Astrophysical and Atmospheric Neutrinos

Spencer Klein,
UC Berkeley

- Intro to Neutrino Astronomy
- Diffuse astrophysical ν
- Toward astrophysical sources
- Particle physics from high-energy natural ν
- Looking ahead

Throughout, I will try to give only post-trials significances

Astrophysical ν

- Believed produced in beam dumps of astrophysical accelerators
- Fermi acceleration on shock fronts

  Olivier Deligny's talk
  - More exotic mechanisms seem less likely
  - Energy spectrum $dN_p/dE_n \sim E_n^{-2}$
    - Somewhat softer in more sophisticated models
- Beam dump may be matter (protons) or photons
  - p & γ lead to different π^+/π^- ratio and energy spectra
- At high-energy, production occurs via pγ–> Δ^+ reaction on cosmic microwave background radiation
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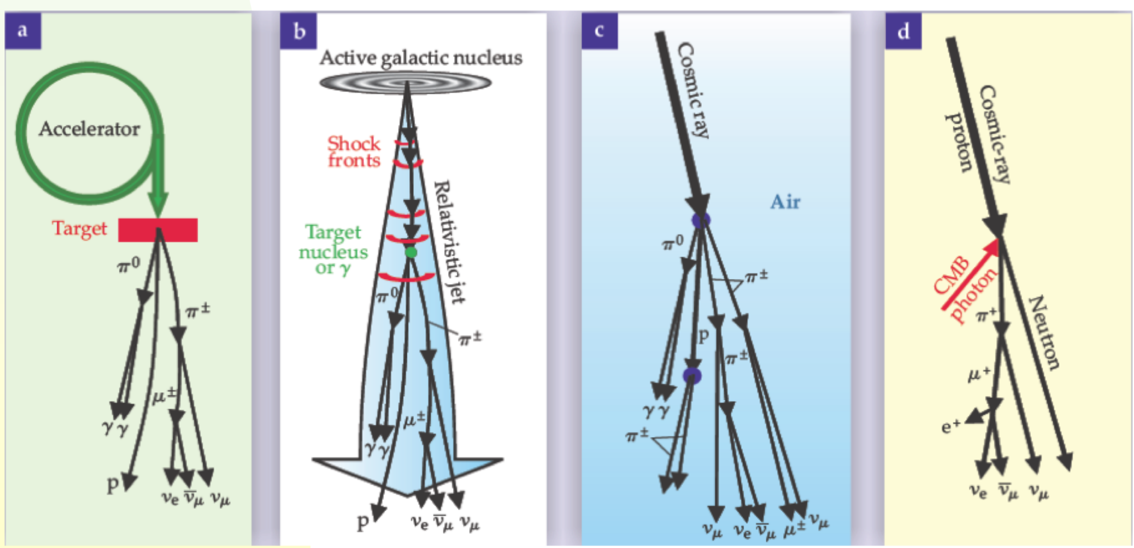


Natural Neutrino Energy Spectrum

- Atmospheric ν from cosmic-ray air showers
  - Fairly well understood, useful to study ν properties
  - Background to astrophysical ν
- Astrophysical ν, presumably from astrophysical sources
- Cosmogenic ν, from p+γ -> Δ+ -> π^+n
  - γ from cosmic-microwave background radiation

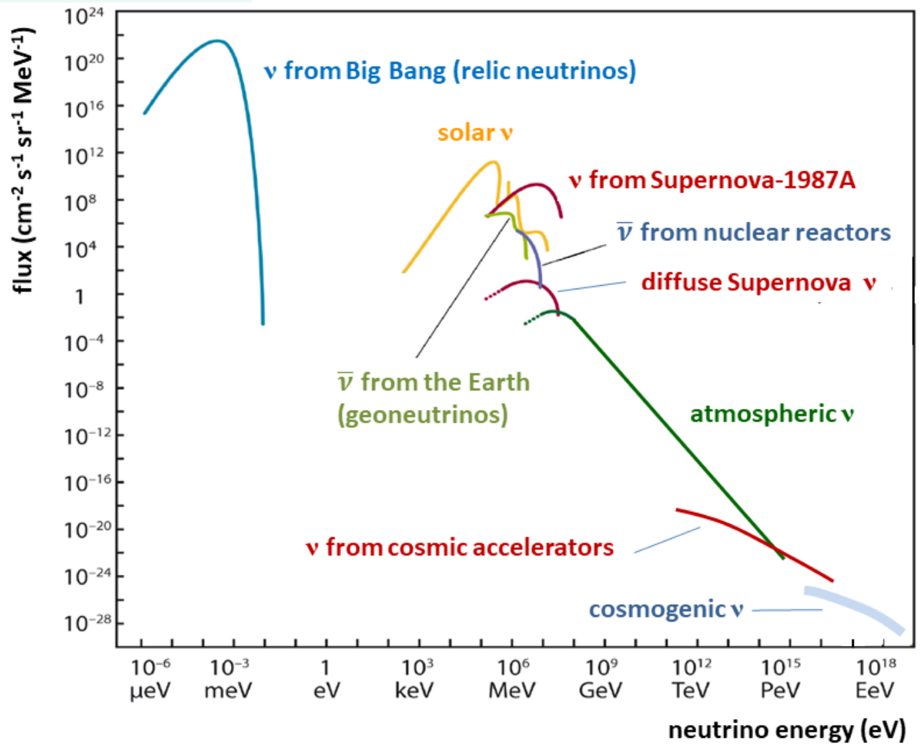
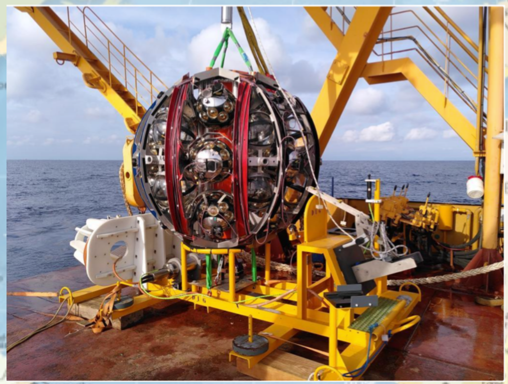
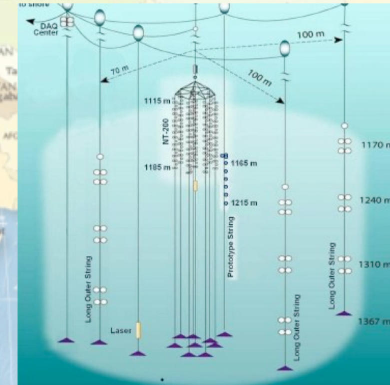


Figure from
Christian Spiering

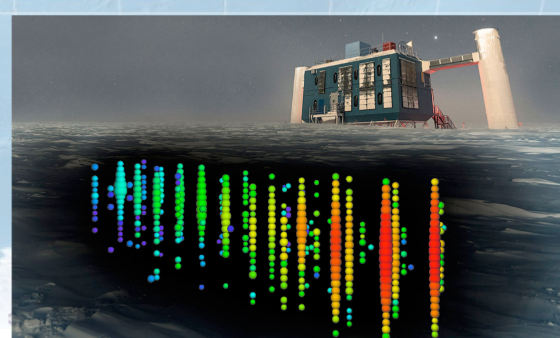
The current experimental landscape
Optical Cherenkov experiments





KM3NeT in Mediterranean Sea
Multi-PMT sensors
ORCA (for ν mass hierarchy)
now: 180 sensors; will be 2120 sensors in 0.07 km^3
ARCA:
now: 144 sensors; will be 4140 sensors in 1.1 km^3

Baikal GVD In freshwater lake
In 2021: ~2300 sensors in 0.4 km^3
In 2024, ~4,000 sensors in 1.5 km^3

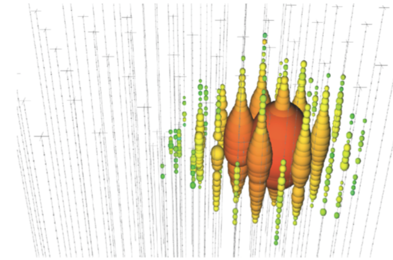


IceCube in Antarctic ice
 5,160 sensors in 1 km^3
Full detector since 2010
Deep Core dense infill
Dense-pack upgrade in progress

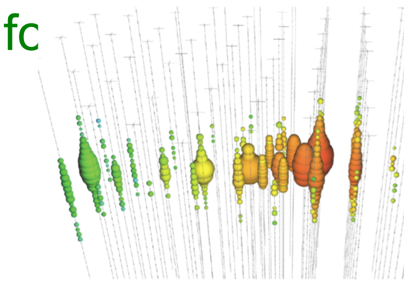
Signatures of astrophysical ν

- Starting events (interactions within the detector)
  - Contained Cascades
    - All flavors NC, ν_e and most ν_τ CC
    - Good energy resolution, moderate/poor directional info
  - Starting tracks
    - ν_μ CC
    - Moderate energy resolution, good directional info
- Through-going muons from ν_μ CC interactions
  - Excellent directional info; poor ν energy resolution
  - Larger effective volume -> higher rates than starting events
  - So far, results only from upward-going ν
  - Work in progress on high-energy downward-going ν
- ν_τ double bang events
- Main backgrounds are atmospheric μ and ν
  - Atmospheric μ are downgoing (or misreconstructed)
  - Astrophysical ν energy spectrum should be harder than atmospheric ν

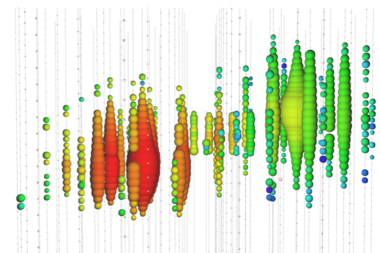
Neutral Current / Charged Current ν_e



Charged Current ν_μ

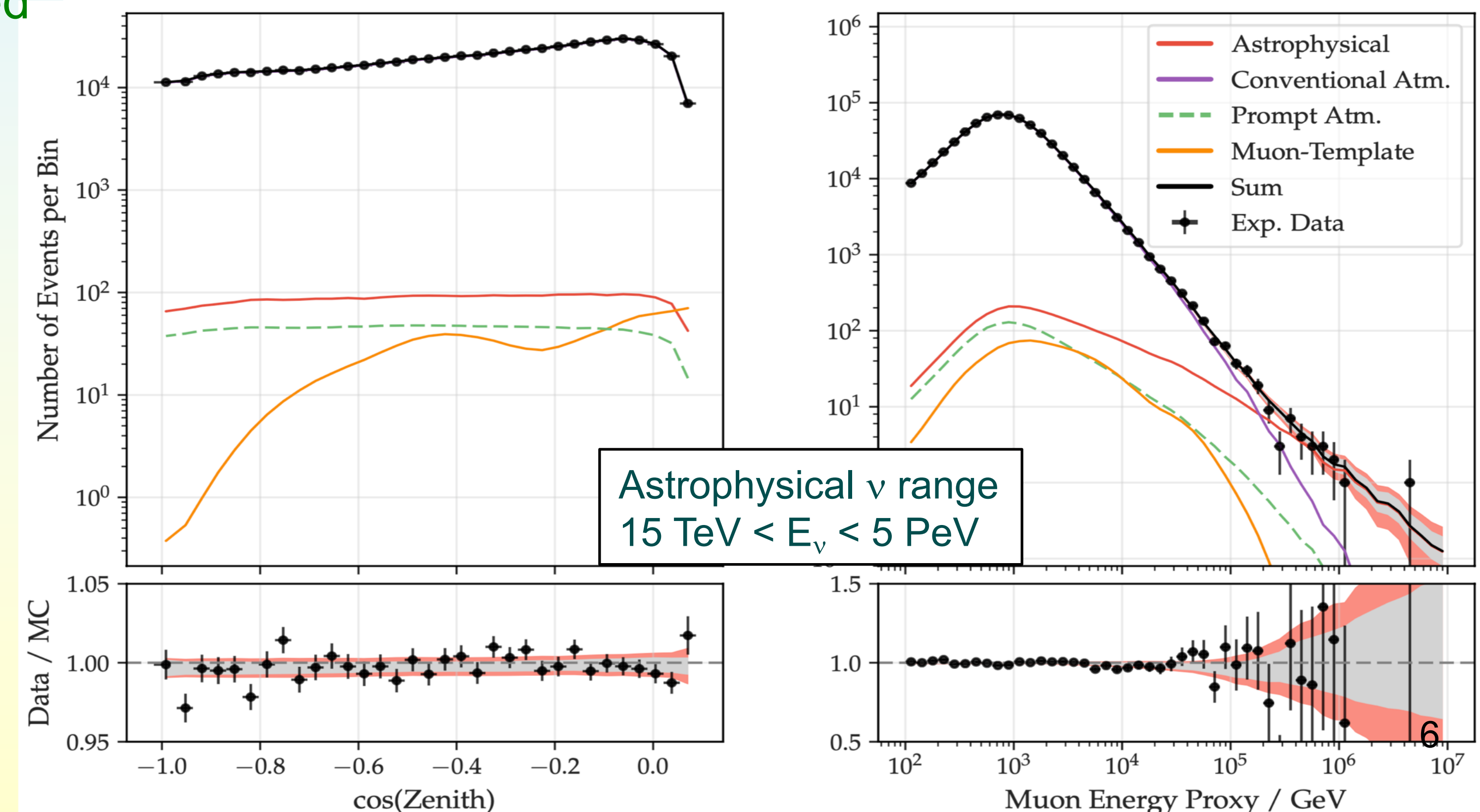


Charged Current ν_τ



Through-going muons

- 650,000 upgoing μ from ν in 9 1/2 years of IceCube data
- Fit to sum of conventional (π/K decay) + prompt atmospheric ν, small misreco'd atmospheric μ, + astrophysical ν
  - 2-d fit in muon energy proxy and zenith angle
  - Astrophysical baseline assumption: single power law
    - More complex models (cutoff, or double power law) favored but not needed

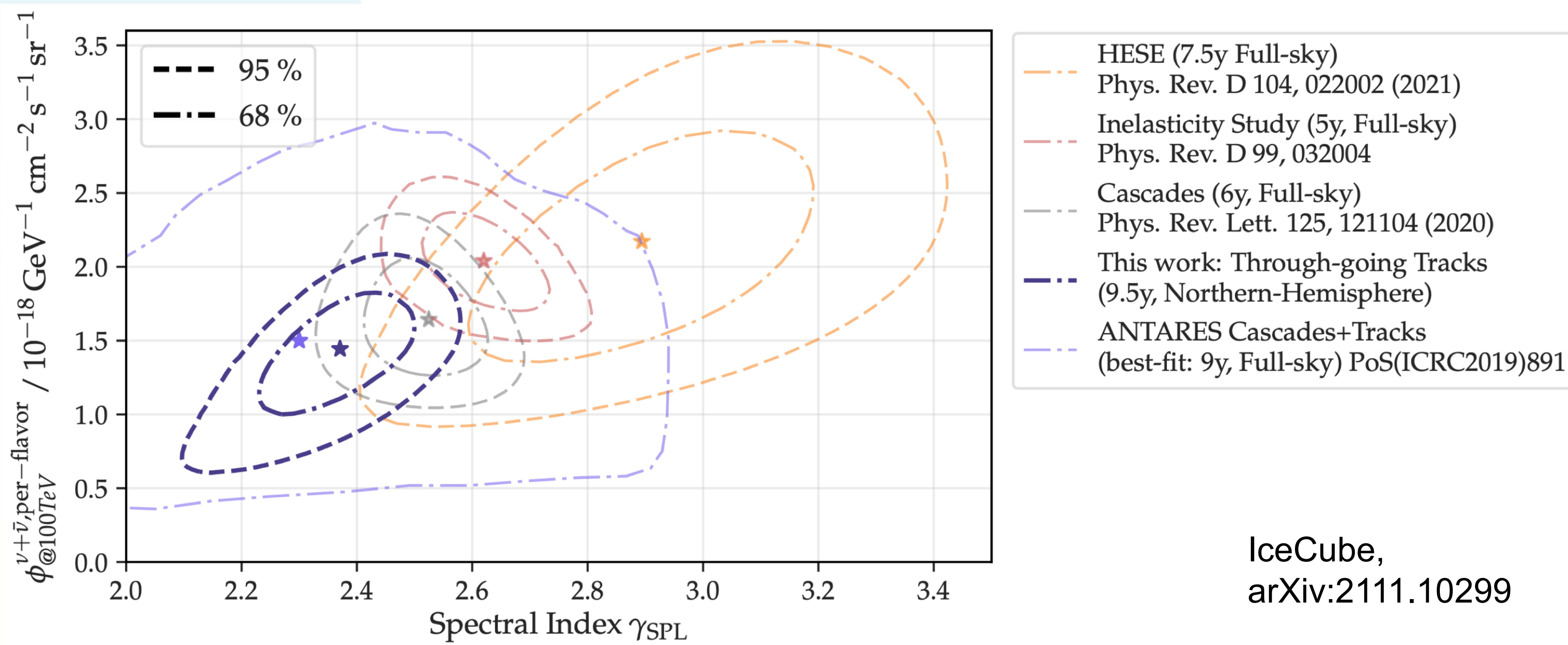


Astrophysical ν range
15 TeV < E_ν < 5 PeV

IceCube, arXiv:2111.10299

Single-power-law comparisons

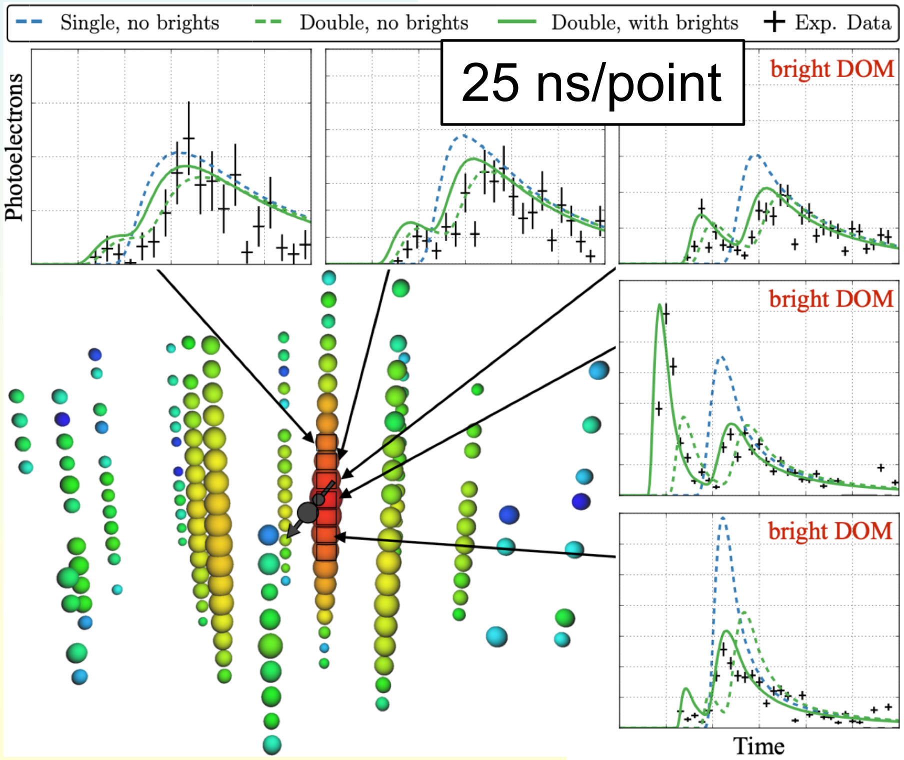
- All results still compatible with single power law: $dN_\nu/dE_\nu \sim E_\nu^{-\alpha}$
  - Best fits for different analyses find $2.3 < \alpha < 2.9$
- Tension between some different results
  - Different flavor ratios, different energy ranges…,
    - Not yet a big concern

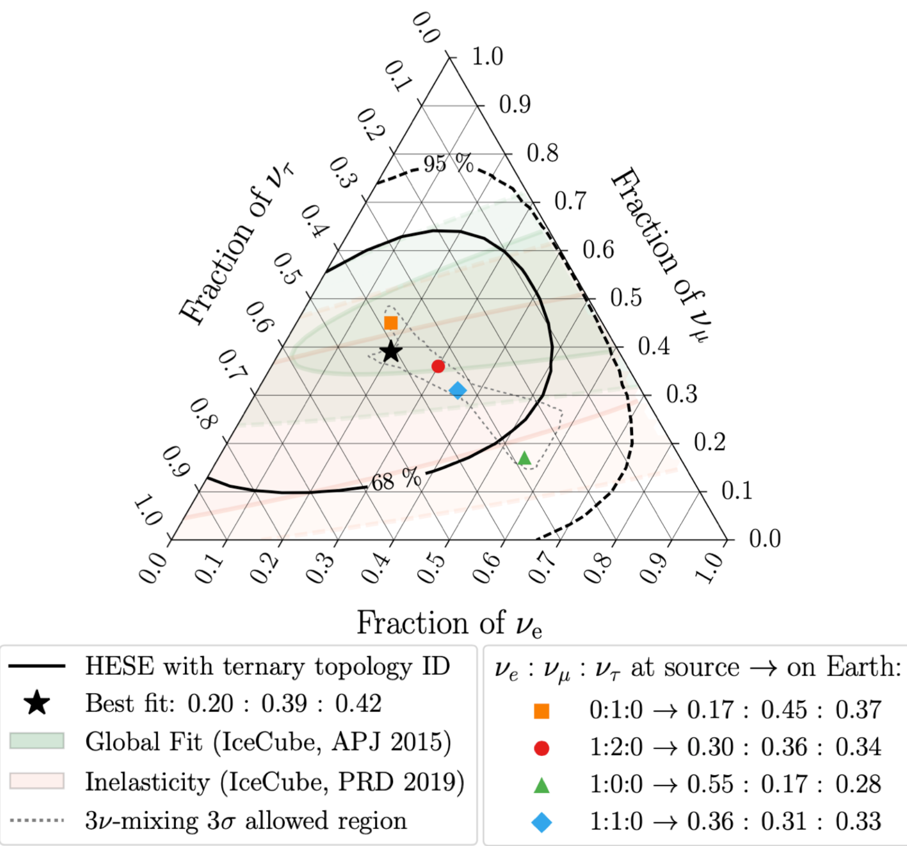


IceCube, arXiv:2111.10299

ν_τ searches and the astrophysical ν flavor ratio

- Identify ν_τ events by double-bang or double-pulse signature
  - Double cascades can be used in ternary (track/cascade/ν_τ) identification
- Starting track inelasticity distribution is sensitive to ν_τ:ν_μ ratio
- Cascade:track ratio provide info on ν_e abundance
- We cannot yet constrain different accelerator models

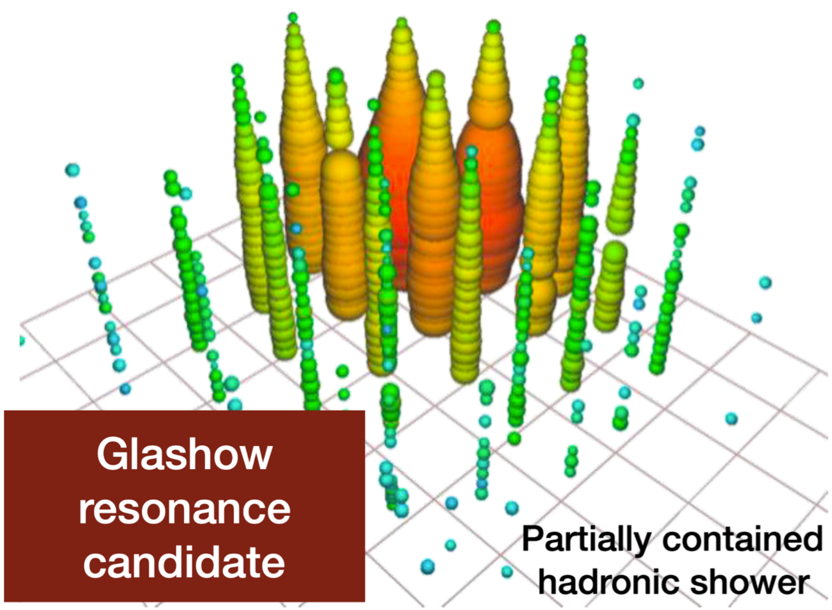


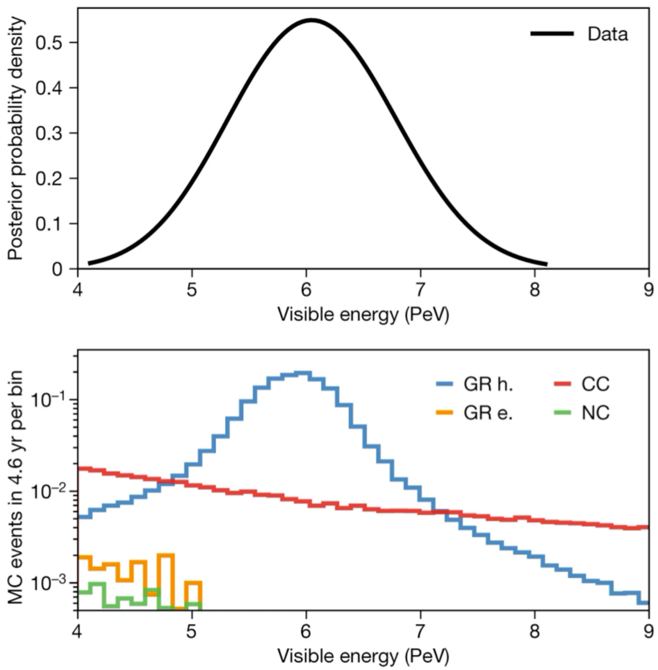


IceCube, arXiv:2011.03561

The Glashow resonance: $\overline{\nu}_e + e^- \rightarrow W^-$

- For an atomic electron, this requires a 6.3 PeV neutrino
- IceCube sees one event – a partially contained hadronic shower
  - Visible (EM equivalent) energy = 6.05 ± 0.72 PeV
- Significance (from energy) to be a Glashow event is 2.3 σ
- +Early light seen, consistent with μ production in the shower
- With enough statistics, can measure ν/νbar ratio





IceCube, Nature **591**, 7849 (2021)

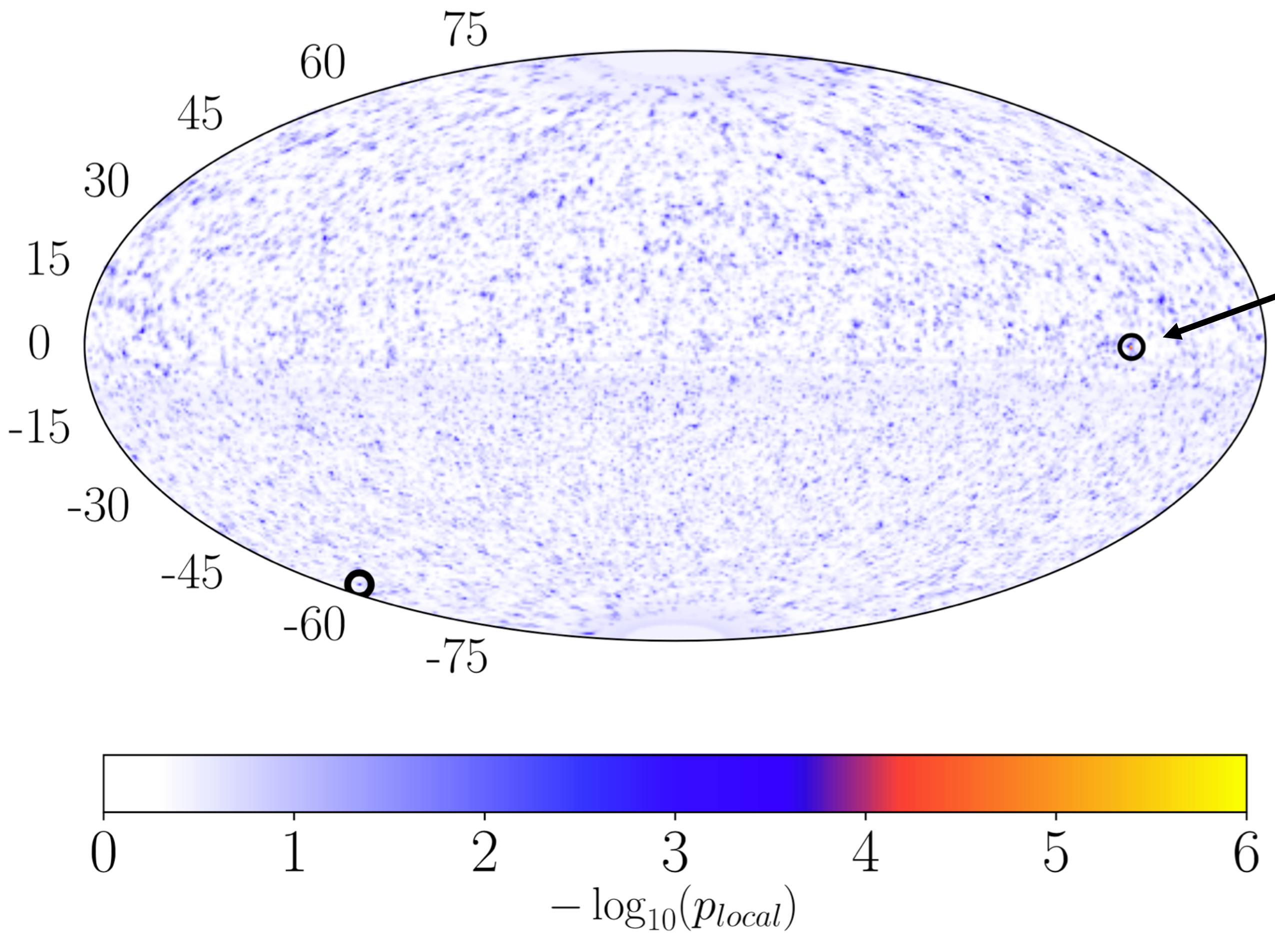
Source search strategies

- All-sky point source searches
  - Constant or variable/episodic (many models)
- Searches of catalogs of ‘likely’ objects
  - Constant, variable/episodic or triggered by high emission
  - Stacked searches for emission from classes of events
    - E. g. active galactic nuclei
- Searches triggered by other observatories, due to enhanced x-ray/gamma-ray emission or gravitational waves
- There are many possible free parameters
  - Optimizations for hard or soft spectra
  - Parameters are fixed (after much discussion) before unblinding
    - Number & selection of sources, time periods etc.
  - Tradeoffs between number of trials factors and breadth of search
- Data is public; analyses by outside theorists

IceCube public data; see arXiV:2101.09836

Sky map

- 1.13 million upgoing μ in 10 years of IceCube data
  - Mostly atmospheric ν
  - Angular resolution < 0.5^0 for E_ν > 10 TeV
- No significant point sources seen

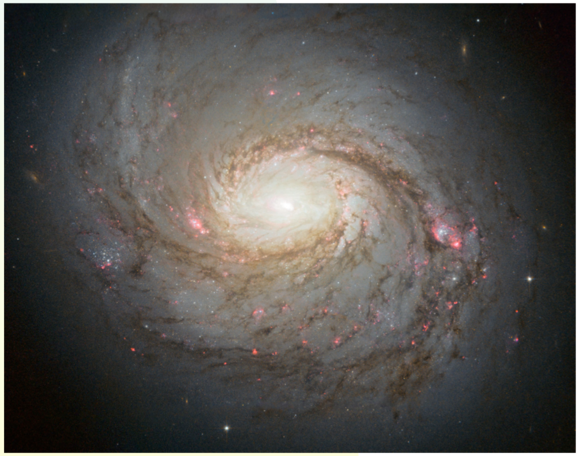


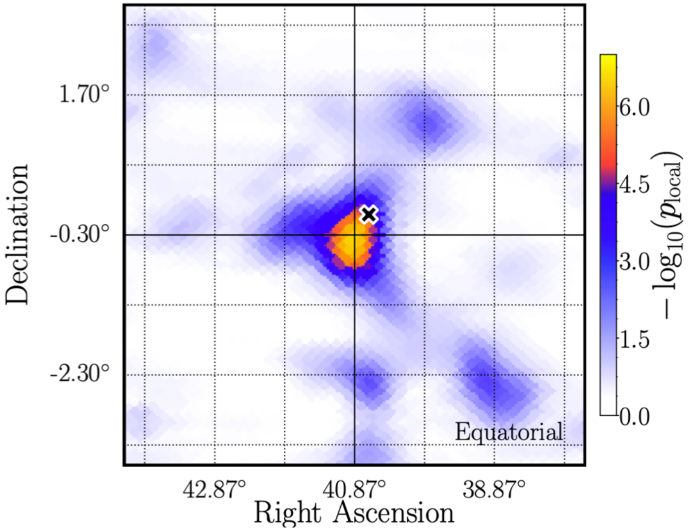
The hottest spot
0.35^0 from NGC1068
2.9 σ significance
(after trials factor)

IceCube, Phys. Rev. Lett. **124**, 051103 (2020)

NGC1068

- NGC1068 is an Active Galactic Nucleus: a galaxy with a supermassive black hole at its center, high-energy particles (likely accretion powered)
  - 14.4 Mpc from Earth
  - Redshift of 0.0035
- Observed with a significance of 2.9 σ
  - NGC1068 fit by a single power law with a soft spectral index: ~ -3.2



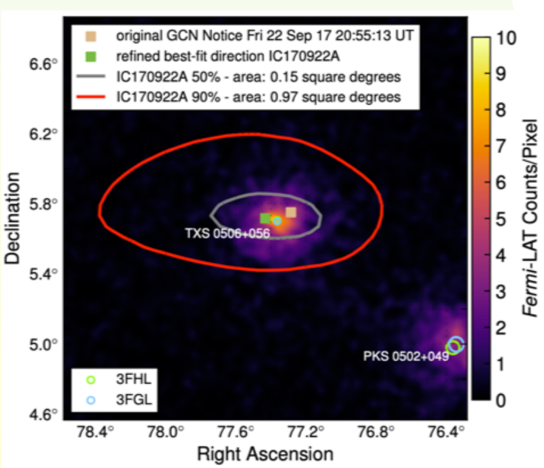


IceCube, Phys. Rev. Lett. **124**, 051103 (2020)

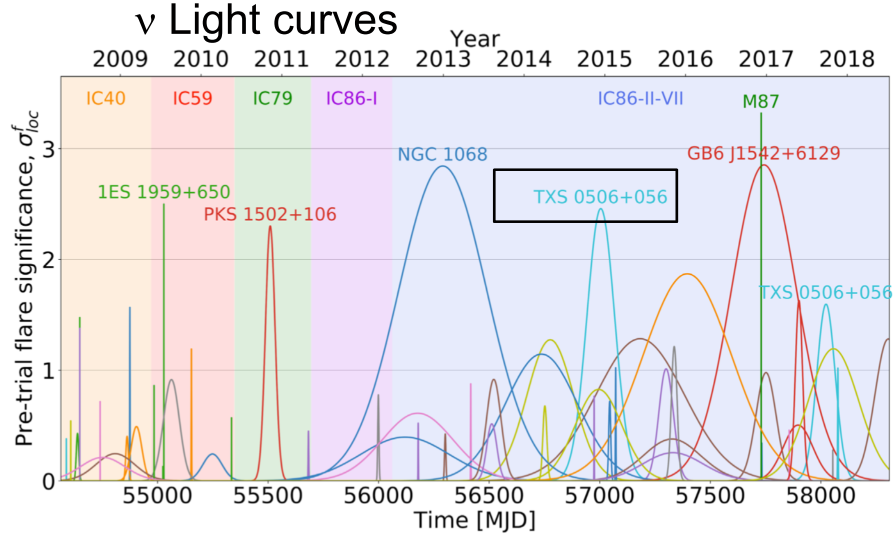
TXS0506 + 056

- A blazar: an AGN with a relativistic jet pointed nearly at Earth
  - Source of high-energy gamma rays
  - 1.75 Gpc from Earth -> Redshift 0.3365
- Sept. 22, 2017: a ~290 TeV ν seen from the direction of TXS0506
  - During a period of high γ-ray emission (flaring)
  - Coincidence has 3 σ significance (after trials for other IceCube alerts)
- A later analysis found a 158 day ν flare in 2014-2015
  - Unaccompanied by enhanced γ-ray emission
  - Significance 2.5-3.5 σ, depending on analysis

ν Direction + 1-300 GeV γ



ν Light curves

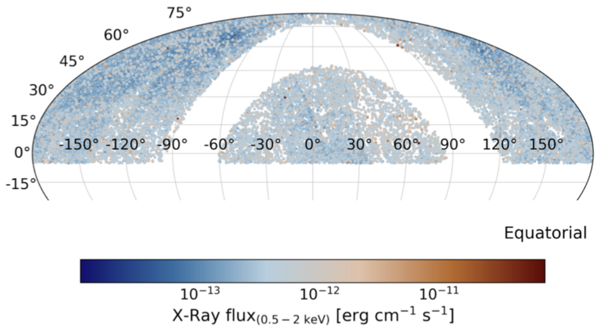


Multi-messenger astronomy
See talk by Elena Cuoco

IceCube *et al*. Science **361**, 6398 (2018); Science **361**, 147 (2018); arXiv: 2011.03561

Astrophysical ν

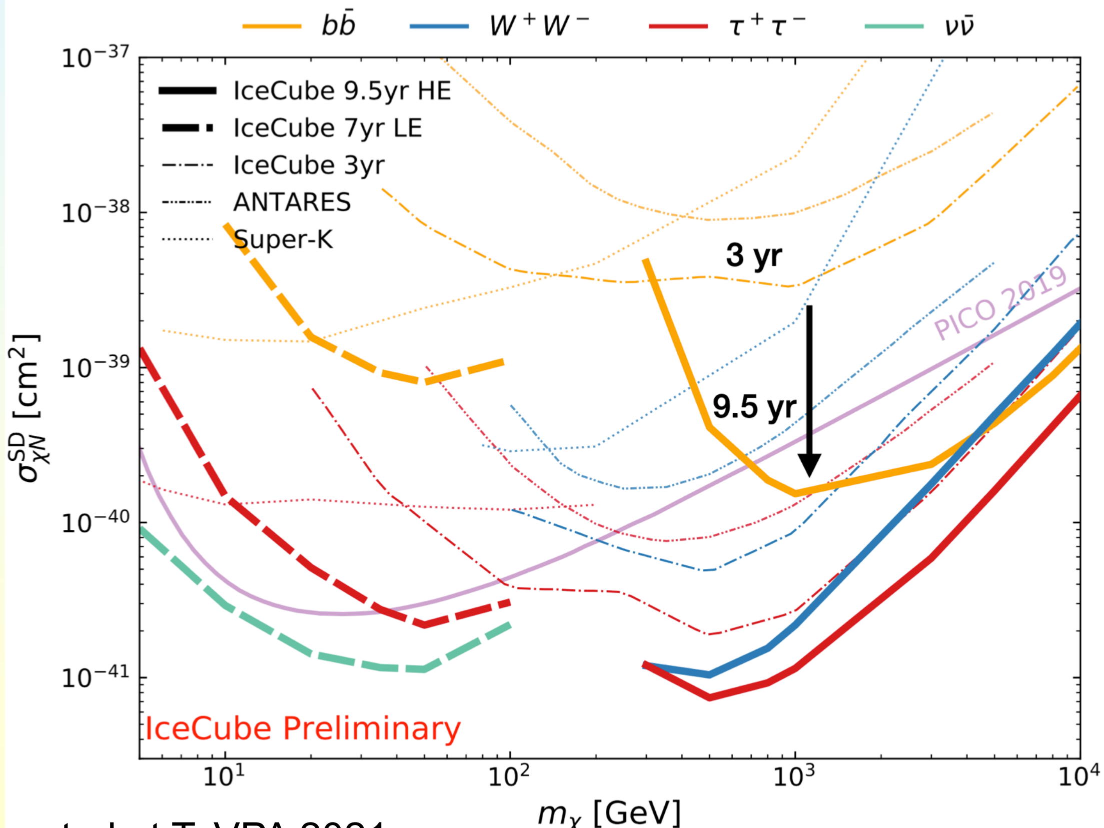
- Flux appears isotropic
  - Predominantly not from our galaxy
  - Autocorrelation studies show that there are many (~>50) sources
- Limits on emission from many source classes
- Evidence of emission from active galactic nuclei
  - TXS0506, NGC1068
  - A study of 32,000 stacked finds 2.6 σ evidence for emission from AGN
    - Multiple scenarios; most significant evidence is for ν emission proportional to accretion disk luminosity in infrared band
- Quenched (opaque to photons, so dark) sources are possible



IceCube: 2111.101169

Dark Matter

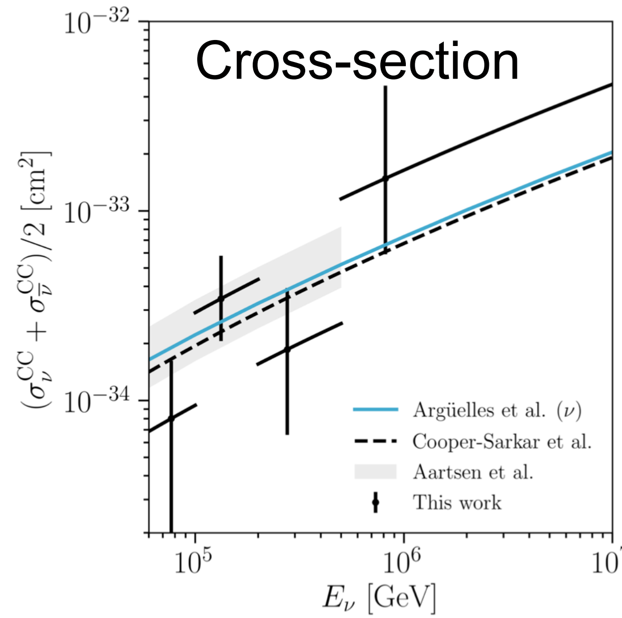
- Dark matter may build up and annihilate, producing ν
  - Dark matter decay to ν is also possible
- Rate depends on mass and annihilation modes
- In the Earth, the Sun, the center of our galaxy and dwarf galaxies
  - The Sun is mostly H, so probes spin-dependent couplings



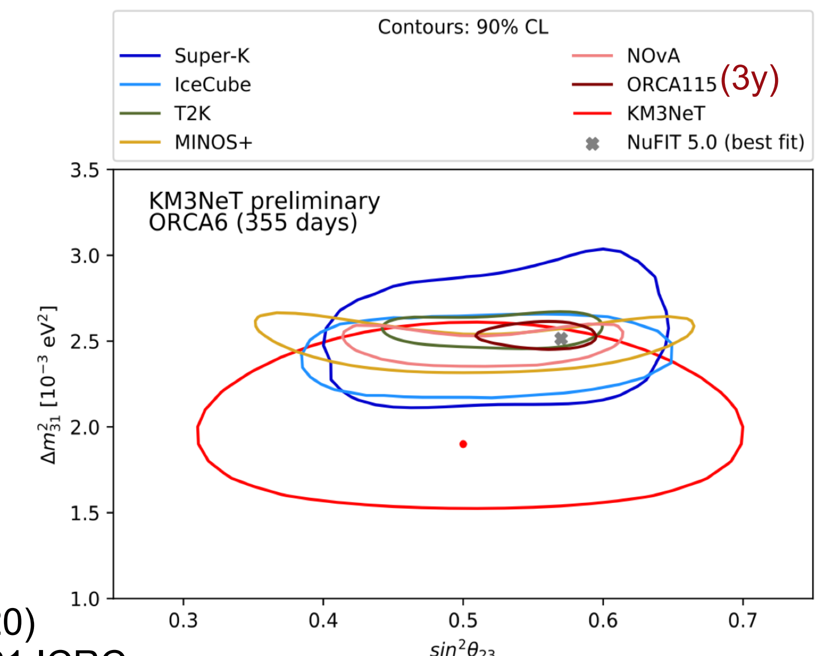
New limits on WIMP Annihilation in the Sun

Q. Li, presented at TeVPA 2021

ν physics with natural ν



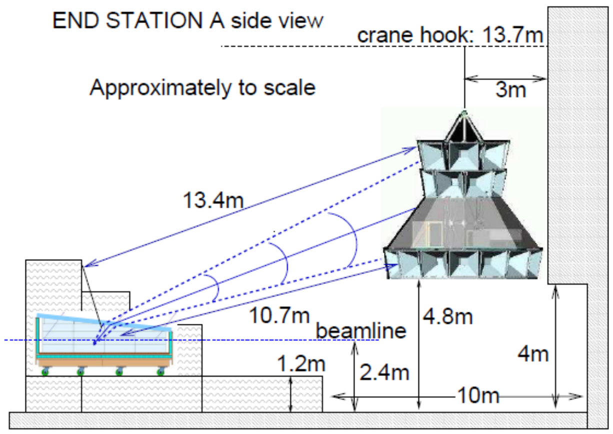
- Disappearance en-route to the detector
  - Studies fit a 2-d(E_ν, Θ_{zenith}) matrix of rates
  - Absorption in the Earth->Cross-sections
  - Vacuum or matter induced oscillations
    - 1st results from ORCA/KM3NeT
  - IceCube search for oscillations to sterile ν
    - Consistent with no sterile ν at 8% level
    - In 3+1 models best fit:
      - $\sin^2(2\Theta_{24})=0.10$ $\Delta m_{41}{}^2= 4.5$ eV^2
  - BSM oscillations to sterile ν or ?
- In-detector interactions
  - Inelasticity distributions
  - Unexpected topologies
- Monopoles,, upgoing track pairs…



IceCube: arXiv:2011.03560, Phys. Rev. Lett. **125**, 141801 (2020)
Phys. Rev. **D104**, 072006 (2021) P. Coyle (KM3NeT) at the 2021 ICRC

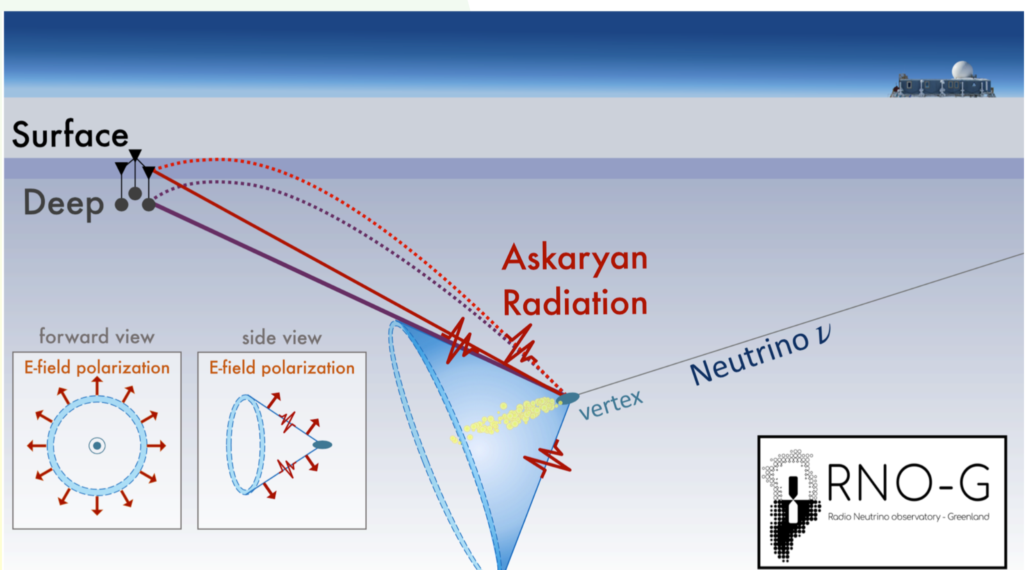
Radiodetection of ν

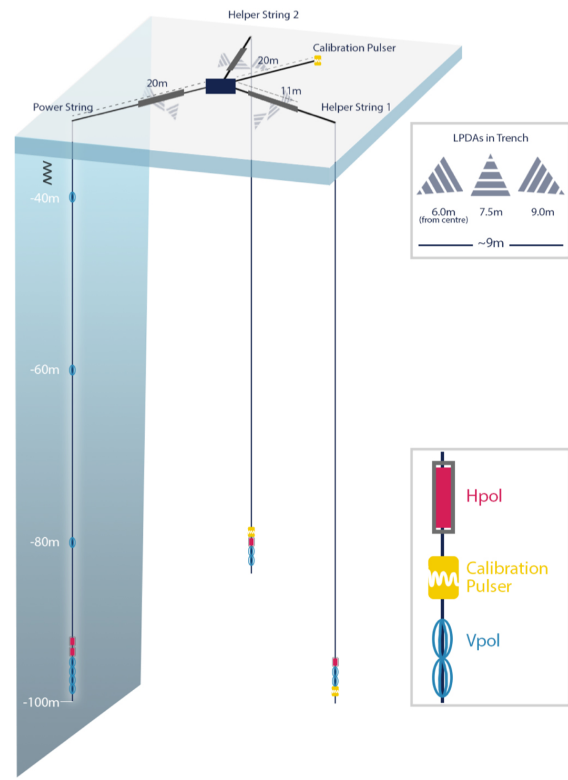
- Above ~ 10^{17} eV, volumes > 100 km^3 are needed to observe a signal
  - Optical Cherenkov cannot scale -> a new technique is needed
- Showers produce large coherent radio-Cherenkov emission
  - In-phase emission -> add amplitudes
  - Radio pulse power ~ E_ν^2 for frequencies < ~ 1 GHz
    - Detectable for E>10^{17} eV (10^{16} with phased array techniques)
  - Requires a non-conducting medium -> Antarctic or Greenland ice
  - Radio absorption lengths vary from 100s of meters to > 1 km
    - 1 km+ detector spacing possible
  - Production studied in experiments at SLAC
- The ν direction may be determined from radio spectrum and polarization fold ambiguity)



RNO-G

- A radio-detection experiment at Summit station in Greenland
  - Logistics may be easier than Antarctica (at least in the Covid era)
- 35 stations funded, with effective volume ~ 10 km^3 at 10^{18} eV
- 3 stations deployed in summer 2021
- Builds on Antarctic experience from ARIANNA and ARA
- Surface and buried (100 m deep) antennas

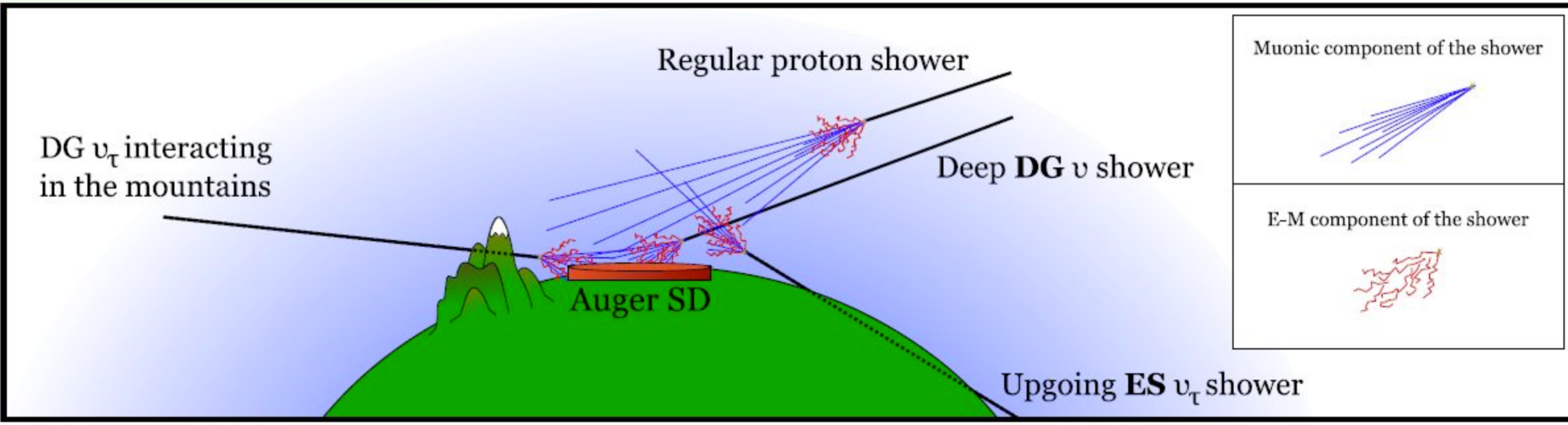




RNO-G, arXiv:2010.12279

Earth-skimming experiments

- ν may interact in the Earth close to its surface, so the products escape into the atmosphere, to produce optical and radio Cherenkov emission
  - In a spherical Earth, or in a mountain
- Current results from the Auger air shower array
- Many experiments plan to look for these events
  - POEMMA satellite pair and EUSO-SPB balloon experiments…
    - Air fluorescence + Cherenkov light



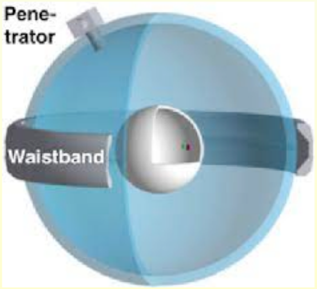
ANITA balloon experiment

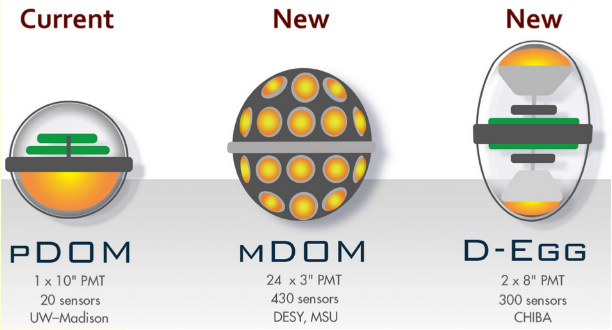
- Horn antennas search for radio pulses from ν interactions in the Antarctic ice
  - Visibility to horizon (~ 600 km)
    - Threshold ~~ $10^{18\text{-}19}$ eV
- Also sees cosmic-ray air showers
  - Polarization shows shower direction (up/down)
    - Radio signal could reflect off the ice surface
- ANITA observes 'anomalous' showers that appear to be going upward
  - Path length through Earth incompatible with standard model cross-section
  - New physics, atmospheric effects or ???
- ANITAs 4th flight observes four Earth-skimming events which are consistent with ν_τ
- Imputed anomalous and earth-skimming flux far exceeds limits from other experiments

ANITA, arXiv:2112.07069

Looking ahead: short term

- Completion of KM3NeT and Baikal GVD
  - Big sensitivity boost in the southern hemisphere
    - Their acceptance sweeps the sky
  - ORCA will find the ν mass hierarchy to 2.5-5 σ in 3 yers
  - Better angular resolution than IceCube, because there is less optical scattering in water. This will boost its sensitivity
- The 7-string IceCube Upgrade:
  - Much smaller spacing & improved optical modules
    - Few GeV threshold
  - Many calibration devices to calibrate the whole array
    - Better angular resolution-> higher sensitivity



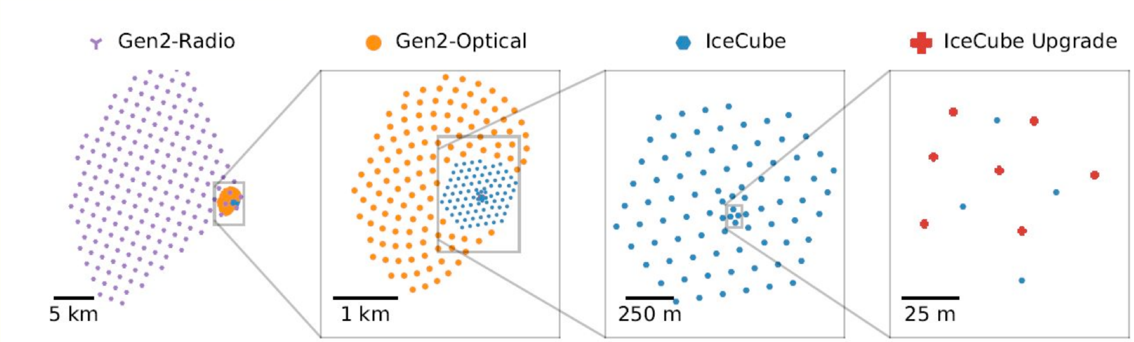


Any dates that could have been here were casualties of Covid

Looking ahead: long term

- IceCube Gen-2
  - ~ 8 km^3 optical Cherenkov array
    - With surface array covering optical footprint
      - To reject atmospheric ν with air showers
  - ~> 1600 km^3 sr aperture radio-detection array

- Radio-detection
  - PUEO (ANITA successor)
  - GRAND radio array for Earth-skimming ν
  - Searches for ν interactions in the Moon with LOFAR and SKA
  - Radio-detector in Pierre Auger array for ν-induced air showers
- P-one array in Pacific Ocean, other Earth-skimming efforts etc.



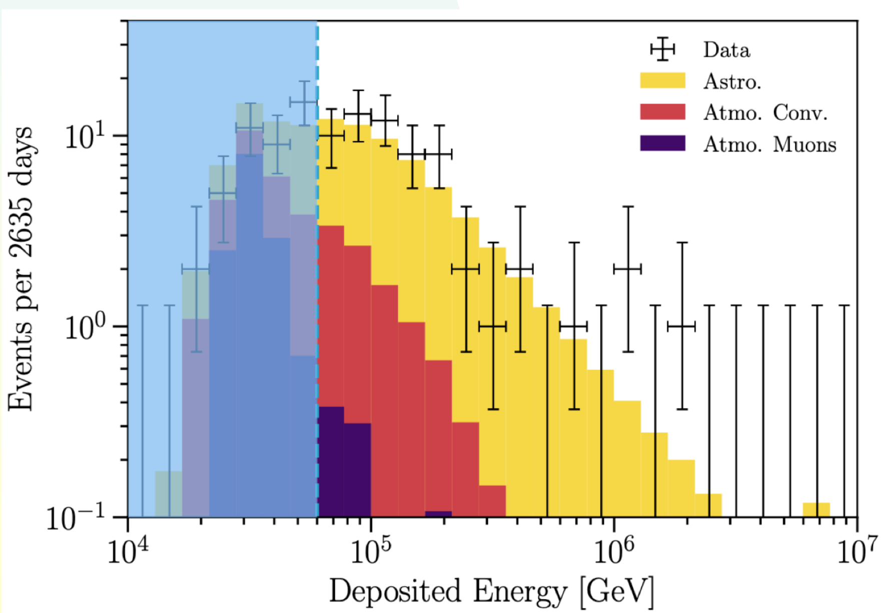
Conclusions

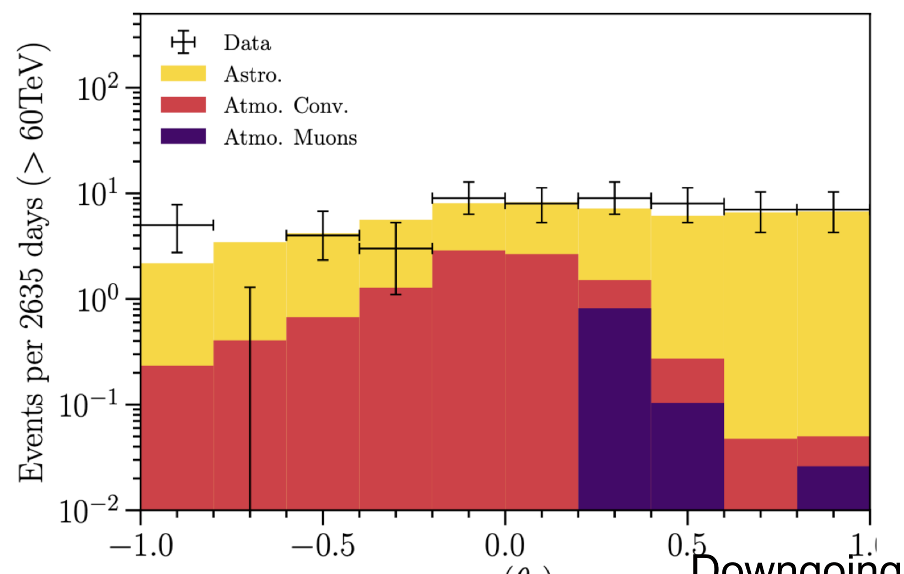
- Optical Cherenkov ν telescopes have collected million-event samples of atmospheric and astrophysical ν.
- We observe diffuse astrophysical neutrinos at energies from 10 TeV to ~ 10 PeV, at a flux near the maximum expected based on photon emission.
  - Quenched (photon-absorbing) sources could be stronger
  - They are largely isotropic, indicating that there are a large number of sources.
  - There is evidence that some/most of these neutrinos may come from active galactic nuclei.
- Natural ν have been used to study neutrino oscillations (including sterile ν), measure $\sigma_{\nu N}$ and inelasticity distributions, and look for a wide variety of beyond-standard-model processes.
- More powerful optical and radio Cherenkov detectors should come online in the next decade, and show us the UHE ν universe.

Backup/surplus

Starting events

- Analysis of 7.5 years of IceCube data
  - Some tension between early and later data
- 0.4 km^3 active volume, surrounded by veto regions
  - Veto will also veto μ that may accompany atmospheric ν
    - Most atmospheric ν are up-going
  - Atmospheric ν follow is $dN_\nu/dE_\nu \sim E_\nu^{-3.7-4.0}$,
    - Softer than astrophysical



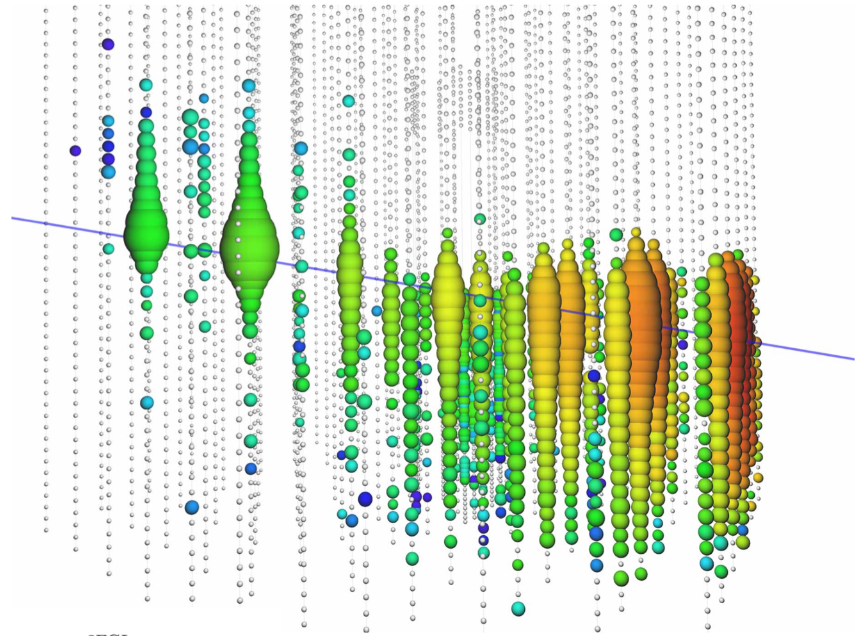


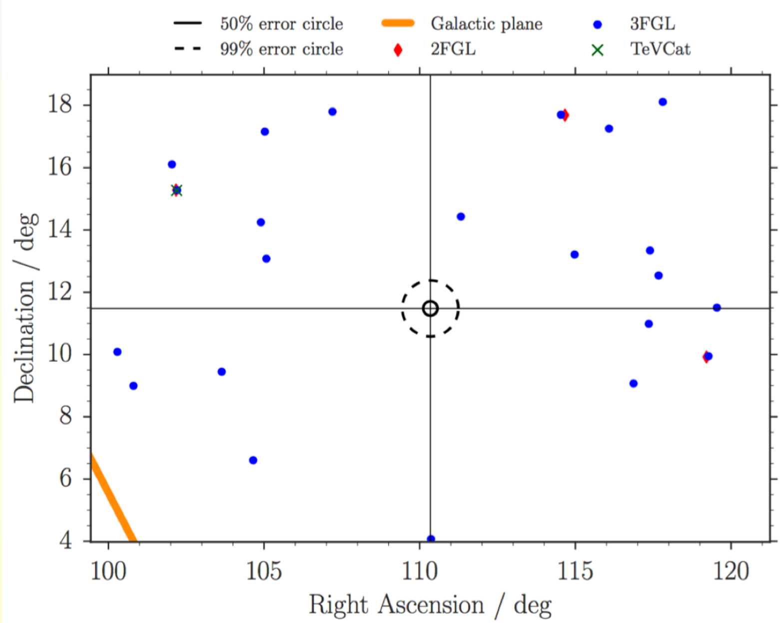
Upgoing
Downgoing

IceCube, Phys. Rev. D104, 022002 (2021)

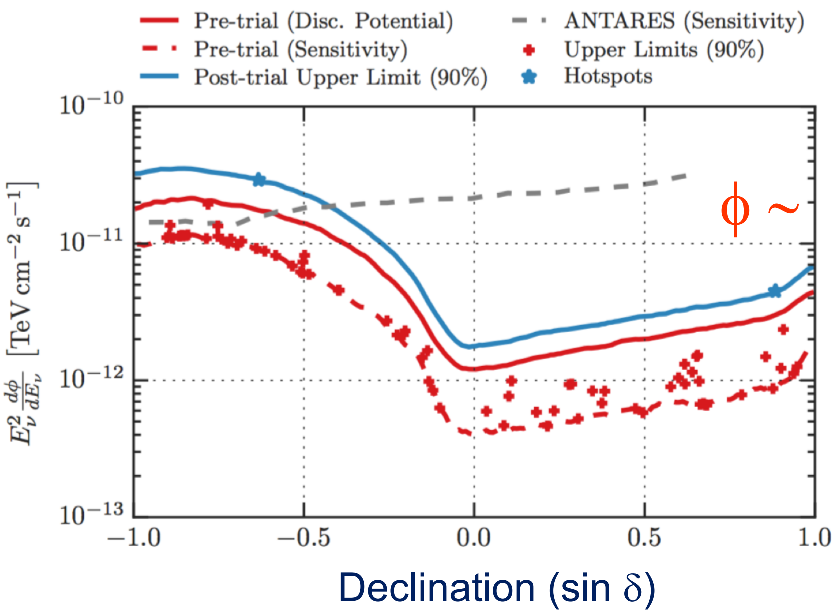
Where do these neutrinos come from?

- Big event seen June 11, 2014
  - 2.6 PeV deposited in detector
  - E_μ likely ~ 3-5 PeV
  - E_ν likely ~ 5-10 PeV
- Direction known to ~ 0.3^o
  - Nothing obviously interesting from that direction





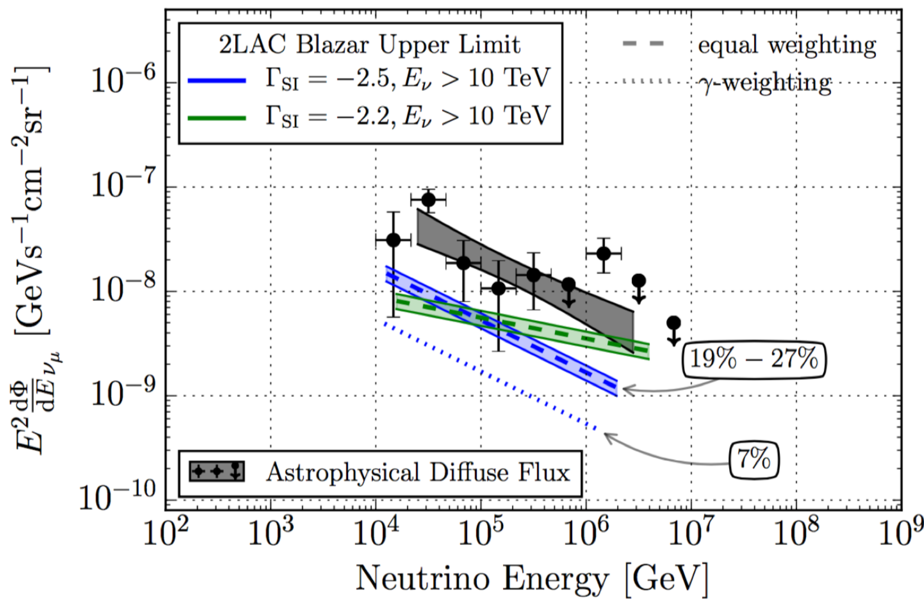
Point source searches



- Flux limits calculated for assumed E^{-2} energy spectrum
  - Limits depend on declination
    - == zenith angle in IceCube
  - $E^2\phi \sim 10^{-12}$ TeV cm^{-2} s^{-1} constrain many older theory predictions
    - ~ Comparable to photon flux
- All-sky survey, pre-selected sources and source class stacking
  - e.g. blazars, supernova remannts, etc.
- Searches for gamma-ray bursts, using GRB position/times determined from photon observations
- Periodic/flaring sources
  - Triggered (by other observations) and untriggered
  - LIGO gravity wave events

Blazar search

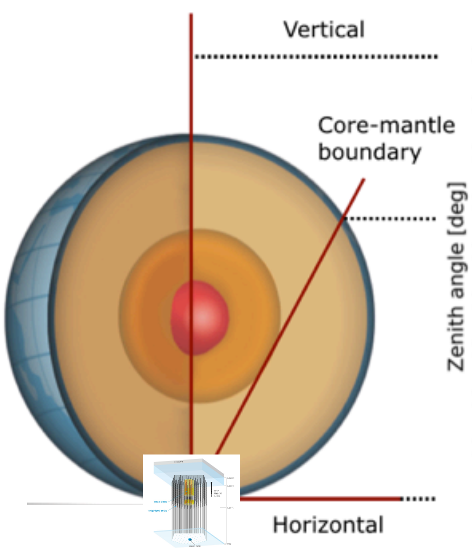
- Stacked search of blazars seen by the Fermi-LAT gamma-ray telescope
  - Sum signal from 862 blazars (and, separately, by some sub-categories)
    - Equal weighting, or weighting by gamma-ray flux
- No excess seen
- For an dN/dE ~ $E^{-2.5}$ neutrino spectrum, blazars produce <27% of the diffuse flux seen by IceCube
  - If spectrum is $E^{-2.2}$, limit loosens to 50% of observed flux

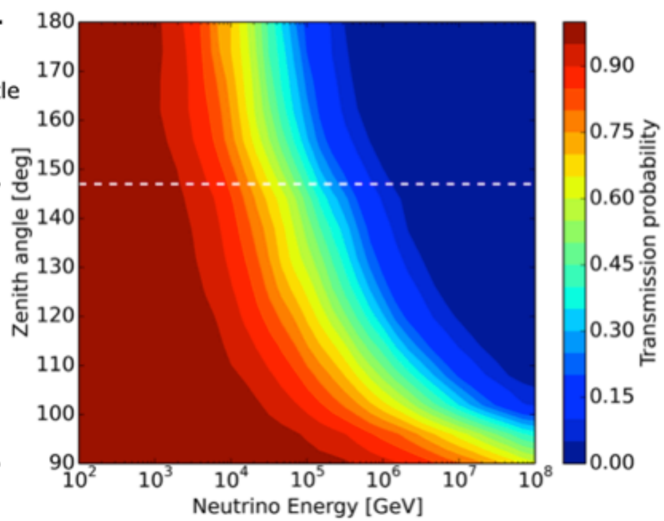


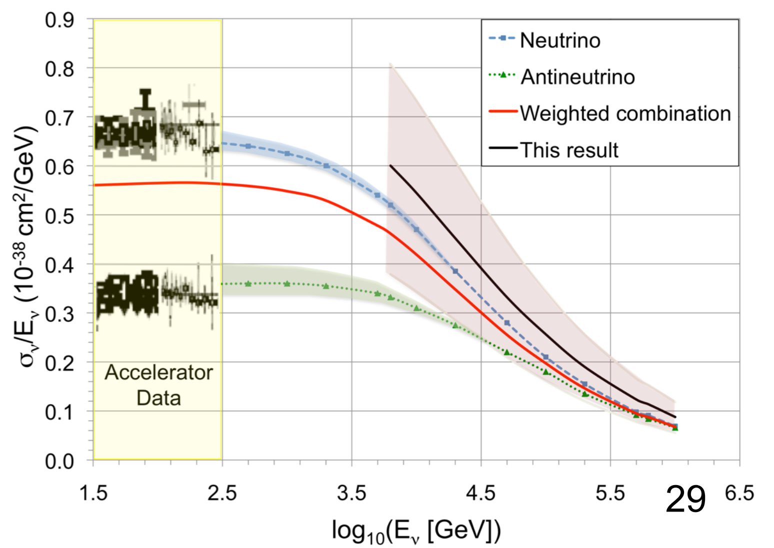
$\sigma_{\nu N}$ measurement

- At energies above 30 TeV, the Earth absorbs neutrinos
- 1 year of up-going ν_μ data was binned in (E_μ, cos(θ_z))
  - Fit to standard cocktail, with absorption allowed to vary
  - Cross-section is a multiple ("R") of standard model cross-section
  - Neutral-current included; reduces neutrino energy

$R=1.30\ ^{+0.21}_{-0.19}\,(\text{stat})\ ^{+0.39}_{-0.43}\,(\text{syst.})$ $\qquad$ $6.3\ \text{TeV} < E_\nu < 980\ \text{TeV}$

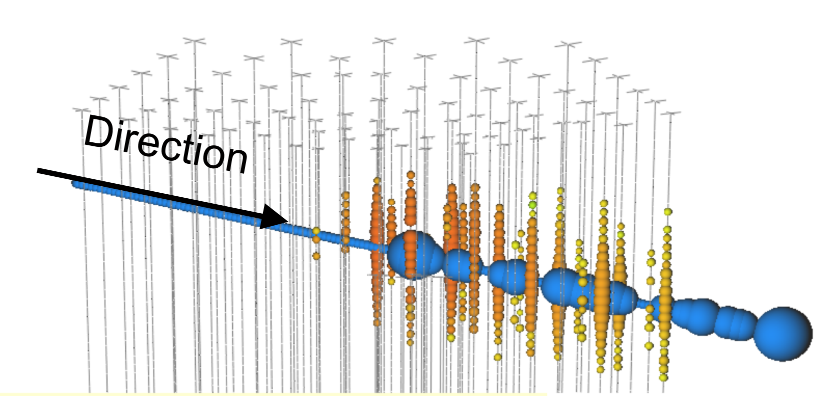






Inelasticity in contained events

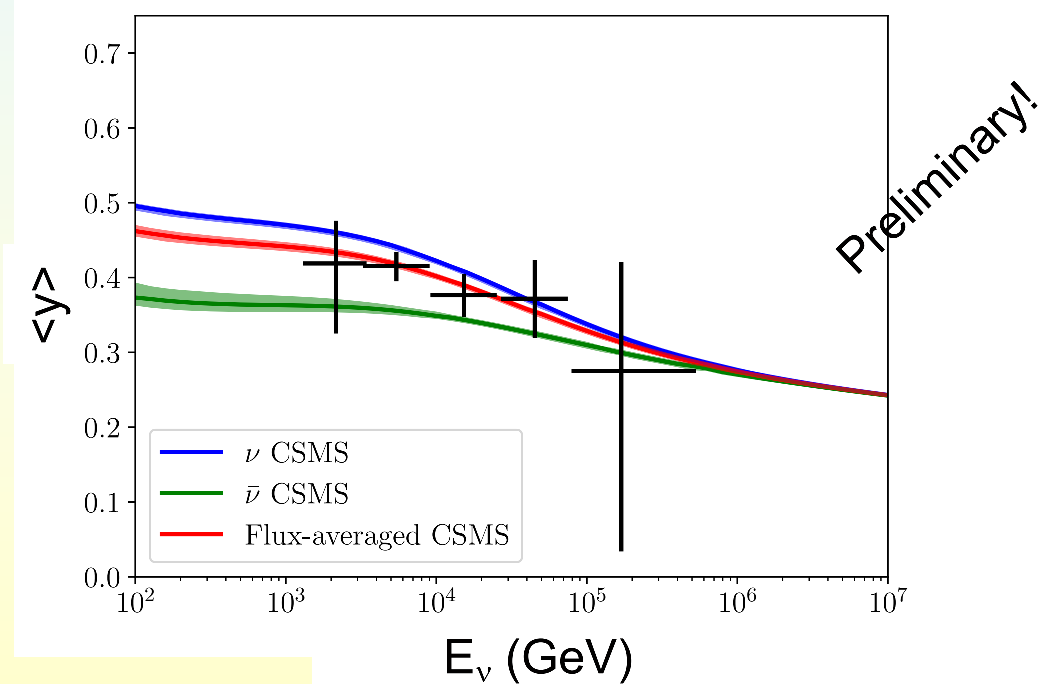
- Inelasticity $y = E_{\text{hadronic shower}}/E_\nu$
  - Predicted by standard weak interaction model
  - Inelasticity distributions are different for ν, $\bar{\nu}$ for $E_\nu < 10$ TeV
- Analysis uses 2650 starting track events (ν_μ) in 5 years of data, selected by a machine learning approach
  - 965 similarly-selected cascades used in some global fits
- A second machine finds E_{cascade}, E_μ, y_{vis}
  - y_{vis} ~ y, but accounts for missing energy



A starting track event with
E_{casc} =64 TeV
E_μ = 724 TeV
y_{vis}=0.08

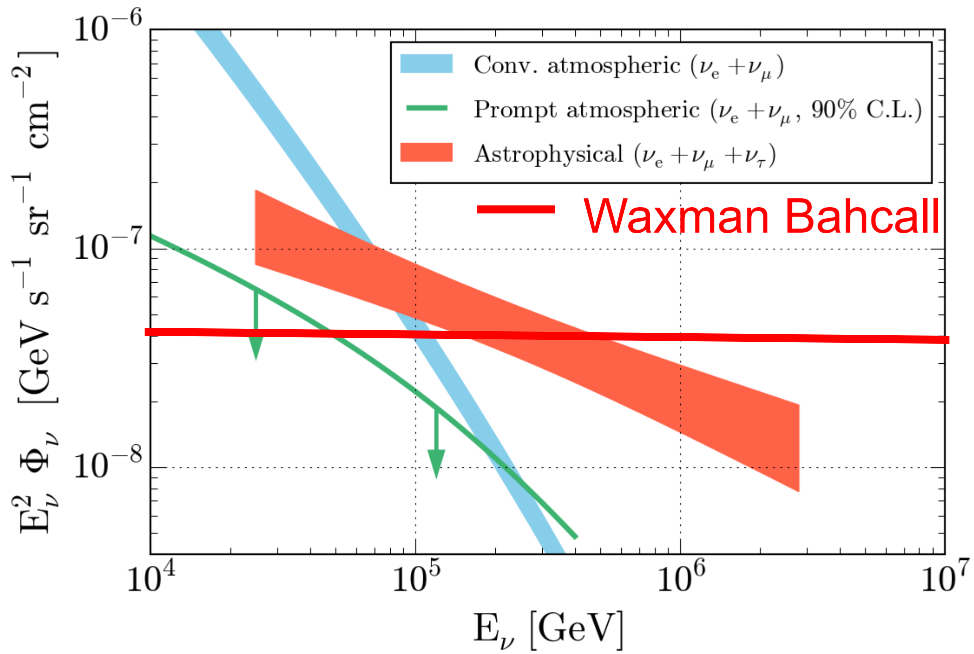
Mean inelasticity <y>

- Parameterize $d\sigma/dy \sim (1+\varepsilon(1-y)^2)y^{\lambda-1}$
  - Motivated by low-x region, where $xq(x,Q^2) \sim x^{-\lambda}$
- ε, λ are heavily correlated, so fit for <y> and λ
  - <y> decreases with energy, as expected
  - In agreement with CSMS calculation
  - Used to measure atmospheric $\bar{\nu}/\nu$ ratio and to observe charm production in ν interactions from 1.5 to 340 TeV



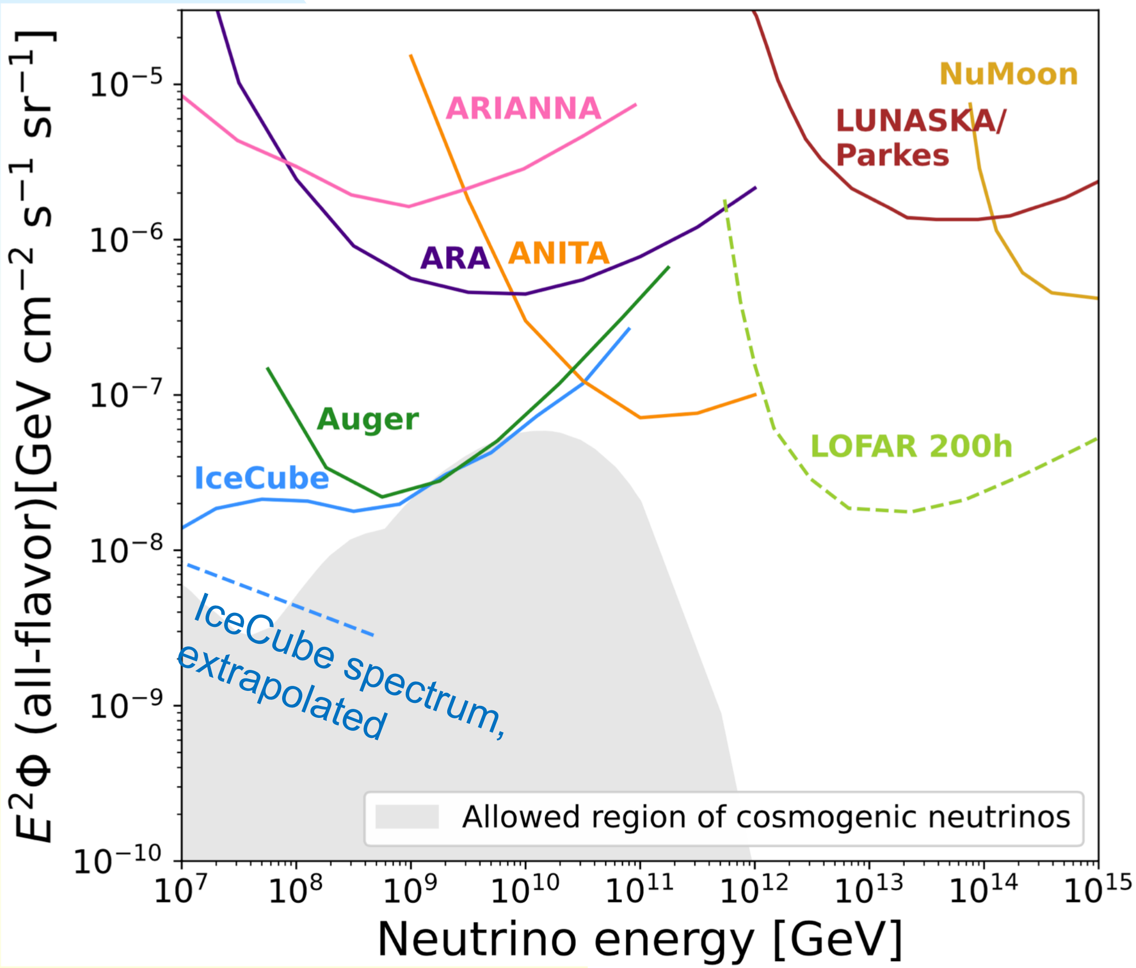
The ν flux is nearly saturated

- The flux is near (or above) the 'Waxman-Bahcall bound, which corresponds to opacity=1
  - Different spectral indices complicate comparison
  - Cosmic-rays just escape from the source
- For most ν prediction models, one must push parameters upward to explain the observed flux
  - It should be easy to find the sources.



EHE neutrino flux limits

- Many competing approaches, with different optimum energy ranges



NuMoon & LUNASKA/Parkes are limits from radio-telescopes searches in the Moon.

LOFAR is a planned search using an existing detector.

Plot from 2022 Particle Data Book