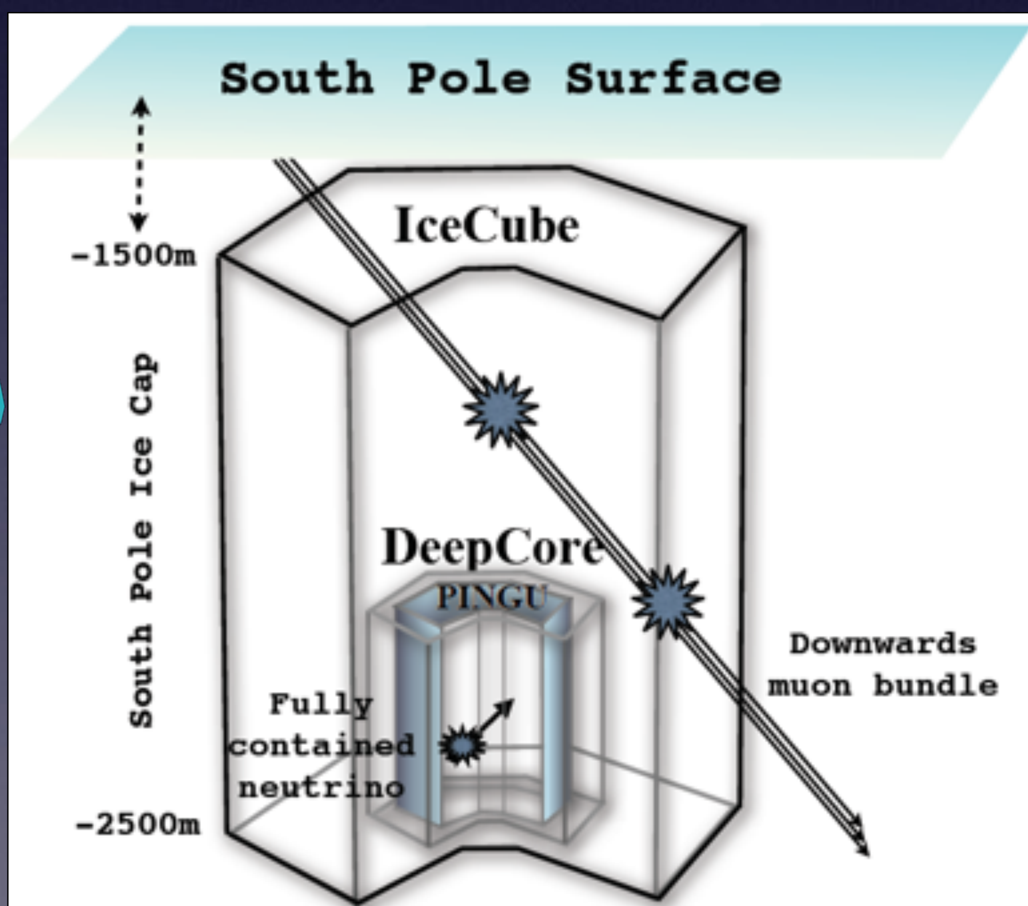


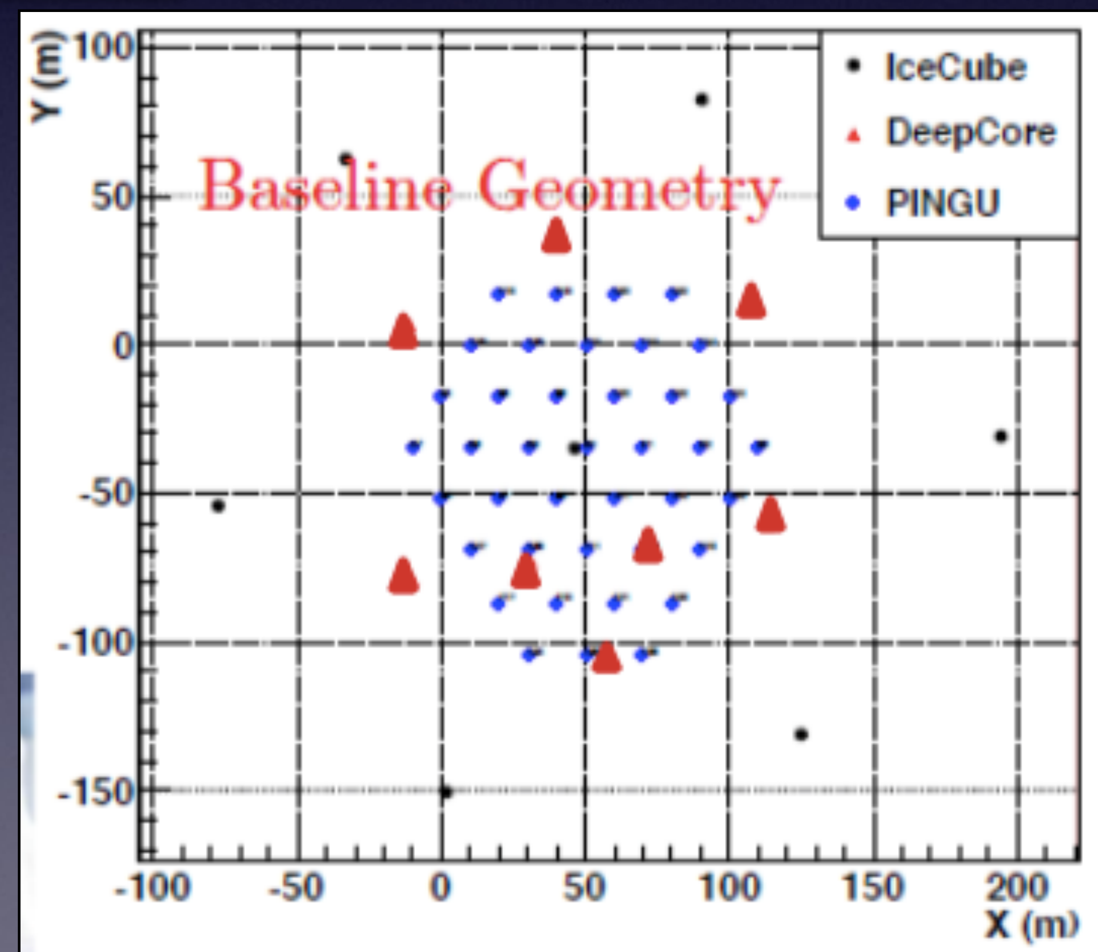
PINGU – Precision IceCube Next Generation Upgrade

Scientific goal:

- precise measurement of ν osc. param;
- determination of the ν mass ordering;
- indirect search for WIMP DM at low energies (PINGU Energy threshold ~ 1 GeV)

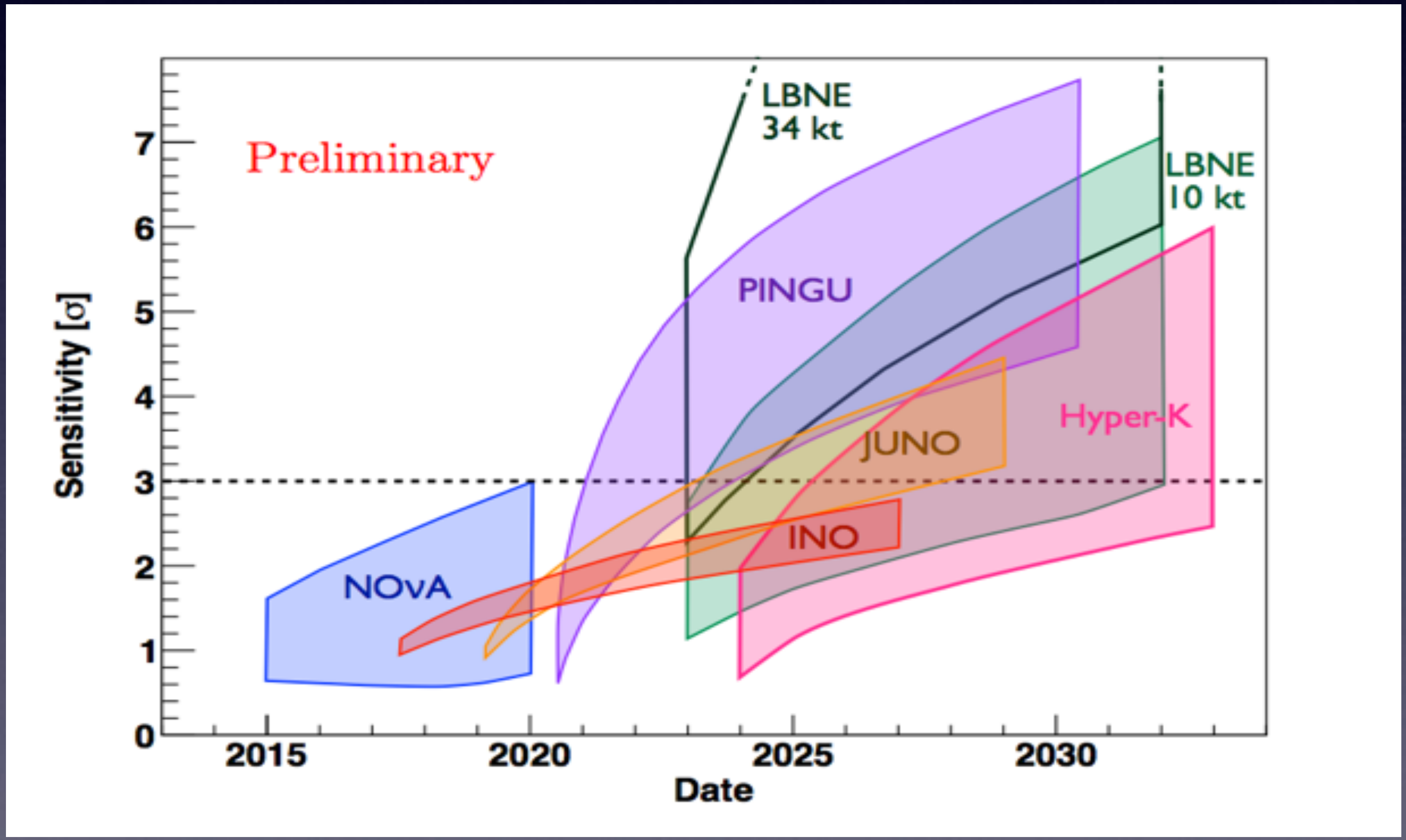
40 strings, 60 (->96) DOMs/ string, ~ 5m spacing, ~ 25 m between strings





PINGU – Precision IceCube Next Generation Upgrade

Several current or planned experiments will have sensitivity to the neutrino mass ordering in the next 10-15 years.

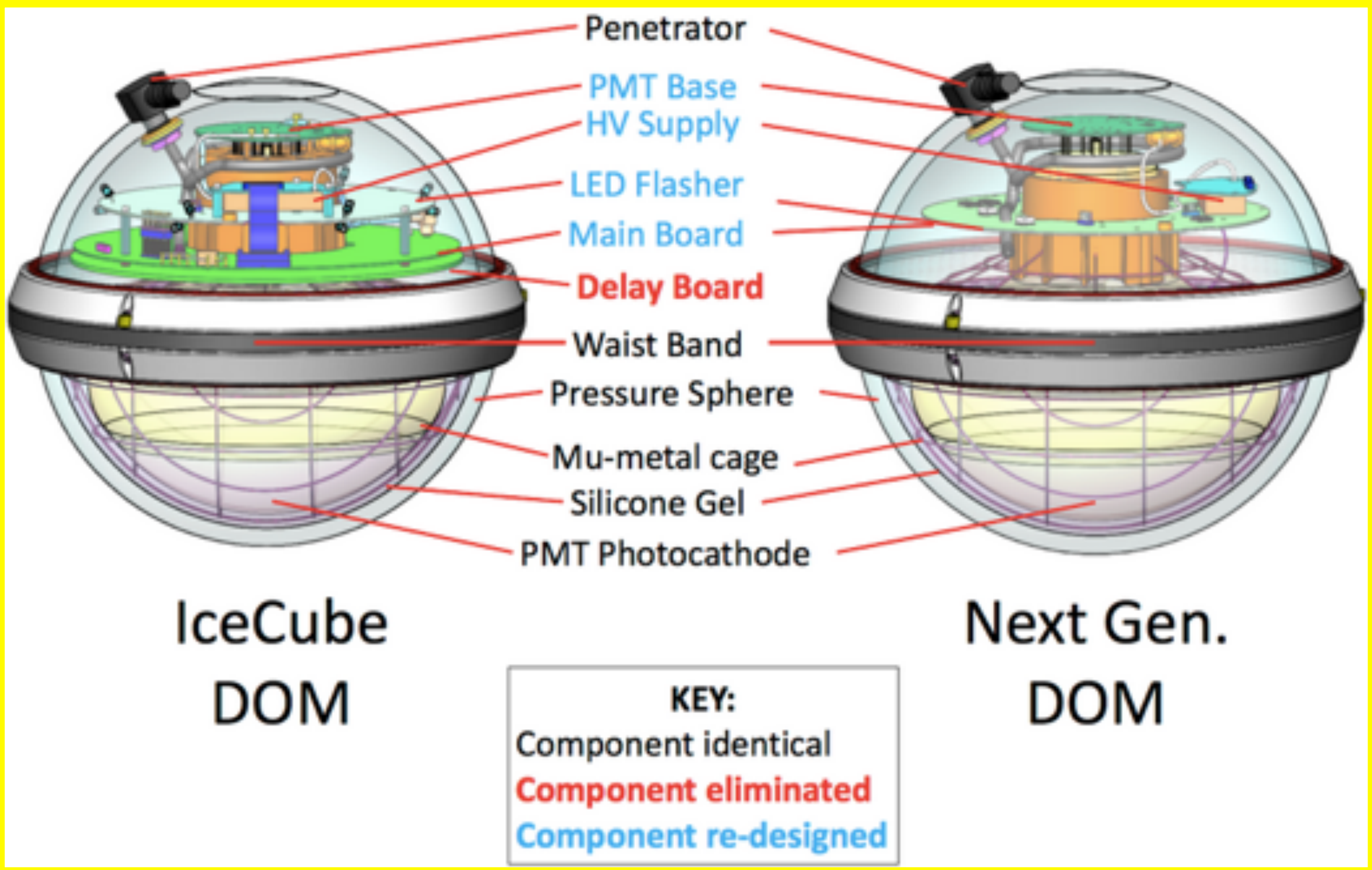


widths of the bands cover the maximum sensitivity differences corresponding to the two hierarchy cases in combination with other parameters (energy resolution difference for JUNO, mixing angle θ_{23} for PINGU and INO)

Expected sensitivities (for rejecting the inverse hierarchy assuming the normal hierarchy) of different experiments with the potential to measure the neutrino mass hierarchy

Photosensor R&D

IceCube DOM - simplified using "modern" technology

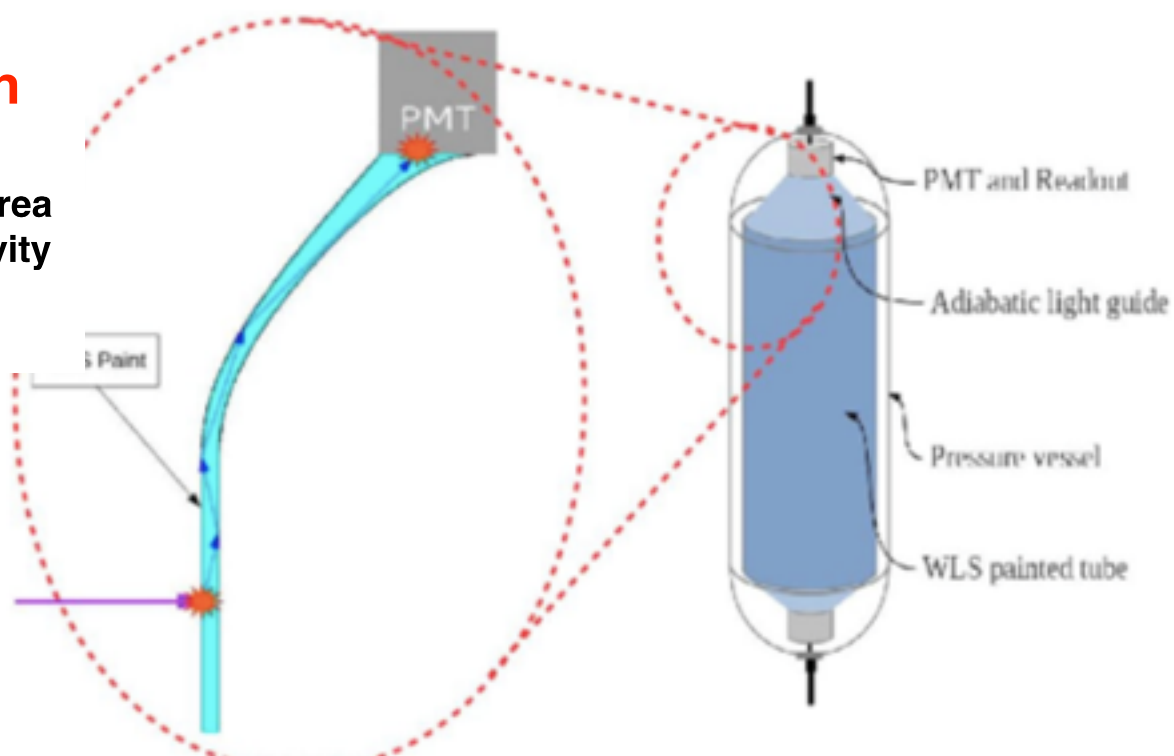


Small PMTs in one module

24 X 3"PMTs in 14" diameter pressure vessel
2x effective area of standard IceCube DOMs
4π coverage

Wavelength shifters:

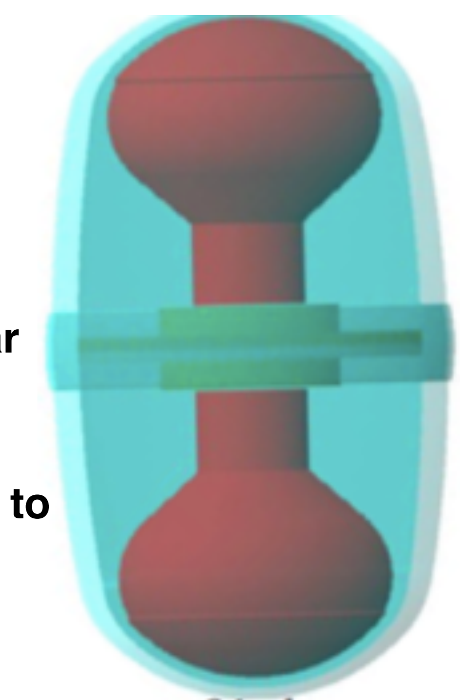
large collection area
better UV sensitivity
low noise rate
cost effective



Dual optical sensors:

Improved angular sensitivity

Better acceptance to UV photons



8 inch D-Egg

Conclusions

- IceCube has observed a diffuse high-energy cosmic neutrino flux paving the road for neutrino astronomy.
- No evidence for point source has been found yet: more data needed to resolve the origin
- **IceCube-Gen2** represents the future for neutrino astronomy
- **High-Energy In-Ice Component:** 10 km^3 - scale detector instrumented with same number of photosensors as IceCube to discover and study the sources of cosmic neutrinos
- **PINGU:** low energy in-fill detector to make precision measurements of ν oscillation and mass ordering
- Surface components: cosmic ray surface array, radio array.

Interesting times for neutrino astronomy…stay tuned!

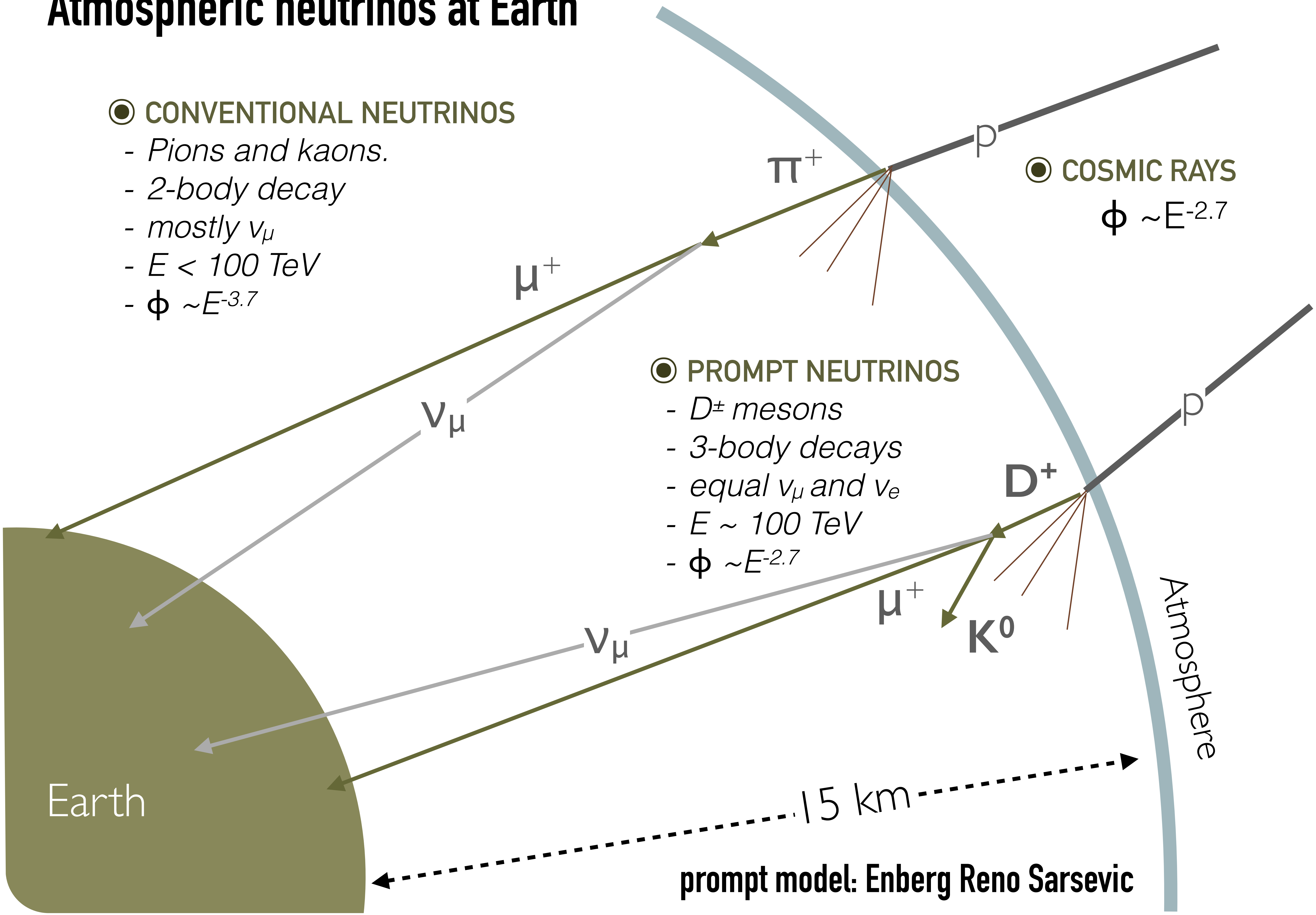
The IceCube–PINGU Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backup

Atmospheric neutrinos at Earth

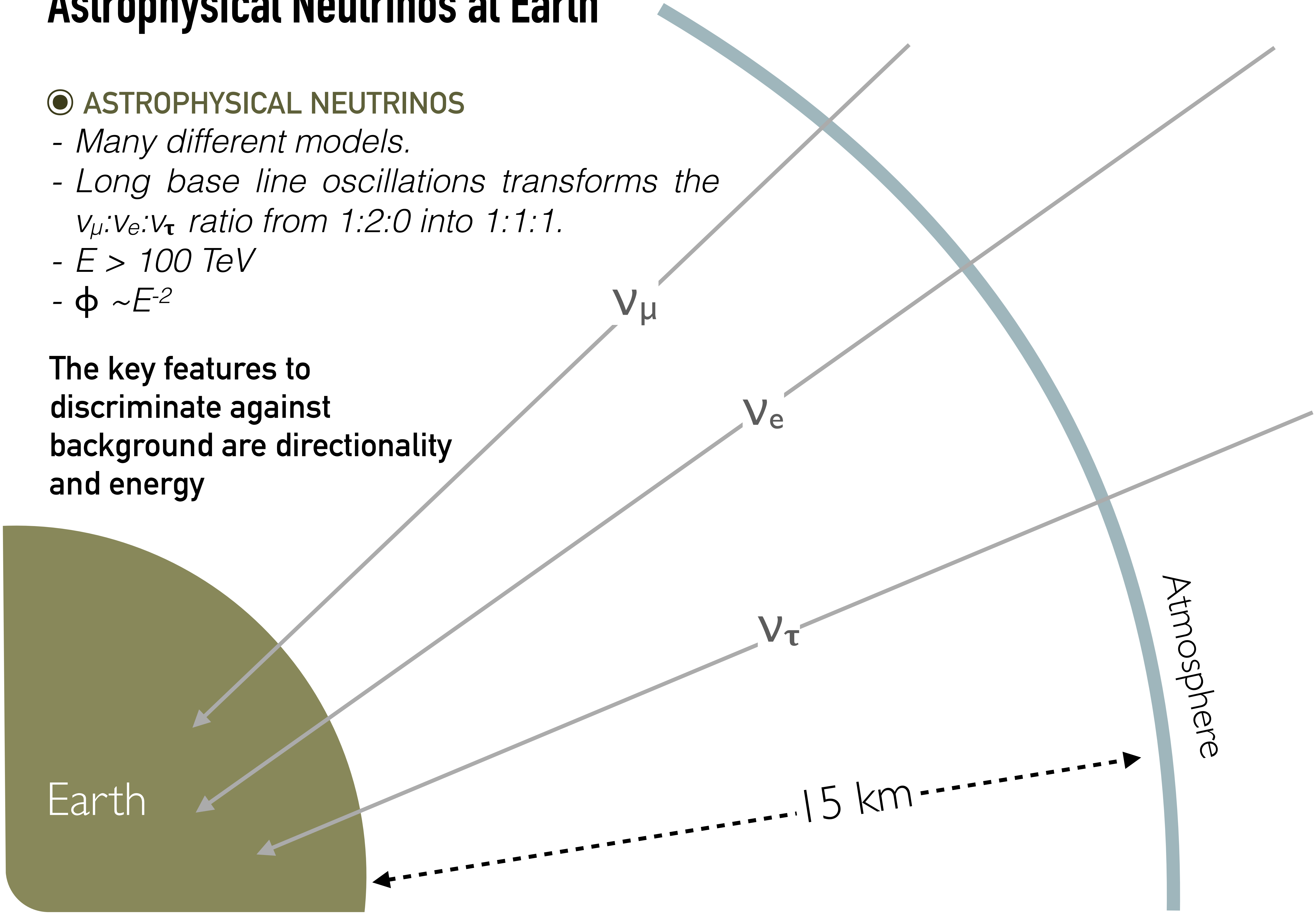


Astrophysical Neutrinos at Earth

ASTROPHYSICAL NEUTRINOS

- *Many different models.*
- *Long base line oscillations transforms the $\nu_\mu:\nu_e:\nu_\tau$ ratio from 1:2:0 into 1:1:1.*
- *$E > 100$ TeV*
- $\phi \sim E^{-2}$

The key features to discriminate against background are directionality and energy



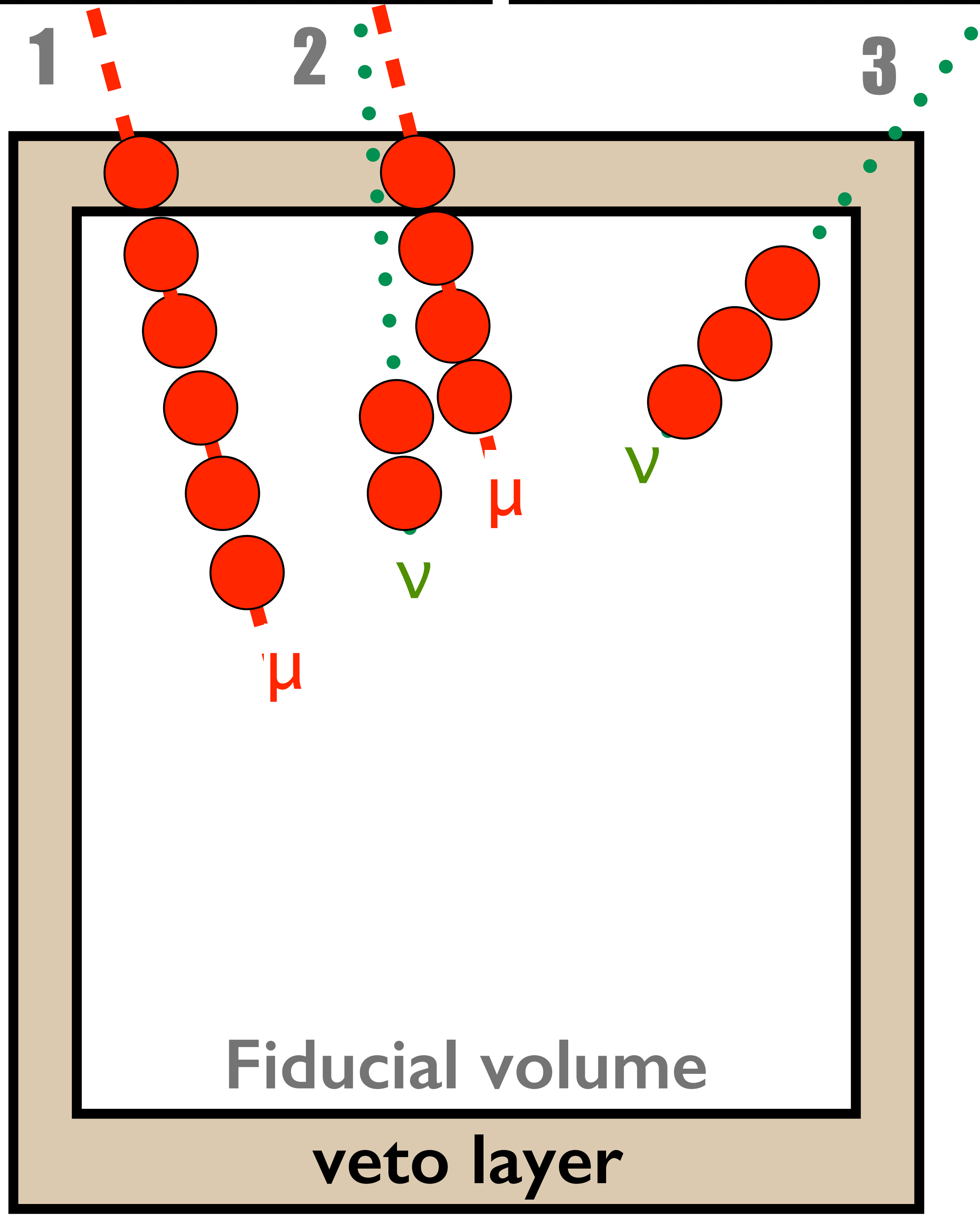
Active Veto technique

Reject events with light deposition in veto layer and high charge in the fiducial volume.

1. Atmospheric muons rejected

2. Atmospheric neutrinos rejected
(due to accompanying muon)

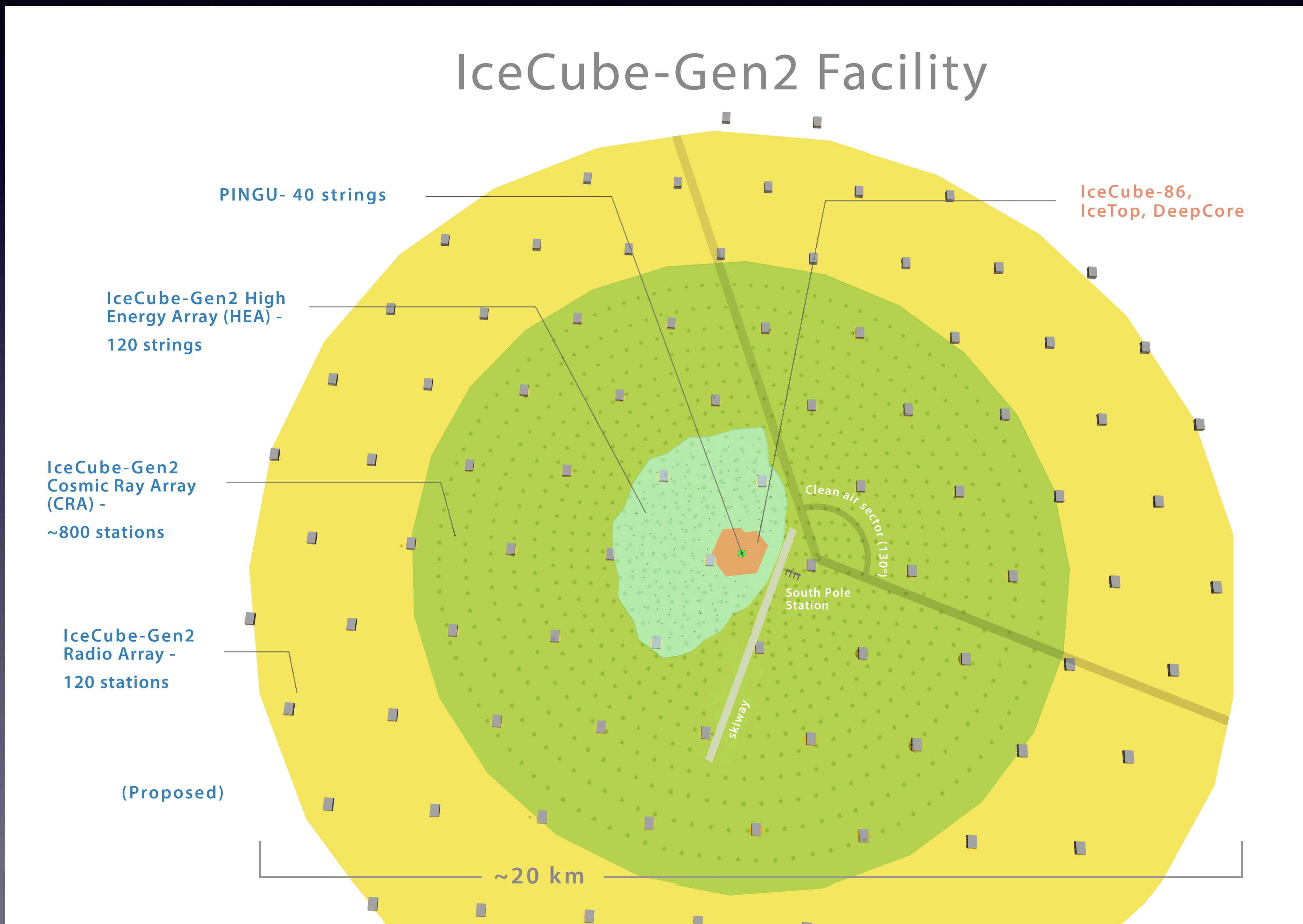
3. High energy astrophysical neutrinos accepted



High-Energy In-Ice Component: Radio Array

Radio technique is cost effective method to detect neutrinos at very high energies.
Coincidentally, South Pole ice is also a unique location for radio (radio quite environment)

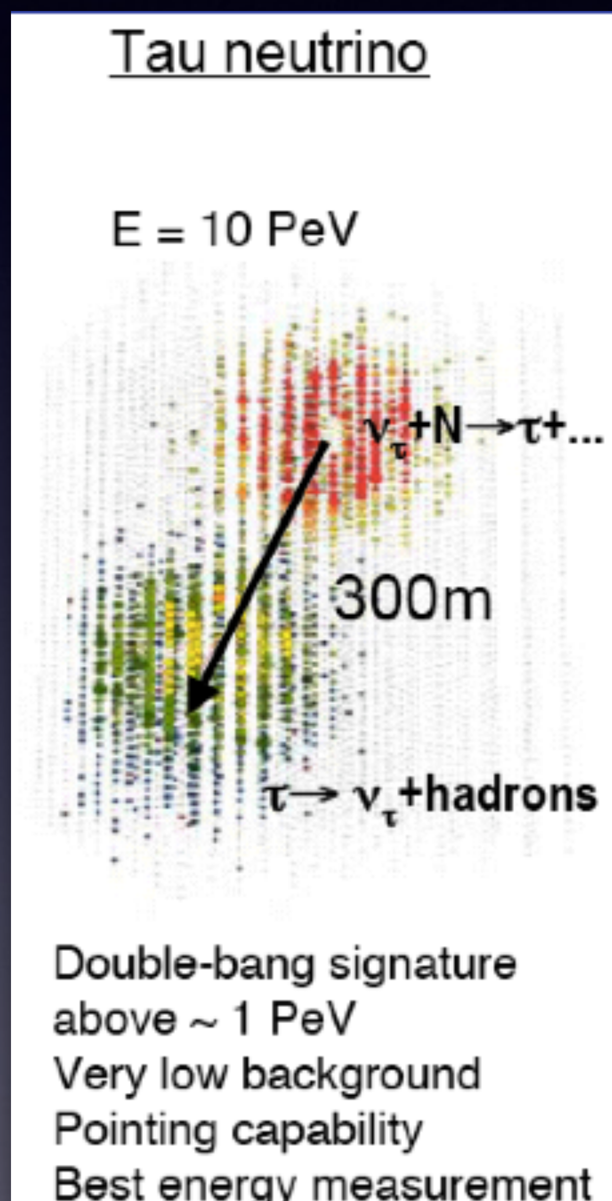
ARA, Arianna coll. already working in this direction.

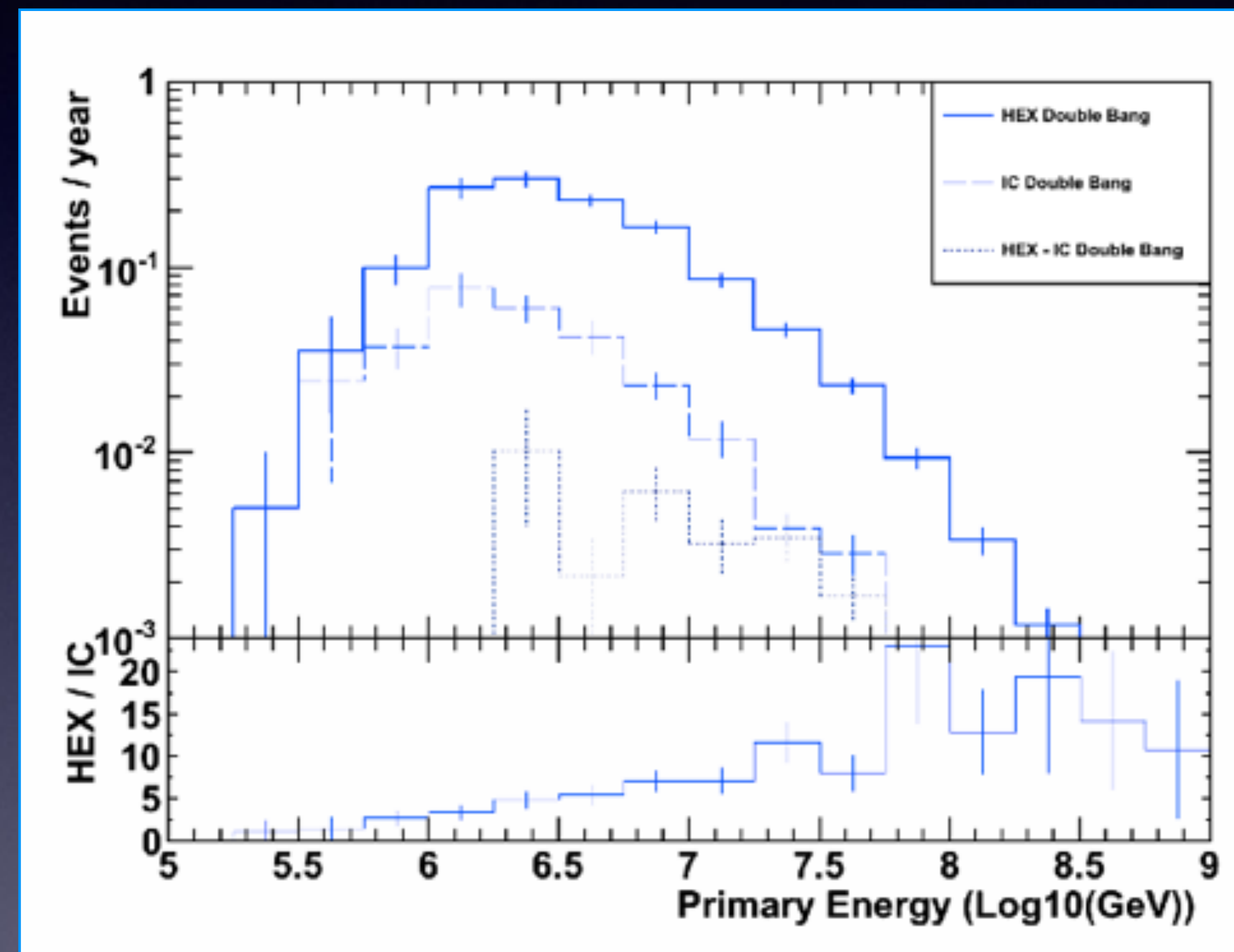


High-Energy In-Ice Component: ν_τ detection

Two cascades:
1st from the ν_τ CC interaction, 2nd (hadronic or electromagnetic) from decay.

Double bang feature: two cascades well separated are unambiguous signature.

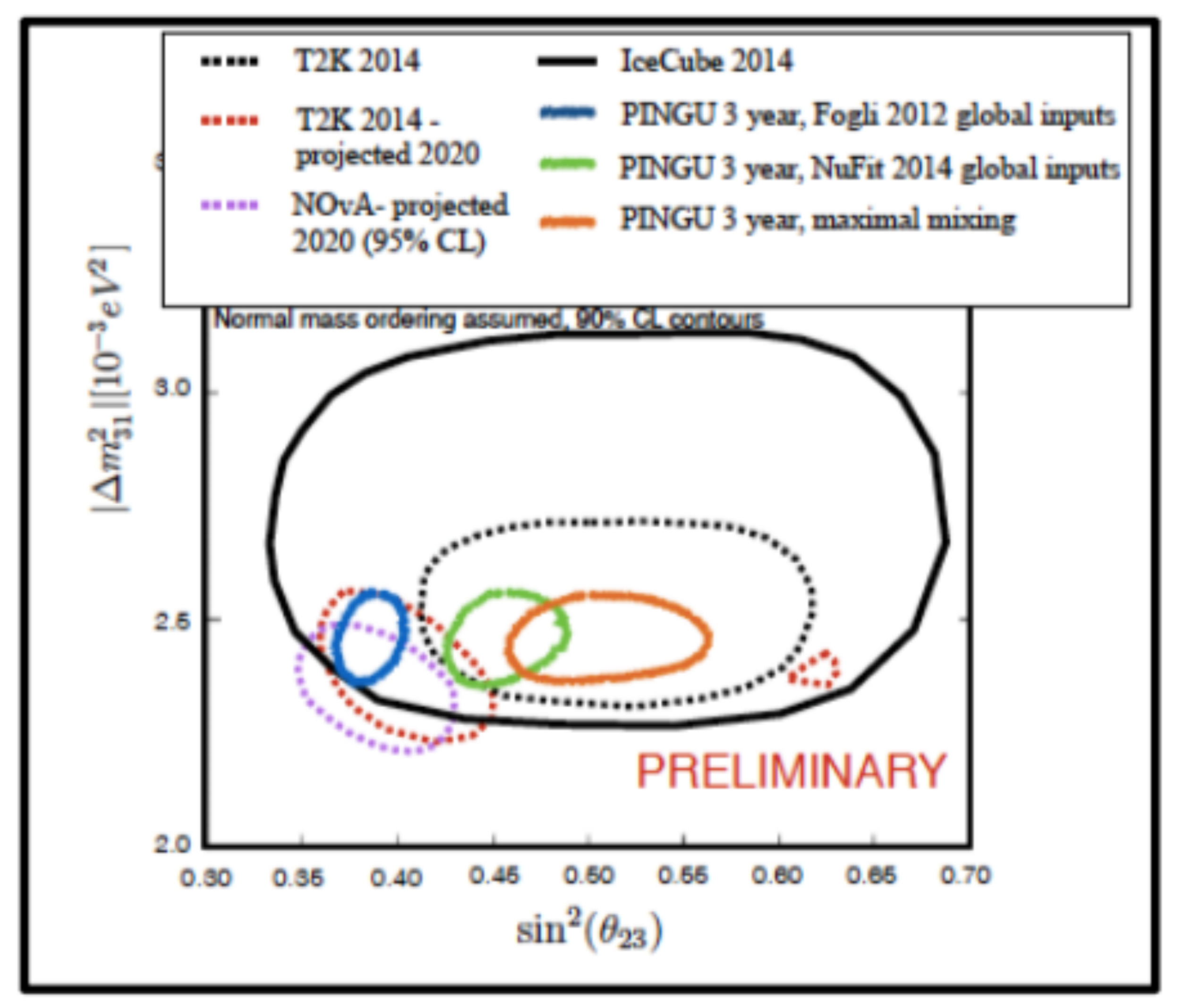


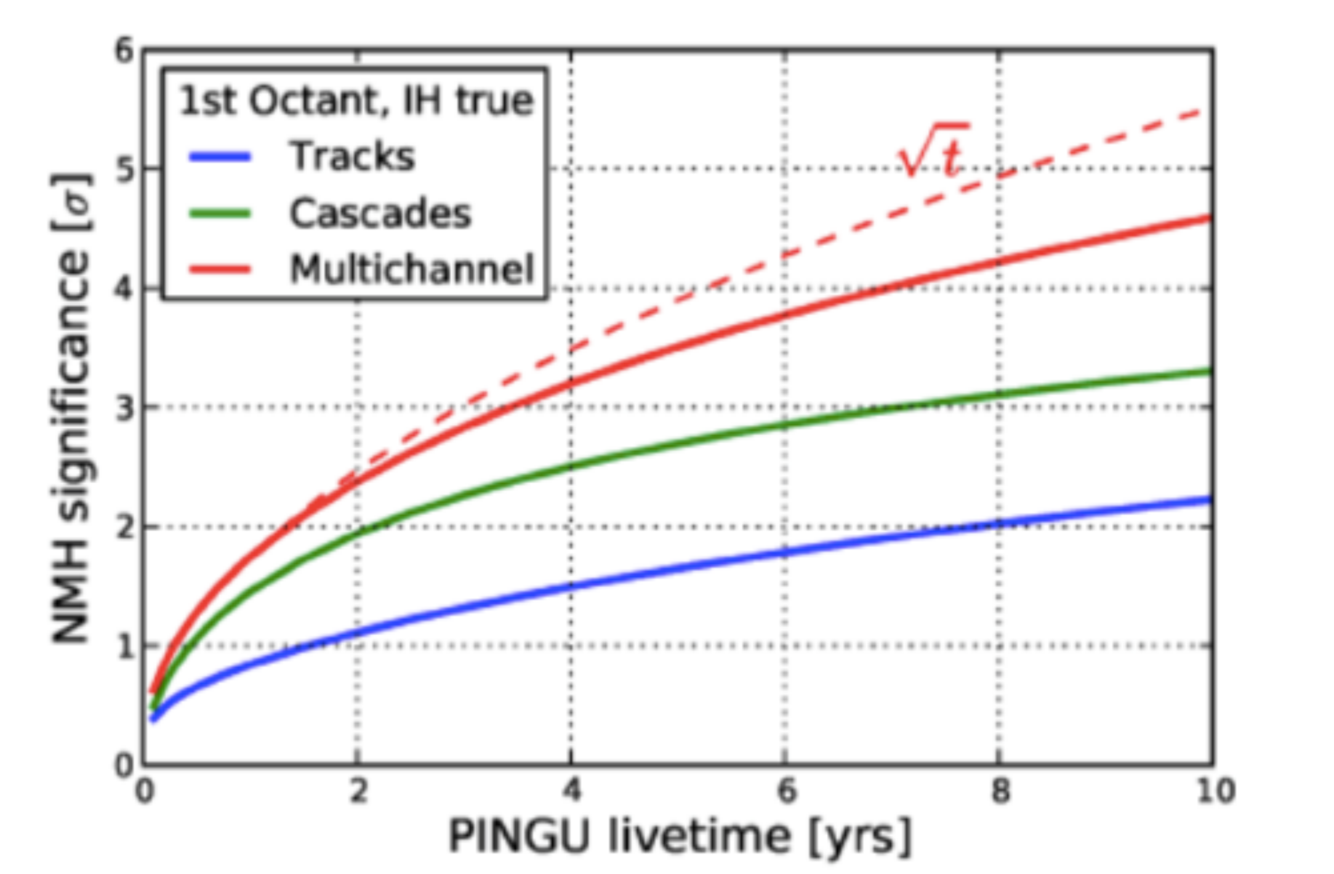


Rate of ν_τ assuming flux as measured in HESE-3yrs and equal flavour ratio at the detector. **Factor of 10 increase w.r.t. IceCube**

PINGU – Precision IceCube Next Generation Upgrade

Predicted sensitivity to ν oscillations after 3 years (96 DOMs/string)





Significance of the ν mass hierarchy determination