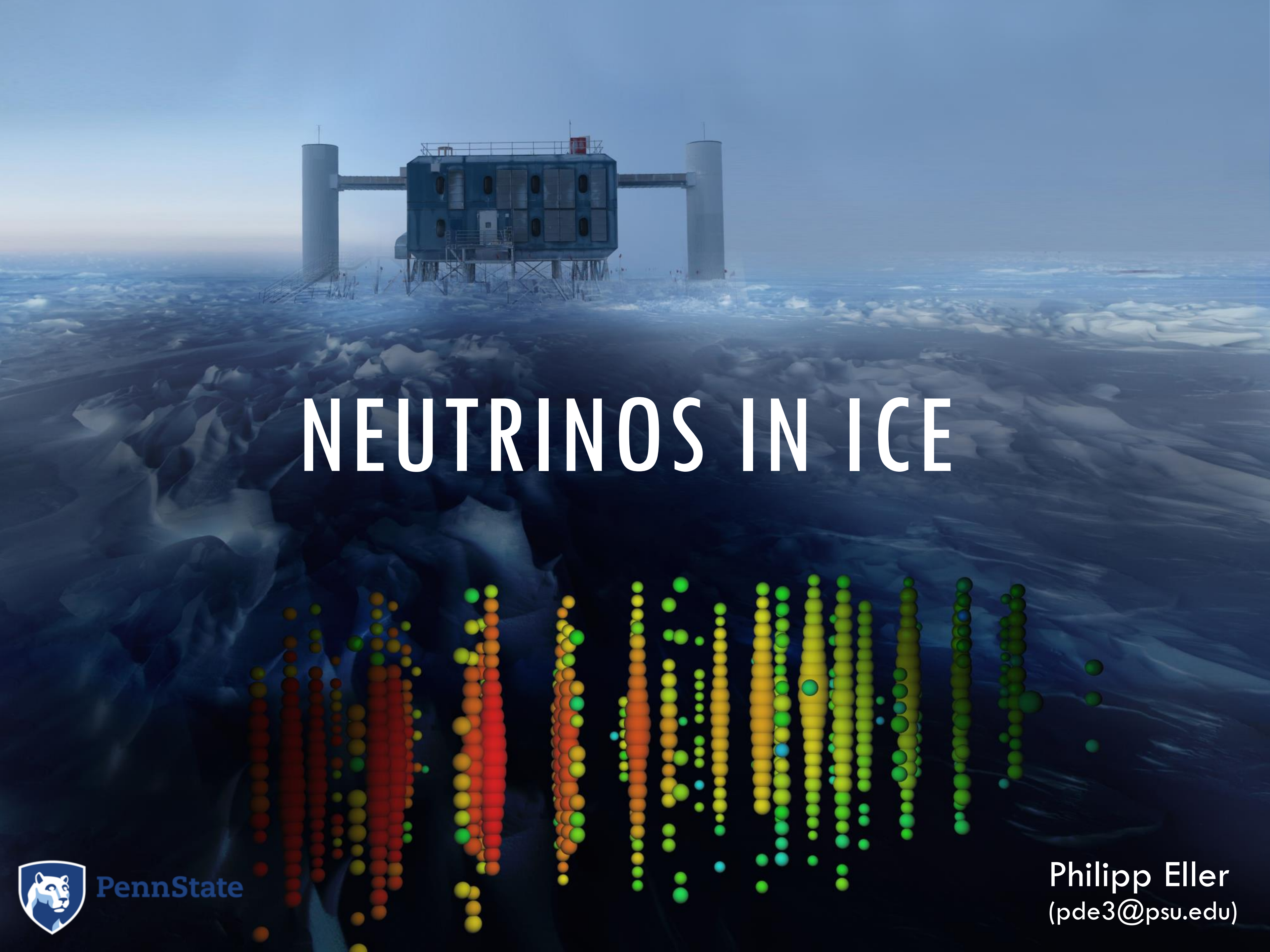
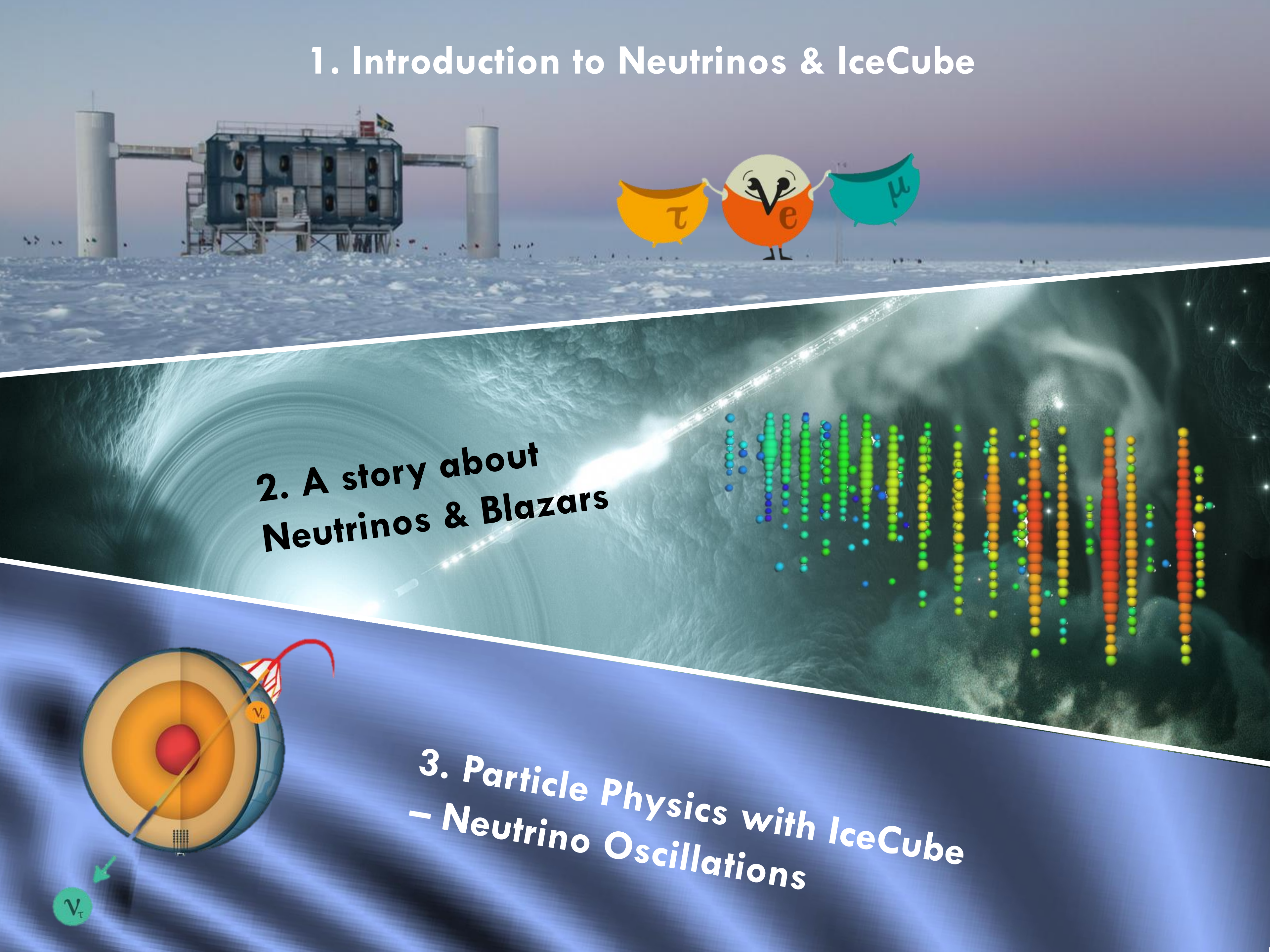


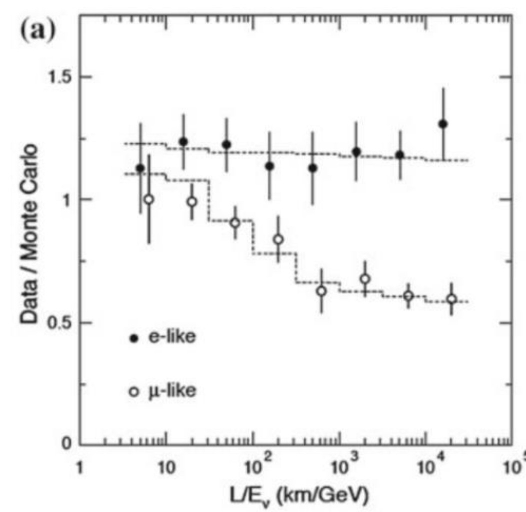
NEUTRINOS IN ICE

Philipp Eller
(pde3@psu.edu)
PennState


1. Introduction to Neutrinos & IceCube
2. A story about
Neutrinos & Blazars
3. Particle Physics with IceCube
– Neutrino Oscillations

VERY BRIEF HISTORY OF THE NEUTRINO

- In **1914**, Chadwick found that the energy spectrum in beta-decays is continuous
- Which led Pauli in **1930** to postulate an additional neutral "neutrino" particle to take part in the interaction
- **1956** Cowan & Reines were able to experimentally detect neutrinos
- **1969** solar neutrinos were observed + "solar neutrino problem"
- **1980**s: similar problems in atmospheric neutrino flux ratio
- **1997**: Super-K: atmospheric neutrino oscillations observed!
- **2002**: SNO solar neutrino oscillation
- **2011-12**: reactor neutrino oscillation (Double Chooz, Daya Bay, RENO)



OPEN QUESTIONS

Neutrino Masses

Neutrino Mixing

…

Generation of masses?

CP violation?

Ordering?

Majorana/Dirac – $0\nu\beta\beta$?

Steriles?

Angles?

Absolute masses?

?

…

PMNS Unitarity?

Supernovae

Neutrino sources?

…

Coherent scattering

Quantum decoherence?

Cosmic ray origin

Glashow resonance?

Non-standard interactions?

Multimessenger

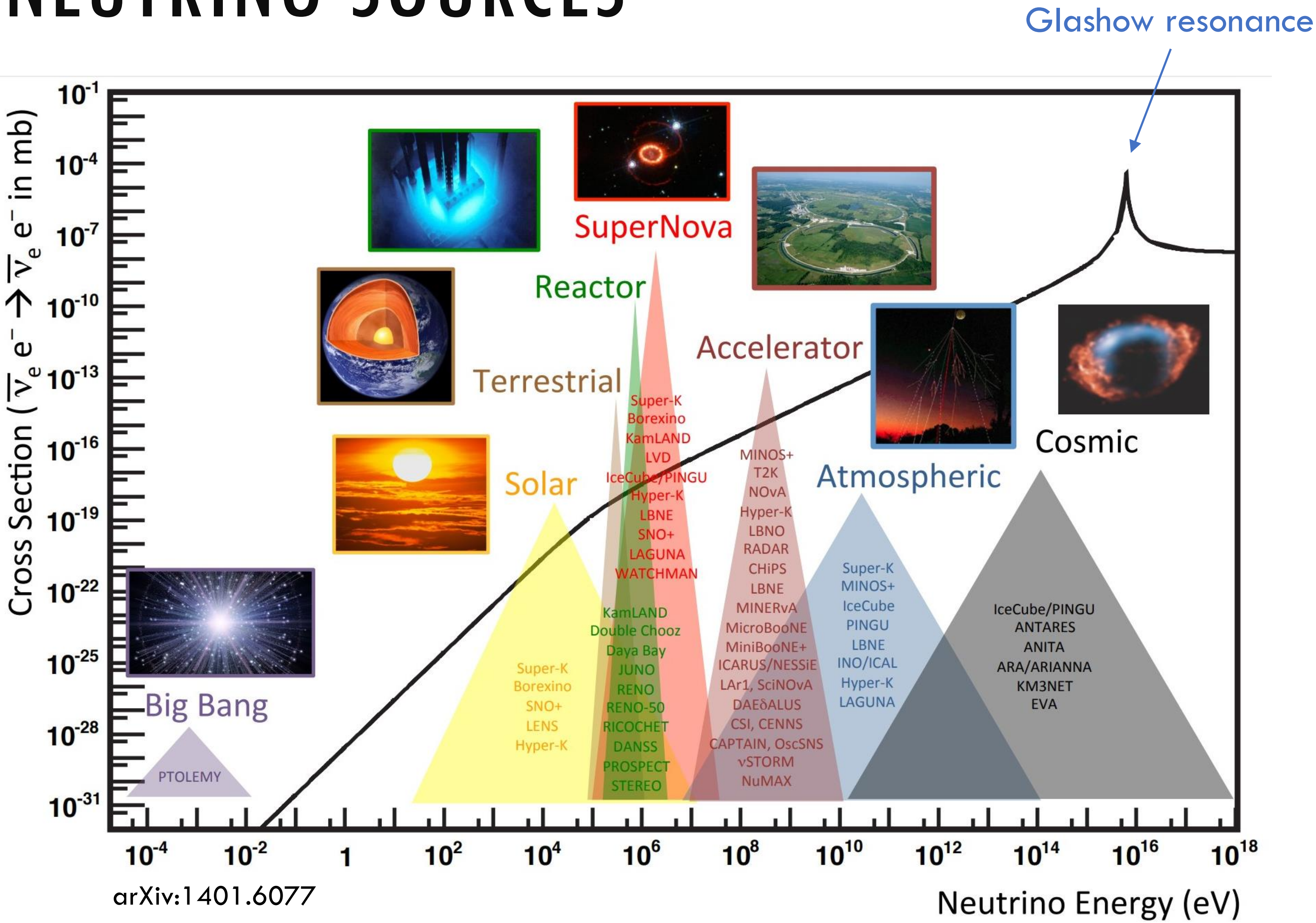
Dark matter decay?

$C\nu B$?

Astro physics

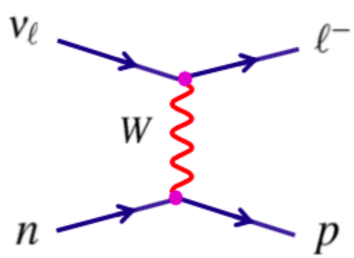
New physics?

NEUTRINO SOURCES

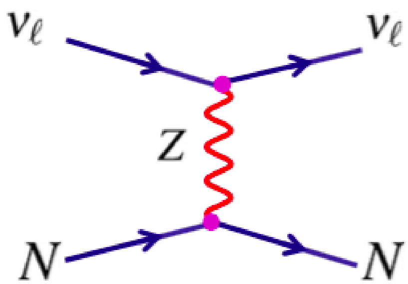


arXiv:1401.6077

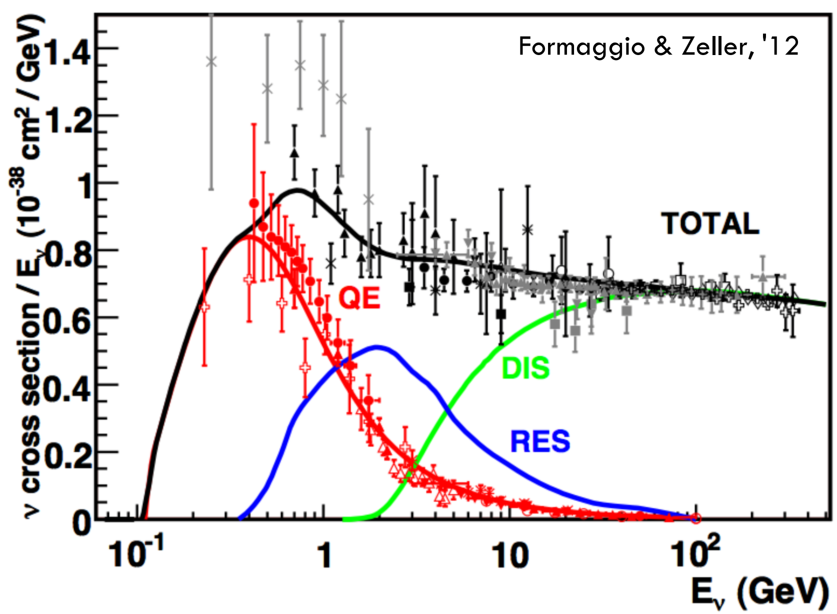
INTERACTIONS



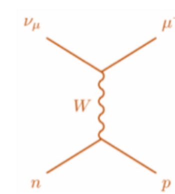
Charged Current (CC) interaction reveals the flavor from the outgoing charged lepton



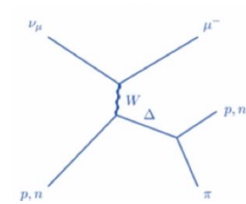
Neutral Current (NC) interactions mediated by Z boson is indistinguishable for the the 3 flavors



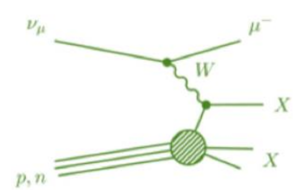
IceCube



Quasi Elastic (QE)
nucleon is left intact, charge changes for CC



Resonant (RES)
Delta resonance producing pion



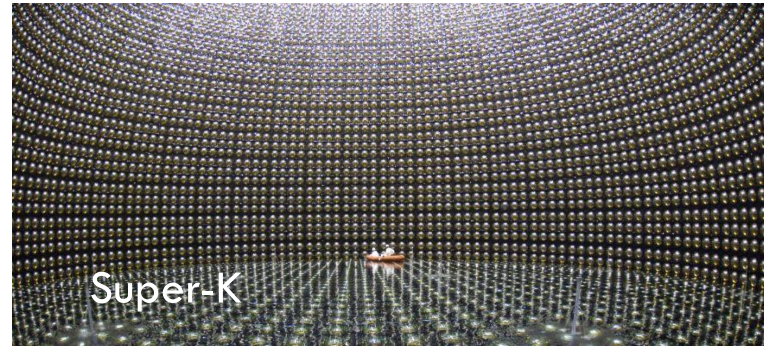
Deep Inelastic (DIS)
nucleon breaks up

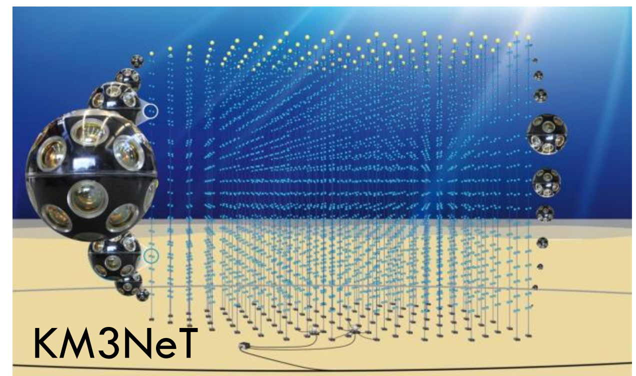
EXPERIMENTS

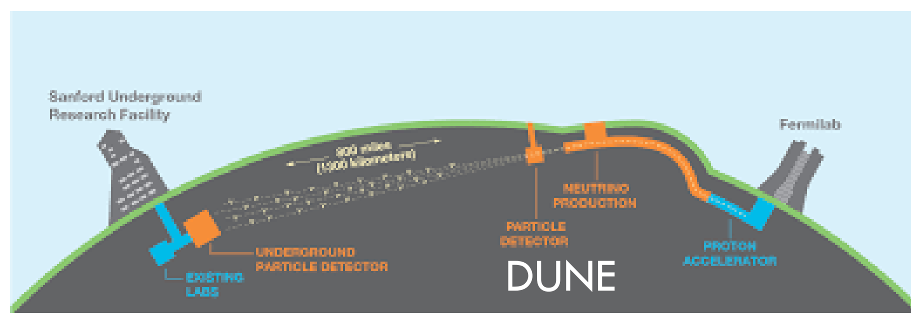
Many neutrino experiments currently exist or are under construction, just to name a few:

- Super-K & Hyper-K
- T2K, NOvA
- ANTARES/KM3NeT
- Juno
- Dune
- SNO+
- …and many more

What they all have in common is being really huge!

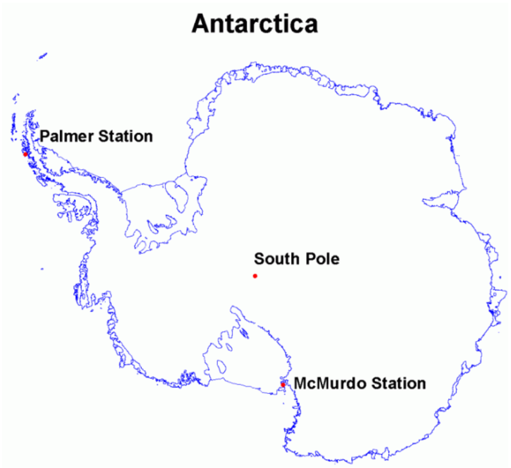


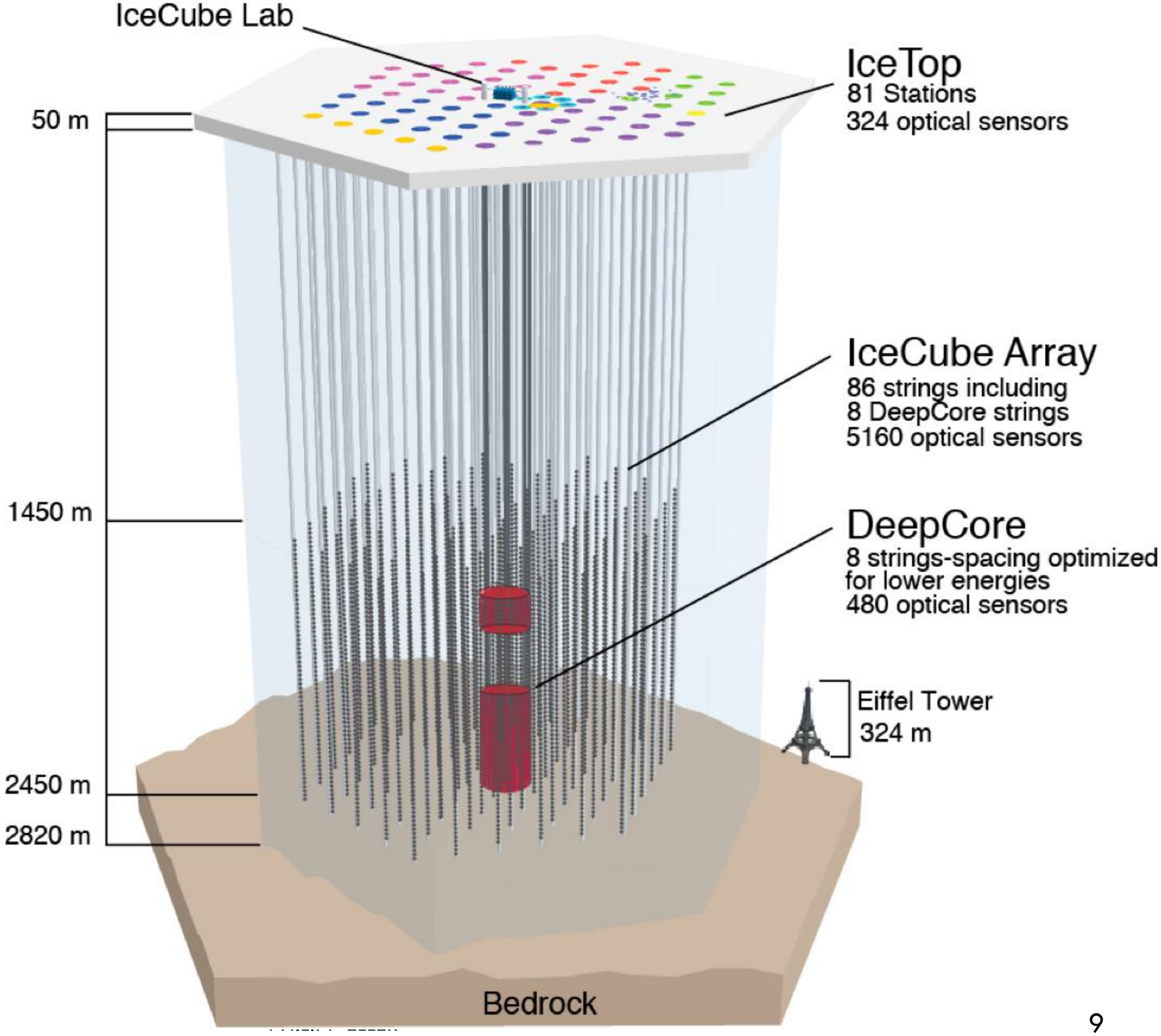




ICECUBE

ICECUBE DETECTOR

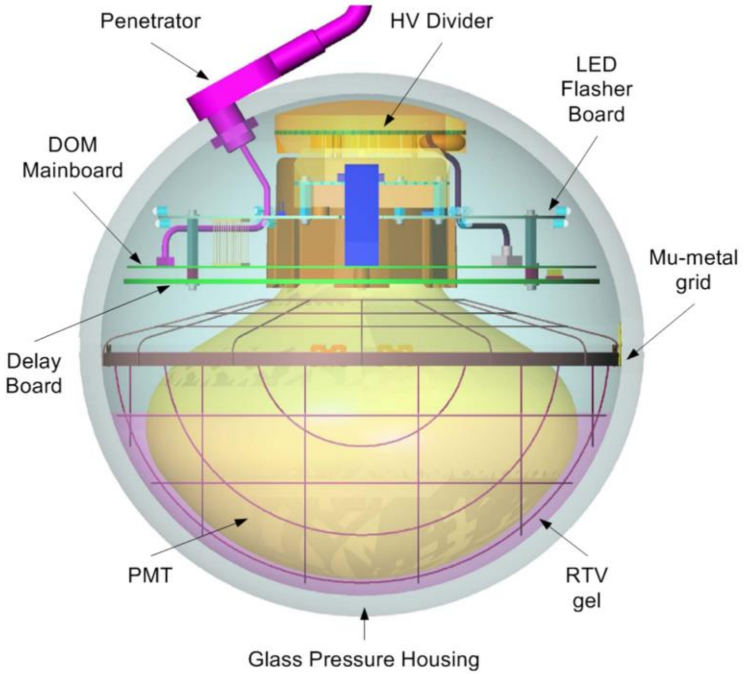


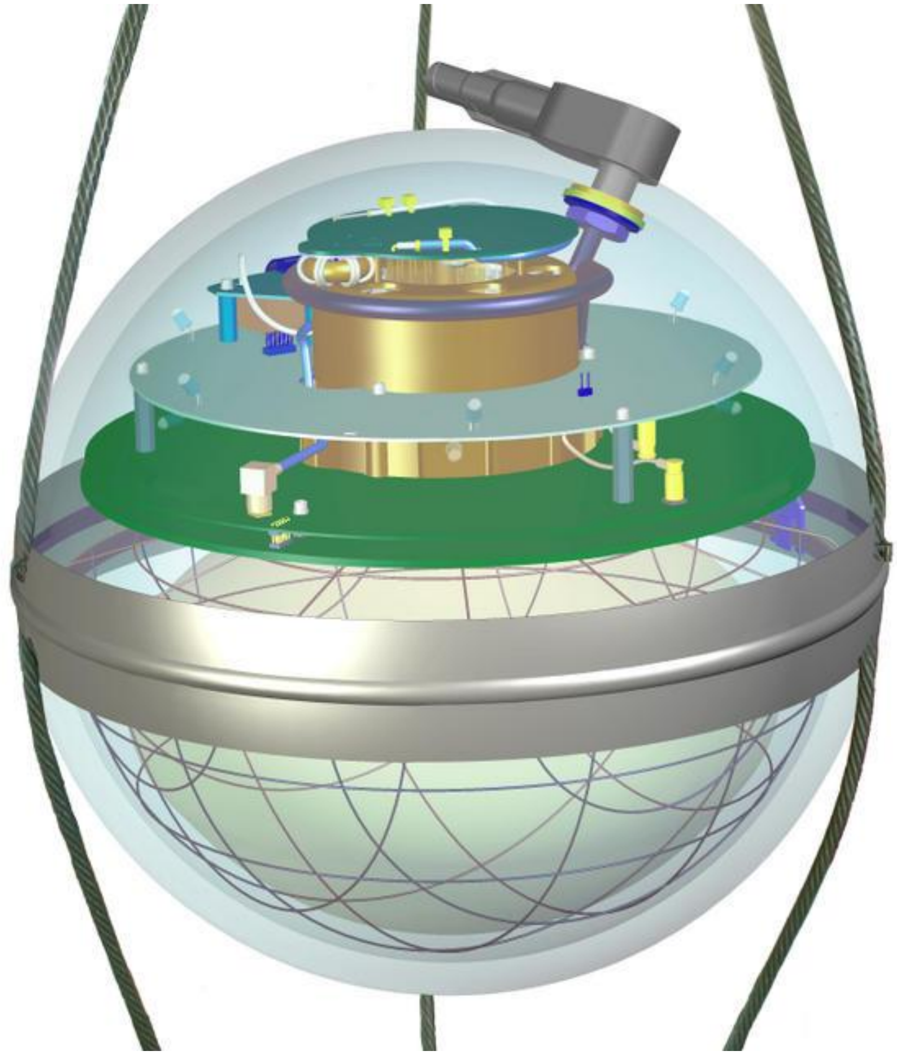


IceCube
South Pole Neutrino Observatory

DIGITAL OPTICAL MODULE

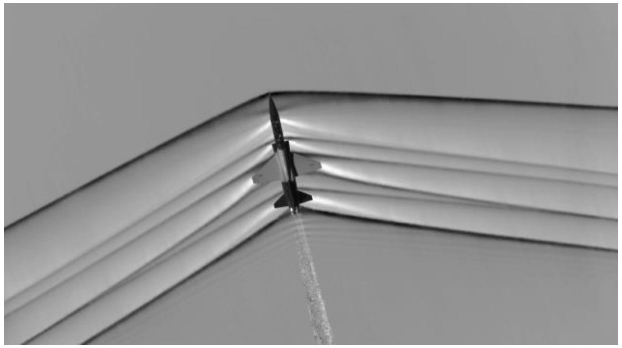
- 60 modules per string
- 10” photomultiplier tube
- Contains readout electronics
- Glass pressure housing

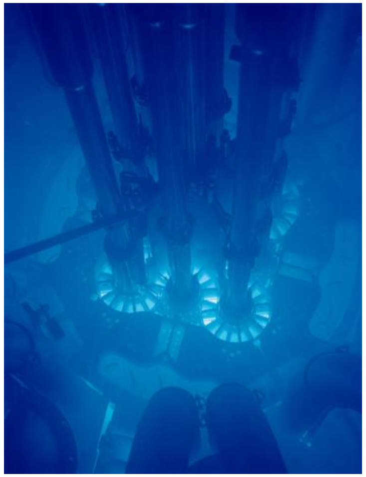


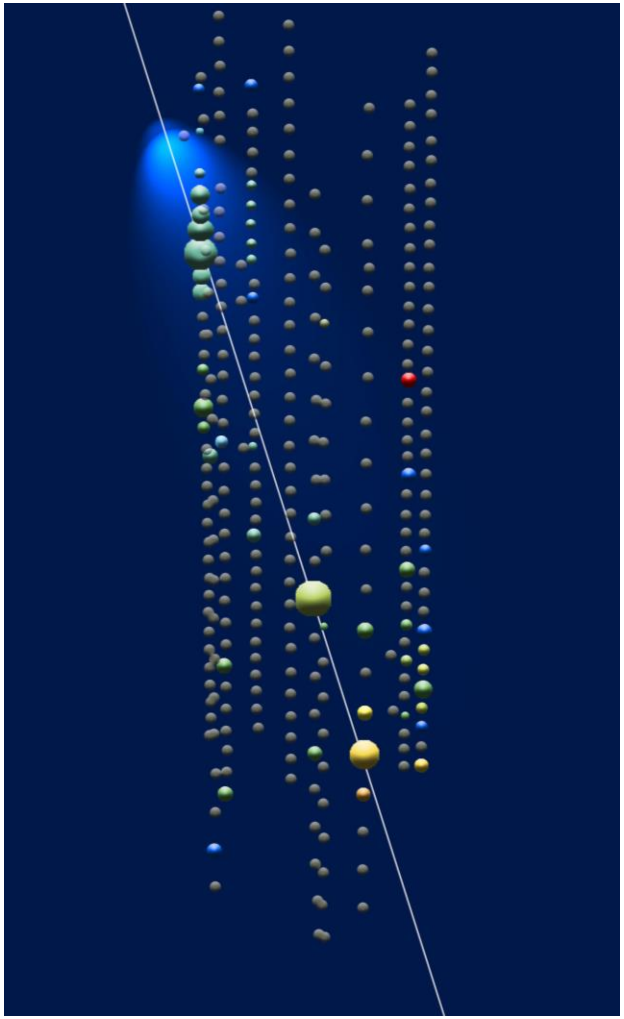


DETECTION PRINCIPLE

- A neutrino interaction will usually create a number of charged particles
- When these travel through the ice faster than light, they emit *Cherenkov* radiation
- This UV/blue light is the same as can be seen in nuclear reactors
- Optically transparent ice allows this light to reach some of the 5160 photosensitive sensors in the ice

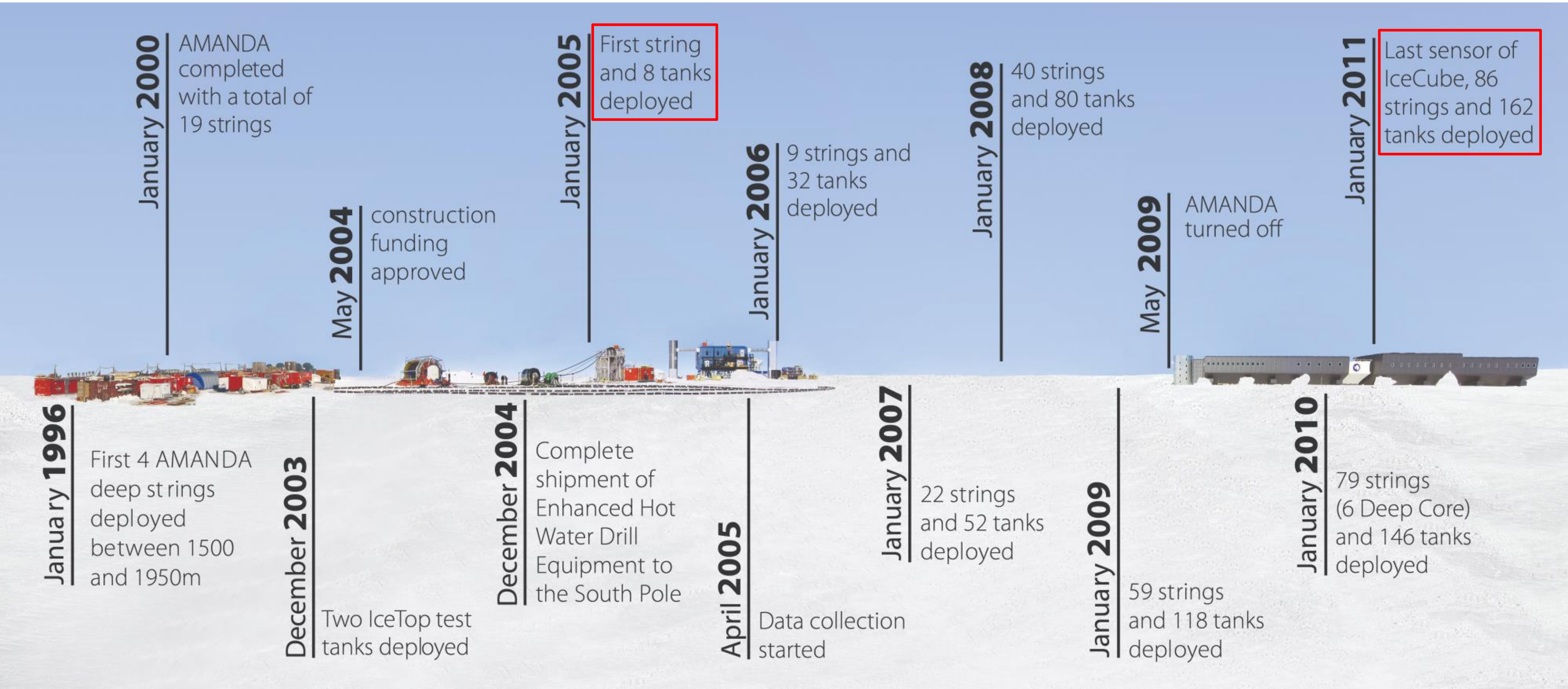






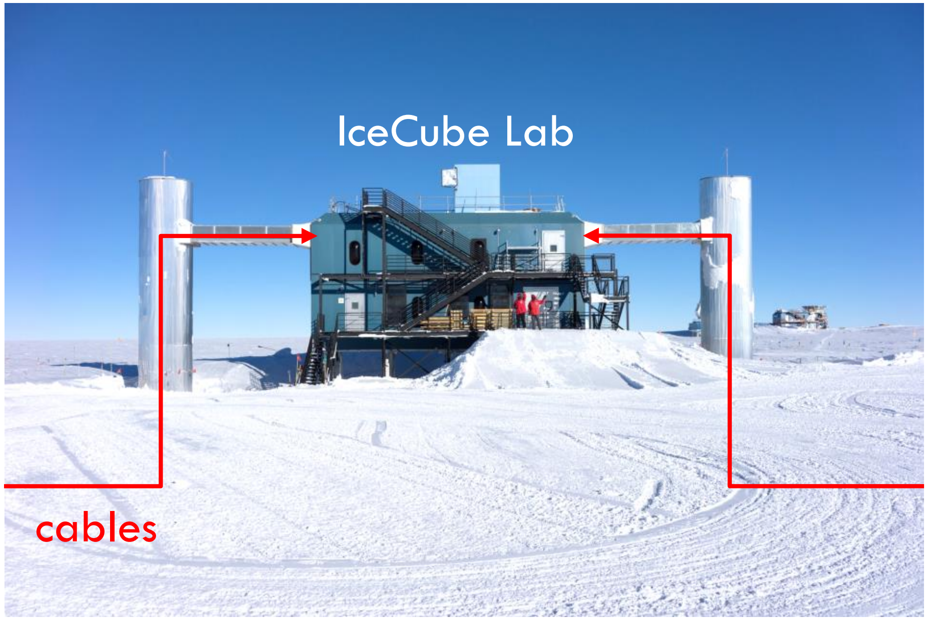
CONSTRUCTION

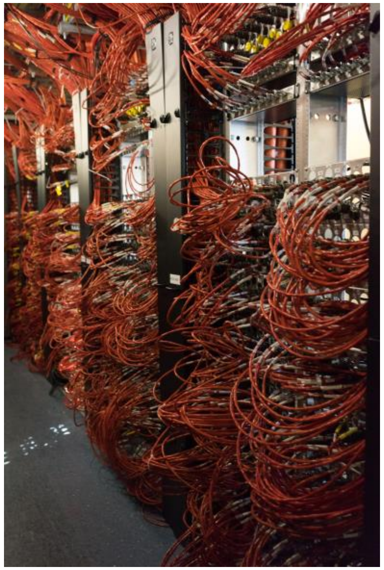
- 5 MW enhanced hot water drill, ca. 48h per hole & 21’000 l jetfuel



DAQ

- The cables of all 86 strings run together in the IceCube Lab
- On-line processing and filtering
- Detector uptime of 99.8% (!)
- Data transfer to North:
  - High priority data (e.g. alerts) can be sent 24/7 over IRIDIUM connections (very low bandwidth)
  - Usually a couple hours per day satellites with higher bandwidth are in reach, can transfer up to ~100 GB/day
  - Rest of data is literally "shipped" out on disk





EVENTS IN ICECUBE

- Every DOM gets around ~500-800 hits per second, mainly from dark noise
  - Hits from physics events are ~1 order of magnitude fewer
- Most of this is suppressed by trigger conditions
- Per year, we read out roughly:
  - **10^{10}** events caused by atmospheric muons
  - **10^{9}** events caused by noise
  - **100'000** events from atmospheric neutrinos
  - A **handful** of very high energy events likely to be of astrophysical origin
- Special triggers exist for example looking for supernovae, they monitor the overall hit rate, where a correlated increase could indicate a nearby supernova

We're around 250 scientists

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
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Technische Universität München
Universität Mainz
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University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

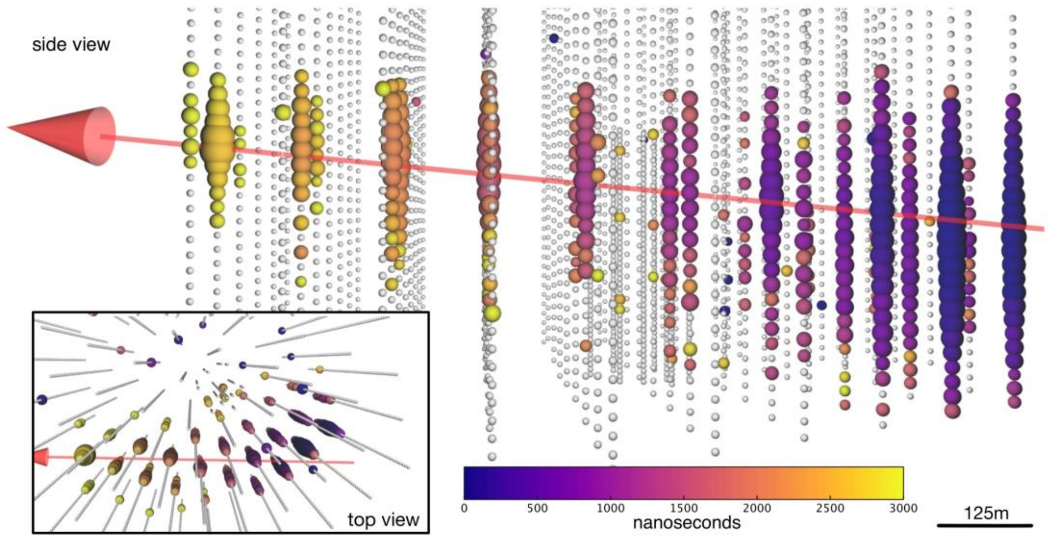
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

BERLIN

NEUTRINOS & BLAZARS

ICECUBE ALERT IC170922A

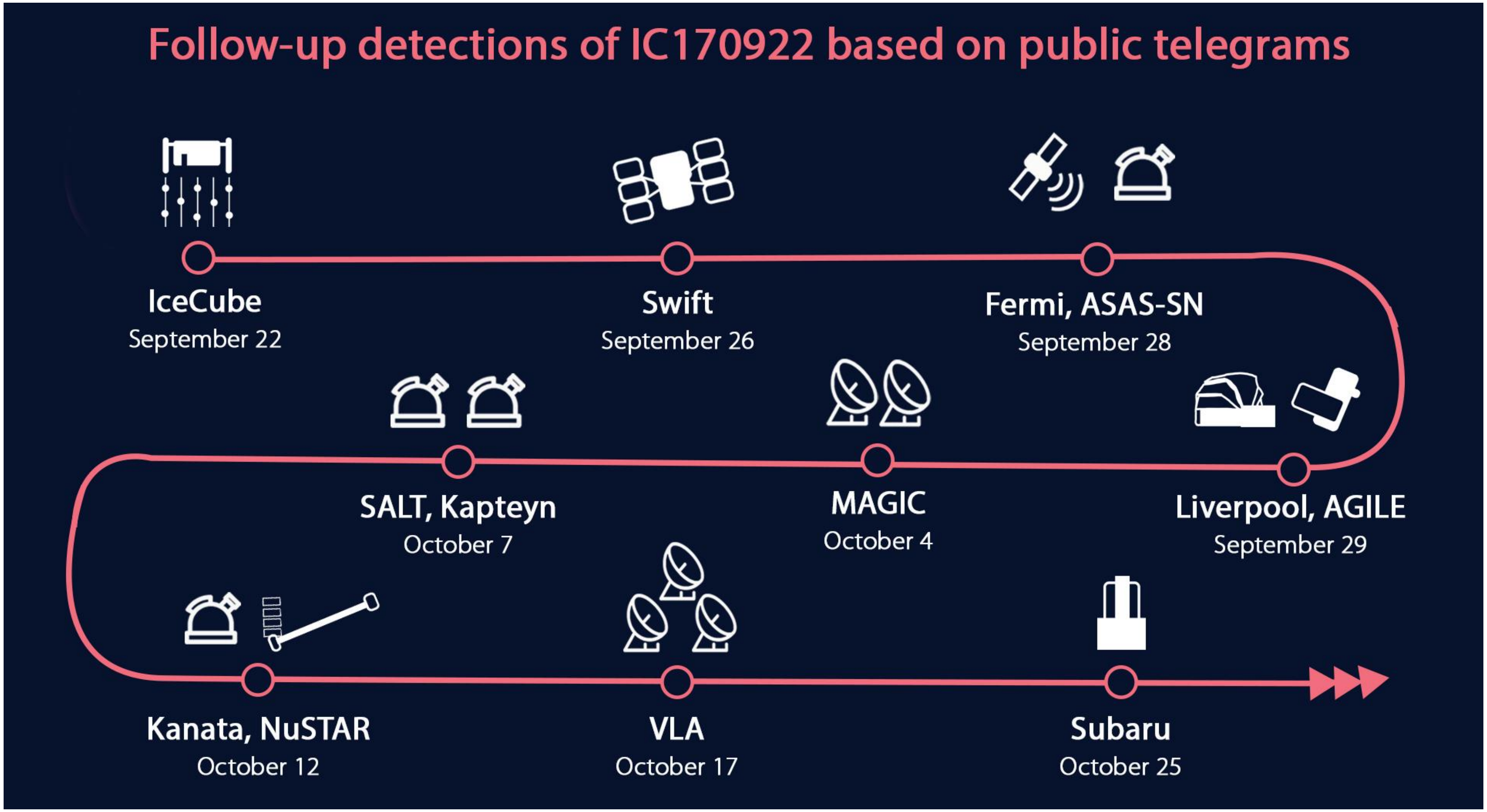
- On September 22, 2017 an extremely high energy neutrino interacted in IceCube



- An event with estimated energy of around 290 TeV and high “signalness”
- Location of origin in the sky was narrowed down to roughly 1 degree
- An alert was sent out worldwide after 43 seconds
- 4h later a GCN circular was sent out including a refined reconstruction

FOLLOW UP CAMPAIGN

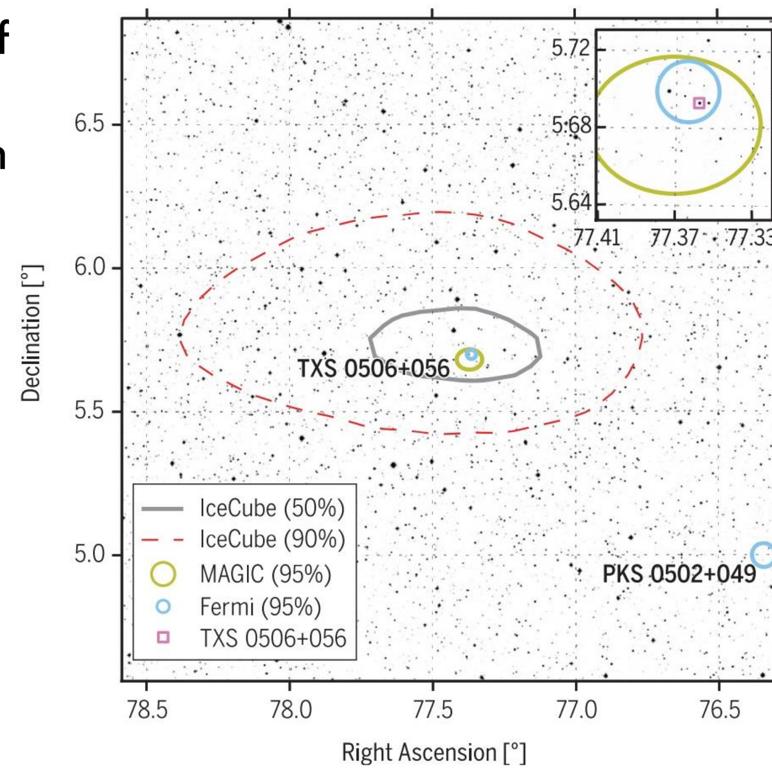
- A global follow-up campaign of the event by many different observatories happened over the following weeks…

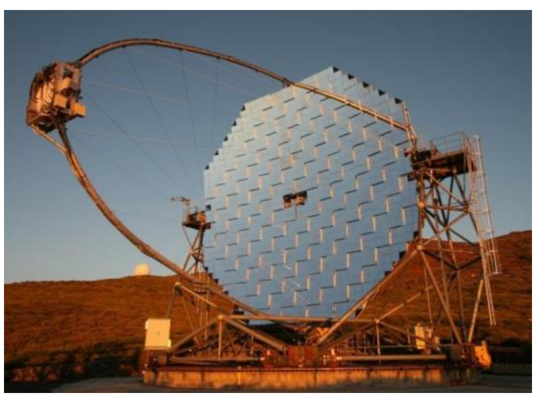


COINCIDENCE WITH FLARING BLAZAR

- FERMI LAT detected the Blazar *TXS 0506-056* in this area to be in a state of high gamma-ray activity (flaring)

- This blazar is situated in the night sky just of the left shoulder of the constellation Orion and is about 4 billion light years from Earth

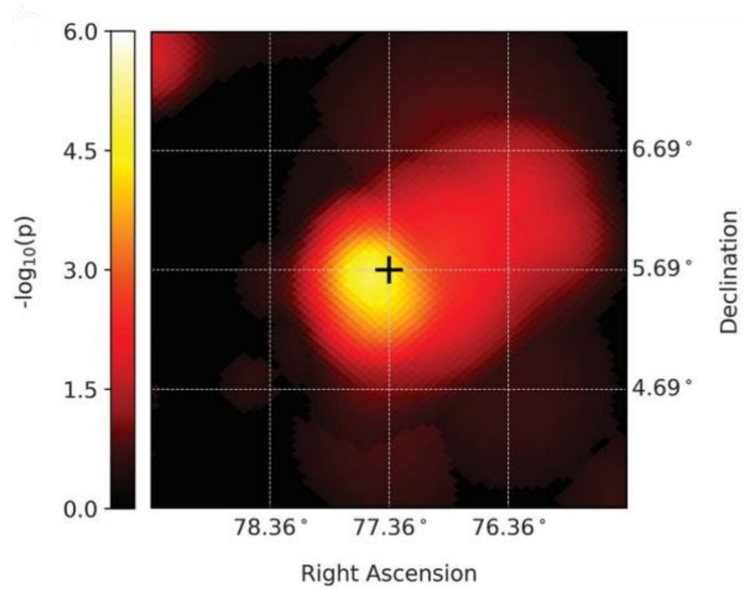


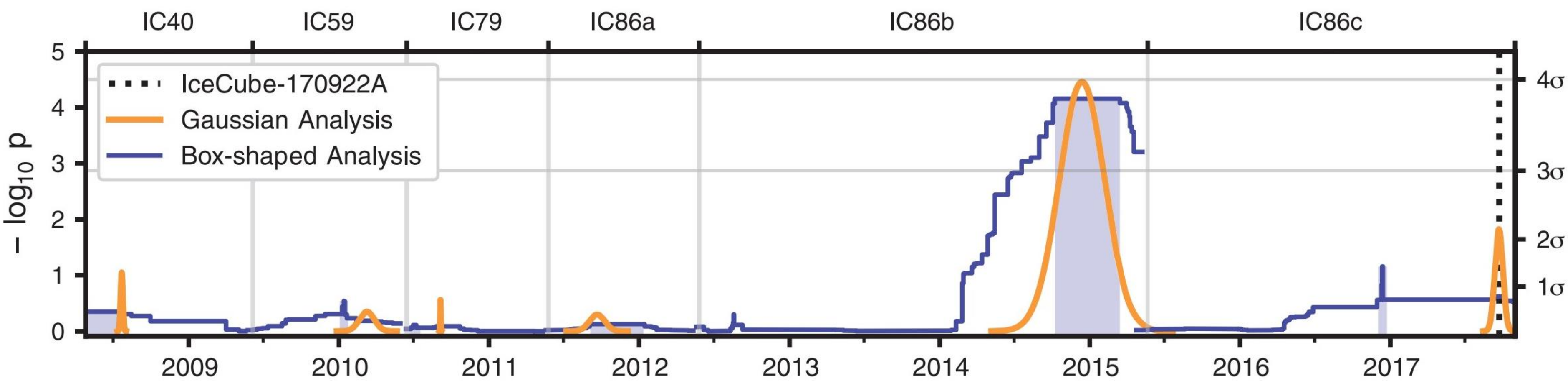


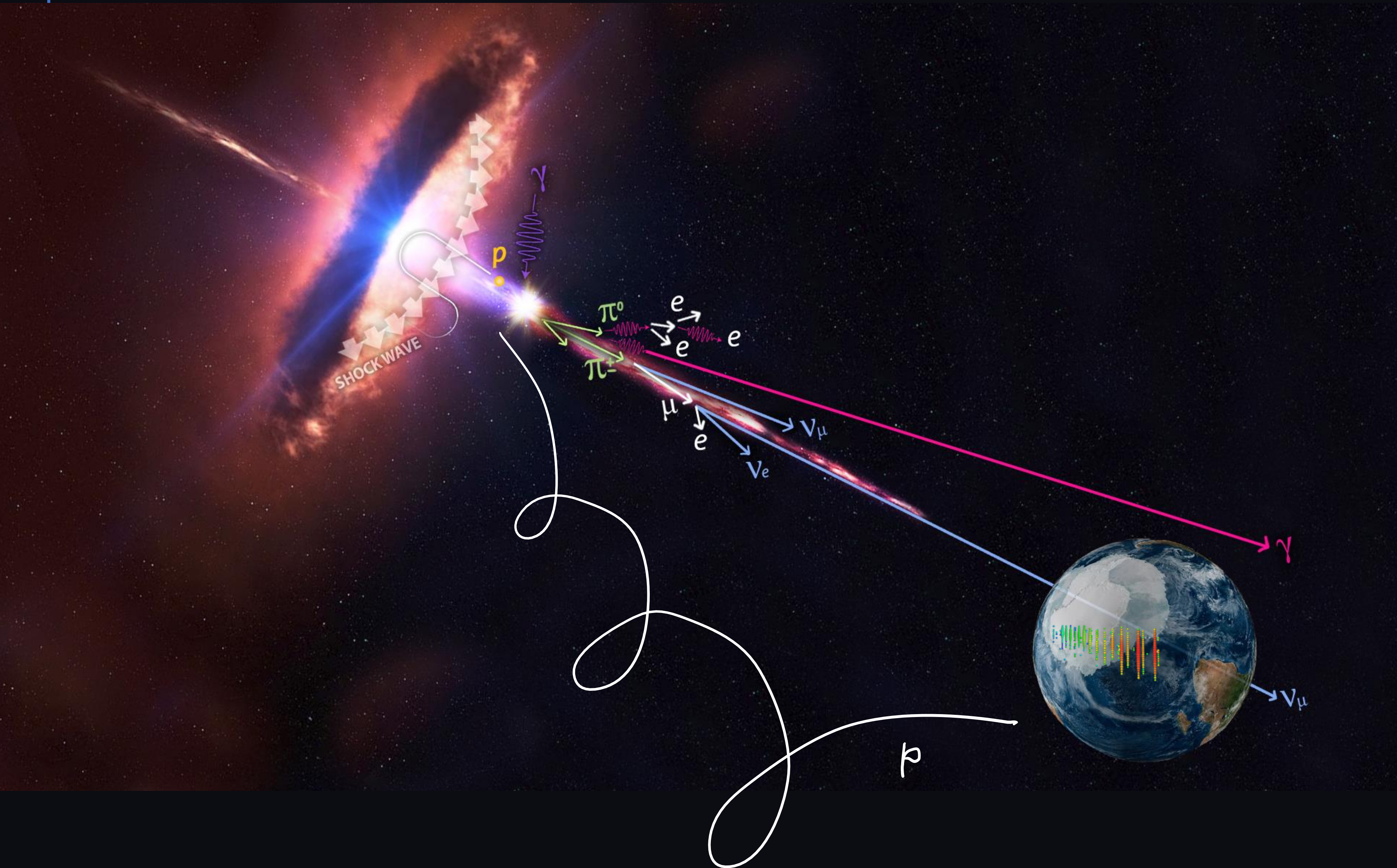
The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope detected gamma-ray flux from this location of up to 400 GeV

HISTORIC DATA

- As we have ~10 years of IceCube data, we wanted to go back an search if there was any clustering of (lower energy) events coming from the same location
- Found 13 ± 5 events above background clustered around December 13 2014

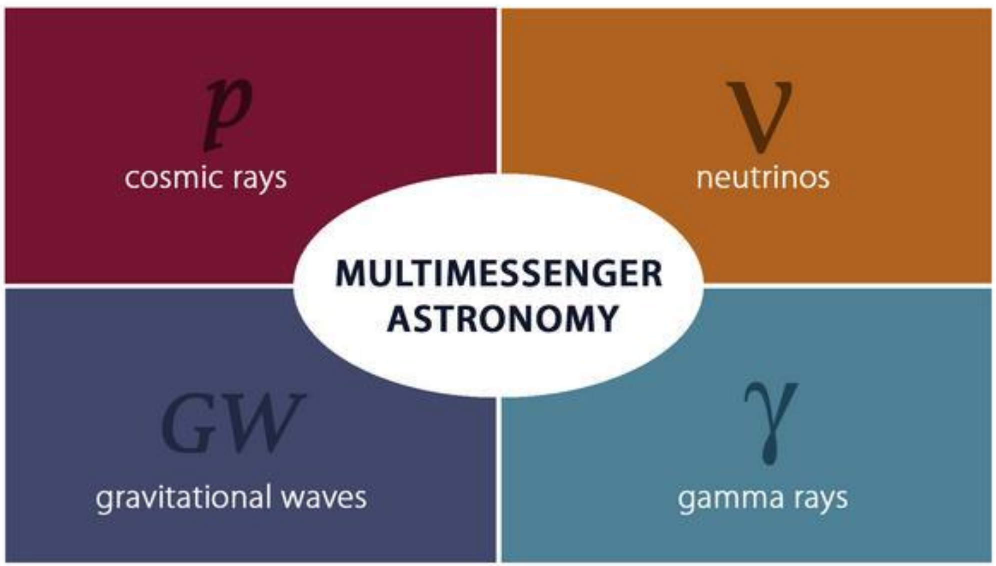





γ
p
SHOCK WAVE
π⁰
π±
e
e
e
μ
e
νμ
νe
γ
νμ
p

NEUTRINOS AND BLAZARS

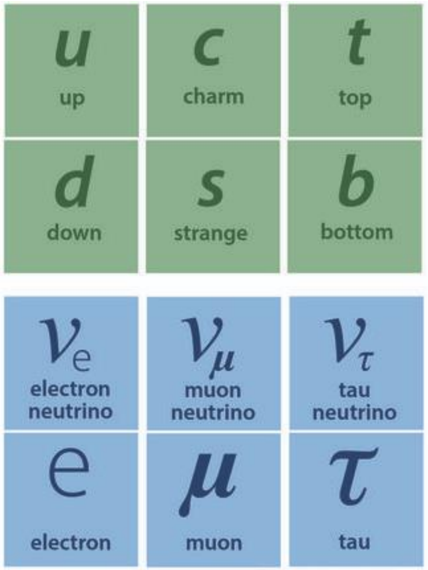
- An important piece in the puzzle of understanding the origin of cosmic rays
- A new chapter in multi-messenger astronomy

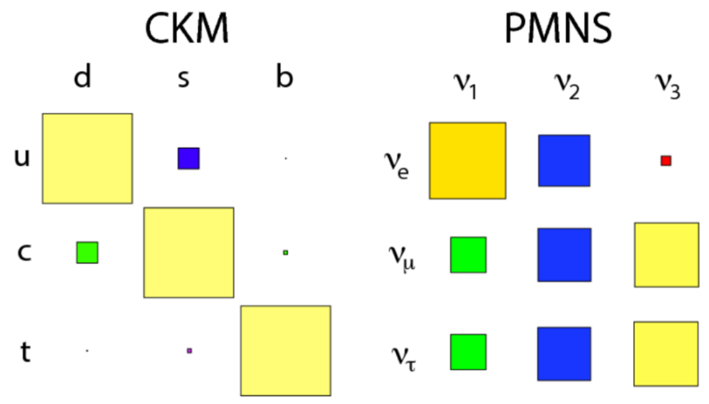


NEUTRINO OSCILLATIONS

NEUTRINO MIXING

- Neutrinos come in three flavours (just like other fermions)
  - These eigenstates are what neutrinos are interacting in, mediated via the weak force (Z/W)
- But, one could instead also look at the mass eigenstates
  - Where the Hamiltonian becomes diagonal (→ propagation)
- Now these two bases are not the same
  - As in the quark sector, matrix to rotate from one basis into the other
  - For quarks (CKM) at first order diagonal
  - For neutrinos (PMNS) there is no such structure





https://arxiv.org/abs/1212.6374

NEUTRINO OSCILLATIONS

- A consequence of this mismatch of flavor and mass eigenstates is neutrino oscillations

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

- Example: simplest 2-flavor, vacuum oscillation probability:

Mass eigenstates

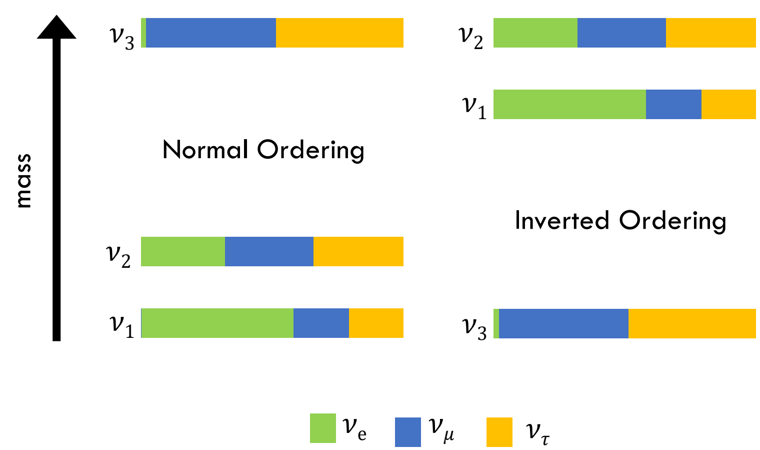
$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$

Length

Energy

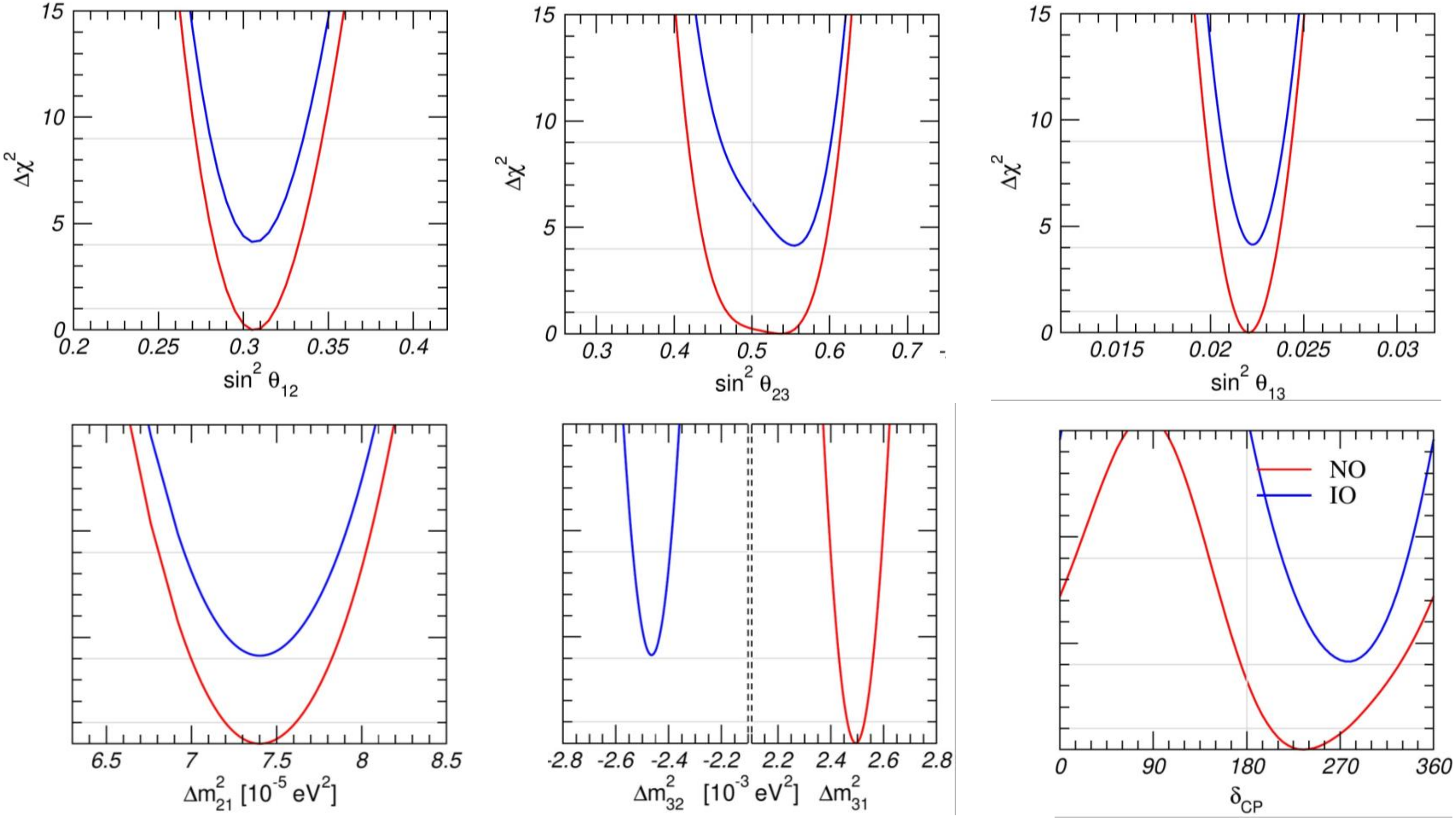
From mixing matrix

- Observing oscillation implies that neutrinos must have non-zero, and different masses
  - Absolute mass scale not accessible
  - Has been established that $m_2 > m_1$ ✓
  - We don't know yet whether m_3 is largest or smallest (NMO) ✗

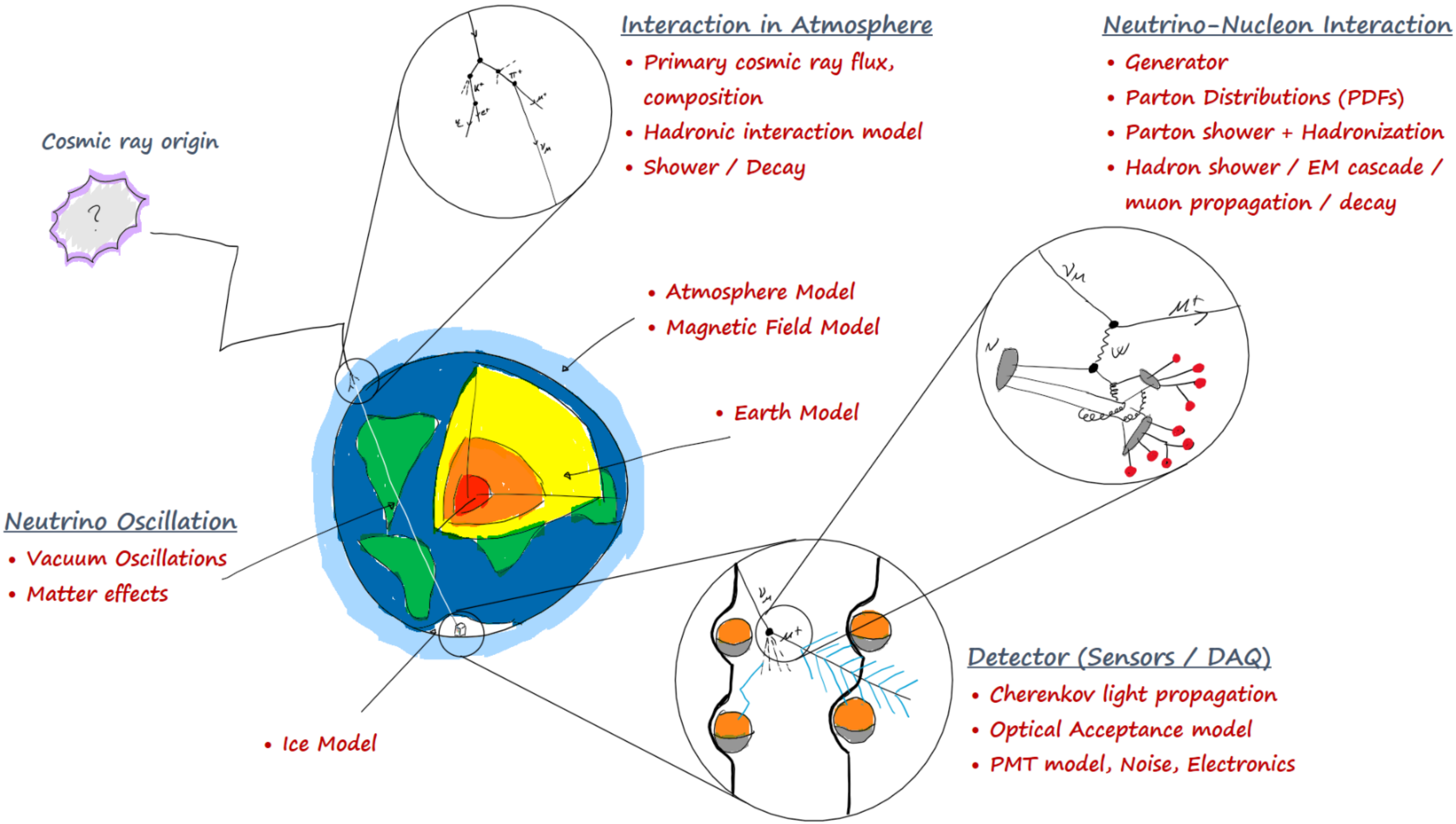


CURRENT EXPERIMENTAL STATUS

- From NuFIT v3.2 (2018) http://www.nu-fit.org/?q=node/166



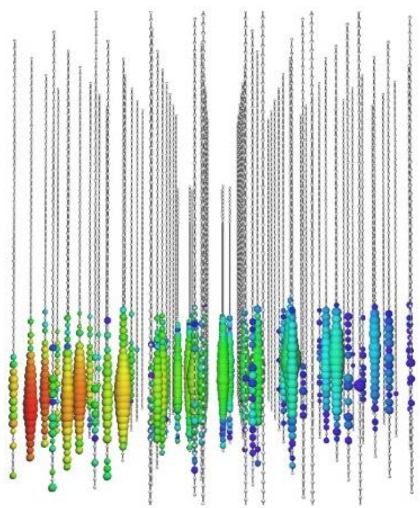
INGREDIENTS



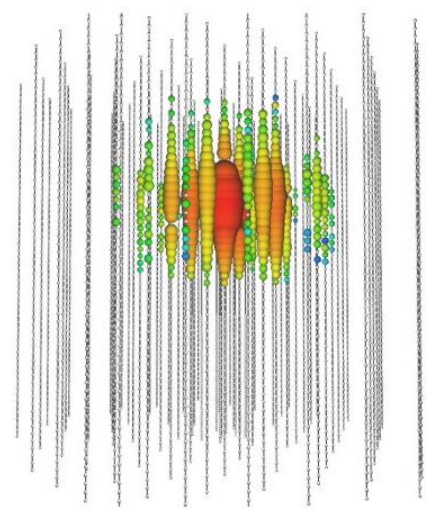
SIGNATURES

- Depending on the neutrino interaction & flavour, we expect certain signatures in our detector

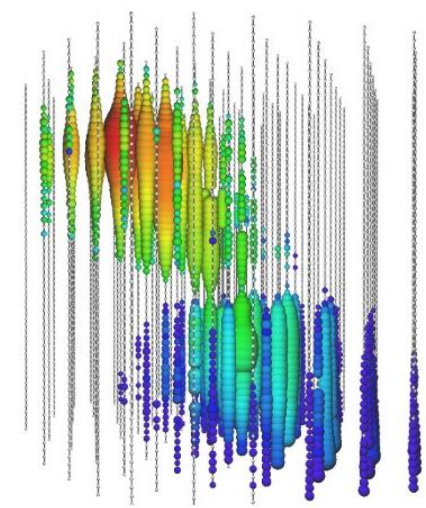
Tracks: mainly numu CC interactions or atmospheric muons, which both have an extended muon track

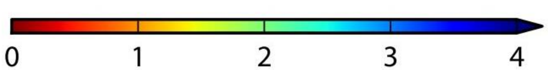


Cascades: nue and nutau, as well as NC interactions that cause more compact charge deposits



"Double Bang": very high energy taus are boosted enough to travel a sizeable distance before decay (~50m/PeV), creating a second, distinct shower

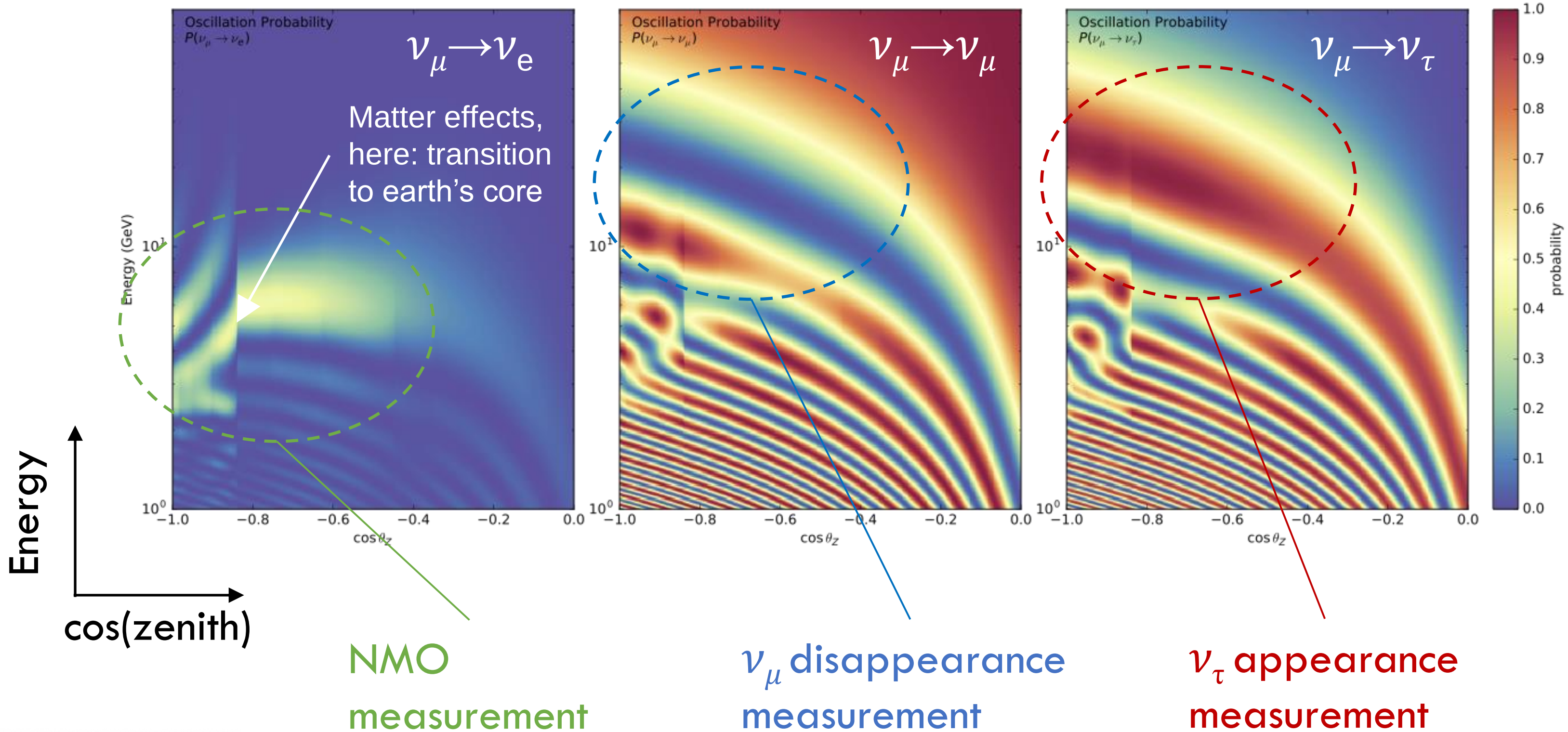




LOW ENERGY ATMOSPHERIC NEUTRINOS

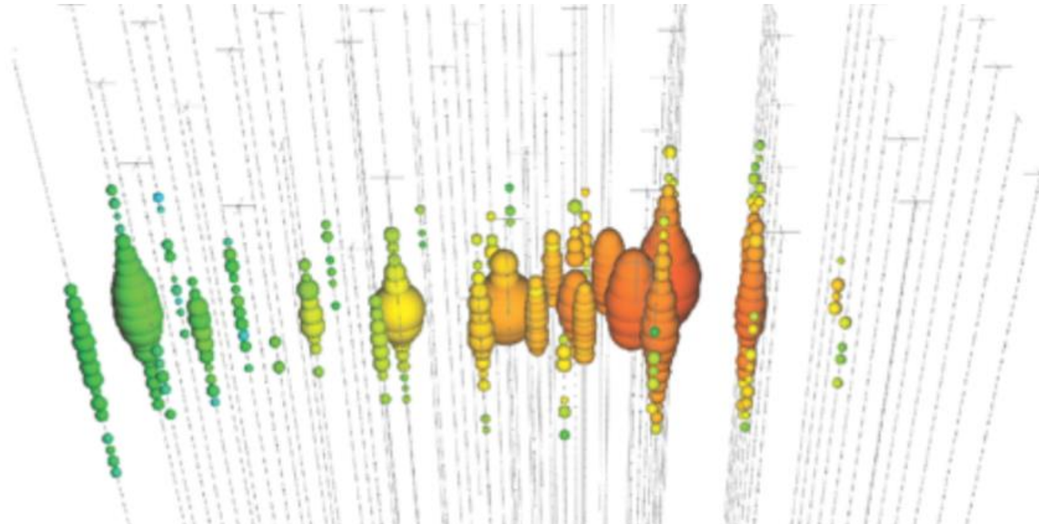
- For O(10) GeV neutrinos and below, earth diameter provides perfect L/E
- We can look at oscillations in the energy-cos(zenith) (∝ E-L) plane

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$



GOING LOWER IN ENERGY

~100m

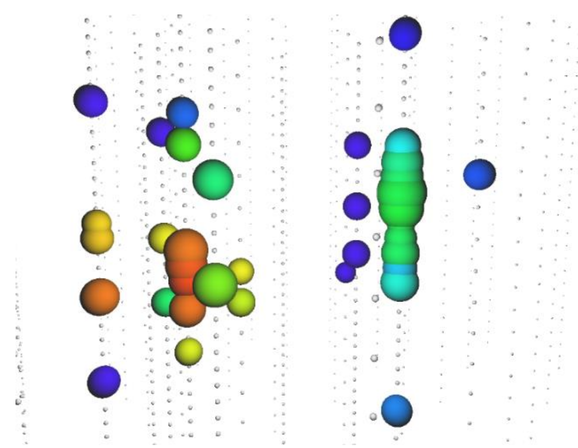


The typical TeV-PeV IceCube event:

- Photons from secondary particles arriving in many strings and modules
- Very clear, extended signature

The typical GeV DeepCore event:

- Photons from secondary particles arriving in few strings, tens of sensors
- Almost impossible to see “by eye” what event it was

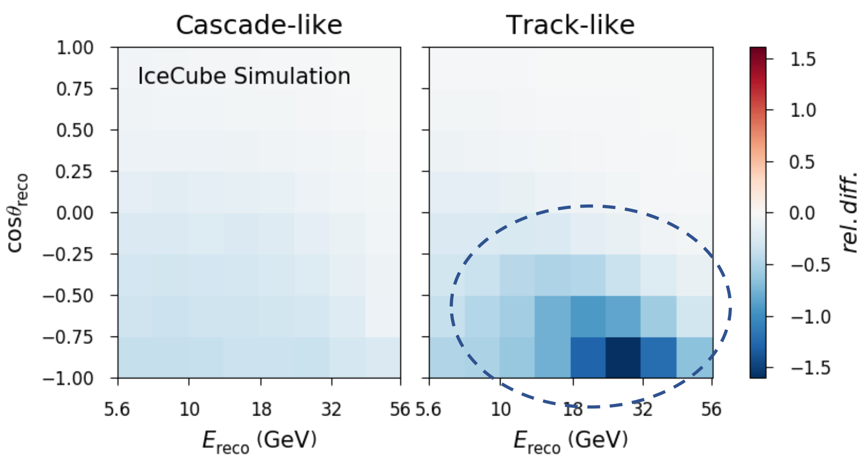


~35m

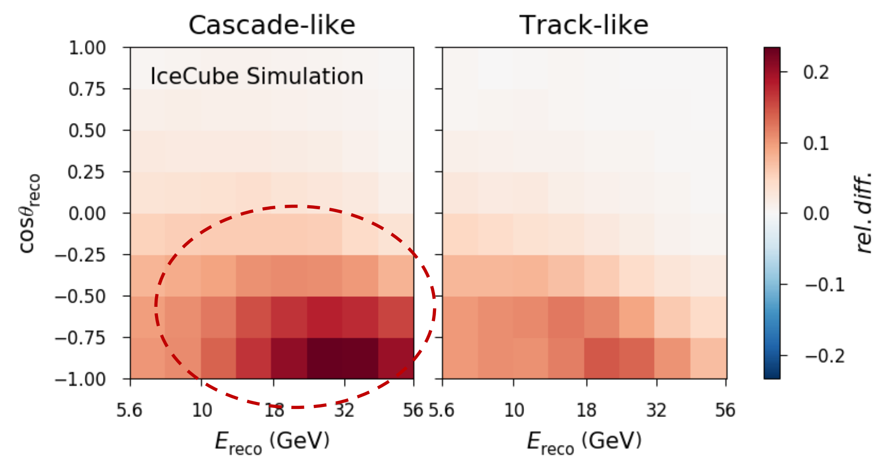
ICECUBE South Pole Neutrino Observatory

ACTUAL SIGNAL

- ν_μ disappearance fit:
  - **Deficit** of events compared to the non-oscillation case
  - mostly visible in the tracks channel
  - For upgoing events, concentrated around the first oscillation maximum of ~25 GeV



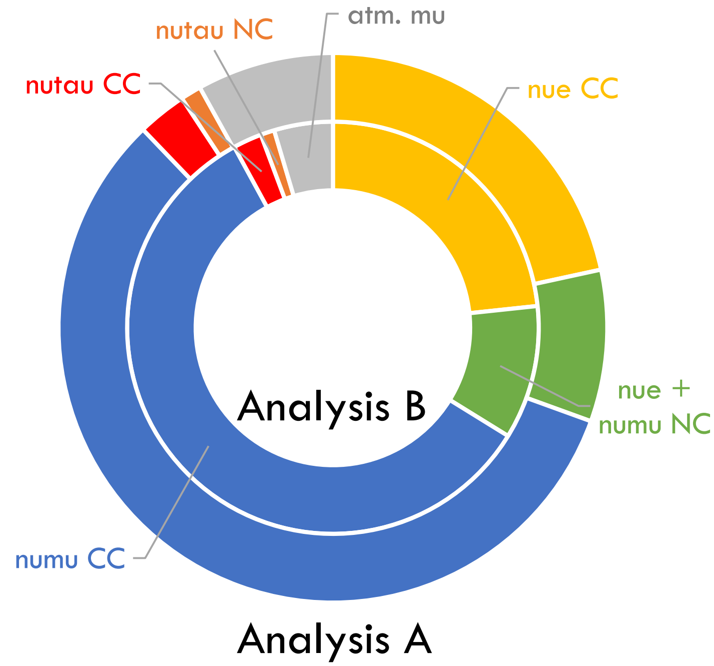
- ν_τ appearance fit:
  - **Excess** of events in the cascades channel compared to the non-appearance case
  - Effect ~order of magnitude suppressed compared to disappearance
  - Slightly worse resolution for cascades than for tracks



DATA SAMPLE

- New DeepCore results are based on 3 years of data

Type	Analysis $\mathcal{A}$ Events	$\pm 1\sigma$	Analysis $\mathcal{B}$ Events	$\pm 1\sigma$
$\nu_e + \bar{\nu}_e$ CC	13462	29	9545	23
$\nu_e + \bar{\nu}_e$ NC	1096	9	923	8
$\nu_\mu + \bar{\nu}_\mu$ CC	35706	48	23852	39
$\nu_\mu + \bar{\nu}_\mu$ NC	4463	19	3368	17
$\nu_\tau + \bar{\nu}_\tau$ CC	1804	9	934	5
$\nu_\tau + \bar{\nu}_\tau$ NC	556	3	445	4
Atmospheric μ	5022	167	1889	45
Noise Triggers	93	27	< 9	2
total (best fit)	**62203**	**180**	**40959**	**68**
observed	**62112**	**249**	**40902**	**202**

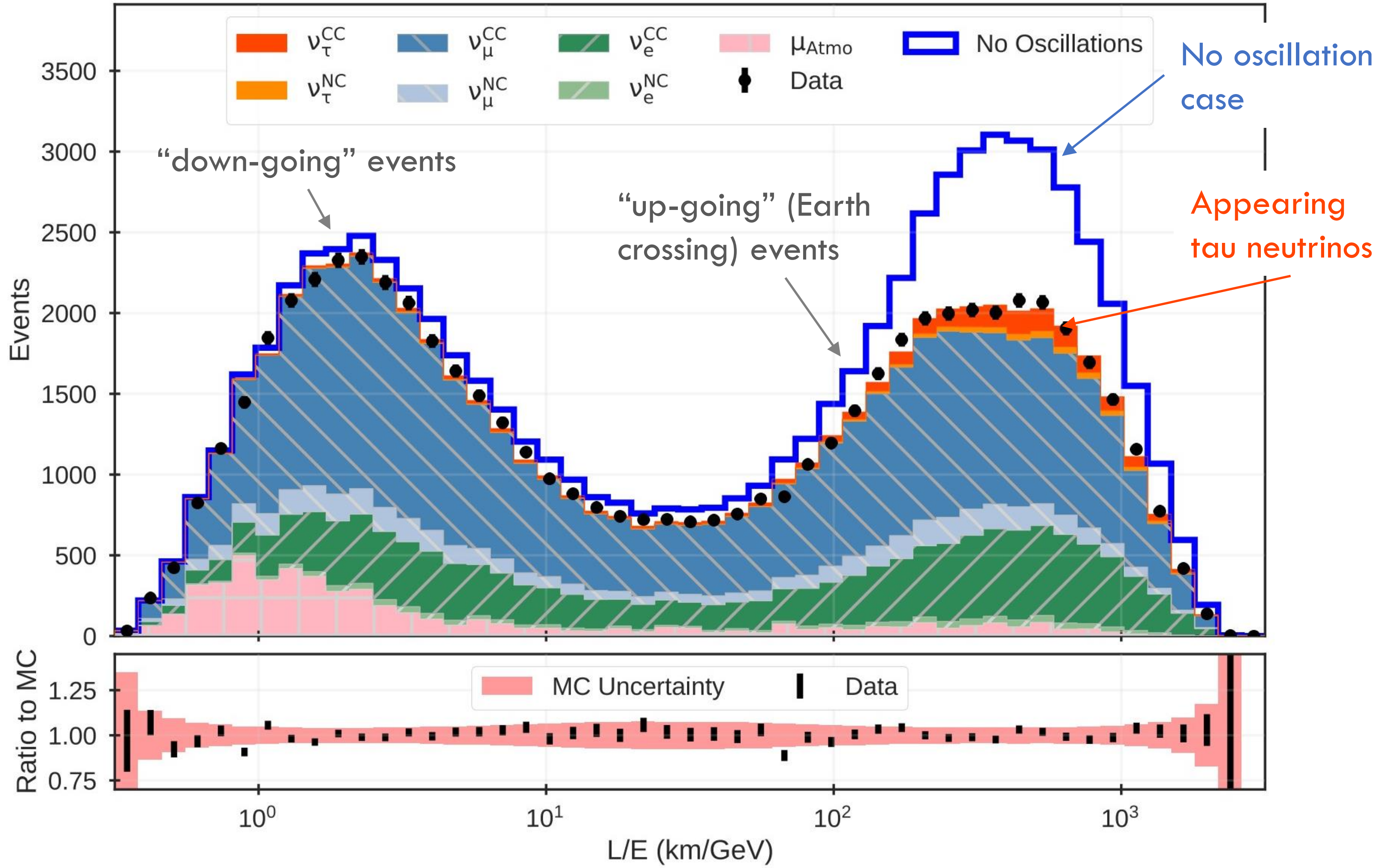


- Excellent data/MC agreement
  - Goodness of fit (p-value) ~20-60%

EVENT DISTRIBUTIONS

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2 L}{4 E_\nu}$$

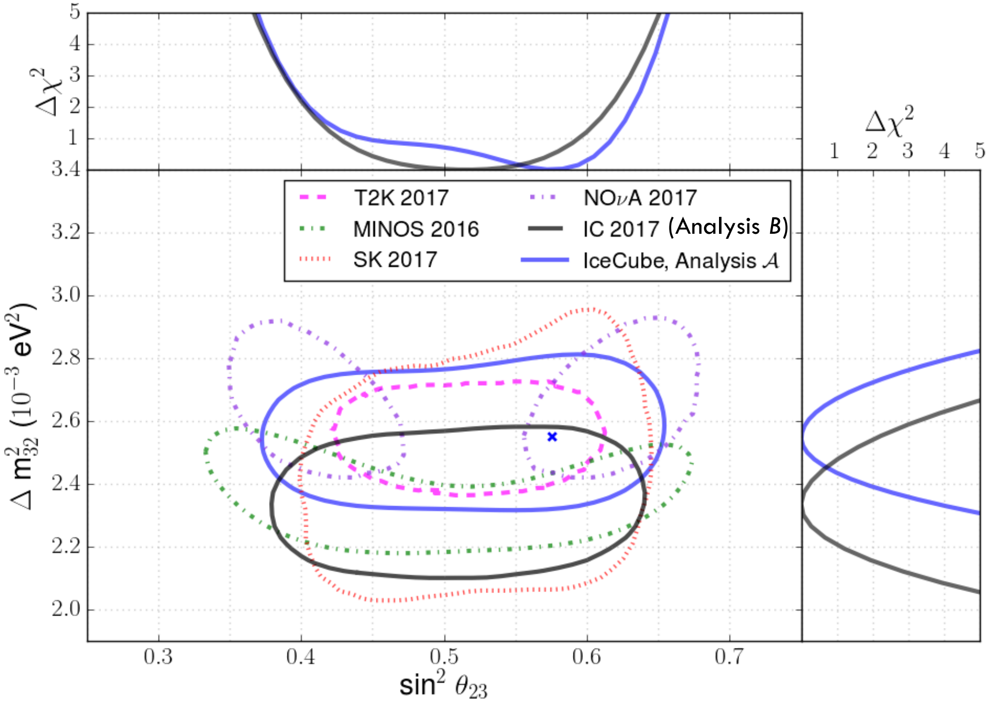
- Projection of events onto the L/E axis



NUMU DISAPPEARANCE RESULTS

- Constraining the atmospheric mixing parameters theta_{23} and dm^2_{32}
- Competitive precision with long baseline experiments

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$



https://arxiv.org/abs/1707.07081

Analysis A best-fit point:

$\sin^2\theta_{23} = 0.58 + 0.04 - 0.13$

$\Delta m^2_{32} = 2.55 + 0.12 - 0.11 \times 10^{-3}\ \text{eV}^2$

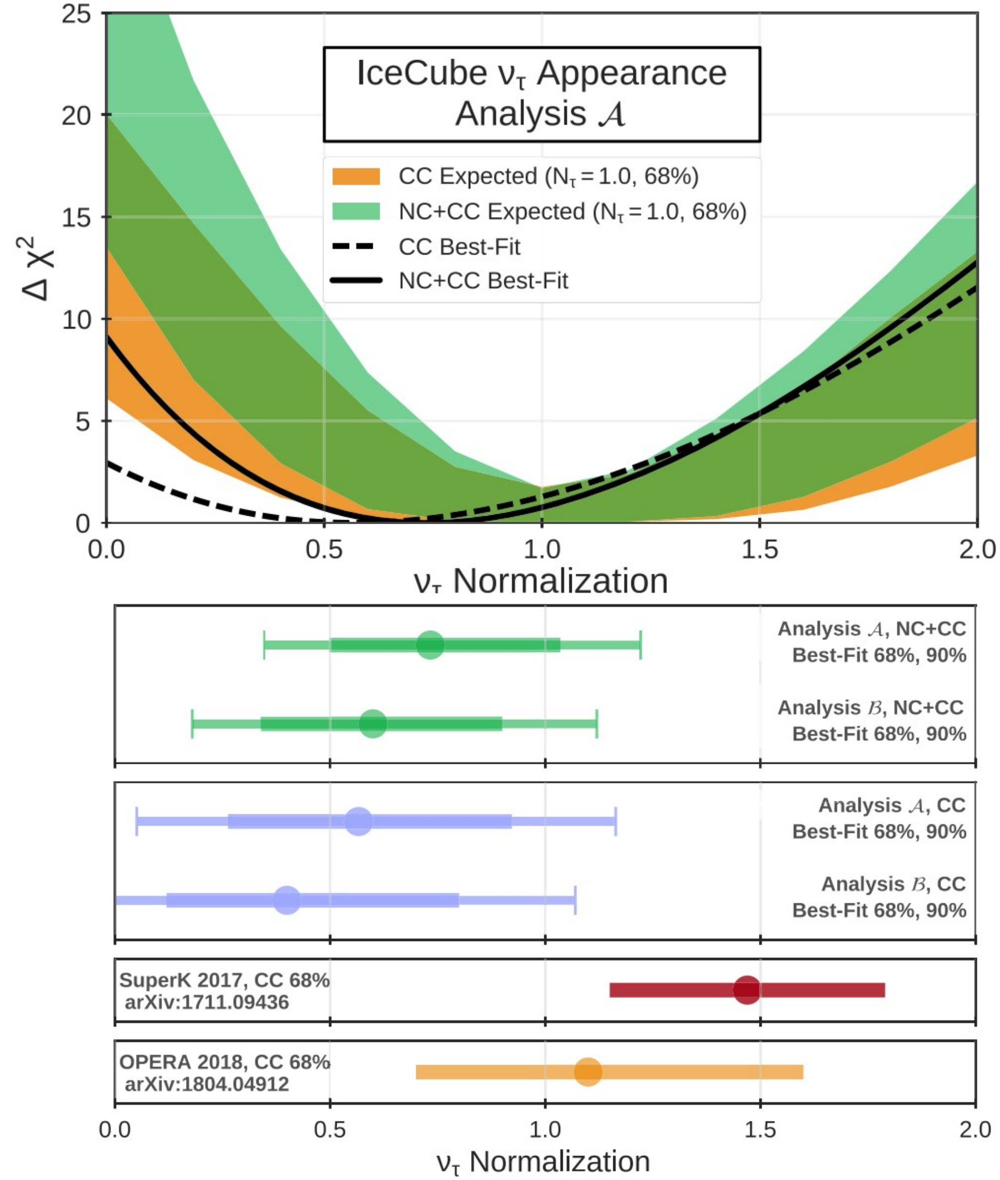
Analysis B best-fit point:

$\sin^2\theta_{23} = 0.51 + 0.07 - 0.09$

$\Delta m^2_{32} = 2.31 + 0.11 - 0.13 \times 10^{-3}\ \text{eV}^2$

NUTAU APPEARANCE RESULT

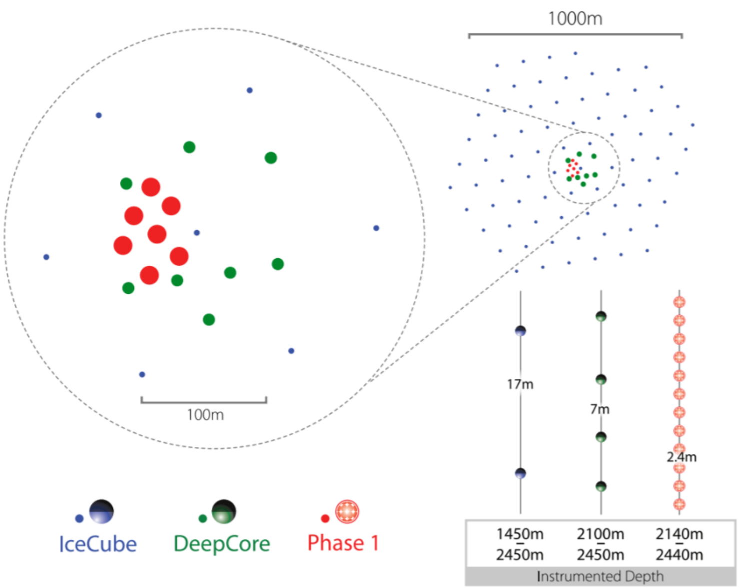
- Quantifying the appearance of tau neutrinos
- ν_τ normalization:
  - 0 = absence of tau neutrinos
  - 1 = SM expectations
- Similar analyses by OPERA and Super-K
- Difference form 1 could indicated:
  - Non-unitarity of mixing
  - Modification of cross section



WHAT THE FUTURE HOLDS

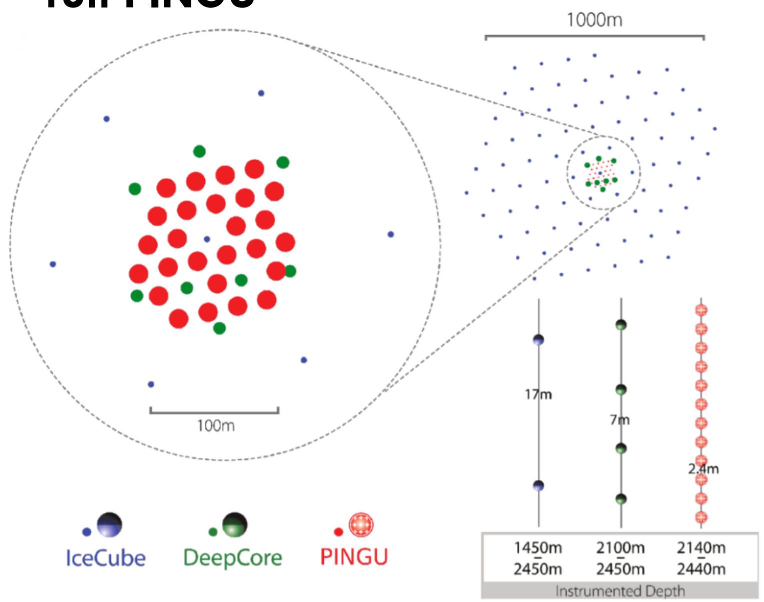
ICECUBE UPGRADE & PINGU

IceCube Upgrade, Phase 1 (funded)



7 additional strings with different DOMs

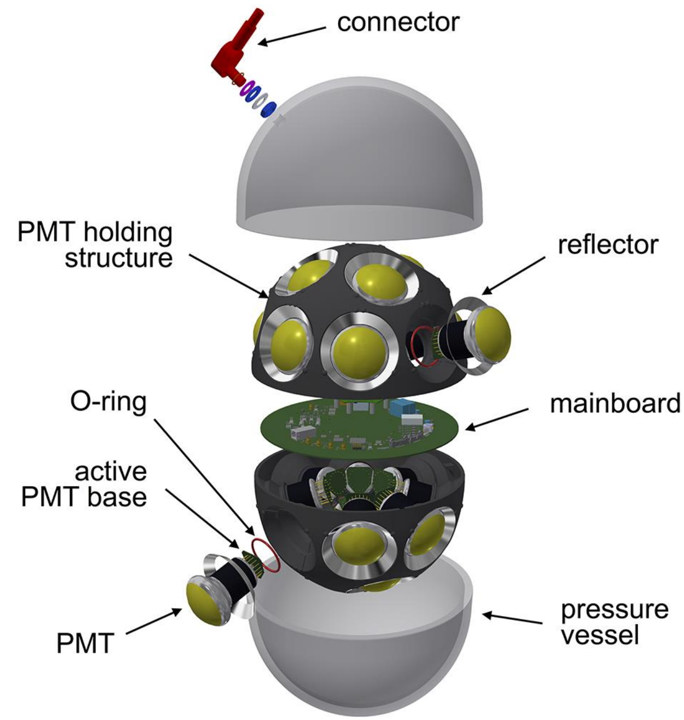
full PINGU



26 strings with ~100 DOMs each

THE NEW SENSORS

- New sensor designs with multiple PMTs, here 21 3” PMTs
  - 4pi coverage, large photocathode area



  - A second design with two large PMTs will also be used

CALIBRATION DEVICES

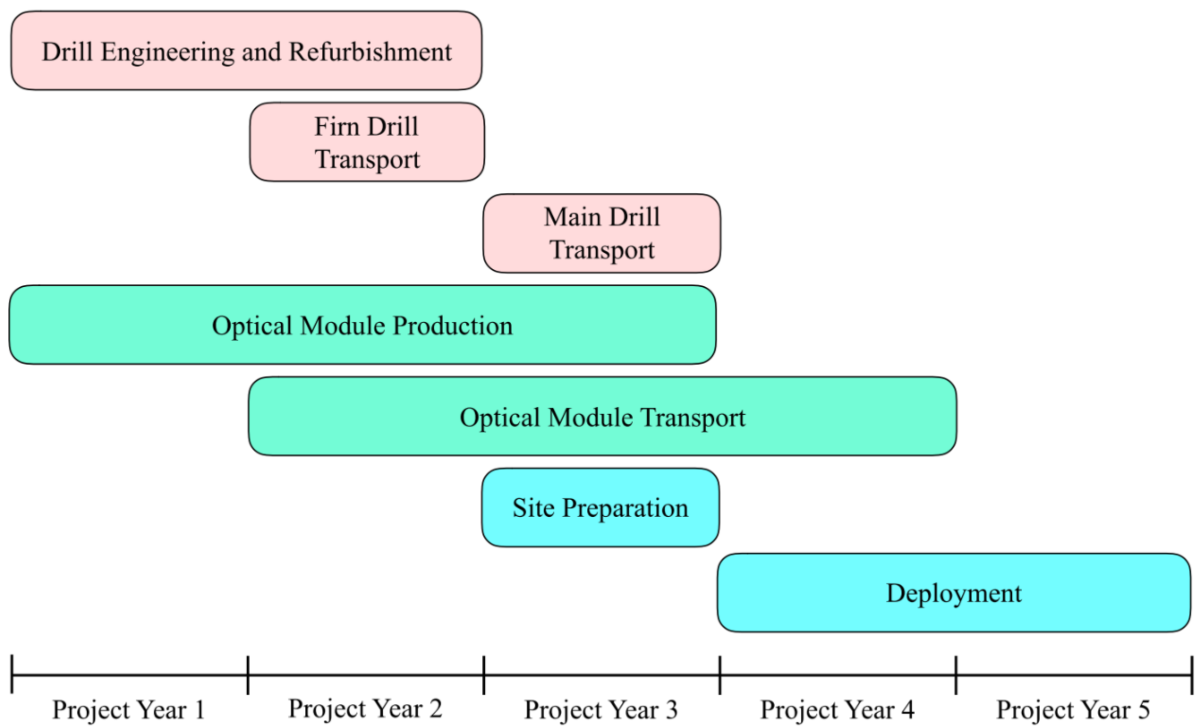
- New calibration devices will be installed
  - Stand-alone Isotropic light sources
  - Integrated LED flashers and
  - Camera systems in every DOM
- Help to understand the optical properties of the ice

POCAM (Precision Optical Calibration Module)

CCD and CMOS prototype boards

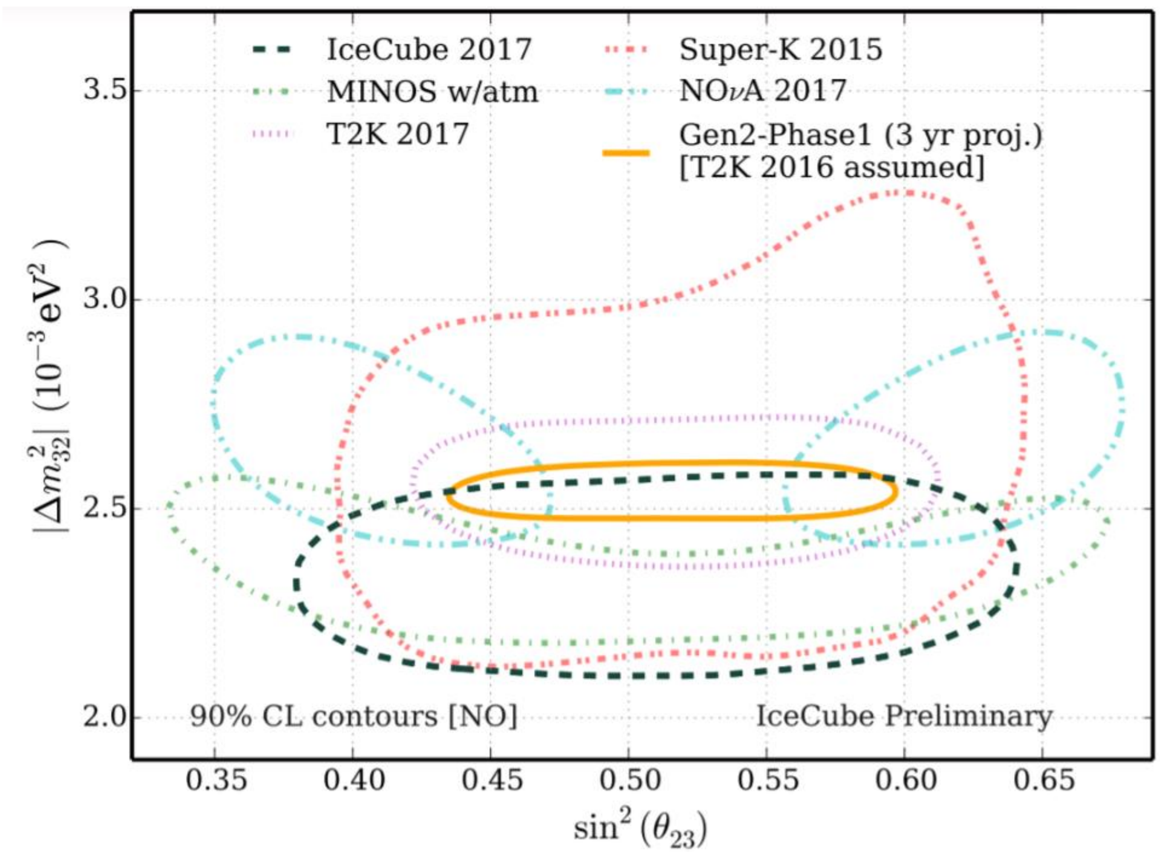
TIMELINE

- 7-string upgrade approved by NSF, deployment planned for 2022/23
- Rough timeline (here for “full” PINGU = even more strings)



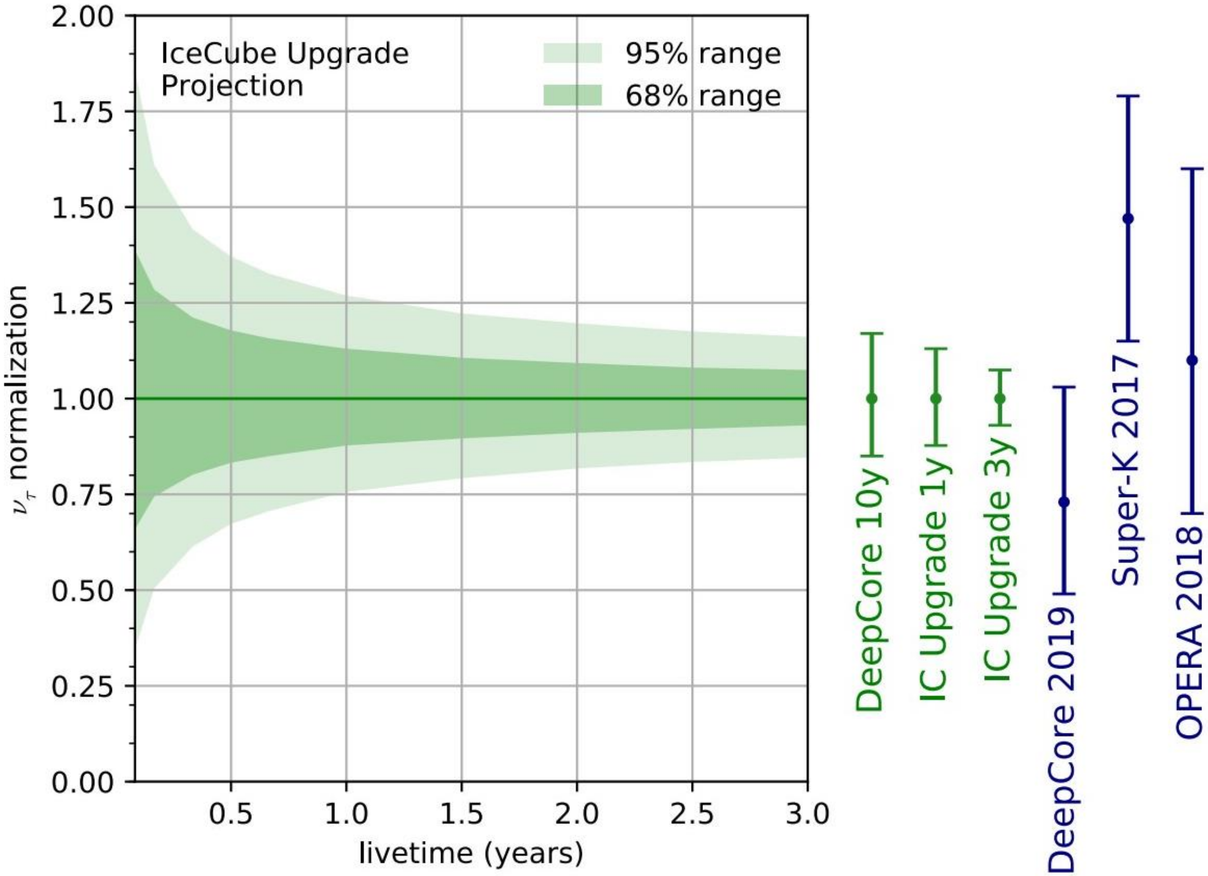
OSCILLATION CONTOURS

- Able to deliver high precision measurements of atmospheric oscillation parameters



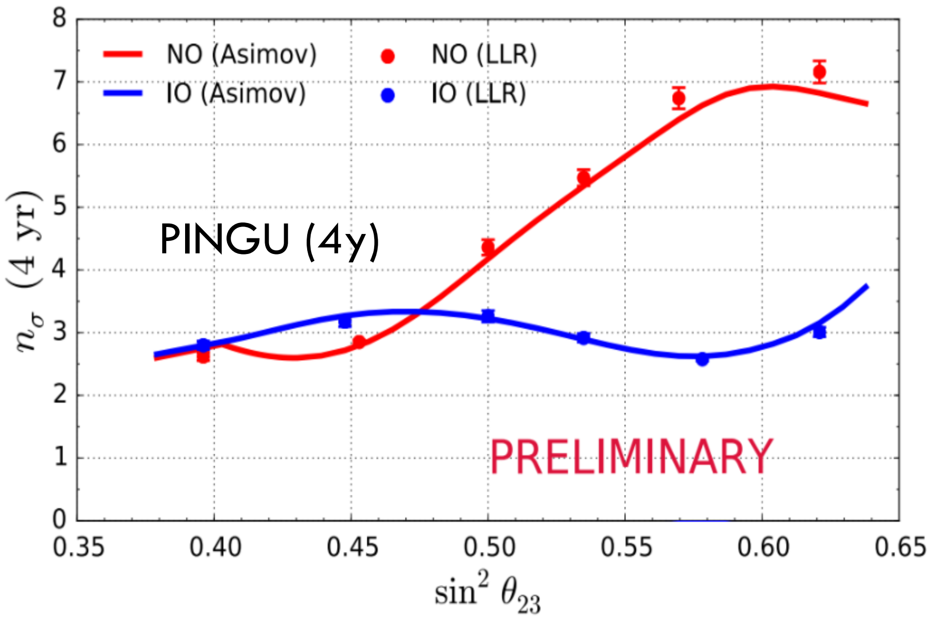
TAU NEUTRINO APPEARANCE

- Better than 10% uncertainty on ν_τ normalization (PMNS unitarity)
- >> 5 sigma significance



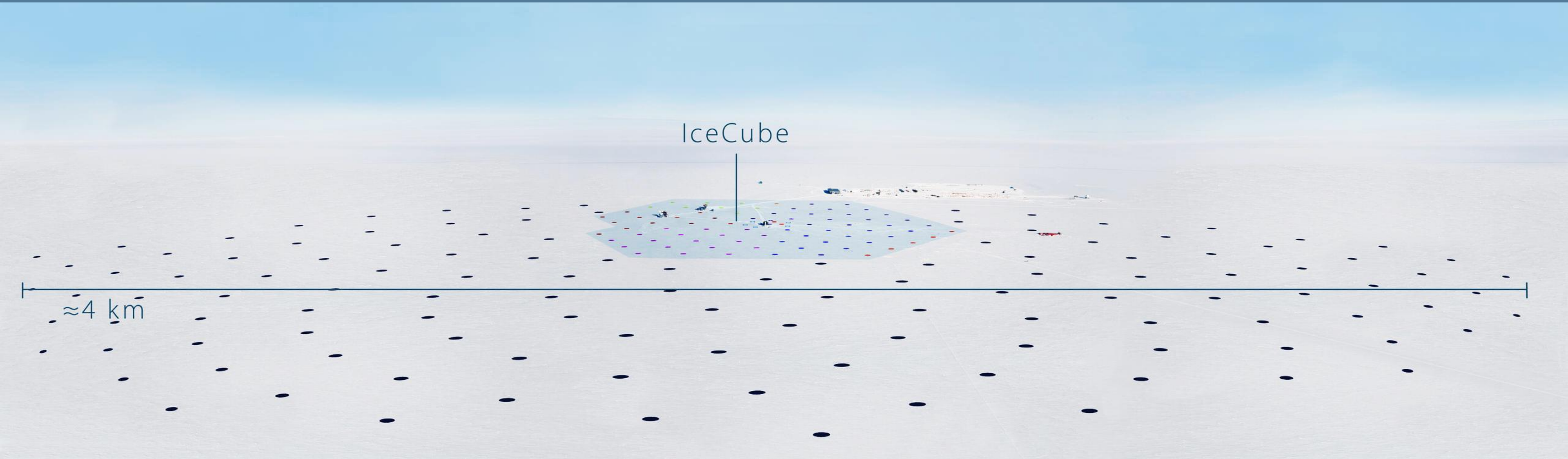
A WAY TO DETERMINE THE NMO

- For atmospheric neutrinos, the relatively small mixing of $\nu_e \leftrightarrow \nu_\mu$ can be drastically enhanced by matter effects
  - For neutrinos under the normal ordering
  - For anti-neutrinos under the inverted ordering
- Combined with initial fluxes differences etc., the wrong mass ordering can be excluded



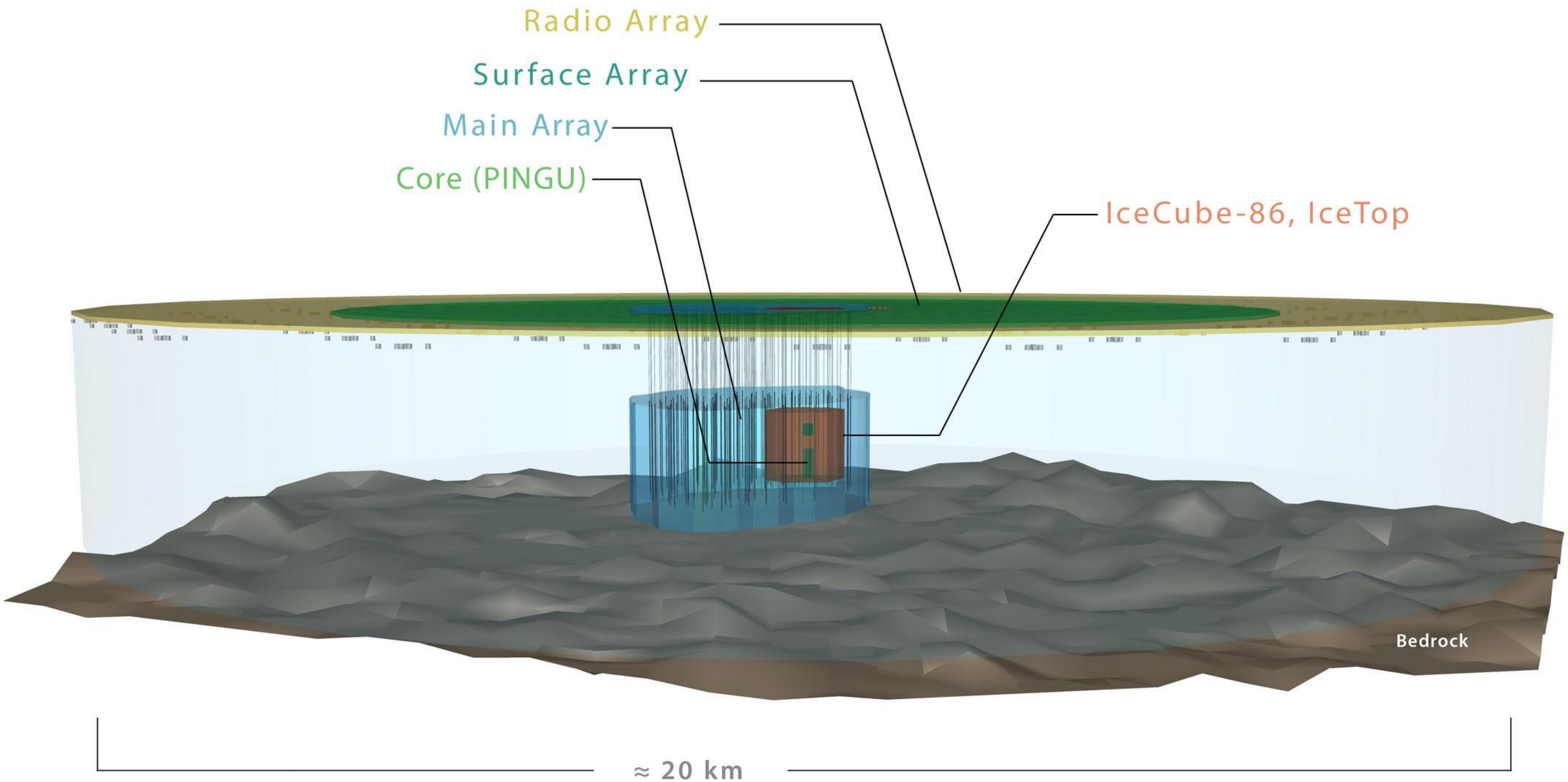
https://arxiv.org/abs/1401.2046

GEN2



- A longer term future project is a much larger detector
- Volume increased by ~10x
- Also includes surface veto (ground stations, air Cherenkov telescopes)
- Radio Array for ultra high energy events based on the Askaryan effect

The IceCube Gen2 Facility



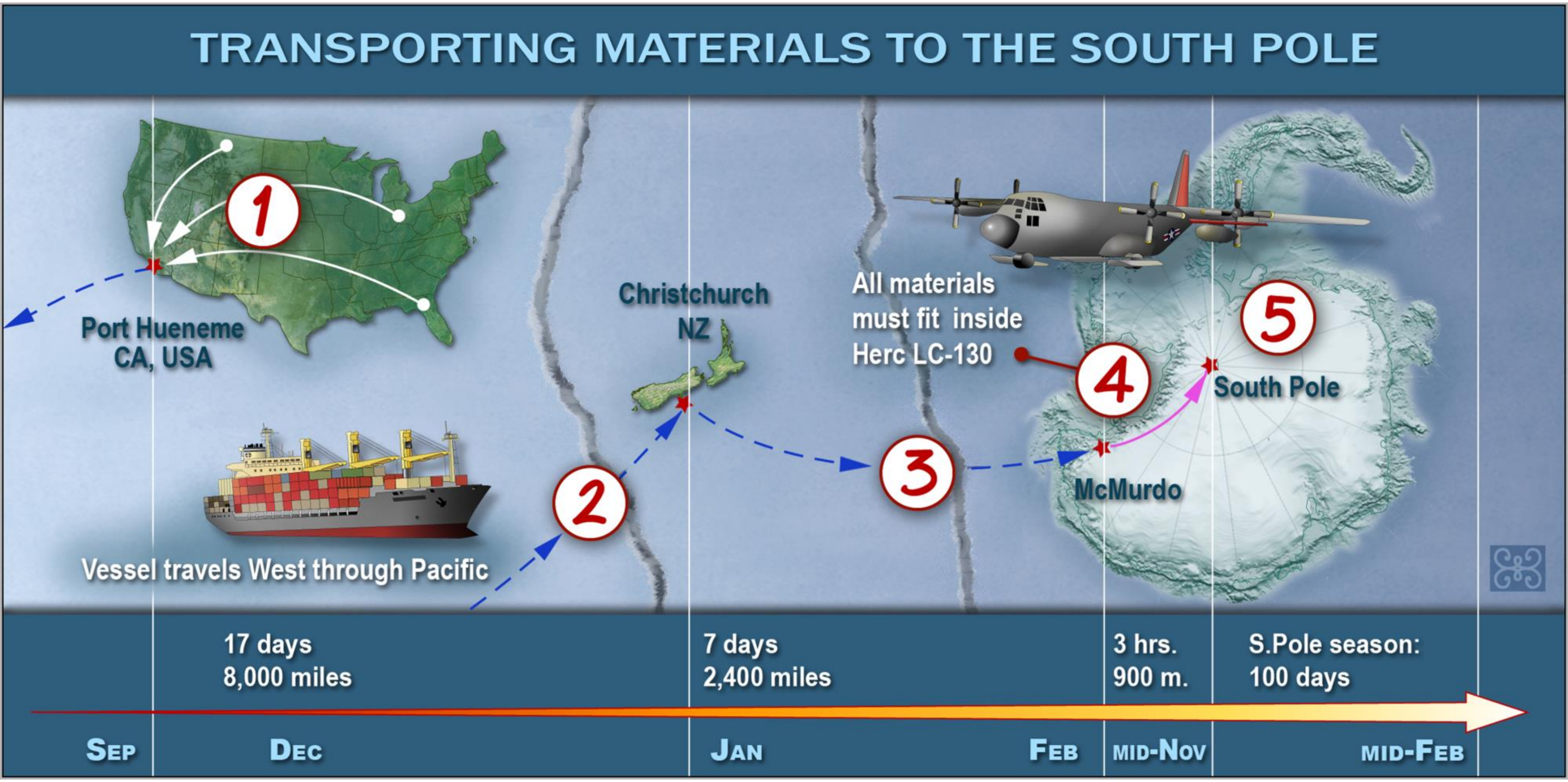
SUMMARY

- IceCube has a diverse science program
  - Neutrinos over a broad range of energies
  - Recording data since > 10y and still going strong
- Astrophysics using high energy neutrinos
  - Observation of neutrinos in coincidence with flaring blazar
- Particle physics using low energy neutrinos
  - Atmospheric neutrinos can be used for precision oscillation measurements
- Several detector extensions are underway or planned
  - 7-string Upgrade
  - New calibration devices
  - PINGU
  - Gen2


Thank you!

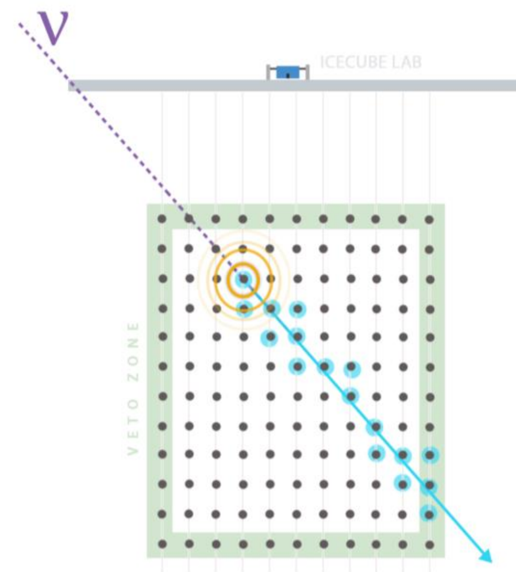
ADDITIONAL MATERIAL

SOUTH POLE LOGISTICS

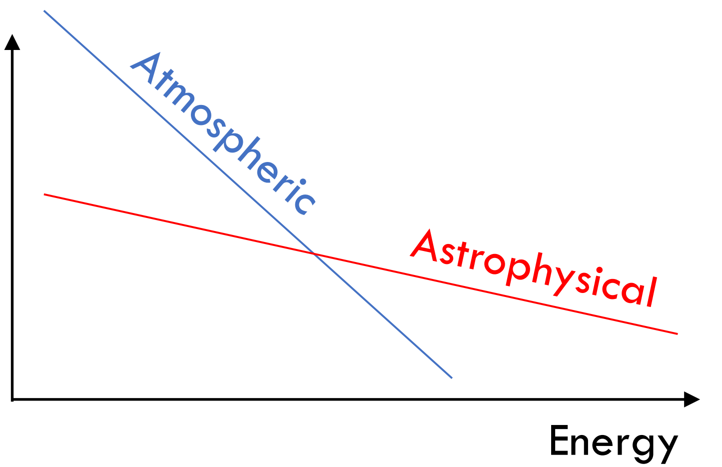


HOW TO FIND ASTROPHYSICAL NEUTRINOS?

- Most events in IceCube are created by atmospheric muons and neutrinos
- To reject muons:
  - Look at northern hemisphere -> earth shields from muons
  - Look at starting events / contained vertex -> use outermost layer of strings as veto

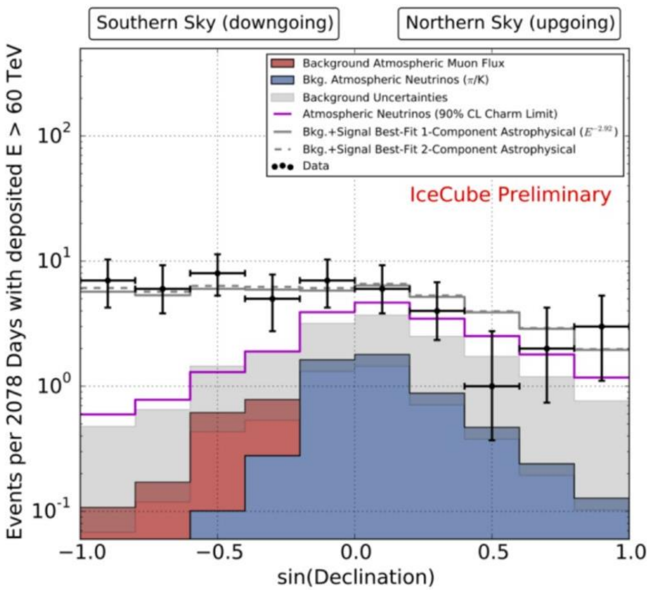


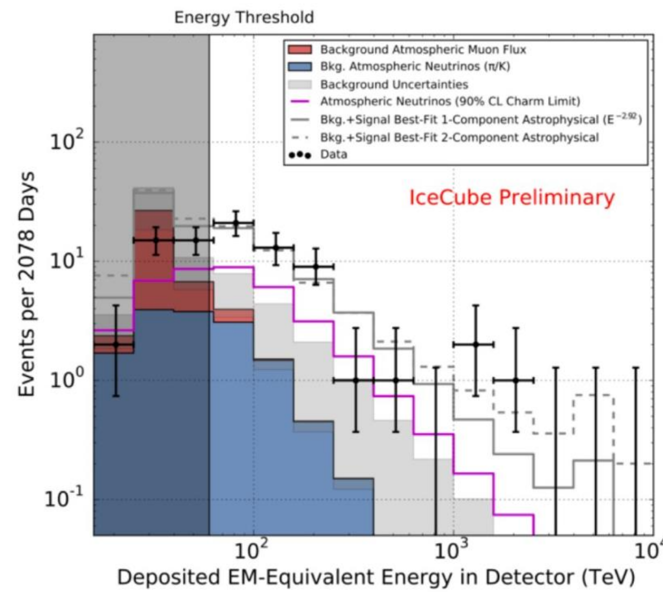
- To distinguish from atmospherics?
  - At very high energies (~100 TeV and above) astro flux starts to dominate
    - Like the IC170922A event
  - Or look at correlations in time or location
    - Like the excess of events clustered in time at the TXS location



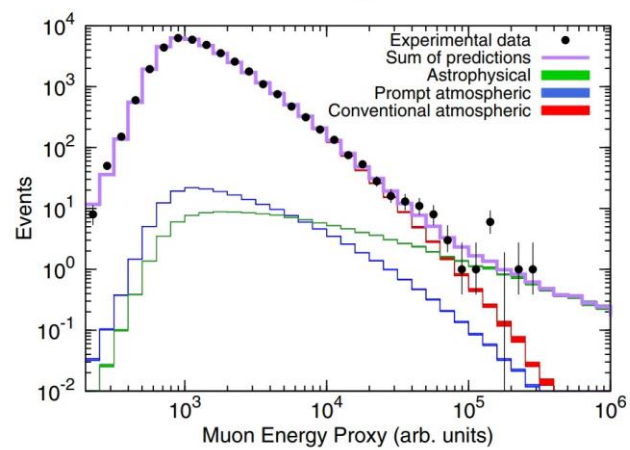
ASTROPHYSICAL NEUTRINOS

- Discovery of astrophysical neutrino flux Phys. Rev. Lett. 113, 101101(2014)



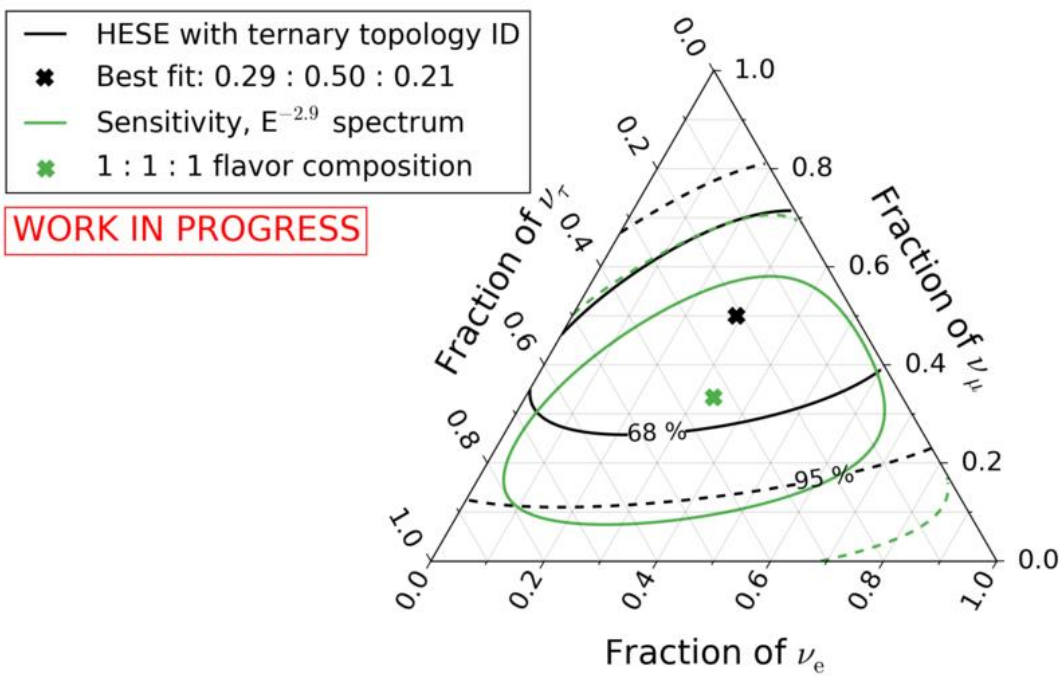


- Independent analysis using thorough-going muon events from the northern hemisphere
  Phys. Rev. Lett. **115**, 081102(2015)

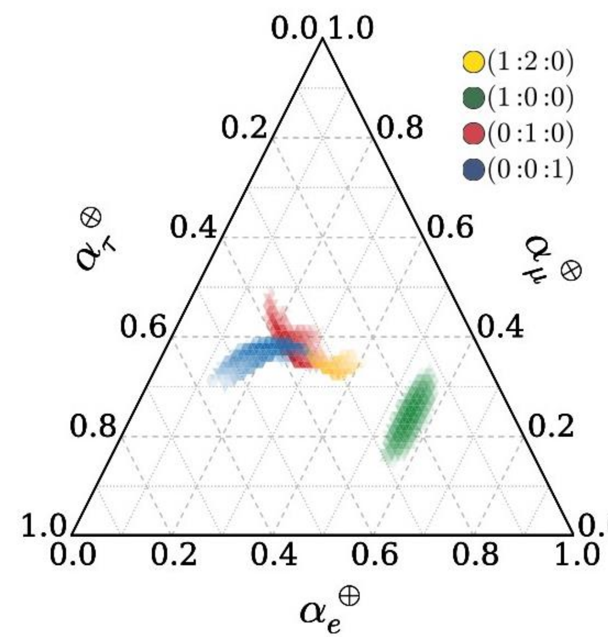


FLAVOUR ANALYSIS

- Studying the flavor composition of astrophysical neutrinos
  - Different production mechanisms will produce different ratios
  - For example 1:2:0 (pion decay) or 1:0:0 (neutron decay), etc
  - When detected at IceCube, flavors will have oscillated
  - most scenarios end up close to 1:1:1

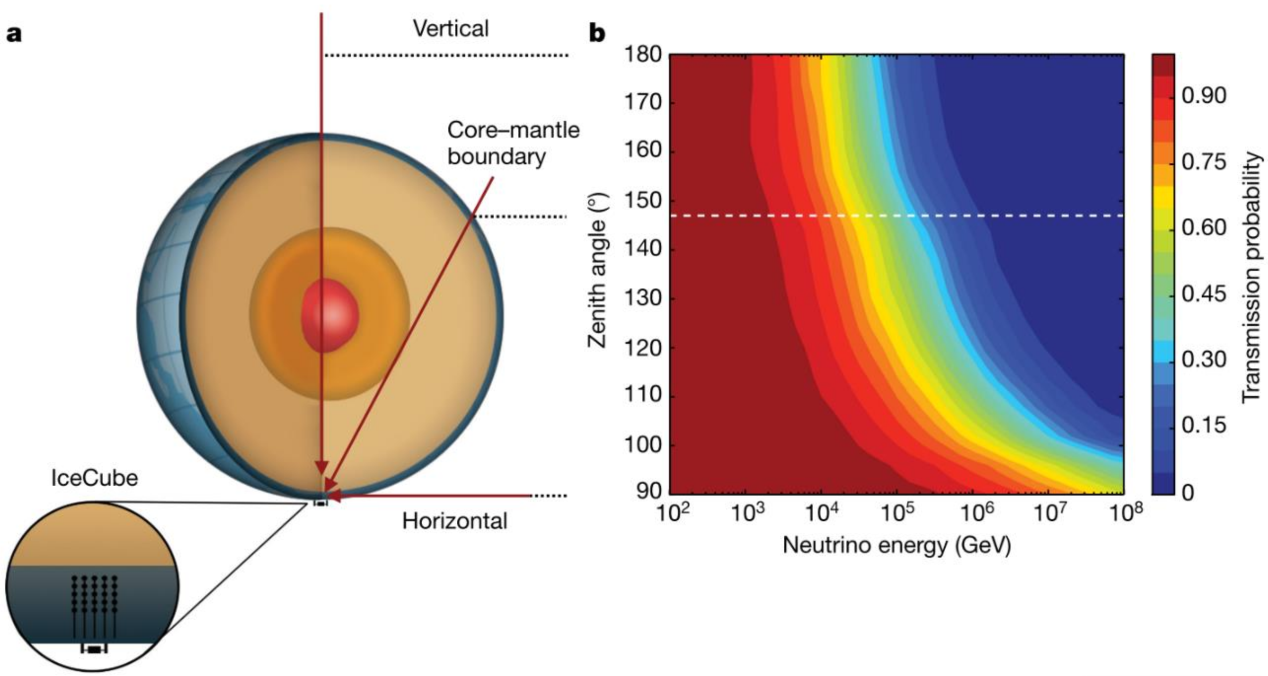


Example expectation (arXiv:1506.02043v2)



EARTH ABSORPTION

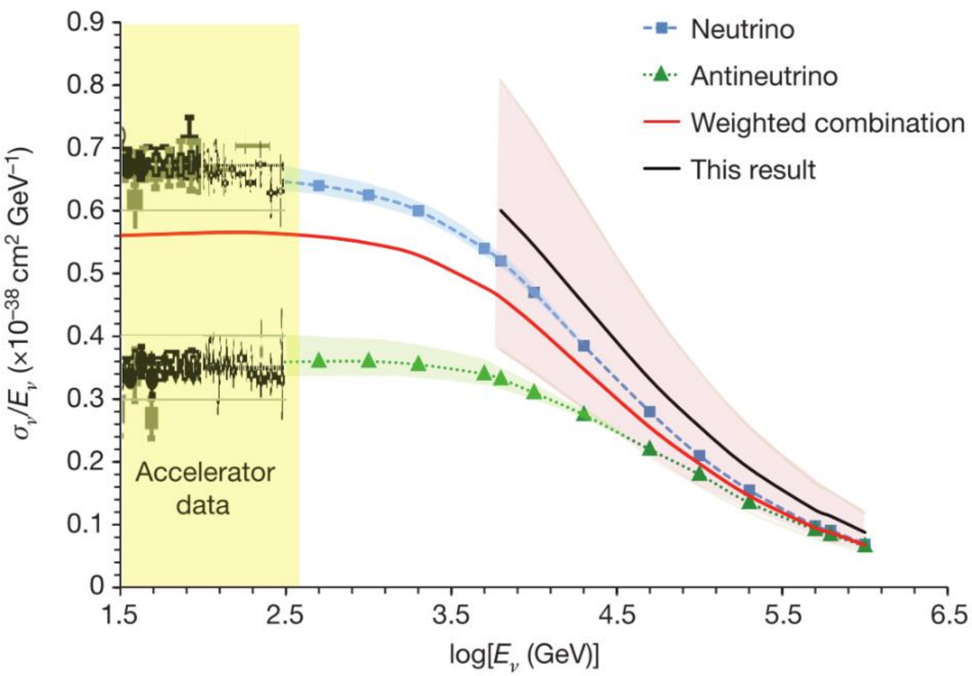
- Using a sample of 10784 (mostly atmospheric + partially astrophysical) neutrinos between 6.3 – 980 TeV
- Studying charged current muon neutrinos from Earth-crossing (vertical) to almost absorption free (horizontal) trajectories
- Estimated background of < 0.1%
- For a 40 TeV neutrino, the Earth represents roughly one absorption length

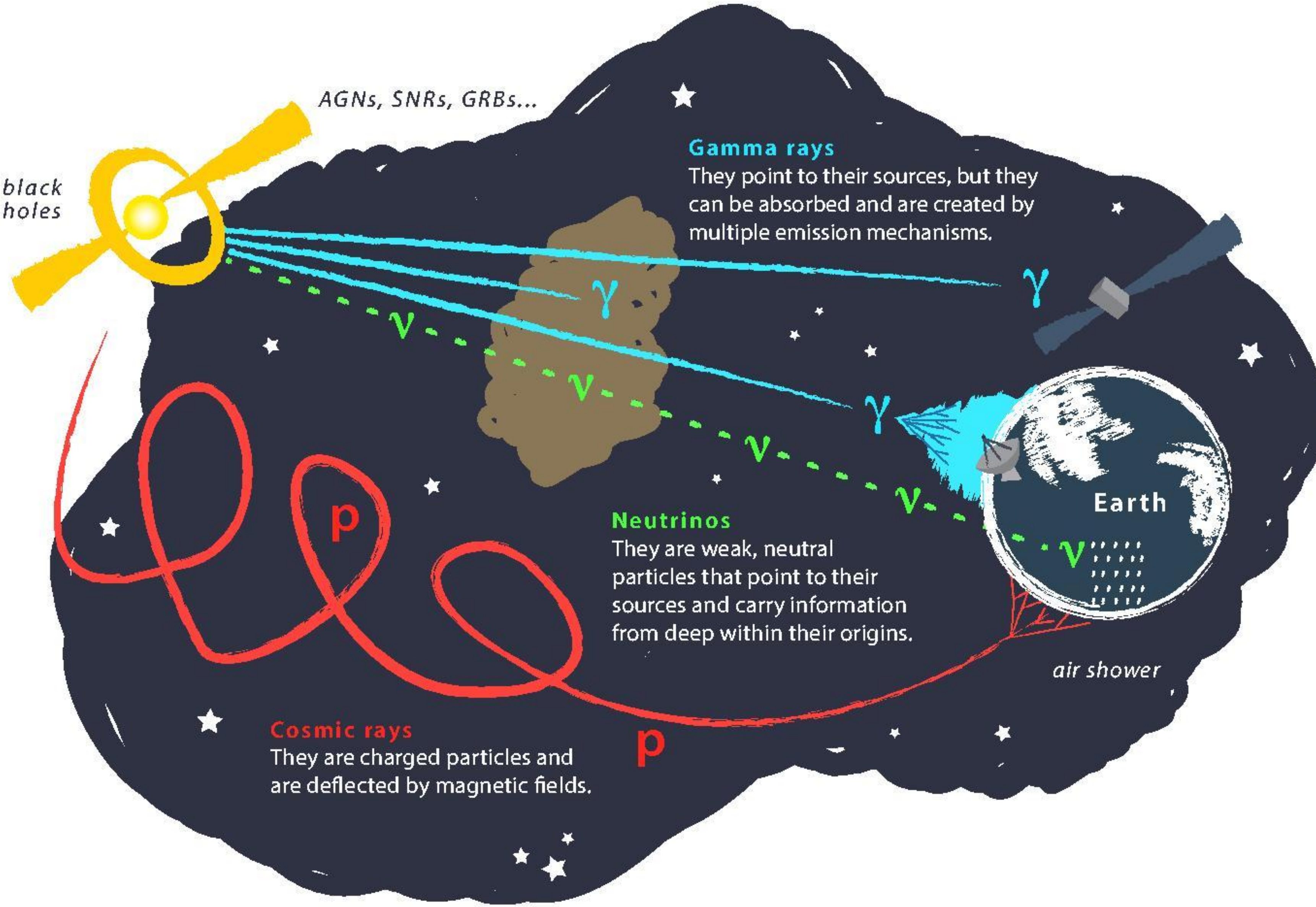


CROSS SECTION RESULTS

Nature **volume 551**, pages 596–600

- Clear attenuation at high energies seen
- Measured cross section 1.3x SM predictions
- Within expectations (+0.21/-0.19 stat., +0.39/-0.43 syst. uncert.)
- No drastic increase with neutrino energy observed (in contrast to some BSM predictions)

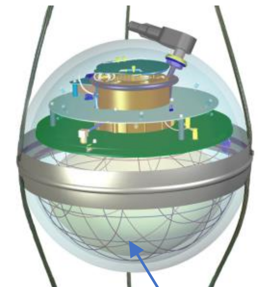



AGNs, SNRs, GRBs...
black holes
Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
γ
γ
ν
ν
ν
ν
ν
Earth
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
p
p
air shower
Cosmic rays
They are charged particles and are deflected by magnetic fields.

SENSOR OPTICAL EFFICIENCY

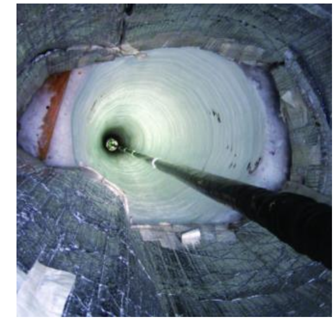
- A closer look at one of the most important sources of systematic uncertainty
- The optical efficiency and angular acceptance of our bare sensors modules is well known from lab measurements
- After deployment in the ice and refreezing, zones of enhanced scattering (air bubbles) formed in the ice
  - This causes an effective change in detection efficiency and acceptance
  - This effect is studied with calibration LEDs and other methods
  - Multiple nuisance parameters allow for changes in the acceptance for our measurements

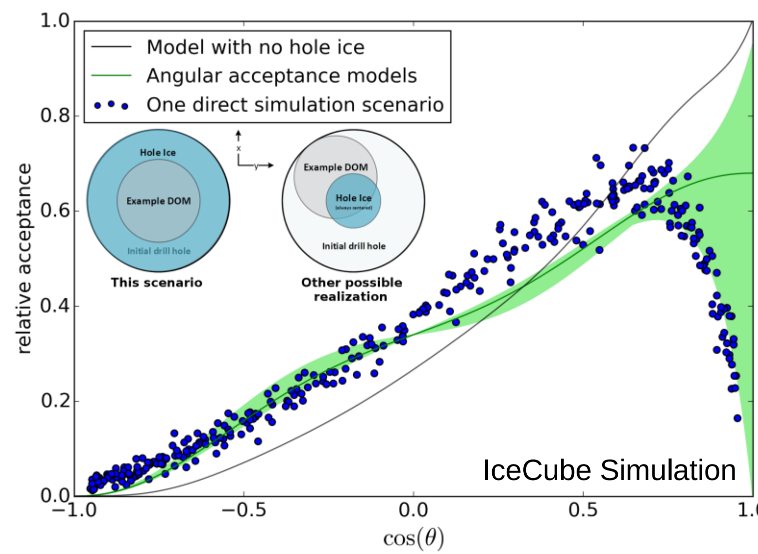
Digital Optical Module



Downward facing PMT

Borehole in the ice





PARAMETERIZATION & UNITARITY

- Standard parameterization for the PMNS matrix, based on 3 angles and one complex phase

$$U_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

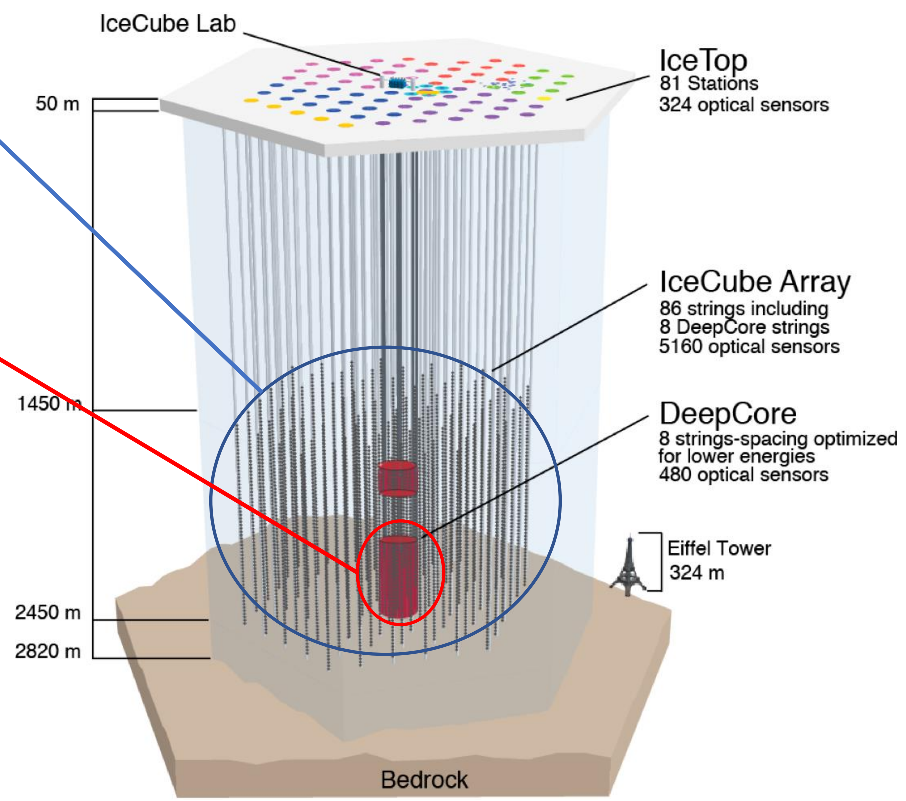
- $S_{12} = \sin(\theta_{12})$ - "solar" angle
- $S_{13} = \sin(\theta_{13})$ - "reactor" angle
- $S_{23} = \sin(\theta_{23})$ - "atmospheric" angle
- δ - CP violating phase

- Using this parameterization imposes unitarity
  - Some BSM theories introduce additional neutrinos
  - For example sterile neutrinos
  - As a consequence the 3x3 PMNS matrix is not the complete picture, and will not be unitary
  - We can test for that

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

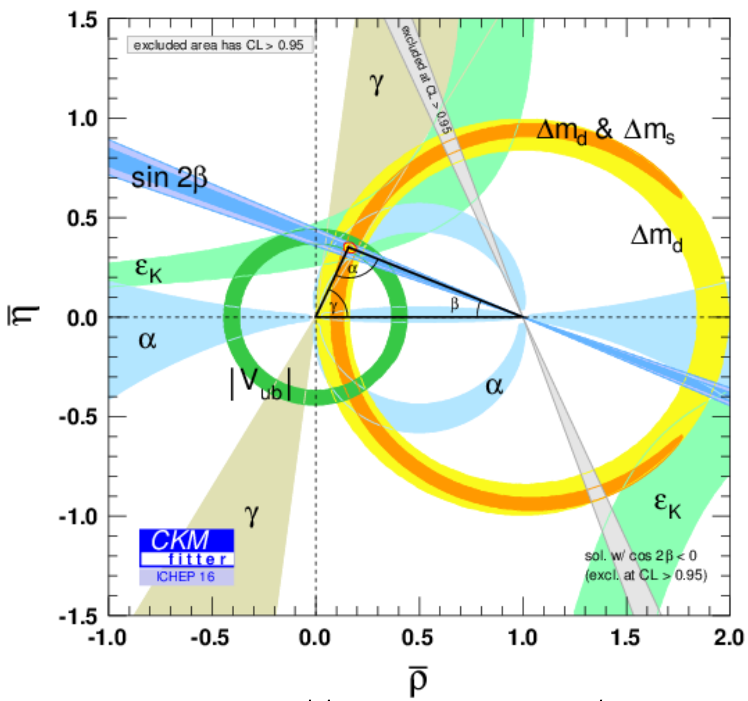
DEEPCORE

- **High energy** - whole IceCube
  - 1 km^3 of instrumented Ice
  - >5000 DOMs (digital optical modules)
  - TeV - PeV energy range
- **Low energy** - DeepCore
  - Additional 8 strings with densely spaced
    high efficiency DOMs
  - In clearest part of ice (below *dust* layer)
  - Surrounded by IceCube strings (used as atm. muon veto)
  - Neutrino energies down to ~5 GeV



UNITARITY

- Unitarity of mixing matrix can be tested for
- Precision tests are done for the quark mixing for many years
- The typical precision on CKM elements: ~0.1% - 0.01%



http://ckmfitter.in2p3.fr/

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} =$$

$$\begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

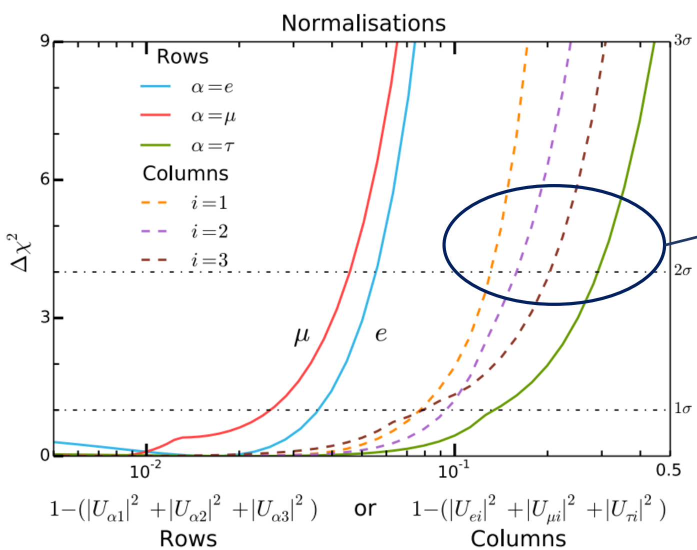
UNITARITY

- For the neutrino sector we're far from drawing triangles…

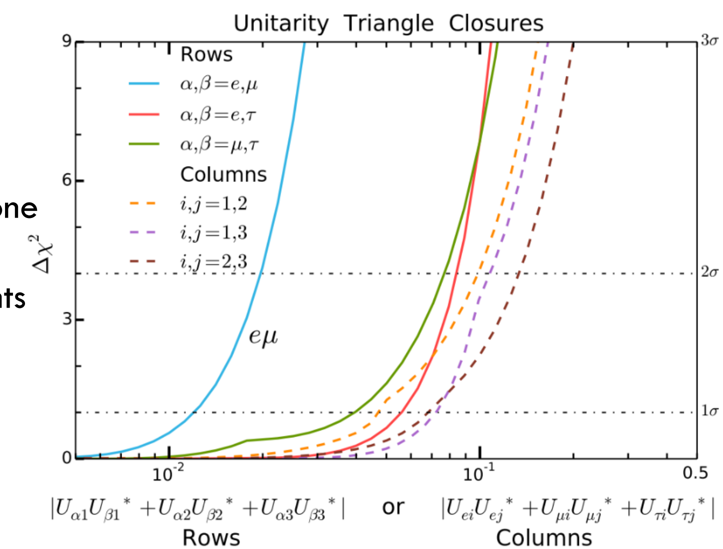
$$|U|^{\text{w/o Unitarity}\ \text{(with Unitarity)}}_{3\sigma} = \begin{pmatrix} \underset{(0.79\to0.85)}{0.76 \to 0.85} & \underset{(0.50\to0.59)}{0.50 \to 0.60} & \underset{(0.14\to0.16)}{0.13 \to 0.16} \\ \underset{(0.22\to0.52)}{0.21 \to 0.54} & \underset{(0.43\to0.70)}{0.42 \to 0.70} & \underset{(0.62\to0.79)}{0.61 \to 0.79} \\ \underset{(0.24\to0.54)}{0.18 \to 0.58} & \underset{(0.47\to0.72)}{0.38 \to 0.72} & \underset{(0.60\to0.77)}{0.40 \to 0.78} \end{pmatrix}$$

Typical precision ~10%

- Experimental constraints in τ-sector ~order of magnitude worse than for e and μ sectors -> need to improve precision



All these contain one or more τ-elements



Park & Ross-Lonergan, 2015

EVENT SELECTION

- Two different event selections for oscillation analyses:
  - **Analysis A**: primary goal nutau measurement, larger sample / more cascade events
  - **Analysis B**: primary goal: numu disappearance measurement, high purity sample

- Main challenge reducing ~5 orders of magnitude of background
  - Atmospheric muons
  - Accidental triggers due to noise

- Using 3y of detector data, resulting in:
  - ~62k events for Analysis A
  - ~41k events for Analysis B

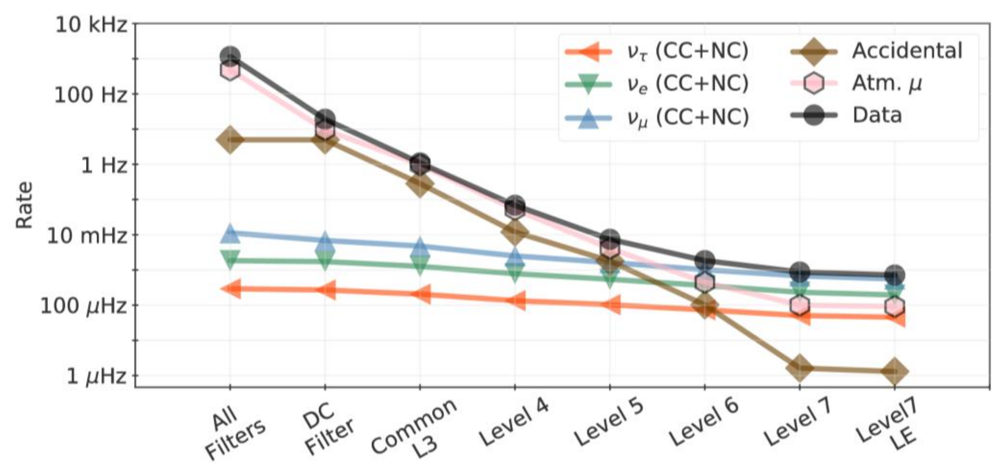
IceCube triggers / online filtering (South Pole)

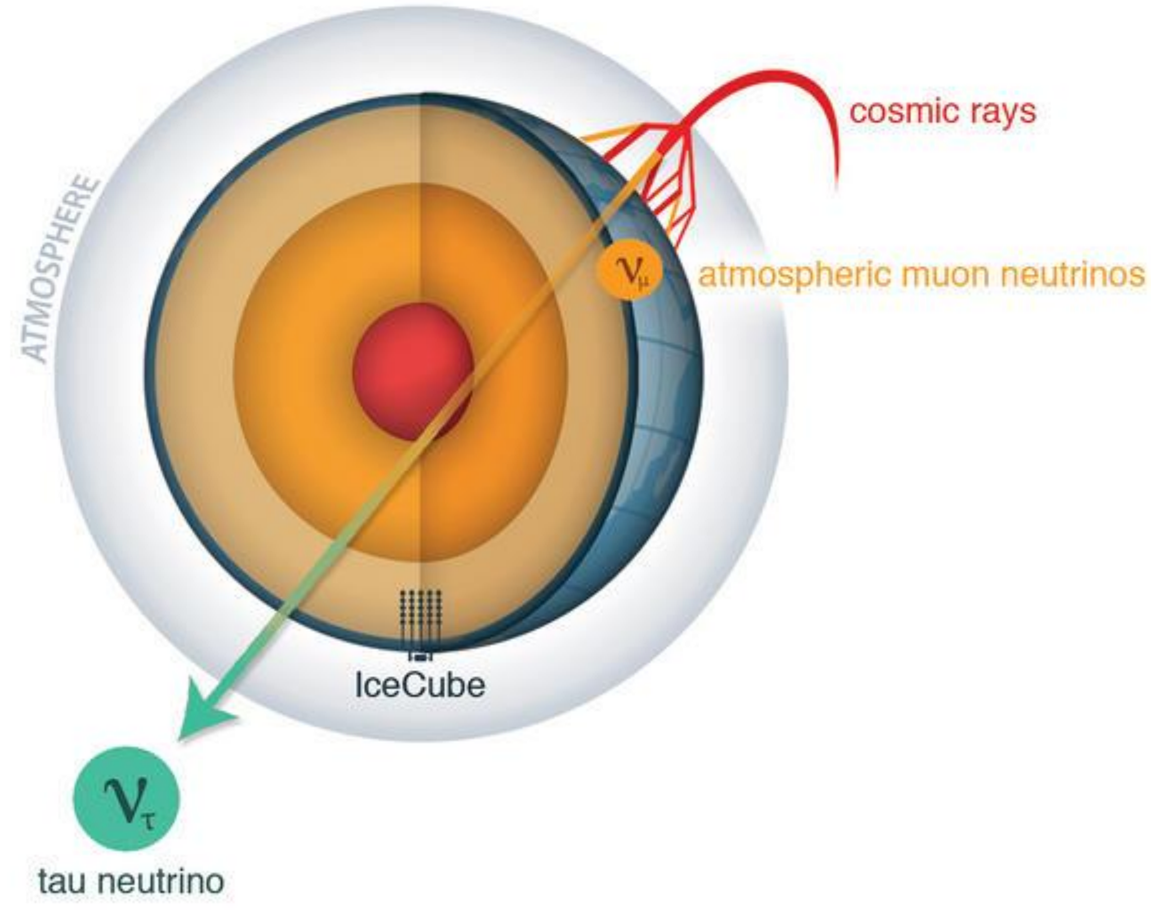
DeepCore offline filter

Atm. muon and noise suppression by straight cuts and BDTs

Full event reconstruction

Final containment in fiducial volume

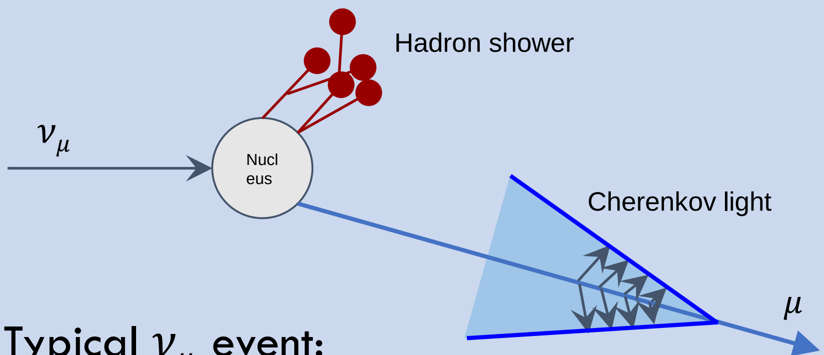




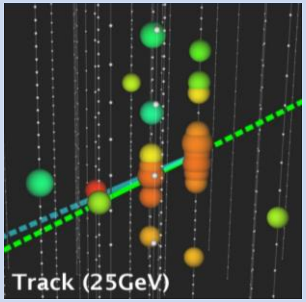
cosmic rays
ATMOSPHERE
ν_μ
atmospheric muon neutrinos
IceCube
ν_τ
tau neutrino

ICECUBE EVENT SIGNATURES

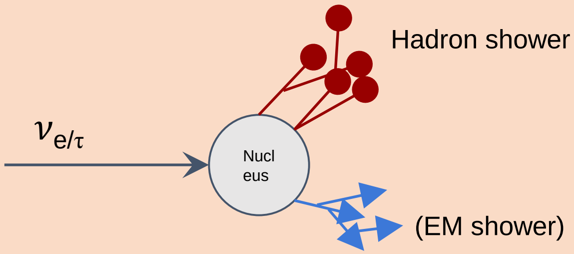
Track-like



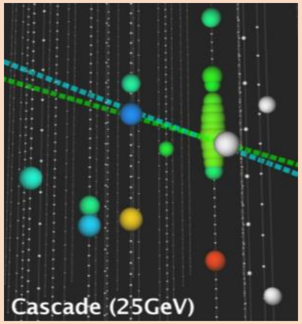
Typical ν_μ event:
Energy deposited in
- Extended muon track (E ~ length)
- Hadron shower from e.g. DIS



Cascade-like



Typical $\nu_{e/\tau}$ event:
All energy deposited in form of showers (hadronic and electromagnetic)
Spatially more compact (no track)

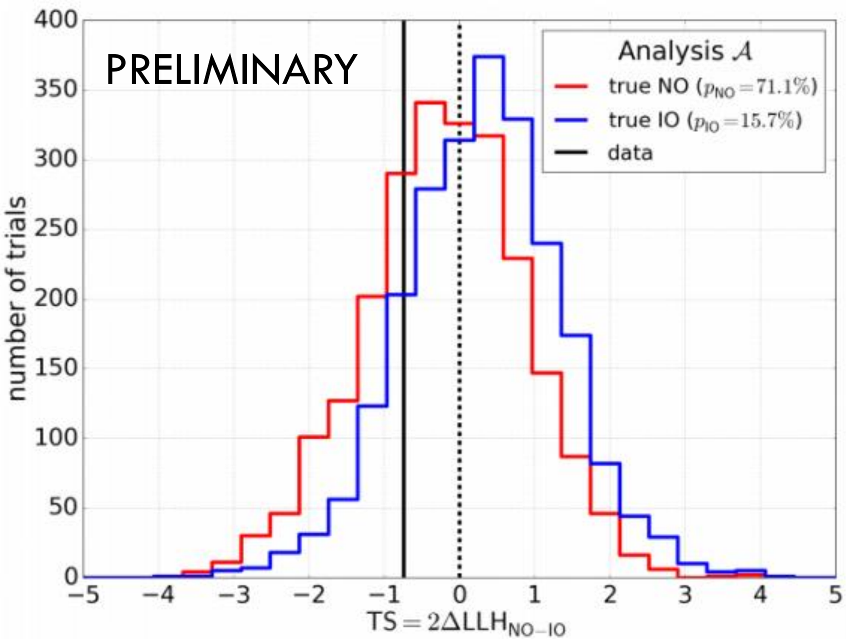


- Reconstructed using a hybrid Cascade + Track hypothesis
  - position, direction, energy and PID (= whether event is track- or cascade-like)

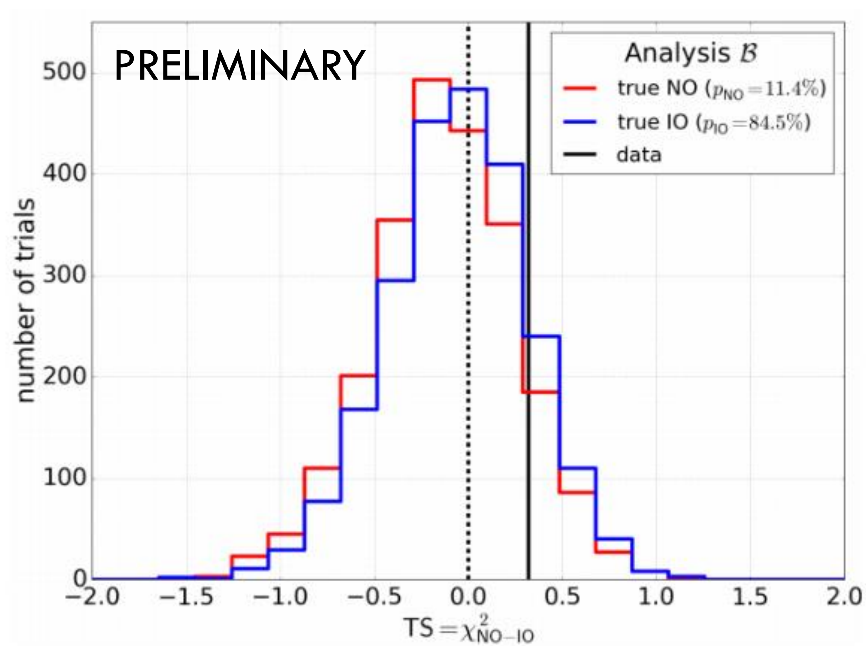
PRELIMINARY NMO RESULT

- These are the very first IceCube/DeepCore results on NMO
  - Based on same 3y dataset as the presented disappearance/appearance analyses
  - Results not significant, more a proof-of-concept exercise

Analysis A

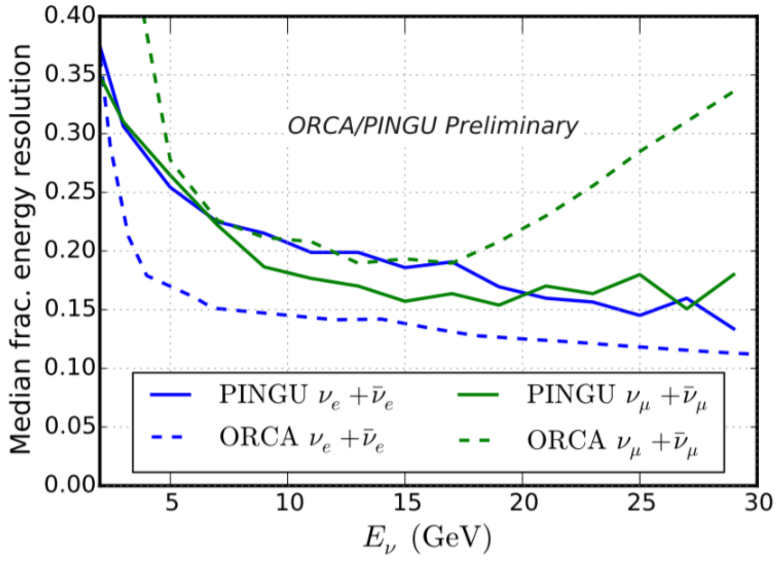


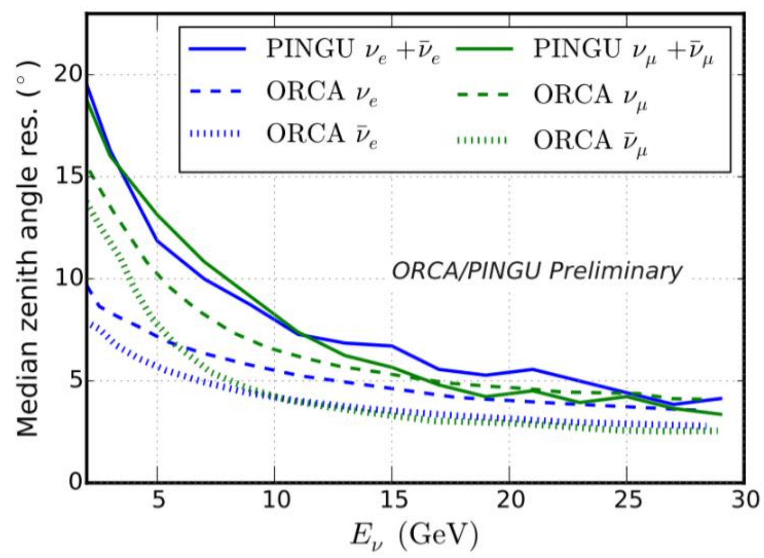
Analysis B



PERFORMANCE

- Similar performance of ORCA and full PINGU
- Some key differences:
  - Seawater homogeneous, absorption dominated medium
  - Ice heterogeneous, scattering dominated medium
  - PINGU contained inside DeepCore/IceCube, ORCA stand alone

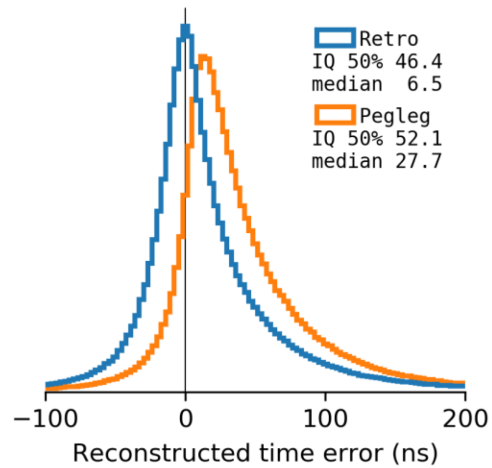


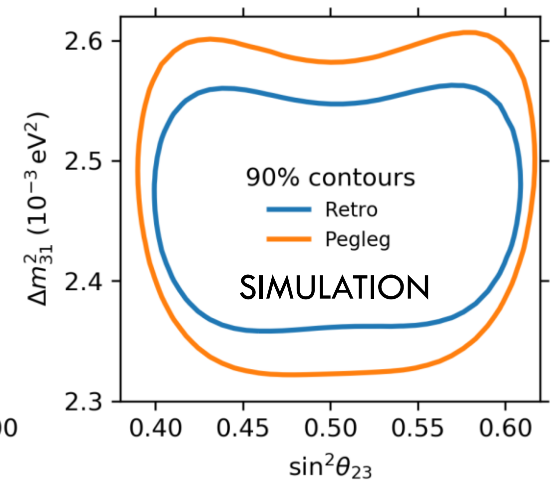


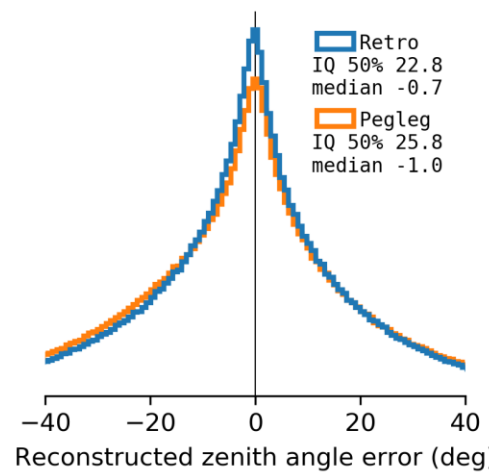
https://arxiv.org/pdf/1509.08404.pdf

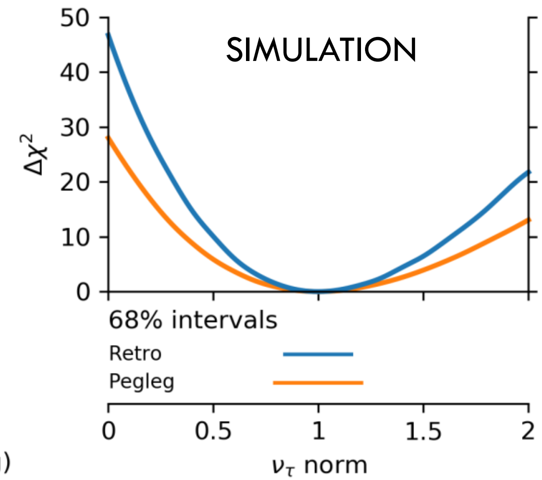
IMPROVED RECONSTRUCTION

- For the past year we developed an improved IceCube reconstruction at PSU
  - Optical properties of the ice eminent for reco
  - receiver based tables for describing photon propagation in ice
  - Finely sampled hypothesis from cascades and tracks
  - Fast fitting process
- Allowing to significantly improve oscillations results

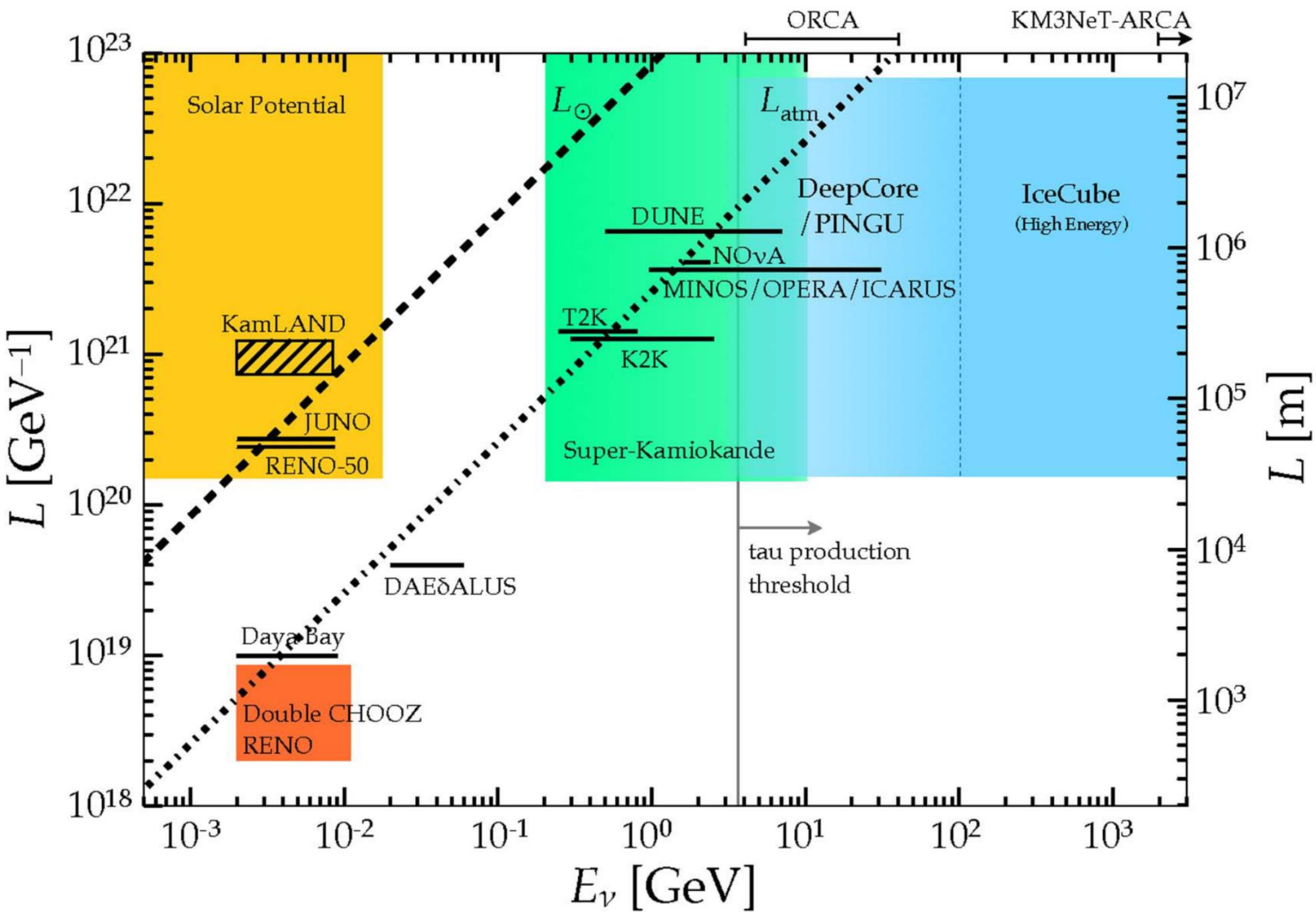








NEUTRINO OSCILLATION LANDSCAPE



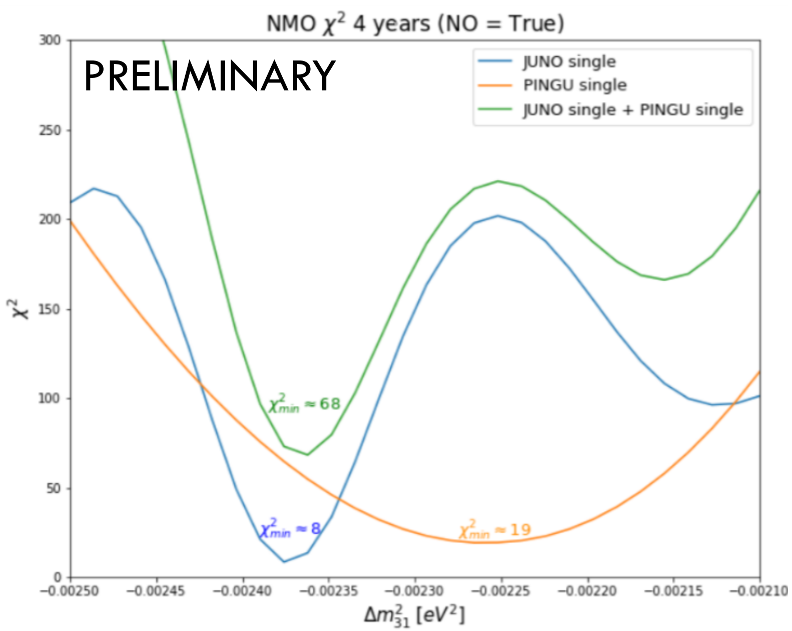
SYSTEMATIC UNCERTAINTIES

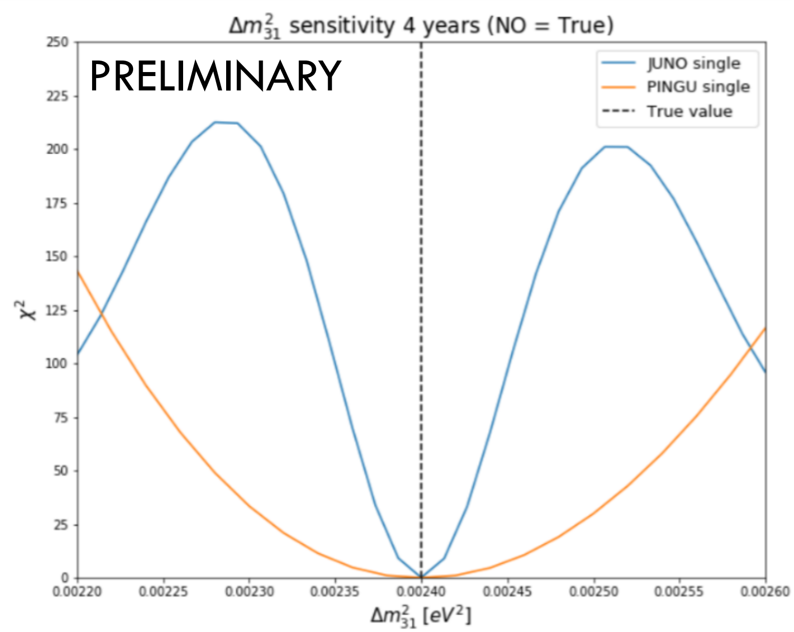
- Incorporating a large variety of nuisance parameters in the measurements
- Covering uncertainties of:
  - **Initial atmospheric neutrino flux**
  - Interaction (cross sections)
  - Oscillation parameters
  - **Detector uncertainties (efficiencies of optical modules and ice uncertainties)**
  - Atmospheric muon background
- More systematic uncertainties were evaluated and deemed unimportant or fully correlated

Parameter Type	Fit Parameter	Analysis A	Analysis B
Oscillations	Δm^2_{32}	✓	✓
	$\sin^2(\theta_{23})$	✓	✓
	$\sin^2(\theta_{13})$		✓
	N_τ	✓	✓
Cross-section	Axial Mass (QE)	✓	✓
	Axial Mass (RES)	✓	✓
	N_{NC}/N_{CC}	✓	✓
Neutrino Flux	ν_μ Normalization	✓	✓
	ν_e/ν_μ Ratio	✓	✓
	γ_ν	✓	✓
	$\nu/\bar{\nu}$ Ratio	✓	✓
	Up/Horizontal Ratio	✓	✓
	$f_{Coincident}$	✓	
Muon Flux	μ Norm	✓	✓
	γ_{CR}	✓	-
Detector	DOM Efficiency	✓	✓
	Hole Ice Model		✓
	Lateral Sensitivity	✓	✓
	Forward Sensitivity	✓	✓
	Absorption	✓	✓
	Scattering	✓	✓

ATMOSPHERIC + JUNO

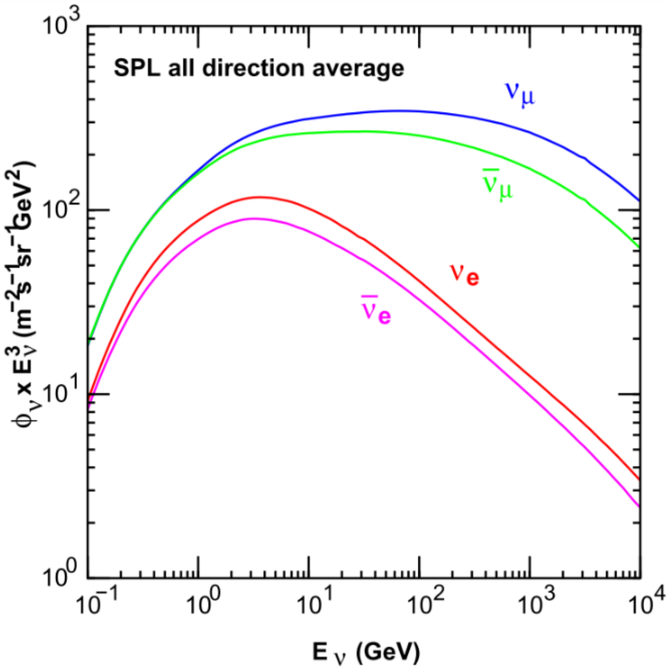
- An interesting way to arrive at a decisive NMO measurement very fast is combining JUNO + atmospheric
  - The constraints on $\Delta m_{31}{}^2$ are very different
  - They align for the true mass splitting, but are shifted for the wrong sign
  - Leading to a better significance to exclude the wrong ordering
    - Here sqrt(chi^2) = 8.2 for joint analysis, 5.2 for naïve combination

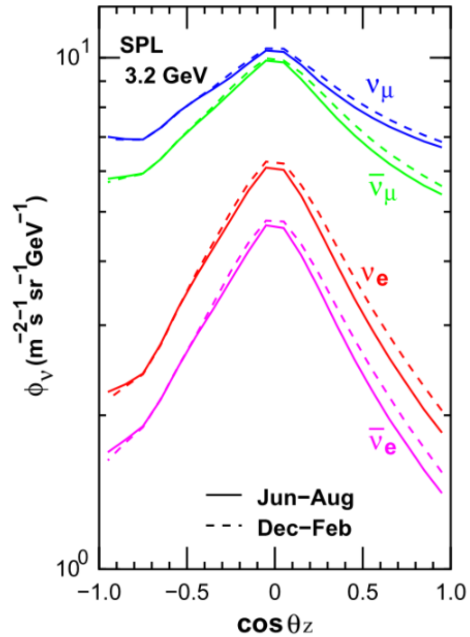




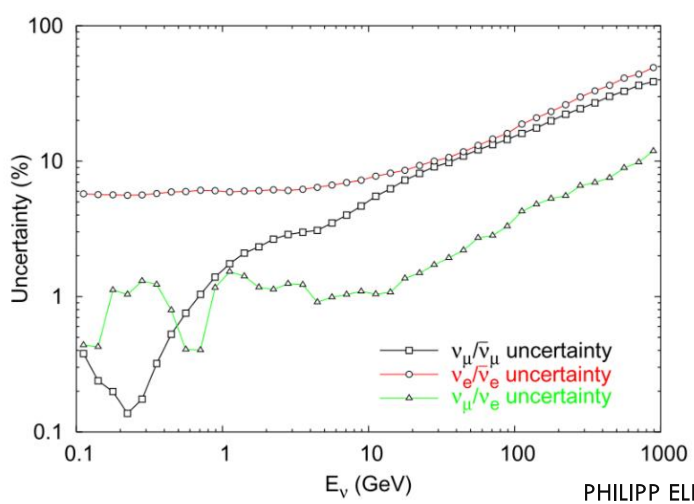
NEUTRINO FLUX AND UNCERTAINTIES

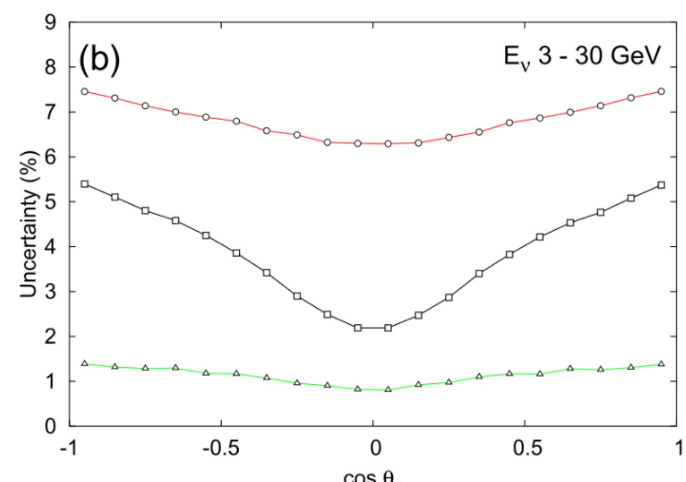
Nominal flux, Honda et. al. 2015





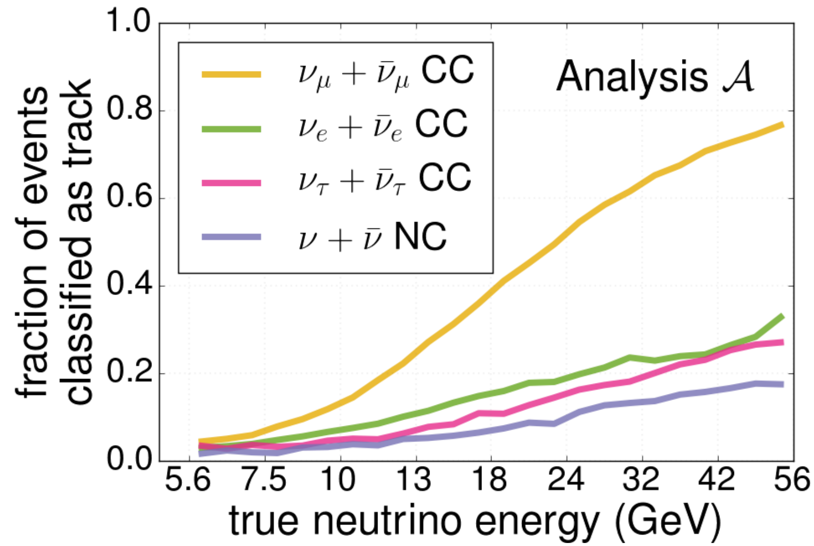
Relative uncertainty, Barr et. al. 2006

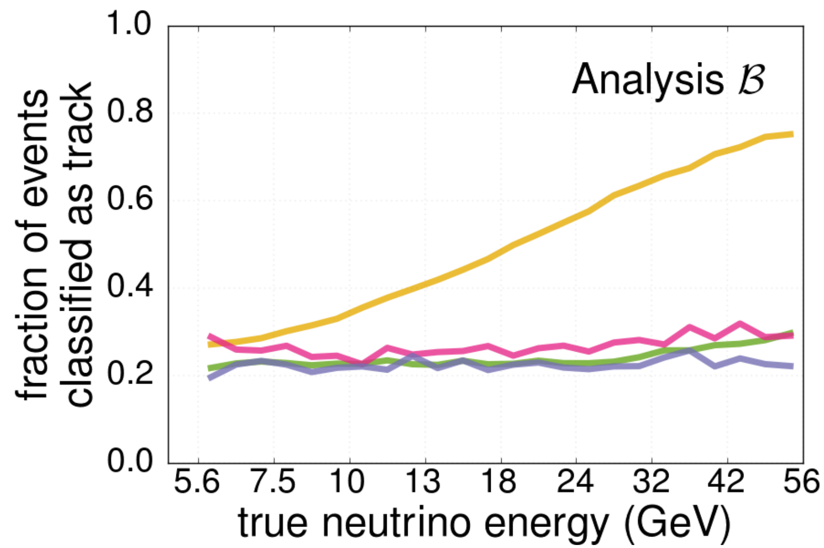




EVENT CLASSIFICATION

- Our ability to distinguish track and cascade-like events mainly depends on neutrino energy
  - Higher energy = longer muon tracks
- Analysis B: Separation based on an additional reconstruction using cascade only (no track)
  - Difference in likelihood to the standard reconstruction used as classifier
- Analysis A is based on a simpler approach using track length (muon energy) as discriminator





MUON BACKGROUND

- Both analyses follow a different strategy to model the background of atmospheric muons
- Muons are inherently difficult to produce in simulation with high enough statistics
  - Since our selections are extremely efficient at removing those

Analysis A:

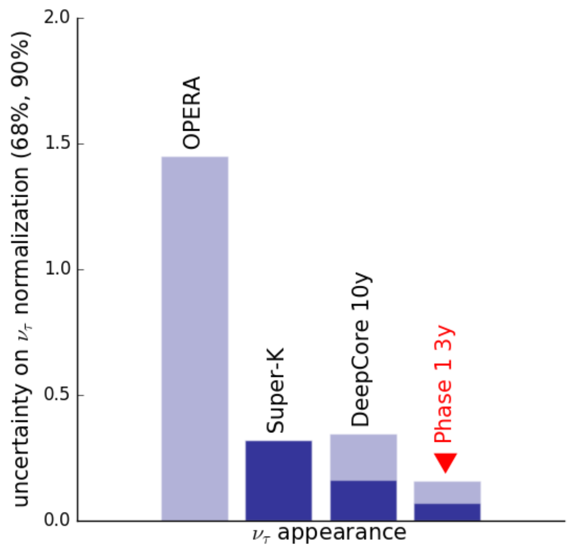
- Simulation using a muon gun targeted at regions where we actually expect contamination
- Needs to take into account simulation uncertainties

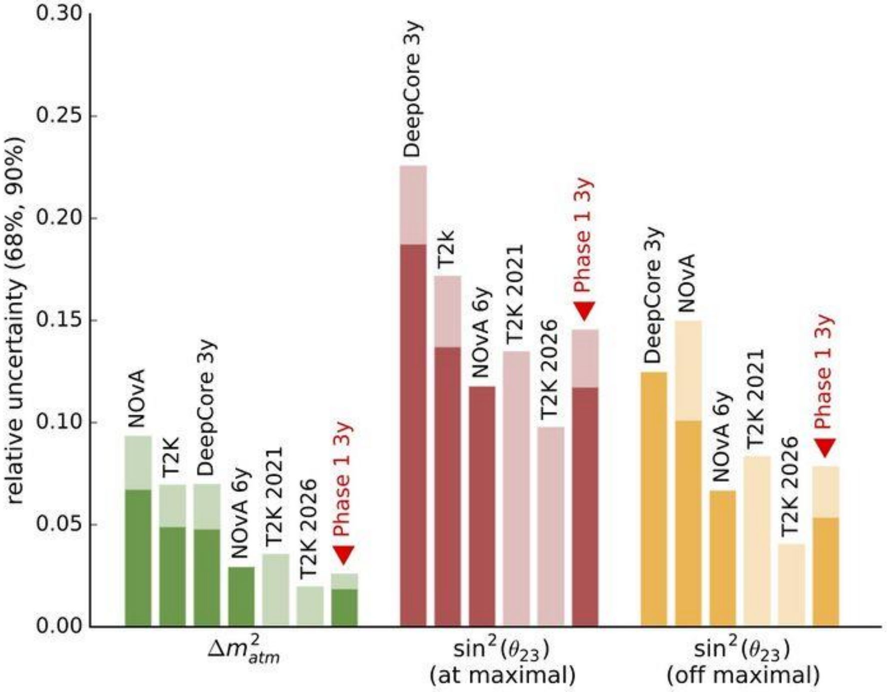
Analysis B:

- Data driven method
- Use a sideband to estimate the shape of the muons in the signal region
- Extrapolation uncertainty

COMPARISON TO OTHER PROJECTIONS

- With 3y of IceCube Upgrade data we project to achieve:
  - Better than 10% nutau normalization
  - Disappearance contours at the level of the NOvA 6y and T2K 2021 projected precision



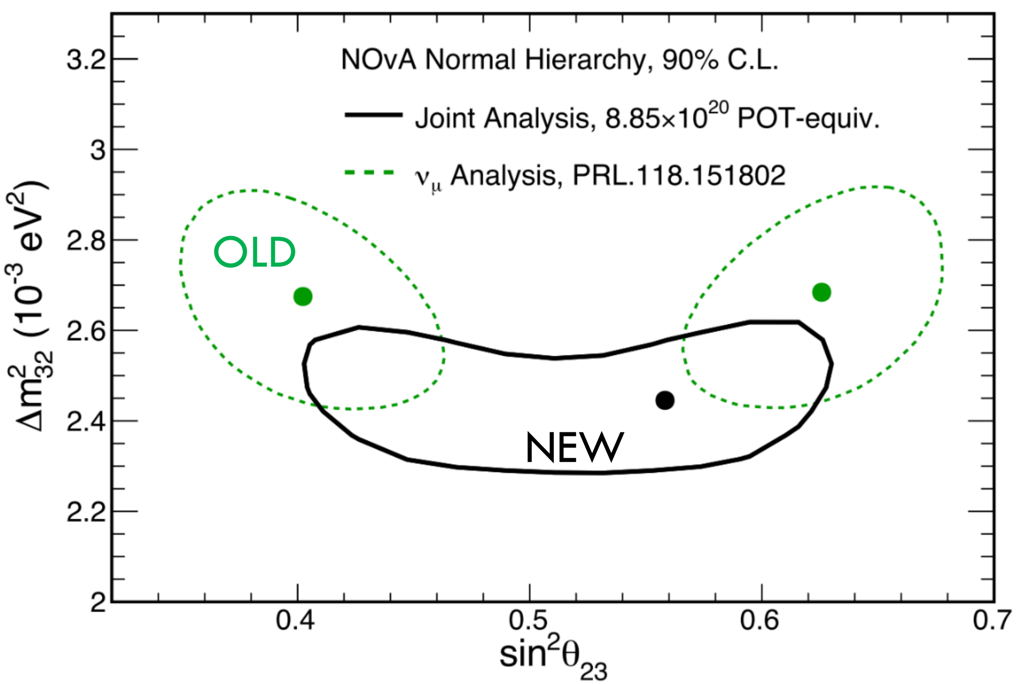


NEW NOVA RESULT

- This January, a seminar talk at Fermilab showed updated NOvA results
  - http://news.fnal.gov/events/event/joint-experimental-theoretical-physics-seminar-latest-neutrino-oscillation-results-from-nova/

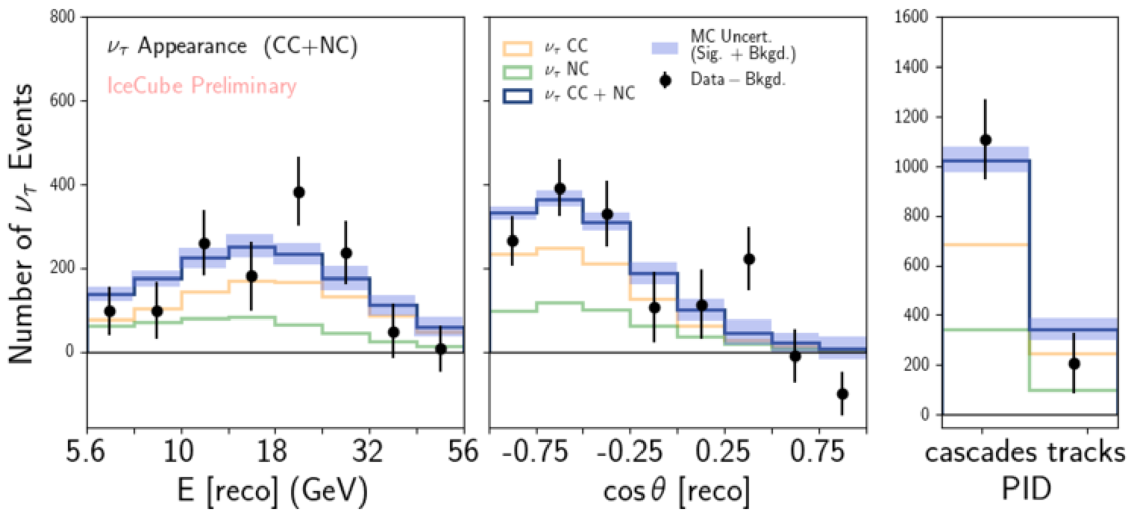
- Joint analysis of different samples
- New reconstruction (using CVN)
- Events sorted by resolution
- Some refined systematics
- Better data/MC agreement
- 50% more data

- Contours changed drastically
- Before in tension with maximal mixing, now in favour of



TAU NEUTRINO DISTRIBUTIONS

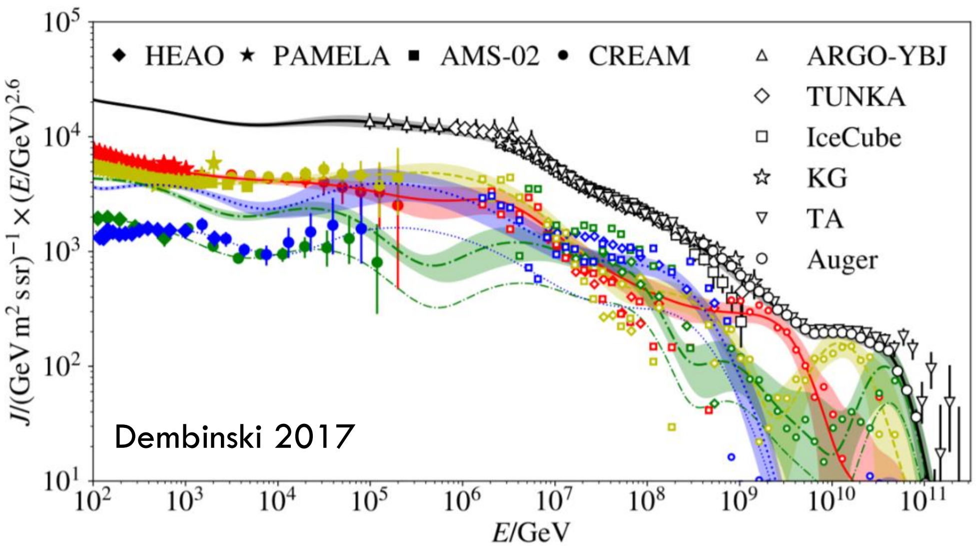
- Visible energies distributed around ~15 GeV (analysis range 5.6 – 56 GeV)
  - This is a higher energy regime than the Super-K nutau analysis
- ν_τ events appear in upgoing region (-1,0) (= earth crossing trajectories)
- Mostly classified as cascade-like events



background subtracted data from Analysis B overlaid with best-fit ν_τ expectations

ATMOSPHERIC NEUTRINOS

- Need to understand the primary flux
  - Composition / Spectral shape



- hadronic interaction model
  - E.g.: DPMJET-III or Sibyll 2.3c
- model for decay, Atmosphere, magnetic field
  - Rely on external calculation: e.g. Honda et. al
  - Or use directly a tool like MCeq

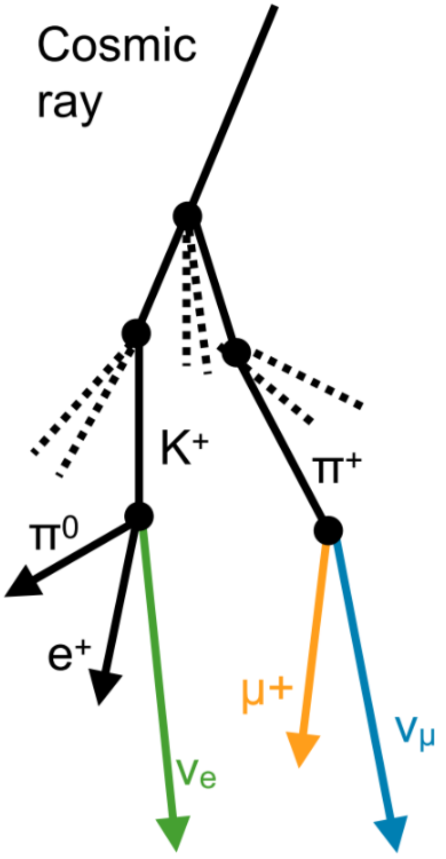


Figure: S. Blot

MEASUREMENT PARAMETERS

- The numu disappearance measurement:
  - Extracting two parameters:
    - θ_{23} : magnitude of disappearance
    - $\Delta m^2{}_{31}$: location of disappearance in terms of L/E

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

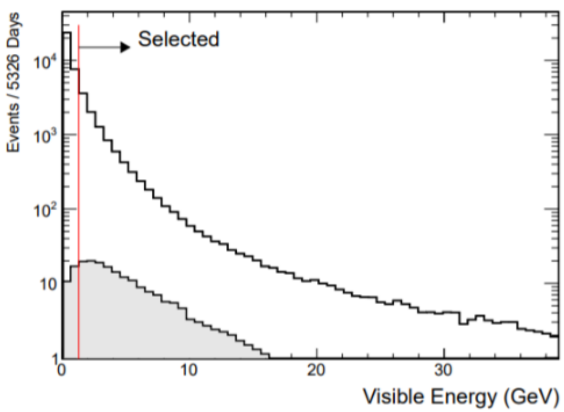
- Nutau appearance measurement:
  - same as disappearance, plus an additional scale factor for tau neutrinos
    - ν_τ norm = 0: no tau neutrinos at all
    - ν_τ norm = 1: standard oscillation expectation
  - Scale factor can be applied to:
    - All tau neutrinos (referred to as "CC+NC")
    - Only tau neutrinos interacting via charged current (CC) (same as OPERA, Super-K)
    - We present results for both

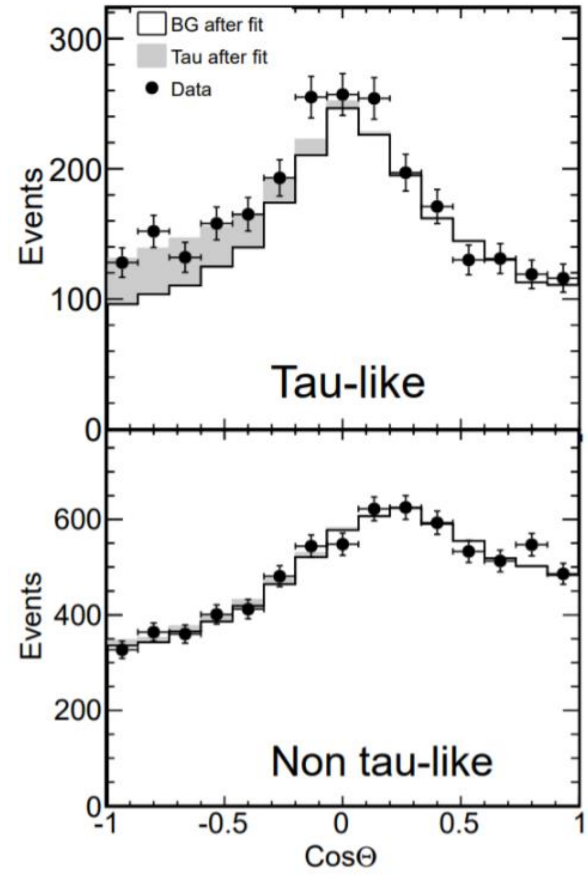
NUTAU CHANNELS

- What oscillation experiments can be done to measure tau sector?
  - **e→tau:**
    - Small mixing **x**
    - nue from atmosphere ✓
    - e/tau signatures in many detectors hard to distinguish **x**
  - **mu→tau:**
    - Large mixing ✓
    - numu from accelerators ✓
      - OPERA: CNGS beam
    - numu from atmosphere ✓
      - Super-K and IceCube/DeepCore
  - **tau→tau:**
    - Large mixing ✓
    - Tau production in atmosphere negligible **x**
    - Currently impossible to have a suitable beam **x**

SUPER-K

- https://arxiv.org/abs/1711.09436
  - Atmospheric neutrinos
  - Evidence with a significance of 4.6 sigma
  - Based on 15 years of data
  - Best constraint on ν_τ normalization with 1.47 +/- 0.32 (68% C.L.)
  - Energies around ~5 GeV
    - Dominated by QE and resonance events

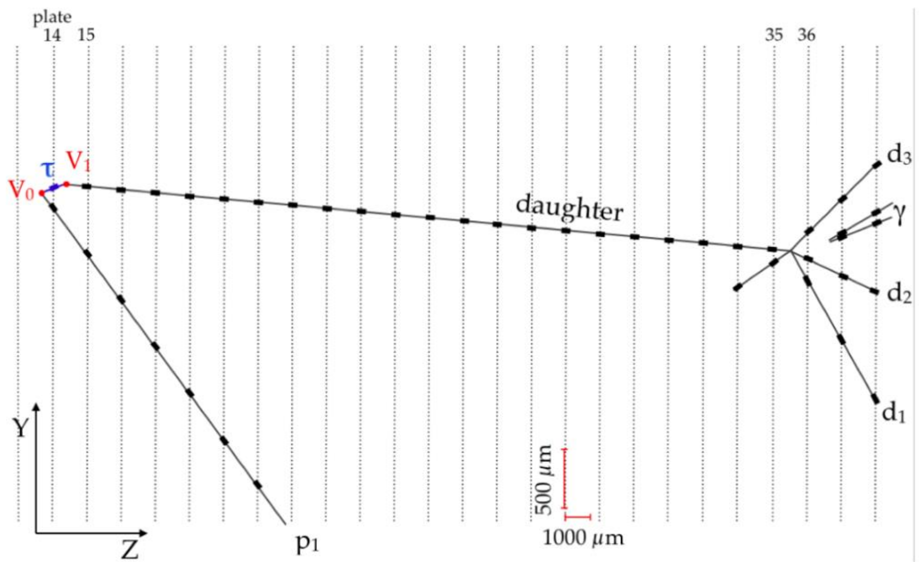




  - Using a neural network classifier output x cos(zenith) distributions for fit

OPERA

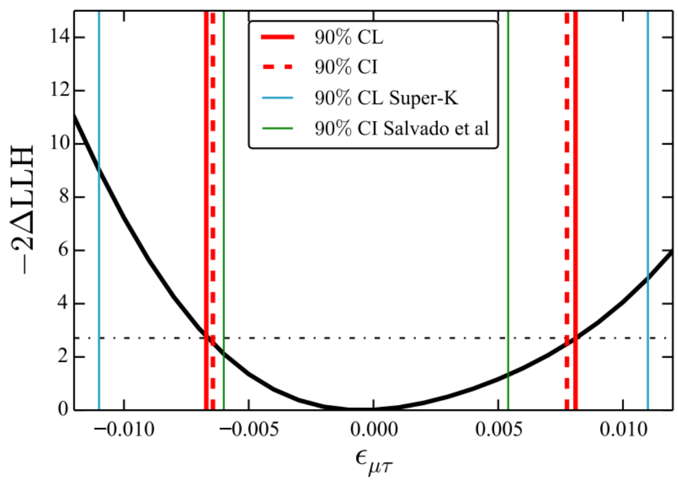
- https://arxiv.org/abs/1804.04912
  - CNGS ~17 GeV muon neutrinos / 732 km baseline
  - Observation of ν_τ appearance with 6.1 sigma significance
  - Total of 10 individually identified ν_τ candidates
  - Low background (estimated 2 total background events)
  - Only weak constraints on ν_τ normalization: 1.1 -0.4 +0.5 (68% C.L.)
  - Example event display:



OTHER ATMOSPHERIC NEUTRINO RESULTS

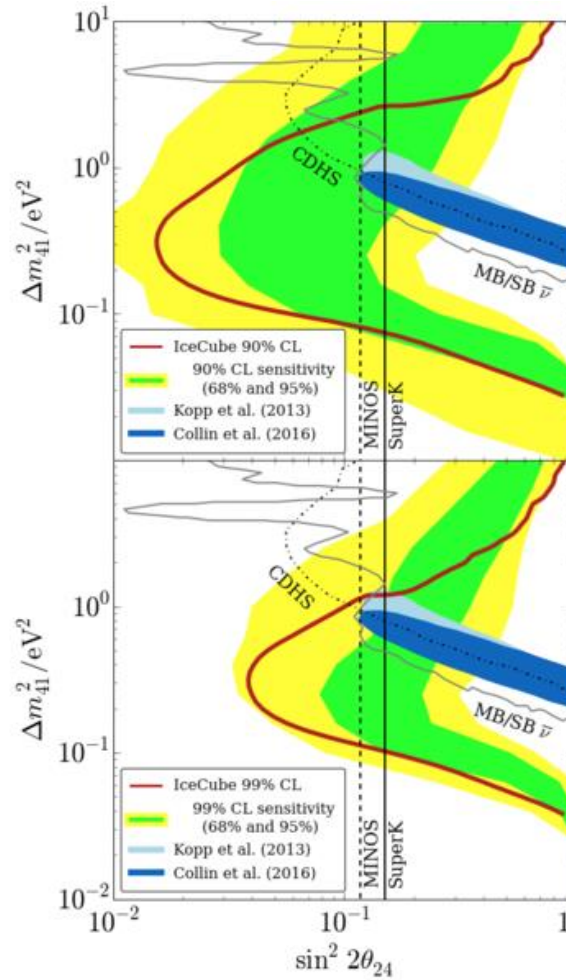
- Non-standard interactions:

  https://arxiv.org/abs/1709.07079



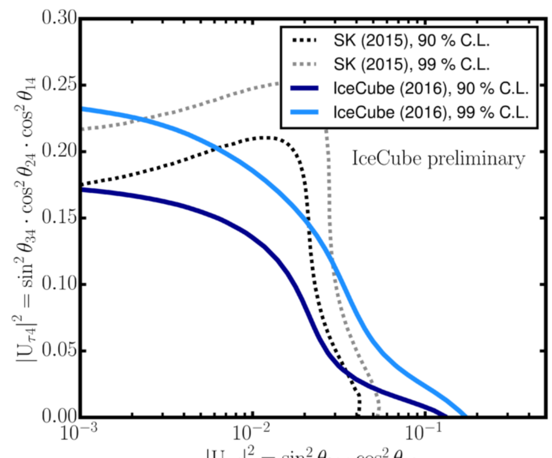
- Sterile neutrinos using high energy events:

  https://arxiv.org/abs/1605.01990



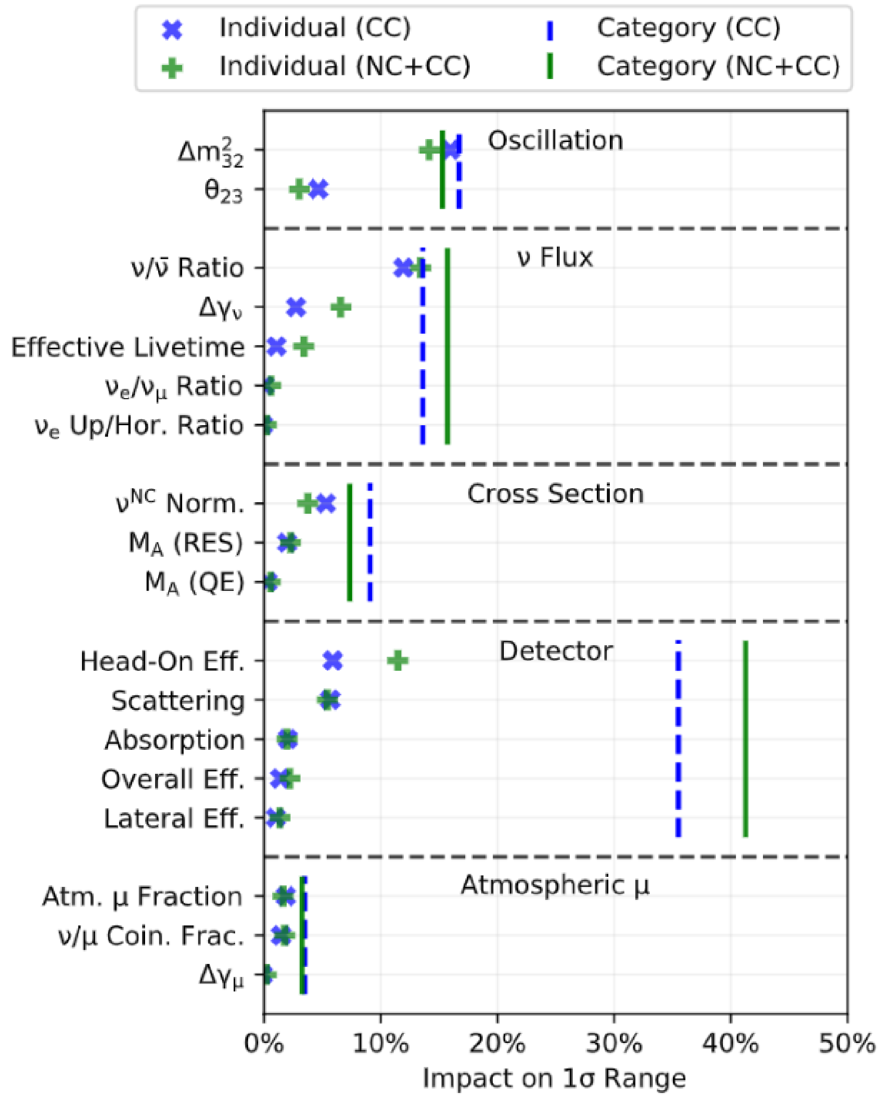
- Sterile neutrinos using low energy events:

  https://arxiv.org/abs/1702.05160

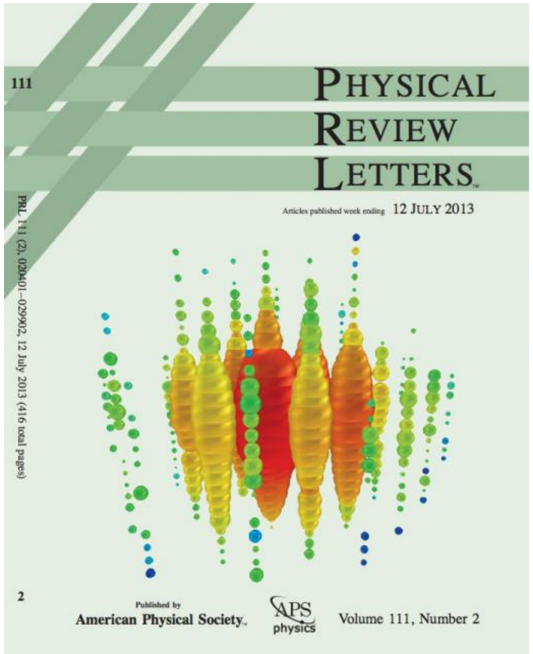


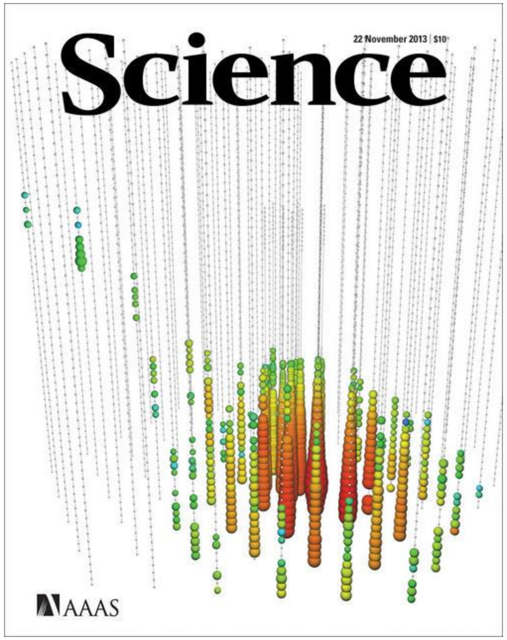
SYSTEMATICS IMPACT

- On Analysis A (nutau)

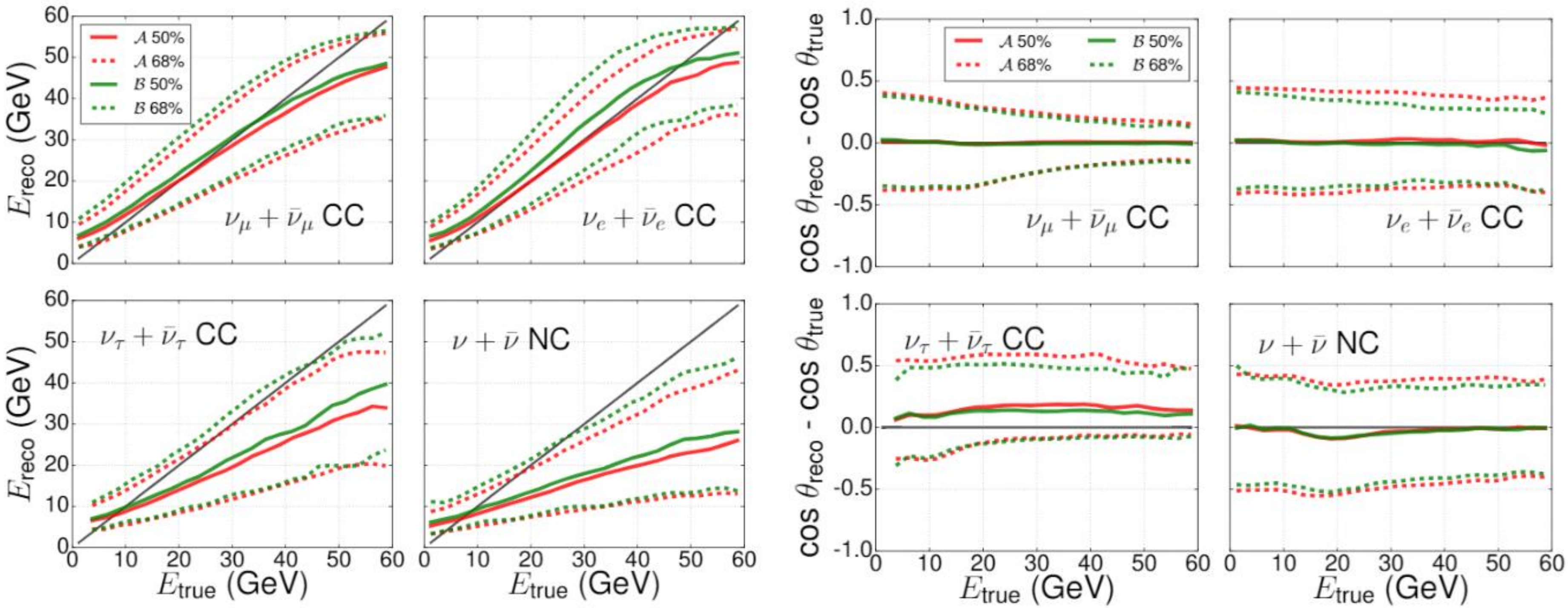


Phys. Rev. Lett. **111**, 021103 (2013)
Science 342, 6161 (2013)

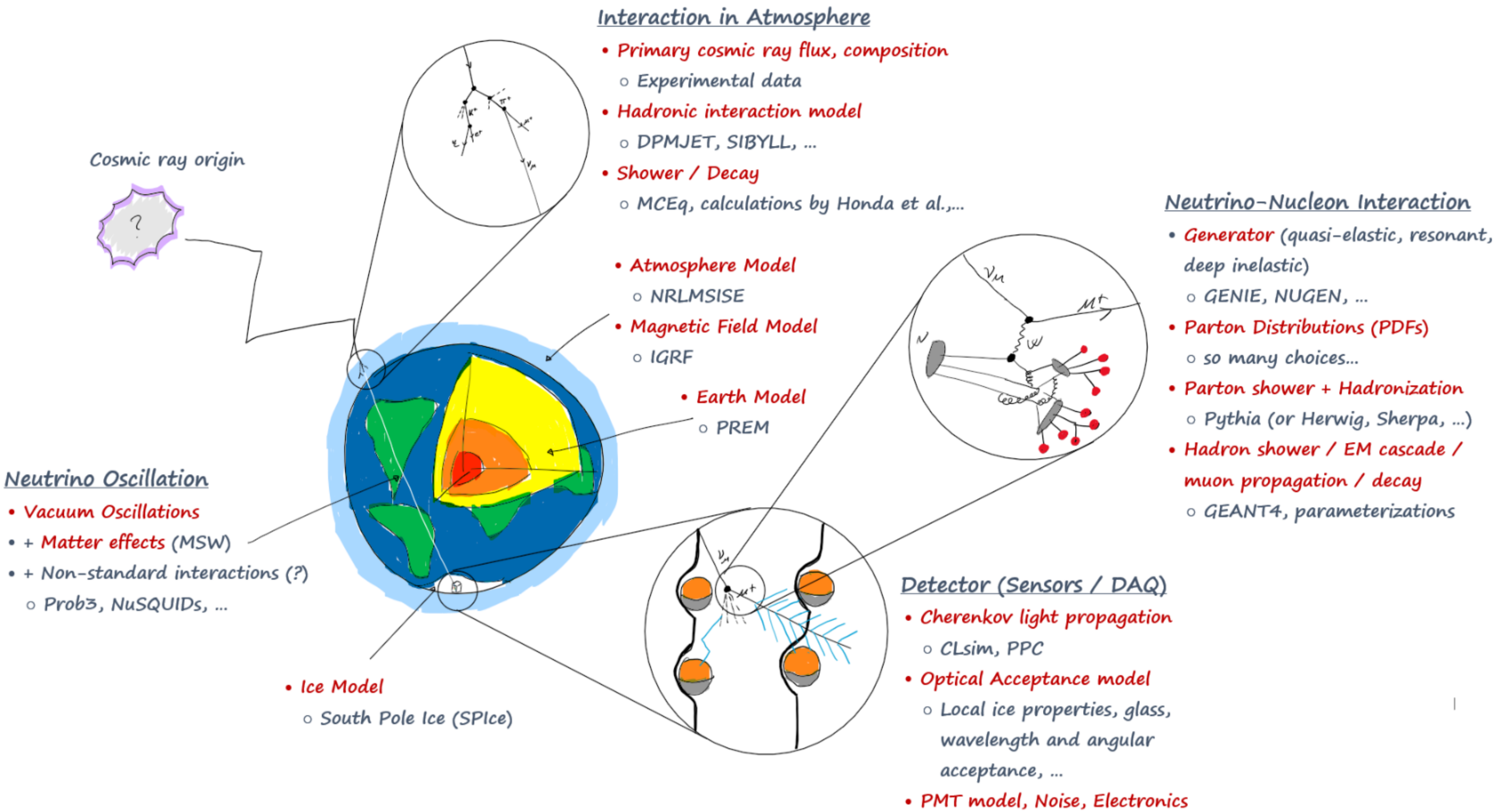




DEEPCORE RESOLUTIONS



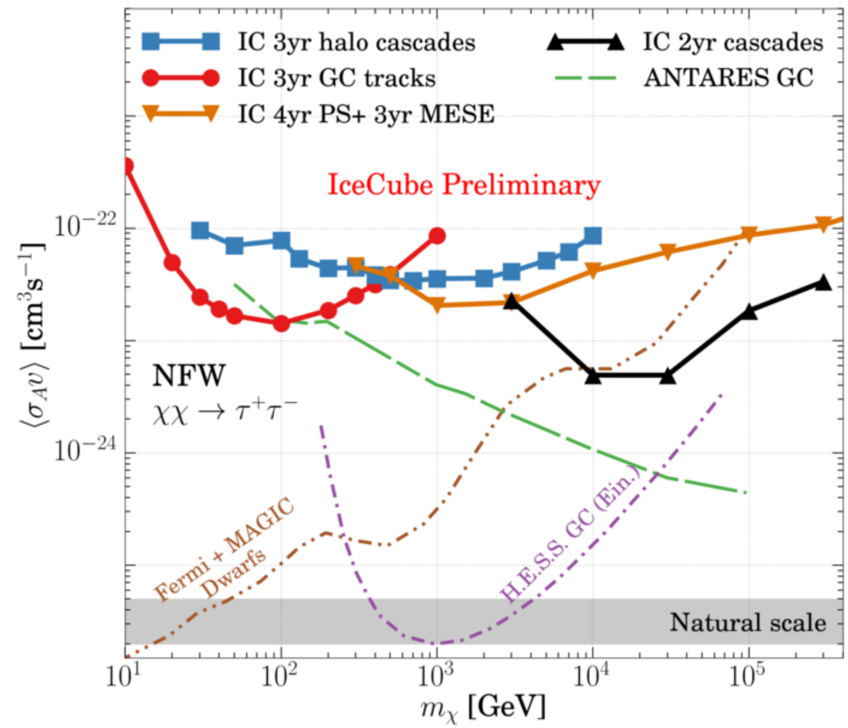
ATM. NEUTRINOS: INGREDIENTS



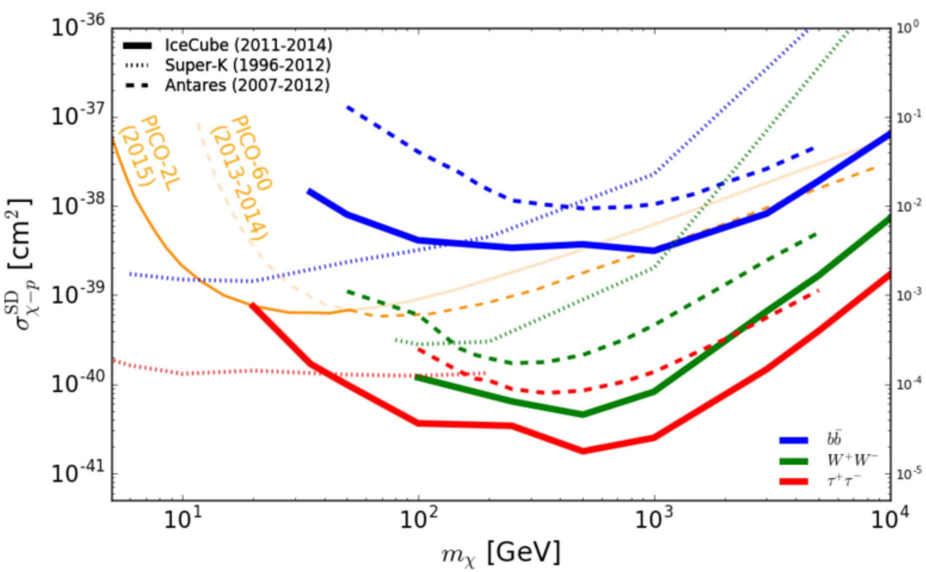
DARK MATTER

- Several searches for WIMPs to neutrinos

Galactic Halo WIMP search



Solar WIMP annihilation (spin-dependent)



STERILES

- High-energy resonance of eV scale (3+1) model sterile neutrino
  - https://arxiv.org/pdf/1605.01990.pdf