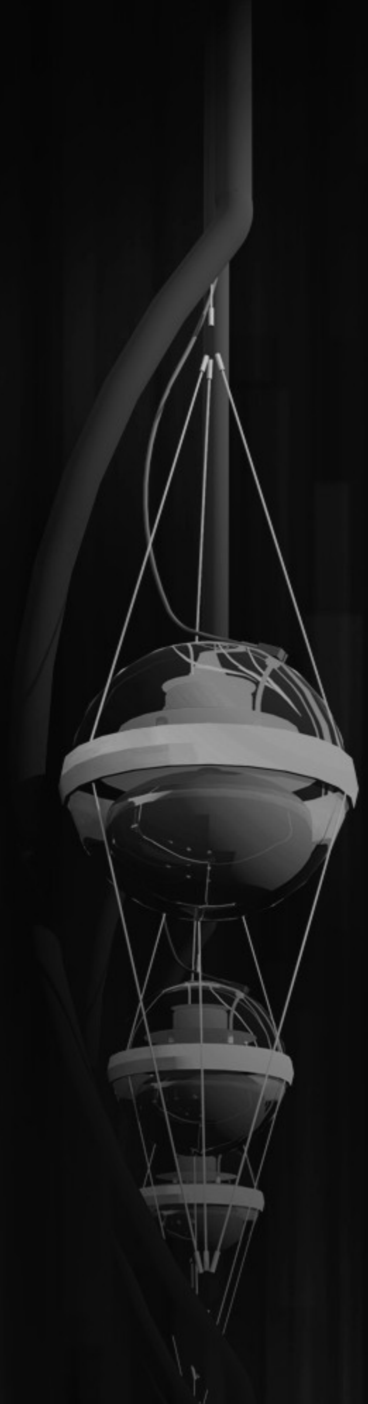


IceCube's low energy side
DeepCore & PINGU

J.P. Yanez for the **IceCube-Gen2 Collaboration**

NNN workshop

Beijing, November 2016

UNIVERSITY OF ALBERTA

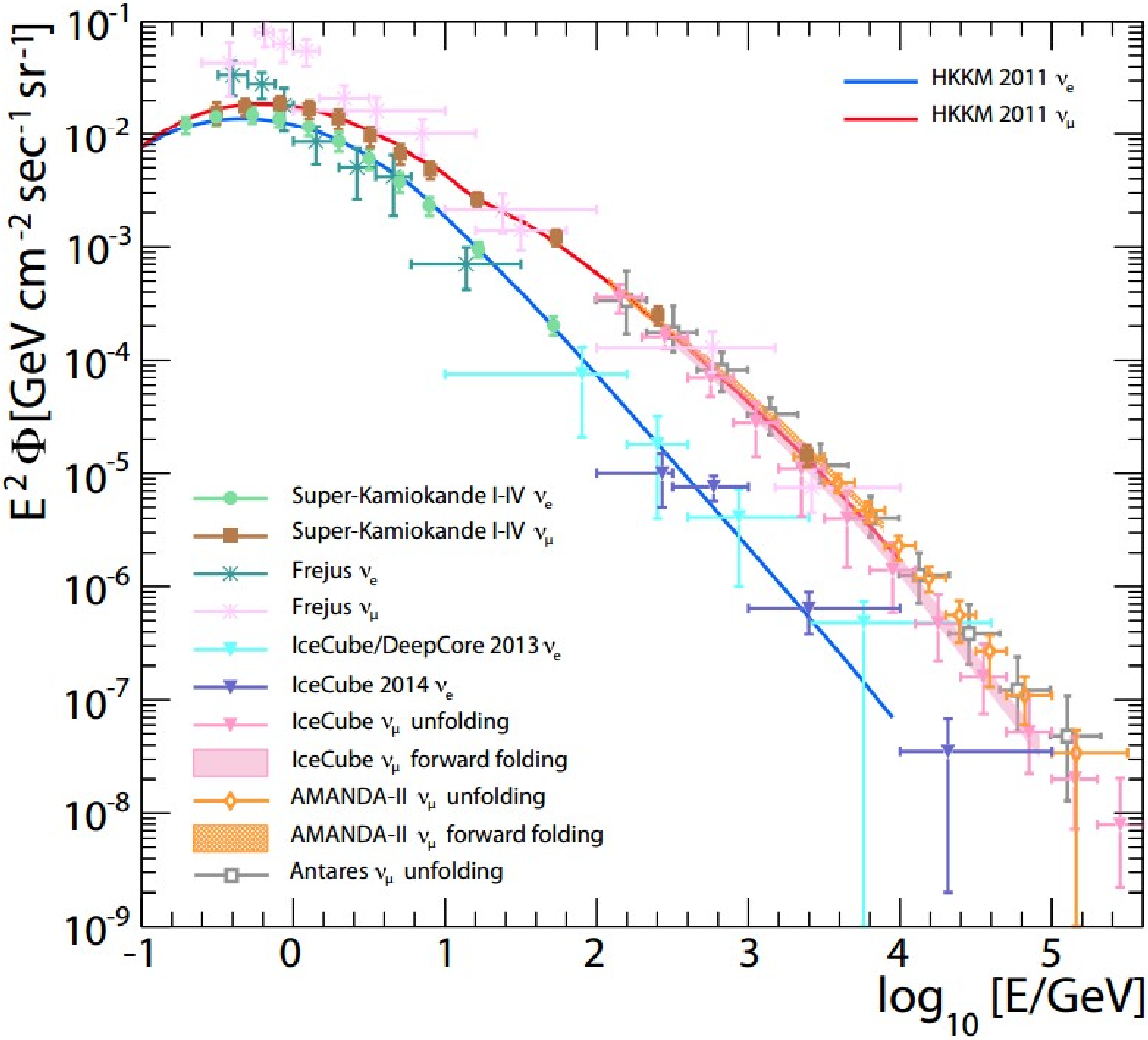
Bourses postdoctorales Banting Postdoctoral Fellowships

j.p.yanez@ualberta.ca

Atmospheric neutrinos: a multi-purpose beam

An atmospheric neutrino flux

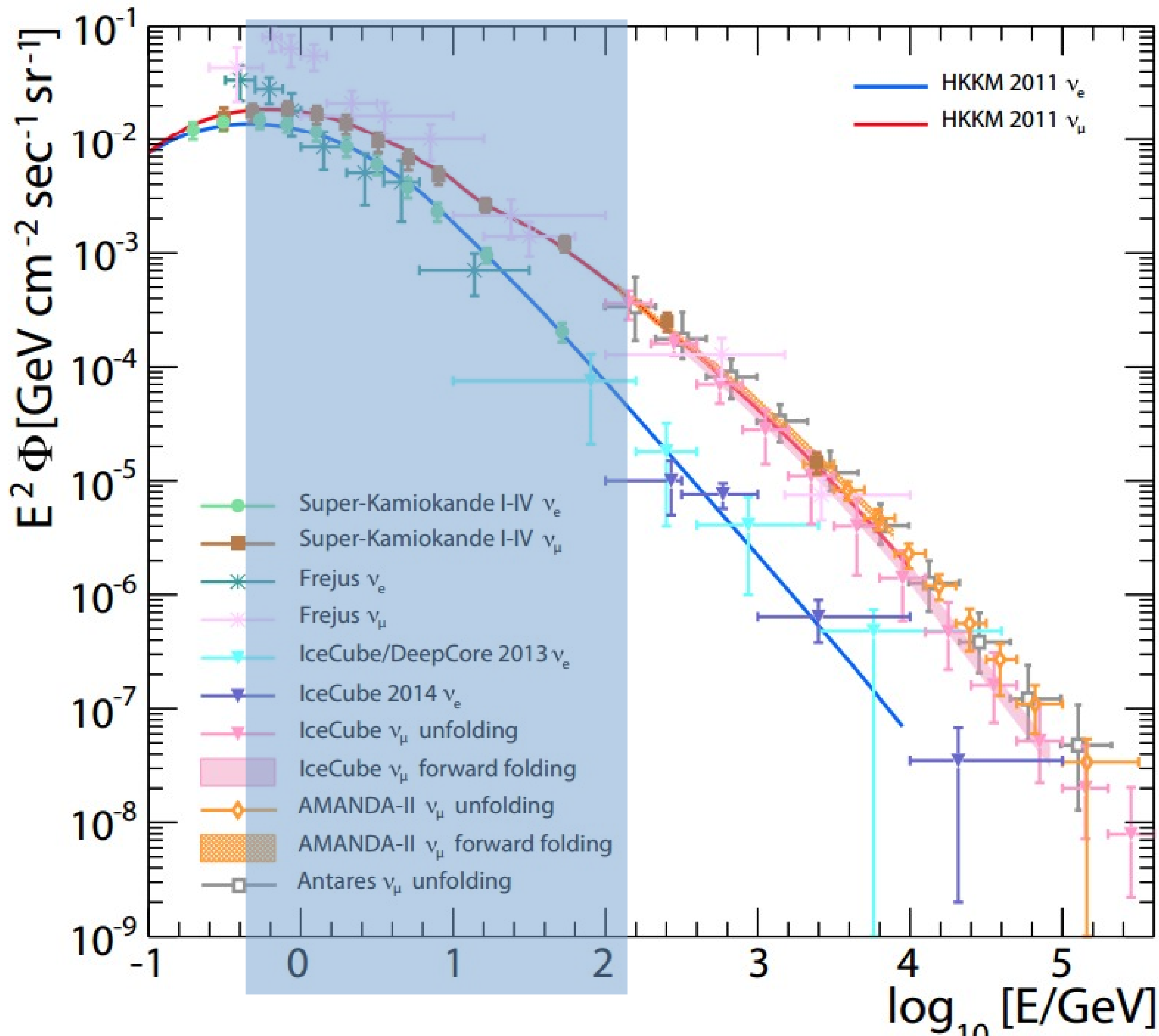
$$CR + N \to X + \pi^{\mp},\, K^{\mp}\,, \quad \to \quad \begin{aligned} \pi^-,\, K^- &\to \mu^- + \bar{\nu}_\mu\,, \\ \pi^+,\, K^+ &\to \mu^+ + \nu_\mu\,, \end{aligned} \quad \to \quad \begin{aligned} \mu^- &\to e^- + \bar{\nu}_e + \nu_\mu\,, \\ \mu^+ &\to e^+ + \nu_e + \bar{\nu}_\mu\,. \end{aligned}$$



An atmospheric neutrino flux

$$CR + N \rightarrow X + \pi^{\mp}, K^{\mp}, \quad \longrightarrow \quad \begin{array}{l} \pi^-, K^- \rightarrow \mu^- + \bar{\nu}_\mu, \\ \pi^+, K^+ \rightarrow \mu^+ + \nu_\mu, \end{array} \quad \longrightarrow \quad \begin{array}{l} \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu, \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu. \end{array}$$

ν oscillations



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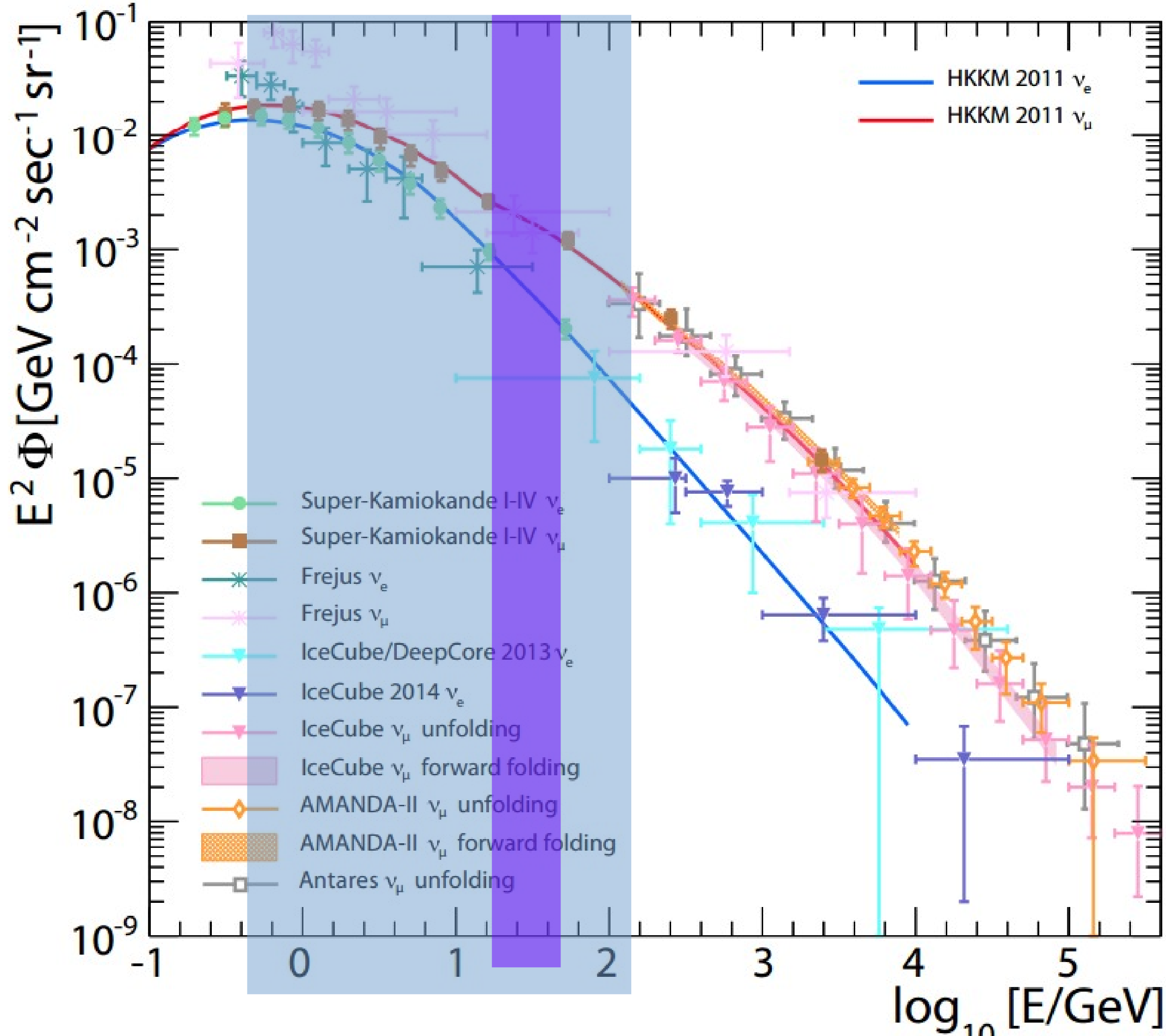
$$CR + N \to X + \pi^{\mp}, K^{\mp}, \quad \to \quad \begin{array}{l} \pi^-, K^- \to \mu^- + \bar{\nu}_\mu\,, \\ \pi^+, K^+ \to \mu^+ + \nu_\mu\,, \end{array} \quad \to \quad \begin{array}{l} \mu^- \to e^- + \bar{\nu}_e + \nu_\mu\,, \\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu\,. \end{array}$$

- ν oscillations
- ν_τ appearance



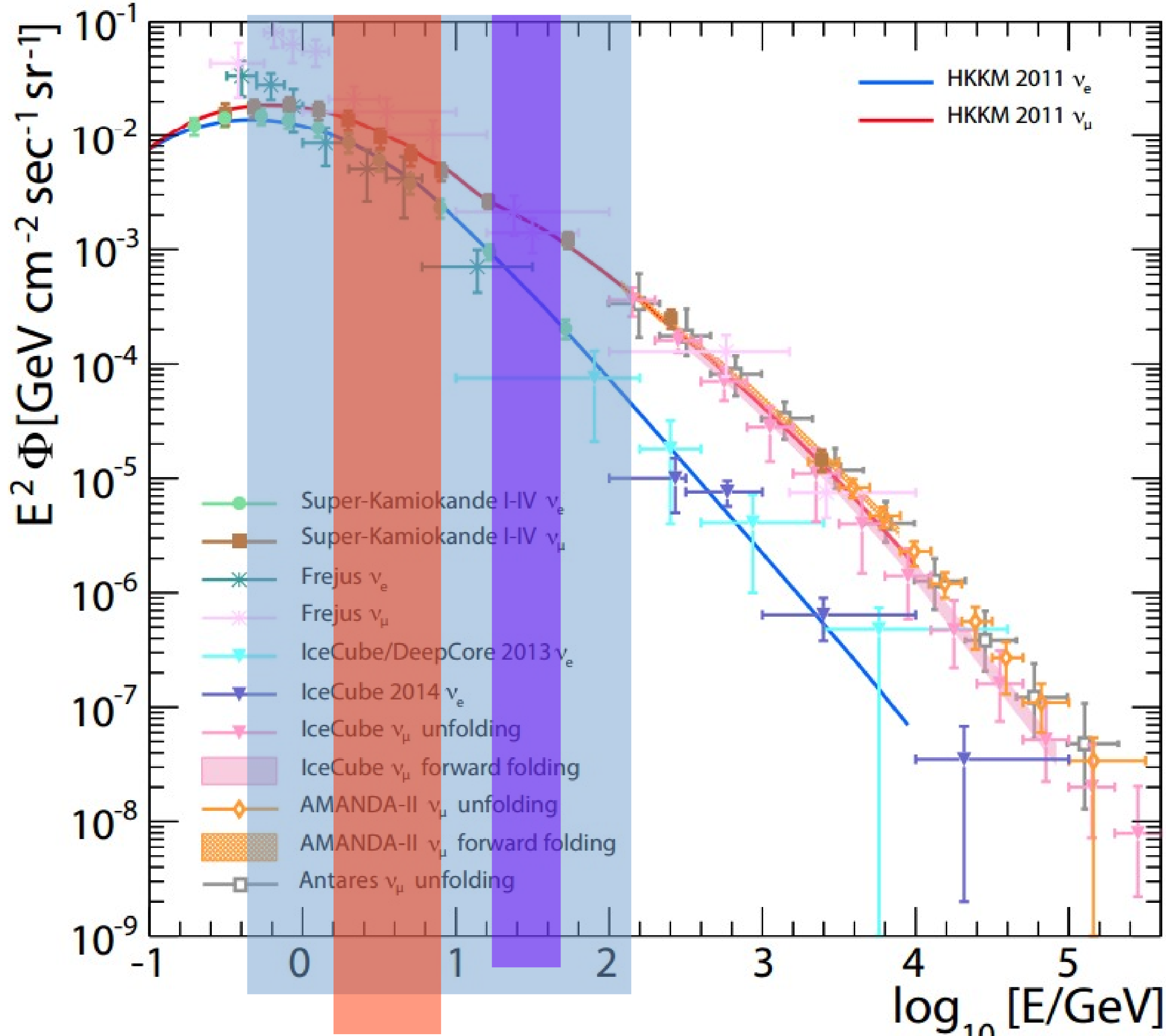
An atmospheric neutrino flux

$$CR + N \to X + \pi^{\mp}, K^{\mp}, \quad \longrightarrow \quad \begin{array}{l} \pi^-, K^- \to \mu^- + \bar{\nu}_\mu , \\ \pi^+, K^+ \to \mu^+ + \nu_\mu , \end{array} \quad \longrightarrow \quad \begin{array}{l} \mu^- \to e^- + \bar{\nu}_e + \nu_\mu , \\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu . \end{array}$$

ν oscillations

ν_τ appearance

ν mass ordering



An atmospheric neutrino flux

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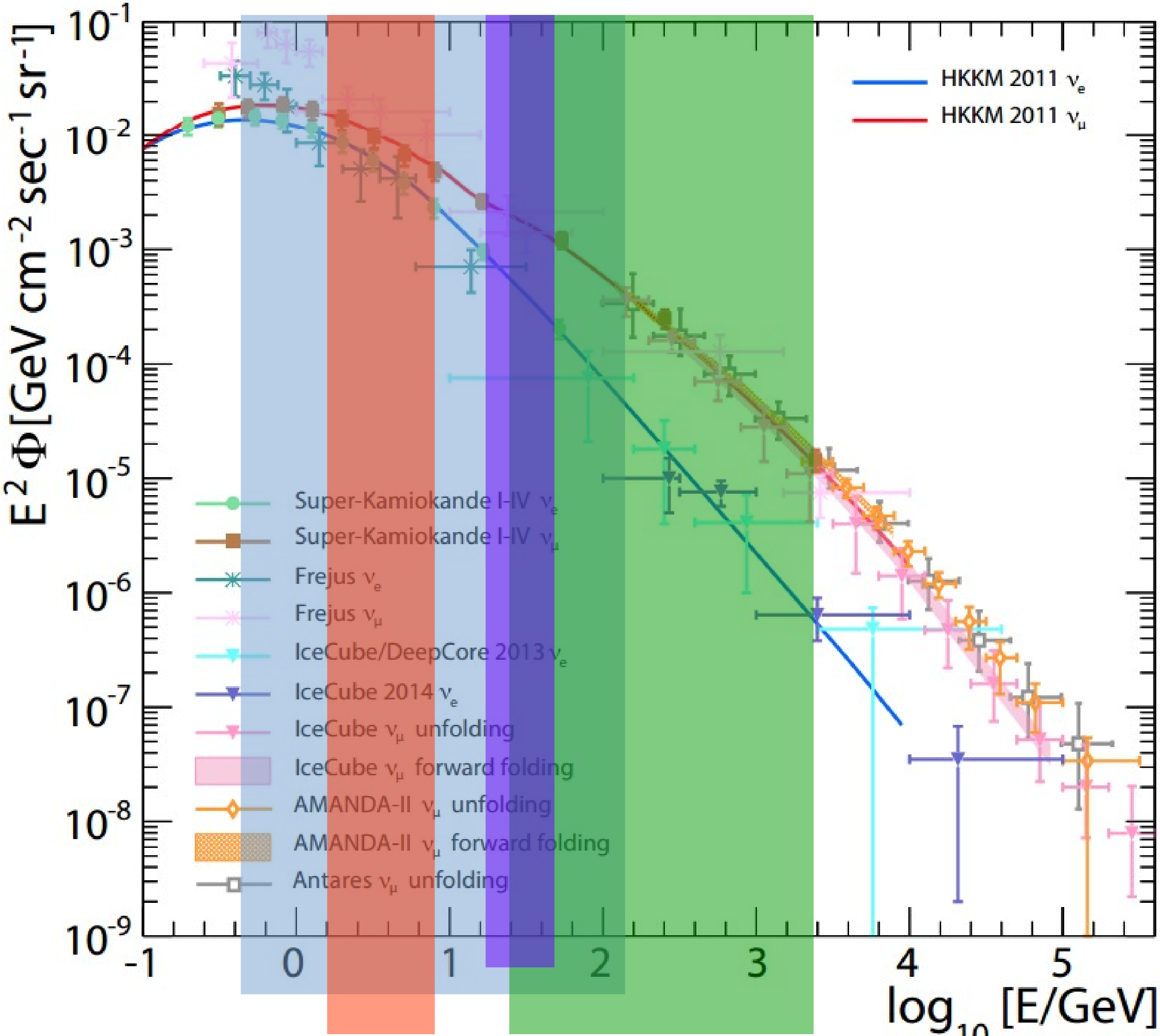
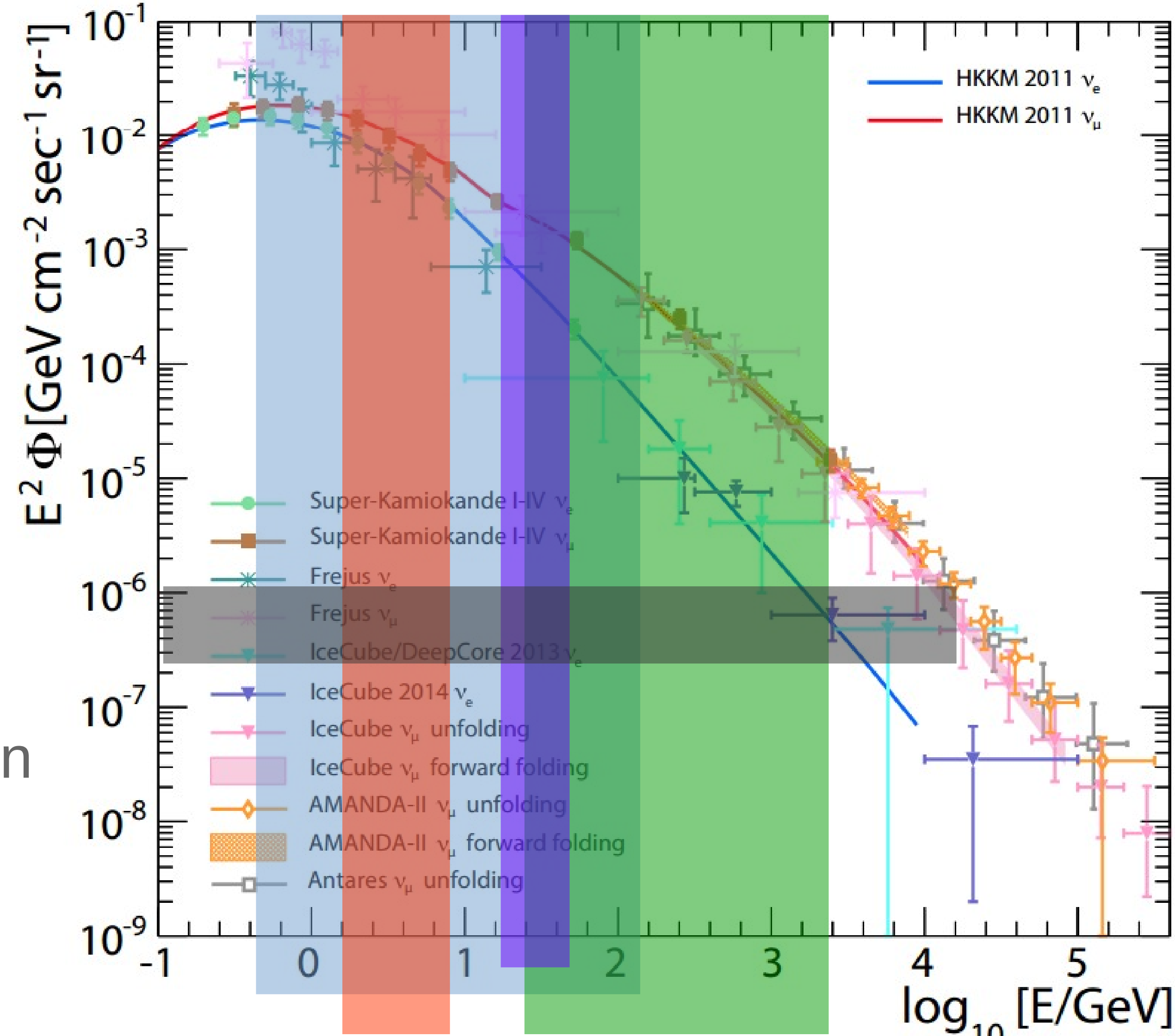
- ν oscillations
- ν_τ appearance
- ν mass ordering
- Sterile ν's



An atmospheric neutrino flux

$$CR + N \to X + \pi^{\mp}, K^{\mp}, \quad \to \quad \begin{matrix} \pi^-, K^- \to \mu^- + \bar{\nu}_\mu , \\ \pi^+, K^+ \to \mu^+ + \nu_\mu , \end{matrix} \quad \to \quad \begin{matrix} \mu^- \to e^- + \bar{\nu}_e + \nu_\mu , \\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu . \end{matrix}$$

- ν oscillations
- ν_τ appearance
- ν mass ordering
- Sterile ν's
- Hadron production



An atmospheric neutrino flux

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- ν oscillations
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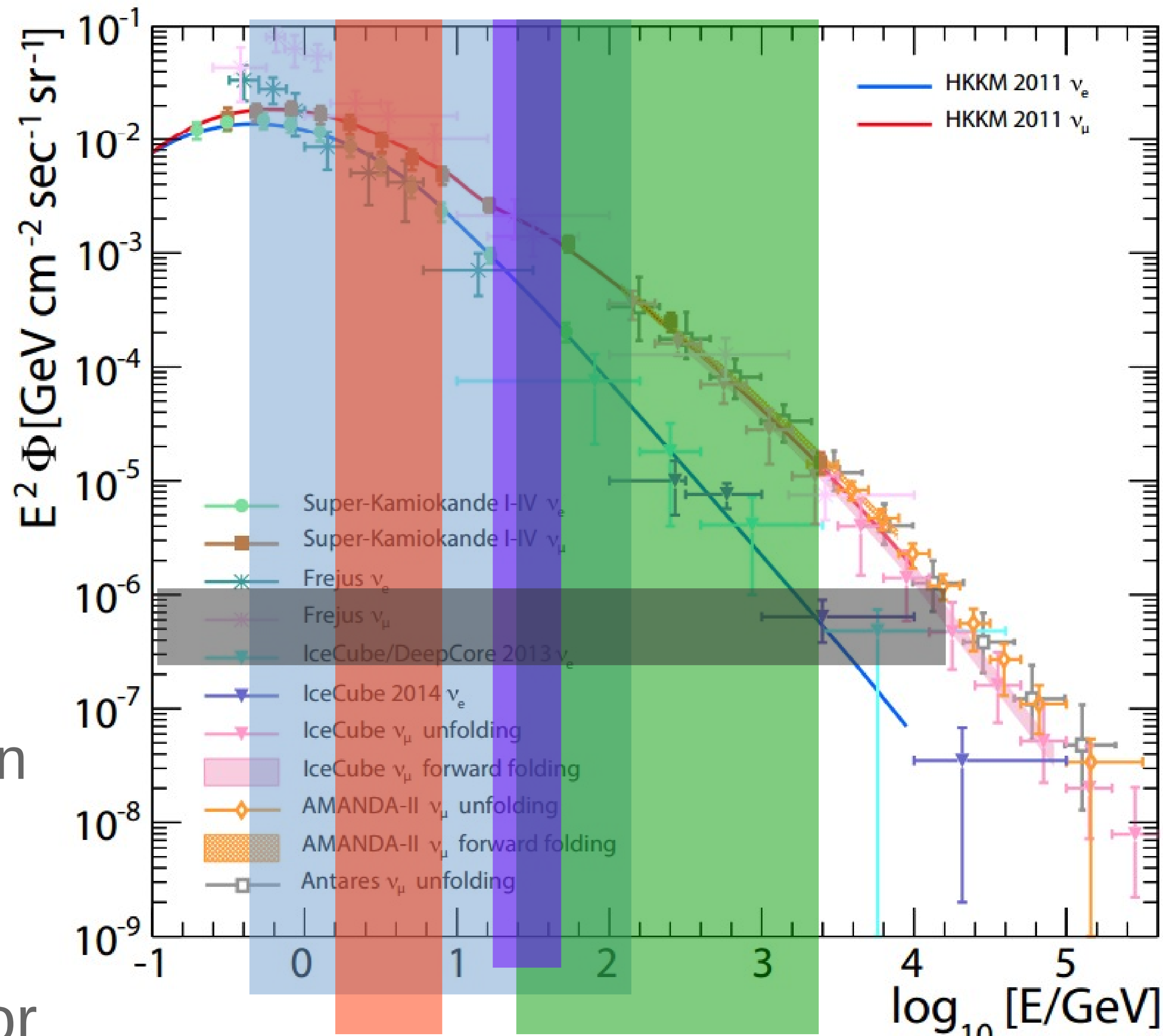
- ν mass ordering
- Sterile ν's
- Hadron production

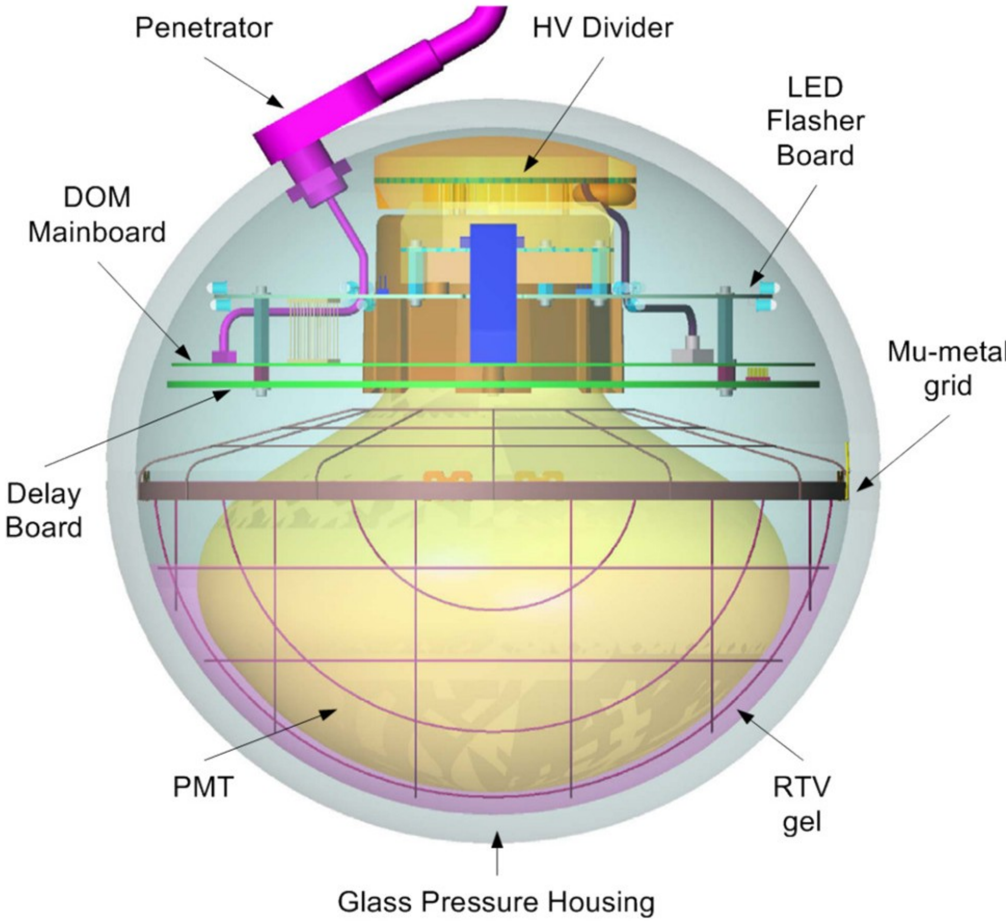


All with a single detector

IceCube DeepCore

A giant, naturally occurring piece of ice deep in Antarctica continuously monitored with over 5000 of the most sensitive cameras invented

Digital Optical Module (DOM)



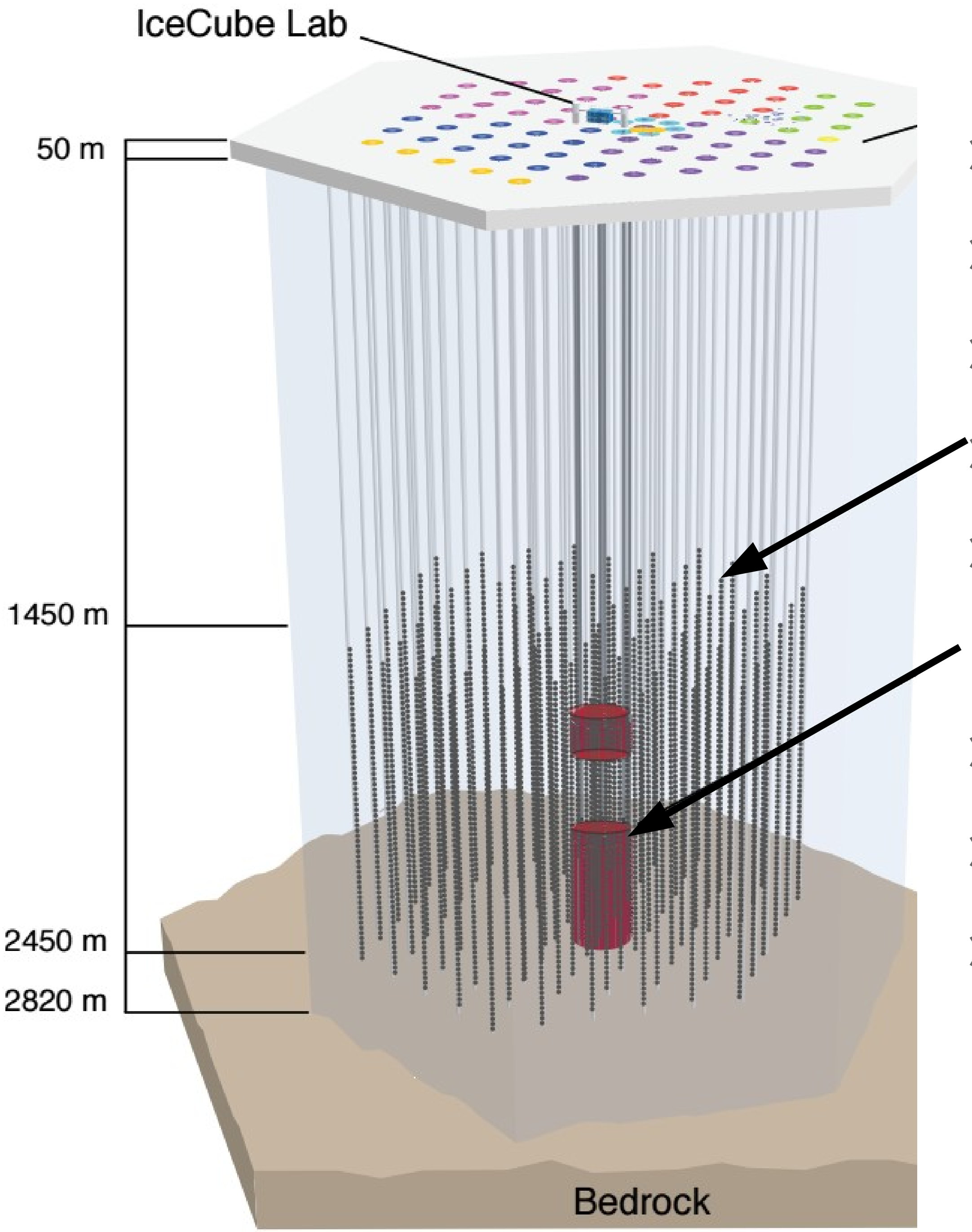
Ice-Cherenkov detector

- At the South Pole (ice)
- Depth of 1450-2450 m
- 5160 digital optical modules
- 86 strings, 125m separation
- 17m between DOMs in a string

<u>DeepCore volume</u>

- ~ 500 DOMs, 7m apart
- 40-70m between strings
- Energy threshold ~ 10 GeV

The IceCube detector



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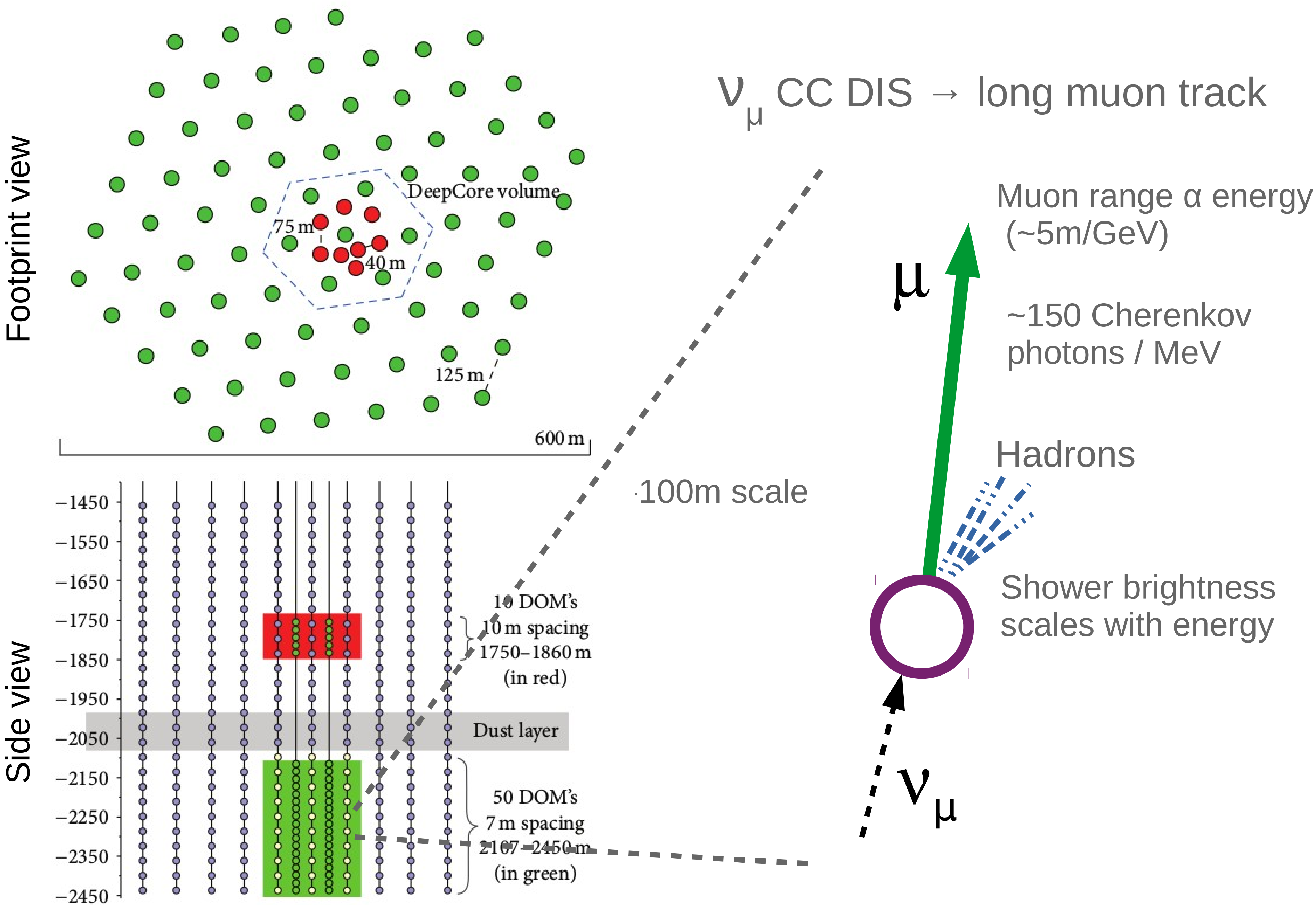
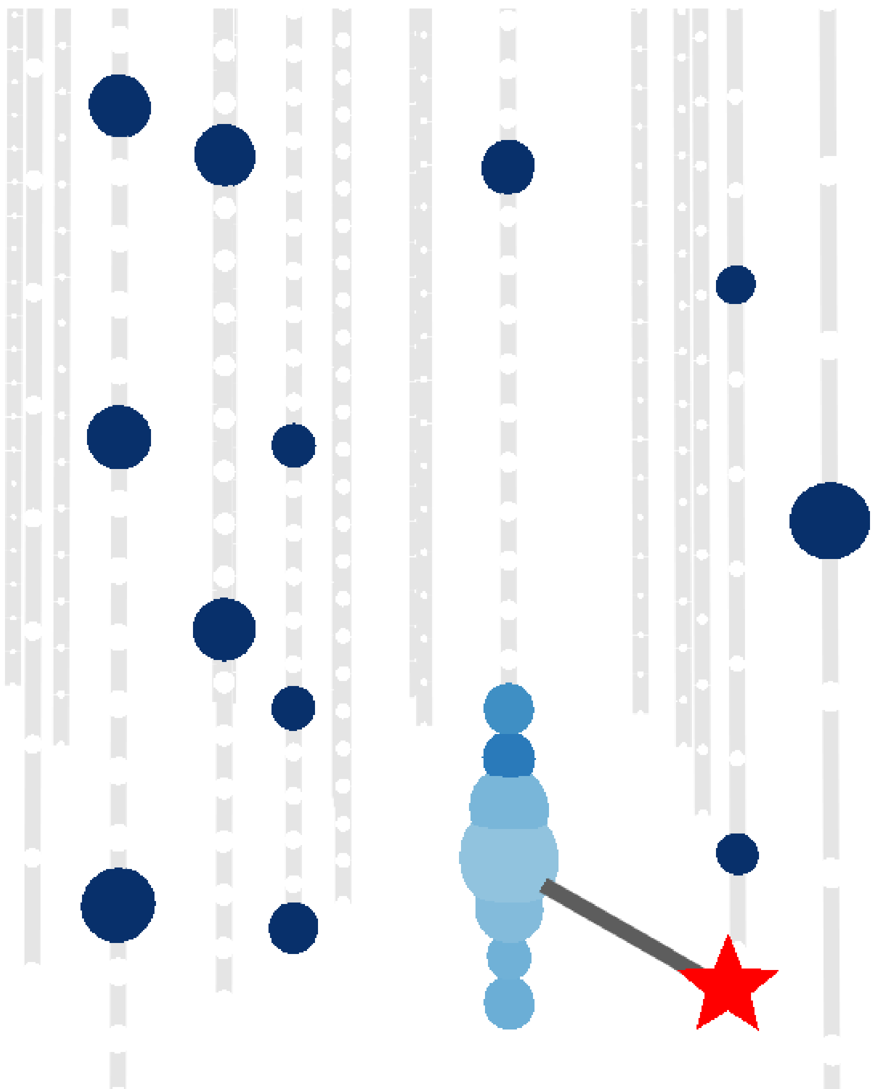
GeV Neutrinos in ice

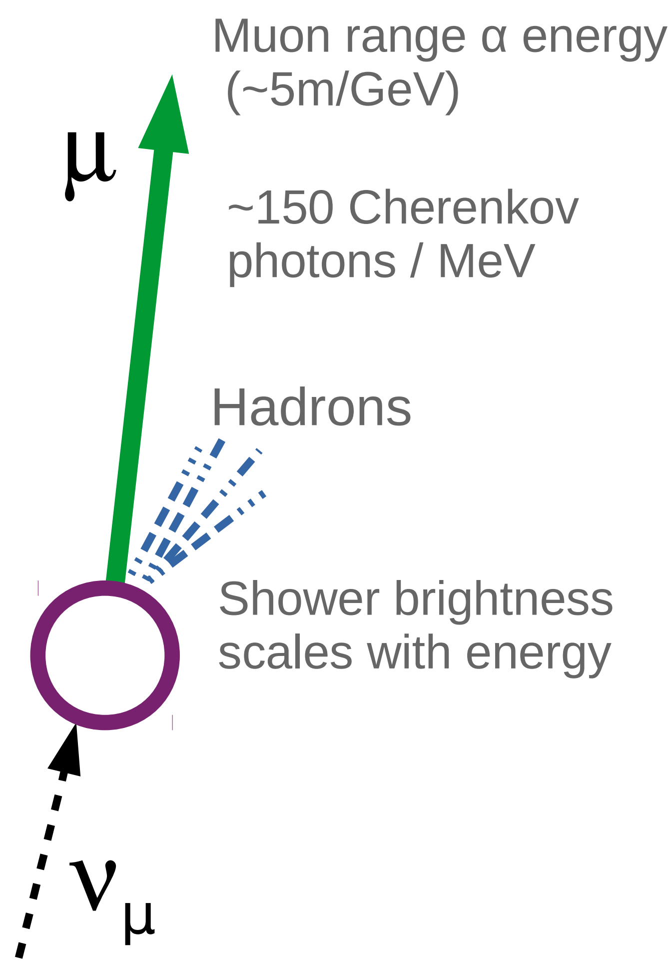


GeV Neutrinos in ice

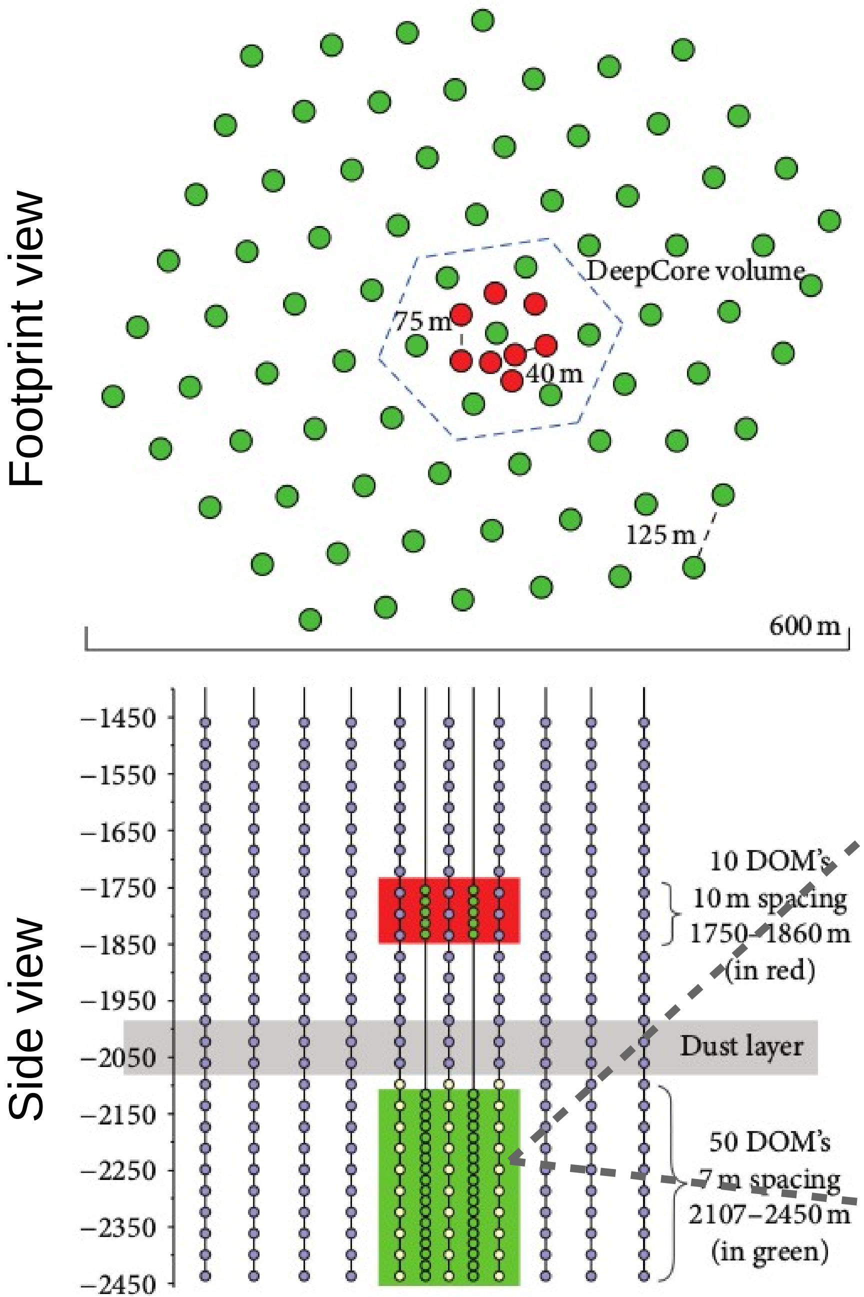


12 GeV ν_μ interaction
8 GeV track (R~40m) + 4 GeV cascade

ν_μ CC DIS → long muon track

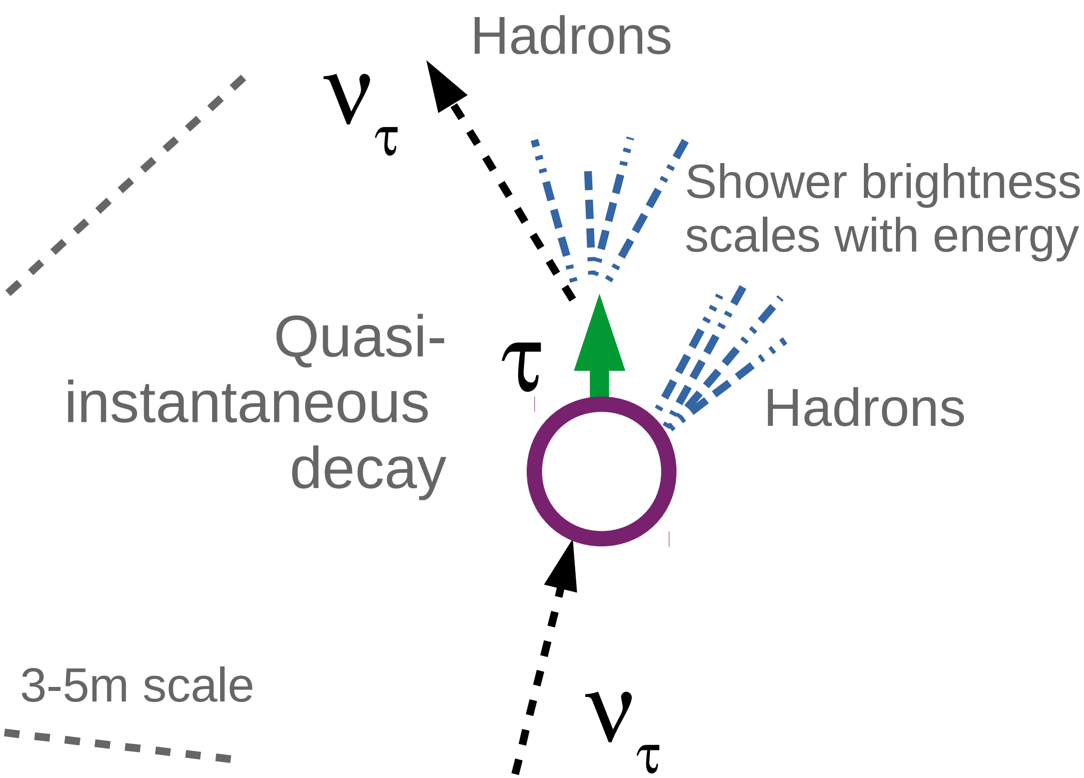


GeV Neutrinos in ice



ν_μ CC DIS
ν_τ CC DIS
ν_e CC DIS
ν_x NC DIS

→ blob of light

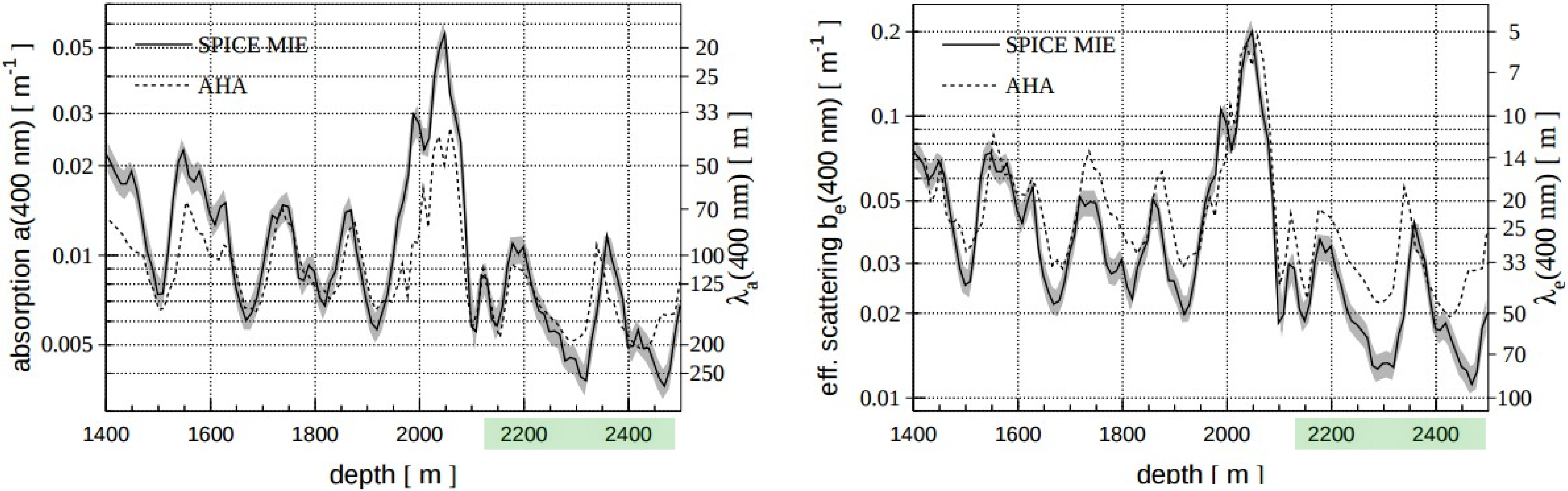


Neutrino signals in Antarctica

The detector medium: global

» Naturally occurring, clear ice … that we have tampered with

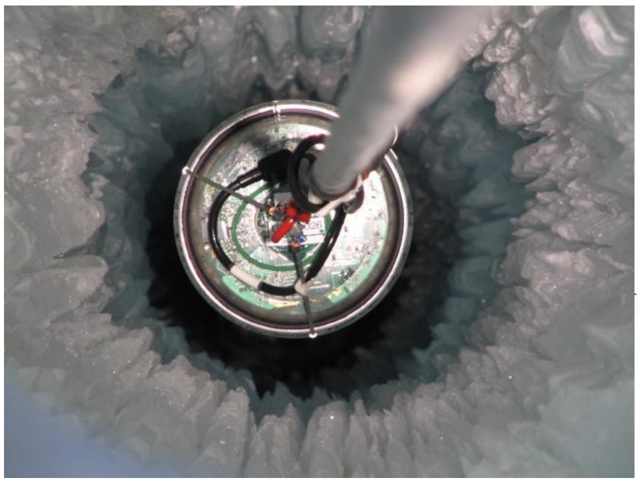
Global ice optical properties

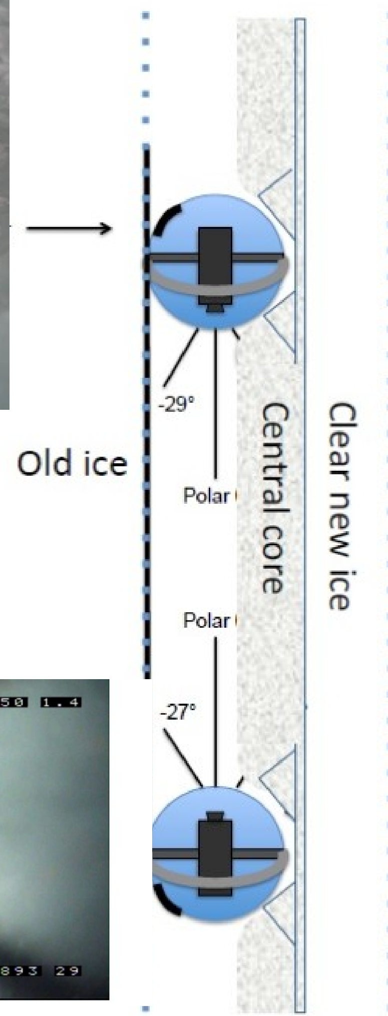


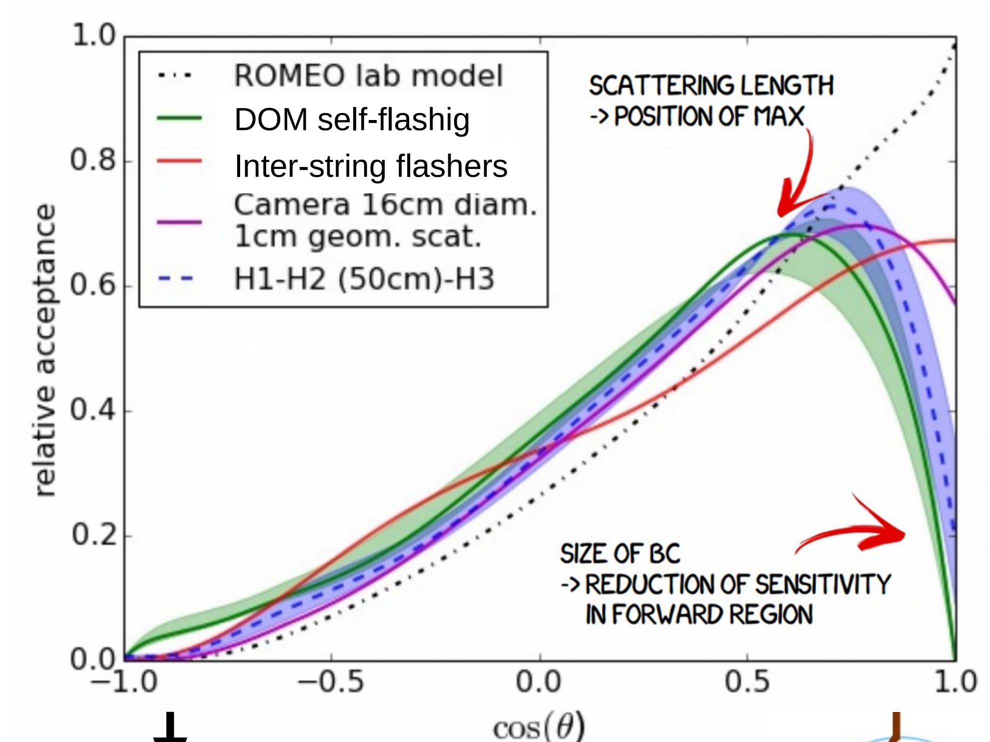
DeepCore is located at the region with best optical properties

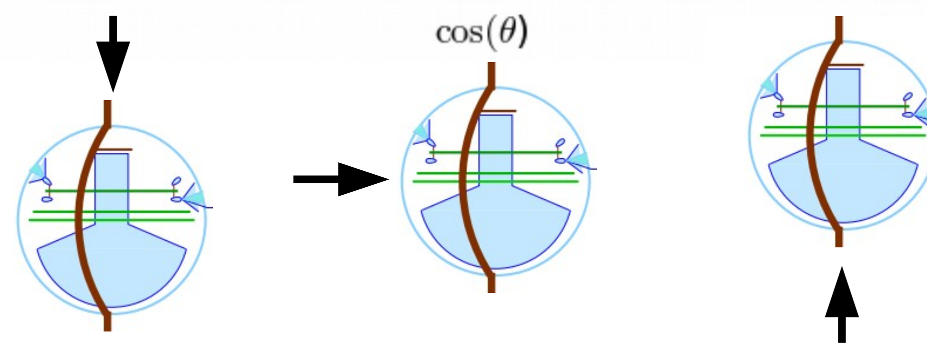
The detector medium: local

Local ice properties → Relative angular acceptance







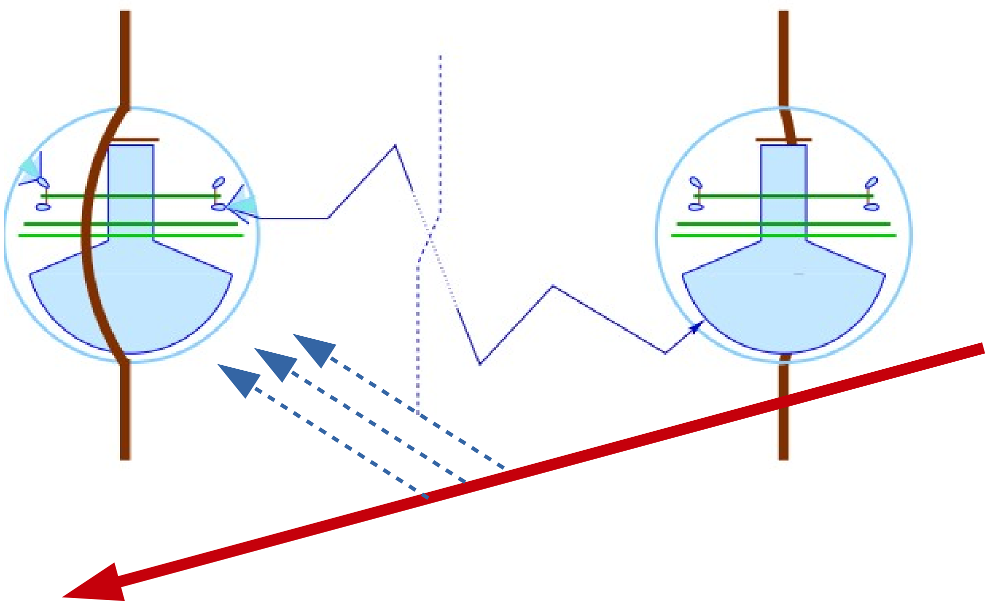


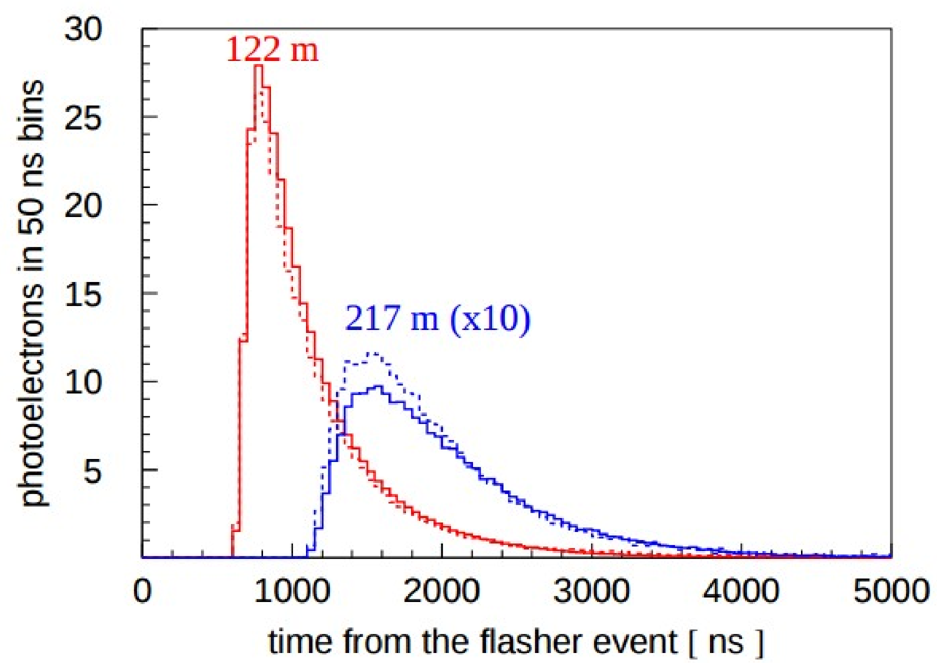
The detector medium: calibration

» Advanced studies: DOM flashers (inter-string)

» Studies being improved: minimum ionizing muons

» New studies: Self DOM flashing, in-situ camera information

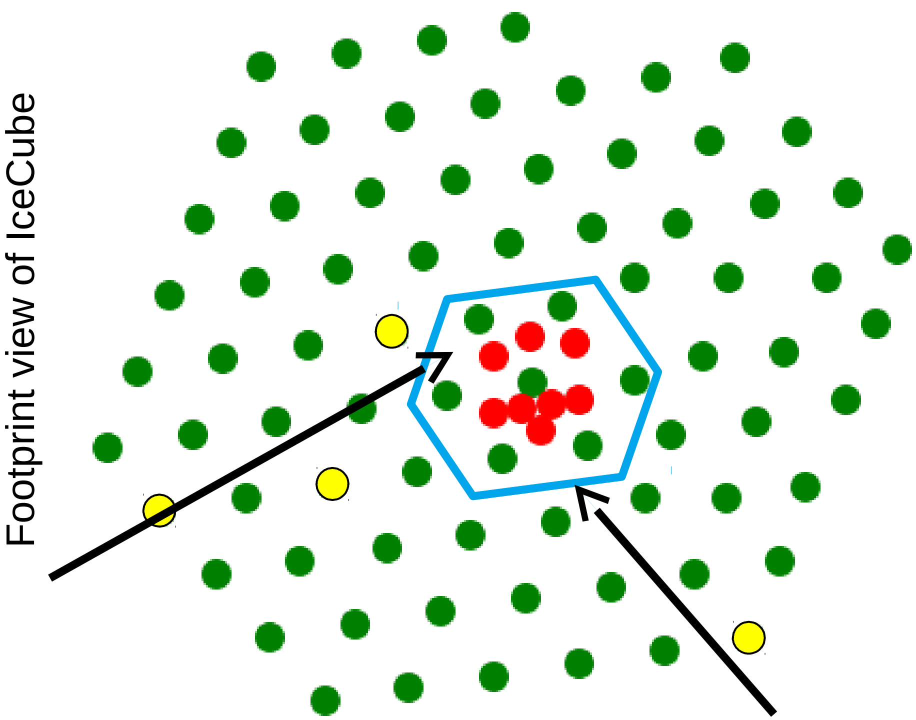


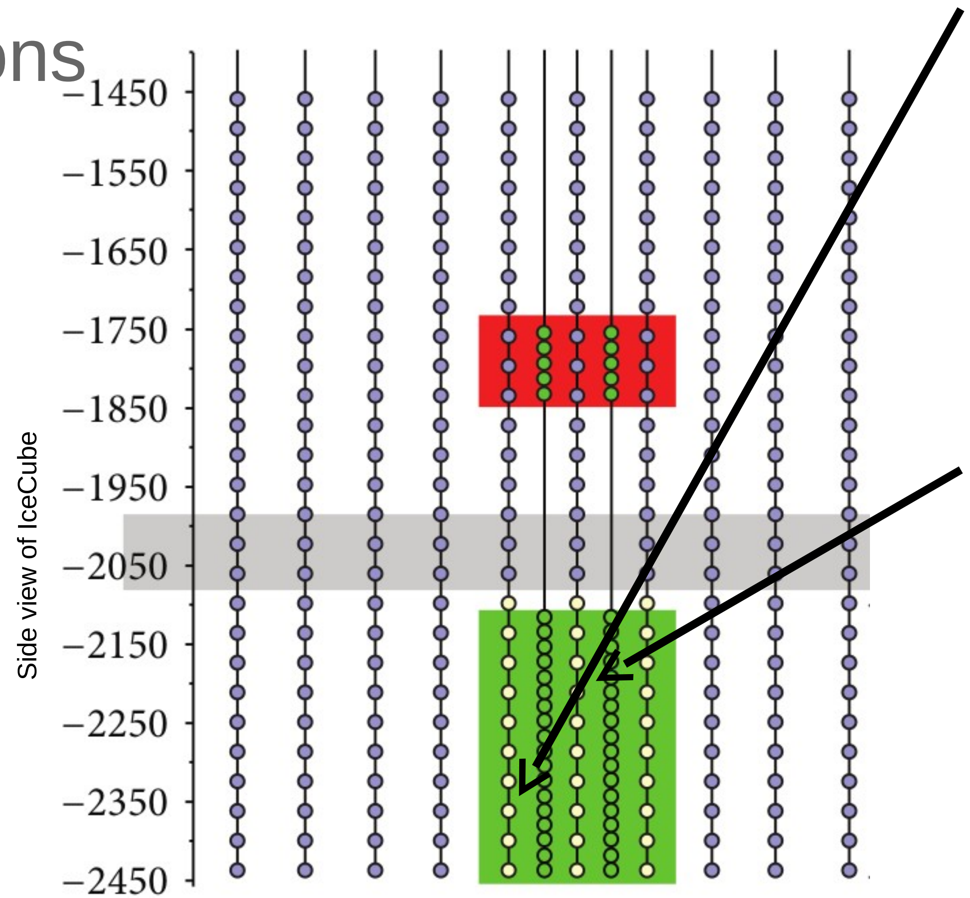


NIM A711:73,2013

Backgrounds: CR muons

- Muons from air showers
  - Muon trigger rate ~ 10^5 neutrino trigger rate
  - Scattering → misreconstructions
  - Known problematic directions

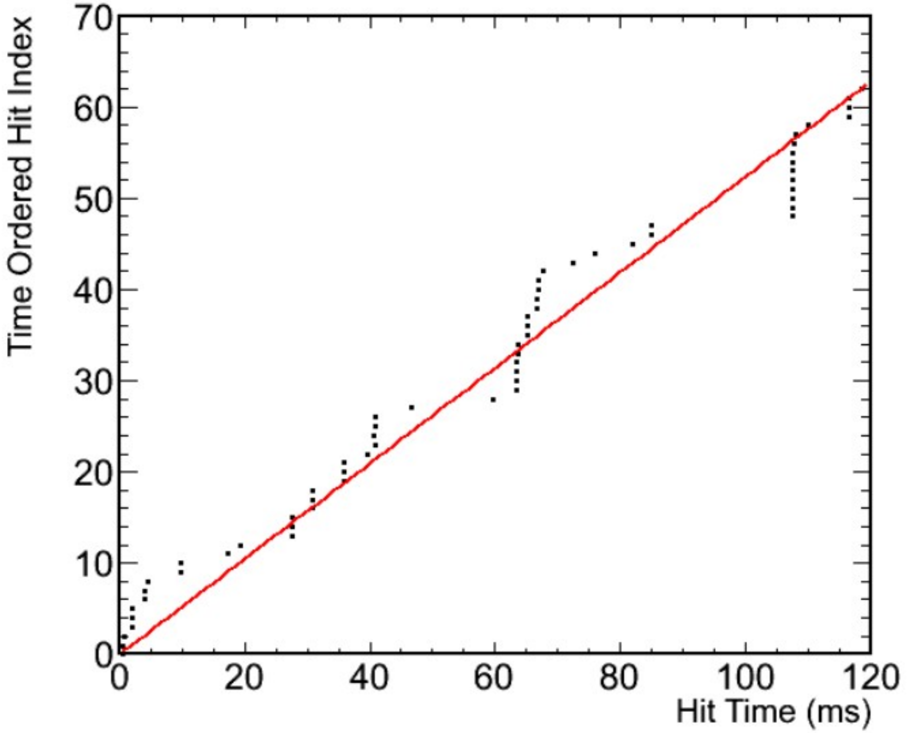




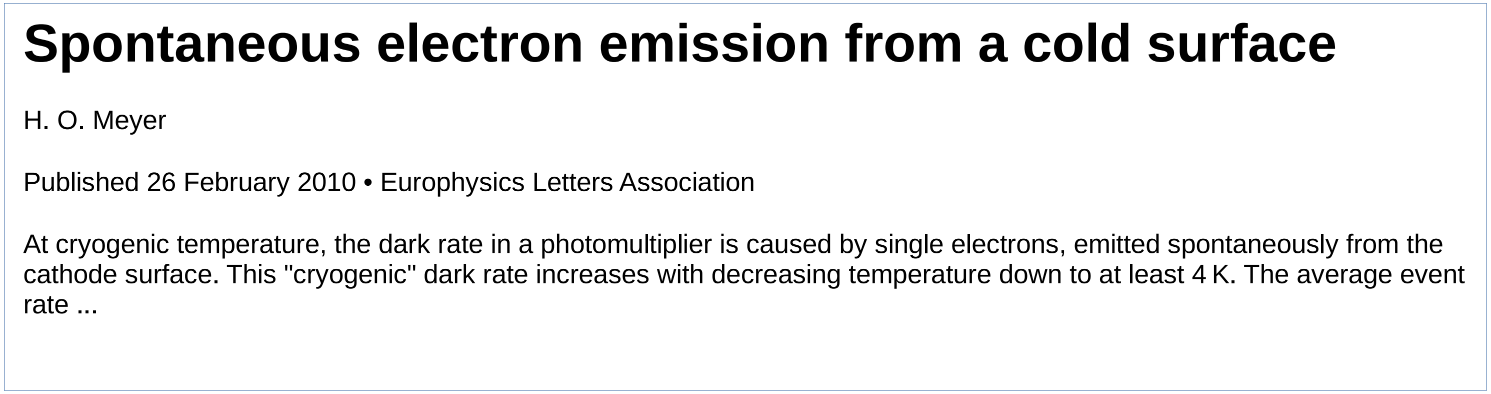
Backgrounds: PMT noise

- Noise
  - Noise rates ~ 500 Hz
  - Two components
    - random noise + correlated burst
  - Pure noise “events” appear

Noise hit times in a DOM in IceCube



Similar effects seen before with cold PMTs



Spontaneous electron emission from a cold surface

H. O. Meyer

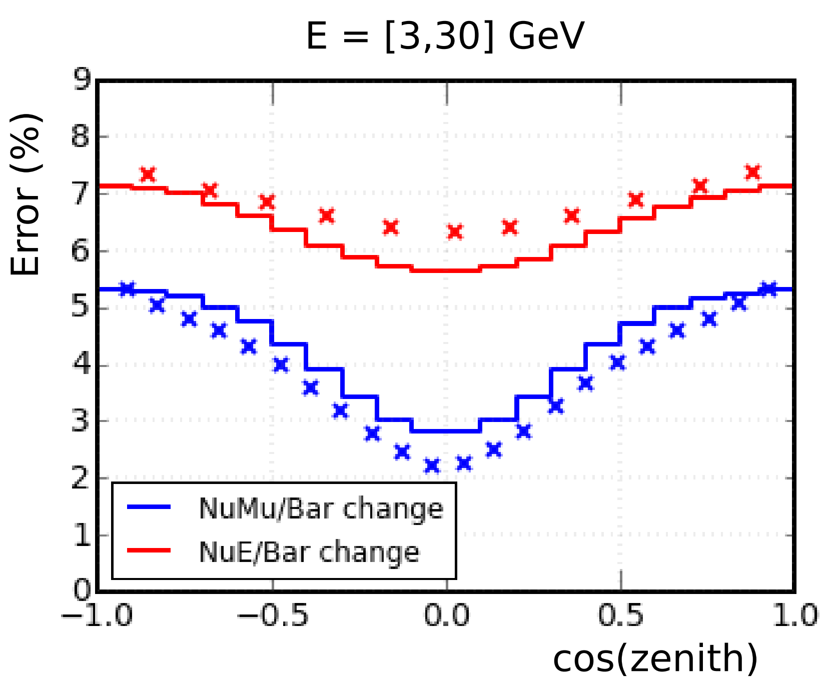
Published 26 February 2010 • Europhysics Letters Association

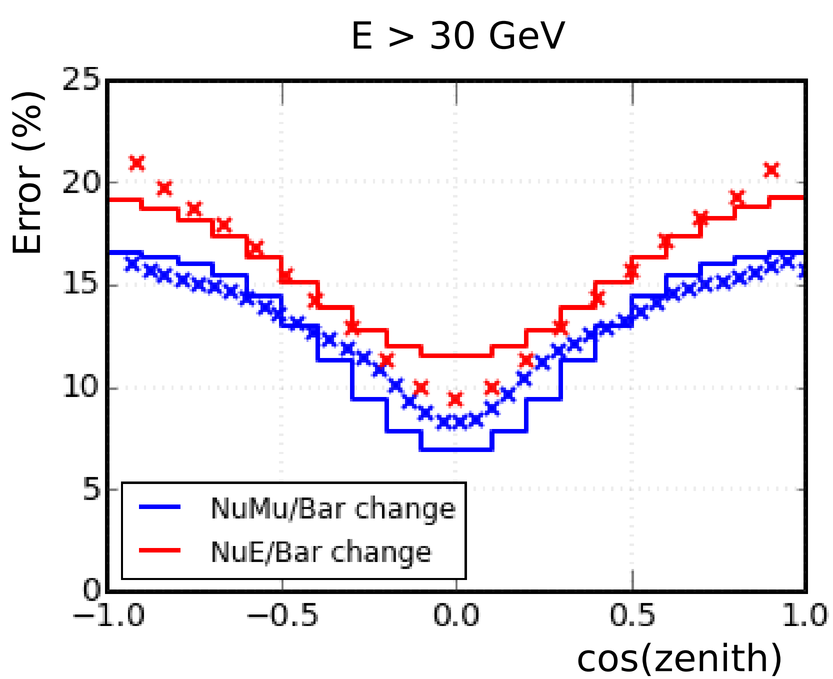
At cryogenic temperature, the dark rate in a photomultiplier is caused by single electrons, emitted spontaneously from the cathode surface. This "cryogenic" dark rate increases with decreasing temperature down to at least 4 K. The average event rate ...

Neutrino flux modeling: now

- Using Honda'15 flux for South Pole - modifying spectral index & normalization
- Uncertainties from Phys.Rev.D74:094009,2006
- Introduce 2 eff. params. → Reproduce changes reported in paper
  - Neutrino-to-antineutrino ratio (NuNubar)
  - Up-to-horizontal flux ratio (UpHor)

Assumptions required!





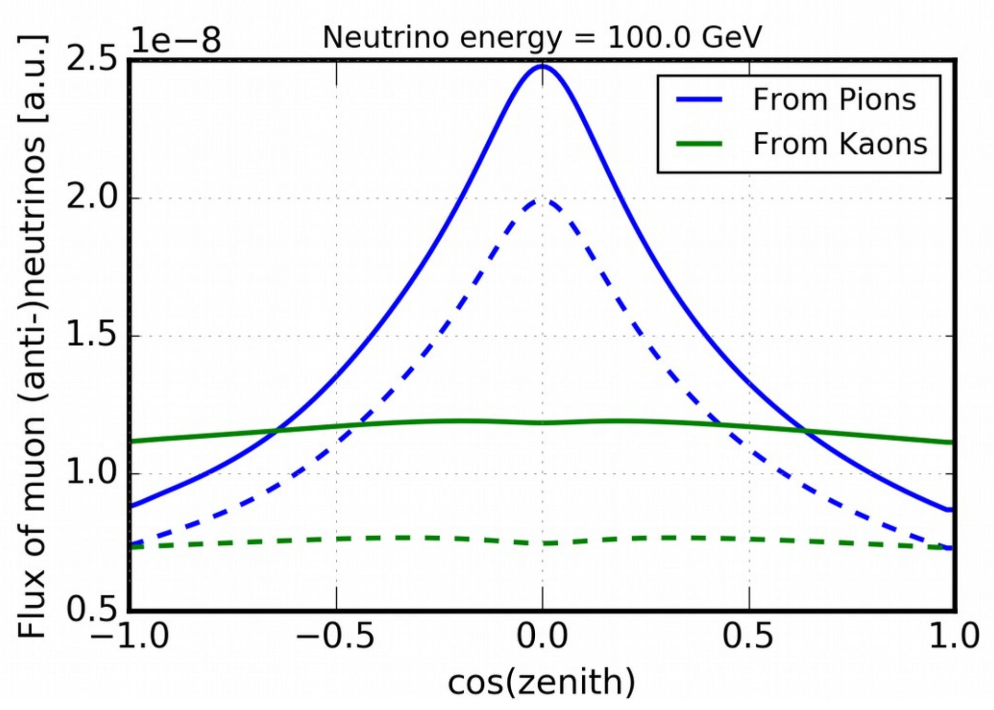
Neutrino flux modeling: future

» Moving towards an open tool: MCEq

Calculation of conventional and prompt lepton fluxes at very high energy
A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, T. Stanev
arXiv:1503.00544, http://mceq.readthedocs.io/en/latest/index.html

» Possible to modify

- » CR spectrum, primaries
- » Hadronic interactions
- » Atmospheric conditions

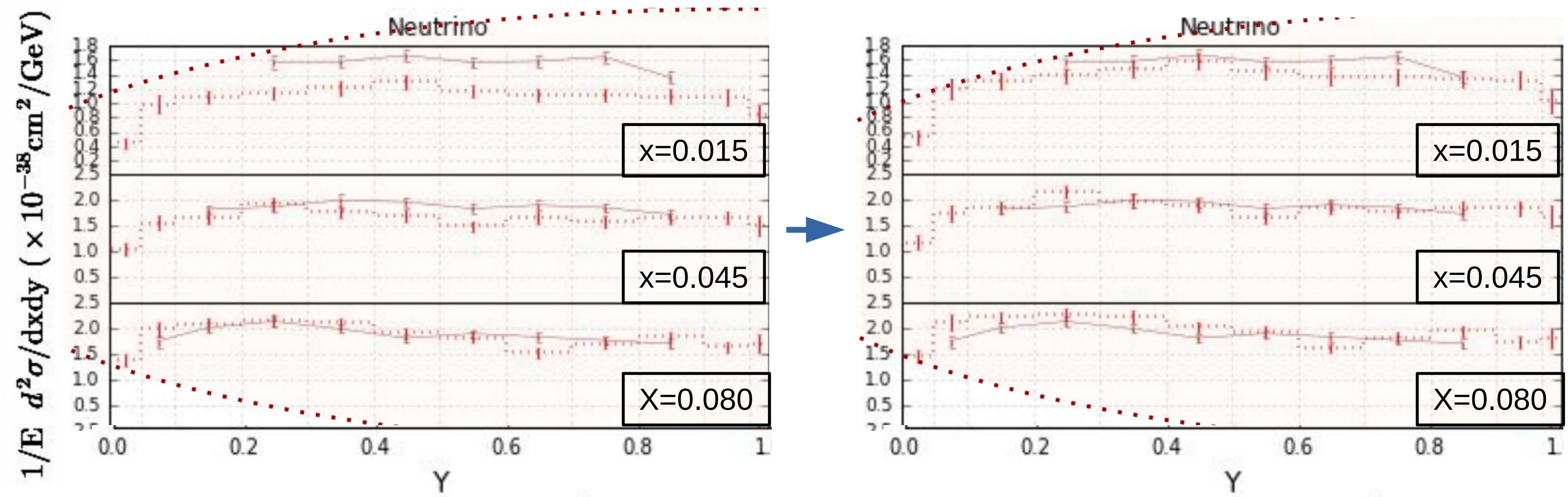


» Goal → better modeling of uncertainties

Neutrino cross sections

- » Using GENIE for simulating interactions
- » Working on corrections to explain

$$F\left(x;a,b\right) = bx^{-a}$$



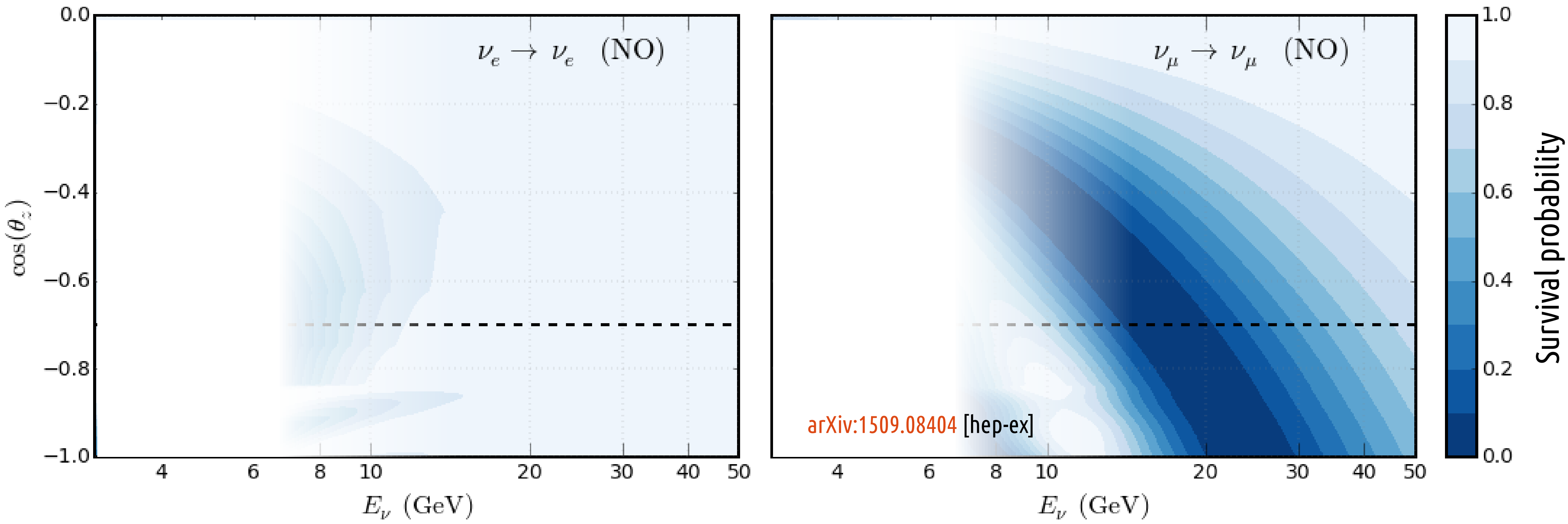
Corrections change bin content in experimental histograms by 1-2%

Analysis of diffuse fluxes

Selected results

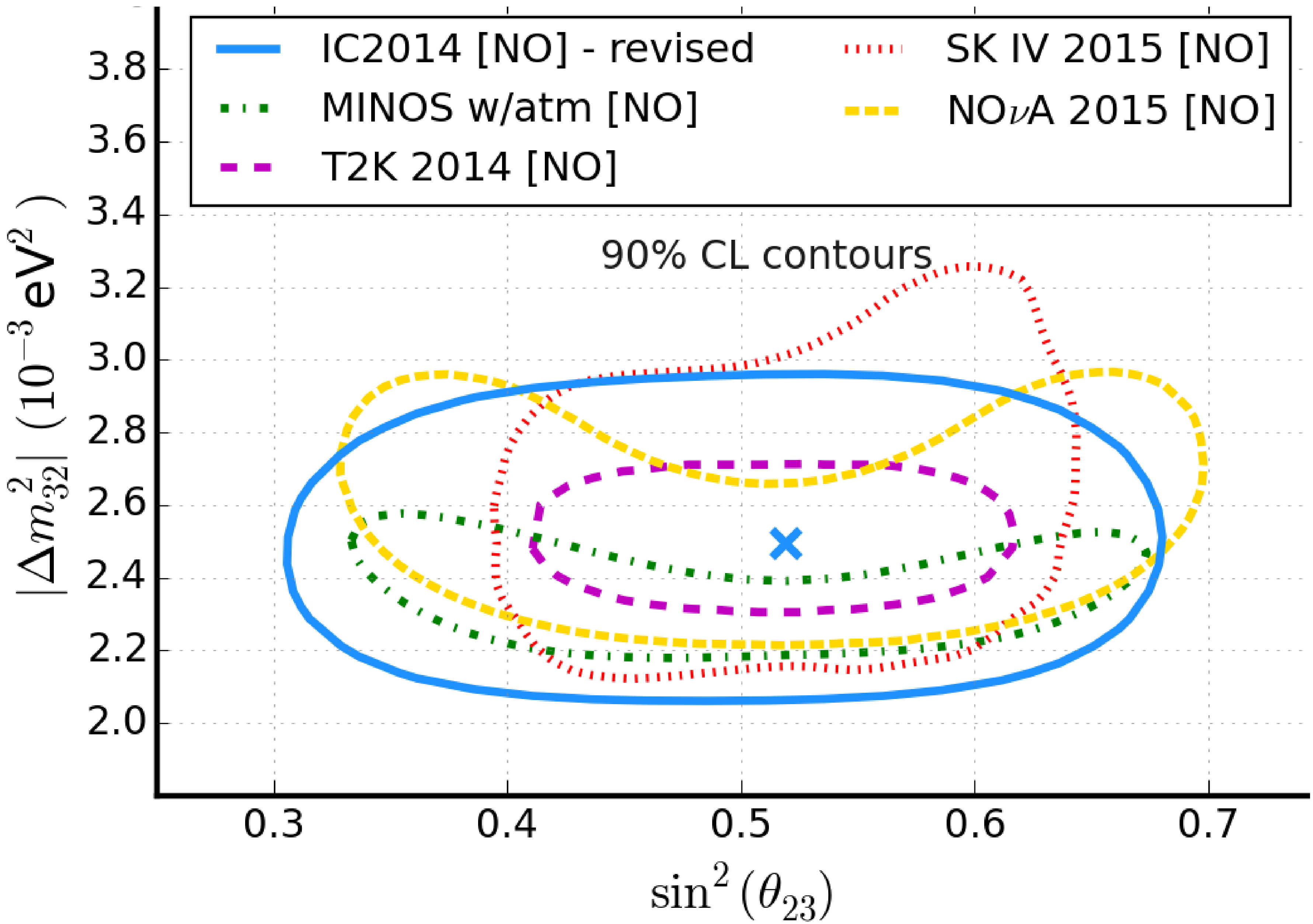
Low energy standard oscillations

- "Low statistics" sample – published PRD 91, 072004, 2015*
  - 5k events/year, "golden events", high neutrino purity (~99%)
  - Events that traverse the Earth, mainly muon neutrinos
  - Muon neutrino disappearance
    - → excellent channel for measuring atmospheric oscillation parameters



* Revised selection - data of this analysis available at http://icecube.wisc.edu/science/data

Low energy standard oscillations



* Revised selection - data of this analysis available at http://icecube.wisc.edu/science/data

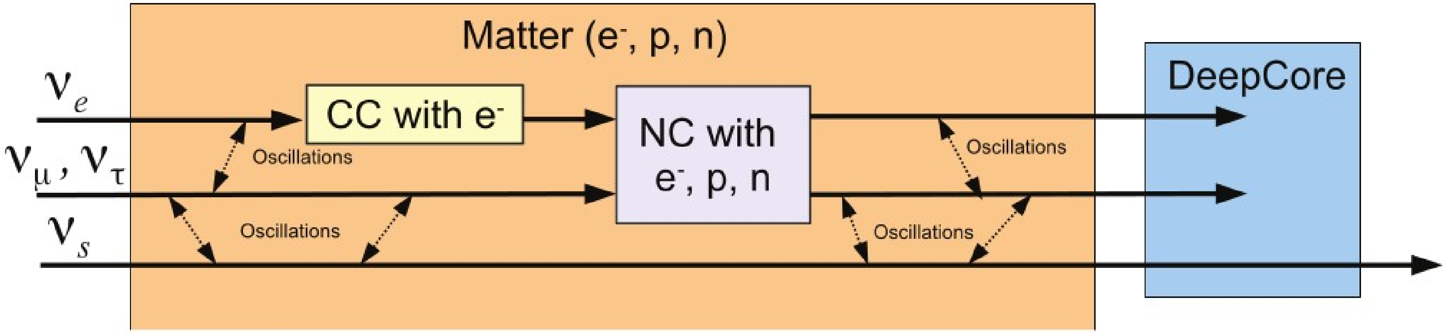
Low energy sterile ν + oscillations

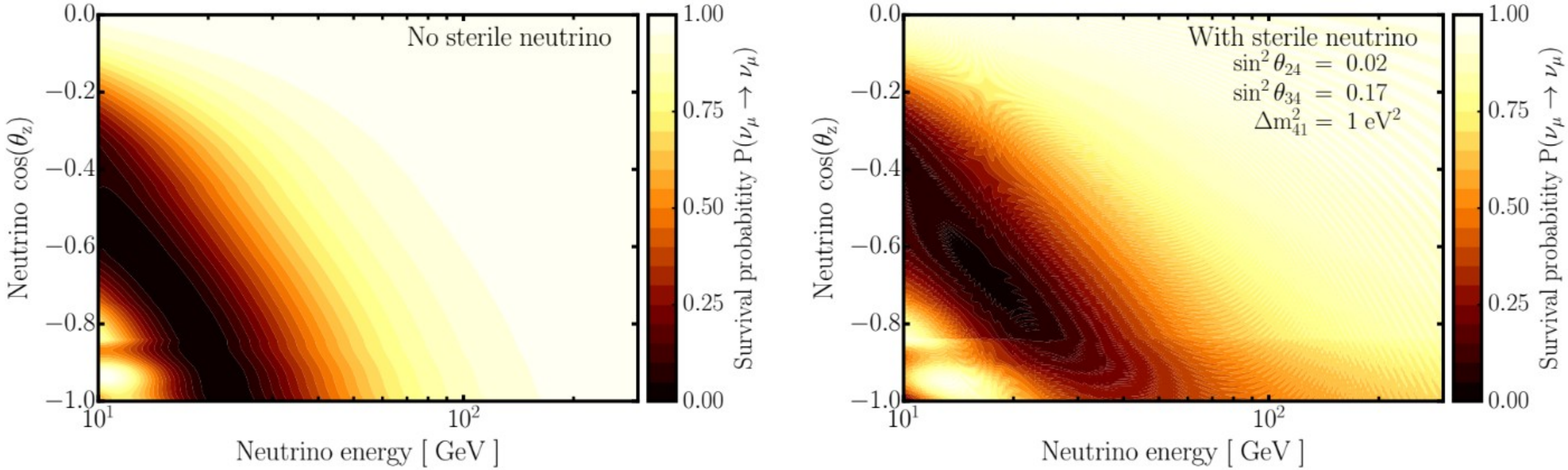
» Sterile neutrino presence

→ additional “negative” potential on NC interactions

→ modification of oscillation probabilities

Diagram by A. Terliuk





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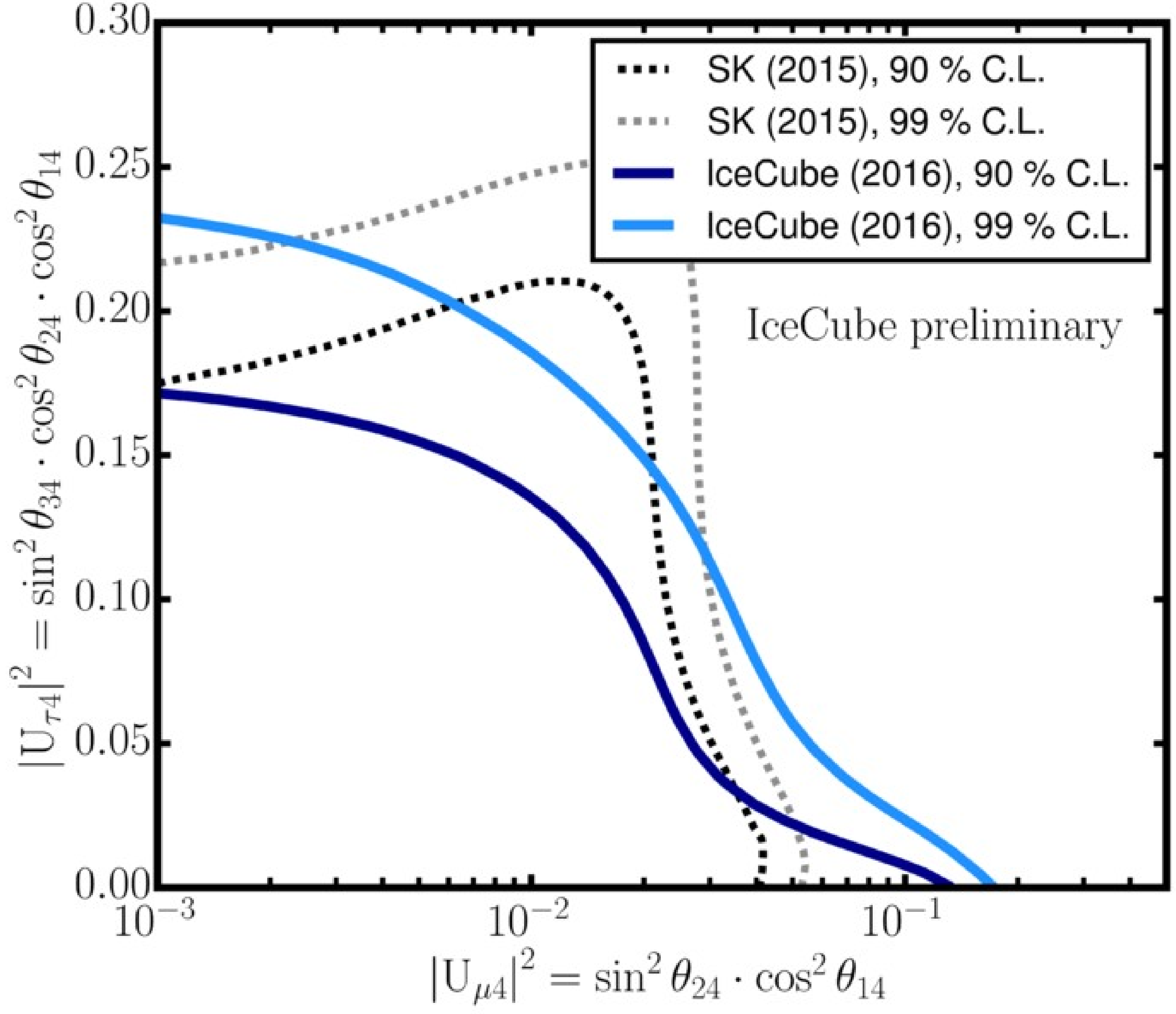
Low energy sterile ν + oscillations



* Revised selection - data of this analysis available at http://icecube.wisc.edu/science/data

Parameters in these analysis

Source of error		Nominal value from	Uncertainty
Neutrino interactions	Total cross-section scaling	GENIE model	Free
	Linear energy dependence		E^(+/-0.03)
	DIS cross section		BodekYang params
	Axial mass of non-DIS events		~ +/-20%*
Atmospheric neutrino flux	Overall normalization	Honda 2015	Free
	Spectral index		E^(+/-0.04)
	Up/Horizontal ratio		E dependent (+/- 8%)
	Nu/NuBar ratio		E dependent (+/- 25%)
	NuE relative normalization		+/- 3%
Detection	Hadronic energy scaling	Geant4 (model)	+/- 5%
	Hadronization/propagation		From models
	DOM overall efficiency	Muons, flashers	+/- 10% → **4%**
	DOM angular acceptance* (scattering in hole-ice)	Fit to flasher data	As large as 50%‡ **Model being changed**
	Bulk-ice model		Two models

* Exact value depends on the individual process

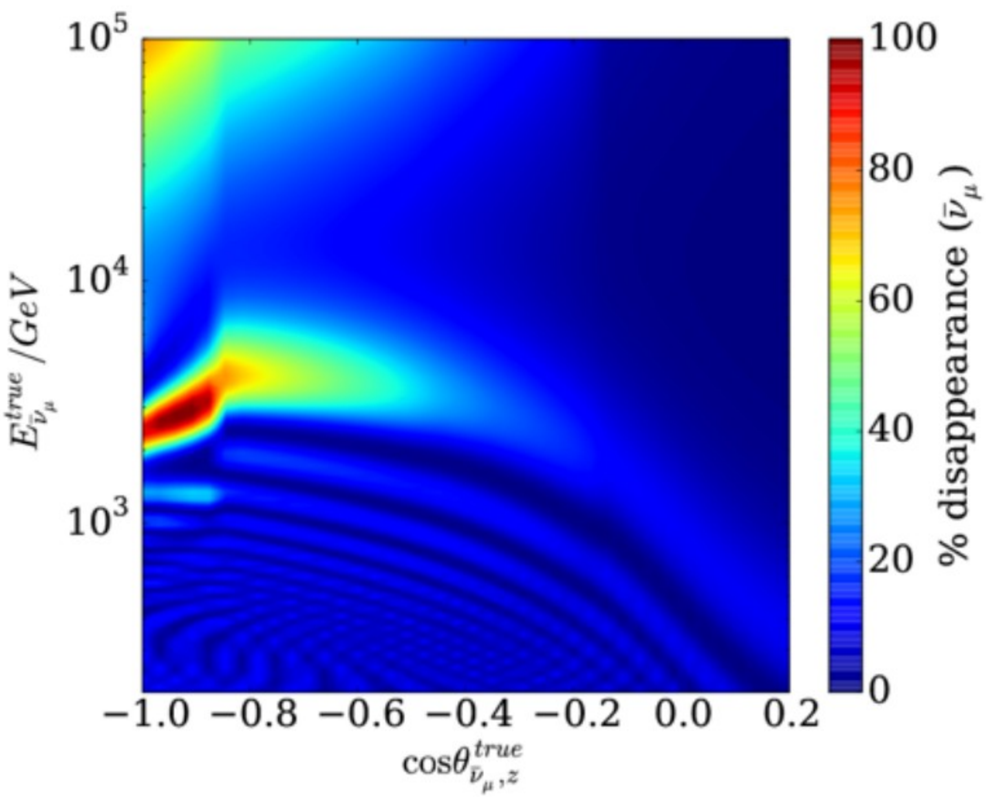
‡ Largest deviation for photons perpendicular to PMT direction

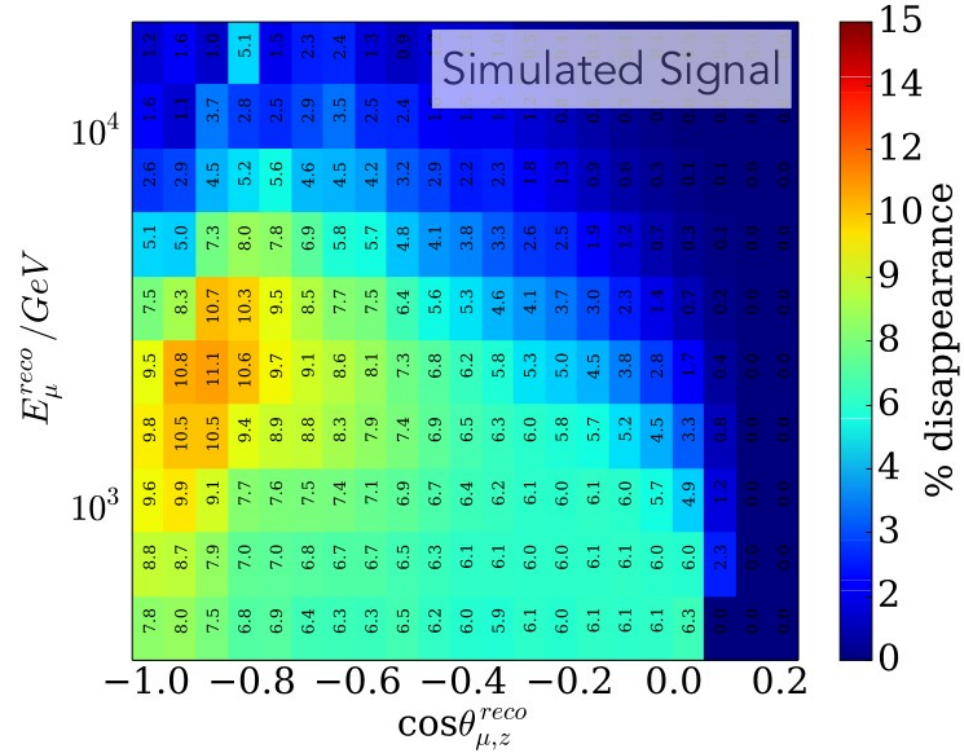
High energy sterile ν oscillations

» Sterile neutrinos of ~ eV mass → oscillations at E_ν ~ 1 TeV

» Matter effects → enhance even small mixing under correct hierarchy

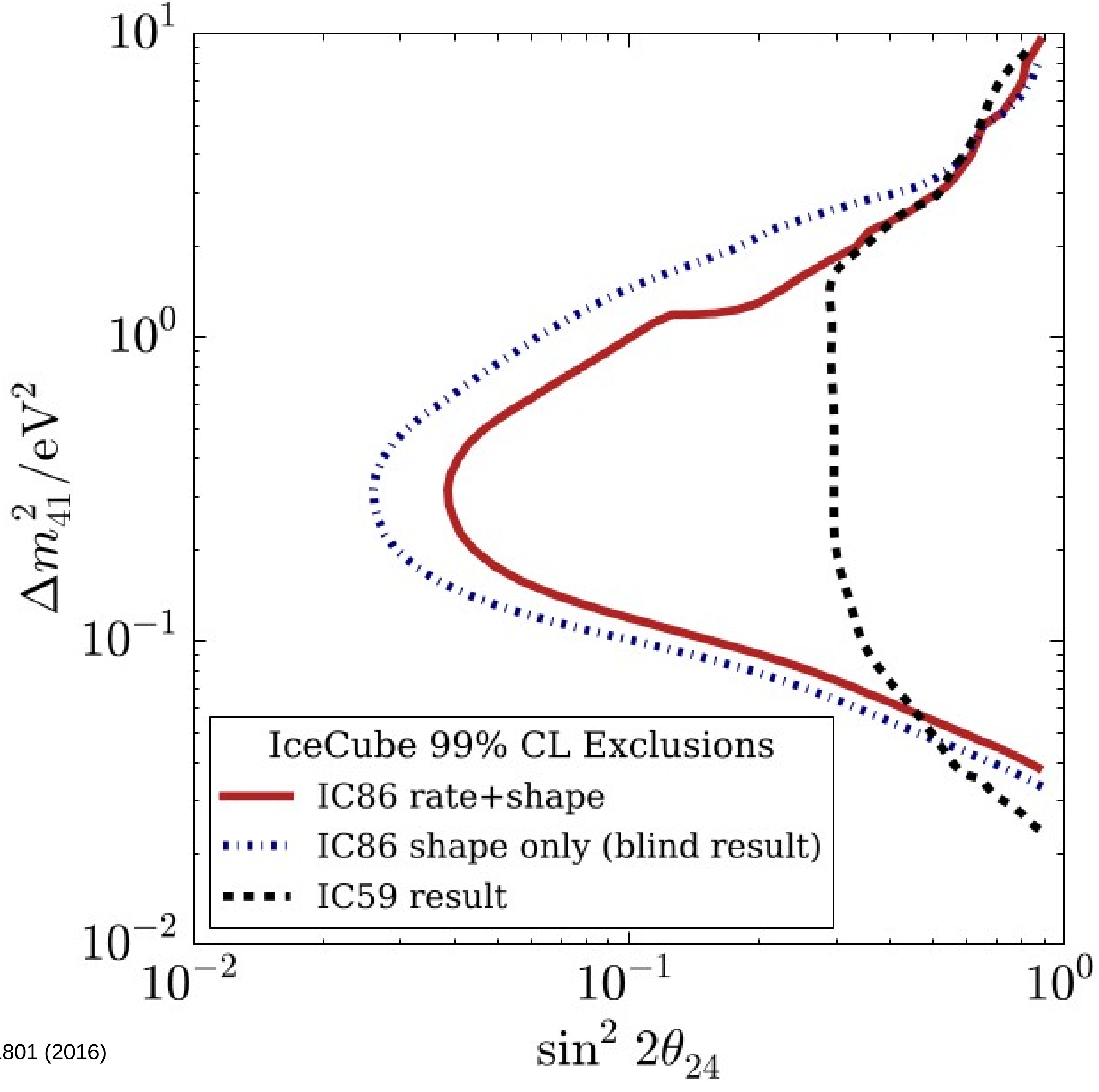
» Using two through going samples of muon neutrinos (half & full detector)





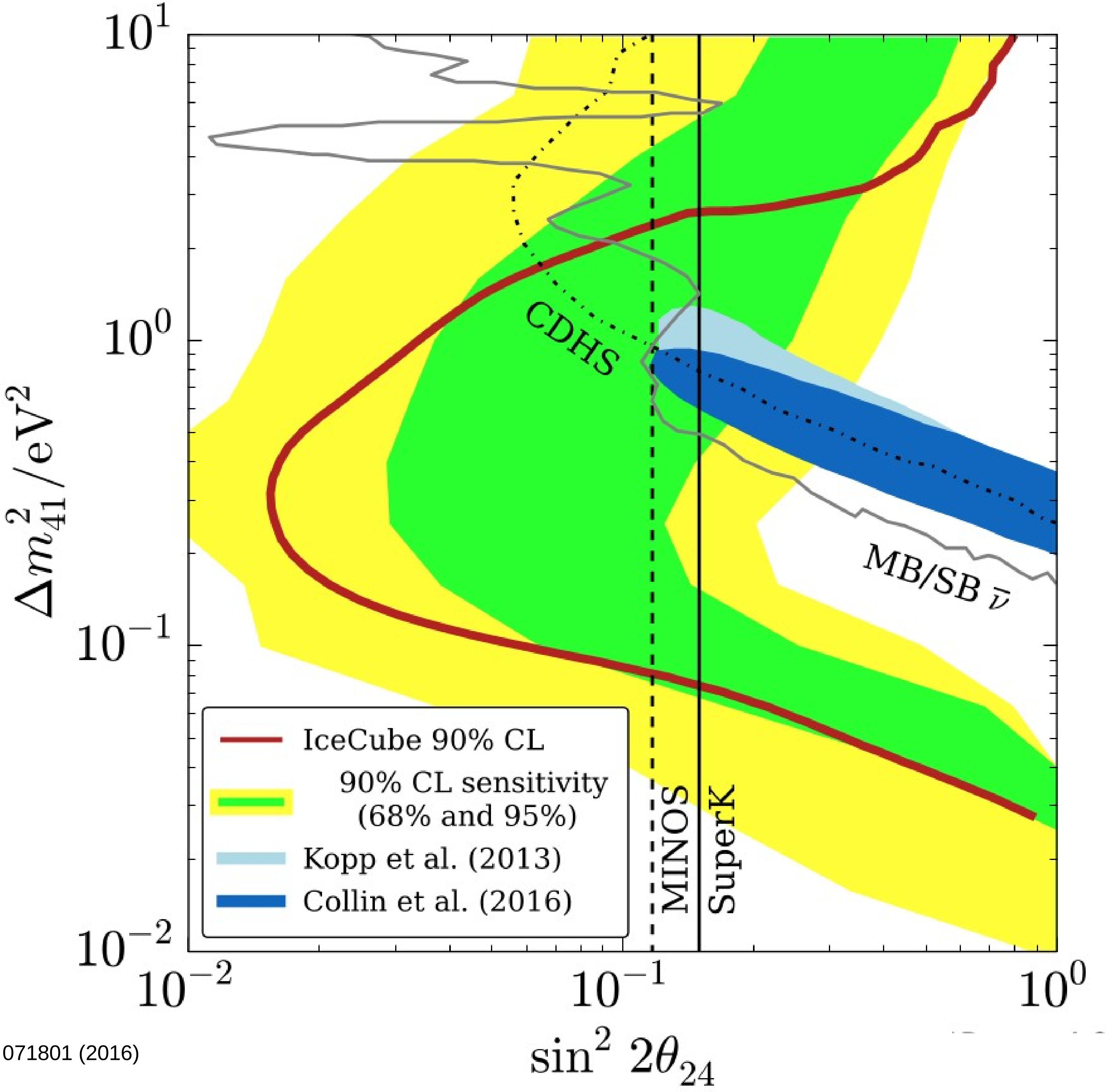
Phys. Rev. Lett. 117, 071801 (2016)

High energy sterile ν oscillations



Phys. Rev. Lett. 117, 071801 (2016)

High energy sterile ν oscillations



Phys. Rev. Lett. 117, 071801 (2016)

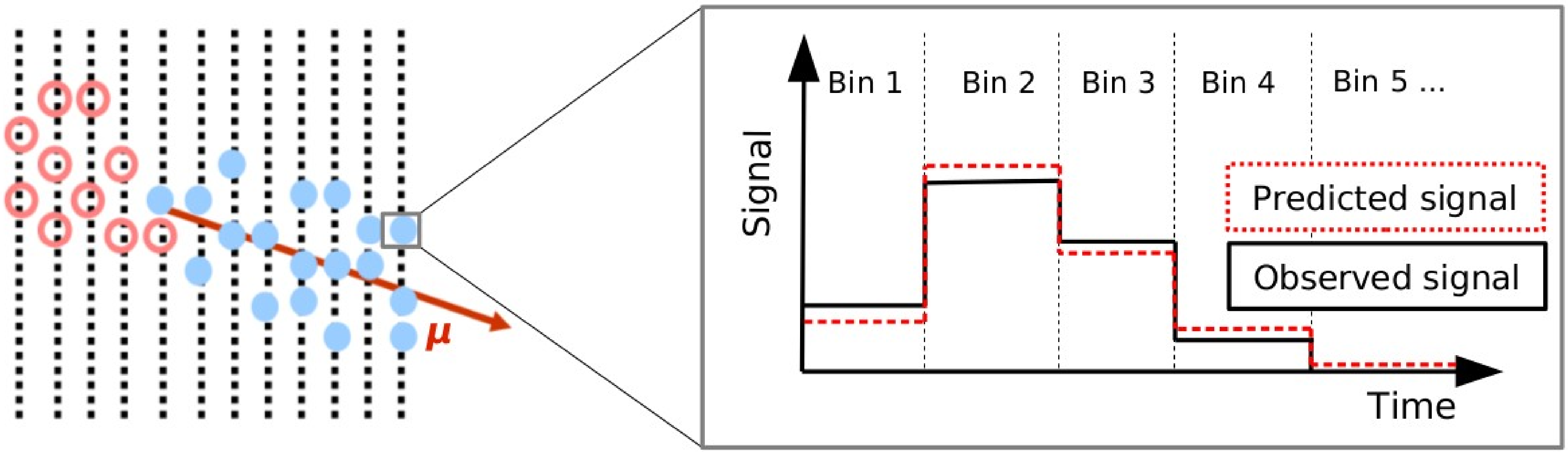
Analysis of diffuse fluxes

Near future

Detailed event reconstruction

- Use arrival time of individual photons
- Fit energy + direction simultaneously
- More inclusive selection allowed
- Include ice properties

- **Similar resolutions in DeepCore**
- **Higher efficiency**
- Working in **DeepCore**, testing vs data
- Used in **PINGU** analyses



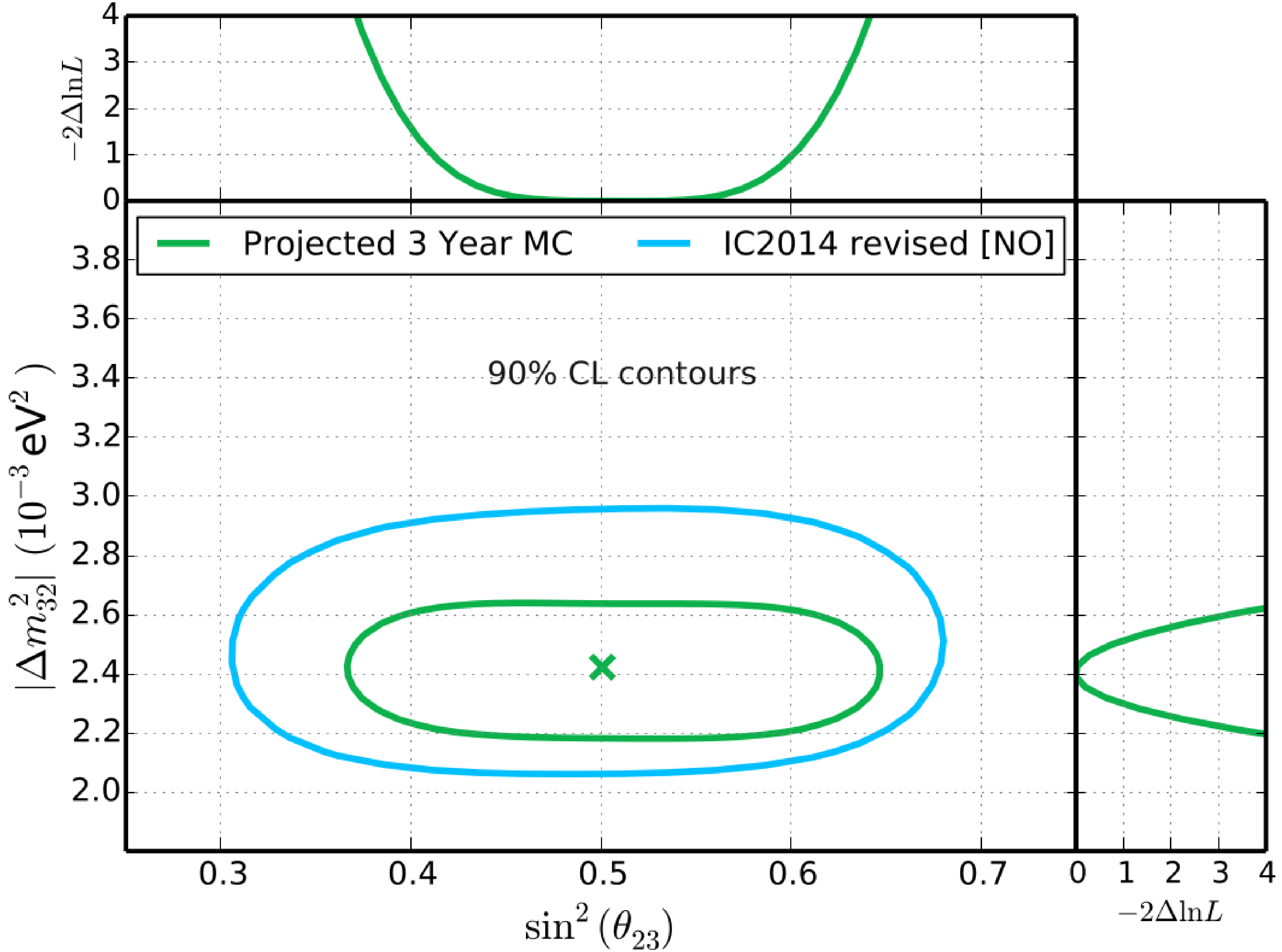
Inclusive data samples

More statistics, same resolutions

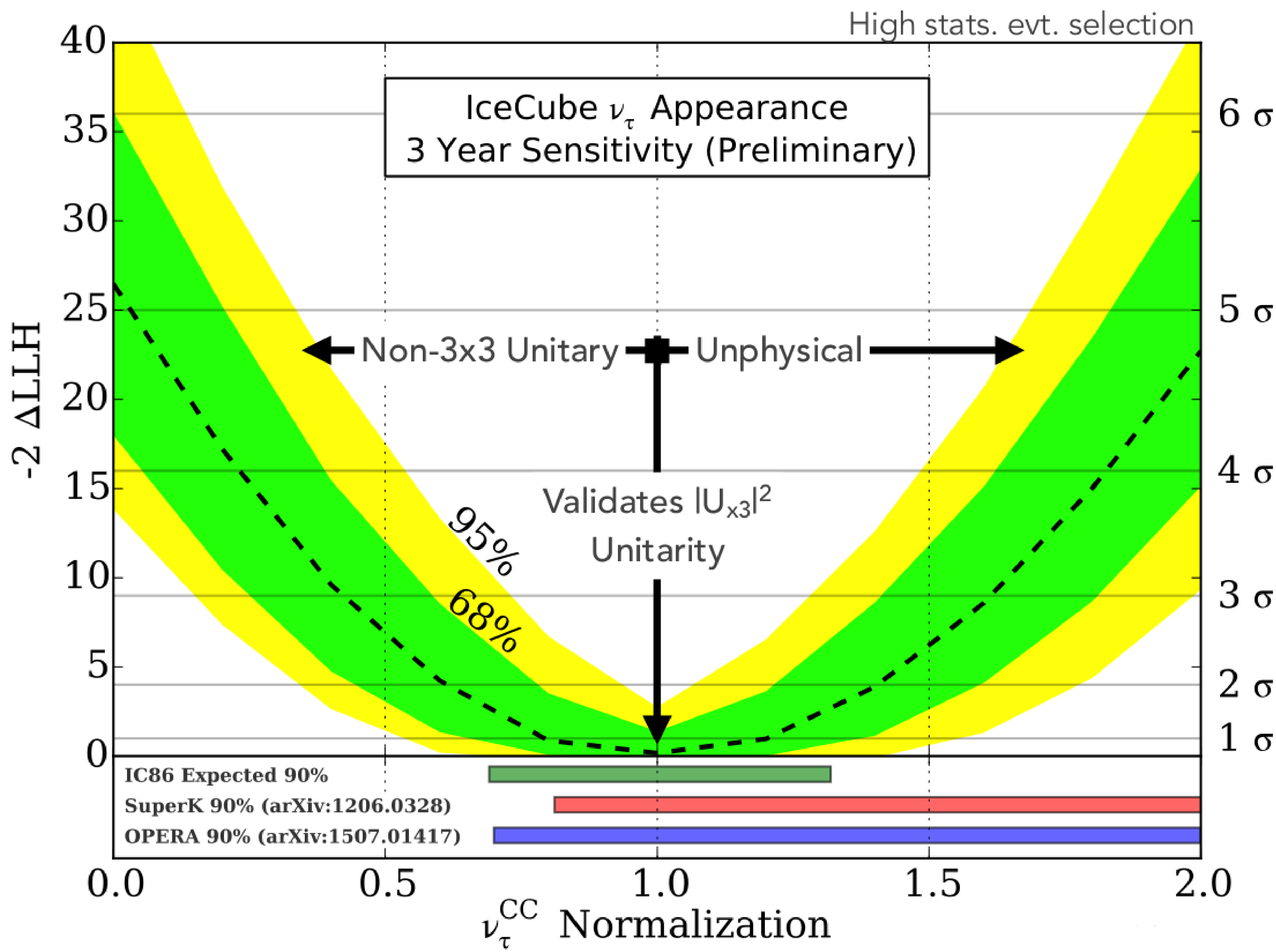
- “Low statistics” - oscillations publication (PRD 91, 072004, 2015)*
  - 5k events/year, “golden events”, high neutrino purity (~99%)
  - Events that traverse the Earth, mainly muon neutrinos
- “Medium statistics” - finalized, being analyzed
  - ~ 15k events/year, 90% neutrinos / 10% CR muons
  - All sky, sophisticated reconstructions, mainly muon neutrinos
- “High statistics” - final stages of development
  - ~ 44k events/year, 77% neutrinos / 23 % CR muons
  - All sky, sophisticated reconstructions, all flavors

* Data of this analysis available at http://icecube.wisc.edu/science/data

MidStats projected precision

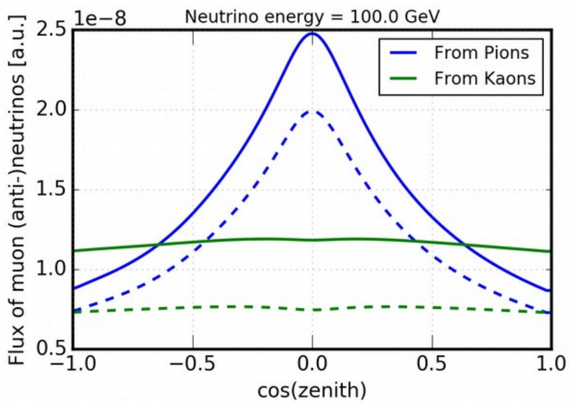


HighStats on ν_τ appearance

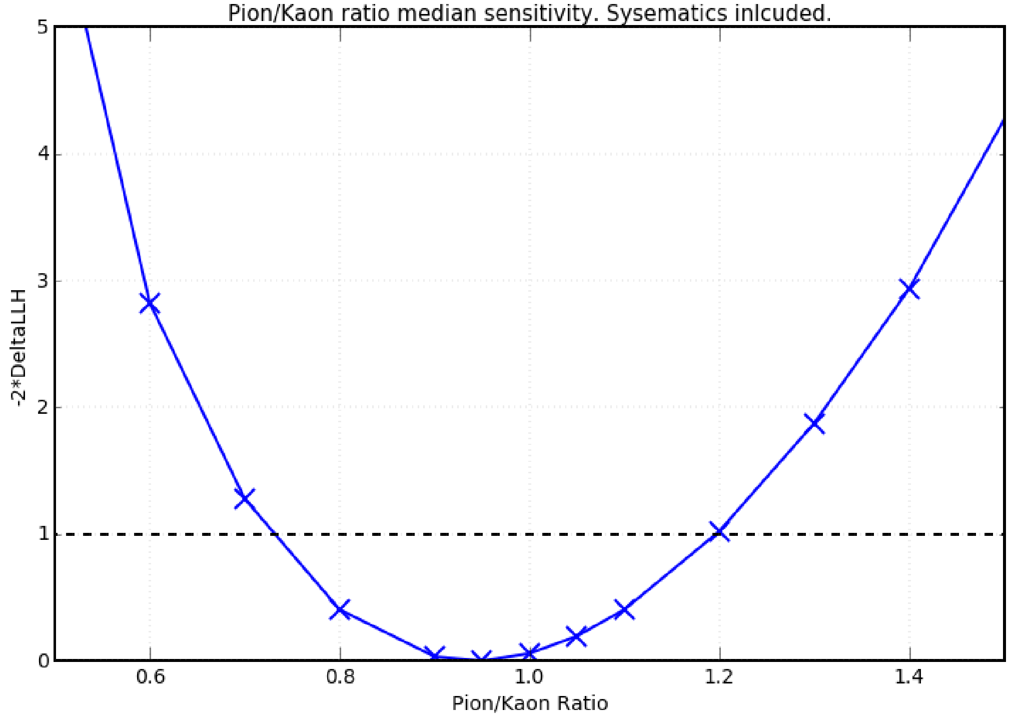


Flux measurements of K/Pi ratio

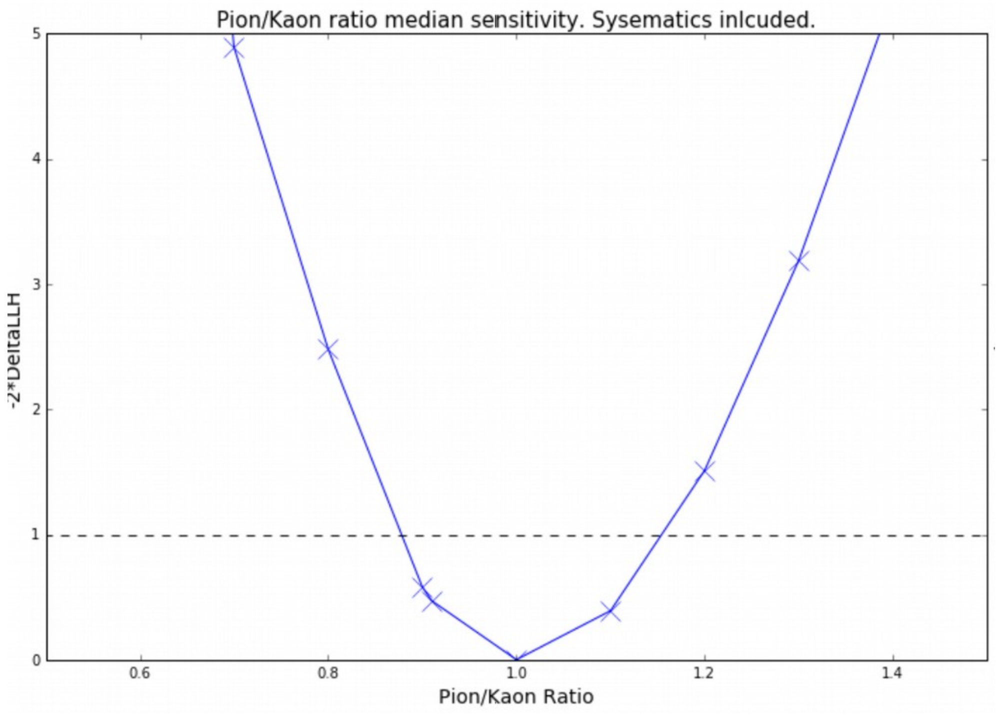
» Neutrinos from Pi & K
→ different flux vs angle



MidStats



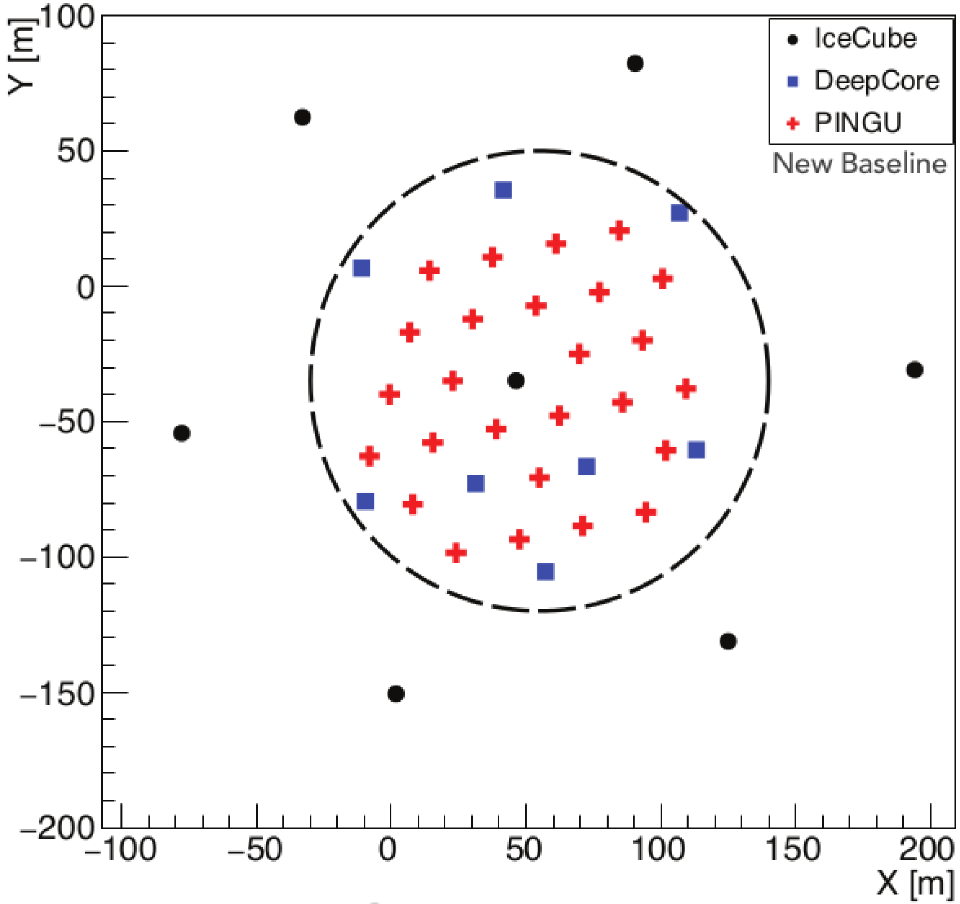
High stats



IceCube-Gen2

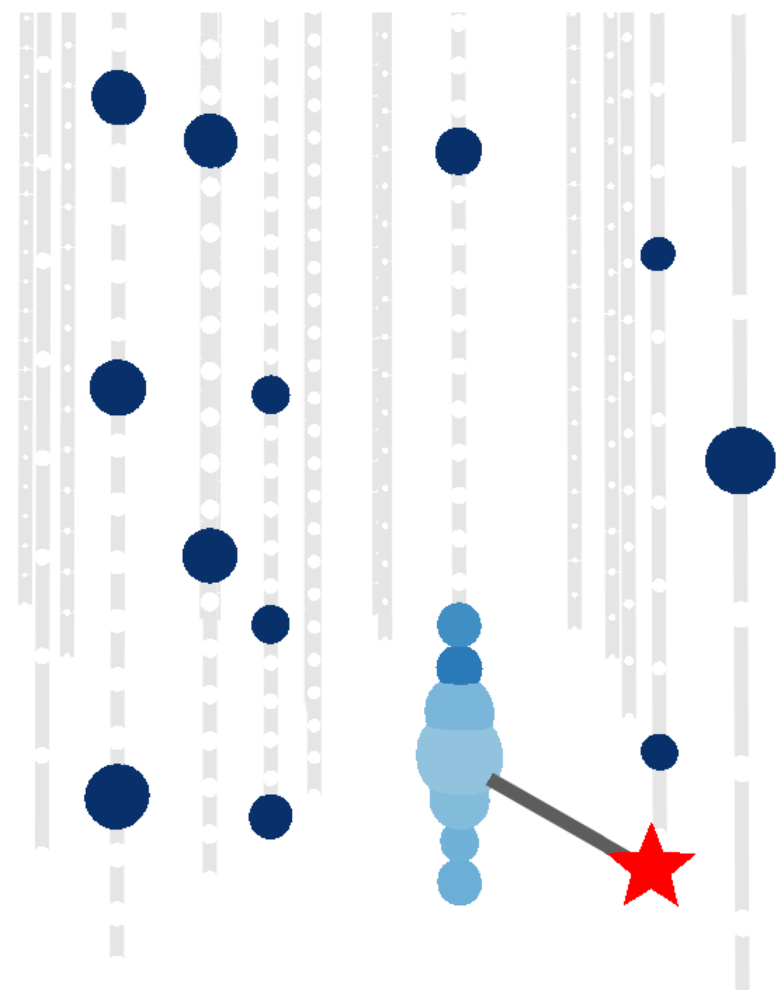
PINGU

IceCube-Gen2 at low energies

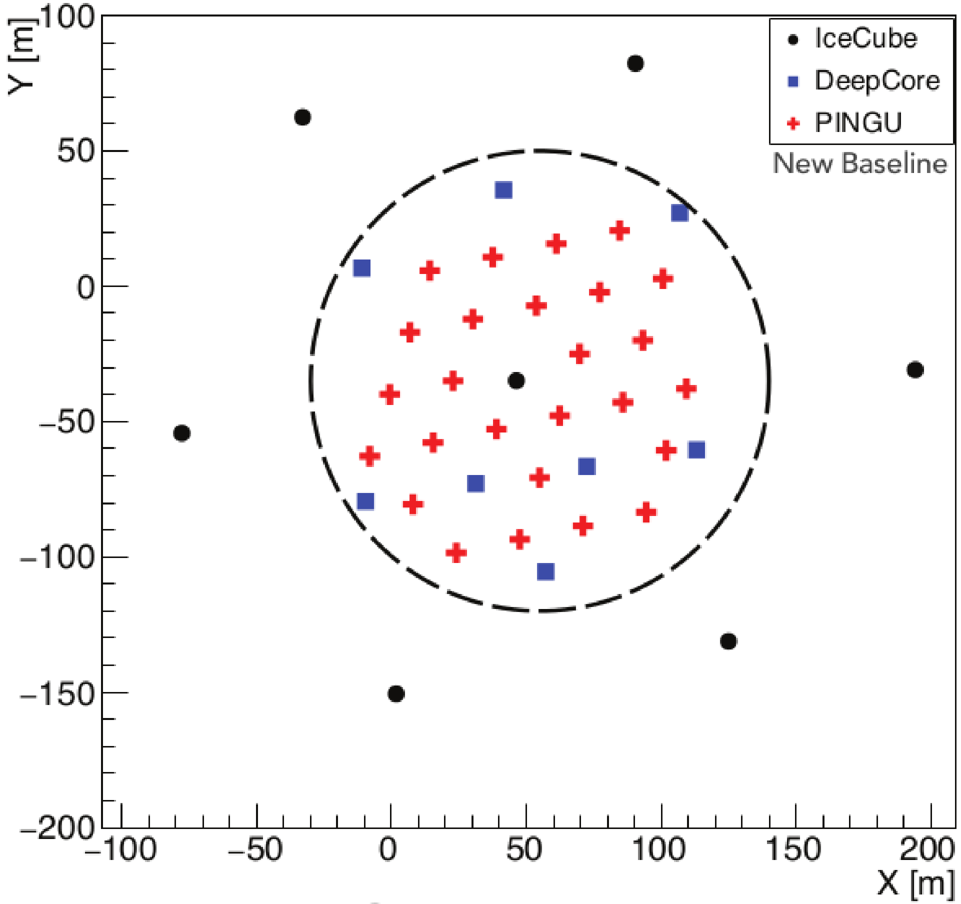


Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

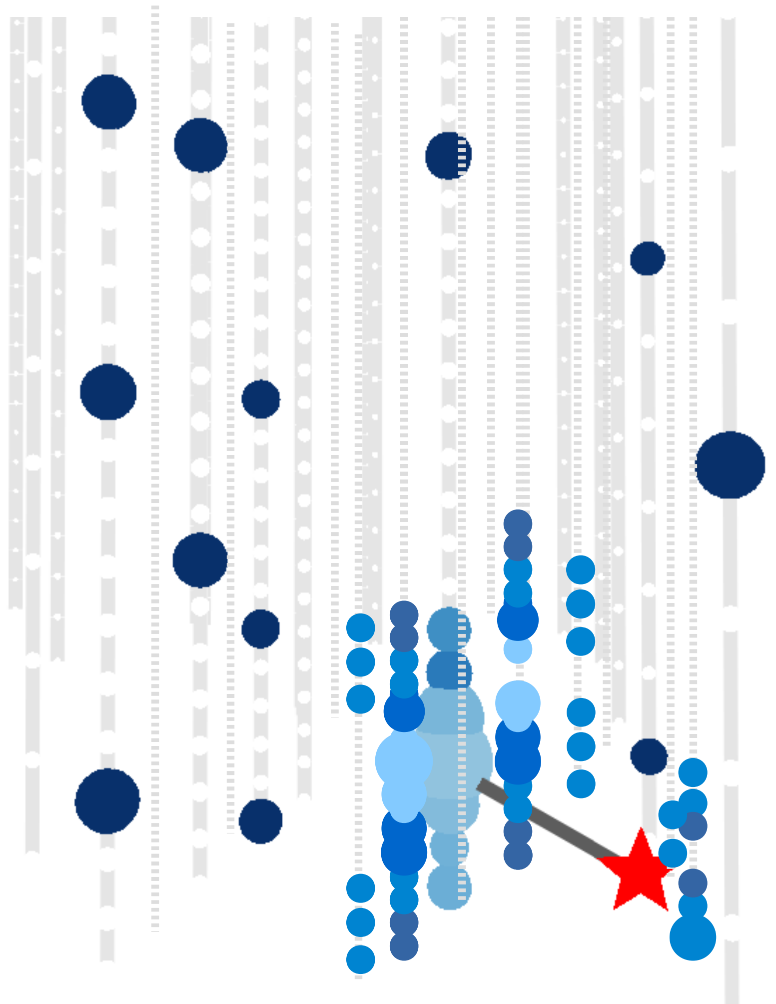


IceCube-Gen2 at low energies

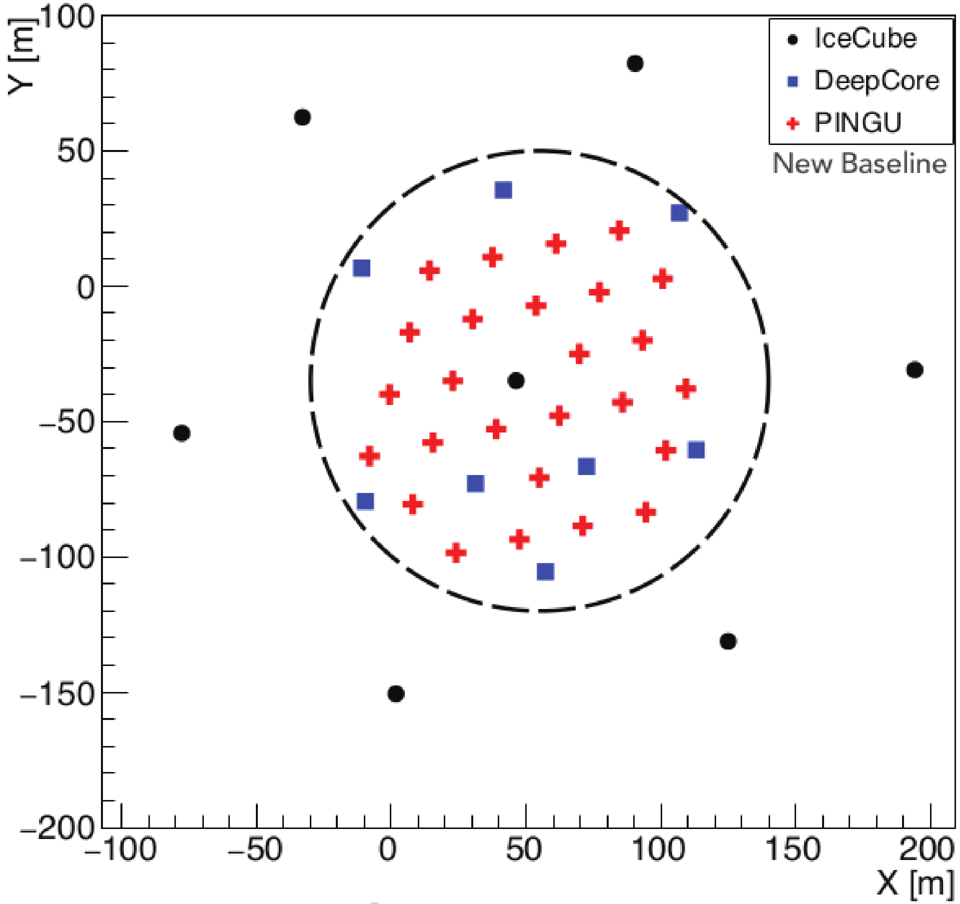


Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing



IceCube-Gen2 at low energies



Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

Improve on all DeepCore studies listed

+ not mentioned:

» Non-standard interactions
» Indirect dark matter searches
» Neutrino flux spectrum

New studies

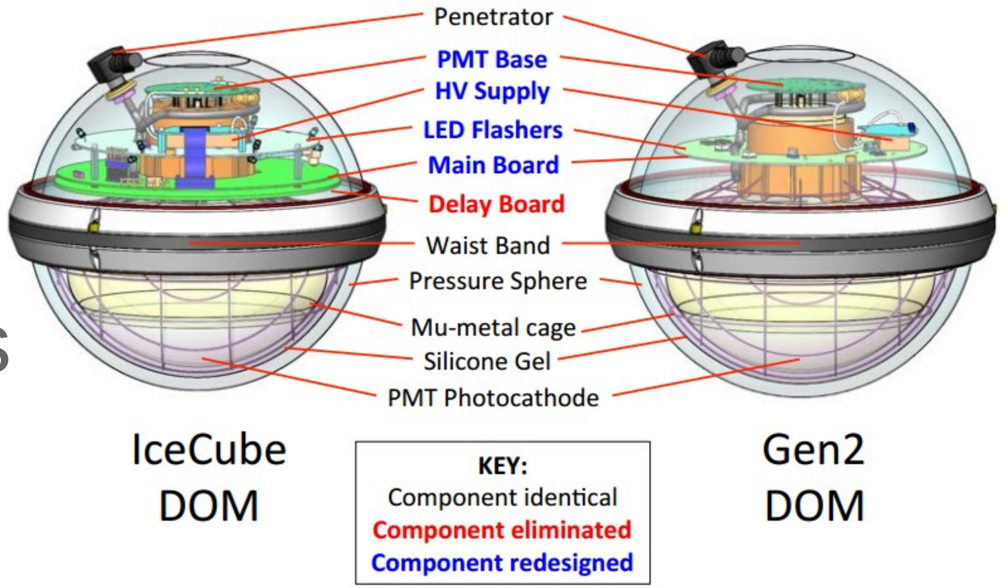
» Neutrino mass ordering
» Octant of θ_{23}

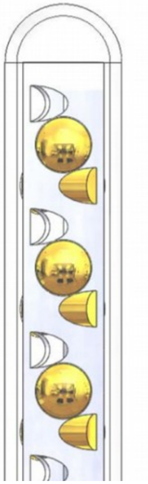
IceCube-Gen2 sensors

» Baseline sensors →

used for sensitivity studies

» Gain of new sensors under evaluation



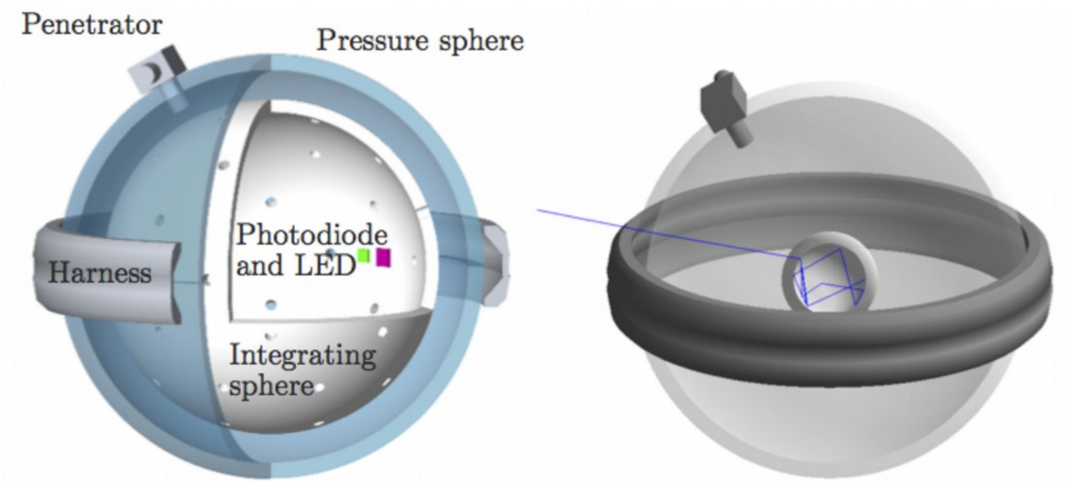


*For details see yesterday's talk

IceCube-Gen2 calibration

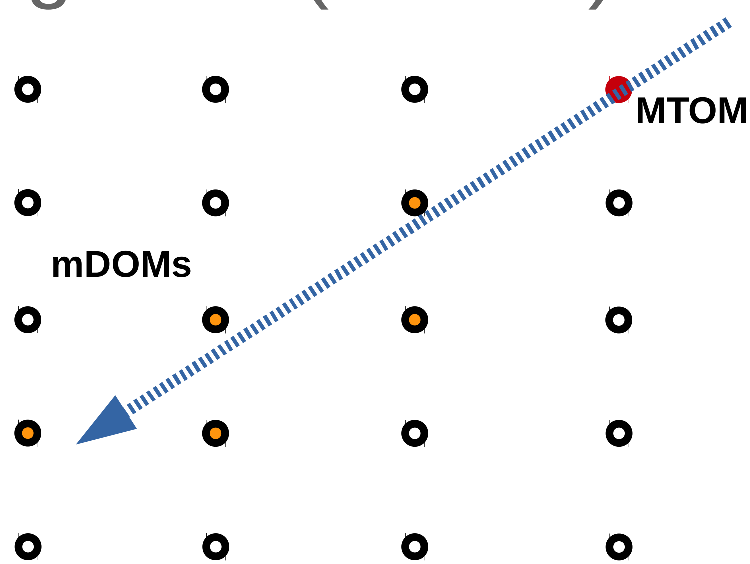
» POCAM → isotropic light emitter

arXiv:1510.05228



Optical properties of ice
Global optical efficiency

» Muon tagging OMs (MTOM) → scintillator



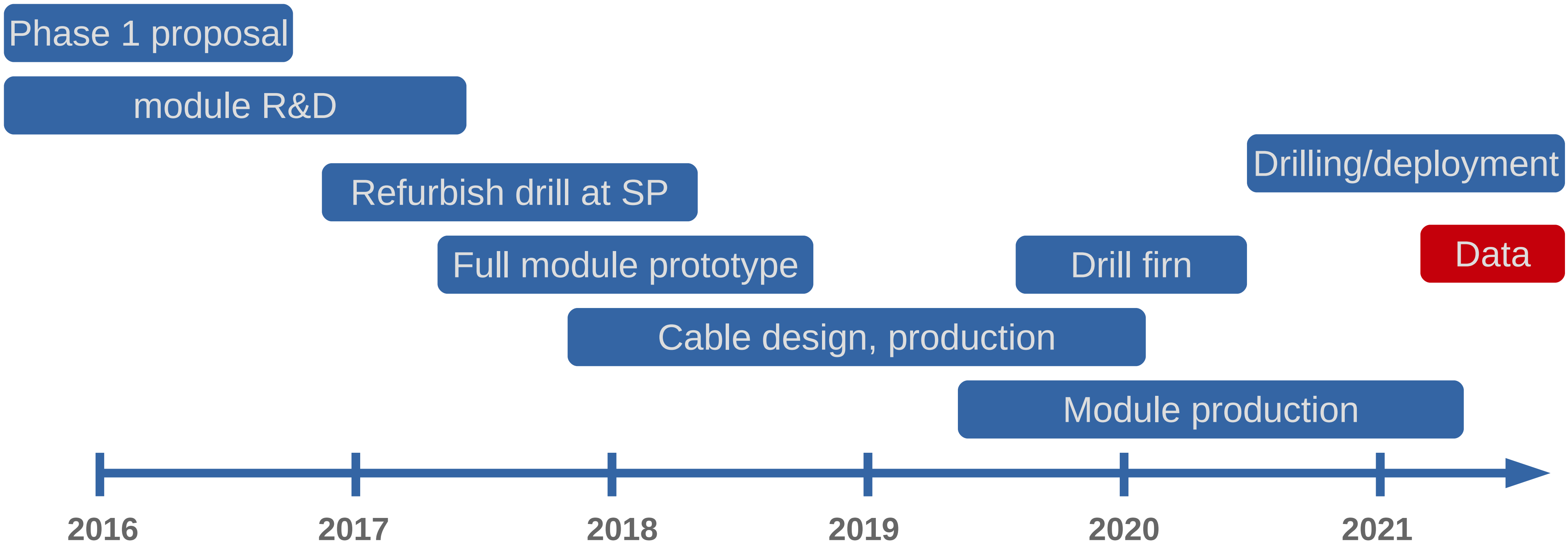
Precise knowledge of point along trajectory → Better understanding of reconstructions

Staged approach: Phase 1

» 7 additional strings in DeepCore region

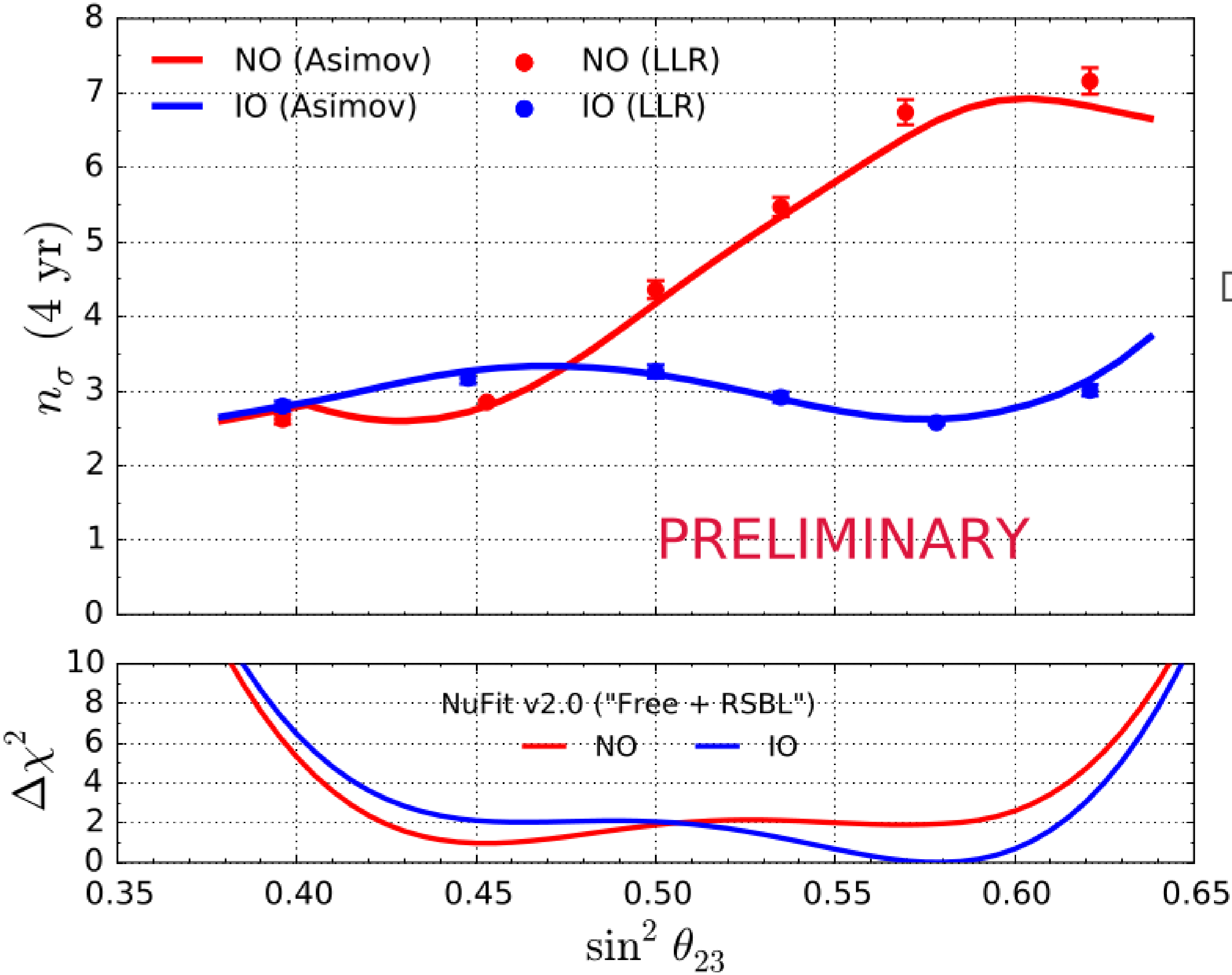
» 125 modules per string

» Additional calibration devices



Full IceCube-Gen2 physics

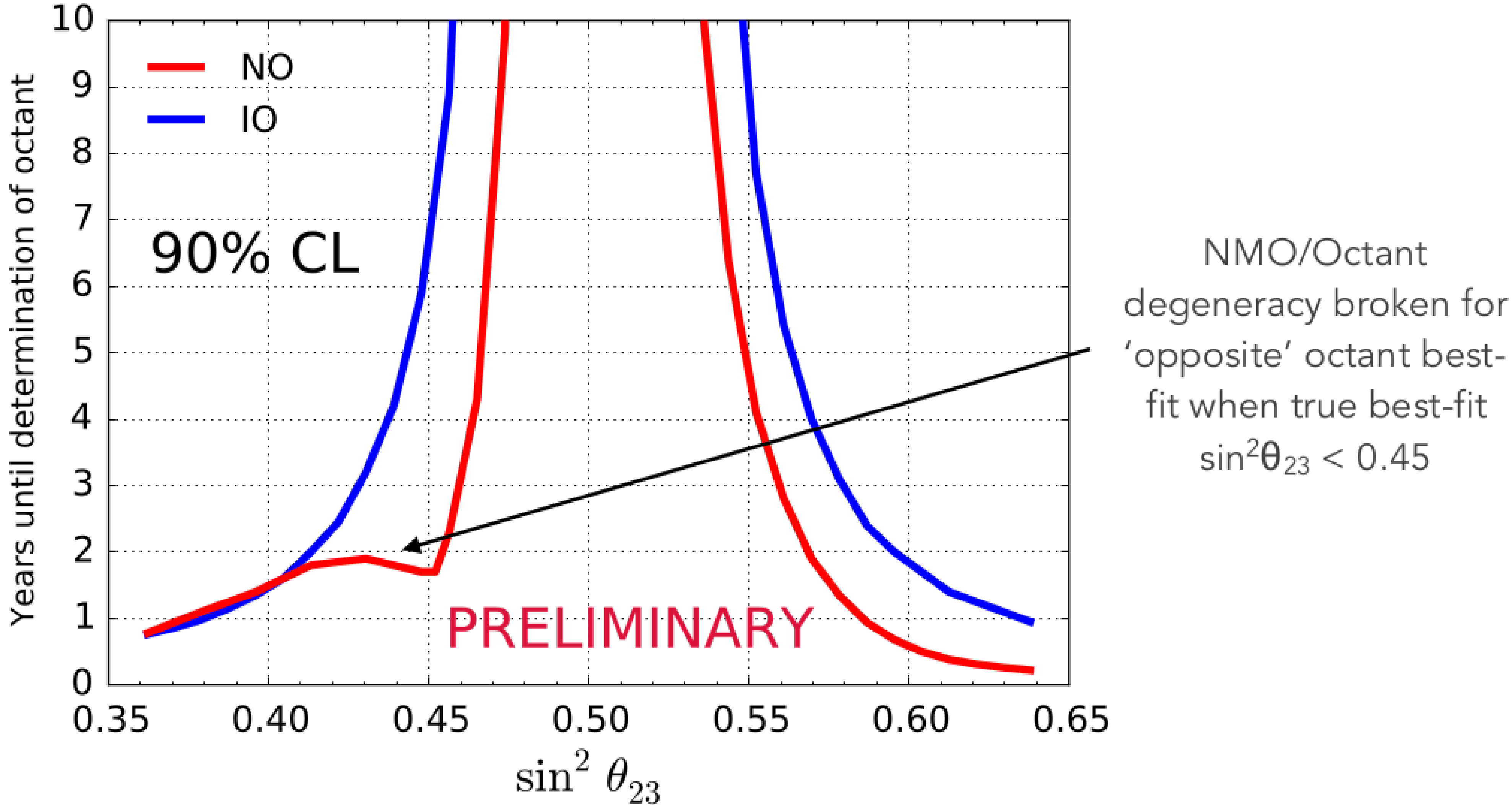
» Neutrino mass ordering



Does not include combination w/ DeepCore or partial detector data

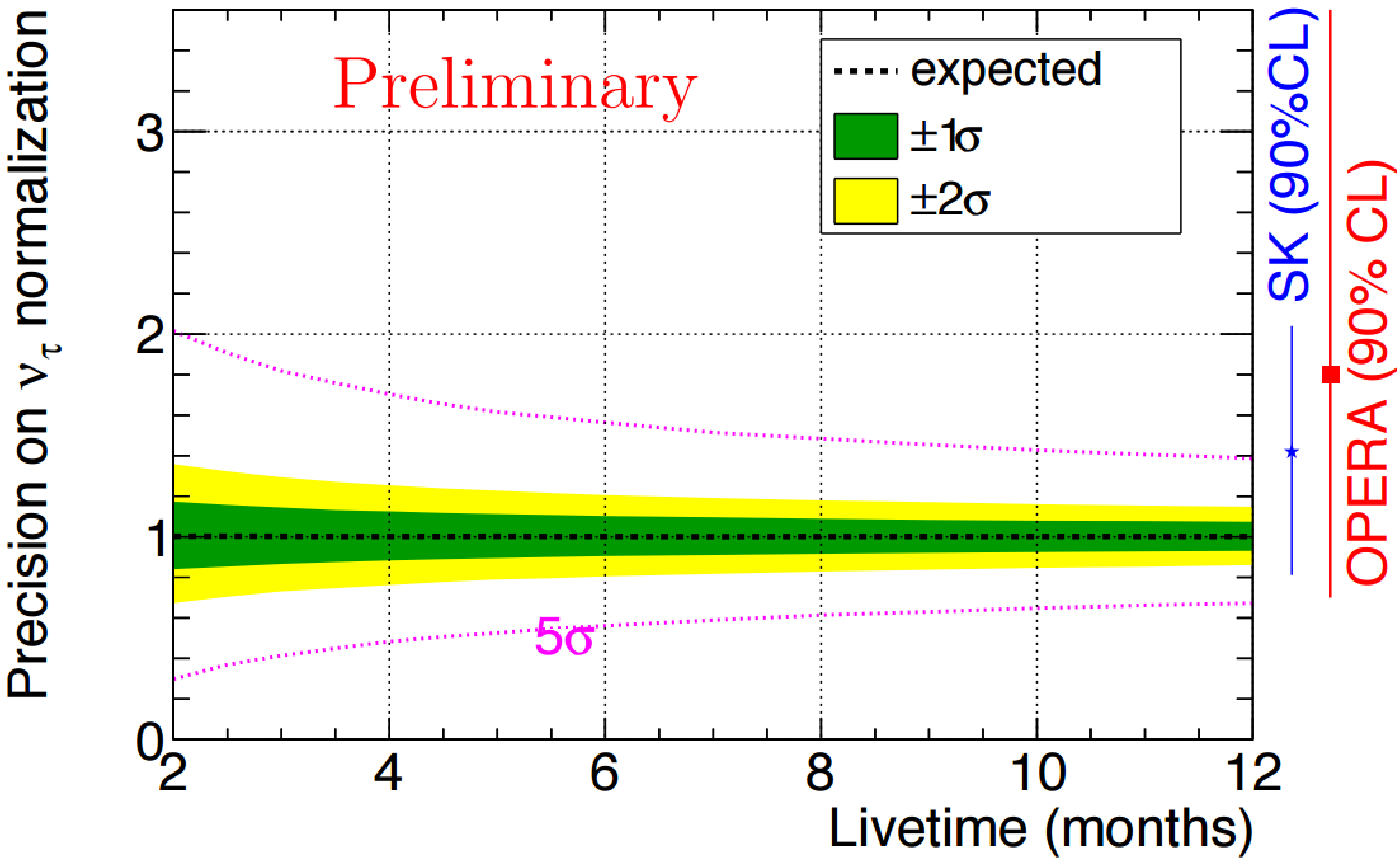
Full IceCube-Gen2 physics

» Octant of θ_{23}



Full IceCube-Gen2 physics

» Tau neutrinos and PMNS unitarity



Conclusion

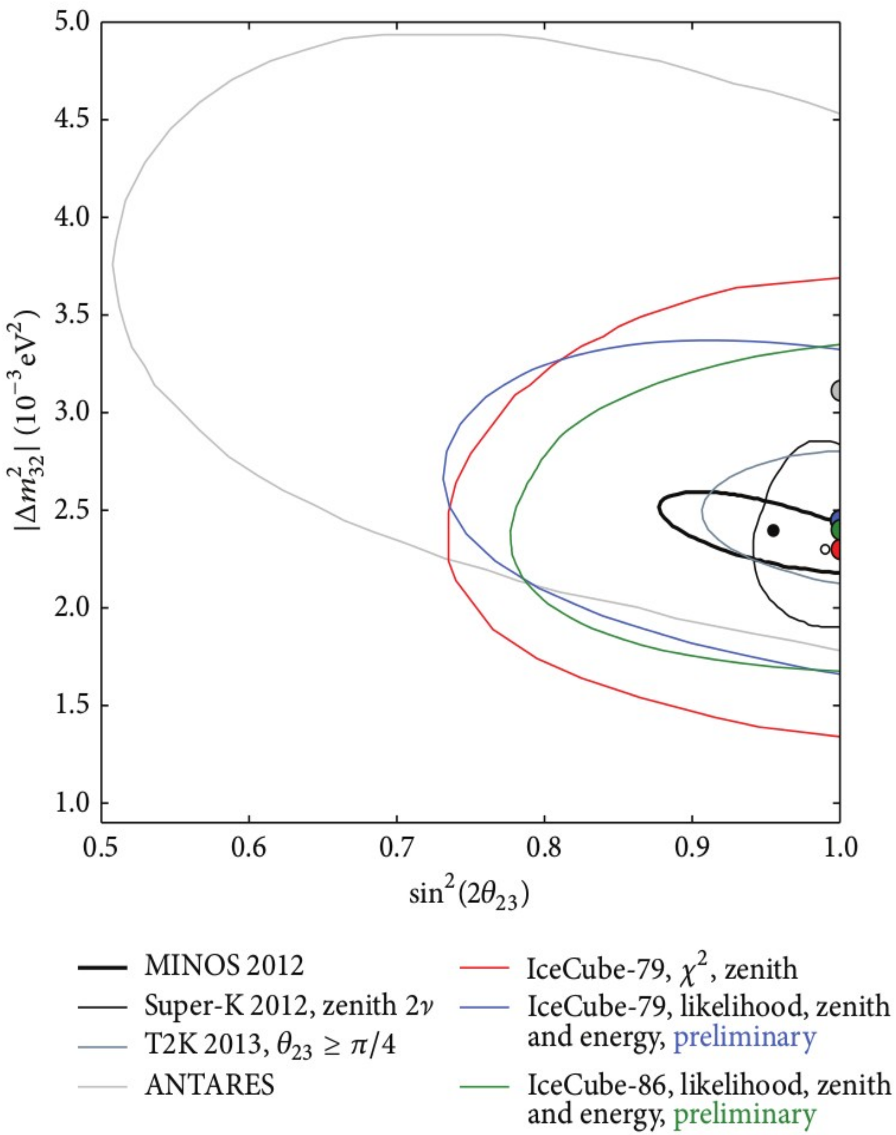
- Atmospheric neutrinos + IceCube
  - Measured standard oscillations parameters
  - Set limits on sterile neutrinos, non-standard interactions
- Continuous improvements in
  - Detector understanding, simulation
  - Selection and event reconstruction
- IceCube-Gen2 (PINGU): unique physics opportunities
  - Phase1 – PMNS unitarity
  - Full detector: NMO & octant of θ_{23}

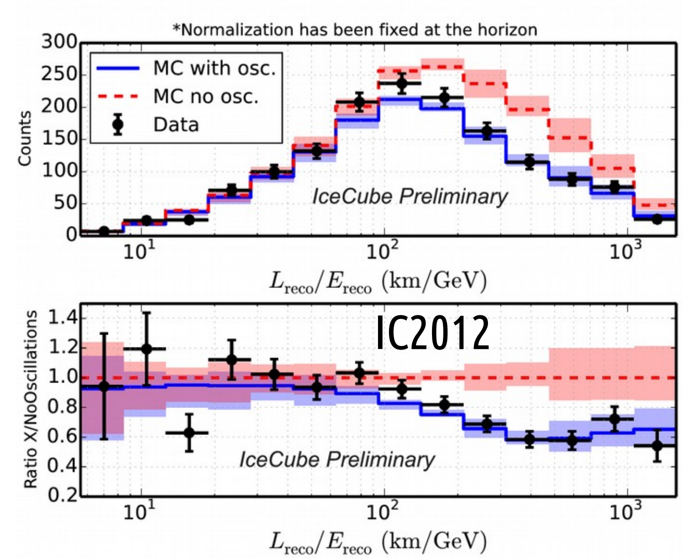
Backup slides

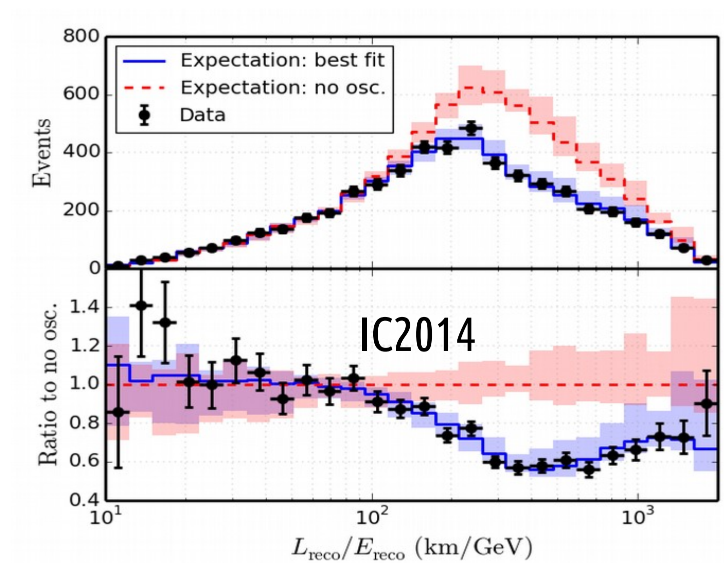
VLVLNT in context

	Parameter	VLVNT: ANTARES	VLVNT: DeepCore	SK	MINOS, T2K, NOvA
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% ± 22%	25% at 20 GeV	3% at 1 GeV	10-15% at 10 GeV
	θ_ν resolution	3° at 20 GeV	$8\ ^\circ$ at 20 GeV	2-3°	–
	Particle ID capabilities	Muon/no muon in interaction		e, μ, π (rings)	Individual particles, charge
Neutrino flux	Source of neutrinos	Atmosphere: mix of ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$			Accelerator: $\nu_\mu/\bar{\nu}_\mu$ modes
	Baseline	10-12700 km			300-800 km
	Flux determination	Atm. ν models, self fit		+ top/down ratios	Near/Far detector
	Energy range	10−100 GeV		few MeV−few GeV	few GeV
	Main interaction channel	DIS		QE	QE, RES, COH, DIS
	ν events expected with osc.	530	1800	2000	30 (T2K), 900 (MINOS)
	and without osc. (per year)	660	2300	2300	120 (T2K), 1050 (MINOS)

Evolution of oscillation analysis in IceCube DeepCore

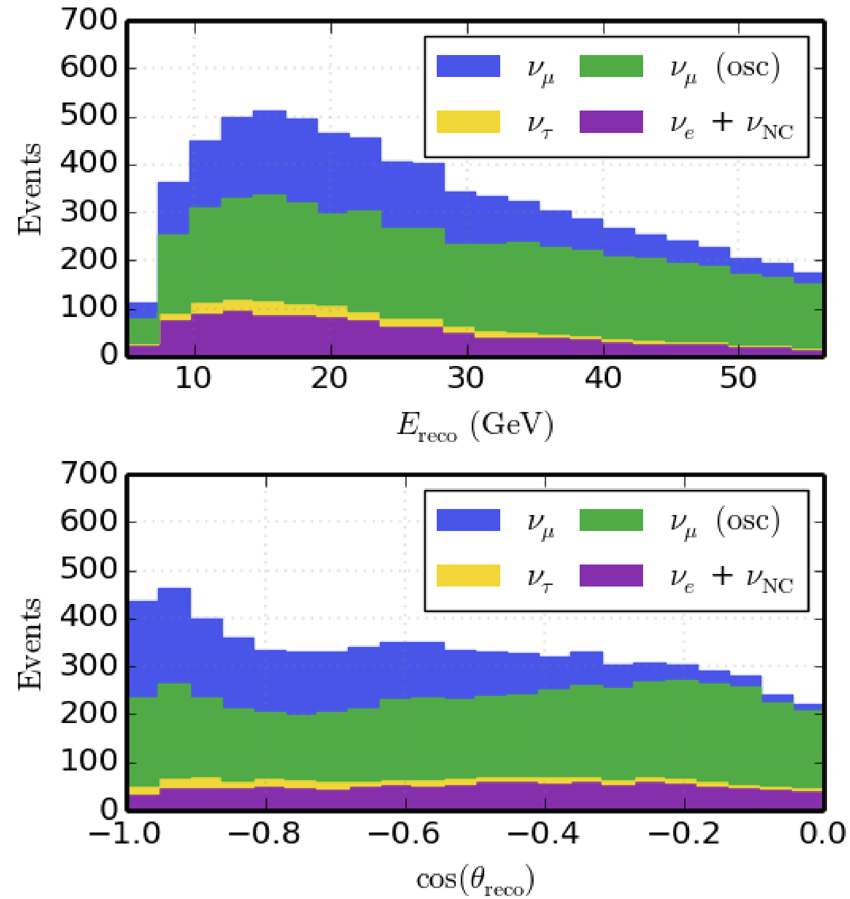






LowStats sample breakdown

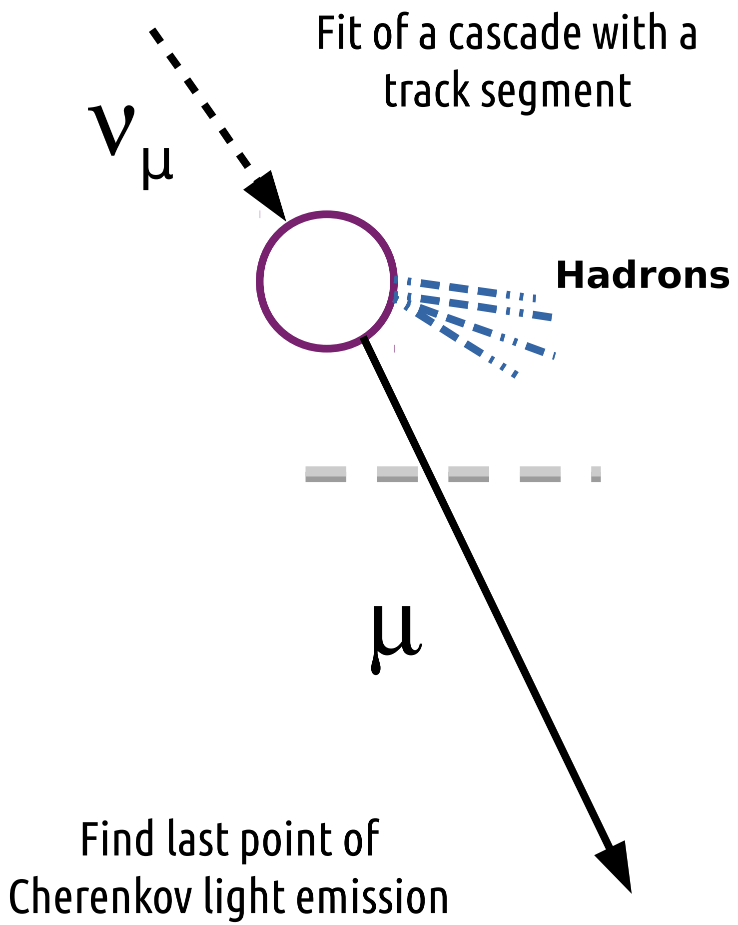
Component	Events in sample	
	Osc.	**No osc.**
ν_μ	3755	5900
ν_τ	273	-
ν_e	678	650
ν_{NC}	418	
Atm. μ	54	



LowStats reconstruction

Latest published DeepCore results

- Zenith: Require a core of *direct* (unscattered) photons
  - Minimize impact of ice properties
  - 30% efficiency
  - Fit zenith angle with direct photons (assume no scattering)
- **Energy: track+cascade hypothesis**
  - Fit track length and vertex position/E
  - Keep direction fixed
  - Assume track and cascade are collinear



$$E_{\text{reco}} = E_\mu(R_\mu) + E_{\text{vertex}}(E_{\text{had}}, \vec{x}_{\text{vertex}})$$

LowStats reconstruction

Latest published DeepCore results

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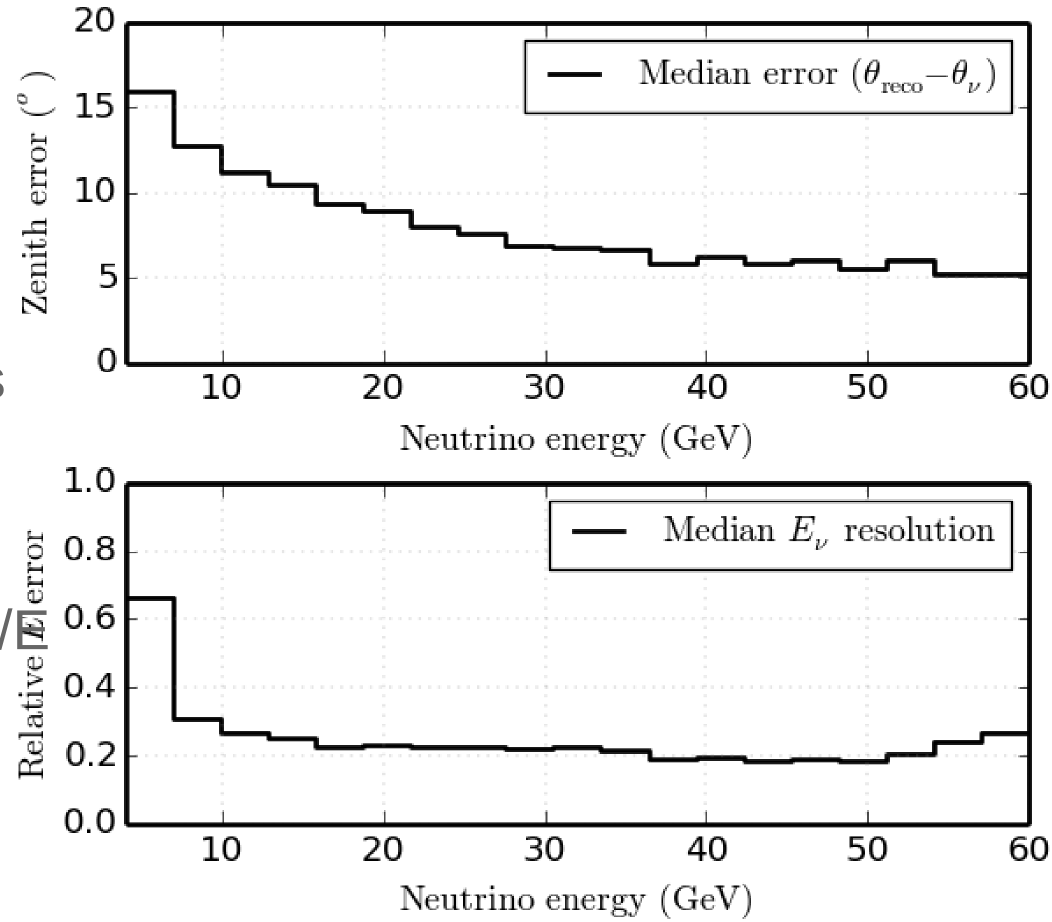
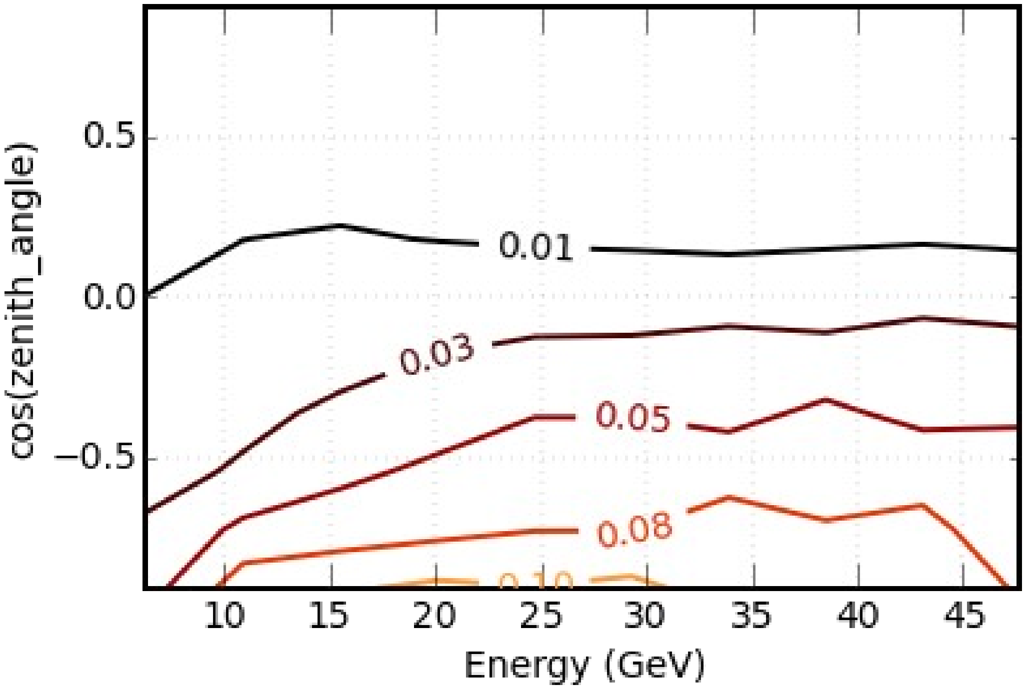
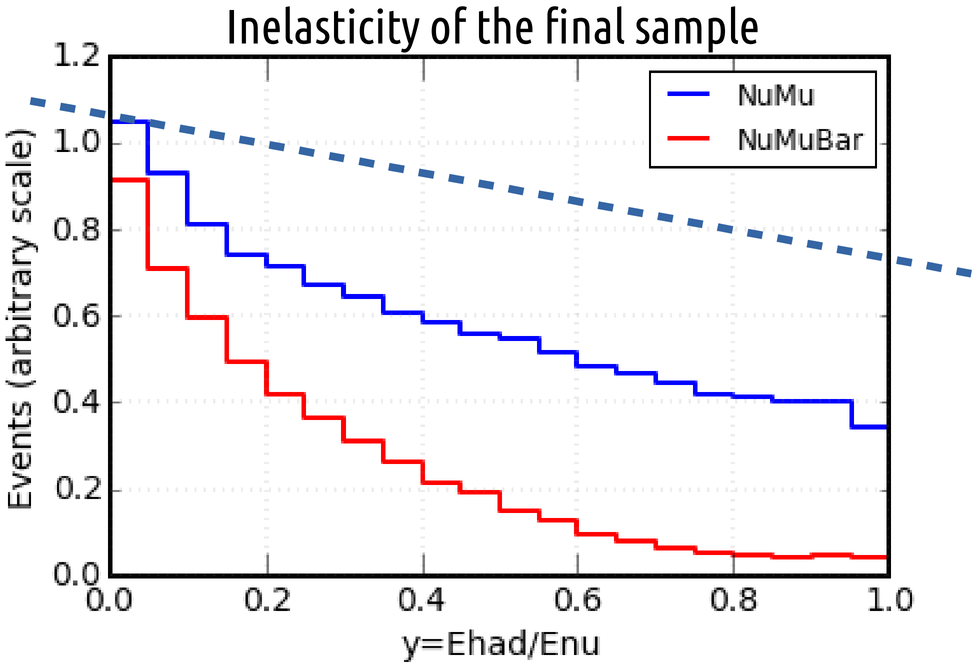
Resolutions for DeepCore (PRD)



LowStats selection efficiency

» Efficiency vs zenith angle





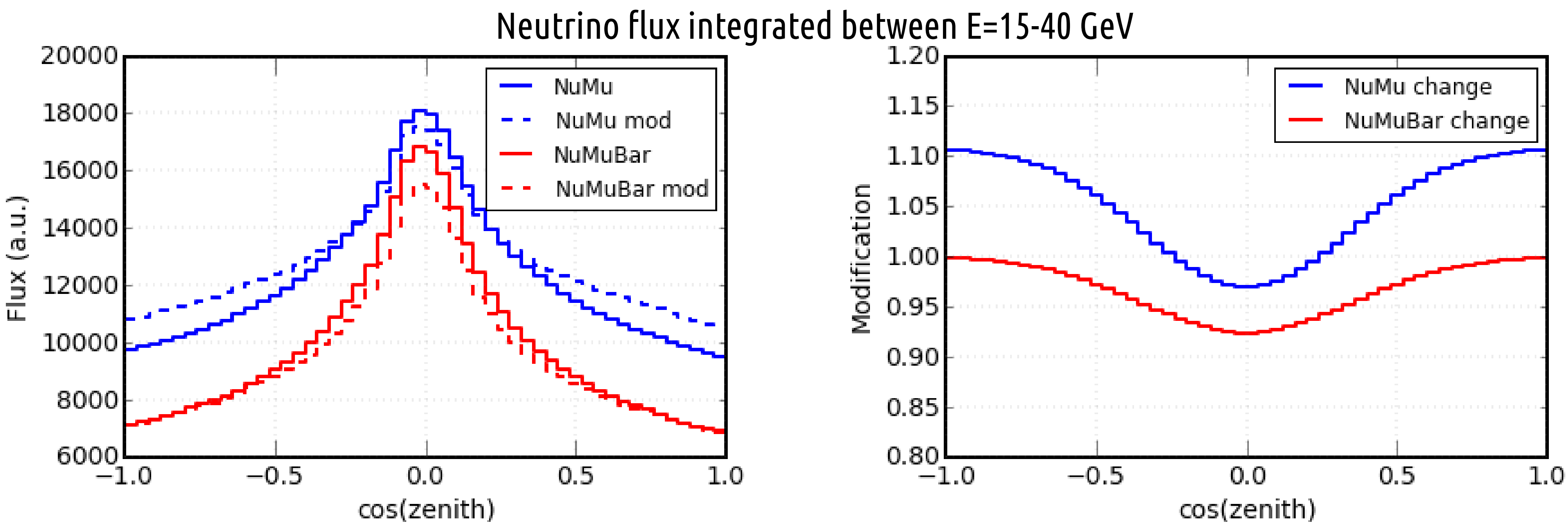
70% NuMu, 30% NuMuBar

Flux uncertainties outcome

» Modifying neutrino/antineutrino **and** up/hor ratio

» Error on nu/nubar ratio can be assigned to either component

» A third parameter decides how to share the error (see below)



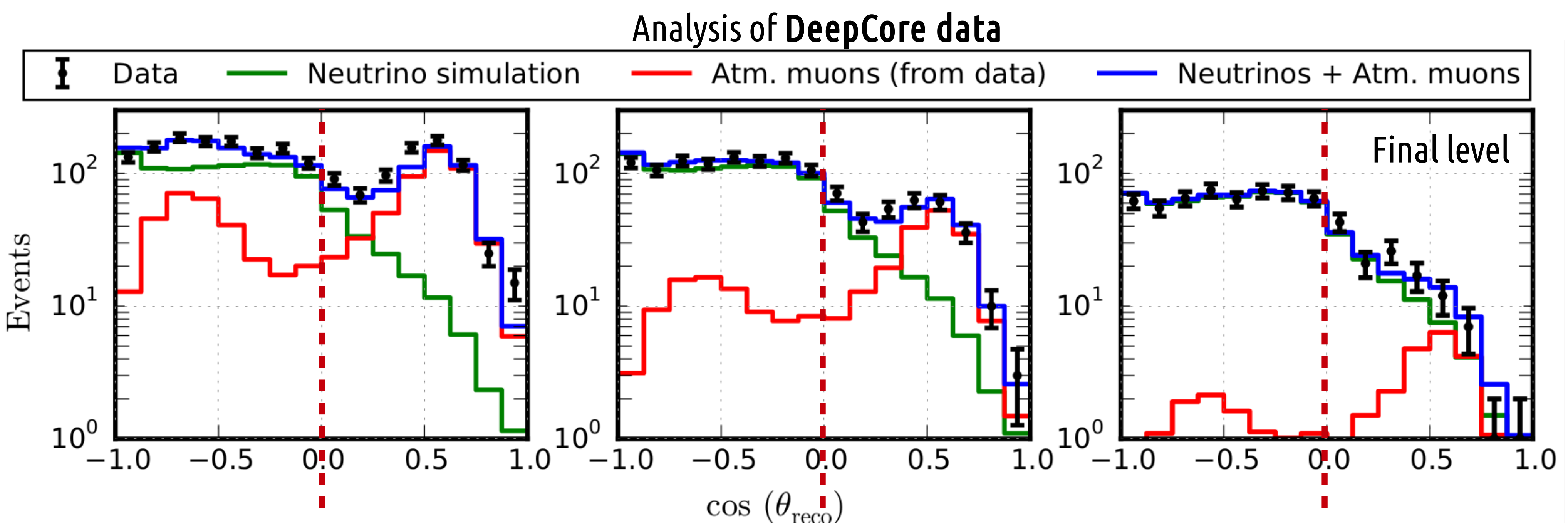
LowStats Background

» Muons from air showers

» Starting events → IceCube as veto for DeepCore

» Tag muons directly from data

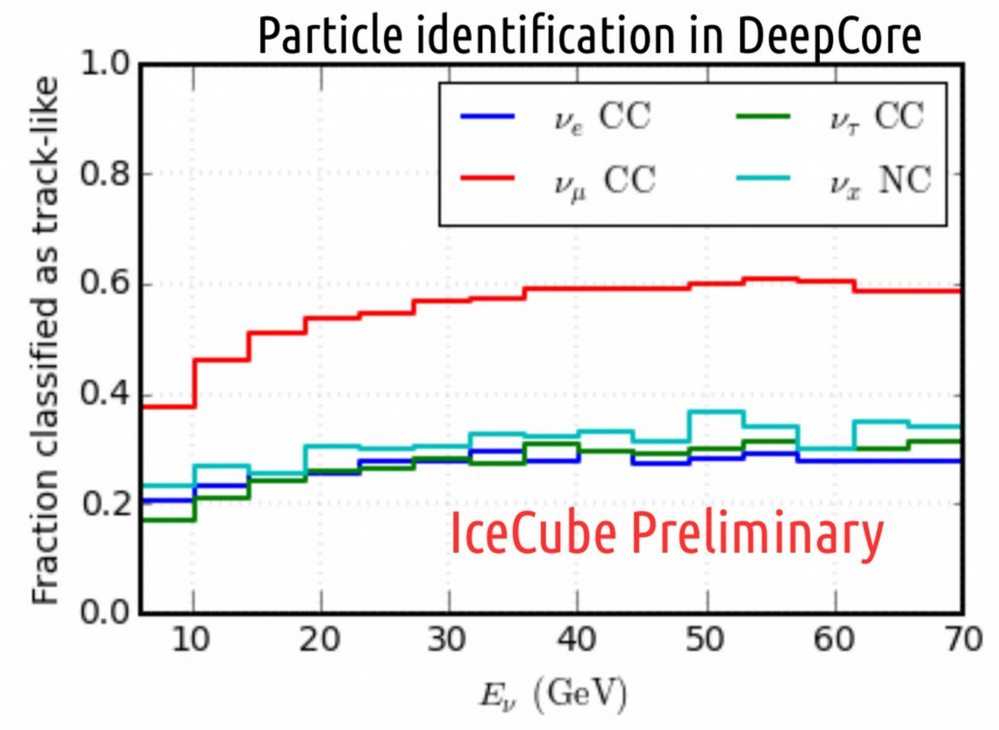
» Use “event quality” to remove misreconstructions



Phys. Rev. D 91, 072004 (2015)

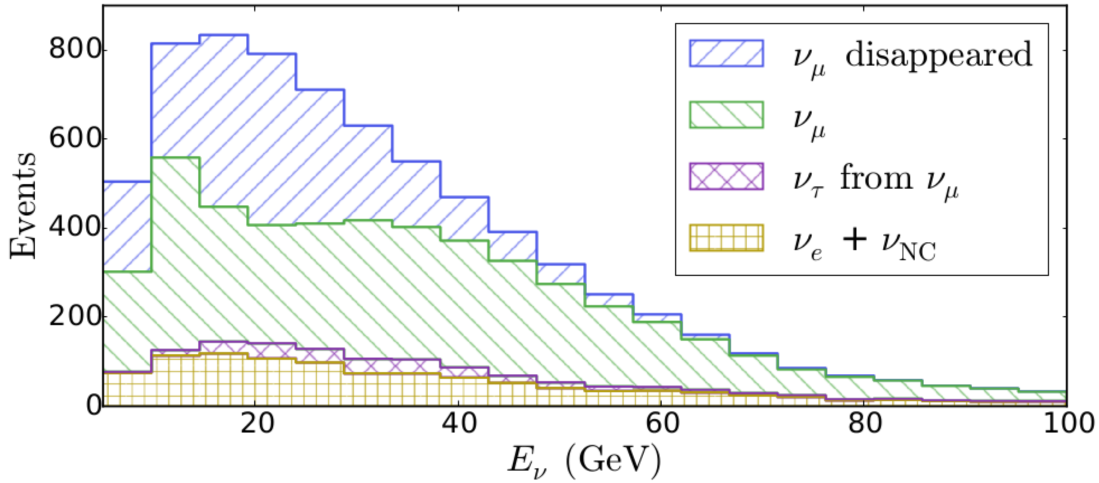
LowStats neutrino identification

- Obtained from comparing fits with different hypotheses
  - Assume track+cascade vs only cascade
  - Ratio of the χ^2 obtained
  - Only track-like events have been used for current results



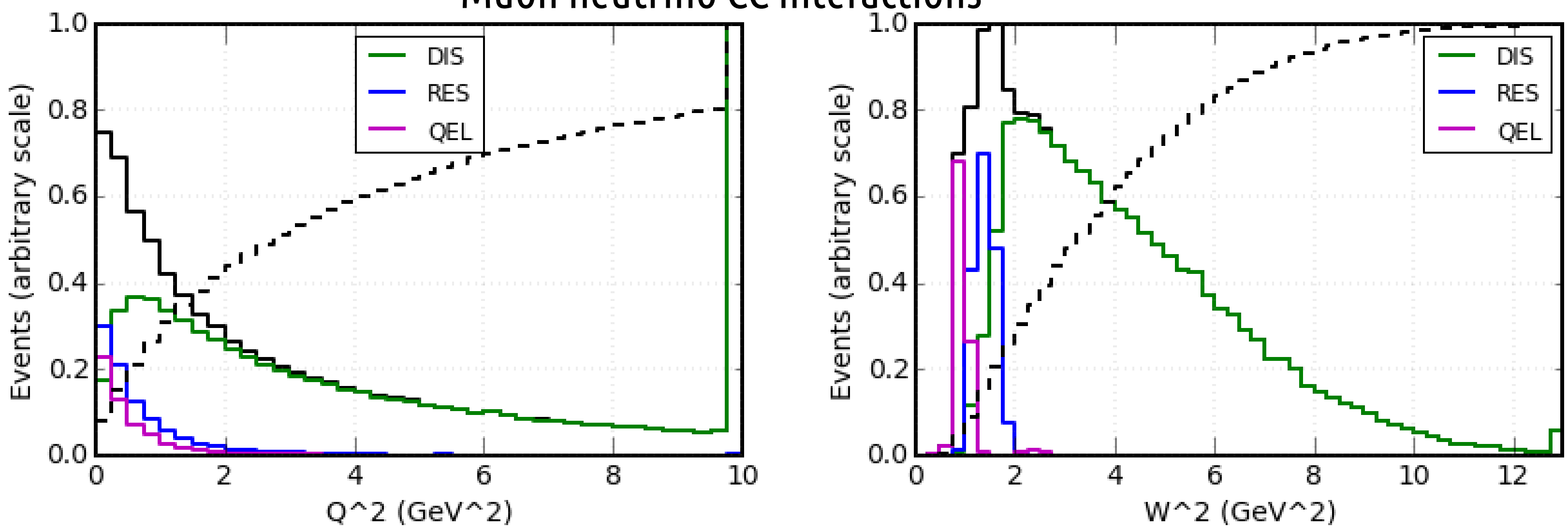
LowStats sample analyzed

» Energy range, W^2 and Q^2 according to GENIE



Muon neutrino CC interactions

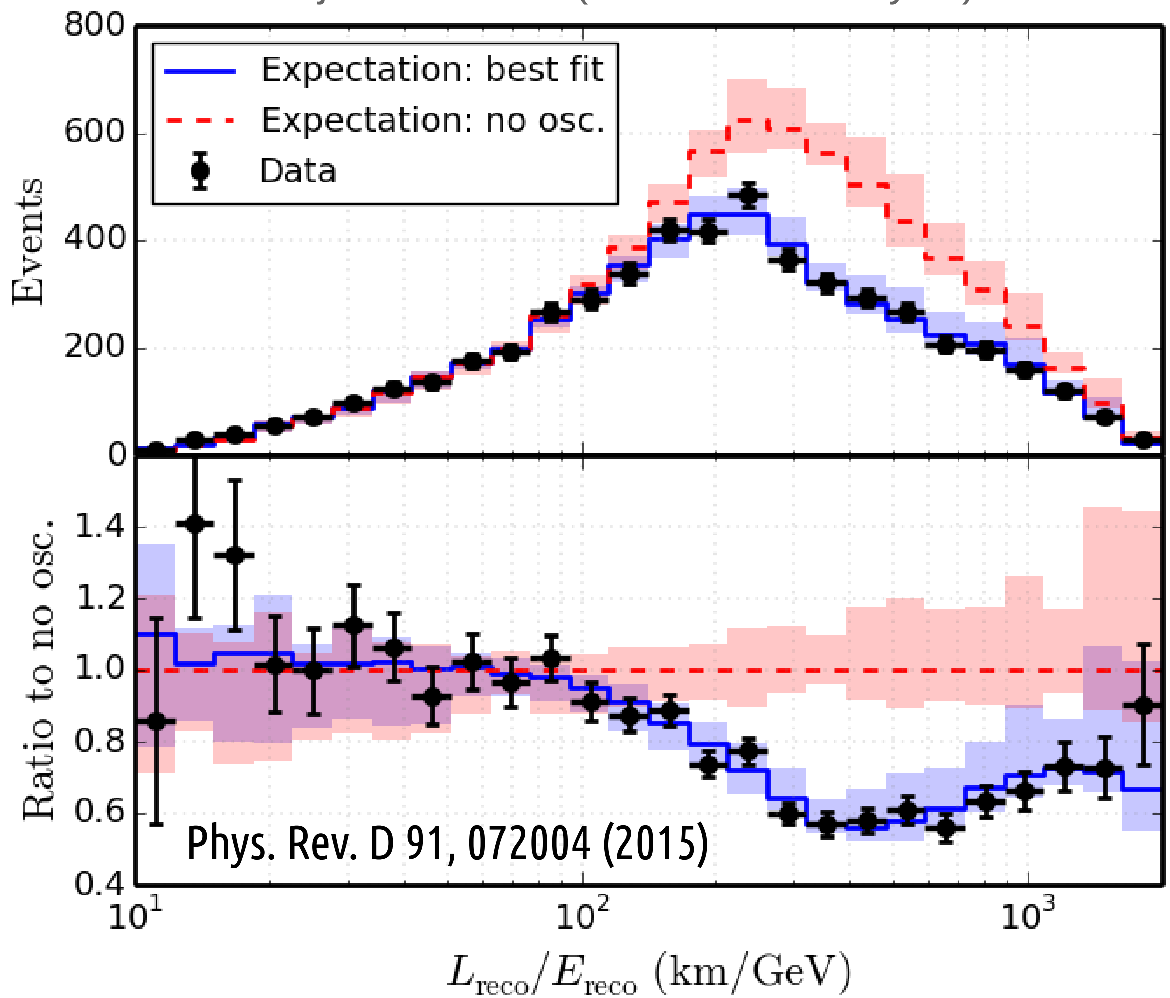
- 84% DIS
- 10% RES
- 6% QEL



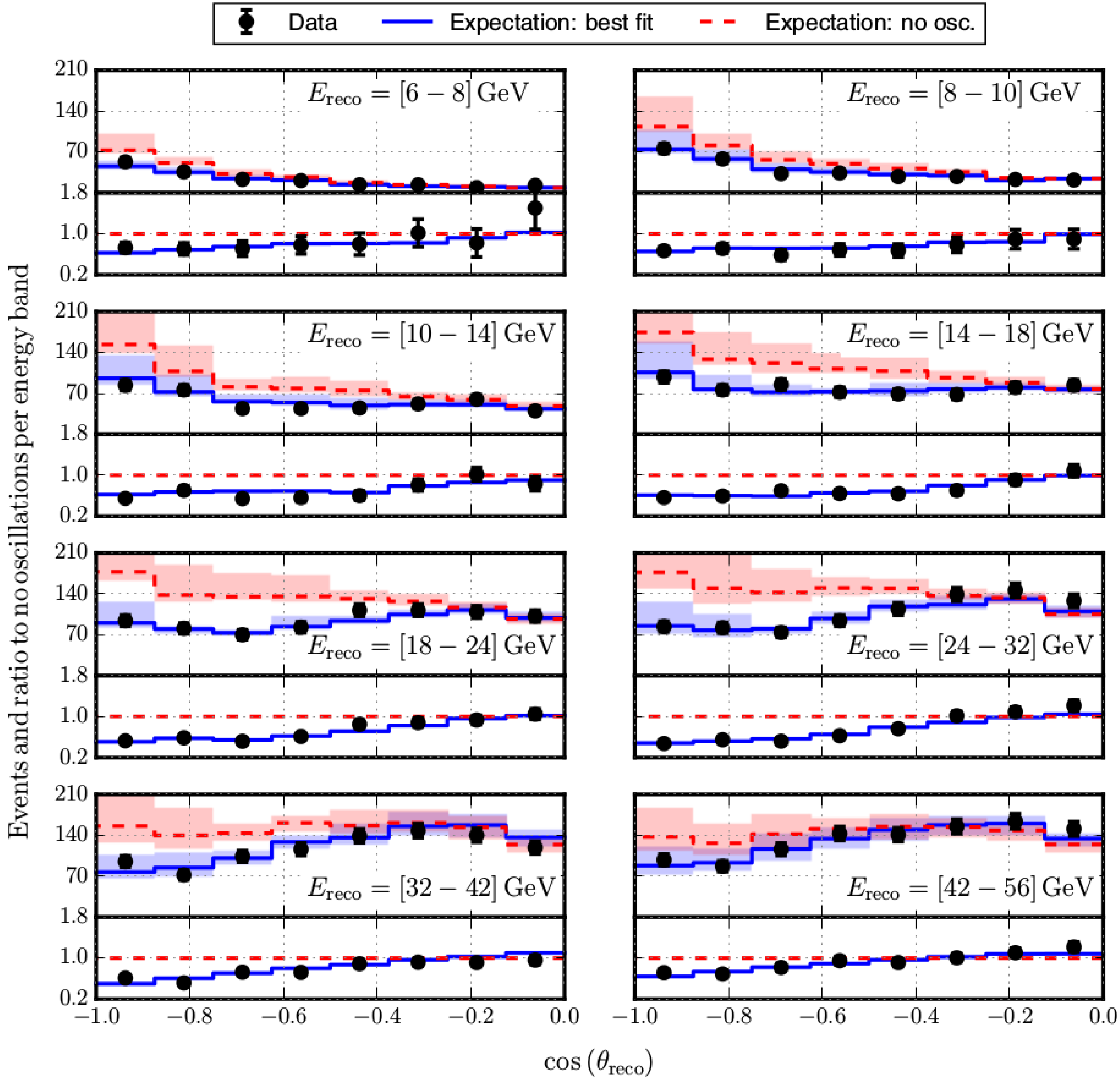
LowStats DeepCore results

- Using **muon tracks only**
- Best fit to the data from a 2D analysis (E, θ)
- Up-going events
- Using E < 56 GeV
- 5174 events in 3 years
- In 2D fit histogram
  - χ^2 = 54.9 / 56 d.o.f.

Projection in L/E (not used in analysis)



Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc



Data
Expectation: best fit
Expectation: no osc.
$E_{\rm reco} = [6 - 8]$ GeV
$E_{\rm reco} = [8 - 10]$ GeV
$E_{\rm reco} = [10 - 14]$ GeV
$E_{\rm reco} = [14 - 18]$ GeV
$E_{\rm reco} = [18 - 24]$ GeV
$E_{\rm reco} = [24 - 32]$ GeV
$E_{\rm reco} = [32 - 42]$ GeV
$E_{\rm reco} = [42 - 56]$ GeV
Events and ratio to no oscillations per energy band
$\cos(\theta_{\rm reco})$

LowStats error budget

» Expected reduction of error by removing individual sources of uncertainty

	$\sin^2(\theta_{23})$	Δm^2_{31} (10^3 eV^2)
PRD errors	~ 0.1	~ 0.2
Hole ice (angular acceptance)	29.88%	2.34%
DOM eff	0.73%	19.06%
Gamma	0.13%	8.67%
NuE	0.05%	0.94%
Atm Mu	0.00%	0.72%
Hadronic energy scale	< 1 %	
Axial mass (non-DIS events)		

Preliminary

LowStats seasonal variations

- » Data used for PRD result (red+blue)
  - » Neutrinos (Earth-crossing): amplitude ~ 4%
  - » Atm. Muons (down-going): amplitude ~10%