Status of (Ultra-) High-Energy Neutrinos

Nathan Whitehorn
UCLA
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Goals of the Field

New ground!
Always room for surprises

GeV+:

- **Measurement of θ_{23}**
- **Indirect detection of dark matter**

TeV+:

- **Very forward p-p physics**
- **Sterile neutrino searches**

PeV+:

- **Direct detection of neutrinos from (ultra-)high-energy cosmic ray sources (concealed, internal dynamics)**
- **Probes of neutrino propagation over long distances**

EeV+:

- **Indirect detection of distant high-energy proton sources through pion production on CMB**

Measurement Techniques

Large scale anisotropies:

- **Measurement of θ_{23}**
- **Sterile neutrino searches**

Astrophysical point sources:

- **Particle acceleration mechanism/source identification**
- **Indirect detection of dark matter**

Energy spectrum:

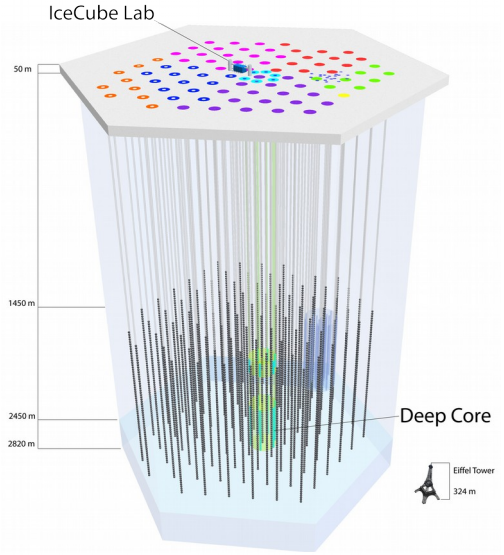
- **Direct detection of neutrinos from (ultra-)high-energy cosmic ray sources (concealed, internal dynamics)**
- **Very forward p-p physics**
- **Probes of neutrino propagation over long distances**

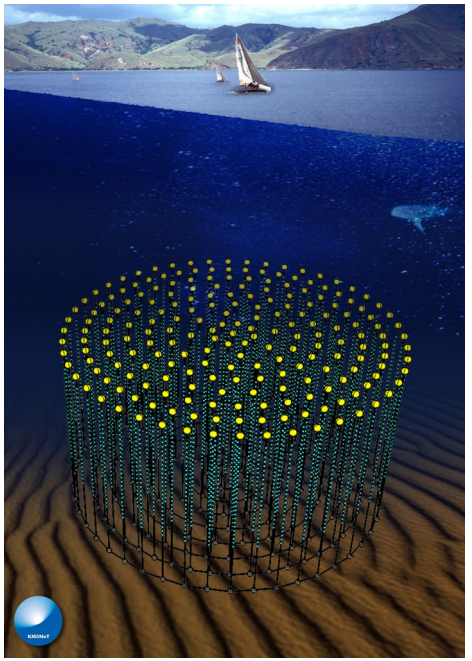
Flavor:

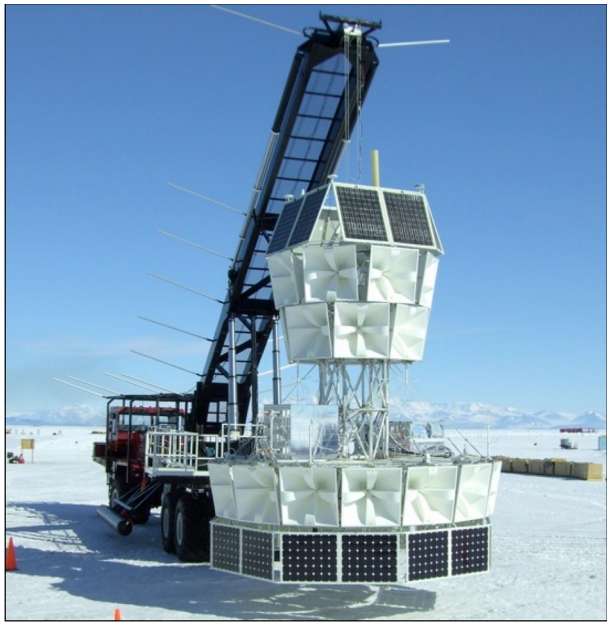
- **Sterile neutrino searches**
- **Measurement of θ_{23}**
- **Astrophysical particle acceleration mechanism**

Natural Detectors: the Size Frontier

Common theme: flux low at > 1 TeV, need giant natural detectors







IceCube(-Gen2), KM3net, Baikal/GVD, ANITA, ARA, ARIANNA, ANTARES

Two Techniques

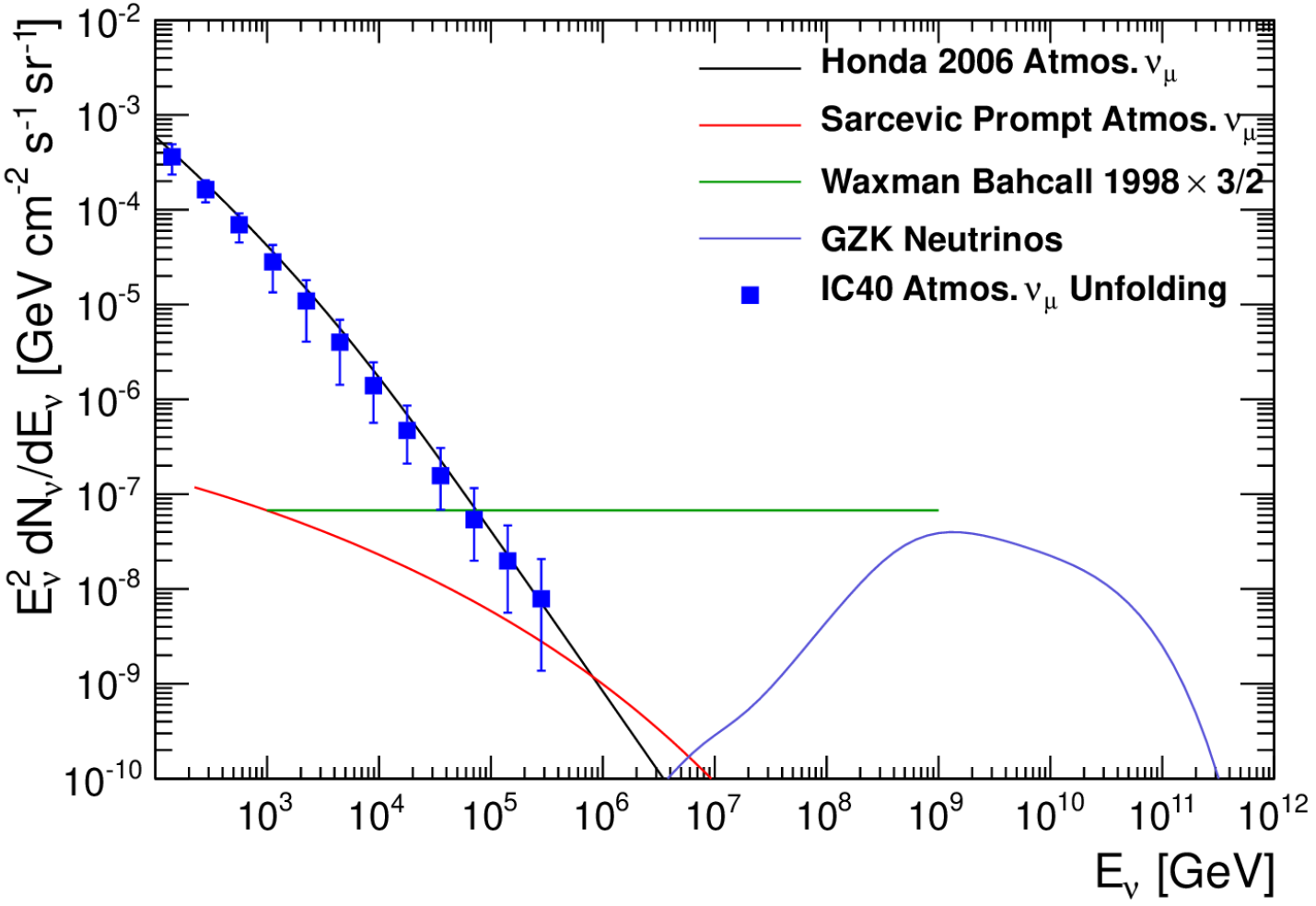
Water/Ice Cherenkov

- **Energy threshold of 10s of GeV**
- **Clear, low-background water**
- **Instrumentation spacing < ~150 meters**

Askaryan Radio

- **Energy threshold of 10^{16} eV**
- **Low radio noise site**
- **Instrumentation spacing of 10s of km**

Signal and Background in a Neutrino Telescope



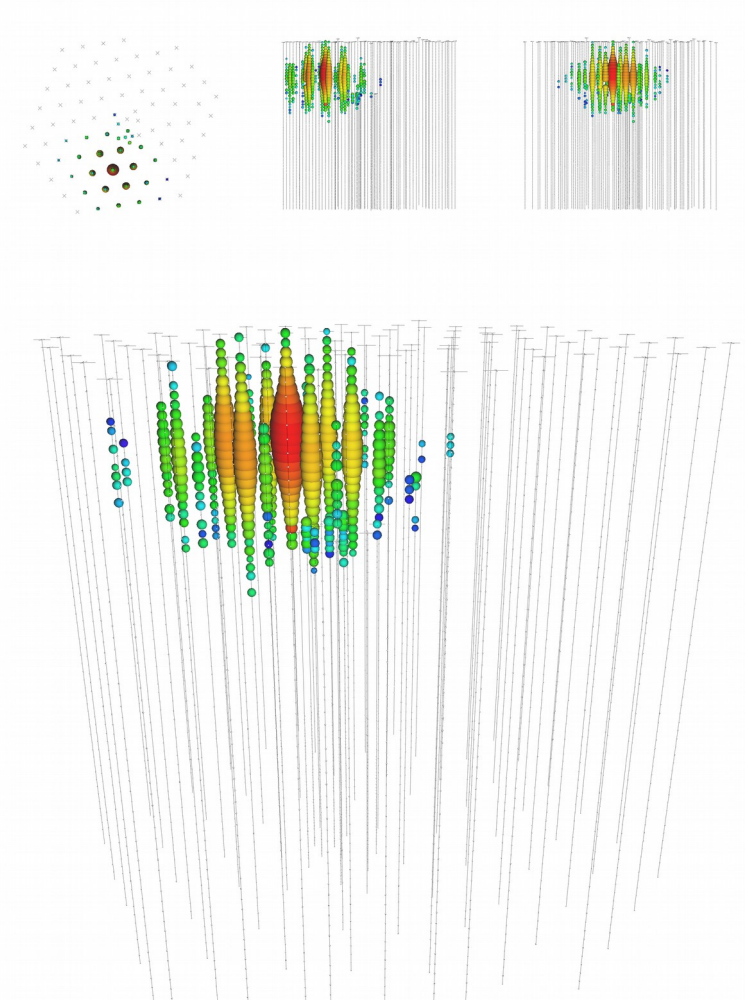
Status of current instruments

First generation mature:

- **IceCube (completed 2011)**
- **ANTARES (2008)**
- **ANITA (flights 2006-2016)**

Second generation coming:

- **IceCube-Gen2 (initial upgrade work started, mid-2020s)**
- **KM3Net (under construction)**
- **ARA/ARIANNA (construction)**



Benchmark Results

Signals of many kinds:

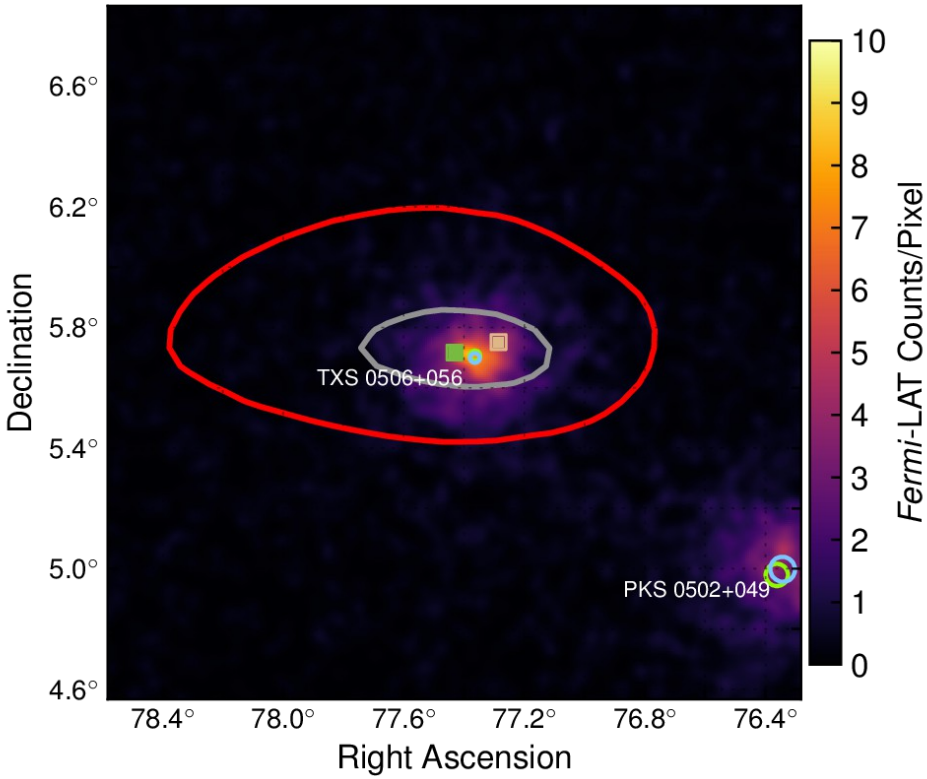
- **Diffuse TeV+ background (2014)**
- **Astrophysical sources (likely 2018)**
- **Neutrino oscillations (2012)**

Constraining limits:

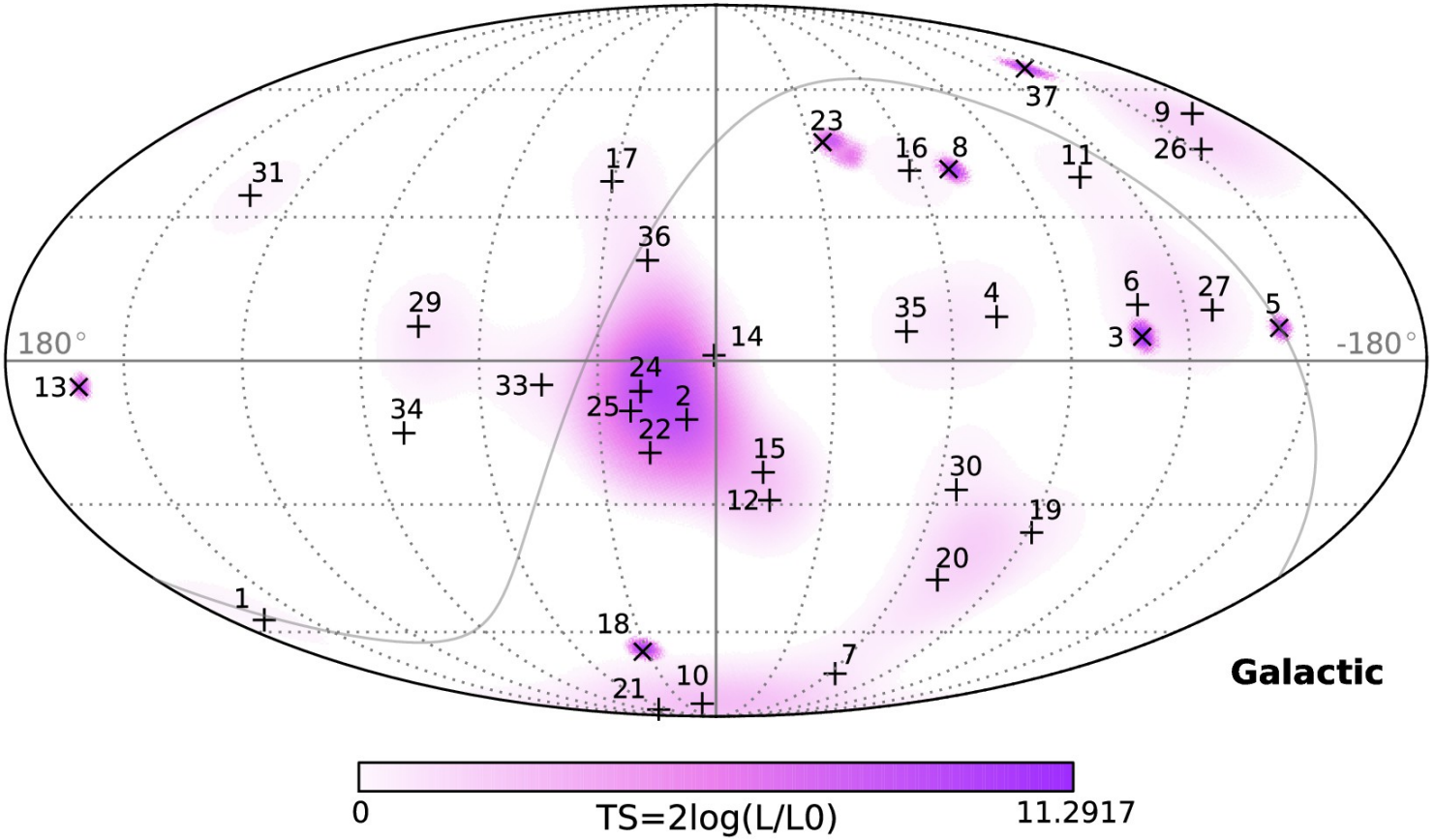
- **Sterile neutrinos from matter effects**
- **Dark matter searches pushing down**
- **Ultra-high-energies (10^{19}) excluding broad swath of models**

Mystery results:

- **Strange ANITA events**

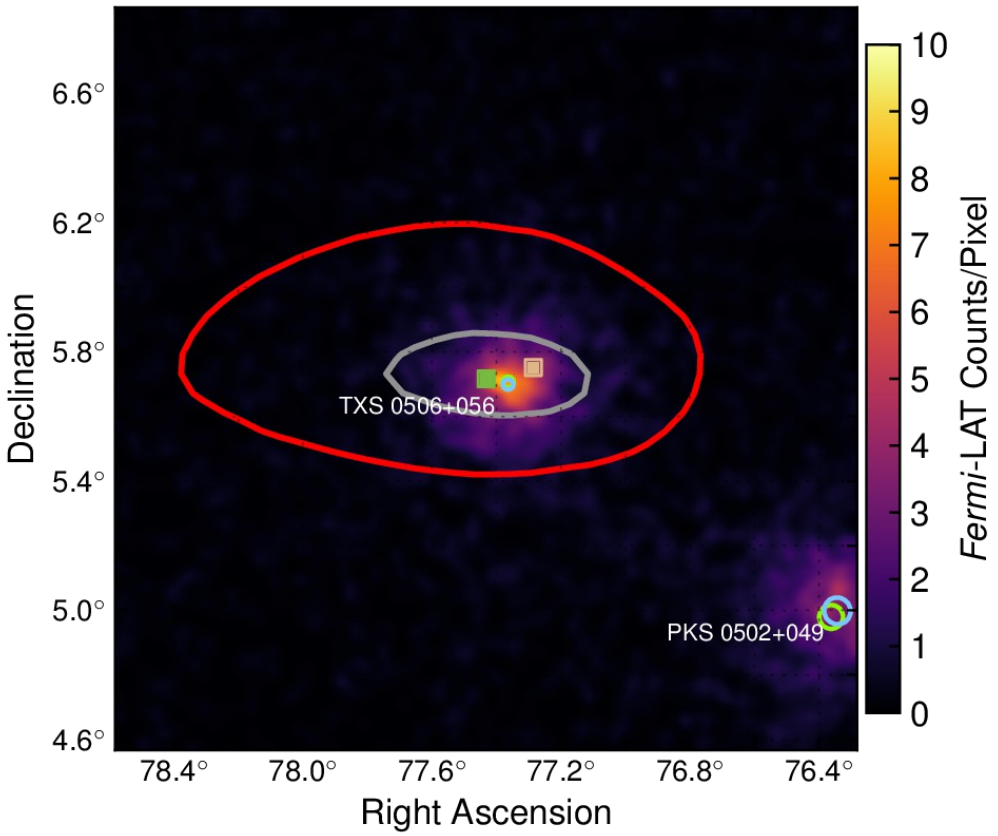


Status of Astrophysical Neutrinos



First view of the neutrino sky (2013)! Lots of sources everywhere!

Status of Astrophysical Neutrinos



Point Source (2018)

- **First hint of anisotropy**
- **At threshold**
- ***Very* far away**
- **Dim in gamma rays**
- **Why this one?**

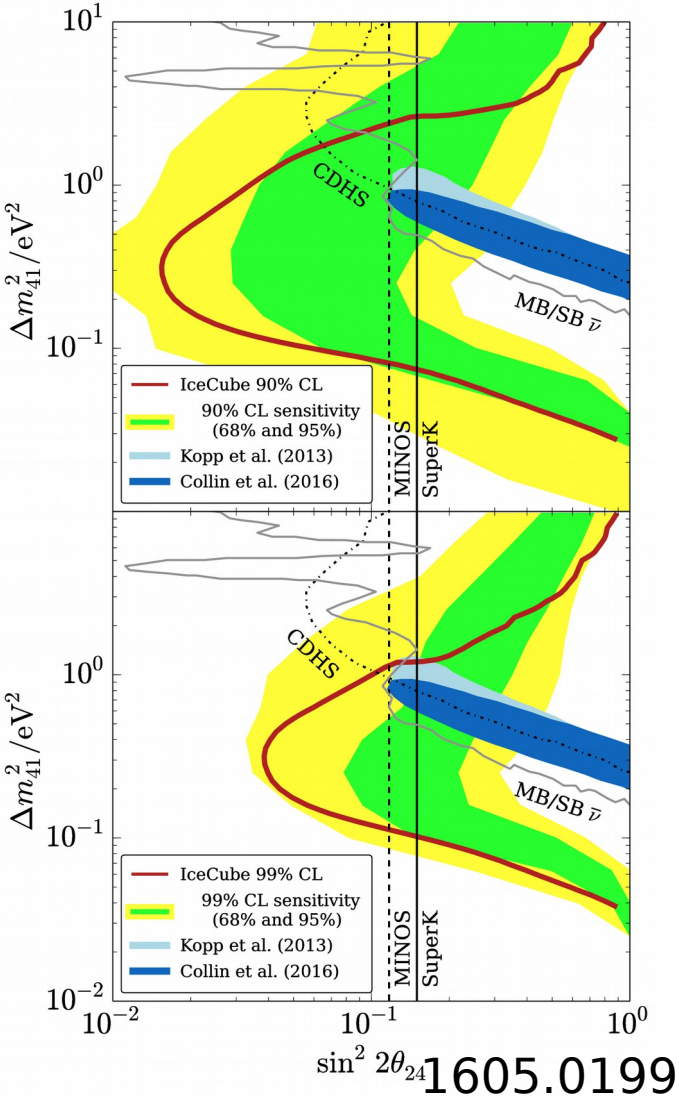
Limited by statistics and angular resolution

Status of Neutrino Physics at High Energies

Major questions:

- **Oscillation Parameters**
- **Steriles**
- **Exotics: most relativistic particles ever seen, longest path length for neutrinos**

Limited by energy and angular resolution and statistics



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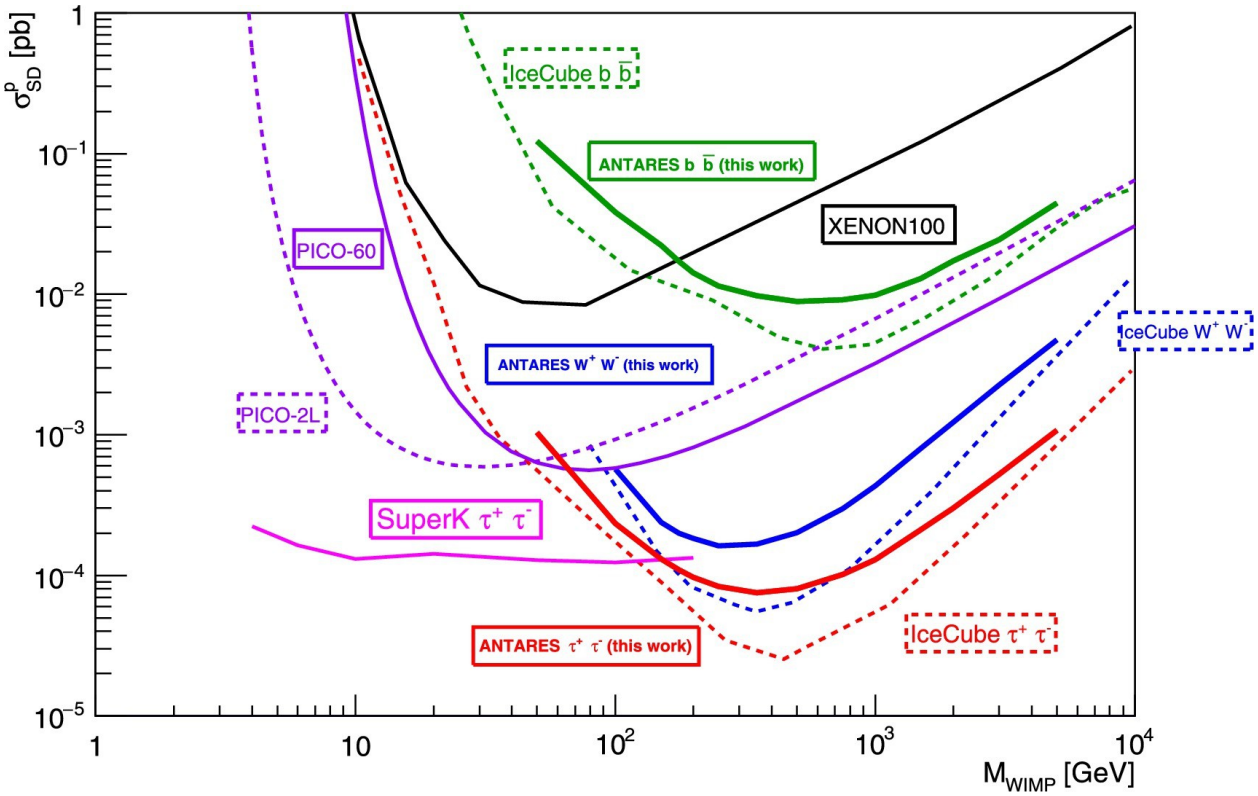
Status of Dark Matter Searches

- **Unique ability to probe high-mass dark matter (indirectly)**
- **Particularly sensitive to spin-dependent interactions in the Sun**



ANTARES, PLB 2016

Limited by angular resolution, statistics

New Questions

With signals come new questions:

- **Where is the GZK flux?**
- **What makes the diffuse TeV background? How?**
- **Why is the brightest spot on the sky 4 billion light years away?**
- **What (if anything) happens to neutrinos when they fly for a billion years?**
- **How we increase precision of the measurements?**

Very different focus for next generation of detectors!

Keys to improve: the measurement regime

Effective area

- **1st generation targeted the first events**
- **More required, scaling between sqrt(N) and linear**
- **1 km³ → 5-10 km³**

Angular resolution

- **Limits source searches (dark matter and astrophysics)**
- **Scaling linear**
- **.5 degree → .1 degree**

Systematics

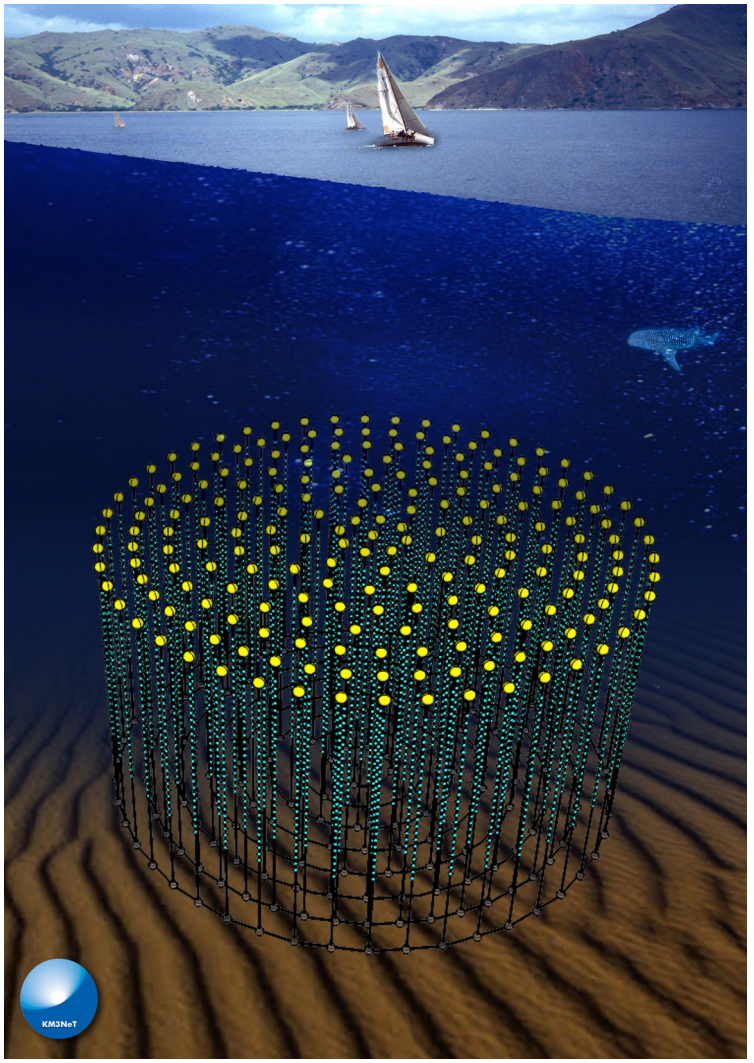
- **Limits spectral measurement, low energies**

Flavor ID

- **Powerful constraint on particle physics, source dynamics**
- **Better reconstruction, more fine-grained data**

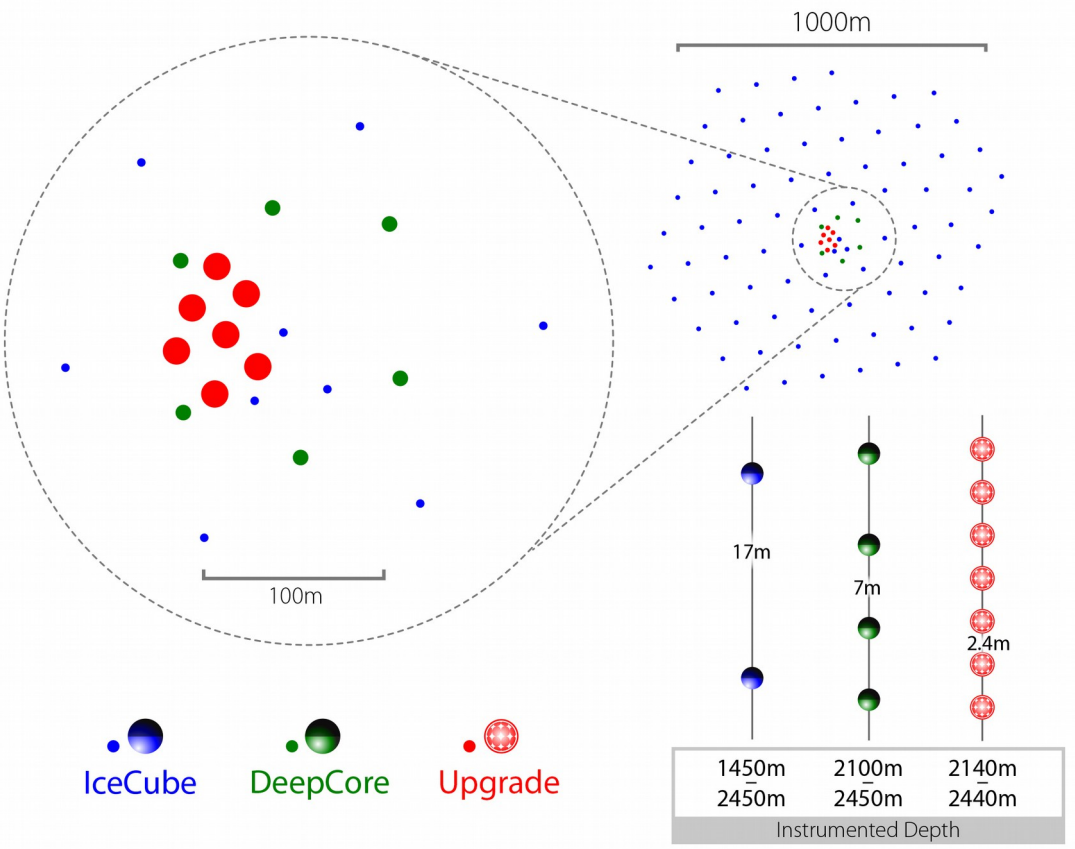
On the Horizon: KM3net

- **Multi-km³ water detector**
- **Superb angular resolution**
- **Very of large areas of sky**
- **Interesting new multi-PMT modules**
- **Under construction!**
- **Next talk**



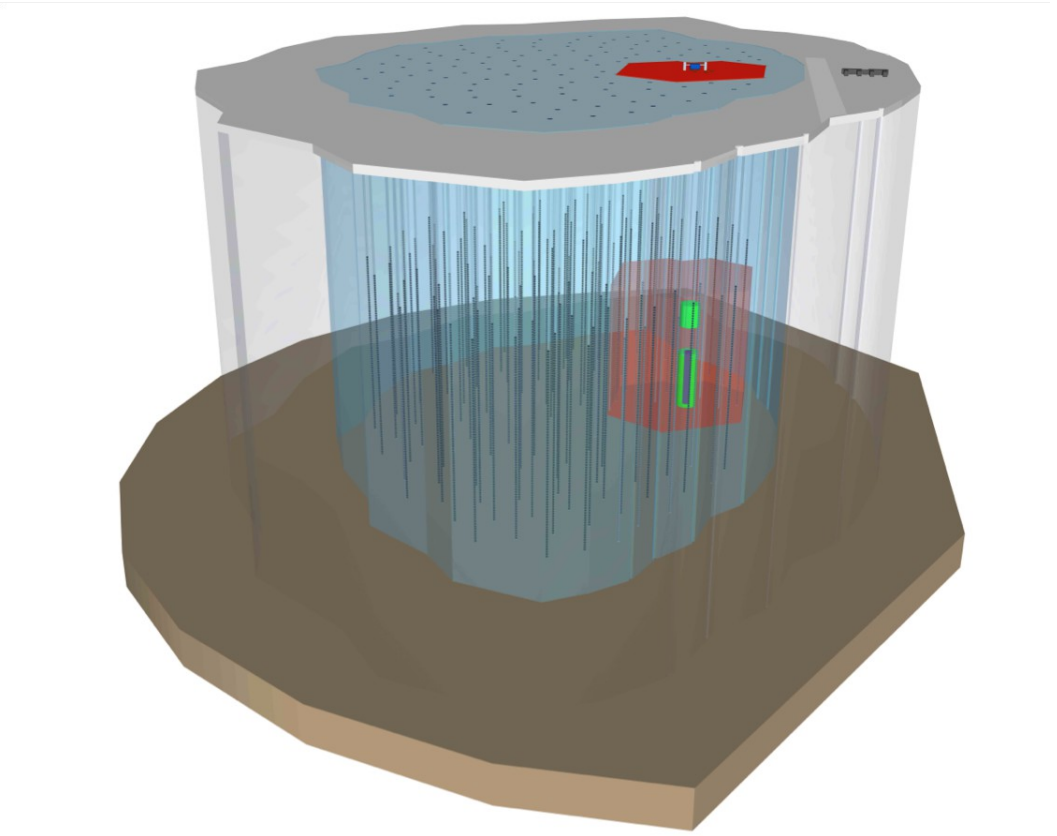
On the Horizon: IceCube Upgrade

- **Small in-fill of IceCube**
- **Better calibration**
- **Improves all of IceCube's angular resolution**
- **Sensitivity enhancement at low energies**
- **R&D Opportunity**
- **Funded!**



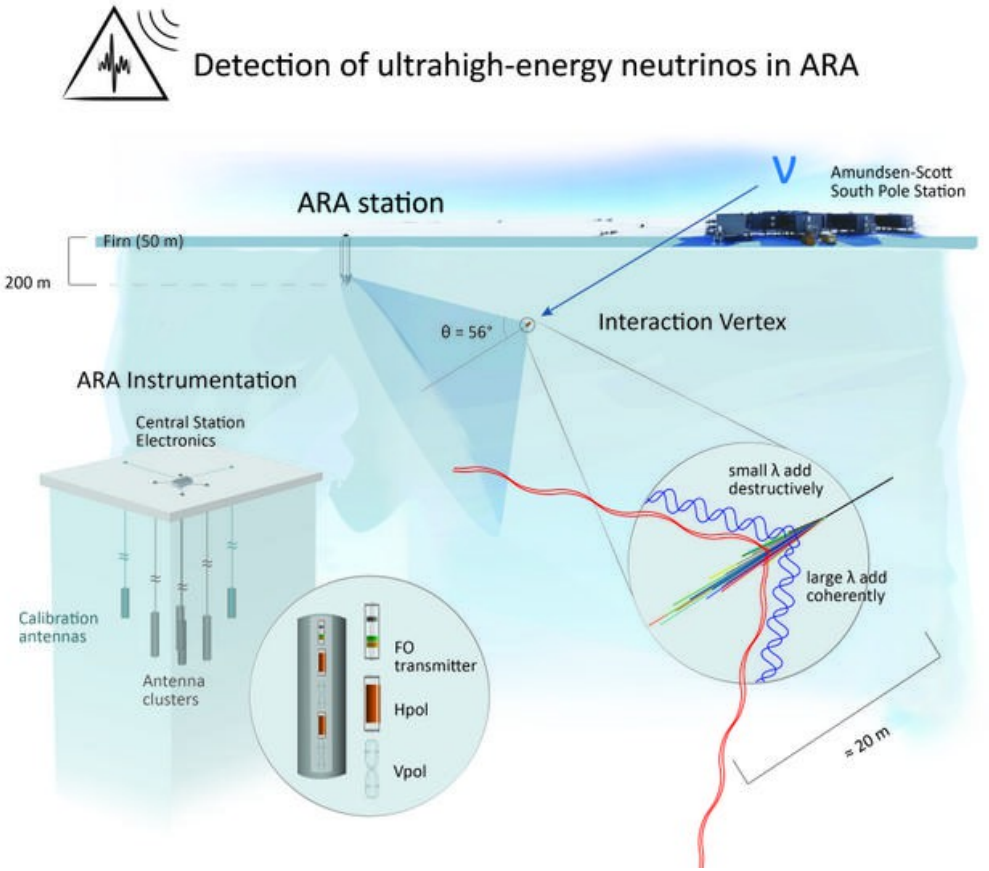
On the Horizon: IceCube Gen2

- **8 km³**
- **0.1 degree resolution**
- **Early design stage**
- **New photo-detector designs**



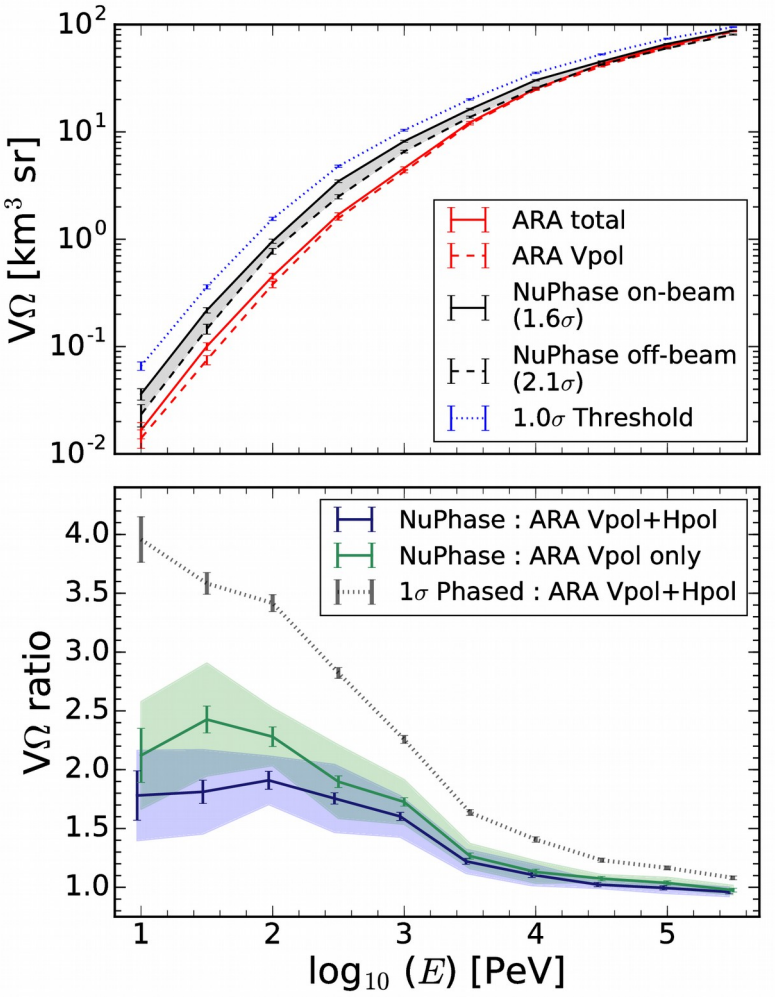
On the Horizon: Ultra-High-Energy Radio

- **How to scale to 100 km^3?**
- **Radio impulses from charge imbalance in showers in matter**
- **Proven technique (ANITA)**
- **Two in-ice instruments building out: ARA and ARIANNA**
- **Threshold of 10^{17} eV**



On the Horizon: (Merely) High-Energy Radio?

- **Radio is cheap, but energy threshold is high**
- **Threshold set by trigger noise**
- **Multi-antenna correlations can pull this down**
- **Possible 10^{15} eV in reach**
- **Test module deployed in ARA in 2018**



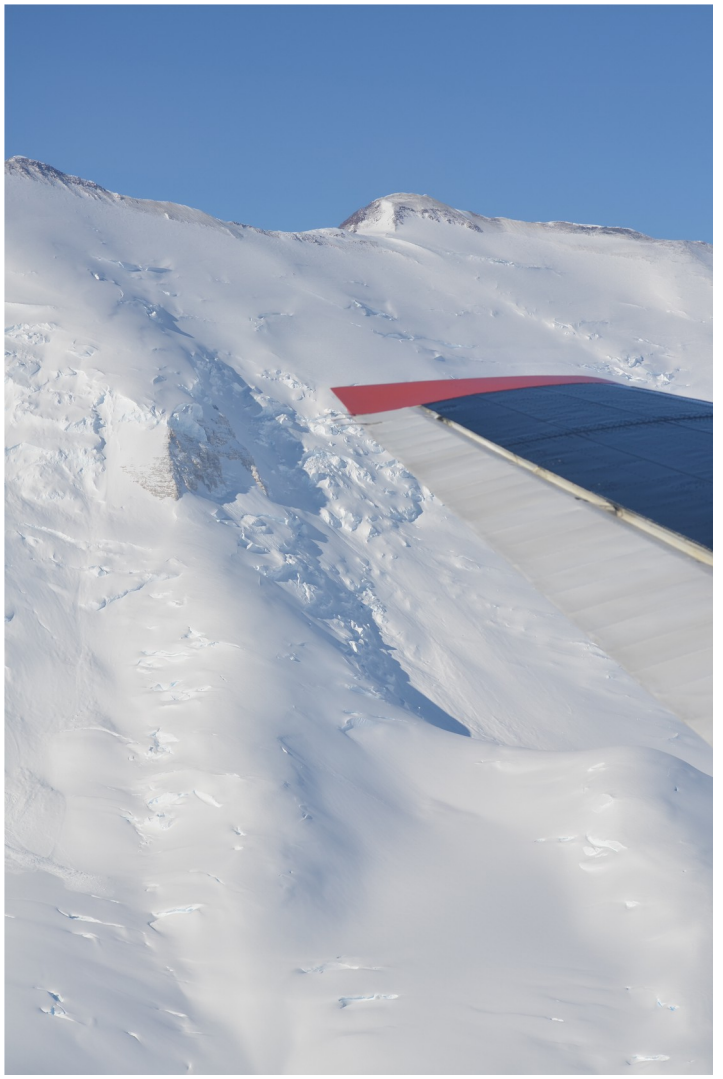
ArXiv: 1809.04573

Prospects for the Next Decade

This decade, we stopped measuring zero:

- **First source – distribution normalized, know what to target**
- **At models for GZK**
- **Diffuse background detected**
- **Oscillation capabilities demonstrated**

Next 10 years, many new instruments coming online – learn what these things have to tell us



The Beginning