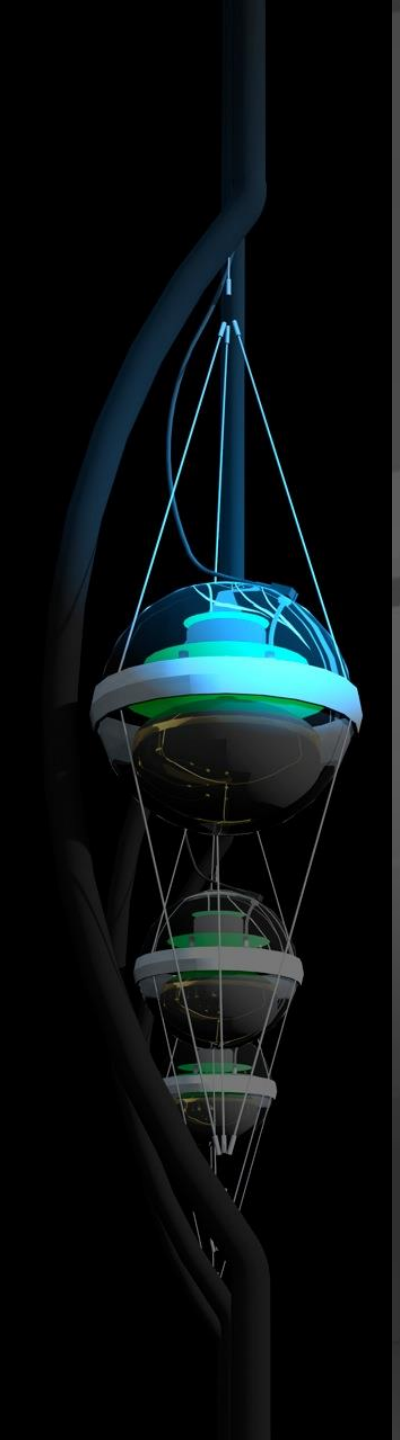
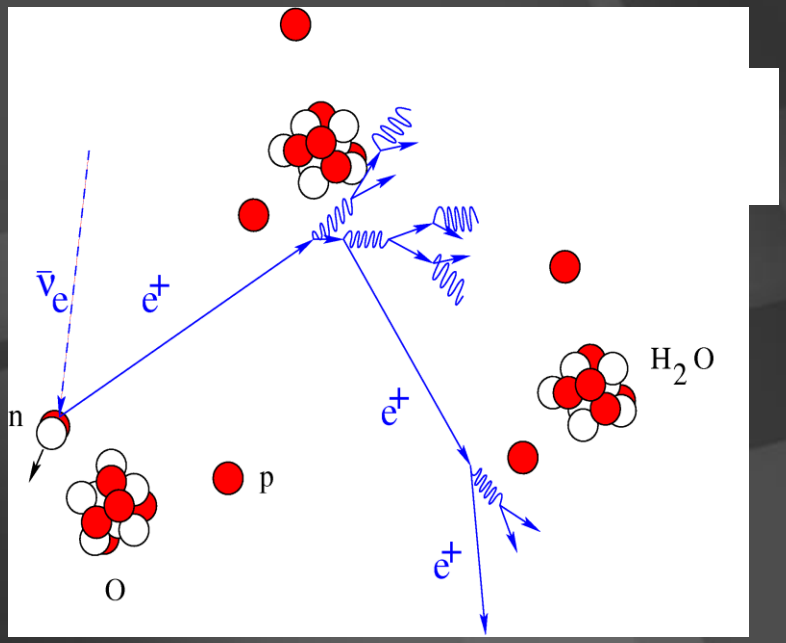
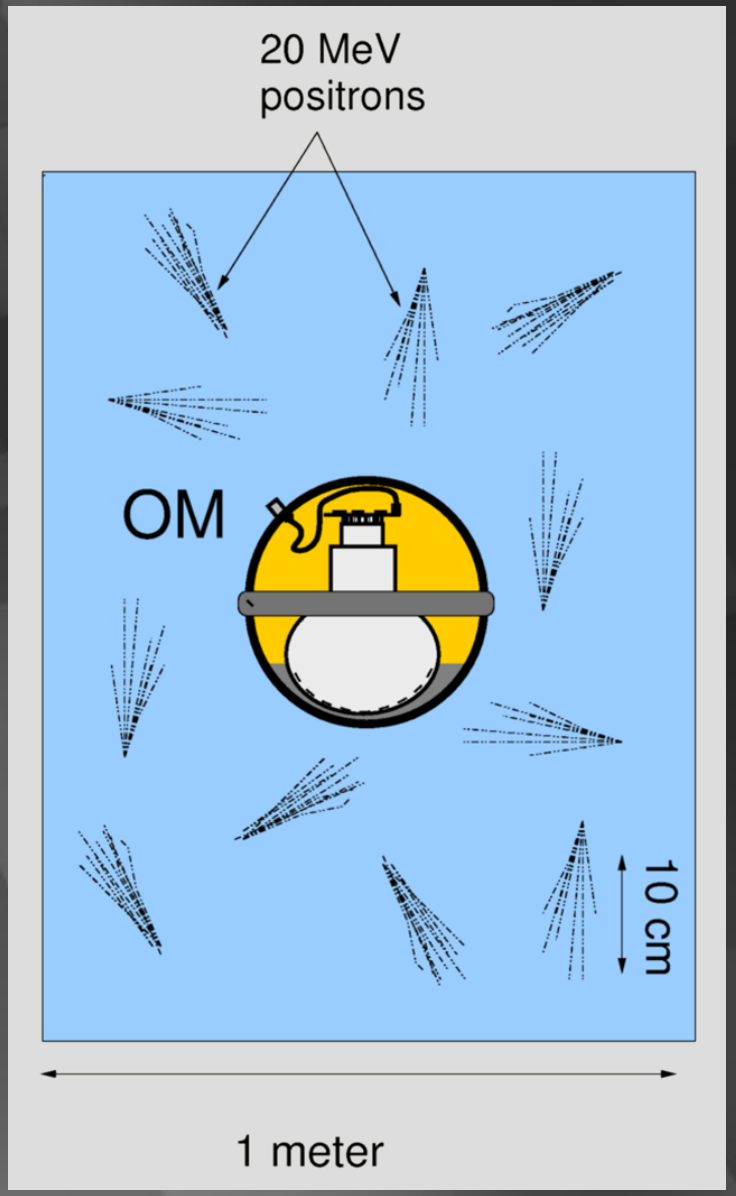


IceCube: beyond neutrino astronomy

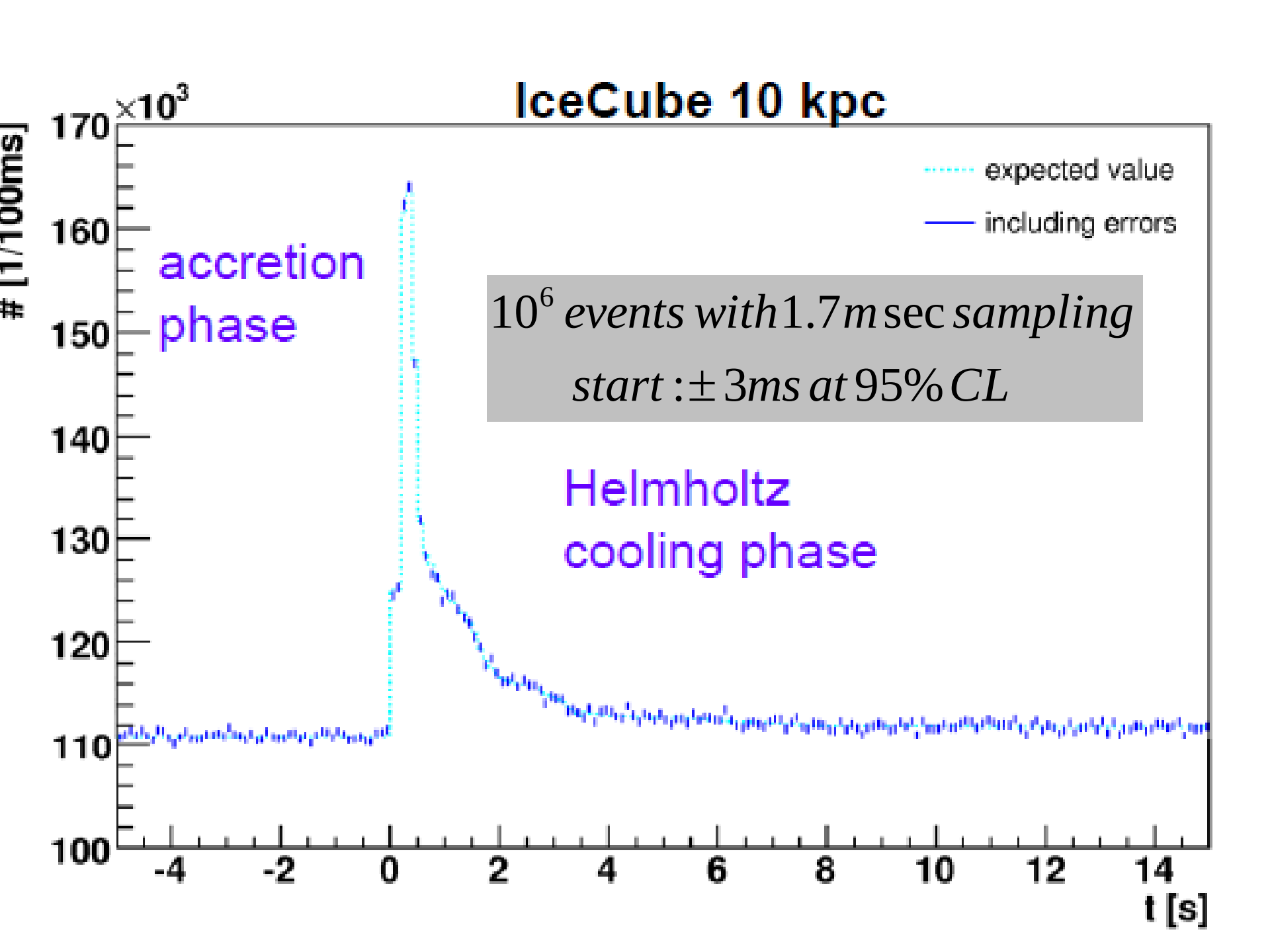
- detecting a Galactic supernova explosion
- neutrino oscillations: the mass hierarchy
- search for sterile neutrinos
- search for dark matter
- muon astronomy: search for the sources of the Galactic cosmic rays
- …

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

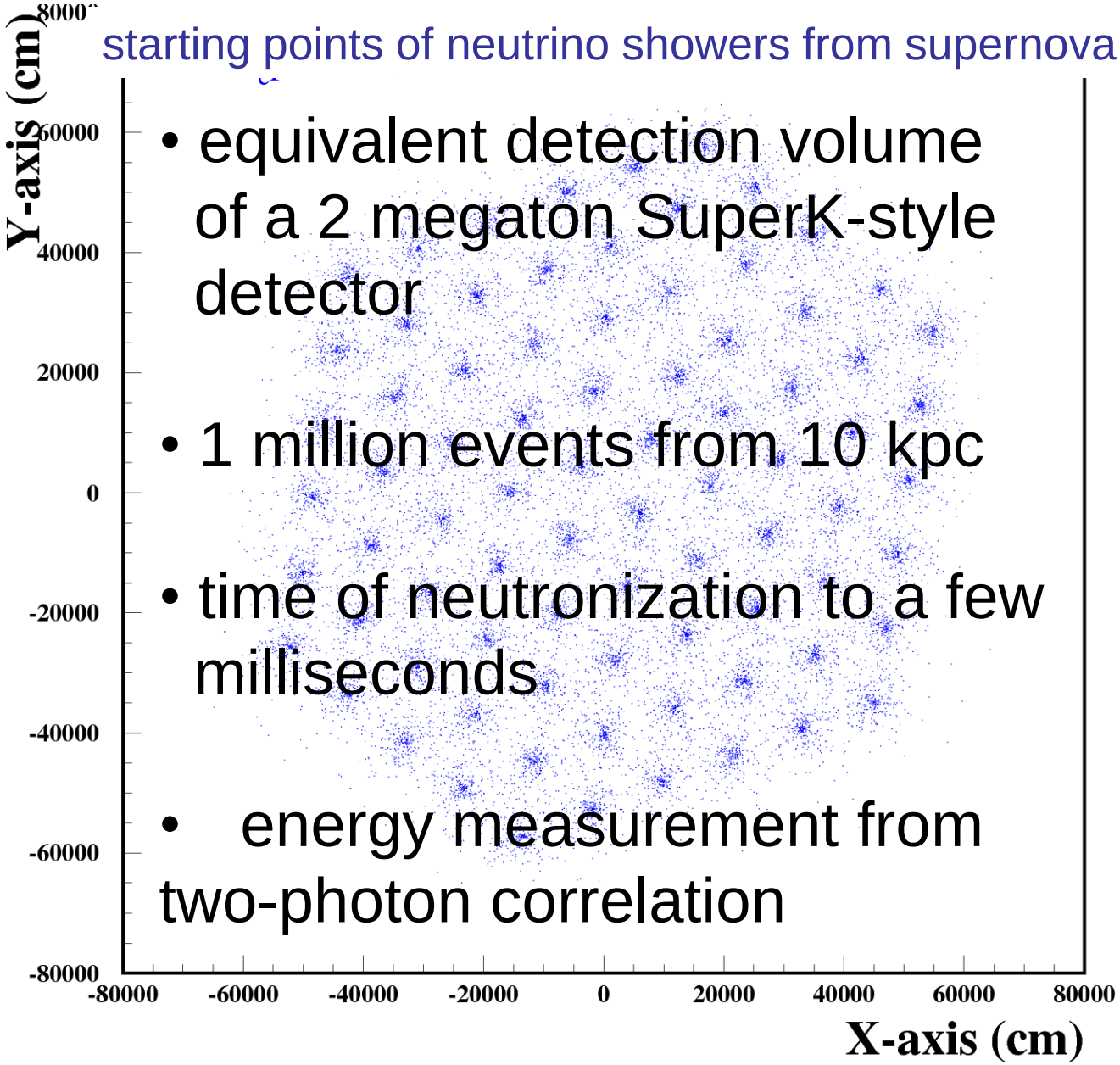




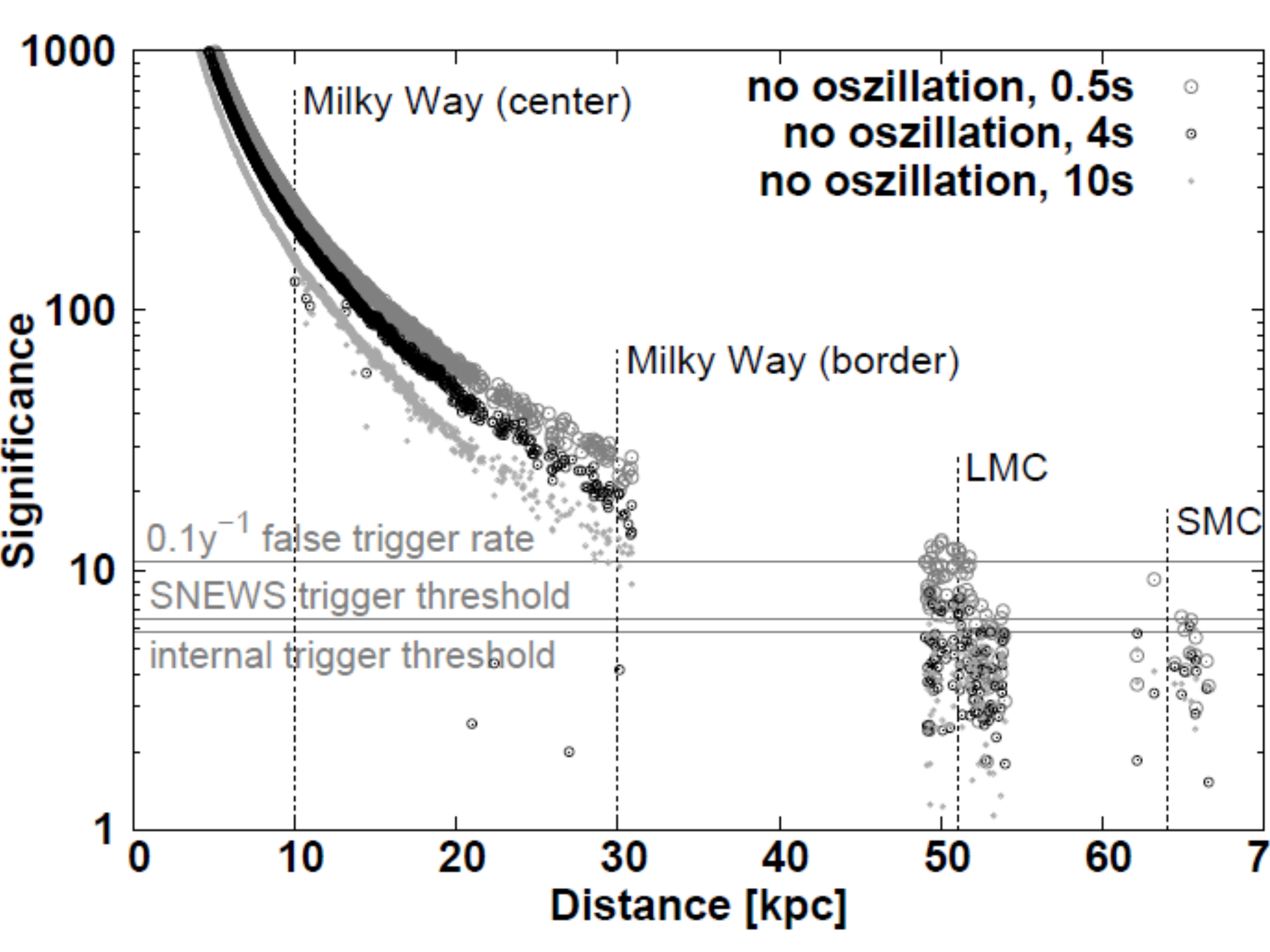
- PMT noise low (280 Hz)
- detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector


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 1.7 msec sampling
start : ± 3ms at 95% CL
Helmholtz cooling phase

starting points of neutrino showers from supernova

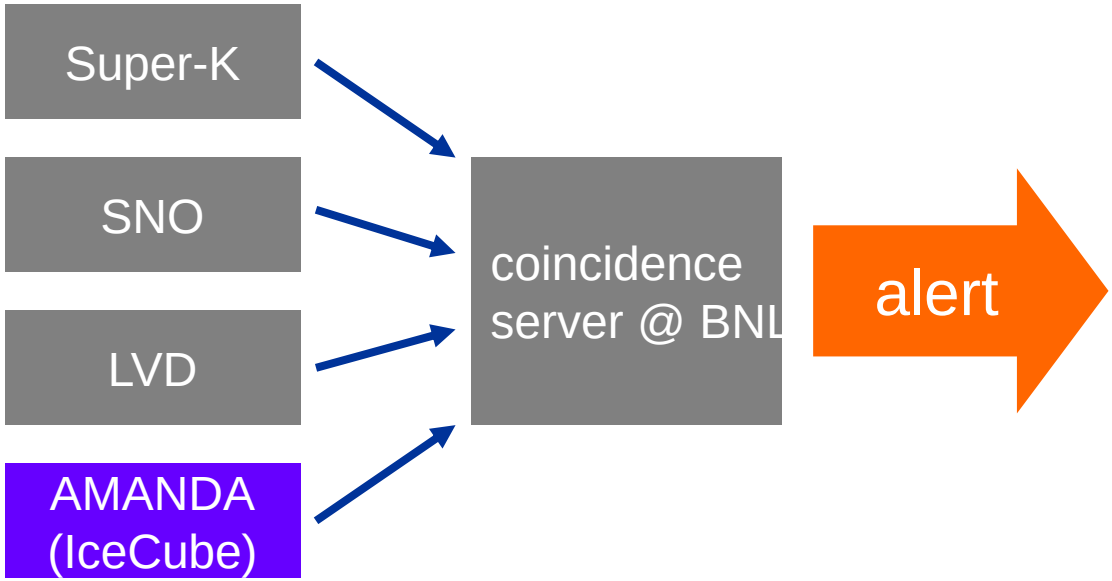


- equivalent detection volume of a 2 megaton SuperK-style detector
- 1 million events from 10 kpc
- time of neutronization to a few milliseconds
- energy measurement from two-photon correlation


1000
100
10
1
Significance
0
10
20
30
40
50
60
7
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

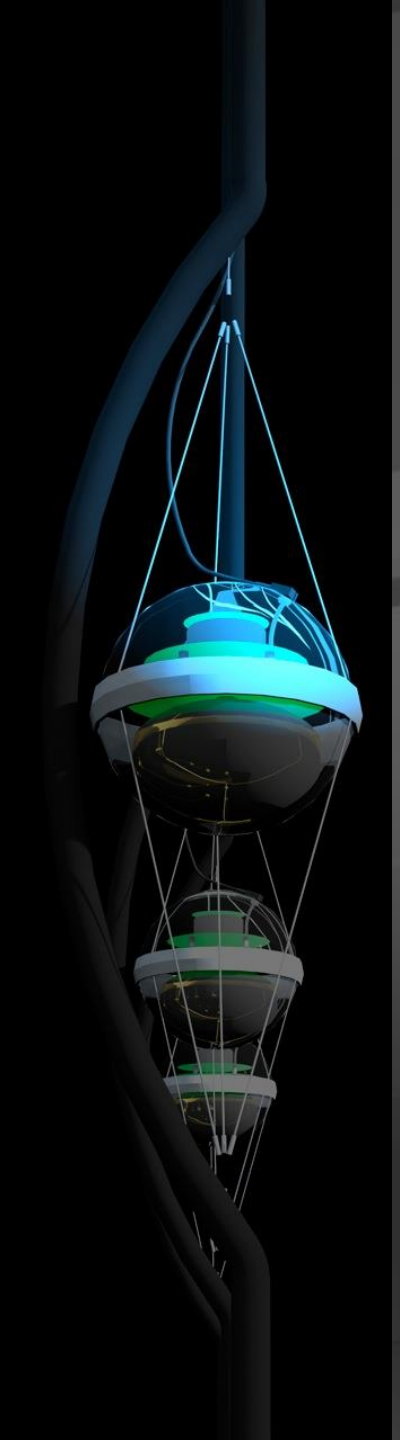
…several hours advanced notice to astronomers …



received iridium messages (last 4 weeks)

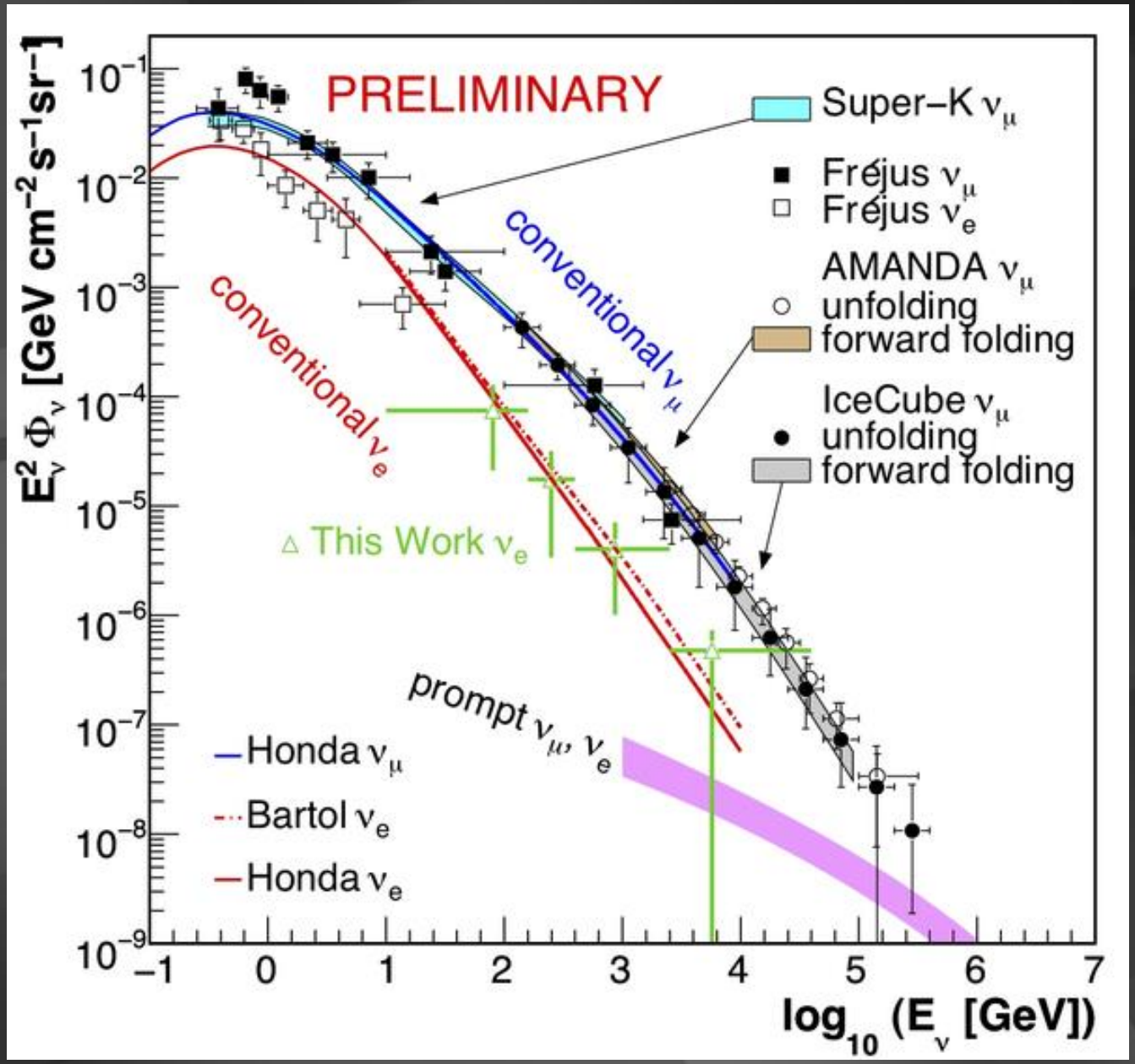
message type	time (UTC)	time delay to reception (seconds)	needed modem dial attempts
missing test message(s)			
test	Mon Jul 10 08:19:38 2006	224	1
test	Sun Jul 9 11:15:12 2006	218	1
test	Sat Jul 8 11:15:12 2006	208	1
test	Fri Jul 7 11:15:12 2006	208	1
test	Thu Jul 6 11:15:11 2006	214	1
test	Thu Jul 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



IceCube: beyond neutrino astronomy

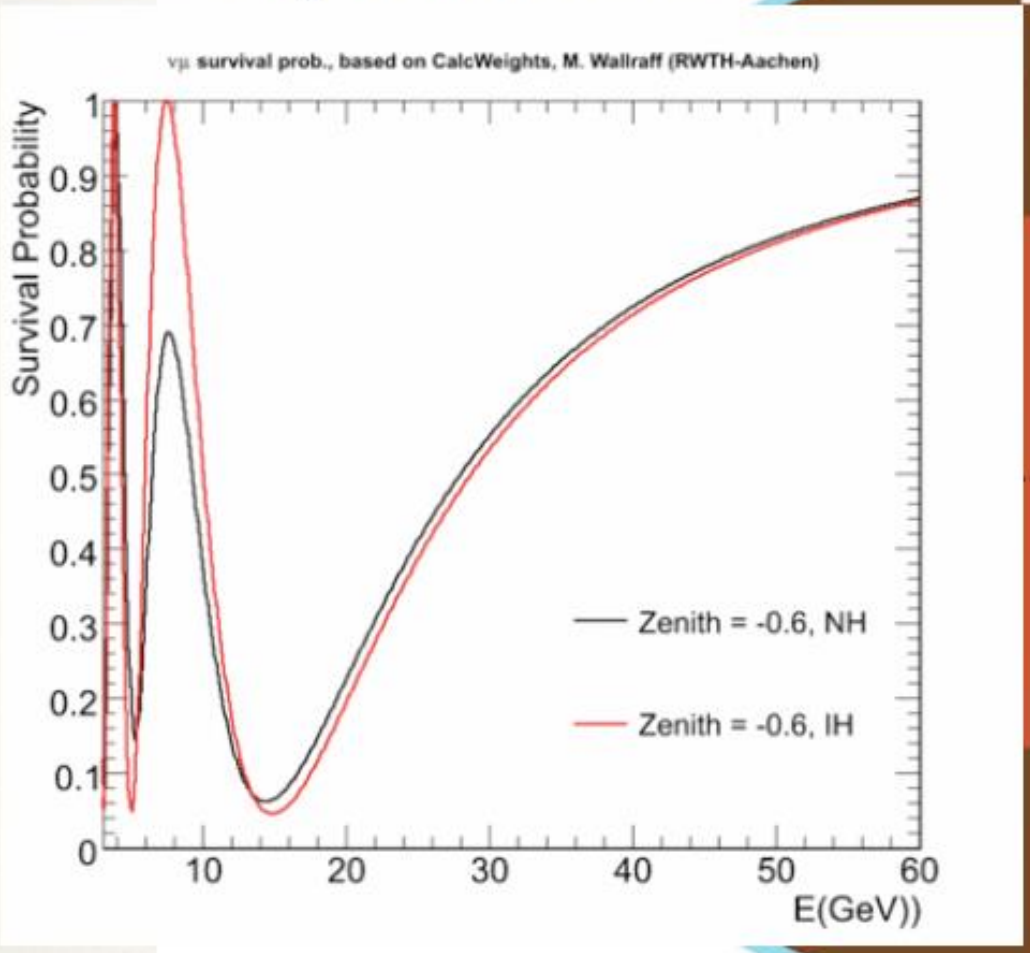
- detecting a Galactic supernova explosion
- neutrino oscillations: the mass hierarchy
- search for sterile neutrinos
- search for dark matter
- muon astronomy: search for the sources of the Galactic cosmic rays
- …

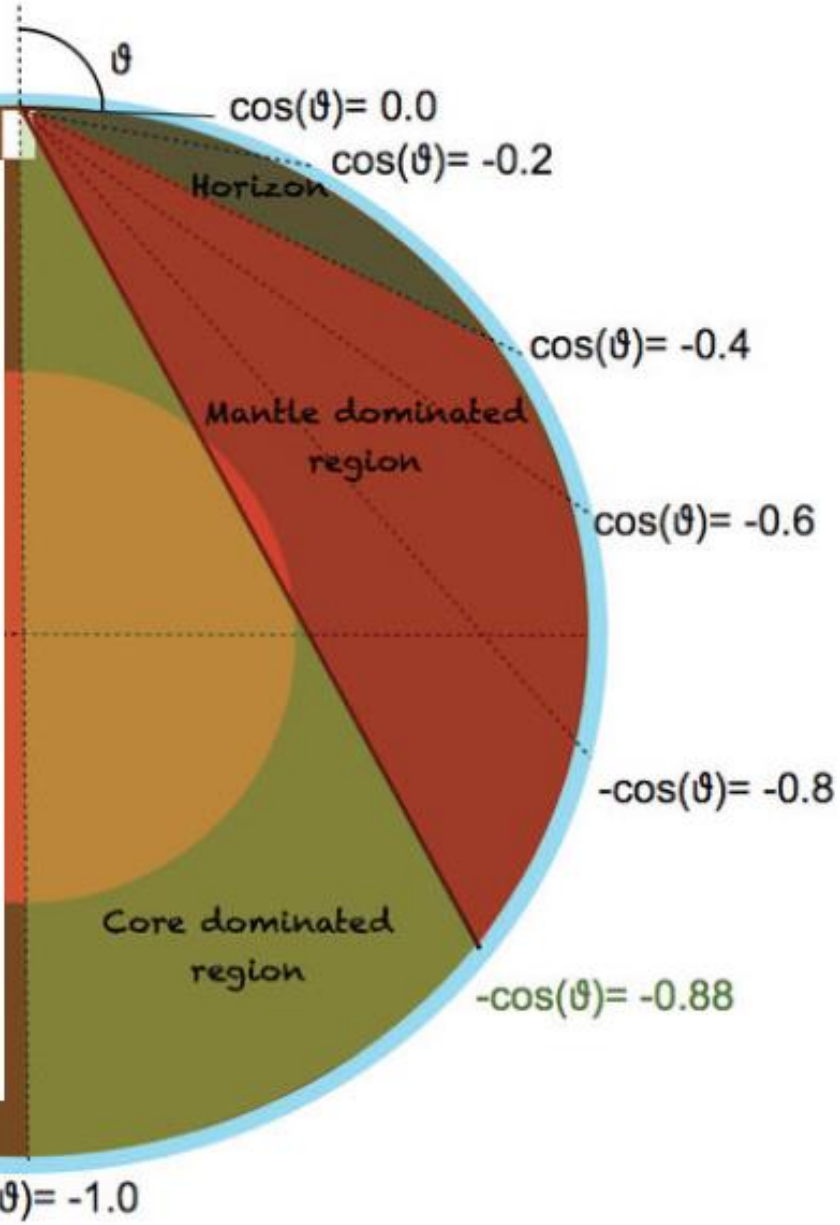


atmospheric neutrino spectrum

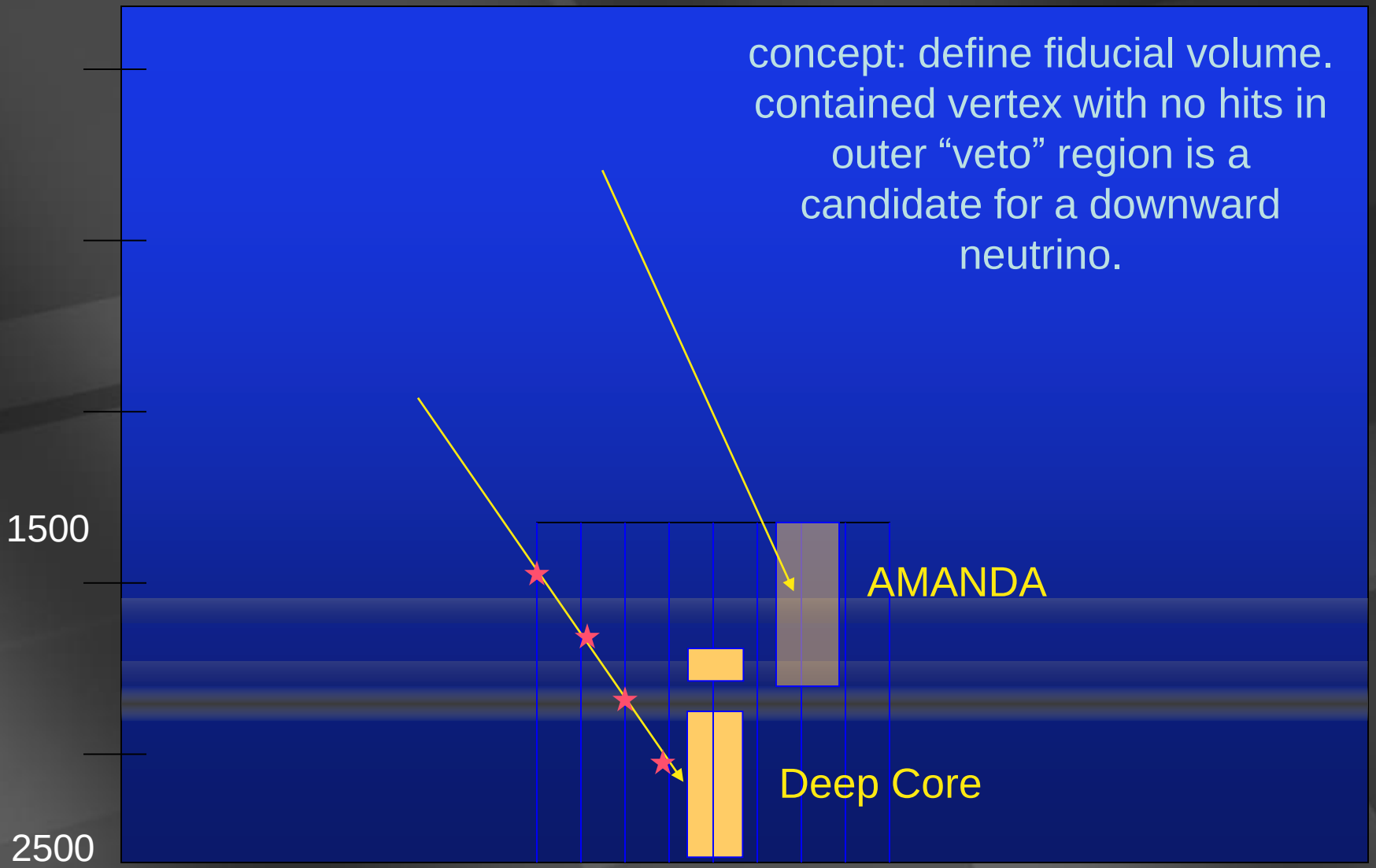
Atmospheric neutrino oscillation

Note: only neutrinos here

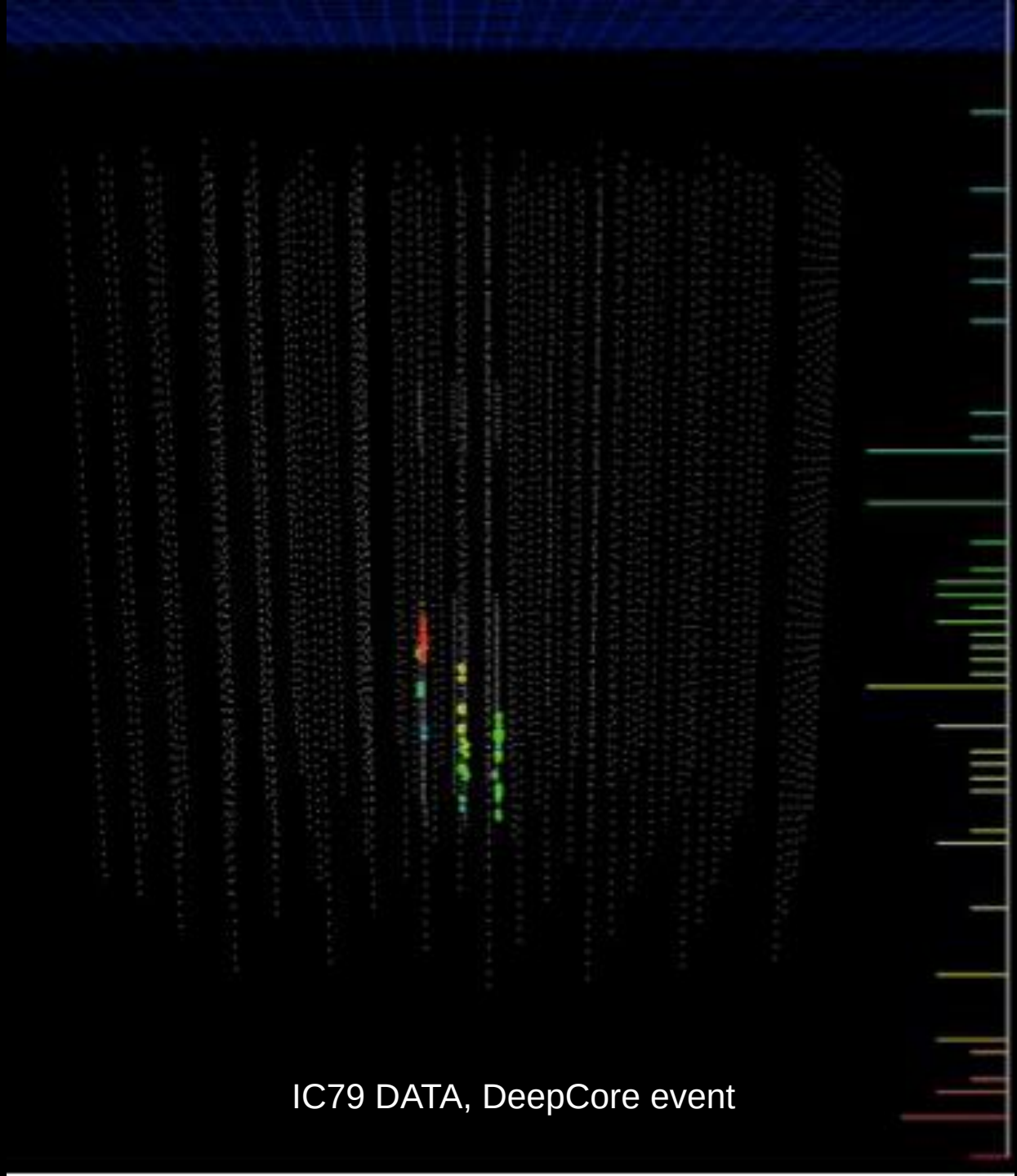




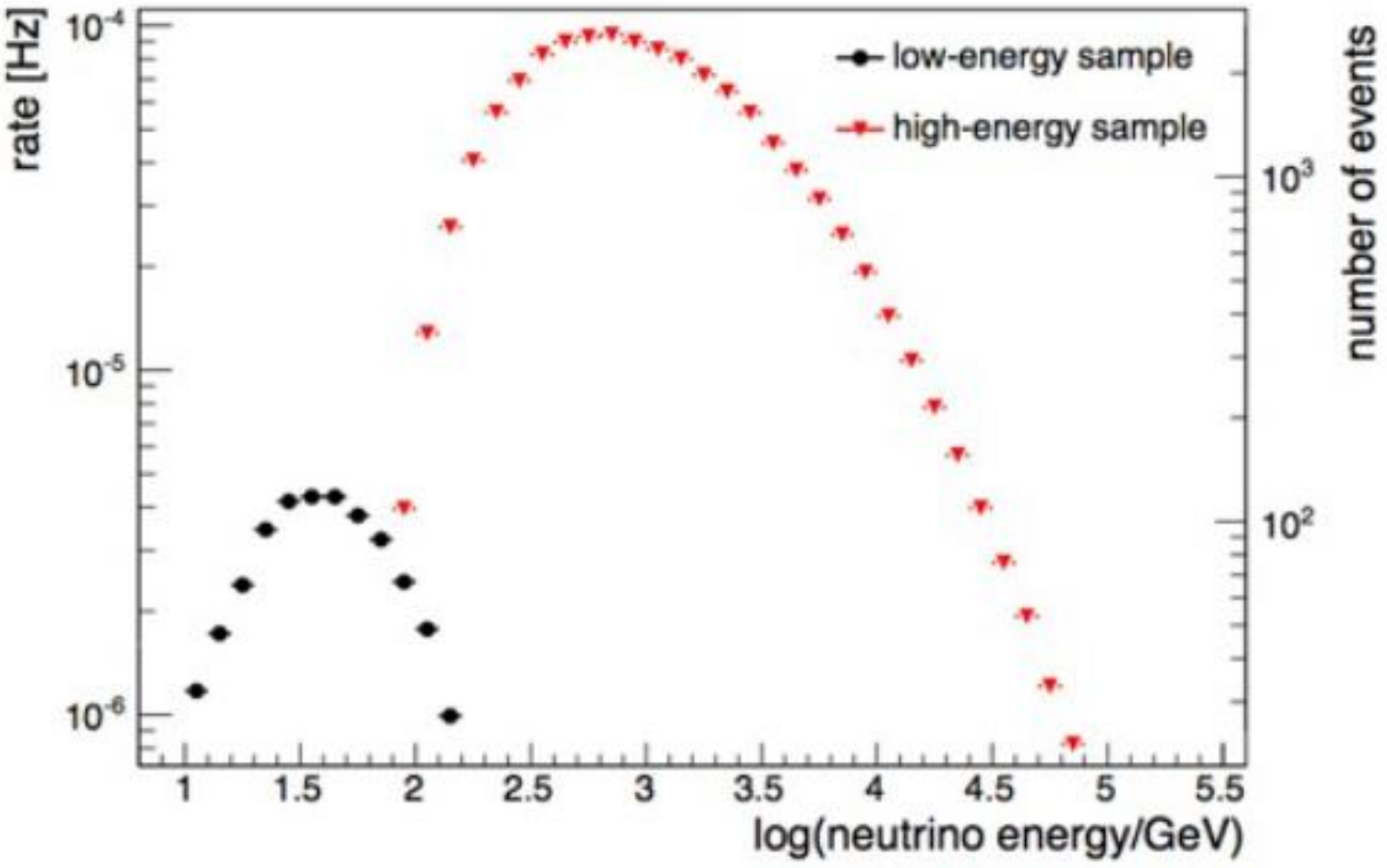
low energy core for IceCube



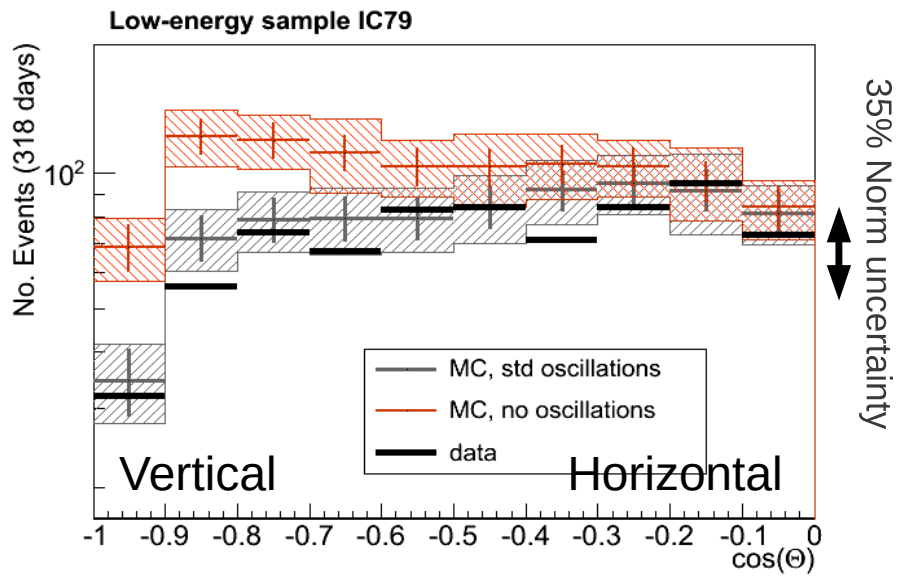
$$n_{strings} \acute{} \; height \acute{} \left(p \, l^{2}_{scatt} \right) \gg ten \; Mton$$

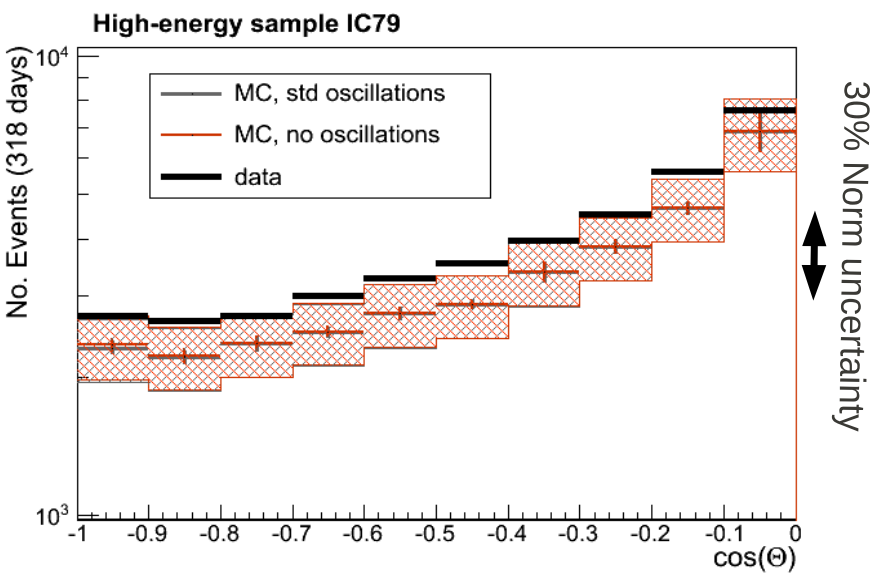


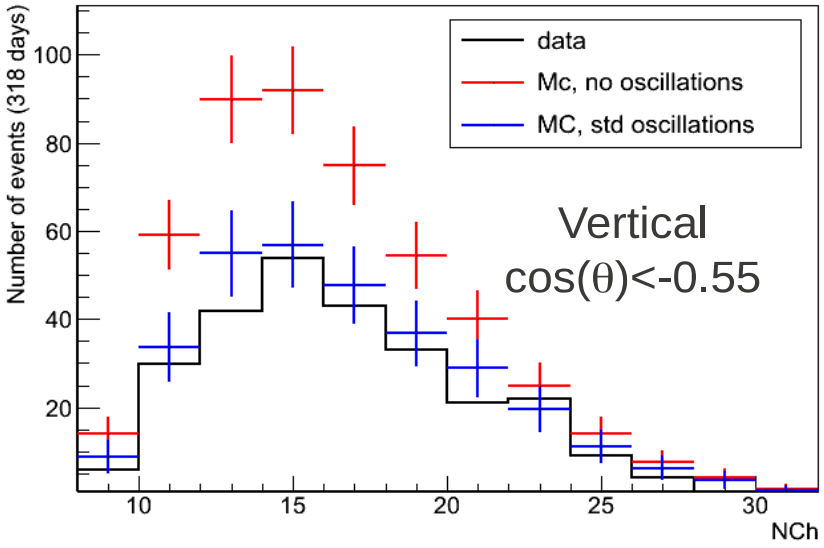
IC79 DATA, DeepCore event

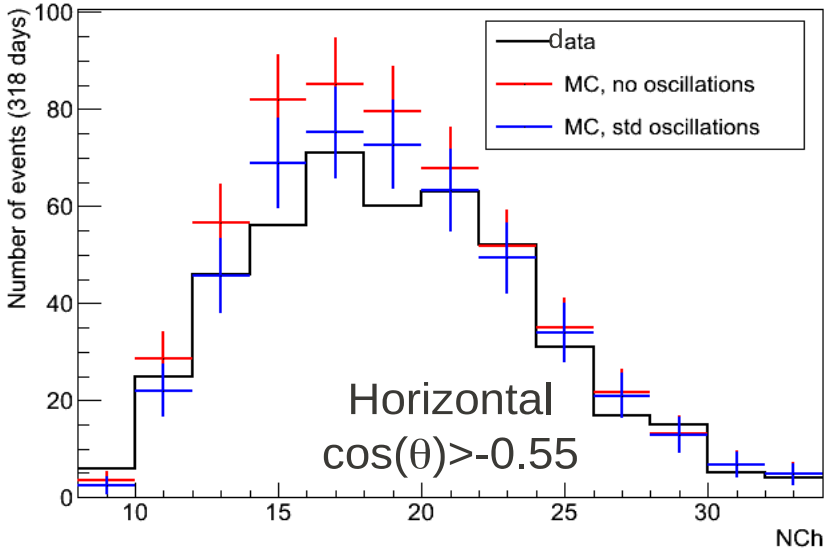

rate [Hz]
10^{-4}
10^{-5}
10^{-6}
low-energy sample
high-energy sample
10^{3}
10^{2}
number of events
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
log(neutrino energy/GeV)

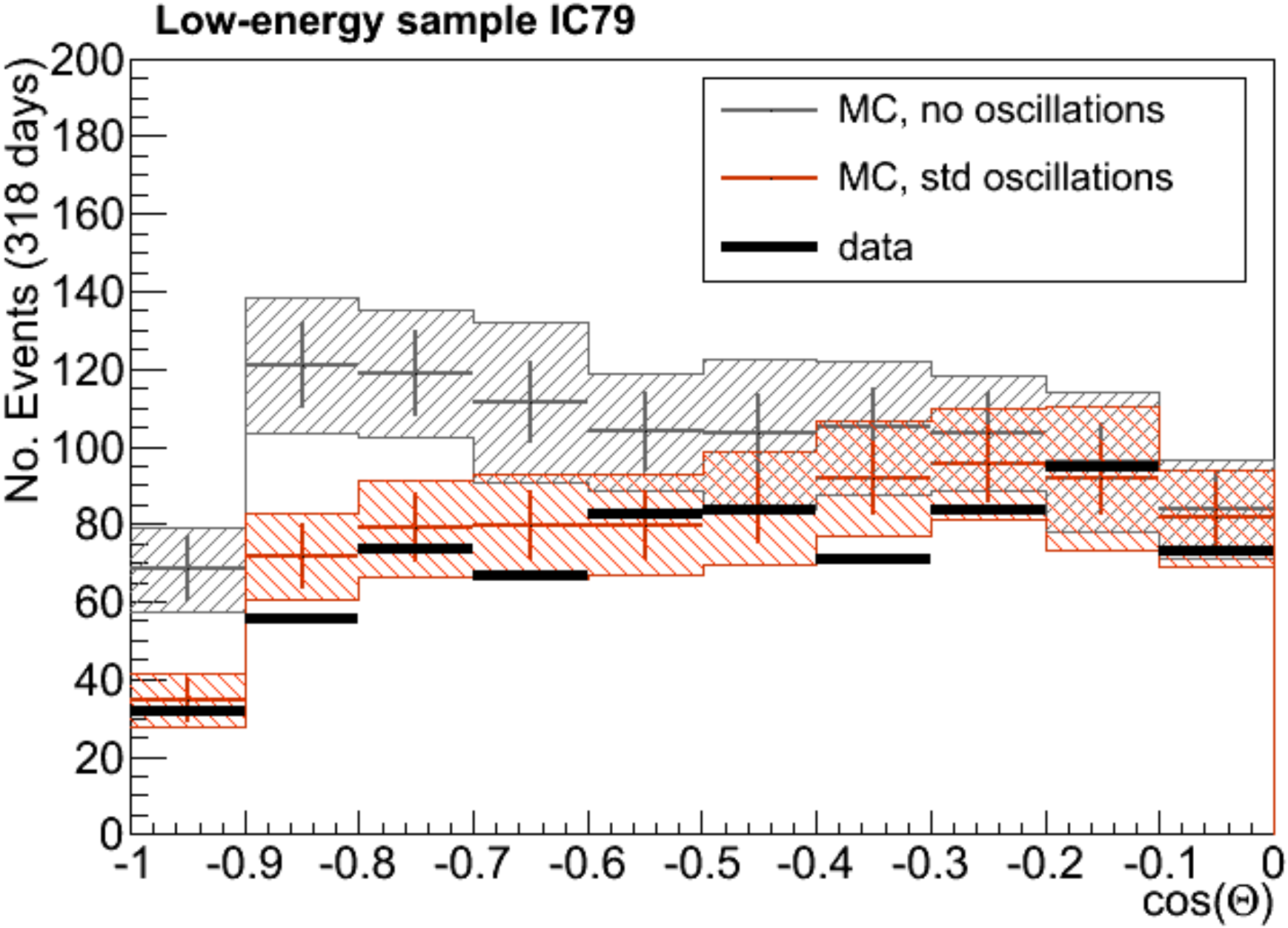
oscillations in DeepCore [energy ~30 GeV; 5.6 sigma]

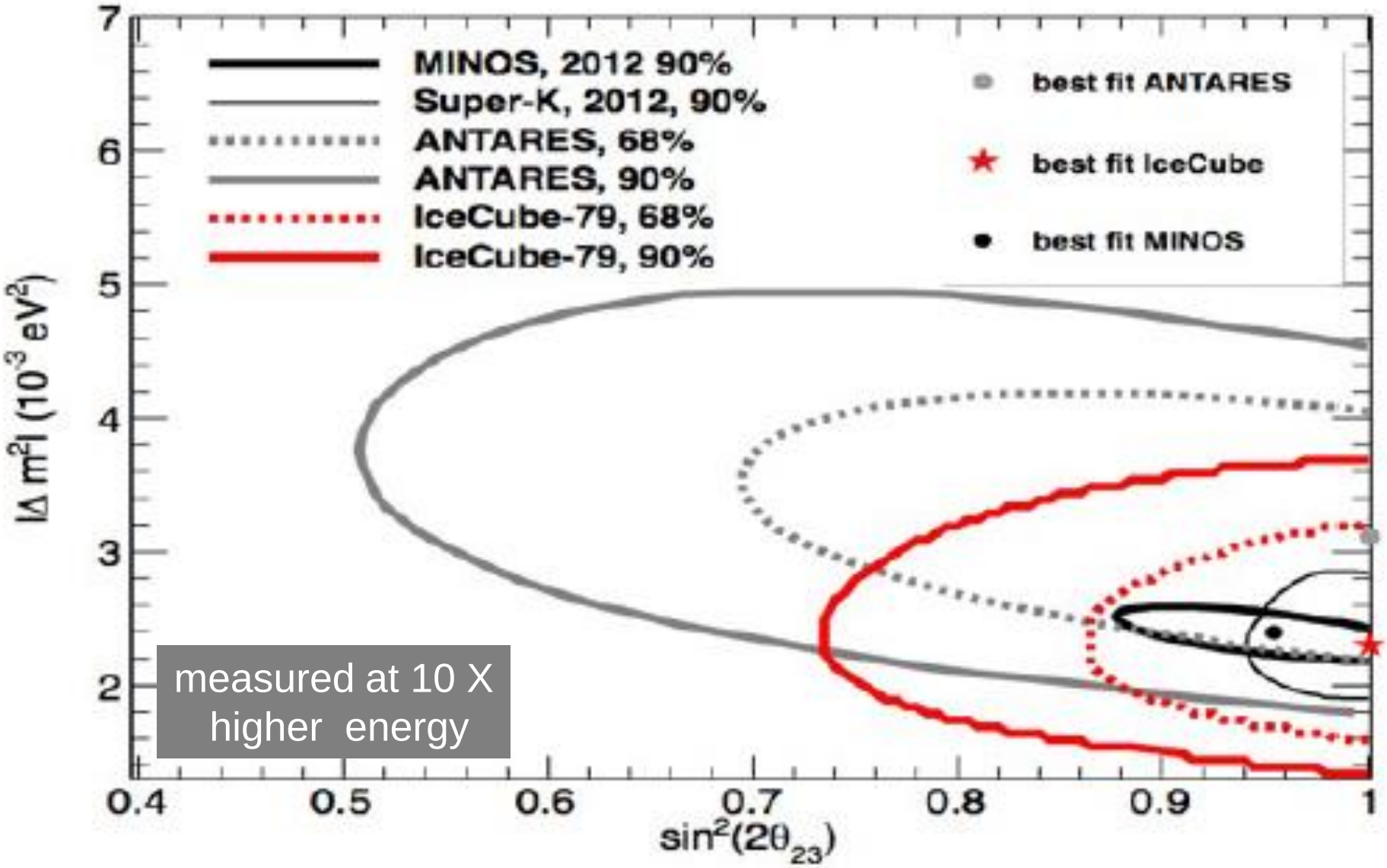






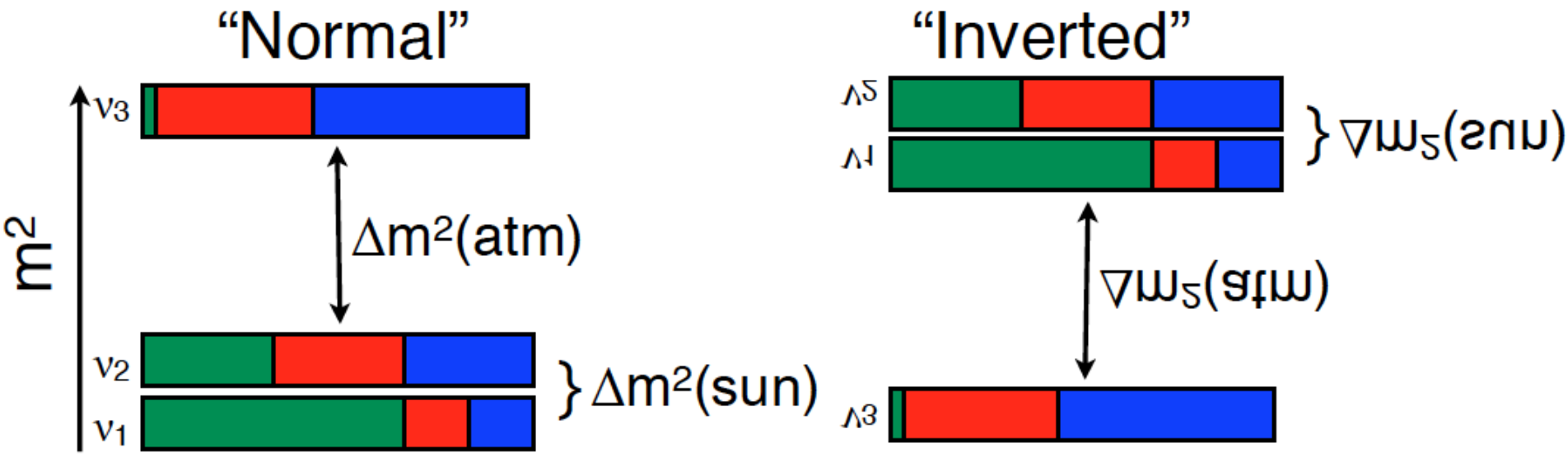



Low-energy sample IC79
No. Events (318 days)
200
180
160
140
120
100
80
60
40
20
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
cos(Θ)
MC, no oscillations
MC, std oscillations
data

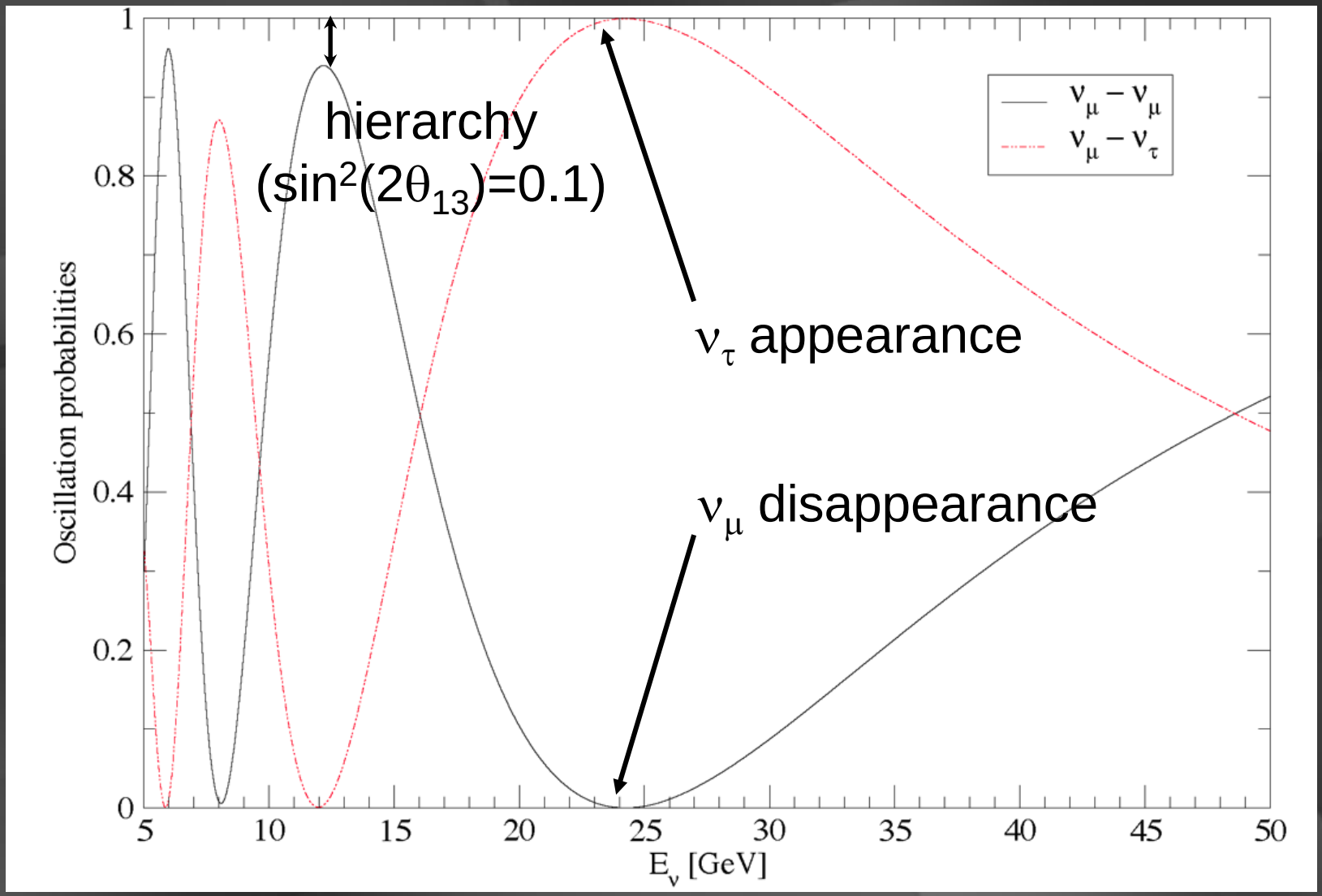


Phys. Rev. Lett. 111, 081801 (2013)

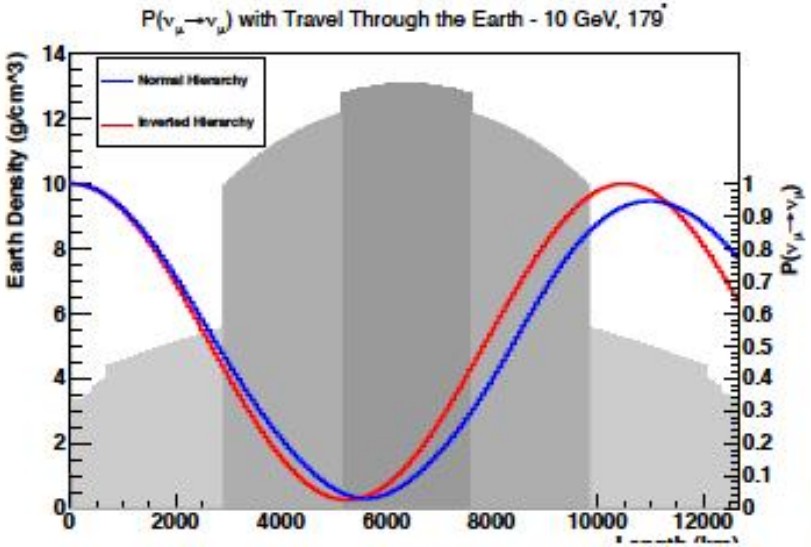
neutrino mass hierarchy ?

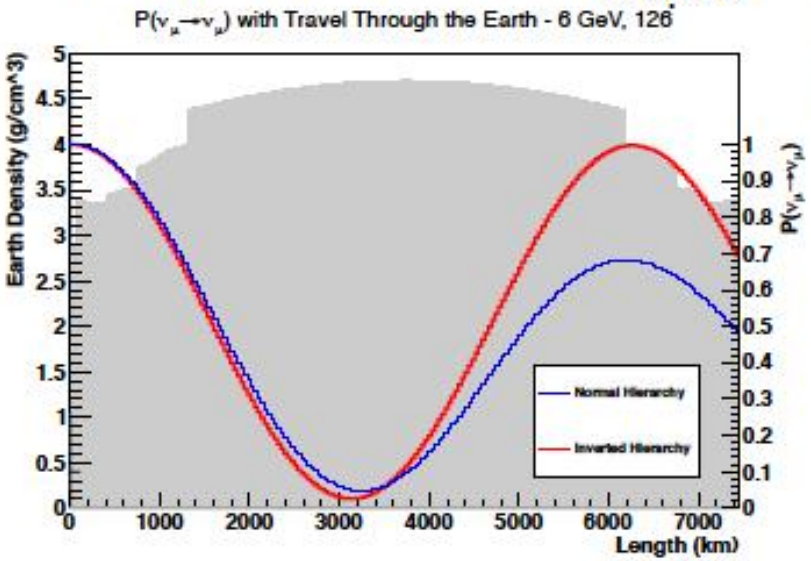


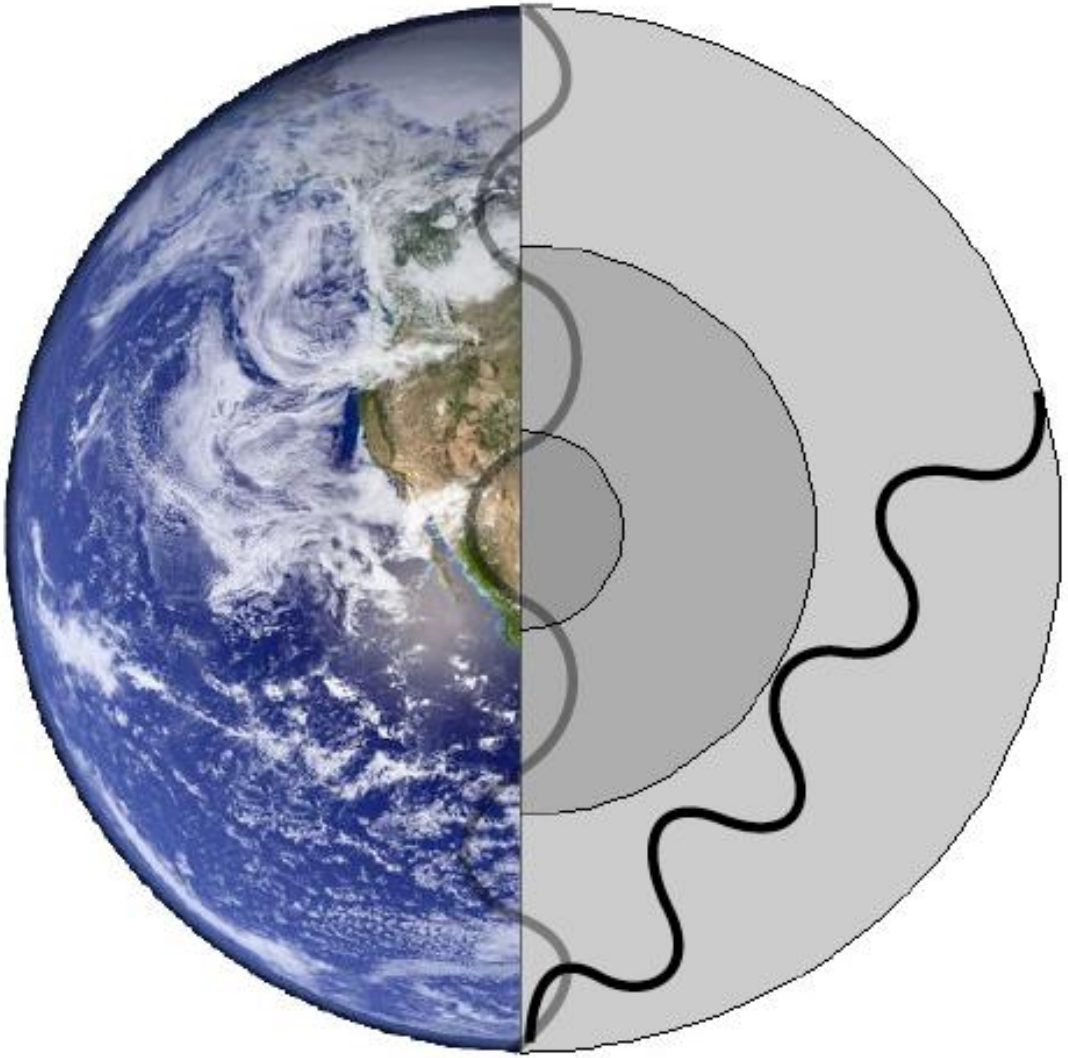
neutrino oscillations in Deep Core



resonance in effective θ_{13} angle traversing the Earth diameter at 10 GeV


P(ν_μ→ν_μ) with Travel Through the Earth - 10 GeV, 179°
Normal Hierarchy
Inverted Hierarchy
Earth Density (g/cm^3)
P(ν_μ→ν_μ)
0
2000
4000
6000
8000
10000
12000


P(ν_μ→ν_μ) with Travel Through the Earth - 6 GeV, 126°
Normal Hierarchy
Inverted Hierarchy
Earth Density (g/cm^3)
P(ν_μ→ν_μ)
0
1000
2000
3000
4000
5000
6000
7000
Length (km)



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

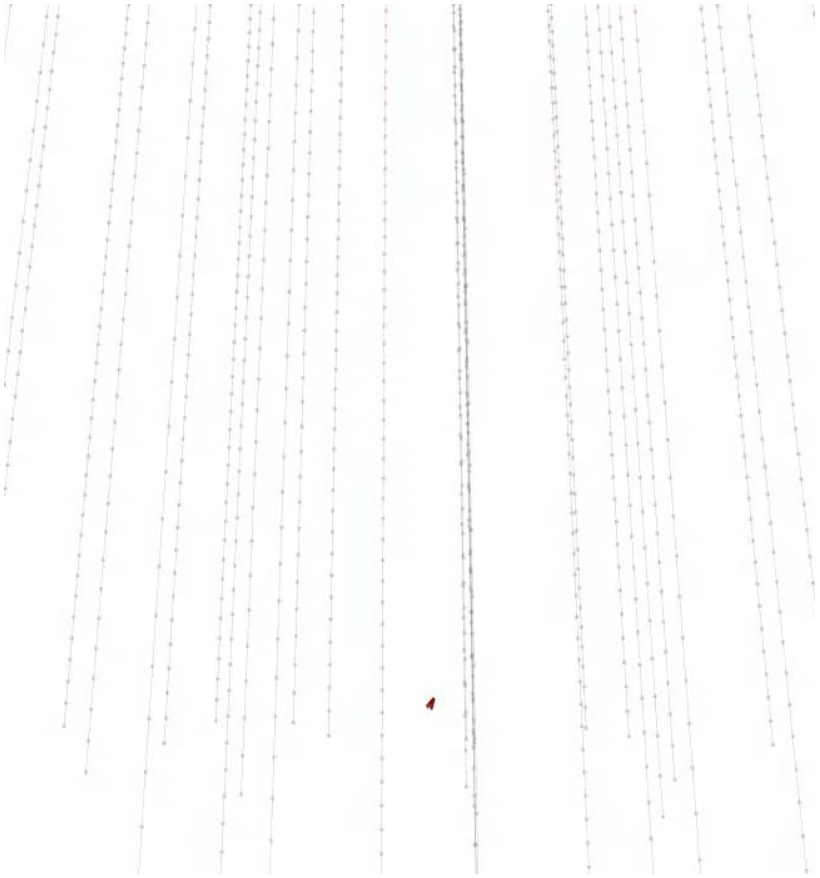
$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2G_F}\, n_e}{\Delta_{13}}\right]}$$

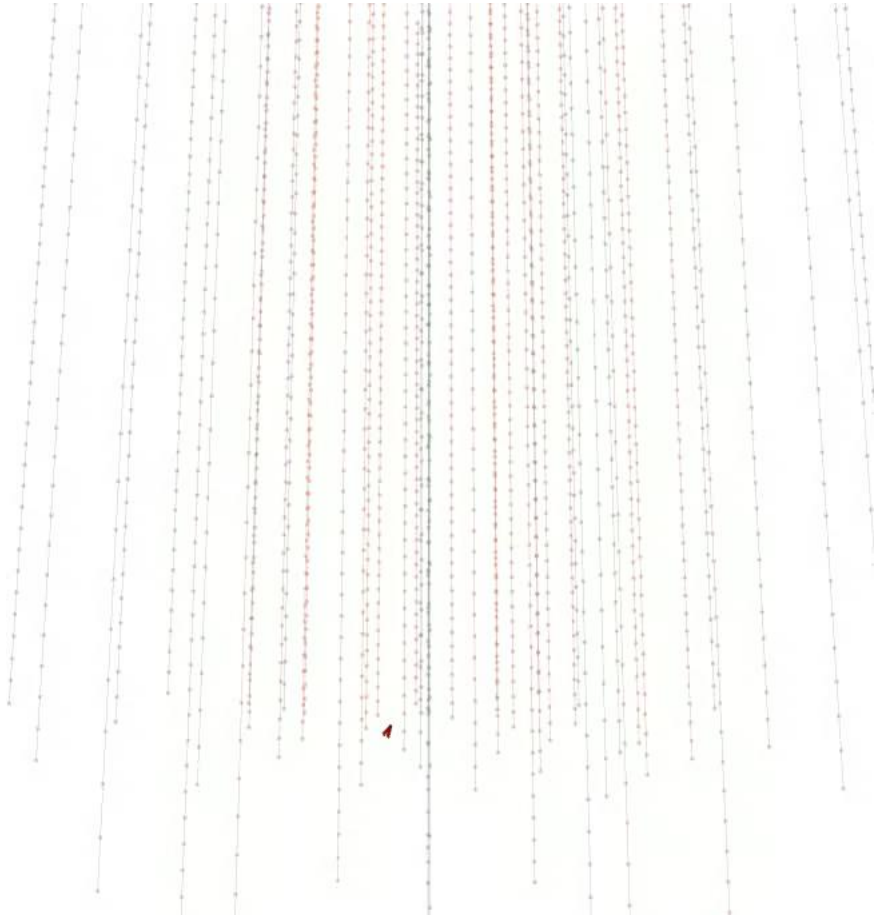
(mostly) neutrino + antineutrino -

sign Δ_{13} : hierarchy !

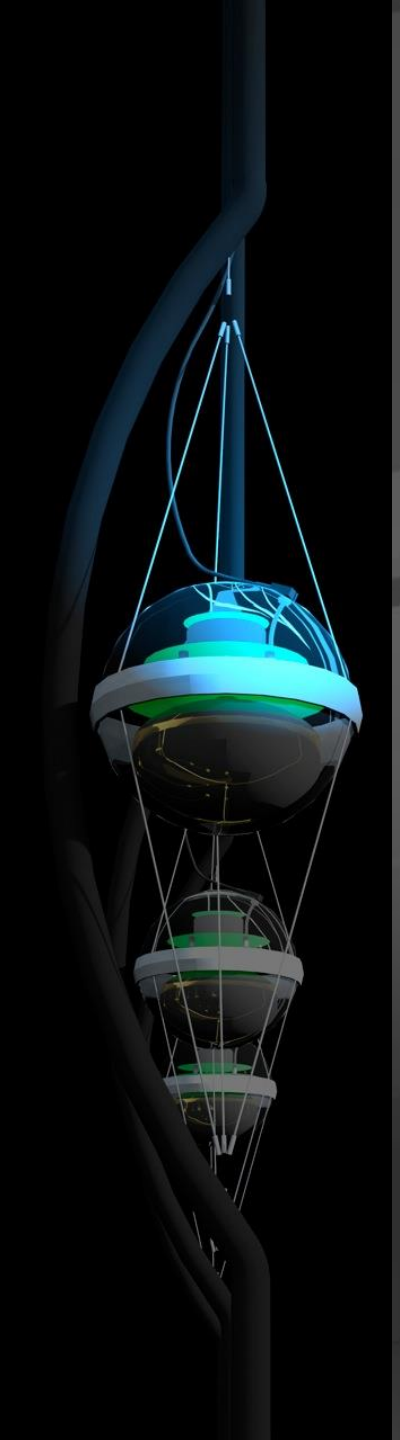
DeepCore (+6 strings):11 hits

PINGU (+20 strings): 83 hits



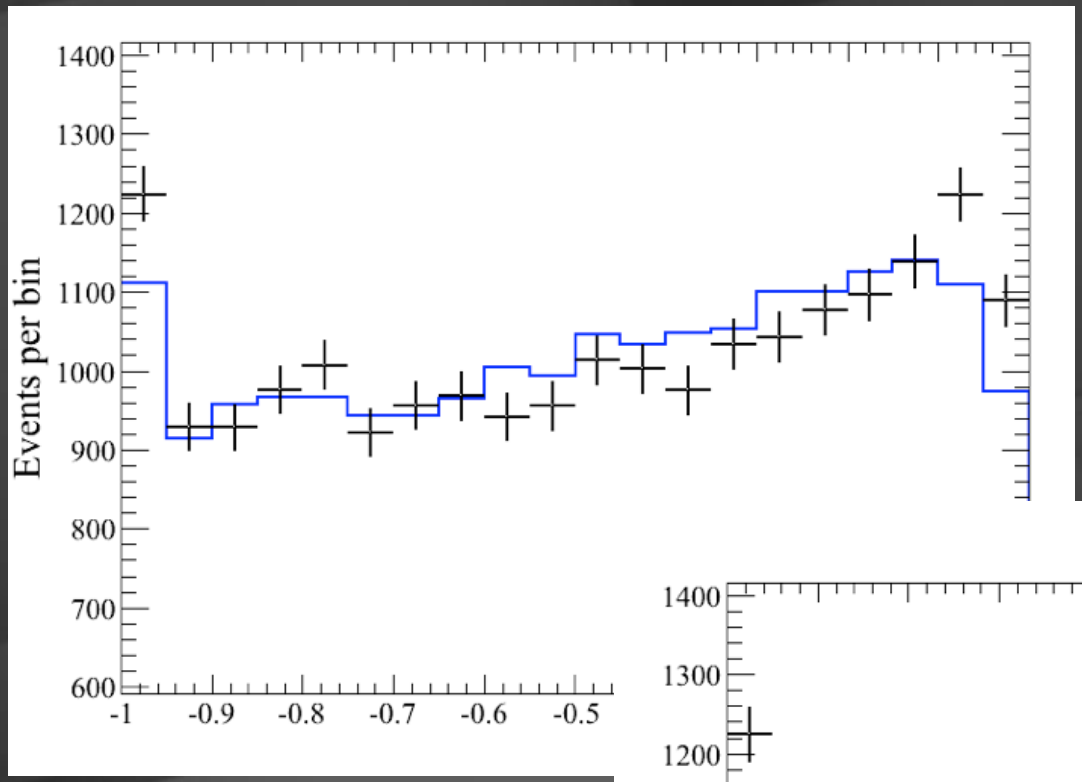


8 GeV muon-neutrino

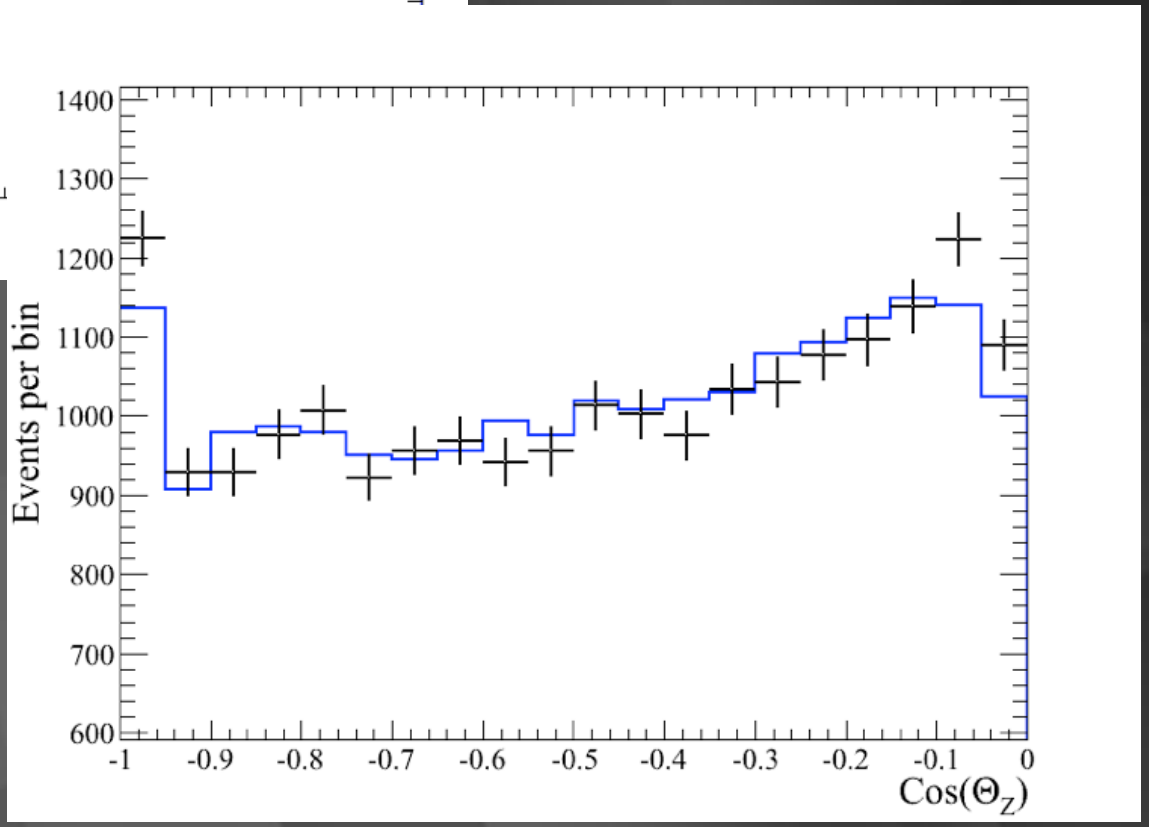


IceCube: beyond neutrino astronomy

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



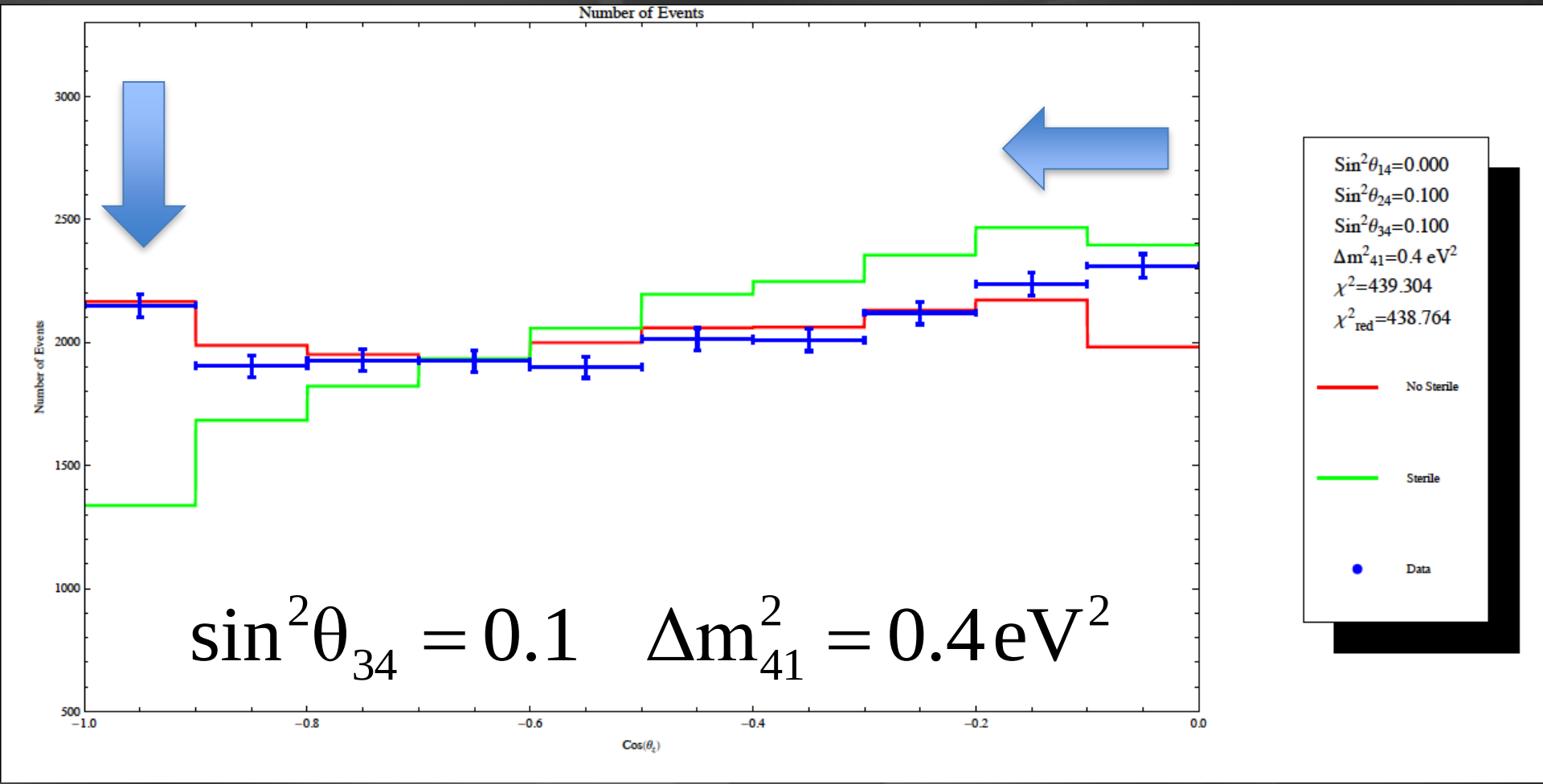
3



3+1

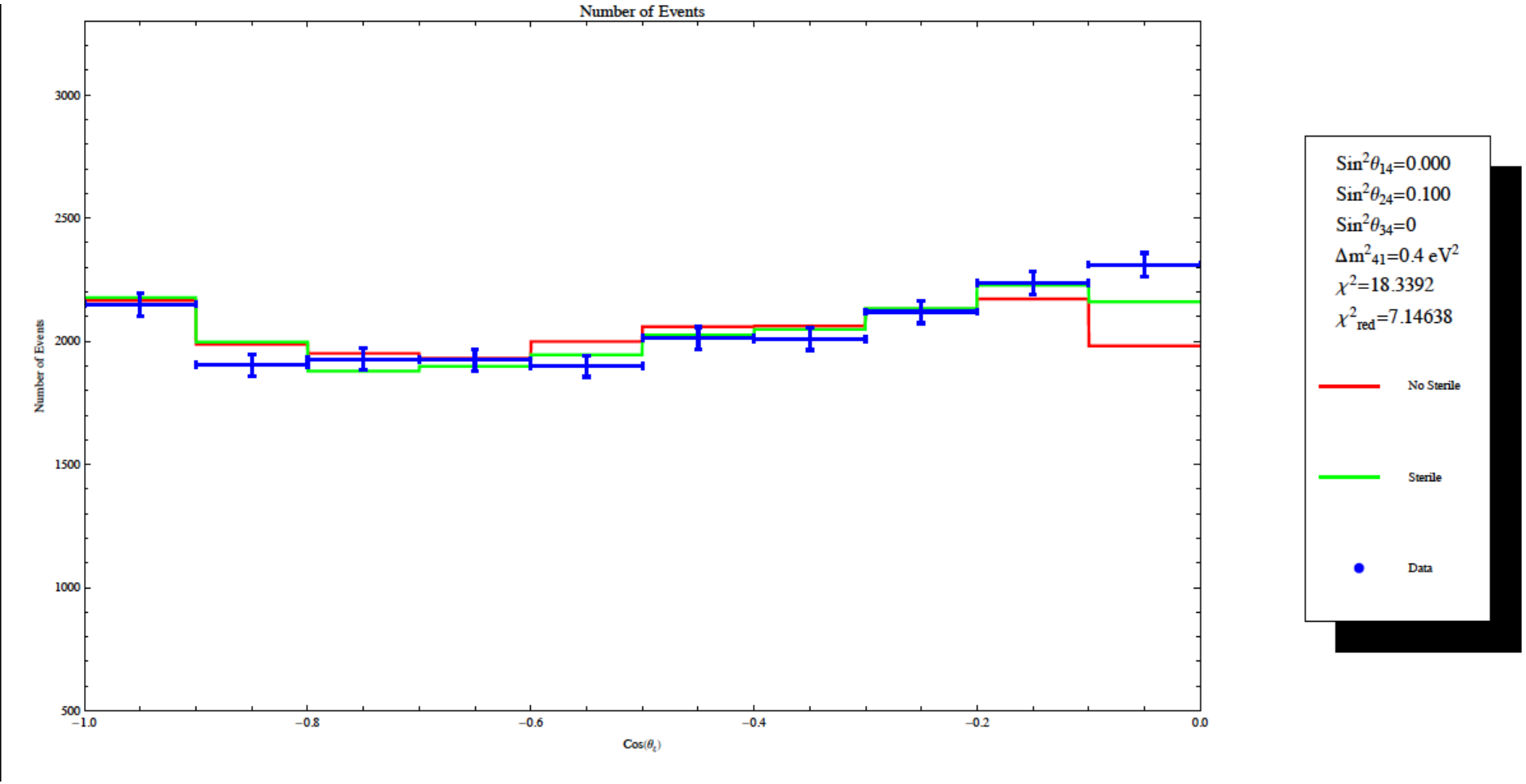
matter effect
of eV sterile ν's ?

number of ν_μ observed versus zenith angle



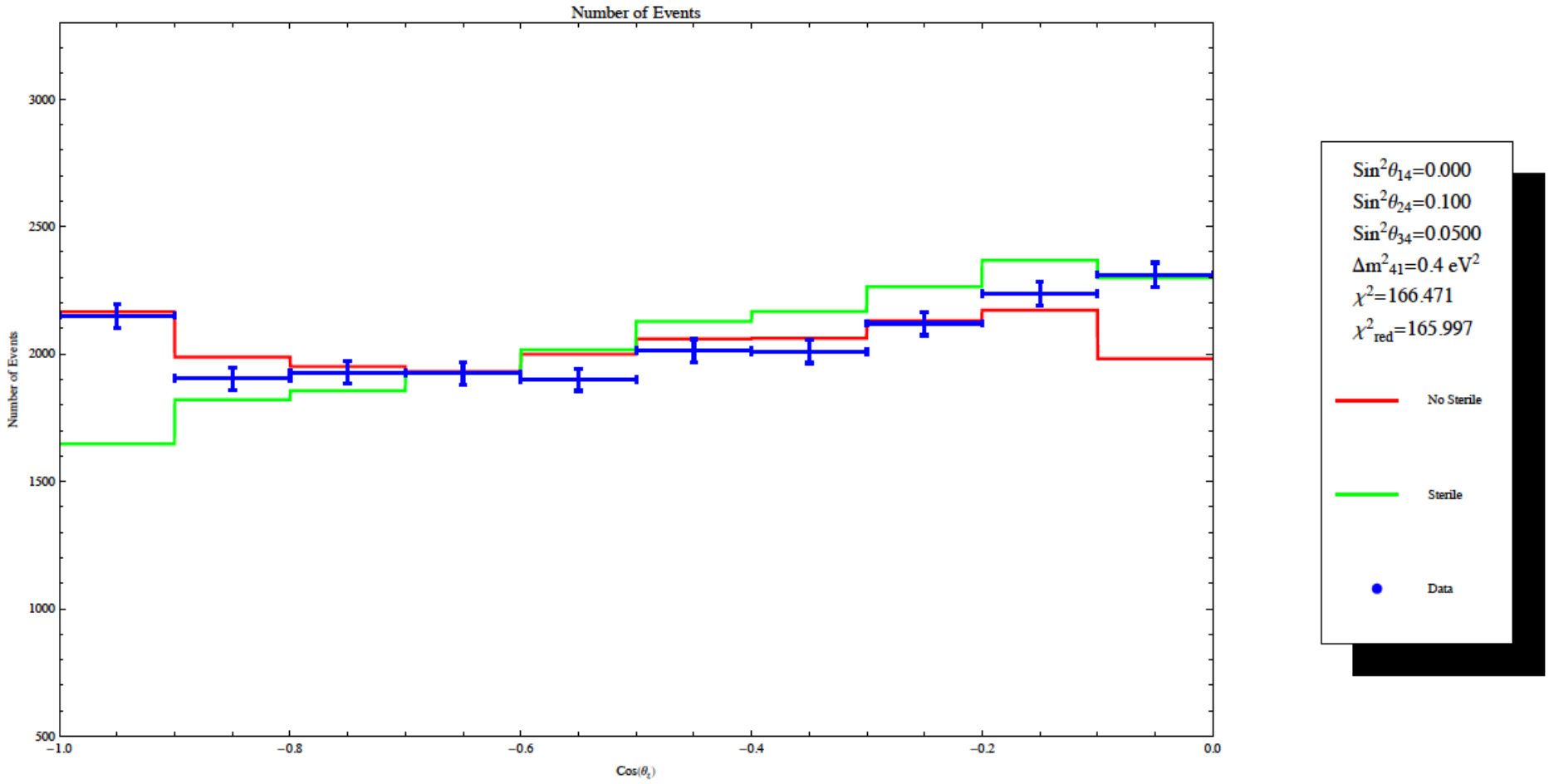
~ 2000 events per bin

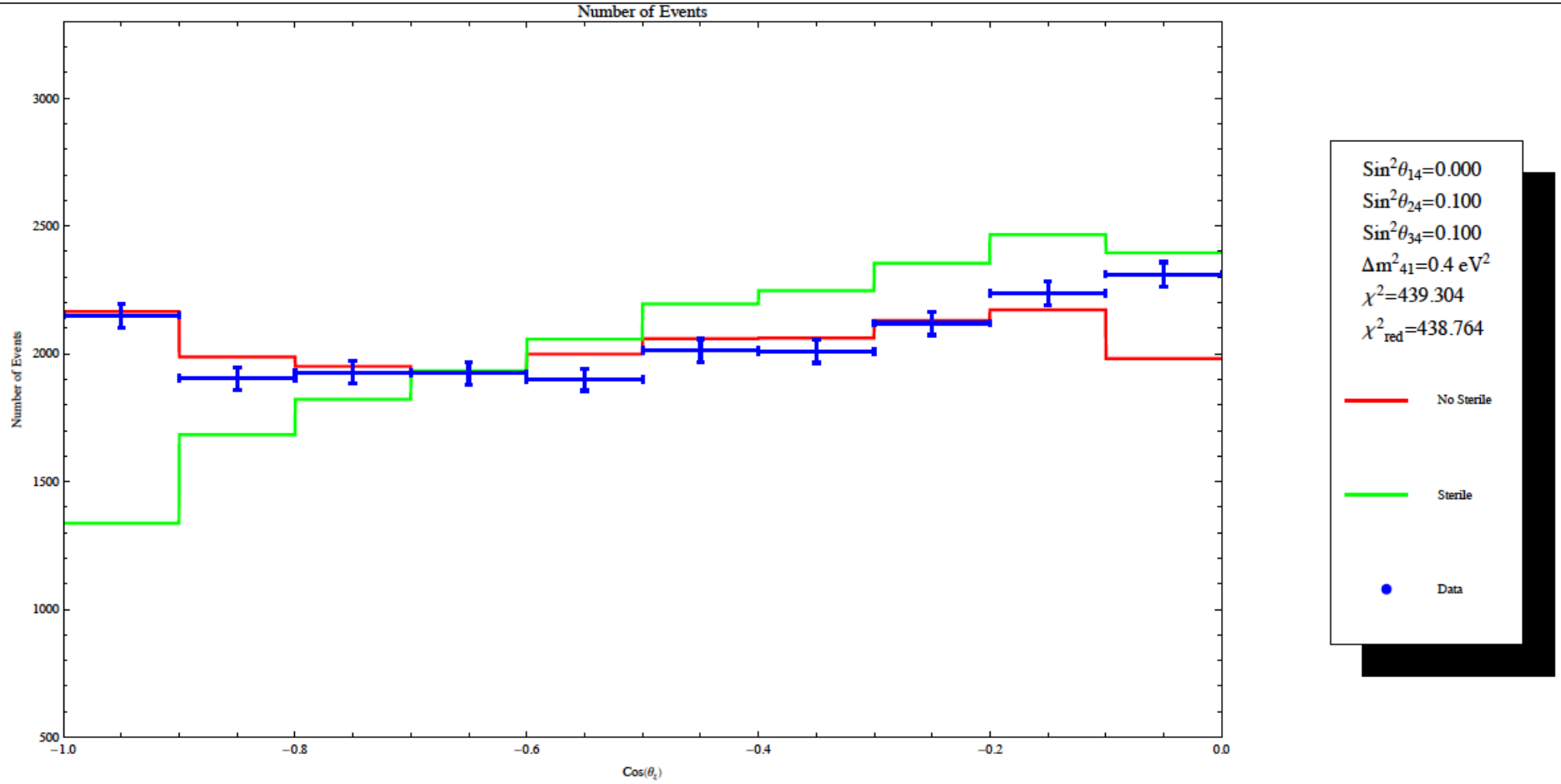
number of nu-mu events versus cosθ in IceCube 40

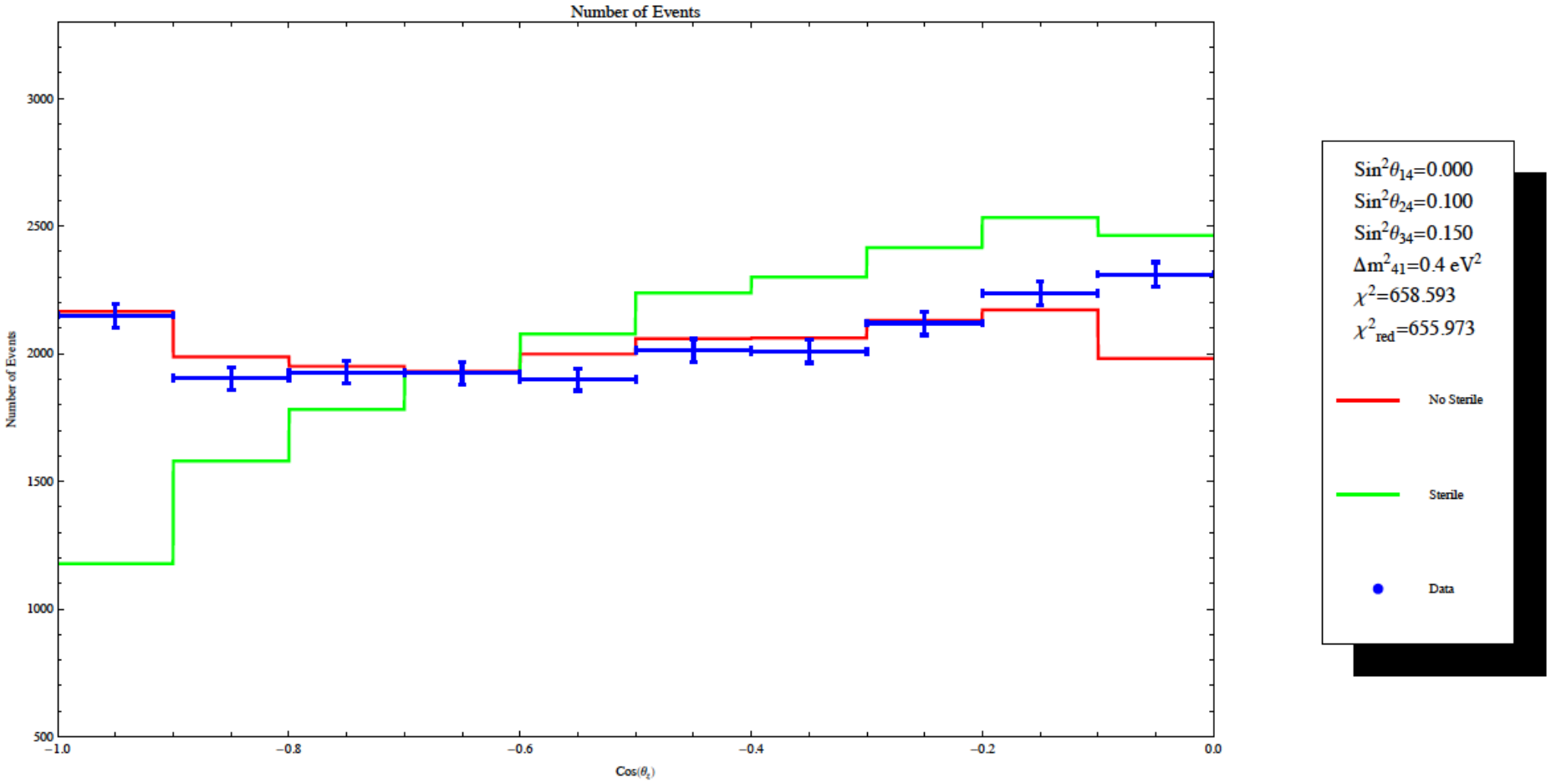


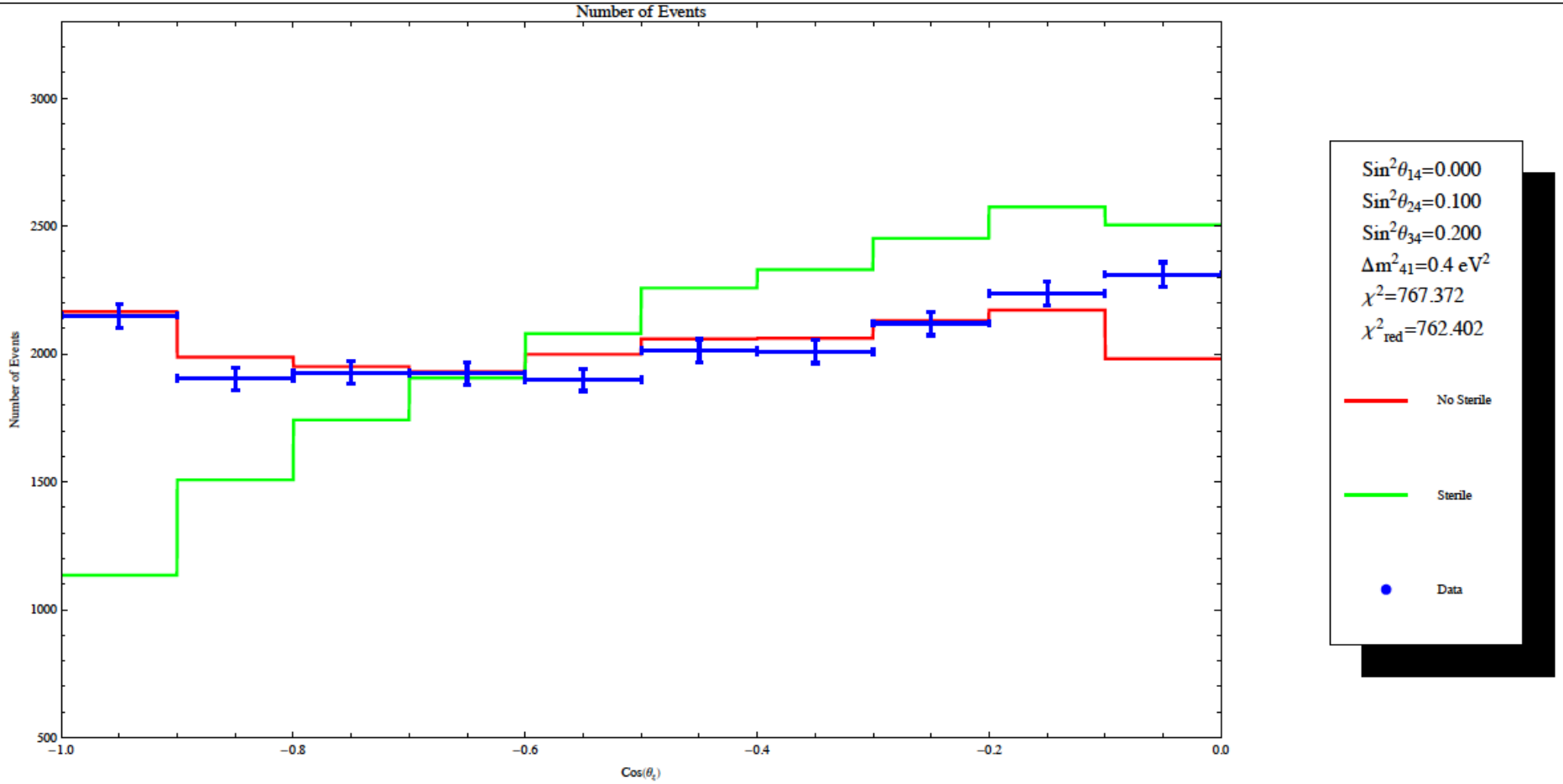
$\Delta m^2 = 0.4\ eV^2$ and $\sin^2\theta_{34} = 0 \rightarrow 0.5$

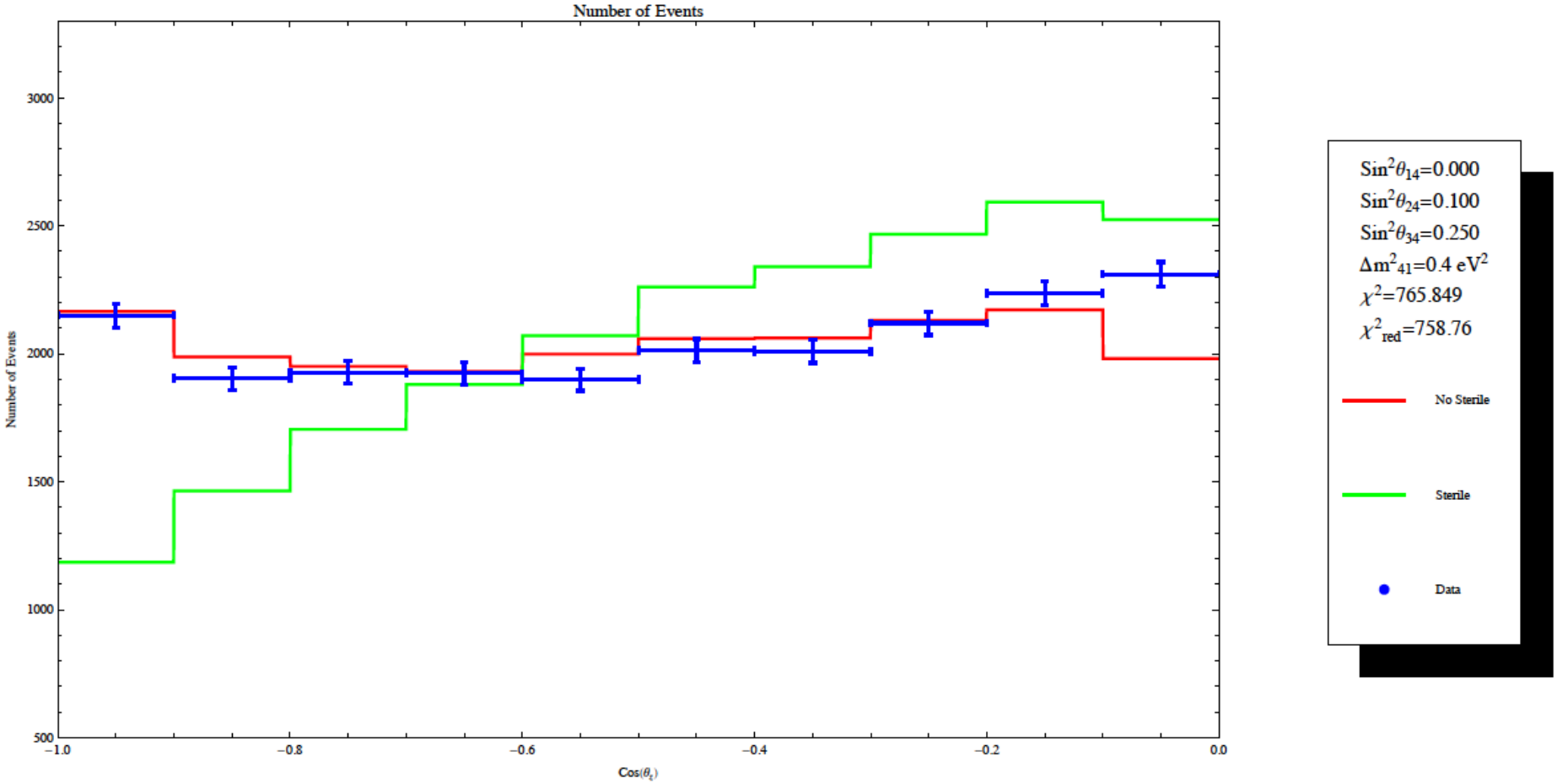
Arman Esmaili

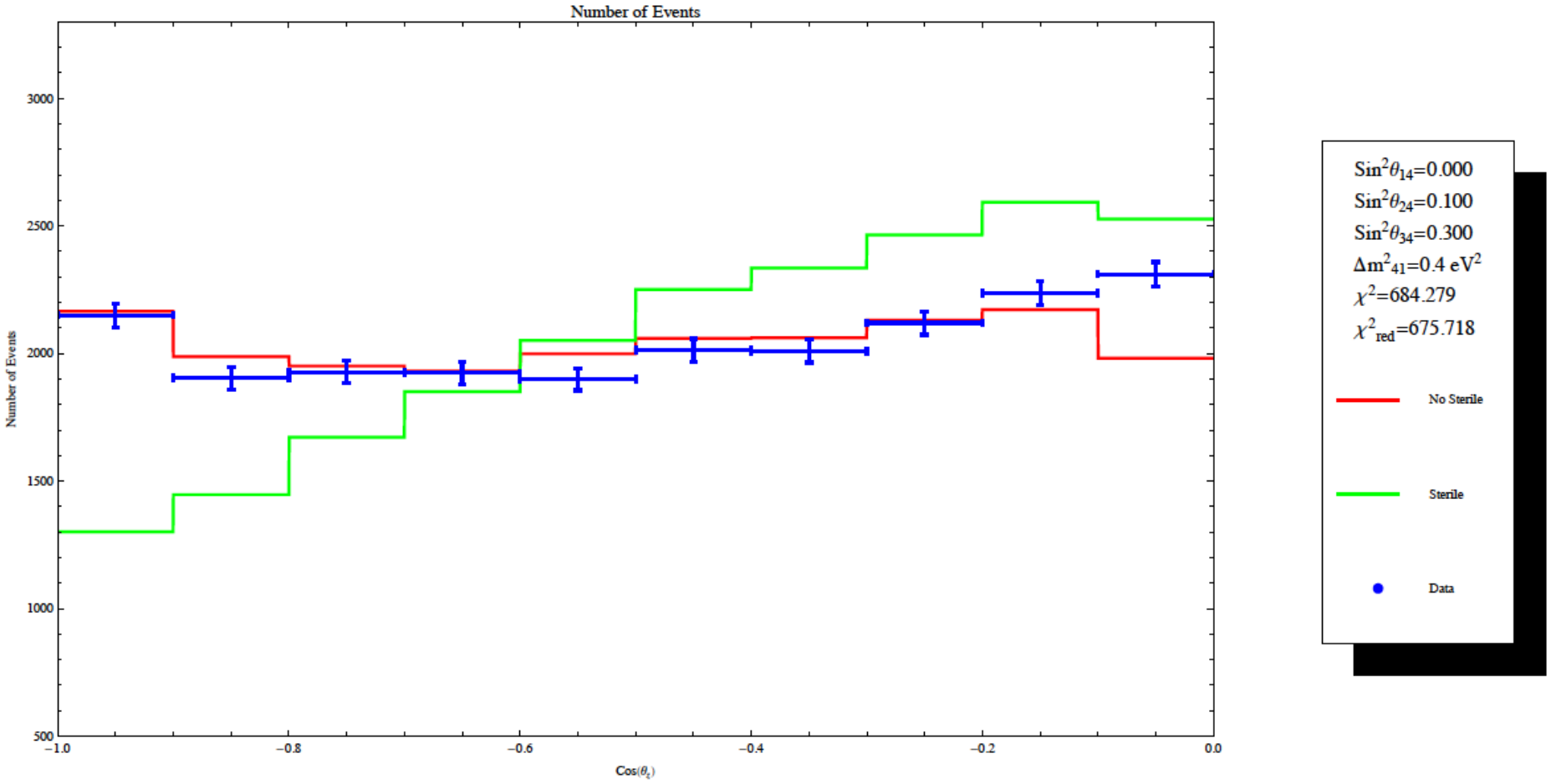

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.0500
Δm²41=0.4 eV²
χ²=166.471
χ²red=165.997
No Sterile
Sterile
Data

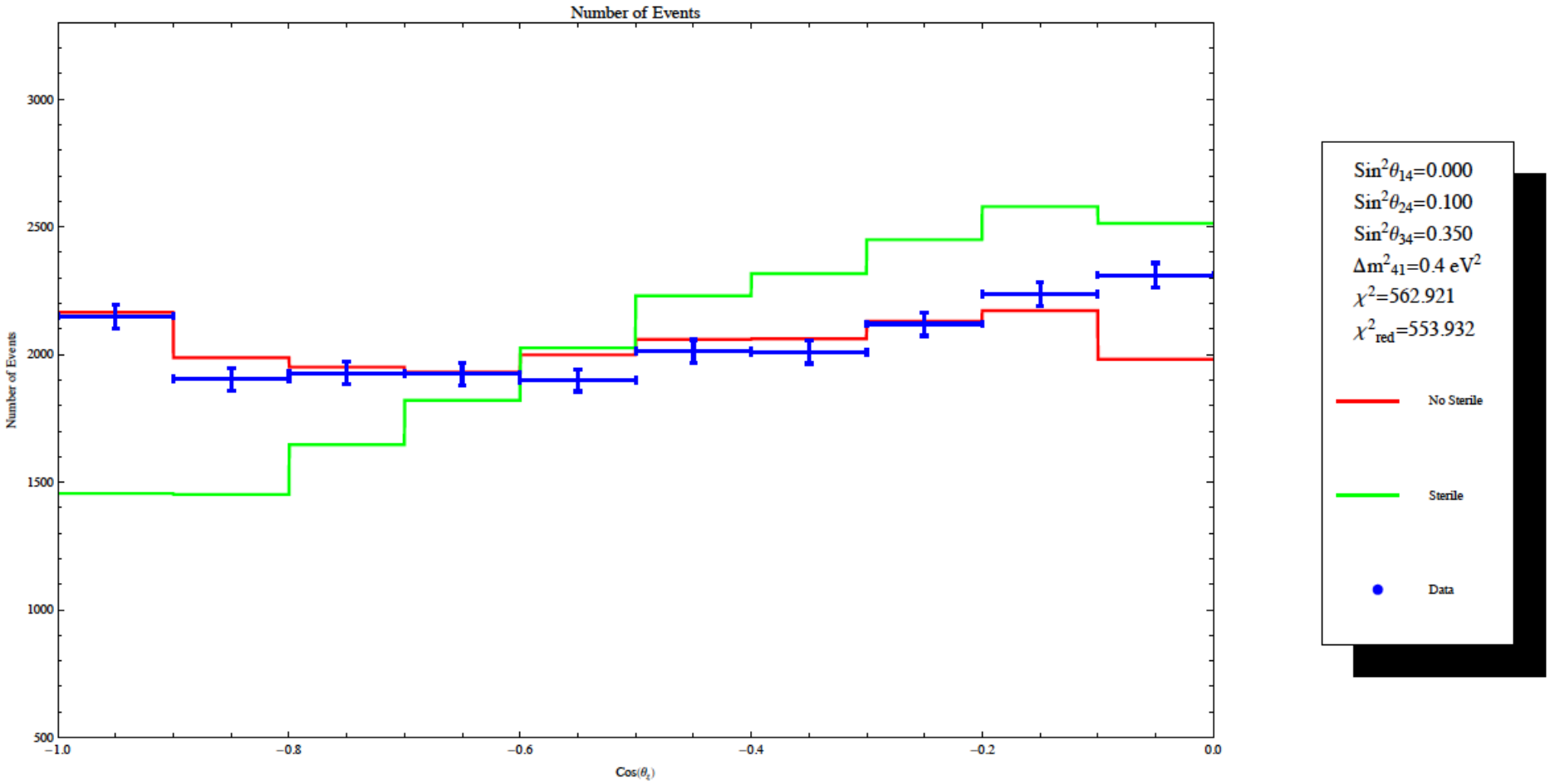

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.100
Δm²41=0.4 eV²
χ²=439.304
χ²red=438.764
No Sterile
Sterile
Data

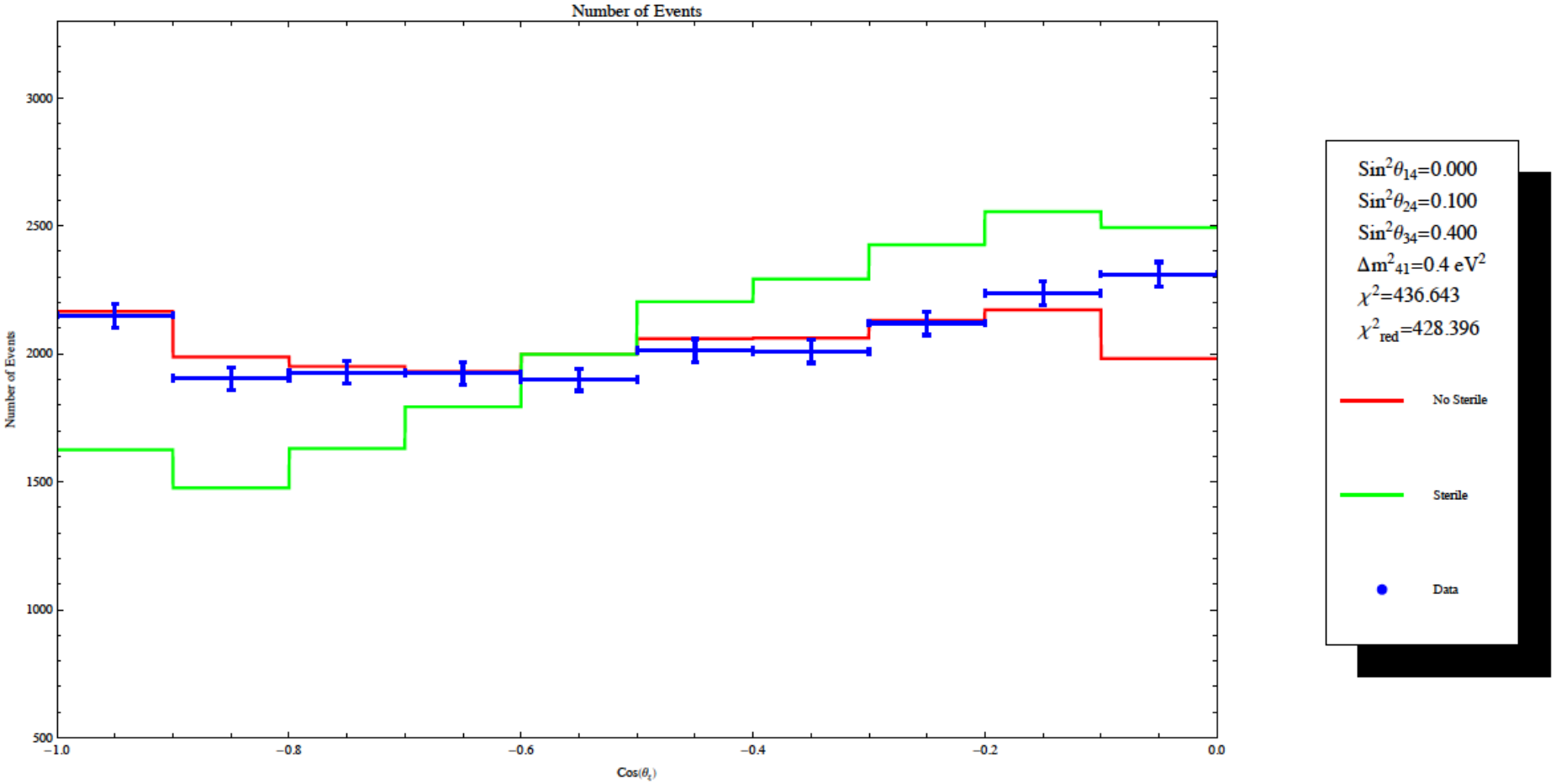

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.150
Δm²41=0.4 eV²
χ²=658.593
χ²red=655.973
No Sterile
Sterile
Data

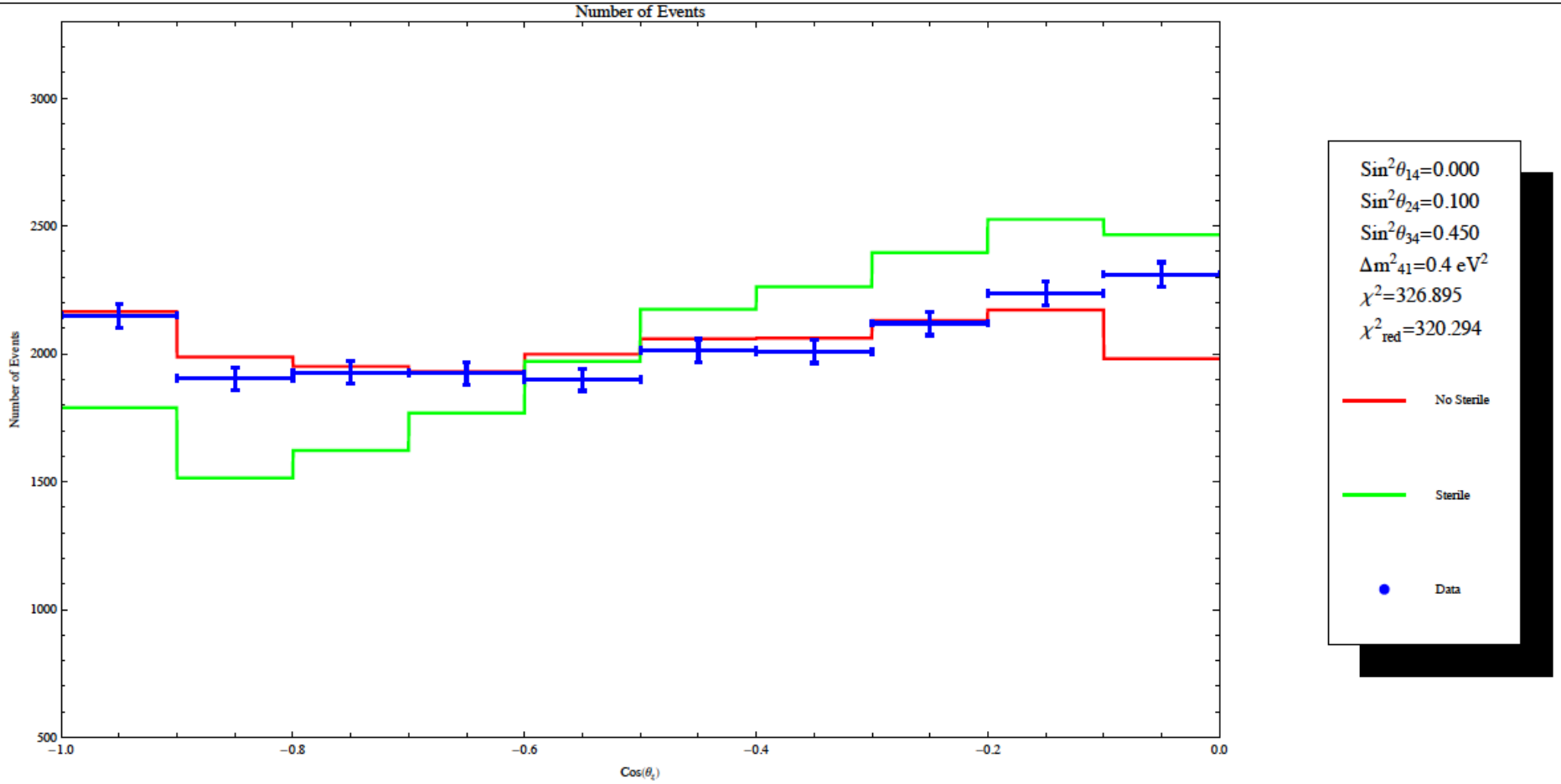

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_ℓ)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.200
Δm²41=0.4 eV²
χ²=767.372
χ²red=762.402
No Sterile
Sterile
Data

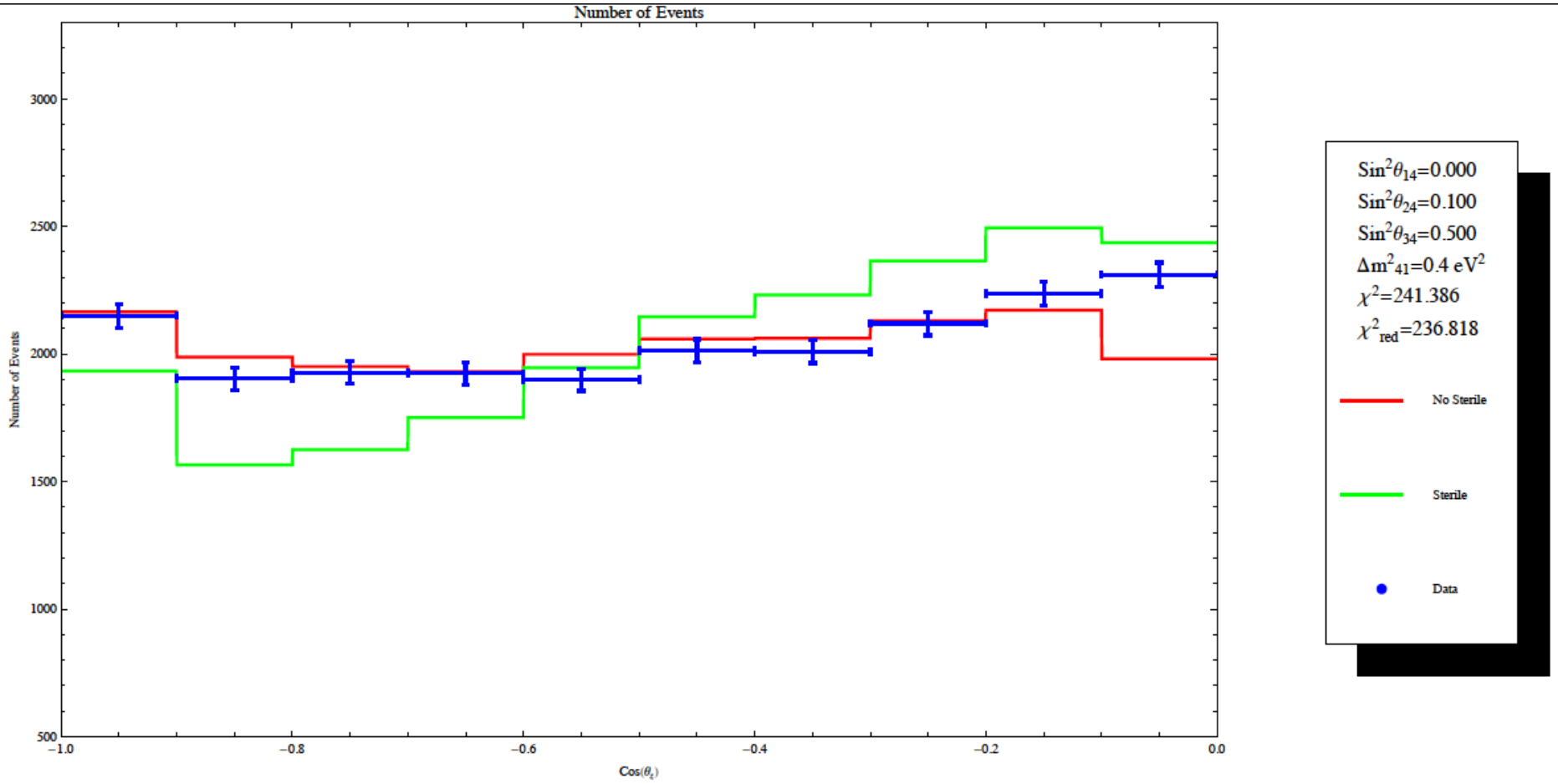

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.250
Δm²41=0.4 eV²
χ²=765.849
χ²red=758.76
No Sterile
Sterile
Data

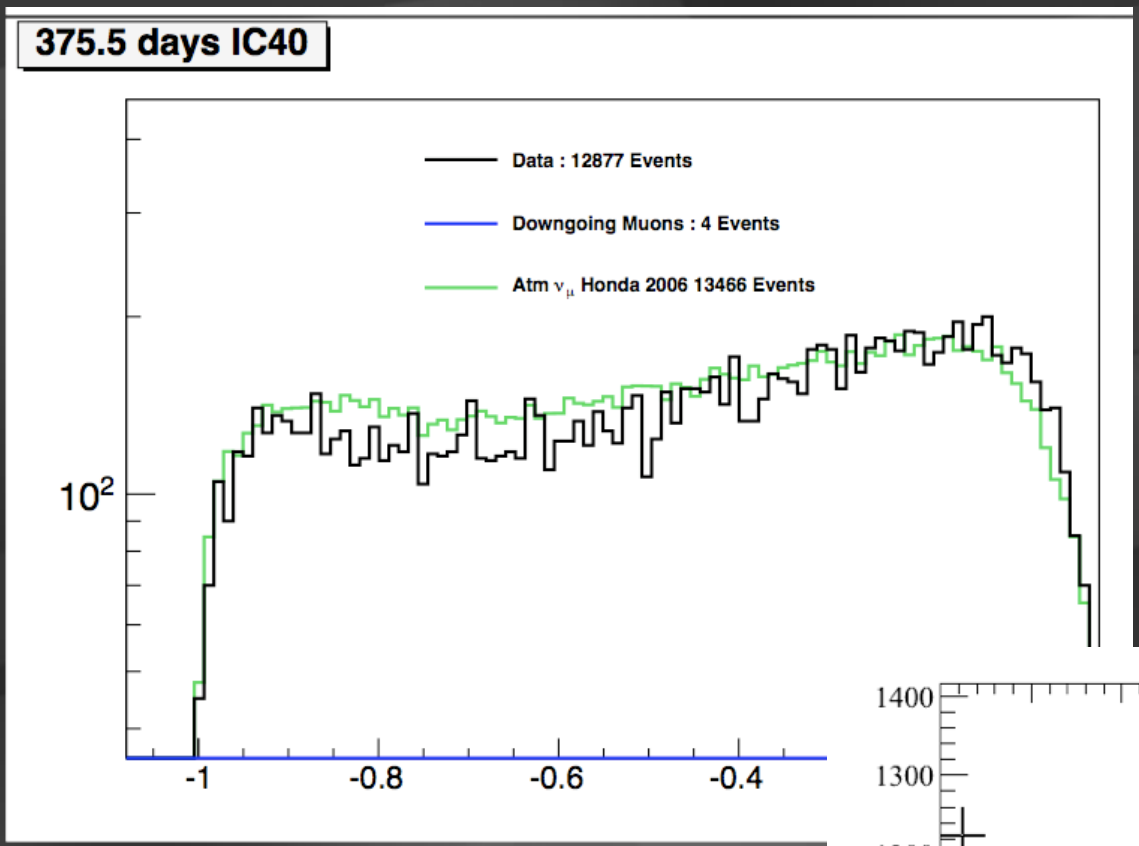

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.300
Δm²41=0.4 eV²
χ²=684.279
χ²red=675.718
No Sterile
Sterile
Data


Number of Events
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=0.350
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

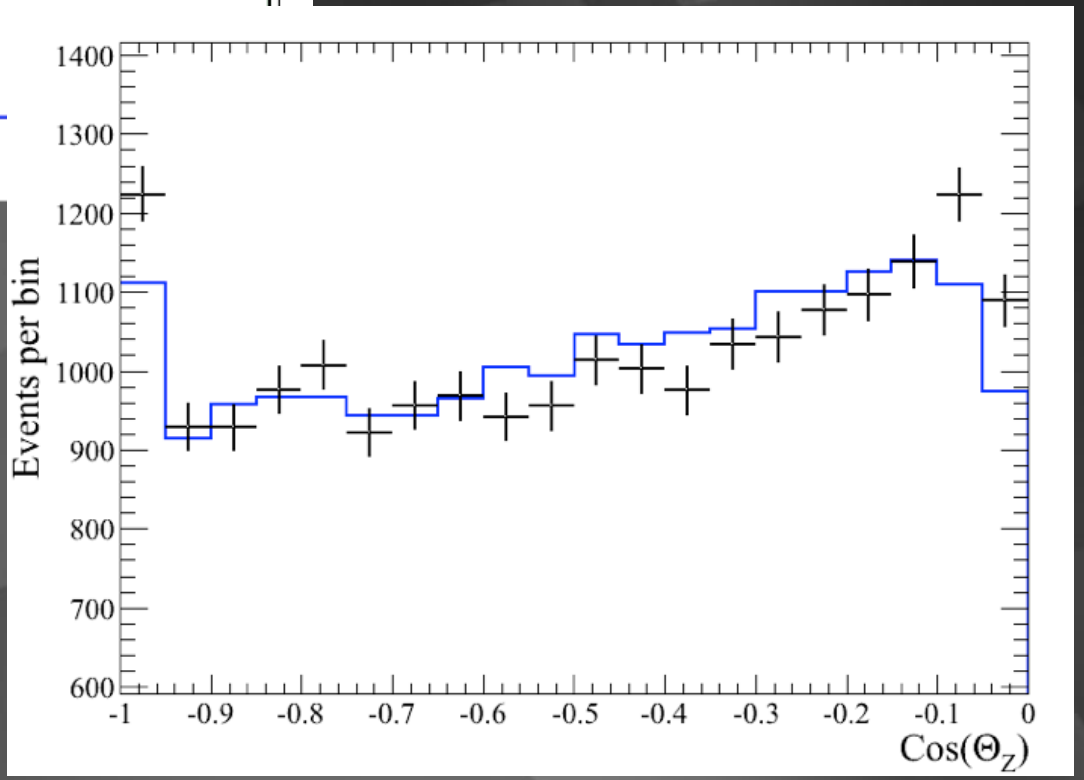

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.450
Δm²41=0.4 eV²
χ²=326.895
χ²red=320.294
No Sterile
Sterile
Data

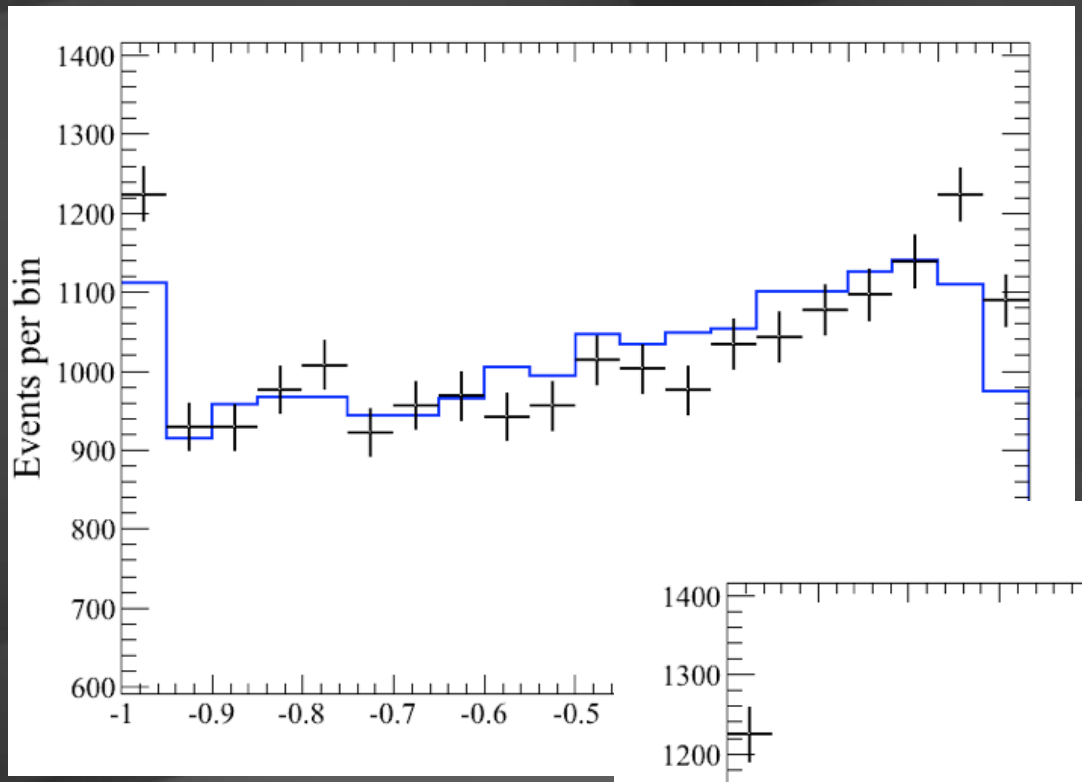

Number of Events
3000
2500
2000
1500
1000
500
Number of Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.500
Δm²41=0.4 eV²
χ²=241.386
χ²red=236.818
No Sterile
Sterile
Data



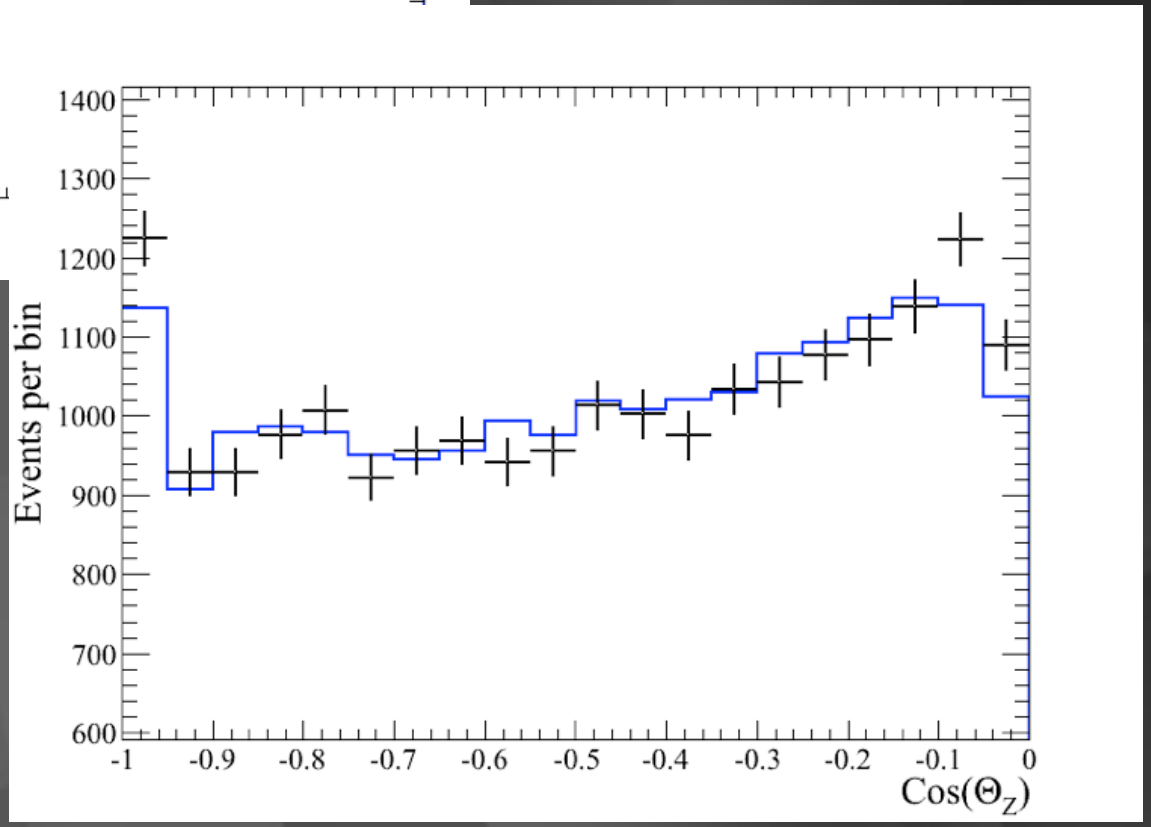
zenith angle
two analyses

matter effect
of eV sterile ν's ?





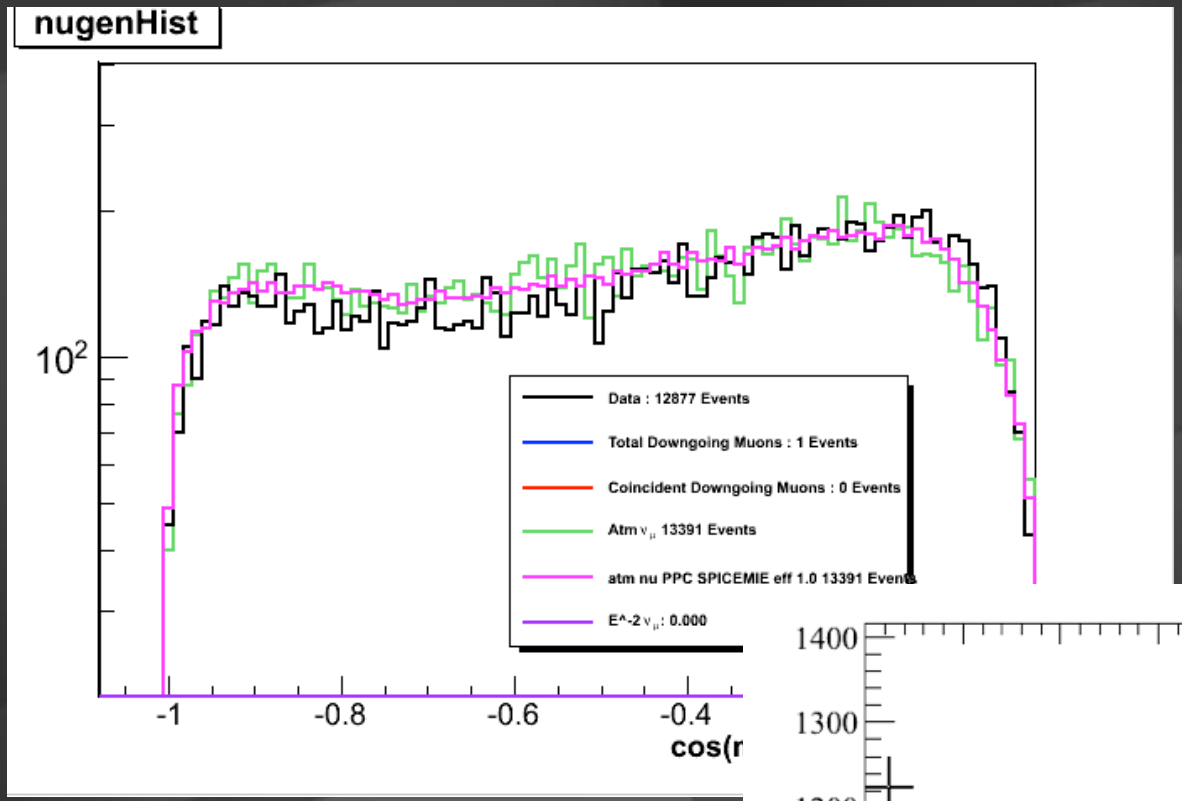
3



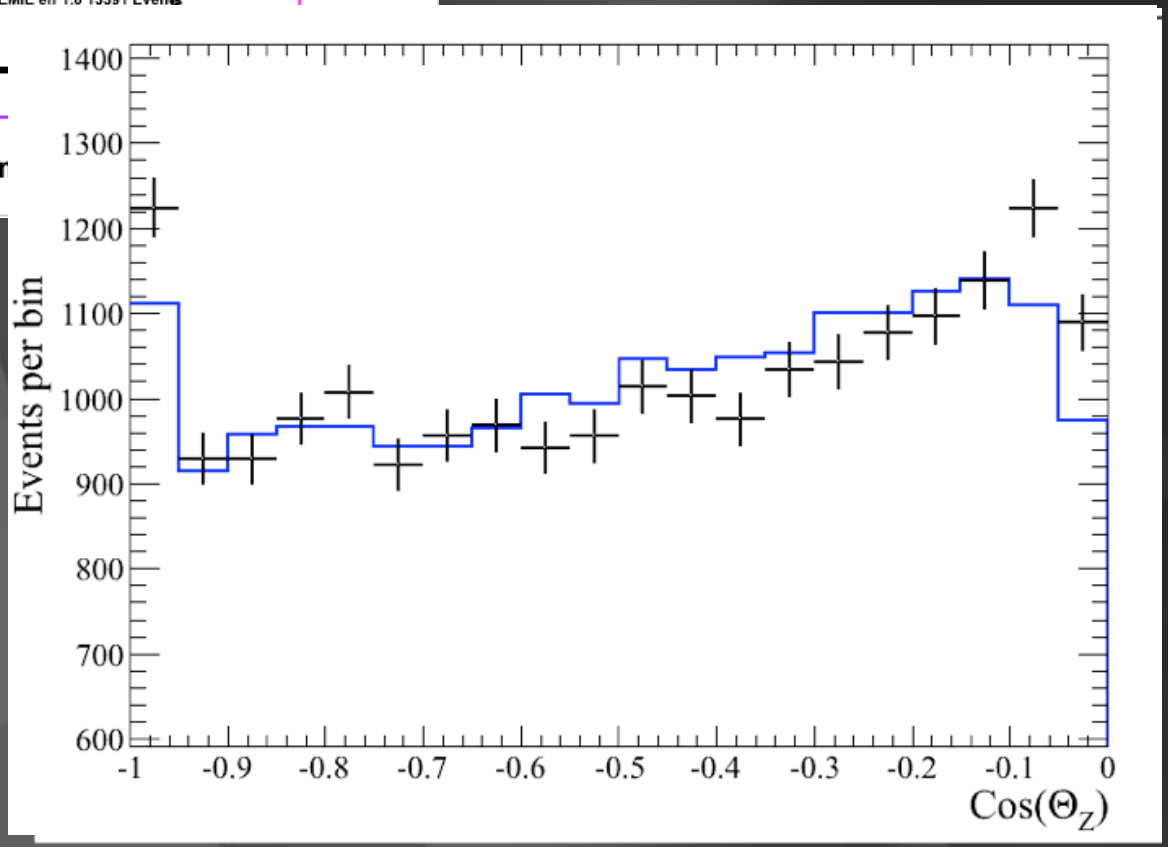
3+1

matter effect
of eV sterile ν's ?

do not try this at home



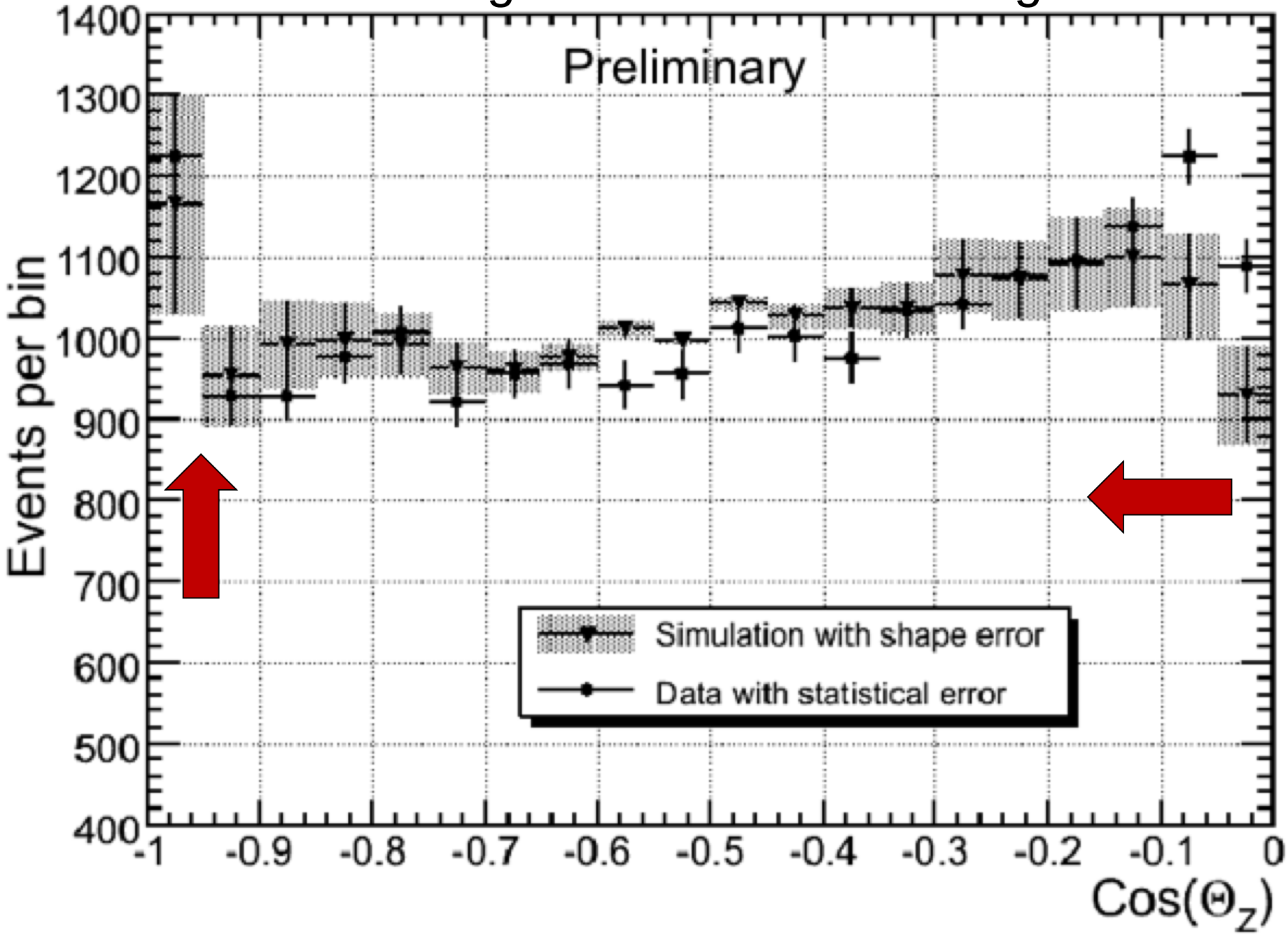
zenith angle
two analyses

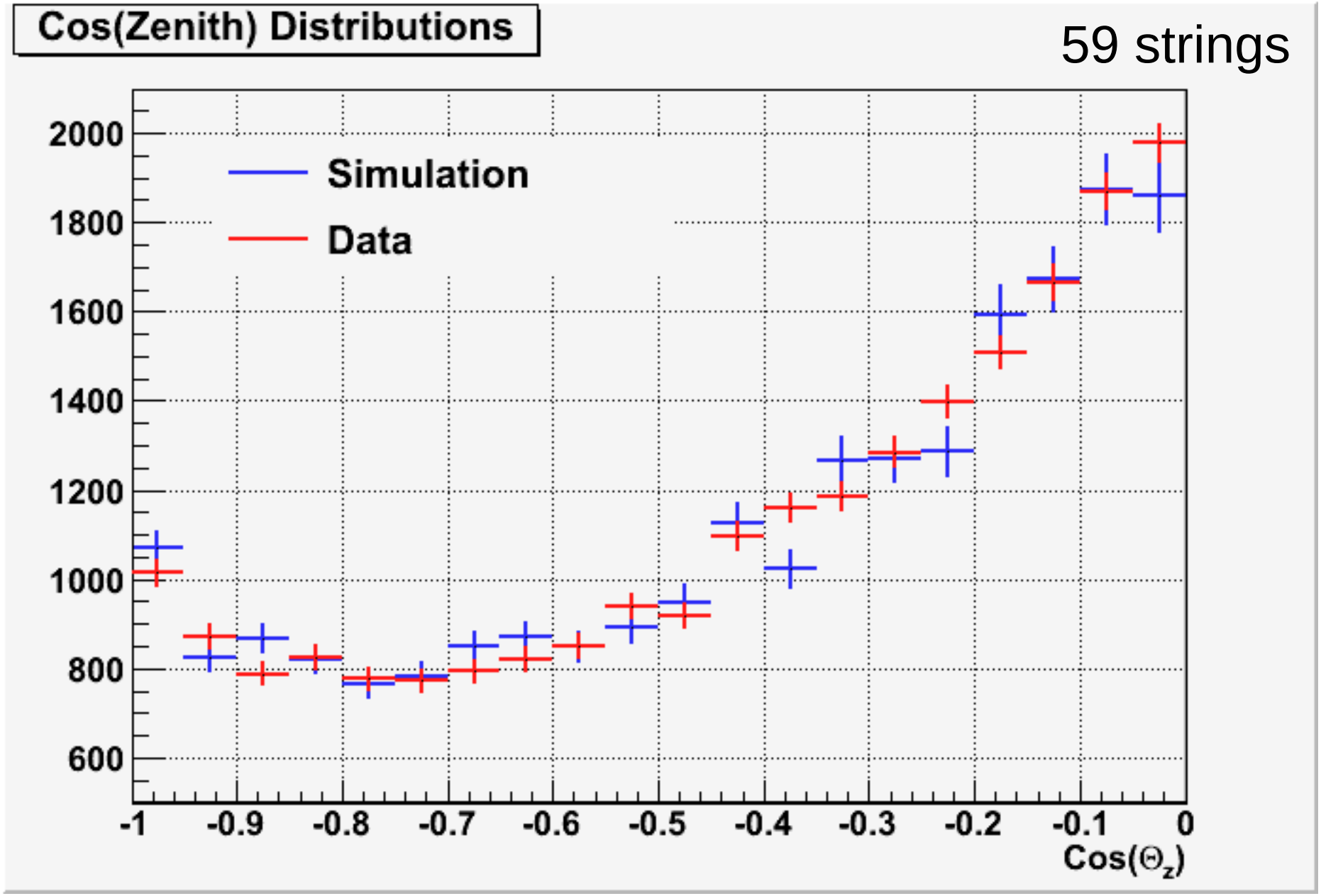


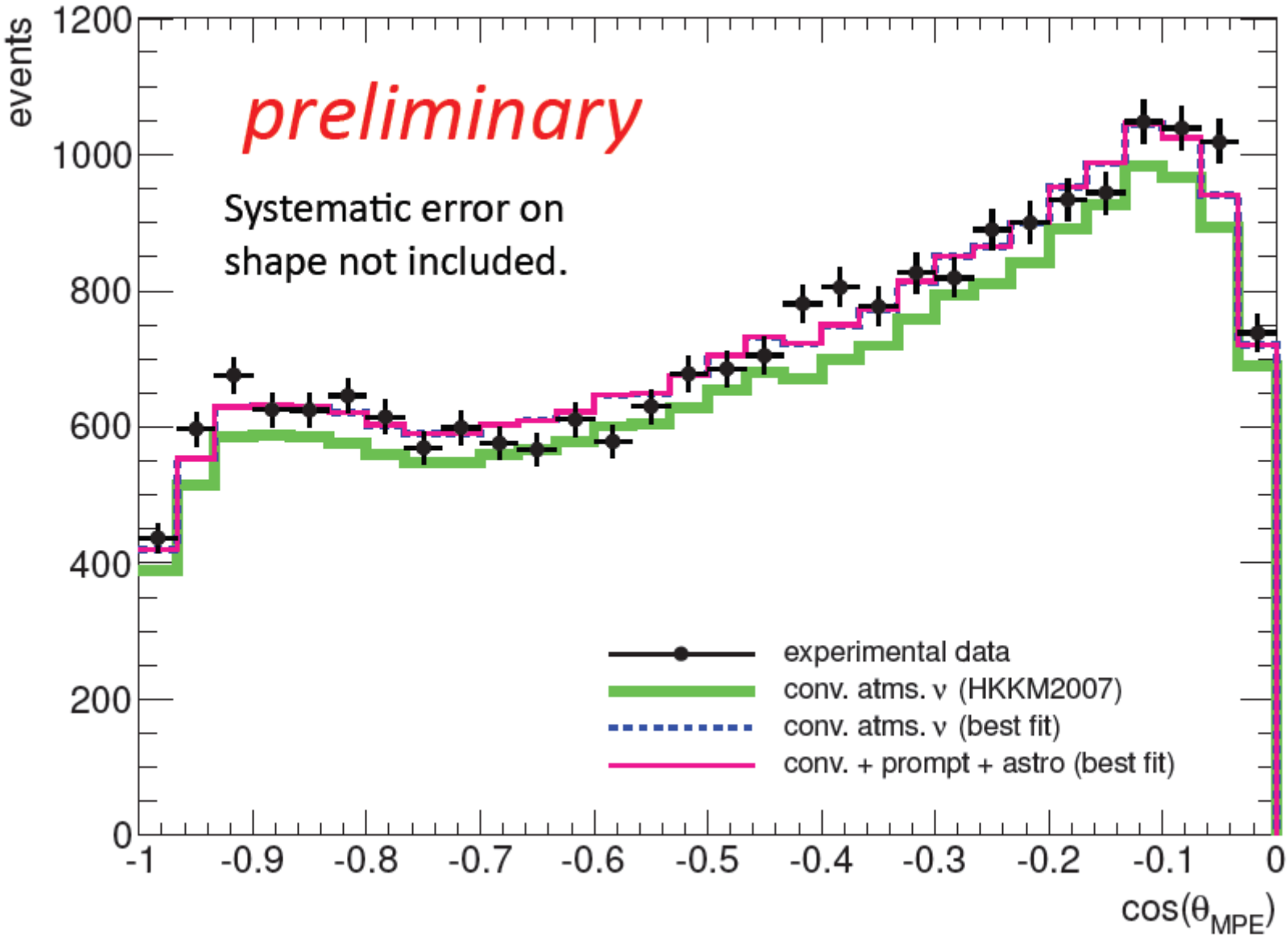
SYSTEMATICS !!!

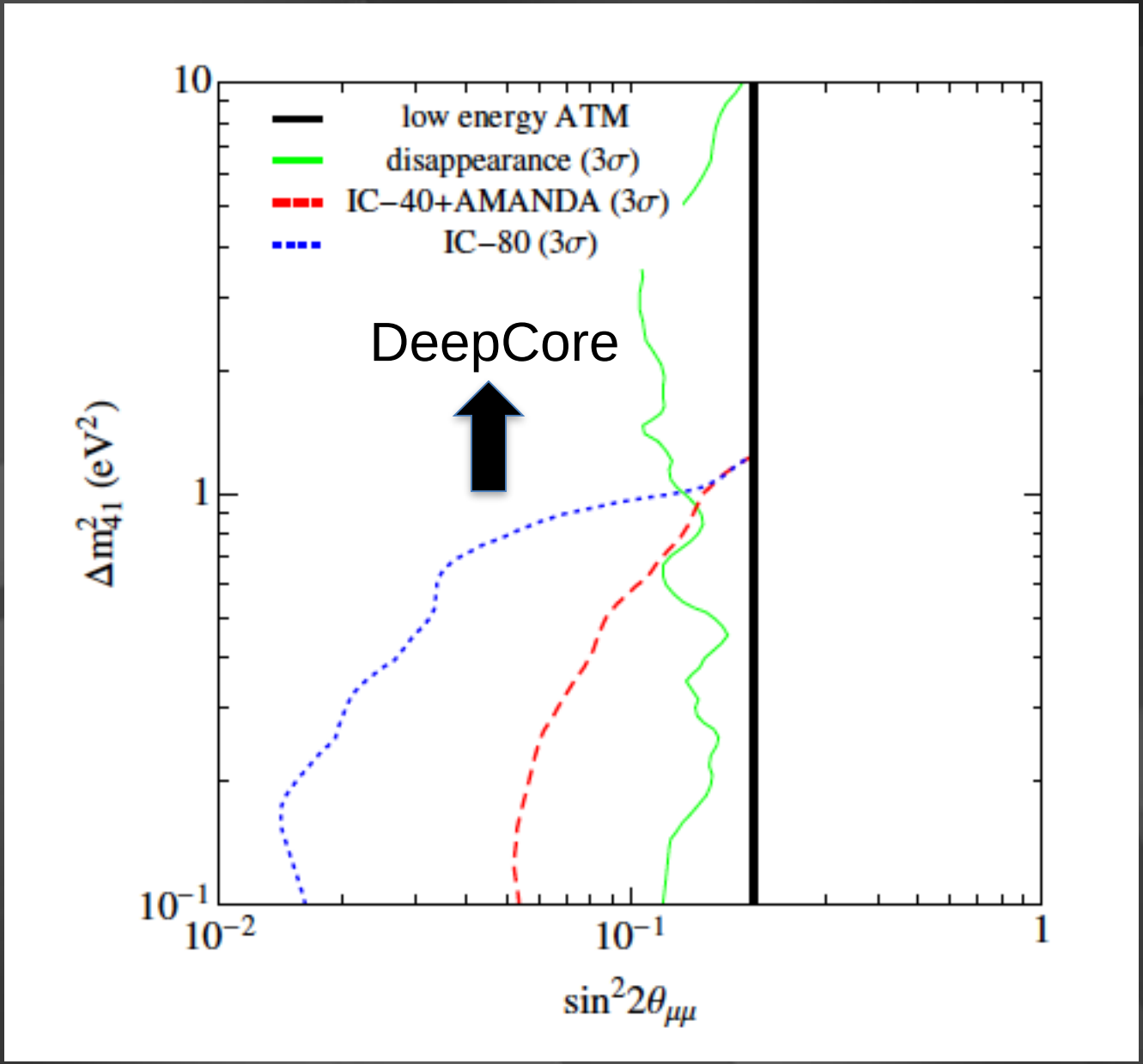
- K/π ratio
- zenith acceptance of modules
- ice
- CR flux,composition [IceTop helps]

zenith angle distribution 40-string data

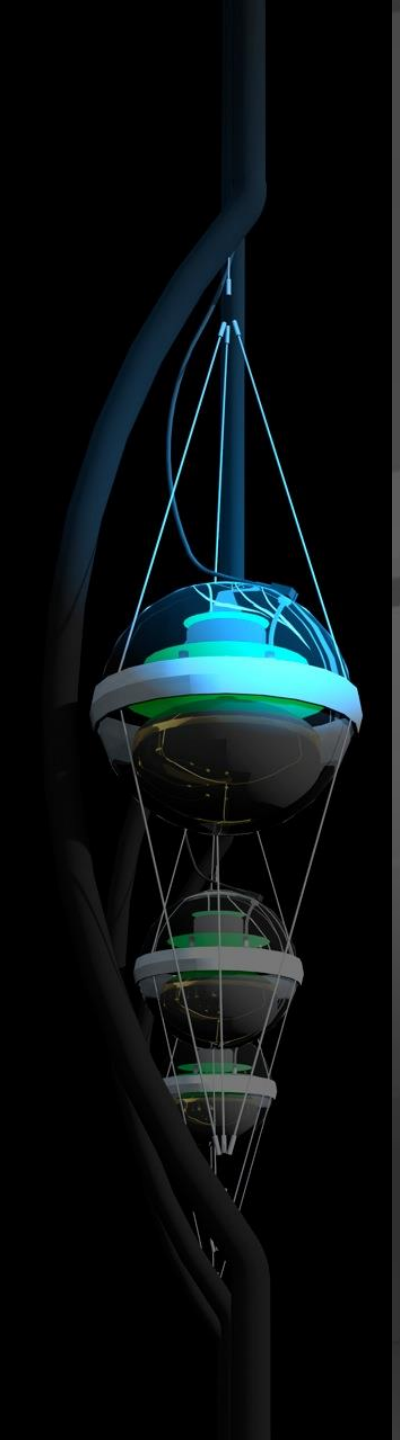



Cos(Zenith) Distributions
59 strings
Simulation
Data
2000
1800
1600
1400
1200
1000
800
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cos(Θz)


preliminary
Systematic error on
shape not included.
events
1200
1000
800
600
400
200
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
cos(θMPE)
experimental data
conv. atms. ν (HKKM2007)
conv. atms. ν (best fit)
conv. + prompt + astro (best fit)



Esmaili et al., 1206.6903

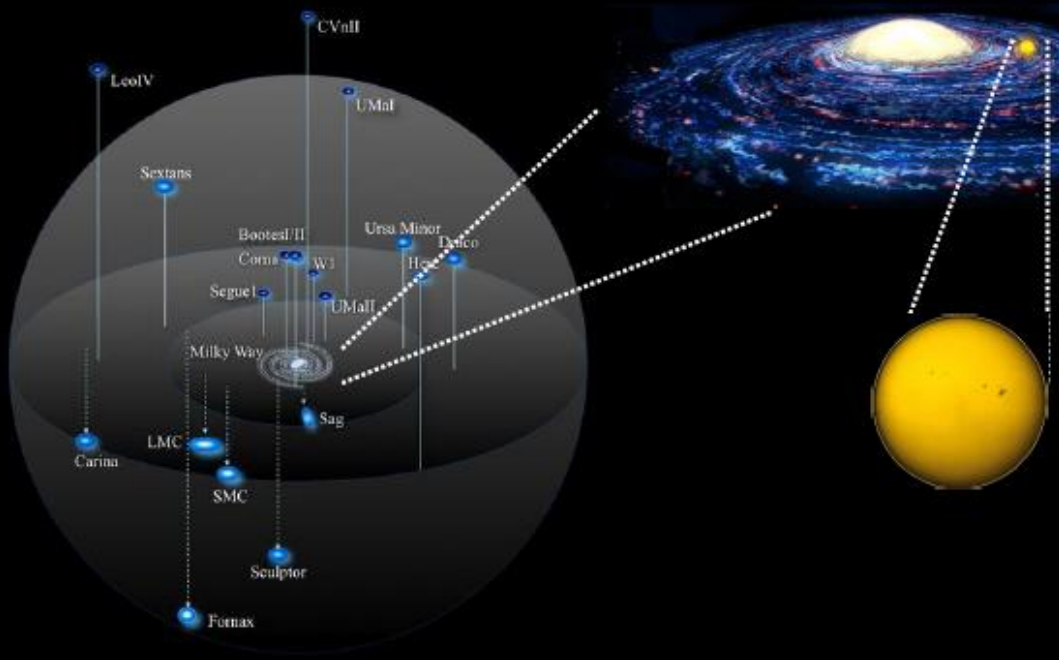


IceCube: beyond neutrino astronomy

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

Indirect Search with IceCube

Look for potential sources that are well defined and have low or understood astrophysical backgrounds



Galactic Center & Halo:
Limits from IceCube-22
Galactic Center:
Limits from IceCube-40

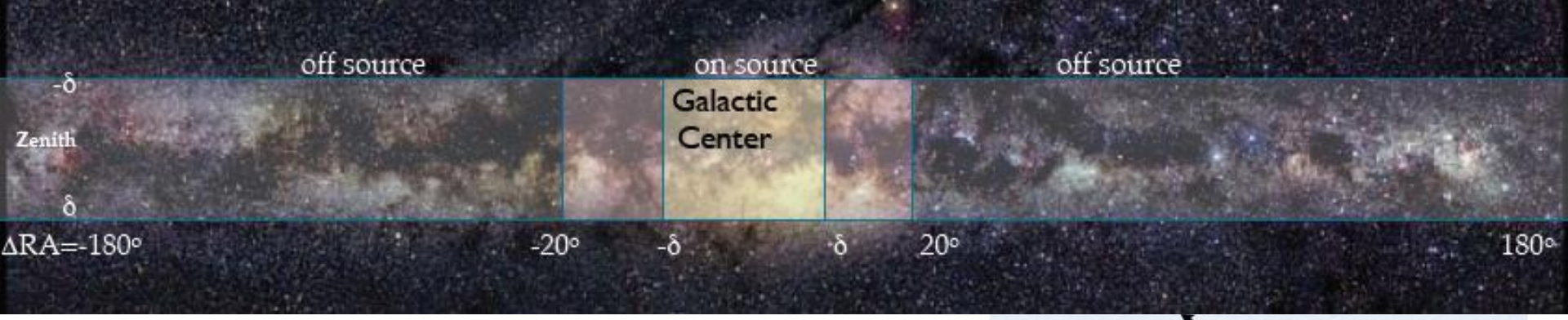
Local sources:

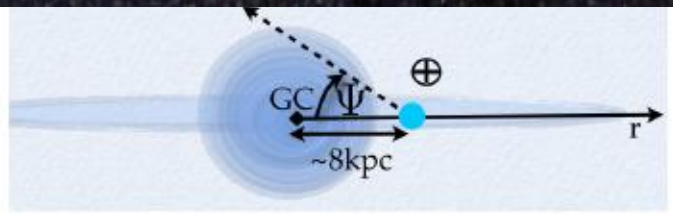
Sun:
Combined Limits form AMANDA, IC22, IC40+AMANDA
→ IceCube-79 final sensitivity *new

Searches beyond "standard" SUSY:
→ secluded dark matter sector *new

Earth:
Limits from AMANDA
(new analysis with IceCube-86 ongoing)

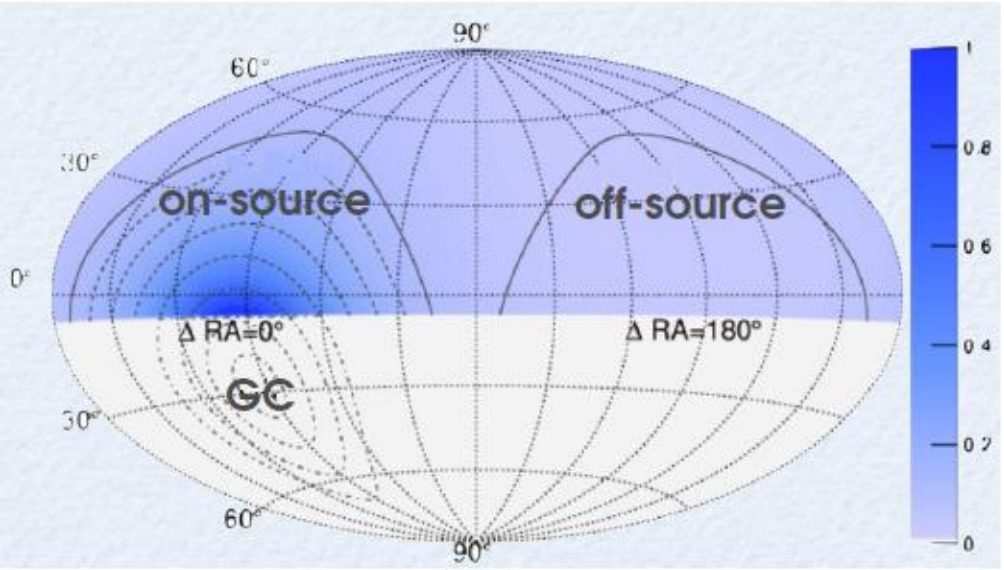
Dwarf spheroidal Galaxies:
→ IceCube-59 limits *new
Clusters of Galaxies:
→ IceCube-59 limits *new





Galactic Center:

- ✗ on-source region below the horizon
- ✗ need to veto downgoing muons.
- ✗ Use central strings of detector as fiducial volume, surrounding layers as veto.



IC22 (Halo analysis – 275 days):
observed on-source: **1367** evts
observed off-source: **1389** evts
Event selection dominated by atm. **ν**

IC40 (G-Center analysis – 367 days):
observed on-source: **798842** evts
predicted from off-source: **798819** evts
Event selection dominated by atm. **μ**

Observations in both analyses were consistent with background-only expectations

Galactic & galaxy cluster limits

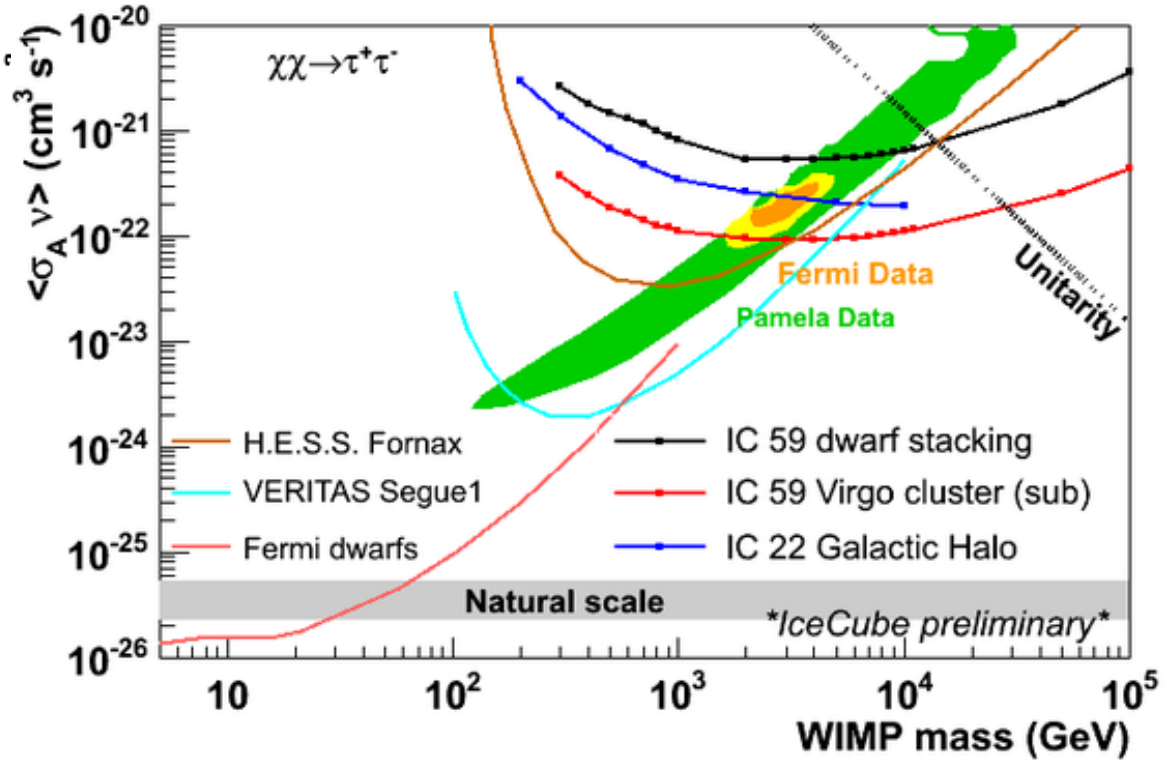
Limits computed at **90% C.L.** as function of WIMP mass and for various annihilation channels assuming branching fractions of 100%

Dwarf galaxies:

- Source stacking analysis
- Optimized size of search window
- NFW profile assumed

Galaxy clusters:

- Extended point source search
- Optimized size of search window
- Substructures taken into account



multi-wavelength approach to dark matter searches:
IceCube can test DM models motivated by PAMELA & Fermi data (e.g. Meade et al. 2008)

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

$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$
$$b + b \rightarrow \nu + \nu$$

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

- $\phi_\chi = \left[\frac{\rho}{m_\chi}\right] v_\chi$
- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_\chi$
- $C_{sun} = 2\, C_{annihilation}$

given a cross section and a branching ratio into neutrinos the model is seen or ruled out

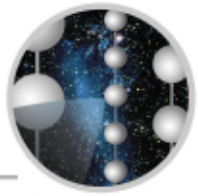
indirect dark matter detection

- 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.

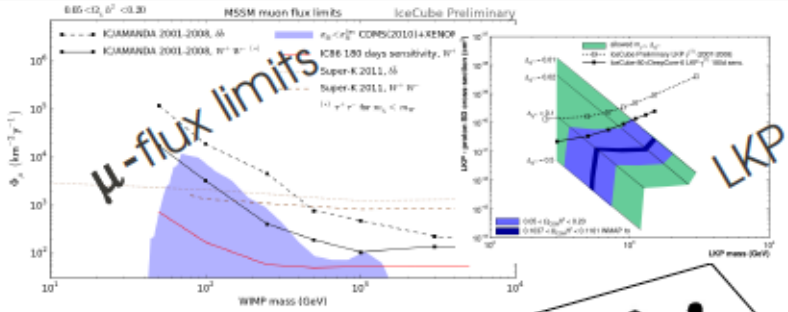
PRD 85, 042002 (2012)

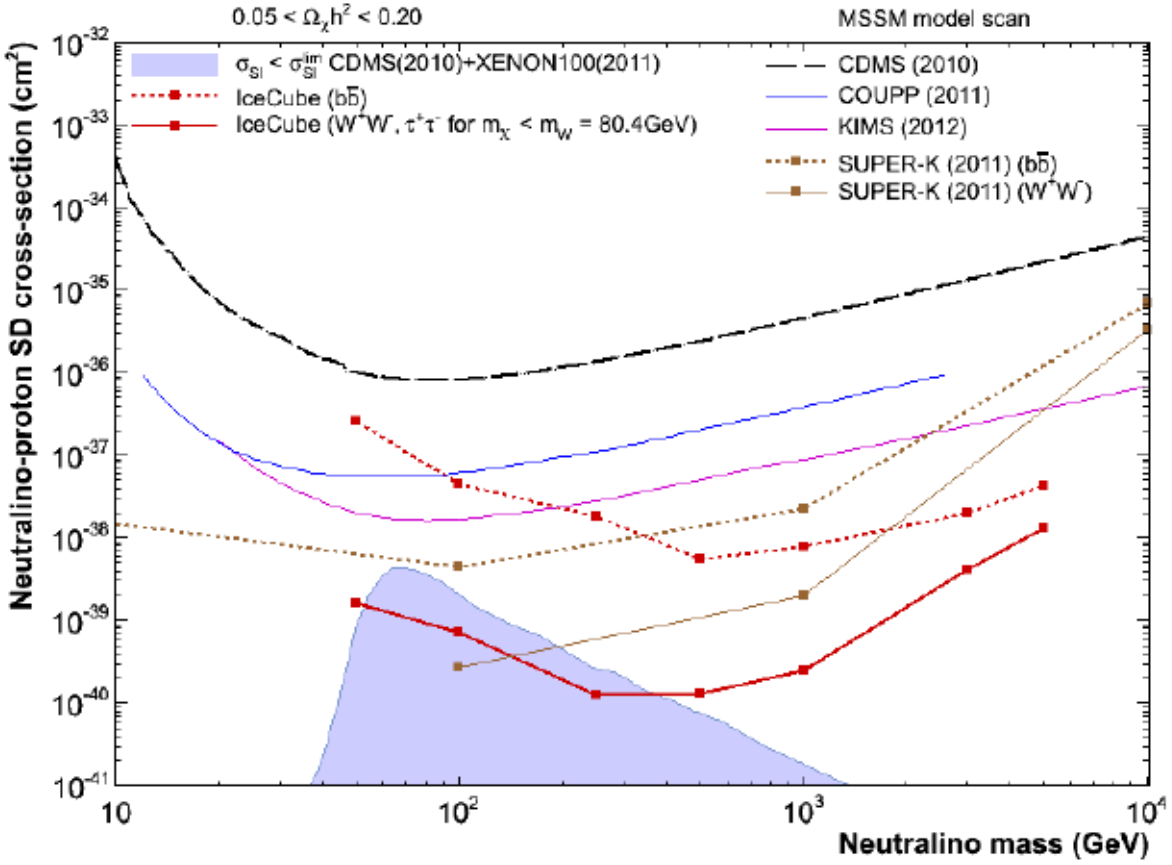
Analysis Results from the Sun

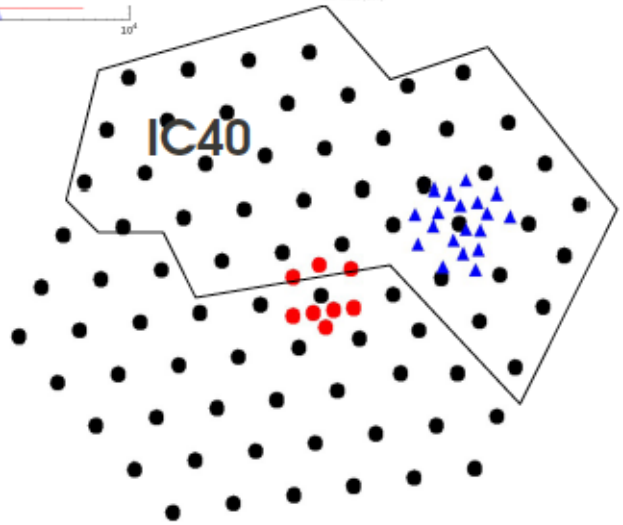


More details on limits

Abbasi et al., ***PRL*. 102**, 201302 (2009) (IC22)
Abbasi et al., ***PRD* 81,** 057101 (2010) (IC22)
Abbasi et al., ***PRD* 85**, 042002 (2012) (IC40+AMANDA)







Combined multi-year limit from AMANDA, IceCube-22 and IceCube-40+AMANDA data
Total livetime of 1065 days

IceCube 79 string analysis

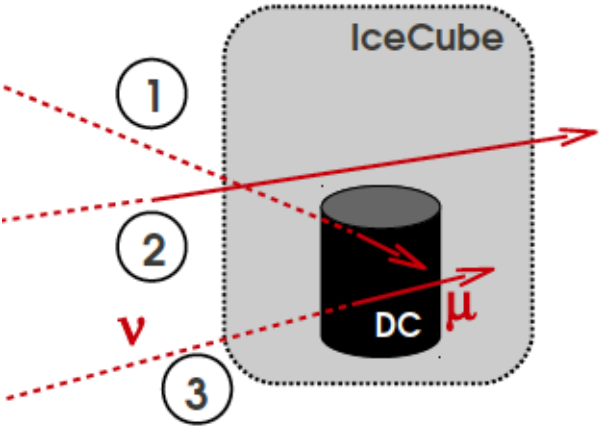
Solar WIMP analysis with 79 strings *(sensitivity)*

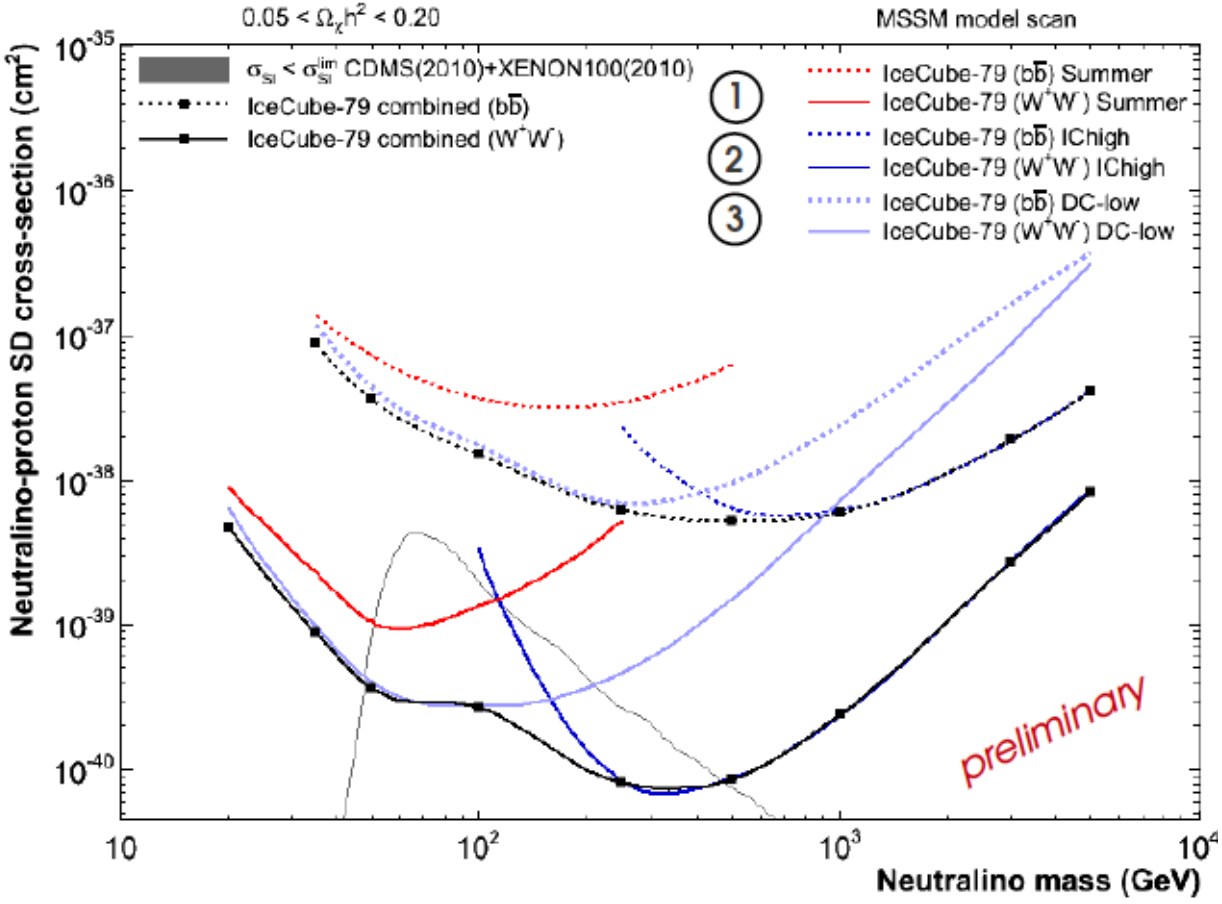
- Incl. DeepCore
- Performed separately for austral winter & summer (152d +167d livetime)
- Low energies (look for contained or partially contained events)

Analysis performed separately for;
austral summer (Sun above horizon)

&

austral winter (Sun below horizon)





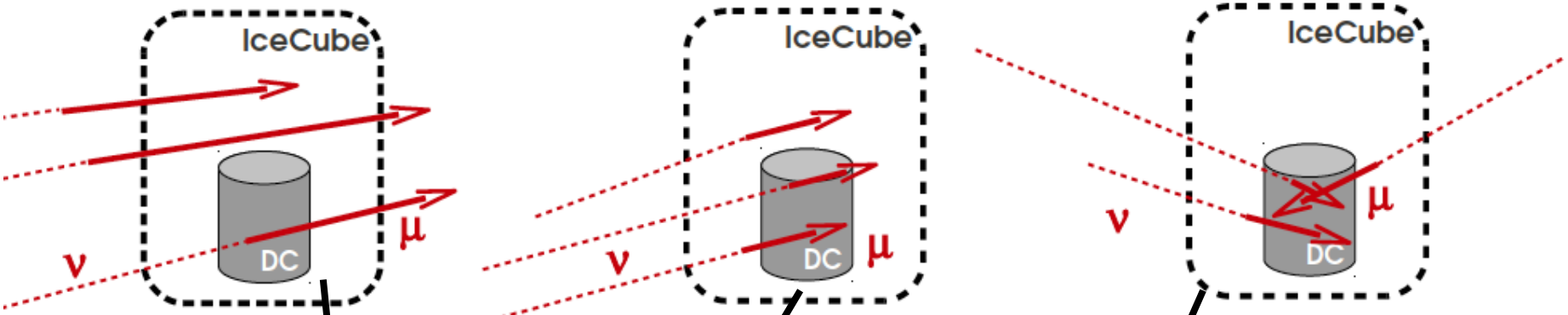
IceCube 79 data

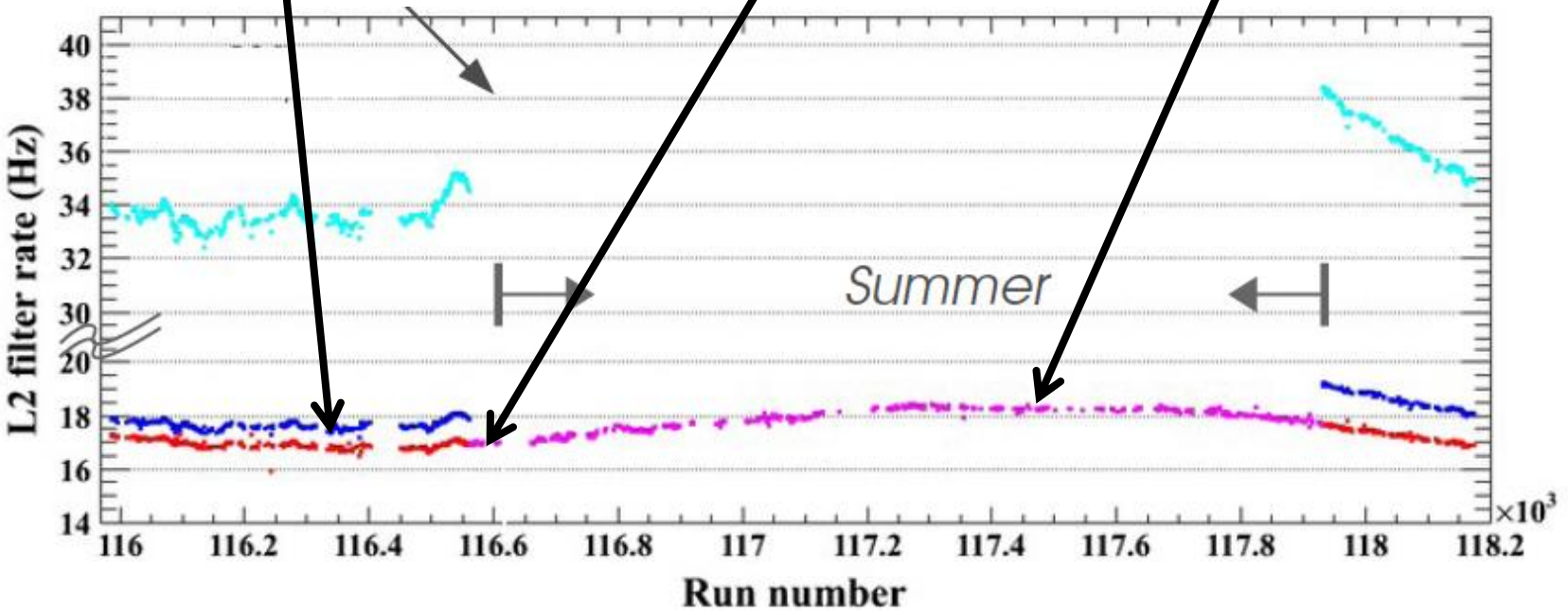
starting events → lower energy

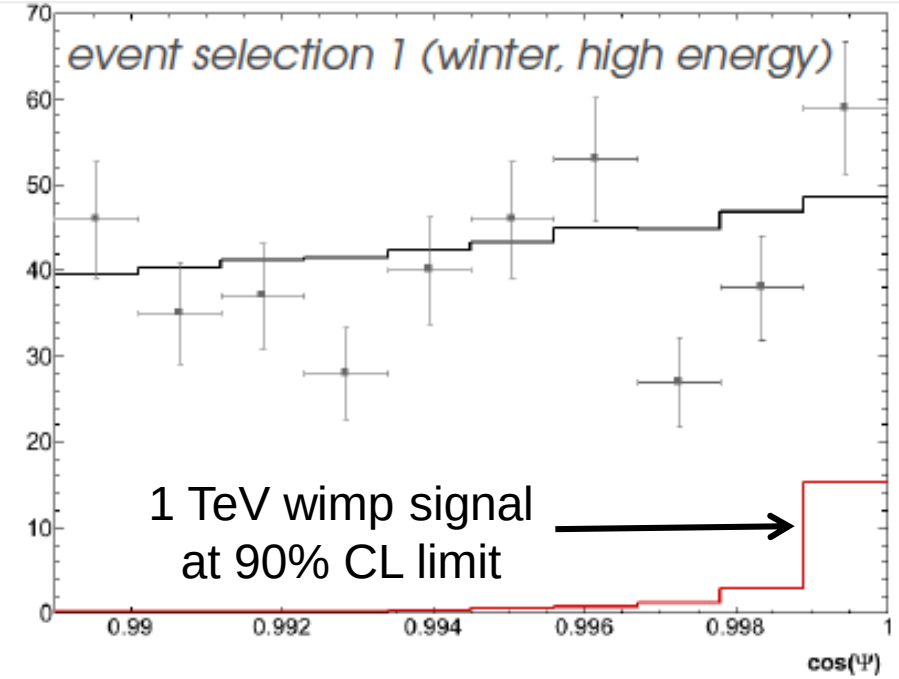
- Up-going ①
- No containment

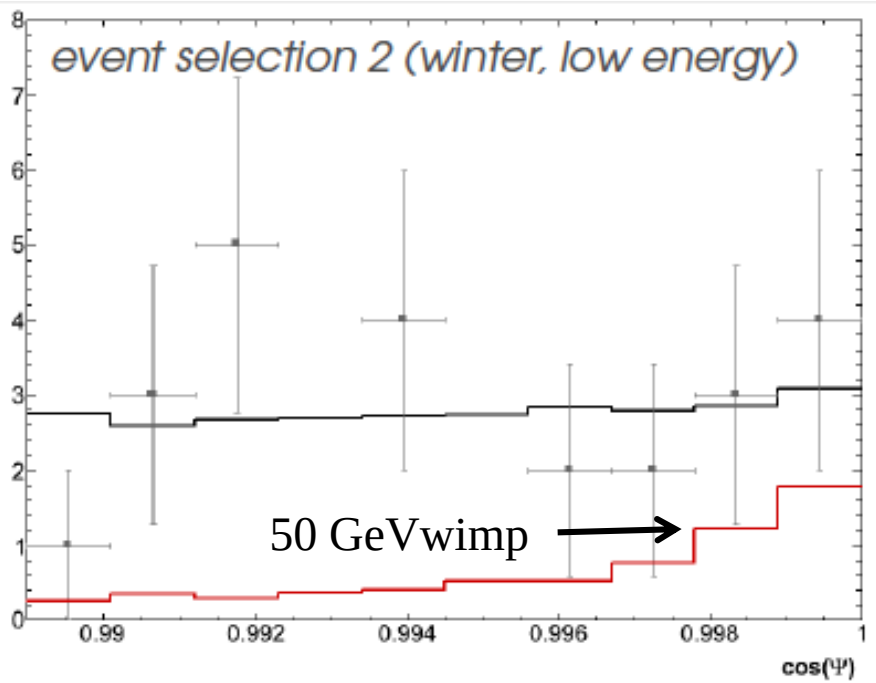
- Up-going ②
- strong containment

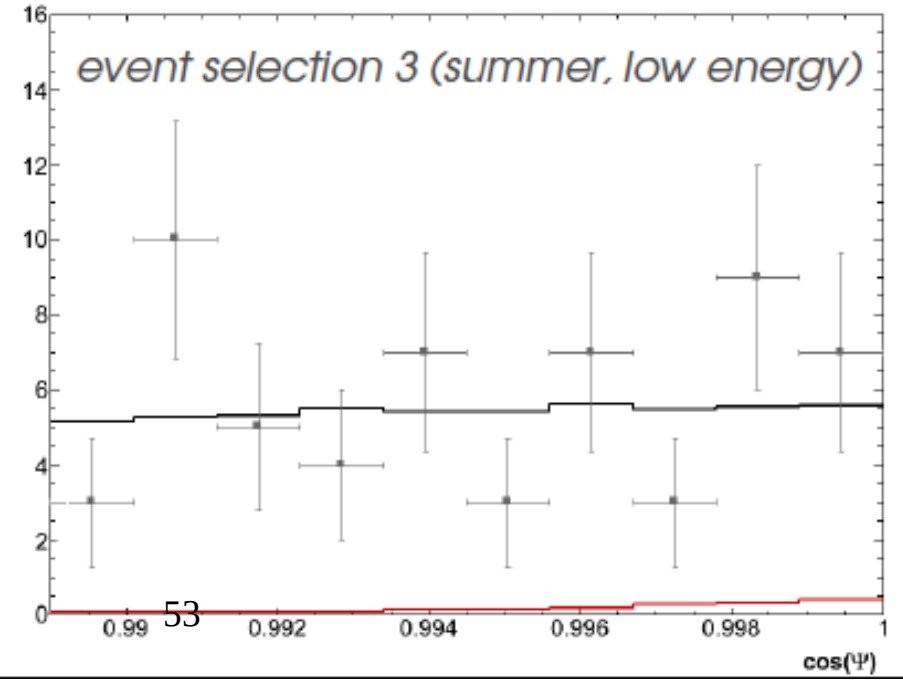
- Down-going ③
- strong containment

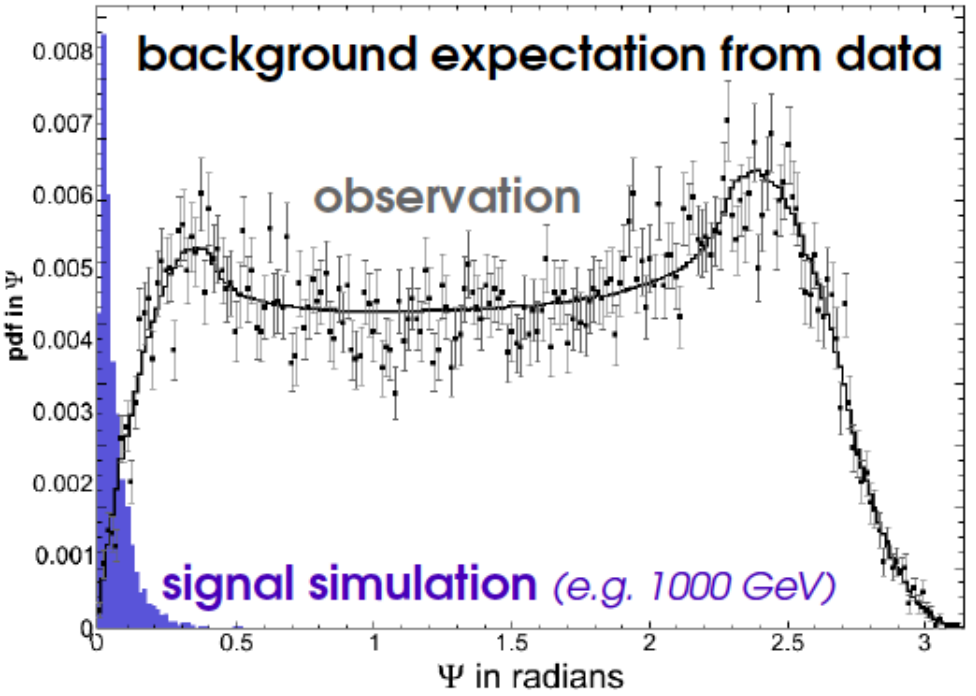




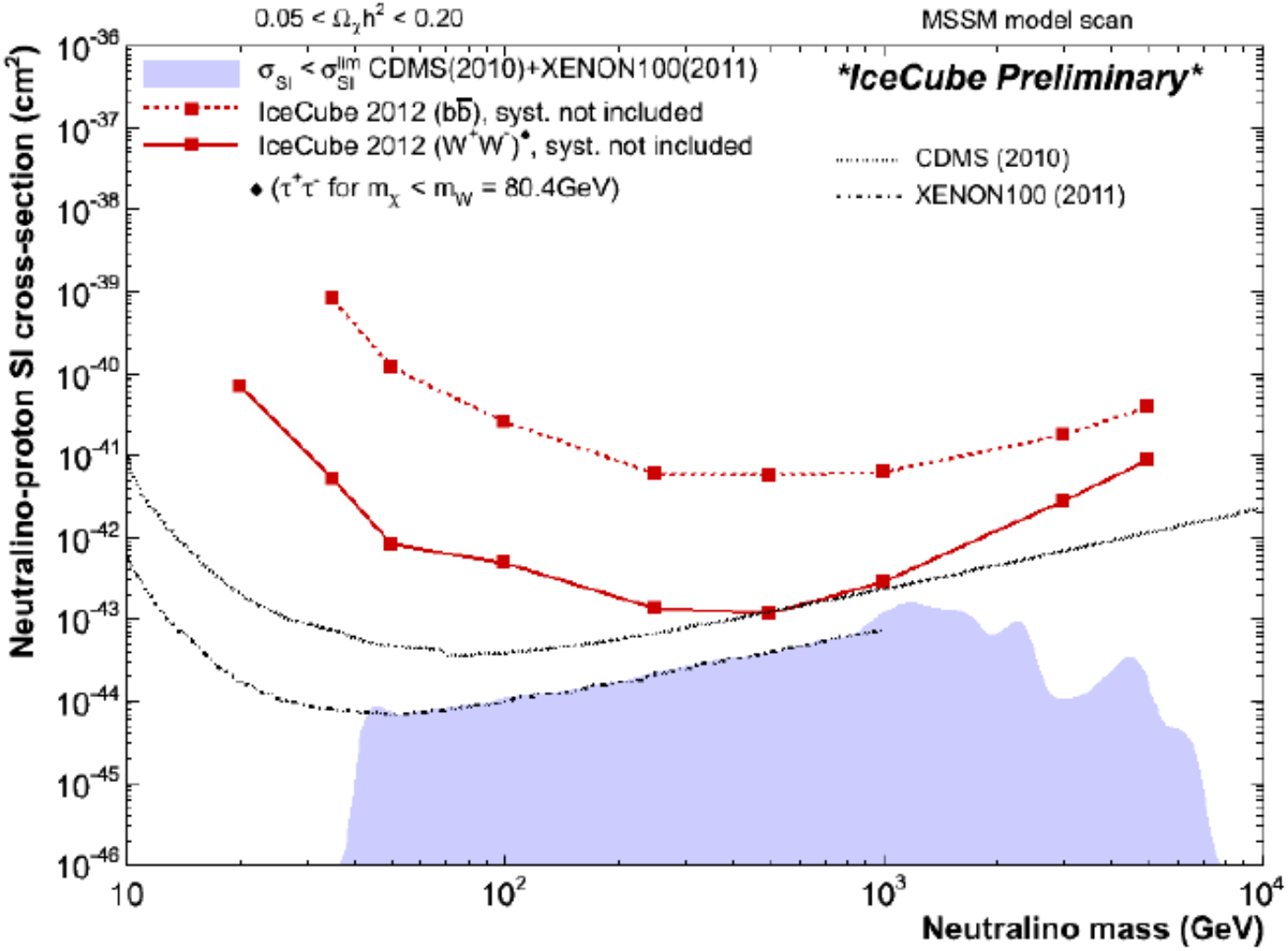

event selection 1 (winter, high energy)
1 TeV wimp signal
at 90% CL limit
cos(Ψ)


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

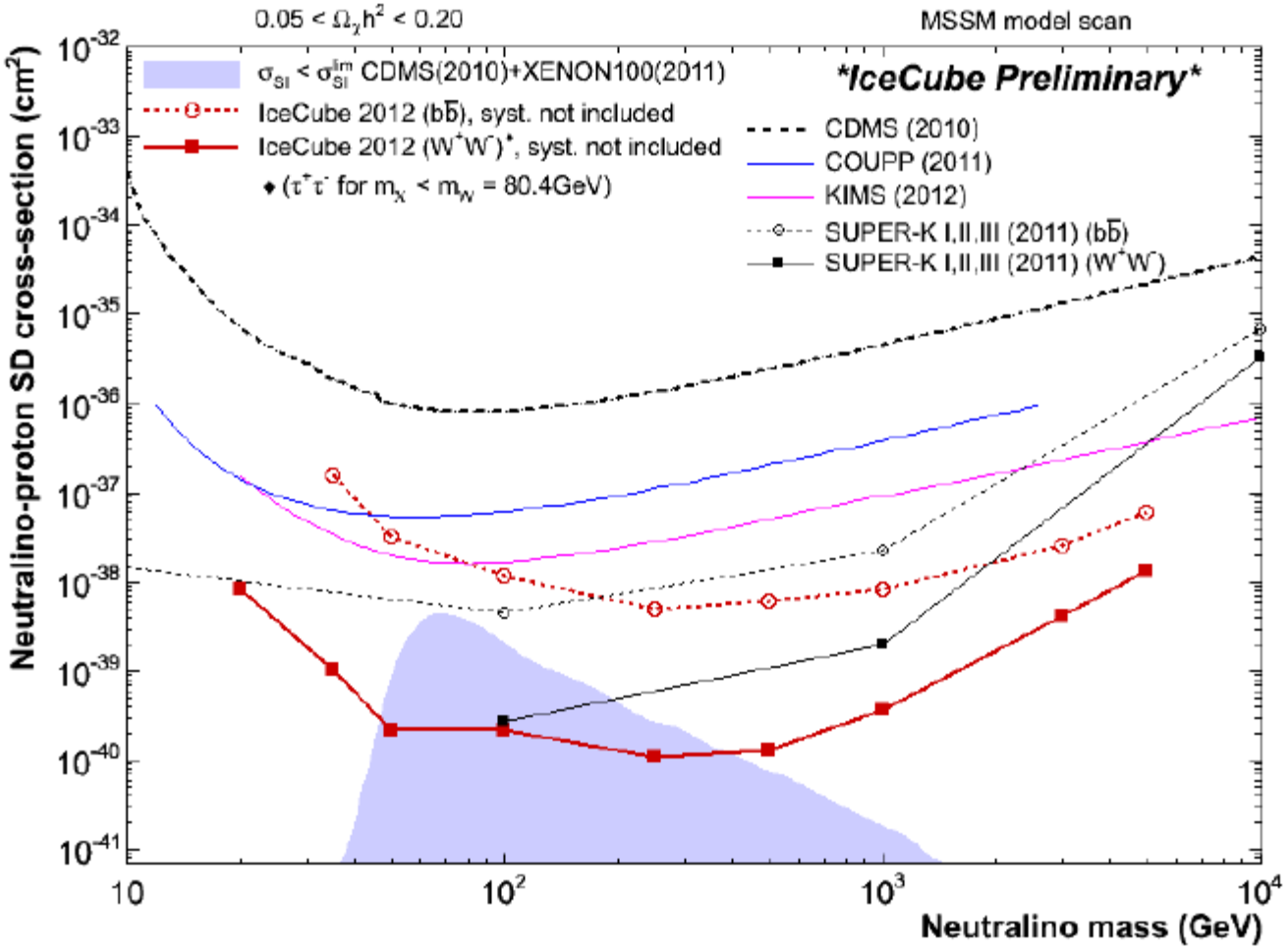

event selection 3 (summer, low energy)
cos(Ψ)


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

Unblinding results (SI-cross-section limit)

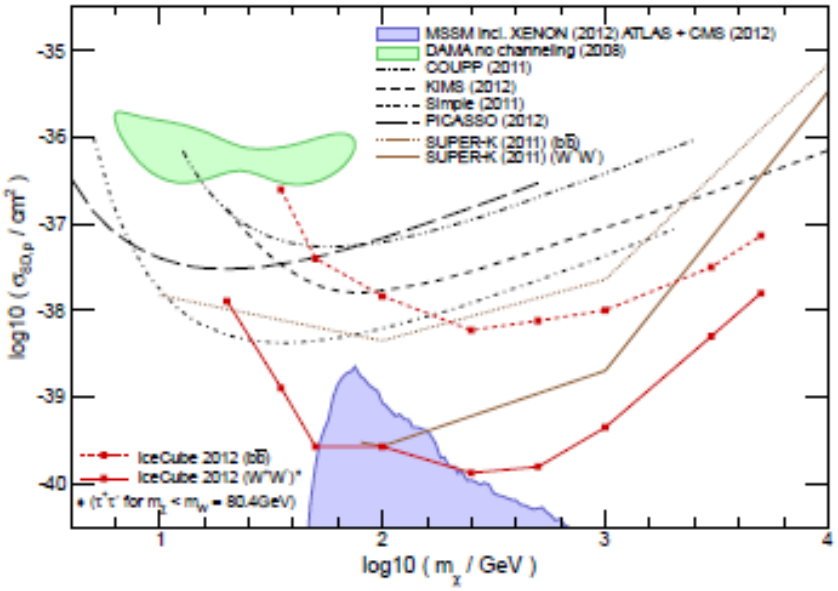


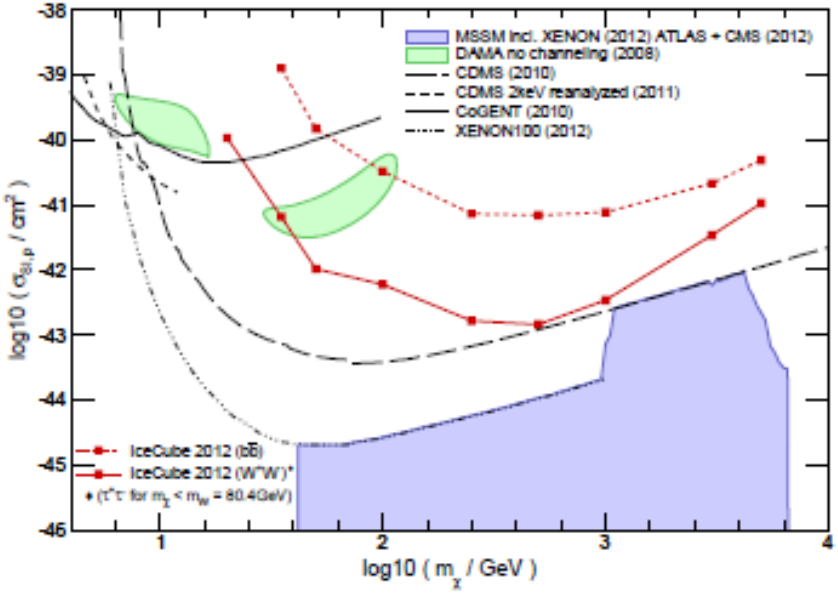
Unblinding results (SD-cross-section limit)



indirect dark matter detection in the sun

Dark Matter accumulates in the center of the sun – high-energy neutrino annihilation signatures from the sun





Threshold ∼ 20 GeV

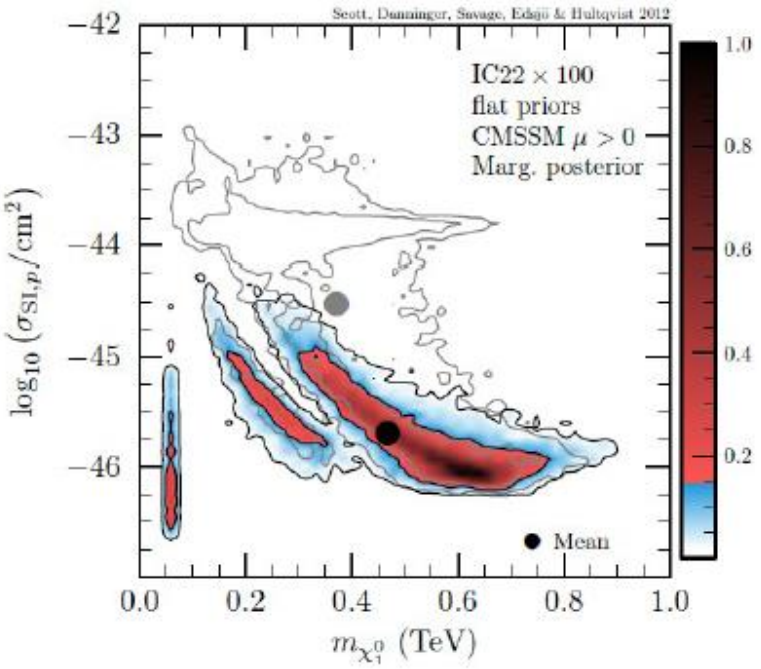
arXiv:1212.4097, accepted PRL

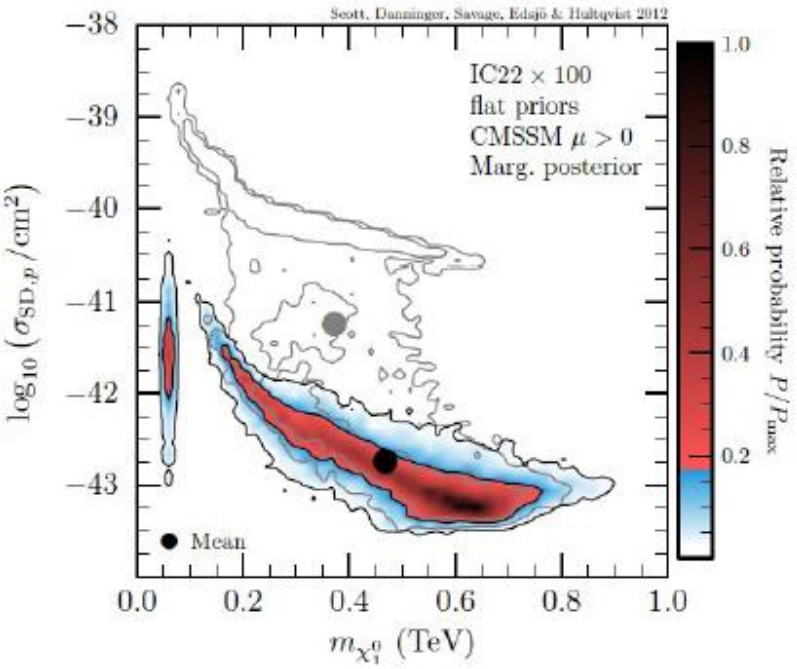
Global SUSY analysis with IceCube

More details: P.Scott, C.Savage, J. Edsjö & the IceCube Collaboration, arXiv:00001v1

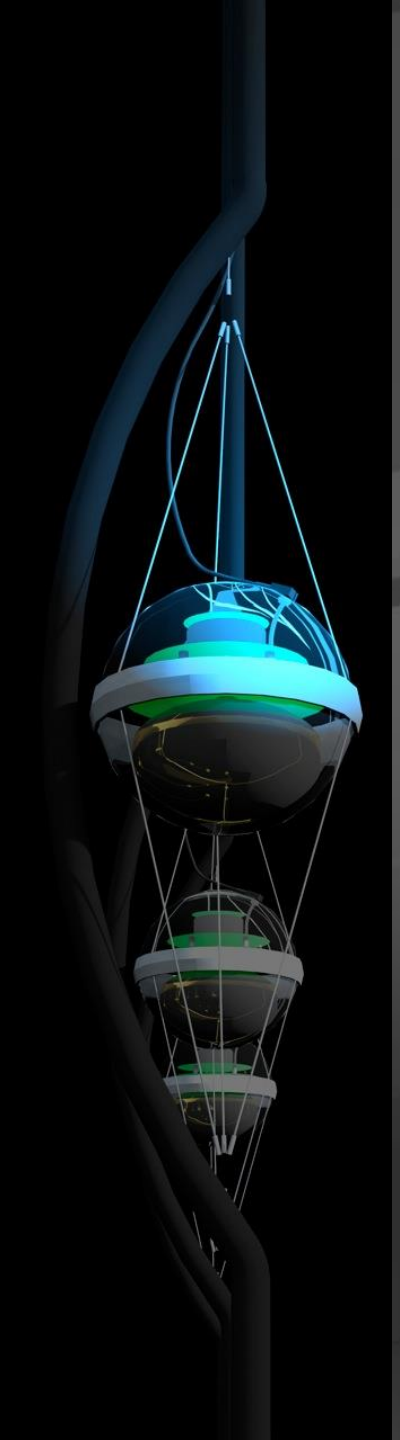
CMSSM, IceCube-22 with 100x boosted effective area
(indication for IceCube-79 and 86-string prospects)

Plots will be substituted with higher quality plots





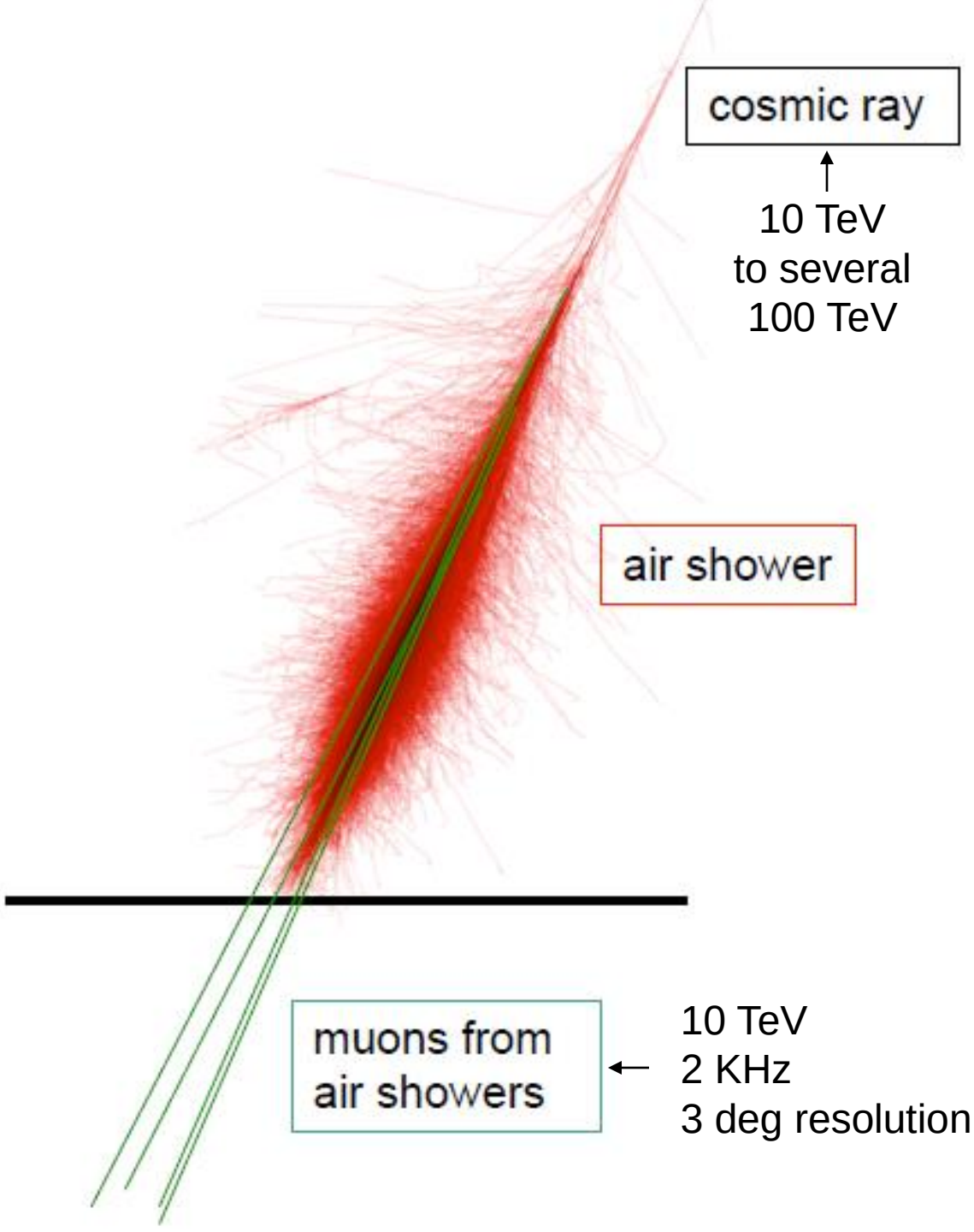
- ✗ Contours indicate 1σ and 2σ credible regions
- ✗ Grey contours correspond to fit *without* IceCube data
- ✗ Shading+contours indicate *relative* probability only, not overall goodness of fit



IceCube: beyond neutrino astronomy

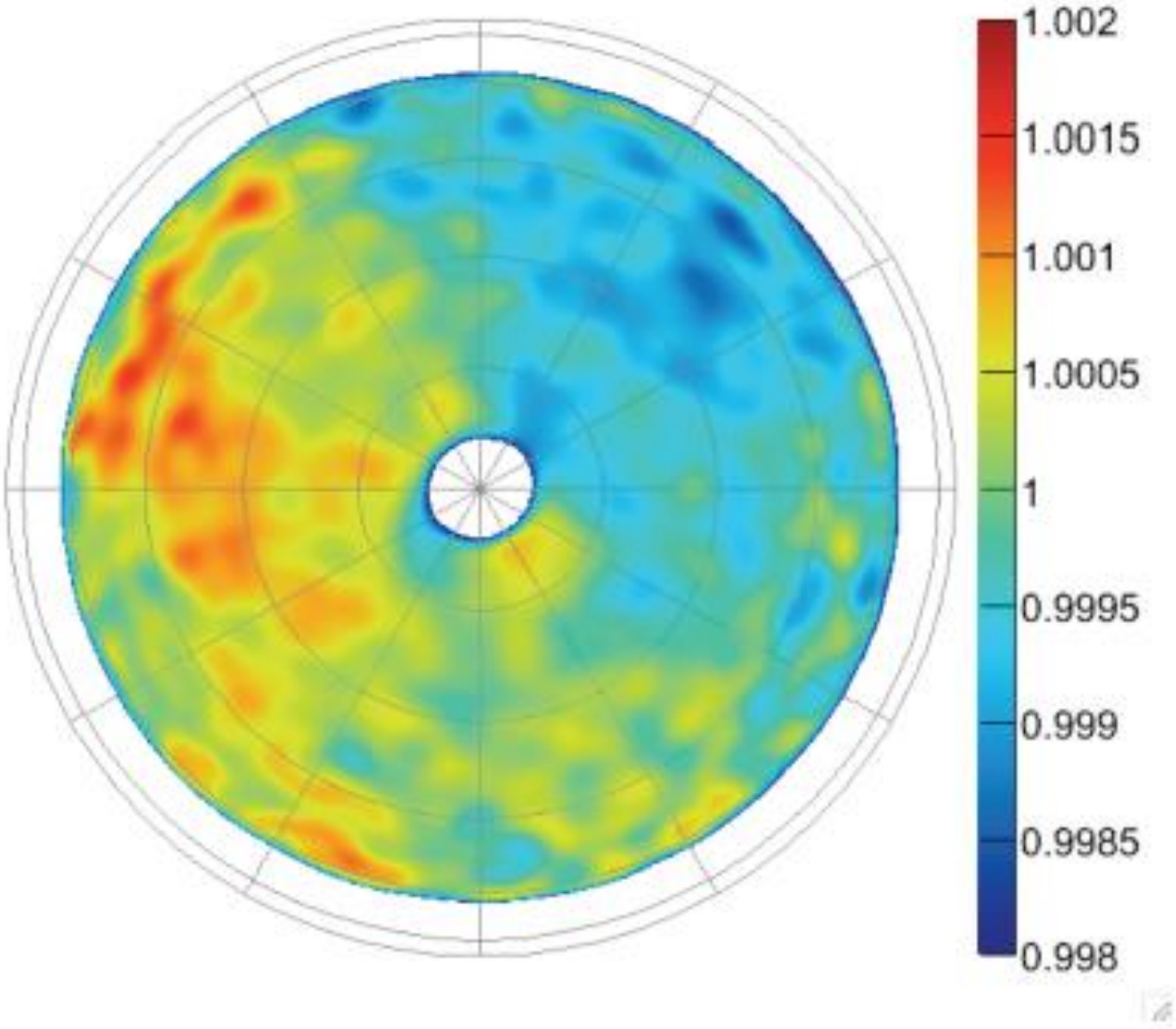
- detecting a Galactic supernova explosion
- neutrino oscillations: the mass hierarchy
- search for sterile neutrinos
- search for dark matter
- muon astronomy: search for the sources of the Galactic cosmic rays
- …

cosmic rays in IceCube

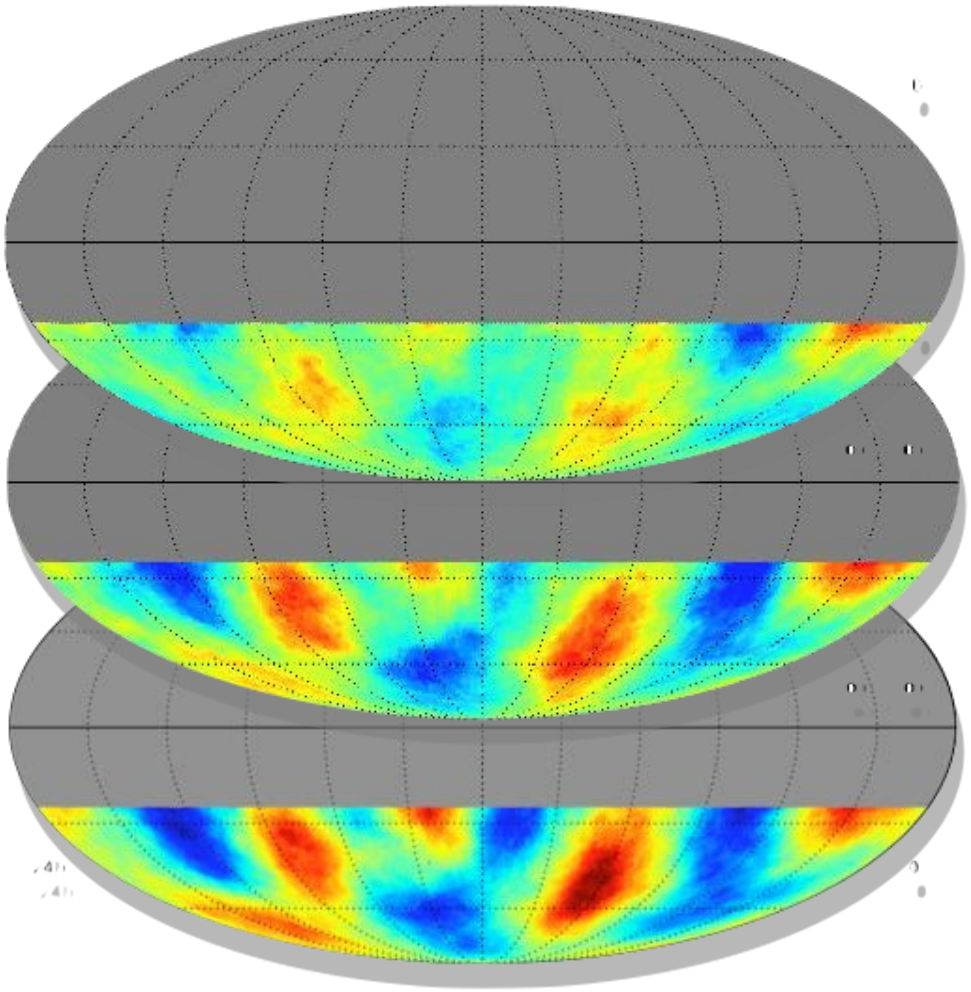


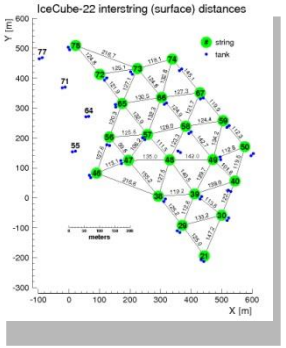
- galactic
- not solar
- highest energies approach the “knee”
- gyroradius < 1 pc in microgauss field
- closest sources > 100 pc

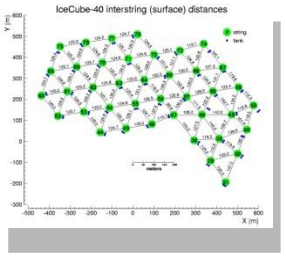
Orthonormal Projection

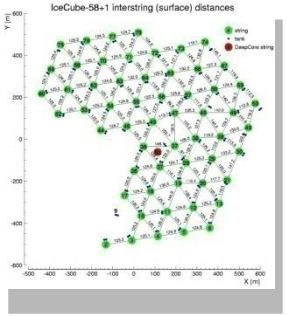


IC22 and IC40 : muon astronomy (!)





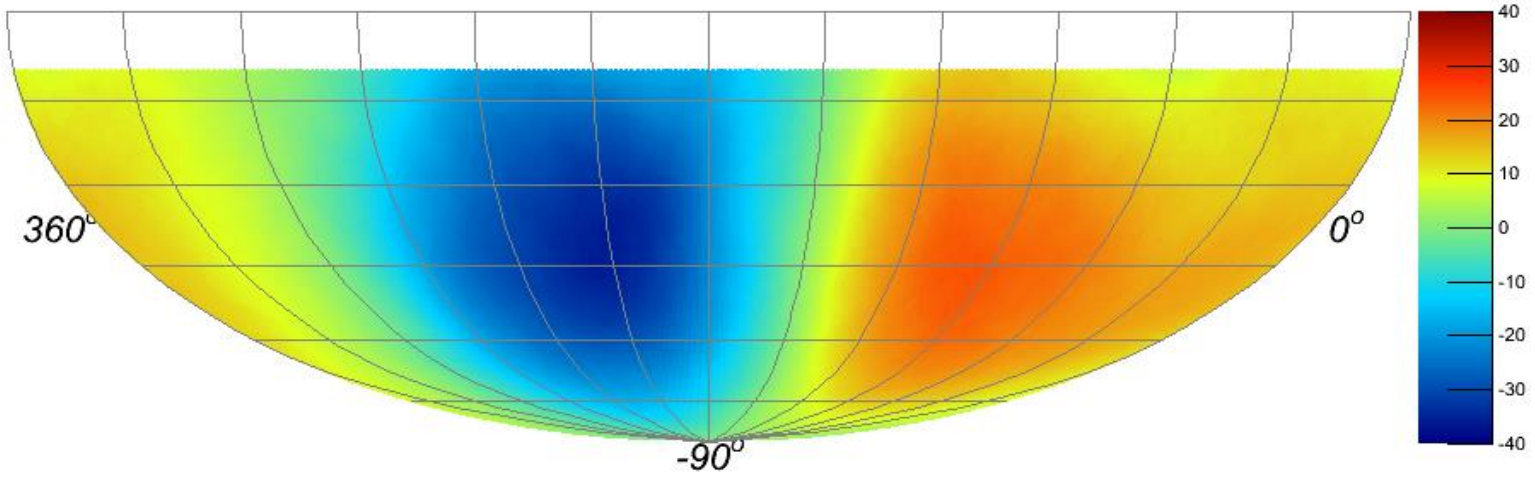




Different geometries, same structure

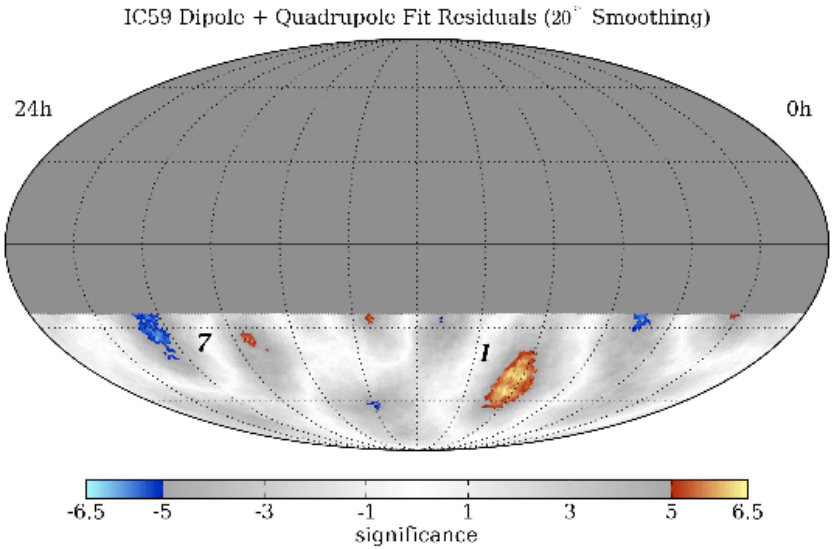
skymap on large scale (>20 degrees)

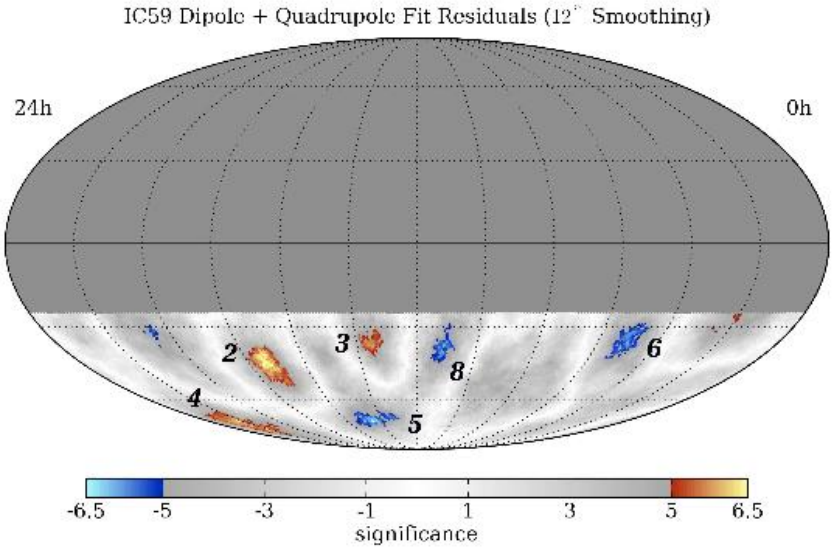
40 TeV



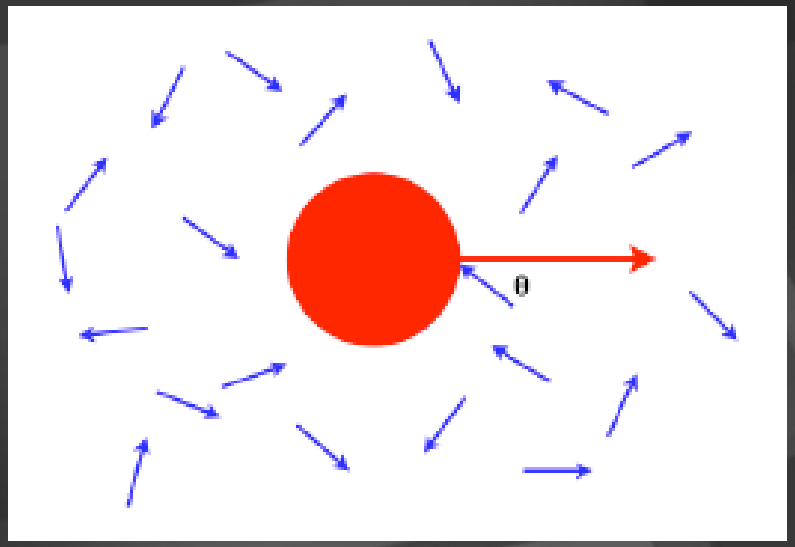
after substraction of dipole and quadrupole: small scale structure

region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	4.4σ
4	$(332.4^{+9.5}_{-7.1})^\circ$	$(-70.0^{+4.2}_{-7.6})^\circ$	12°	6.2σ	4.2σ
5	$(217.7^{+10.2}_{-7.8})^\circ$	$(-70.0^{+3.6}_{-2.3})^\circ$	12°	-6.4σ	-4.5σ
6	$(77.6^{+3.9}_{-8.4})^\circ$	$(-31.9^{+3.2}_{-8.6})^\circ$	13°	-6.1σ	-4.1σ
7	$(308.2^{+4.8}_{-7.7})^\circ$	$(-34.5^{+9.6}_{-6.9})^\circ$	20°	-6.1σ	-4.1σ
8	$(166.5^{+4.5}_{-5.7})^\circ$	$(-37.2^{+5.0}_{-5.7})^\circ$	12°	-6.0σ	-4.0σ





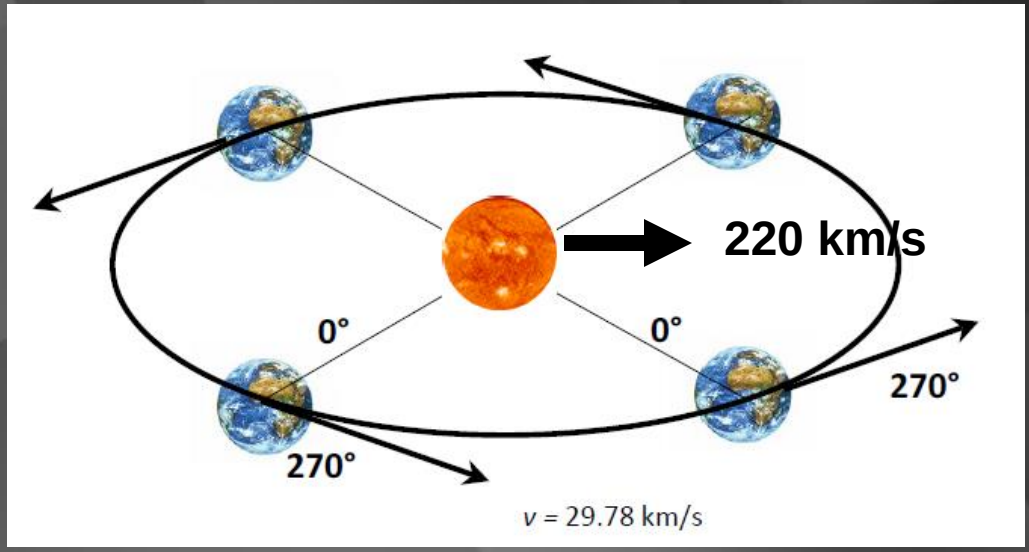
Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326



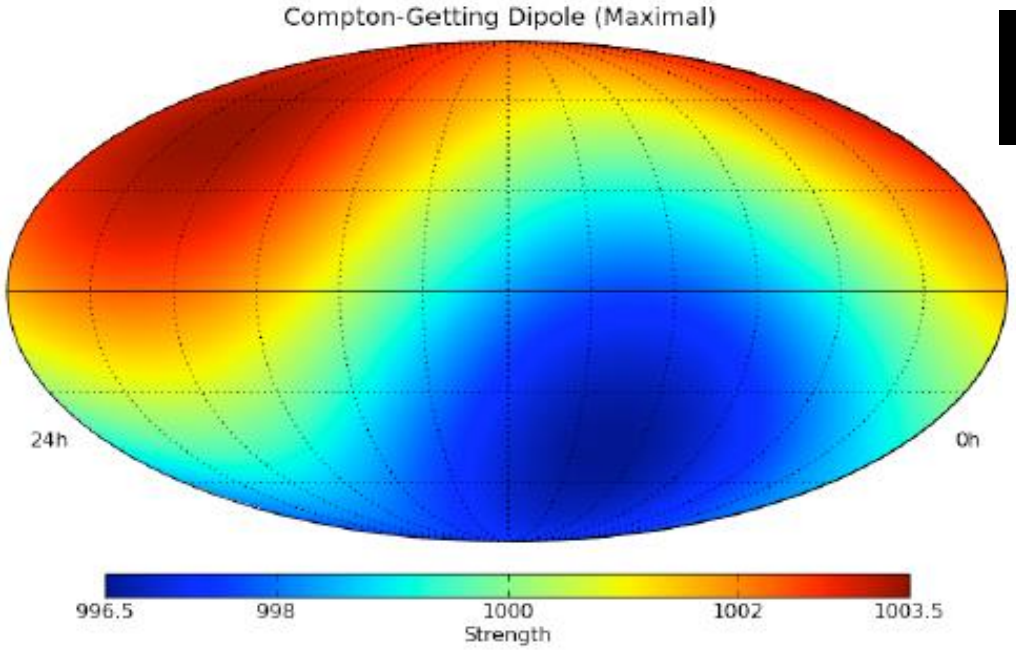
dipole anisotropies

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)



Compton-Getting effect



equatorial coordinates:
right ascention and declination

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\,\frac{v}{c}\,\cos\vartheta$$

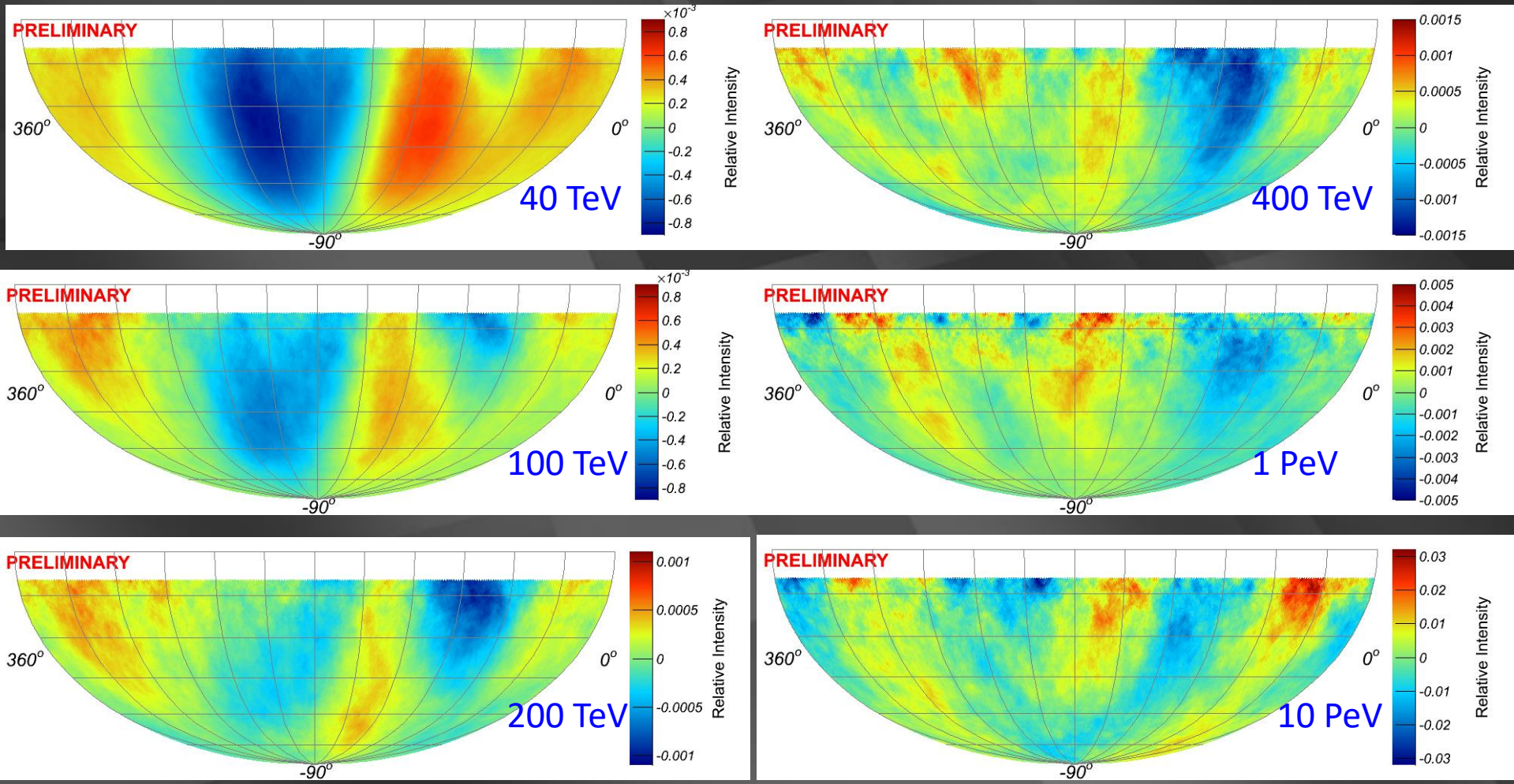
$\gamma = 2.7$ cosmic ray spectral index

$v = 220$ km/s speed

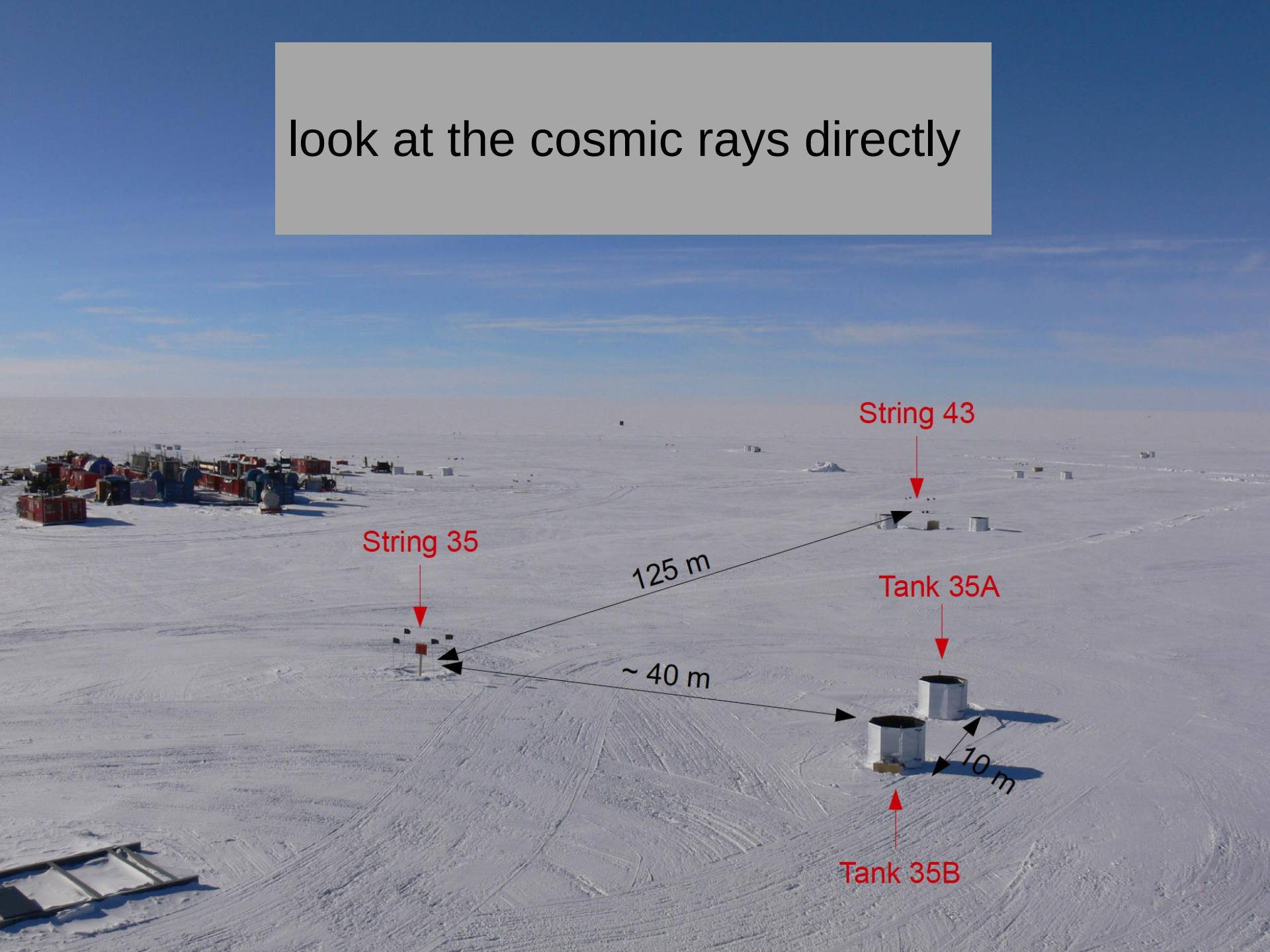
- 0.35% effect (if frame of the CR is the Galaxy)
- inclined relative to the equatorial plane
- easy !
- not seen

IceCube 79 → energy dependence of anisotropy

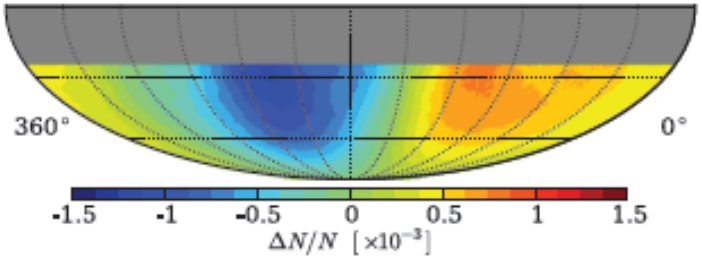
- non-diffusive effects in propagation of the particles?
- nearby supernova remnant(s)?

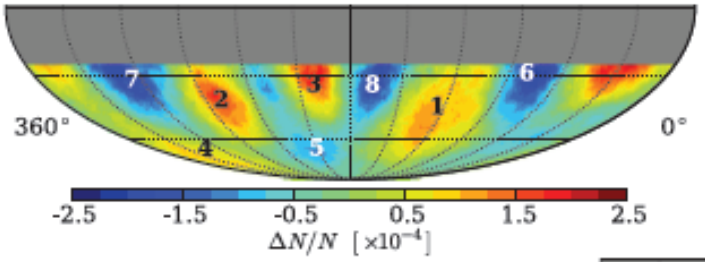


look at the cosmic rays directly



20 TeV

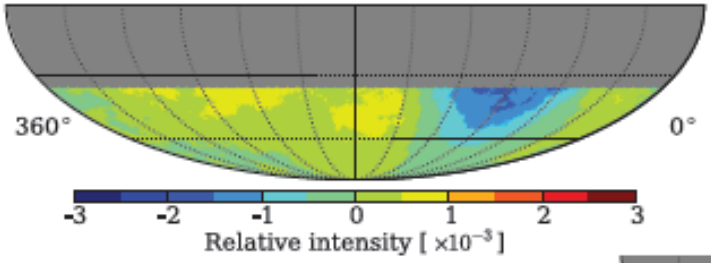




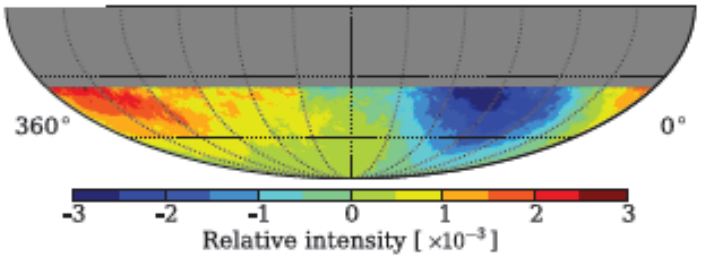
- Anisotropy changes in phase and amplitude with energy.

energy

400 TeV

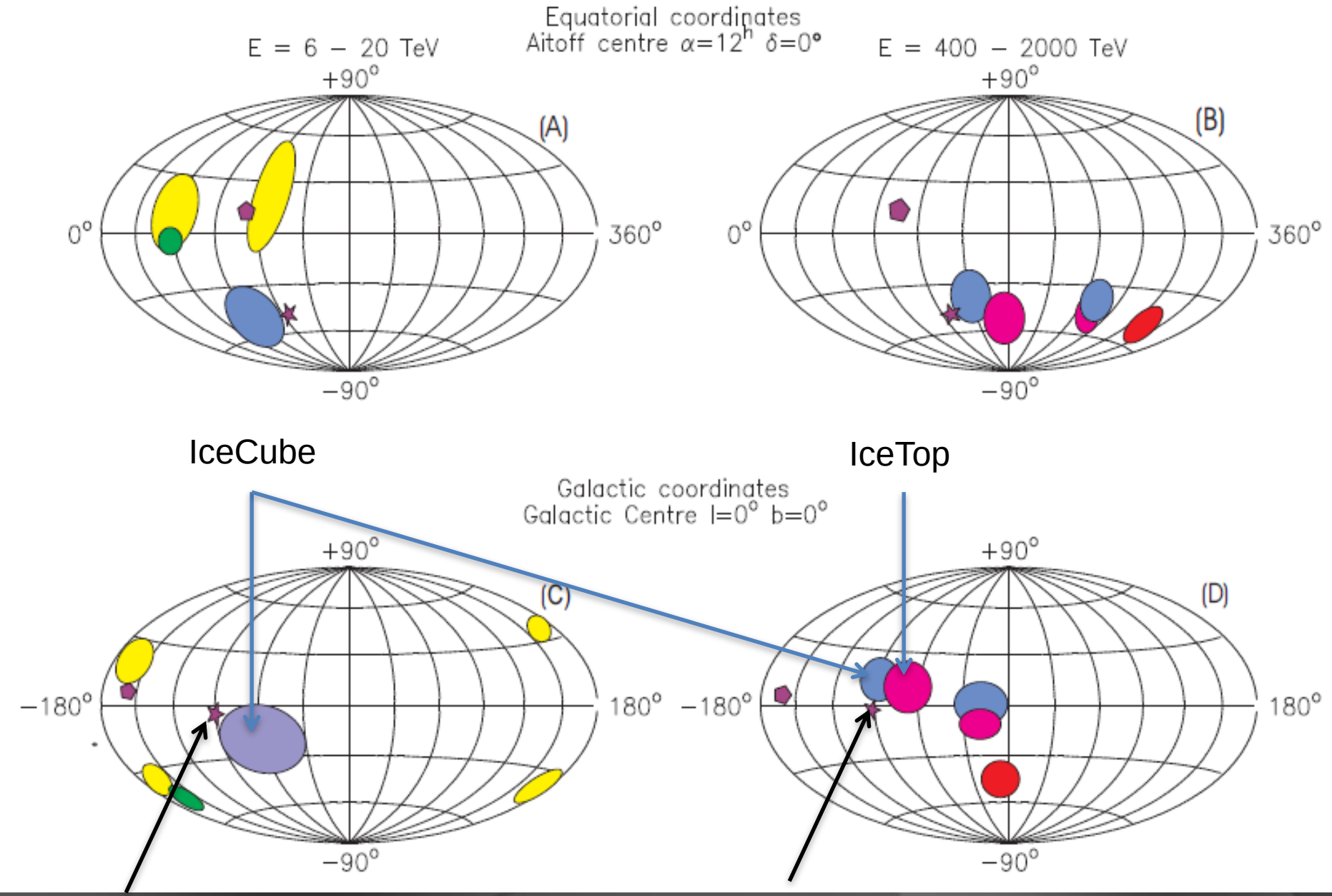


2 PeV



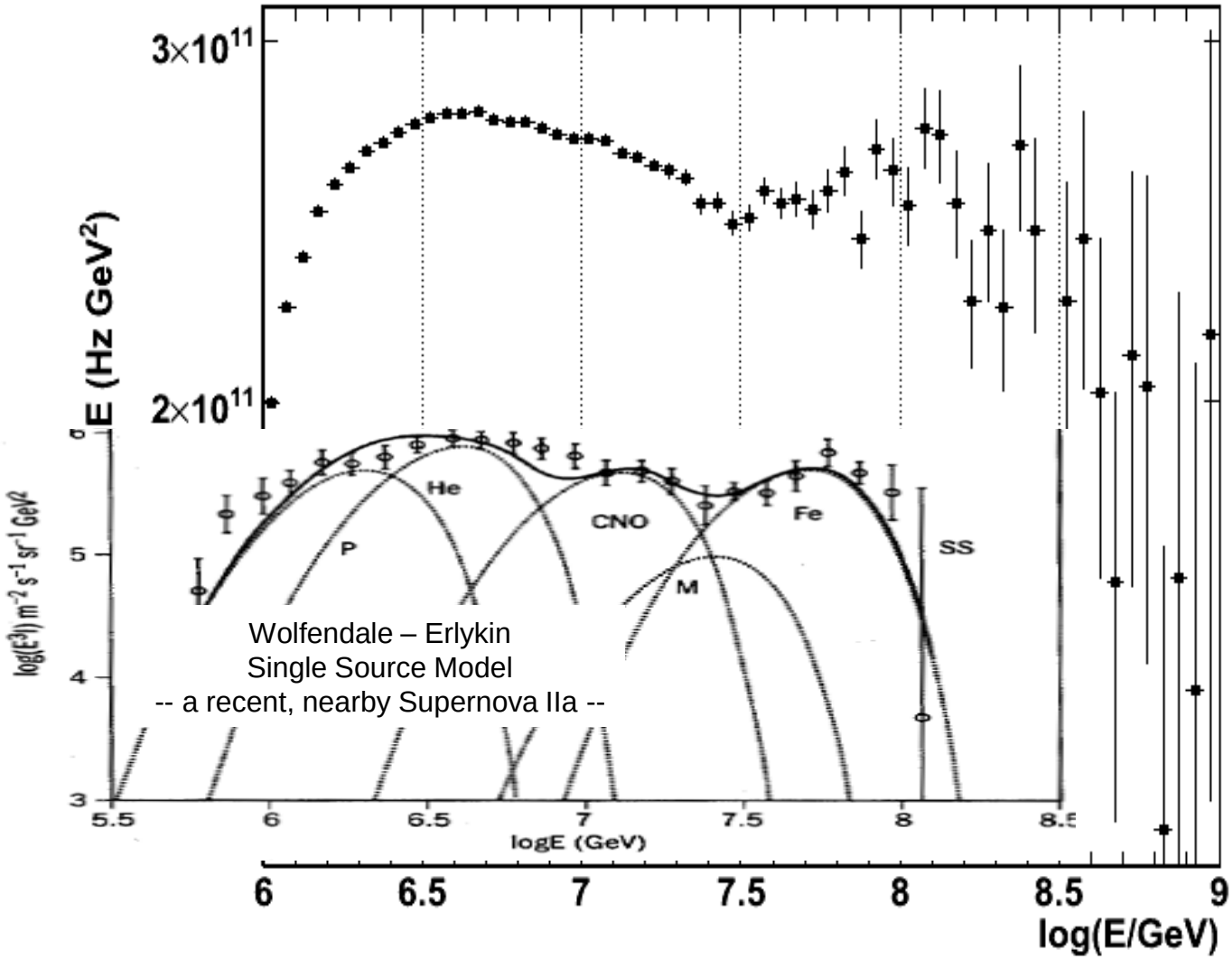
IceCube
ApJ 718 (2010) L194
ApJ 740 (2012) 16

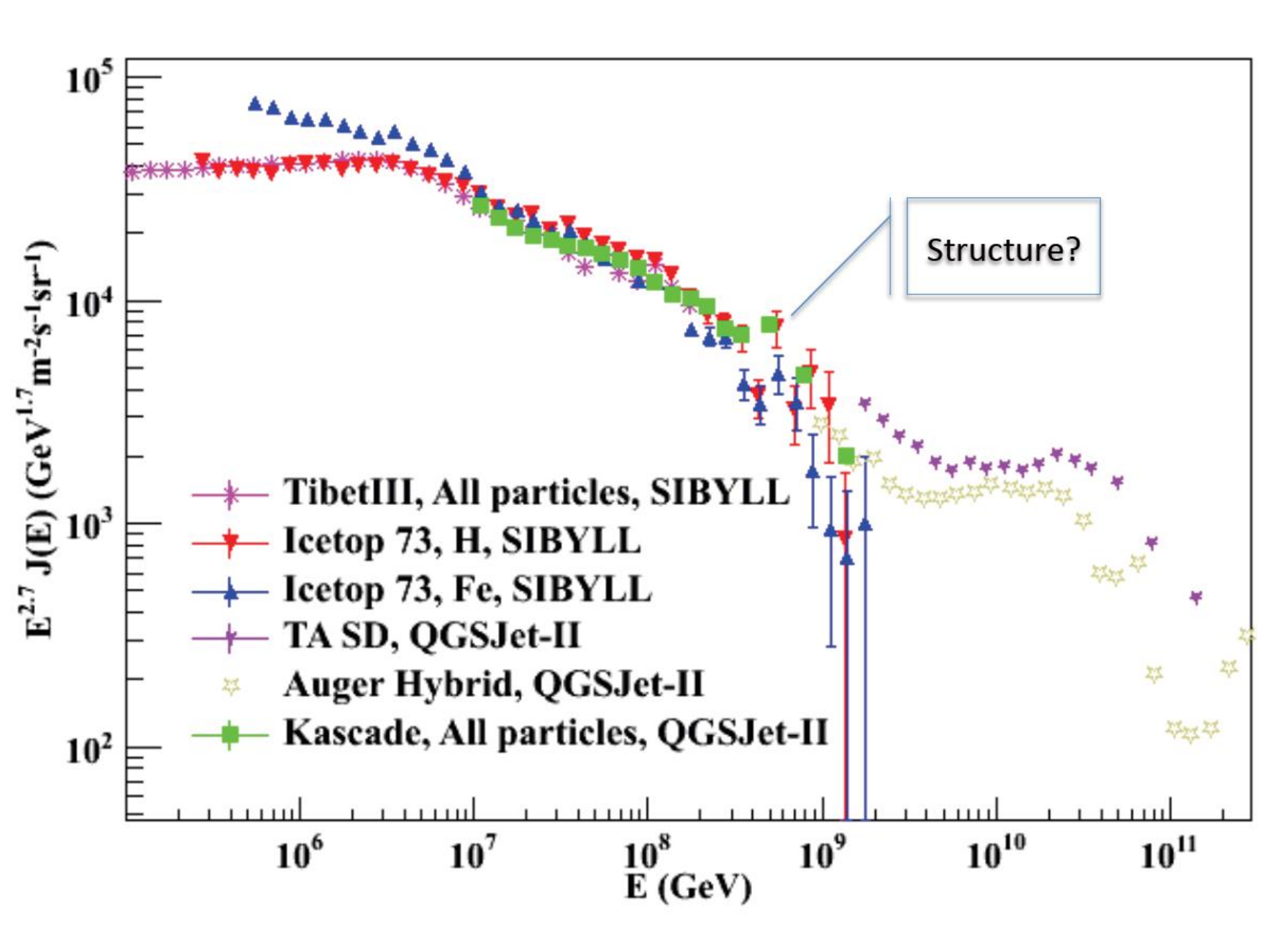
IceCube/IceTop
ApJ 746 (2012) 33



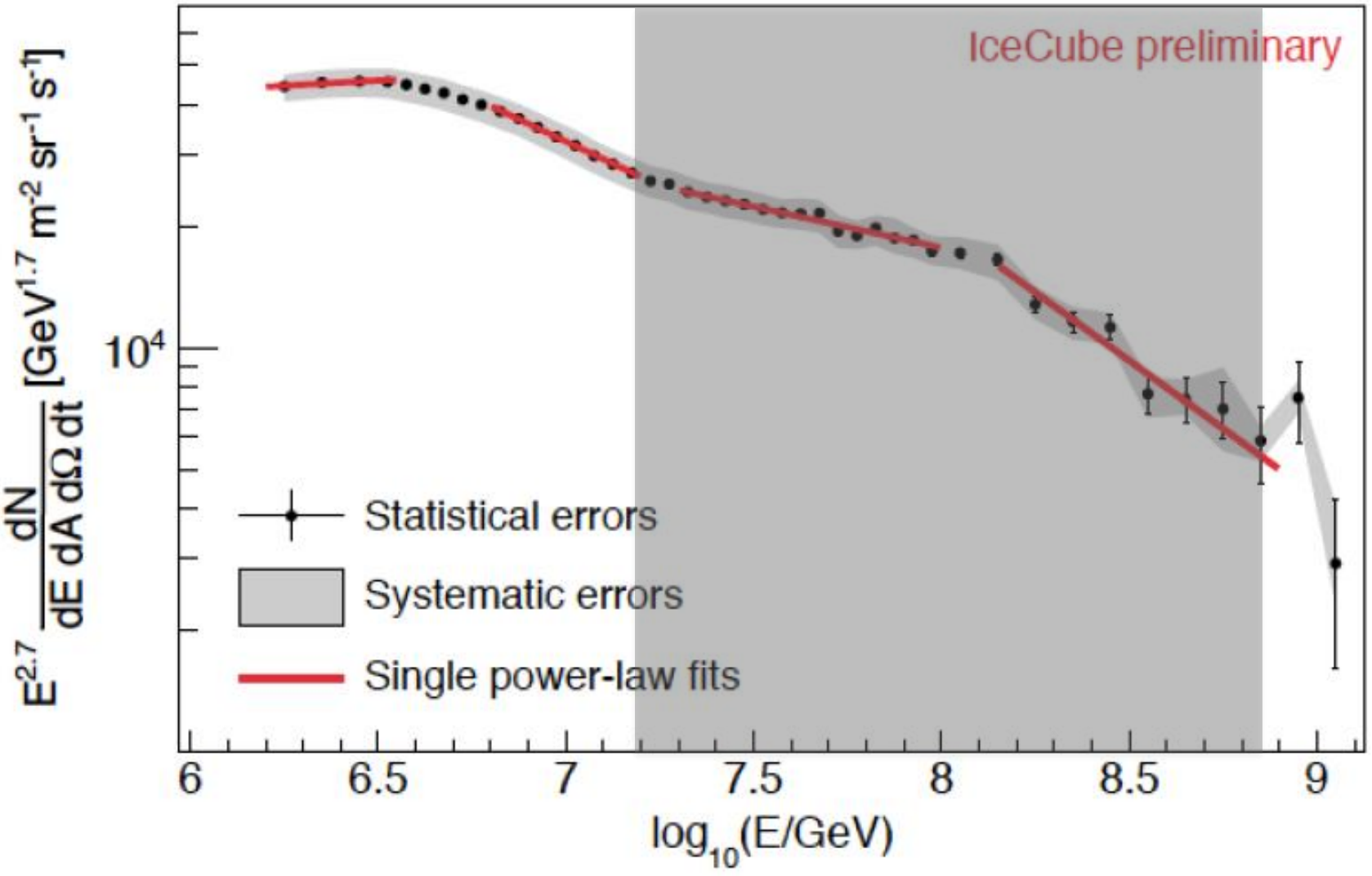
Vela: nearest supernova remnant
and strongest gamma source in the sky

the rare high energy particles at the end of the spectrum are produced by the closest source




Structure?
TibetIII, All particles, SIBYLL
Icetop 73, H, SIBYLL
Icetop 73, Fe, SIBYLL
TA SD, QGSJet-II
Auger Hybrid, QGSJet-II
Kascade, All particles, QGSJet-II
$E^{2.7}$ J(E) ($GeV^{1.7} m^{-2} s^{-1} sr^{-1}$)
E (GeV)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

the relevant energy range of cosmic rays producing PeV neutrinos



Galactic or extragalactic?

IceCube & PINGU collaborations

Collaborating Organizations

Chiba University
Clark Atlanta University
DESY-Zeuthen
Ecole Polytechnique Fédérale de Lausanne
FAU Erlangen-Nürnberg
Georgia Institute of Technology
HU Berlin
JGU Mainz
Lawrence Berkeley National Laboratory
Niels Bohr Institute
Ohio State University
Pennsylvania State University
RU Bochum
RWTH Aachen
Southern University and A&M College
Stockholms universitet
Stony Brook University
Sungkyunkwan University
TU Dortmund
TU München
Universität Bonn
Universität Wuppertal
Université libre de Bruxelles
Université de Mons
Universiteit Gent
University of Adelaide
University of Alabama
University of Alberta
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Canterbury
University of Delaware
University of Geneva
University of Kansas
University of Manchester
University of Maryland
University of Oxford
University of Wisconsin-Madison
University of Wisconsin-River Falls
Uppsala universitet
Vrije Universiteit Brussel