Photo: Martin Wolf

The IceCube Neutrino Observatory

—

Recent Results and Future Plans

Chad Finley
Oskar Klein Centre
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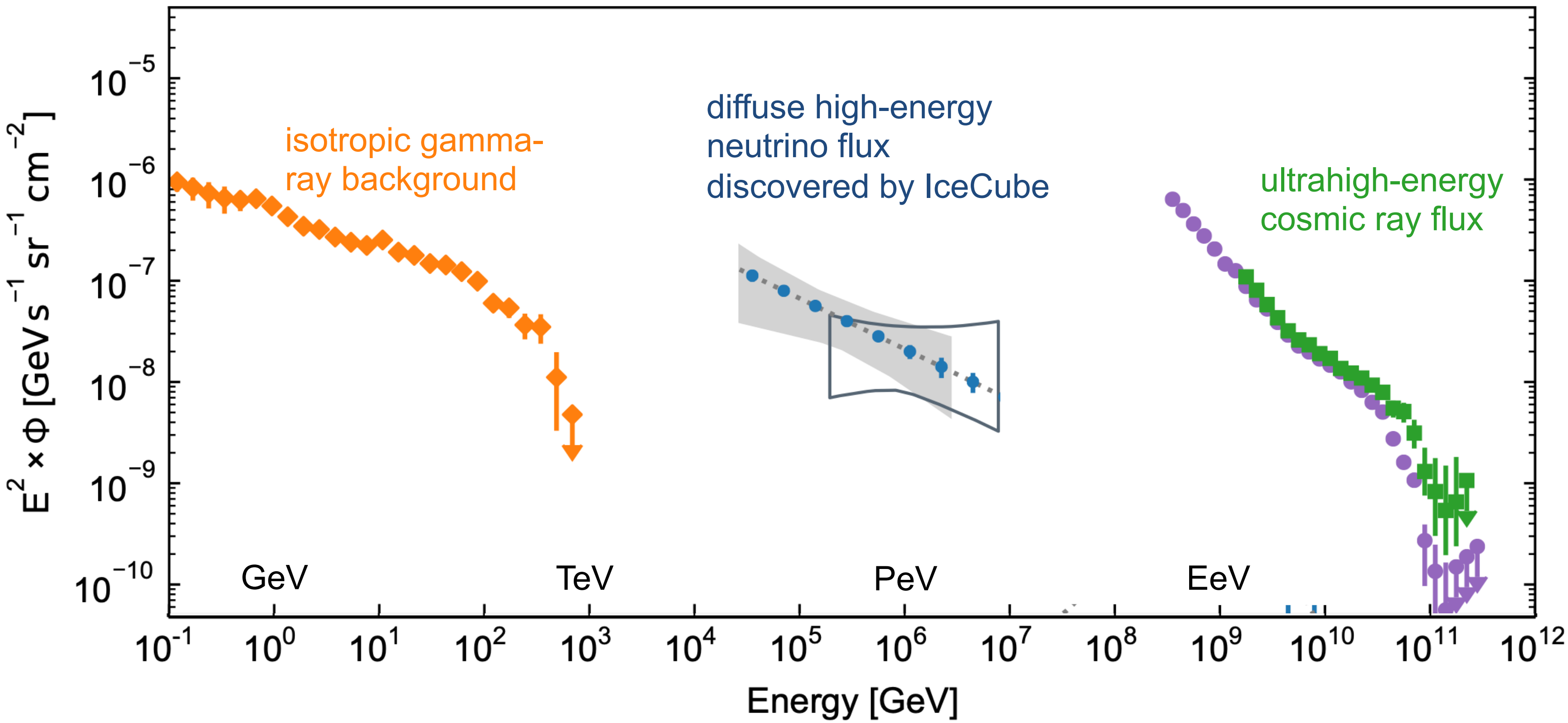
IPA, Vienna

2022 September 5

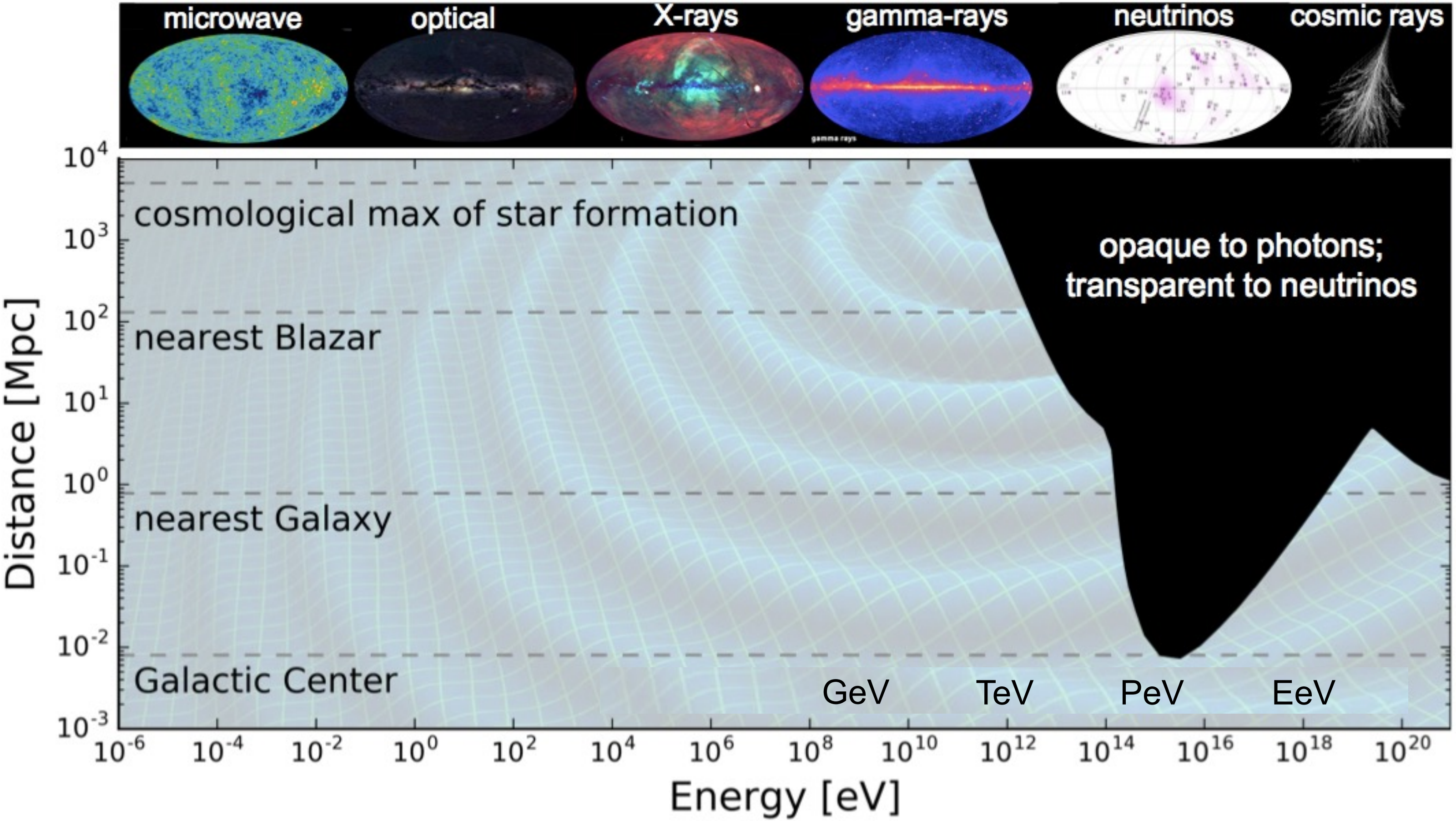
Cosmic Particle Accelerators – What, where, how?



Neutrinos are unique tracers of hadronic interactions – sites of CR interactions

Above TeV, universe starts to become opaque for photons, due to pair-production off background radiation fields

$\gamma + \gamma_{IR,CMB,radio} \rightarrow e^+ + e^-$



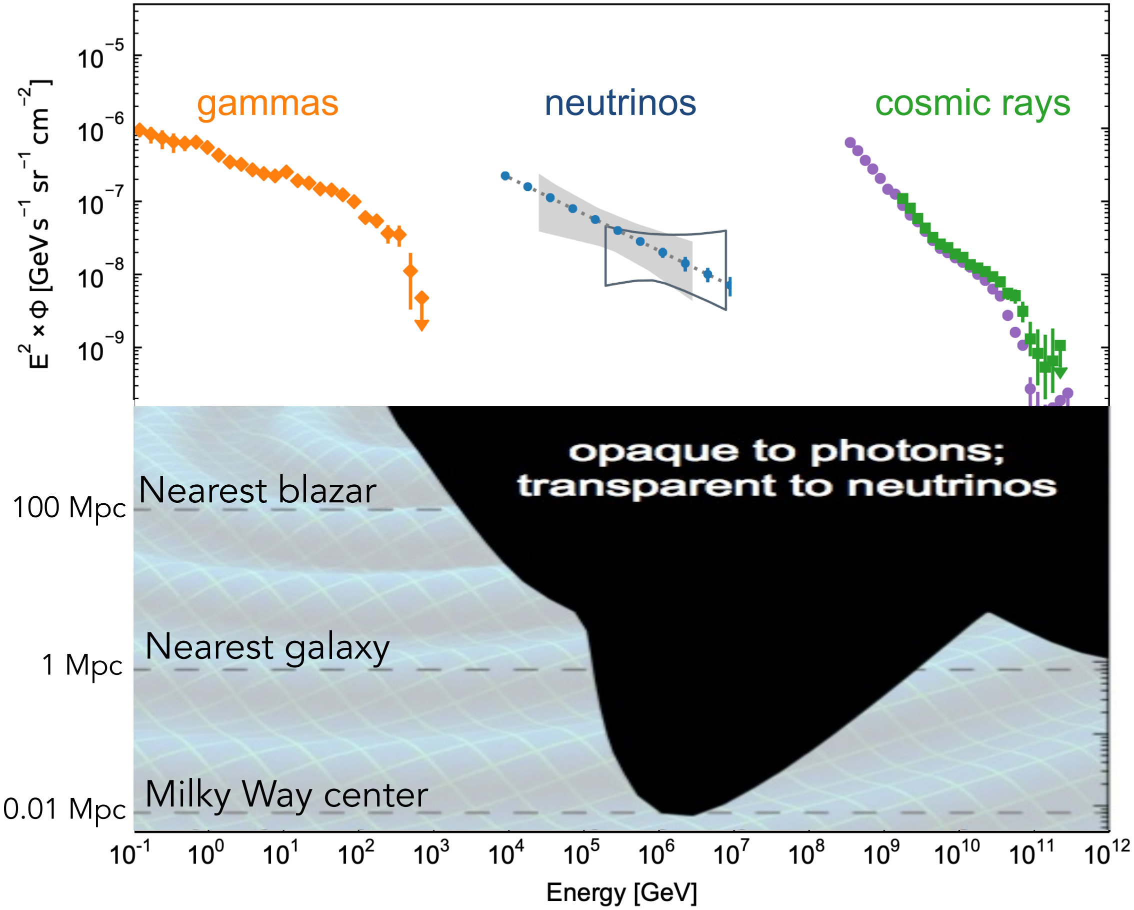
Neutrinos: Window onto the High Energy Universe

Multimessenger astronomy: complementary messenger to photons, probing higher energy range

Not only universe; sources may also be obscured:

High density of target material around cosmic accelerator =>

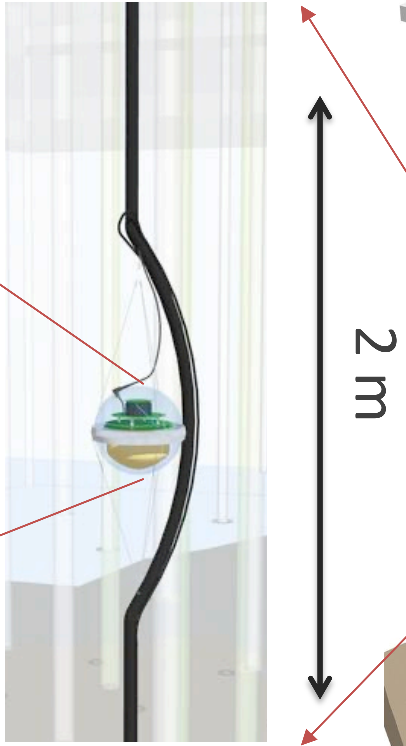
- more neutrinos produced
- more gammas absorbed

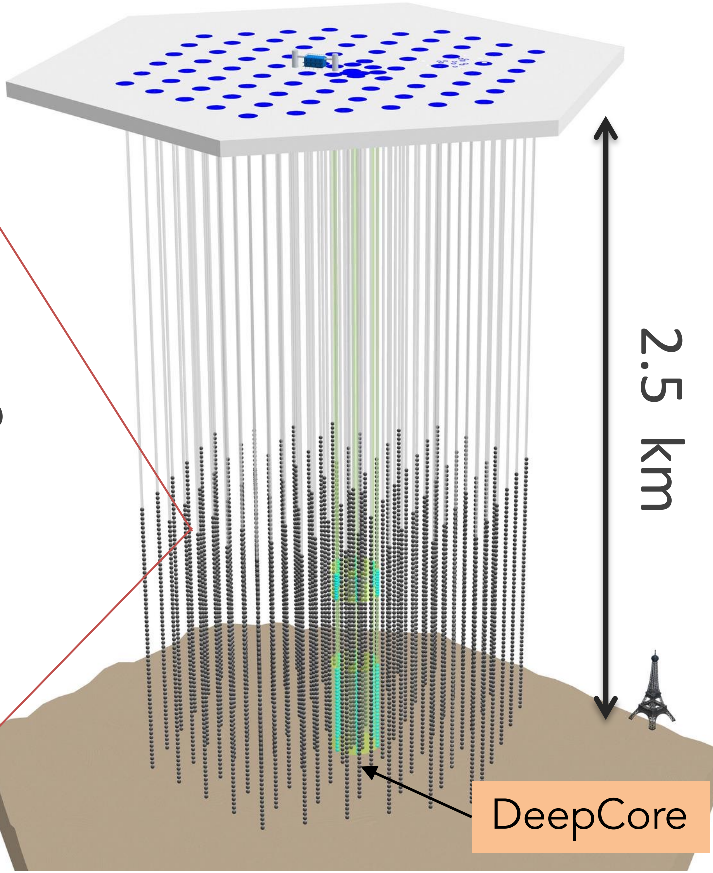


IceCube Neutrino Observatory

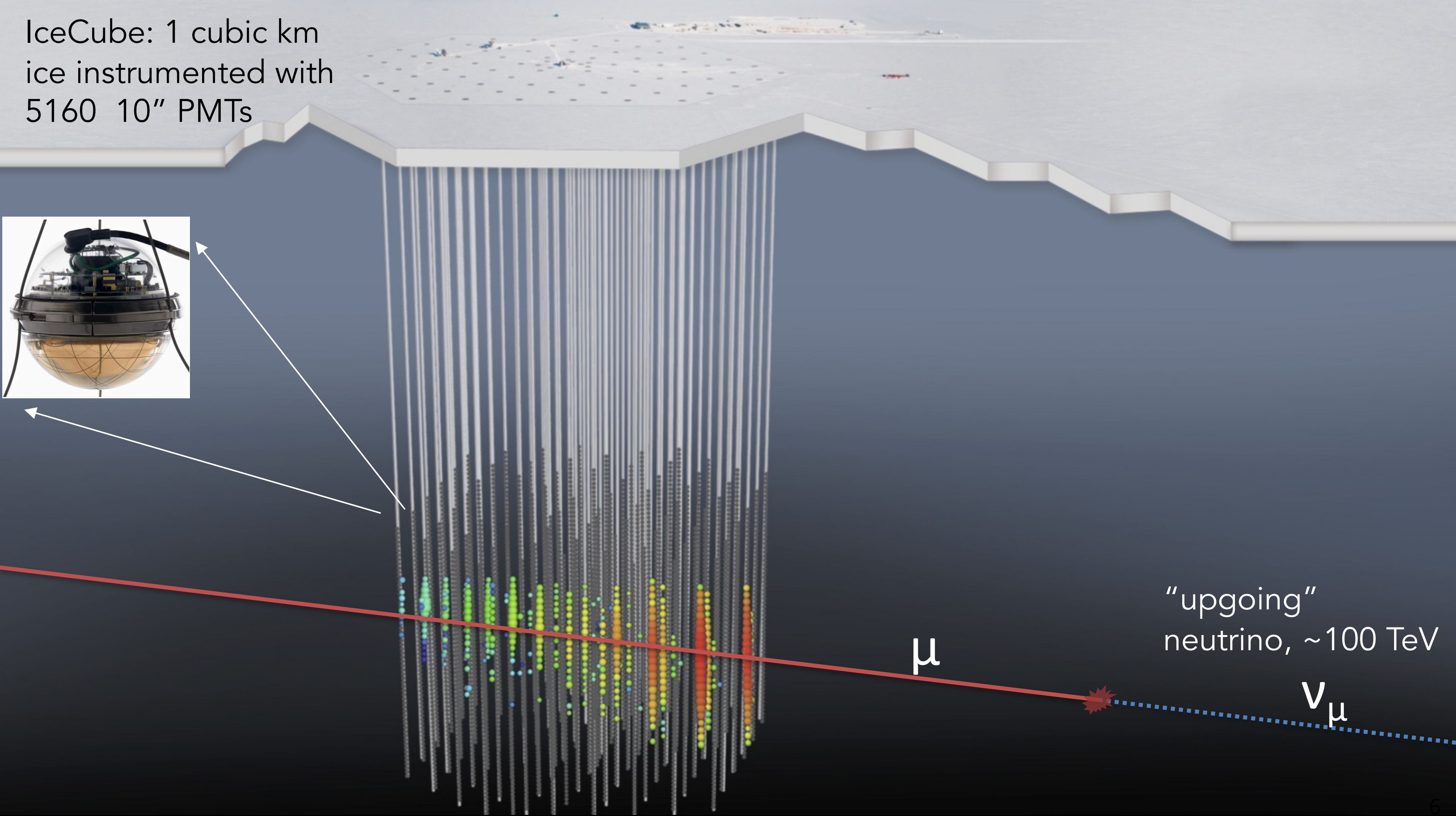
DOM: Digital Optical Module

10″ PMT Hamamatsu

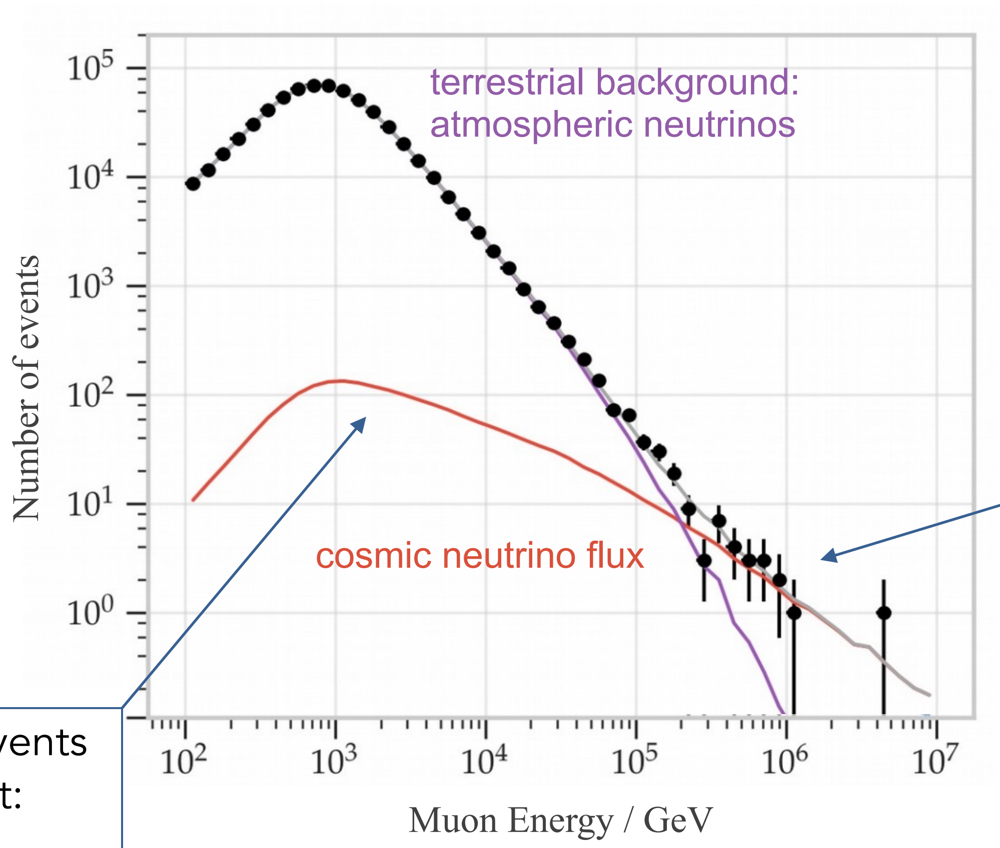




5160 DOMs spread over 1 km^3 = 1 Gigaton instrumented volume


IceCube: 1 cubic km
ice instrumented with
5160 10″ PMTs
μ
“upgoing”
neutrino, ~100 TeV
ν_μ

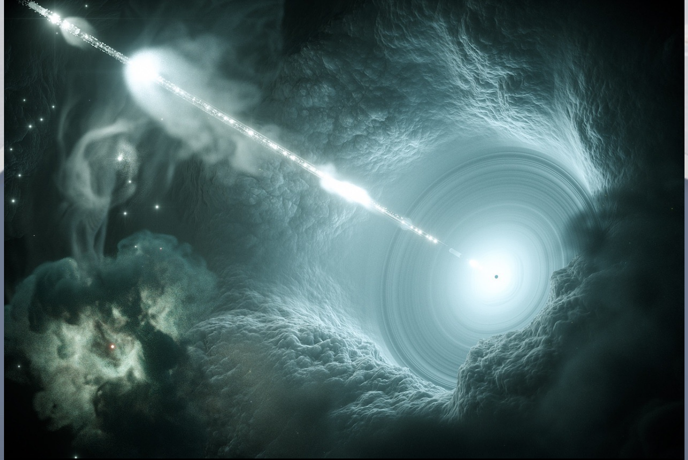
The Challenge for identifying sources



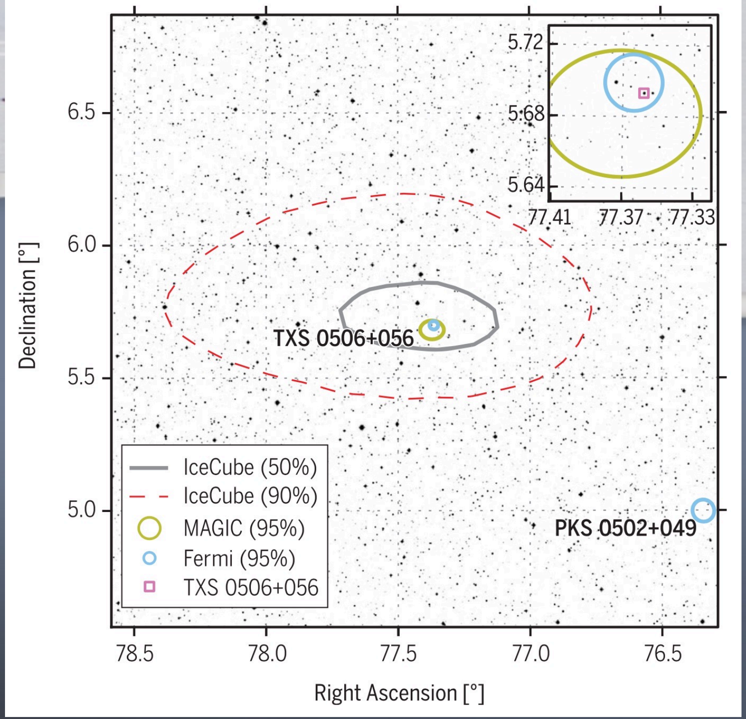
Muon Neutrino track events 2010-2018

These events can become individual high-energy neutrino alert evets

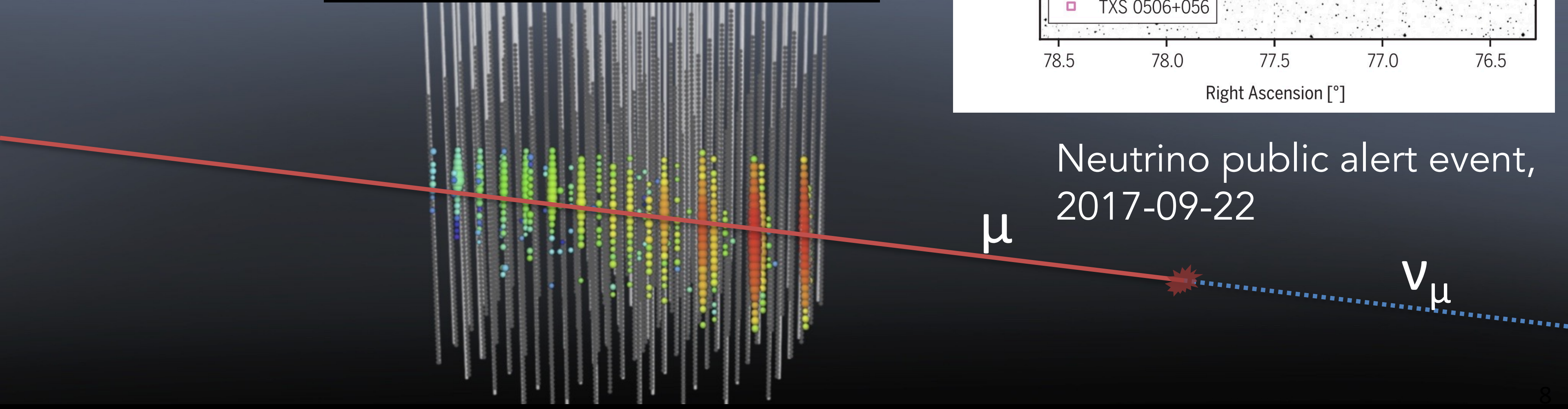
Requires cluster of events to become significant: point sources



Multi-messenger association with blazar galaxy TXS 0506+056

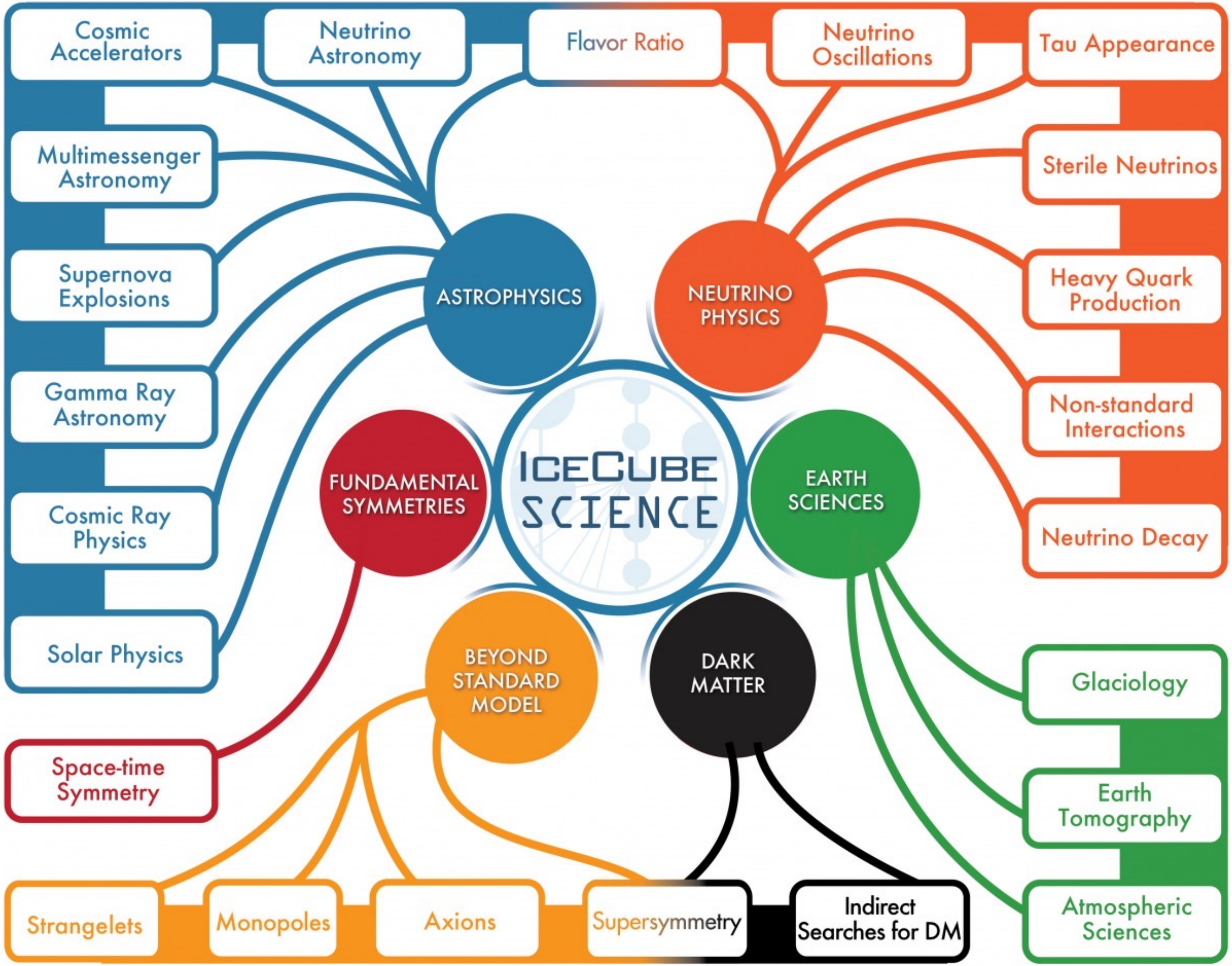


Neutrino public alert event, 2017-09-22

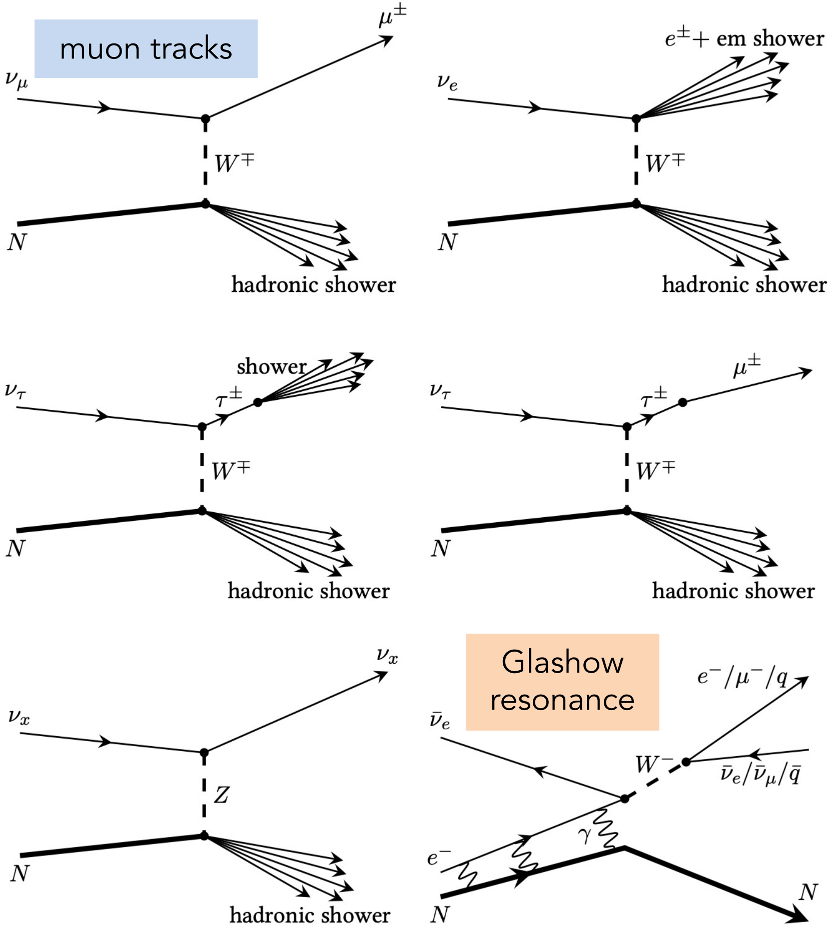


Neutrino Astronomy, and the quest to understand Nature’s most powerful particle accelerators, is the chief science driver.

Unique detector makes many further science topics accessible.



High-energy Neutrino Interaction Signatures

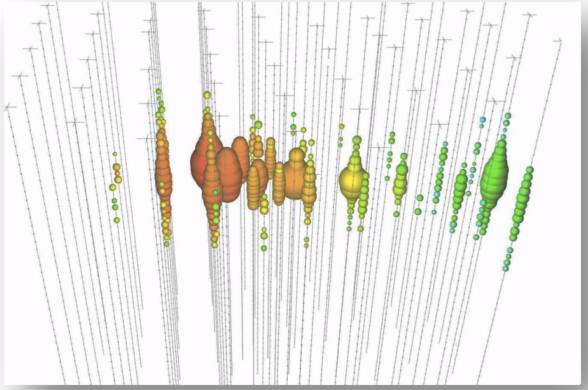


Michael Tino

Event Topologies

Tracks:

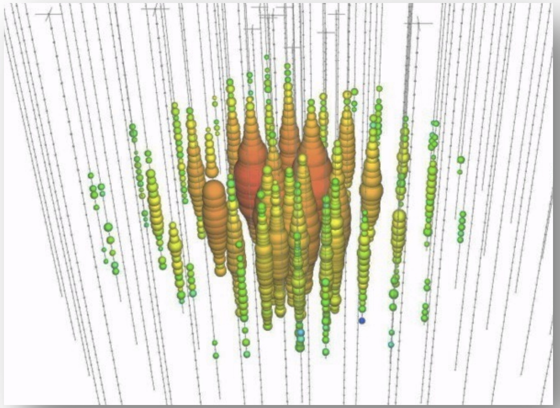
Charged-current muon neutrino interaction



Cascades:

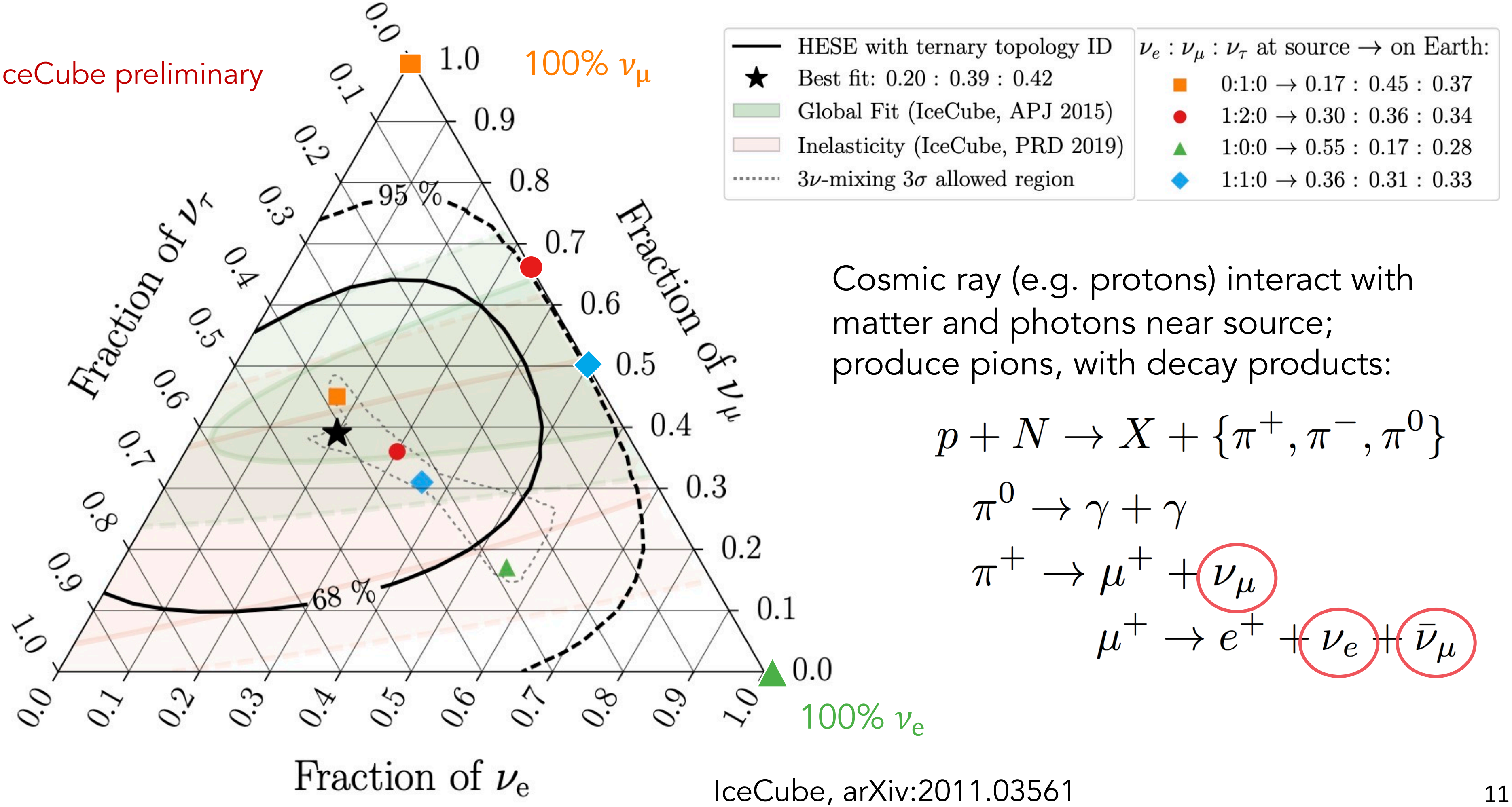
Nearly all other CC and NC neutrino interactions

Glashow resonance interactions (except if W decays to muon)



High-energy neutrino flavor ratio: Clues about origins

IceCube preliminary



Cosmic ray (e.g. protons) interact with matter and photons near source; produce pions, with decay products:

$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

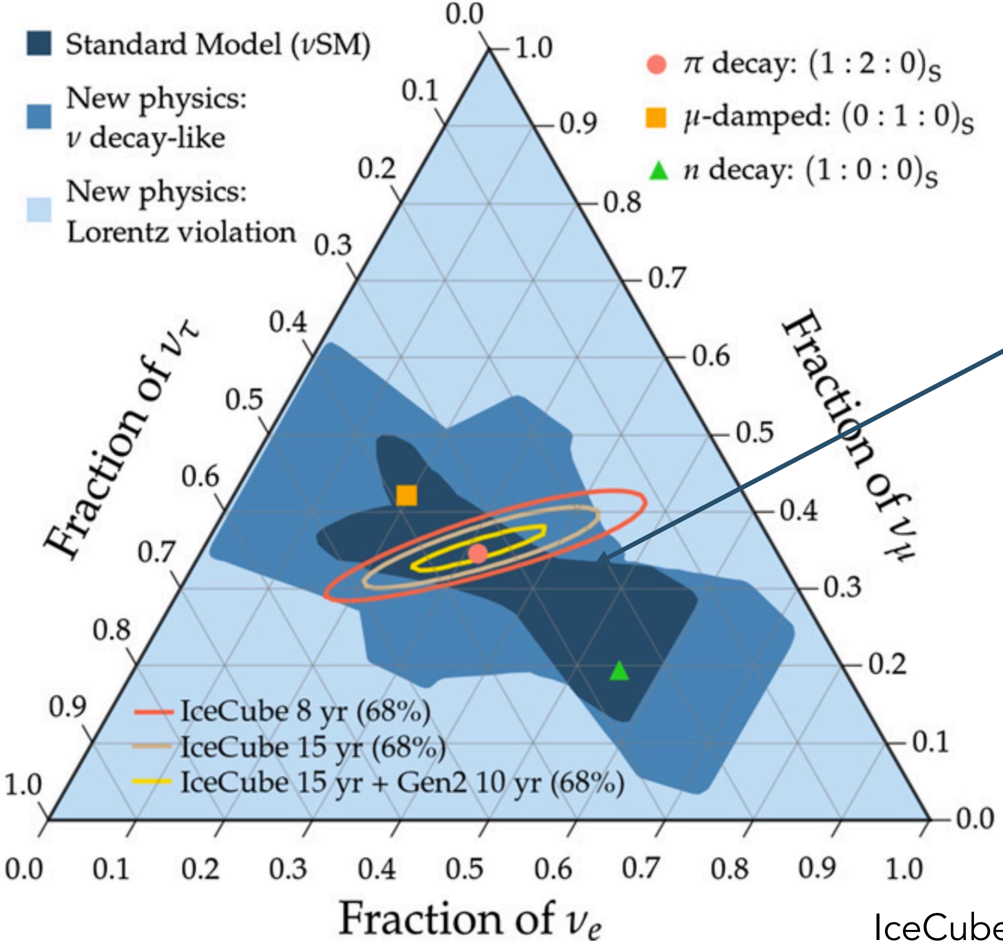
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

IceCube, arXiv:2011.03561

Range of flavor ratios allowed by SM is small

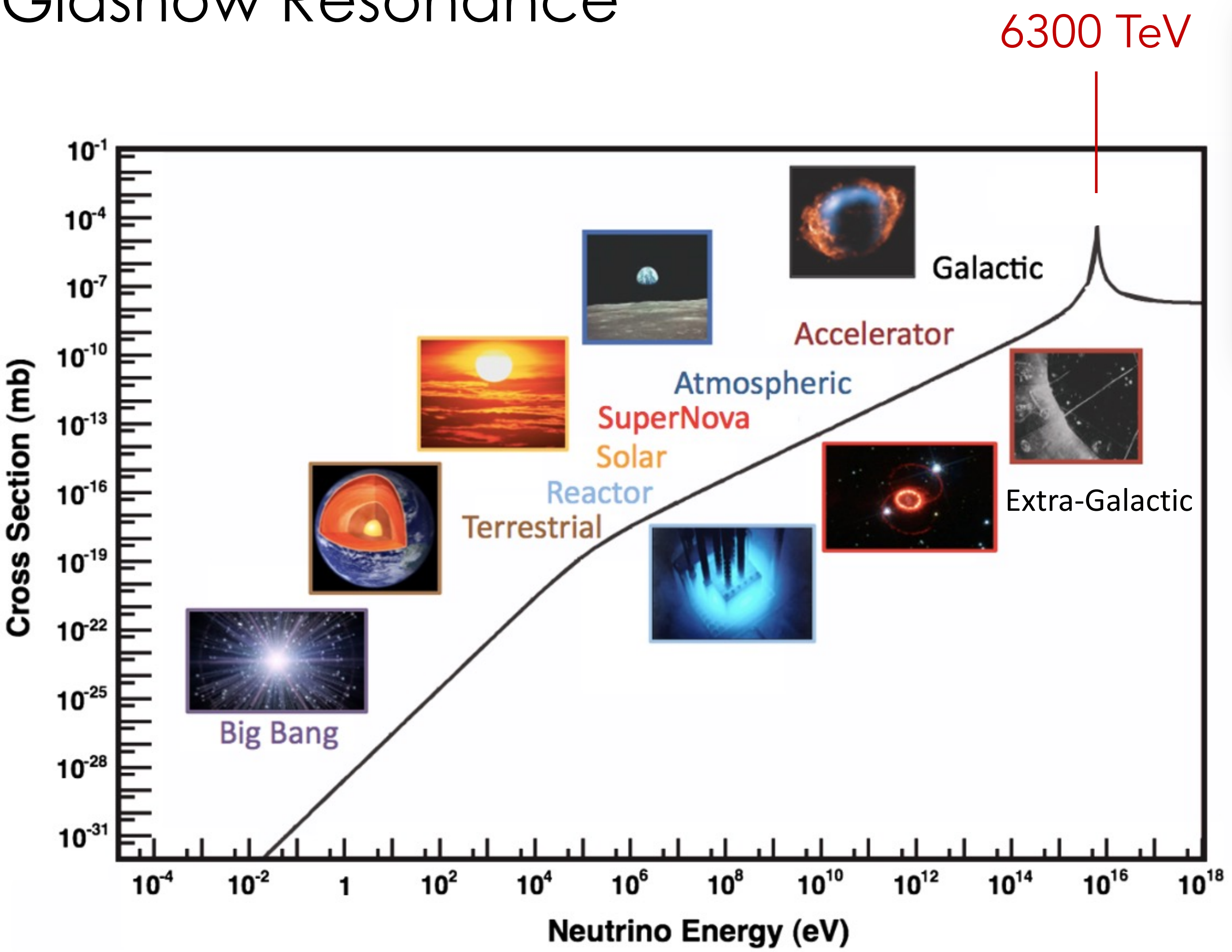


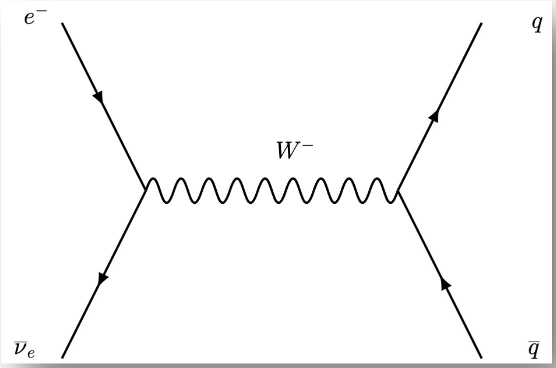
Regardless of initial flavor ratio at origin, after SM oscillations all flavor ratios converge to small range observed at Earth

Observing flavor ratio outside this area indicates BSM physics

IceCube-Gen2 (2021) J. Phys. G: 48 060501

Glashow Resonance





Cross section for <u>electron anti-neutrino</u> scattering on free electrons (as a function of nu energy)

Formaggio and Zeller, Rev.Mod.Phys. 84, 1307

Original idea in 1960 – Sheldon Glashow

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW*
Institute for Theoretical Physics, Copenhagen, Denmark

(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

THE interaction responsible for muon decay also permits an inelastic scattering of antineutrinos by electrons,

$$\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-.$$

With the conventional four-Fermion form of decay interaction, the cross section for this process is

$$\sigma_0 = (E/m_e) 1.5\times 10^{-45} \text{ cm}^2,$$

where E is the energy of an antineutrino incident upon

coupling strengths of the Z meson to muon and electron currents chosen equal (in accordance with universality) and of magnitude determined by the muon lifetime, we find

$$\tau_Z = (m_N/m_Z)^3 10^6 m_N^{-1} \hbar c^2 \text{ sec.}$$

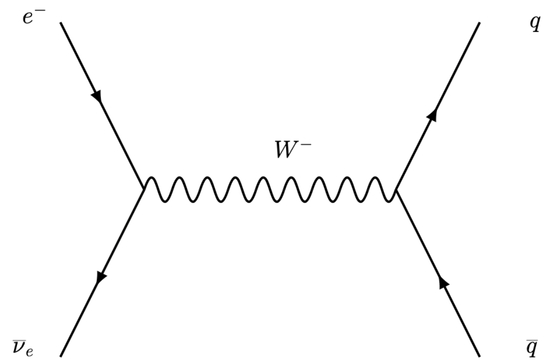
With $m_Z = m_N$, the energy of the incident antineutrino energy at the resonance is 9×10^{11} ev and the width of the resonance is 2×10^6 ev, while with $m_Z = m_K$, $E_0 = 2.3\times 10^{11}$ ev and $\Gamma = 1.5\times 10^5$ ev.

Although the natural width of the resonance is quite

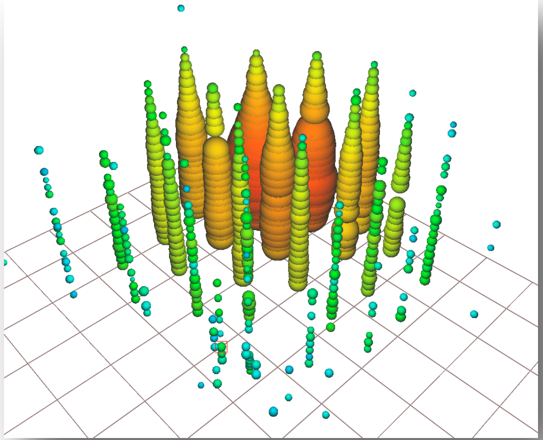
* National Science Foundation Post-Doctoral Fellow.

[1] A. Subramanian and S. D. Verma, Nuovo cimento 8, 572 (1959).

Nature **591**, 220–224 (2021)



Electron anti-neutrino at 6.3 PeV interacts with electron at rest, produces W^- boson



Detection of a particle shower at the Glashow resonance with IceCube

https://doi.org/10.1038/s41586-021-03256-1

Received: 28 July 2020

Accepted: 18 January 2021

Published online: 10 March 2021

Check for updates

The IceCube Collaboration*

The Glashow resonance describes the resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron[1], peaking at an antineutrino energy of 6.3 petaelectronvolts (PeV) in the rest frame of the electron. Whereas this energy scale is out of reach for currently operating and future planned particle accelerators, natural astrophysical phenomena are expected to produce antineutrinos with energies beyond the PeV scale. Here we report the detection by the IceCube neutrino observatory of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance. A shower with an energy of 6.05 ± 0.72 PeV (determined from Cherenkov radiation in the Antarctic Ice Sheet) was measured. Features consistent with the production of secondary muons in the particle shower indicate the hadronic decay of a resonant W^- boson, confirm that the source is astrophysical and provide improved directional localization. The evidence of the Glashow resonance suggests the presence of electron antineutrinos in the astrophysical flux, while also providing further validation of the standard model of particle physics. Its unique signature indicates a method of distinguishing neutrinos from antineutrinos, thus providing a way to identify astronomical accelerators that produce neutrinos via hadronuclear or photohadronic interactions, with or without strong magnetic fields. As such, knowledge of both the flavour (that is, electron, muon or tau neutrinos) and charge (neutrino or antineutrino) will facilitate the advancement of neutrino astronomy.

Beyond Confirmation – a tool to explore the Cosmos

Glashow resonance is the only probe of the $\bar{\nu}:\nu$ fraction of the cosmic neutrino flux

$\bar{\nu}:\nu$ fraction directly related to production mechanism of astro. neutrinos

At or near sources, cosmic rays (mostly protons) interact either with ambient matter (mostly protons) and / or radiation (gammas)

Generic model expectation for $\bar{\nu}:\nu$ ratio at Earth (after flavor oscillations in route):

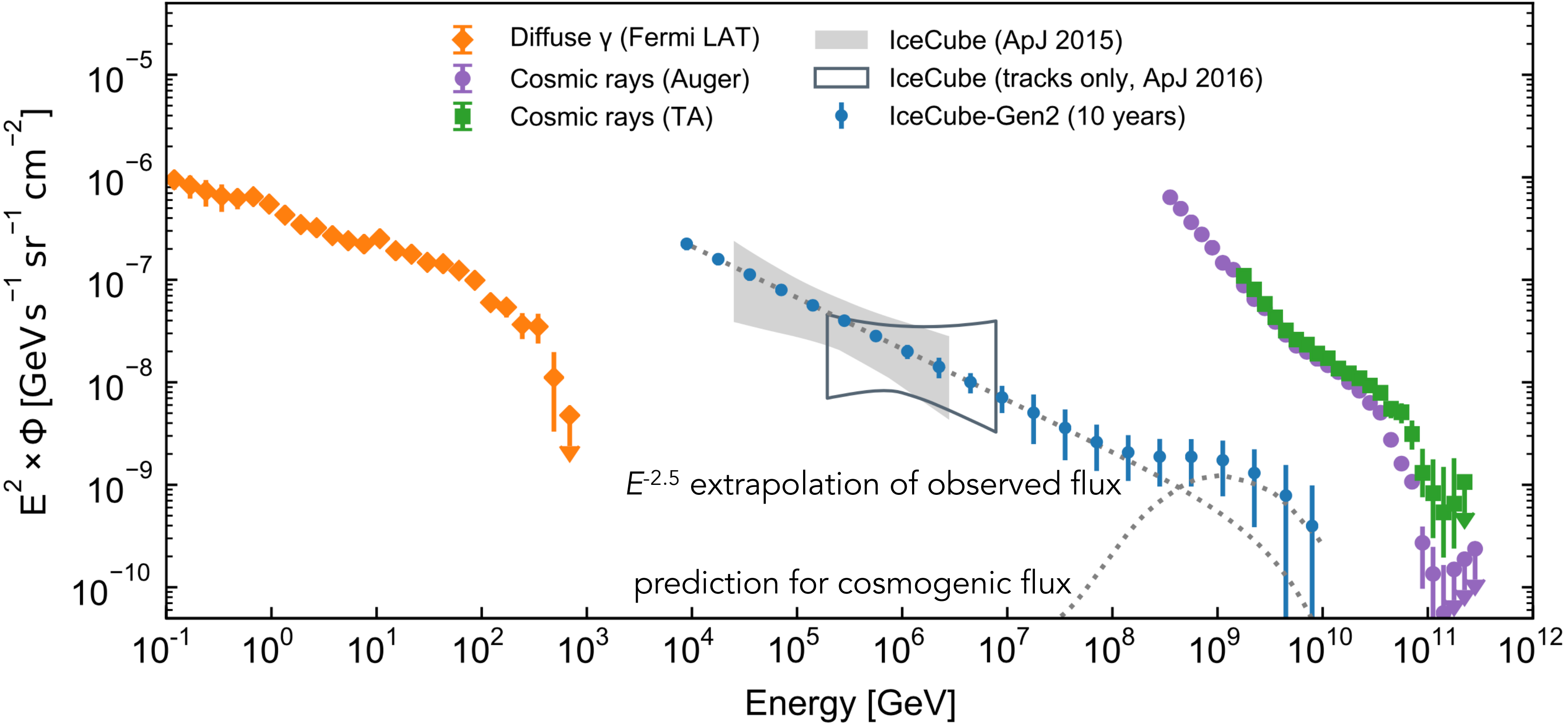
pp: $\bar{\nu}_e : \nu_e = 1 : 1$ — 1.55

$p\gamma$: $\bar{\nu}_e : \nu_e = 1 : 3.5$ — 0.69

(1.55 and 0.69: expected GR events in current analysis)

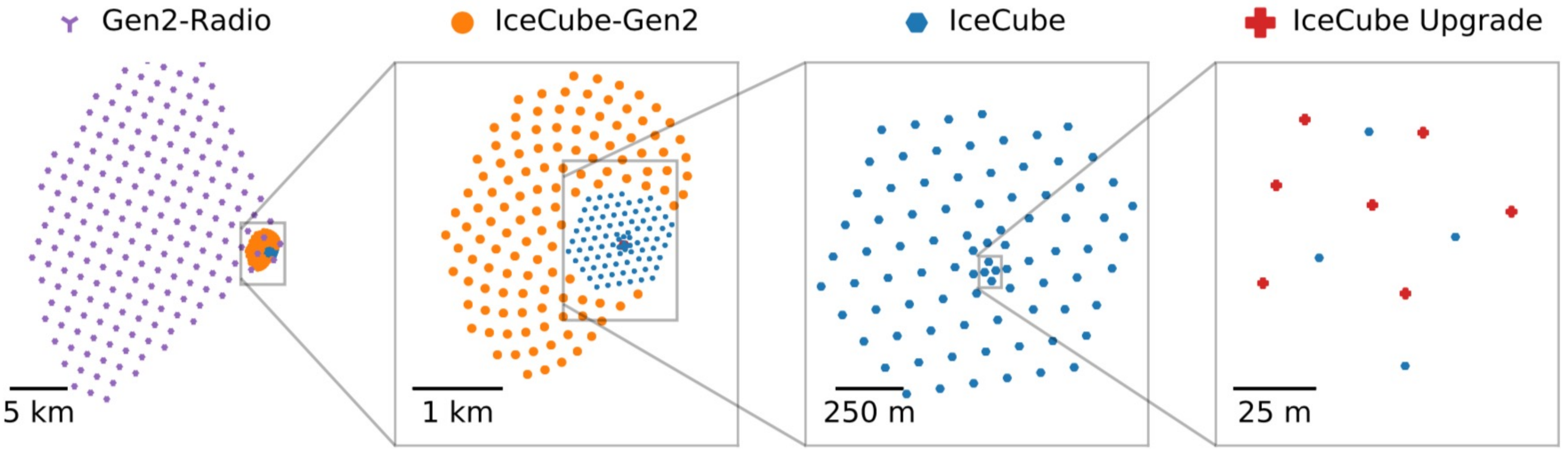
$p\gamma$: $\bar{\nu}_e : \nu_e = 0 : 1$ (strong B fields, muon synchrotron losses before decay)

Towards the Future: IceCube-Gen2



IceCube-Gen2 (2021) J. Phys. G: 48 060501

IceCube Present & Future



Build: after Upgrade

Completed: 2011

Build: 2025-26

IceCube-Gen2

Neutrino Astronomy from TeV to EeV

IceCube Upgrade

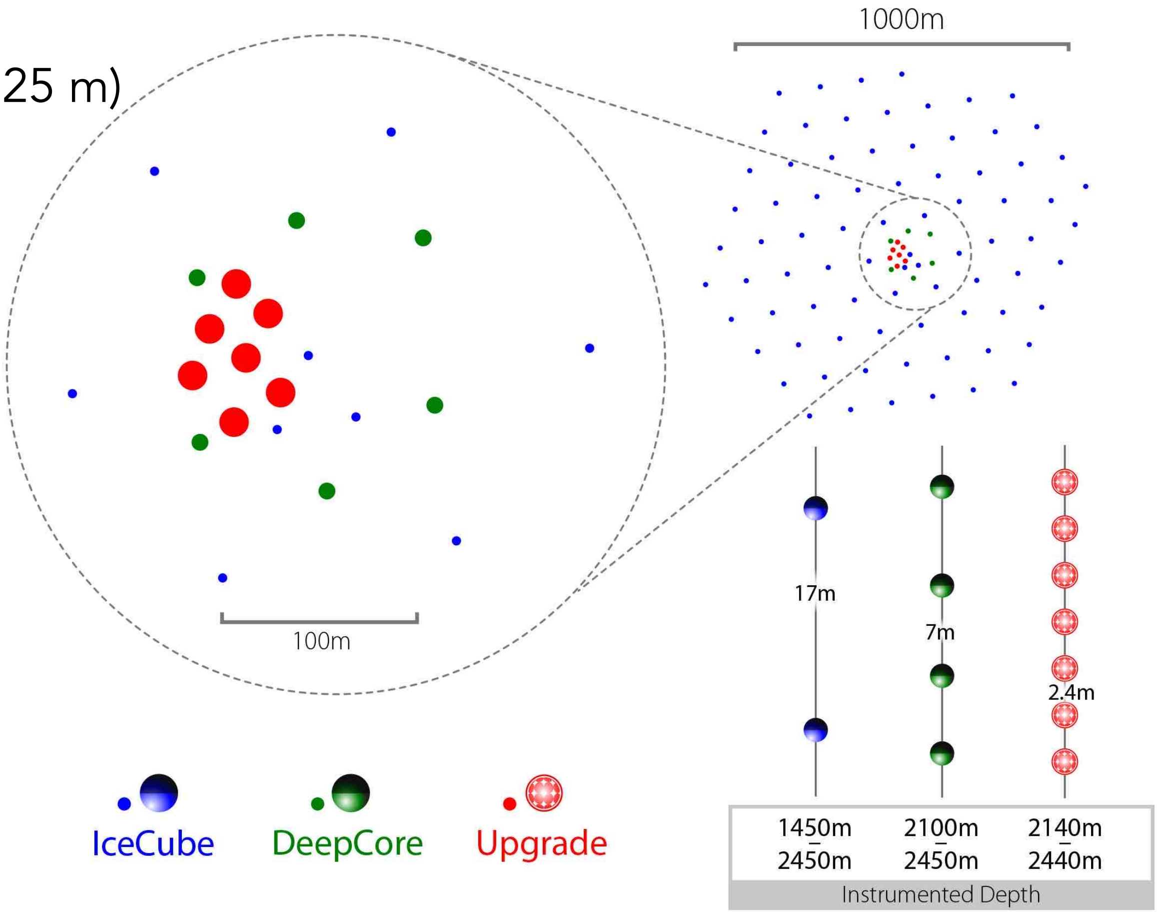
IceCube Upgrade 2025/26

7 new strings, close together (~25 m)

Goals:

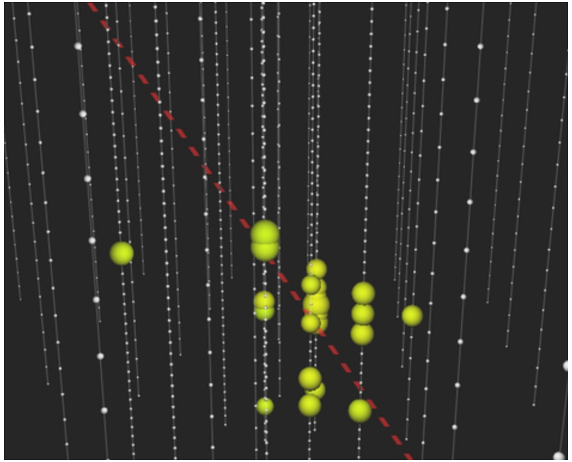
- Neutrino oscillation physics
- New calibration devices
  - Better detector/ice modelling will allow re-analysis of all existing IceCube data
- R&D for IceCube-Gen2

Fully funded; delayed by Covid

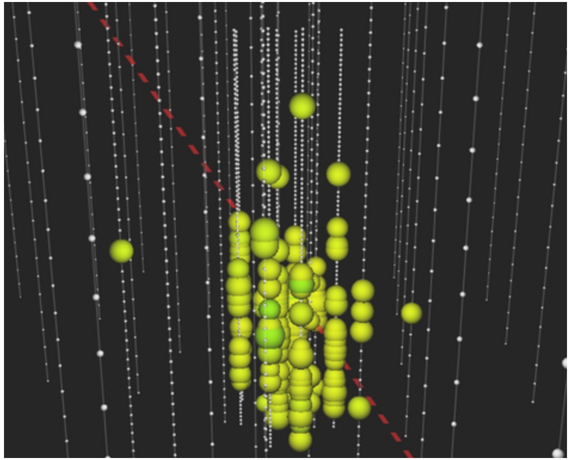


IceCube Upgrade: improve event rate and reconstruction

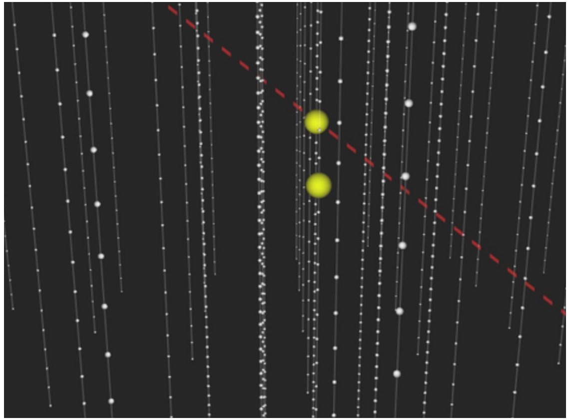
30 GeV event in DeepCore



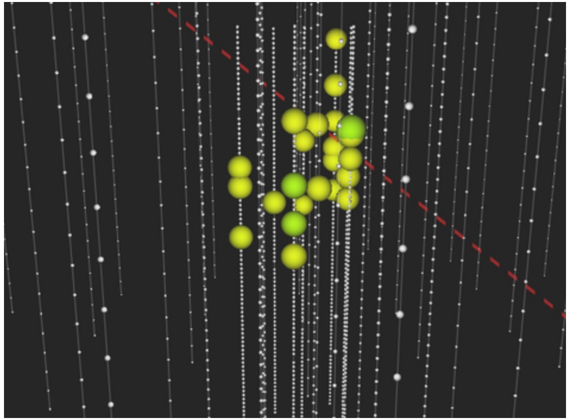
+ Upgrade =



4 GeV event in DeepCore



+ Upgrade =

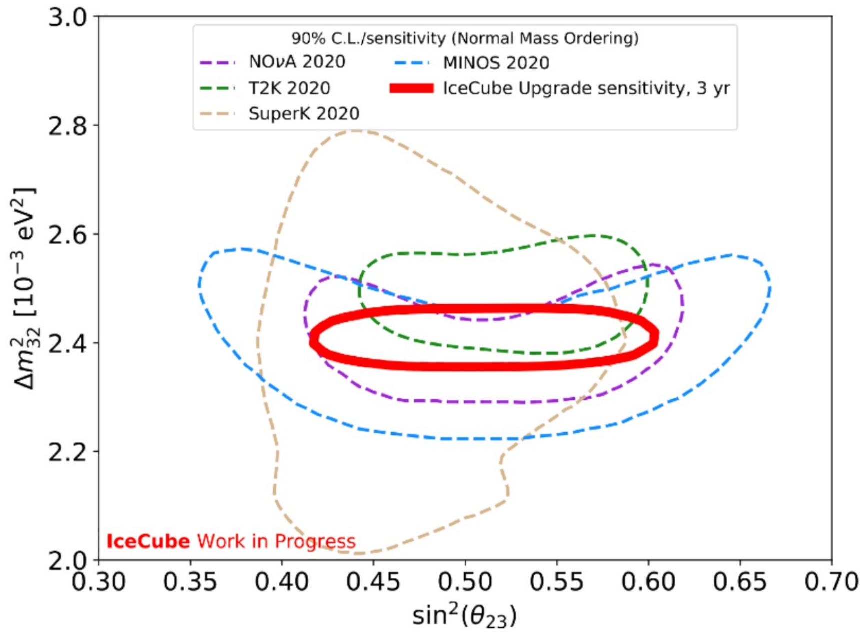


Upgrade Performance

Conservative experimental choices still illustrate potential of IceCube Upgrade for physics

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

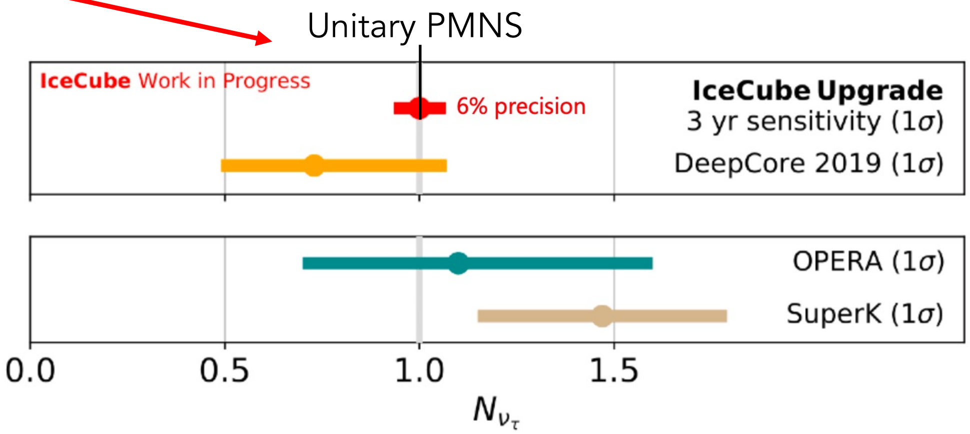
tau neutrino appearance -- test unitarity of PMNS mixing matrix



~6% N_{ν_τ} resolution with 1-year data

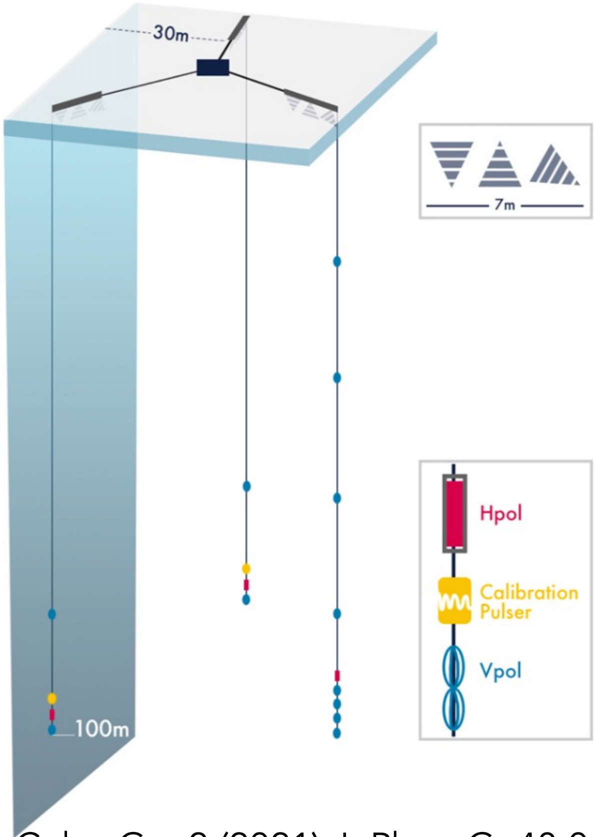
Excludes improvements from new recon-struction techniques, improved detector systematic uncertainties, better flux treatment, and no combination of 10+ years of DeepCore data

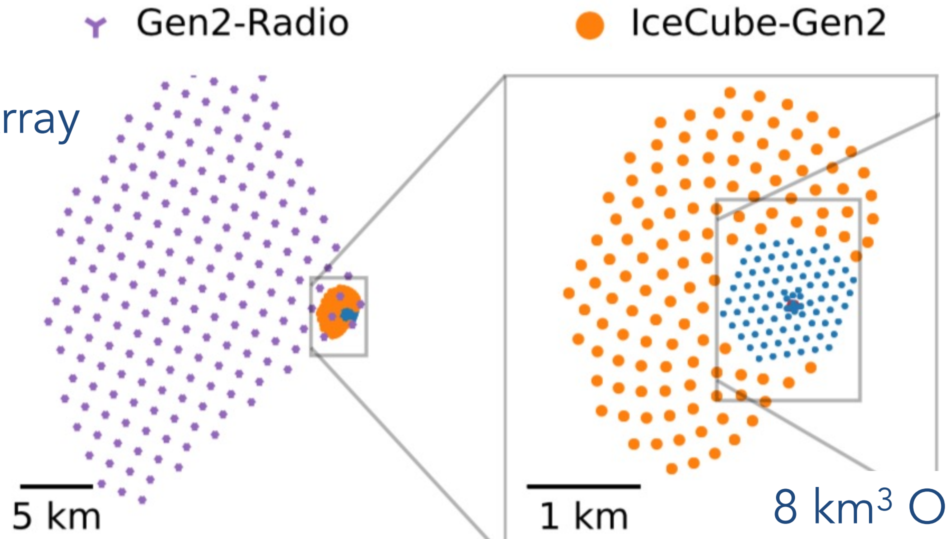
see talk by J. Koskinen, TeVPA 2022



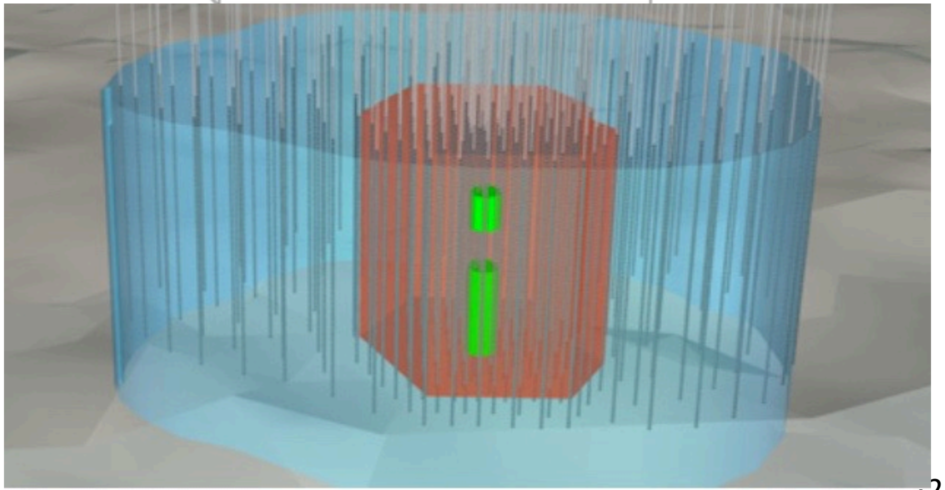
IceCube-Gen2

$500\ km^2$ Radio Array





$8\ km^3$ Optical Array



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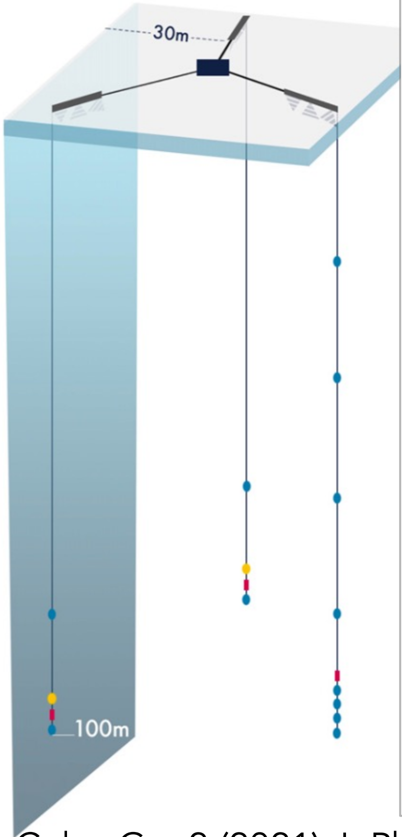
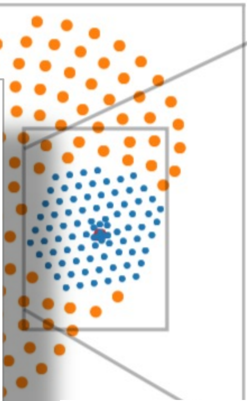
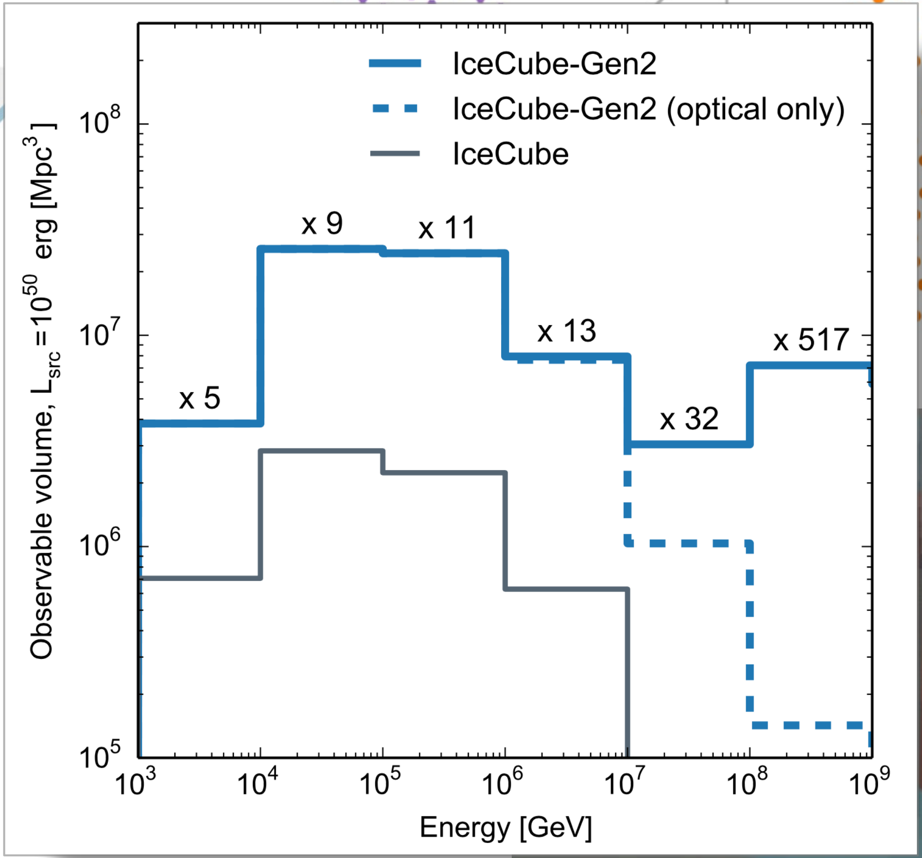
IceCube-Gen2

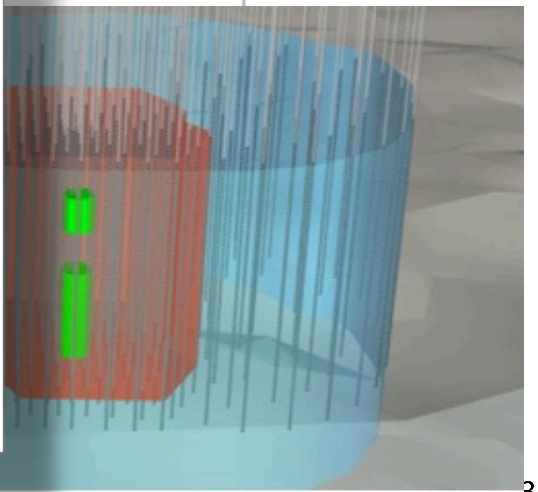
500 km² Radio Array







8 km³ Optical Array



IceCube-Gen2 (2021) J. Phys. G: 48 060501

Summary

High-energy neutrino flux discovered – Neutrino window on the Universe is opening

Evidence of neutrino emission from blazars and active galactic nuclei:
If confirmed, finally identifies (some of!) the cosmic accelerators

From GeV (e.g. unitarity tests) to PeV (e.g. Glashow Resonance):
IceCube is unique facility for probing neutrino physics and particle physics

Precision ν measurements; characterizing cosmic sources; searching up to UHE:
Bright neutrino future for IceCube Upgrade and IceCube-Gen2