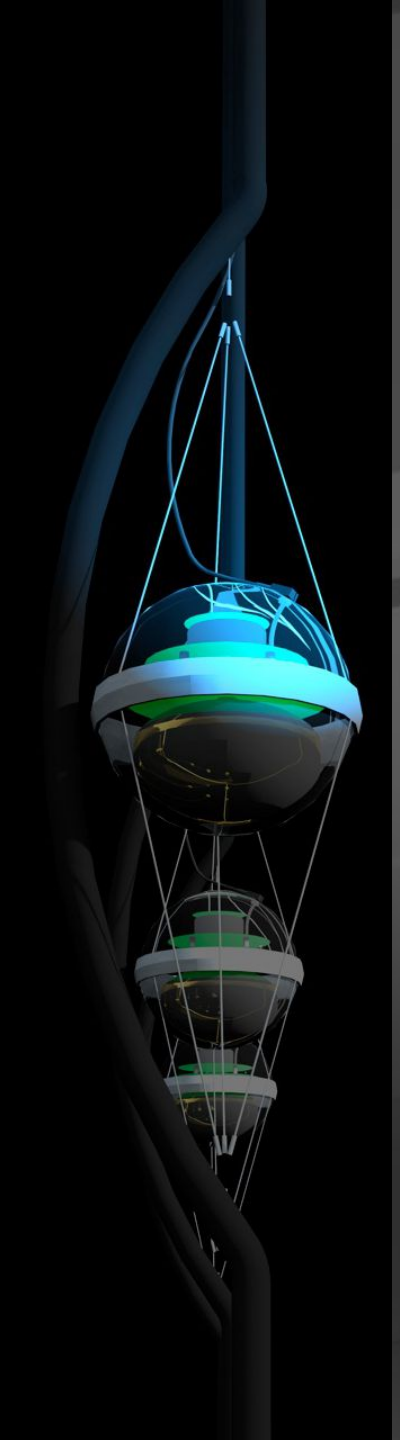


IceCube: beyond neutrino astronomy

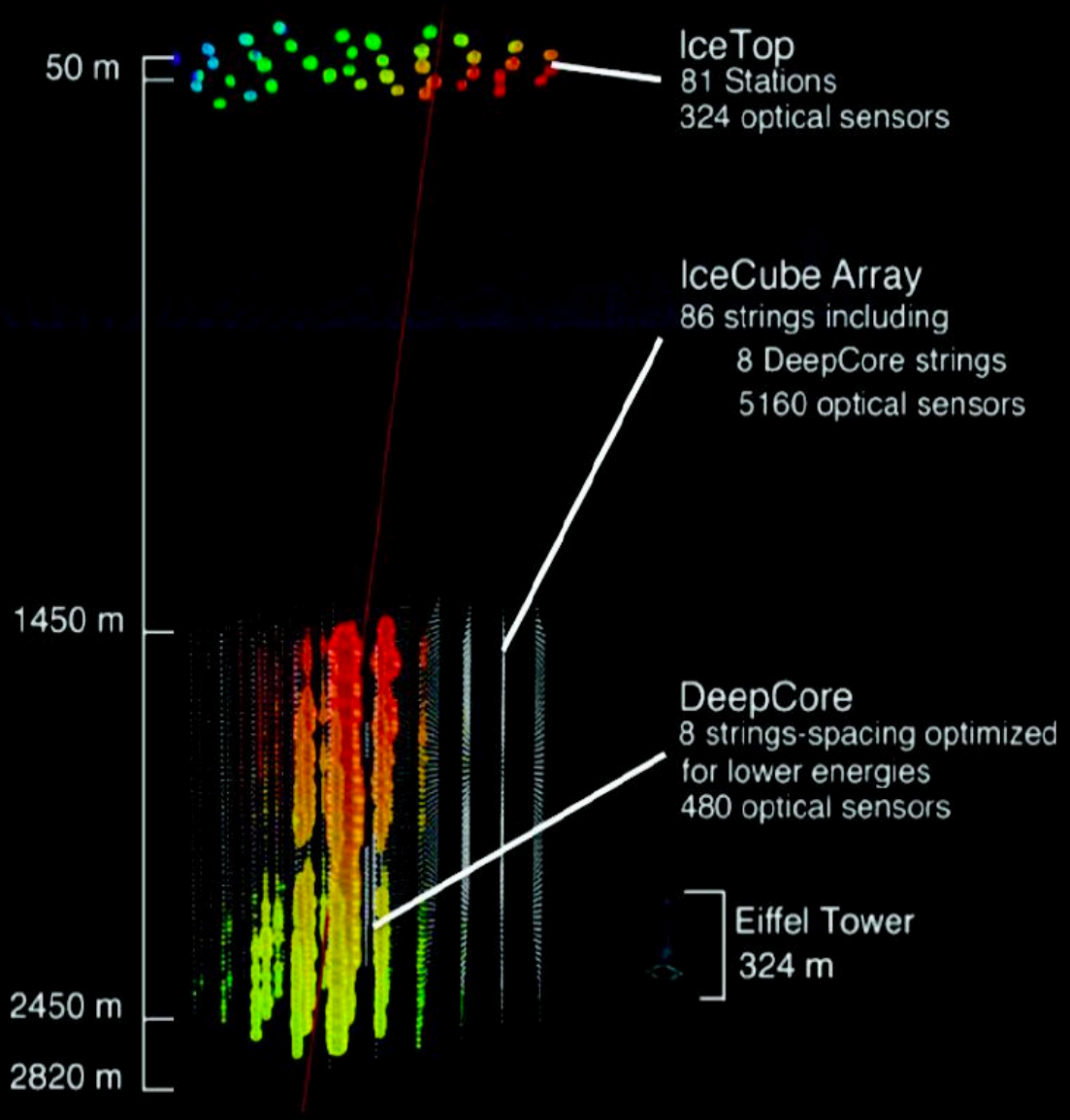
Francis Halzen

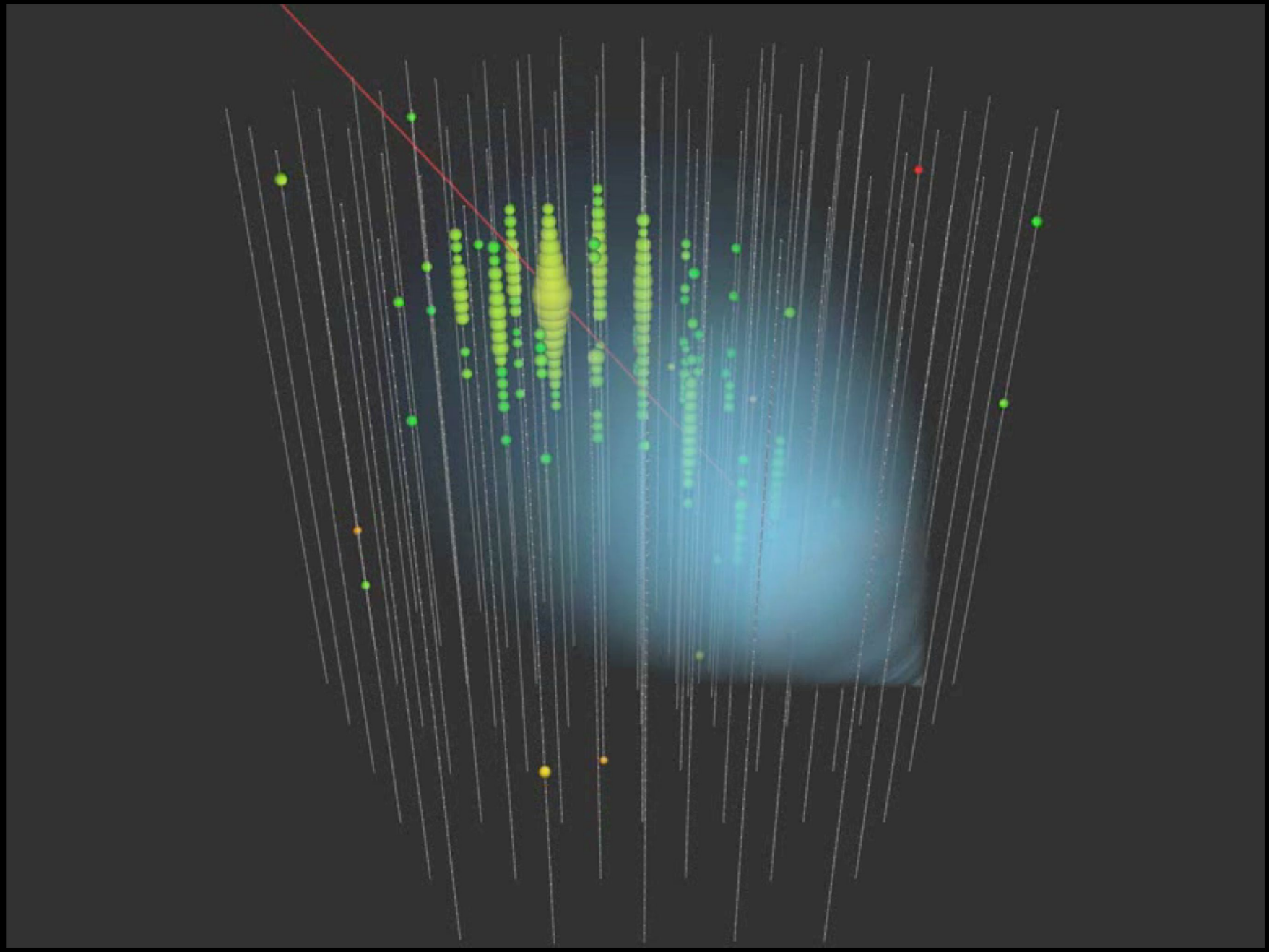
- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- …

the IceCube Neutrino Observatory

5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

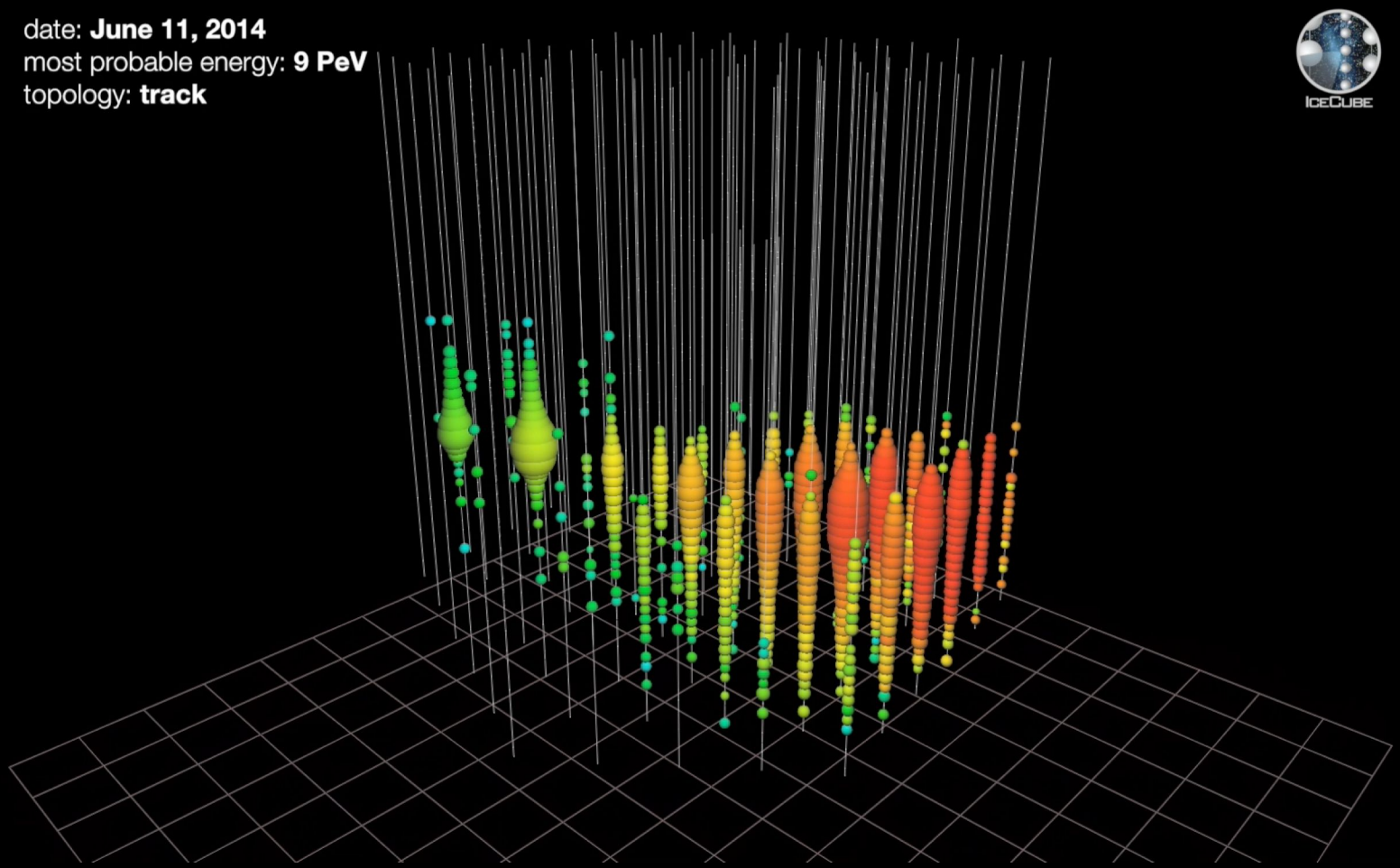
2 ns time resolution



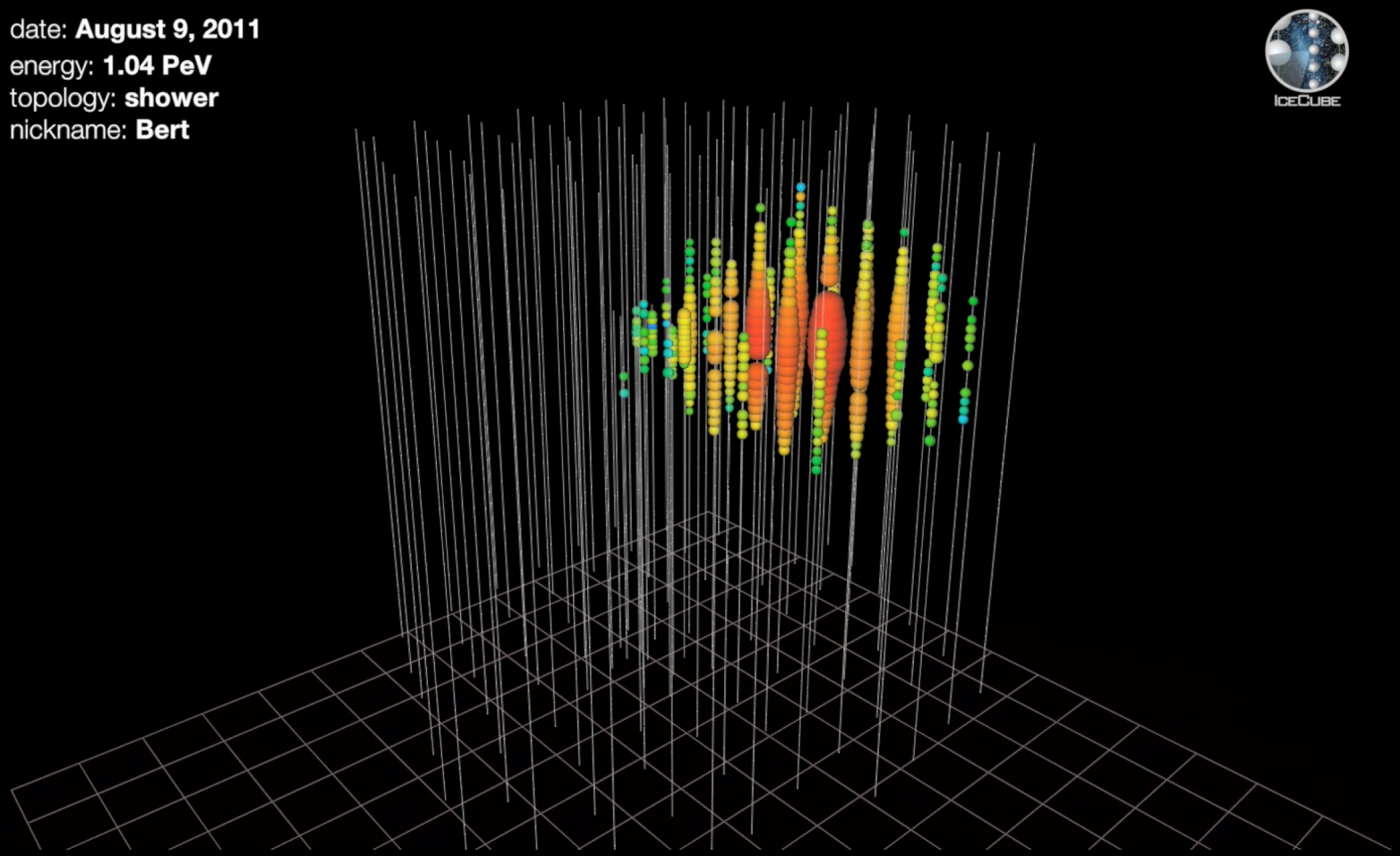


muon track: time is color; number of photons is energy

up-going muon track from muon neutrino (9 PeV)



shower initiated inside the detector by electron neutrino (1 PeV)



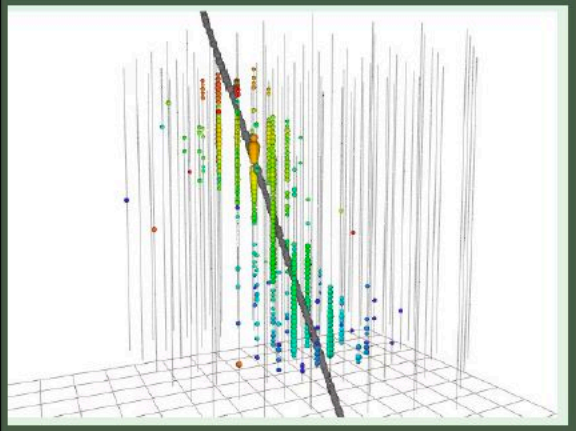
muons detected per year:

- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ 10~100

* 3000 per second ** 1 every 6 minutes

neutrino signatures in neutrino telescopes

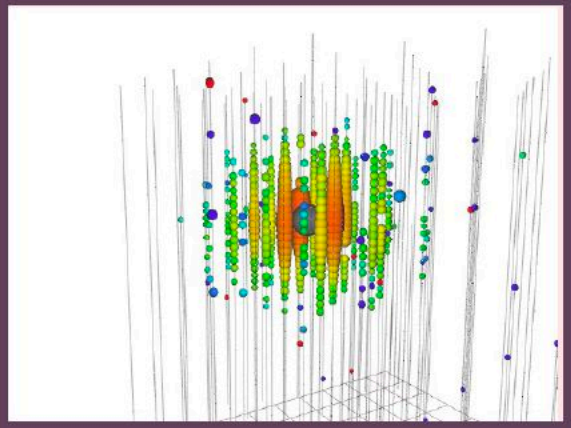
Track



- CC ν_μ
- Angular resolution <1°
- Energy resolution dE/E ≈25%

$$\nu_\mu + N \rightarrow \mu + X$$

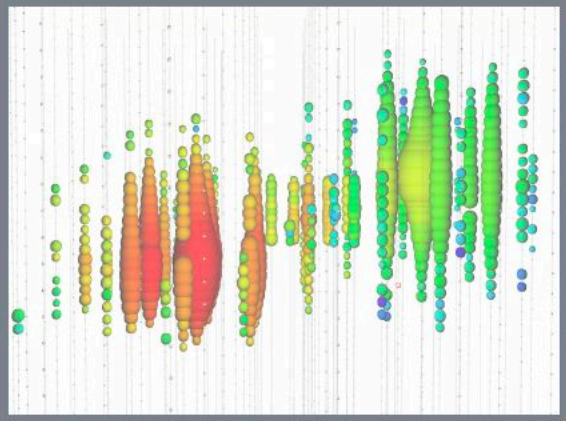
Cascade



- NC or CC ν_e/ν_τ
- Angular resolution ≈10°
- Energy resolution dE/E ≈10%

$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double-bang

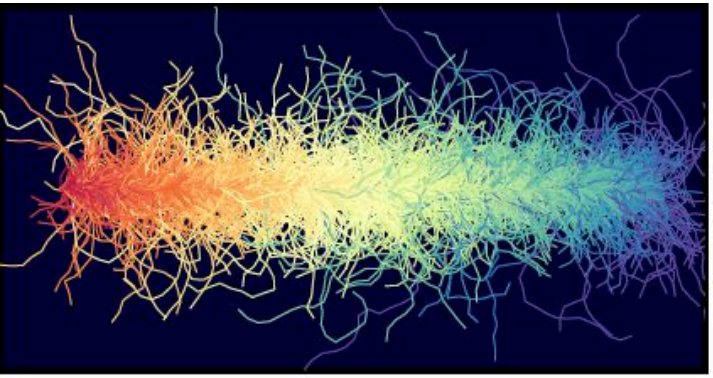
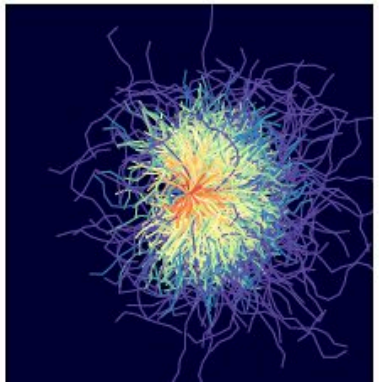
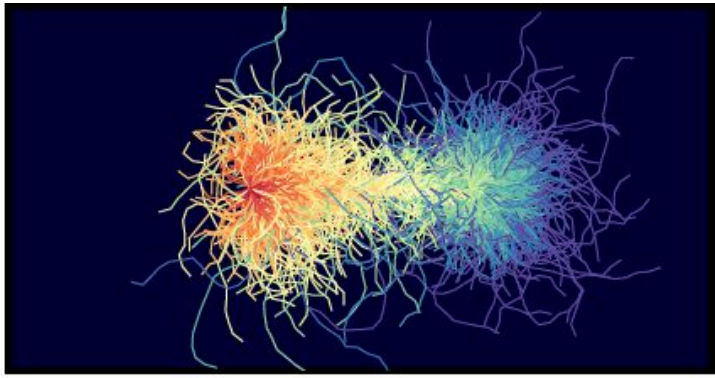


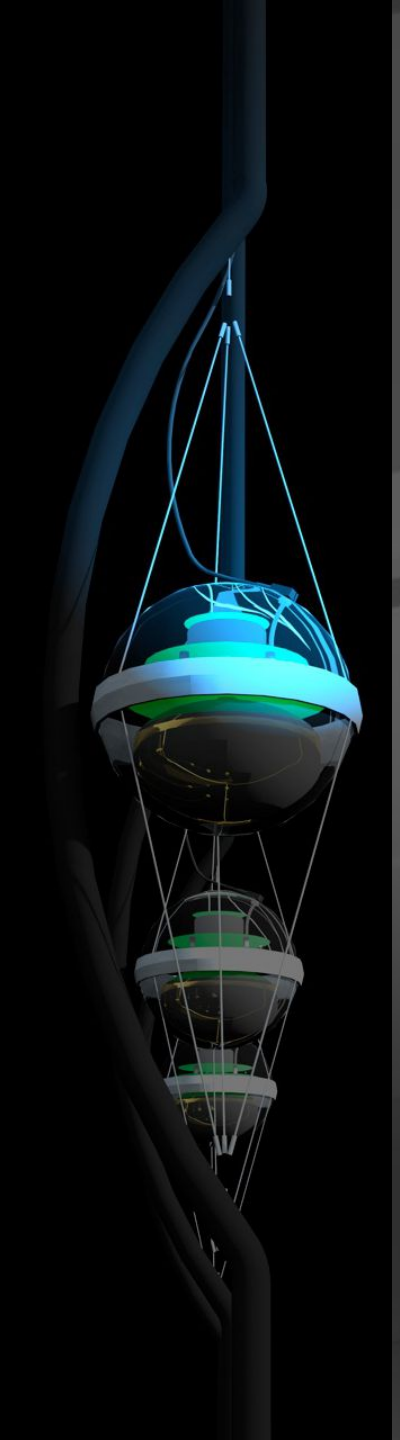
- High energy ν_τ ($\gtrapprox$ 100s TeV)
- Double-pulse structure in single cascades @ low energies

$$\nu_\tau + N \rightarrow \tau + X$$

early — late

amount of light in detector $\propto$ ν energy



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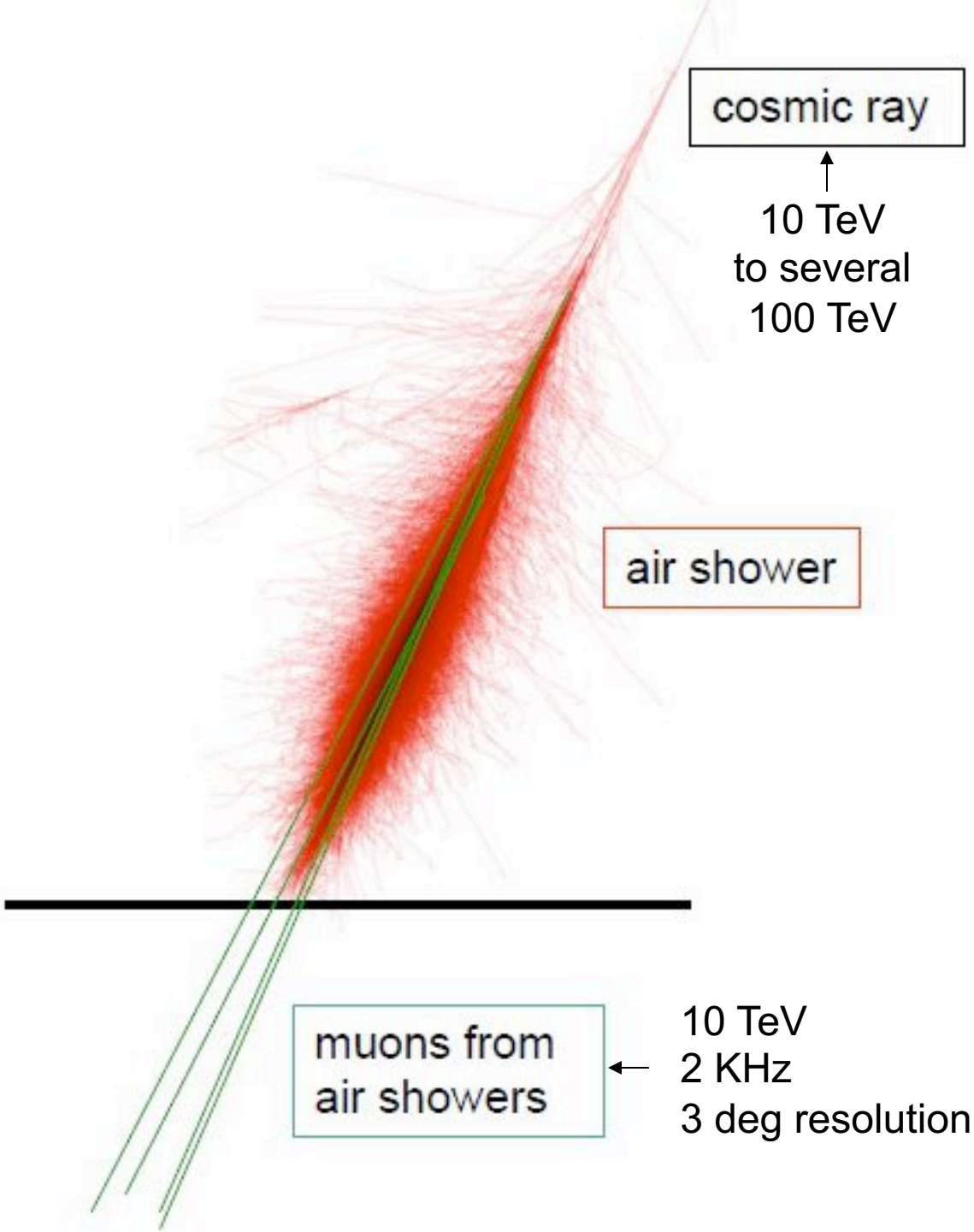
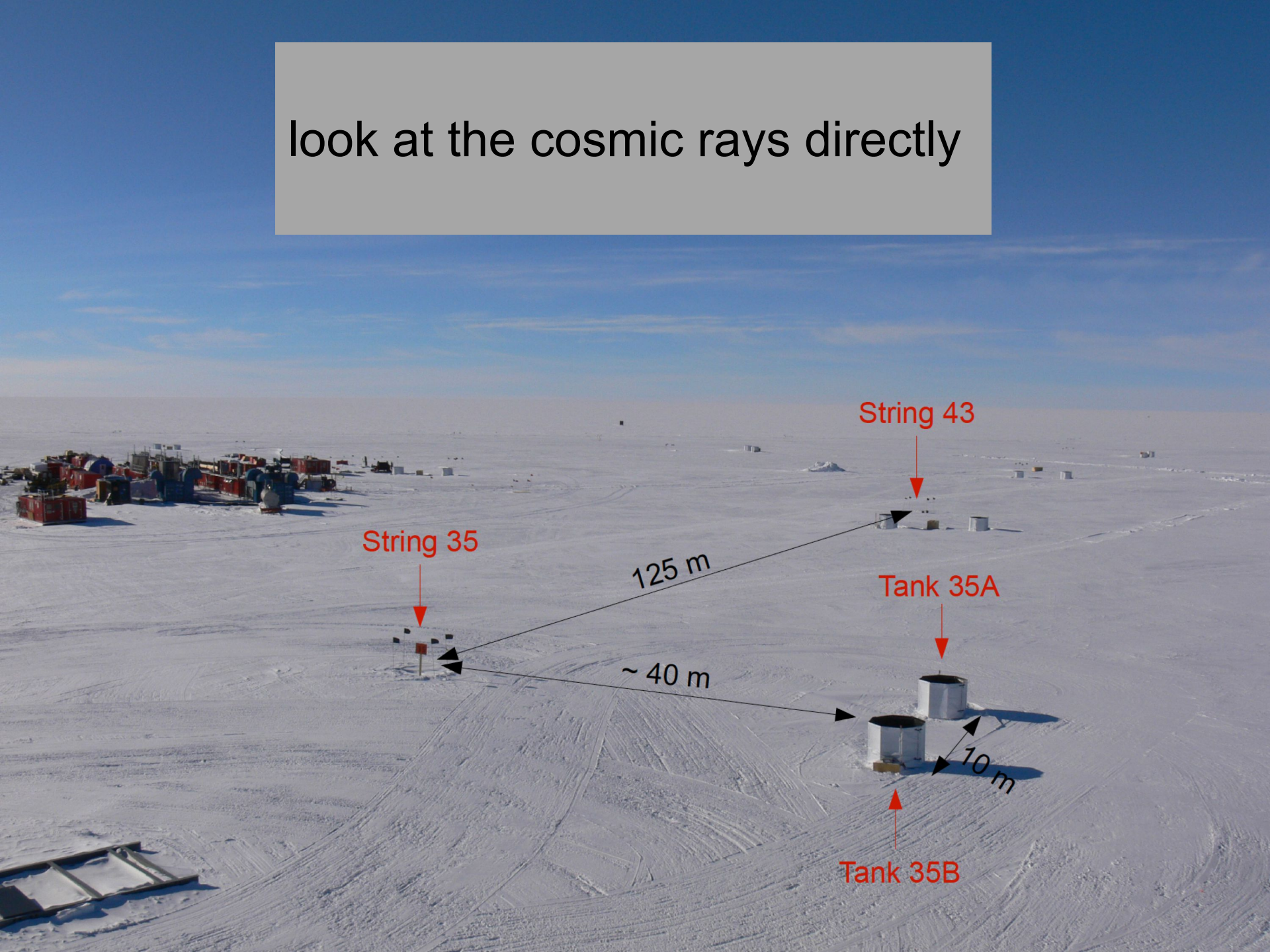
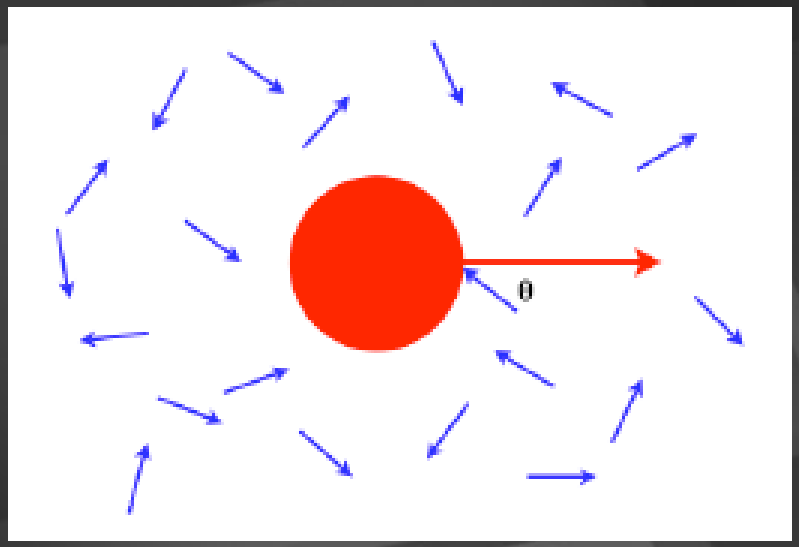
cosmic rays in IceCube



- galactic
- not solar
- highest energies approach the “knee”
- gyroradius < 1 pc in microgauss field
- closest sources < 100 pc

look at the cosmic rays directly

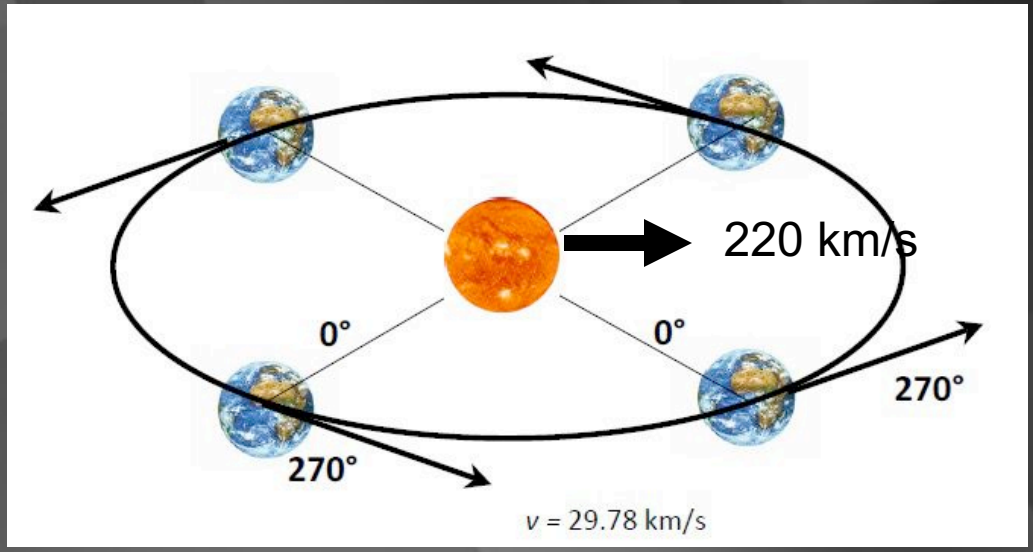


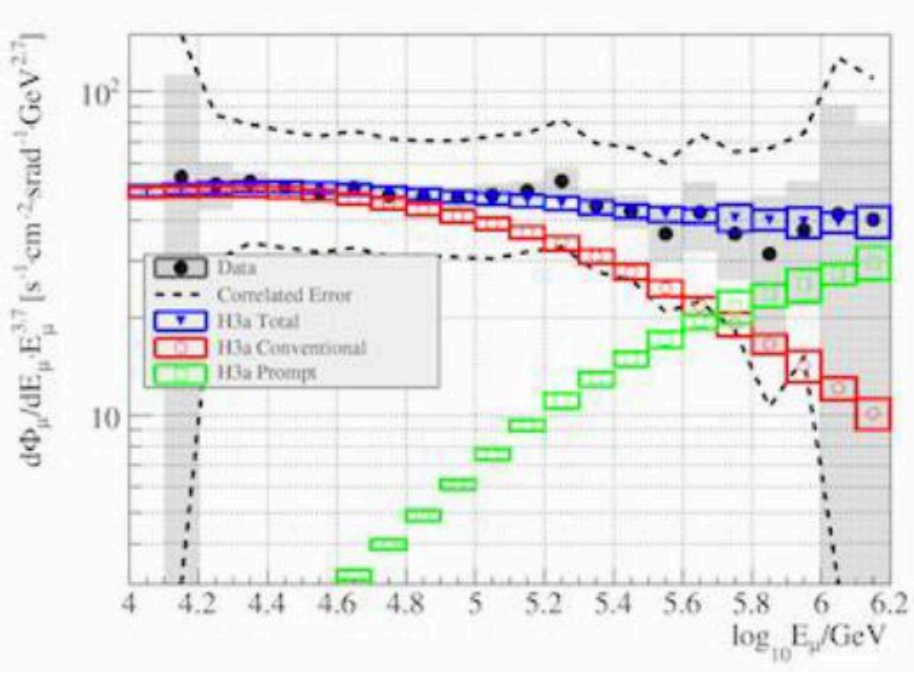


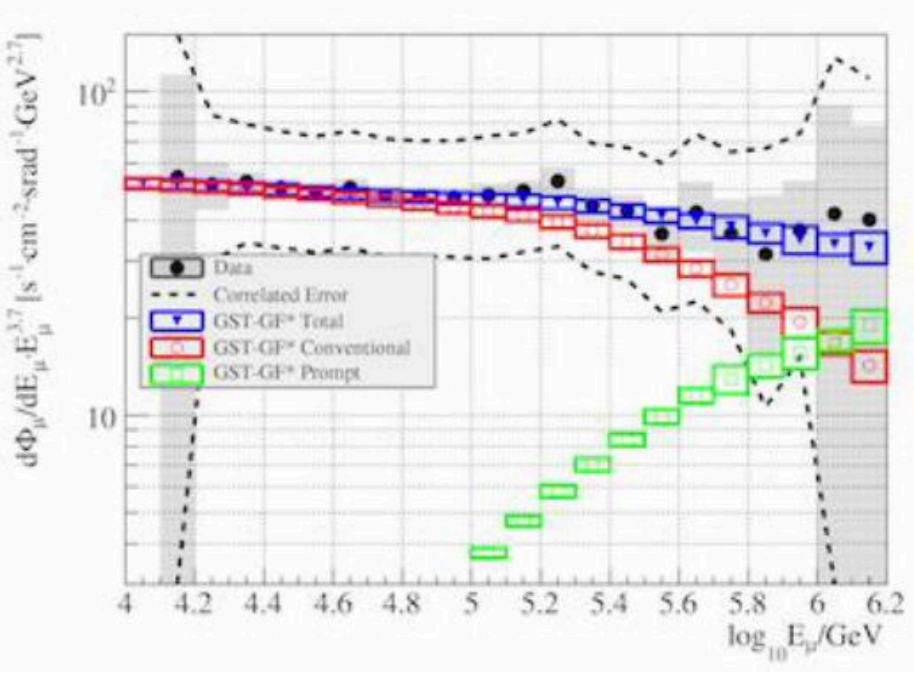
dipole anisotropies

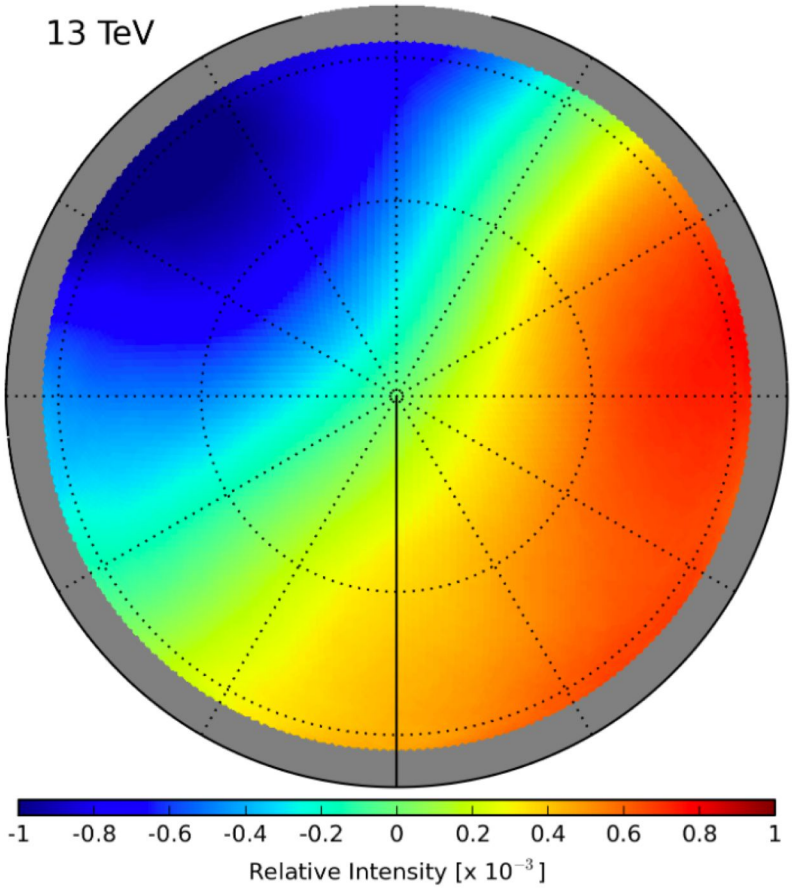
motion of the Earth in the frame of the cosmic rays?

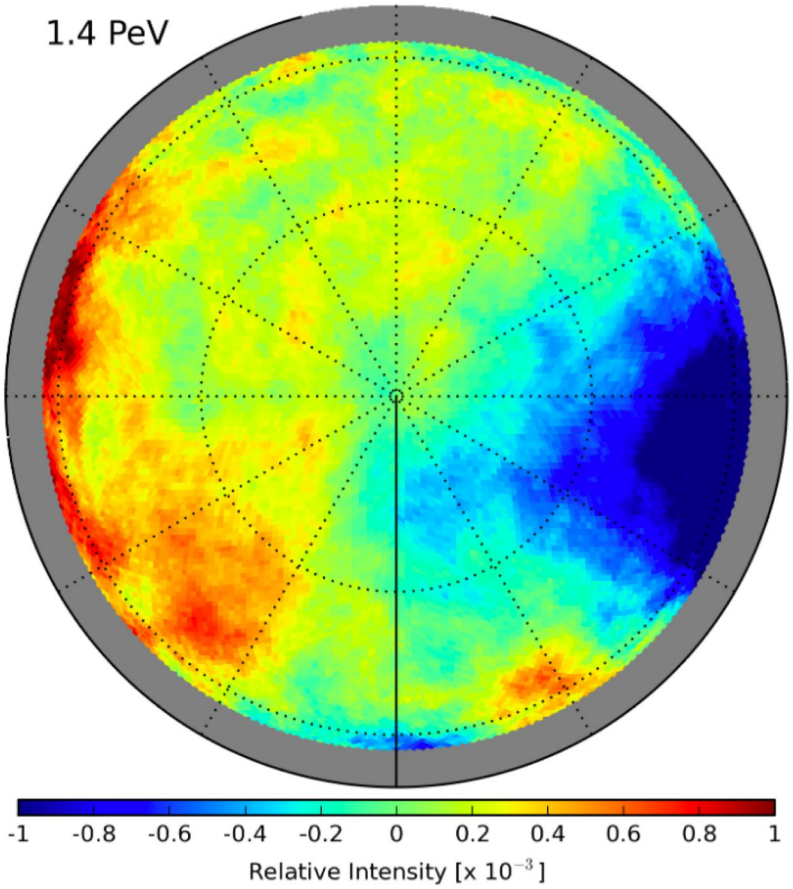
- solar dipole: motion of the Earth around the sun
- motion of the Sun relative to the Galaxy (Compton-Getting)

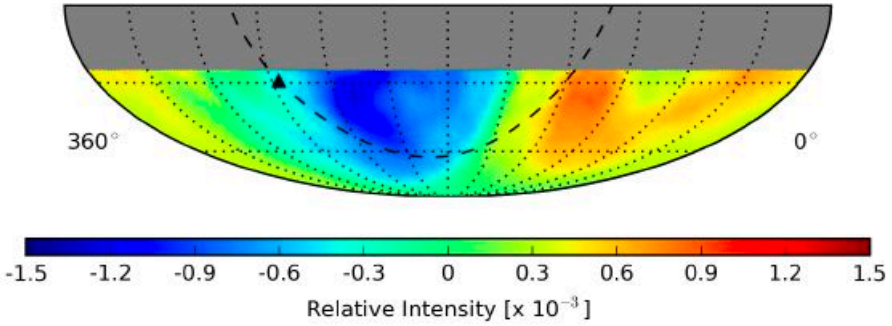


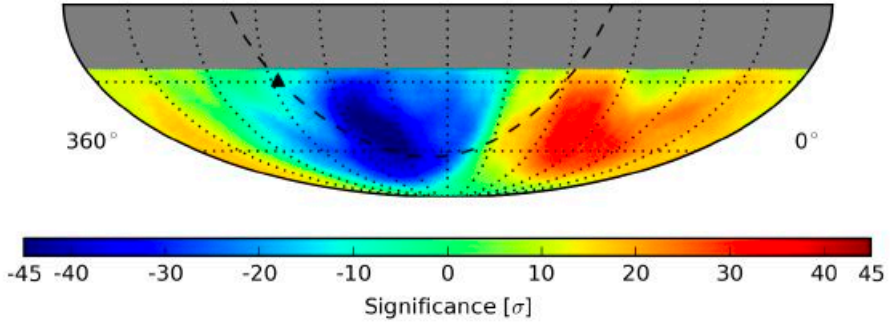

$d\Phi_\mu/dE_\mu E_\mu^{3.7}$ [s^{-1}·cm^{-2}·$srad^{-1}$·$GeV^{2.7}$]
10^2
10
Data
Correlated Error
H3a Total
H3a Conventional
H3a Prompt
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
$\log_{10} E_\mu$/GeV

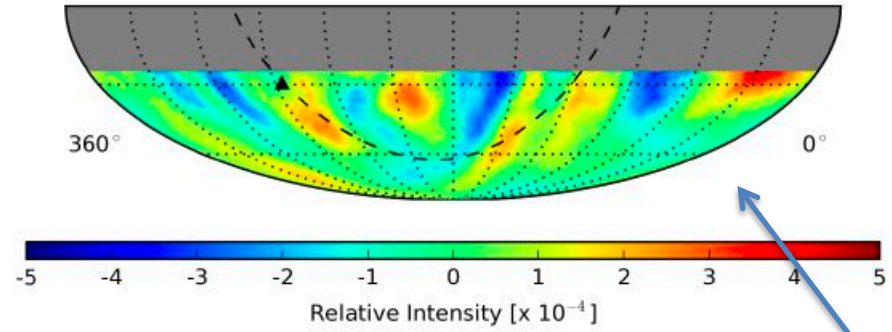

$d\Phi_\mu/dE_\mu E_\mu^{3.7}$ [s^{-1}·cm^{-2}·$srad^{-1}$·$GeV^{2.7}$]
10^2
10
Data
Correlated Error
GST-GF* Total
GST-GF* Conventional
GST-GF* Prompt
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
$\log_{10} E_\mu$/GeV

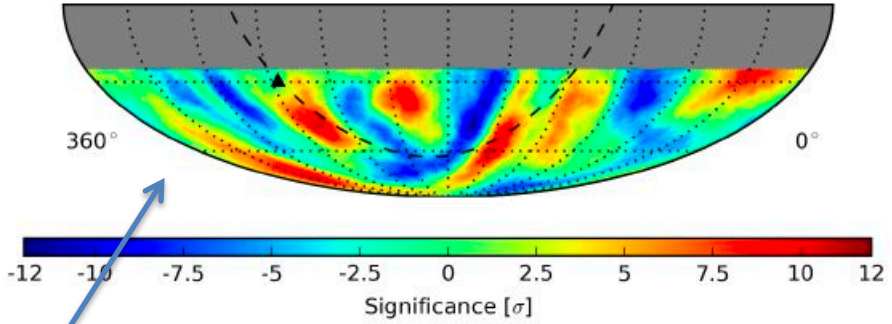

13 TeV
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Relative Intensity [x 10^{-3}]


1.4 PeV
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Relative Intensity [x 10^{-3}]



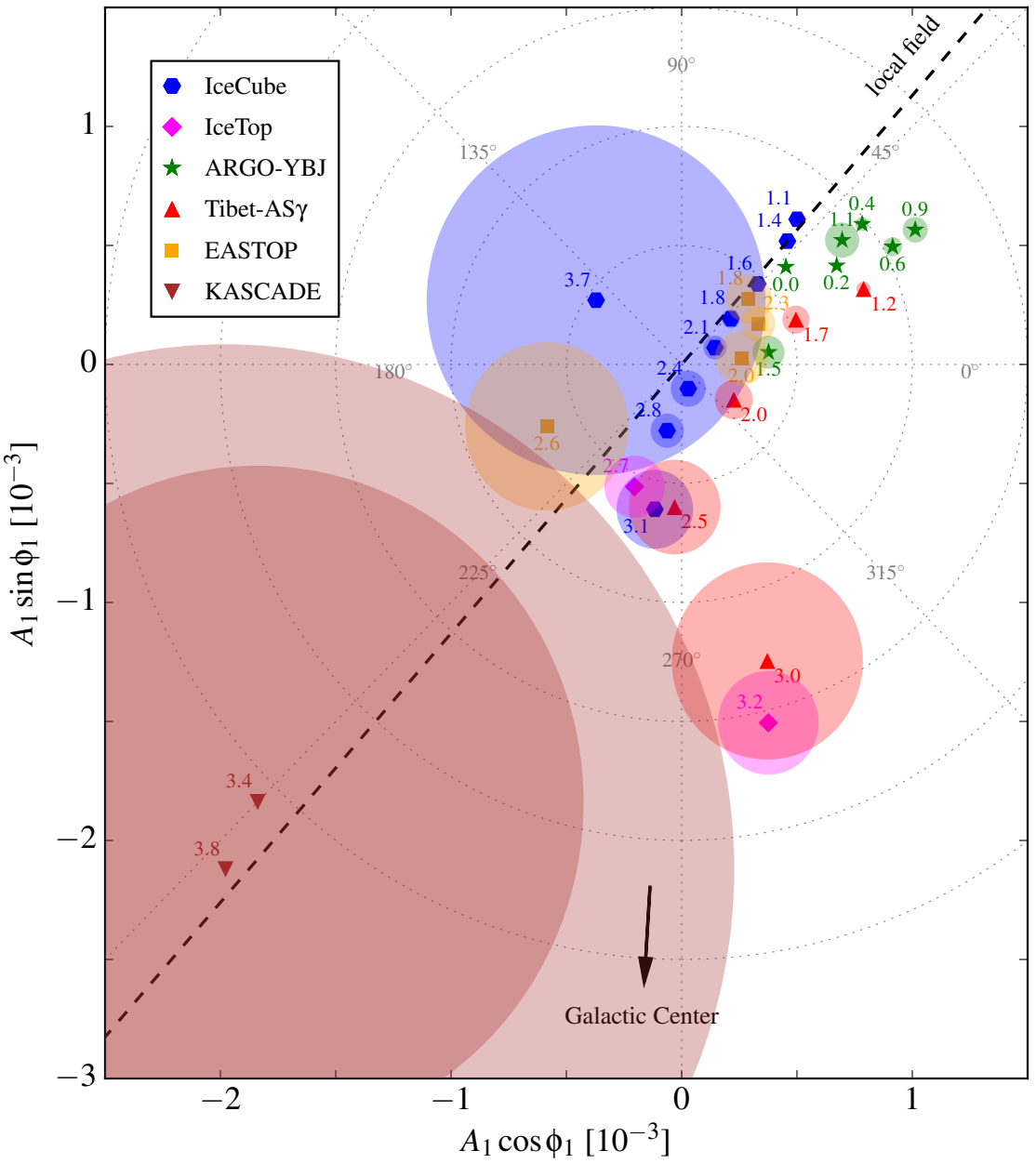


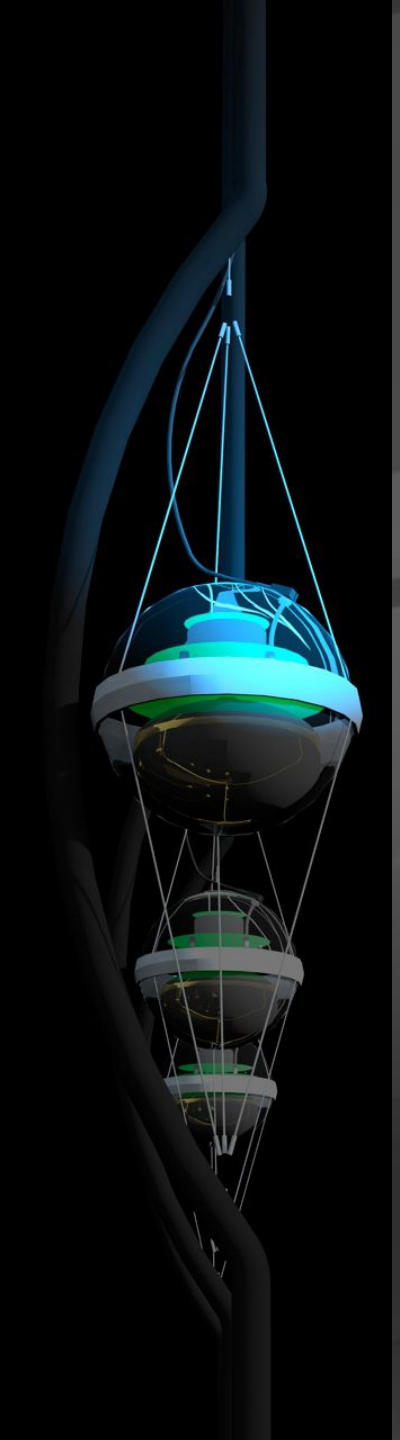




after subtraction of dipole and quadrupole

dipole rotates from the direction of the local magnetic field at TeV energy to the direction of the Galactic center at PeV energy possibly reflecting nearby sources (Vela?)





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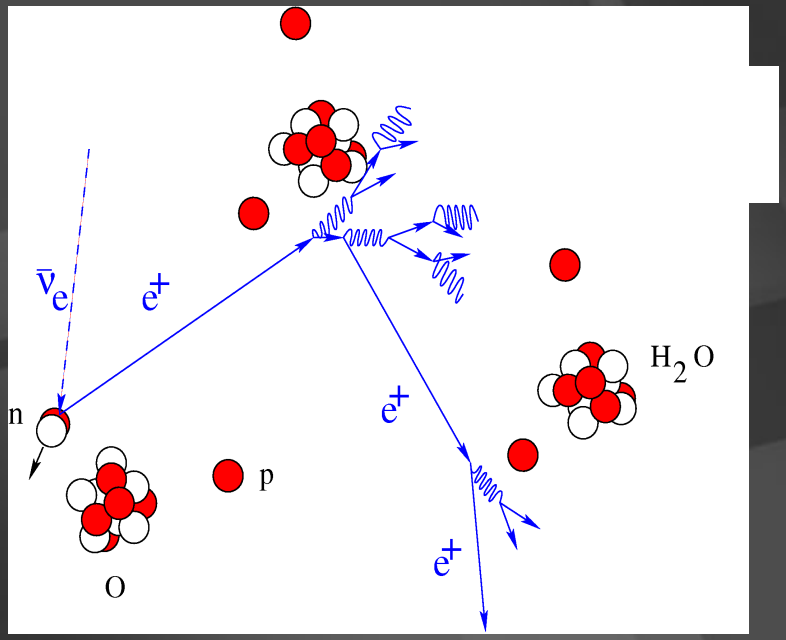
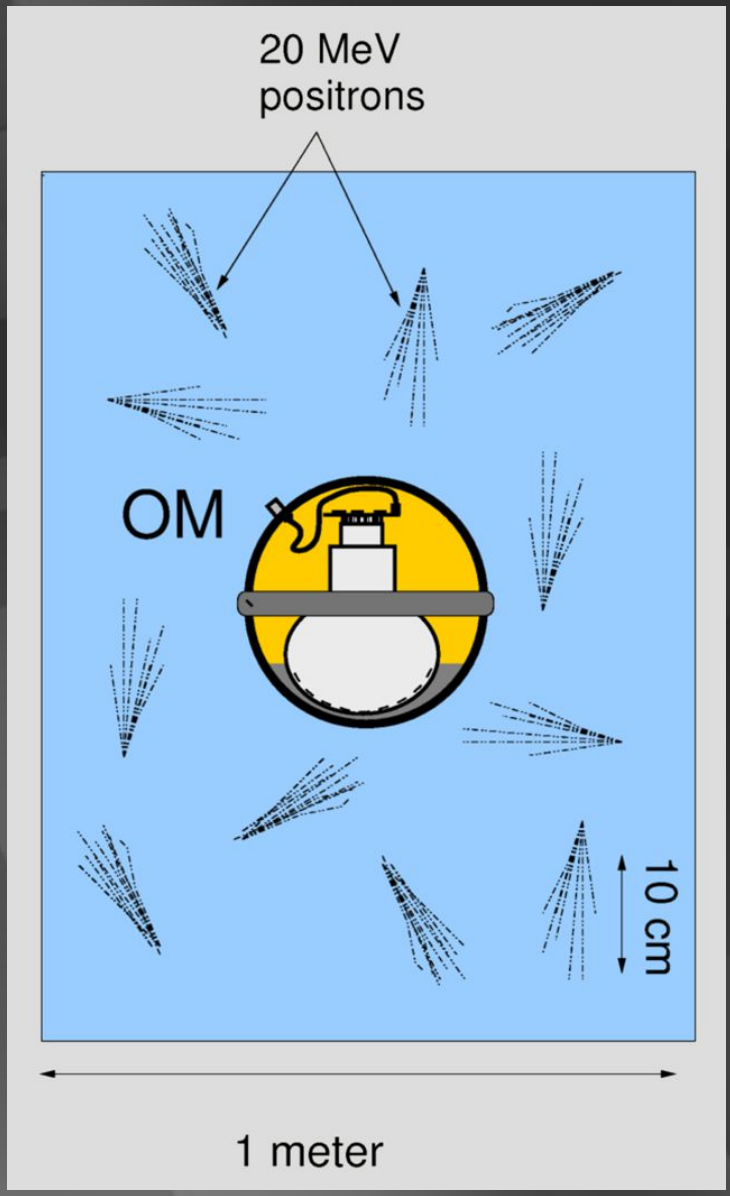
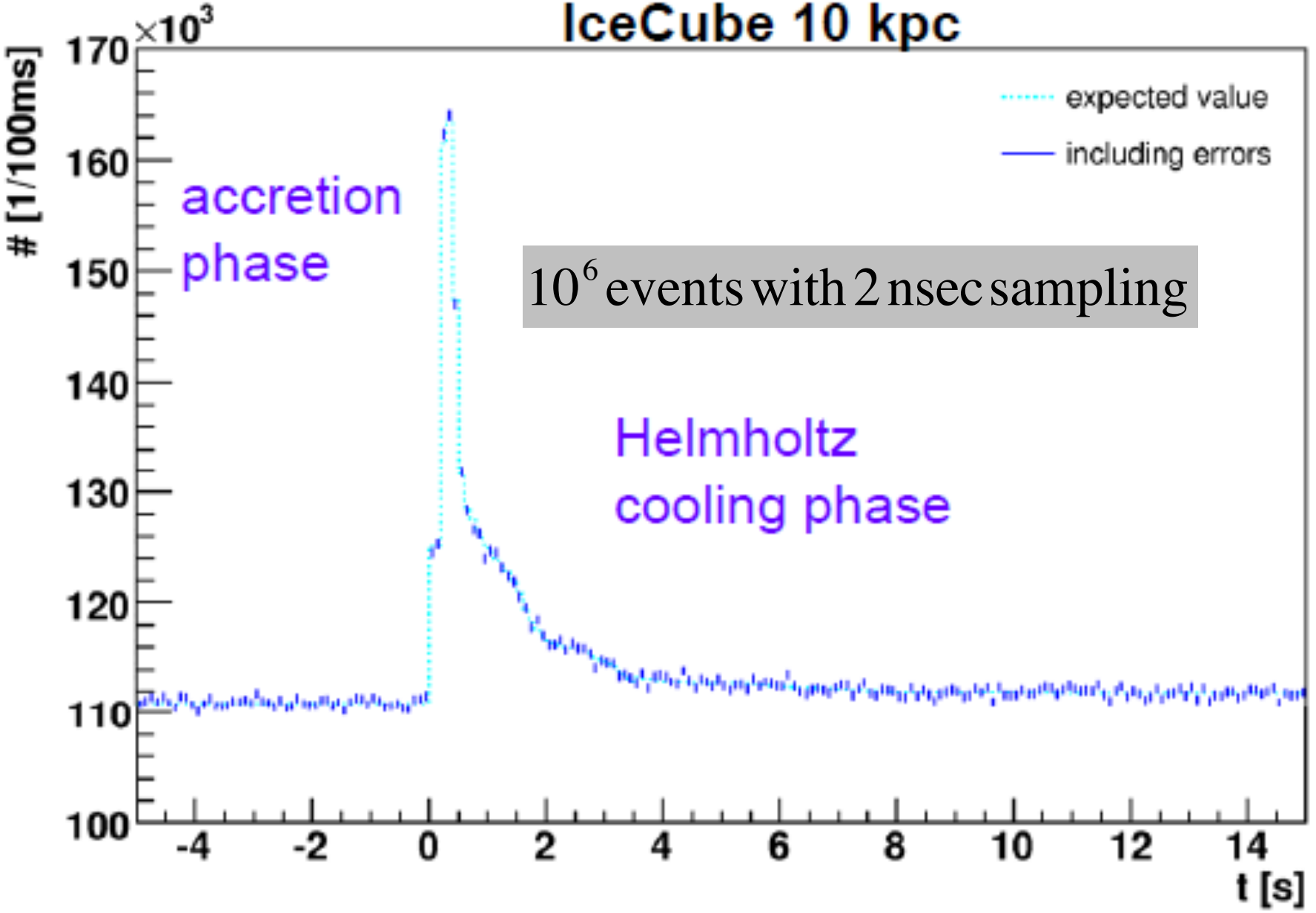
- …

supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

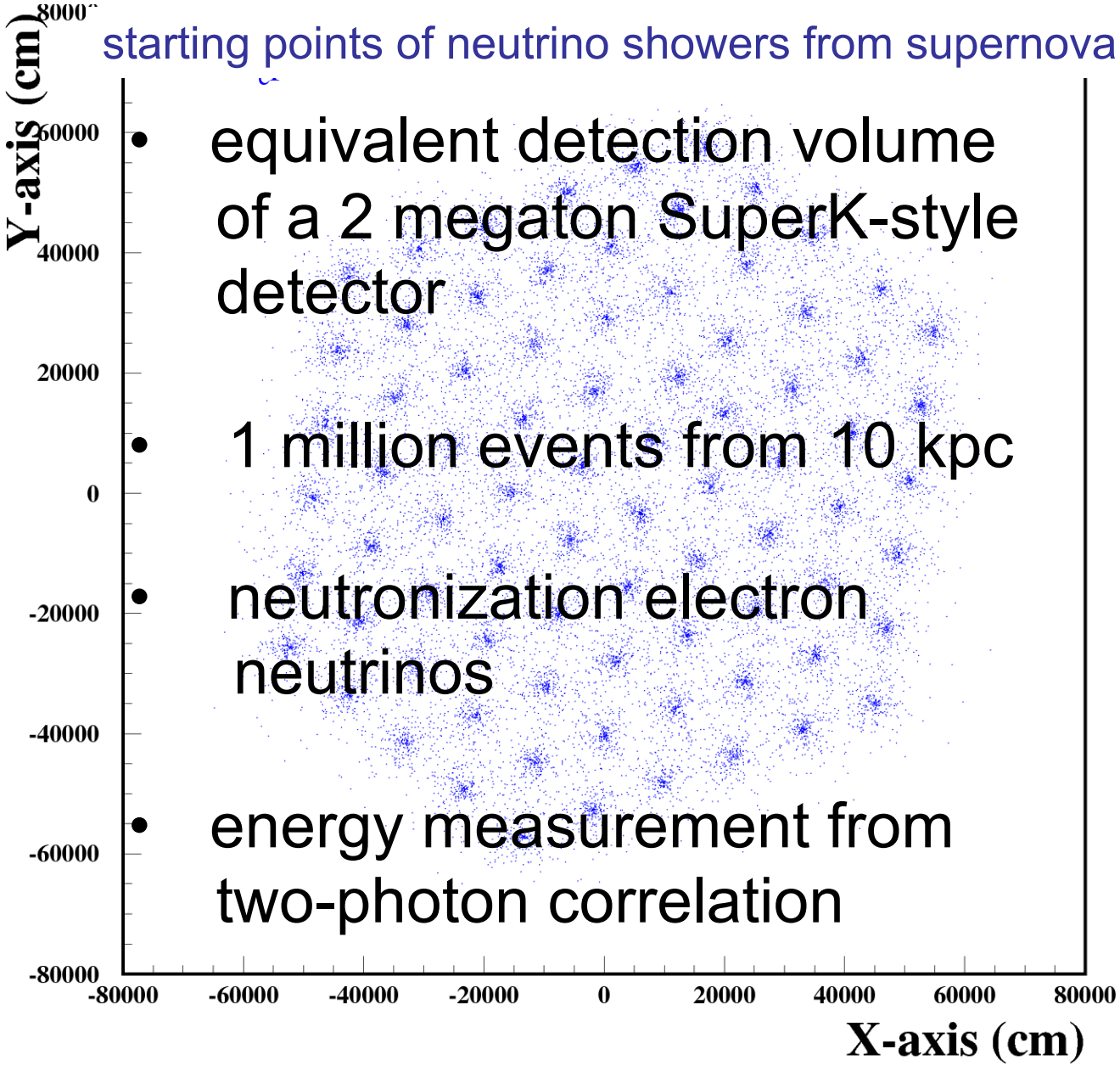




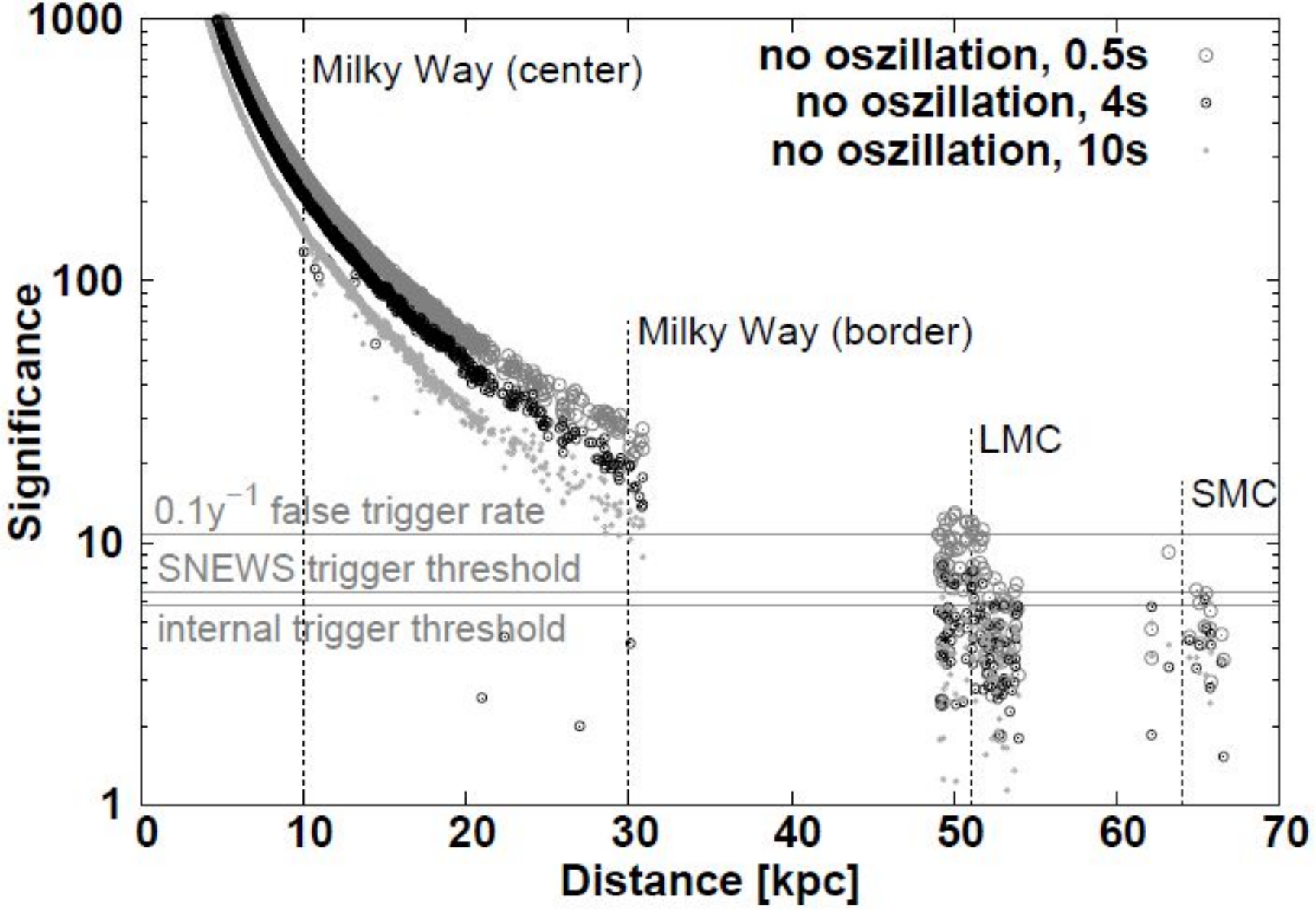
- PMT noise low (280 Hz)
- detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector


IceCube 10 kpc
×10^3
[1/100ms]
170
160
150
140
130
120
110
100
-4
-2
0
2
4
6
8
10
12
14
t [s]
expected value
including errors
accretion phase
10^6 events with 2 nsec sampling
Helmholtz cooling phase

starting points of neutrino showers from supernova

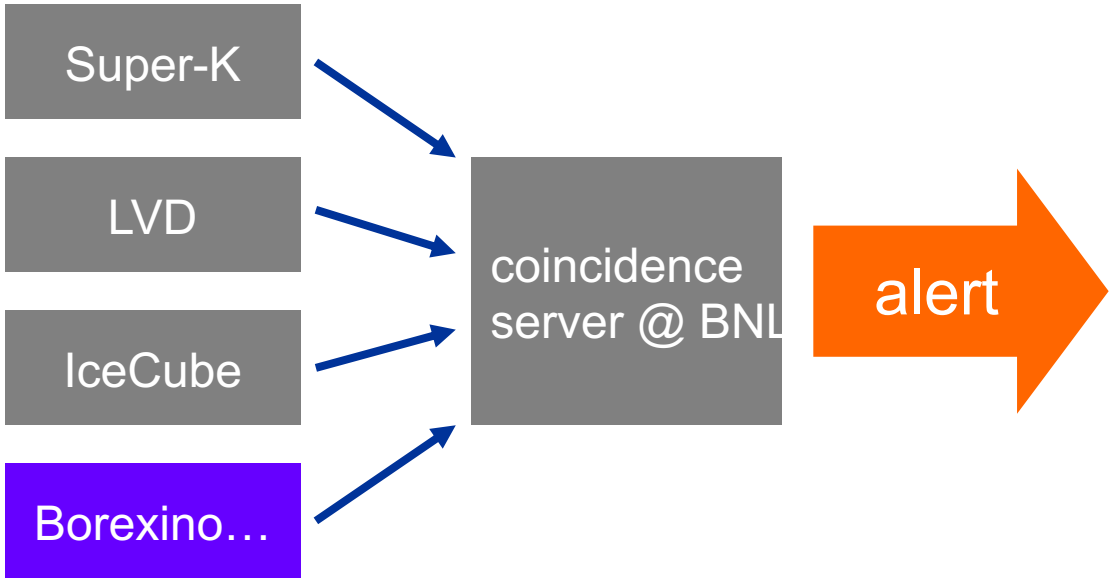


- equivalent detection volume of a 2 megaton SuperK-style detector
- 1 million events from 10 kpc
- neutronization electron neutrinos
- energy measurement from two-photon correlation


1000
100
10
1
Significance
0
10
20
30
40
50
60
70
Distance [kpc]
Milky Way (center)
Milky Way (border)
LMC
SMC
no oszillation, 0.5s
no oszillation, 4s
no oszillation, 10s
0.1y^{-1} false trigger rate
SNEWS trigger threshold
internal trigger threshold

Participation in SNEWS

…several hours advanced notice to astronomers …

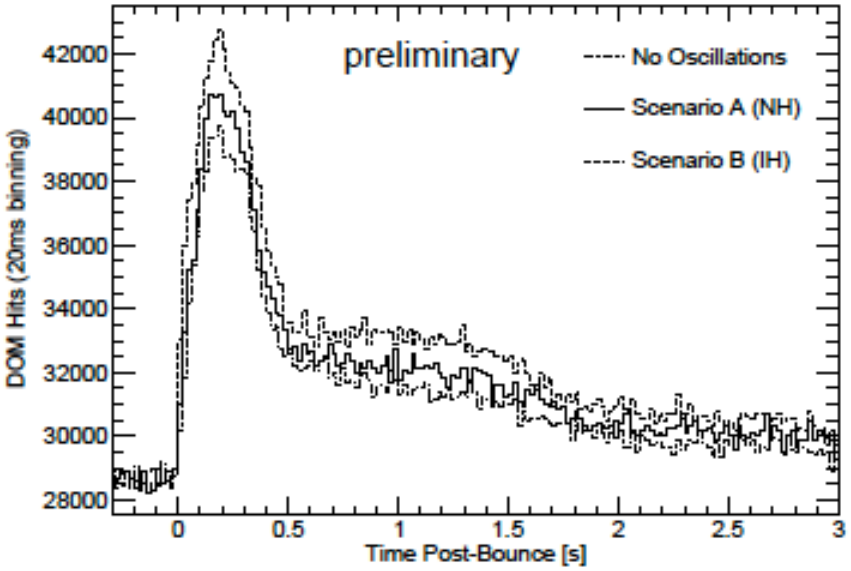


received iridium messages (last 4 weeks)

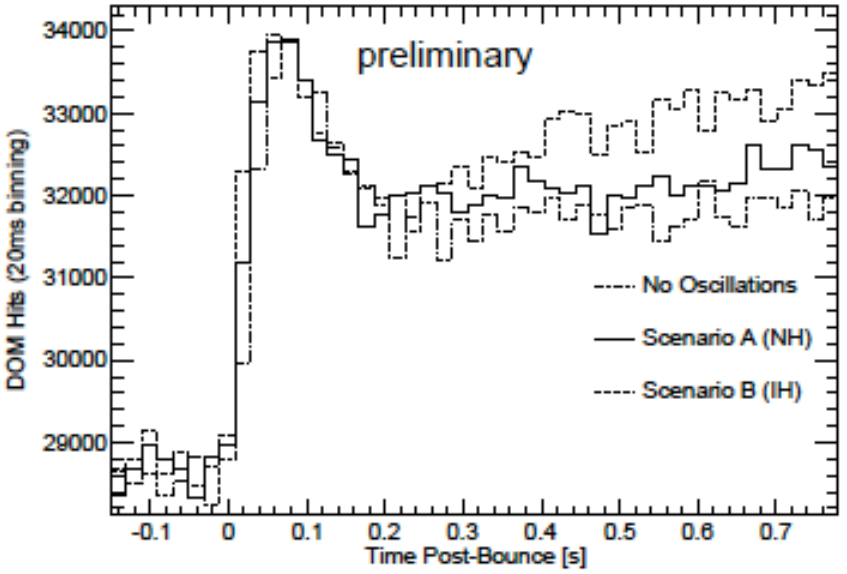
message type	time (UTC)	time delay to reception (seconds)	needed modem dial attempts
missing test message(s)			
test	Mon Jul 10 08:19:38 2006	224	1
test	Sun Jul 9 11:15:12 2006	218	1
test	Sat Jul 8 11:15:12 2006	208	1
test	Fri Jul 7 11:15:12 2006	208	1
test	Thu Jul 6 11:15:11 2006	214	1
test	Thu Jul 6 11:09:05 2006	205	1
missing test message(s)			
test	Mon Jul 3 09:45:12 2006	195	1
sn	Sun Jul 2 11:17:12 2006	445	1
	signal strength is [8.716532e+00 ± 1.325448e+00] Hz analysis timebase is [4] sec, active channels are [476], χ^2 is [5.421858e+02]		
test	Sun Jul 2 09:45:11 2006	196	1
test	Sat Jul 1 09:45:12 2006	195	1
test	Fri Jun 30 09:45:12 2006	185	1
test	Thu Jun 29 09:45:12 2006	181	1
sn	Wed Jun 28 11:20:29 2006	448	1
	signal strength is [7.296678e+00 ± 8.447978e-01] Hz analysis timebase is [10] sec, active channels are [474], χ^2 is [5.770201e+02]		
test	Wed Jun 28 09:45:12 2006	185	1
test	Tue Jun 27 09:45:12 2006	175	1
test	Mon Jun 26 09:45:12 2006	175	1
test	Sun Jun 25 09:45:12 2006	176	1
sn	Sun Jun 25 02:15:47 2006	571	2
	signal strength is [9.946102e+00 ± 1.333087e+00] Hz analysis timebase is [4] sec, active channels are [475], χ^2 is [5.061309e+02]		
test	Sat Jun 24 09:45:12 2006	165	1
test	Fri Jun 23 09:45:12 2006	165	1
test	Fri Jun 23 09:26:21 2006	170	1
test	Fri Jun 23 08:59:13 2006	732	10
test	Thu Jun 22 10:33:23 2006	162	1
test	Thu Jun 22 09:45:12 2006	160	1
test	Thu Jun 22 09:38:29 2006	163	1
test	Thu Jun 22 09:27:30 2006	167	1
test	Thu Jun 22 08:45:12 2006	173	1
missing test message(s)			
test	Tue Jun 20 09:30:12 2006	154	1

http://snews.bnl.gov astro-ph/0406214

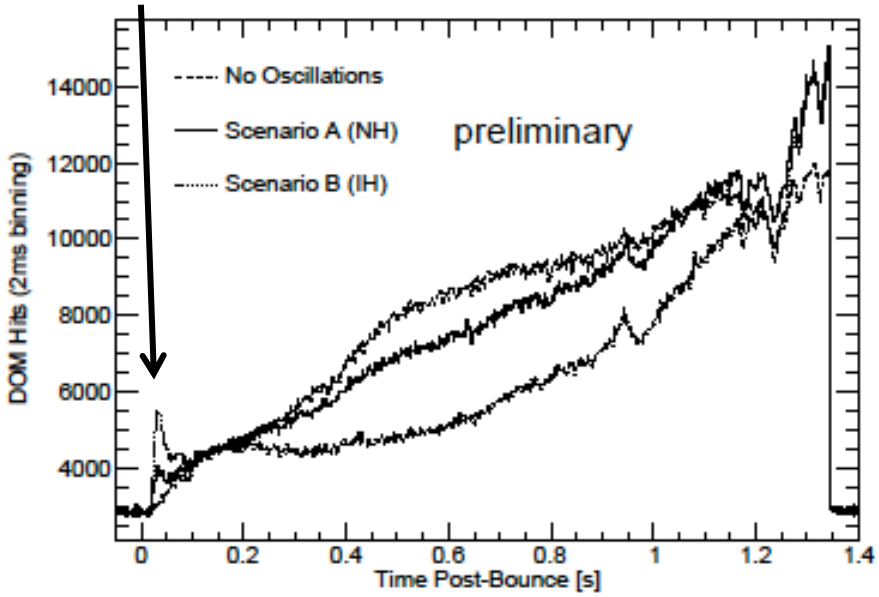
Livermore



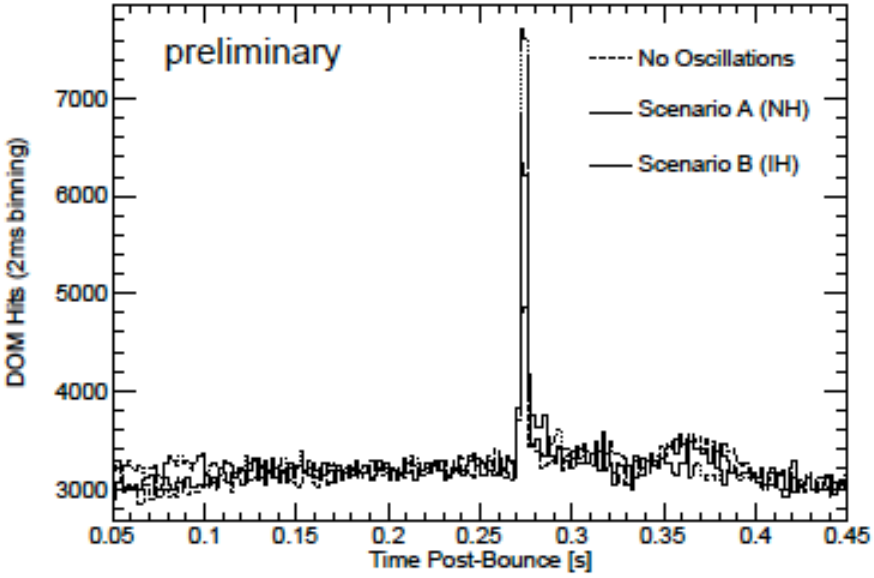
Garching

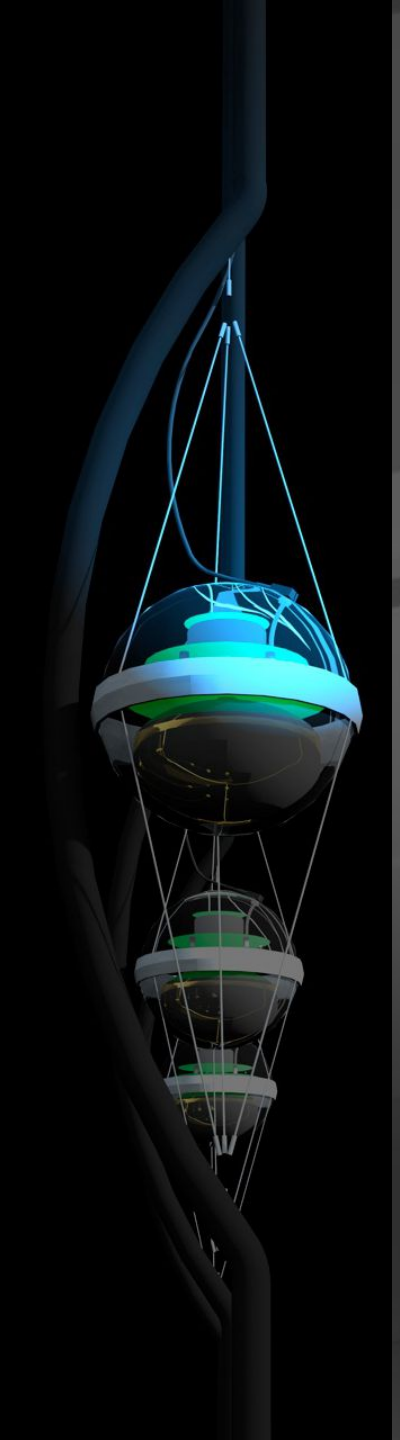


black hole



quark star





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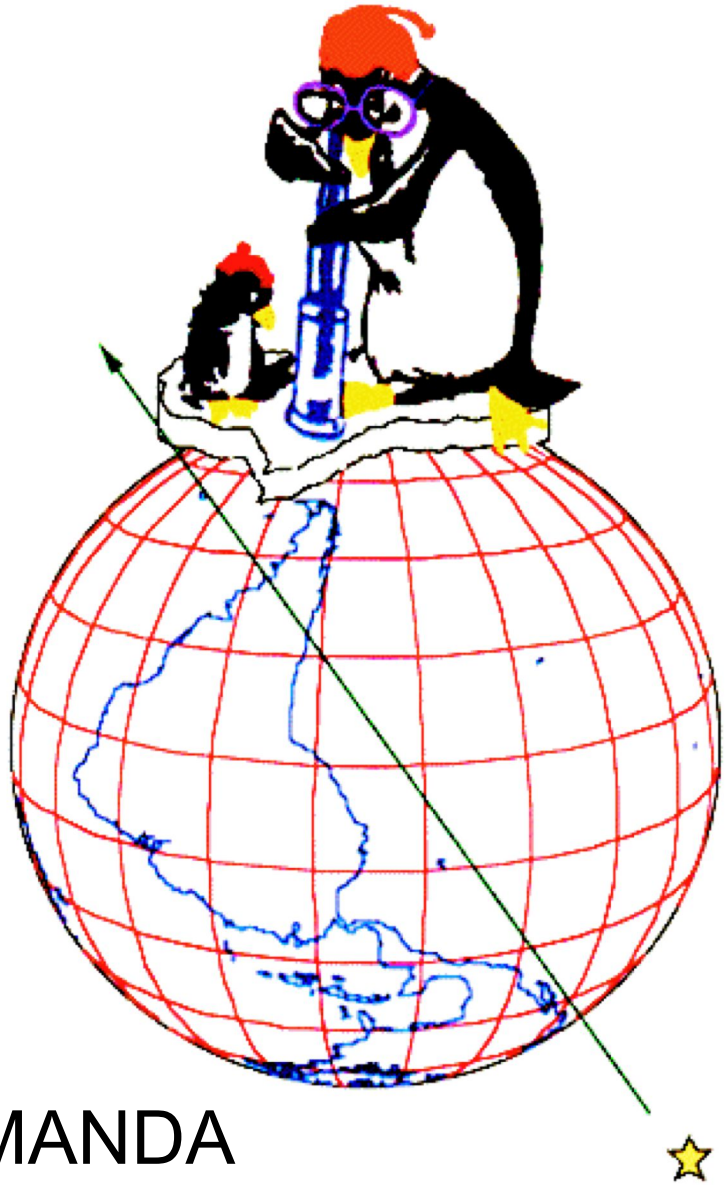
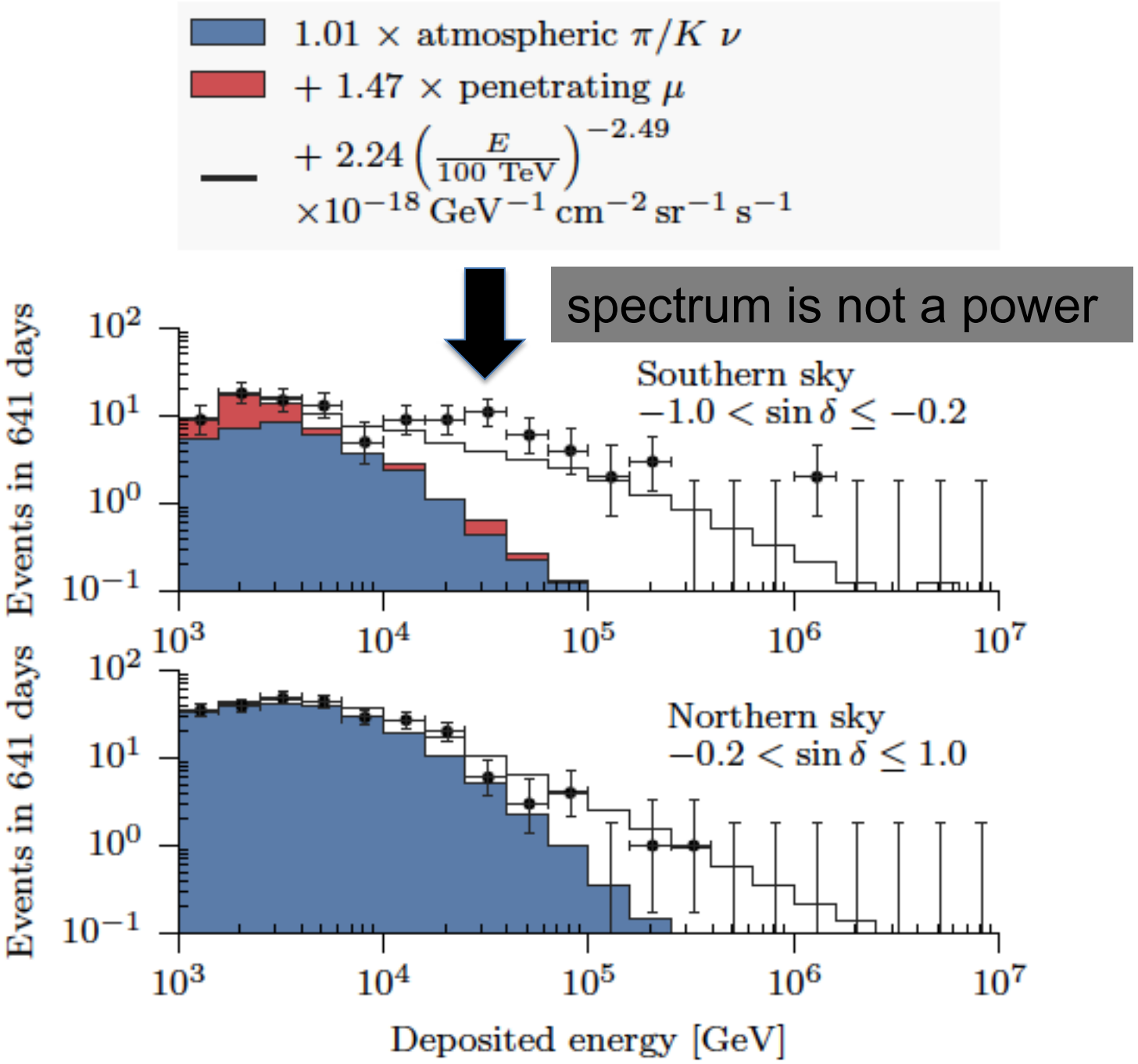
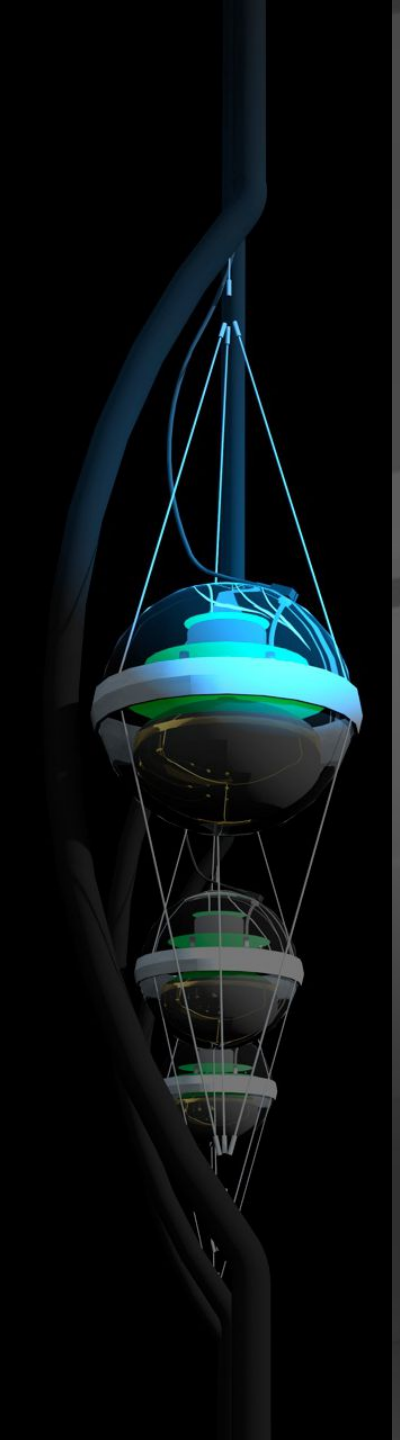
1992 Cline meeting at UCLA



AMANDA


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
$+ 2.24 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.49}$
$\times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$
spectrum is not a power
Southern sky
$-1.0 < \sin\delta \leq -0.2$
Northern sky
$-0.2 < \sin\delta \leq 1.0$
Events in 641 days
Events in 641 days
Deposited energy [GeV]



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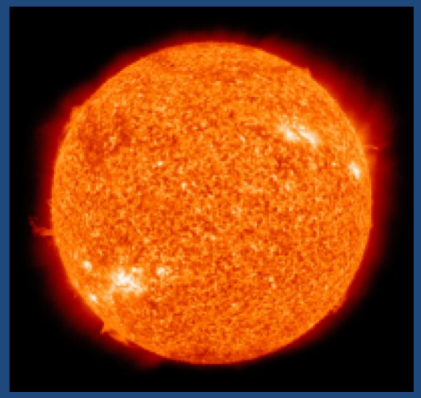
IceCube targets for dark matter annihilation

Sun



Galactic Centre

Dwarf galaxies

Earth

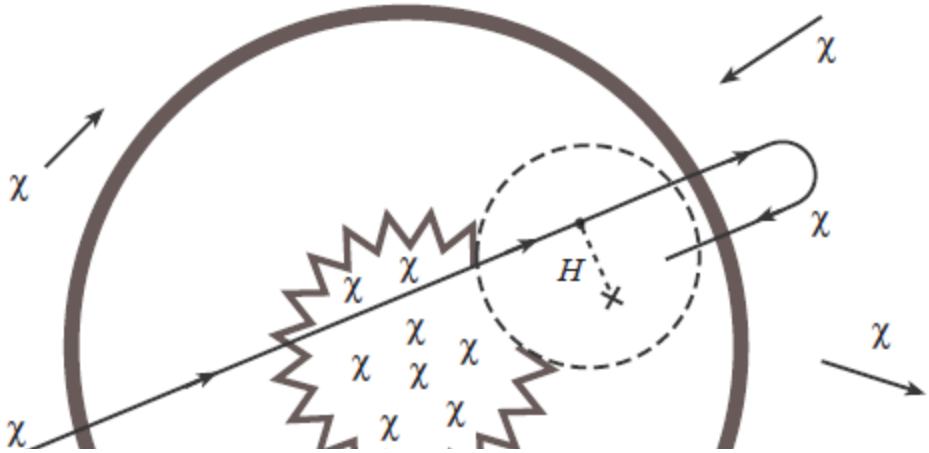
Galactic Halo

Galaxy clusters

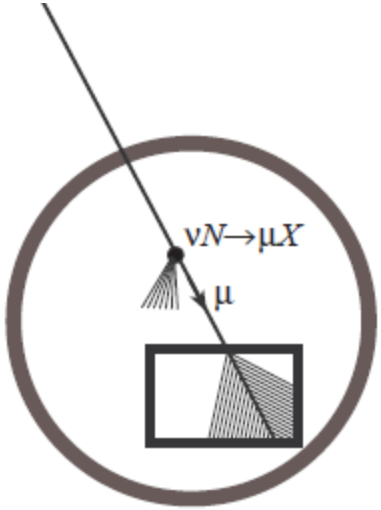
WIMP Capture and Annihilation

1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the south pole, convert into muons in the ice

$$\chi + \chi \rightarrow W^+ + W^- \rightarrow \nu + \nu$$
$$\text{or} \quad \rightarrow \tau^+ + \tau^- \rightarrow \nu + \nu$$



$$C^{\odot} \approx 3.35 \times 10^{20}\,\mathrm{sec}^{-1} \left(\frac{\rho_{\mathrm{local}}}{0.3\,\mathrm{GeV/cm}^3}\right) \left(\frac{270\,\mathrm{km/s}}{\bar{v}_{\mathrm{local}}}\right)^3 \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2$$
$$\times \left(\frac{\sigma_{\chi\mathrm{H,SD}} + \sigma_{\chi\mathrm{H,SI}} + 0.07\,\sigma_{\chi\mathrm{He,SI}} + 0.0005\,S(m_\chi/m_{\mathrm{O}})\,\sigma_{\chi\mathrm{O,SI}}}{10^{-6}\,\mathrm{pb}}\right).$$



supersymmetry on the back of an envelope
arXiv 9404252

$$\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}$$

- $\varphi_\chi = \left[\frac{\rho}{m_\chi}\right] \mathrm{v}_\chi$
- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}$
- $C_{sun} = 2\, C_{annihilation}$ (equilibrium)

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ, b or W for instance) the model is seen or ruled out

$$\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}$$

- $\varphi_\chi = \left[\frac{\rho}{m_\chi}\right] \mathrm{v}_\chi$
- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}$
- $C_{sun} = 2\, C_{annihilation}$ (equilibrium)

astrophysical assumptions !!!

number of protons in the sun

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ, b or W for instance) the model is seen or ruled out

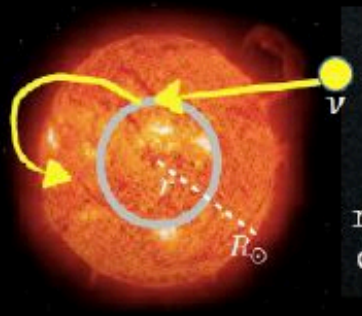
detection is a smoking gun

- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
  → no unknown astrophysics

- in the neutrino case there is a direct connection between theory and observation and the background is understood.

3yrs of WIMP search from the Sun

WIMP Capture and Annihilation in the Sun



$$\Gamma_{capt} = \frac{\rho_{DM}}{M_{DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\, 4\pi r^2\, n_i(r) \int_0^{\infty} dv\, 4\pi v^2\, f_\odot(v)\, \frac{v^2 + v_{\odot esc}^2}{v}\, \varphi_i(v, v_{\odot esc})$$

DM number density

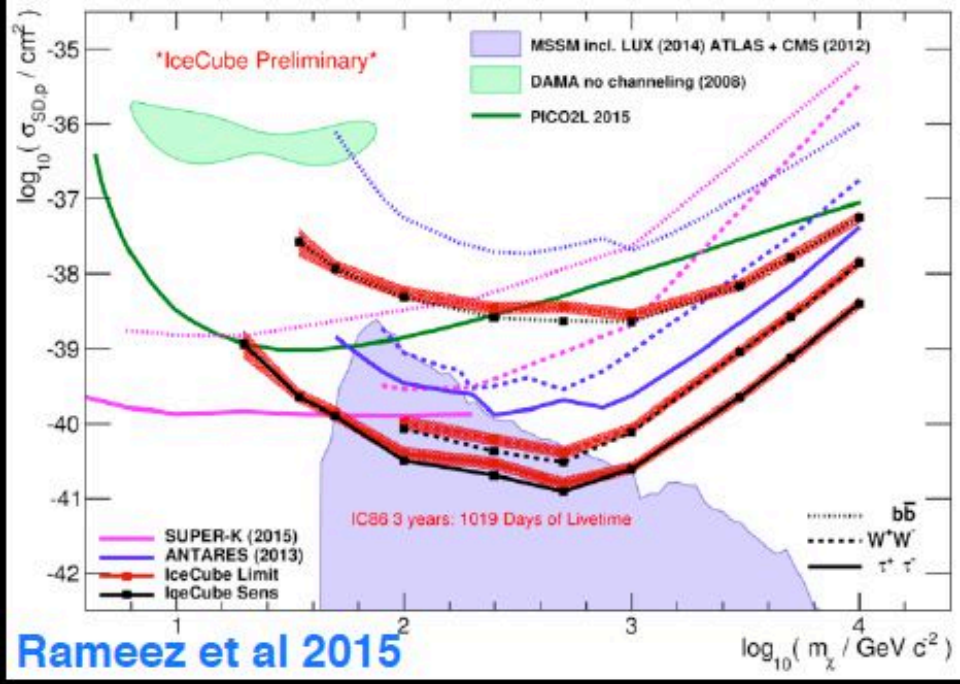
Scattering Cross Section
$\sigma_{SD} \propto J(J+1)$
$\sigma_{SI} \propto A^2$

Number density of element i -> Solar Model

velocity distribution (in solar frame, without Sun's gravity)

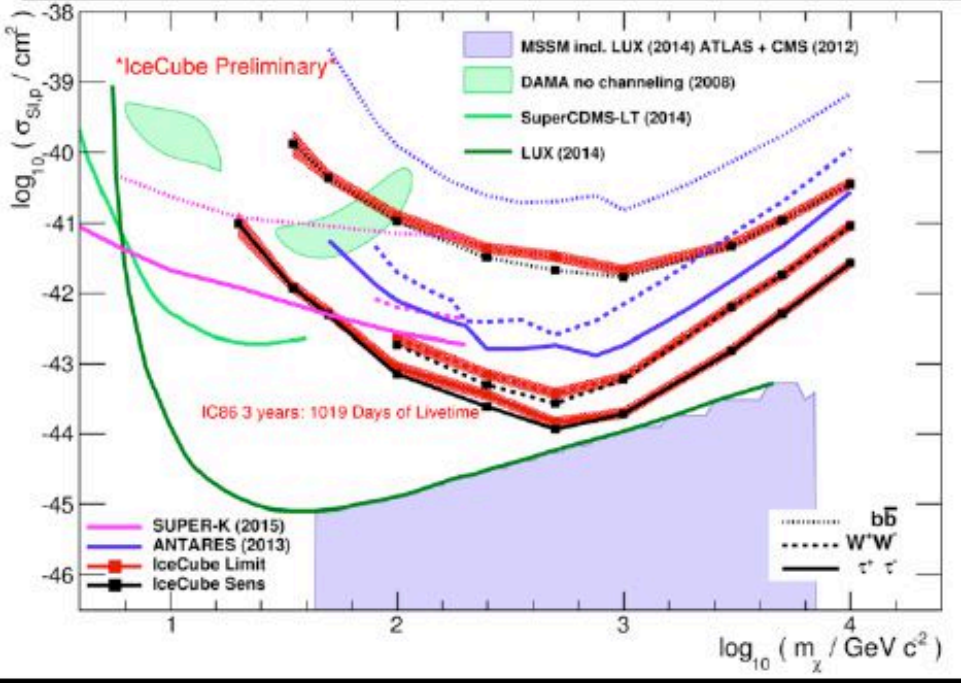
effect of solar gravity

Spin dependent

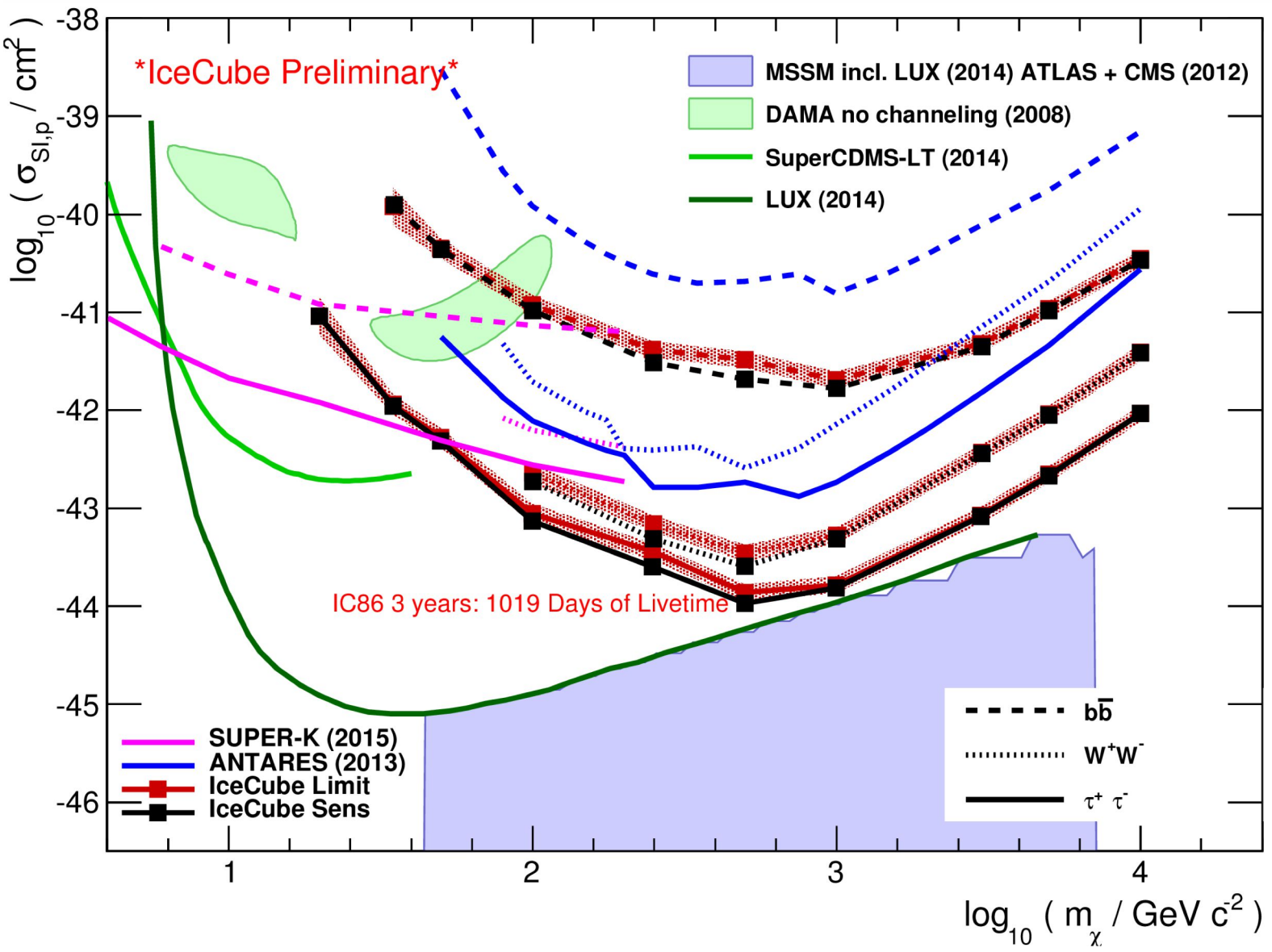


Rameez et al 2015

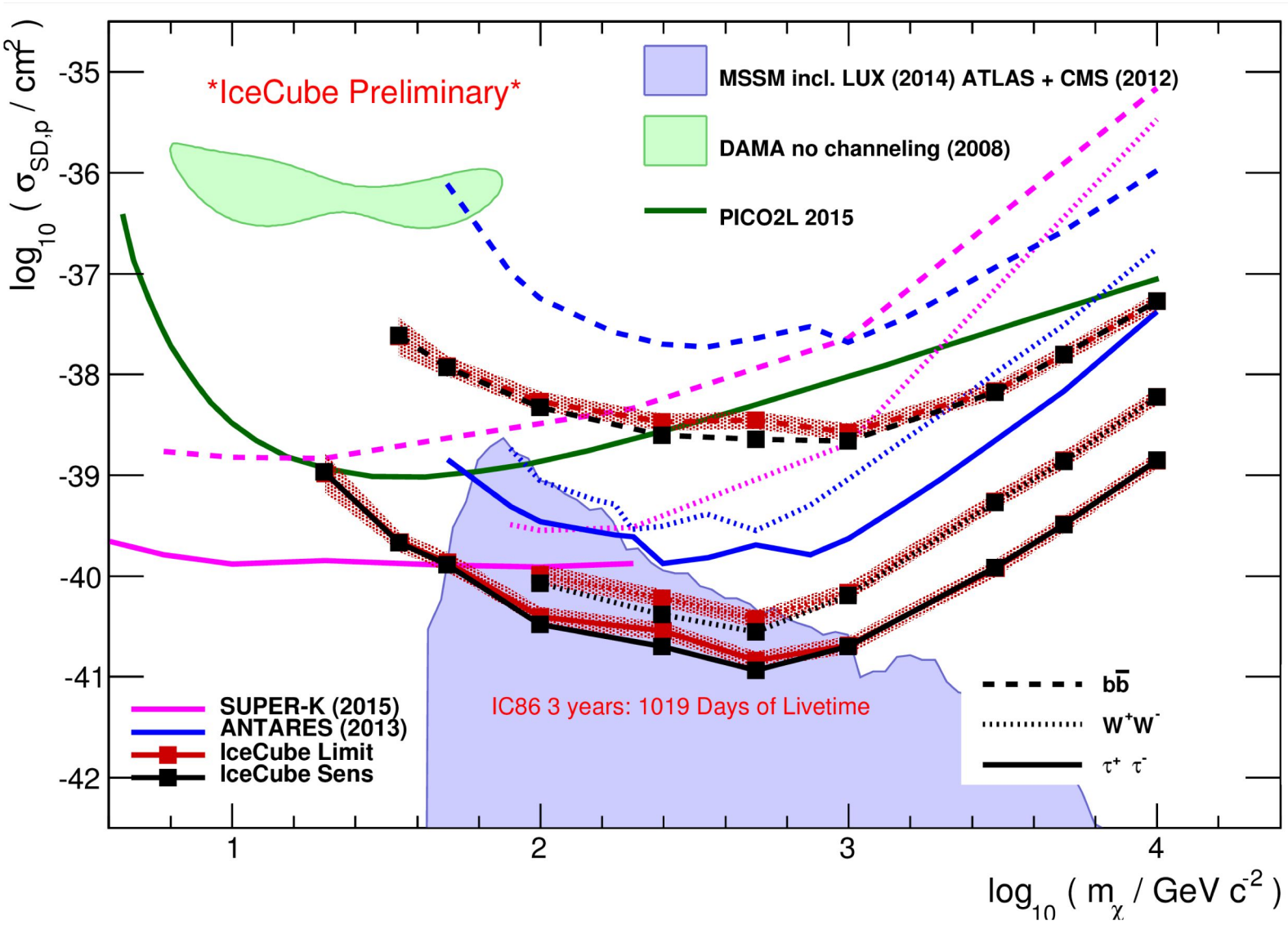
Spin independent



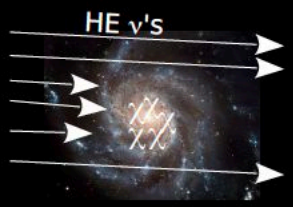
Limits after 3 years (6 soon) spin independent (A^2 handicap)

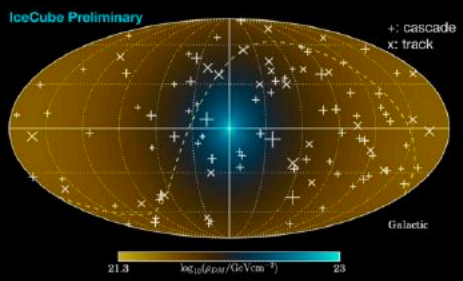


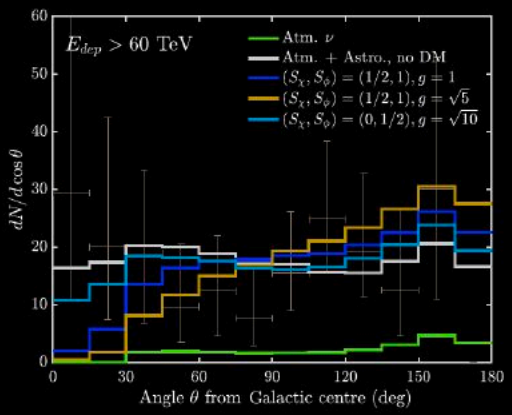
Limits after 3 years (6 soon) spin dependent (A^2=1)



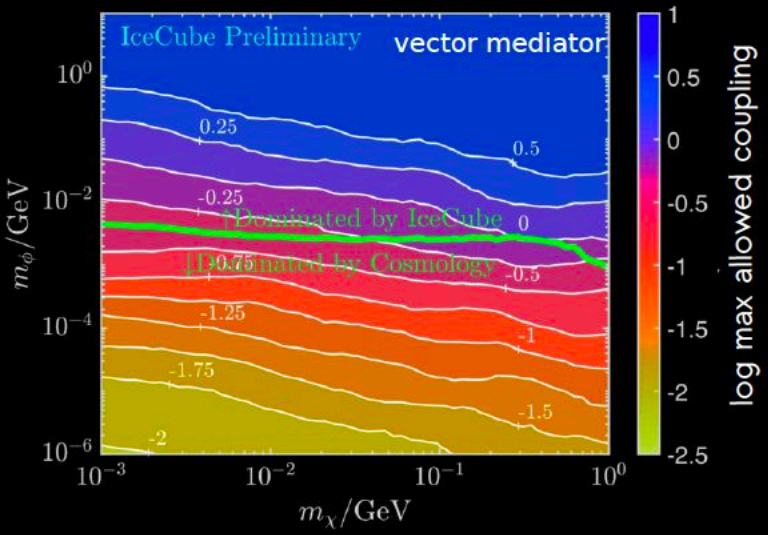
searches dark matter: neutrino-DM scattering





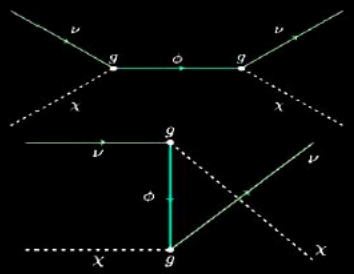


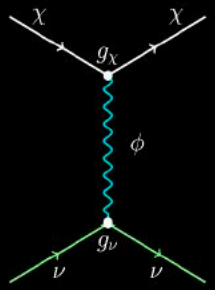
PRL 119, 201801 (2017)



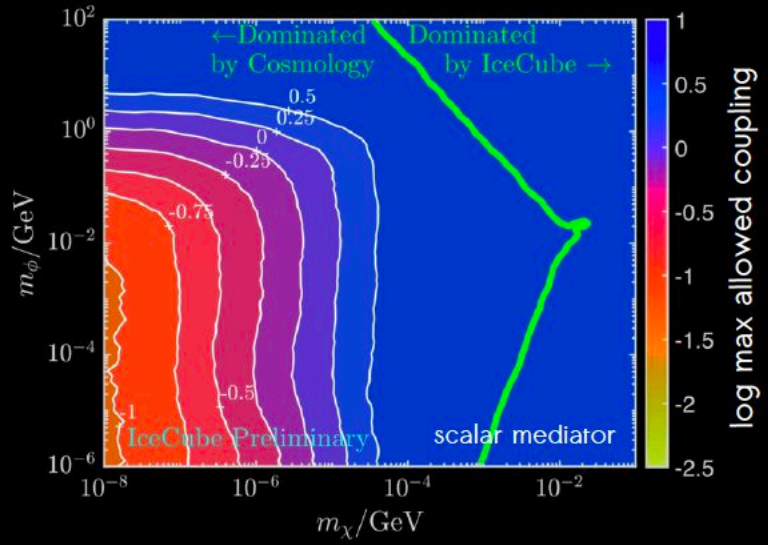
- Scattering of high energy cosmic neutrinos on DM in the halo can lead to a deficit of high energy neutrinos from the GC

- neutrino-DM interactions mediated by a scalar or vector mediator ϕ.





- limits on coupling constant, g, possible by measuring the isotropy of the HE neutrino flux

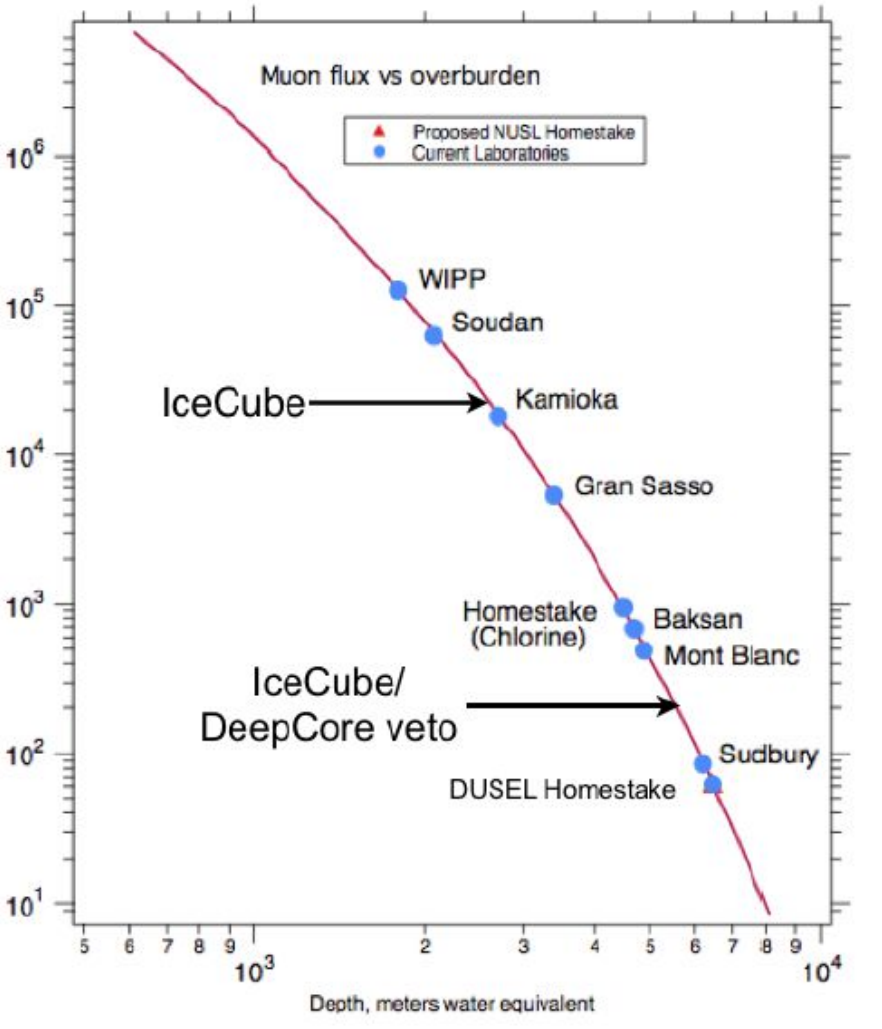


IceCube drilling to best low background site on Earth:

→ radio-pure ice
→ no seasonal variations (temperature, humidity,…)
→ shielded from cosmic rays by IceCube veto

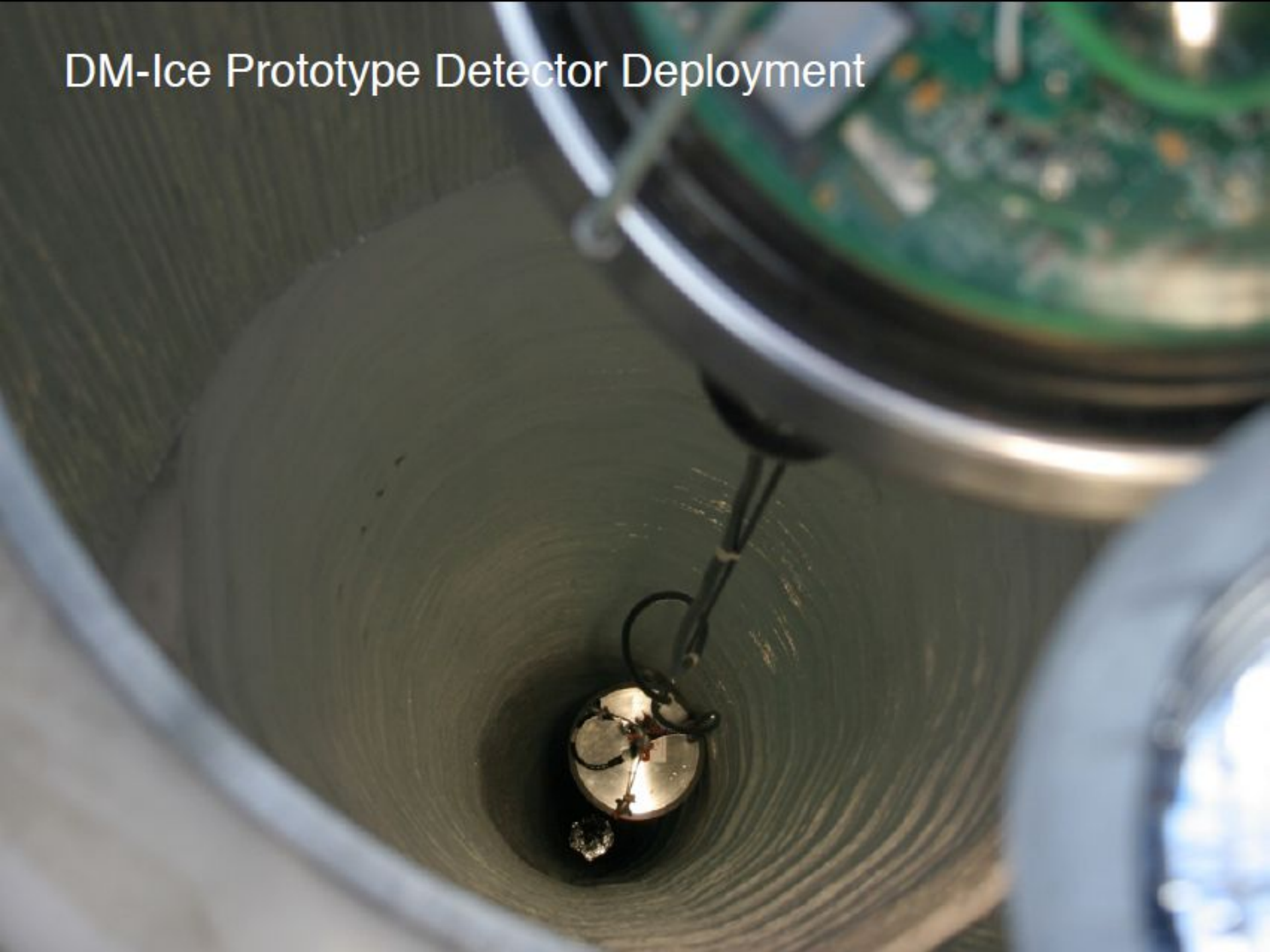
• DM-ice, DeepCore upgrades

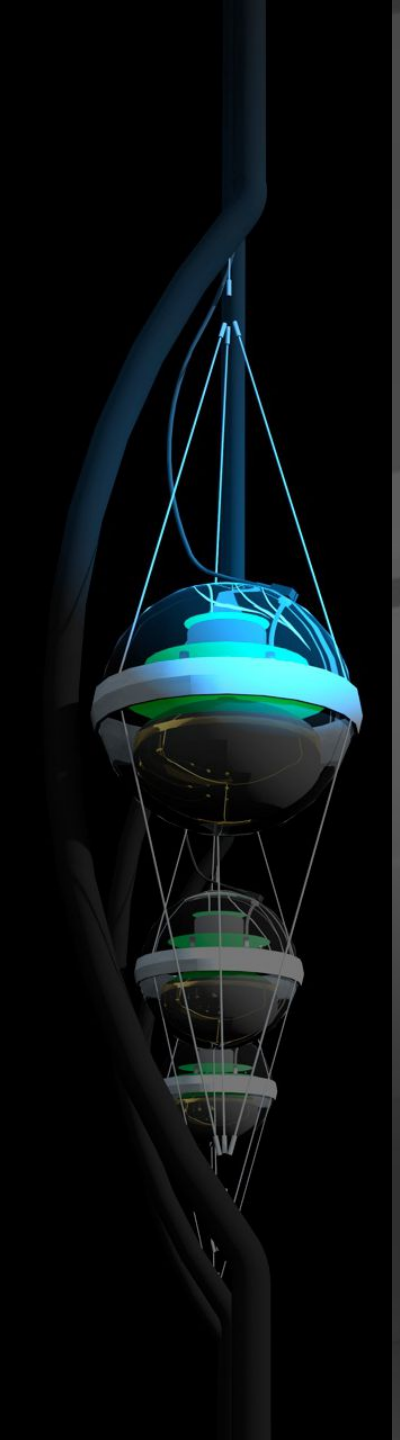
• $1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)



DM-Ice Prototype Detector

DM-Ice Prototype Detector Deployment





IceCube: beyond neutrino astronomy

Francis Halzen

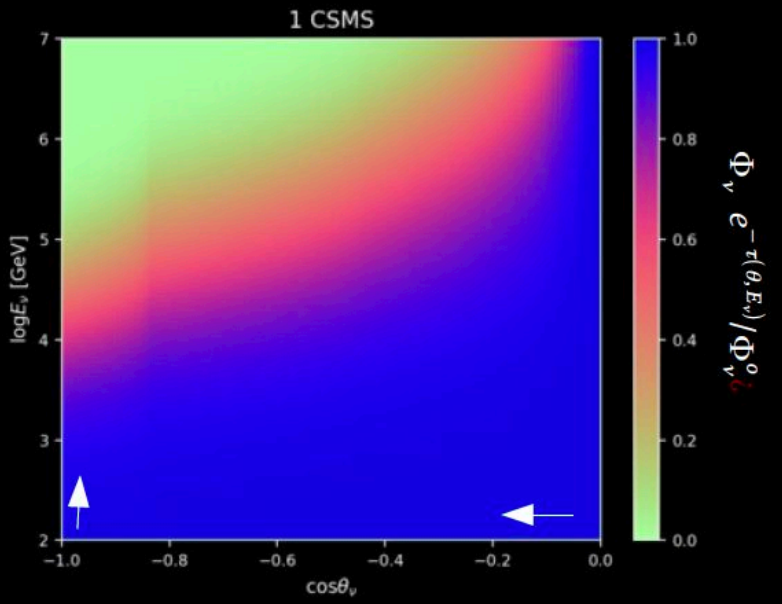
- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- …

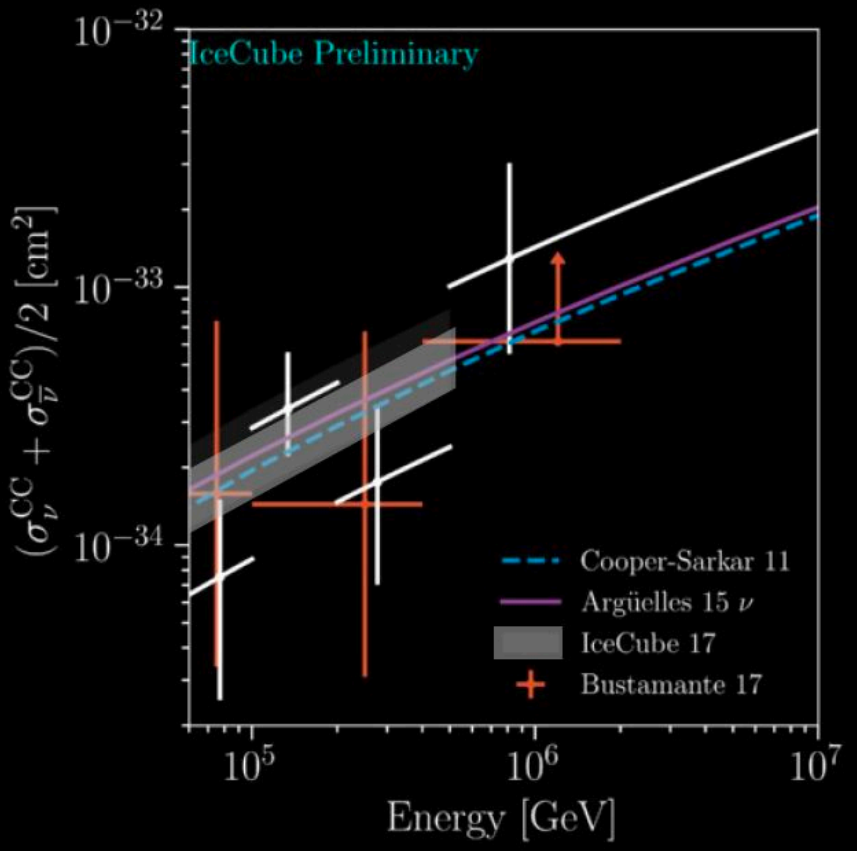
all-flavour neutrino cross section

- Use HESE sample → 60 TeV < E_ν < 10 PeV

$$N_{evts}(\theta, E_\nu) = (\sigma_{CC} + \sigma_{NC}) \frac{\rho}{m_N} \Phi_\nu \, e^{-\tau(\theta, E_\nu)} \, L(\theta)$$

- (σ,Φ) degeneracy broken by **up***(attenuated)*/**down***(not attenuated)* flux
- Assume fixed $\sigma_\nu/\sigma_{\bar{\nu}}$





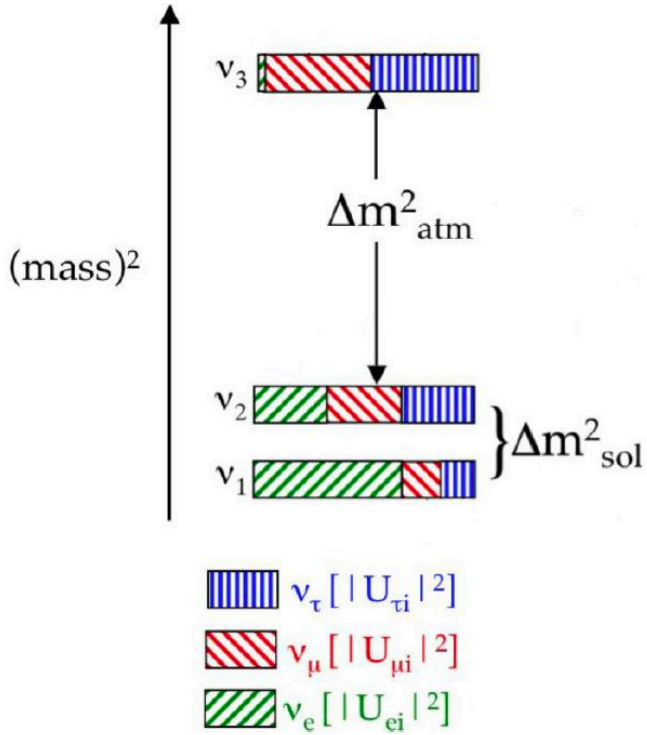
flavor composition of the astrophysical flux at the source evolves to a flavor composition at IceCube by oscillations

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} \, |\nu_k\rangle$$

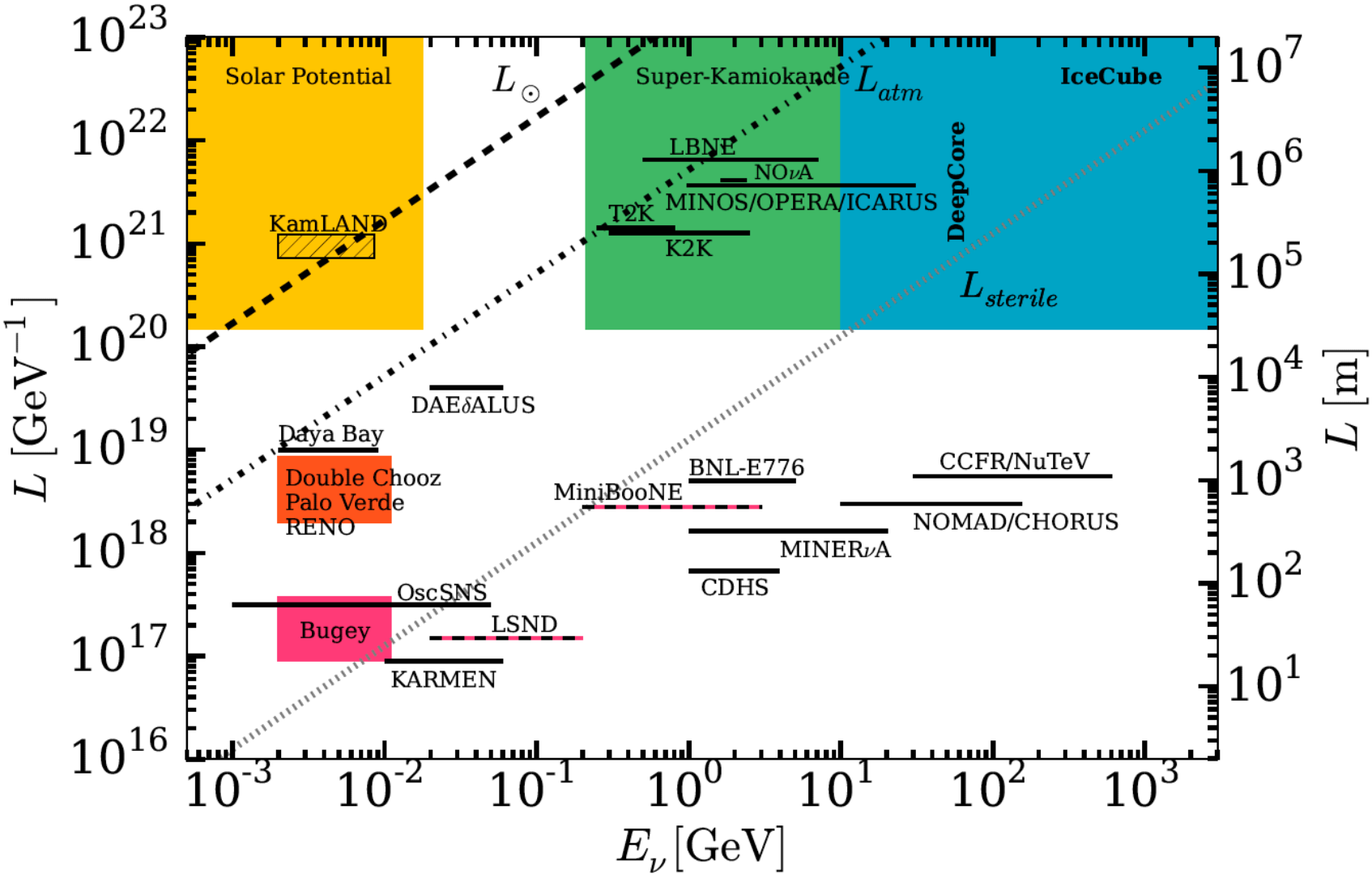
Flavor Basis

Mass Basis

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$



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

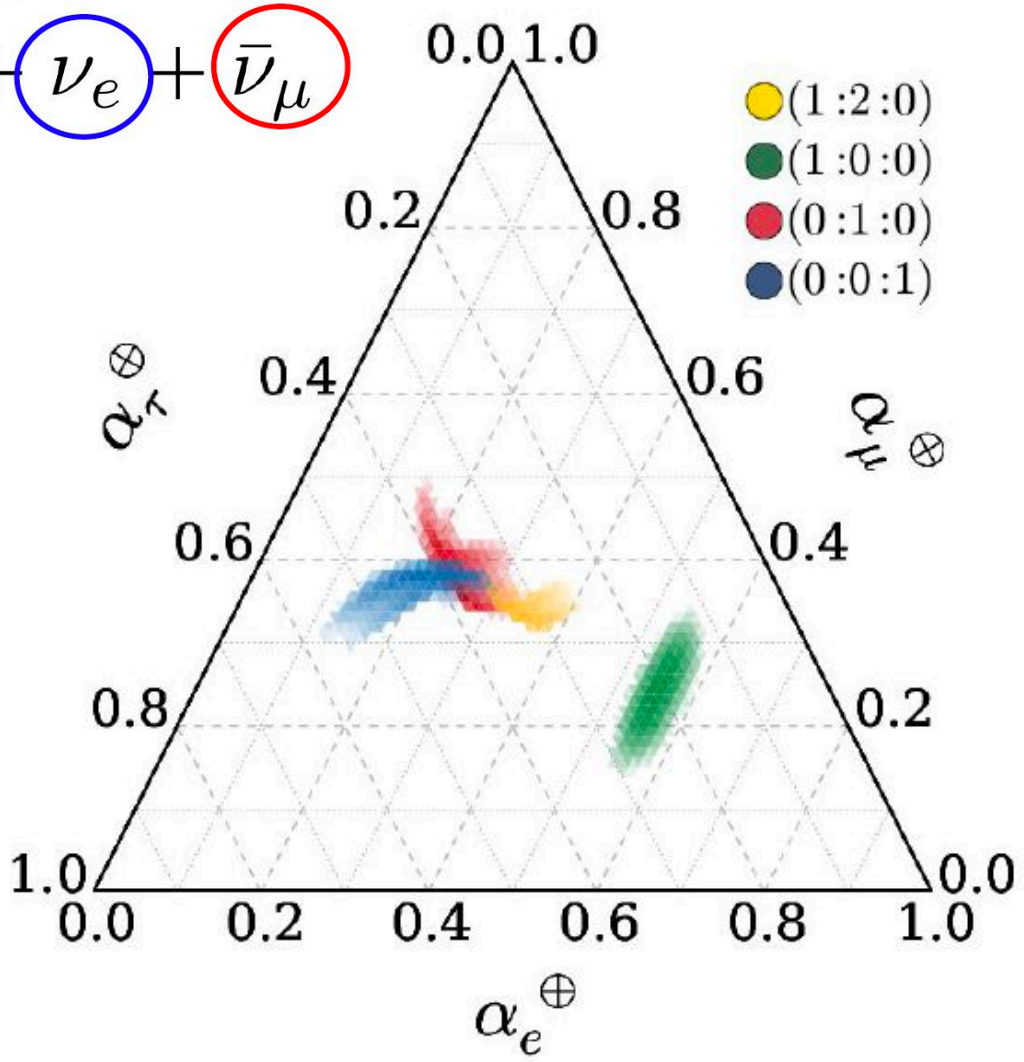


$$p + p \rightarrow \pi^+ + X$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

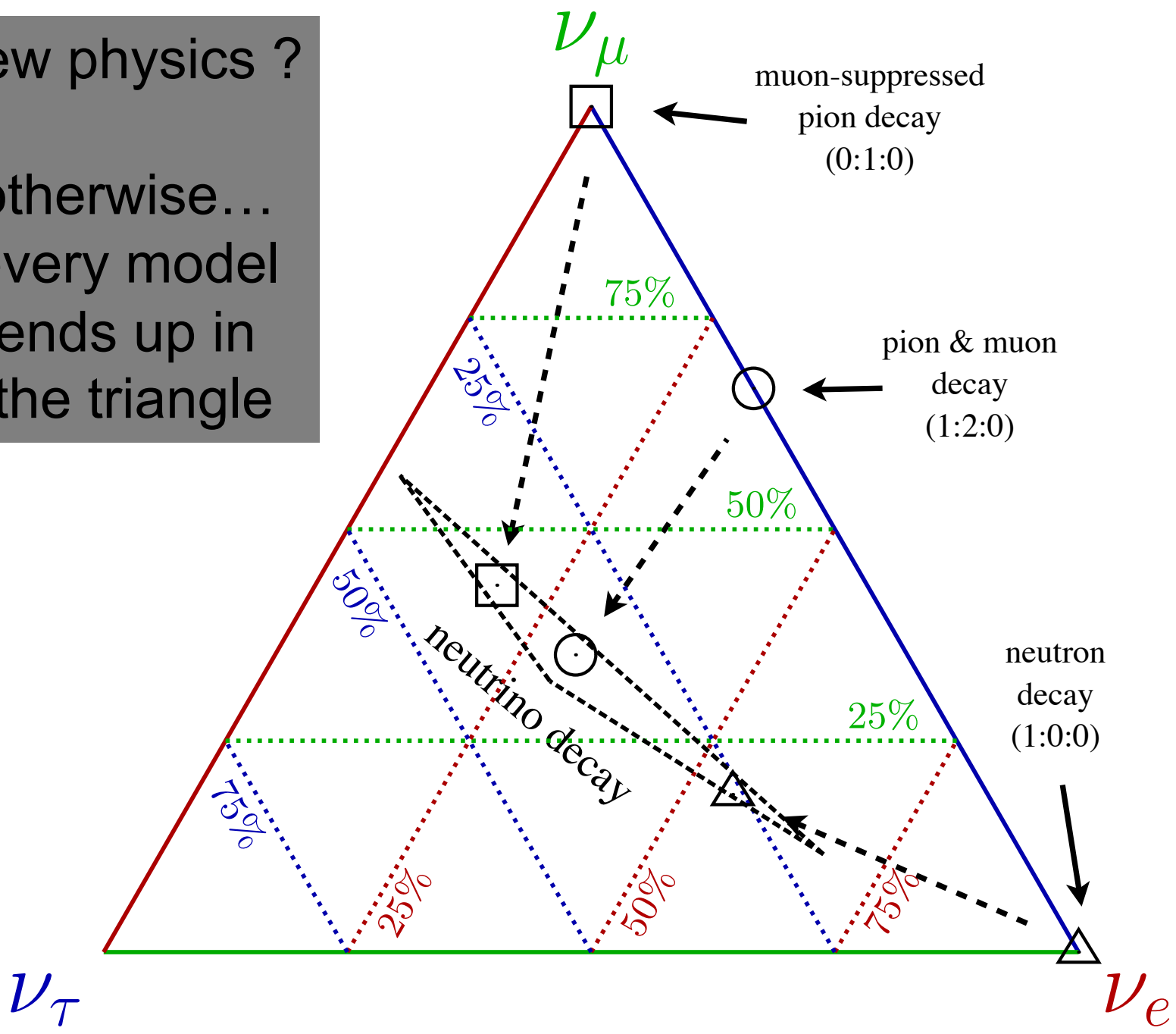
1:2:0

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

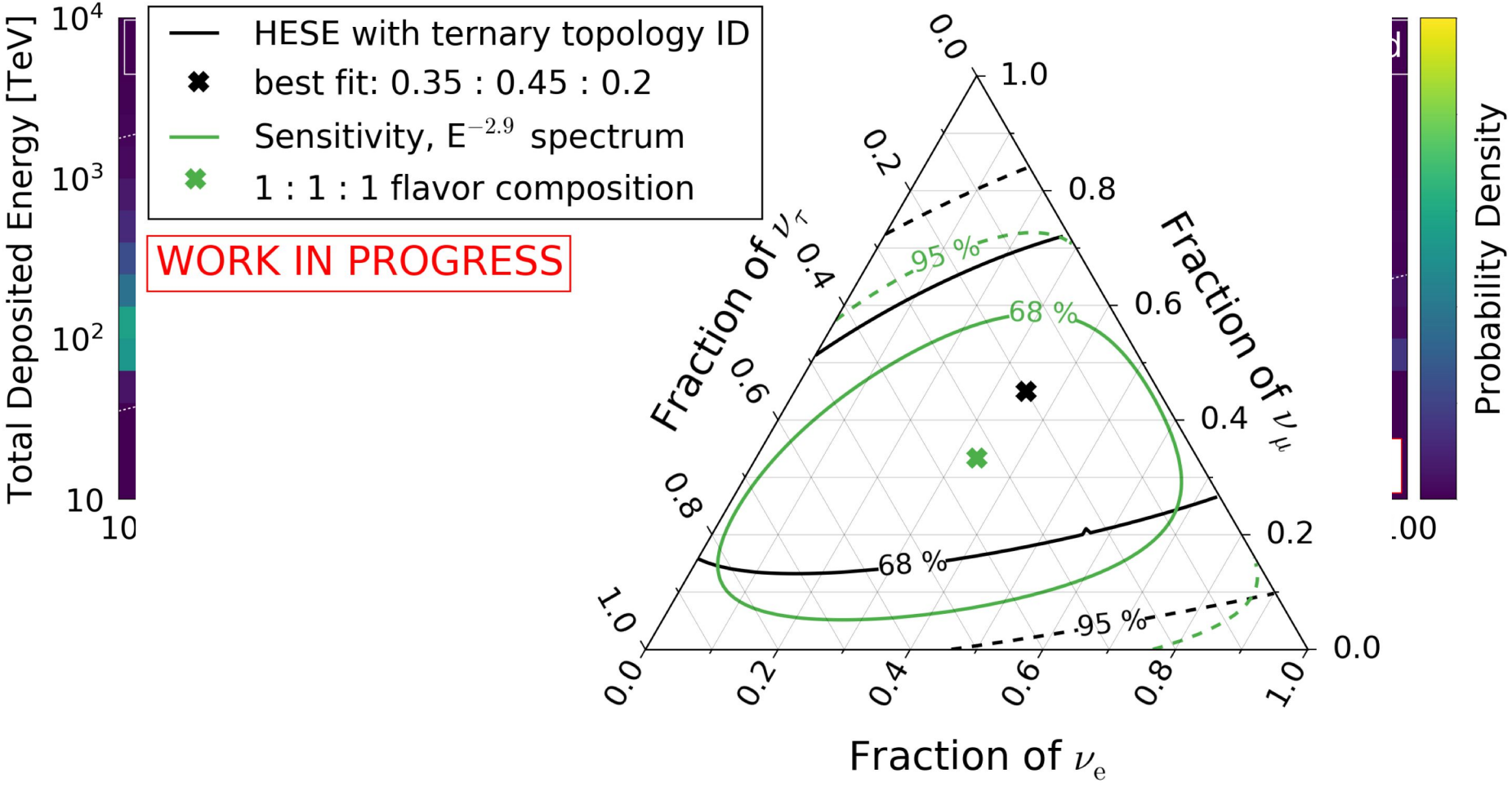


new physics ?

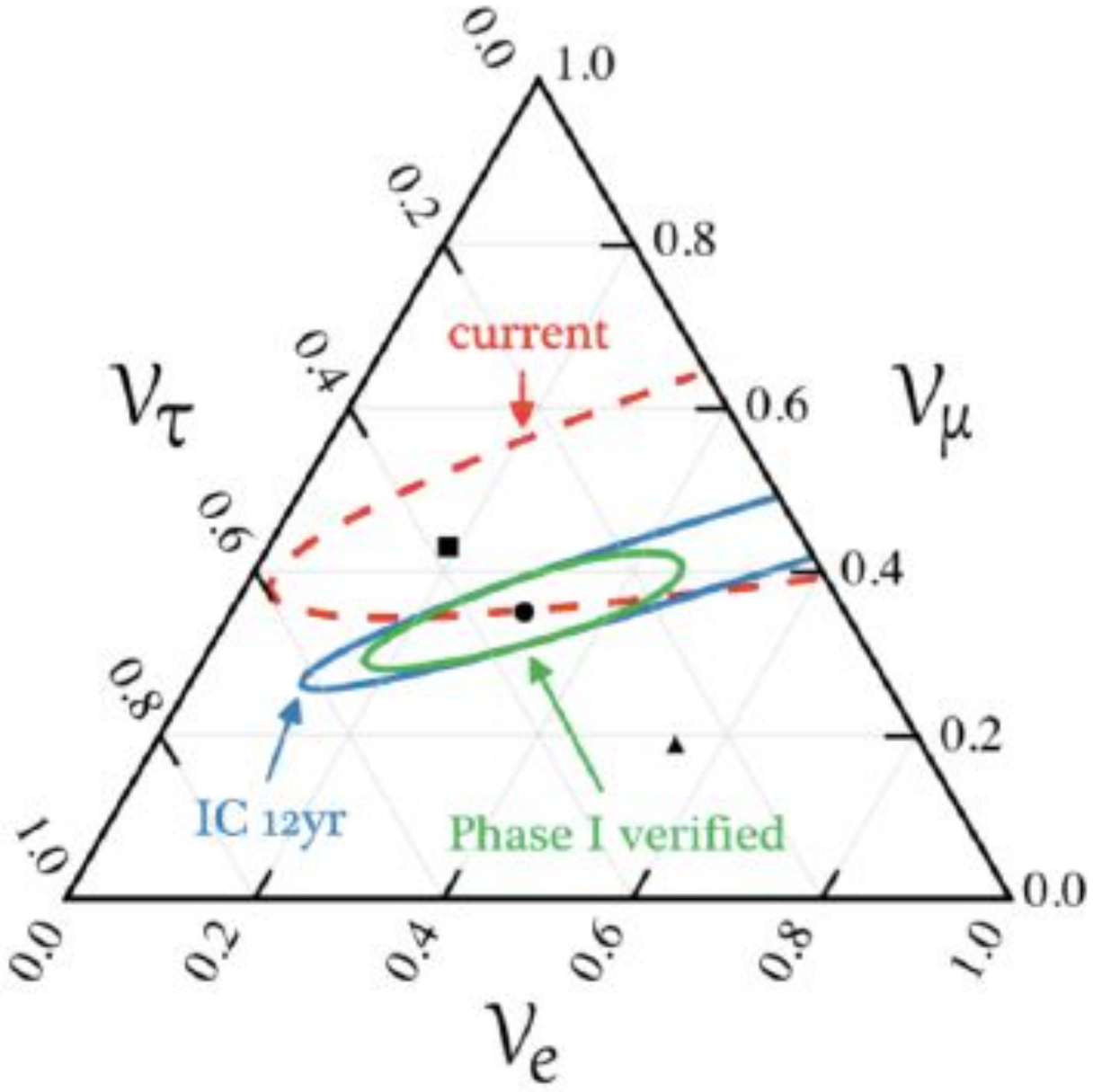
otherwise…
every model
ends up in
the triangle

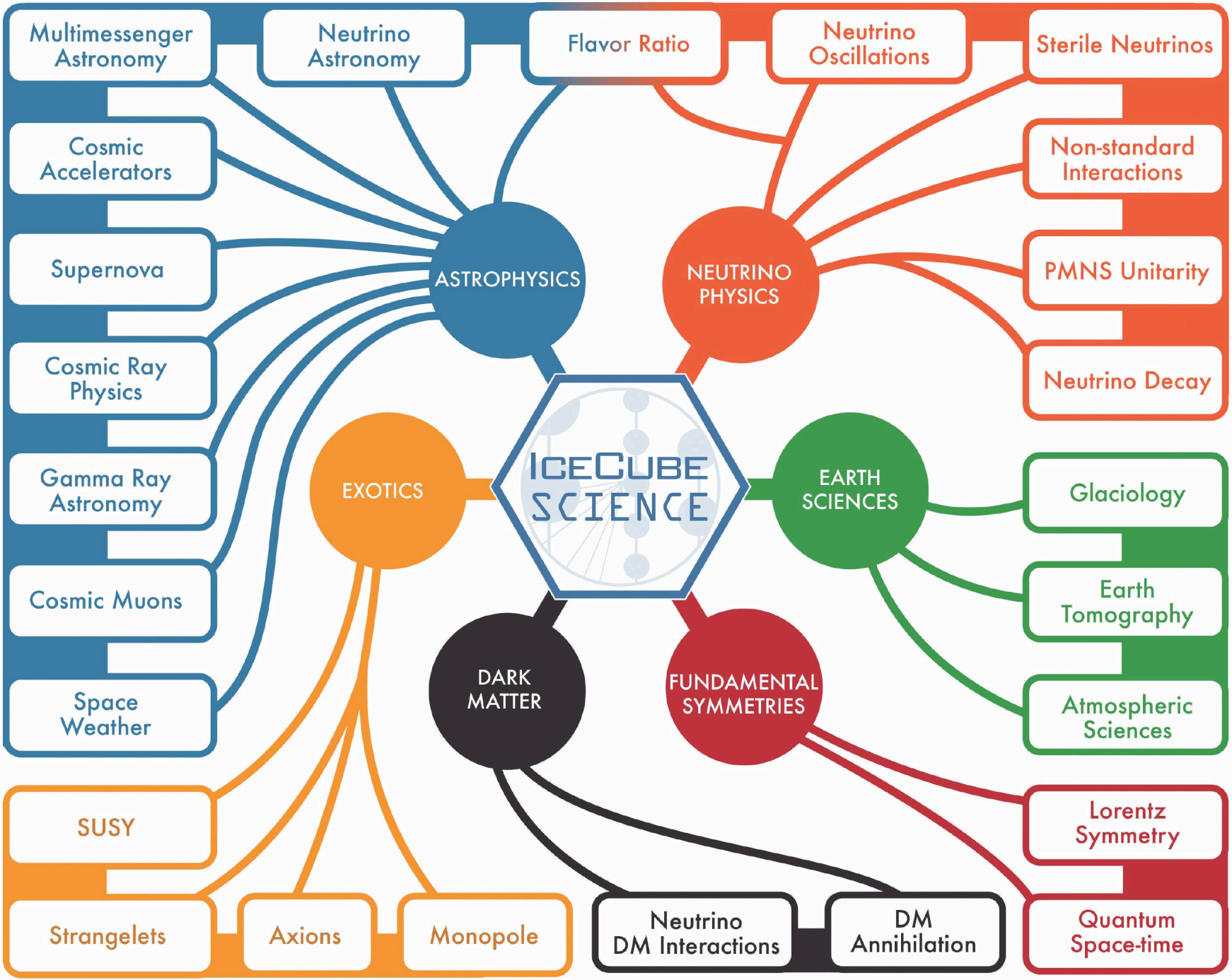


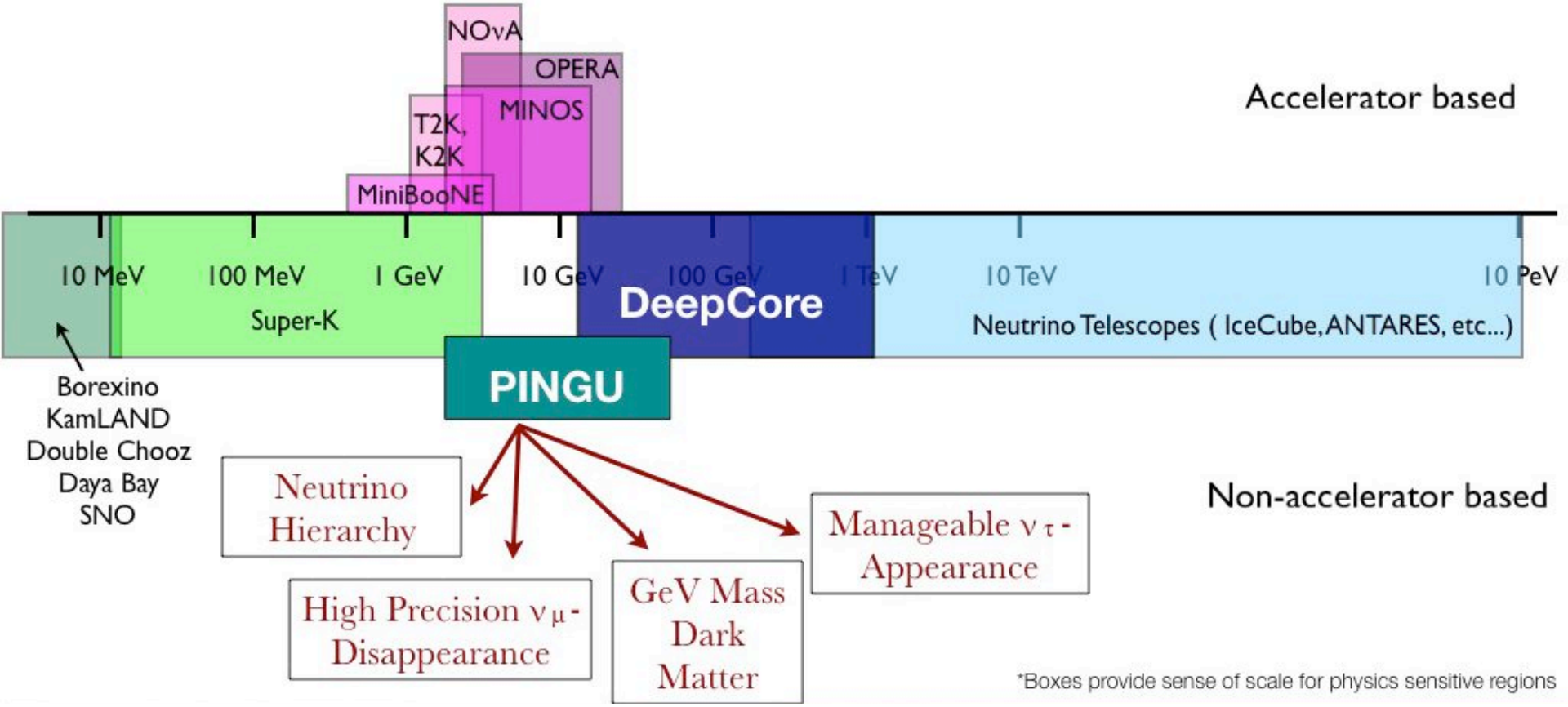
high-energy starting events — 7.5 yr



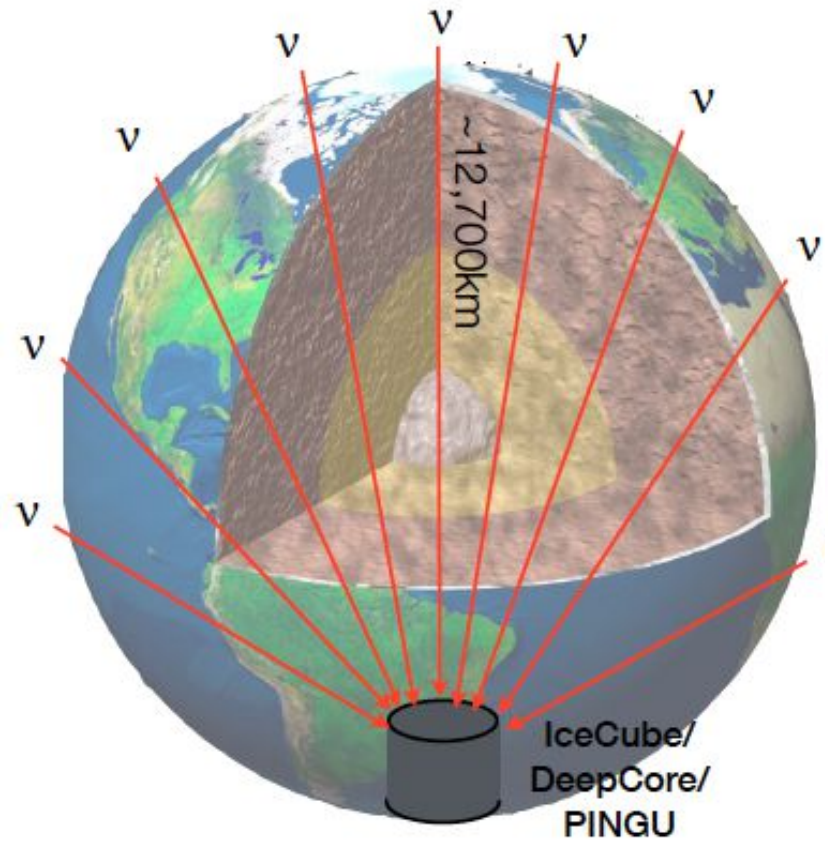
oscillations of PeV neutrinos over cosmic distances to 1:1:1

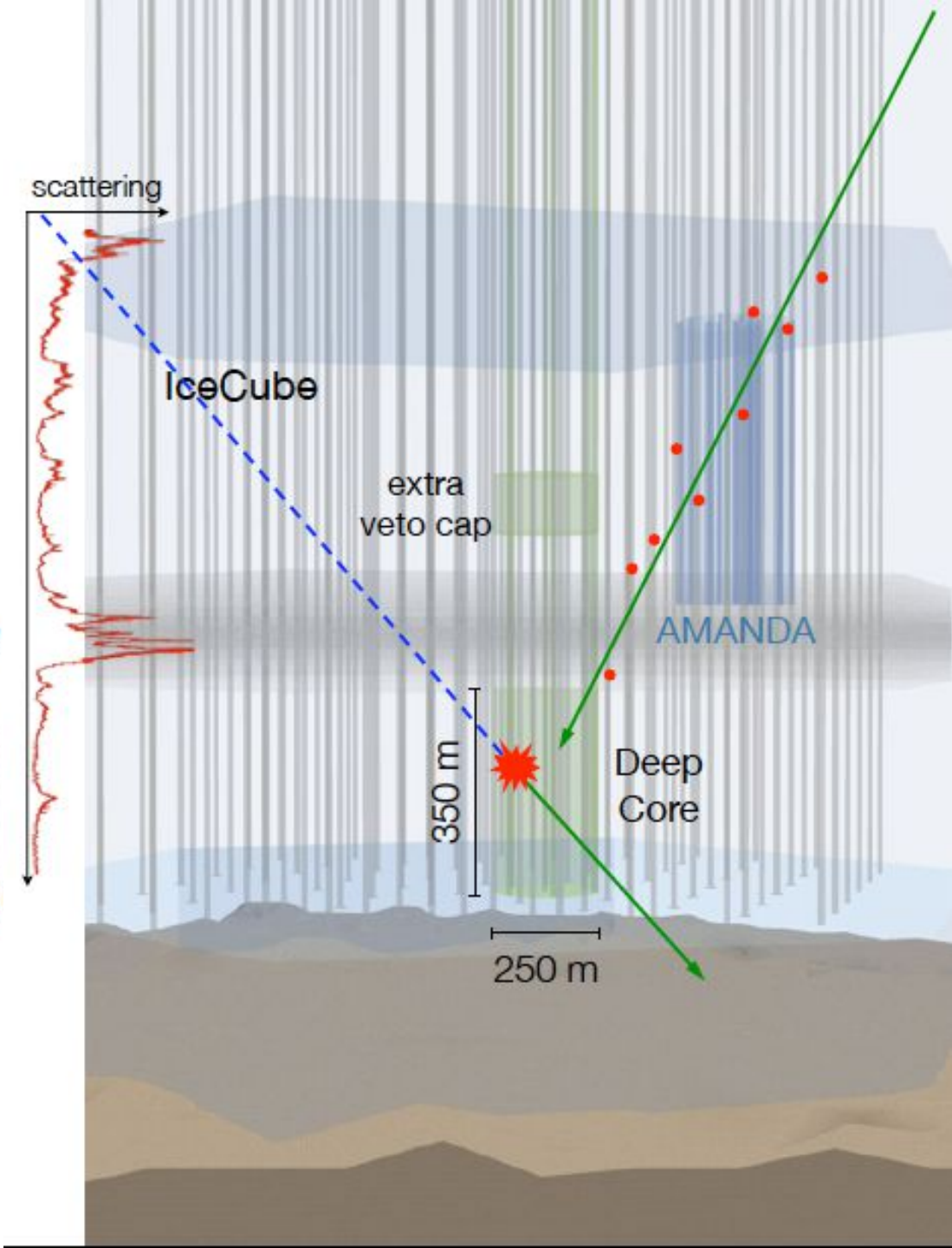

ν_τ
ν_μ
ν_e
current
IC 12yr
Phase I verified
0.0
0.2
0.4
0.6
0.8
1.0

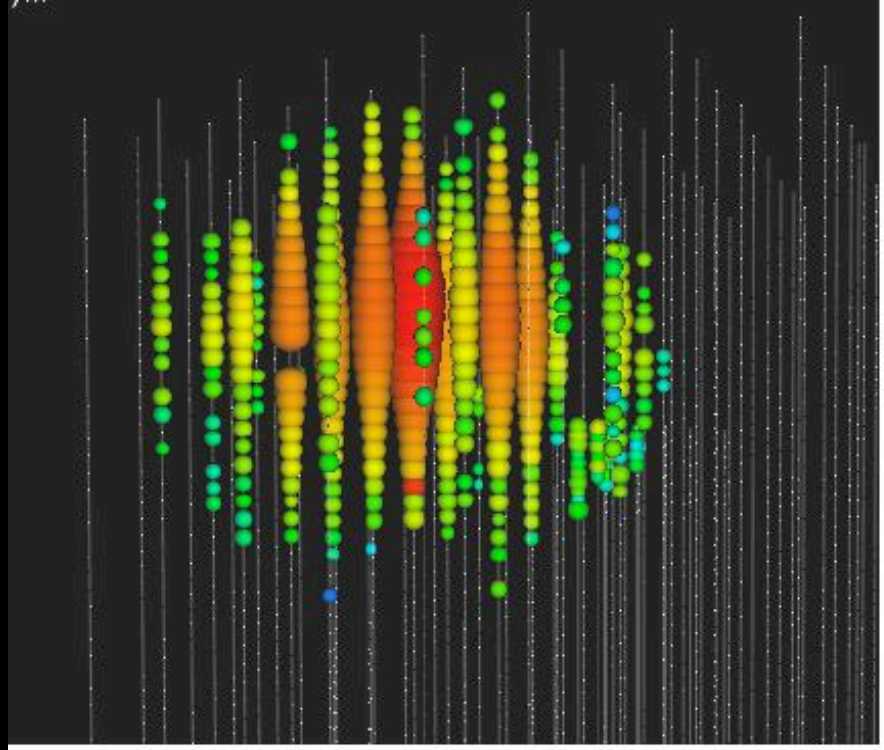
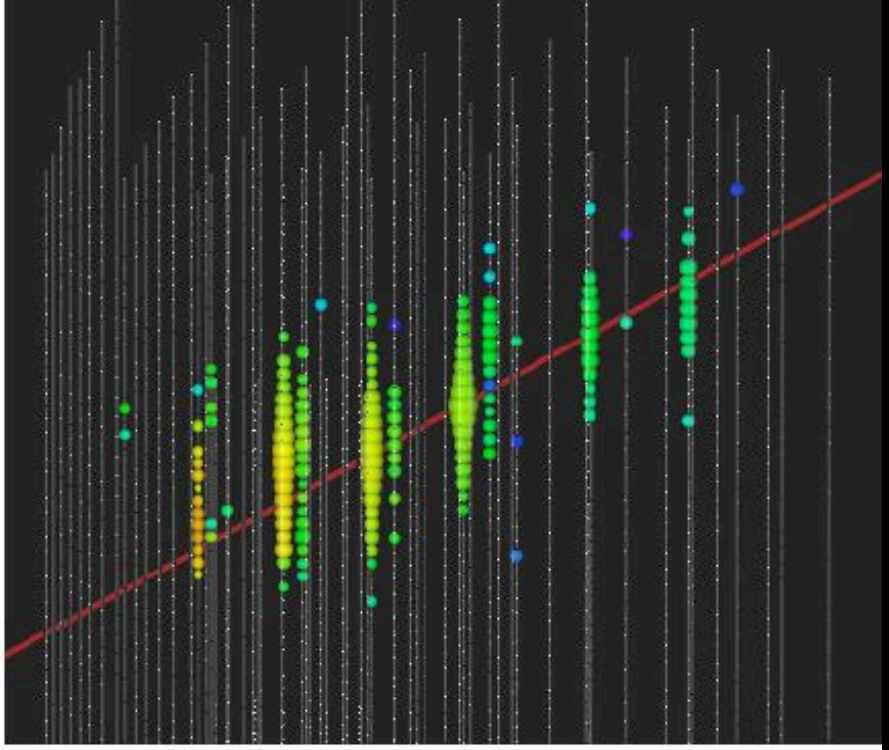
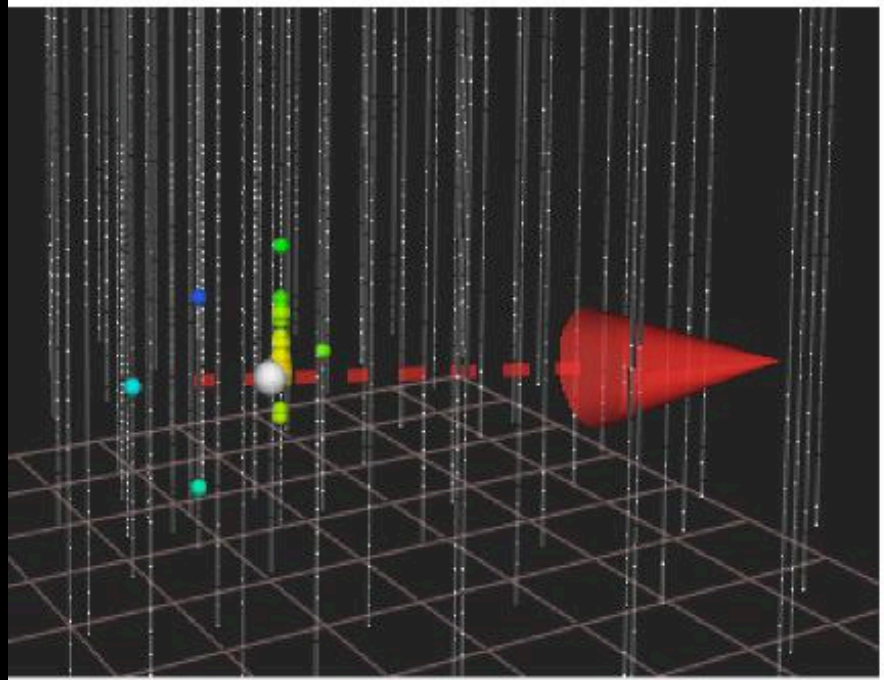
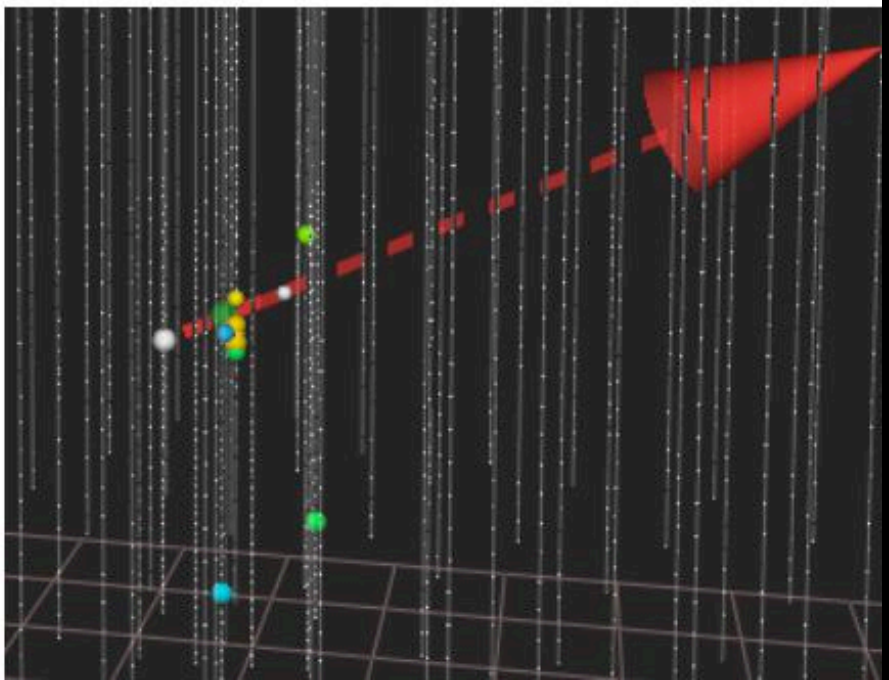

IceCube Science
Astrophysics
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
Neutrino Physics
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
Exotics
SUSY
Strangelets
Axions
Monopole
Earth Sciences
Glaciology
Earth Tomography
Atmospheric Sciences
Dark Matter
Neutrino DM Interactions
DM Annihilation
Fundamental Symmetries
Lorentz Symmetry
Quantum Space-time


NOνA
OPERA
MINOS
T2K,
K2K
MiniBooNE
Accelerator based
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
10 PeV
Super-K
DeepCore
Neutrino Telescopes (IceCube, ANTARES, etc...)
PINGU
Borexino
KamLAND
Double Chooz
Daya Bay
SNO
Neutrino Hierarchy
High Precision νμ - Disappearance
GeV Mass Dark Matter
Manageable ντ - Appearance
Non-accelerator based
*Boxes provide sense of scale for physics sensitive regions

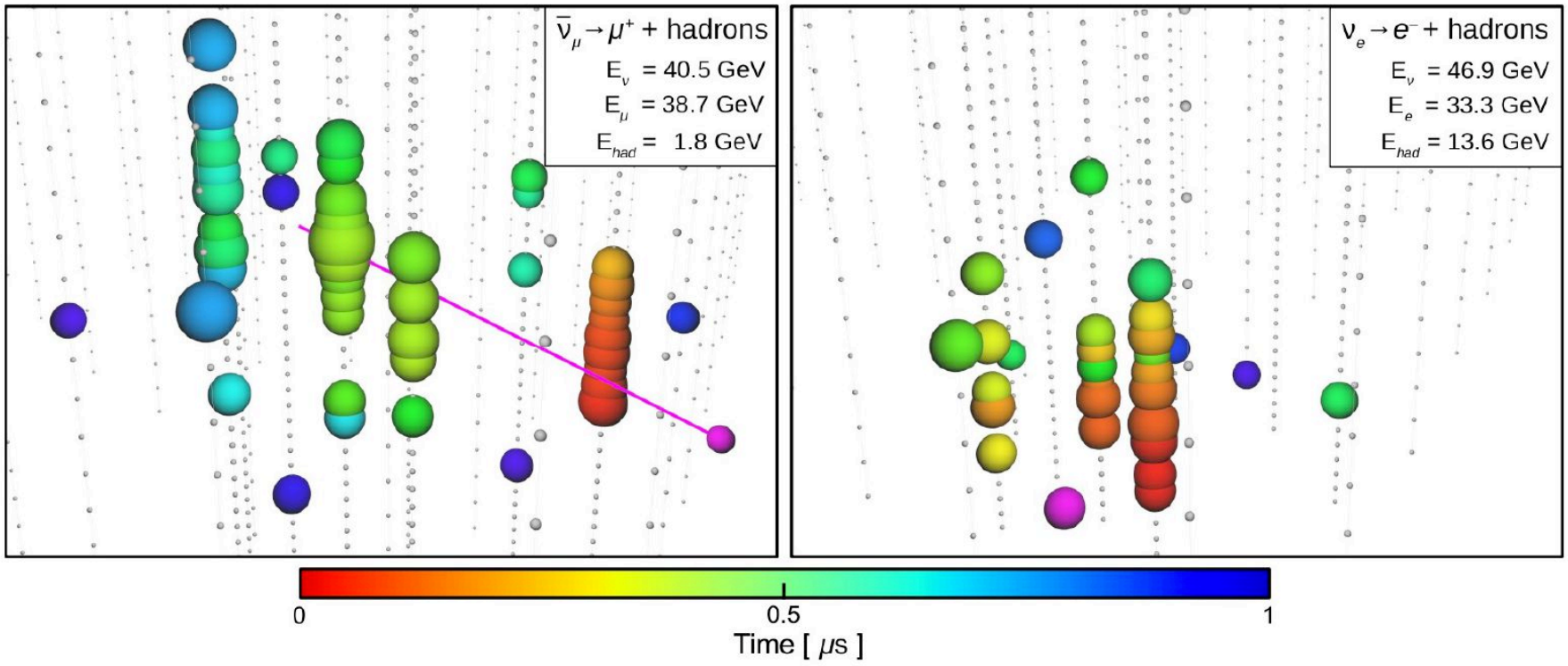
one half million atmospheric neutrinos…





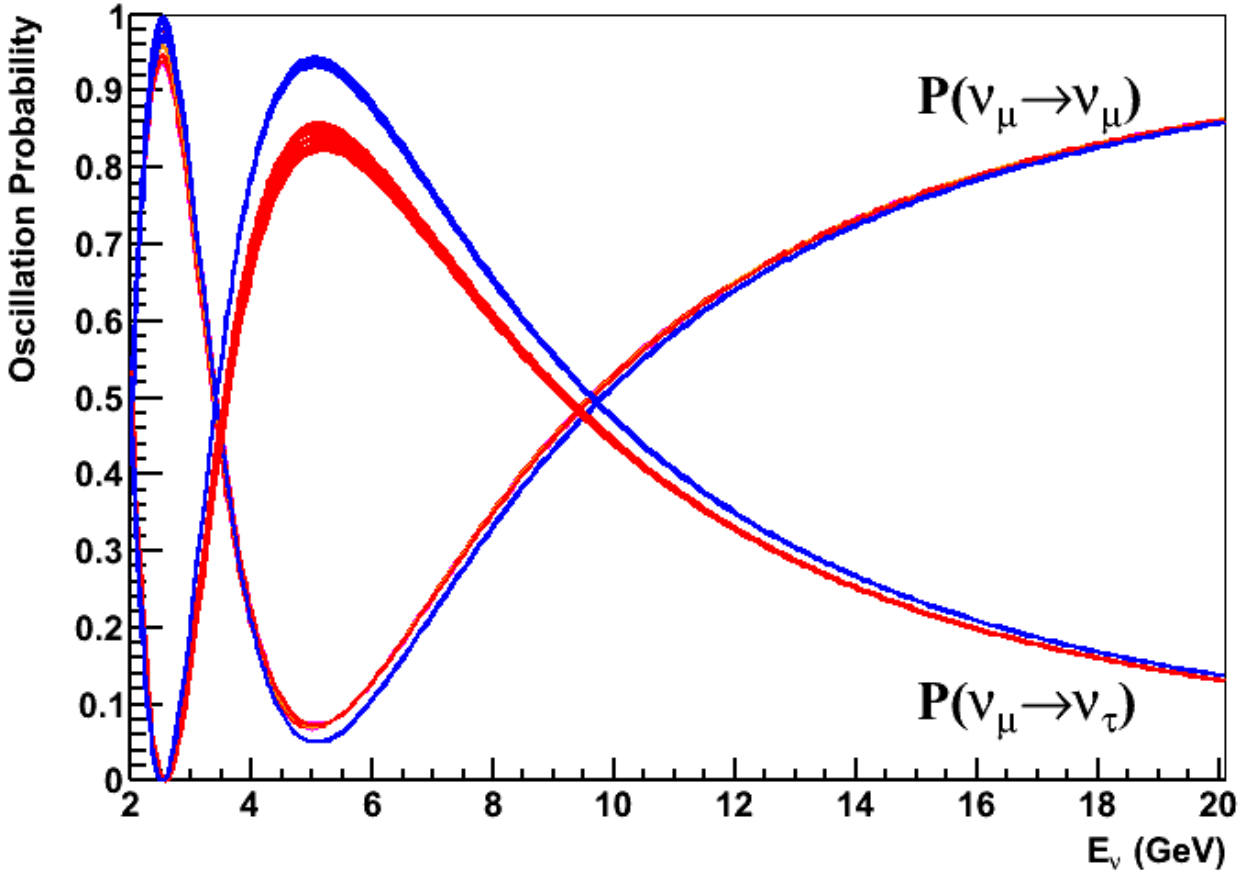





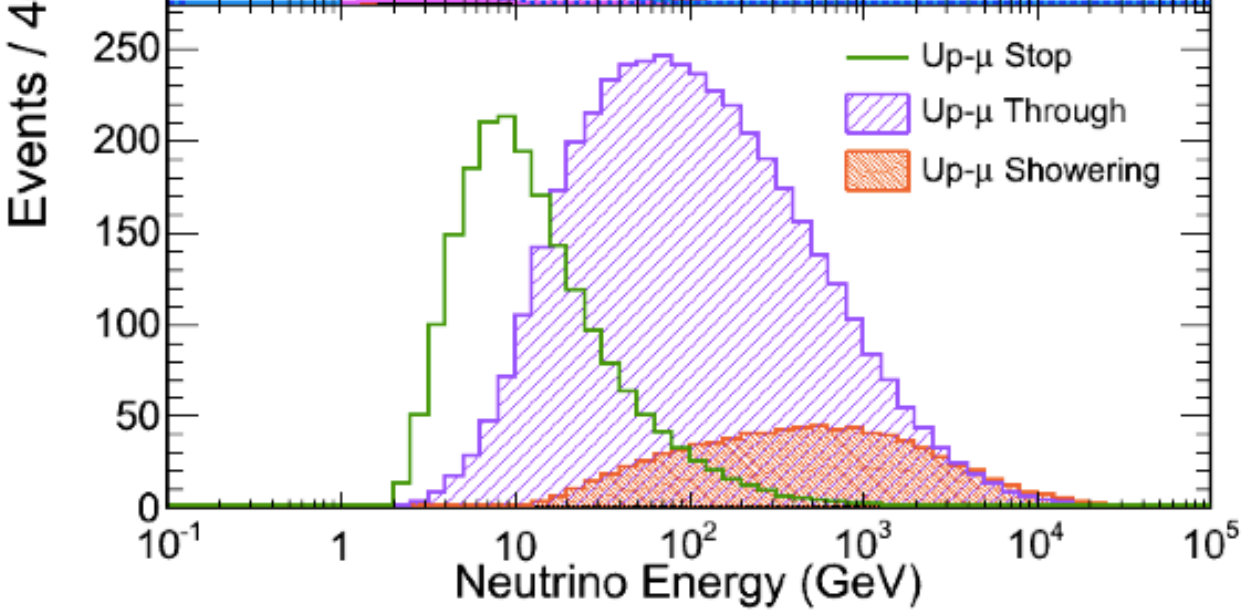
Events in DeepCore



- Events below 50 GeV:

- oscillations at 5-55 GeV energy
- same oscillation parameters measured in a new energy range

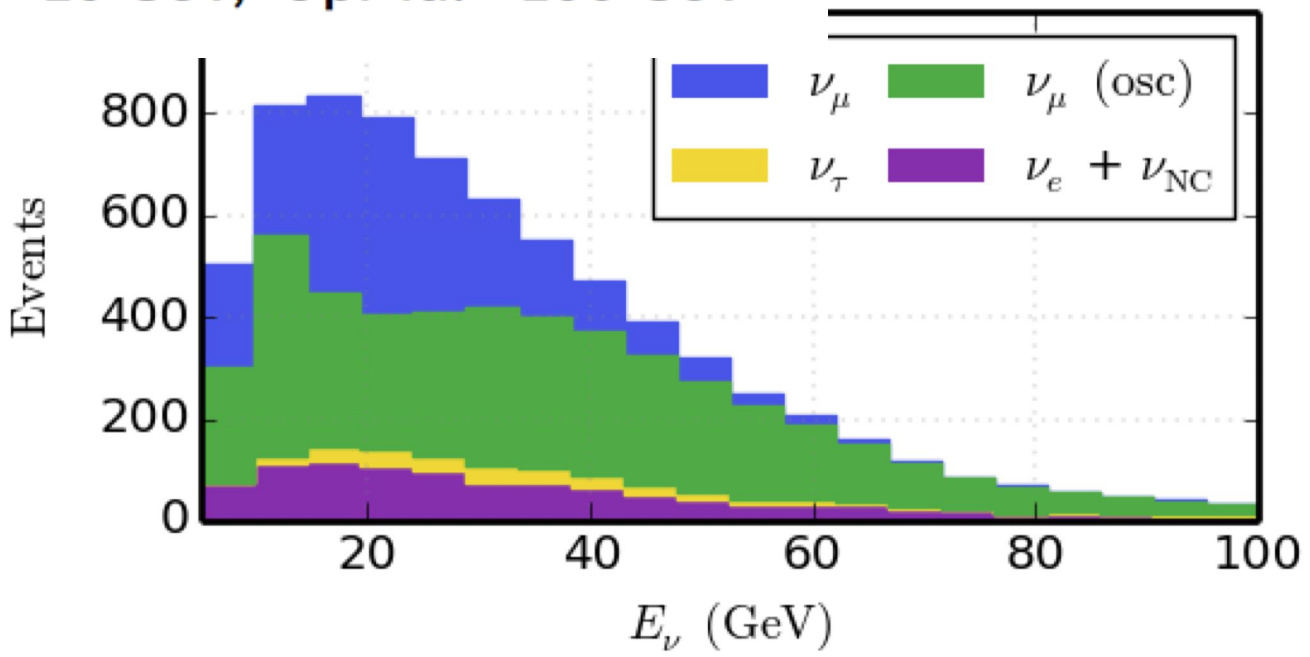




SuperK

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

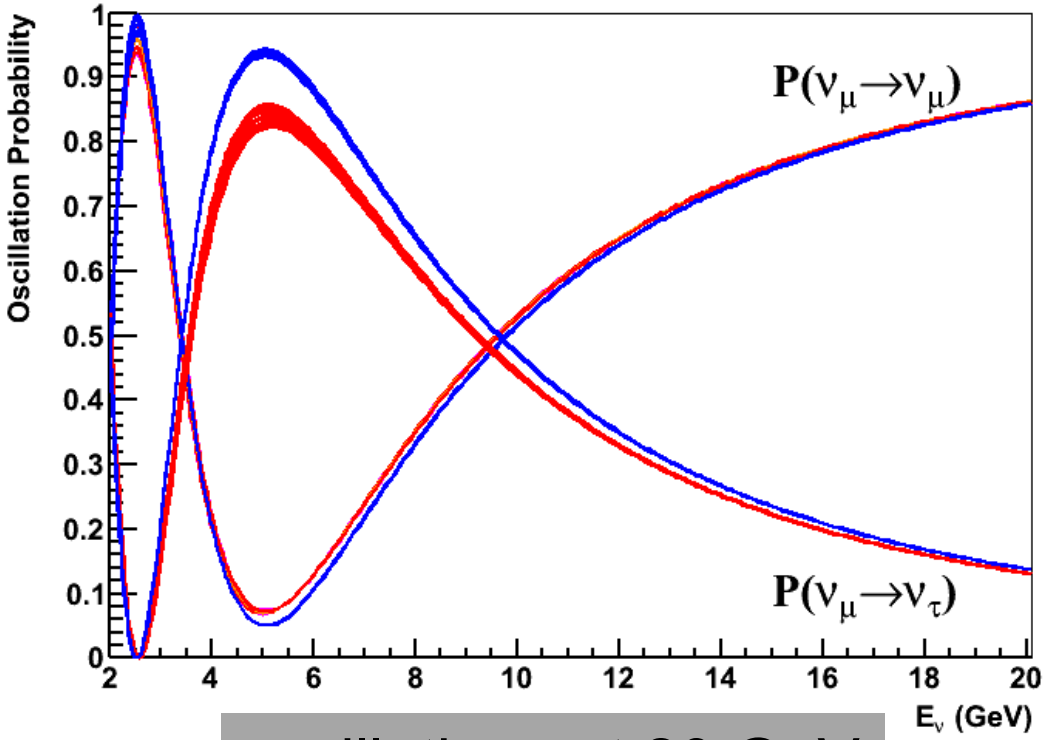
IceCube



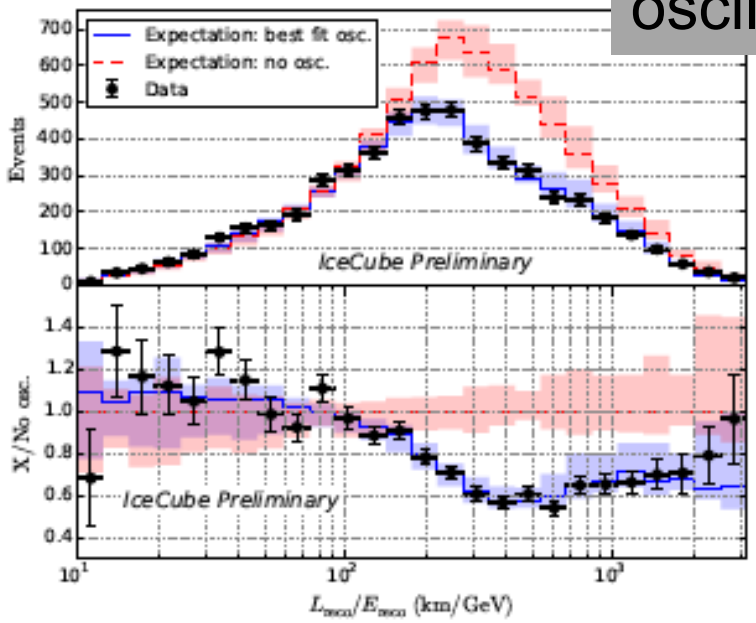
IceCube

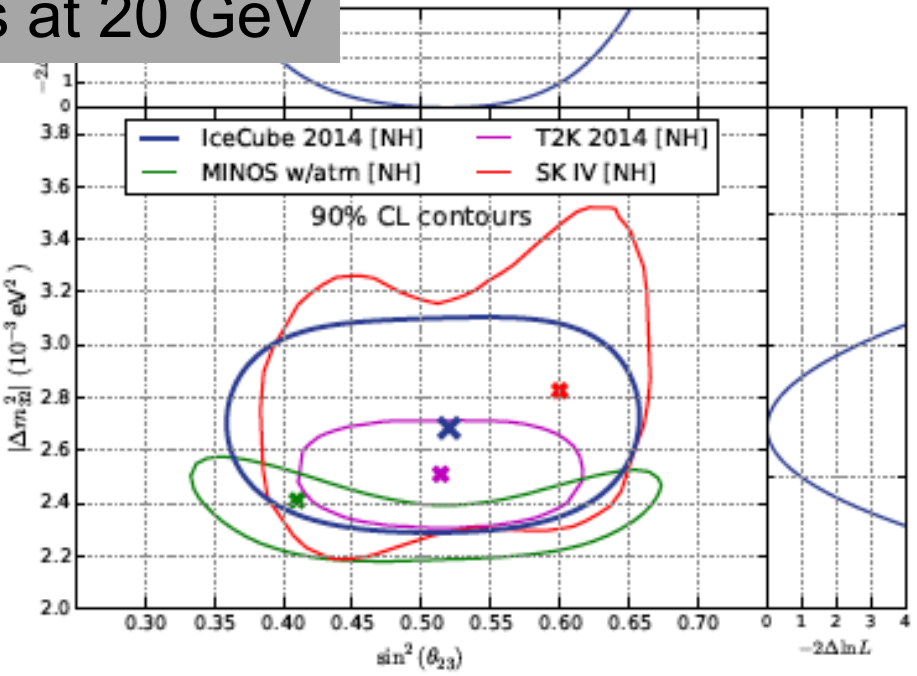
DeepCore

PINGU

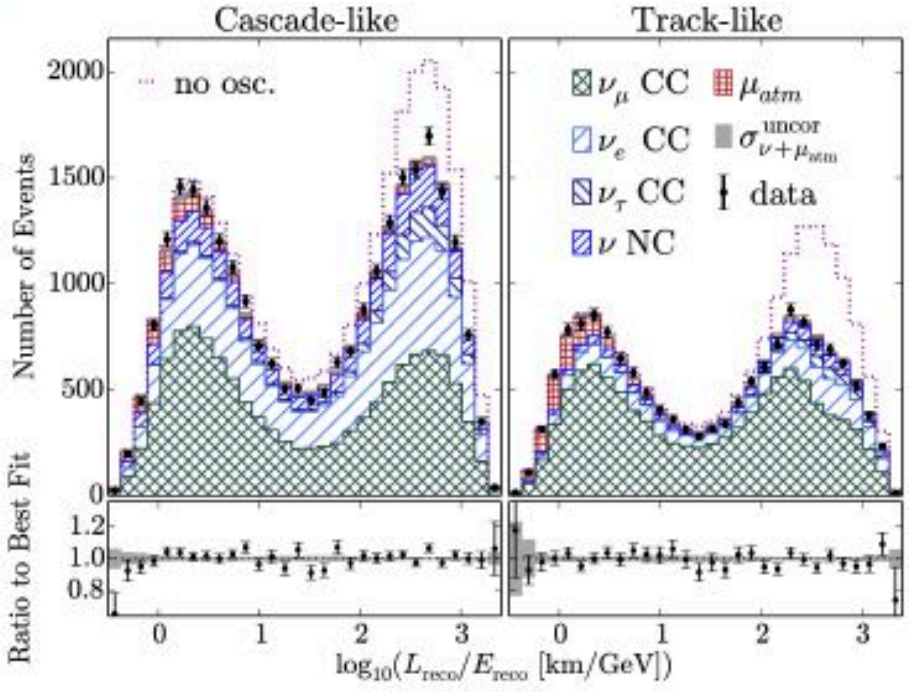


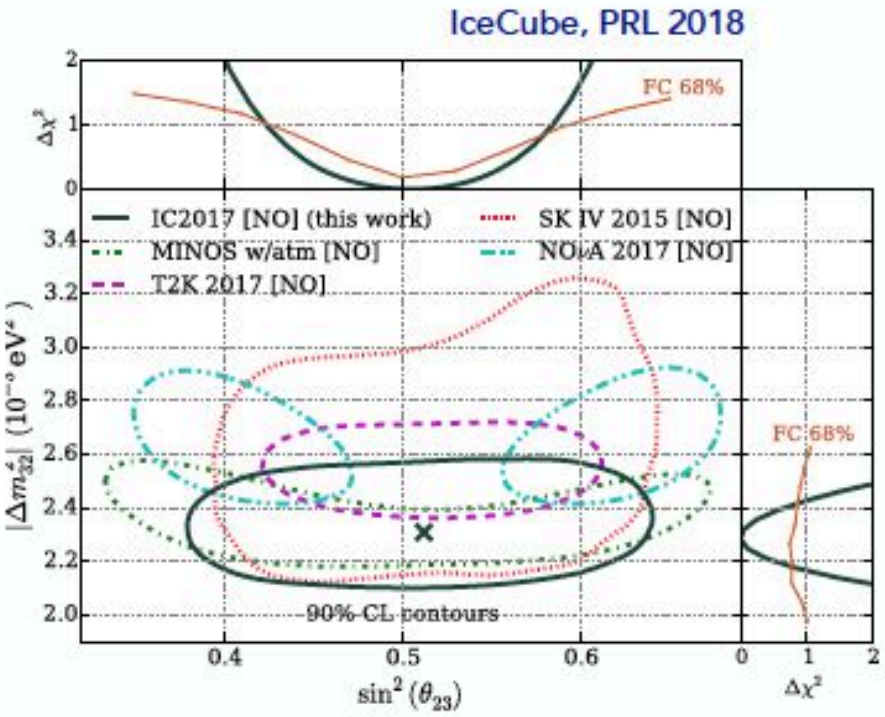
oscillations at 20 GeV





Neutrino Oscillation





- 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

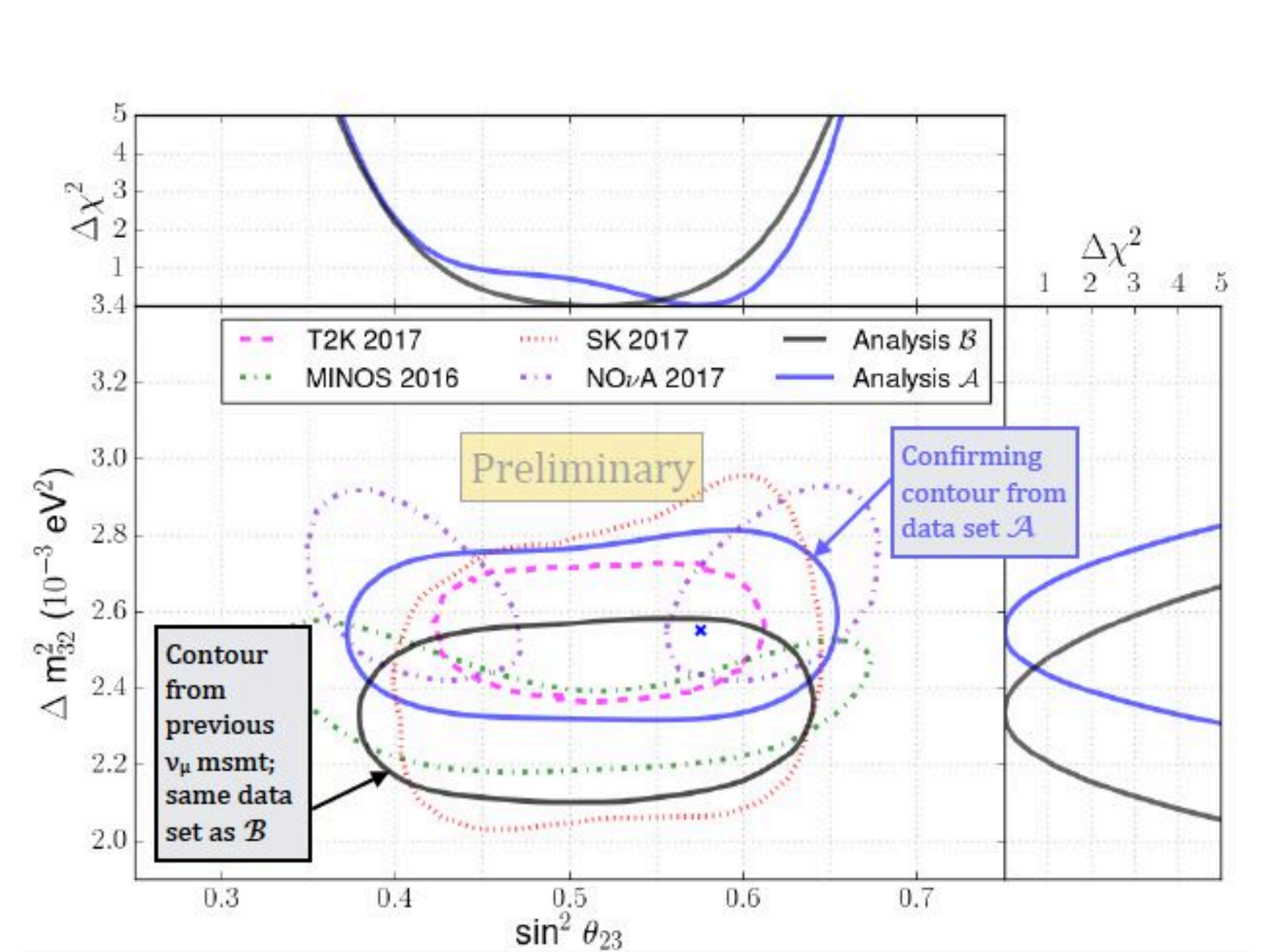
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\text{eV}^2$$

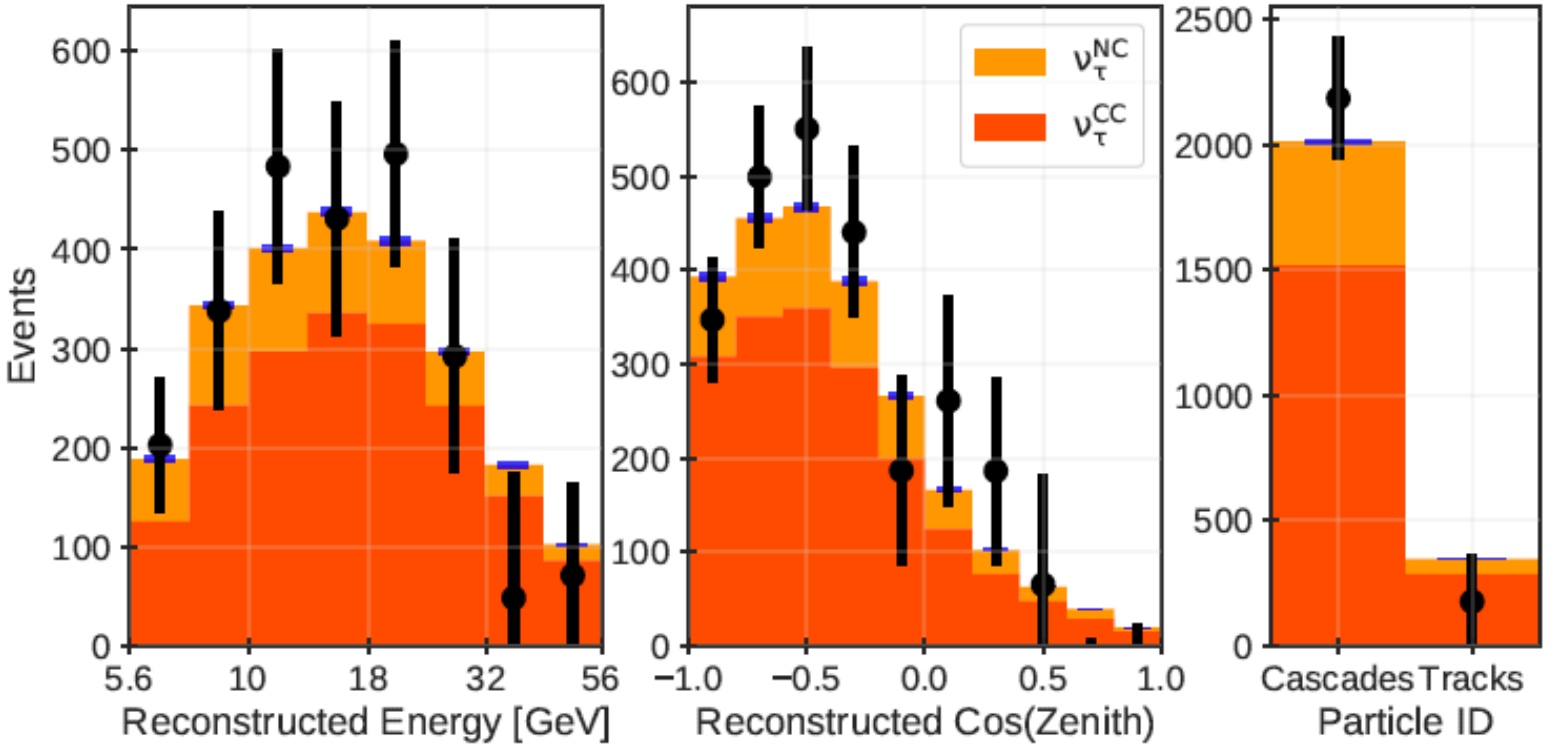
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

- 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 Level 2 “Filter”	At least 3 pairs of locally coincident DeepCore DOMs detect hits in a 2.5 microsecond time window 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 1st and 4th hits consistent with $v \leq c$.
	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 ?

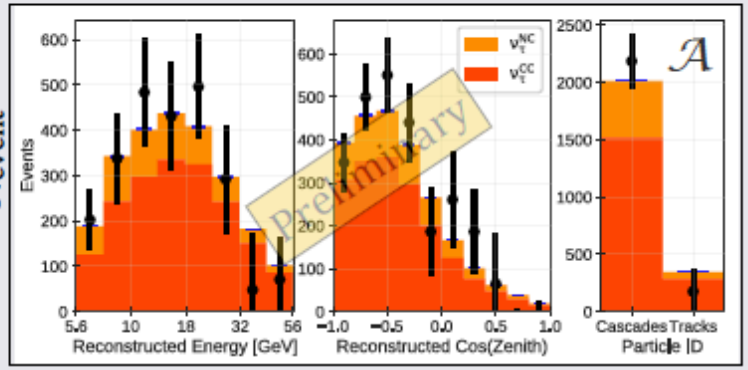
	Similarities	Differences
Simulation	Neutrino Simulation Chain • GENIE • PROPOSAL & GEANT4 • Photon Propagation • Noise	Muon Background Estimation • Analysis A: Simulation based on H4a Cosmic Ray flux model • Analysis B: Data-driven based on muons in "corridors"
Selection	• Trigger • Veto regions • Both use combo of BDTs & straight cuts, but different variables for each	• Charge, vertex estimators, non-isolated hits, etc.
Reconstruction	Likelihood-based method with 8 parameters • Vertex *x, y, z, t* • Track zenith, azimuth • Energy of primary cascade • Length of minimum ionizing track	Track discretization • Analysis A: 5 meter segments (finer track) • Analysis B: 15 meter segments (coarser track)
Classification (track vs. cascade)	----------	• Analysis A: track length < or > 50 meters • Analysis B: Force cascade only and cascade + track, determine fit, compute log-likelihood ratio.
Analysis Binning	Energy binning: • Range: 5.6 to 56 GeV • Bins: 10 bins spaced logarithmically	Coszenith binning: • Range: -1 to 1 • Bins: Analysis A 10 bins, Analysis B 8 bins
Analysis Calculation	Chi-squared minimization for nutau normalization and nuisance parameters. Nuisance parameters: • $\boldsymbol{\nu_e / \nu_\mu}$ ratio, $\boldsymbol{\nu}$ /anti-$\boldsymbol{\nu}$ ratio, θ_{23}, Δm^2_{32} • Optical efficiency of detector • Bulk ice scattering & absorption • Atmospheric muon fraction	Nuisance parameters: • Analysis A: Did *not* fit θ_{13} • Analysis B: Did fit θ_{13}


$\Delta\chi^2$
5
4
3
2
1
3.4
$\Delta\chi^2$
1 2 3 4 5
T2K 2017
MINOS 2016
SK 2017
NOνA 2017
Analysis $\mathcal{B}$
Analysis $\mathcal{A}$
Preliminary
Confirming contour from data set $\mathcal{A}$
Contour from previous ν_μ msmt; same data set as $\mathcal{B}$
$\Delta\, m^2_{32}$ (10^{-3} eV^2)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$

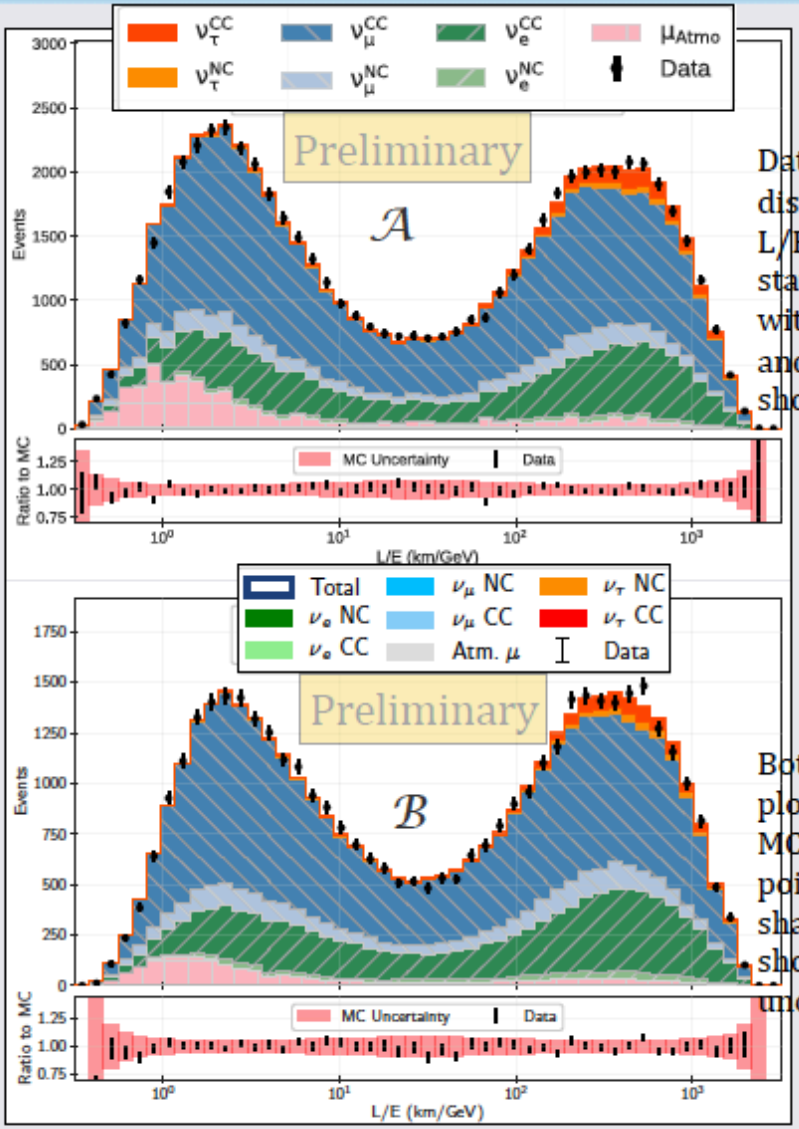


tau events: Distributions of the data with best-fit neutrino and muon backgrounds subtracted, overlaid with the best fit ν_τ hypothesis projected onto the reconstructed energy axis (left), the cosine of the reconstructed zenith angle (middle) and PID categories (right), for Analysis $\mathcal{A}$. Error bars are statistical only.

Data distributions with best-fit $\nu_e+\nu_\mu$ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.



E_{reco} (GeV) $\cos(\theta_{zen})_{reco}$ PID_{reco}



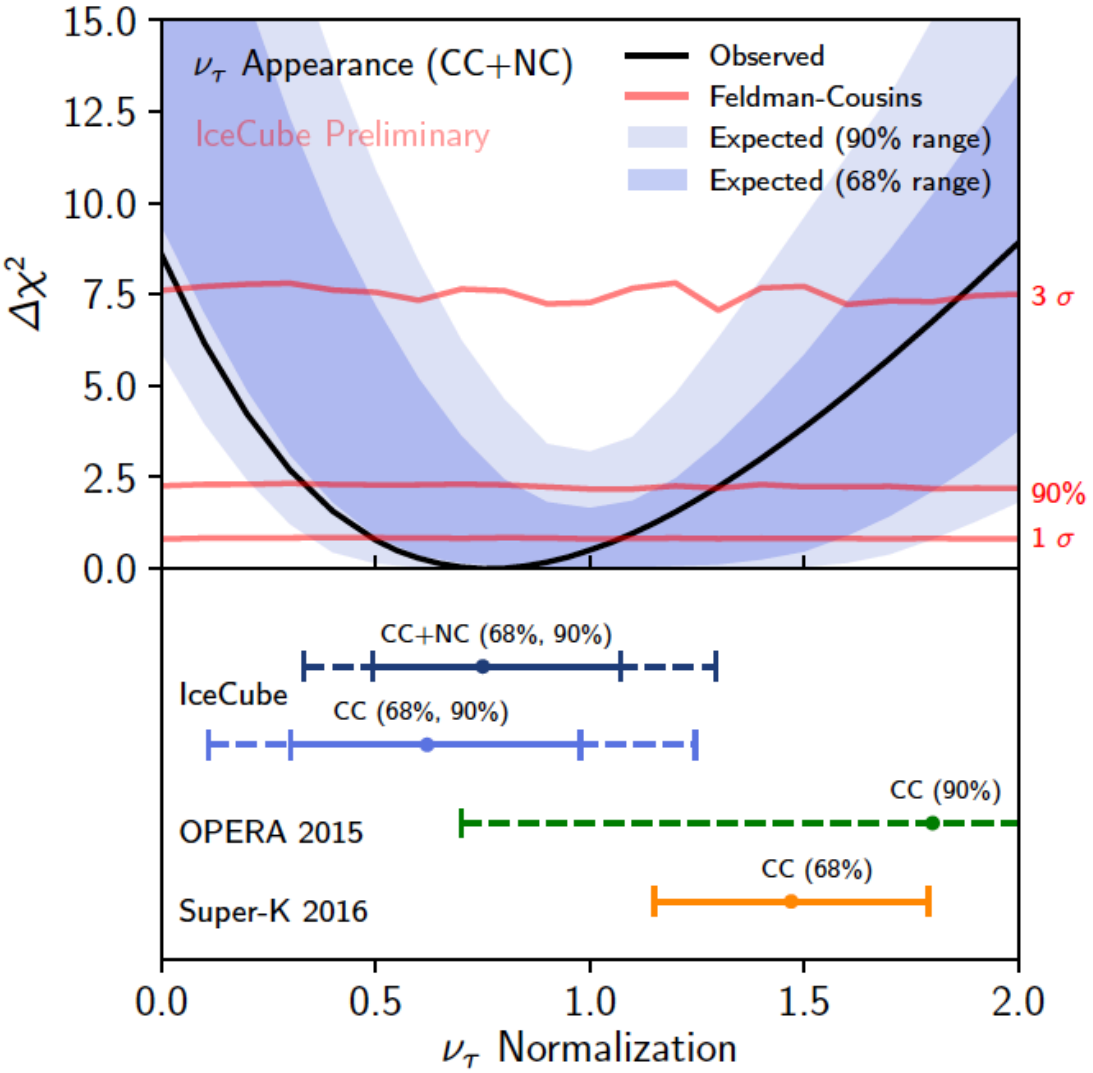
$(L/E)_{reco}$ (km/GeV)

Data distributions vs. L/E (points with stat. error bars), with best-fit ν and μ bkgds. shown (hists.).

Bottom of each plot shows data/MC at best fit point, with shaded region showing stat. unc. of best fit.

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

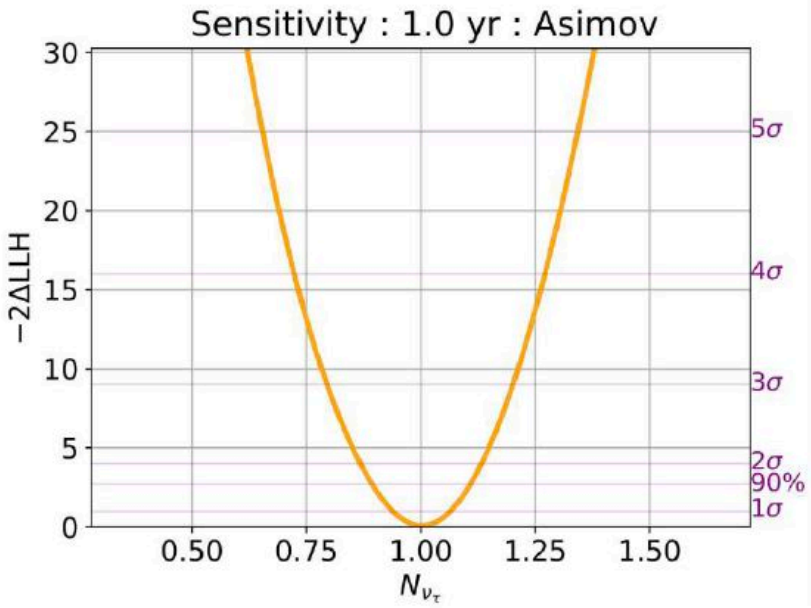


upgrade!

Not approved for public use

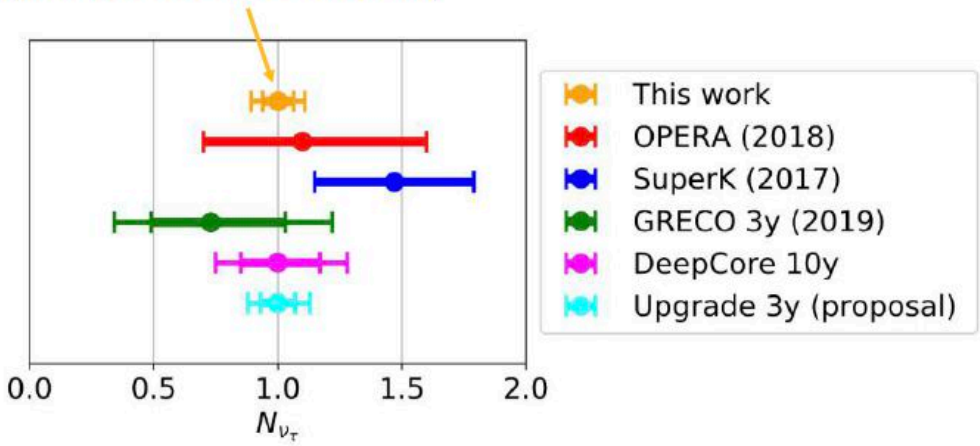
υ_τ appearance sensitivity

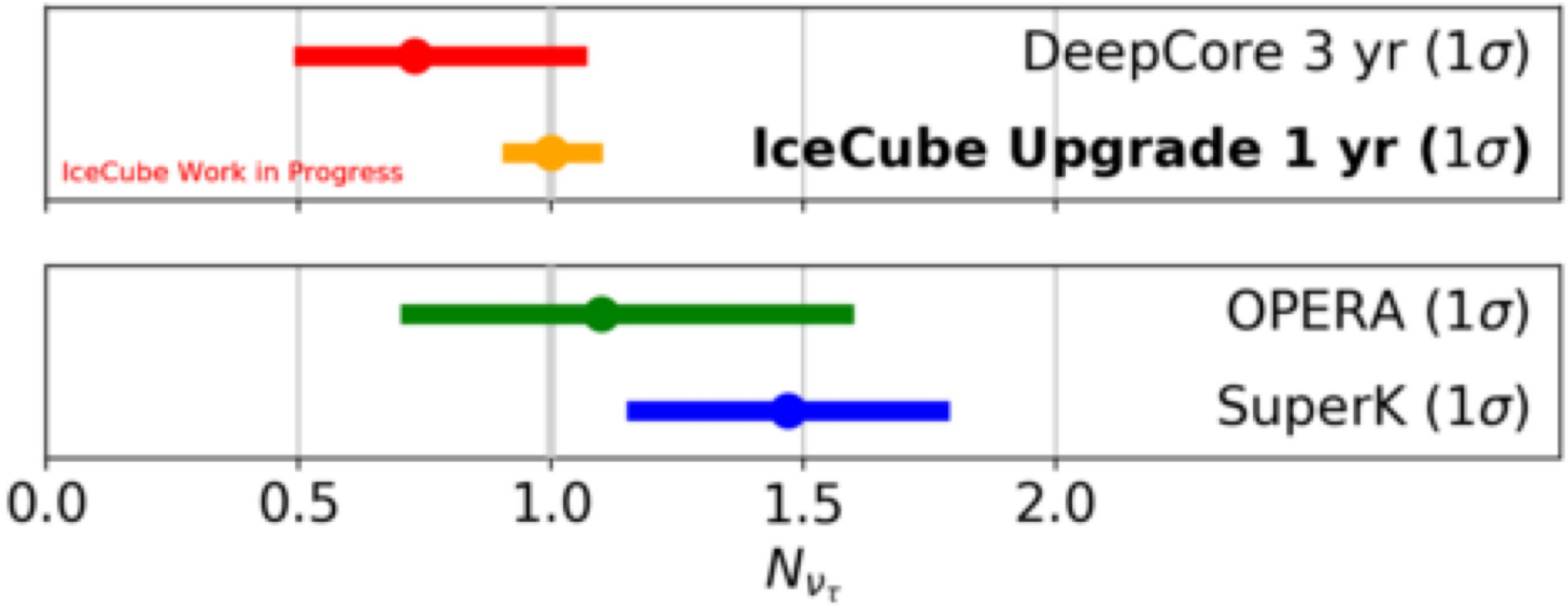
- Test sensitivity of analysis
  - Assuming 1 year livetime



10% 1σ precision target achieved using baseline simulation/reco/analysis

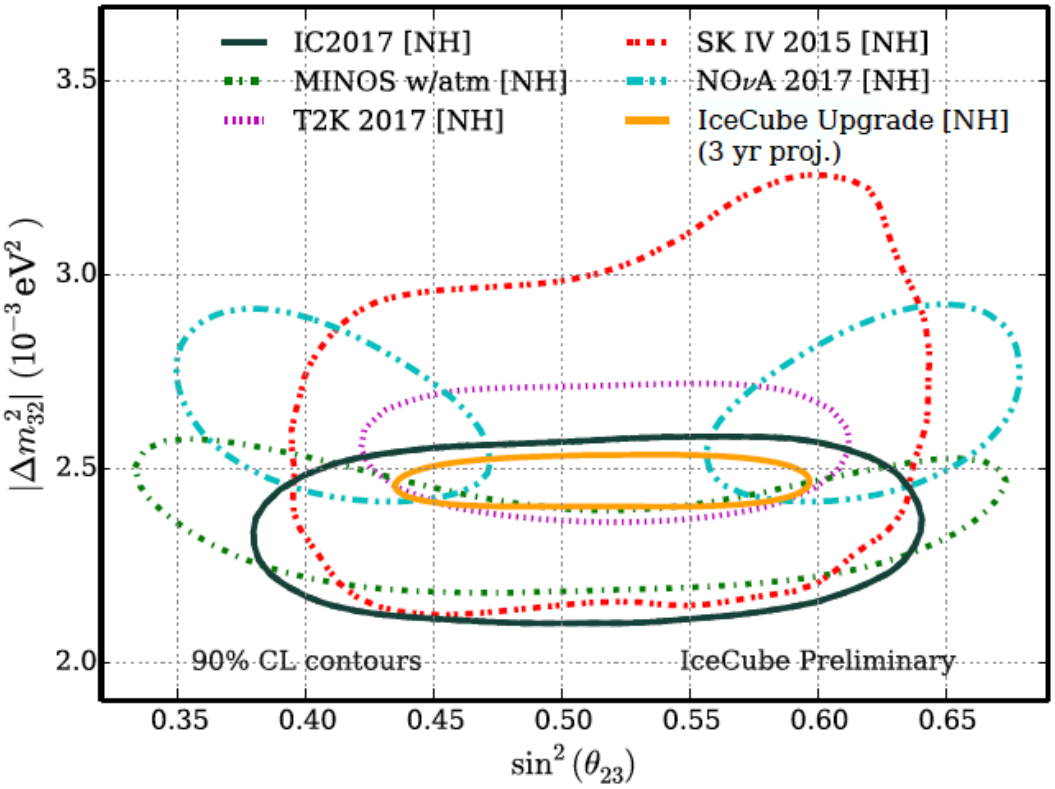
(... but, remember caveats...)



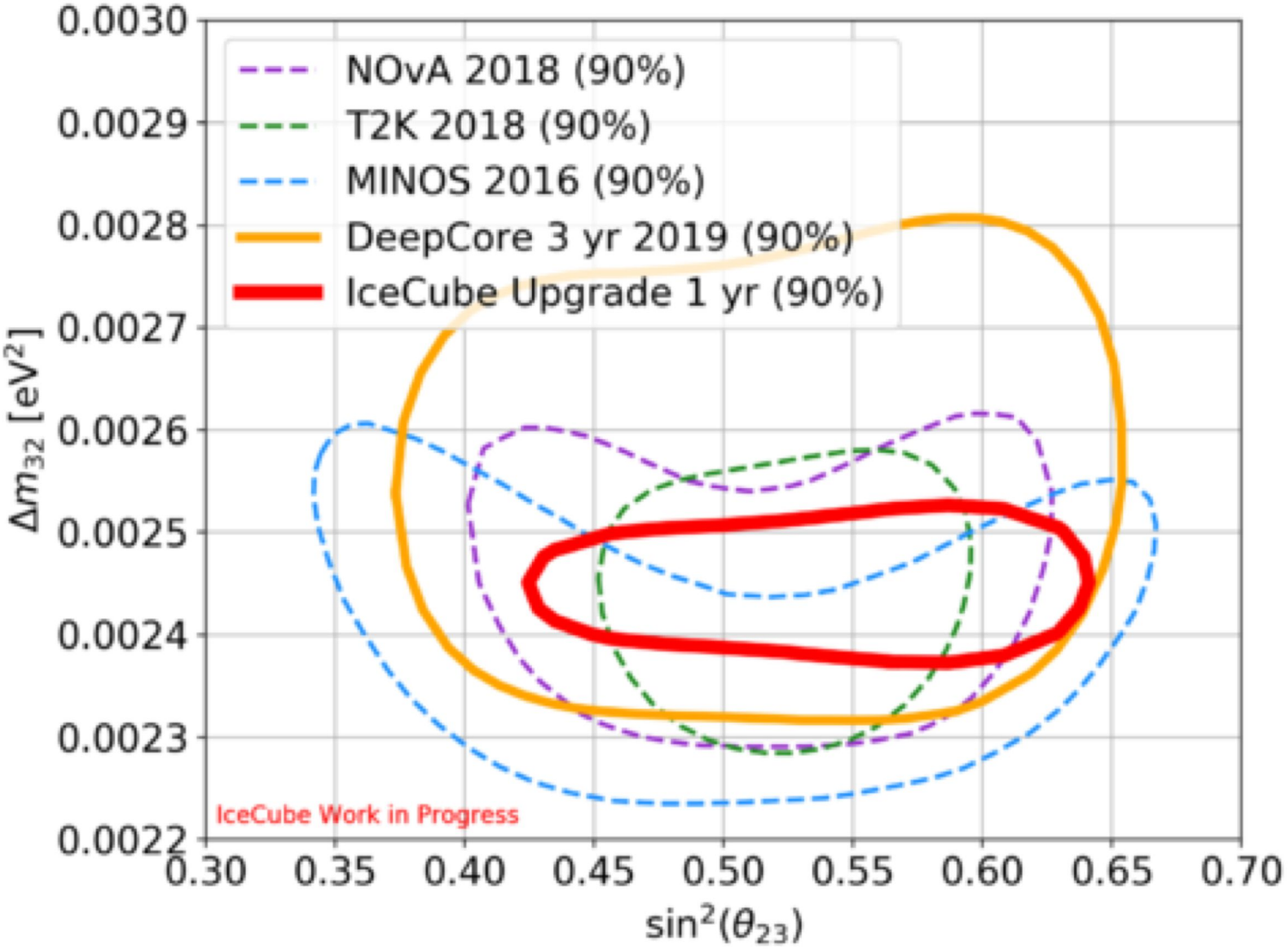

DeepCore 3 yr (1σ)
IceCube Upgrade 1 yr (1σ)
IceCube Work in Progress
OPERA (1σ)
SuperK (1σ)
0.0
0.5
1.0
1.5
2.0
N_{ν_τ}

Atmospheric Oscillation Parameters

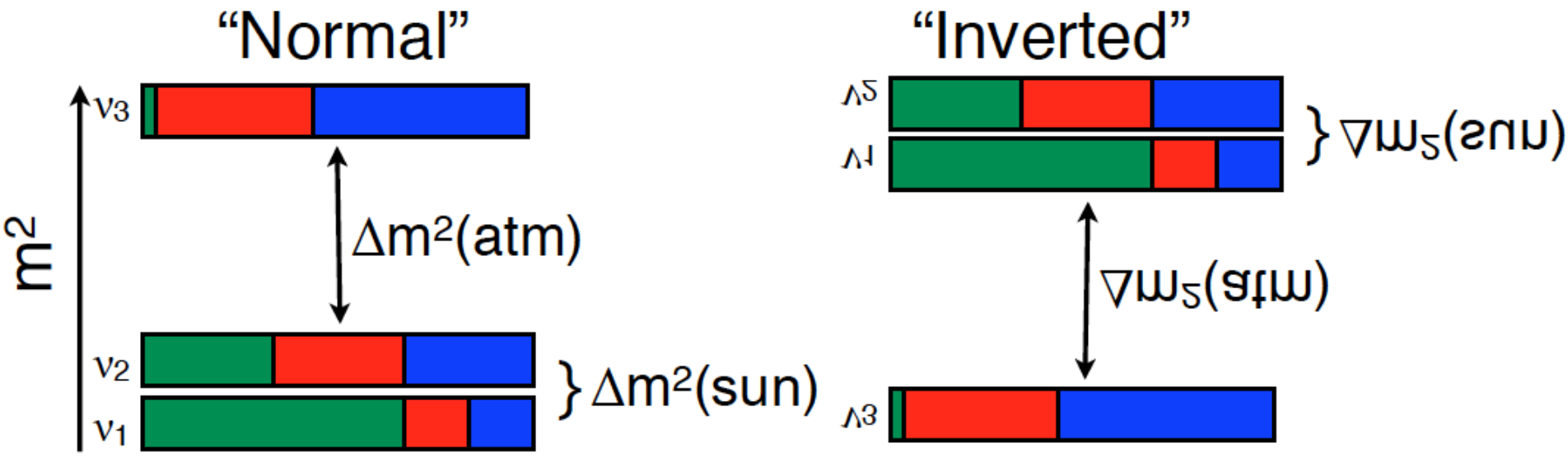
- Currently unclear whether $\sin^2 \theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)


NOvA 2018 (90%)
T2K 2018 (90%)
MINOS 2016 (90%)
DeepCore 3 yr 2019 (90%)
IceCube Upgrade 1 yr (90%)
IceCube Work in Progress
Δm_{32} [eV^2]
$\sin^2(\theta_{23})$
0.0030
0.0029
0.0028
0.0027
0.0026
0.0025
0.0024
0.0023
0.0022
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70

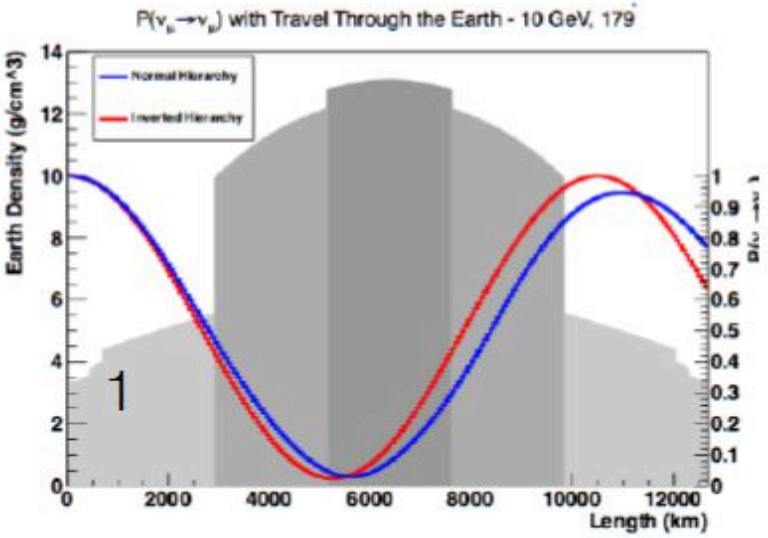
neutrino mass hierarchy ?

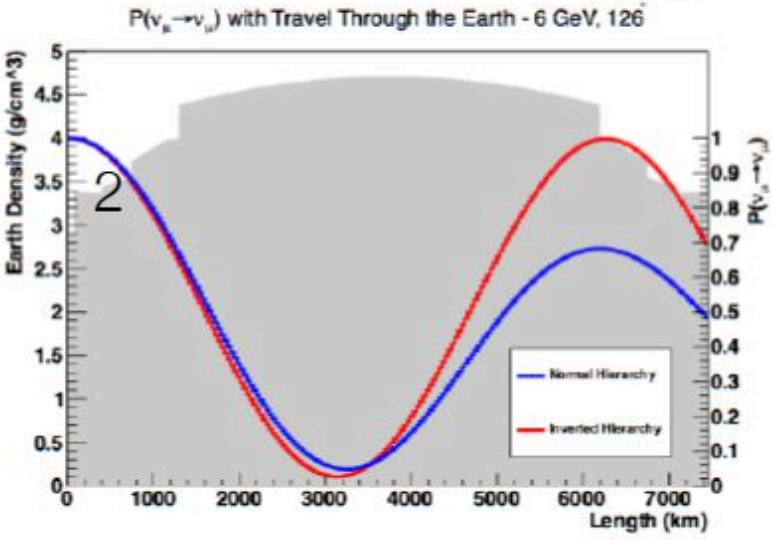


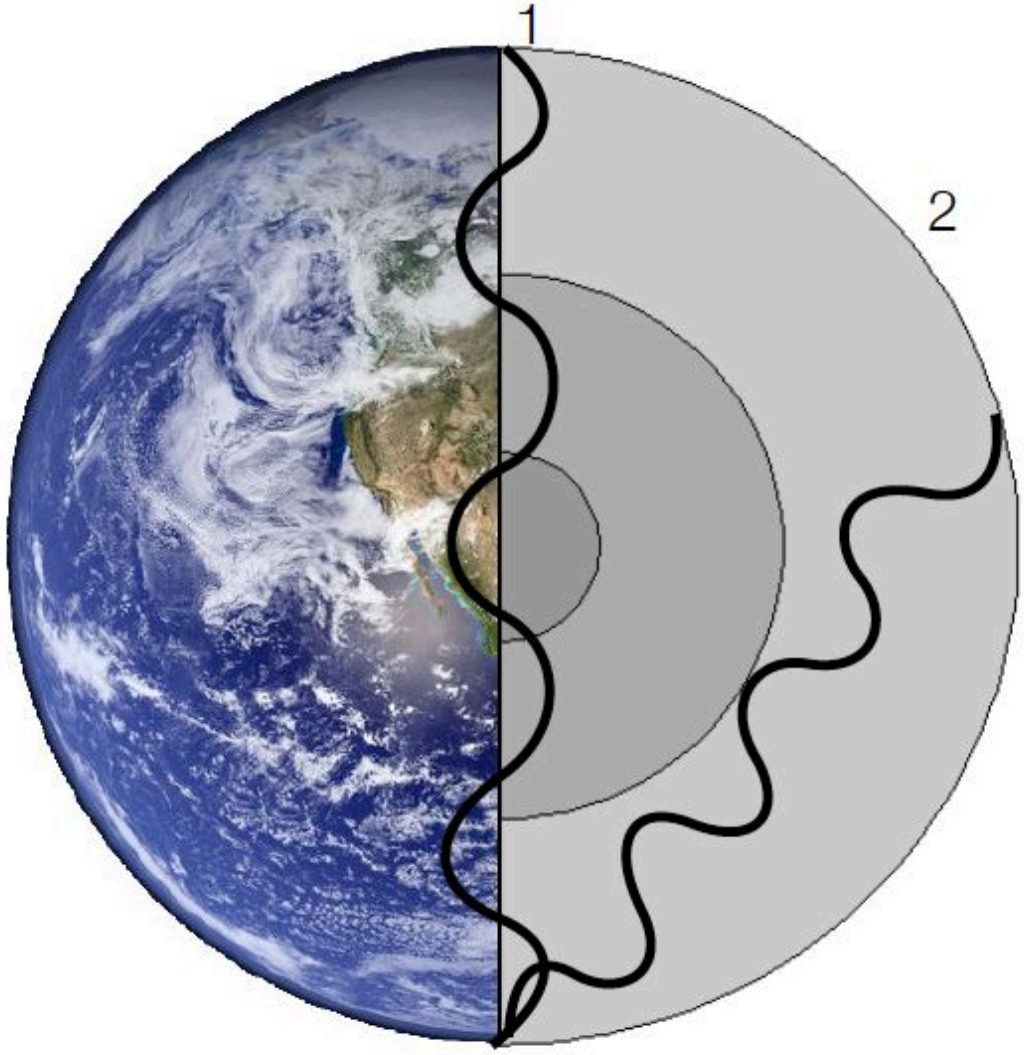
present status: probability inverted ordering <15.3%

Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy

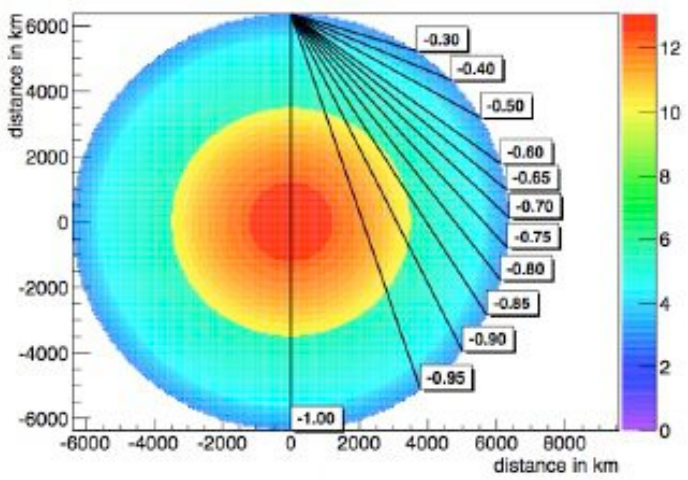




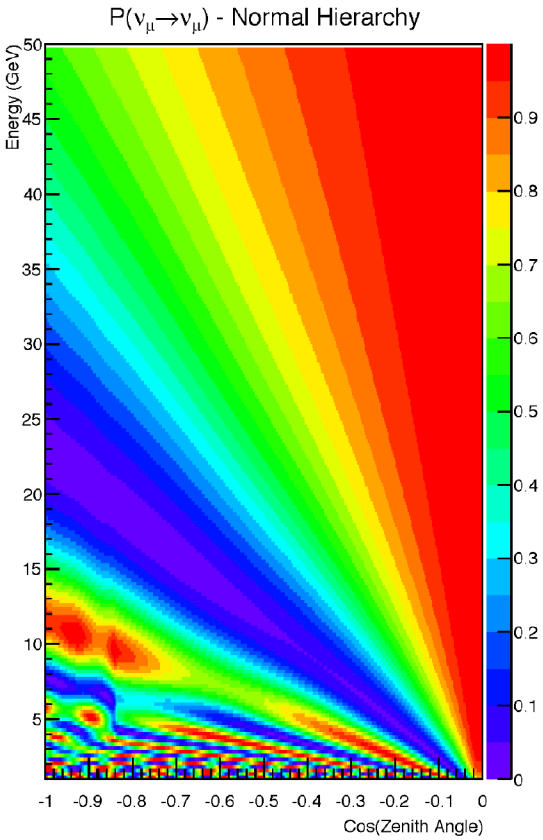


$P(\nu_\mu \rightarrow \nu_\mu)$

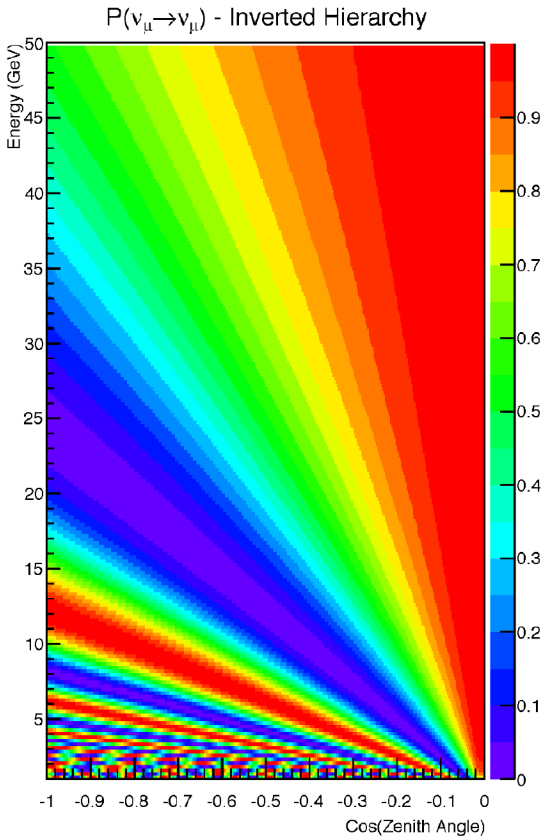
- Map upward ν flux in bins of (E,cosθ);
- cosθ= -1 L~12000 Km;



Normal Hierarchy



Inverted Hierarchy



Letter of Intent PINGU- arXiV:1401.2046

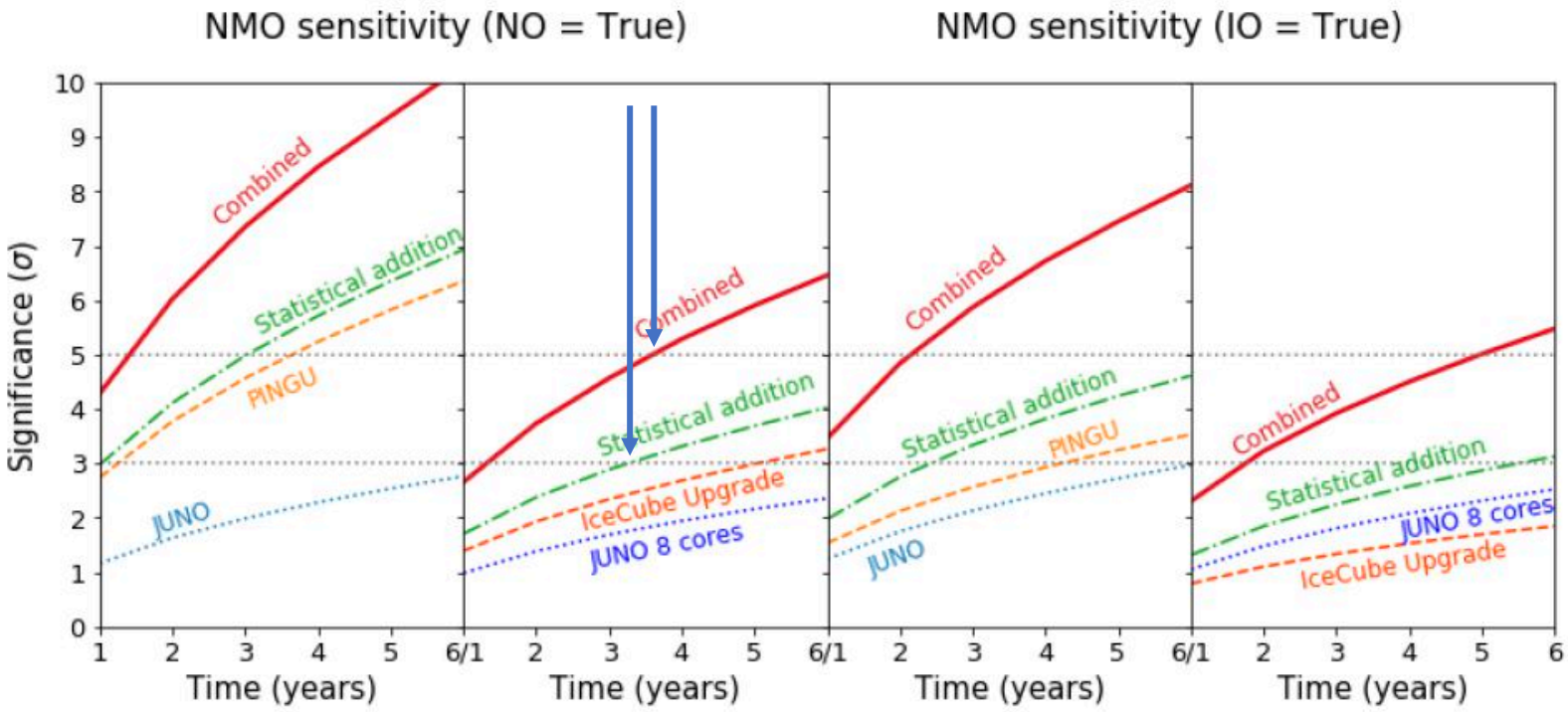
~ 10 GeV : hierarchy revealed by
“large” matter effects in the Earth

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2G_F}\, n_e}{\Delta_{13}}\right]}$$

(mostly) neutrino + antineutrino -

sign Δ_{13} : hierarchy !

upgrade!

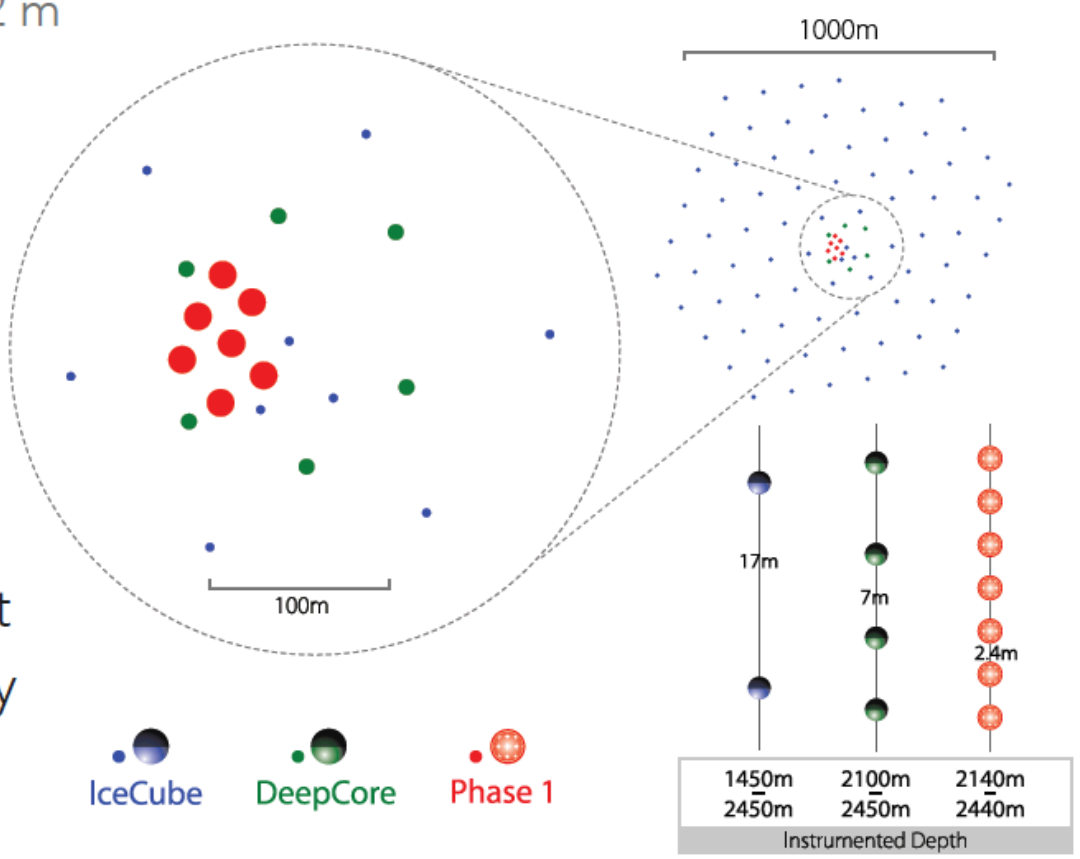


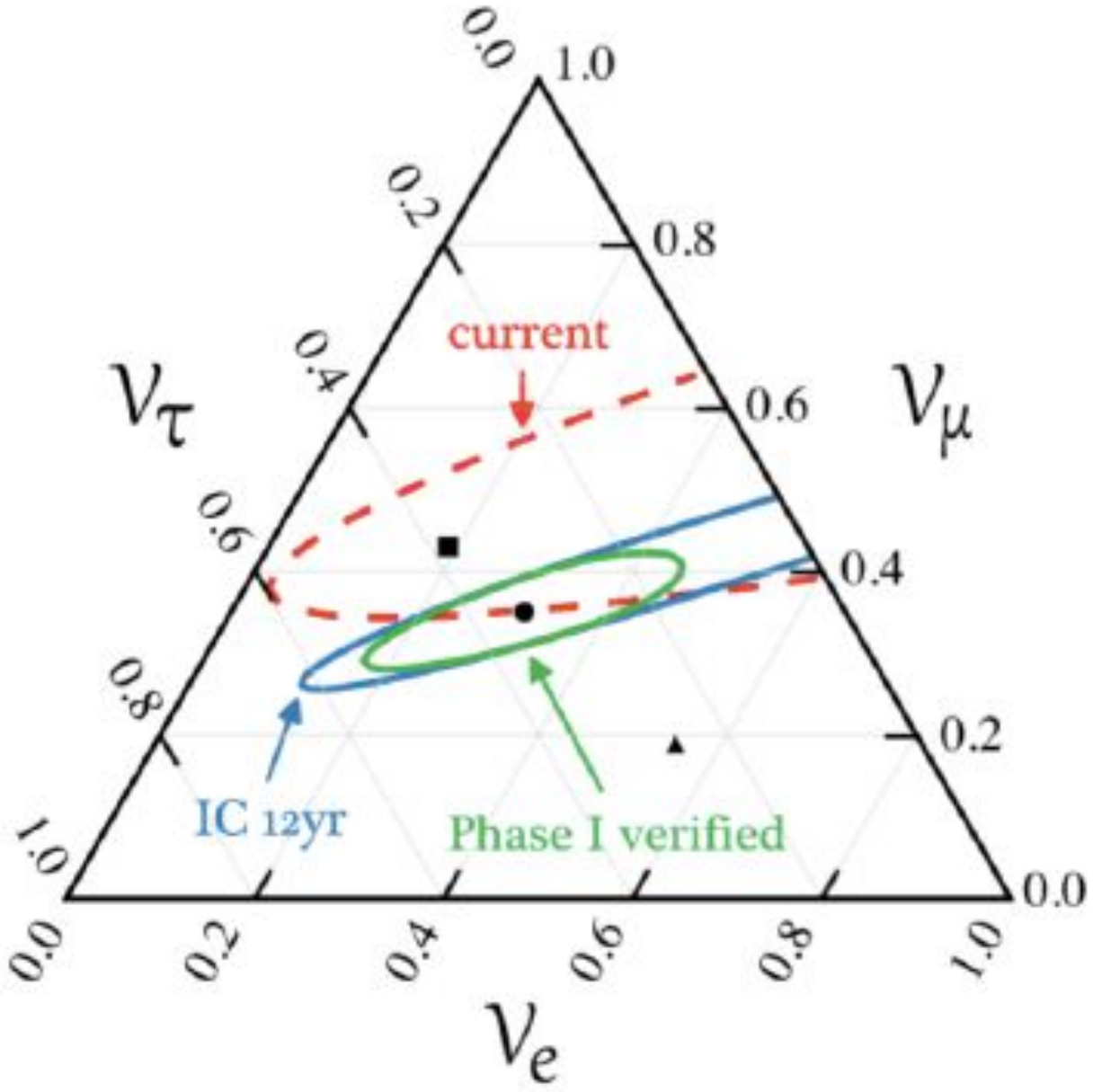
difference between between “statistical combined” and “combined” results from the different tension in the determination of the mass-squared difference of JUNO and Upgrade if one wrongly defines the mass ordering:

$$\Delta m^2_{31} = m^2_3 - m^2_1$$

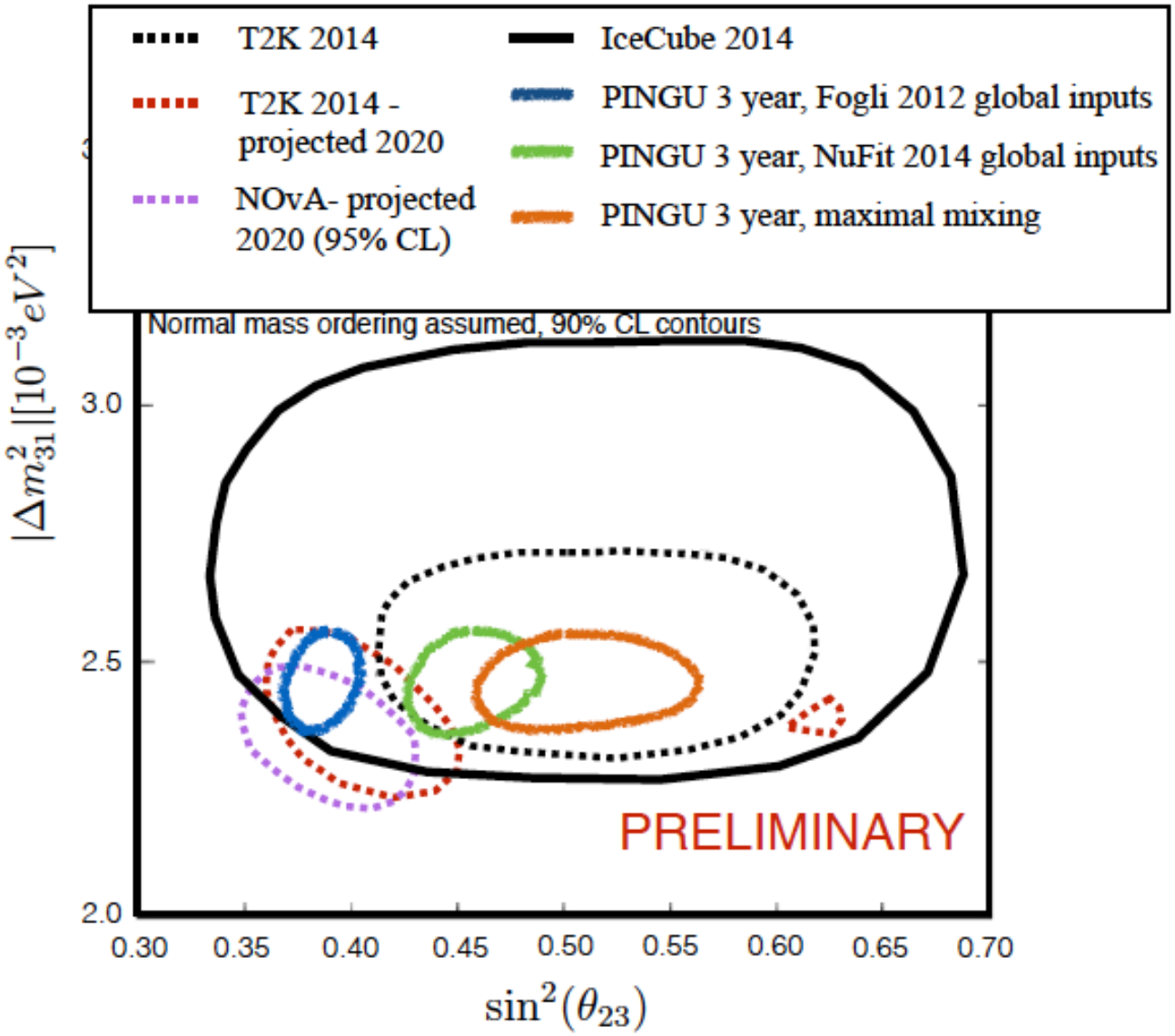
Next Step: the IceCube Upgrade

- 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




ν_τ
ν_μ
ν_e
current
IC 12yr
Phase I verified
0.0
0.2
0.4
0.6
0.8
1.0

and with PINGU

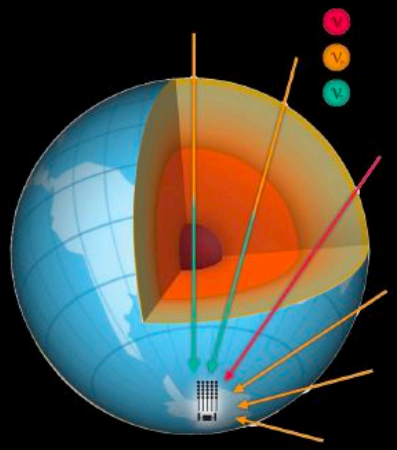


the atmospheric neutrino flux

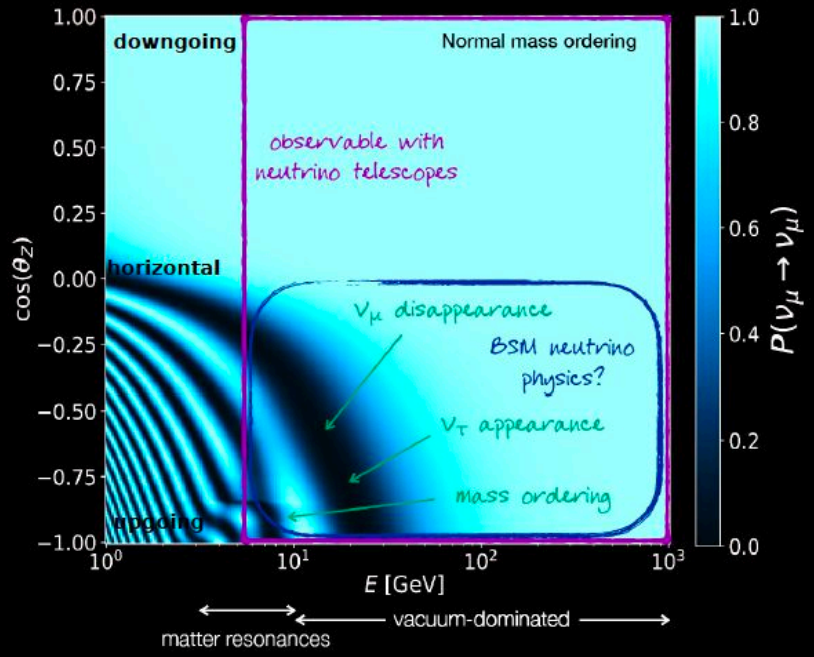
An enormous wealth of information can be obtained from the energy and pathlength of atmospheric neutrinos through the Earth to the detector

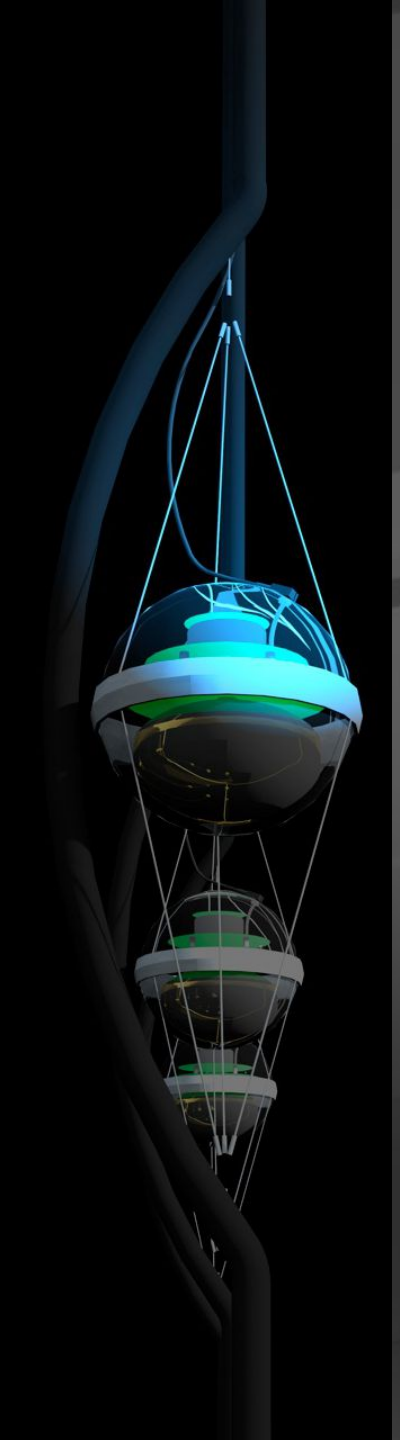
Neutrinos available over a wide range of baselines, with energies from a few GeV to ~100 TeV.

Oscillations produce distinctive patterns in narrow regions of 3D energy/angle/PID oscillogram



$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$





IceCube: beyond neutrino astronomy

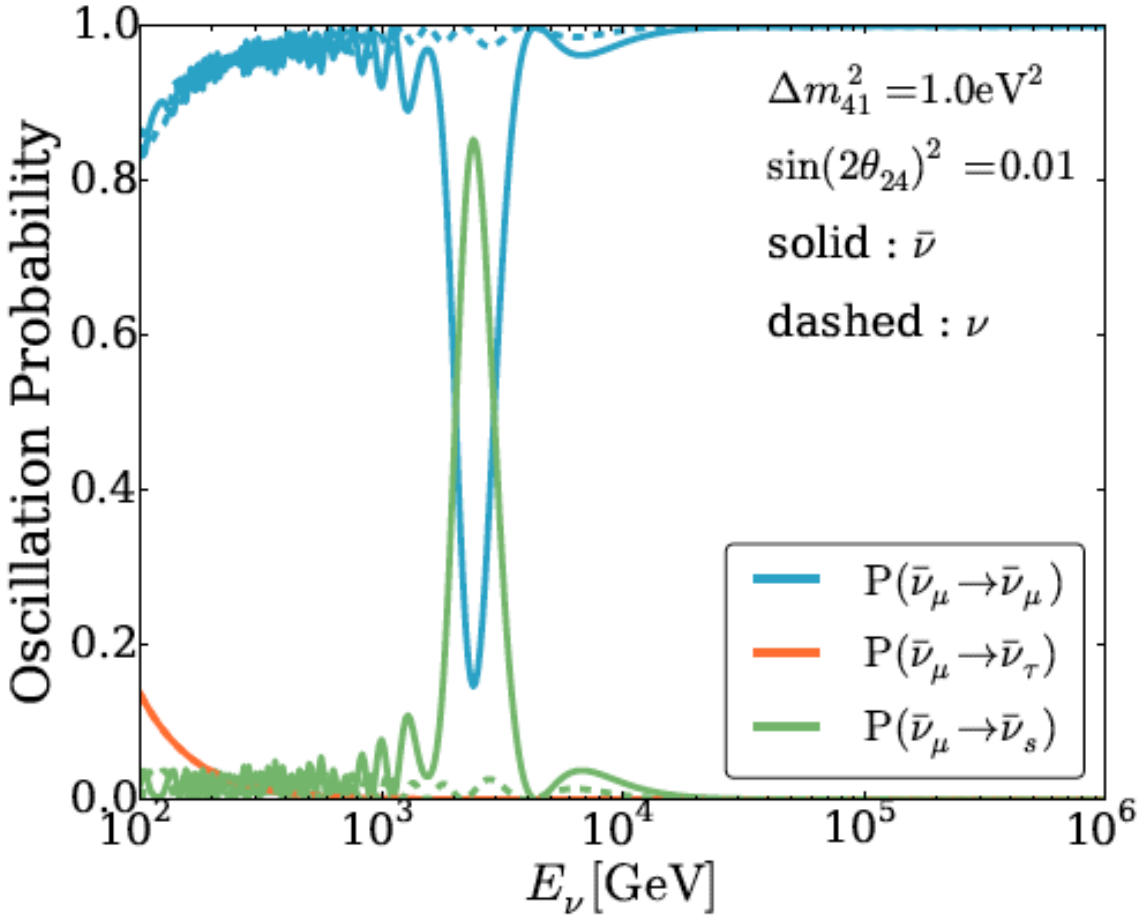
Francis Halzen

- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- …

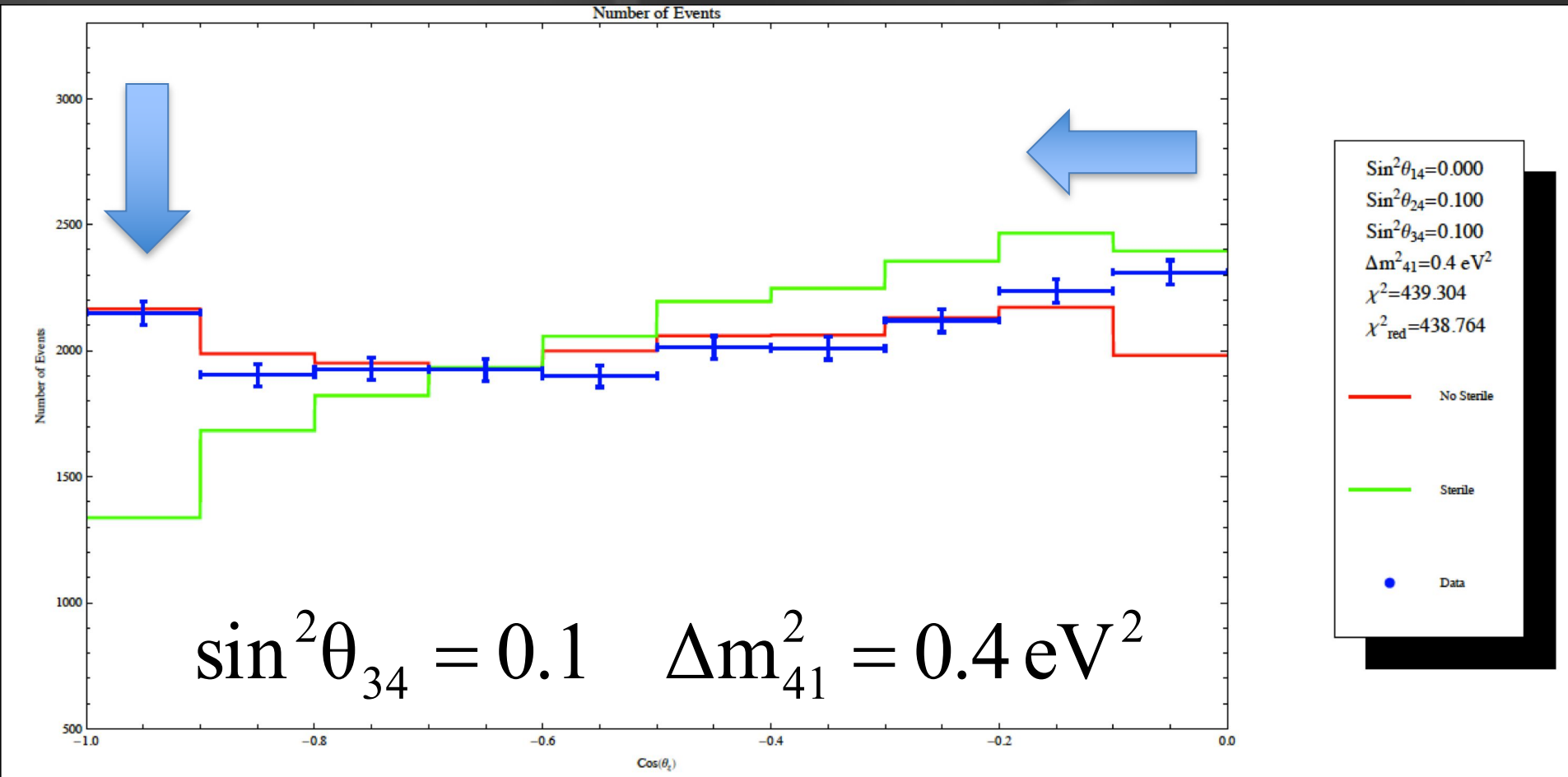
eV sterile neutrino → Earth MSW resonance for TeV neutrinos

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

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

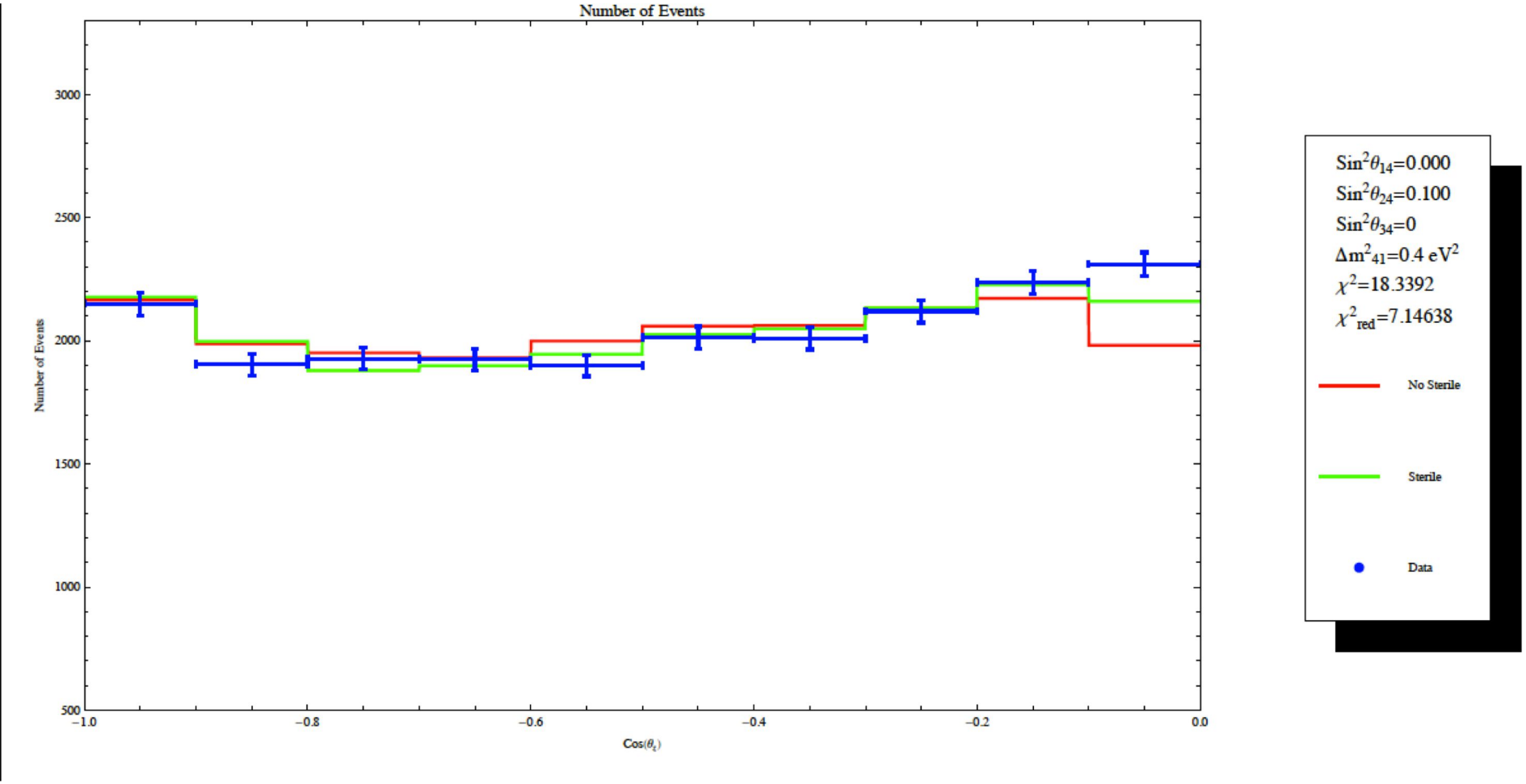


number of ν_μ observed versus zenith angle



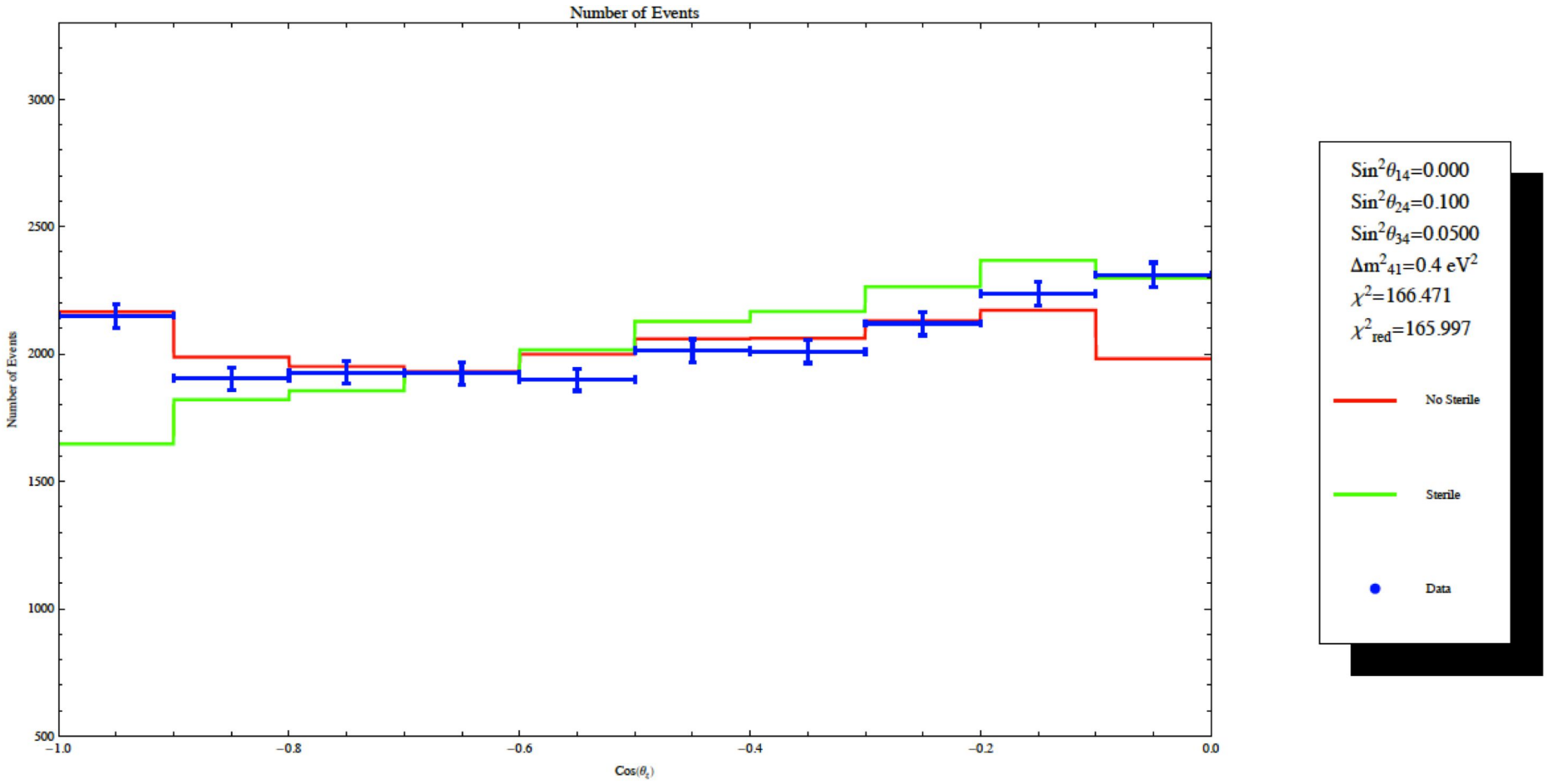
~ 2000 events per bin

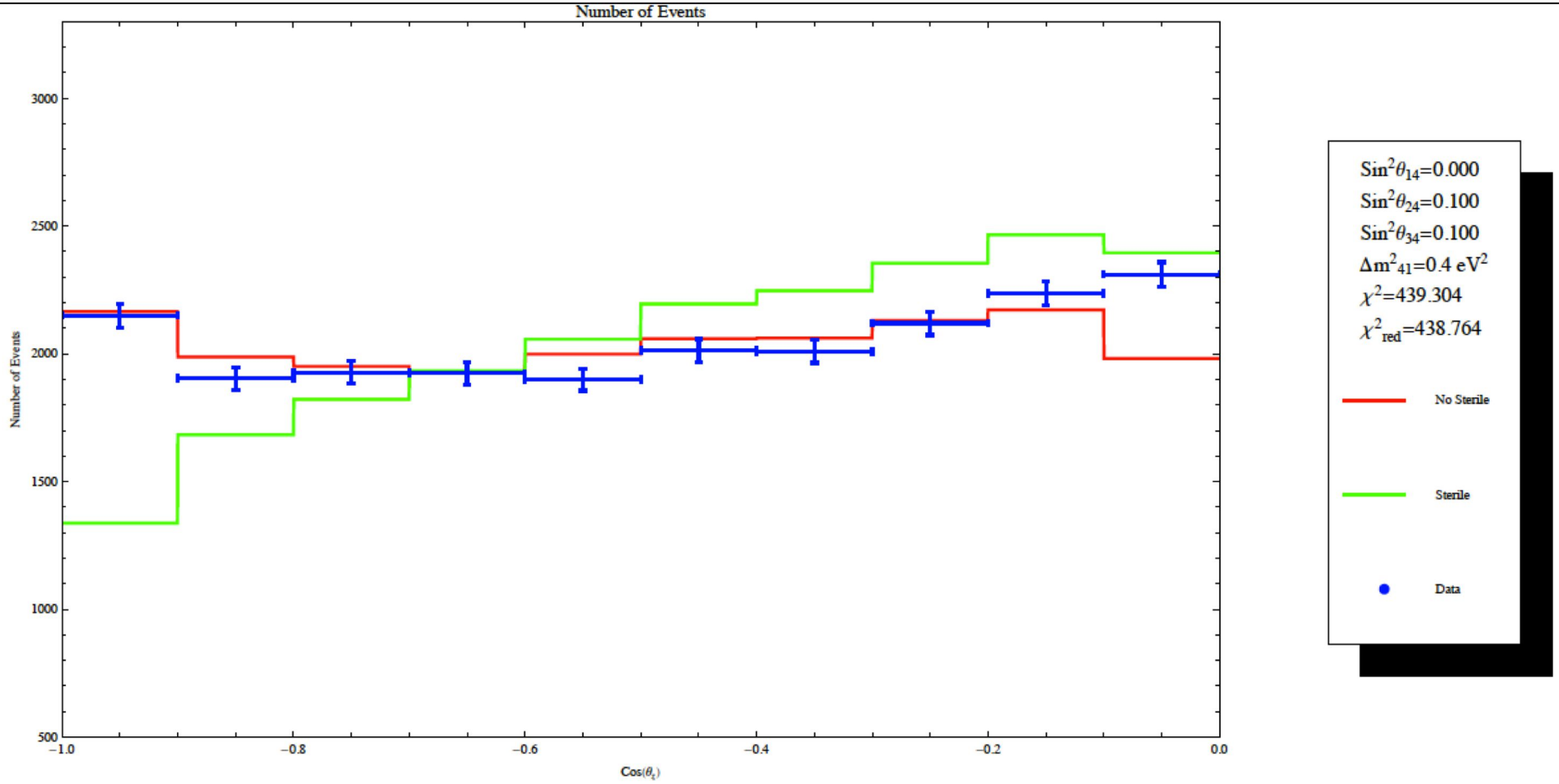
number of nu-mu events versus cosθ in IceCube 40

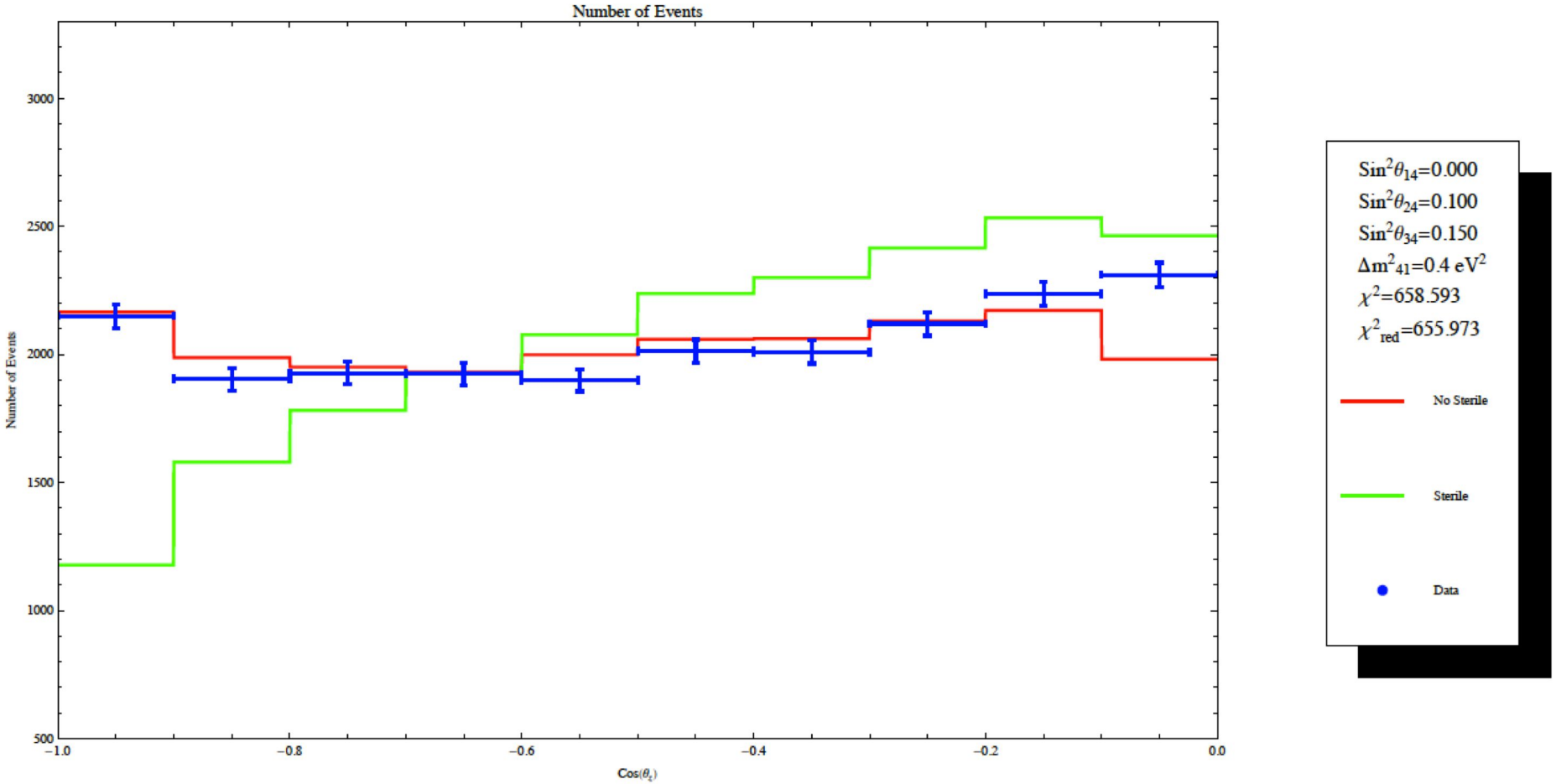


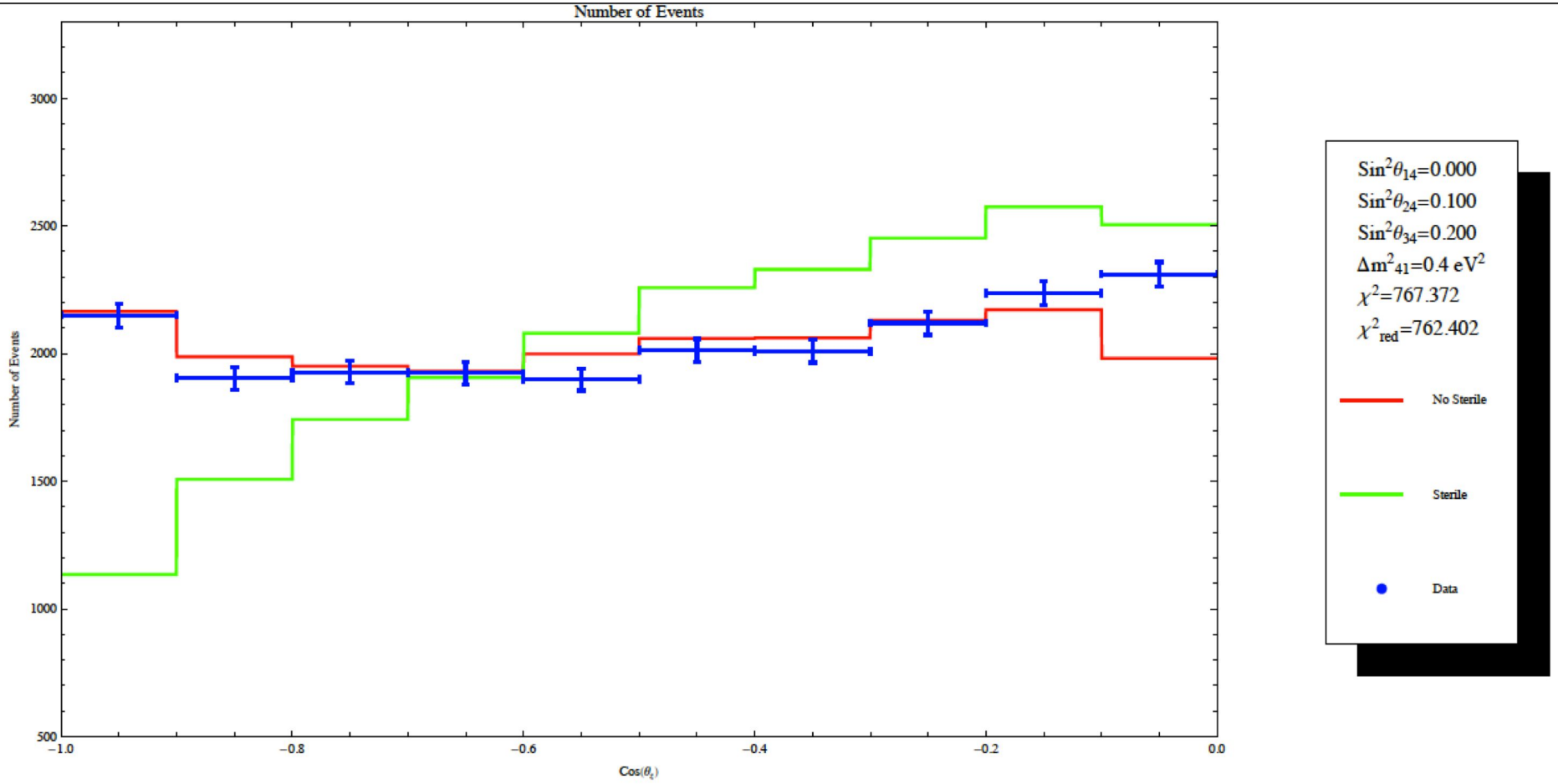
$\Delta m^2 = 0.4\ eV^2$ and $\sin^2\theta_{34} = 0 \rightarrow 0.5$

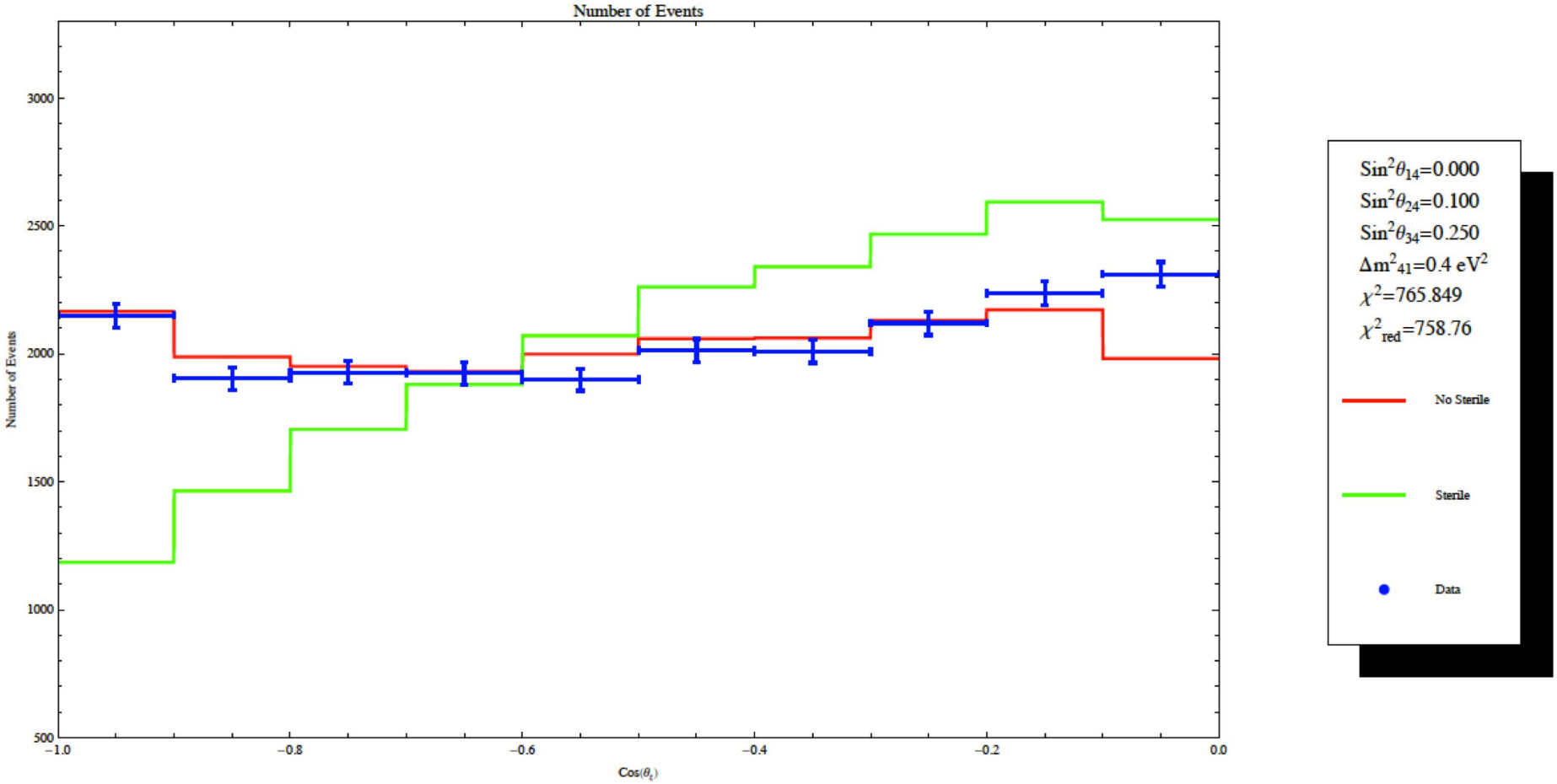
Arman Esmaili

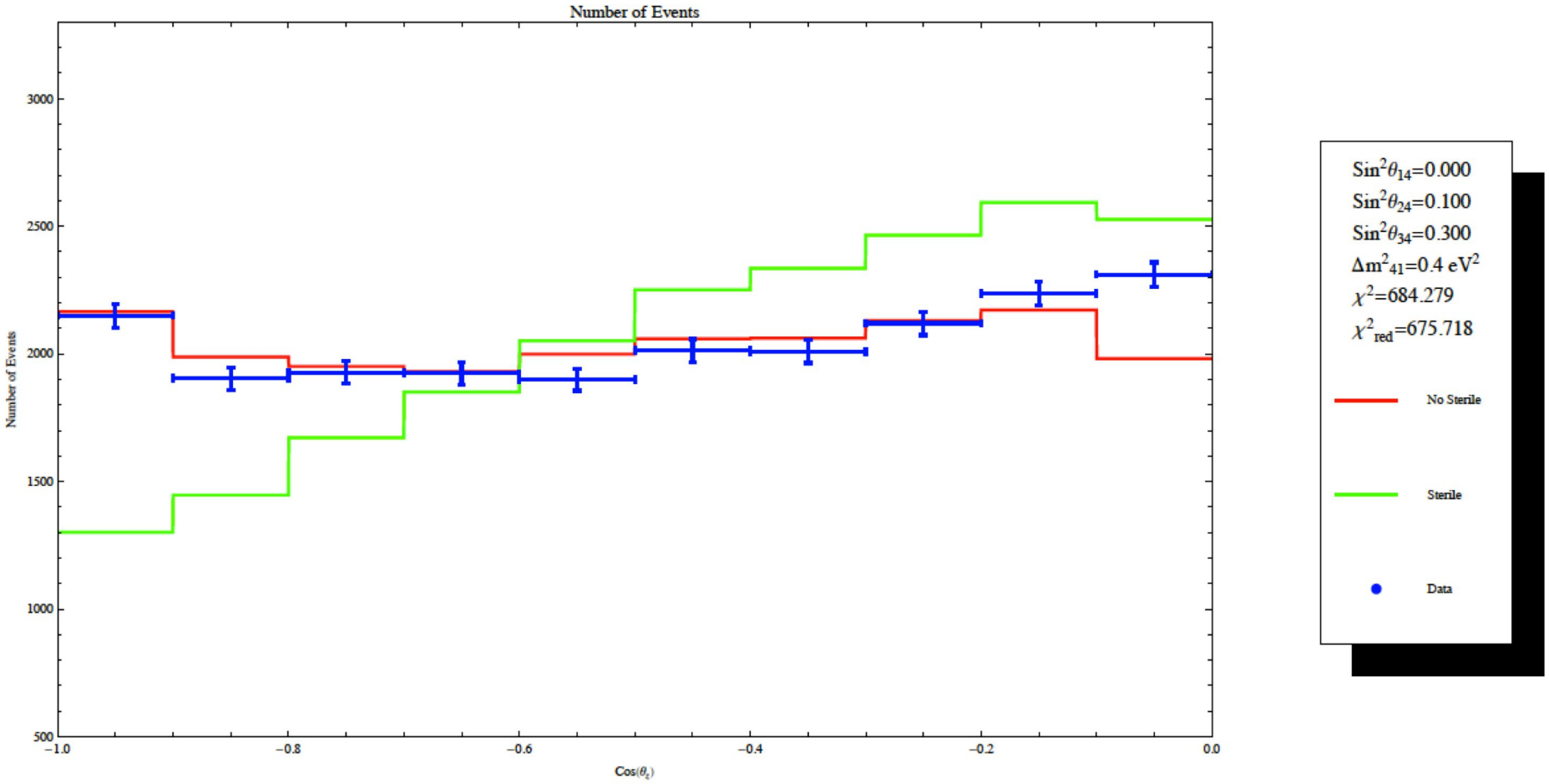

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.0500
Δm²41=0.4 eV²
χ²=166.471
χ²red=165.997
No Sterile
Sterile
Data

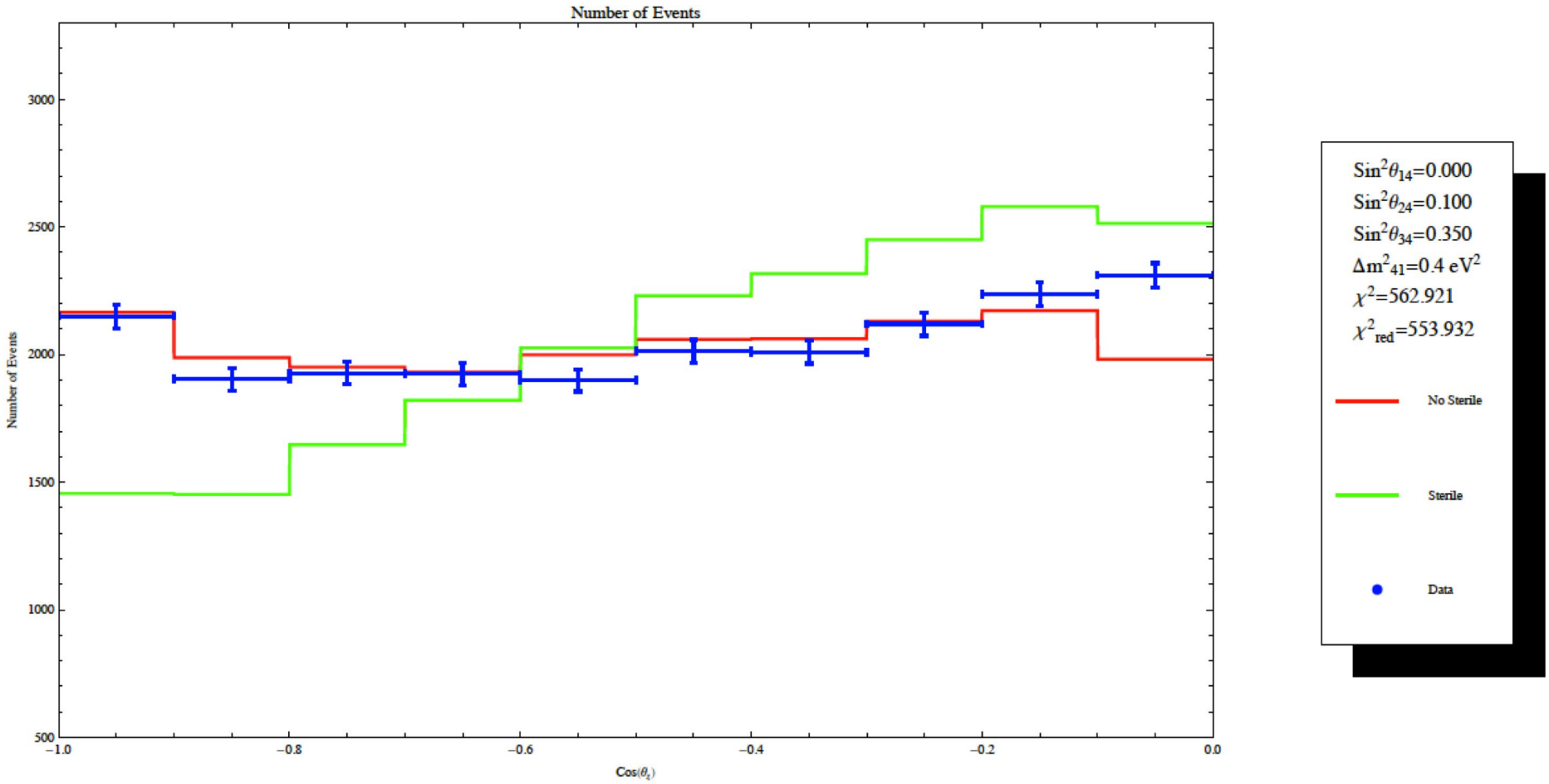

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.100
Δm²41=0.4 eV²
χ²=439.304
χ²red=438.764
No Sterile
Sterile
Data

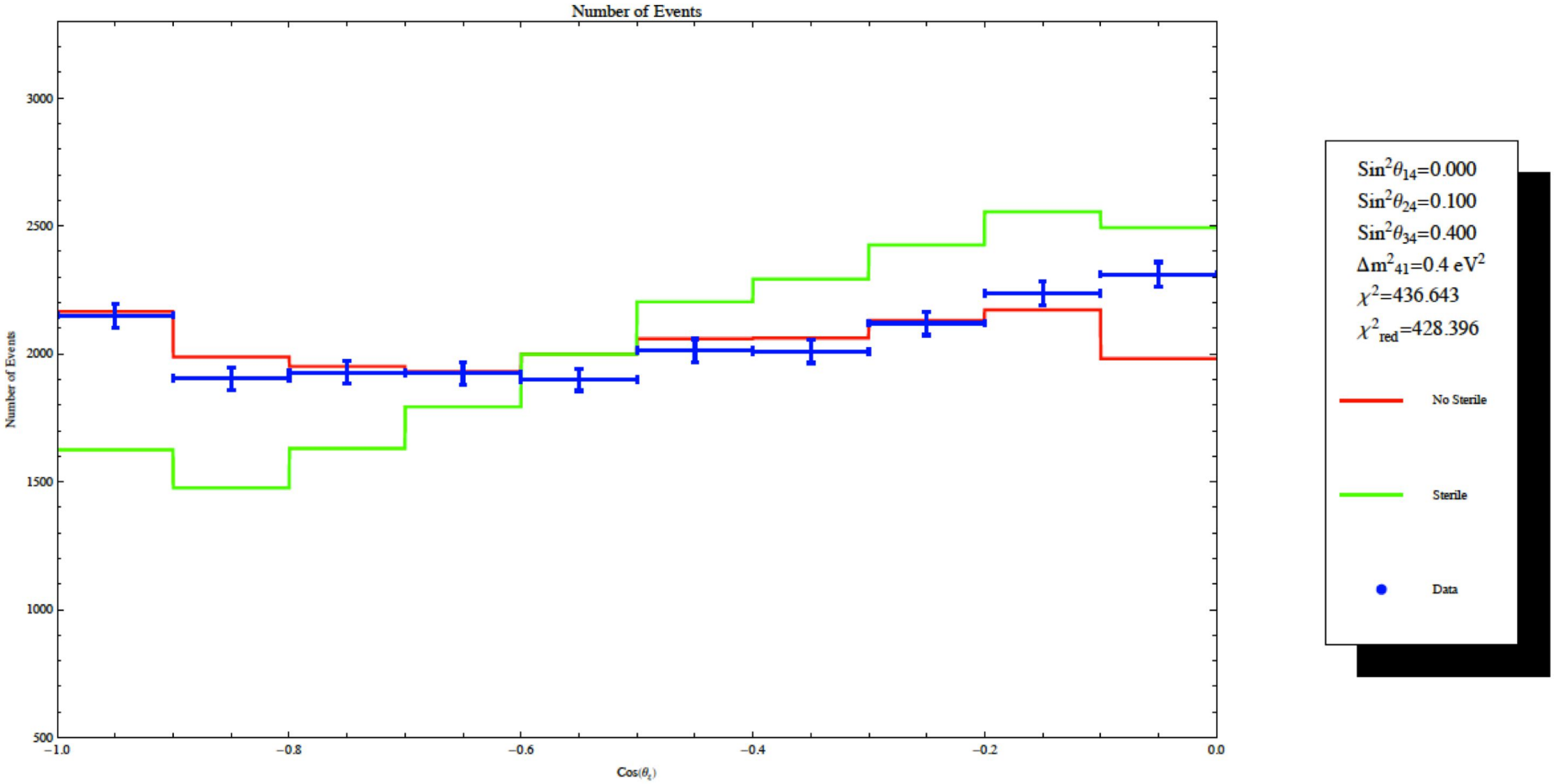

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_ℓ)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.150
Δm²41=0.4 eV²
χ²=658.593
χ²red=655.973
No Sterile
Sterile
Data

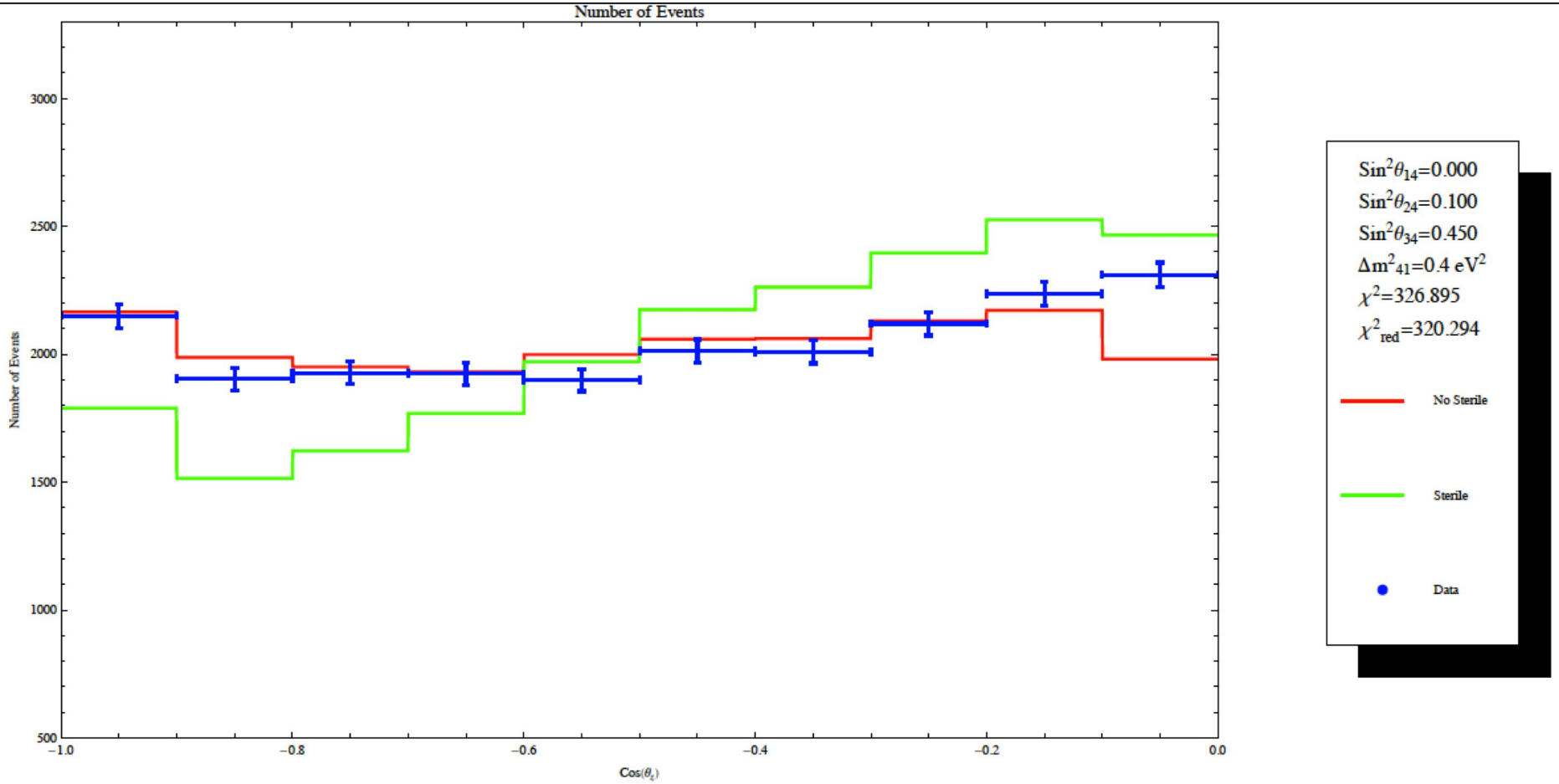

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.200
Δm²41=0.4 eV²
χ²=767.372
χ²red=762.402
No Sterile
Sterile
Data

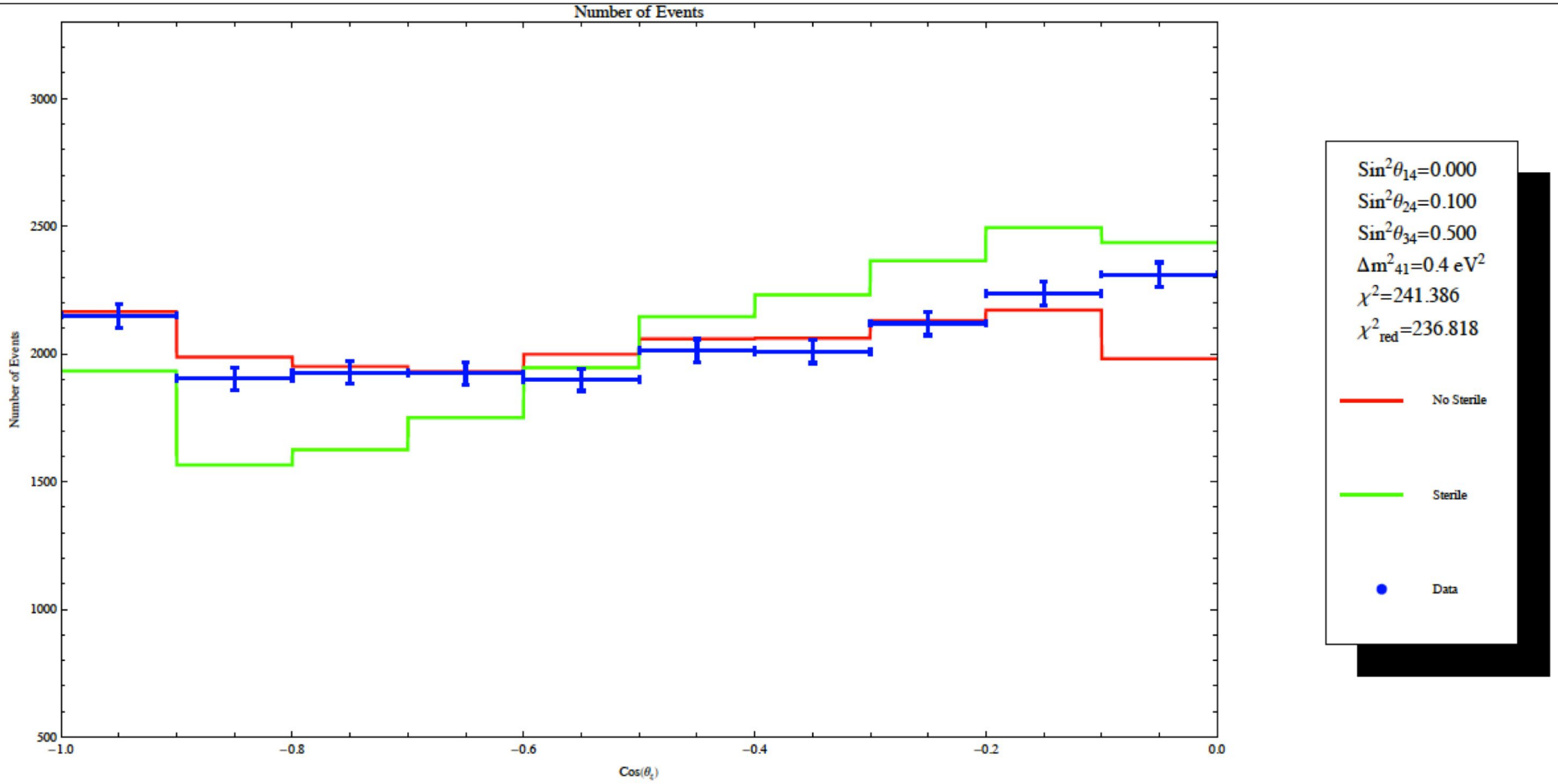

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.250
Δm²41=0.4 eV²
χ²=765.849
χ²red=758.76
No Sterile
Sterile
Data

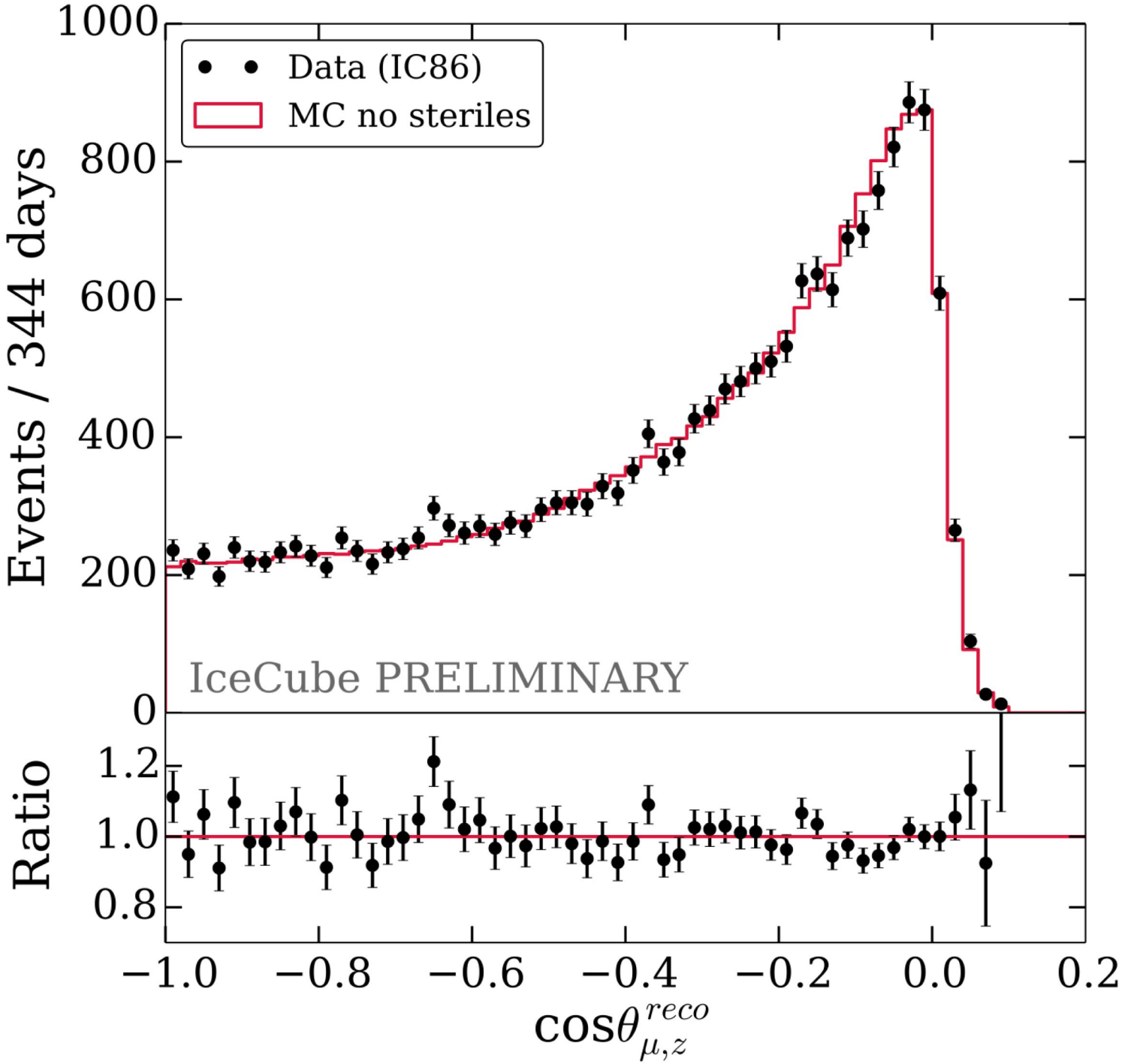

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.300
Δm²41=0.4 eV²
χ²=684.279
χ²red=675.718
No Sterile
Sterile
Data

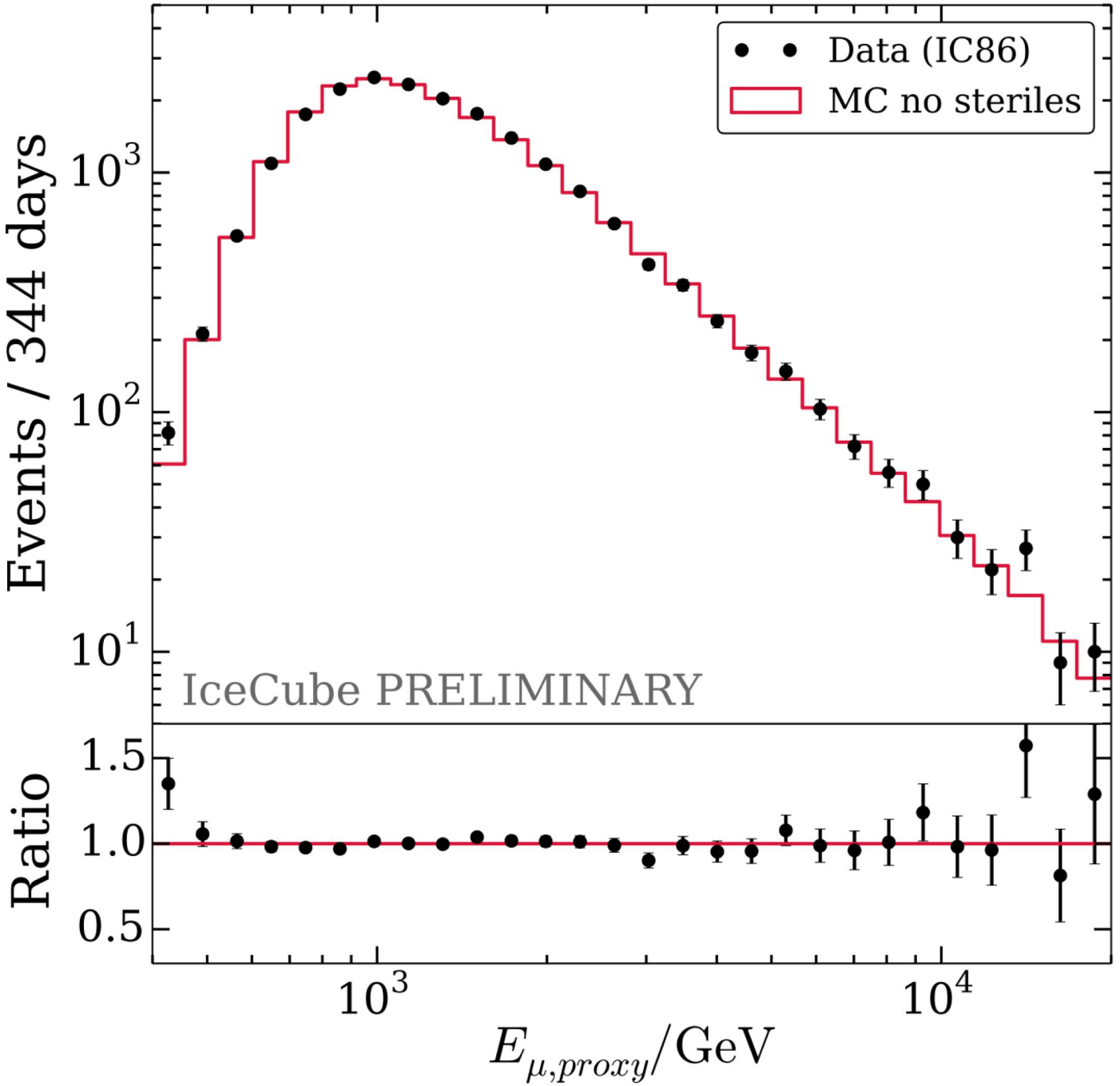

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.350
Δm²41=0.4 eV²
χ²=562.921
χ²red=553.932
No Sterile
Sterile
Data

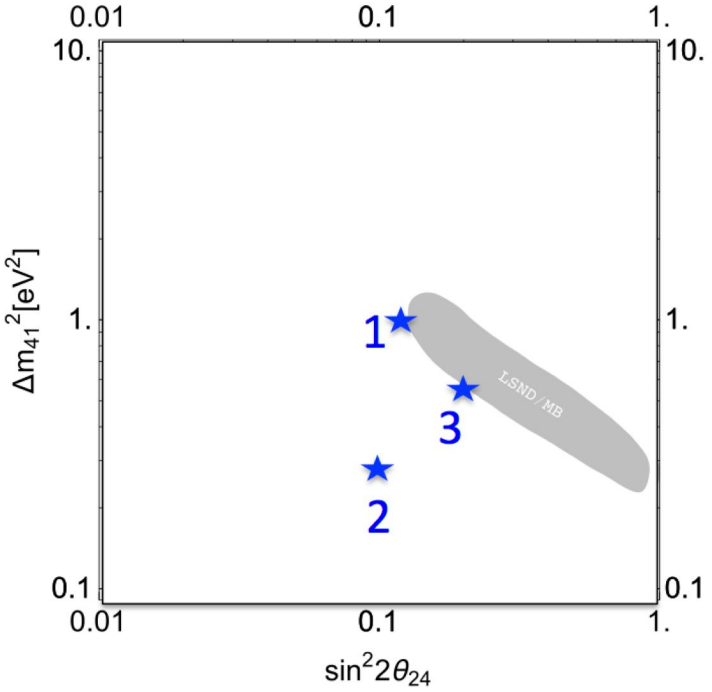

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_ℓ)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.400
Δm²41=0.4 eV²
χ²=436.643
χ²red=428.396
No Sterile
Sterile
Data

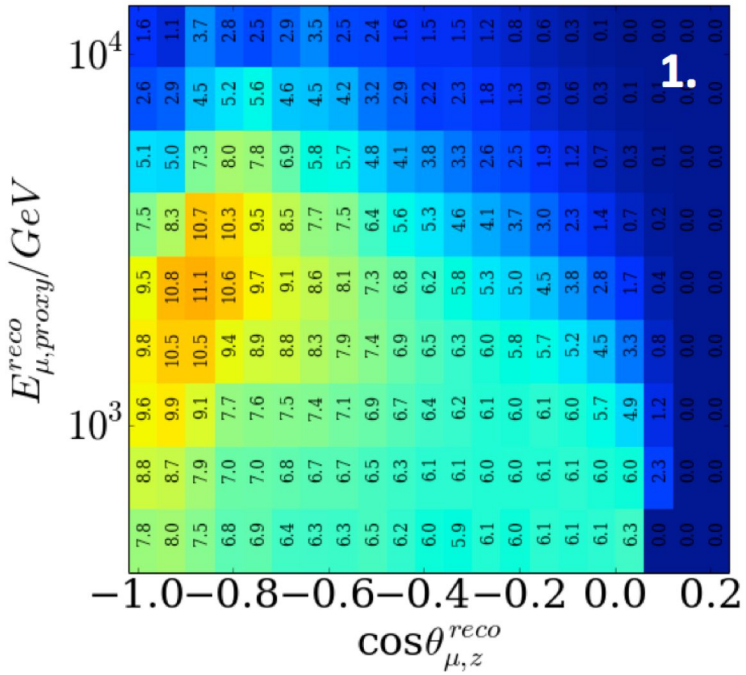

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.450
Δm²41=0.4 eV²
χ²=326.895
χ²red=320.294
No Sterile
Sterile
Data

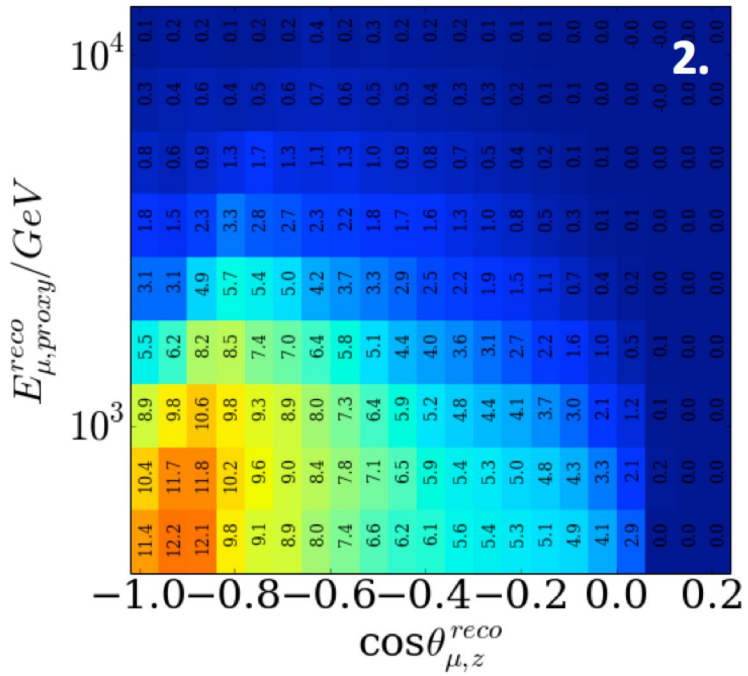

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_ℓ)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.500
Δm²41=0.4 eV²
χ²=241.386
χ²red=236.818
No Sterile
Sterile
Data

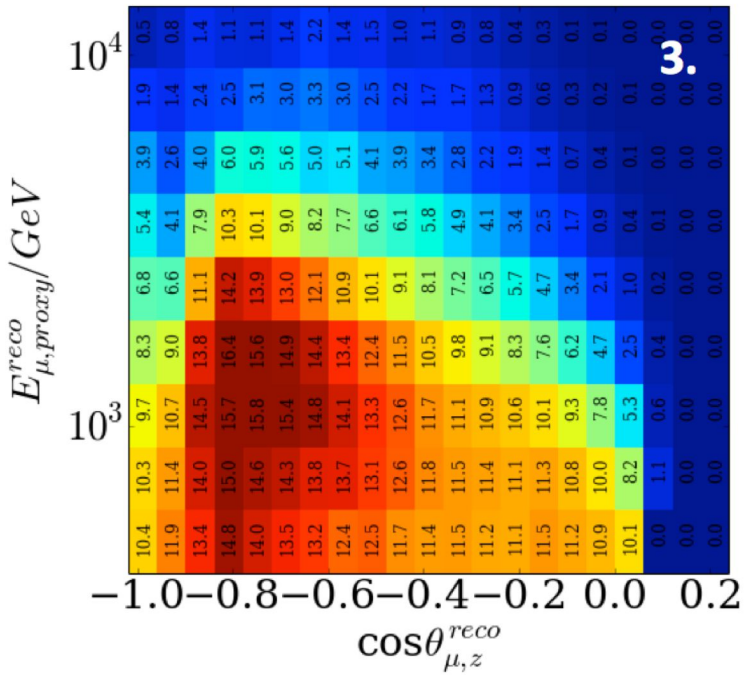

Data (IC86)
MC no steriles
IceCube PRELIMINARY
Events / 344 days
Ratio
1000
800
600
400
200
0
1.2
1.0
0.8
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
$\cos\theta^{reco}_{\mu,z}$

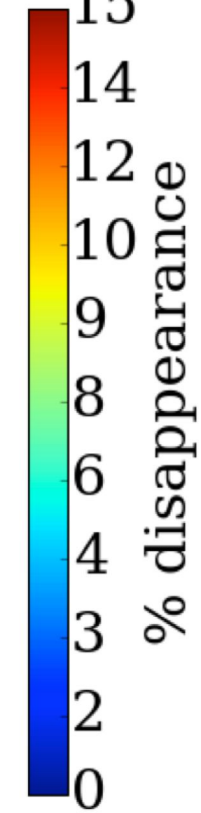

Data (IC86)
MC no steriles
Events / 344 days
10^3
10^2
10^1
IceCube PRELIMINARY
Ratio
1.5
1.0
0.5
10^3
10^4
$E_{\mu,proxy}$/GeV

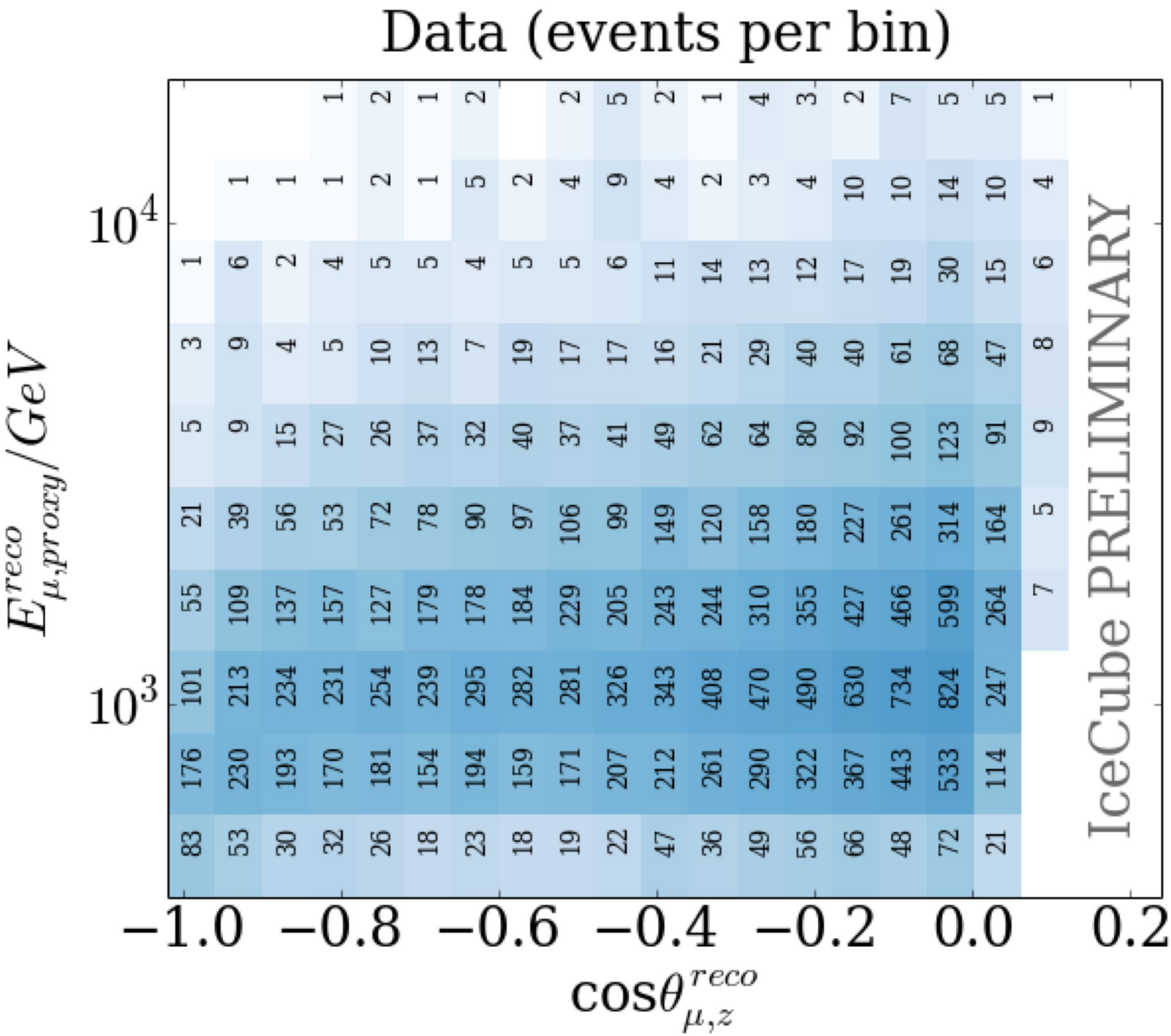

0.01
0.1
1.
10.
1.
0.1
Δm_{41}^2[eV^2]
$\sin^2 2\theta_{24}$
1
2
3
LSND / MB


1.
10^4
10^3
$E^{reco}_{\mu,proxy}/GeV$
$-1.0\ -0.8\ -0.6\ -0.4\ -0.2\ 0.0\ 0.2$
$\cos\theta^{reco}_{\mu,z}$


2.
10^4
10^3
$E^{reco}_{\mu,proxy}/GeV$
$-1.0\ -0.8\ -0.6\ -0.4\ -0.2\ 0.0\ 0.2$
$\cos\theta^{reco}_{\mu,z}$

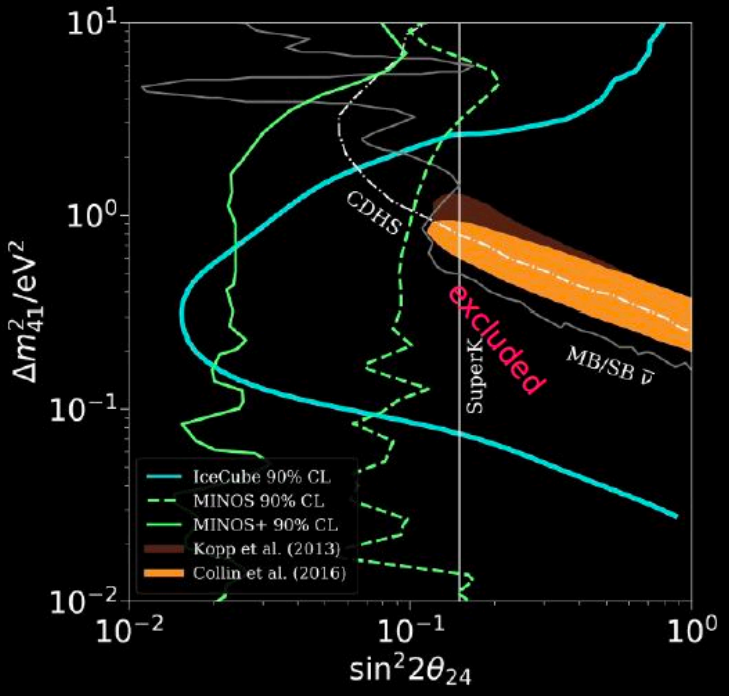

3.
10^4
10^3
$E^{reco}_{\mu,proxy}/GeV$
$-1.0\ -0.8\ -0.6\ -0.4\ -0.2\ 0.0\ 0.2$
$\cos\theta^{reco}_{\mu,z}$


15
14
12
10
9
8
6
4
3
2
0
% disappearance

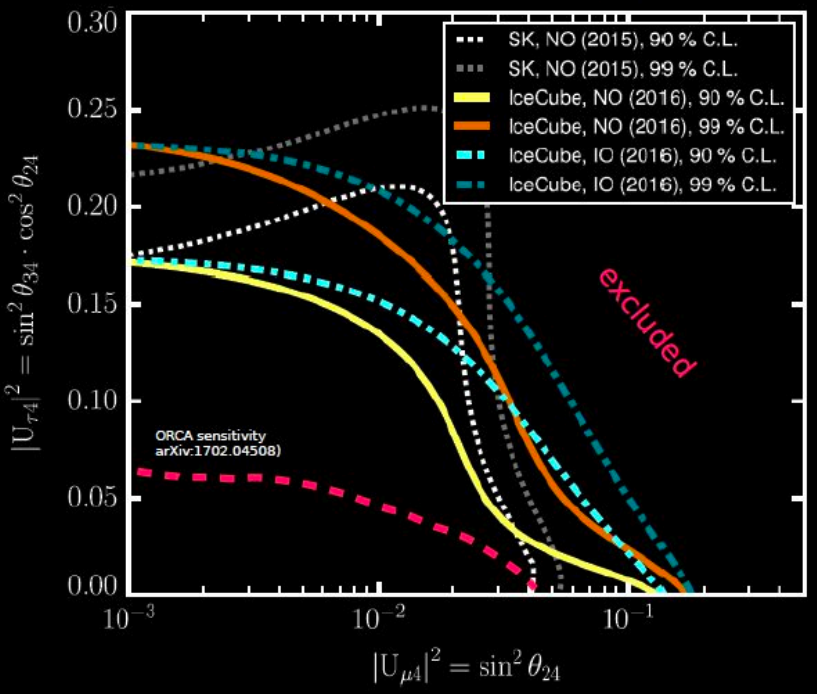


Data (events per bin)
1 2 1 2 2 5 2 1 4 3 2 7 5 5 1
1 1 1 2 1 5 2 4 9 4 2 3 4 10 10 14 10 4
1 6 2 4 5 5 4 5 5 6 11 14 13 12 17 19 30 15 6
3 9 4 5 10 13 7 19 17 17 16 21 29 40 40 61 68 47 8
5 9 15 27 26 37 32 40 37 41 49 62 64 80 92 100 123 91 9
21 39 56 53 72 78 90 97 106 99 149 120 158 180 227 261 314 164 5
55 109 137 157 127 179 178 184 229 205 243 244 310 355 427 466 599 264 7
101 213 234 231 254 239 295 282 281 326 343 408 470 490 630 734 824 247
176 230 193 170 181 154 194 159 171 207 212 261 290 322 367 443 533 114
83 53 30 32 26 18 23 18 19 22 47 36 49 56 66 48 72 21
IceCube PRELIMINARY
10^4
10^3
$E^{reco}_{\mu,proxy}/GeV$
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
$\cos\theta^{reco}_{\mu,z}$

NTs sensitive to disappearance effects in atmospheric neutrinos, ie, mainly to Δm^2_{41} and $\sin 2\theta_{24}$



Phys. Rev. D 95, 112002 (2017)

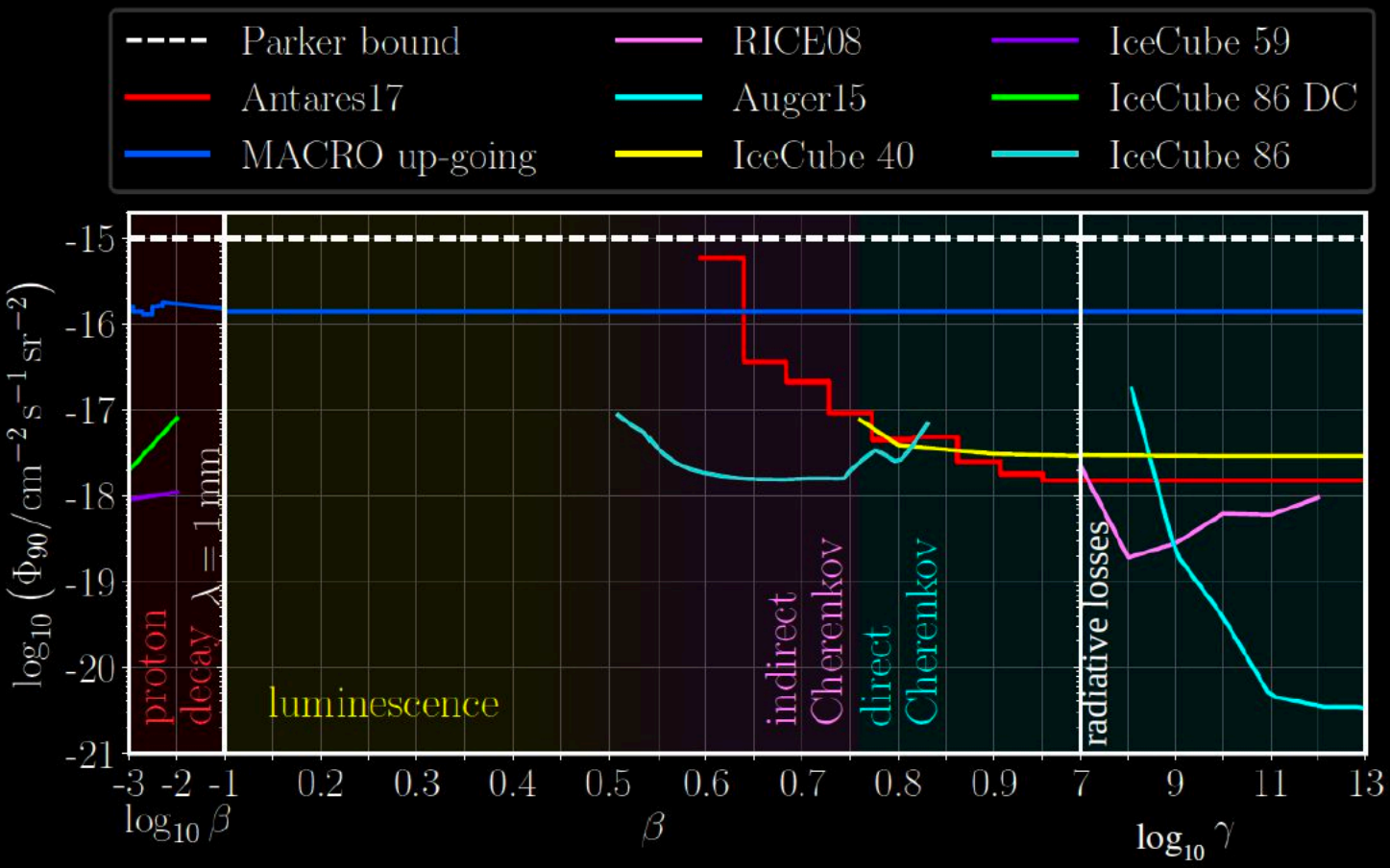


High energy analysis: $E_\nu \gtrapprox 300$ GeV

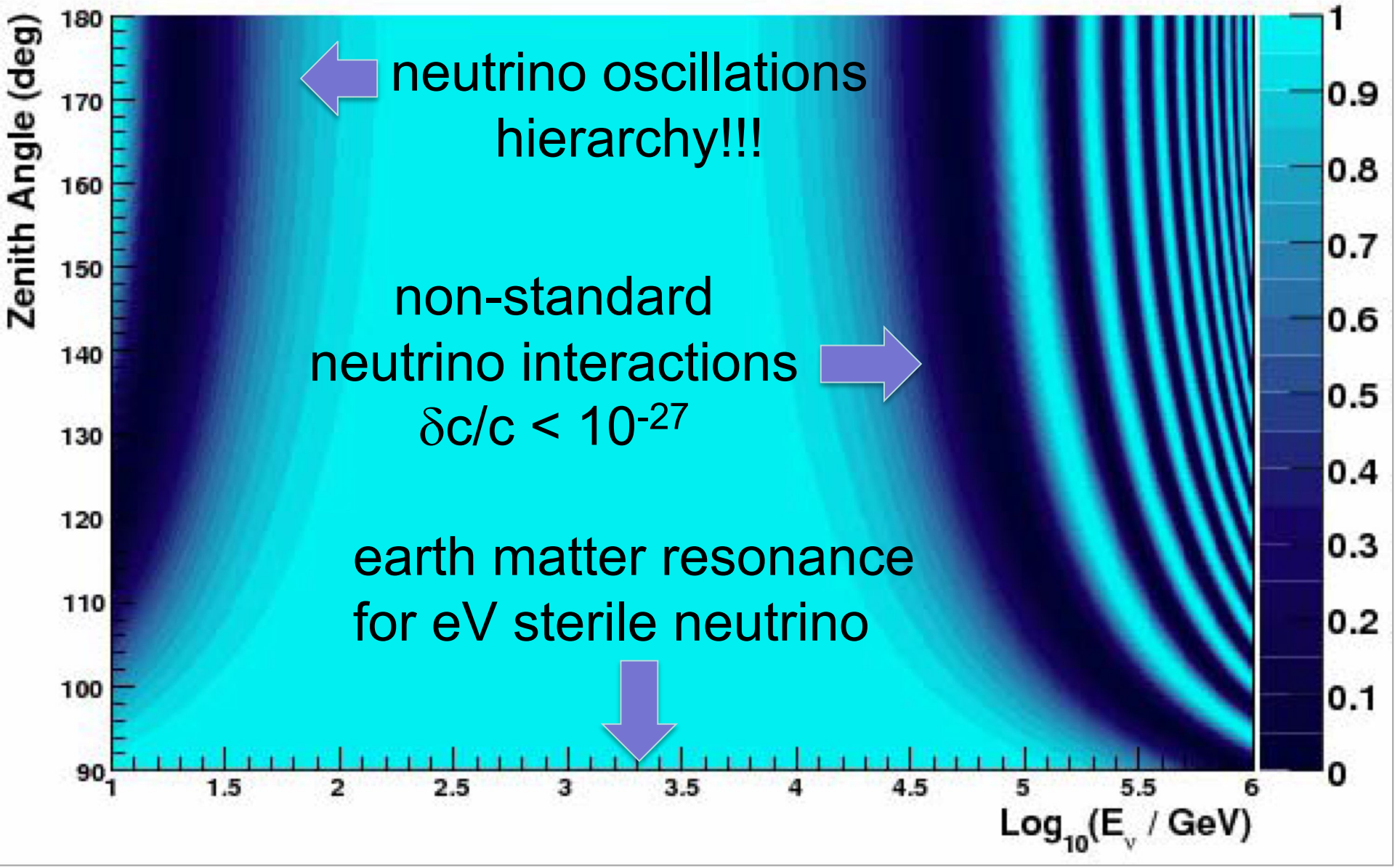
Low energy analysis: $E_\nu \lessapprox 60$ GeV

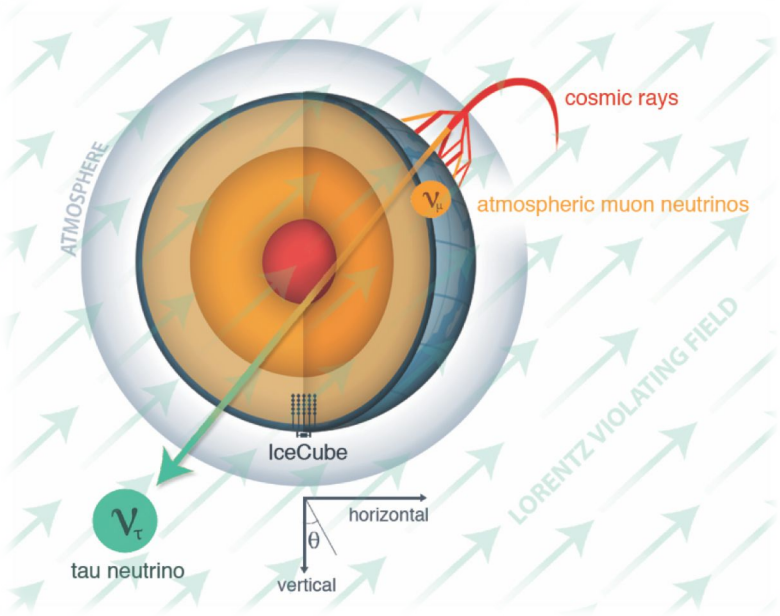
So far, results consistent with the standard three-neutrino hypothesis

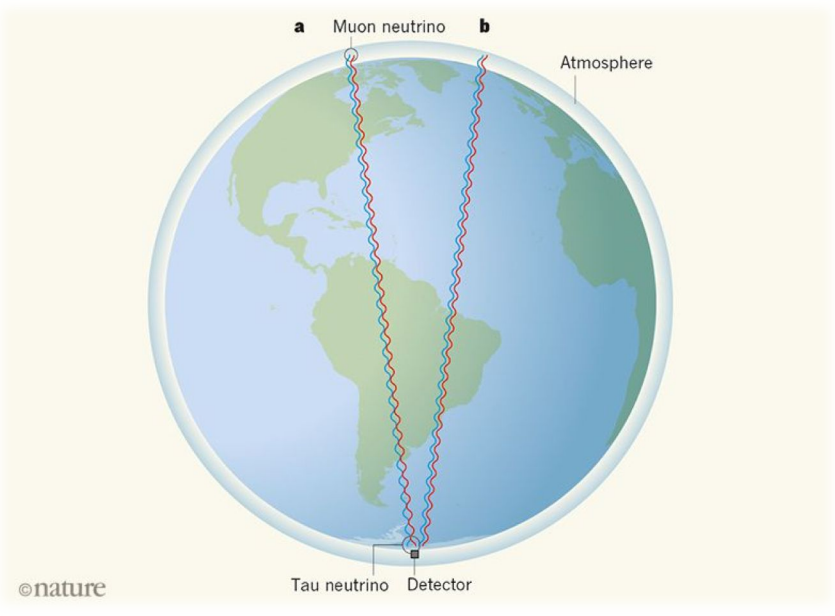
current results



new physics with atmospheric neutrinos…

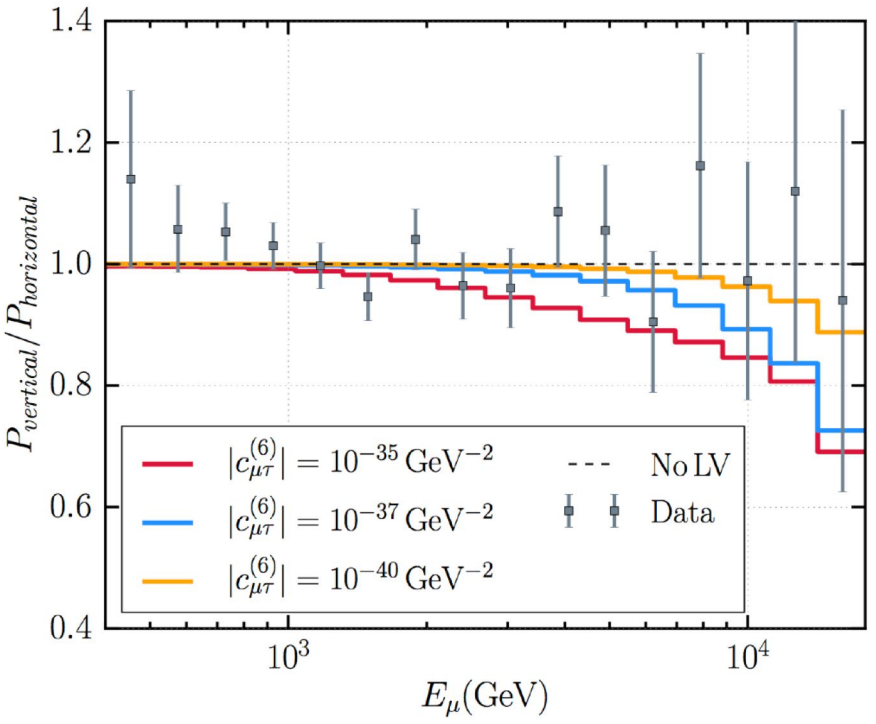






neutrino interferometry tests Lorentz symmetry:

- e.g. ratio of the vertical vs horizontal oscillation probability
- result for dimension 6 μ-τ operator shown here



IceCube

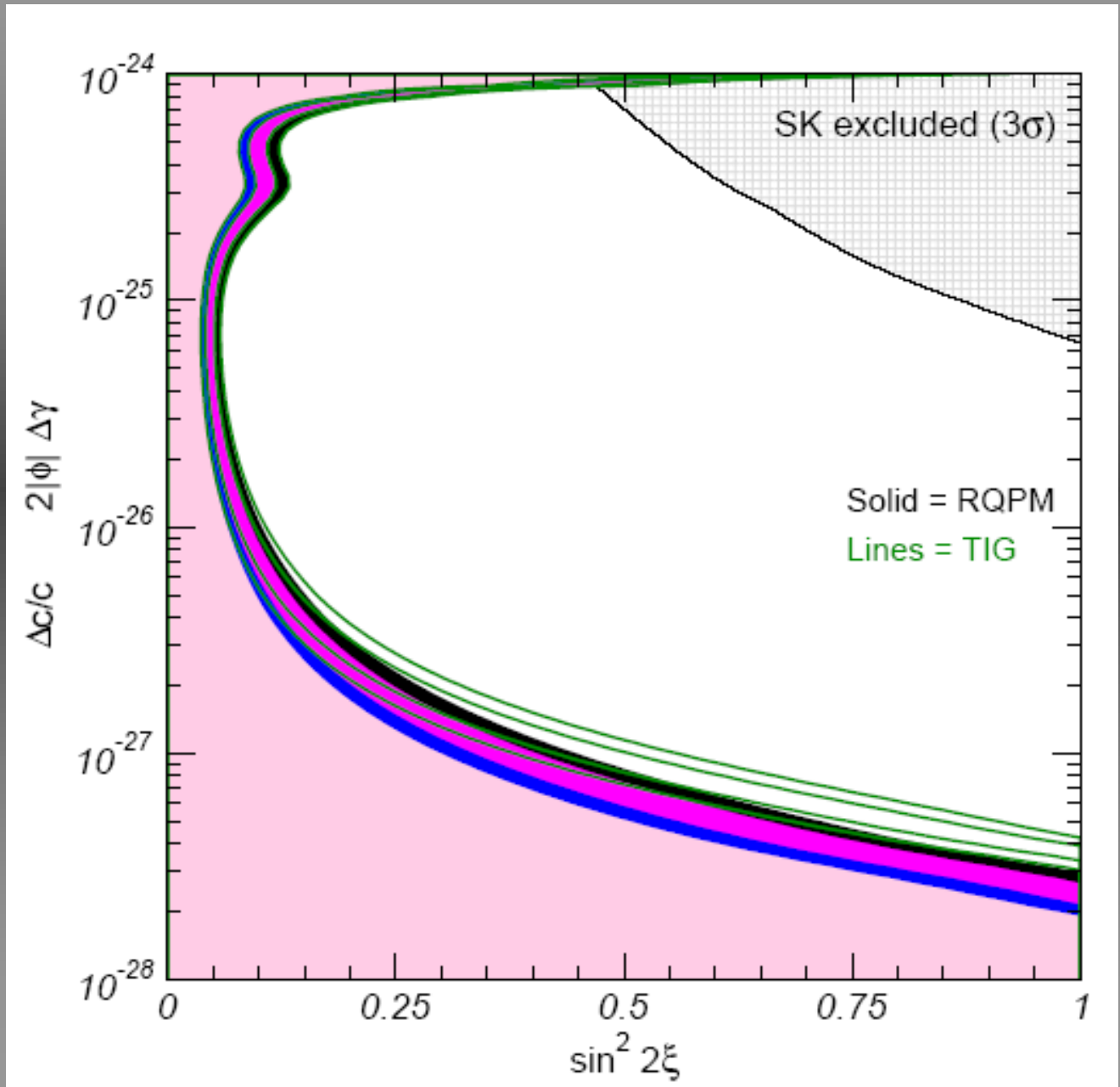
tests

- equivalence principle

and

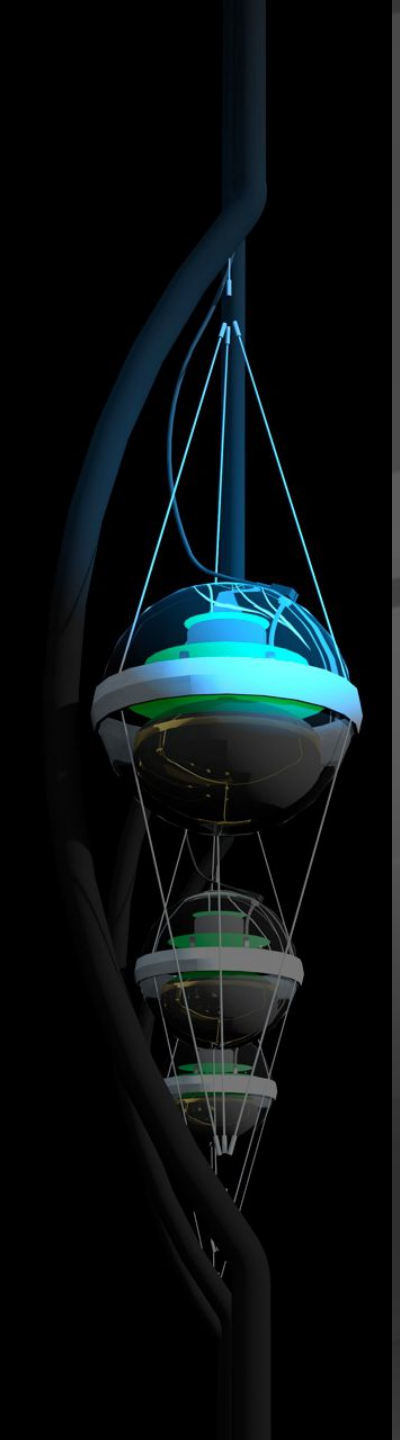
- Lorentz invariance

…general relativity will not last 200 years…
M. Turner



soon:

- 10-year point source analysis
- first HAWC-IceCube search for Galactic sources
- dark matter annihilation in the sun: 3→8 years
  (world-best spin-dependent WIMP limit)
- sterile neutrino: 1→7 years
- joint searches with LIGO, ANTARES, AUGER/TA
- study of the composition between the knee and ankle with IceTop/scintillator/radio array (beam that produces the TeV-PeV atmospheric neutrino background!)
- …
- first observation of the core of the Earth

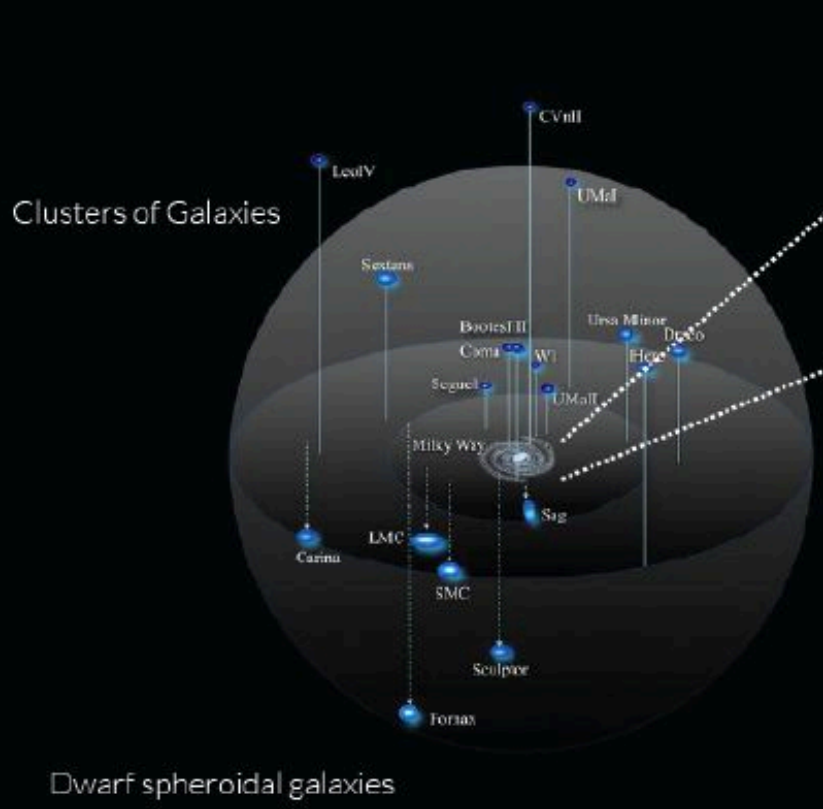


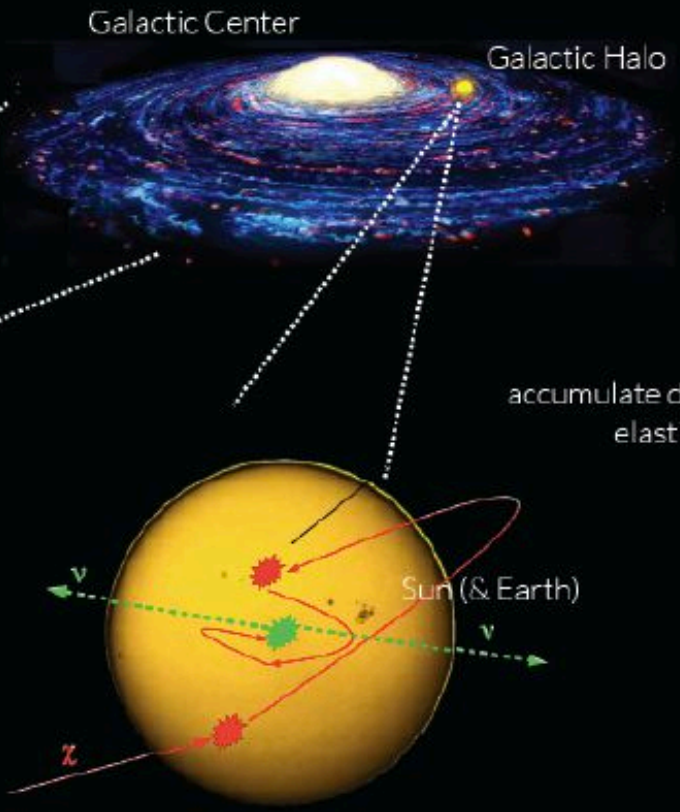
IceCube: beyond neutrino astronomy

Francis Halzen

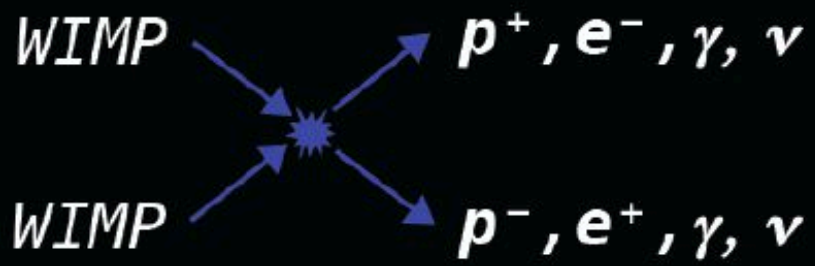
- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- …

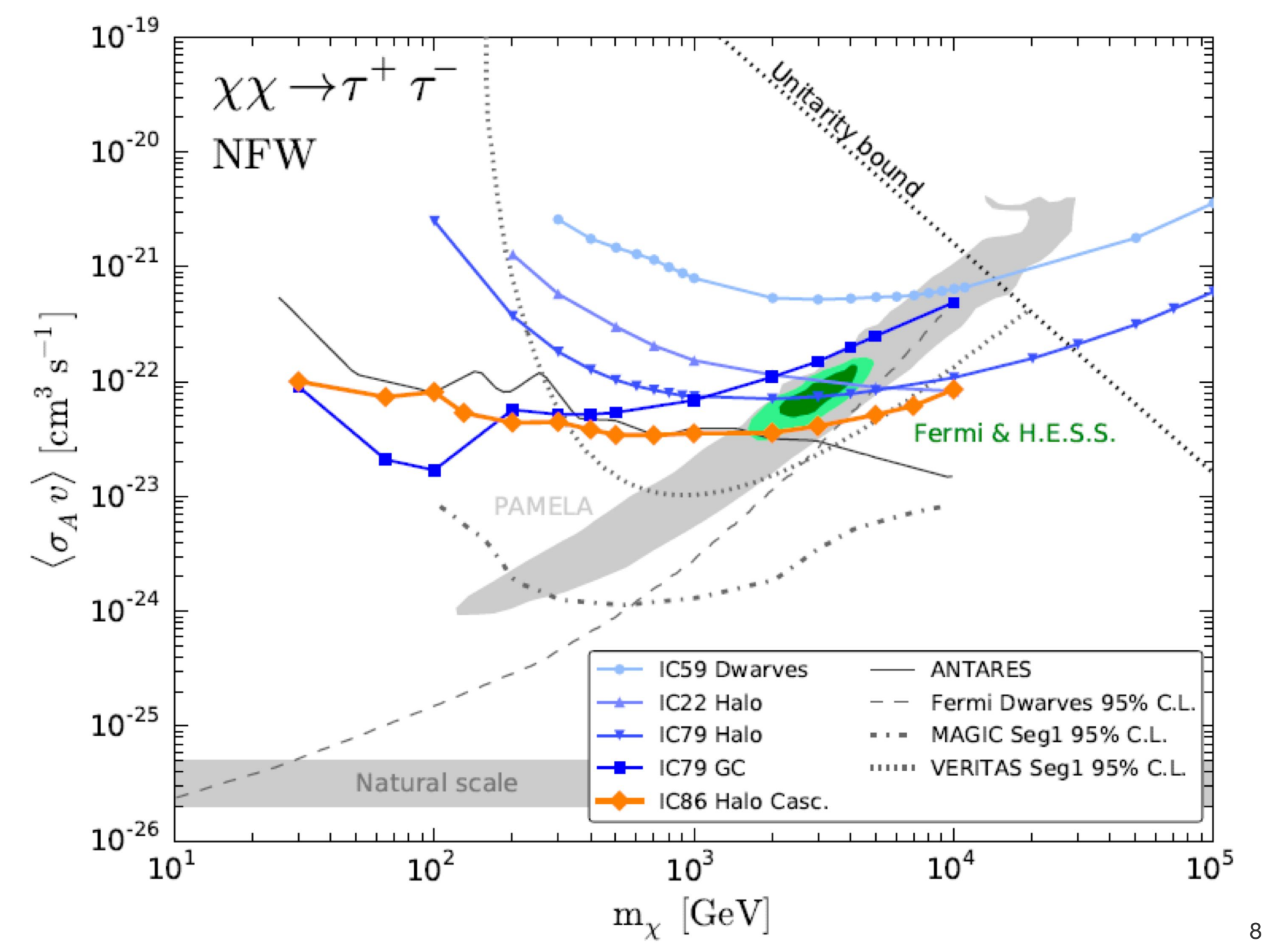
IceCube DM targets





MSSM - neutralino




$\chi\chi \to \tau^+ \tau^-$
NFW
Unitarity bound
Fermi & H.E.S.S.
PAMELA
Natural scale
IC59 Dwarves
IC22 Halo
IC79 Halo
IC79 GC
IC86 Halo Casc.
ANTARES
Fermi Dwarves 95% C.L.
MAGIC Seg1 95% C.L.
VERITAS Seg1 95% C.L.
$\langle \sigma_A v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^1
10^2
10^3
10^4
10^5

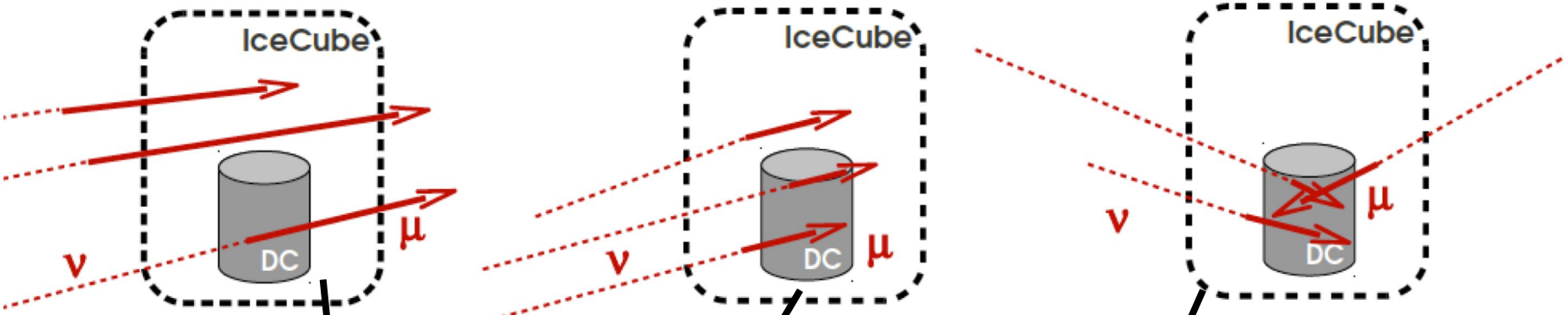
IceCube 79 data

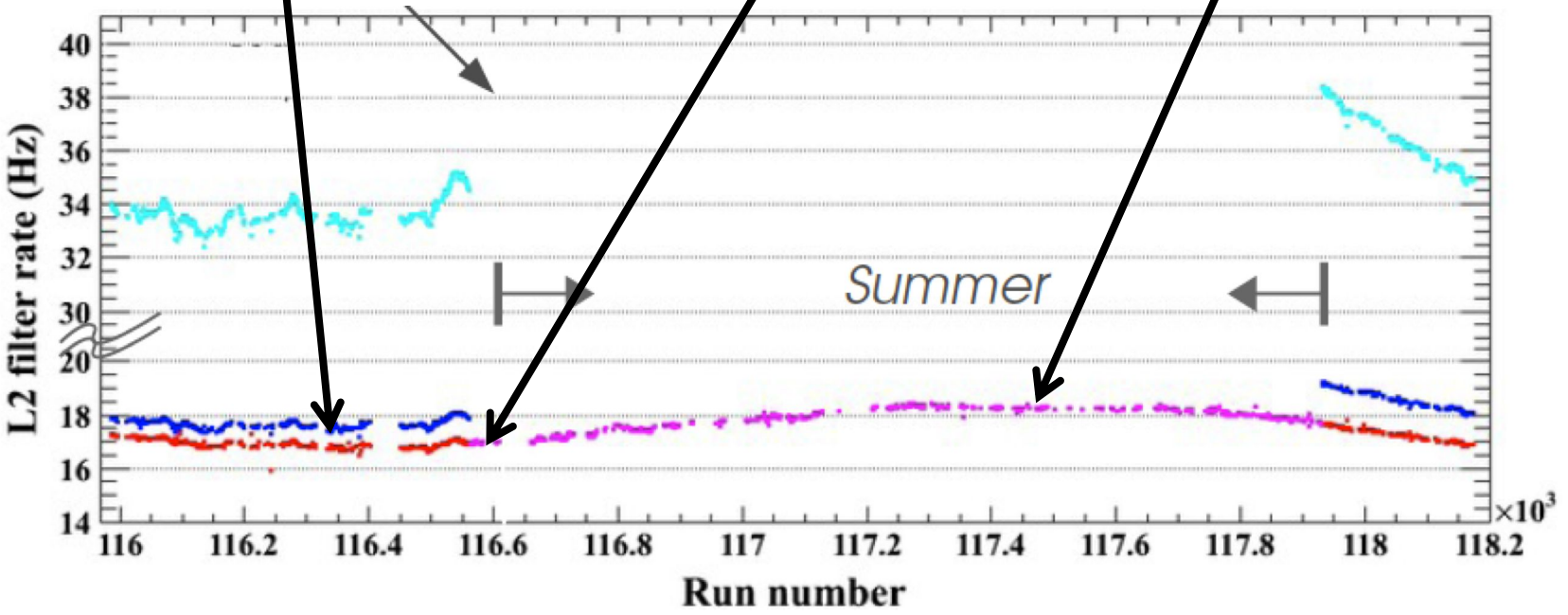
starting events → lower energy

- Up-going ①
- No containment

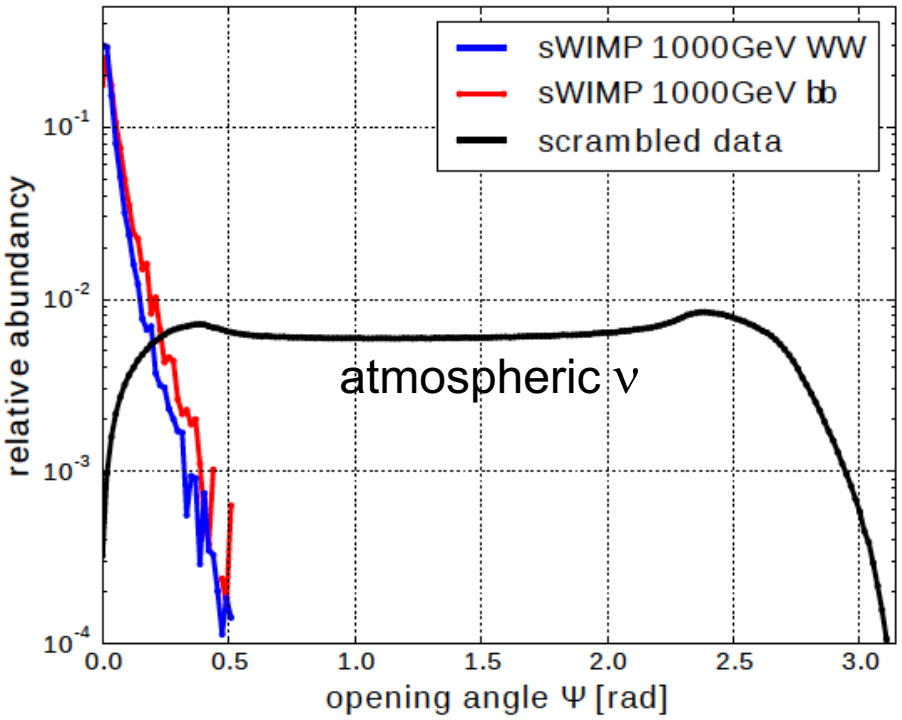
- Up-going ②
- strong containment

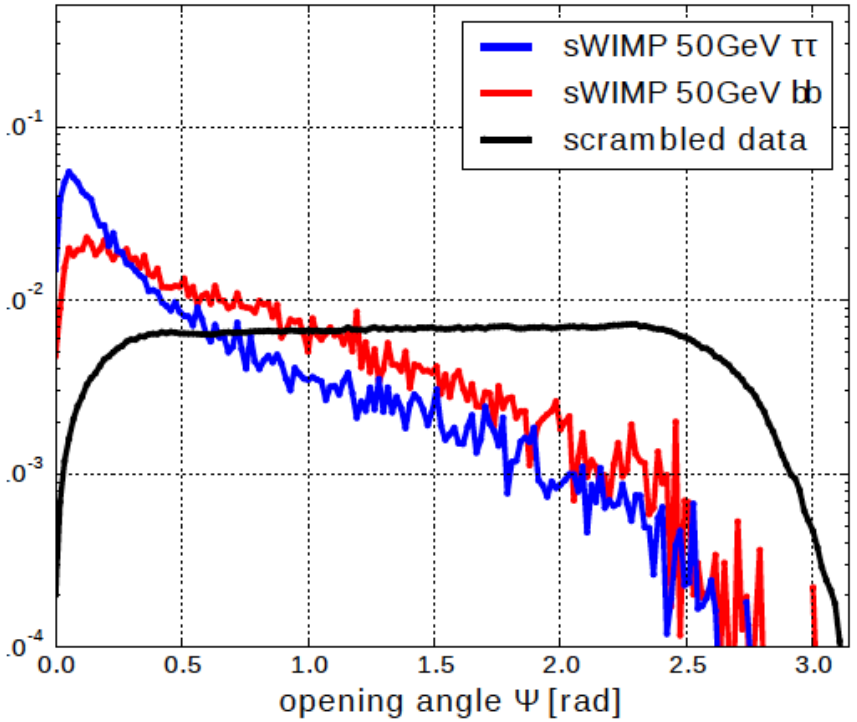
- Down-going ③
- strong containment





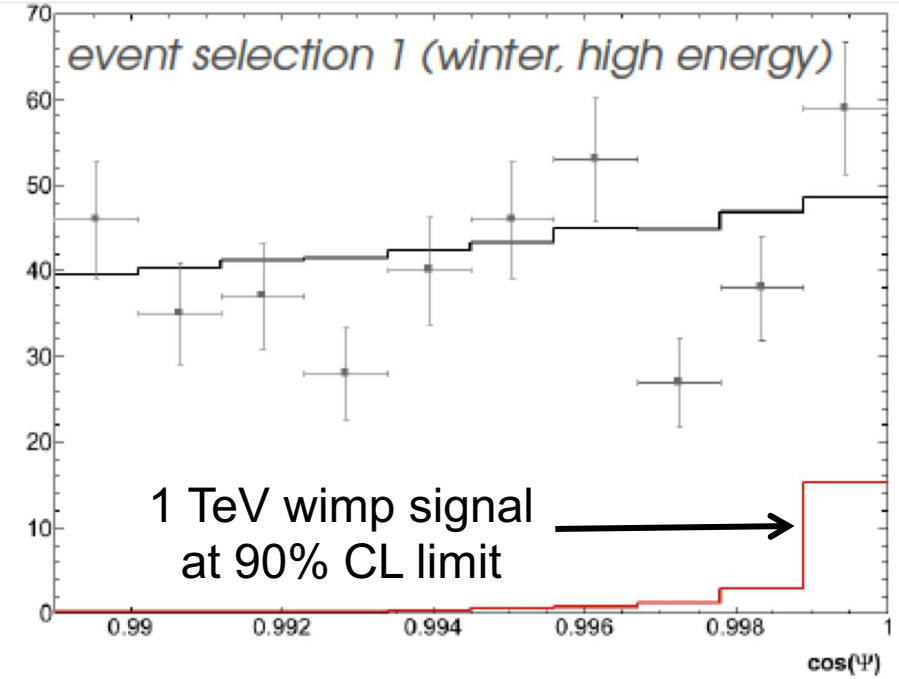
sun

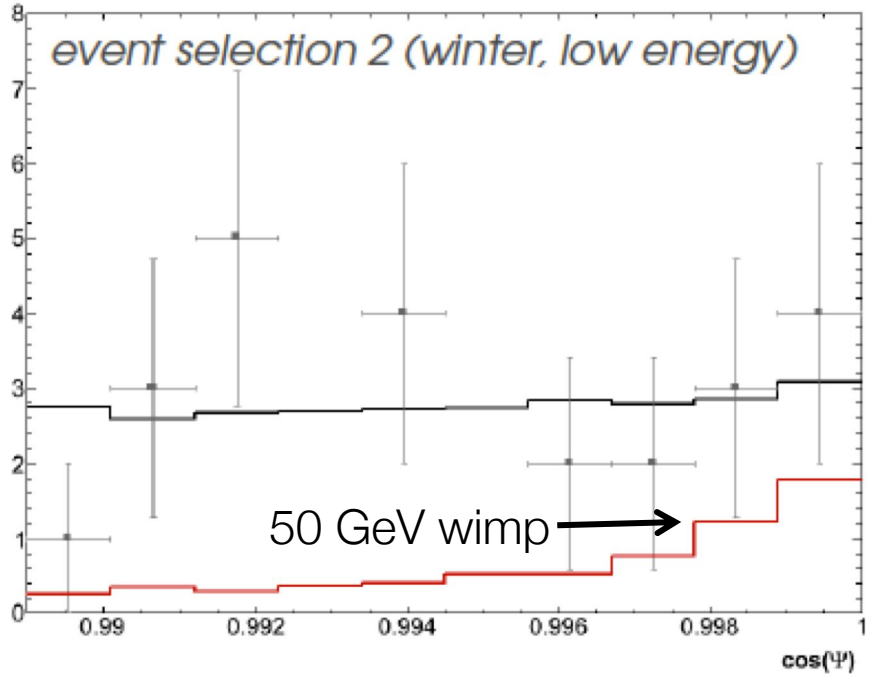


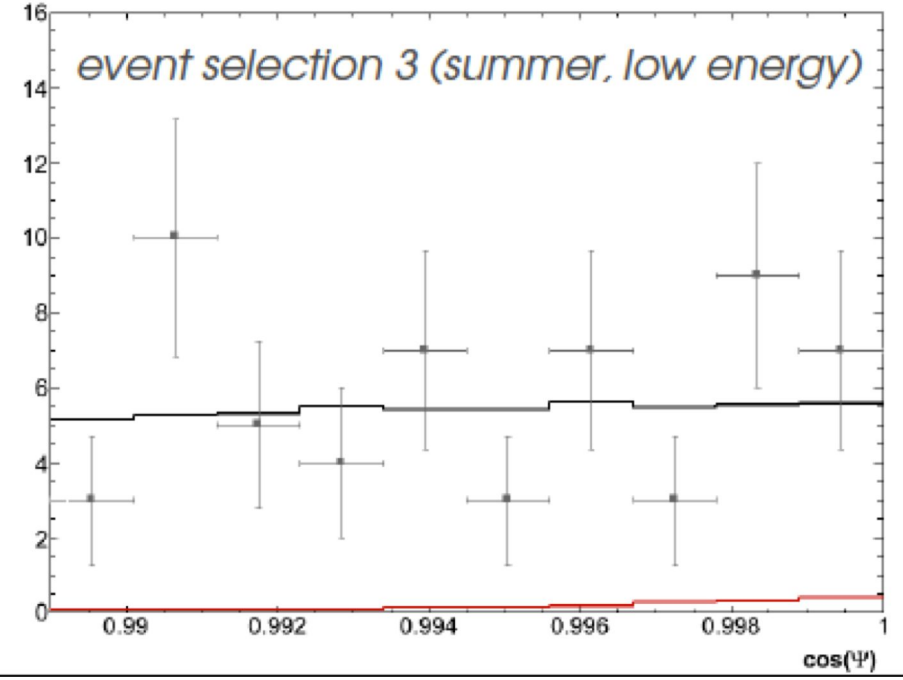


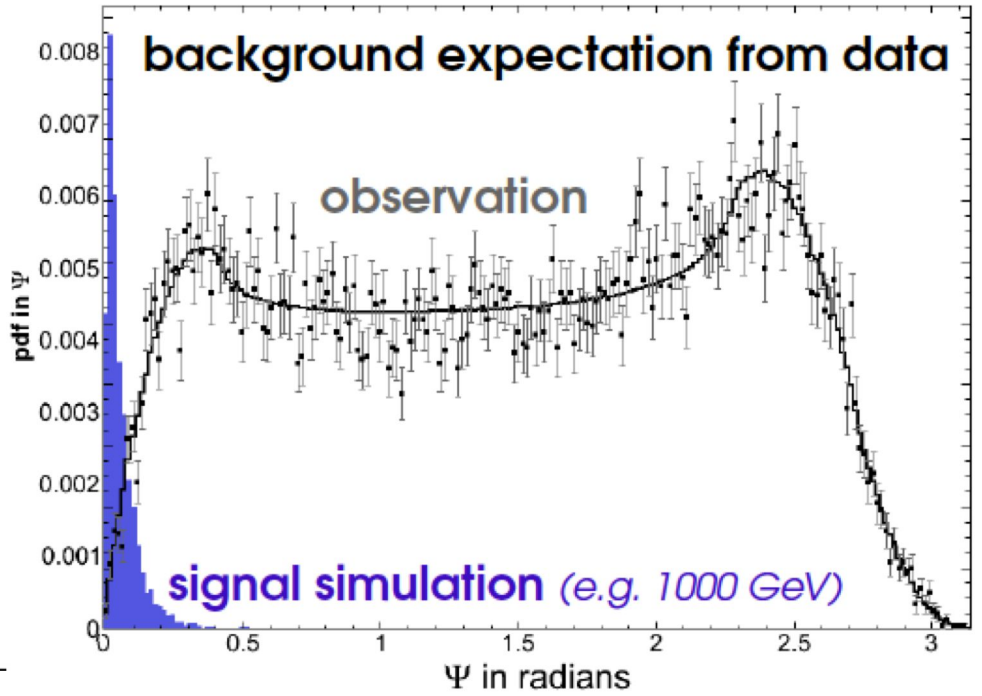
$m_\chi = 1\,\mathrm{TeV}$

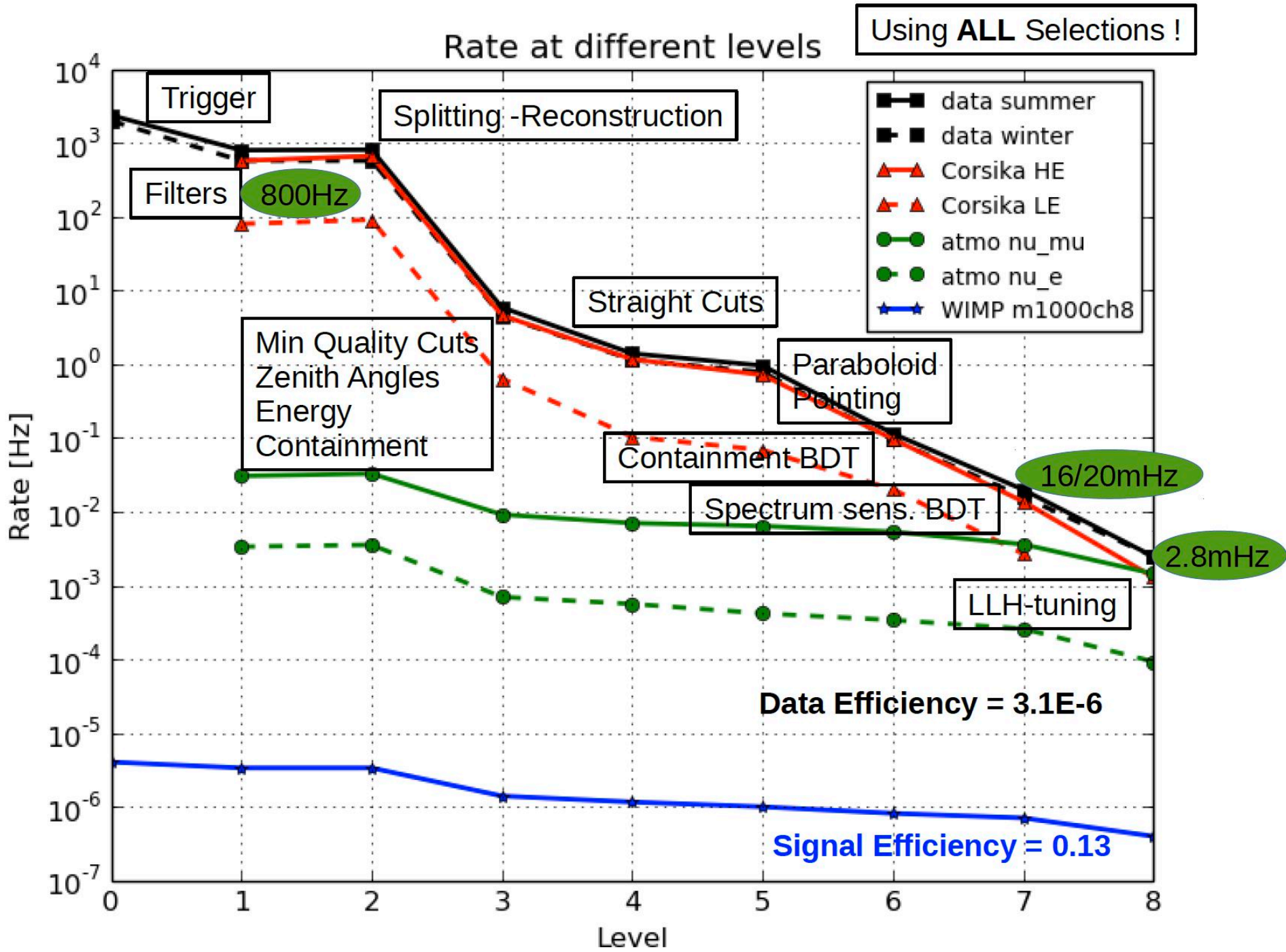
$m_\chi = 50\,\mathrm{GeV}$


event selection 1 (winter, high energy)
1 TeV wimp signal
at 90% CL limit
cos(Ψ)

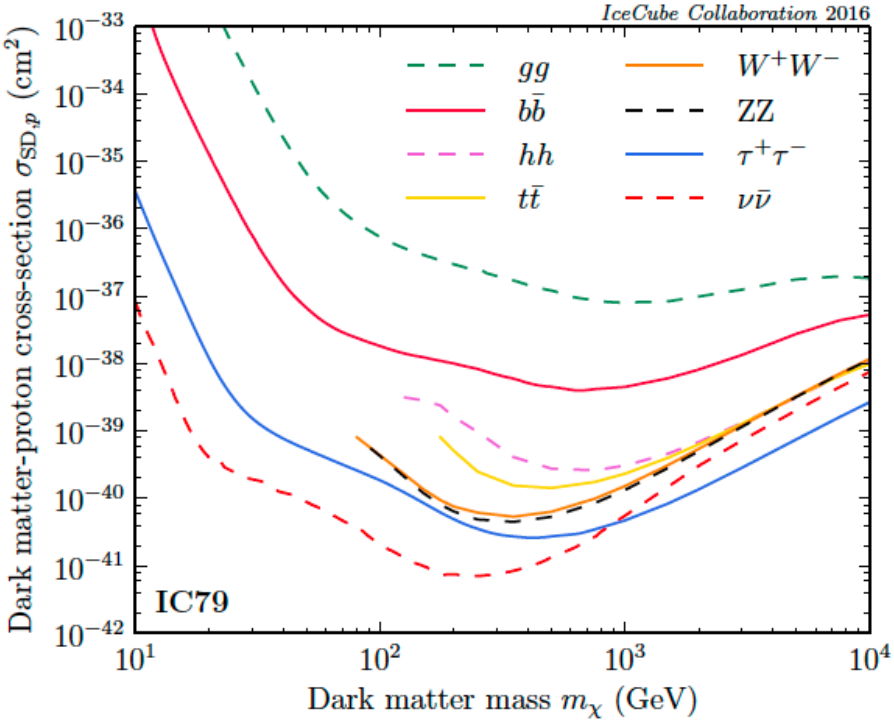

event selection 2 (winter, low energy)
50 GeV wimp
cos(Ψ)

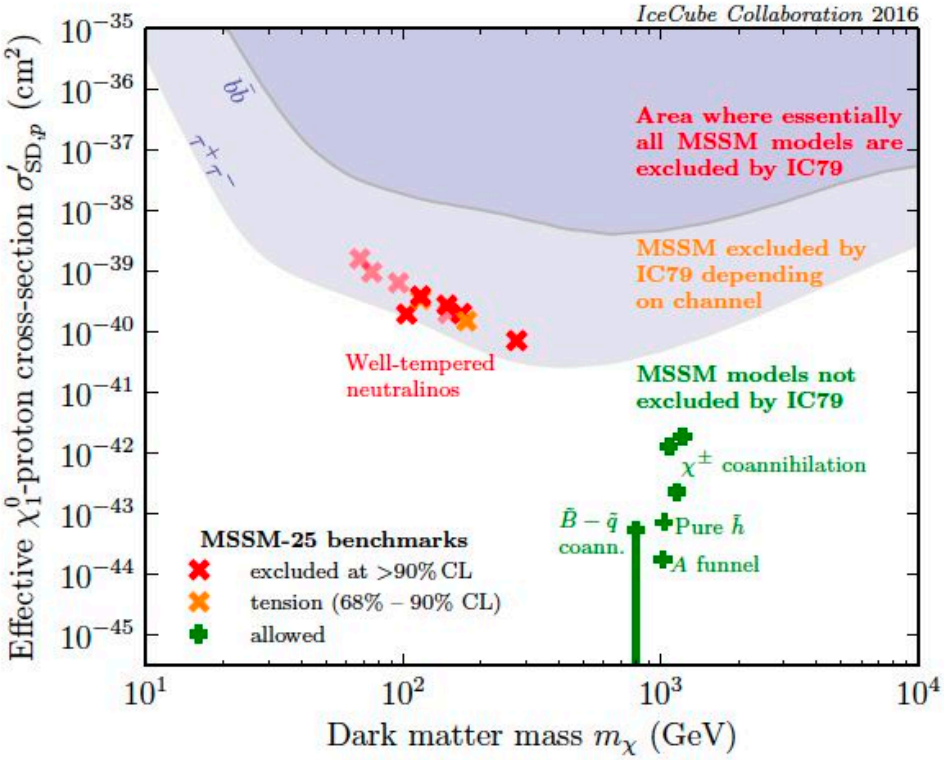

event selection 3 (summer, low energy)
cos(Ψ)


background expectation from data
observation
signal simulation (e.g. 1000 GeV)
pdf in Ψ
Ψ in radians


Rate at different levels
Using ALL Selections !
Trigger
Filters
800Hz
Splitting -Reconstruction
Straight Cuts
Min Quality Cuts
Zenith Angles
Energy
Containment
Paraboloid
Pointing
Containment BDT
Spectrum sens. BDT
16/20mHz
2.8mHz
LLH-tuning
Data Efficiency = 3.1E-6
Signal Efficiency = 0.13
data summer
data winter
Corsika HE
Corsika LE
atmo nu_mu
atmo nu_e
WIMP m1000ch8
Rate [Hz]
Level

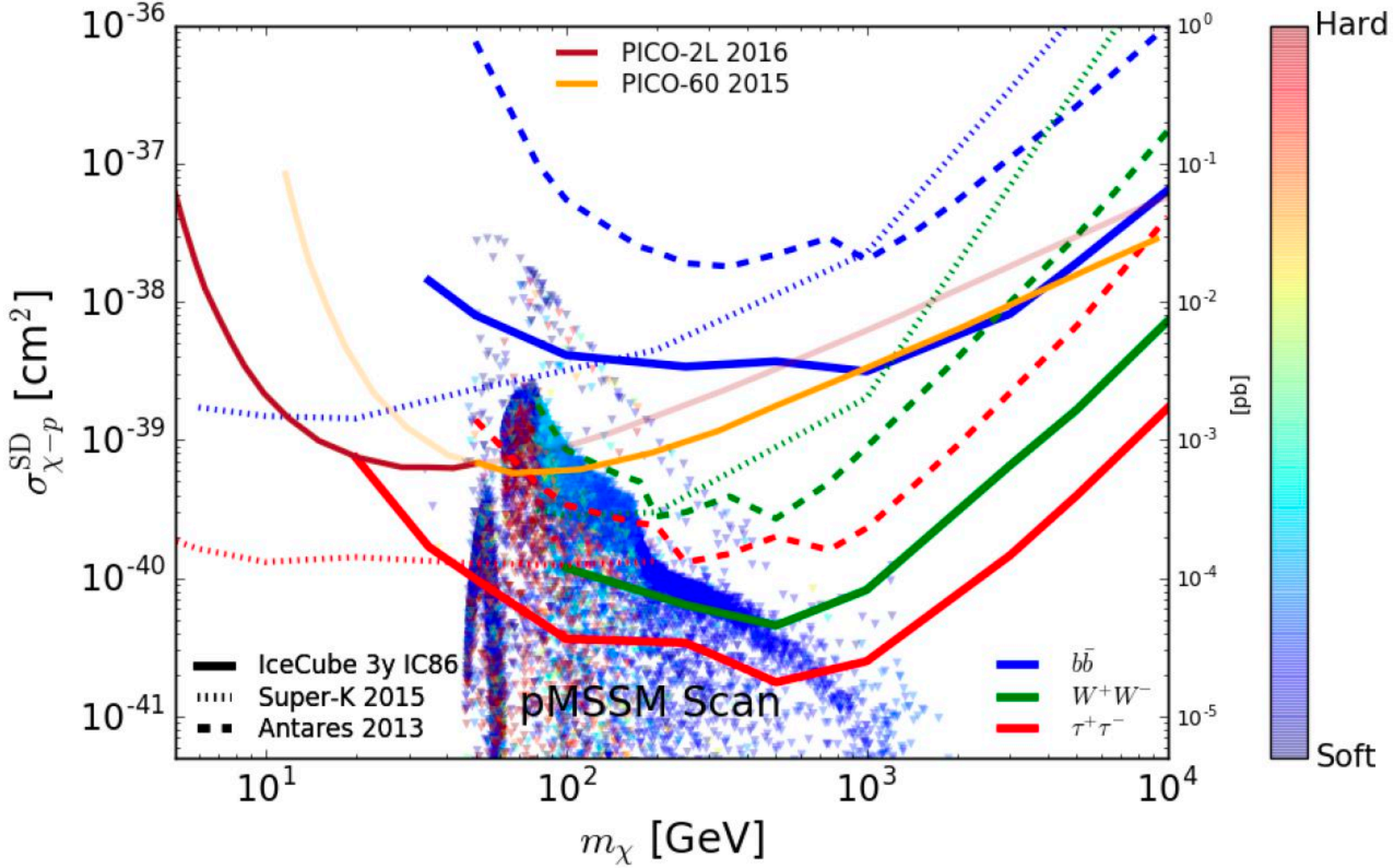
perform your own
IceCube dark matter search



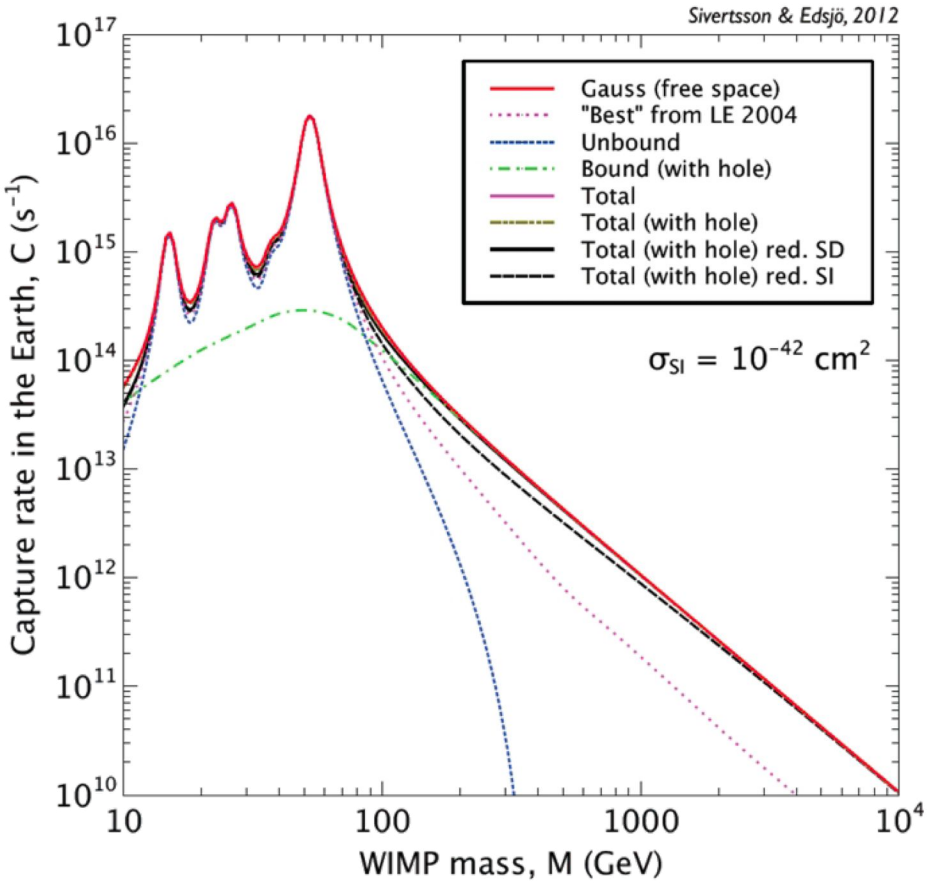


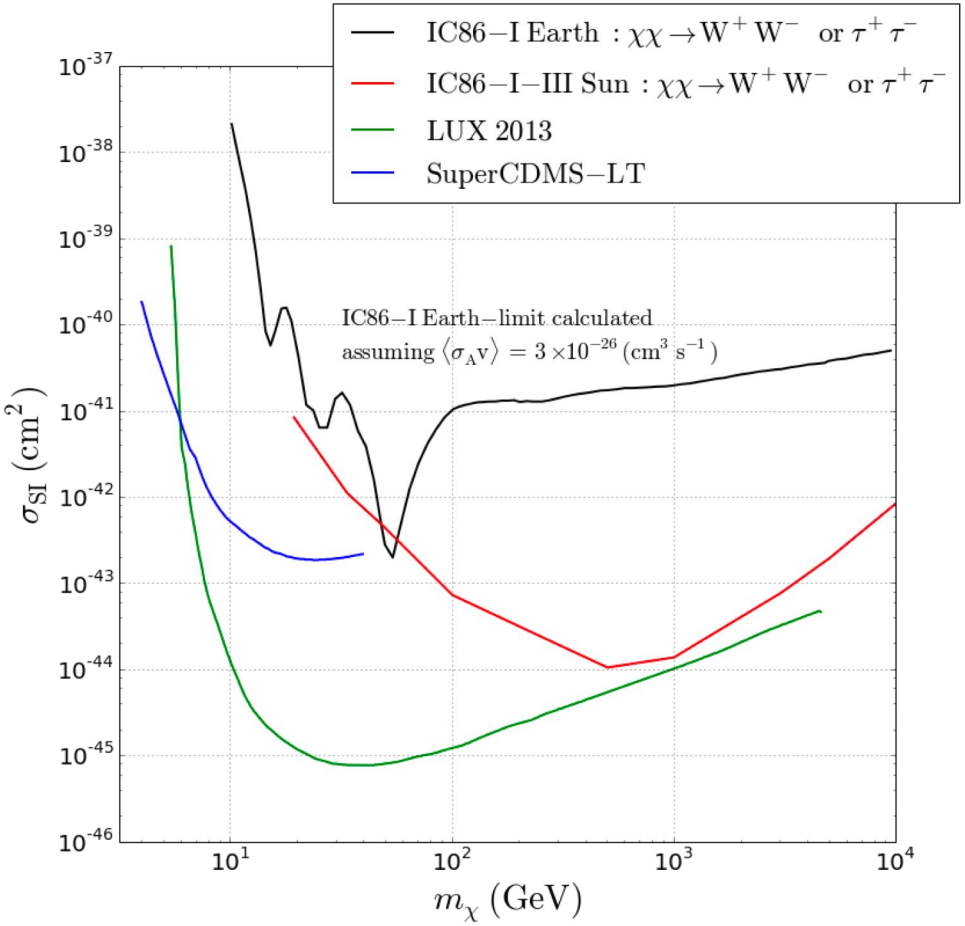
http://arxiv.org/abs/1601.00653

- software to test your own model (cross section/branching ratios)
- IceCube data available

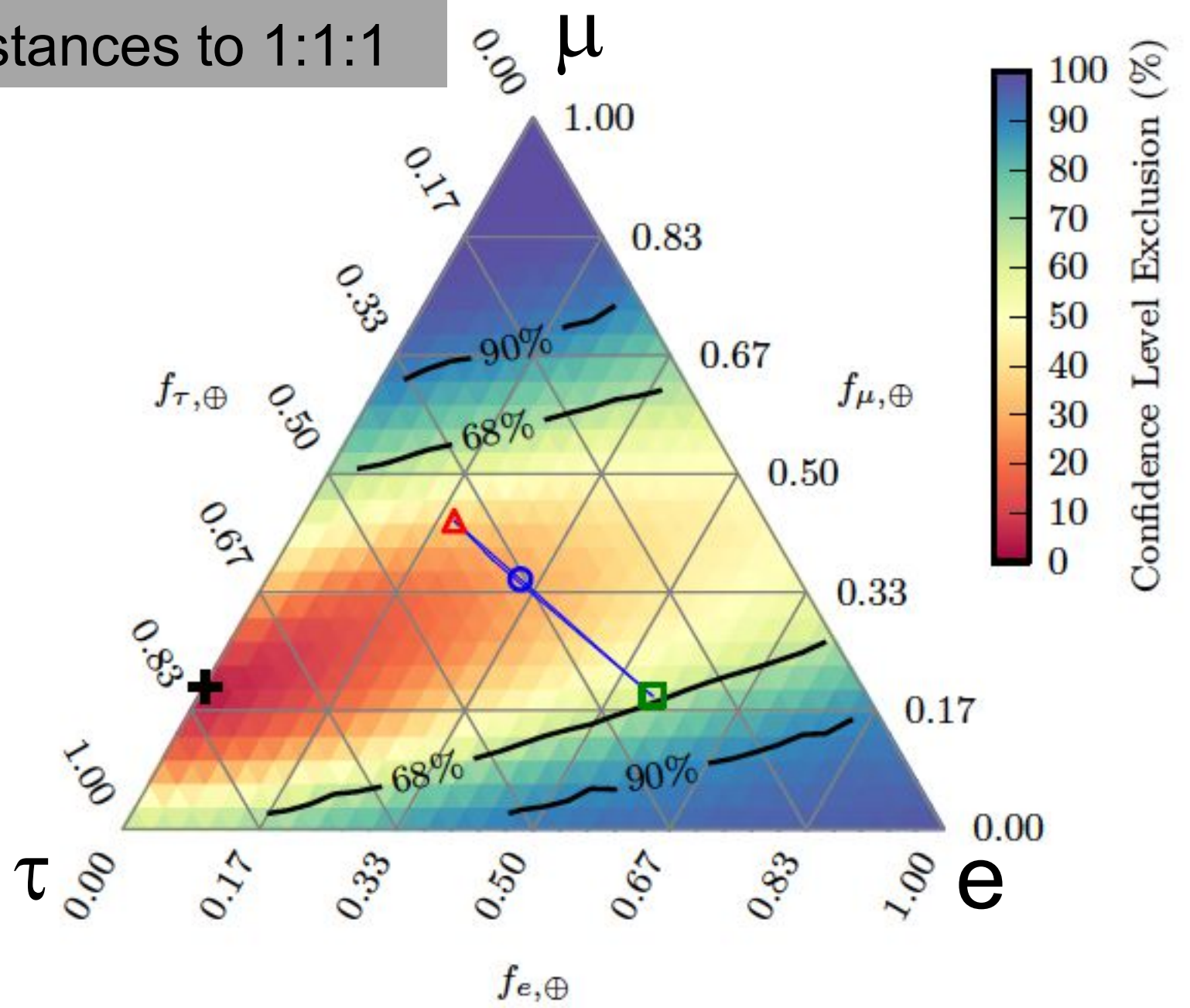

PICO-2L 2016
PICO-60 2015
IceCube 3y IC86
Super-K 2015
Antares 2013
pMSSM Scan
$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
$\sigma^{SD}_{\chi-p}$ [cm^2]
m_χ [GeV]
[pb]
Hard
Soft

wimp annihilation in the center of the Earth

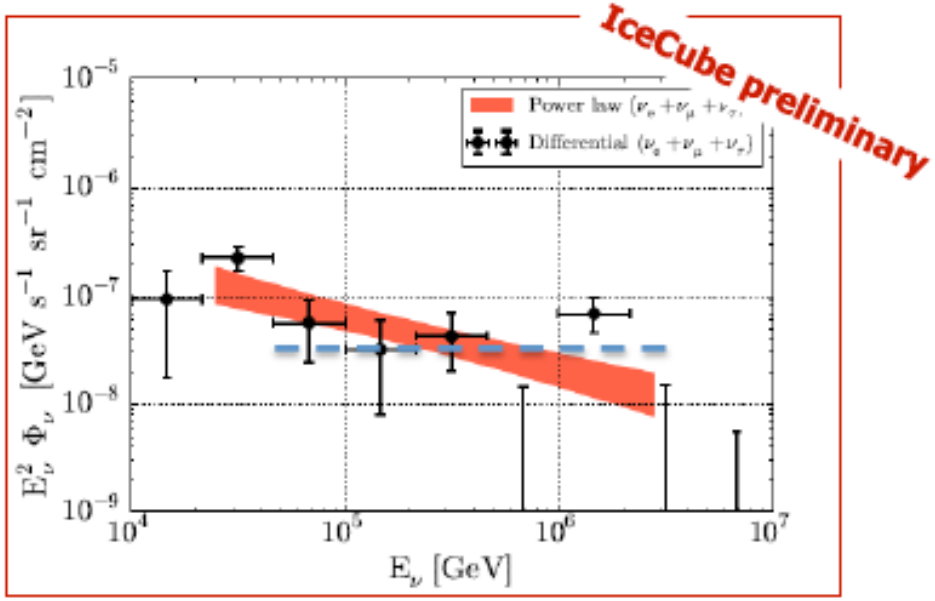


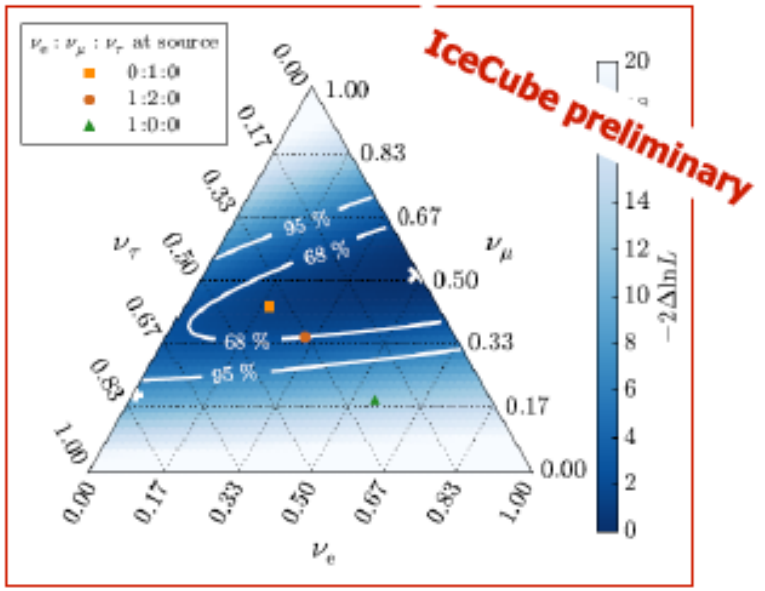


oscillate over cosmic distances to 1:1:1



- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events



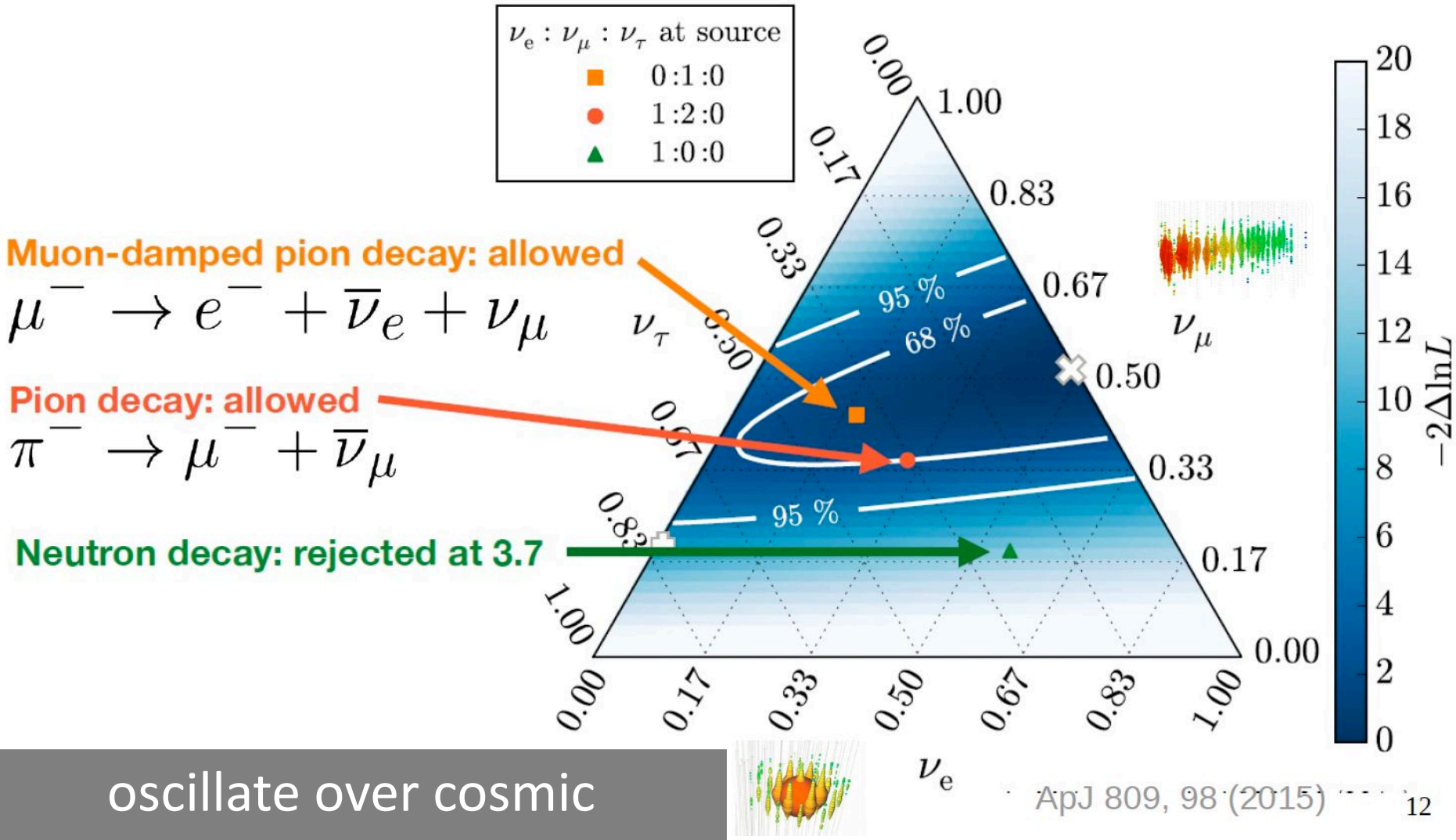


assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 at Earth →

unbroken power-law between	25 TeV and 2.8 PeV	
spectral index	-2.5 ± 0.09	(-2 disfavored at 3.8 σ)
flux at 100 TeV	$(6.7 \pm 1.2)\times10^{-18}$ (GeV · cm^2 · s · sr)$^{-1}$	

the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

- Different event signatures allow flavor separation → primarily μ vs. e, τ



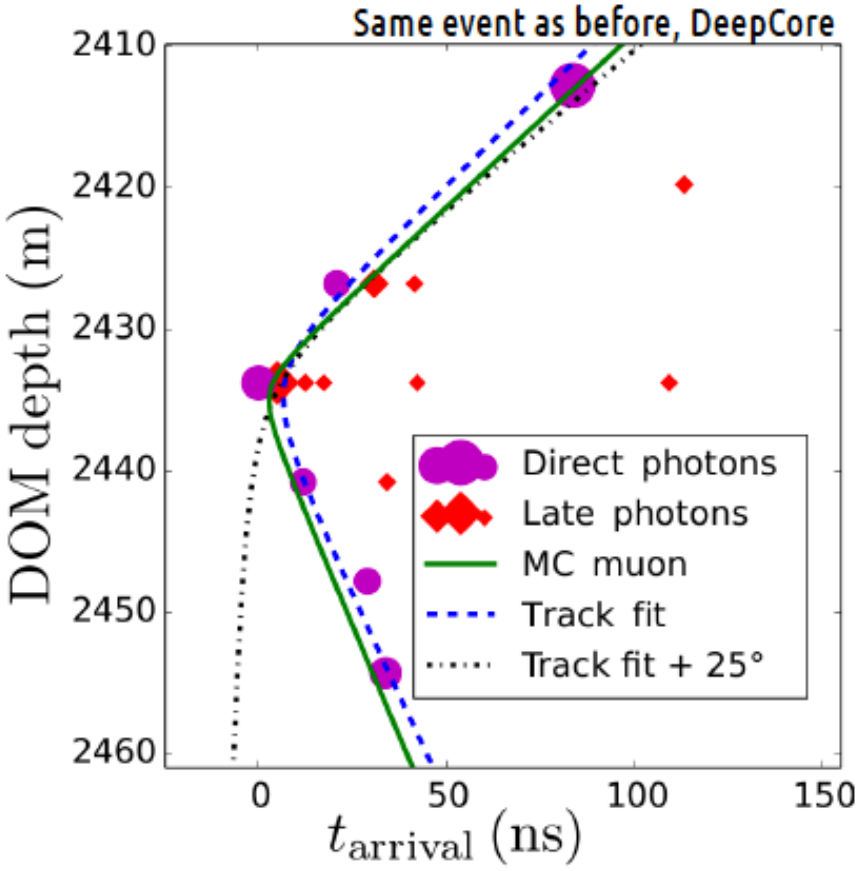
oscillate over cosmic distances to 1:1:1

ApJ 809, 98 (2015)

neutrino reconstruction

Latest published DeepCore results

- Zenith: Require a core of *direct* (unscattered) photons
  - **Minimize impact of ice properties**
  - 30% efficiency
  - **Fit zentih 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



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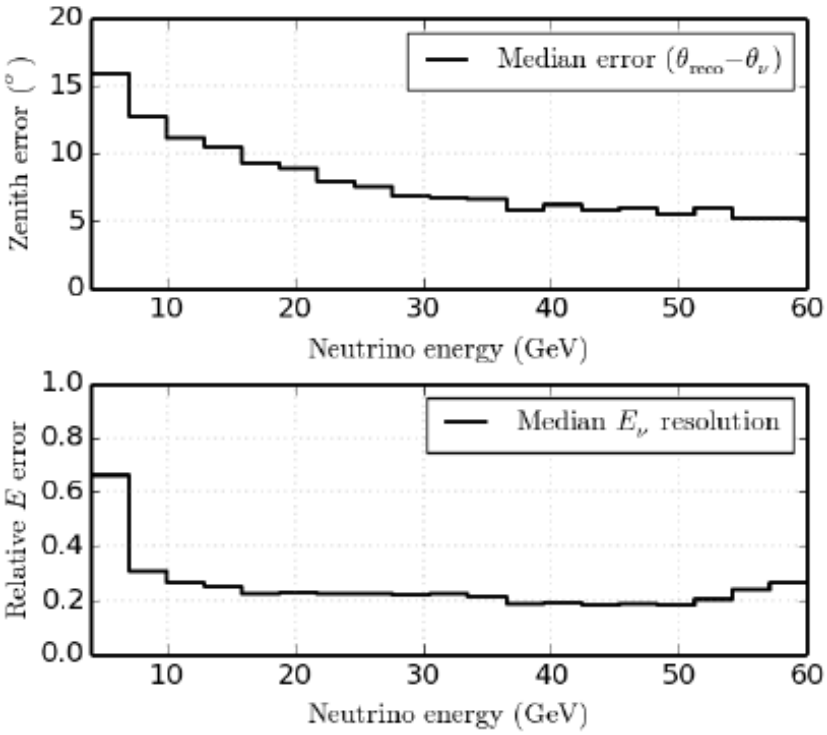
- Energy: track+cascade hypothesis
  - Fit track length and vertex position/E
  - Keep direction fixed
  - Assume track and cascade are collinear

Resolutions for DeepCore (published result)



coming soon

More sophisticated reconstruction

» Use arrival time of individual photons

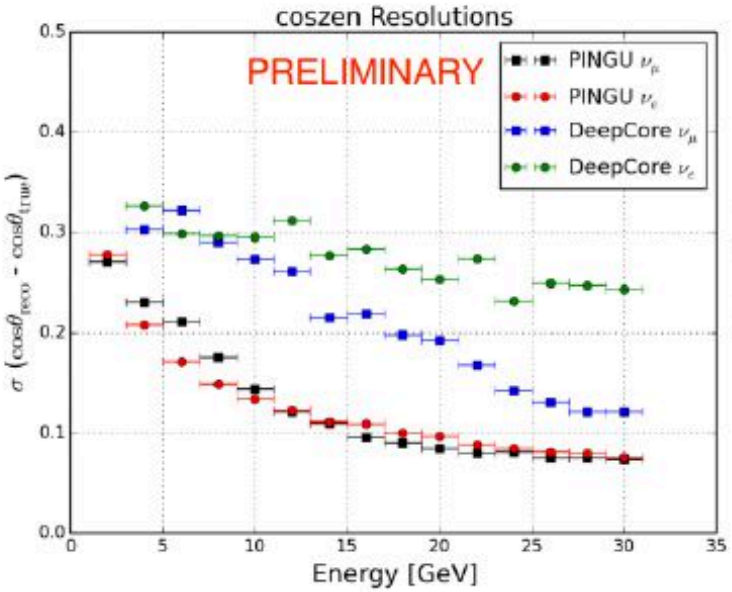
» Fit energy + direction simultaneously

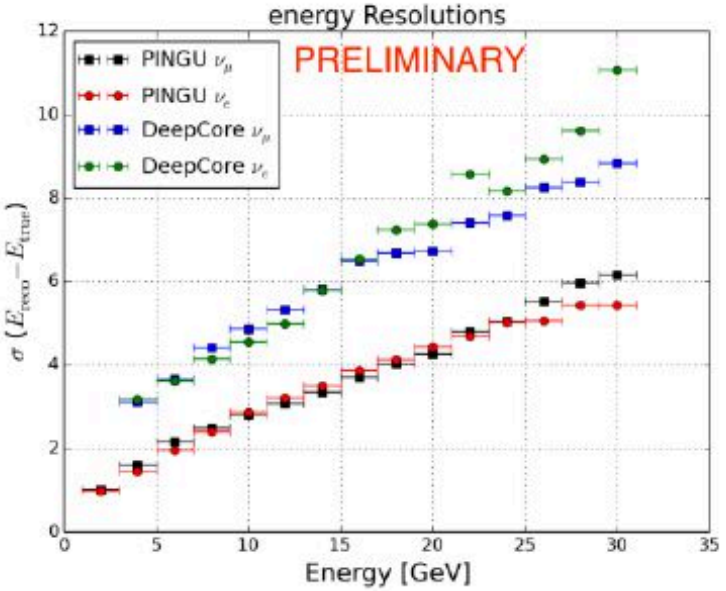
» No need for direct photons, use all events

» **Similar resolutions in DeepCore**

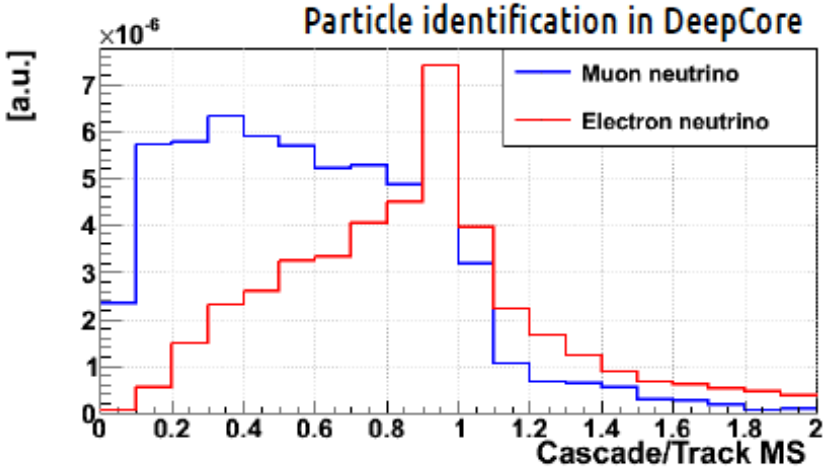
» **Higher efficiency**

» Working in **DeepCore**, testing vs data

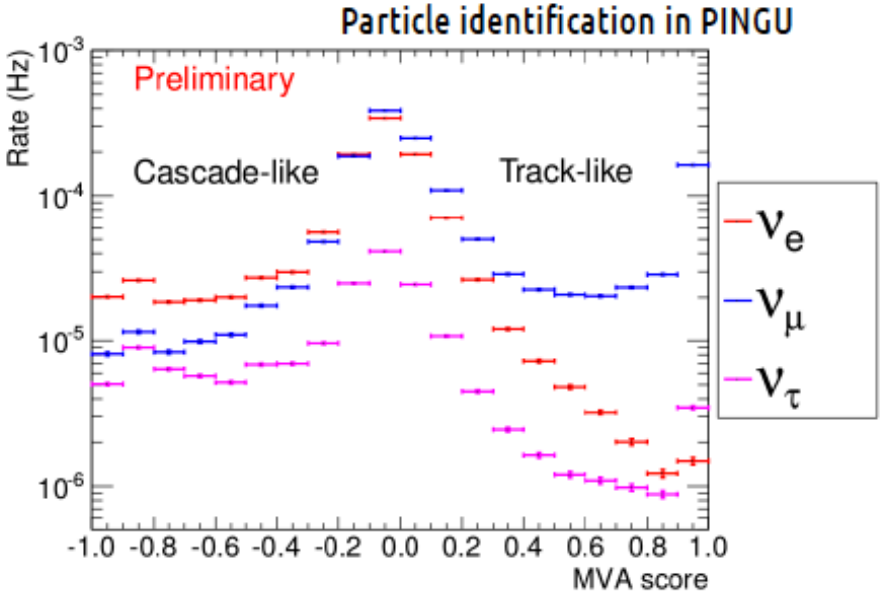




- In **DeepCore** → ratio of 2 fits
  - Assume track+cascade vs only cascade
  - Current results: x^2 in directional fit
  - ΔLLH in sophisticated reconstruction



- In **PINGU** → multivariate method
  - Exploid topological variables
  - Combine discrimination power
  - Can be optimized for sensitivity



projected sensitivity

Projected MC sensitivity from re-analysis of 3 years of DeepCore data*

- Classify interactions:
  - Between track- and cascade-like
- Inclusive selection:
  - Direct hits required (5 → 3)
- Sophisticated reconstruction
  - Global fit of all parameters
- Including events from all directions
  - Also down-going (atm. Muons)
- Renewed calibration efforts
  - Noise modeling, angular acceptance, individual DOM behavior