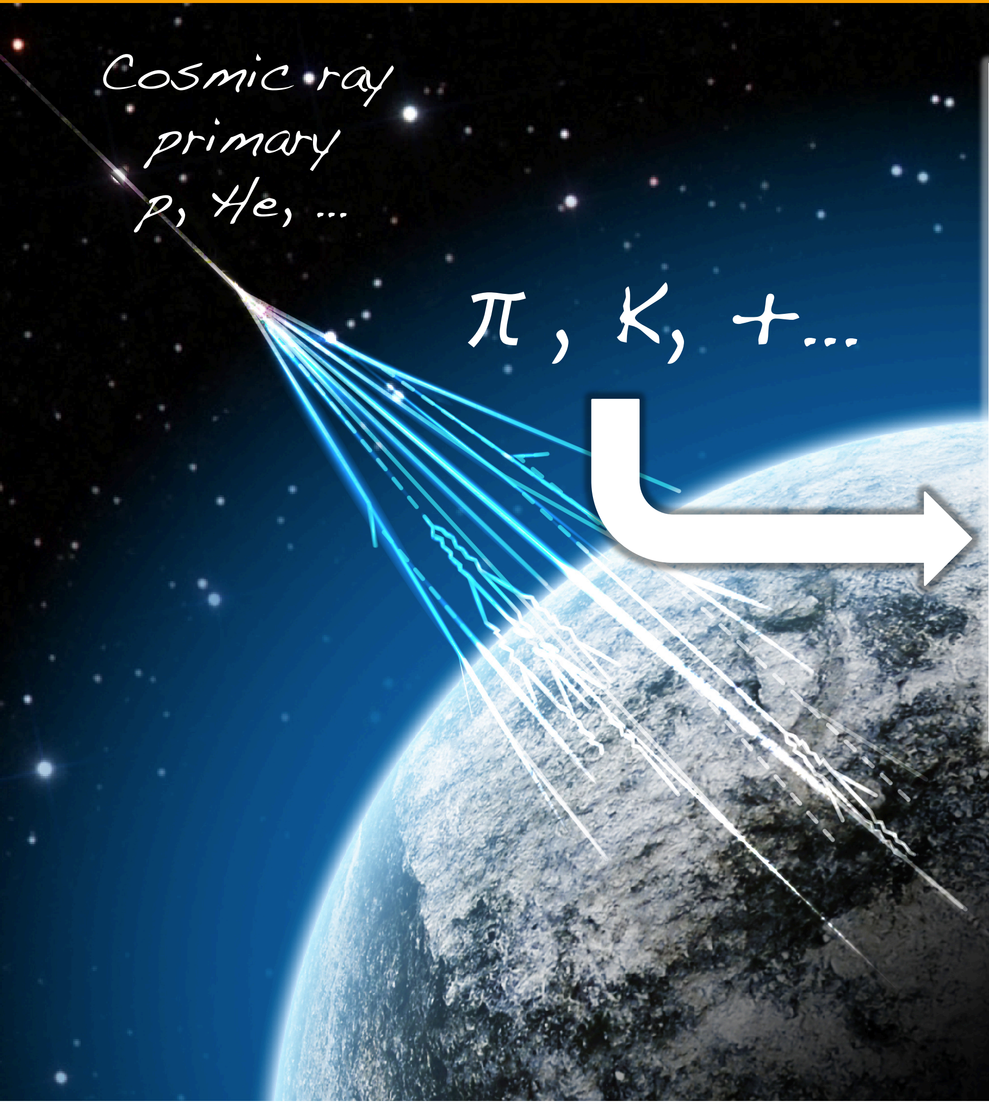
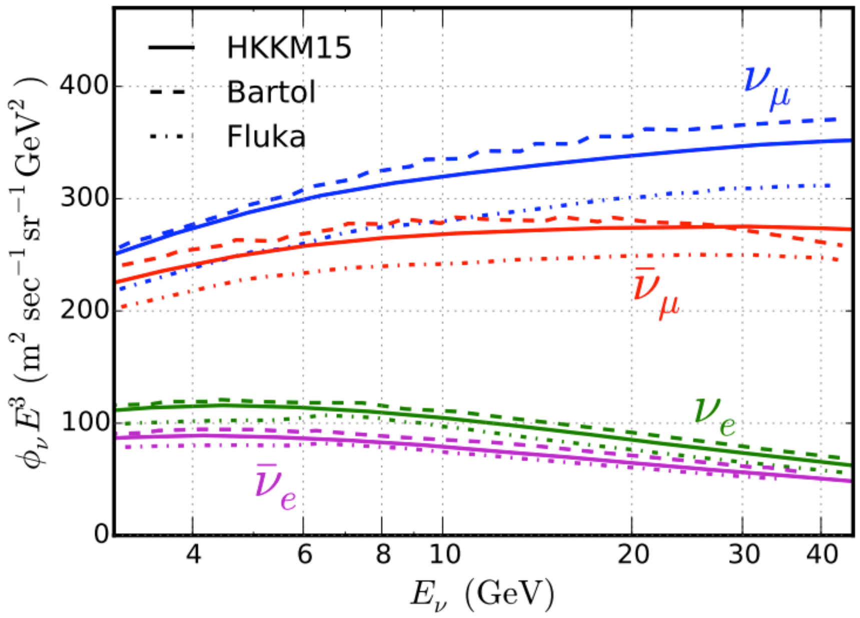
Atmospheric Neutrino Physics with IceCube DeepCore

Summer Blot
Seminar CEA-Saclay
16/01/2017

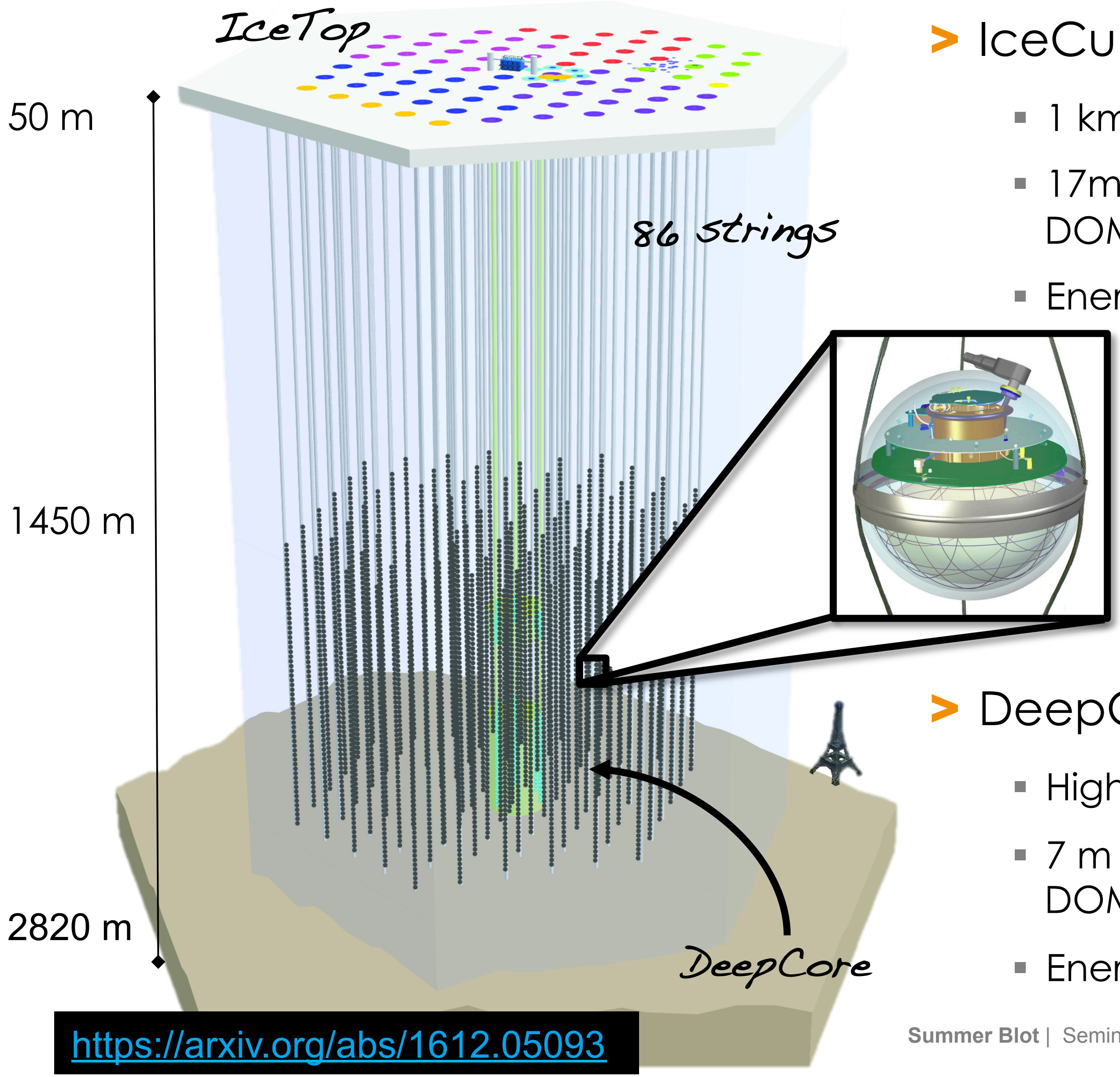
Atmospheric neutrino production



Adv.High Energy Phys. 2015 (2015) 271968



IceCube Neutrino Observatory



https://arxiv.org/abs/1612.05093

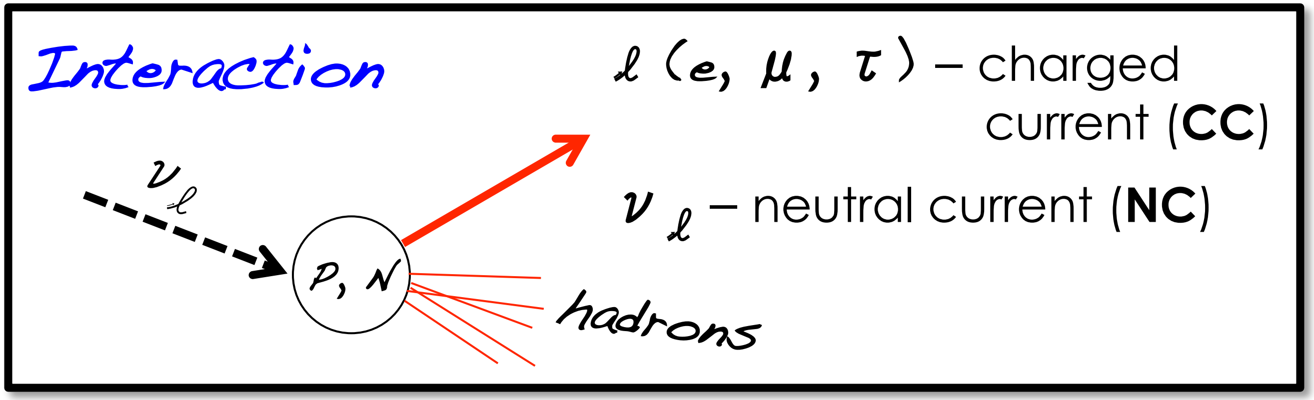
> IceCube

- 1 km^3 ice Cherenkov detector
- 17m vertical, 125m horizontal DOM spacing
- Energy threshold ~100 GeV

> DeepCore

- High QE DOMs
- 7 m vertical, 40-60 m horizontal DOM spacing
- Energy threshold ~10 GeV

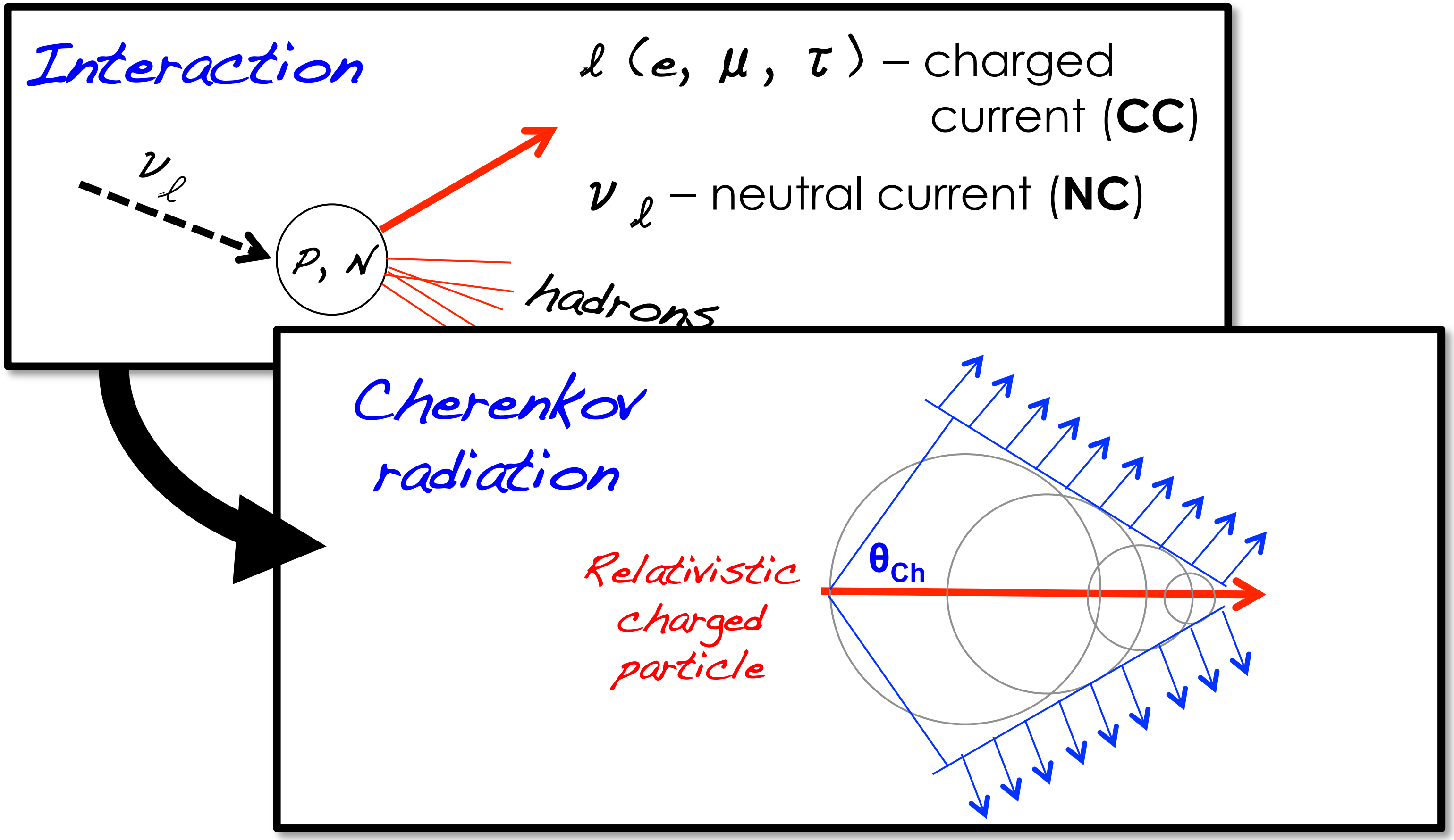
Neutrino detection in IceCube



ℓ (e, μ, τ) – charged current (**CC**)

ν_ℓ – neutral current (**NC**)

Neutrino detection in IceCube



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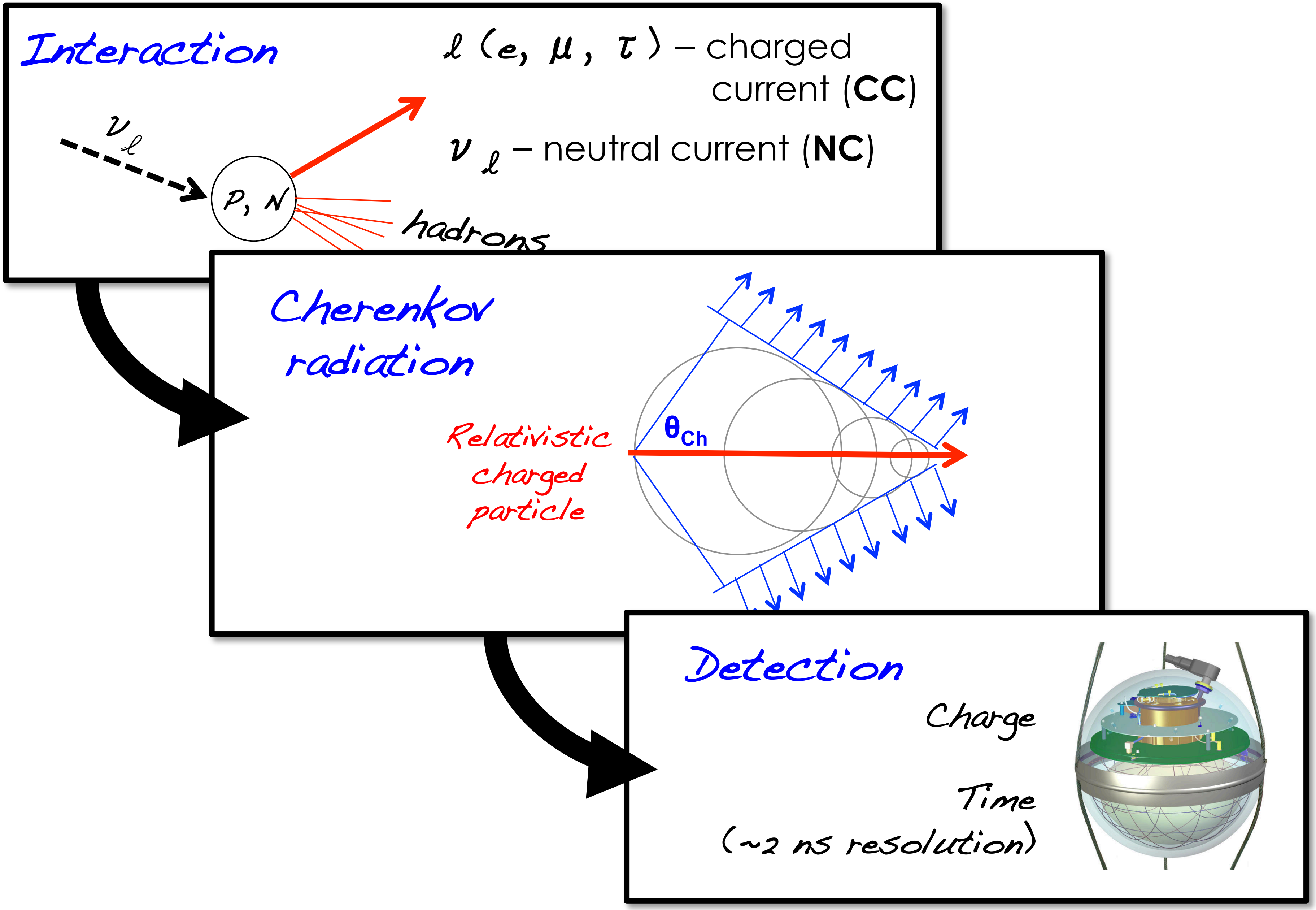
Neutrino detection in IceCube



$\ell\ (e, \mu, \tau)$ – charged current (**CC**)

ν_ℓ – neutral current (**NC**)

Detector medium – ice properties

- Natural medium
- Layers formed over different periods
- Structure of layers can reflect topology of underlying bedrock
- Bulk ice "calibration"
  - Scattering/absorption coefficients
  - Anisotropy
  - Tilt

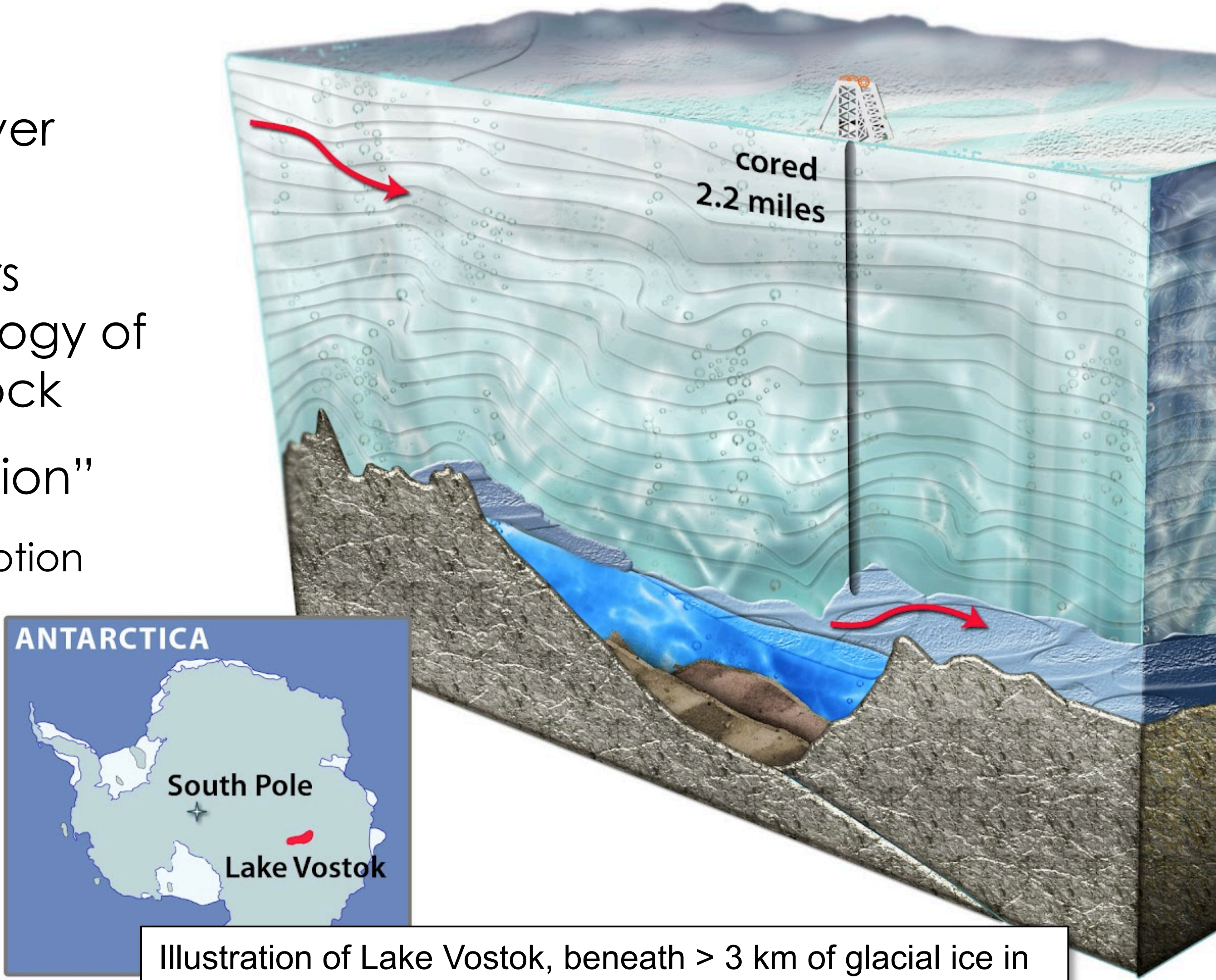
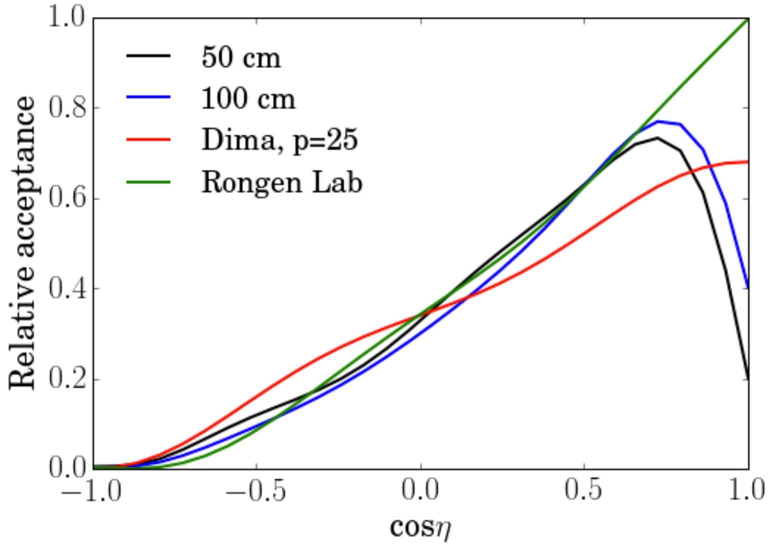
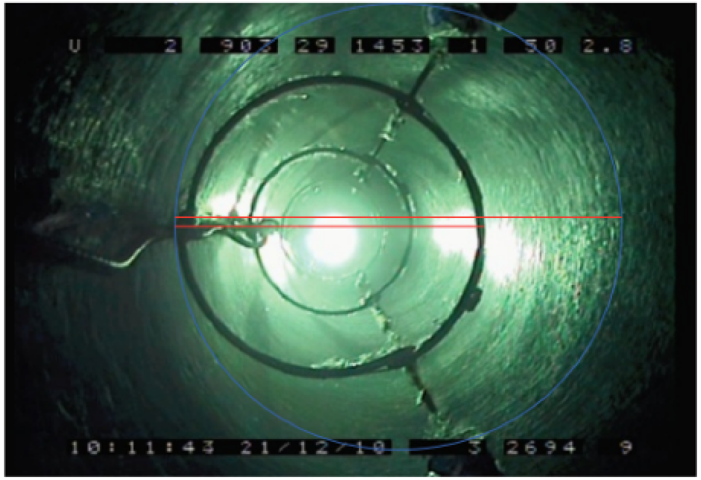


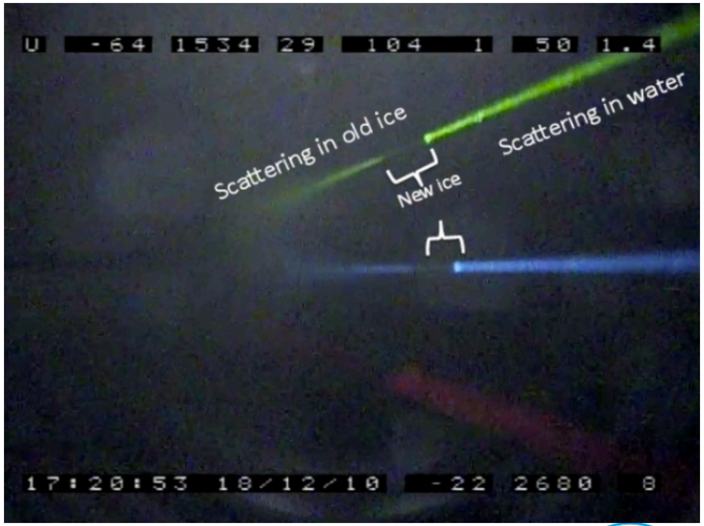
Illustration of Lake Vostok, beneath > 3 km of glacial ice in East Antarctica (Credit: Nicolle Rager Fuller / NSF)

Detector medium – ice properties

- Bore-hole ice (a.k.a. hole ice)
  - Refrozen ice column contains bubbles
- Can watch the refreezing process on YouTube
  - “IceCube camera freeze”
  - https://www.youtube.com/watch?v=YWdn3InbsY0
- Modifies DOM angular acceptance

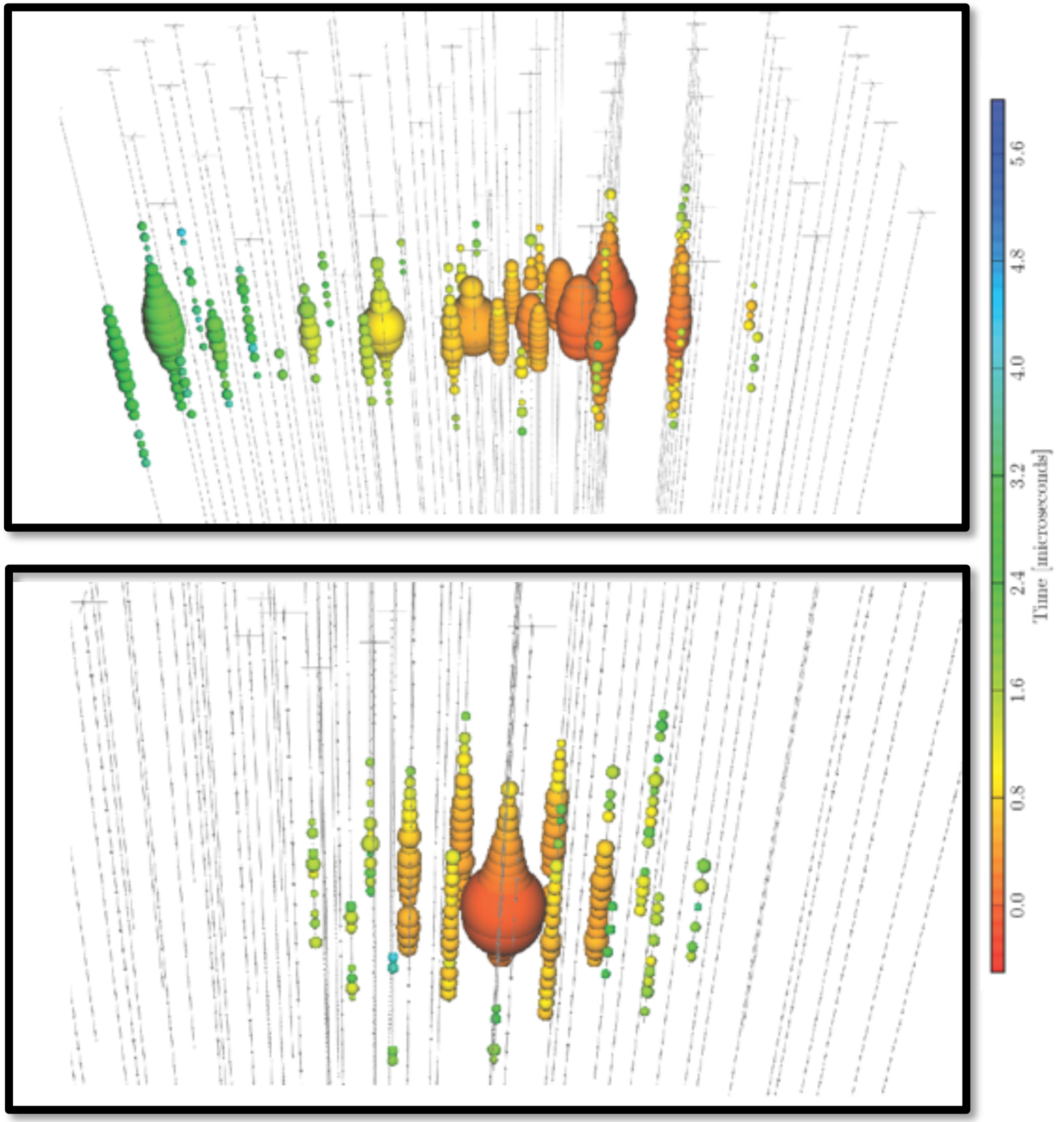






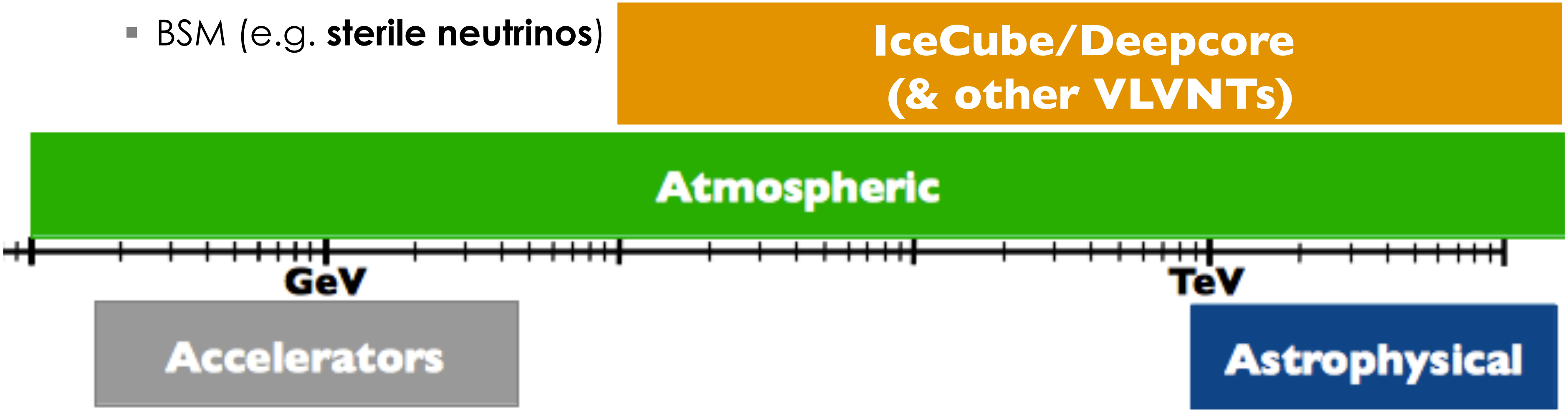
Event topology

- Track-like events
  - ν_μ CC interactions
- Cascade-like events
  - ν_e, ν_τ CC
  - All NC interactions
- Other event topologies (i.e. double bang) currently being explored



IceCube DeepCore physics potential

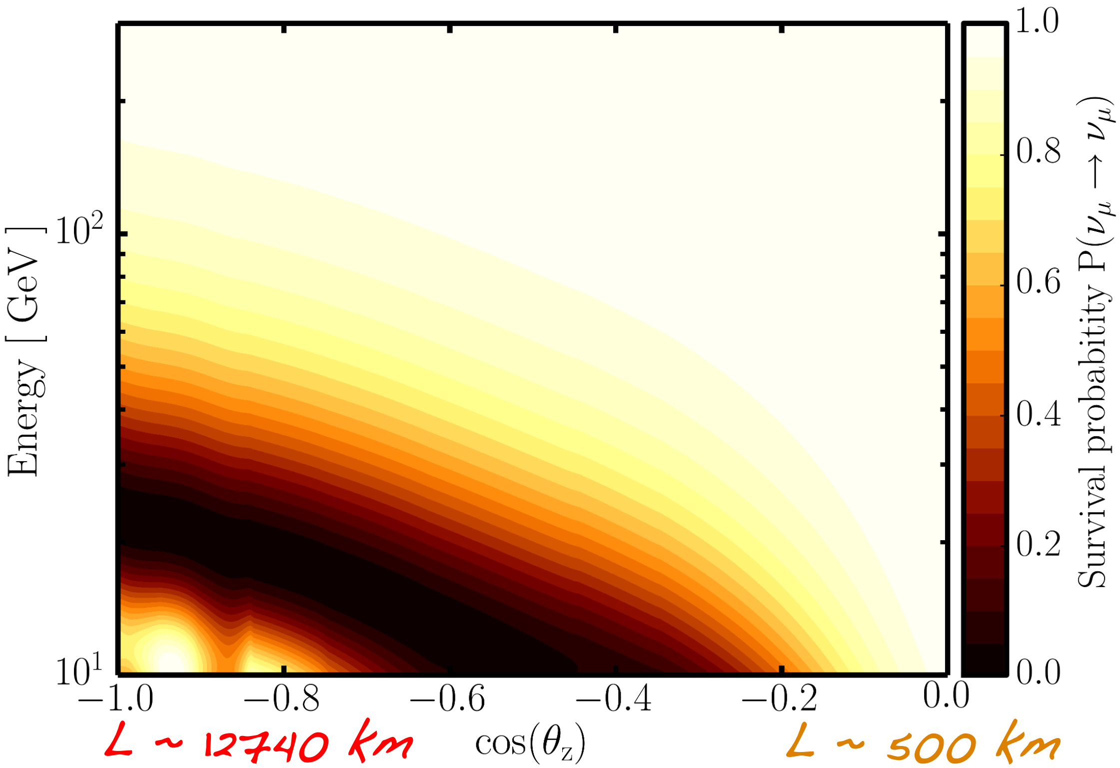
- Sensitive to atmospheric and astrophysical neutrinos over a wide range in energy
- With **atmospheric neutrinos**, we can probe many physics topics:
  - **Neutrino oscillations** (e.g. ν_μ disappearance, ν_τ appearance)
  - Cross sections
  - Cosmic ray models
  - ν flux unfolding
  - BSM (e.g. **sterile neutrinos**)



Atmospheric neutrino oscillations

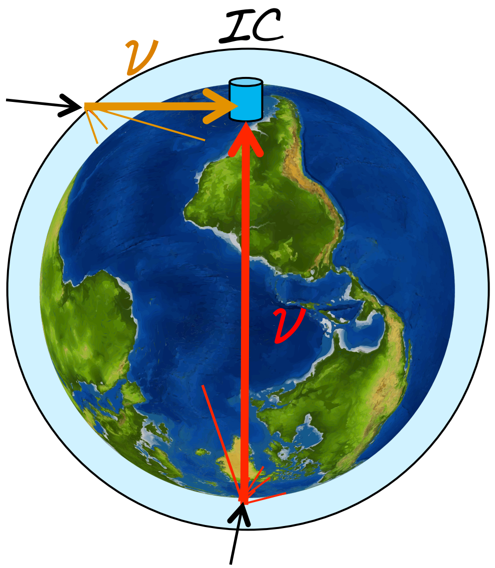
Flavour eigenstate ≠ Mass eigenstate & $m_1 \neq m_2 \neq m_3$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \longrightarrow P^{2\nu}_{\nu_\alpha \to \nu_\beta} = 1 - \sin^2 2\underset{\text{Amplitude}}{\theta_{23}} \sin^2\left(\frac{\overset{\text{Frequency}}{\Delta m^2_{32}} L}{4E}\right)$$



L ~ 12740 km

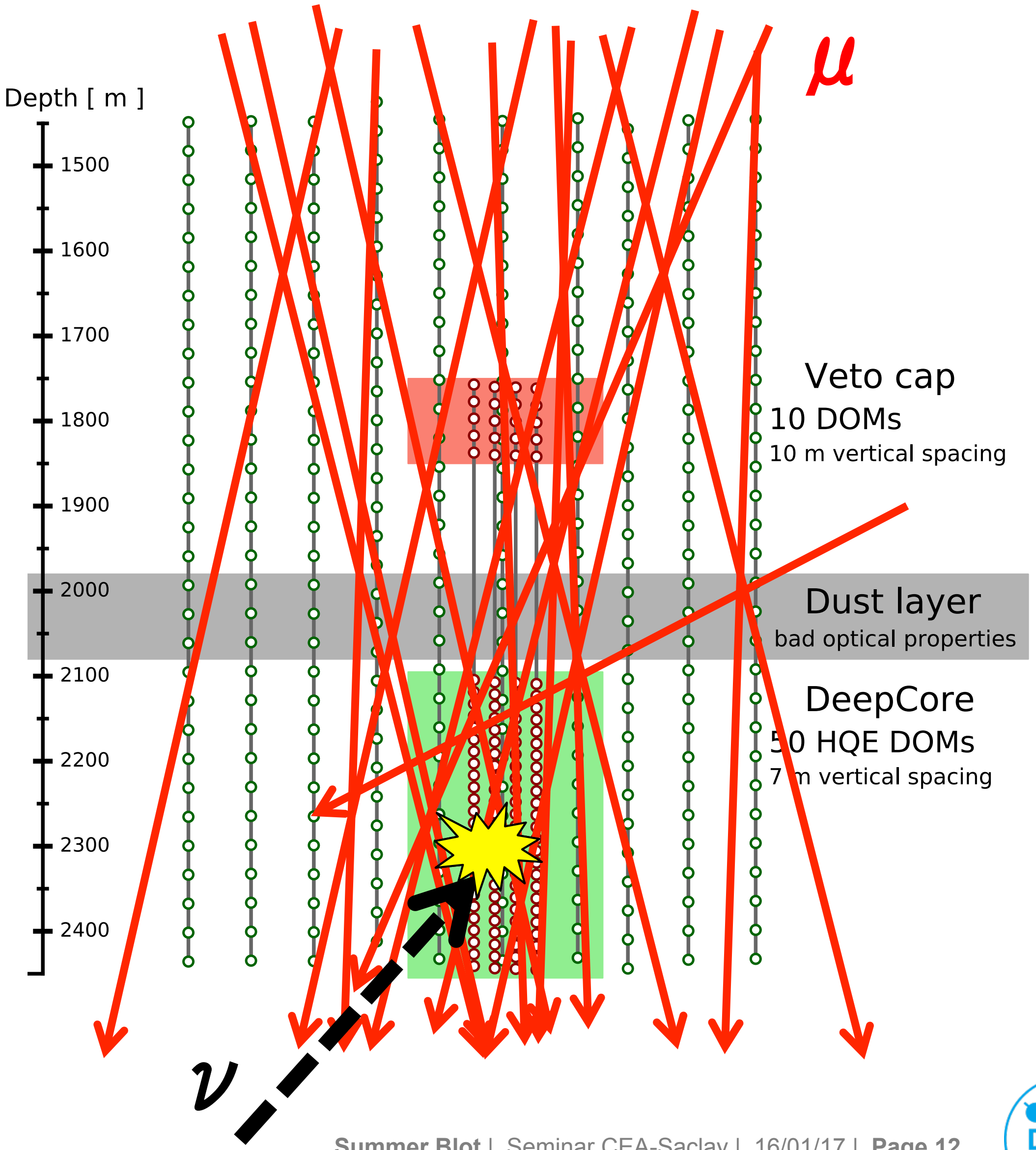
L ~ 500 km



Beating the background

Trigger level

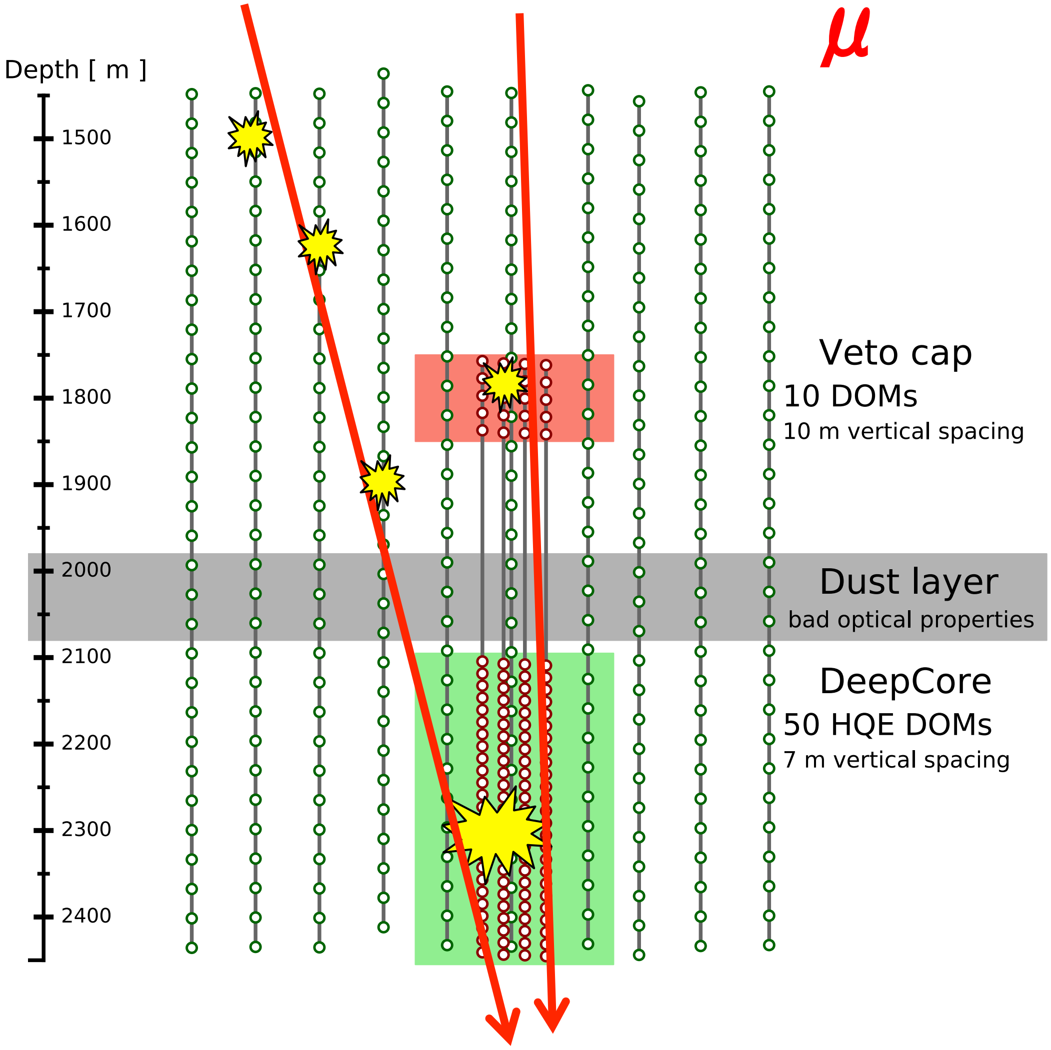
~$10^7 \mu : 1 \nu$



Beating the background

Trigger level
~$10^7 \mu$: 1ν

- Veto
  - Up-going events: use Earth as a veto
  - Outer layers of IceCube
  - Veto cap



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Trigger level

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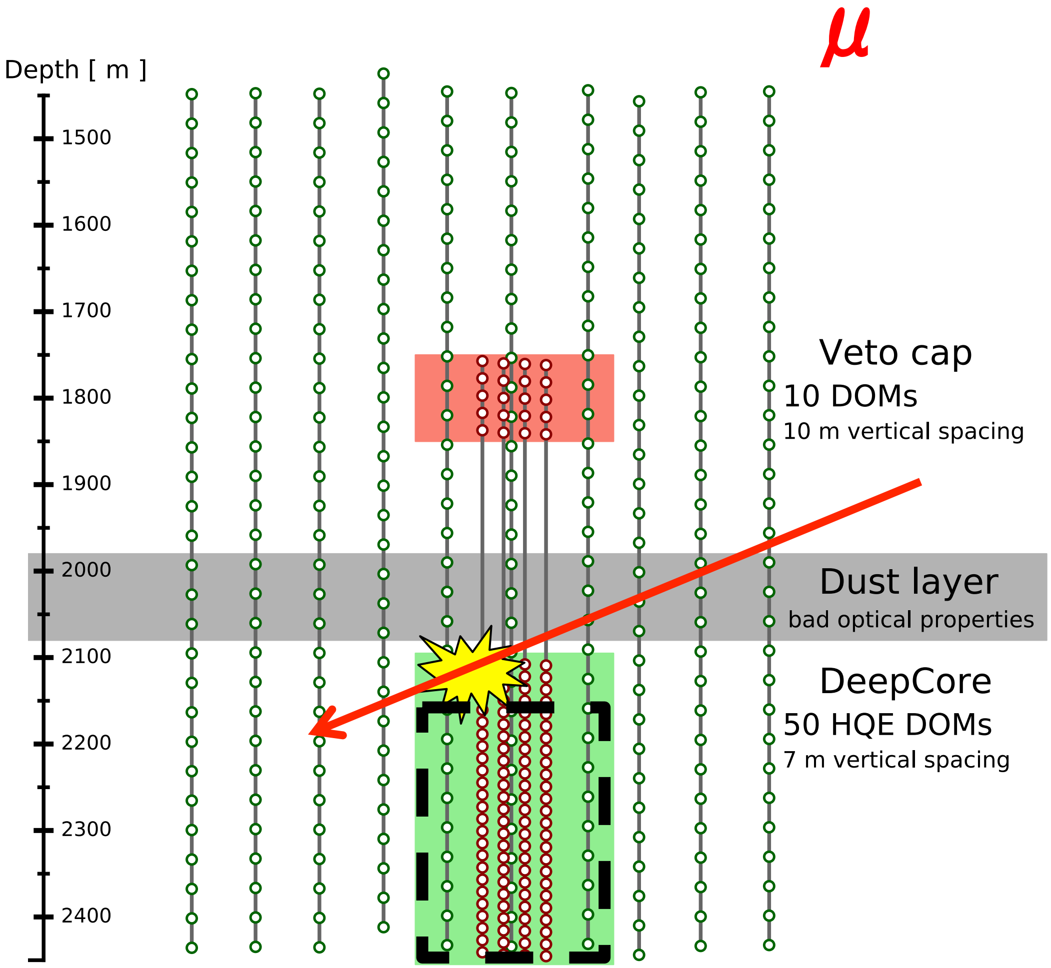
- Starting events with first hits inside fiducial volume



Beating the background

Trigger level

$\sim 10^7 \mu : 1 \nu$

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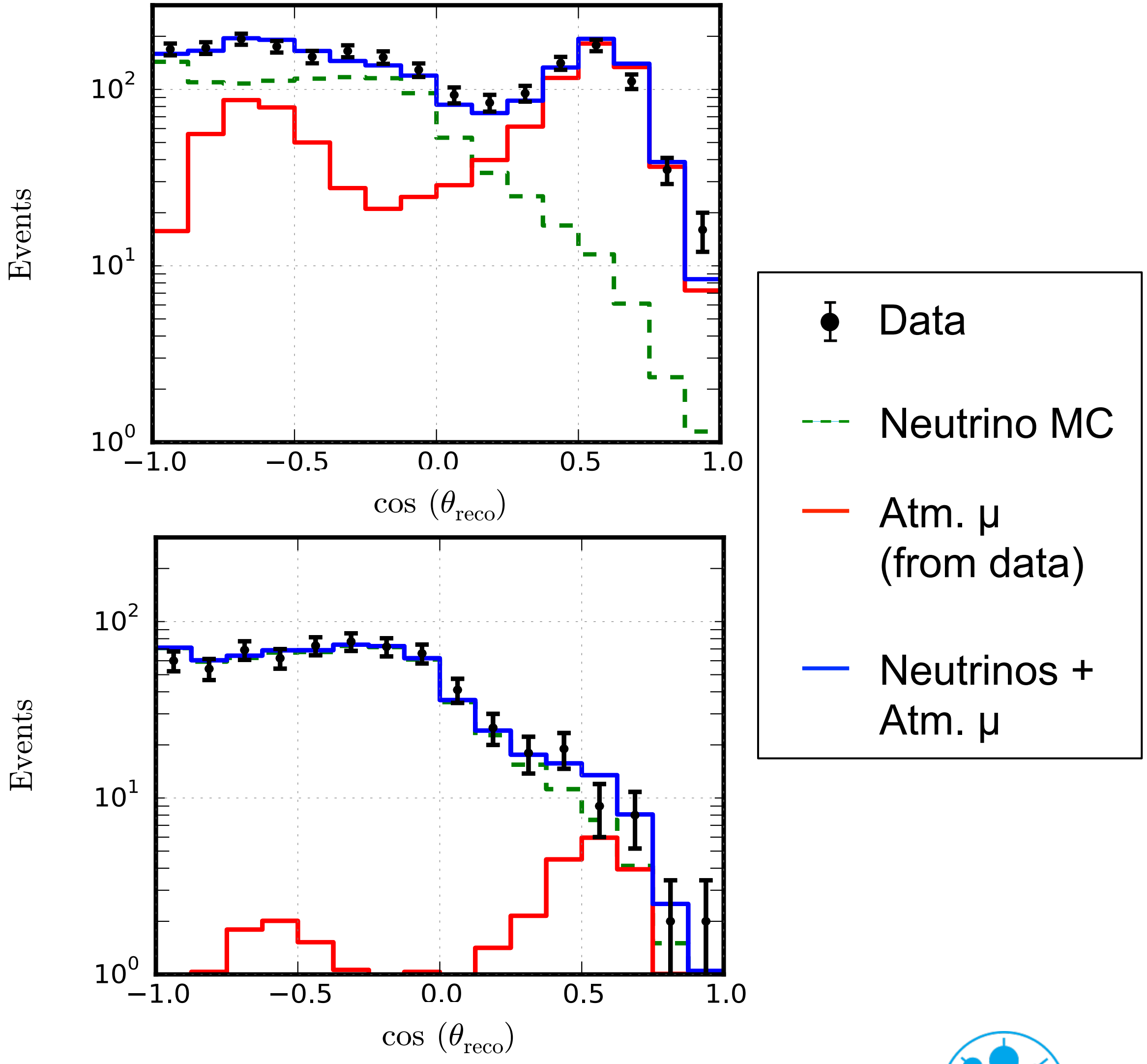
- Starting events with first hits inside fiducial volume

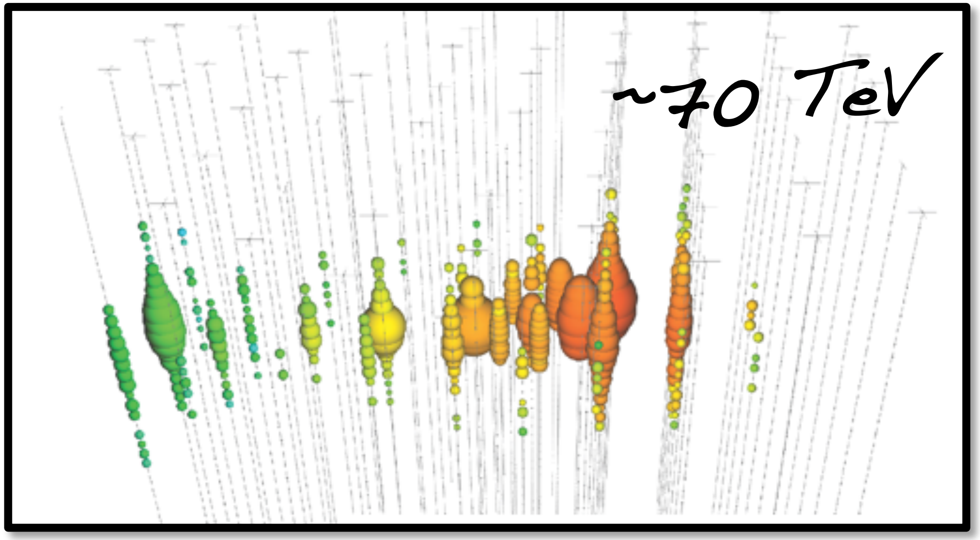
Final level

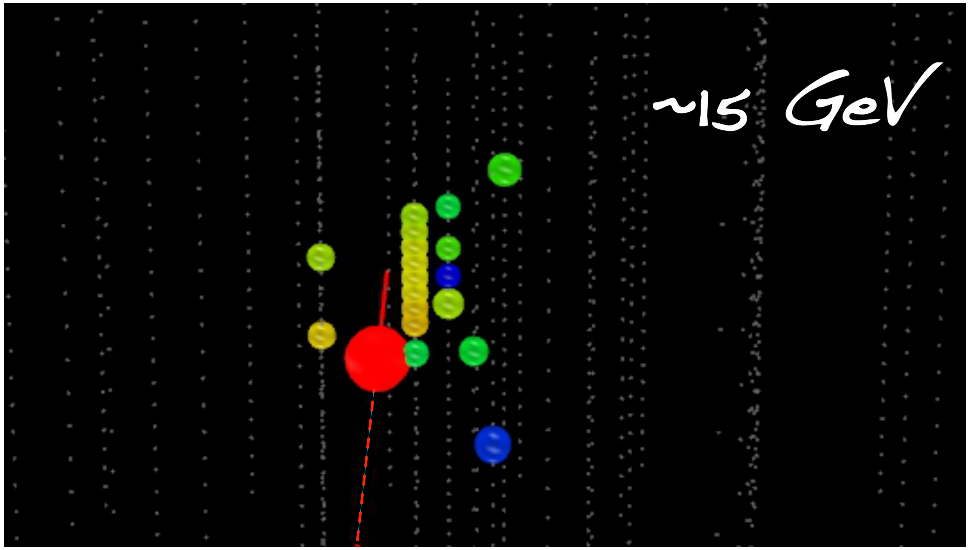
$< 1\% \ \mu$



Event reconstruction

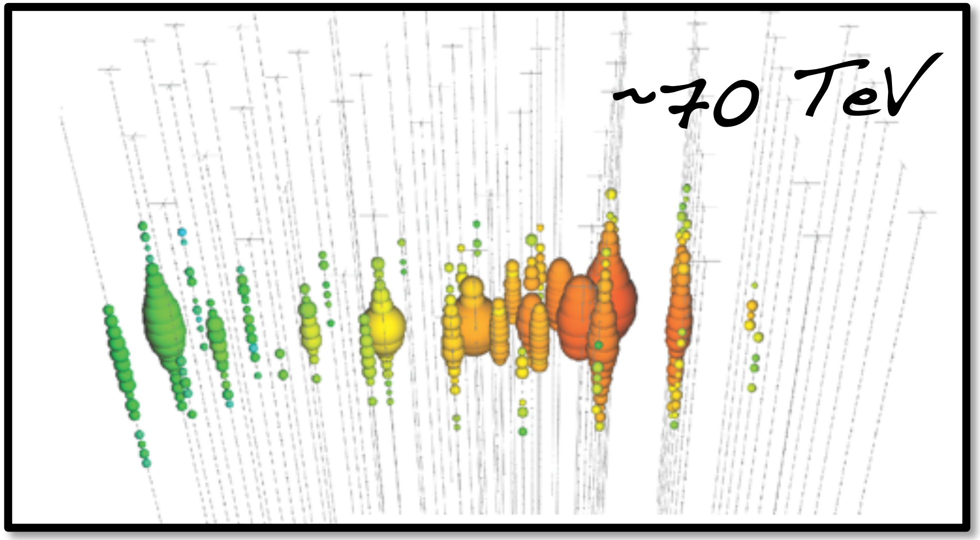
- Lower energy means fewer photons, and therefore less information
- Uncertainties in ice properties play larger role

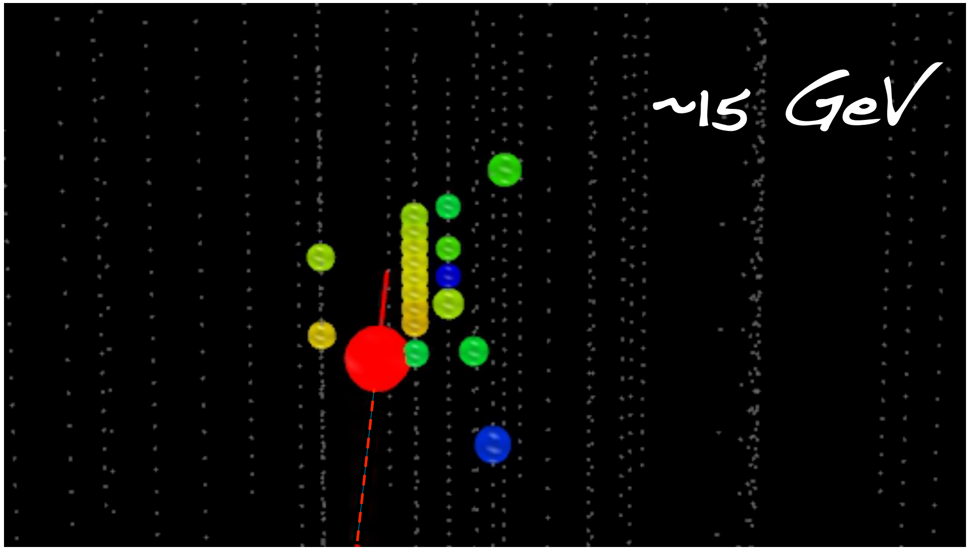




Event reconstruction

- Lower energy means fewer photons, and therefore less information
- Uncertainties in ice properties play larger role
- Solution:
  - Focus on "Golden" channel, ν_μ CC interactions
  - Look for clear muon tracks
  - Use ***unscattered*** (i.e. direct) photons

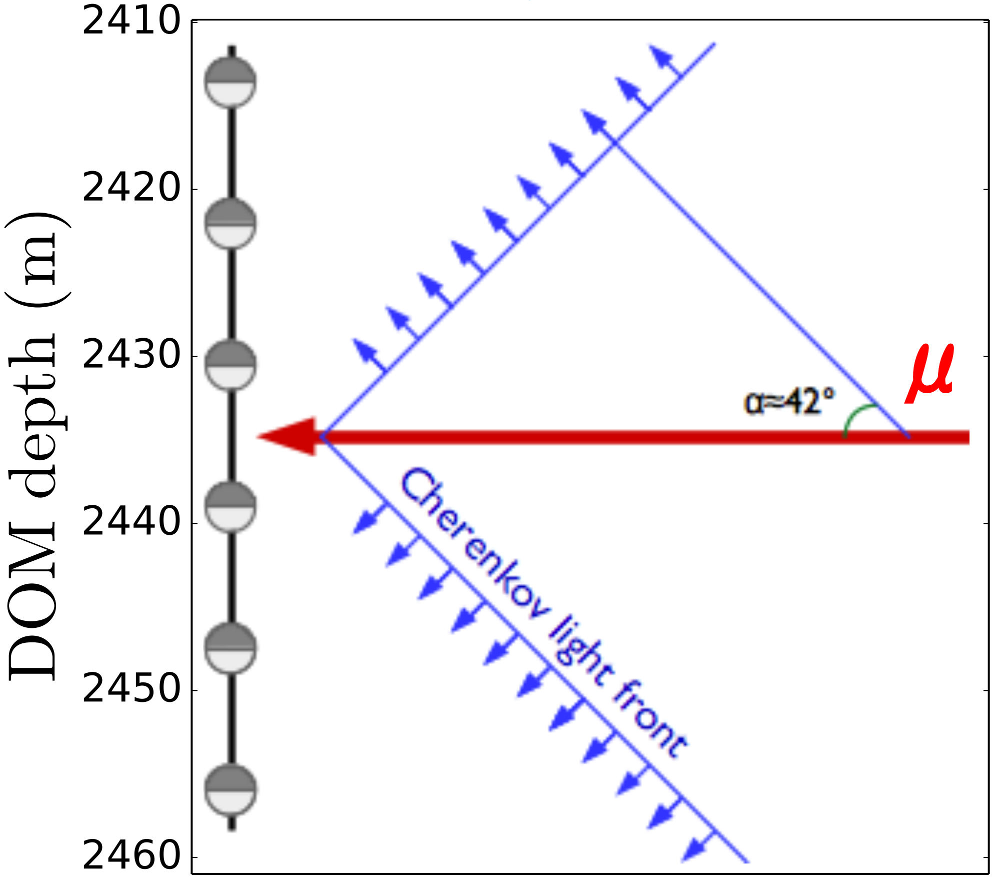

~70 TeV


~15 GeV

Event reconstruction

- Unscattered photons from tracks
  - Hit pattern in DOMs follows hyperbola
  - Track direction extracted from hyperbola orientation
  - Use track direction as proxy for incoming neutrino direction

Astropart.Phys.34:652-662,2011



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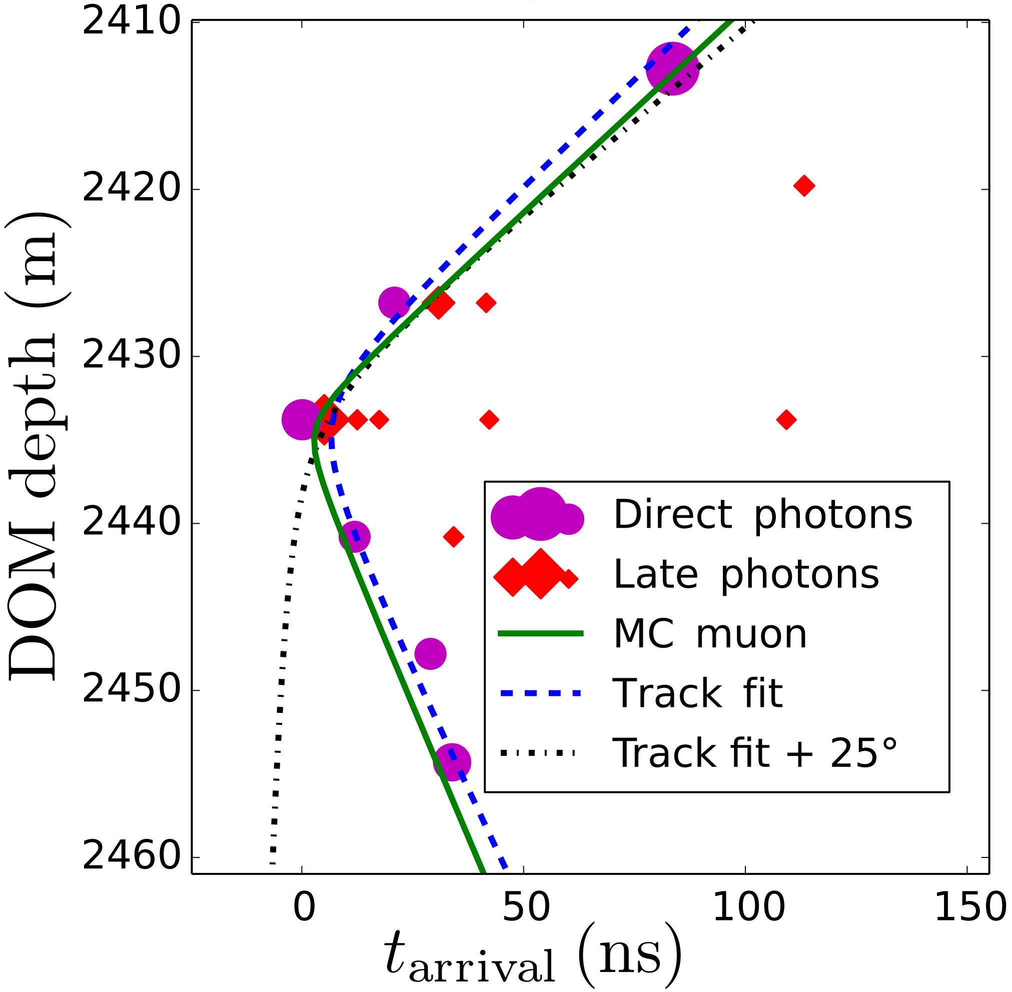
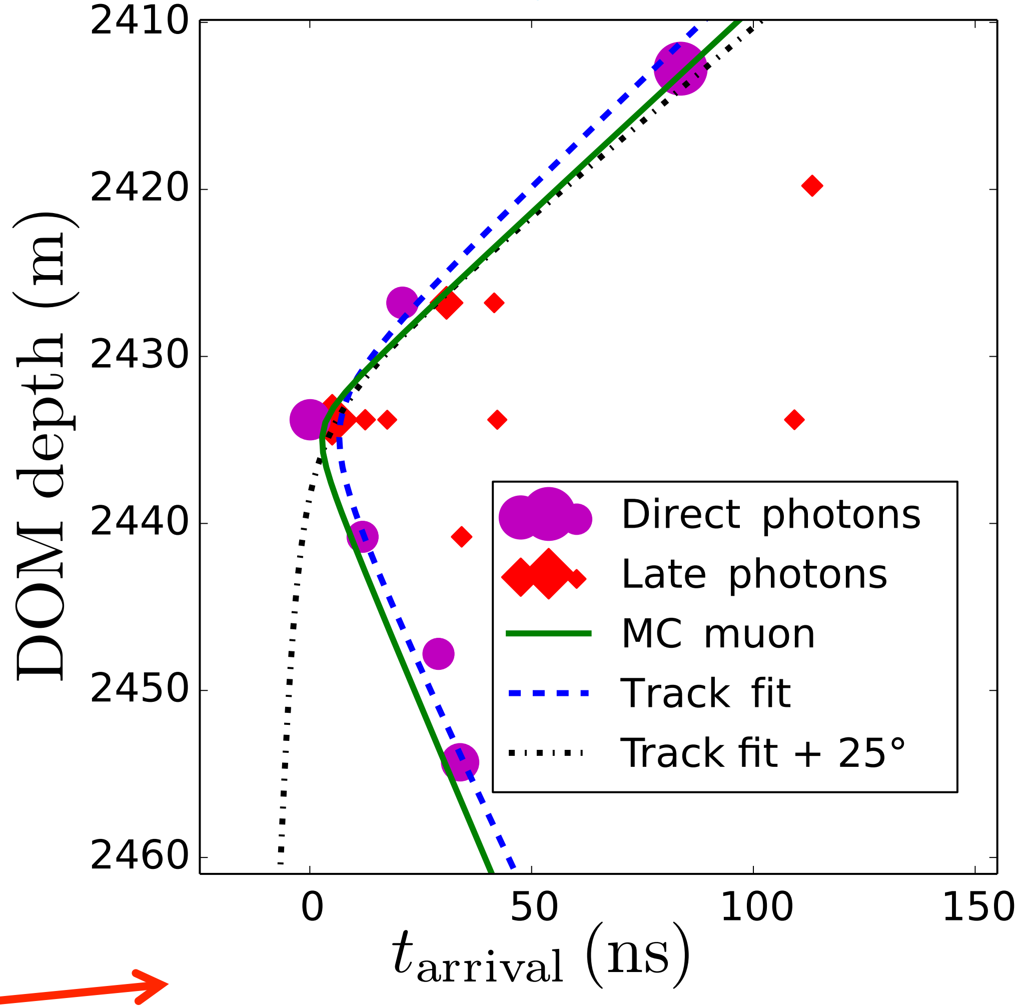


Event reconstruction

- Unscattered photons from tracks
  - Hit pattern in DOMs follows hyperbola
  - Track direction extracted from hyperbola orientation
  - Use track direction as proxy for incoming neutrino direction
- Energy reconstructed from observed charge
  - Hypothesis is track + hadronic cascade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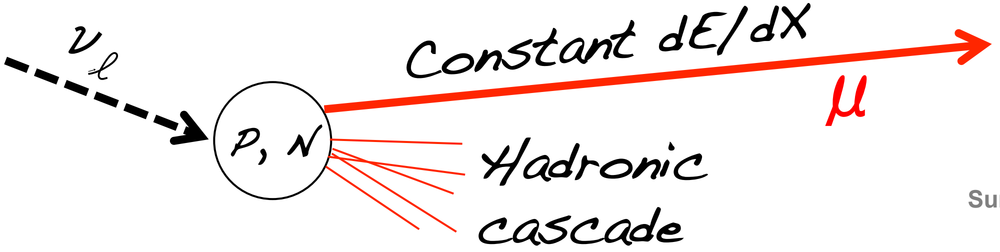
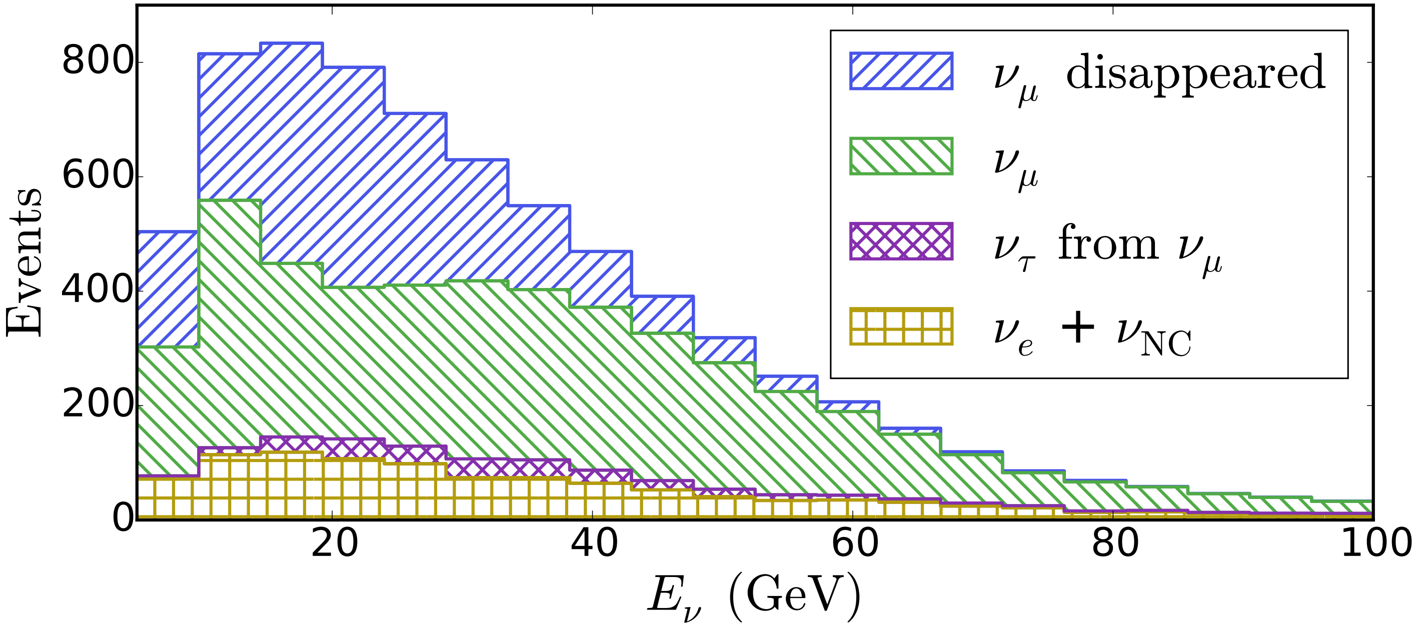


Analysis sample

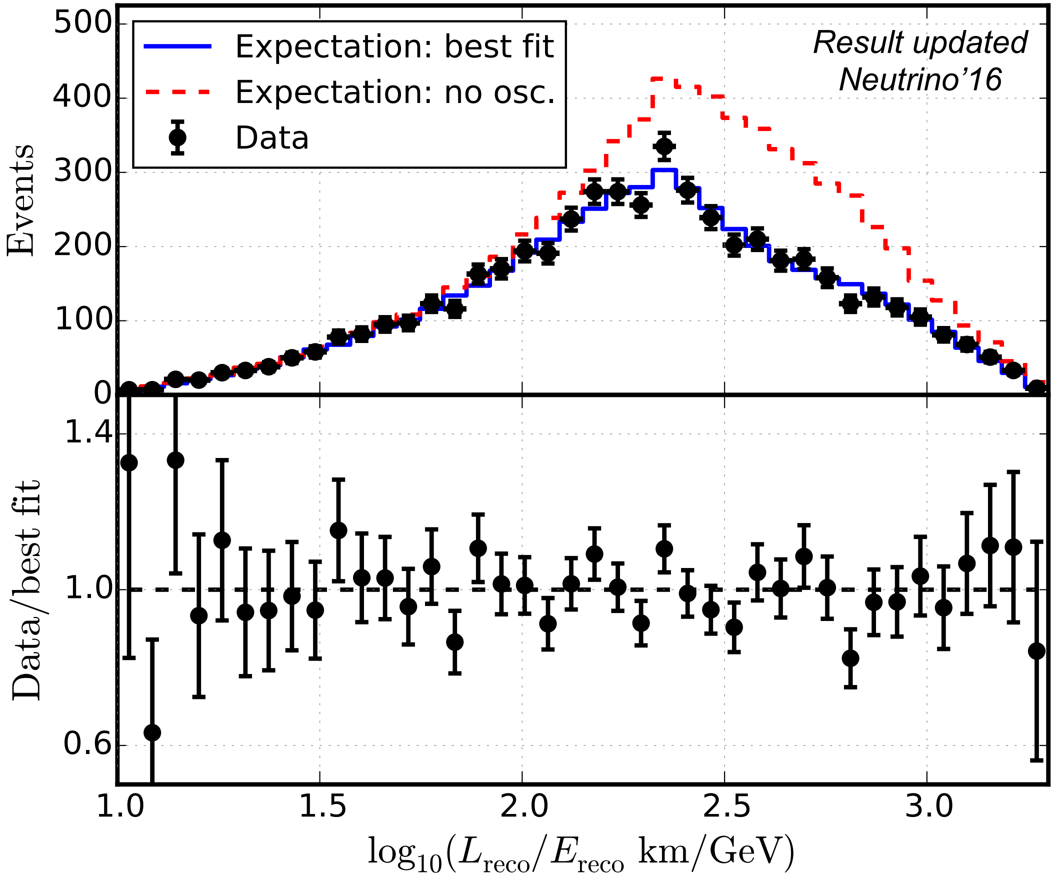


- ~30 % signal (ν_μ CC) efficiency
- ~10° zenith resolution, ~25% energy resolution
- Composition of data sample at analysis level
  - **74% ν_μ CC,** 13% ν_e CC, 8% NC (all flavours) and 5% ν_τ

ν_μ disappearance analysis

- Poisson likelihood fit to data in 8x8 bins (***E***, ***θ* zenith**)
  - Up-going events
  - Energy [6-56] GeV
- 5174 events in 3 years
- Clear evidence of neutrino oscillation
- Good data/MC agreement
  - χ^2/d.o.f. = 52.4 / 56

Phys. Rev. D 91, 072004 (2015)



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

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- Clear evidence of neutrino oscillation
- Good data/MC agreement
  - χ^2/d.o.f. = 52.4 / 56
- Best fit:
  - $\sin^2\theta_{23} = 0.52$
  - $|\Delta m^2_{32}| = 2.50 \times 10^{-3}$ eV^2

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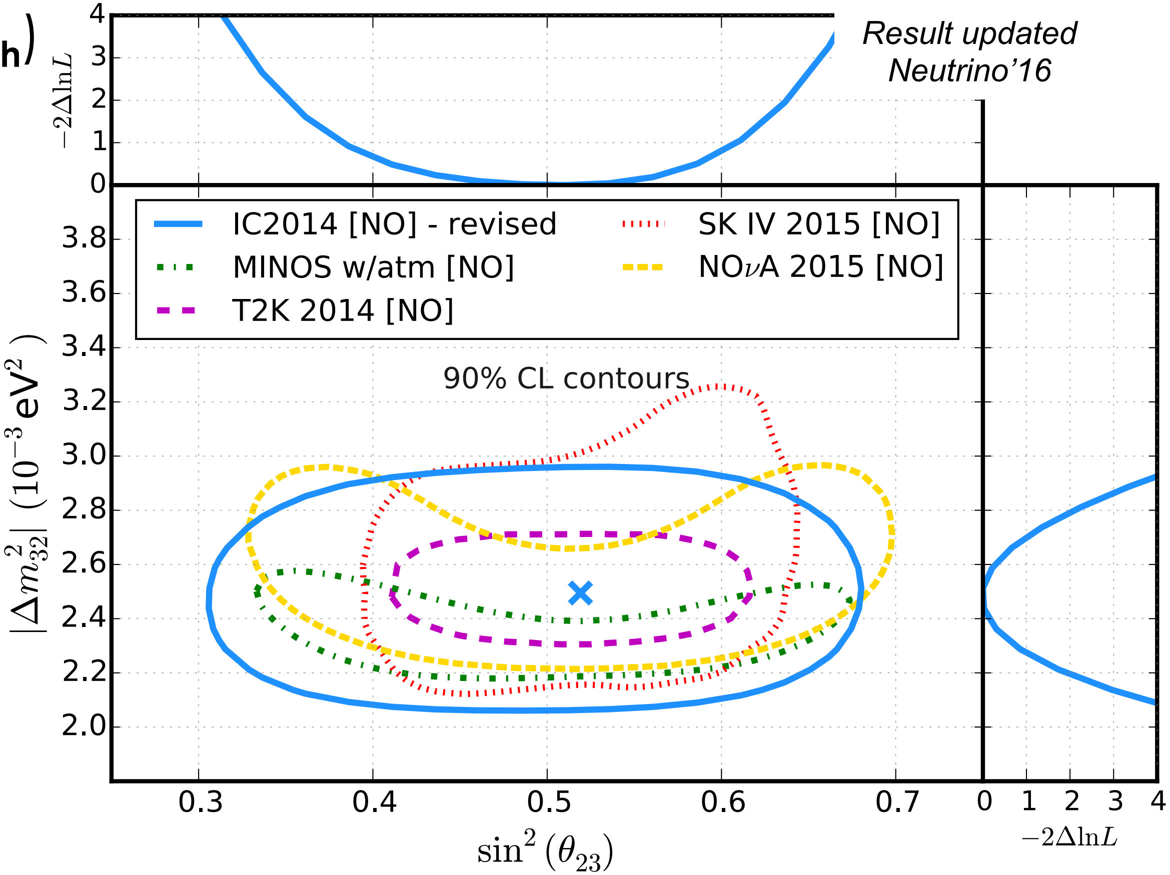


Result updated Neutrino'16

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

Treatment of systematic uncertainties

- 10 nuisance parameters to account for systematic uncertainties
  - Gaussian priors for relevant parameters
- Event-by-event reweighting where possible
  - i.e. cross section, spectral index
- Impact of detector systematics assessed at histogram level
  - Discrete MC sets used to determine change in event rate per bin due to σ in parameter
  - i.e. DOM efficiency, ice properties

Flux modifications

γ – effective spectral index

ν_e normalization

$\Delta\ \nu / \nu$ bar (energy & zenith dependence)

Cross section

M_A (resonant)

M_A (quasi-elastic)

Detector

Refrozen hole ice scattering [cm^{-1}]

DOM efficiency %

Atm. μ

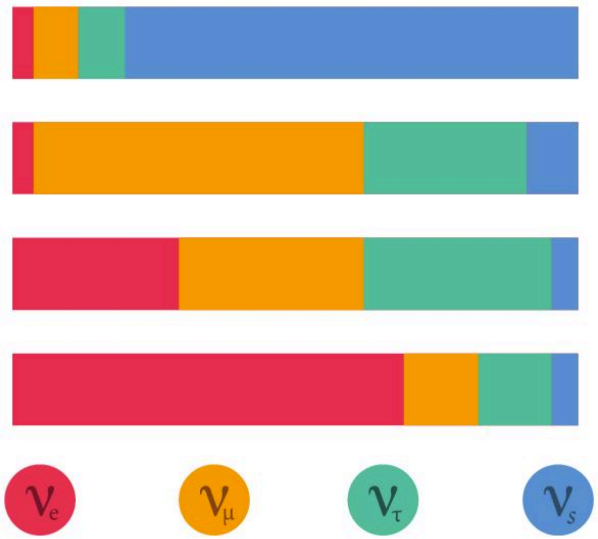
Mixing

θ_{13}

Sterile neutrinos

- Is there a 4th (5th, +…) neutrino mass state?
  - From Z decay width, number of active neutrinos constrained to 3
  - Any additional states can not couple to weak interaction → ***sterile***
  - Massive sterile neutrinos could oscillate with active neutrinos
- Tension between several experiments *could* be explained by ν_s('s)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix} \overset{PMNS}{\boxed{\begin{matrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{matrix}}} & \begin{matrix}U_{e4}\\ U_{\mu4}\\ U_{\tau4}\end{matrix}\\ \begin{matrix}U_{s1} & U_{s2} & U_{s3}\end{matrix} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$



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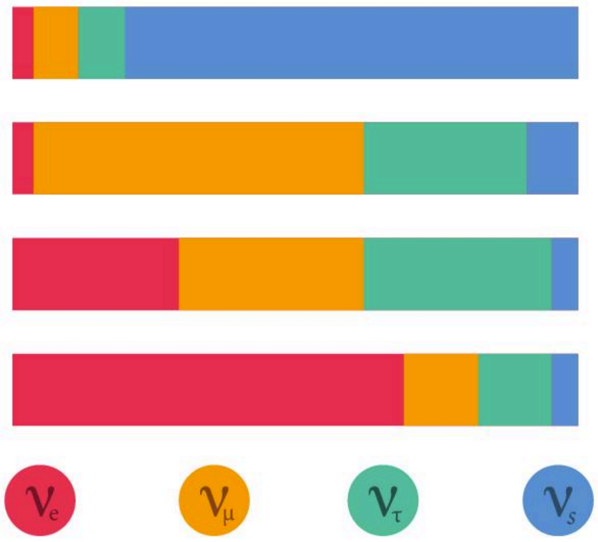
PMNS

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left(\begin{array}{|ccc|c} \cline{1-3} U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}}\\ \cline{1-3} \multicolumn{1}{c}{U_{s1}} & U_{s2} & U_{s3} & U_{s4}\end{array}\right)\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

$$\boxed{\begin{aligned} \left|U_{\mu 4}\right|^2 &= \sin^2\theta_{24} \\ \left|U_{\tau 4}\right|^2 &= \sin^2\theta_{34}\cdot\cos^2\theta_{24} \end{aligned}}$$

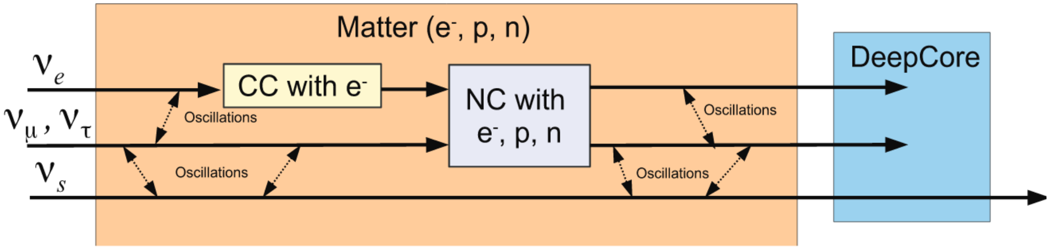


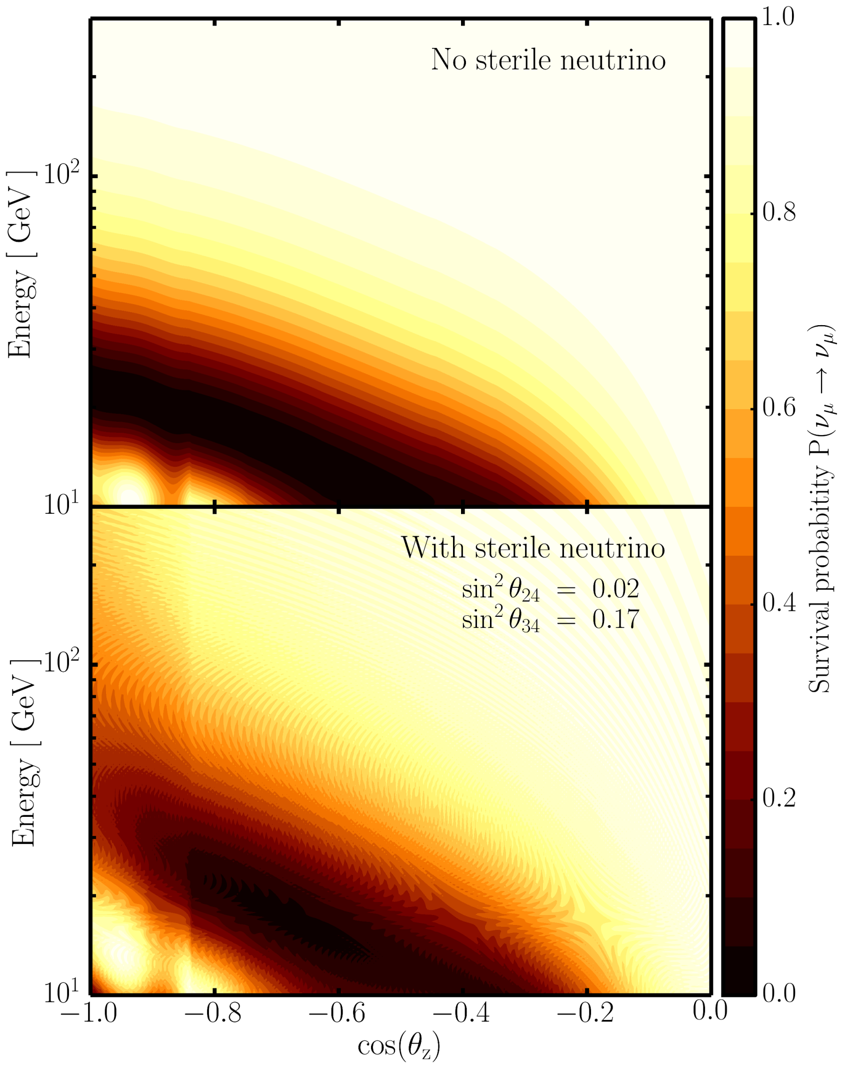
Sterile neutrinos at low energies

- Below 100 GeV, sterile neutrino
  - Shifts oscillation minimum
  - Changes amplitude

- Effects are proportional to matter density

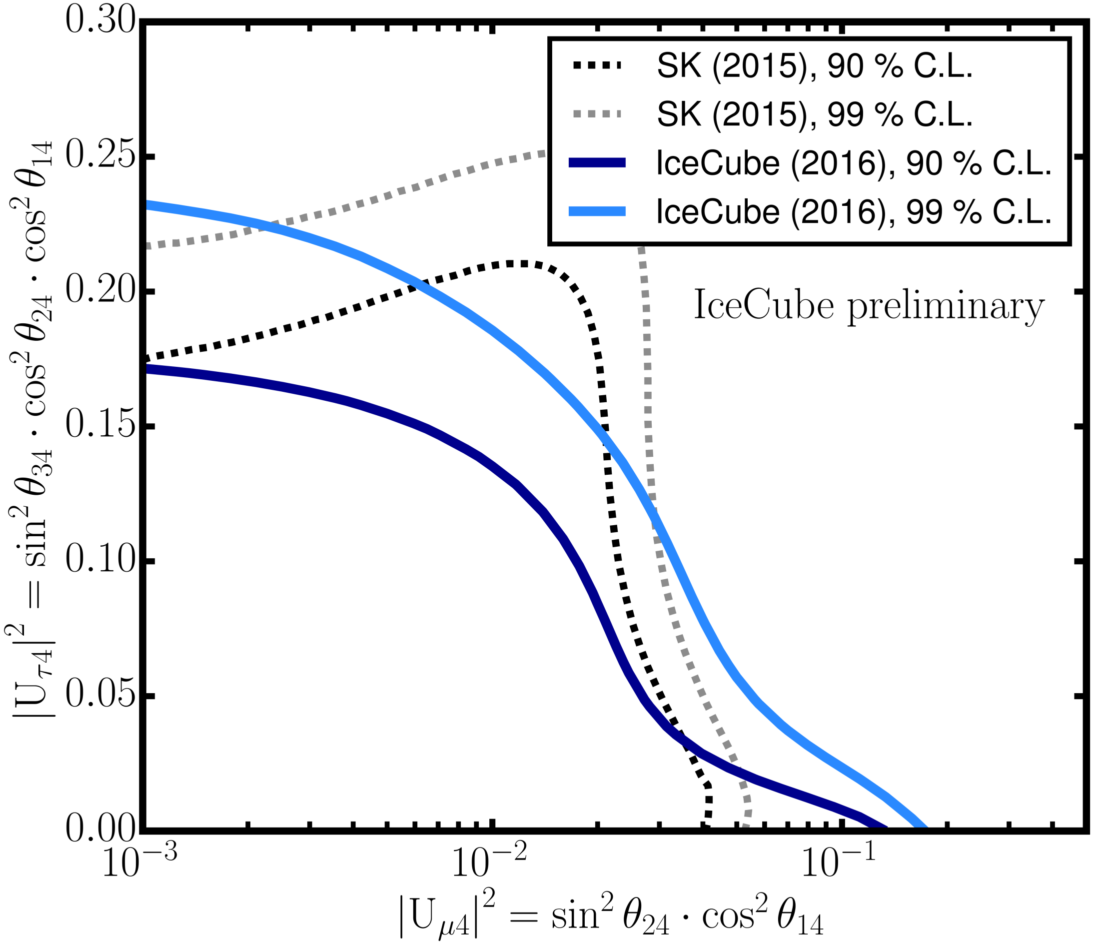
- Independent of sterile neutrino mass (for Δm^2_{41}> ~0.3 eV^2)





Sterile neutrinos at low energies

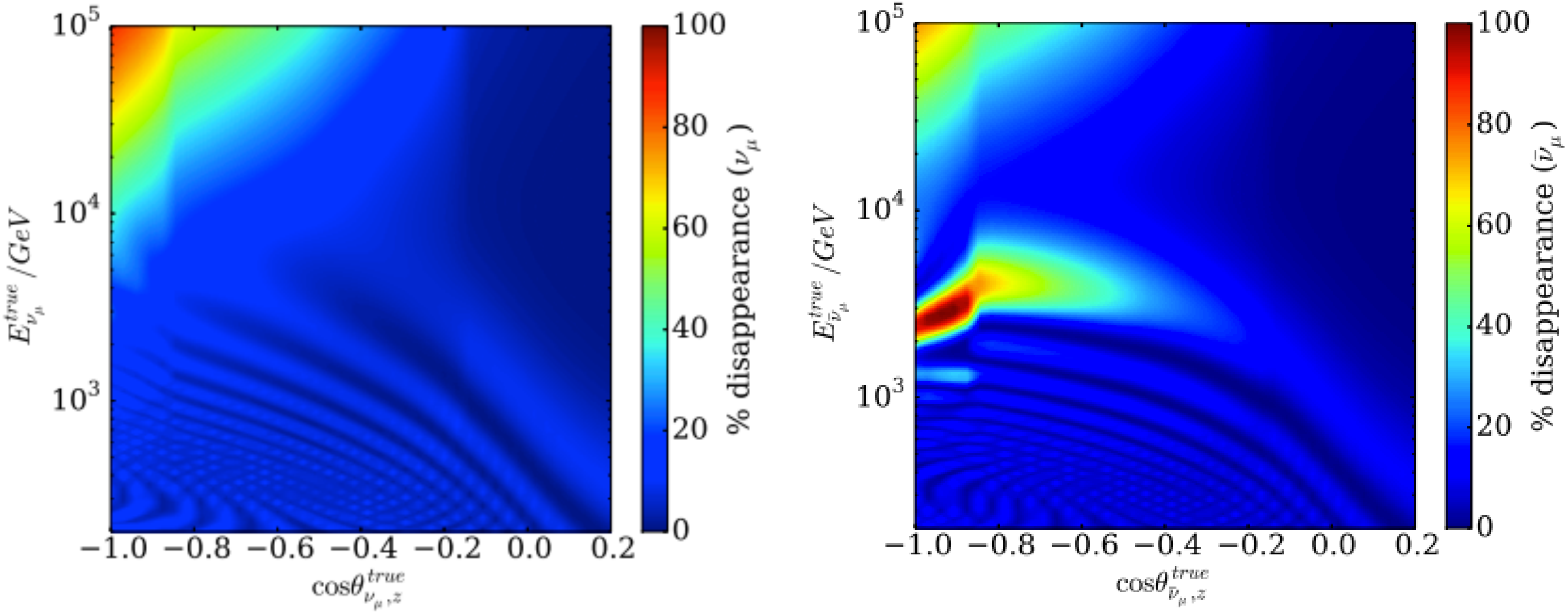
- Same sample used for ν_μ disappearance analysis
    - Track-like events, 3 years
- **No evidence for sterile neutrino**
- Strongest constraint on $|U_{\tau 4}|^2$
- *Publication coming soon!*



Sterile neutrinos at high energies

- Above ~100 GeV standard oscillation λ > Earth diameter
- Existence of sterile neutrino produces MSW-like resonance for $\overline{\nu}_{\mu}$
- Resonance energy $\propto \Delta m^2_{41}$, sensitive to θ_{24}

3+1 model oscillograms*



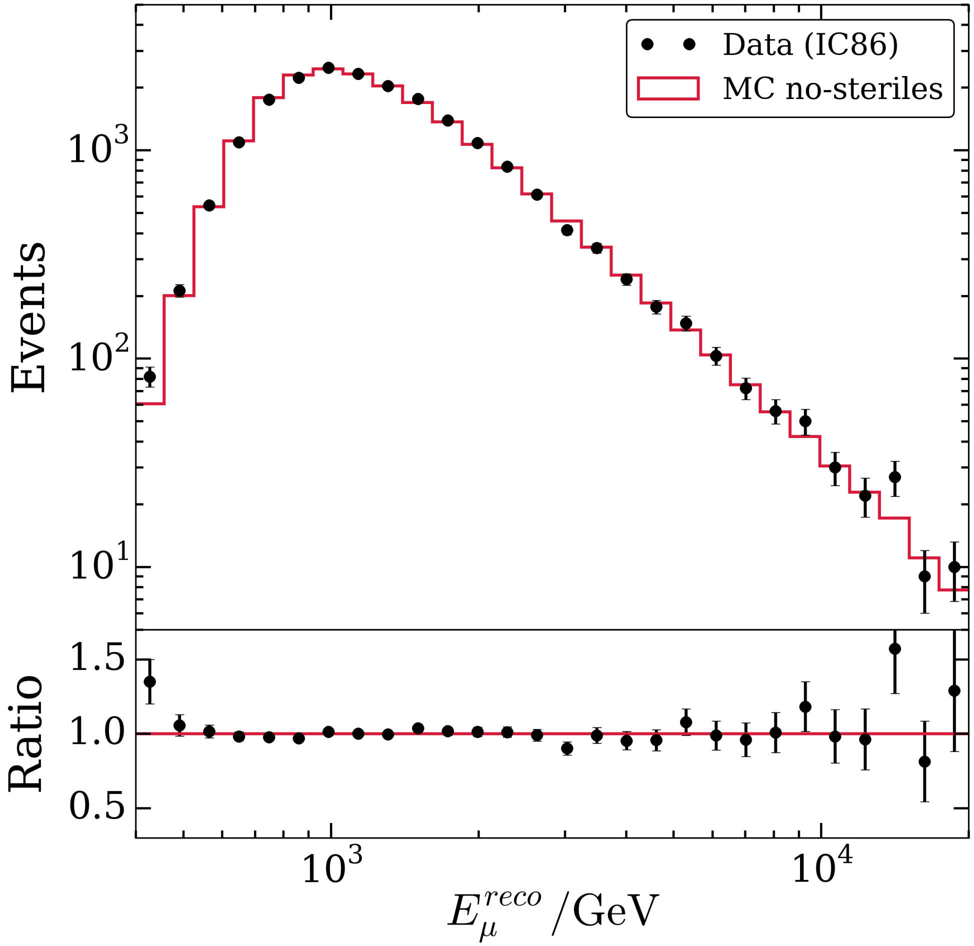
*global best fit point assumed

Sterile neutrinos at high energies

- 1 year of track-like events
  - 99.9% atm. ν_μ

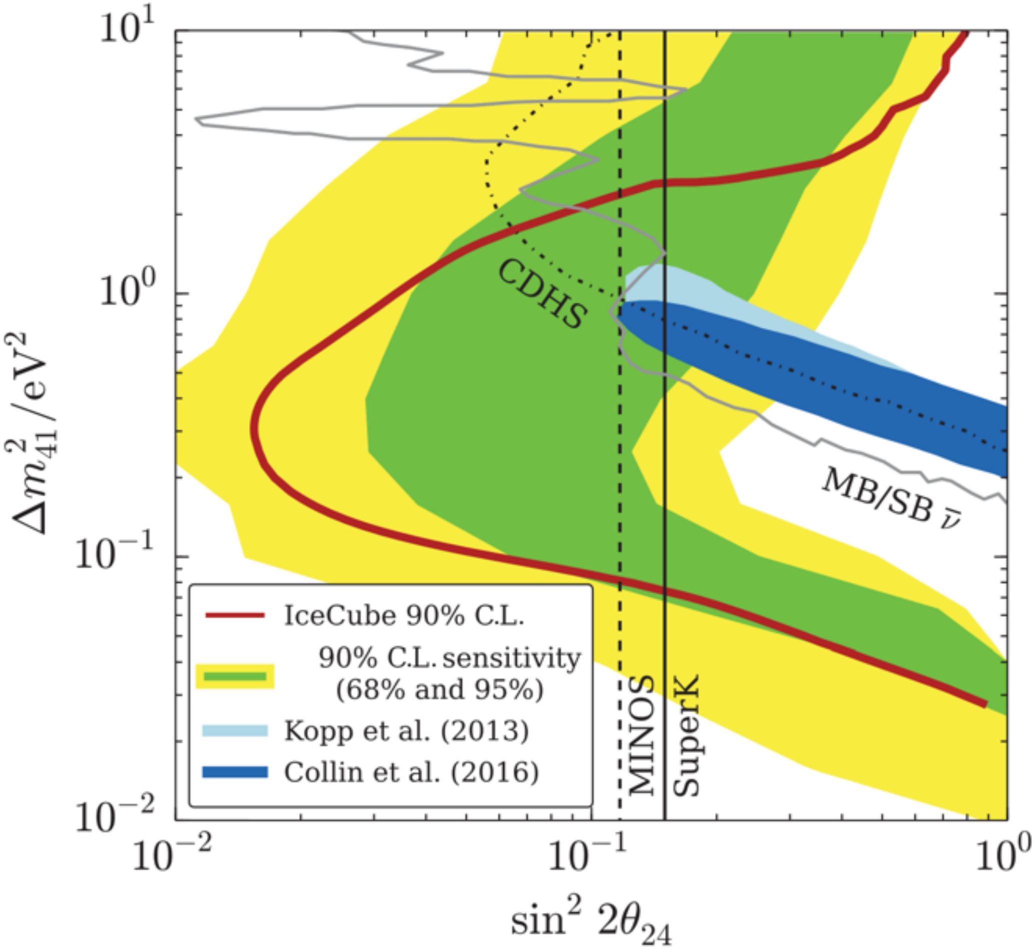
- 320 GeV – 20 TeV, up-going events

- **No evidence for sterile neutrino**



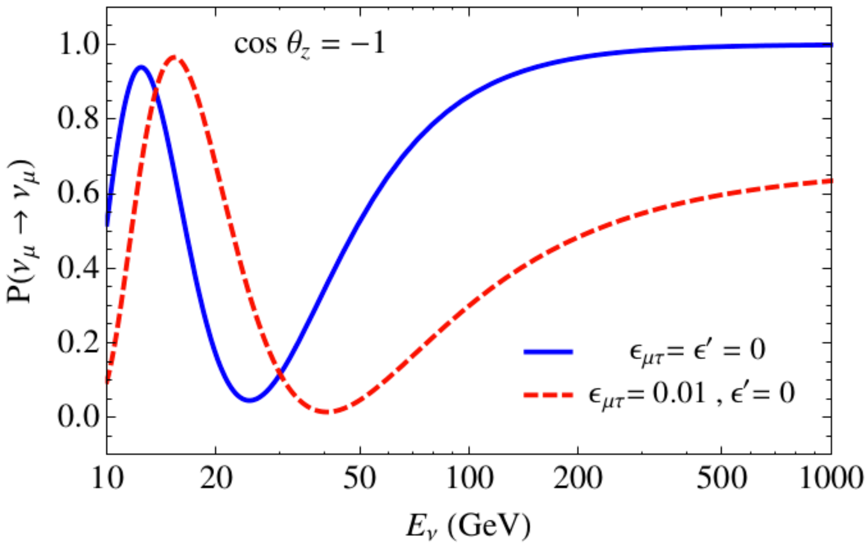
Sterile neutrinos at high energies

- 1 year of track-like events
  - 99.9% atm. ν_μ
- 320 GeV – 20 TeV, up-going events
- **No evidence for sterile neutrino**
- ***Strong constraints*** on sterile mixing
- *Analysis of more years ongoing!*



Non-standard interactions

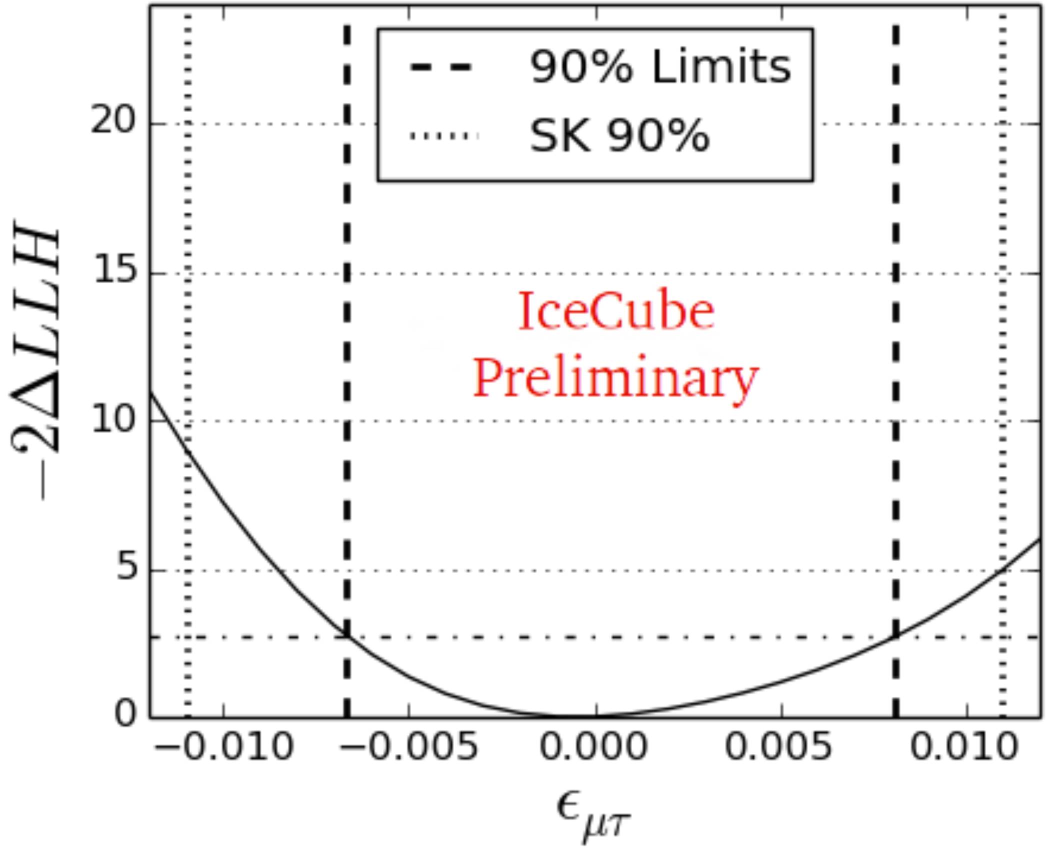
- New vector bosons (e.g. W', Z') could mediate weak interaction



- Impacts effective potential for neutrinos crossing the earth
  - Matter effects

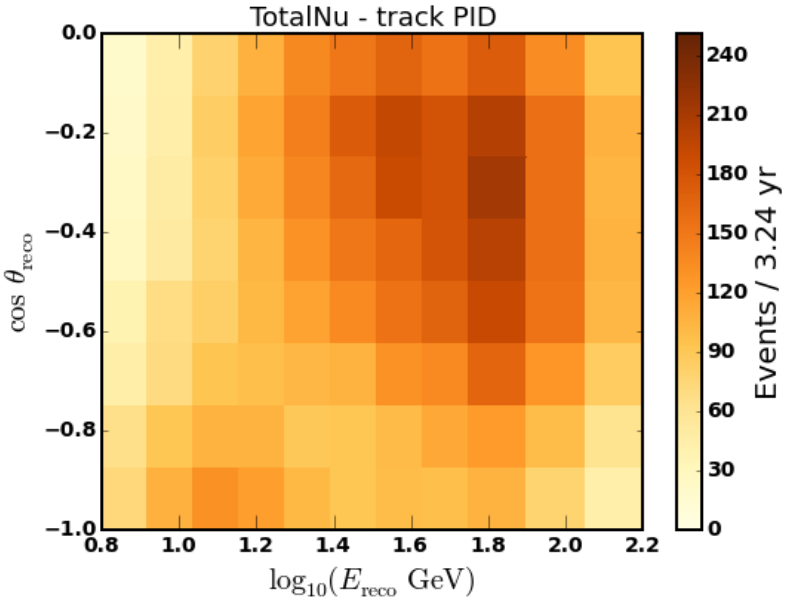
Non-standard interactions

- Using 3-year low energy up-going track sample
- Data consistent with null-hypothesis
  - Only standard interactions
- Exclusion contour derived for non-standard coupling $\varepsilon_{\mu\tau}$



What’s next for DeepCore

- Improvements to the event selection and reconstruction can lead to higher precision measurements of oscillation parameters



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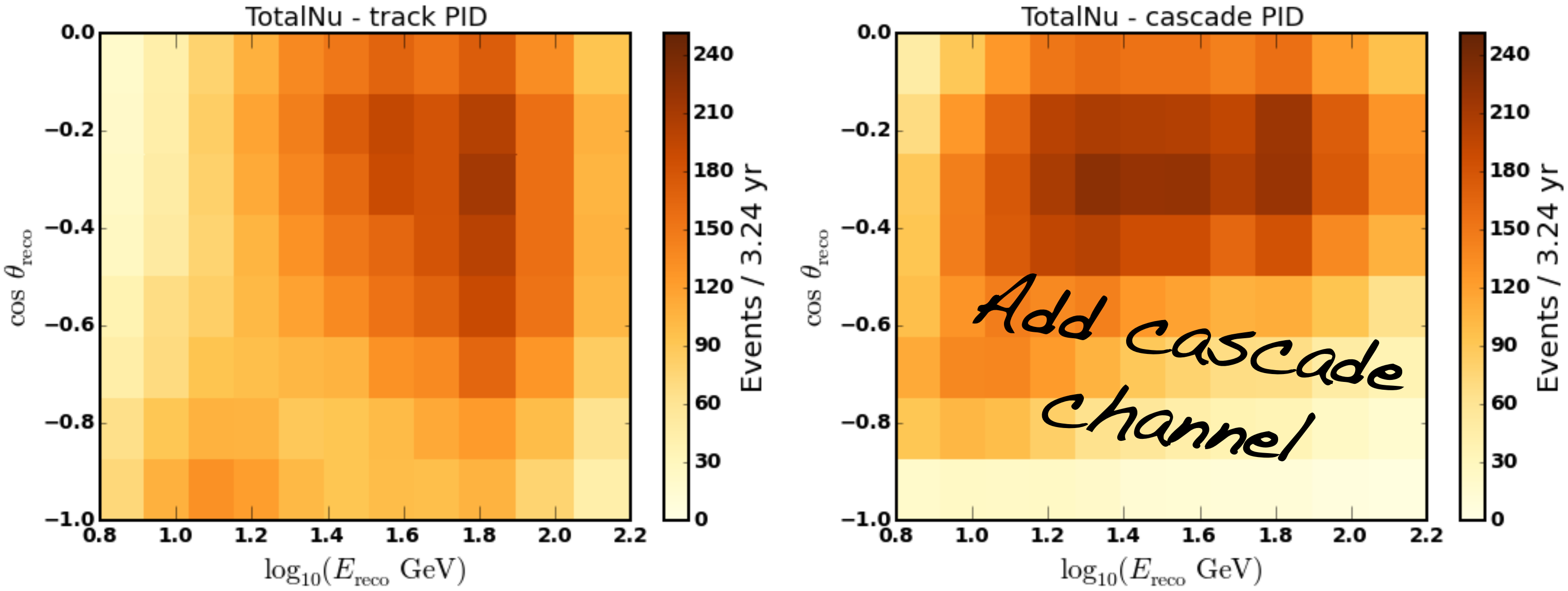

Add cascade channel

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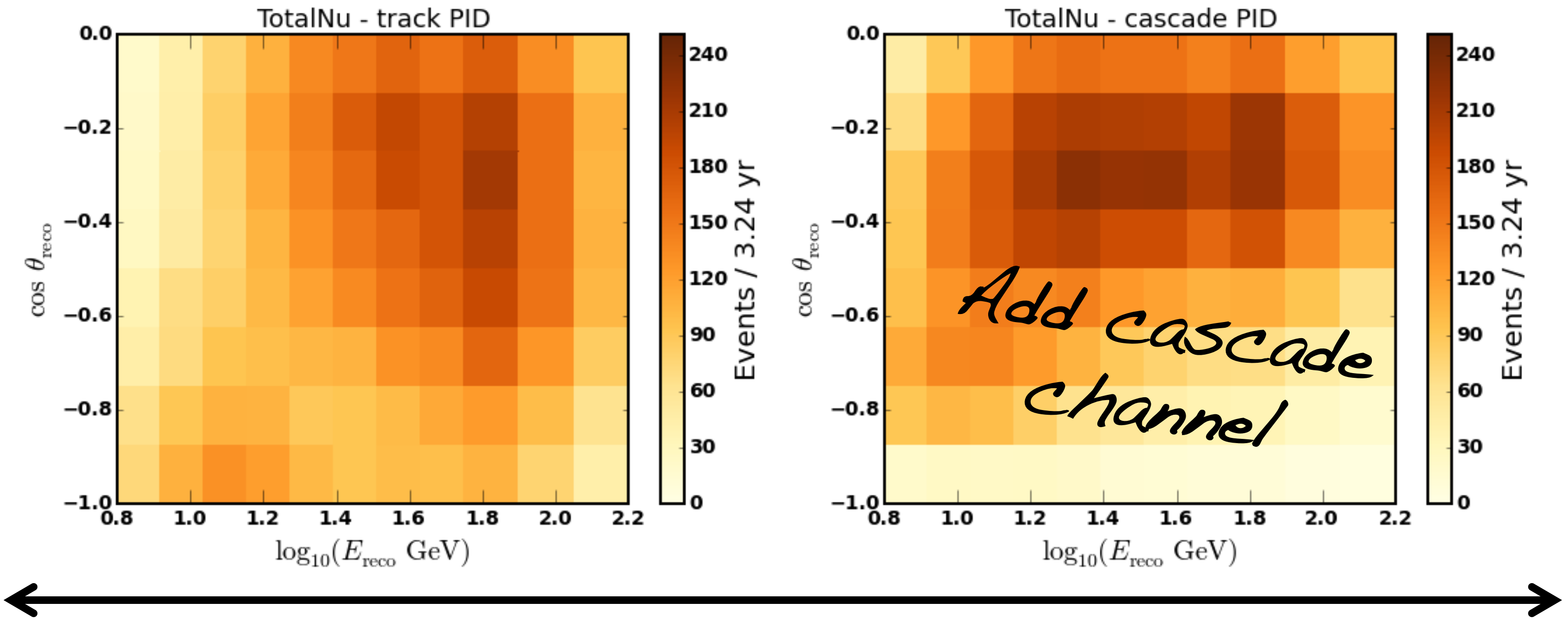

Add cascade channel

Expand energy range

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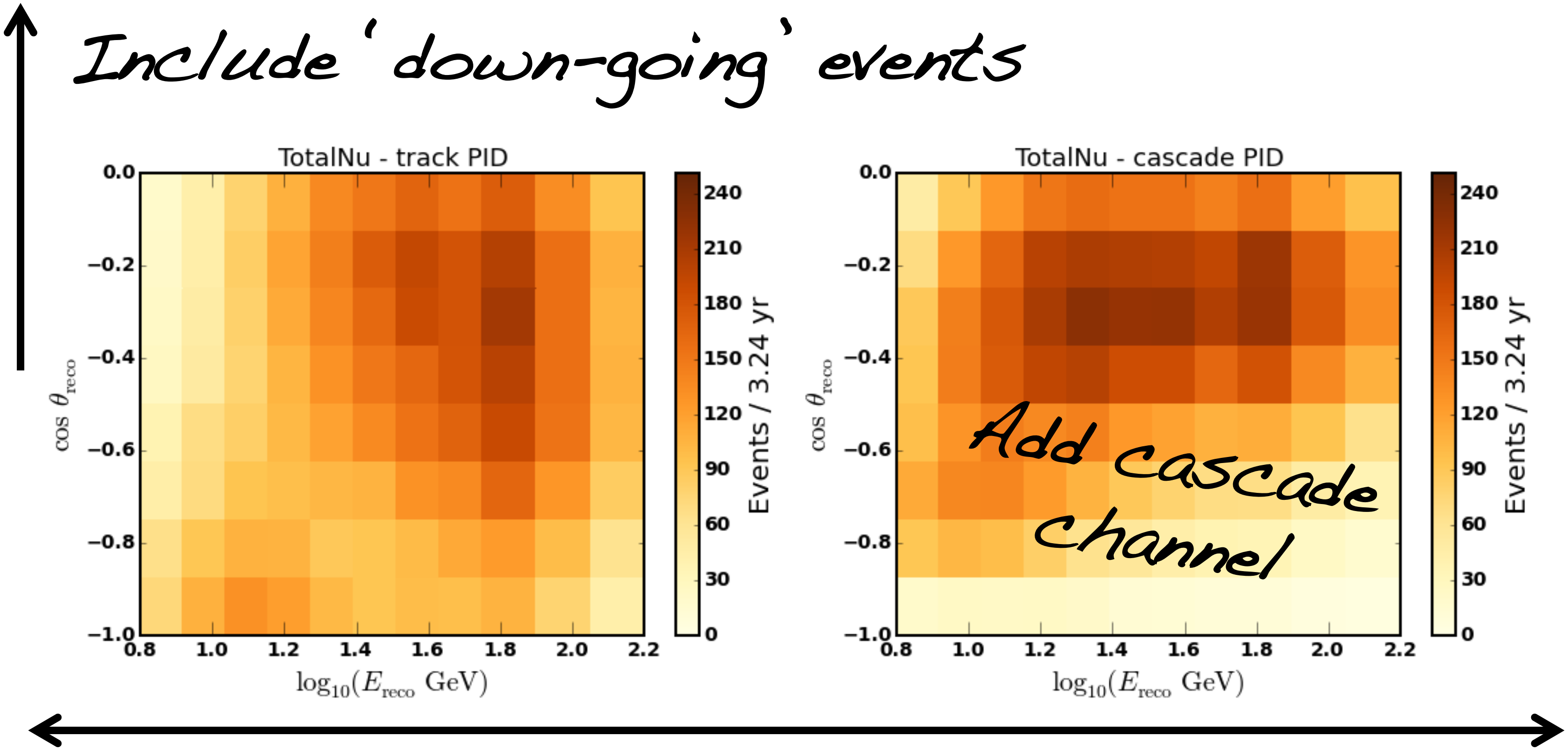


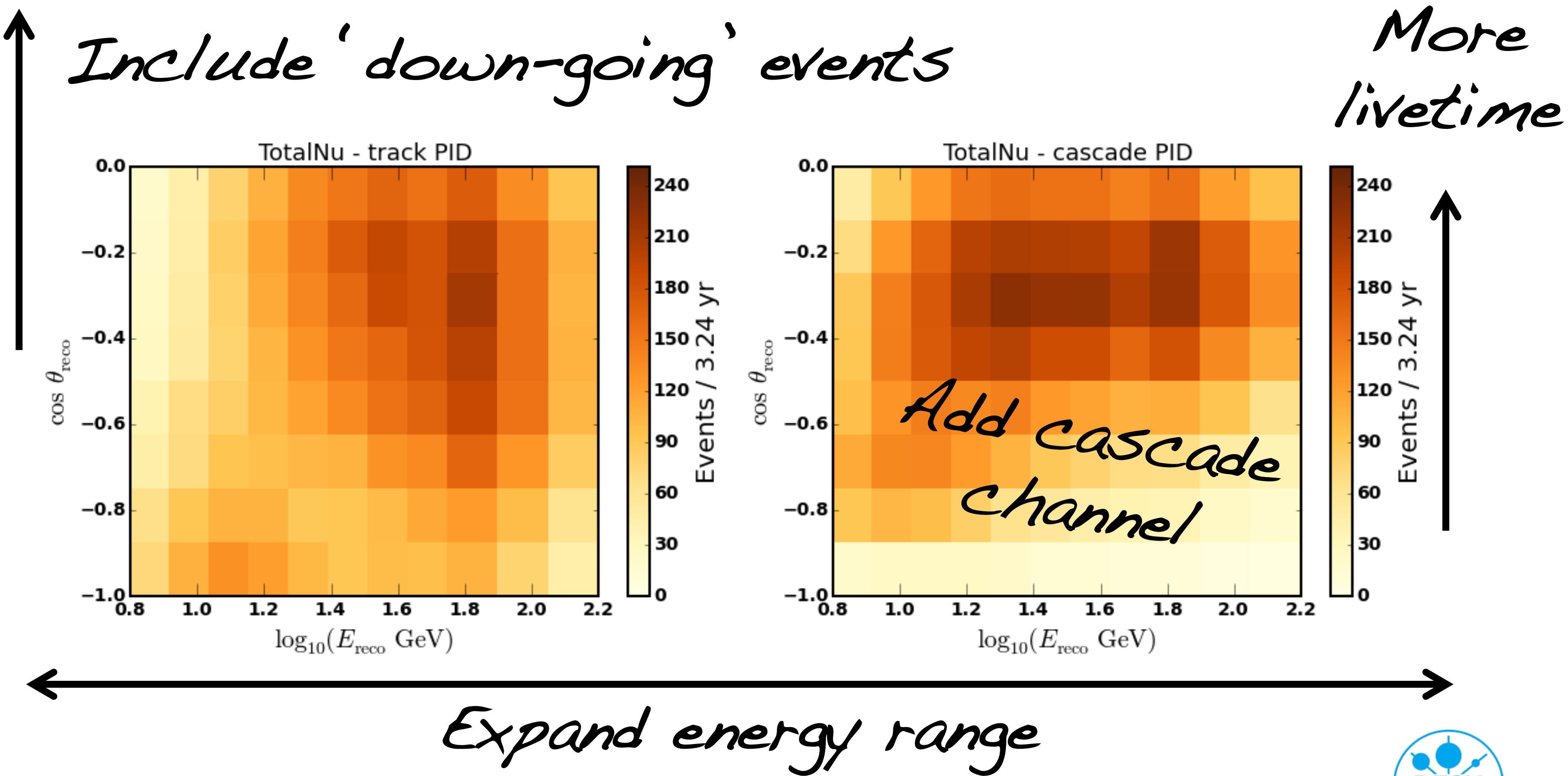
Include 'down-going' events

Add cascade channel

Expand energy range

What’s next for DeepCore

- Improvements to the event selection and reconstruction can lead to higher precision measurements of oscillation parameters



Include ‘down-going’ events

More livetime

Add cascade channel

Expand energy range

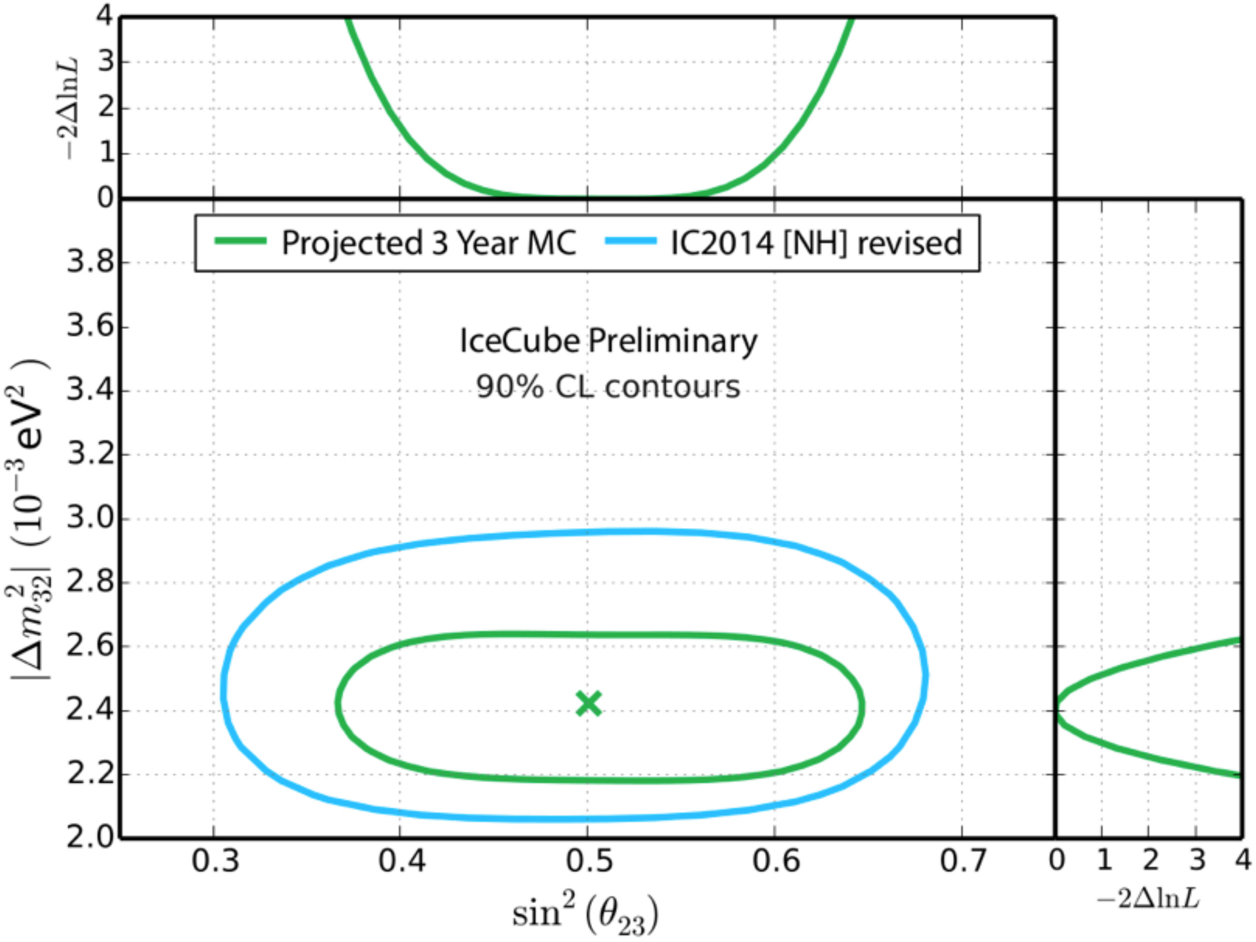
What's next for DeepCore

- New reconstruction includes scattered photons
  - More complicated likelihood space to fit track + cascade hypothesis
- This leads to a few complications
  - More time consuming reconstruction
  - Need for re-assessment of systematic uncertainties & their impact
  - Larger atmospheric μ background
  - Increased noise due to lower E threshold

- Also comes with increased sensitivity to
  - Mixing parameters θ_{23} and Δm^2_{32}
  - ν_τ appearance
  - Sterile neutrinos

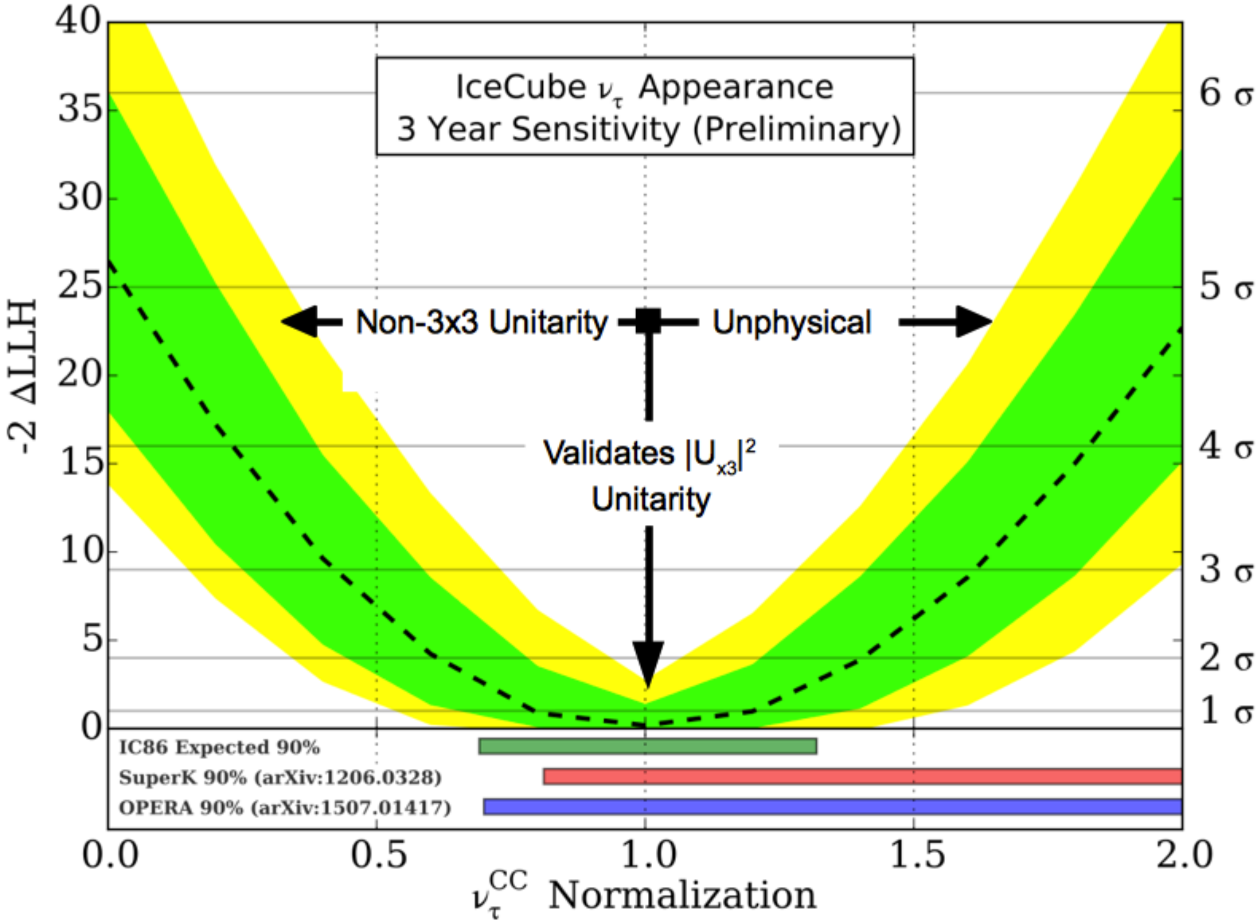
What's next for DeepCore

- Expected improvement in θ_{23} and Δm^2_{32} with new reconstruction
- Still using only 3 years of data



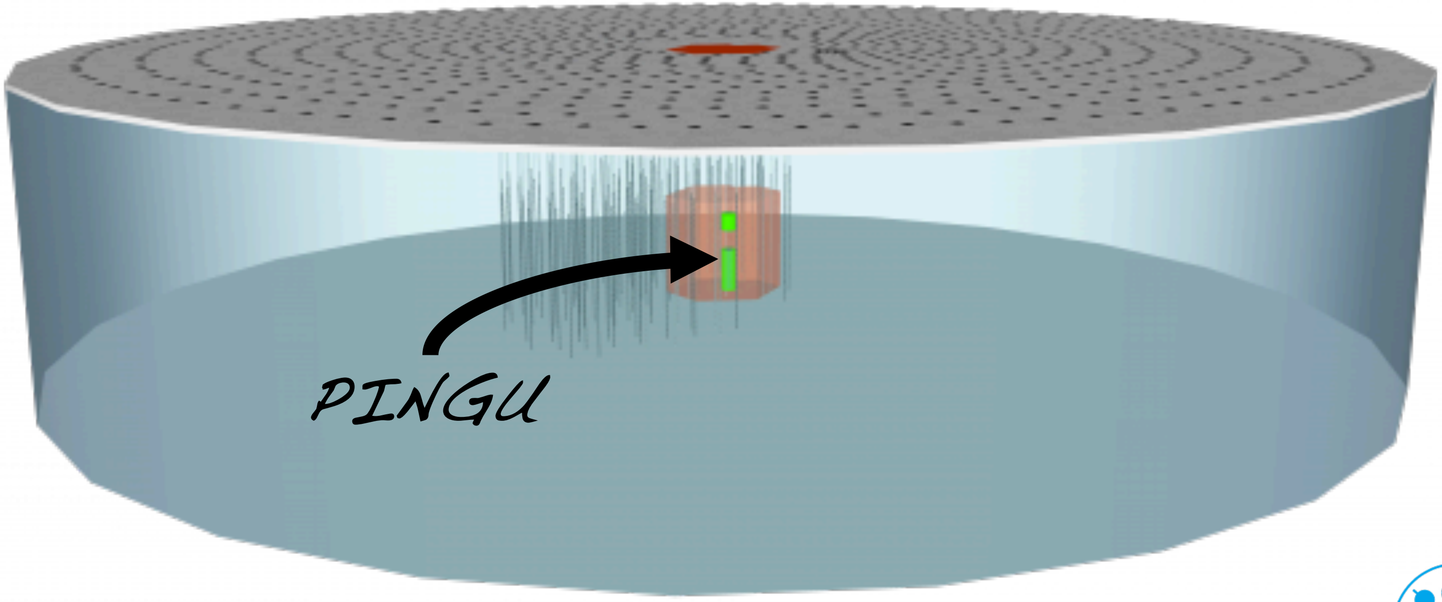
What’s next for DeepCore

- Lower energy threshold and addition of cascade channel improve sensitivity to ν_{τ}



Next installment – IceCube Gen2

- Extension of both low and high energy arrays
- Low E extension a.k.a. **P**recision **I**ceCube **N**ext **G**eneration **U**pgrade
  - Precise measurement of θ_{23}, Δm^2_{32}
  - Neutrino mass ordering
  - ν_τ normalization
  - New Physics



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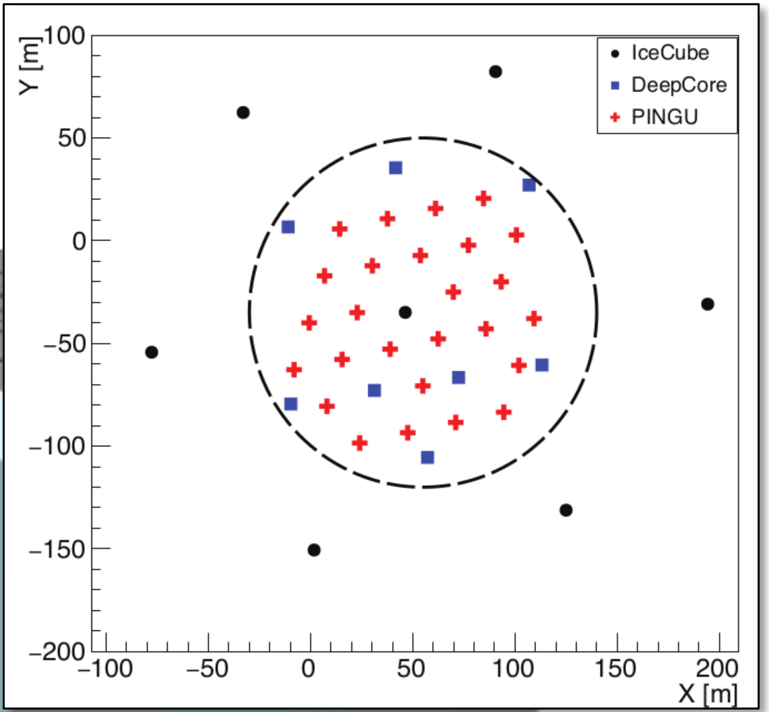
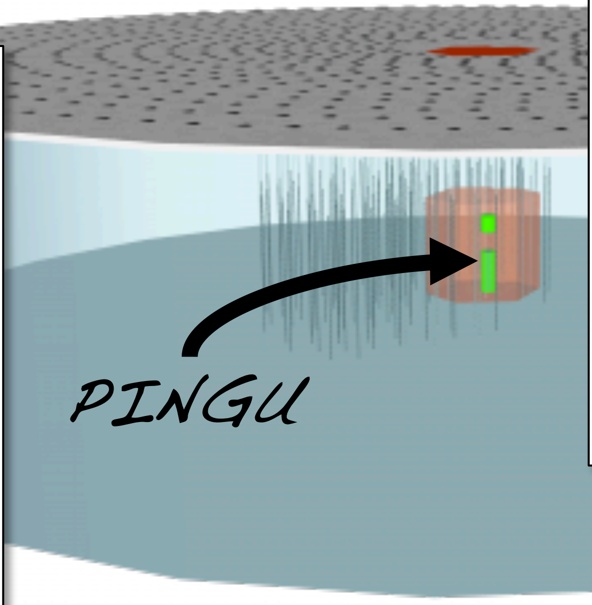


26 strings

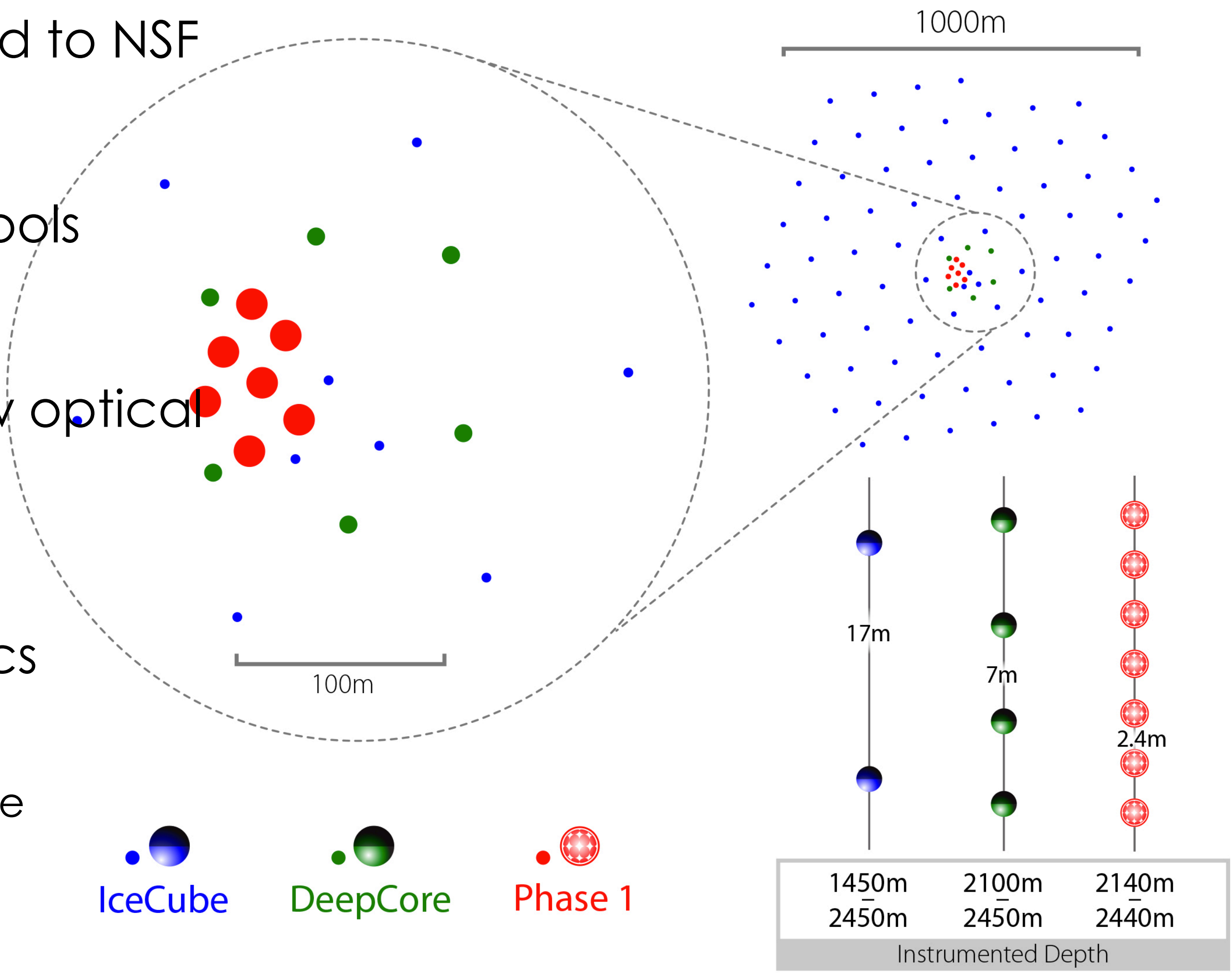
Dom Spacing:
20 m lateral
2 m vertical

E threshold:
-> few GeV



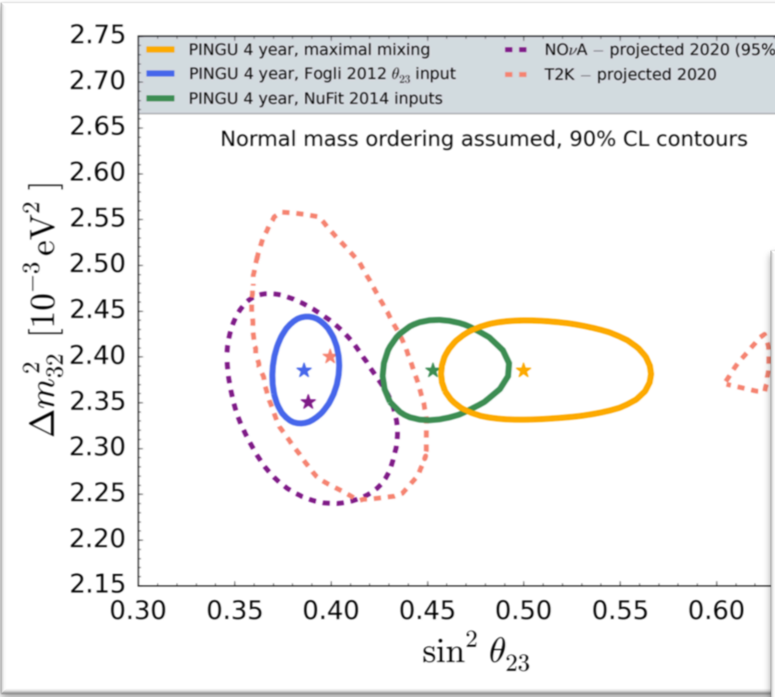
IceCube Gen2 – Phase 1

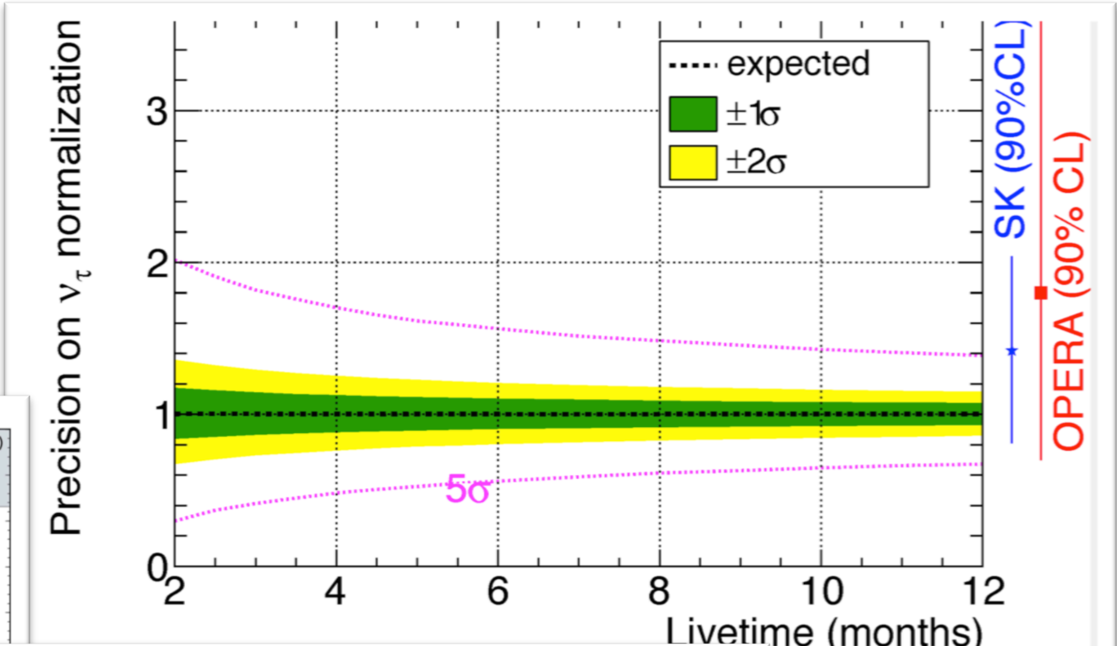
- Proposal submitted to NSF
- New calibration tools
- *in situ* R&D for new optical modules
- Low energy physics measurements
  - Yearly rate increase by factor of ~3

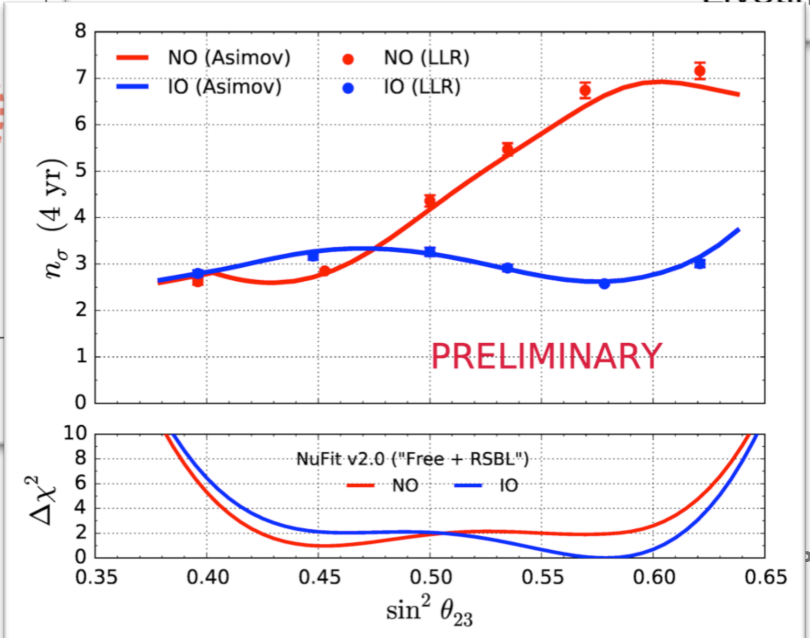


PINGU physics potential

- Wide physics potential
  - Multi-purpose detector
- High precision







Summary

- IceCube & DeepCore have become powerful tools for studying fundamental properties of neutrinos
- Measurement of neutrino oscillation parameters θ_{23} and Δm^2_{32} comparable to dedicated experiments
- Searches for *new physics* have turned up null
  - Tight constraints on 3+1 (1+3) sterile neutrino phase space
  - Limits on non-standard interactions
  - + *Lots of Dark Matter/SUSY searches not discussed here*
- Many more years of data to analyze and improved reconstruction tools available
- Already looking towards the next level of precision with IceCube-Gen2

Want more IceCube?

https://icecube.wisc.edu/pubs

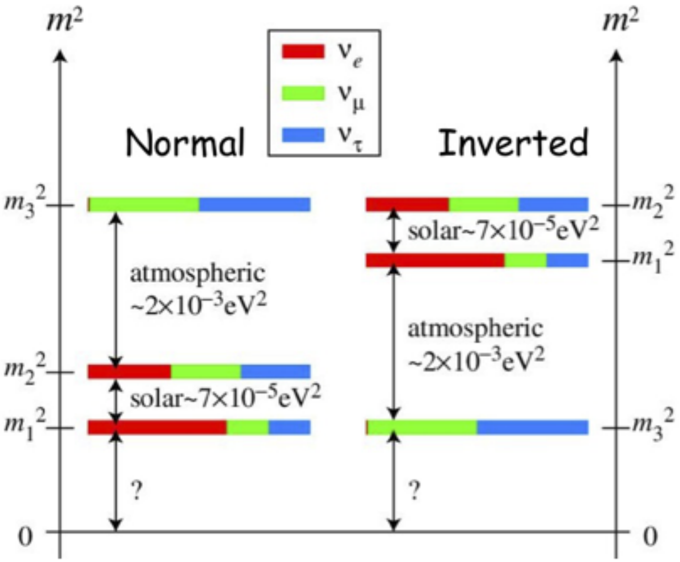
Looking forward to a *bright* future…

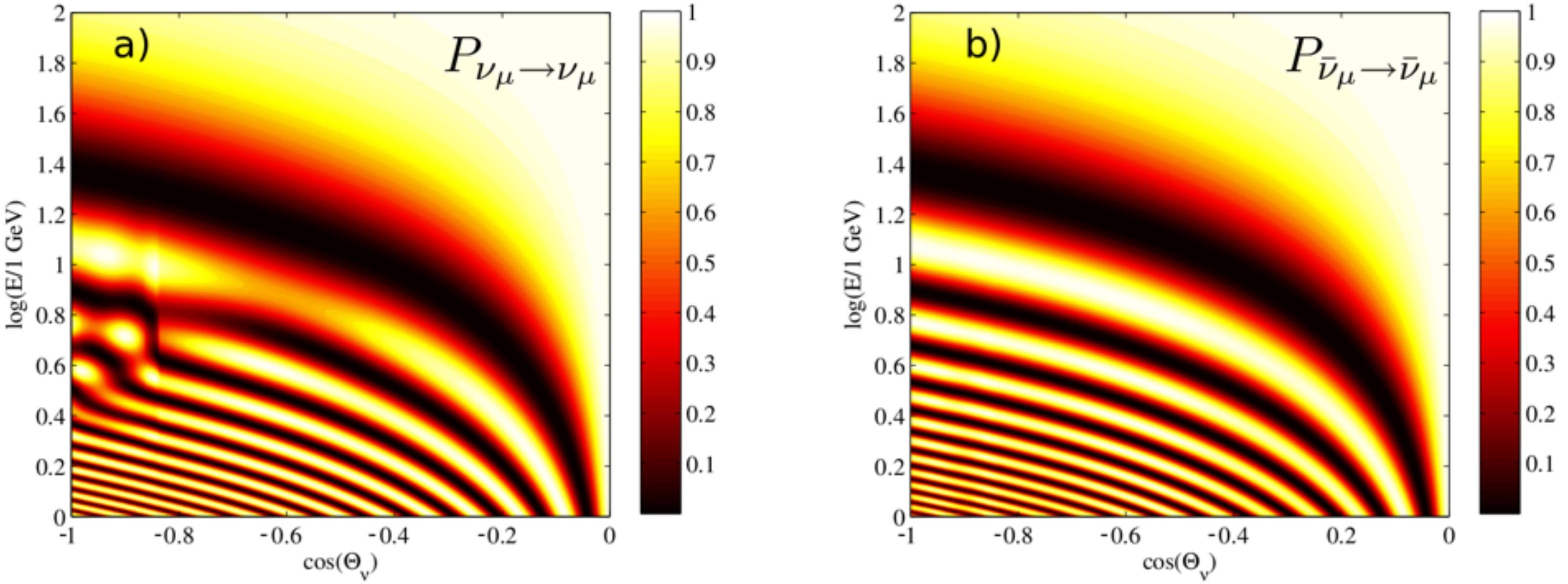
Thank you, any questions?

Backup

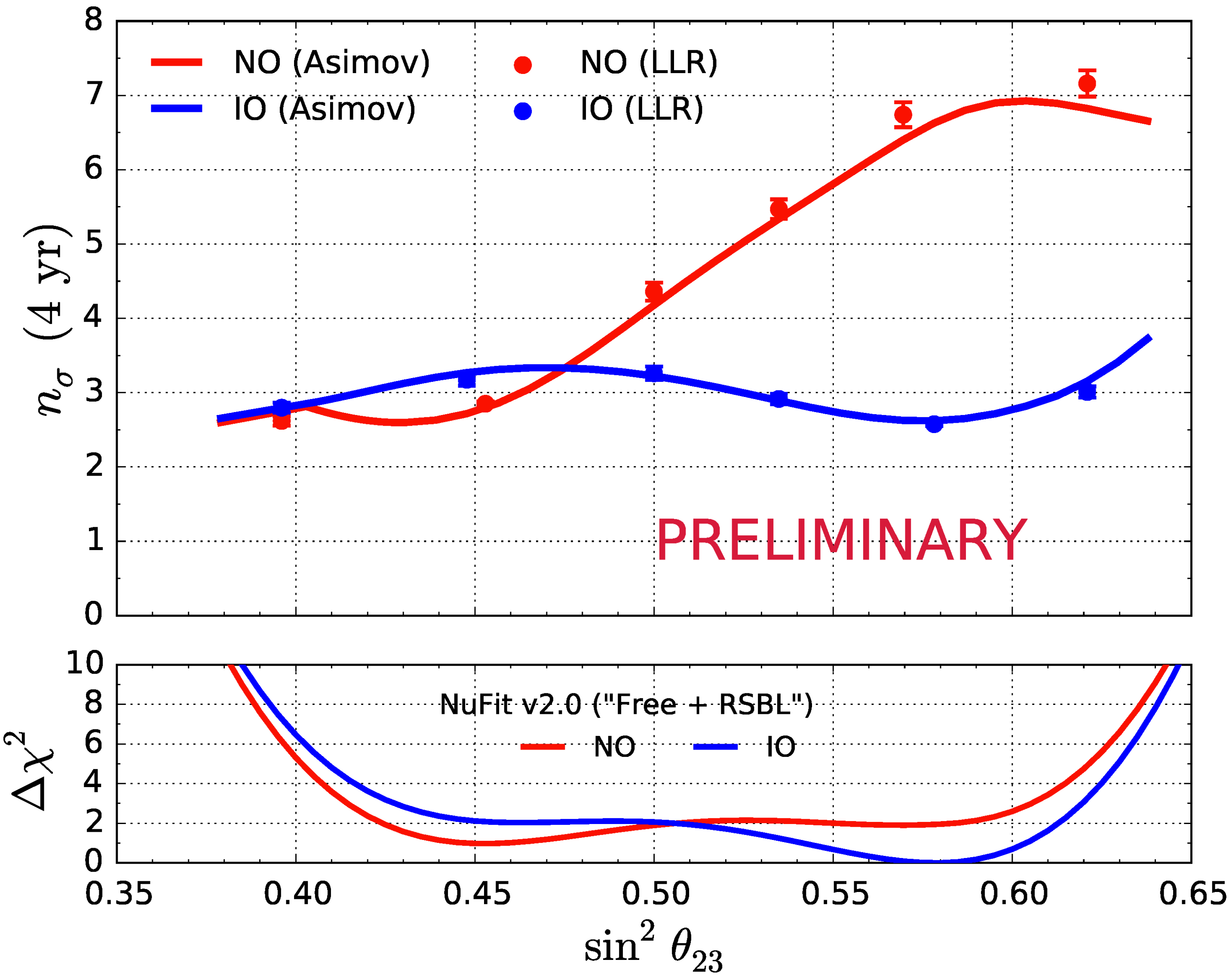
PINGU – neutrino mass ordering

- Ordering of mass states 3 and 1(2) not known
- Matter effects induce resonance for
    - Neutrinos for normal ordering
    - Anti-nu's for inverted ordering
- Difference in flux & cross section

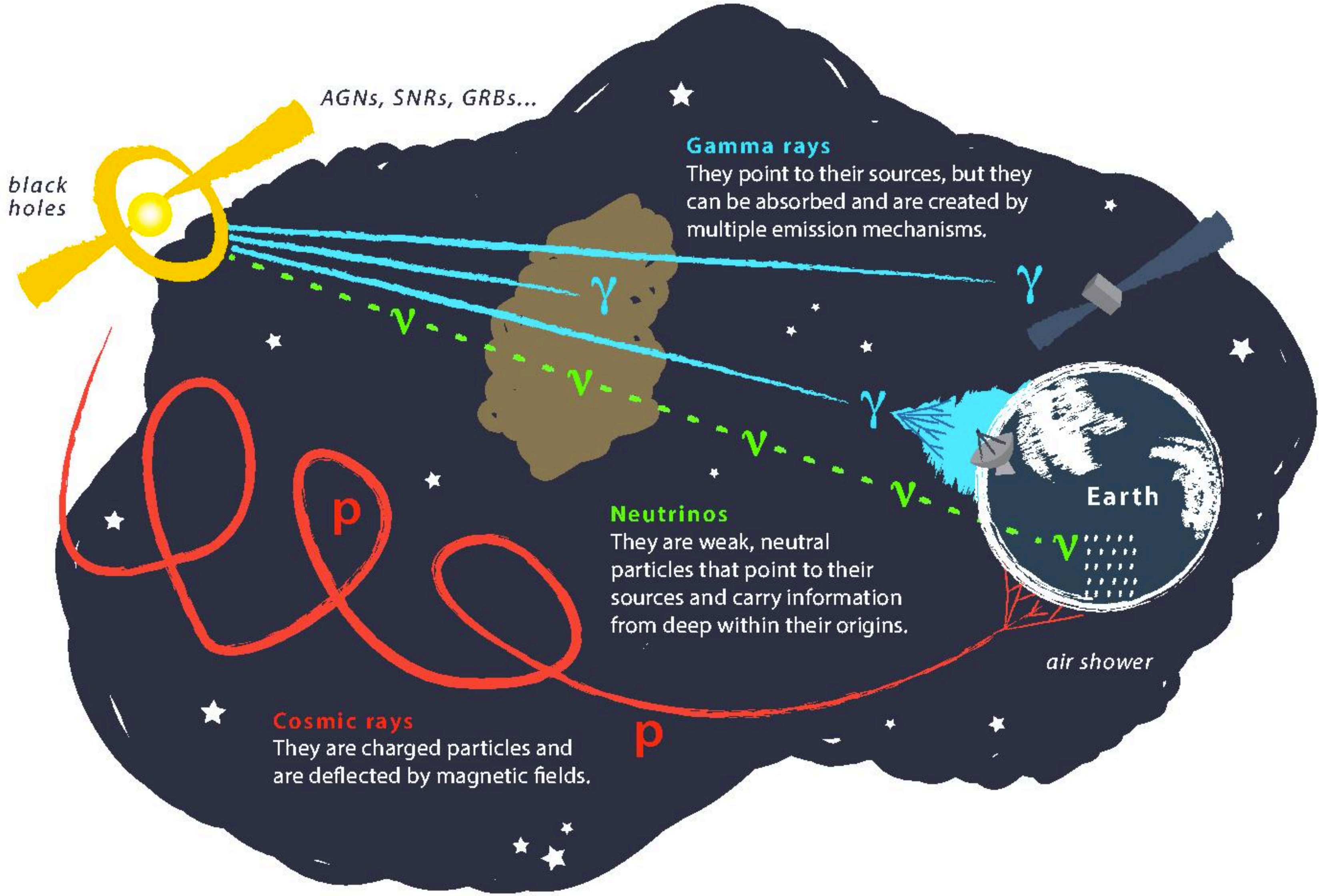




PINGU – neutrino mass ordering



The search for cosmic ray sources

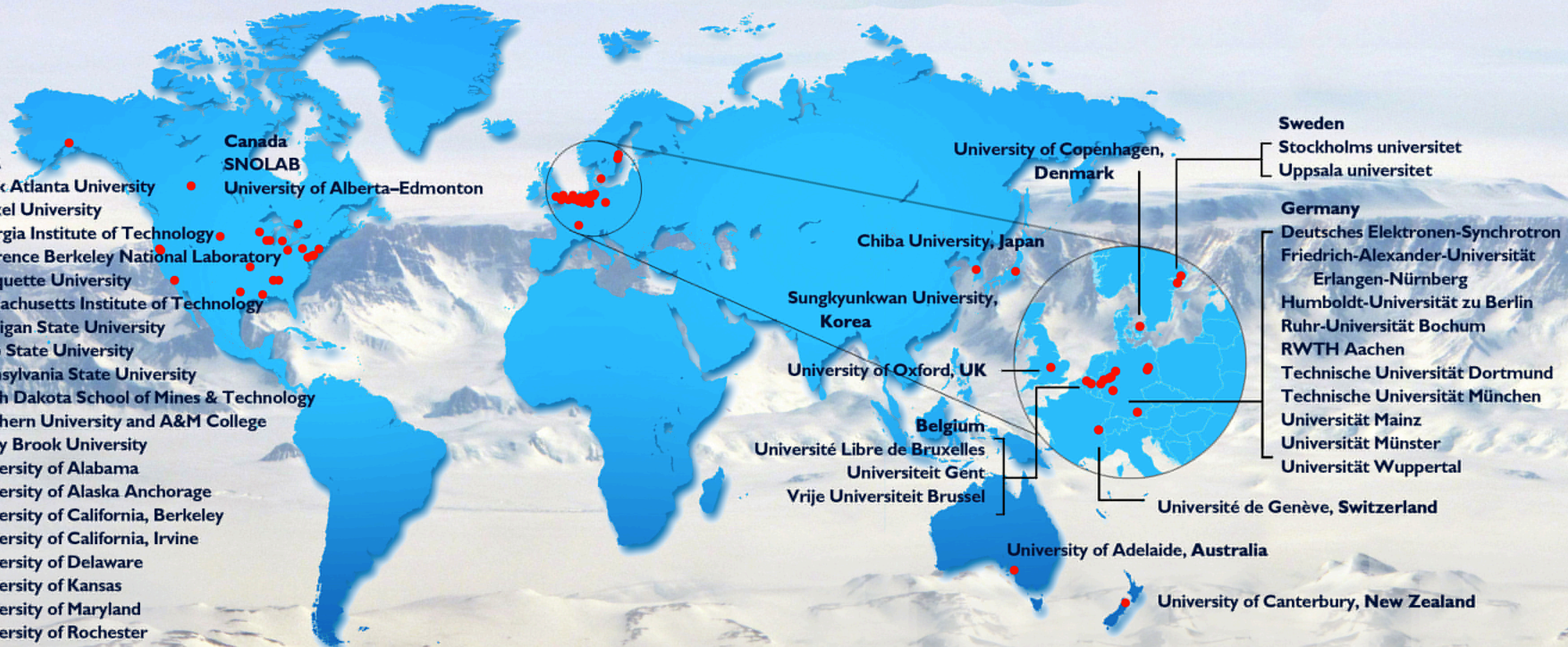


Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays
They are charged particles and are deflected by magnetic fields.

IceCube – an international endeavor



USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
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University of Delaware
University of Kansas
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University of Texas at Arlington
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Universität Münster
Universität Wuppertal

Université de Genève, Switzerland

University of Adelaide, Australia

University of Canterbury, New Zealand

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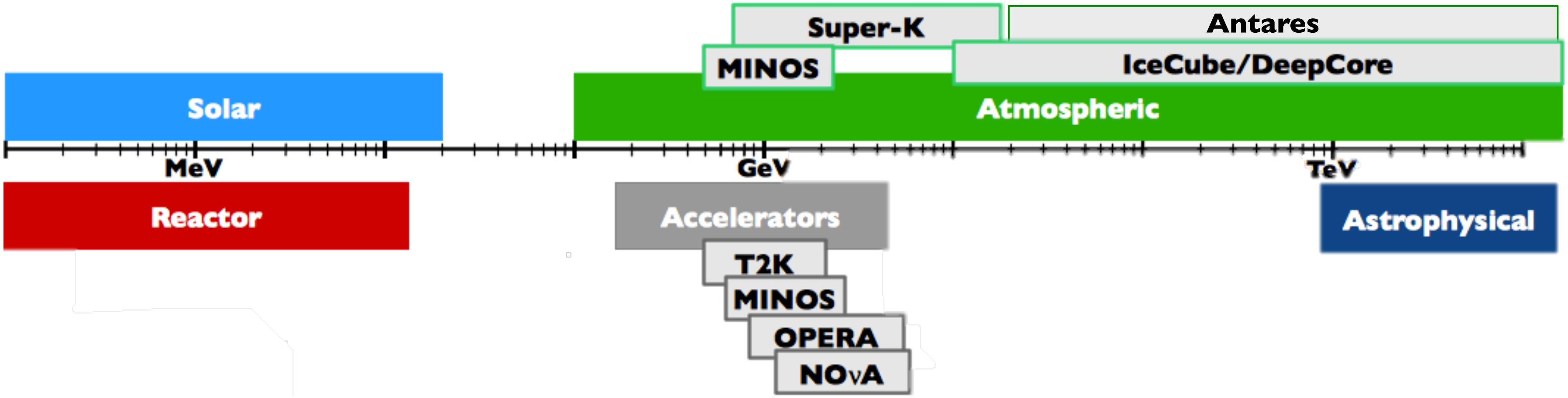
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg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

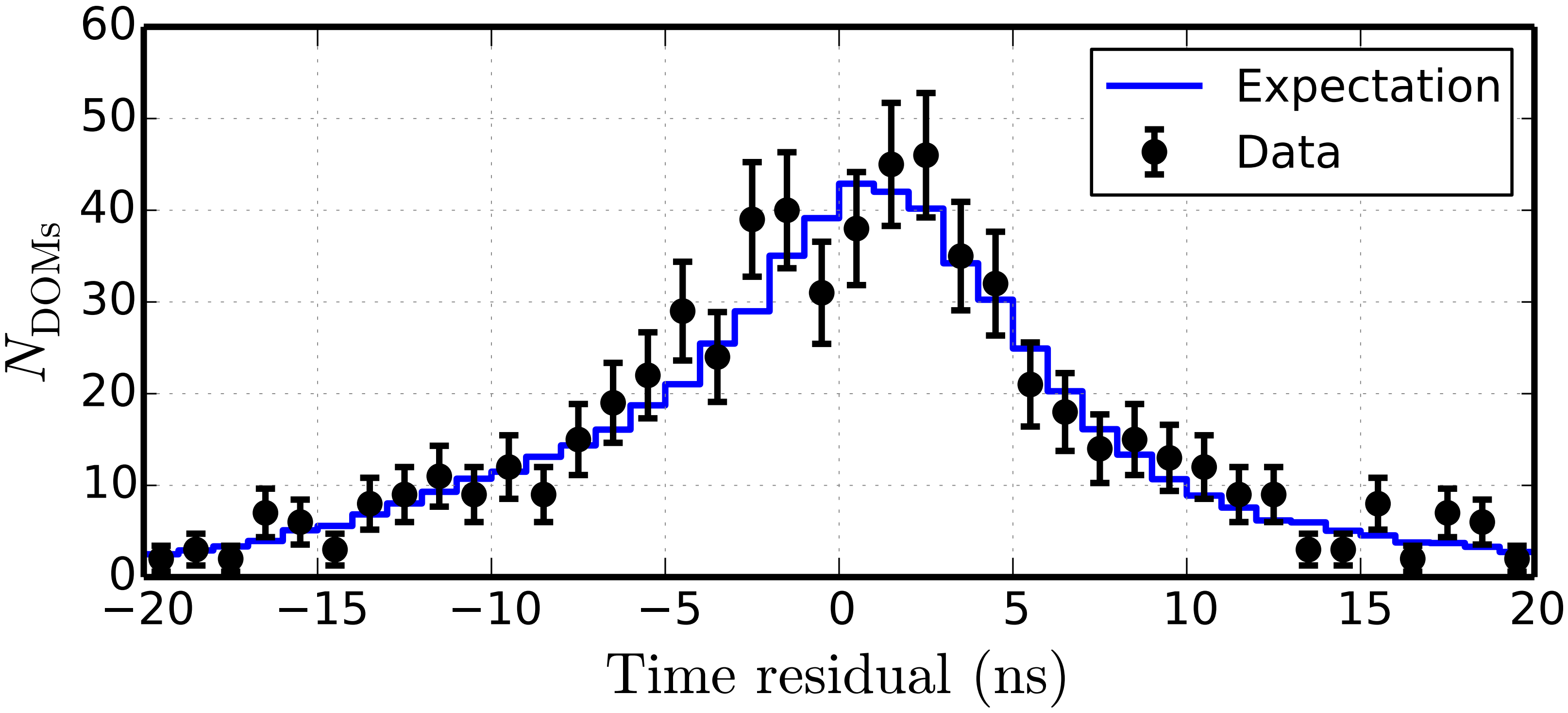
IceCube DeepCore in context

- Incomplete list of neutrino oscillation experiments

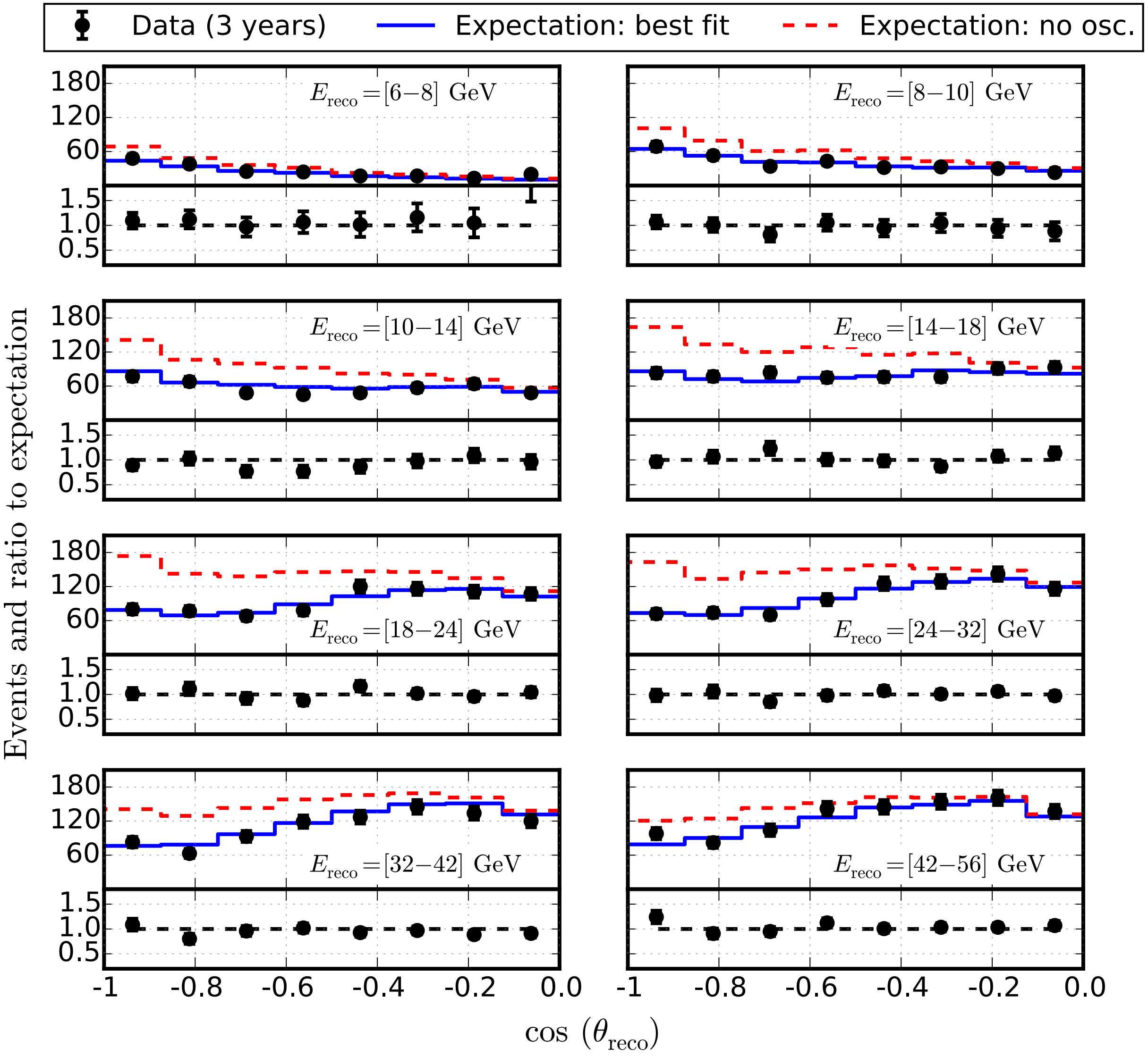


Direct photon selection

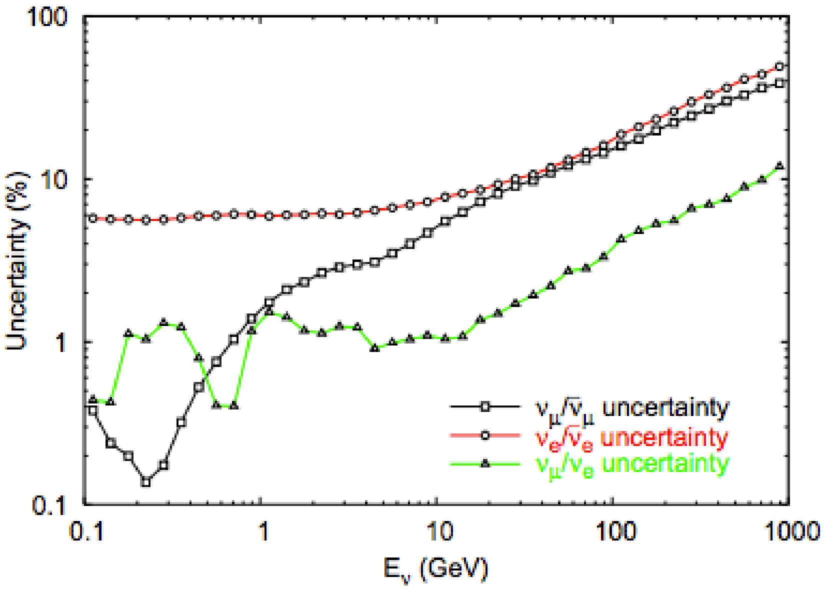
- Good data/MC agreement in expected – measured photon arrival time

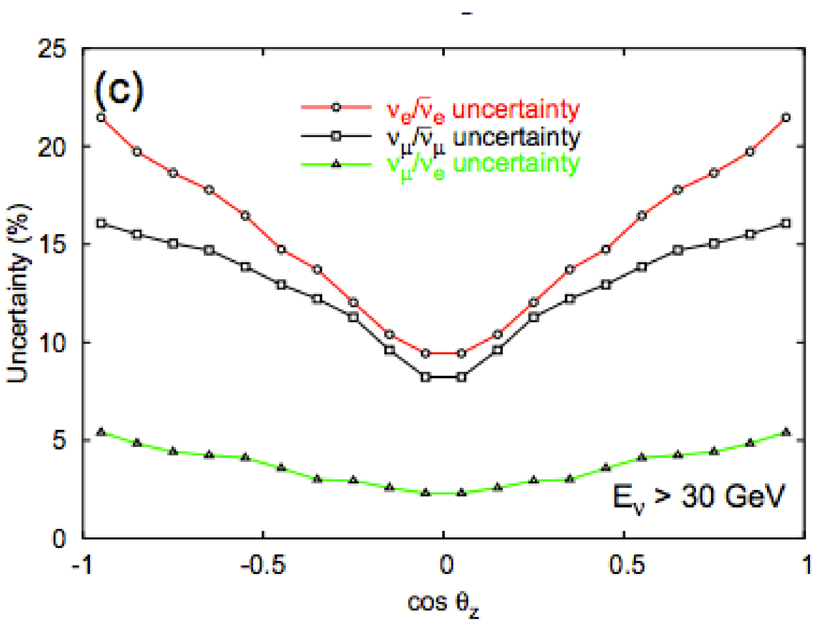


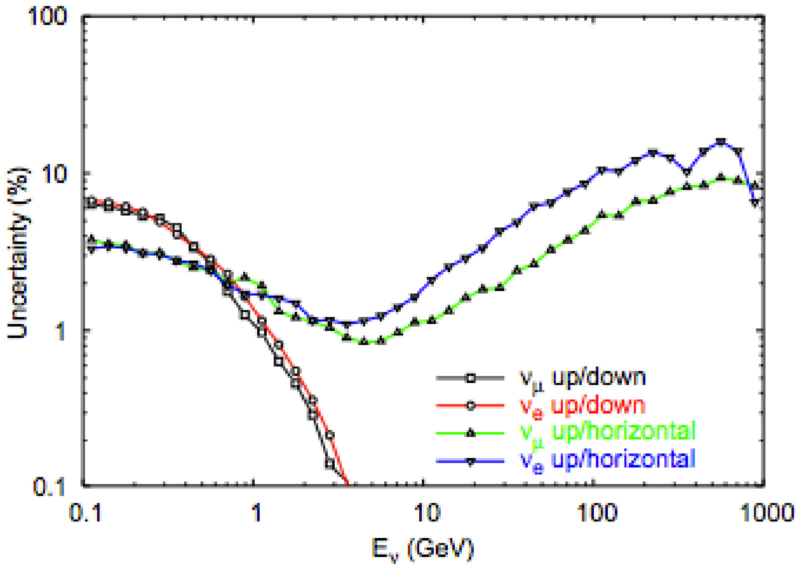
ν_μ disappearance



Atmospheric flux uncertainties in detail



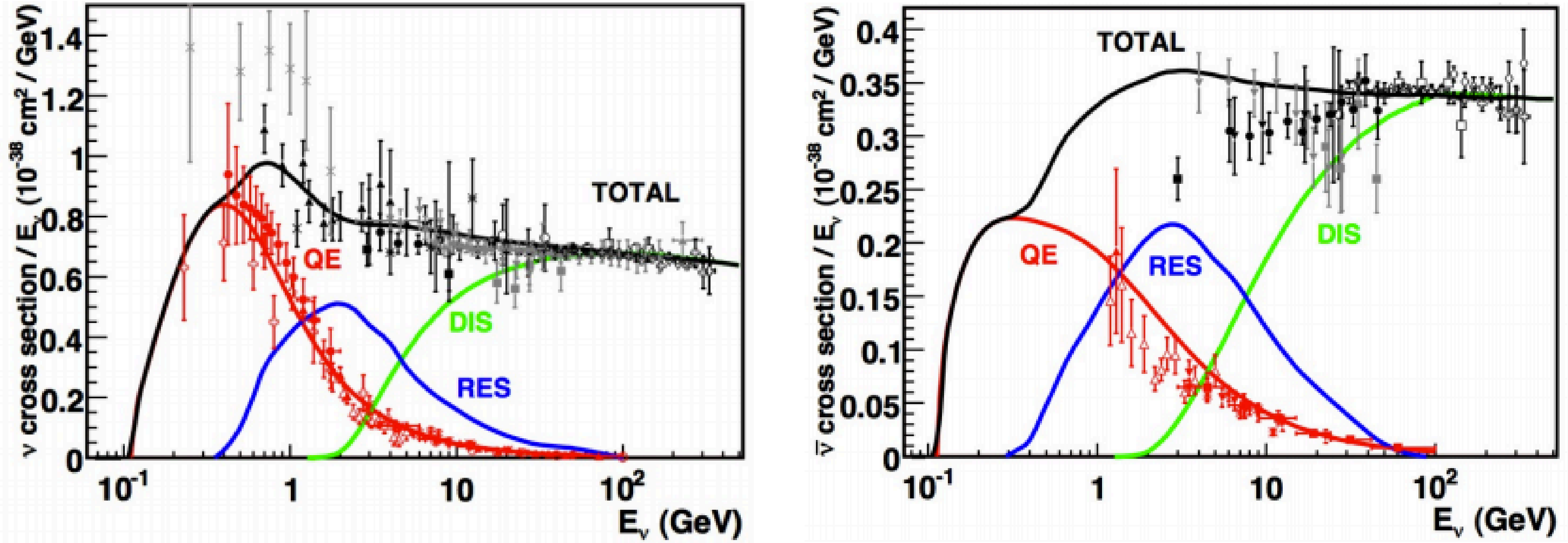




Uncertainties based on Barr *et al*: https://arxiv.org/pdf/astro-ph/0611266v1.pdf

Atmospheric flux uncertainties in detail

- Mainly deep inelastic scattering (DIS)
  - Well understood, calculated
- Production of resonances not negligible below ~20 GeV
  - Not that well understood or calculated



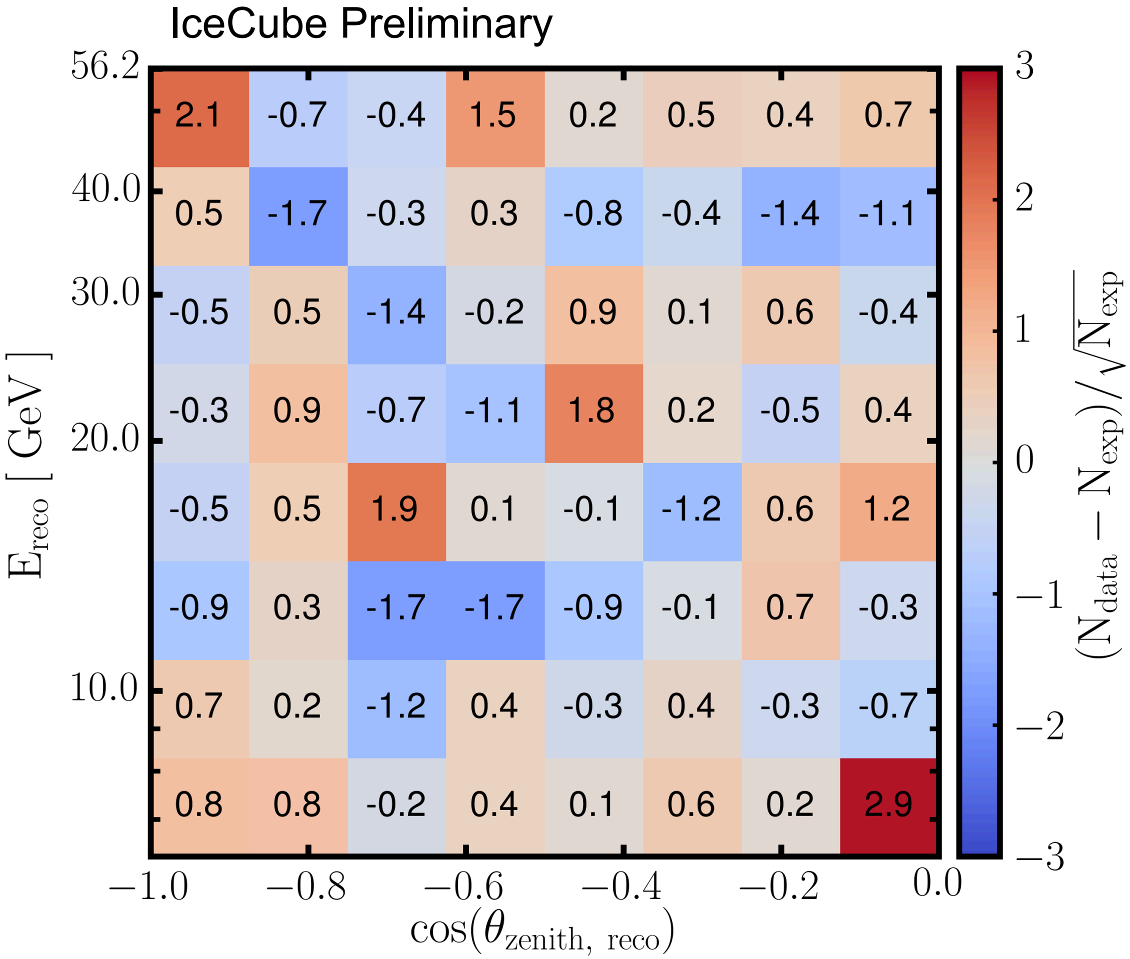
Rev. Mod. Phys. 84, 1307 (2012)

Sterile neutrinos at low energies

- Same sample used for ν_μ disappearance analysis
  - Track-like events, 3 years

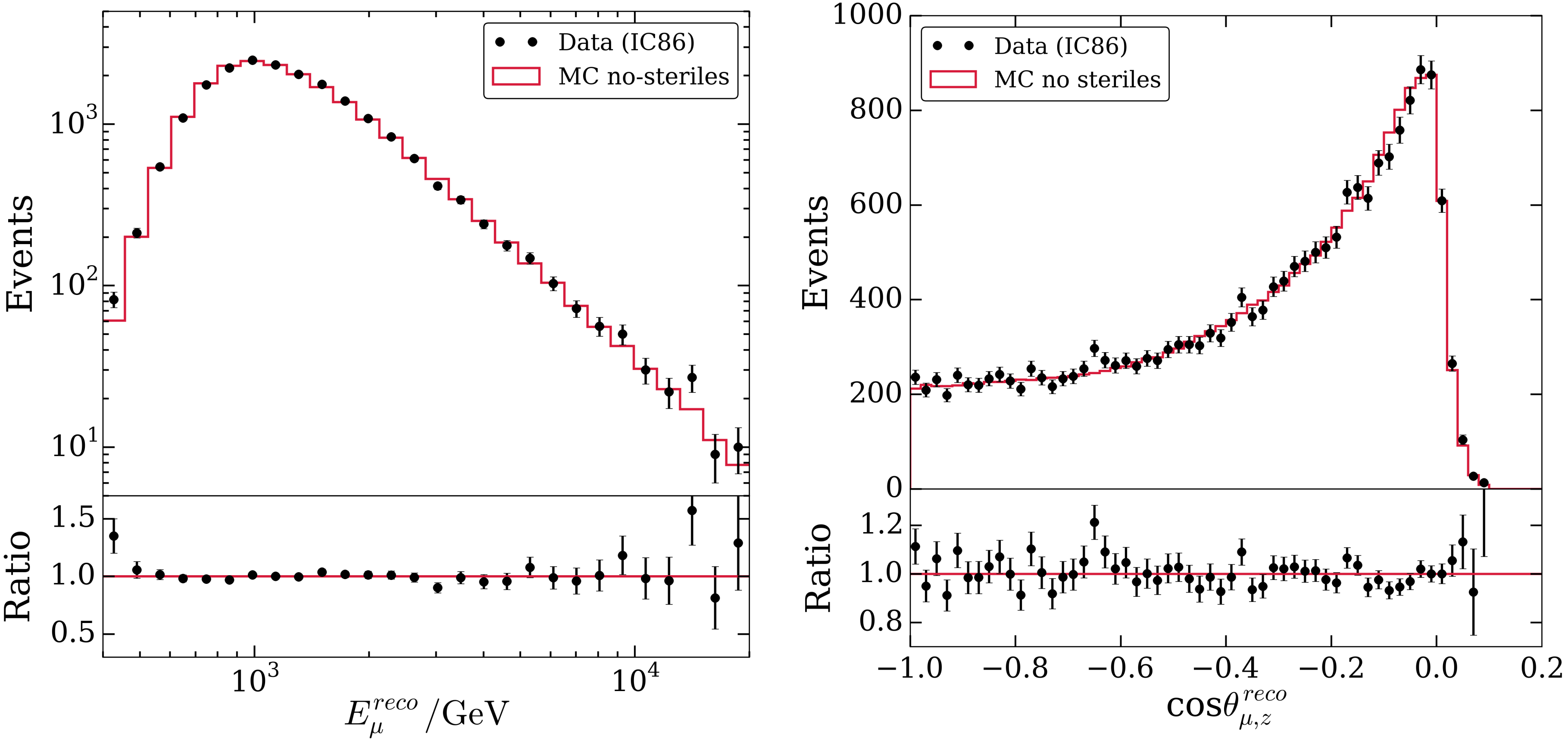
- **No evidence for sterile neutrino**
  - χ^2/d.o.f. = 55.2/57

- Strongest constraint on $|U_{\tau 4}|^2$

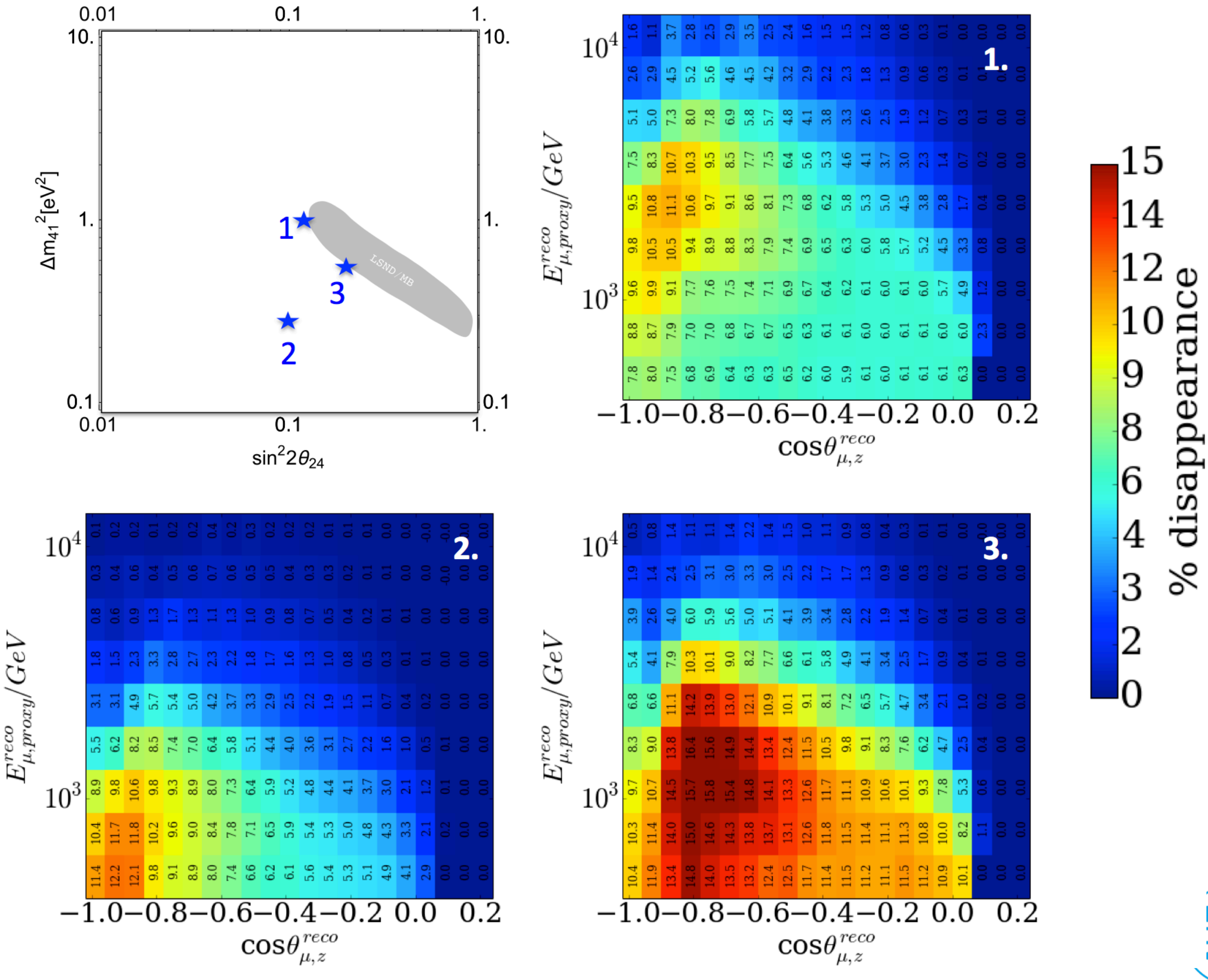


2.1	-0.7	-0.4	1.5	0.2	0.5	0.4	0.7
0.5	-1.7	-0.3	0.3	-0.8	-0.4	-1.4	-1.1
-0.5	0.5	-1.4	-0.2	0.9	0.1	0.6	-0.4
-0.3	0.9	-0.7	-1.1	1.8	0.2	-0.5	0.4
-0.5	0.5	1.9	0.1	-0.1	-1.2	0.6	1.2
-0.9	0.3	-1.7	-1.7	-0.9	-0.1	0.7	-0.3
0.7	0.2	-1.2	0.4	-0.3	0.4	-0.3	-0.7
0.8	0.8	-0.2	0.4	0.1	0.6	0.2	2.9

Sterile neutrinos at high energies

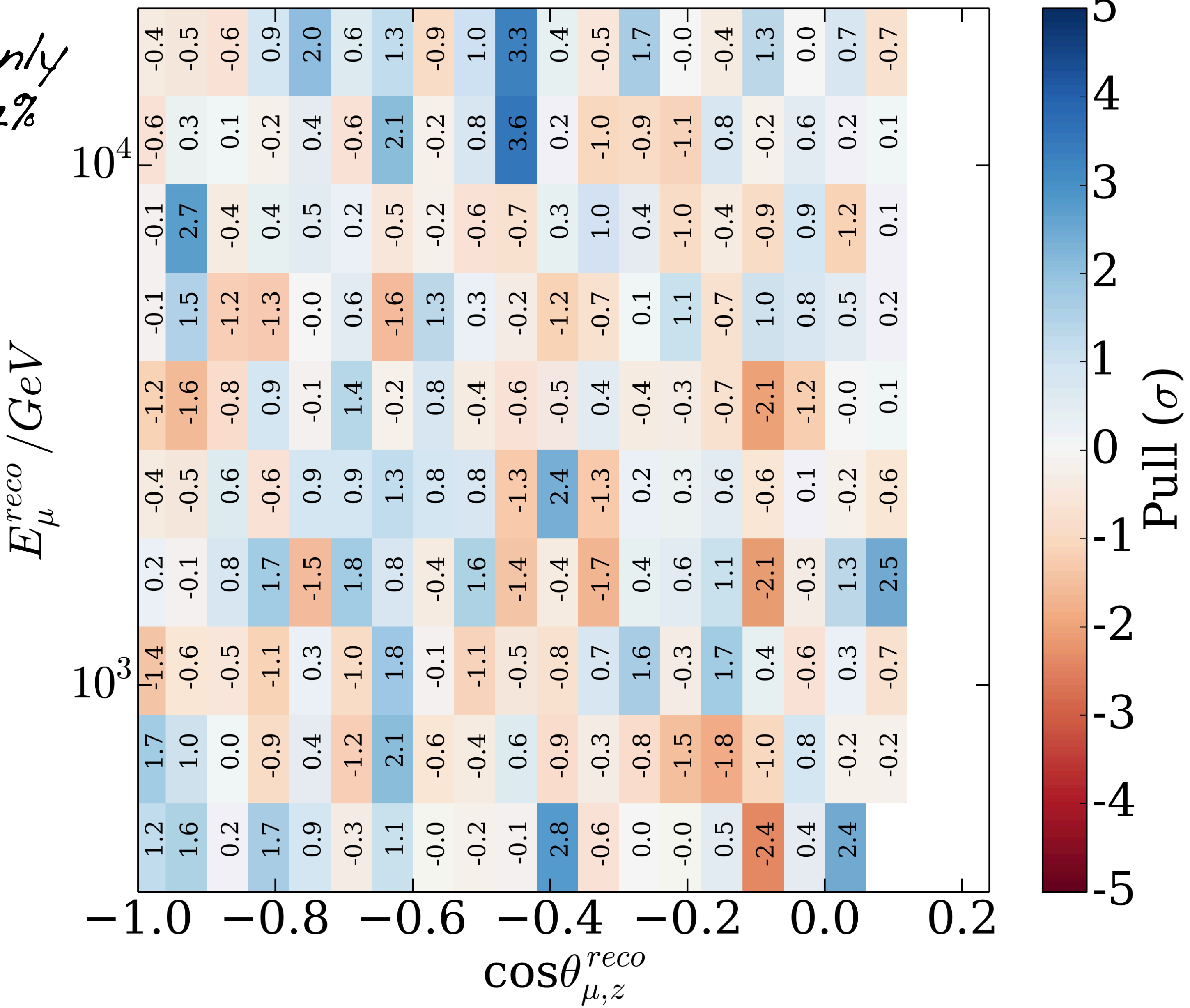


Sterile neutrinos at high energies: e.g. Reco distributions



Sterile neutrinos at high energies

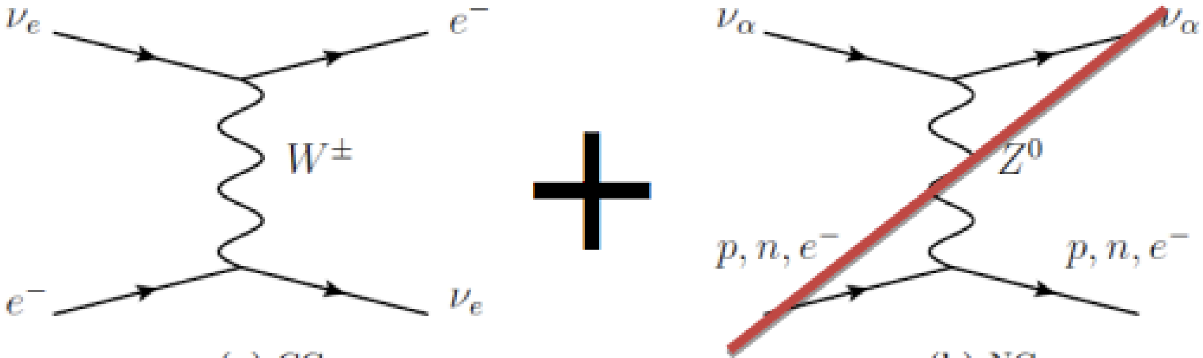
Statistics only
p-value = 17%



-0.4	-0.5	-0.6	0.9	2.0	0.6	1.3	-0.9	1.0	3.3	0.4	-0.5	1.7	-0.0	-0.4	1.3	0.0	0.7	-0.7
-0.6	0.3	0.1	-0.2	0.4	-0.6	2.1	-0.2	0.8	3.6	0.2	-1.0	-0.9	-1.1	0.8	-0.2	0.6	0.2	0.1
-0.1	2.7	-0.4	0.4	0.5	0.2	-0.5	-0.2	-0.6	-0.7	0.3	1.0	0.4	-1.0	-0.4	-0.9	0.9	-1.2	0.1
-0.1	1.5	-1.2	-1.3	-0.0	0.6	-1.6	1.3	0.3	-0.2	-1.2	-0.7	0.1	1.1	-0.7	1.0	0.8	0.5	0.2
-1.2	-1.6	-0.8	0.9	-0.1	1.4	-0.2	0.8	-0.4	-0.6	-0.5	0.4	-0.4	-0.3	-0.7	-2.1	-1.2	-0.0	0.1
-0.4	-0.5	0.6	-0.6	0.9	0.9	1.3	0.8	0.8	-1.3	2.4	-1.3	0.2	0.3	0.6	-0.6	0.1	-0.2	-0.6
0.2	-0.1	0.8	1.7	-1.5	1.8	0.8	-0.4	1.6	-1.4	-0.4	-1.7	0.4	0.6	1.1	-2.1	-0.3	1.3	2.5
-1.4	-0.6	-0.5	-1.1	0.3	-1.0	1.8	-0.1	-1.1	-0.5	-0.8	0.7	1.6	-0.3	1.7	0.4	-0.6	0.3	-0.7
1.7	1.0	0.0	-0.9	0.4	-1.2	2.1	-0.6	-0.4	0.6	-0.9	-0.3	-0.8	-1.5	-1.8	-1.0	0.8	-0.2	-0.2
1.2	1.6	0.2	1.7	0.9	-0.3	1.1	-0.0	-0.2	-0.1	2.8	-0.6	0.0	-0.0	0.5	-2.4	0.4	2.4	

Neutrino oscillations & matter effects

» Scattering processes in ordinary matter



(a) CC (b) NC

$$\mathcal{H}_0 \rightarrow \mathcal{H} = \mathcal{H}_0 + V(n_e)$$

$$V(n_e) = \pm\sqrt{2}\, G_F\, n_e(x)\, \beta,$$

» Recycling the formalism: effective parameters in matter

In constant electron density:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}\,,$$

$$A = \pm 2\sqrt{2}\, E\, G_F\, n_e.$$

$$\boxed{\tan 2\theta_M = \frac{\tan 2\theta}{1 - \dfrac{A_{CC}}{\Delta m^2 \cos 2\theta}}.}$$

*See Phys.Rev.D64:053003,2001 for a full derivation

*Courtesy of J.P.Yanez

Neutrino oscillations & matter effects

» MSW resonance and saturation, a local effect

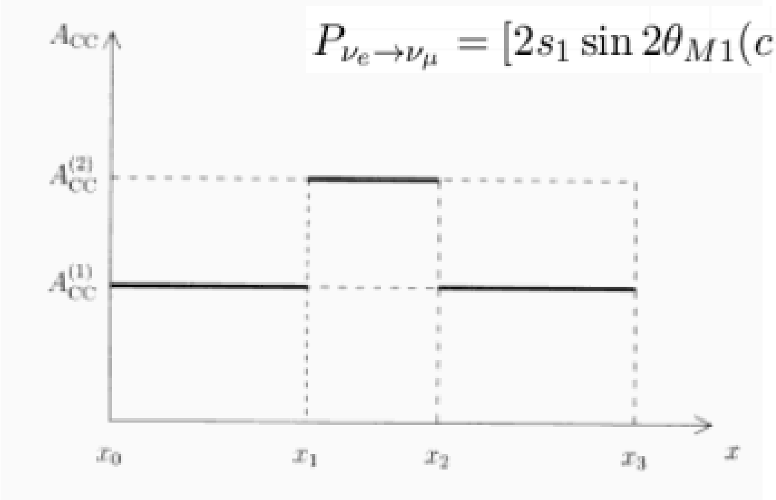
if $A_{\mathrm{R}} = \Delta m^2_{31}\cos(2\theta_{13}).$ $\rightarrow$ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \underbrace{\dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}_{\text{goes to zero}}}$ $\rightarrow$ $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{4}$ maximal (resonance)

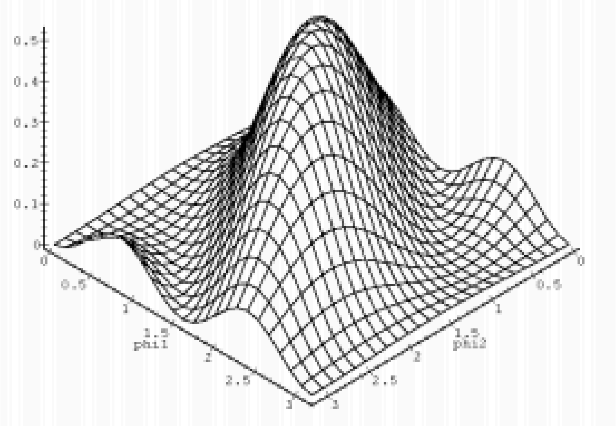
---

if $\left|A_{\mathrm{R}}\right| \gg \Delta m^2_{31}\cos(2\theta_{13}).$ $\rightarrow$ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \underbrace{\dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}_{\text{becomes large}}}$ $\rightarrow$ $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{2}$ no mixing (saturation)

» Parametric resonance, a global effect

$$P_{\nu_e\rightarrow\nu_\mu} = [2s_1\sin 2\theta_{M1}(c_1c_2 - s_1s_2\cos 2\underline{(\theta_{M1} - \theta_{M2})}) + s_2\sin(2\theta_{M2})]^2$$





*Courtesy of J.P.Yanez