what do we learn from the past for neutrino physics in the future?

not much, however…

a brief history of particle physics

- prehistory with cosmic rays to ~ 1977:

  experiment drives theory (with notable exceptions)
  with many serendipitous discoveries (the neutrino, the muon, strange particles, P and CP violation, J/psi, upsilon…

- era of the Standard Model*:

  most successful theory ever constructed, precision tests
  we find what we look for, and no more**…

* first textbooks on the Standard Model appeared in early 80's
** BSM: lepton universality violation in b-decay, g-2,…?

a brief history of neutrino physics

- the era of serendipitous discovery never happened
- we only found what we looked for and no more (with possible exceptions*)

dedicated experiments found

the neutrino discovery at a reactor
the second neutrino with a dedicated accelerator beam
atmospheric neutrinos in underground muon detectors
solar neutrinos in radiochemical experiment
oscillations with SuperK
a supernova with Kamioka and IMB
….
cosmic neutrinos with IceCube

*sterile neutrinos, < 100 TeV atmospheric neutrino excess in IceCube,…

- the neutrino is a coy mistress
- by building dedicated precision and exploratory experiments we may find physics beyond the Standard Model whose existence in the neutrino sector is well motivated by the non-vanishing neutrino mass and the puzzling hierarchy of the neutrino and electron mass

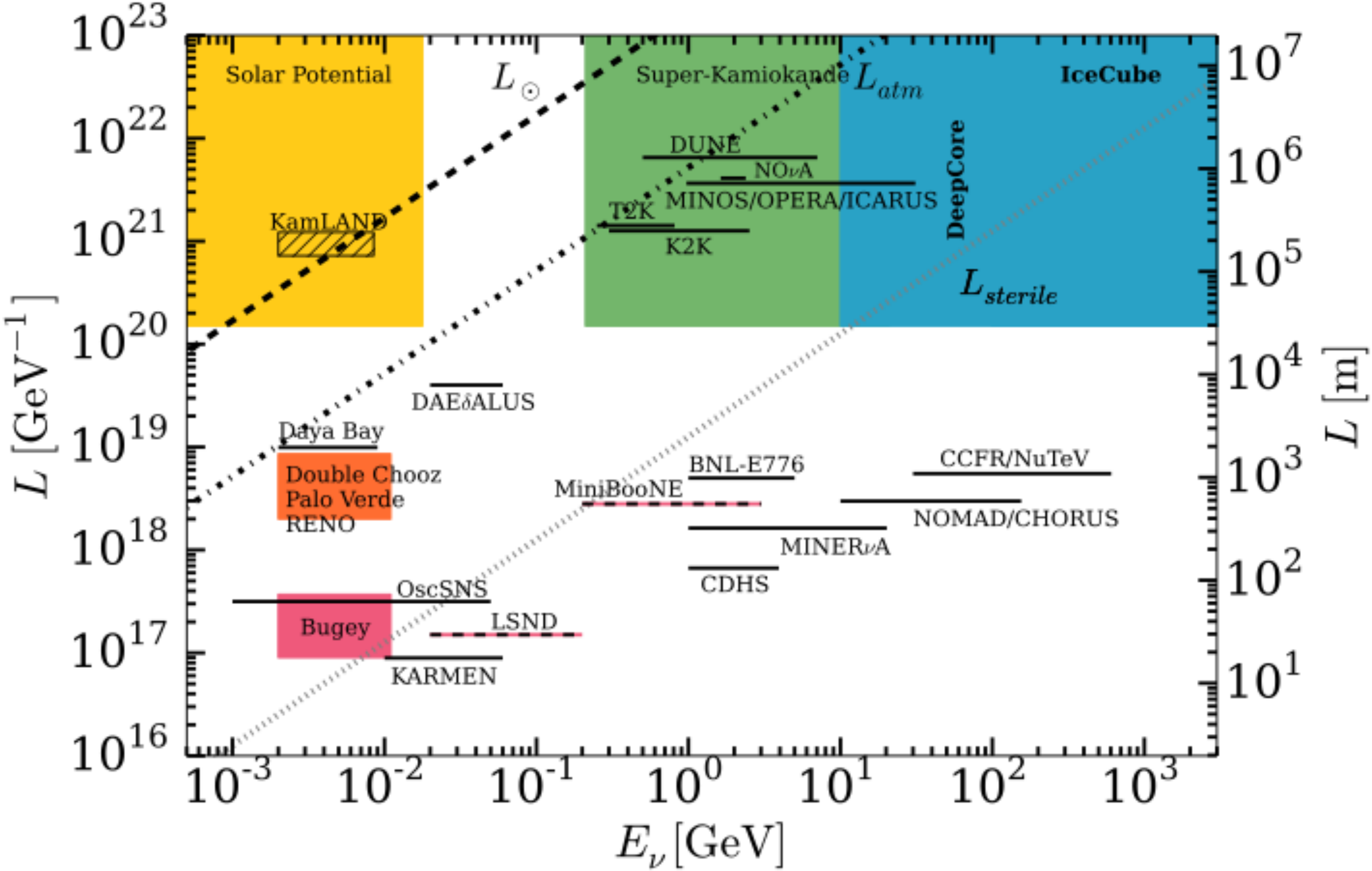
the future of neutrino physics is instrumentation and the future is bright:

- precision:
  intense accelerator beams, short-baseline, DUNE, HyperK,…
  ORCA, neutron factories…
  neutrino factory?

- exploration:
  double-beta decay, supernova detectors, short-baseline reactor beams, neutrino “telescopes”, …

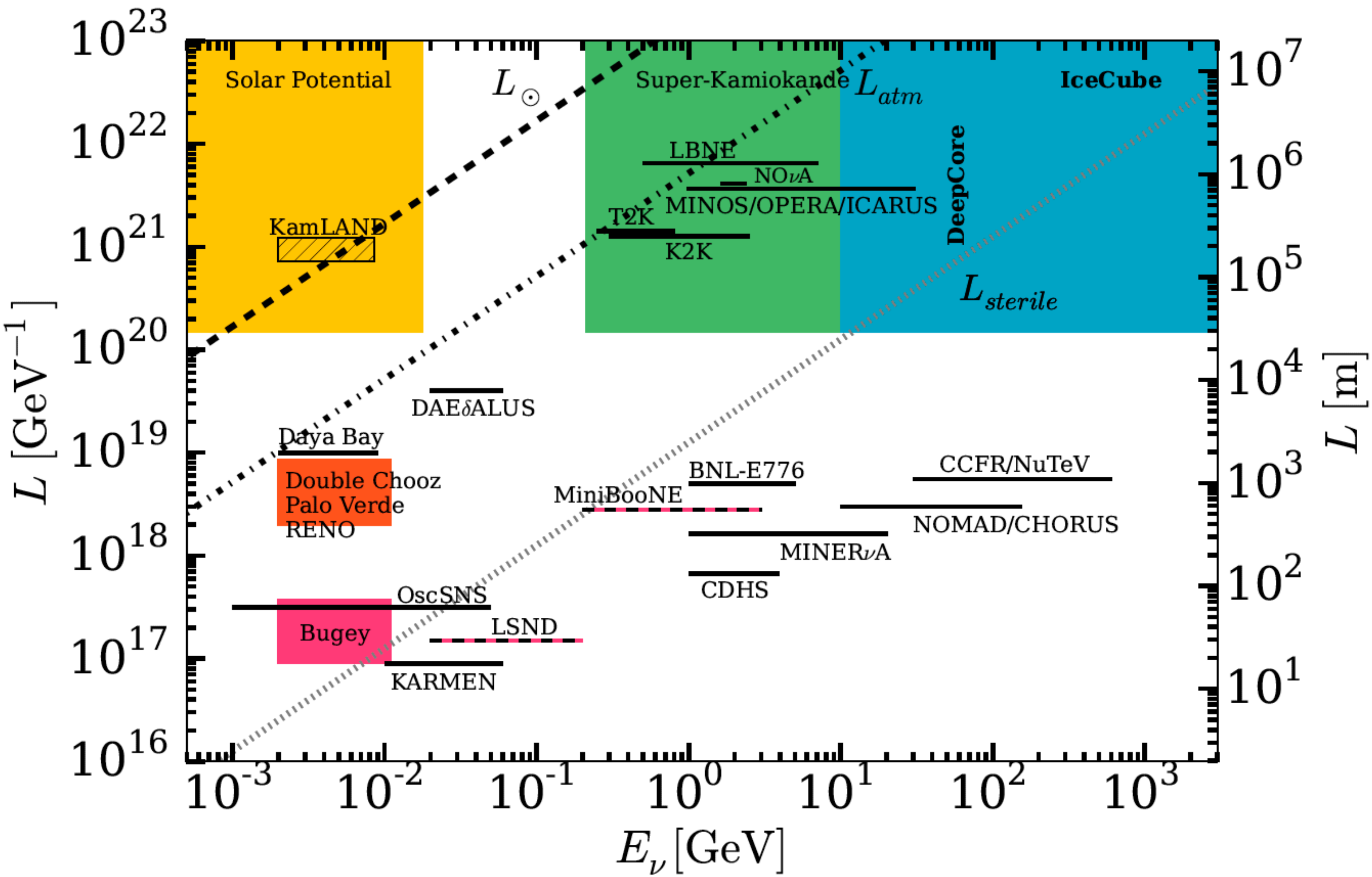
- …

- results to be discussed in the next History of Neutrino Physics organized by Daniel and Michel.



Solar Potential
$L_\odot$
Super-Kamiokande
L_{atm}
IceCube
DUNE
NOνA
MINOS/OPERA/ICARUS
DeepCore
T2K
KamLAND
K2K
$L_{sterile}$
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
BNL-E776
CCFR/NuTeV
MiniBooNE
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
Bugey
LSND
KARMEN
L [GeV^{-1}]
L [m]
E_ν [GeV]

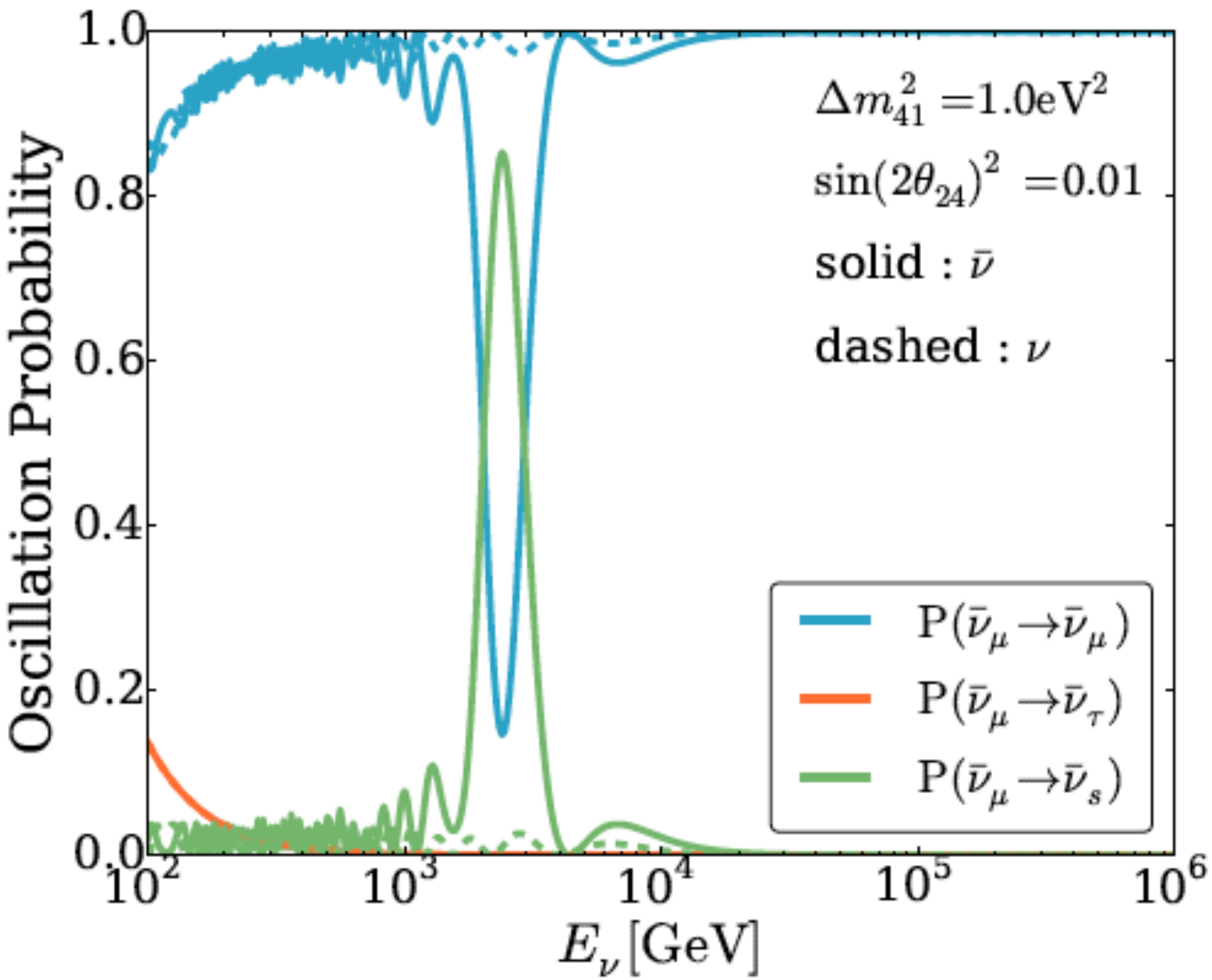
Experiments: $L_{\mathrm{osc}} = 2\pi \frac{E}{\Delta m^2}$ | $\Delta m^2_{\mathrm{LSND}} = 1eV^2$

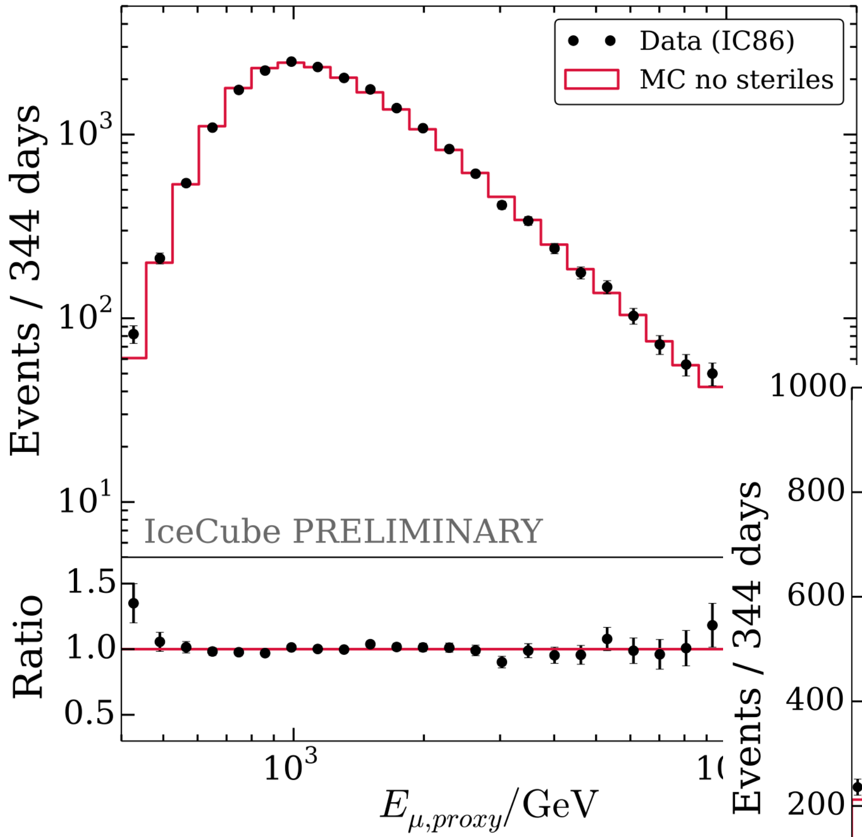


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

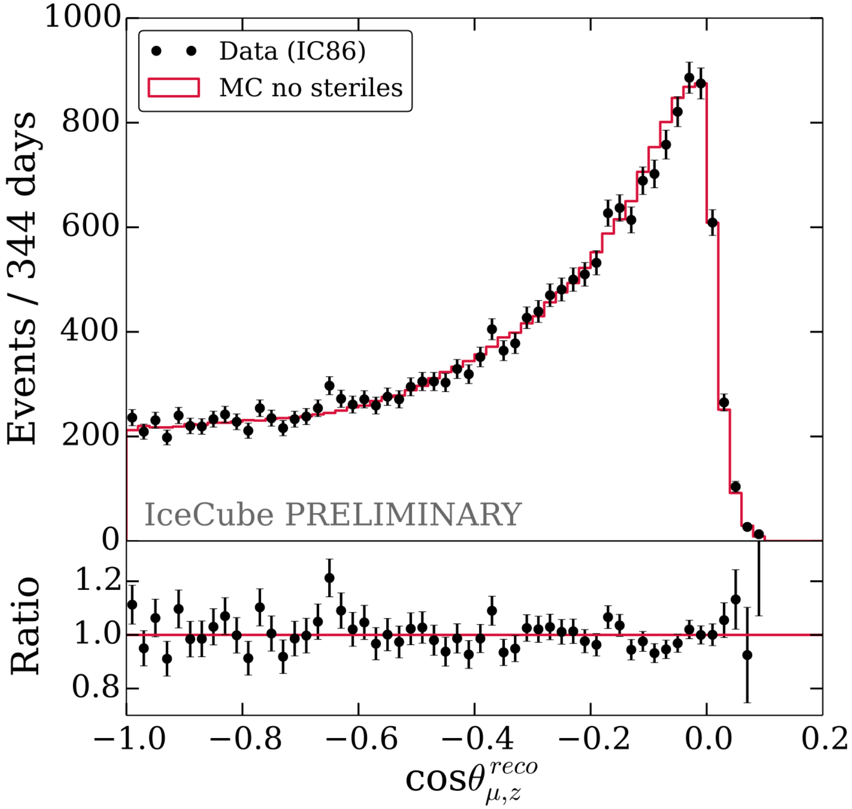
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

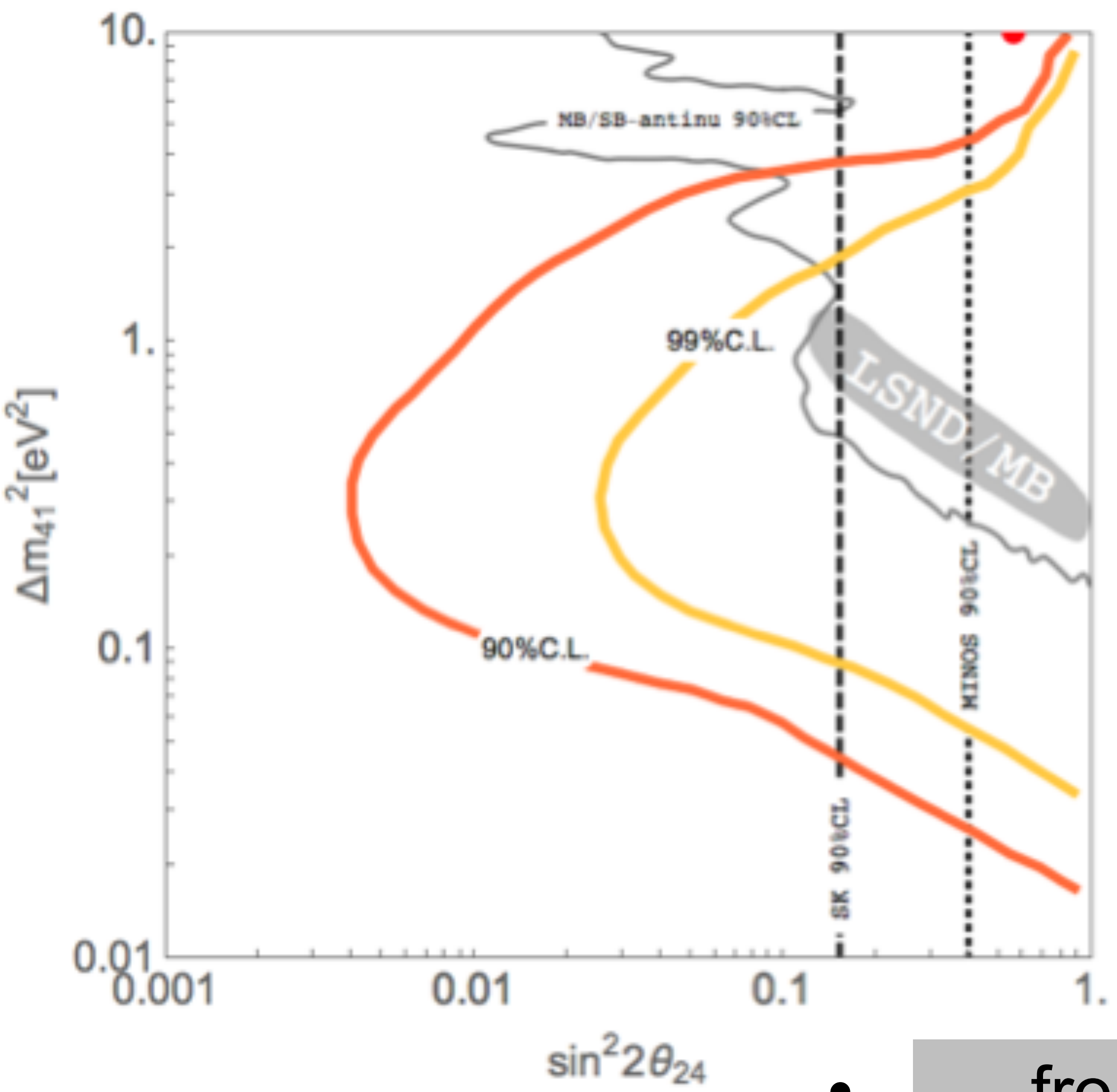
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



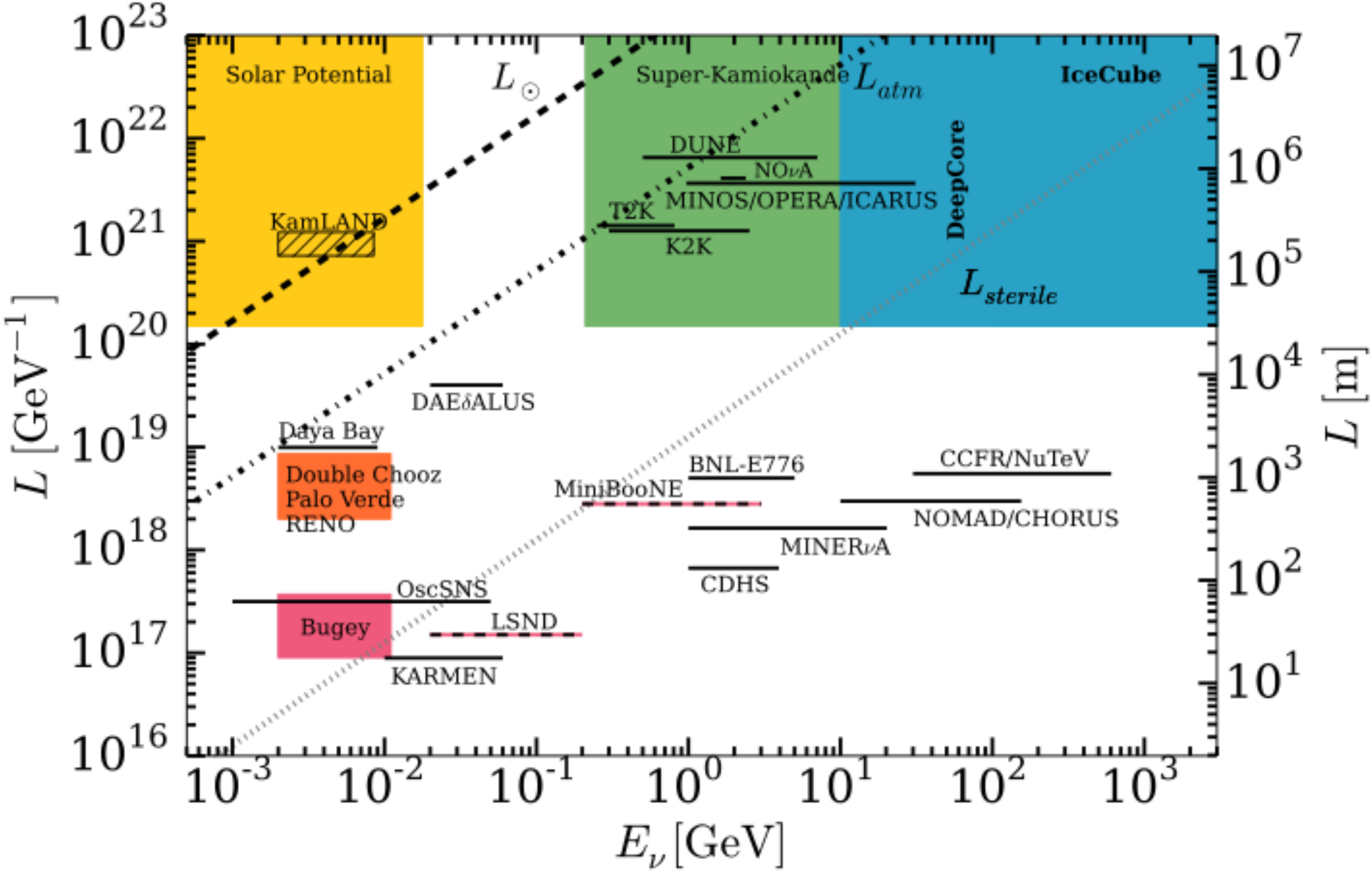


no telltale structure in the zenith angle distribution





- from 1 → 7 years of data soon
- the short baseline program at Fermilab
- “very” short baseline near reactors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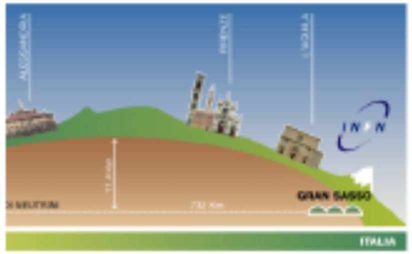
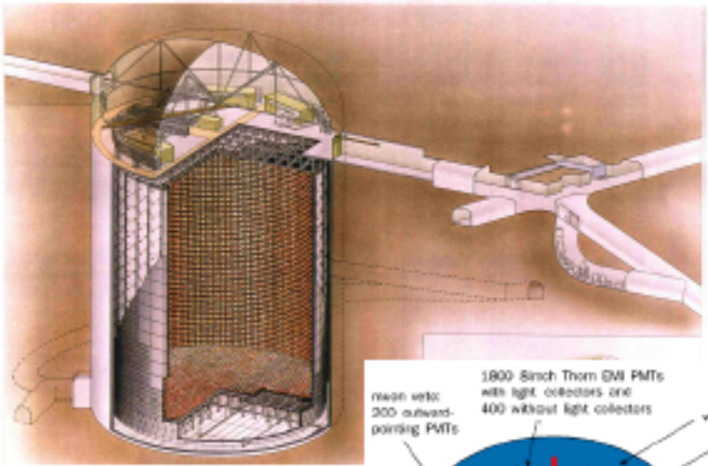
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
Bugey
LSND
KARMEN
$L\ [\mathrm{GeV}^{-1}]$
$L\ [\mathrm{m}]$
$E_\nu\ [\mathrm{GeV}]$

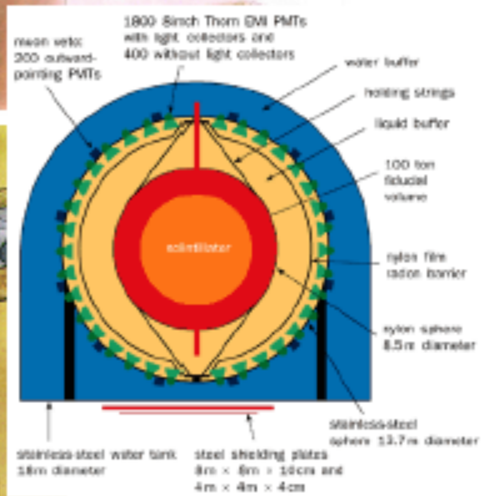
Thanks to:

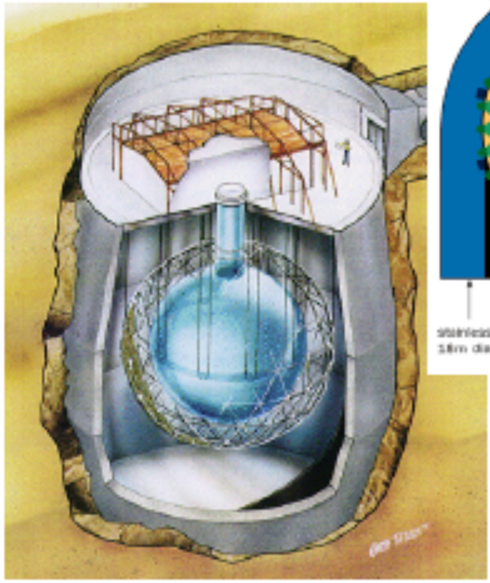
MINOS, Opera



SuperKamiokande







Borexino

SNO

...and more

neutrinos: the sun and the Earth

$$\nu_1 = \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}} \right)$$

$$\nu_2 = \sin\theta_\odot \nu_e + \cos\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}} \right)$$

$$\nu_3 = -\cos\theta_\odot \nu_e + \sin\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}} \right)$$

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

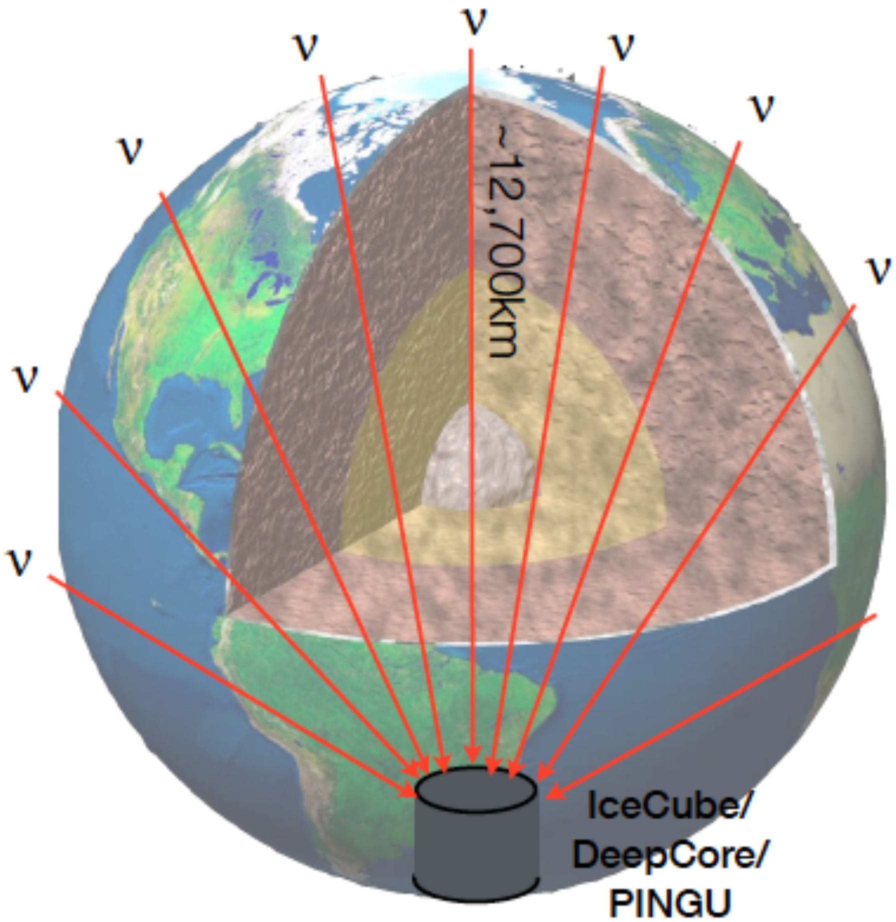
why so different?
main result: CP-violation

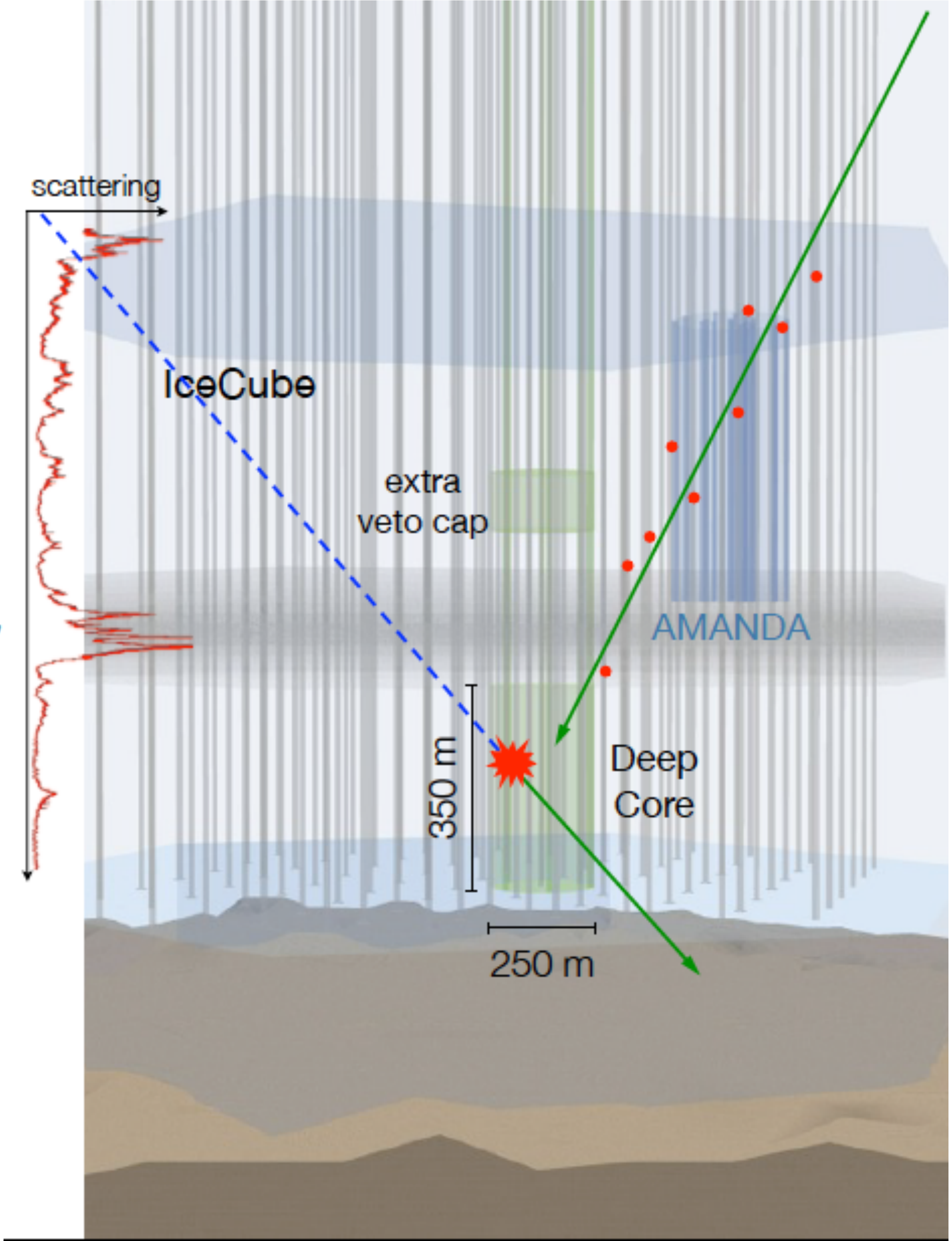
PMNS

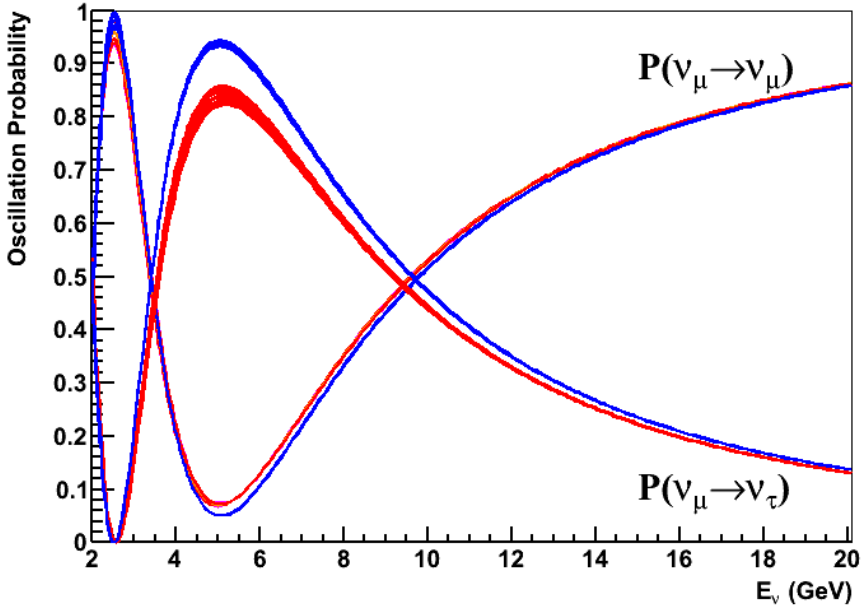
3σ

$$|U| = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

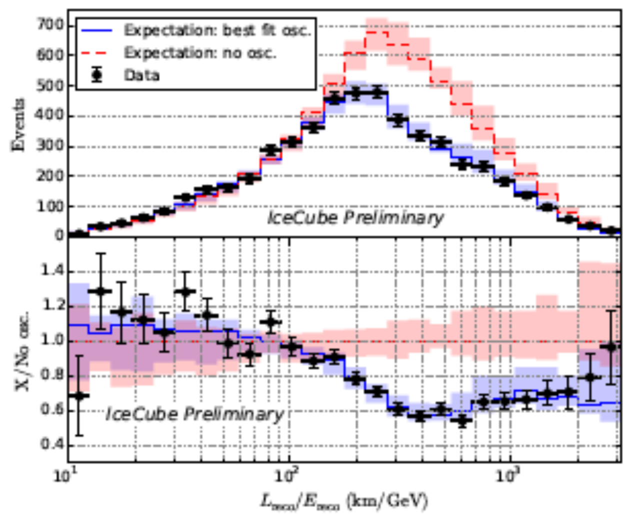
one half million atmospheric neutrinos…

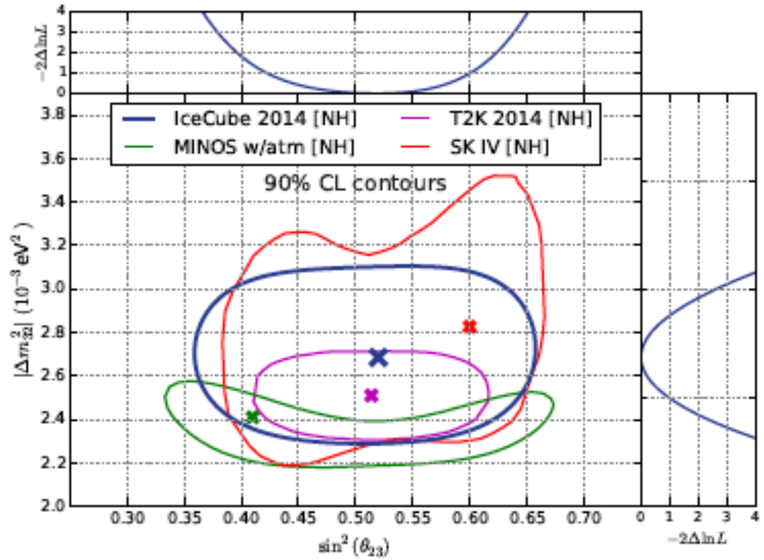






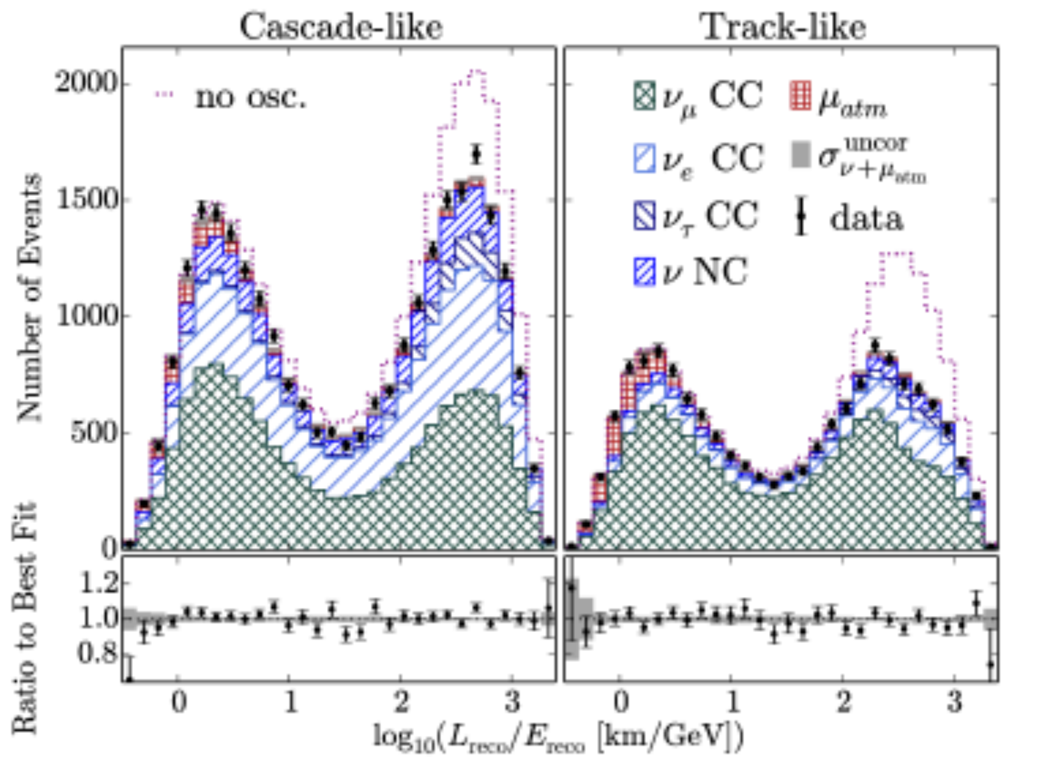
oscillations at 20 GeV

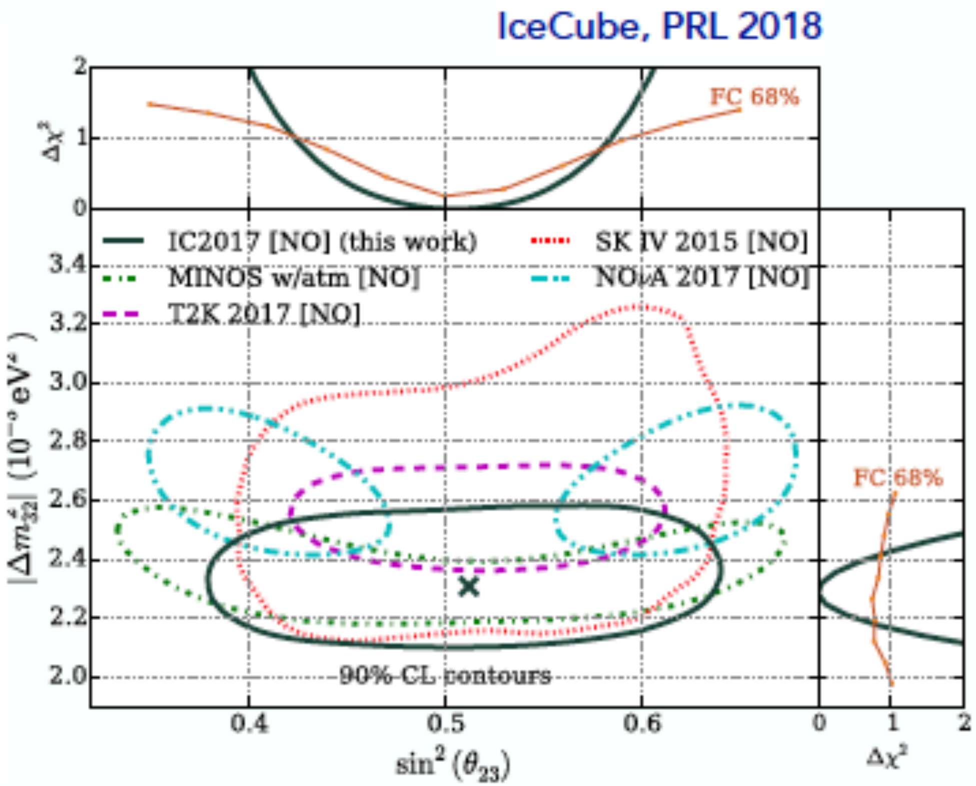




DeepCore: →map the first oscillation dip at 10x higher energy
→new physics?

IceCube/DeepCore

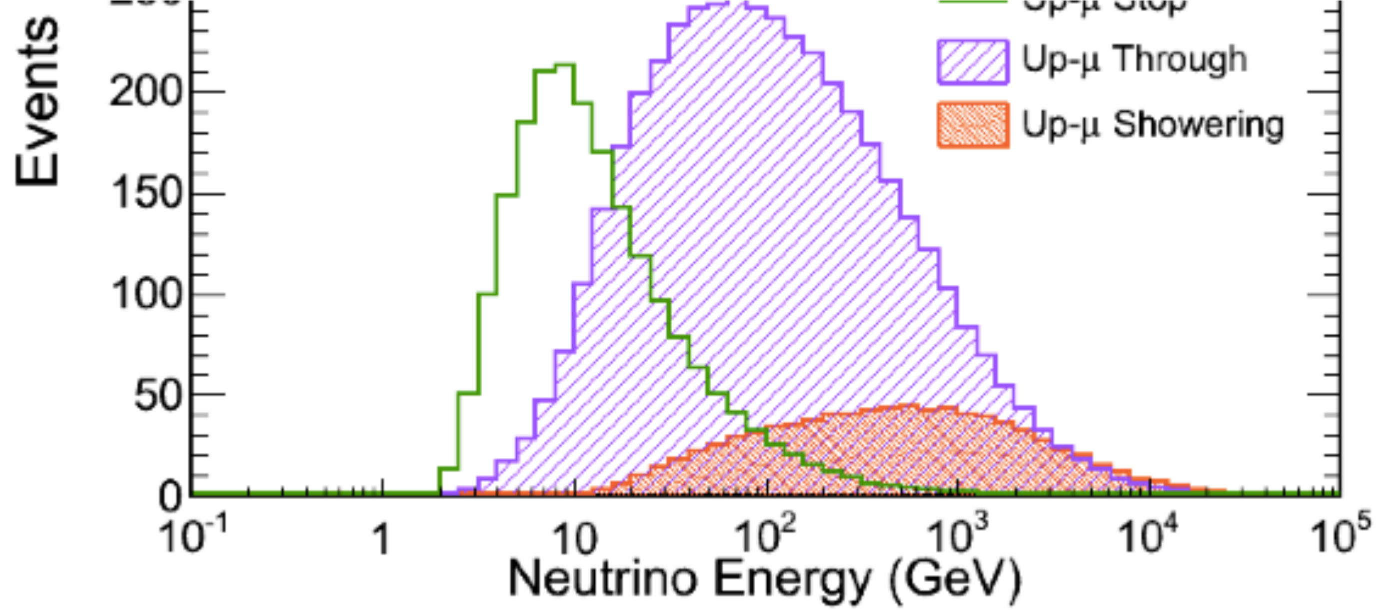




- 3 years of IceCube Deep Core data
- measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

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

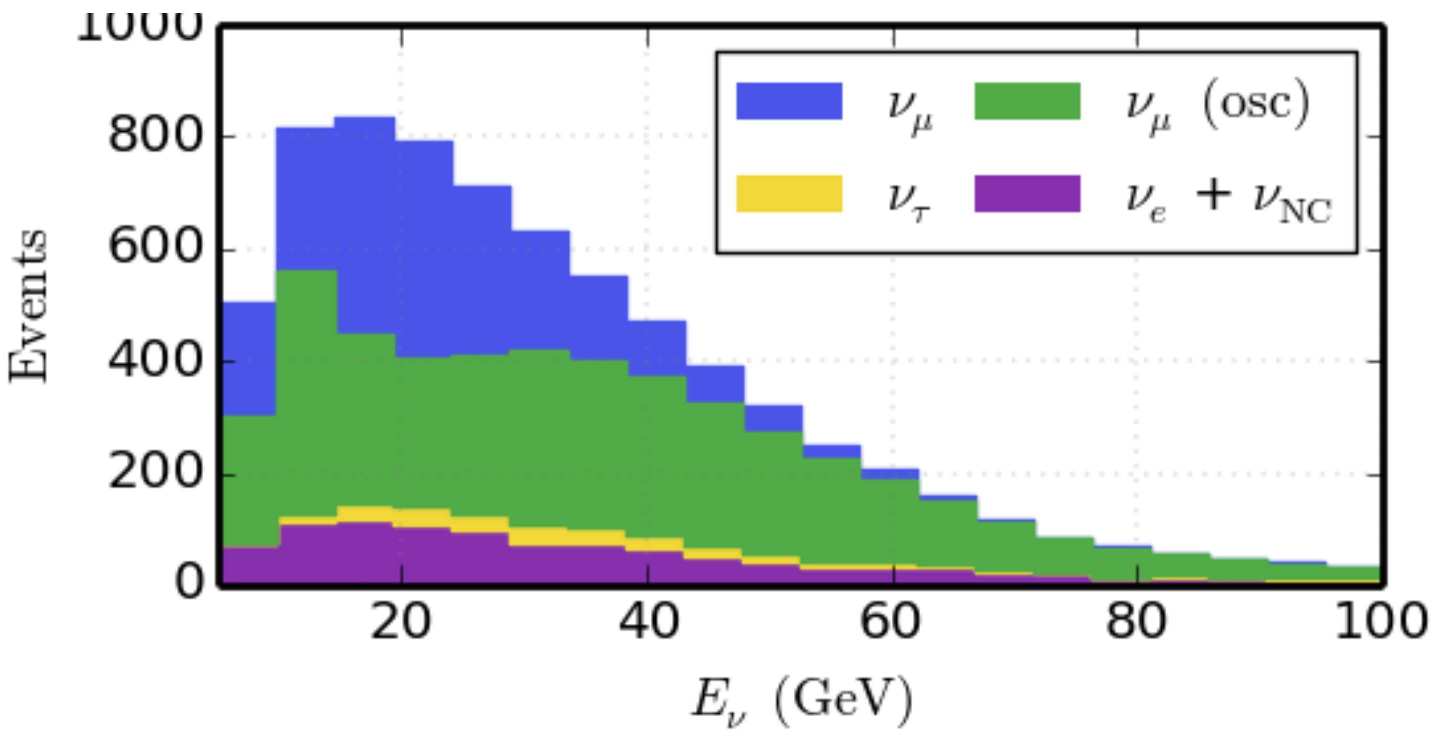
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$



SuperK

- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

IceCube



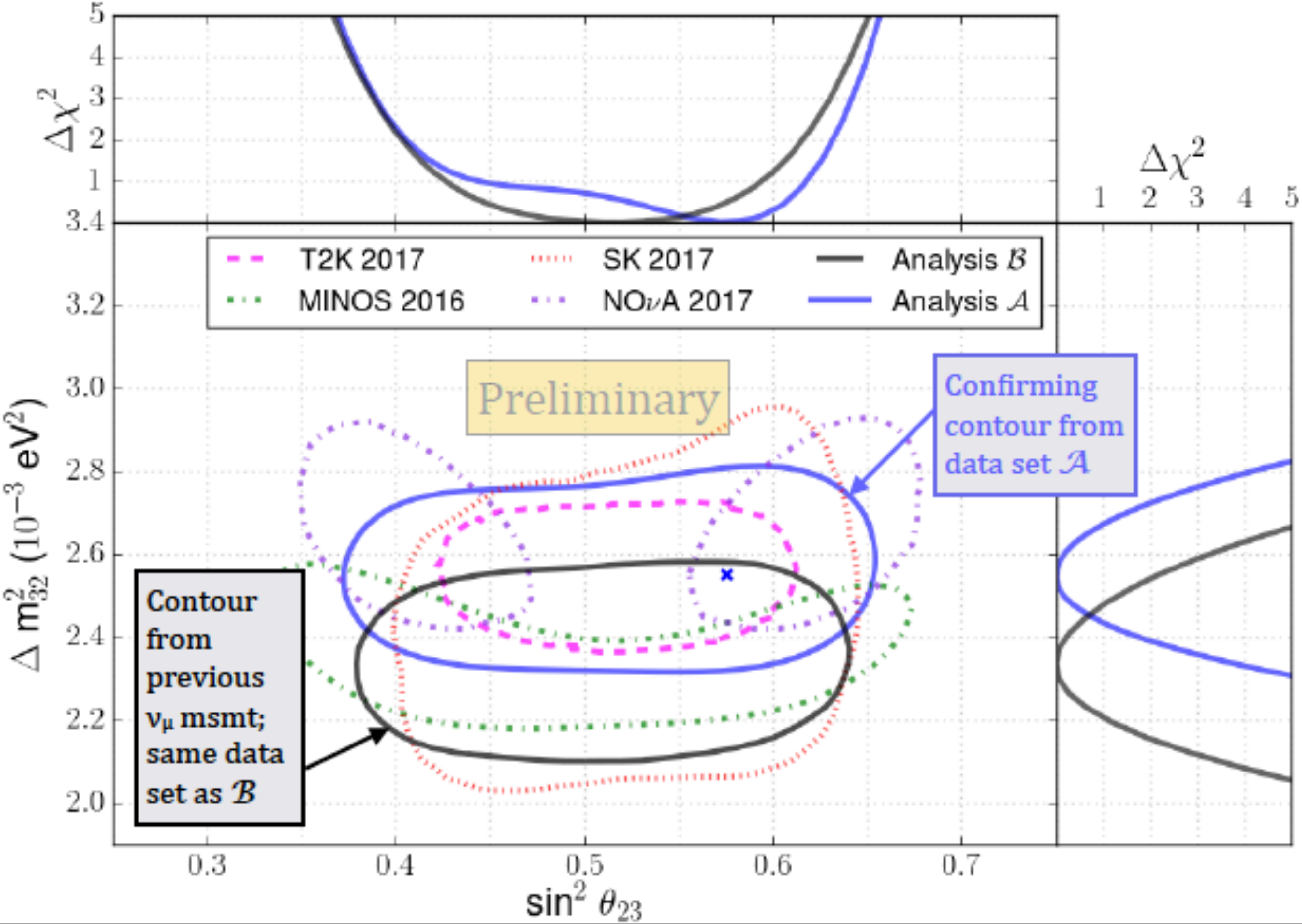
two independent analyses

one for quality of events

one for statistics

both blind

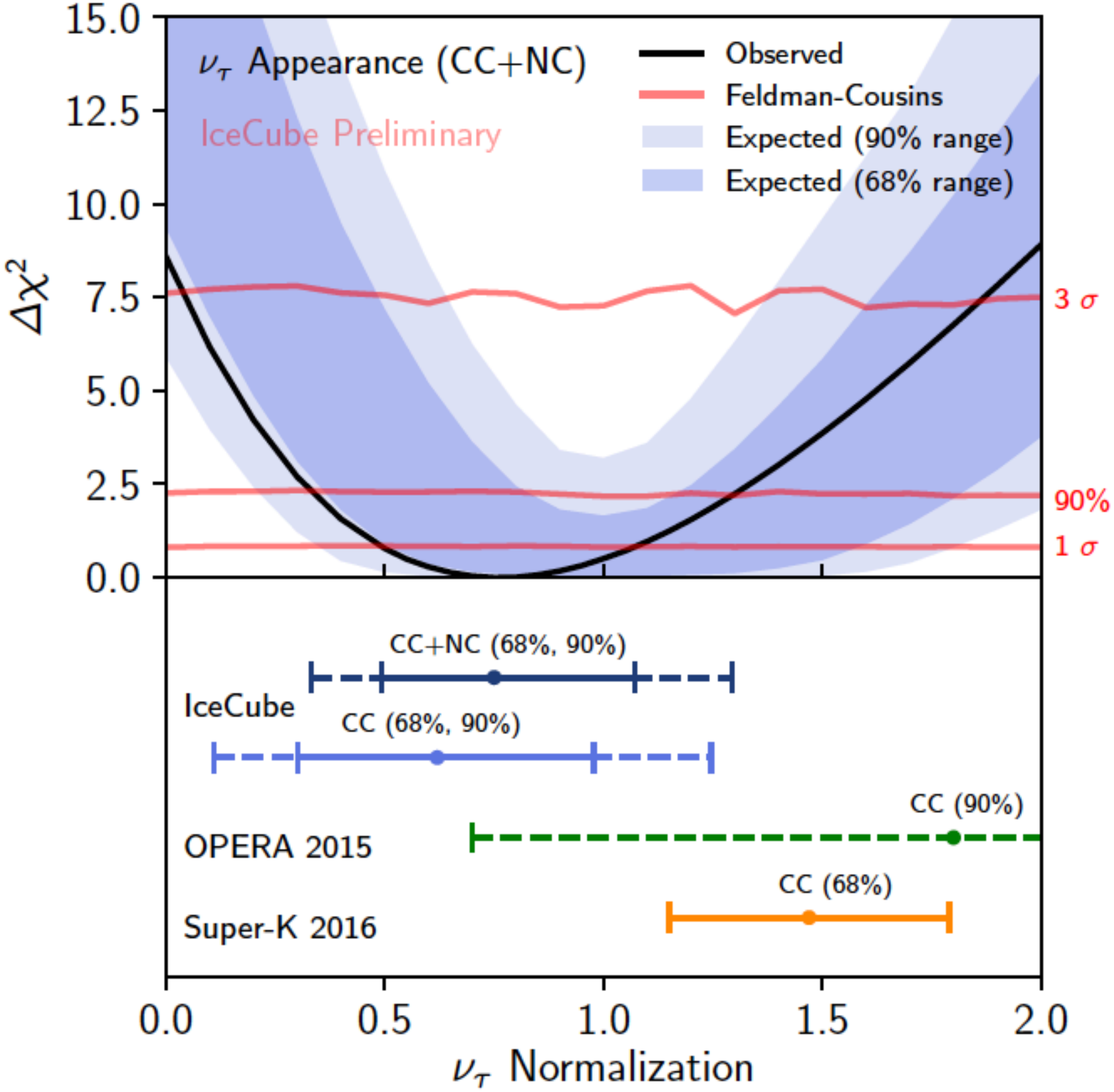
		Analysis A GRECO "High statistics sample"	Analysis B DRAGON "High purity sample"
Simulation	Neutrino Simulation	1. Neutrino interactions / lepton generation: GENIE 2. Lepton propagation / photon generation: PROPOSAL & GEANT4 3. Photon propagation: CLSim (GPU-based software) 4. Noise addition 5. PMT response & readout elections	
	Muon Background Simulation	CORSIKA + MuonGun • Uses H4a Cosmic Ray flux model to directly predict muon background. Run through standard simulation chain.	CORSIKA + Data-Driven • Any muon that would have made it to final level had it not been for a hit in the corridor region is considered a background muon
Selection	Goal	High signal acceptance "High statistics sample"	High signal purity "High purity sample"
	Trigger	At least 3 pairs of locally coincident DeepCore DOMs detect hits in a 2.5 microsecond time window	
	Level 2 "Filter"	Veto events with hits in "veto region" consistent with a muon travelling from there to interaction vertex at $v=c$	
	Level 3	Eliminates events with more than 7 hits in veto region, too many noise hits, too many hits in outer region of DeepCore (i.e. not fully contained),	
	Other low-level cuts	Removes events with too many non-isolated hits in veto region and/or too few non-isolated hits in DeepCore fiducial volume	Fast reconstruction to insure enough DOMs to be consistent with either track or shower signature
	Level 4	BDT to remove atmospheric muons (6 variables) • Charge measured by PMTs (3 vars.) • Simple vertex estimator • Event speed simulator • Calculation of event shape	Straight Cuts • Number of photoelectrons deposited in largest cluster of hits • Event vertex in fiducial volume (contained) • No more than 5 p.e. in veto region total • No more than 2 p.e. in veto region consistent with speed-of-light travel from hit to vertex • Minimum number of non-isolated hits • Space-time interval between 1^{st} and 4^{th} hits consistent with $v \le c$.
	Level 5	Another BDT to remove atmospheric muons (6 variables) • Time to accumulate charge • Vertex estimator • Center-of-gravity information (2 var.) • Causal hit identifier • Zenith angle estimation	BDT (11 variables) • Charge, time, and location of hit DOMs (multiple variables) • Reconstructed zenith angle & event speed using fast construction
	Level 6	Straight cuts • Inconsistent with intrinsic PMT noise • Spatially compact • Require likelihood-based vertex estimator to be well contained in DeepCore fiducial volume • Reject events with hits along "corridors" in surrounding IceCube volume	Straight cuts • Events with reconstructed paths through corridor region • Starting & stopping position in or near DeepCore (contain)
	Level 7	Reconstruction (better & more accurate than fast reconstruction information above) & reconstructed energy must be 5.6-56 GeV	Reconstruction & no cuts on L7 ?



Preliminary
T2K 2017
SK 2017
Analysis $\mathcal{B}$
MINOS 2016
NOνA 2017
Analysis $\mathcal{A}$
Confirming contour from data set $\mathcal{A}$
Contour from previous ν_μ msmt; same data set as $\mathcal{B}$
$\Delta\chi^2$
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

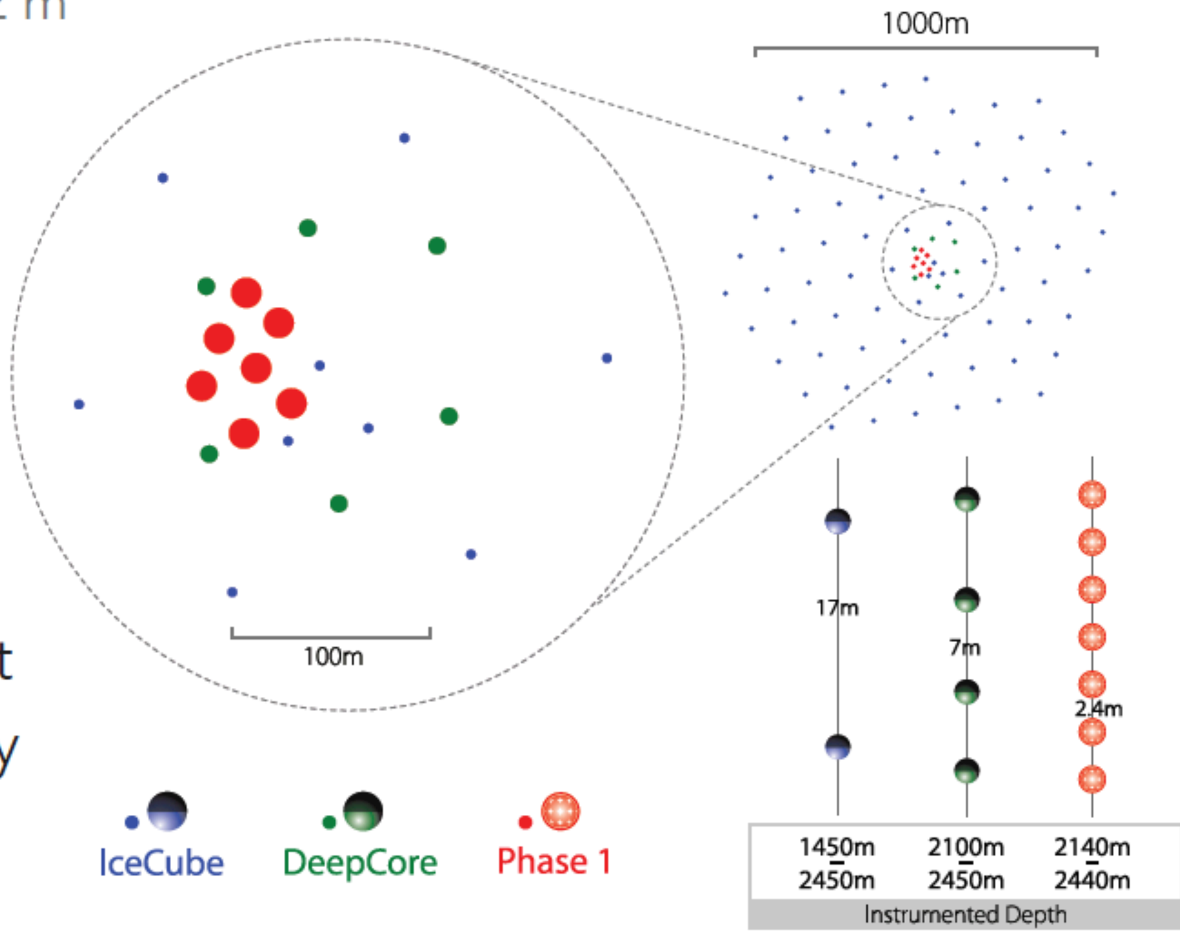
Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix



Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy

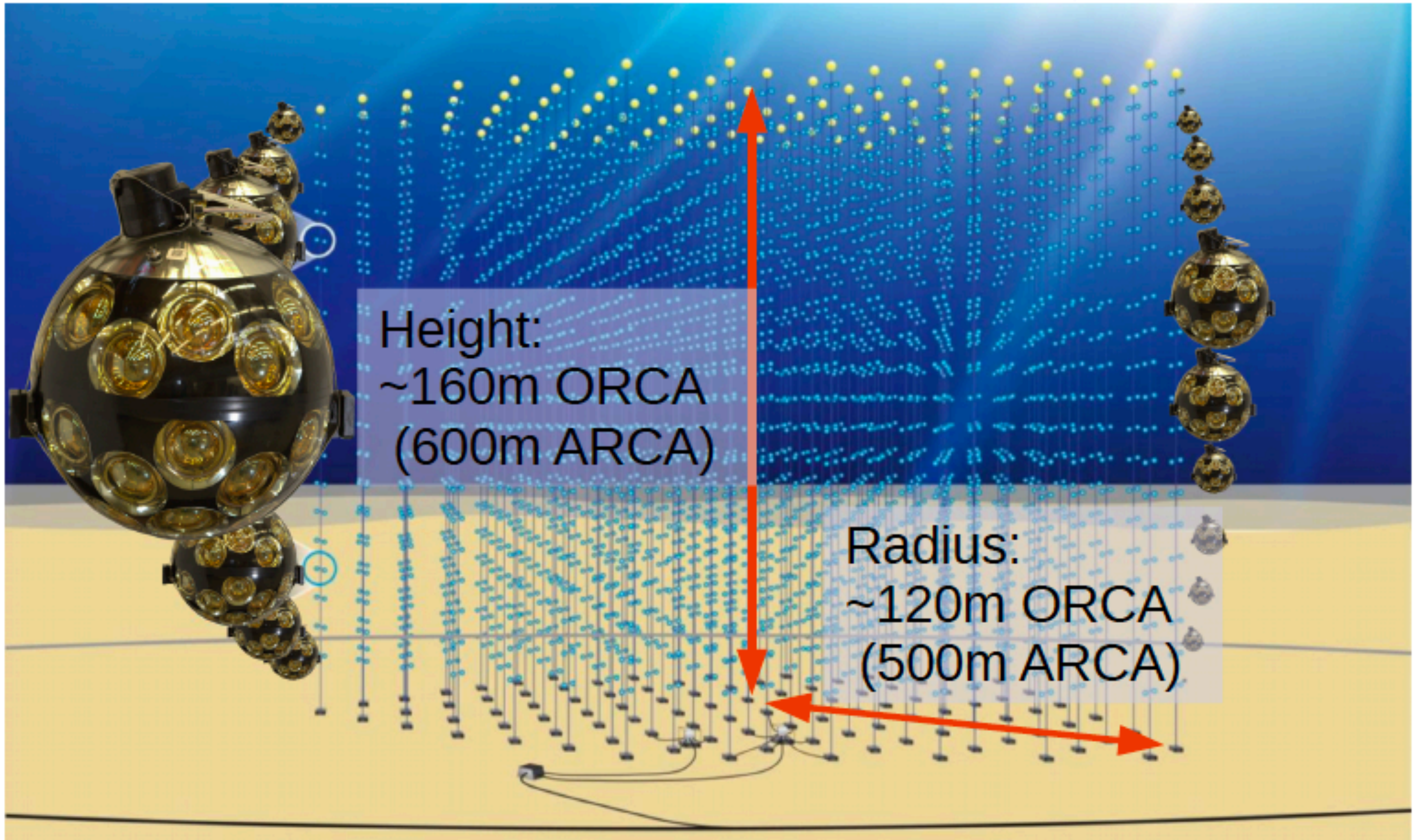


→ soon ORCA with 110 highly instrumented strings

ORCA will consist of one dense
KM3NeT Building Block:

115 detection lines
Total: 64k * 3" PMTs

	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton



Why the precision measurement of another matrix?

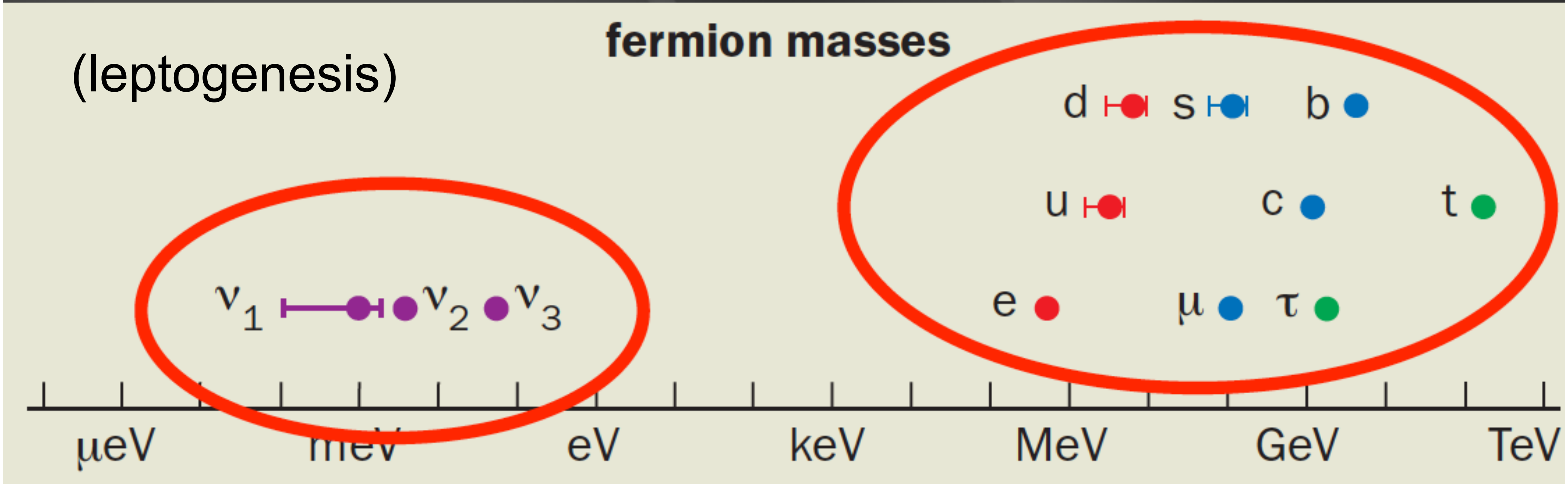
new insights: leptonic CP connection to baryogenesis, origin of flavor,…

proton decay, supernova, dark matter search…

discover new physics: high energy scale and a hierarchy problem

what is the alternative?

neutrinos probe BSM physics just like LHC



mn = 0 → new symmetry

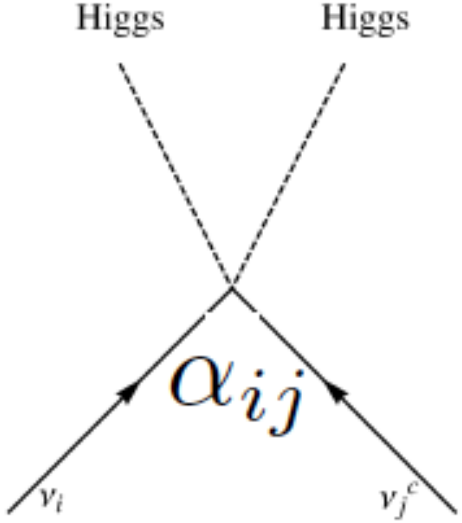
mn 0 → new degrees of freedom beyond the SM

mn small → new high mass scale

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi}\;\alpha\;\tilde{\Phi}L^c + h.c.$$

Weinberg

$$\alpha = \frac{Y_\nu}{\Lambda}$$



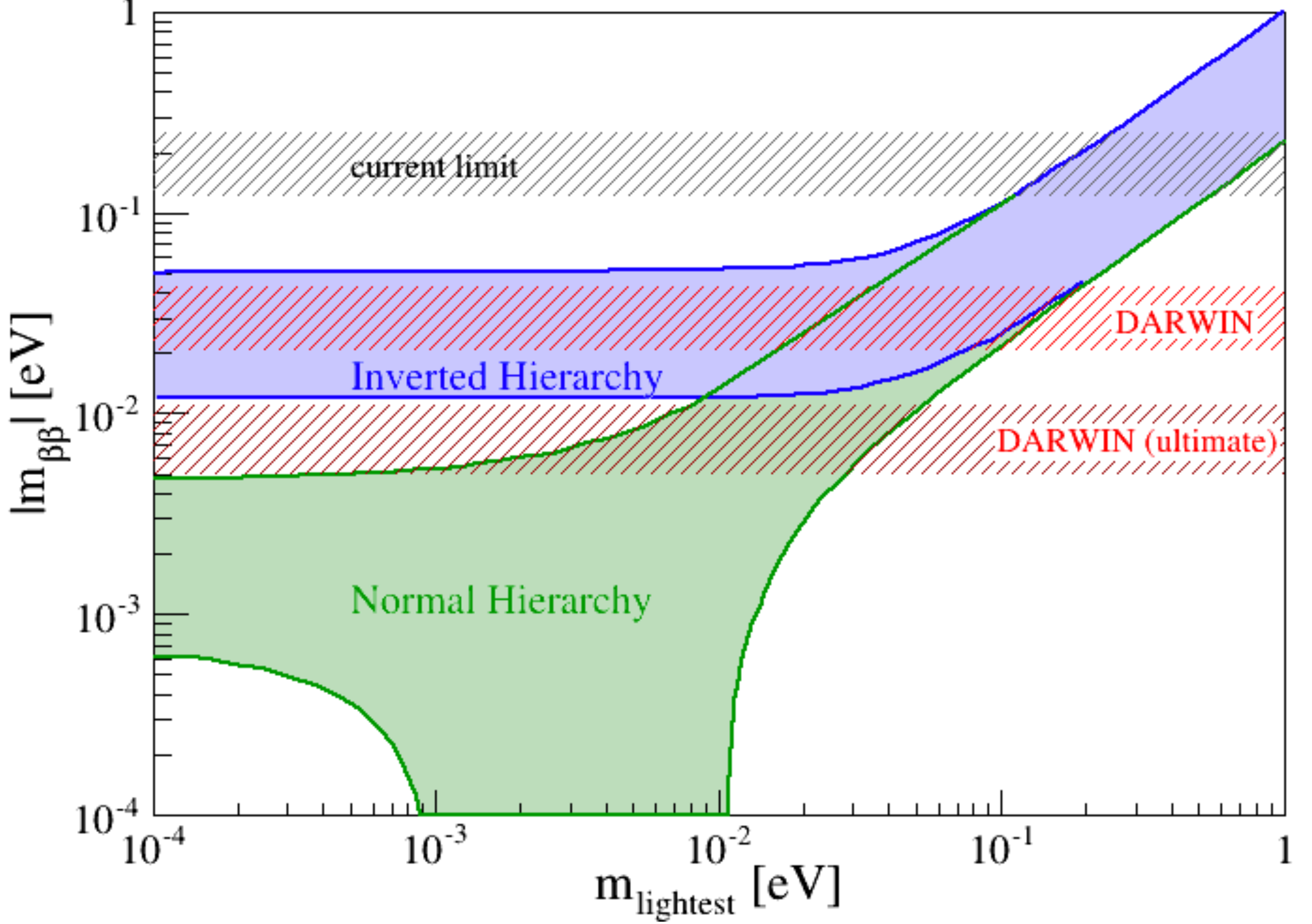
$$m_\nu = Y\frac{v^2}{\Lambda}$$

$$m_f(\text{charged}) \sim Yv, \quad m_\nu \sim Y\frac{v^2}{\Lambda}$$

BSM with large scale L naturally accommodates small neutrino masses discover new physics: go and look for it

double-beta decay: lepton number violation

EXO, GERDA, SNO+, MAJORANA, … NEXT…



absolute neutrino mass: KATRIN, Project 8, Holmium, …