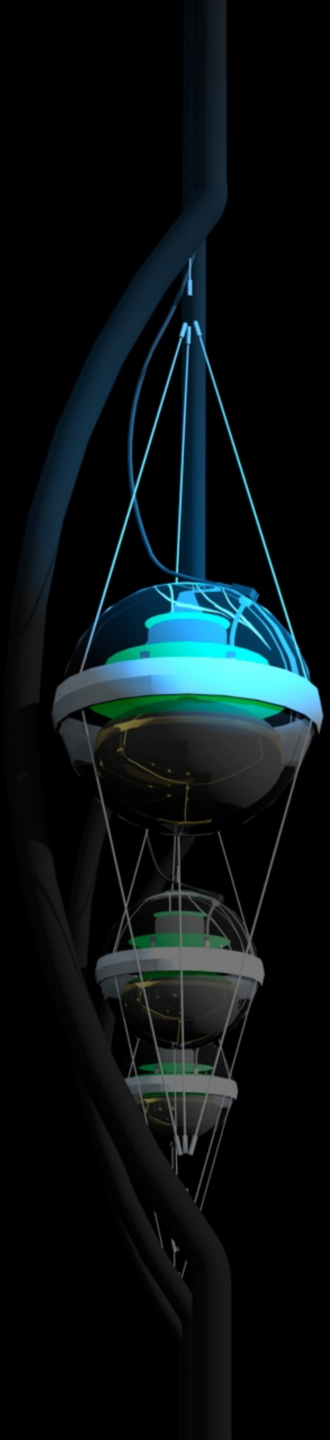


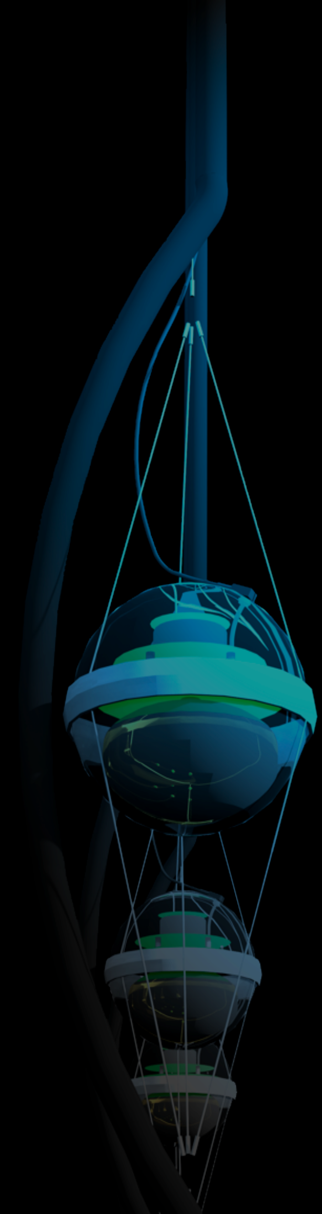
IceCube Science

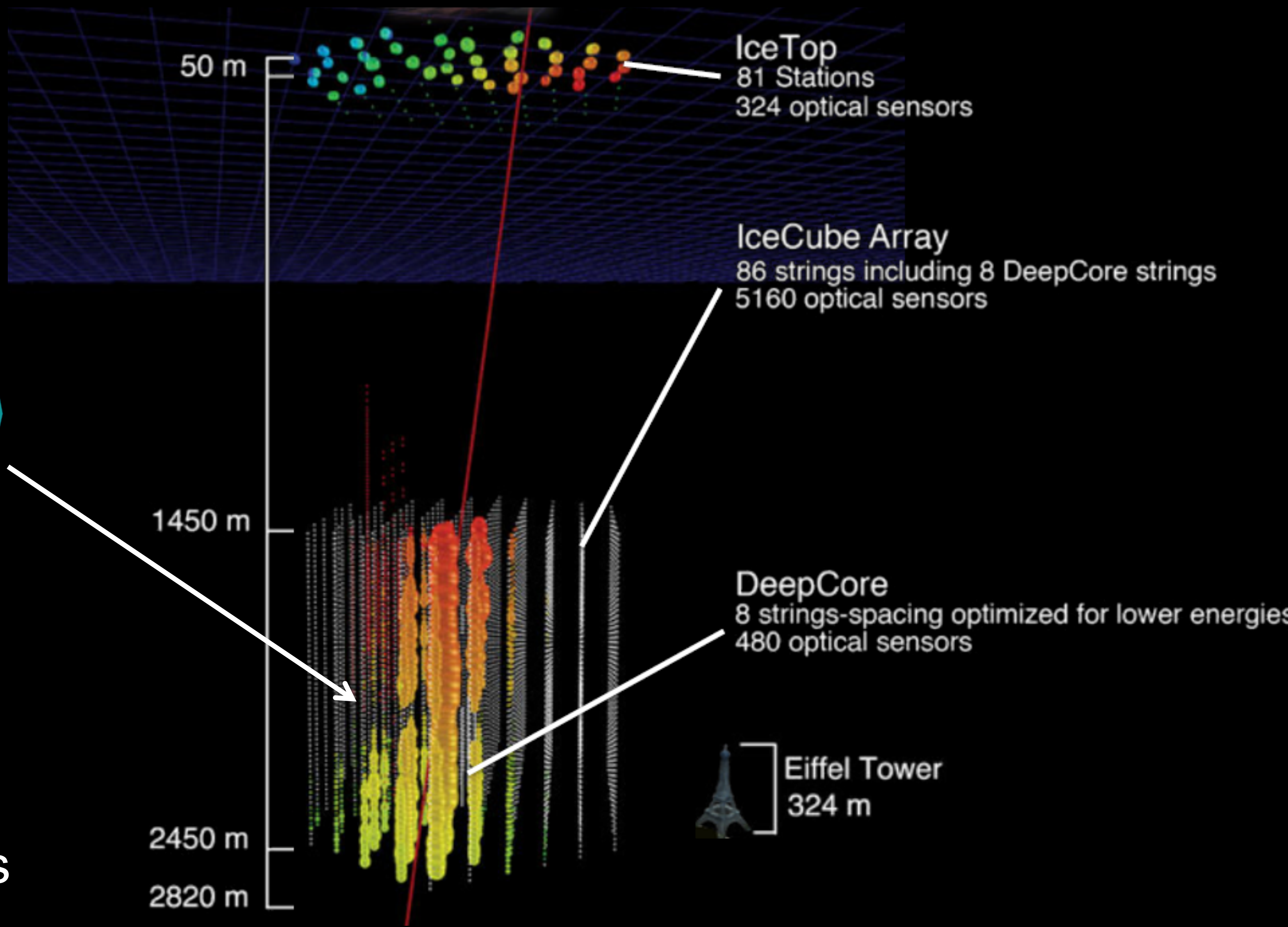
francis halzen

- cosmic neutrinos: discovery and confirmation
- the origin of cosmic neutrinos
- from PeV to GeV: neutrino physics with IceCube
- what next?

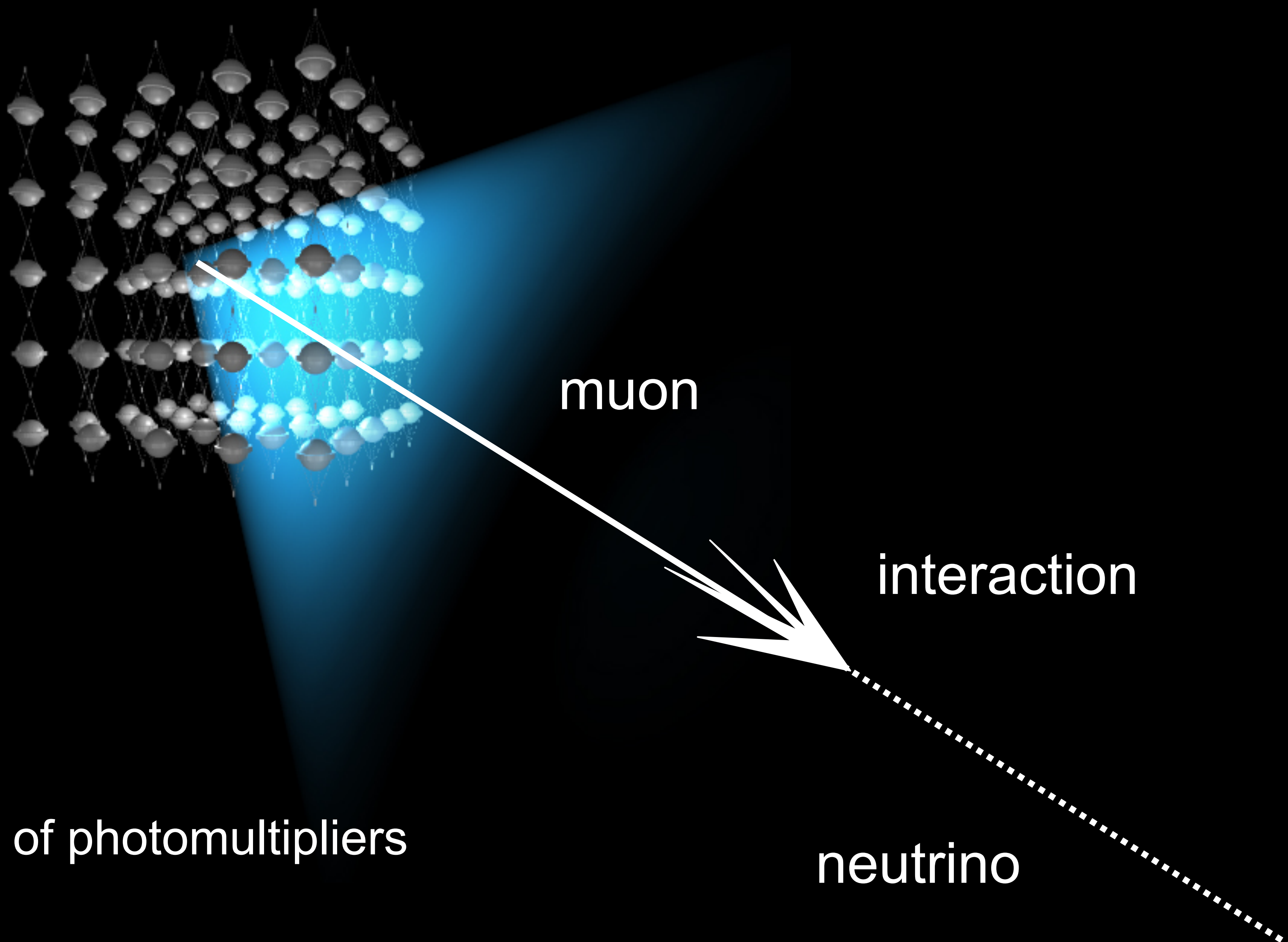
IceCube.wisc.edu

IceCube



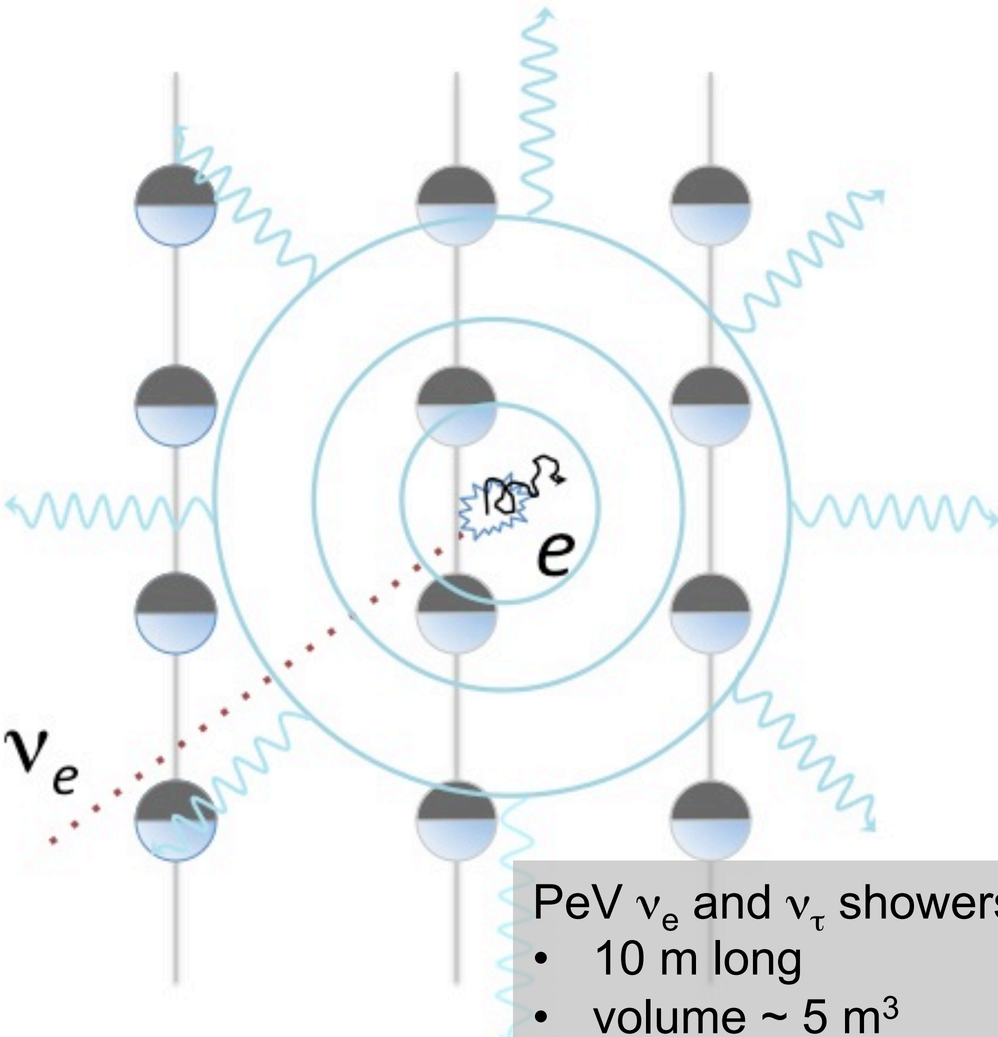


5160 PMs
in 1 km^3



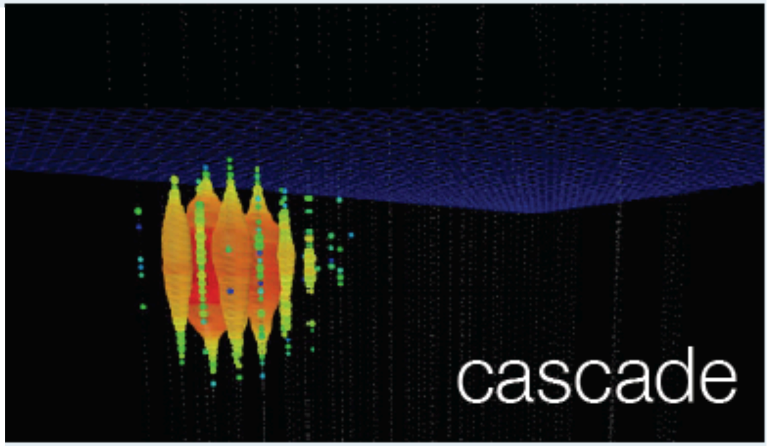
- lattice of photomultipliers

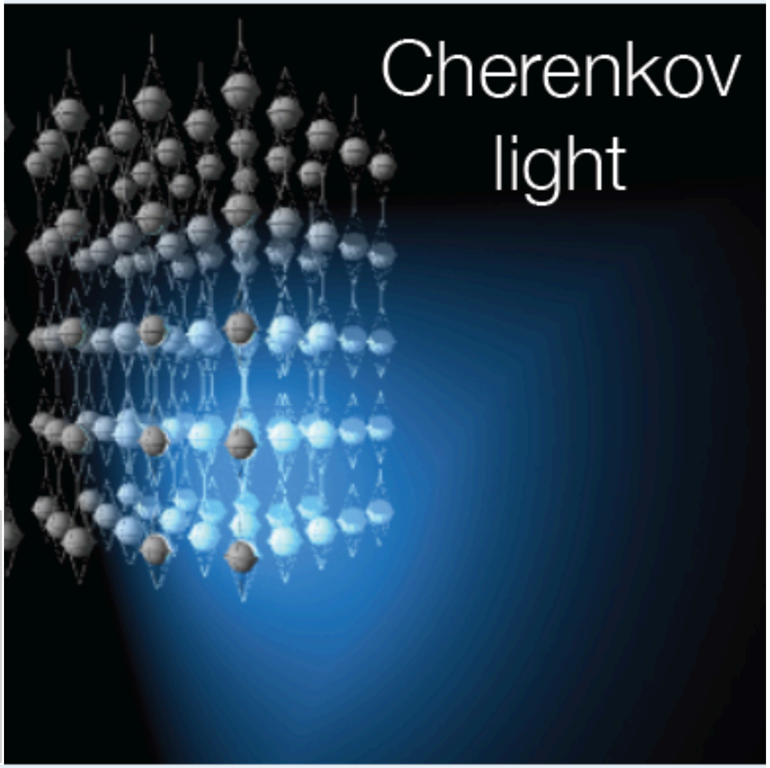
tracks and showers



PeV ν_e and ν_τ showers:

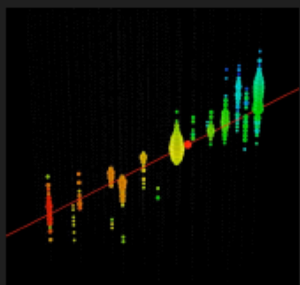
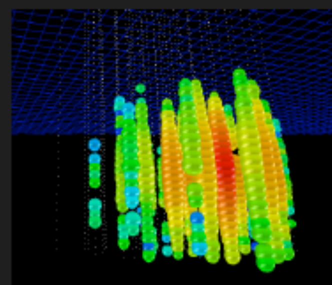
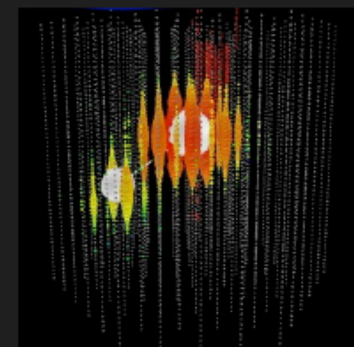
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m





neutrino flavors in IceCube

time →

cc muon neutrino	neutral current/ electron neutrino	cc tau neutrino
		
$\nu_\mu + N \to \mu + X$	$\nu_e + N \to e + X$ $\nu_x + N \to \nu_x + X$	$\nu_\tau + N \to \tau + X$
track (data)	cascade (data)	“double-bang” (≳10PeV) and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution at high energies	≈ ±15% deposited energy resolution ≈ 10° angular resolution (in IceCube) (at energies ≳ 100 TeV)	(not observed yet: τ decay length is 50 m/PeV)

… you looked at 10msec of data !

muons detected per year:

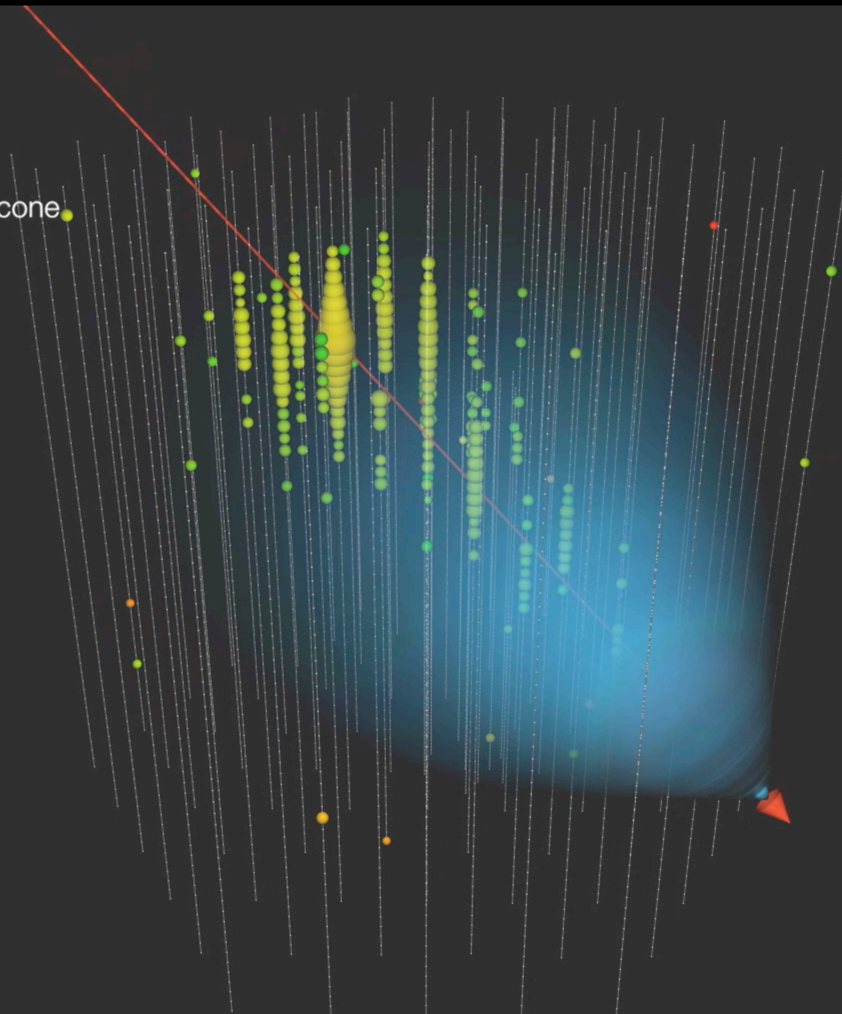
• atmospheric*	μ	~ 10^{11}
• atmospheric**	$\nu \rightarrow \mu$	~ 10^{5}
• cosmic	$\nu \rightarrow \mu$	~ 10

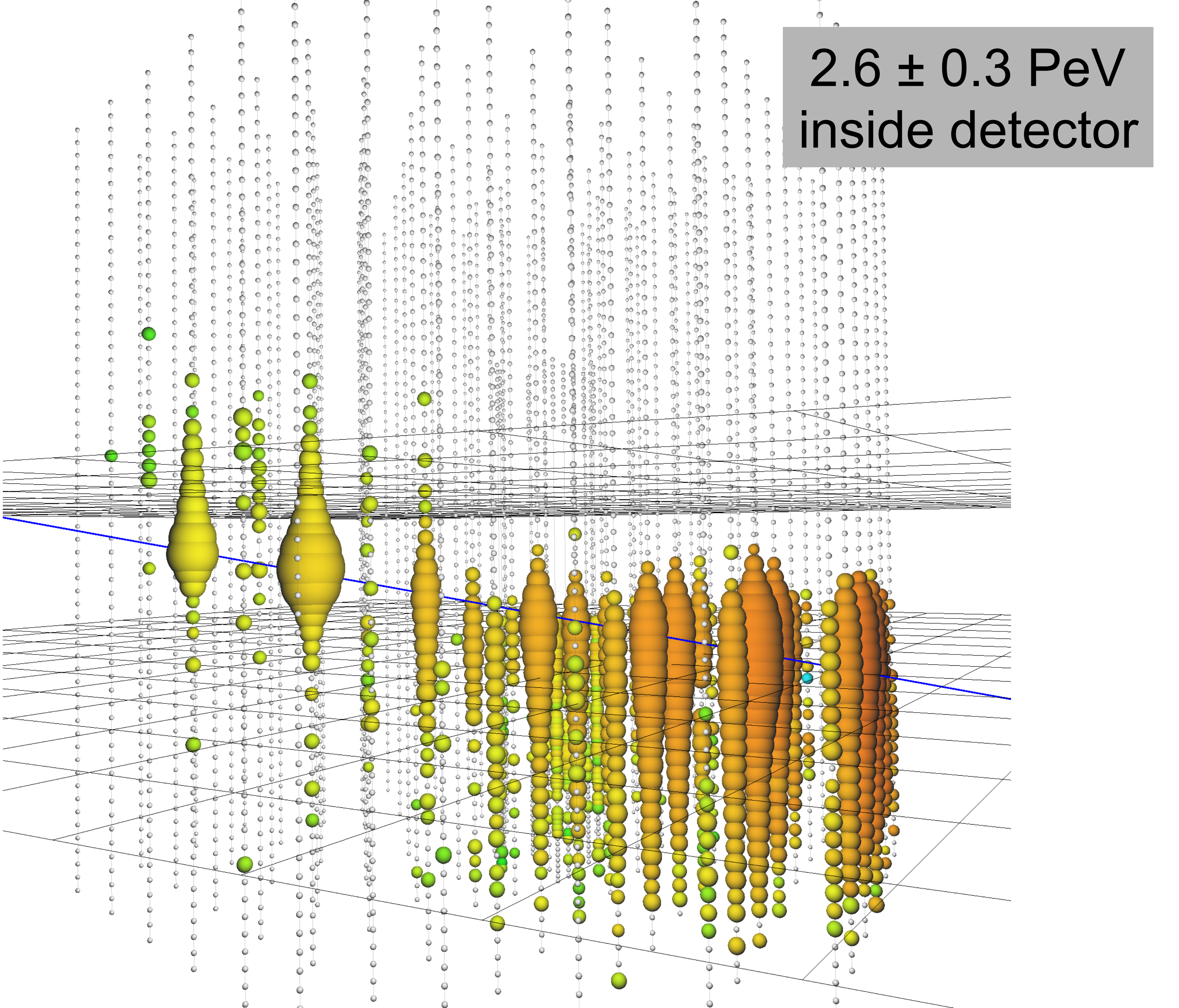
* 3000 per second

** 1 every 6 minutes

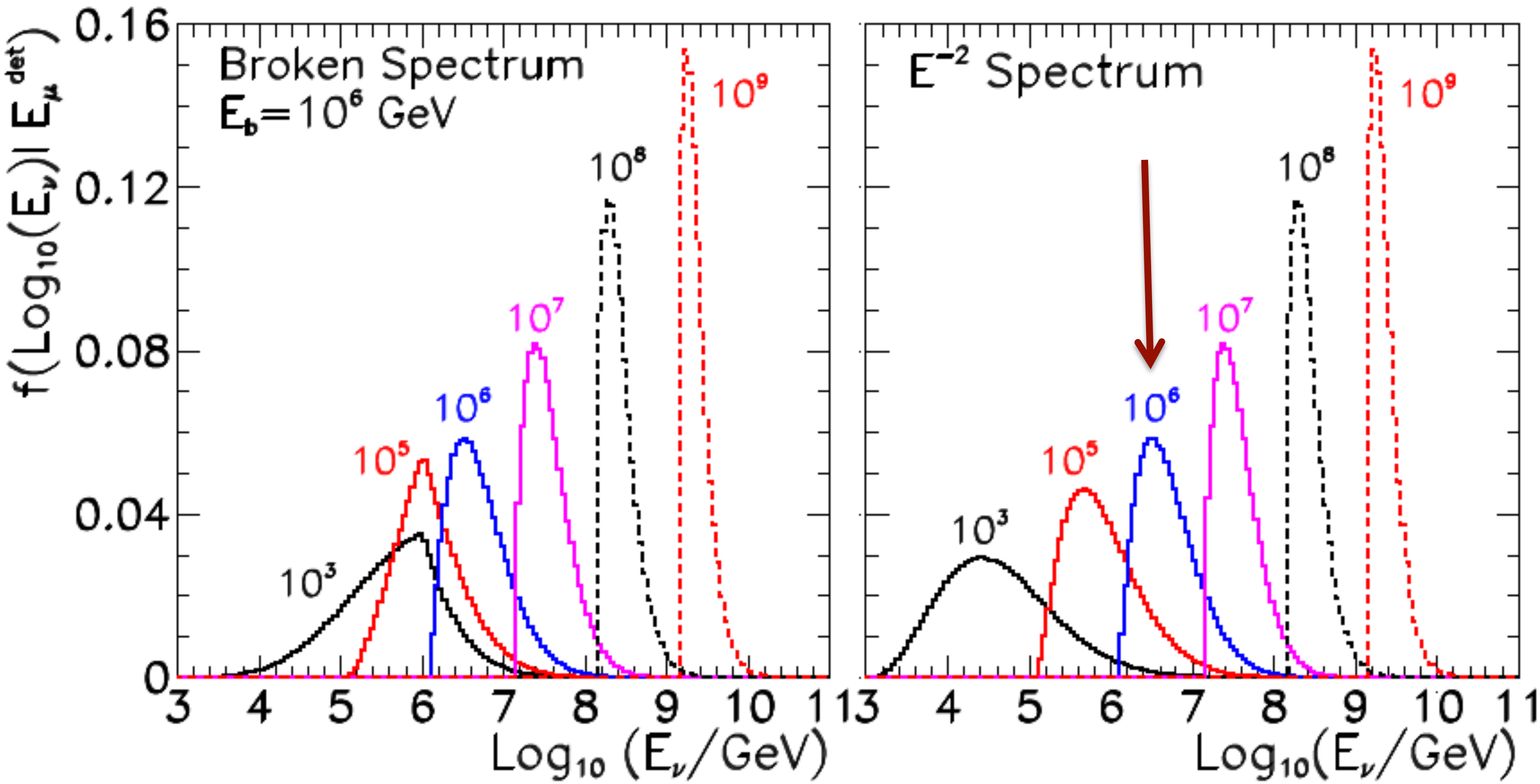
IceCube event

with simulated Cherenkov cone



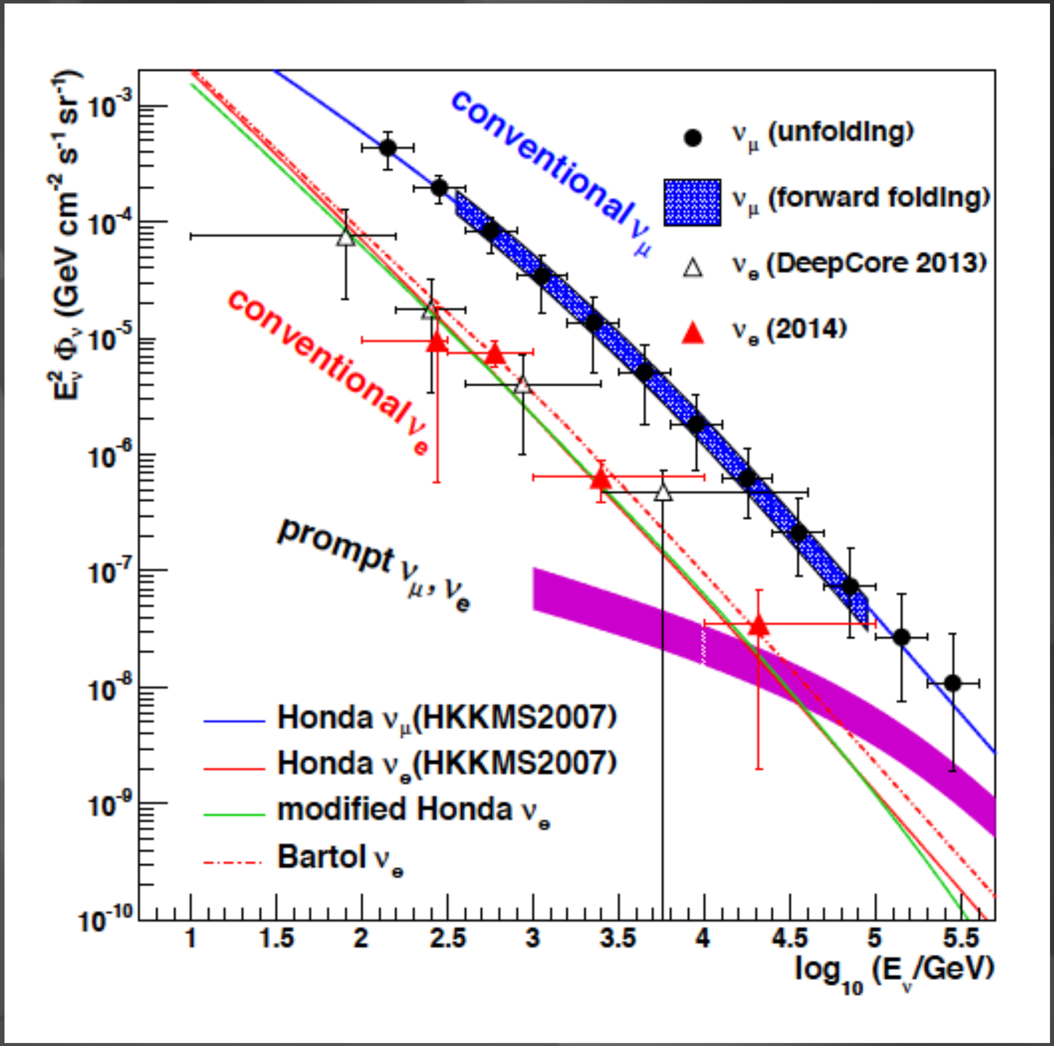

2.6 ± 0.3 PeV
inside detector

distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube



what is wrong with this picture?

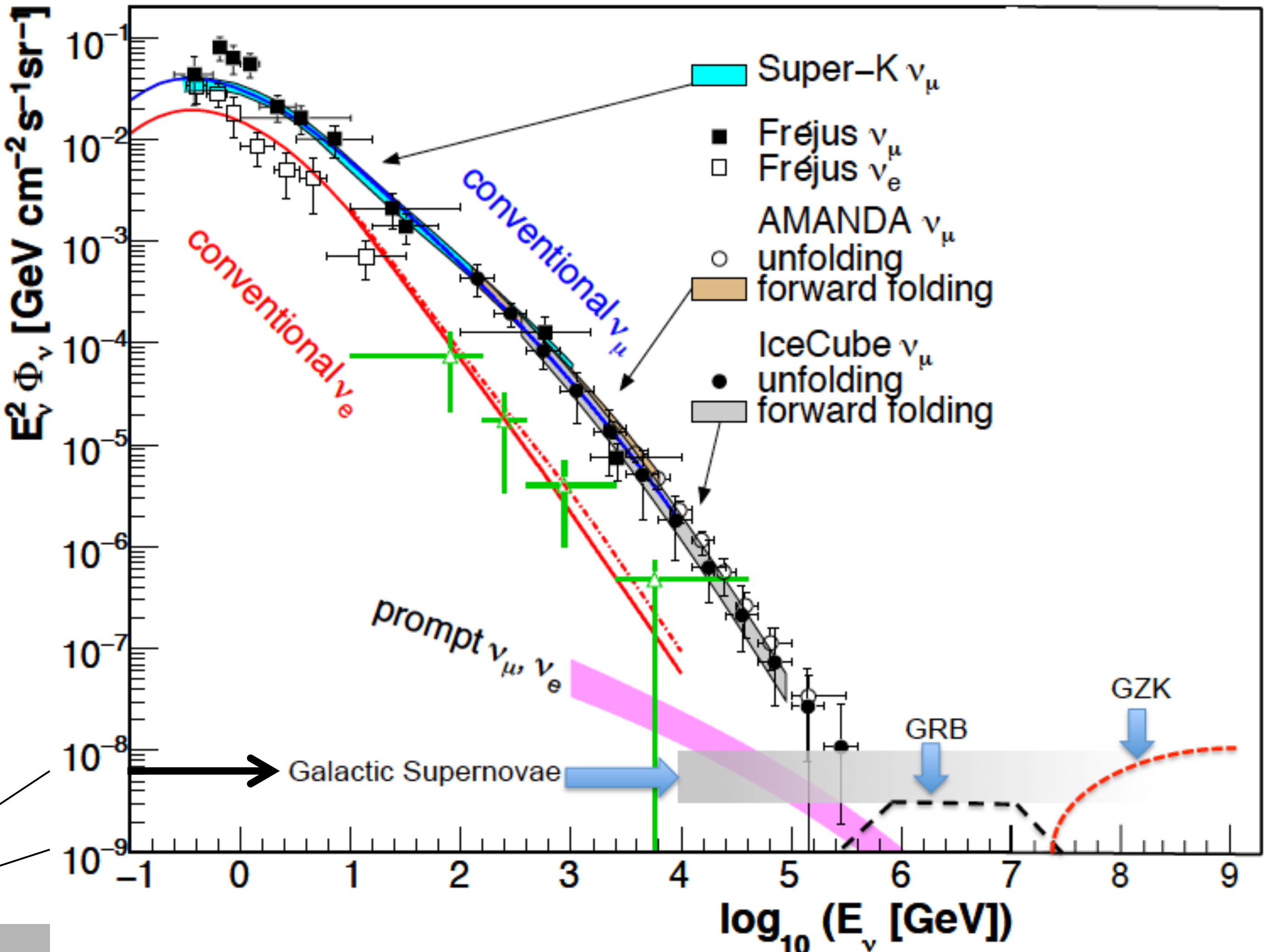
1 event per year



at 100 TeV

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



$dN/dE \sim E^{-2}$

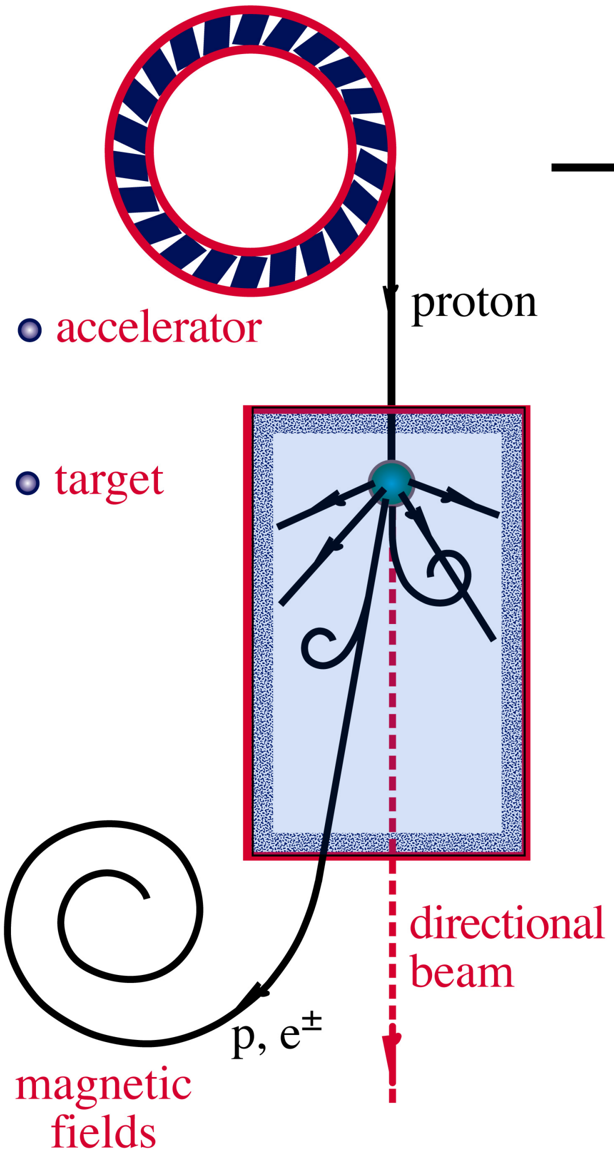
10—100 events per year for fully efficient 1 km^3 detector

atmospheric

cosmic

100 TeV

cosmic accelerators/beam dumps



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

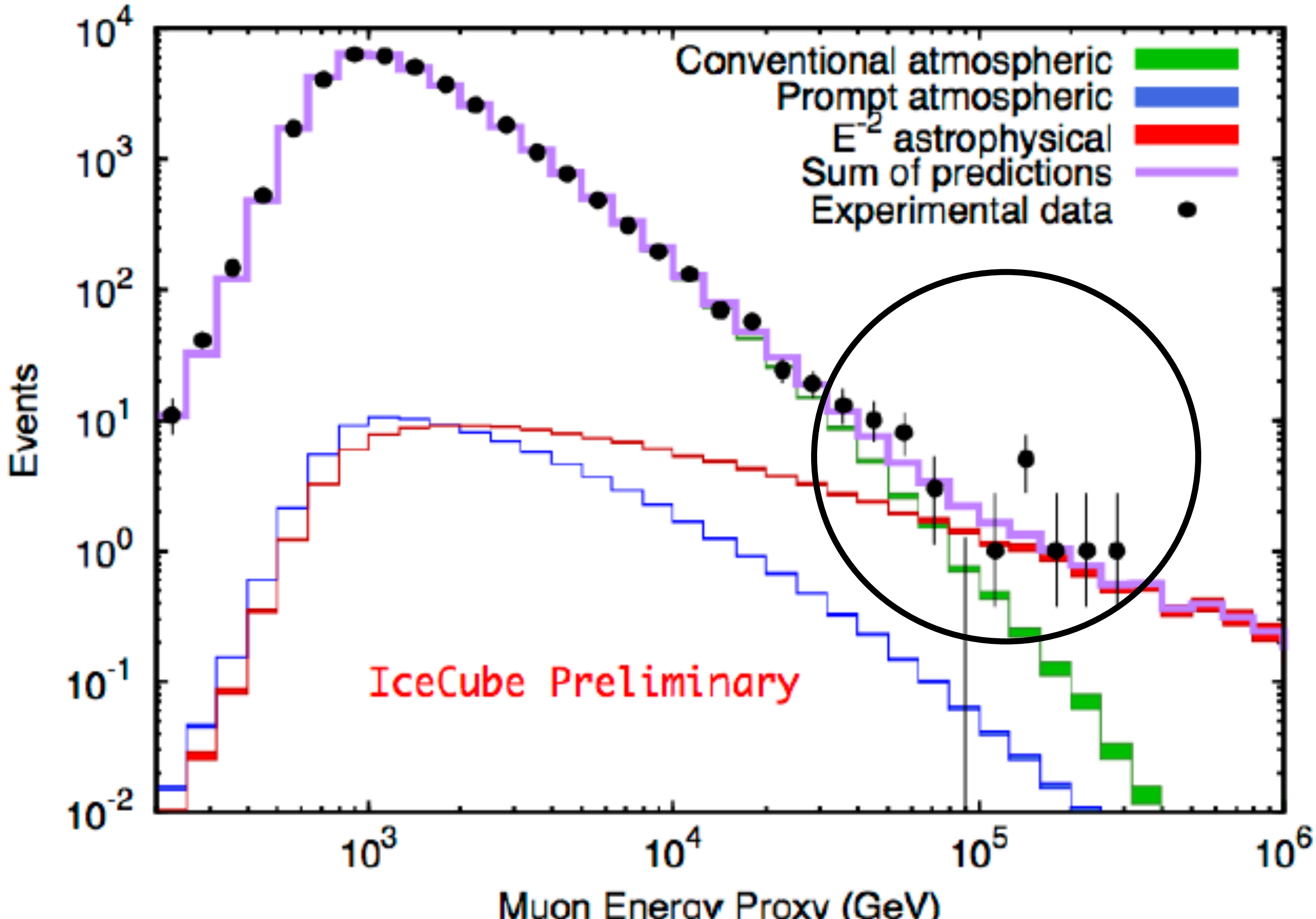
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

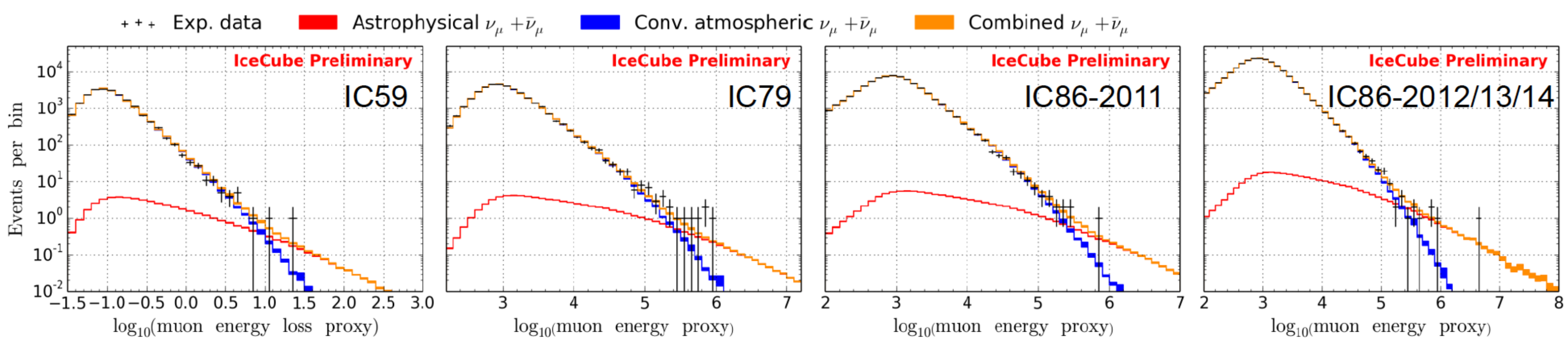
$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

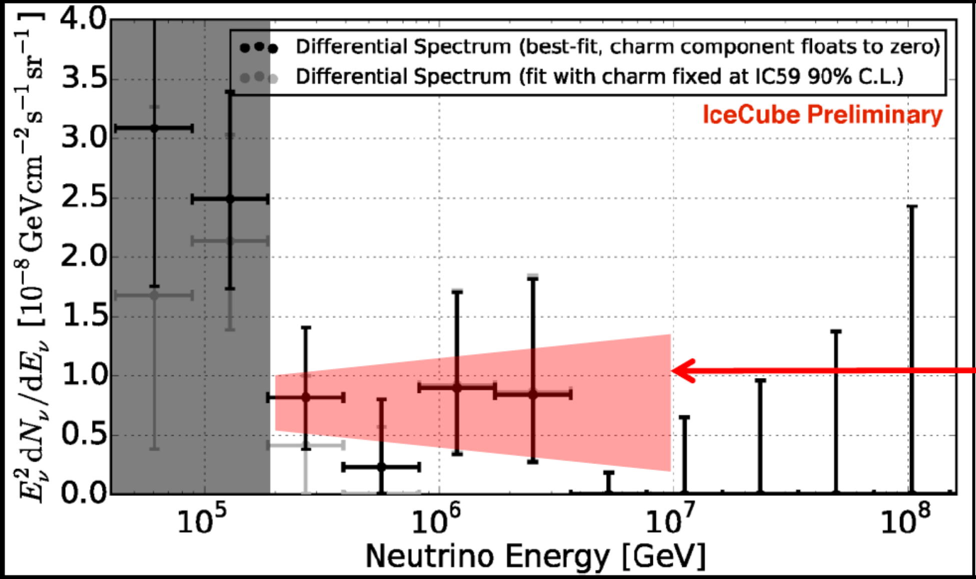
cosmic neutrinos in 2 years of data at 3.7 sigma



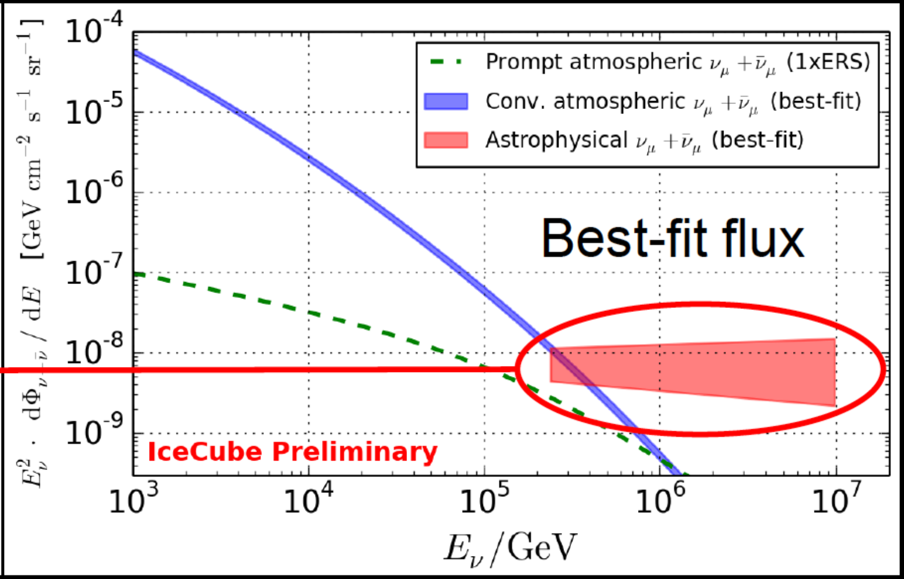
after 6 years: 3.7→ 6.0 sigma



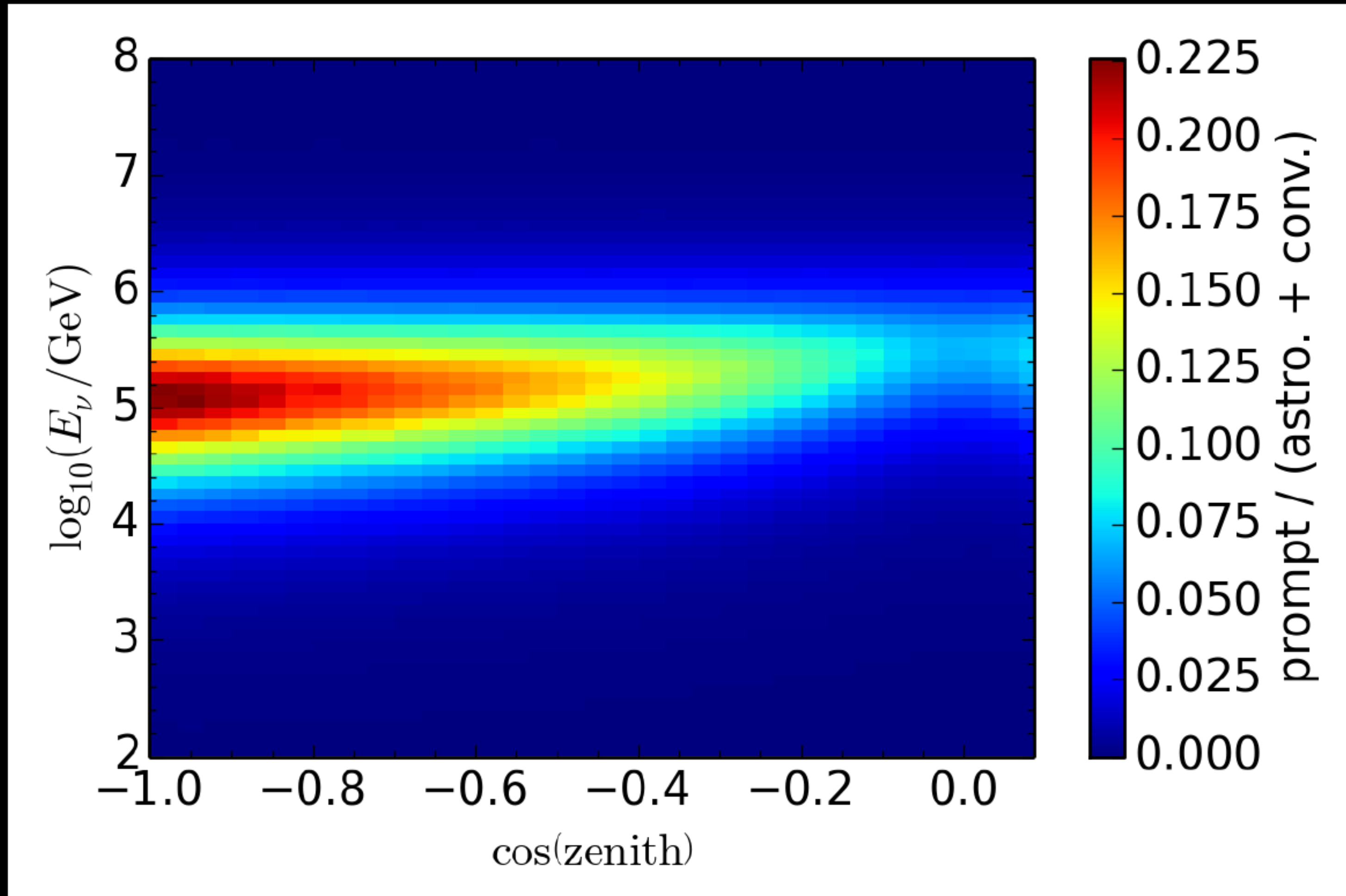
HESE 4 year unfolding
(→ dominated by shower-like events)



6 year up-going numu analysis

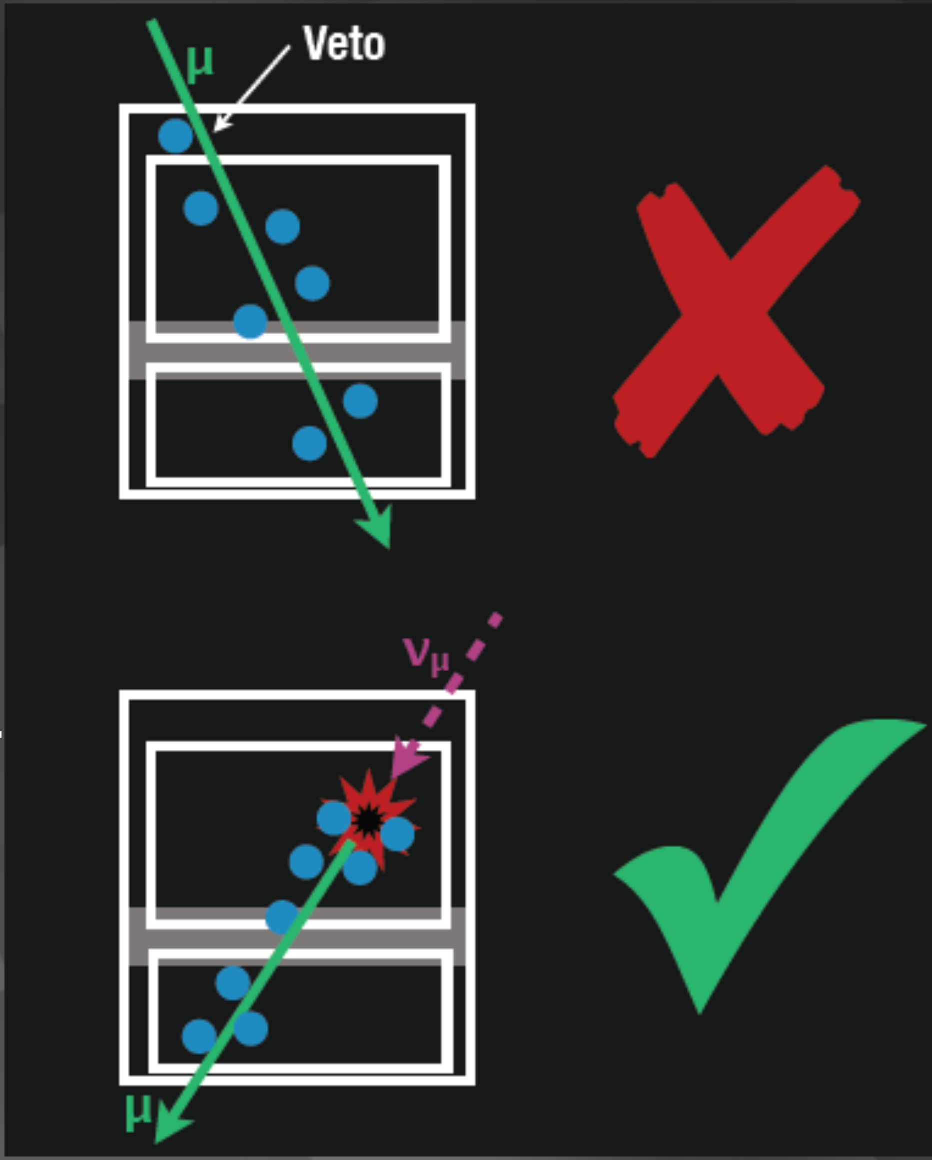


not atmospheric charm



- Prompt flux would appear @ around 100 TeV
  → ~ 20% effect in straight up-going region

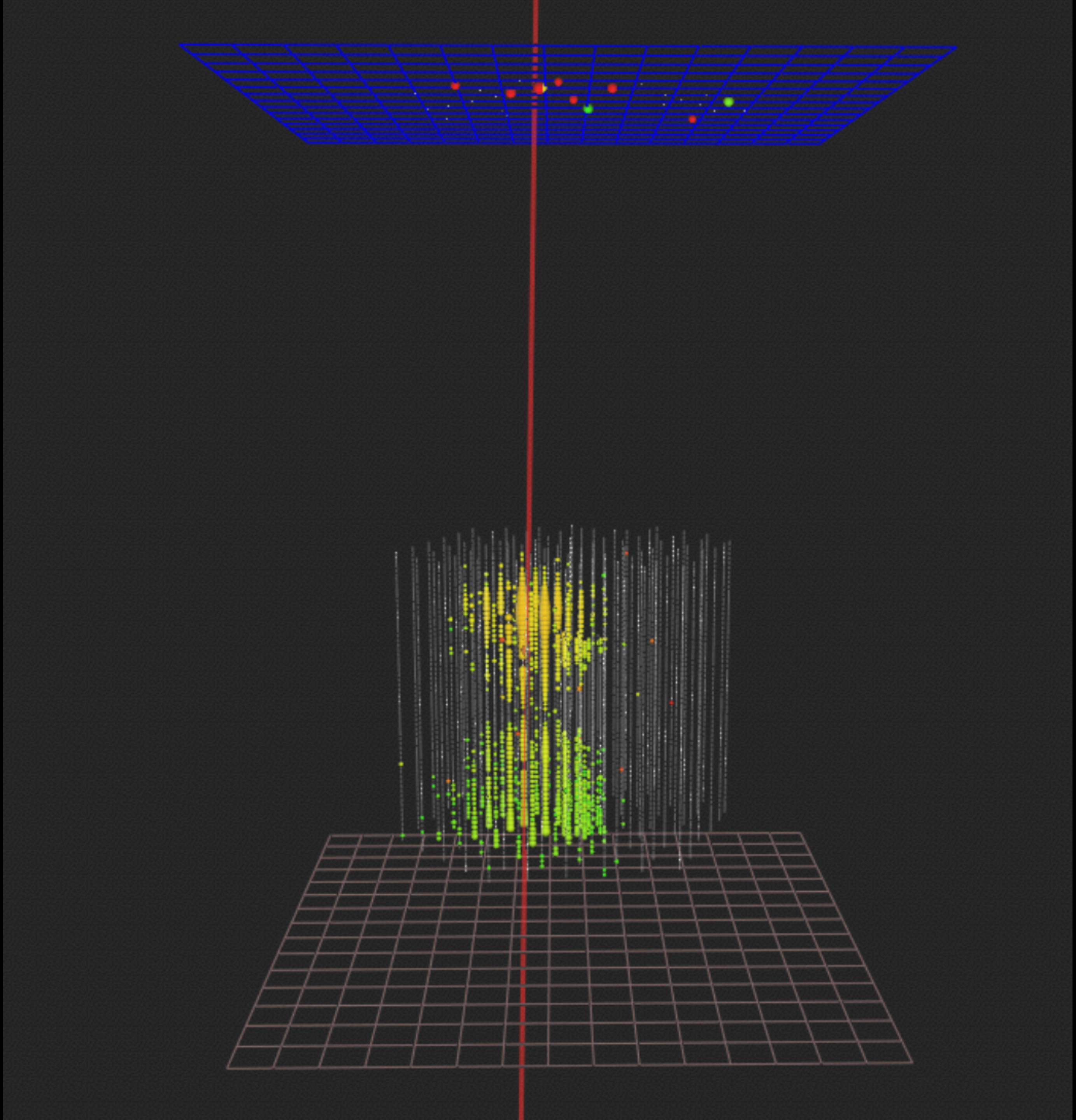
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



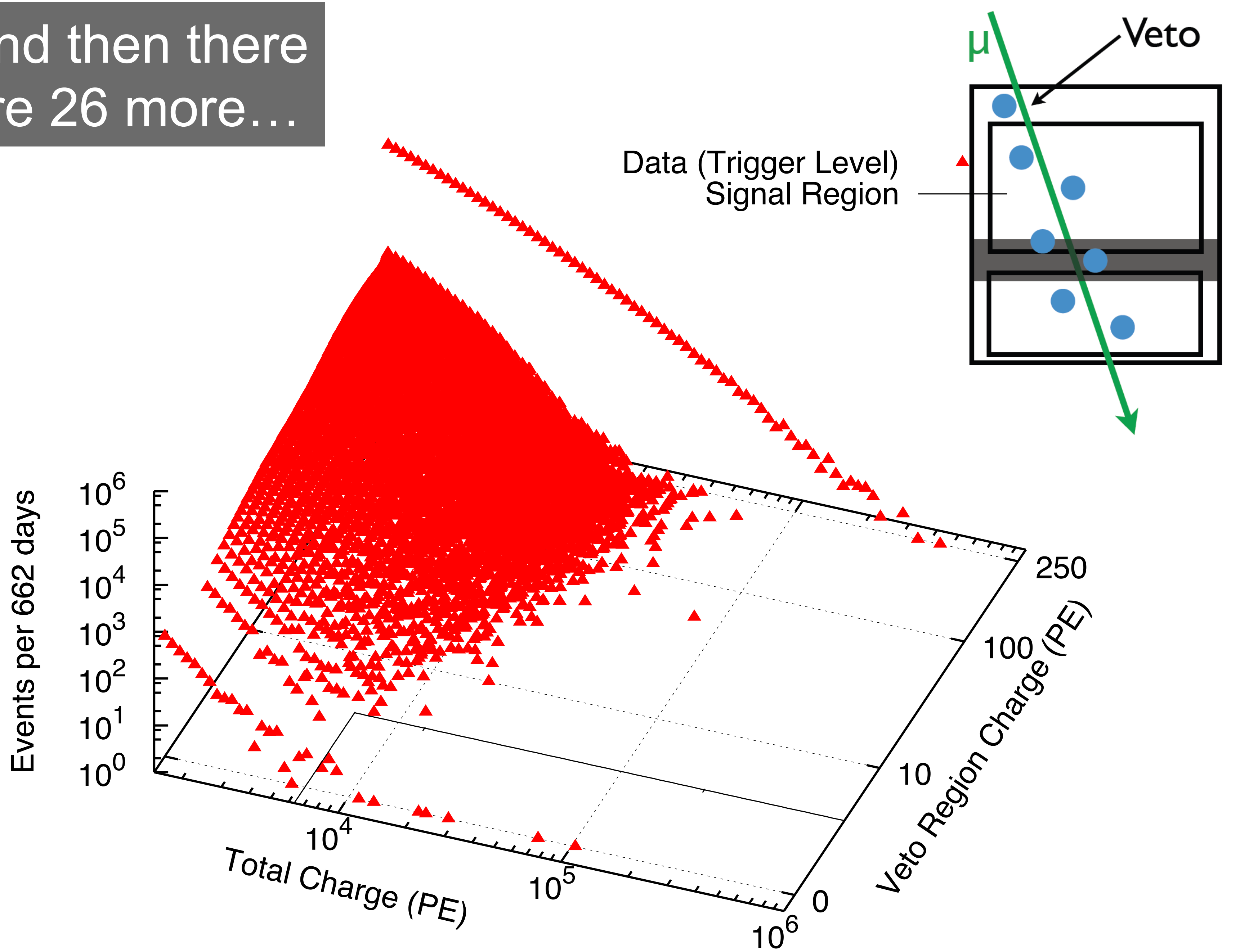
430 TeV

1 event:
~ 5 sigma
discovery

> PeV ν_μ

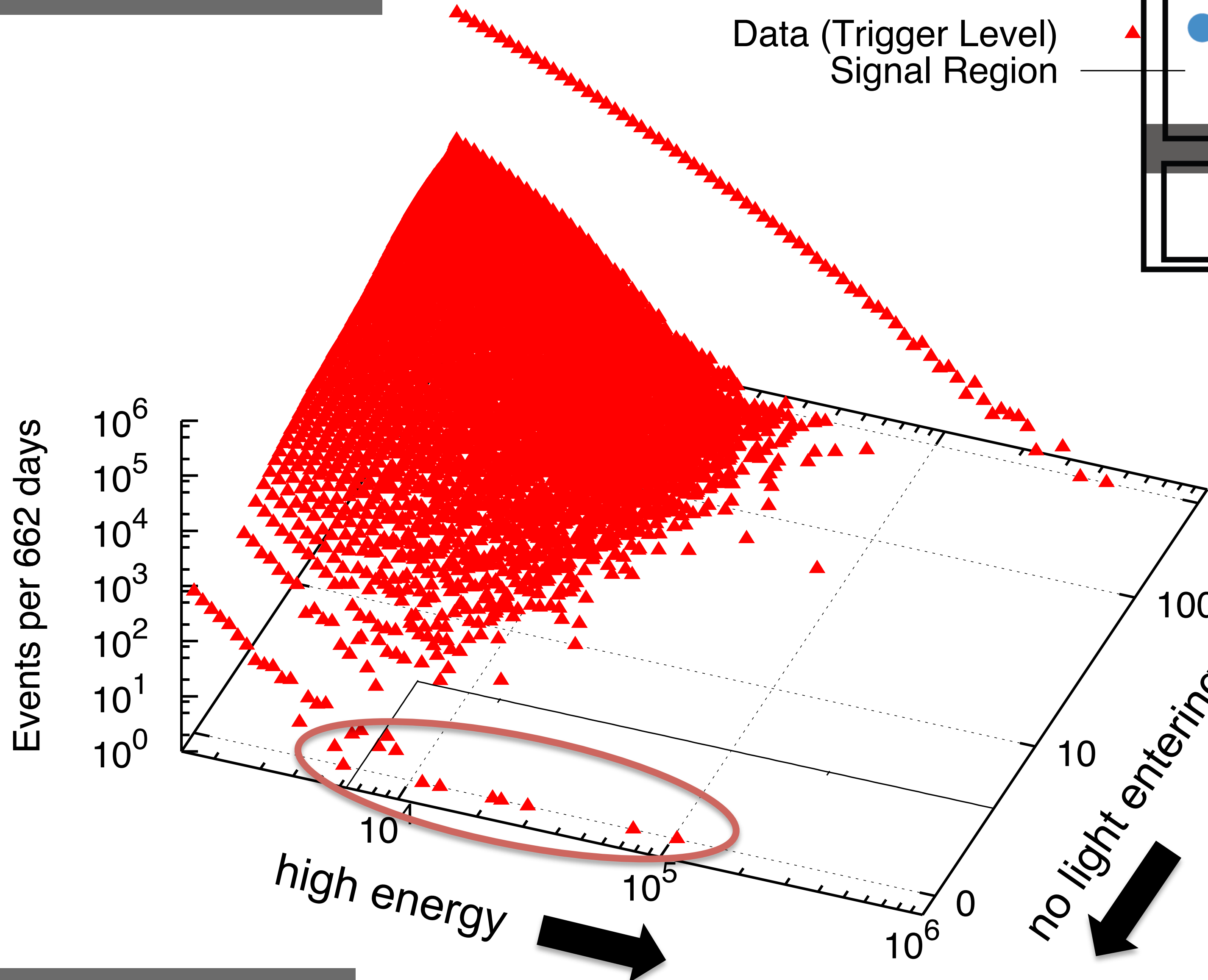


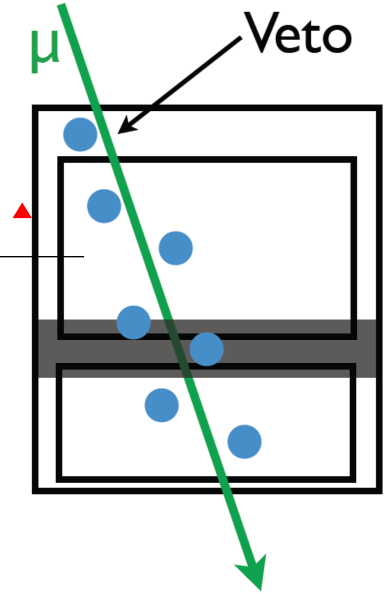
…and then there were 26 more…



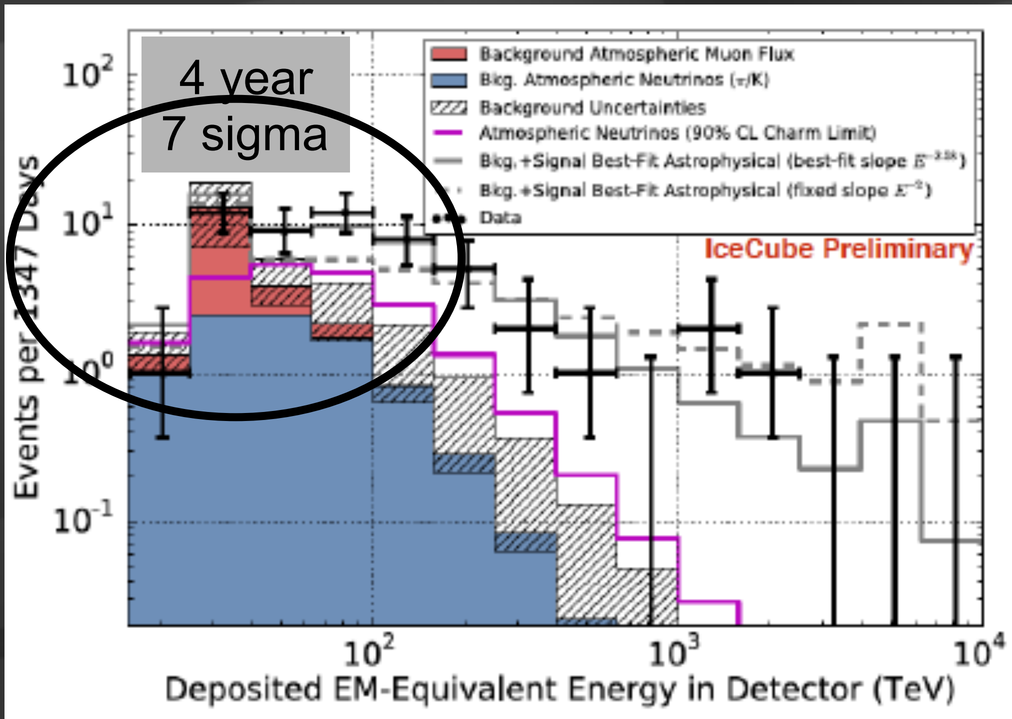
data: 86 strings one year

…and then there were 26 more…



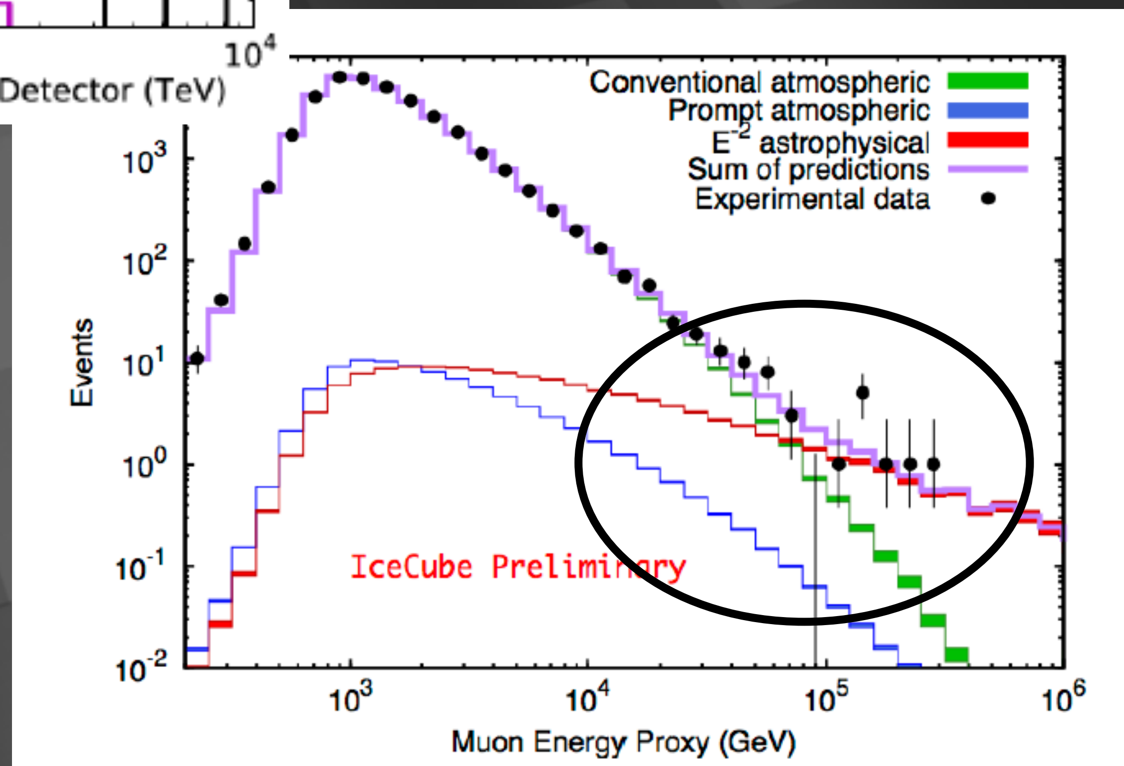


data: 86 strings one year

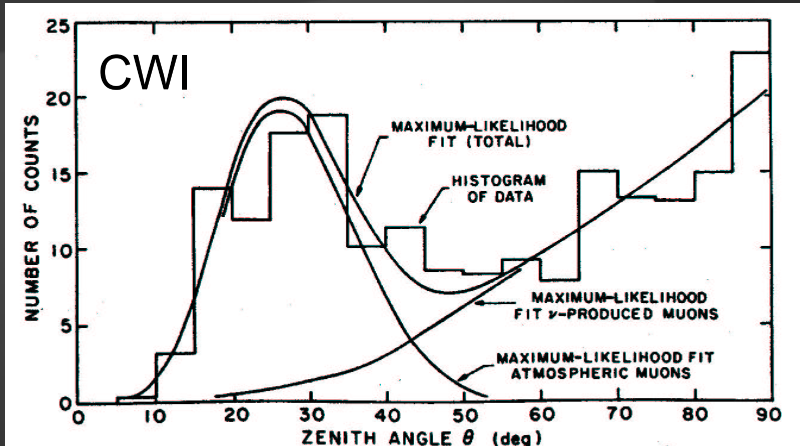


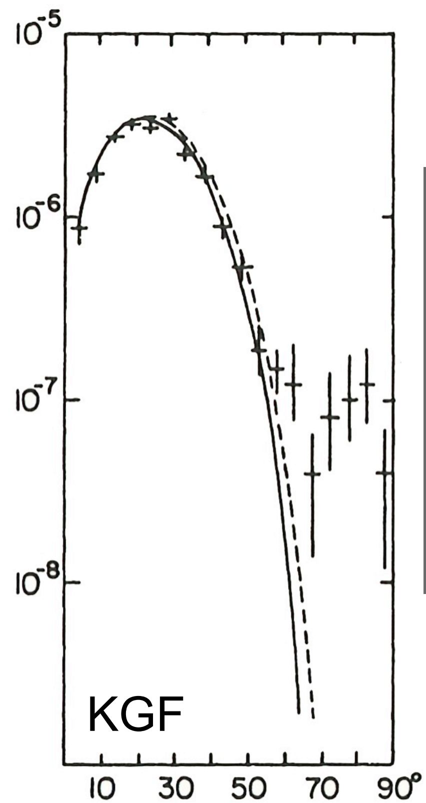
confirmation!
flux of muon neutrinos
through the Earth

neutrinos of all flavors
interacting inside
IceCube



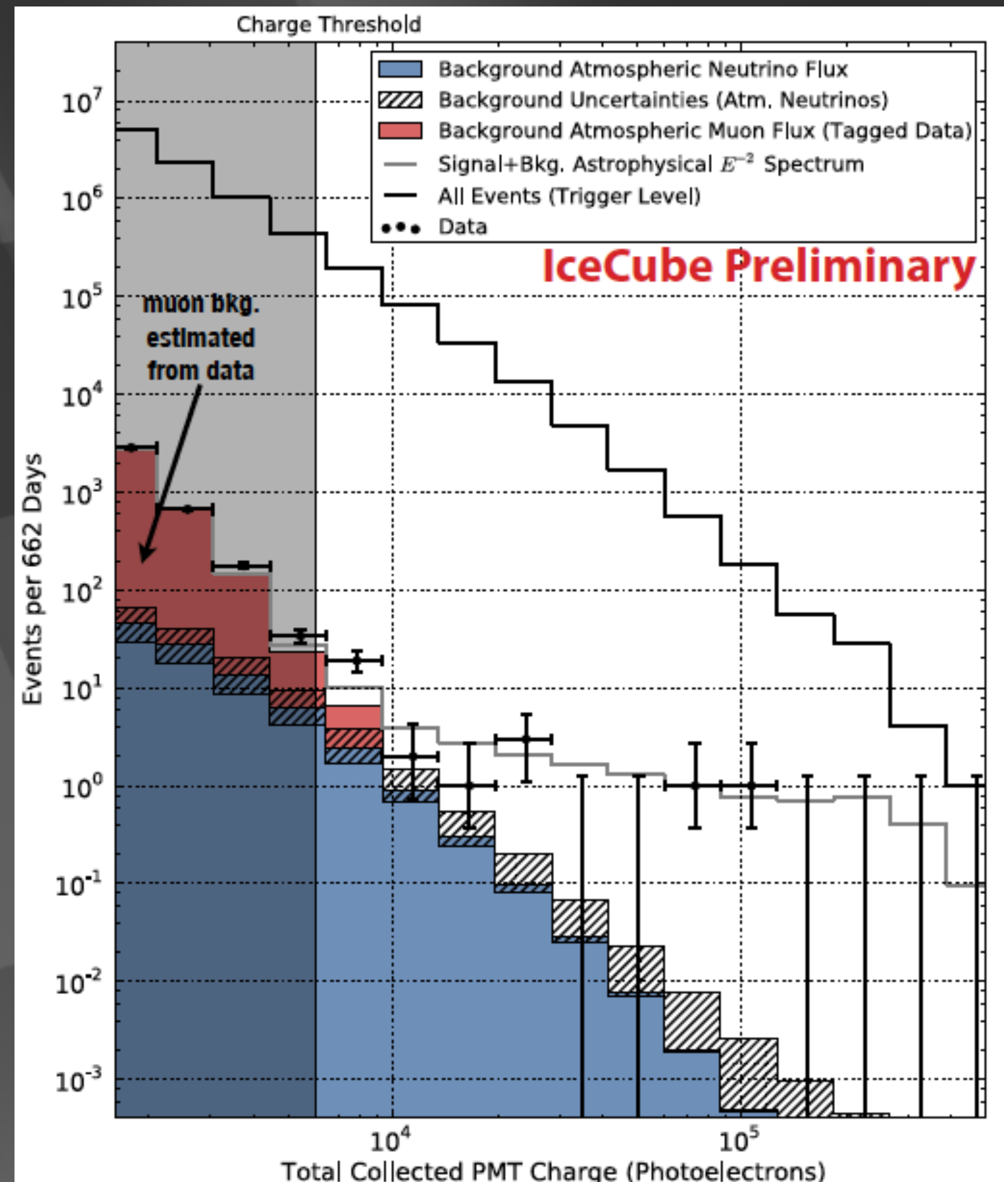
2013 atmospheric and cosmic neutrinos

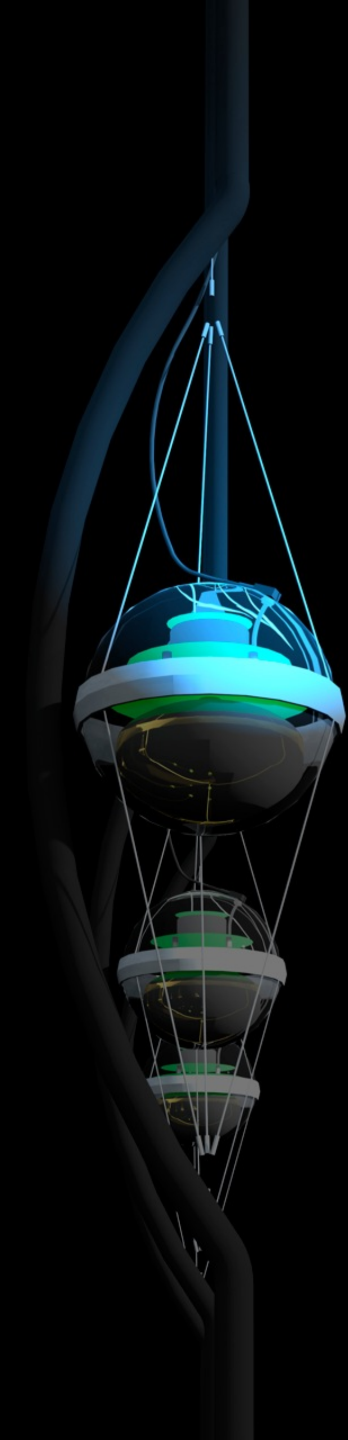




1965

cosmic ray muons and atmospheric neutrinos





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francis halzen

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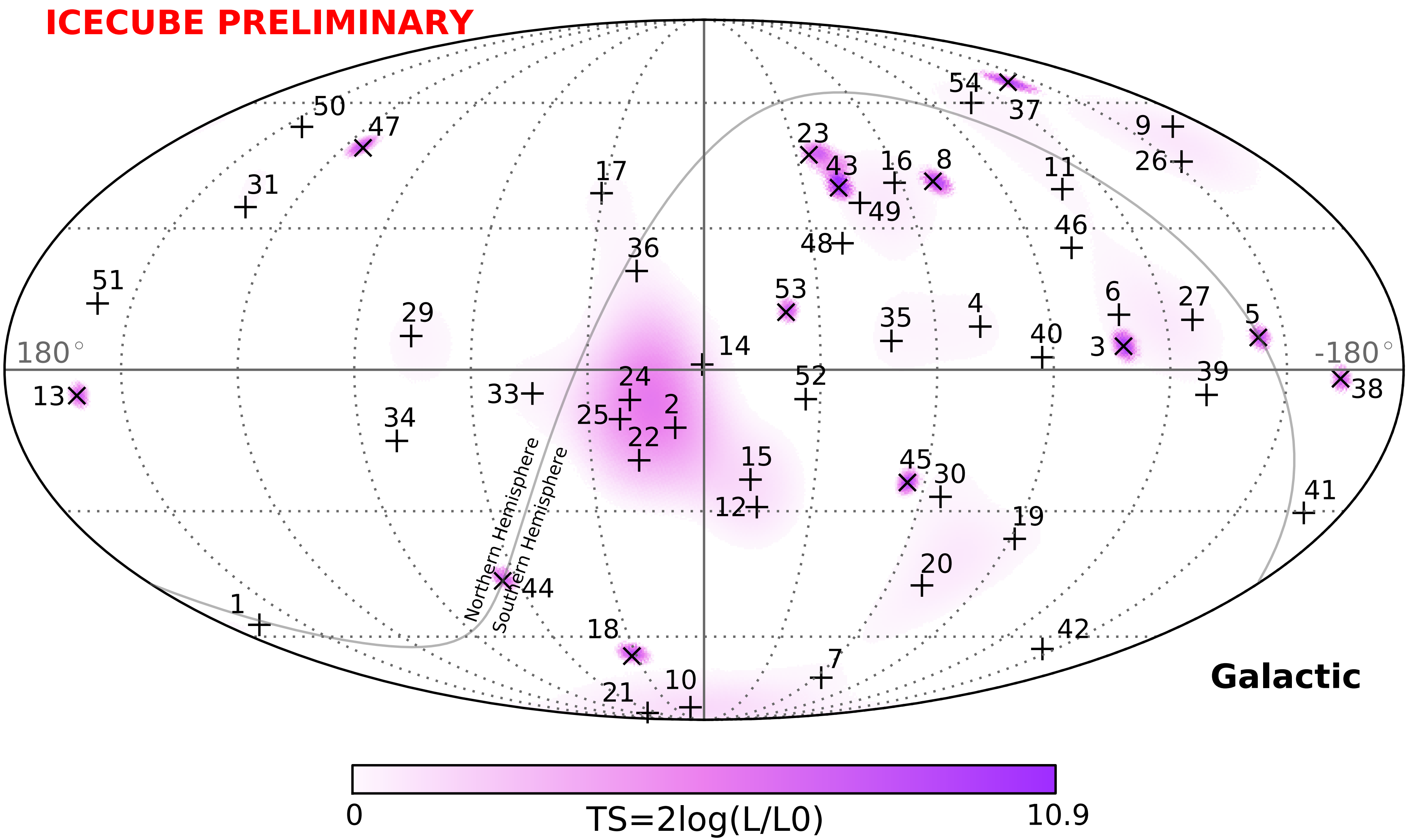
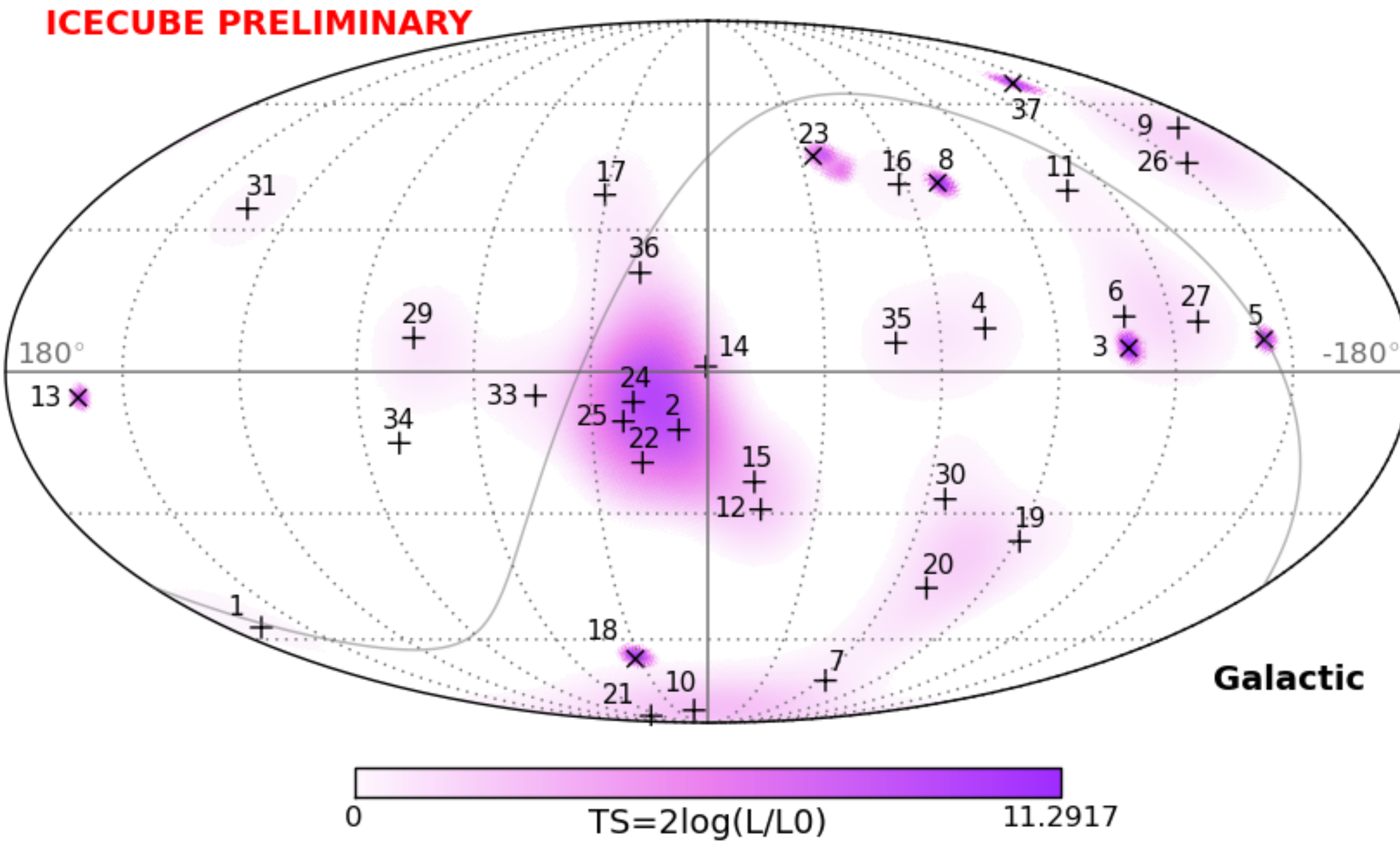
4 year HESE



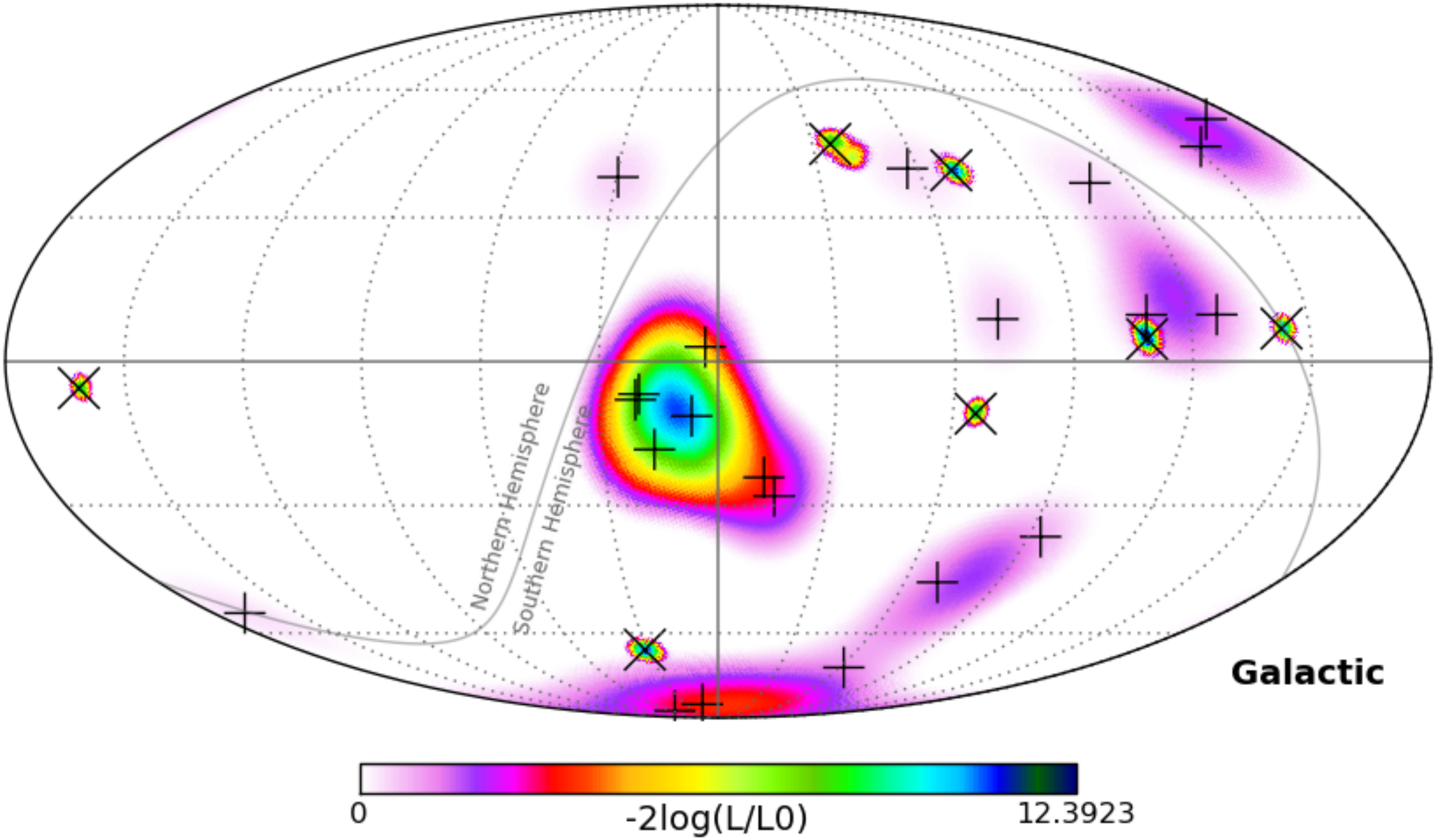
where do they come from?

2 year HESE



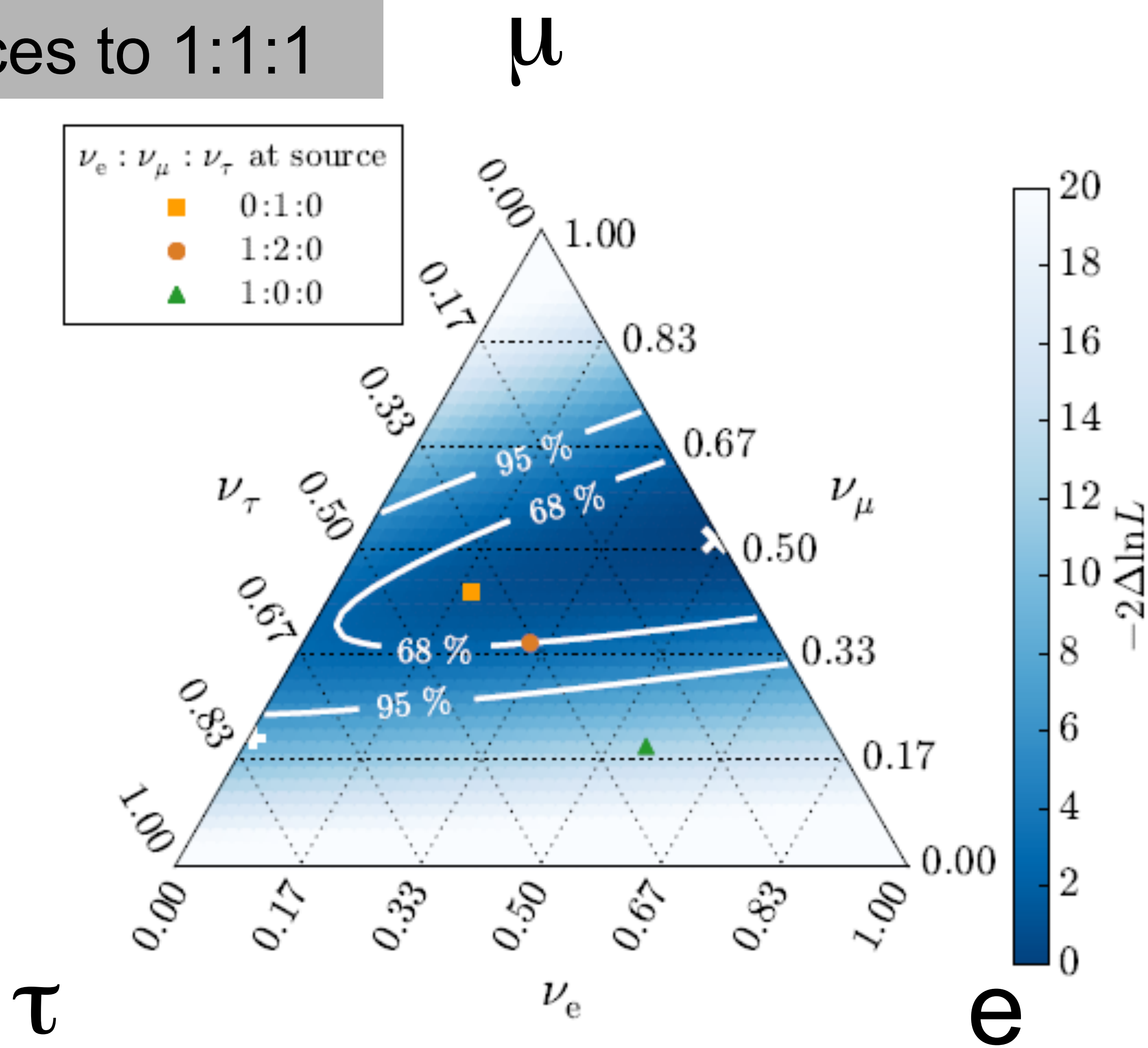
ICECUBE PRELIMINARY
180°
-180°
13
31
1
29
34
33
17
36
24
25
22
2
14
18
21
10
15
12
23
37
16
8
35
30
19
20
7
4
11
9
26
6
3
27
5
Galactic
0
TS=2log(L/L0)
11.2917

2 year HESE



Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

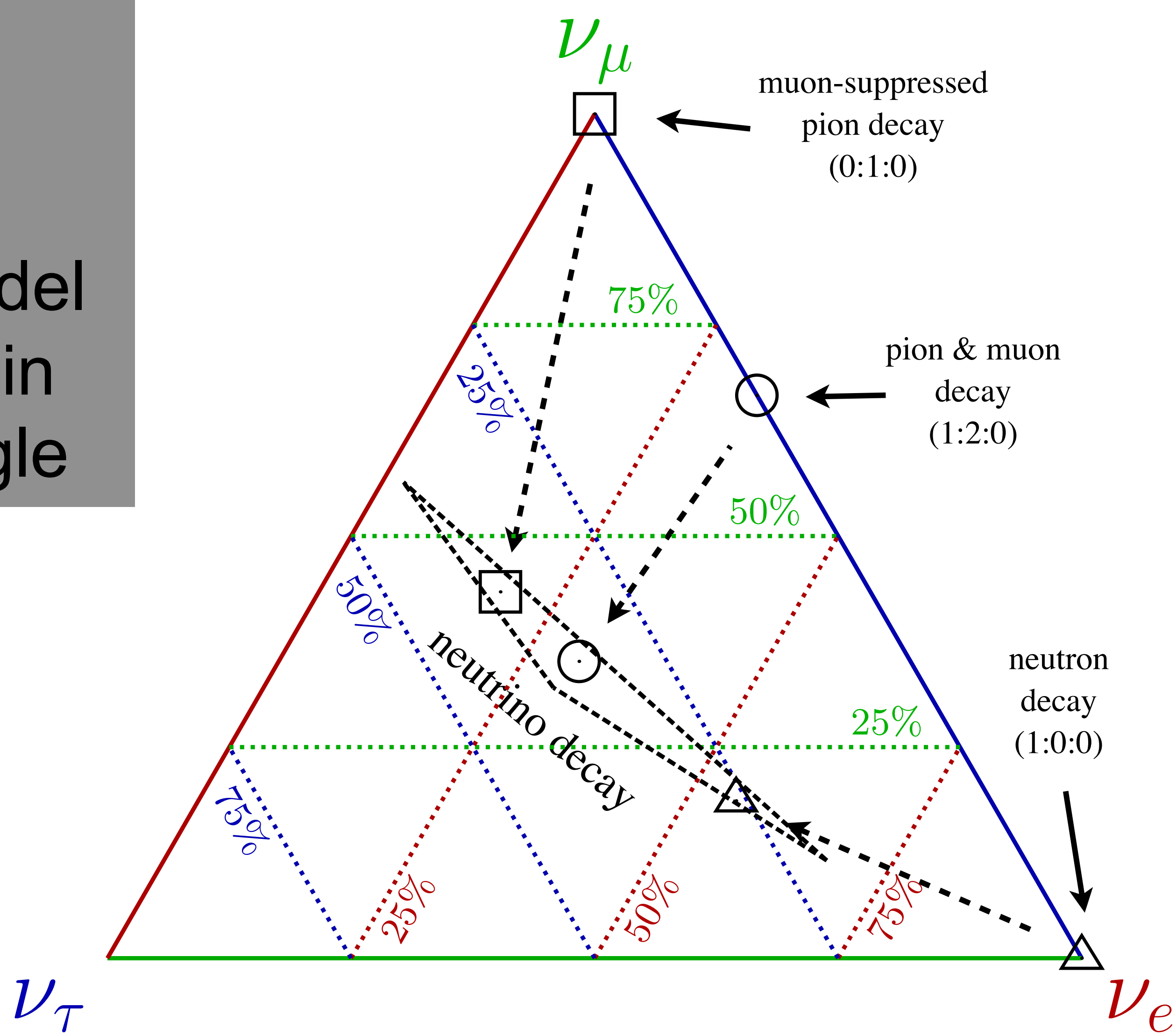
oscillate over cosmic distances to 1:1:1



new physics ?

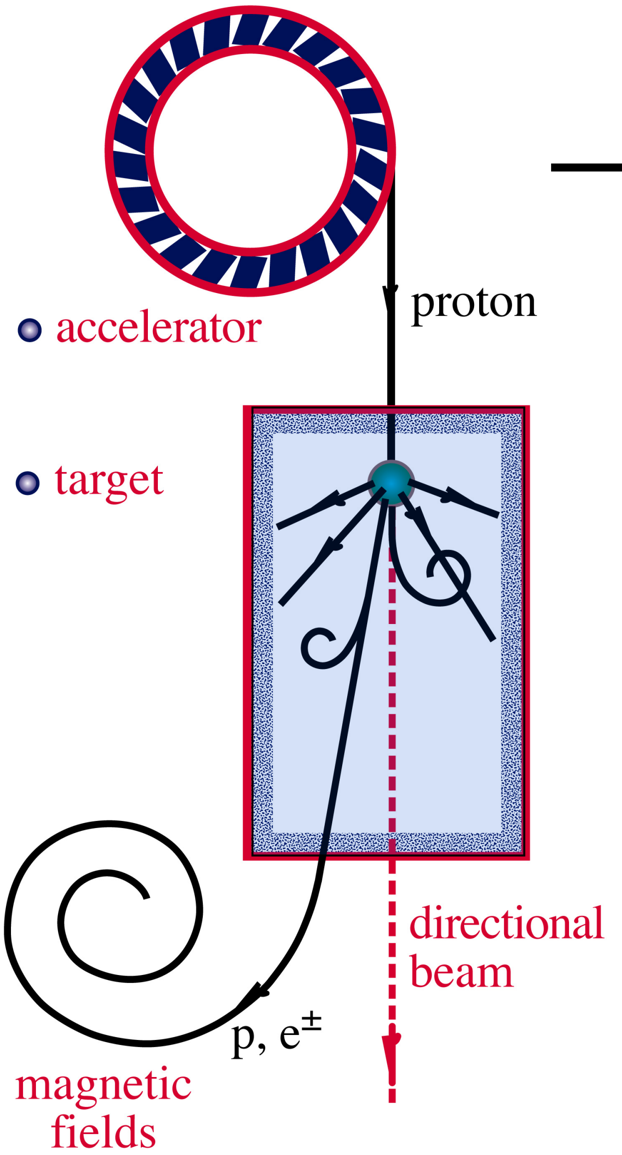
if not…

every model ends up in the triangle



- we observe a diffuse extragalactic flux
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

cosmic accelerators/beam dumps



accelerator is powered by large gravitational energy

black hole
neutron star

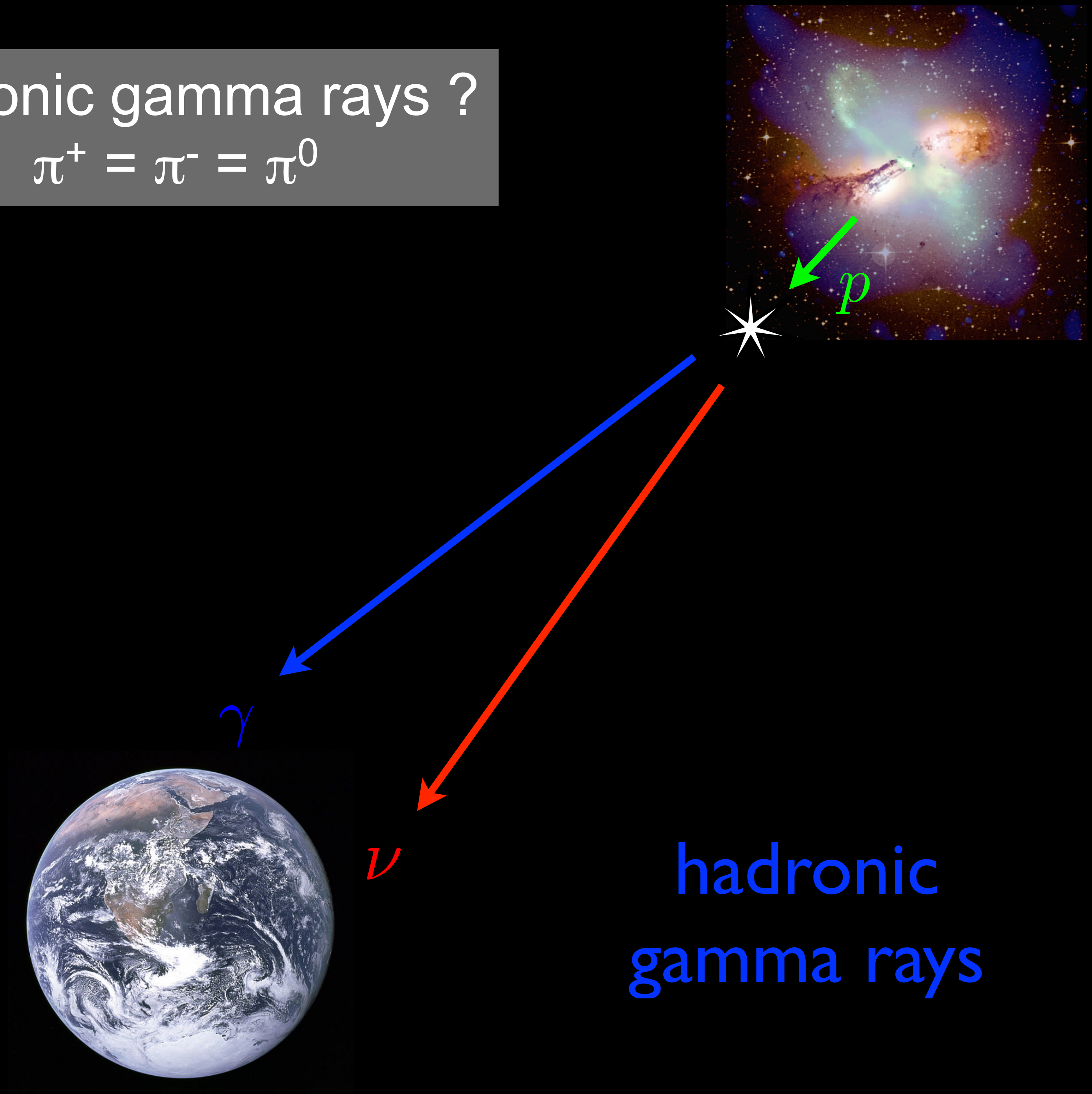
radiation and dust

$p + \gamma \rightarrow n + \pi^+$
~ cosmic ray + neutrino

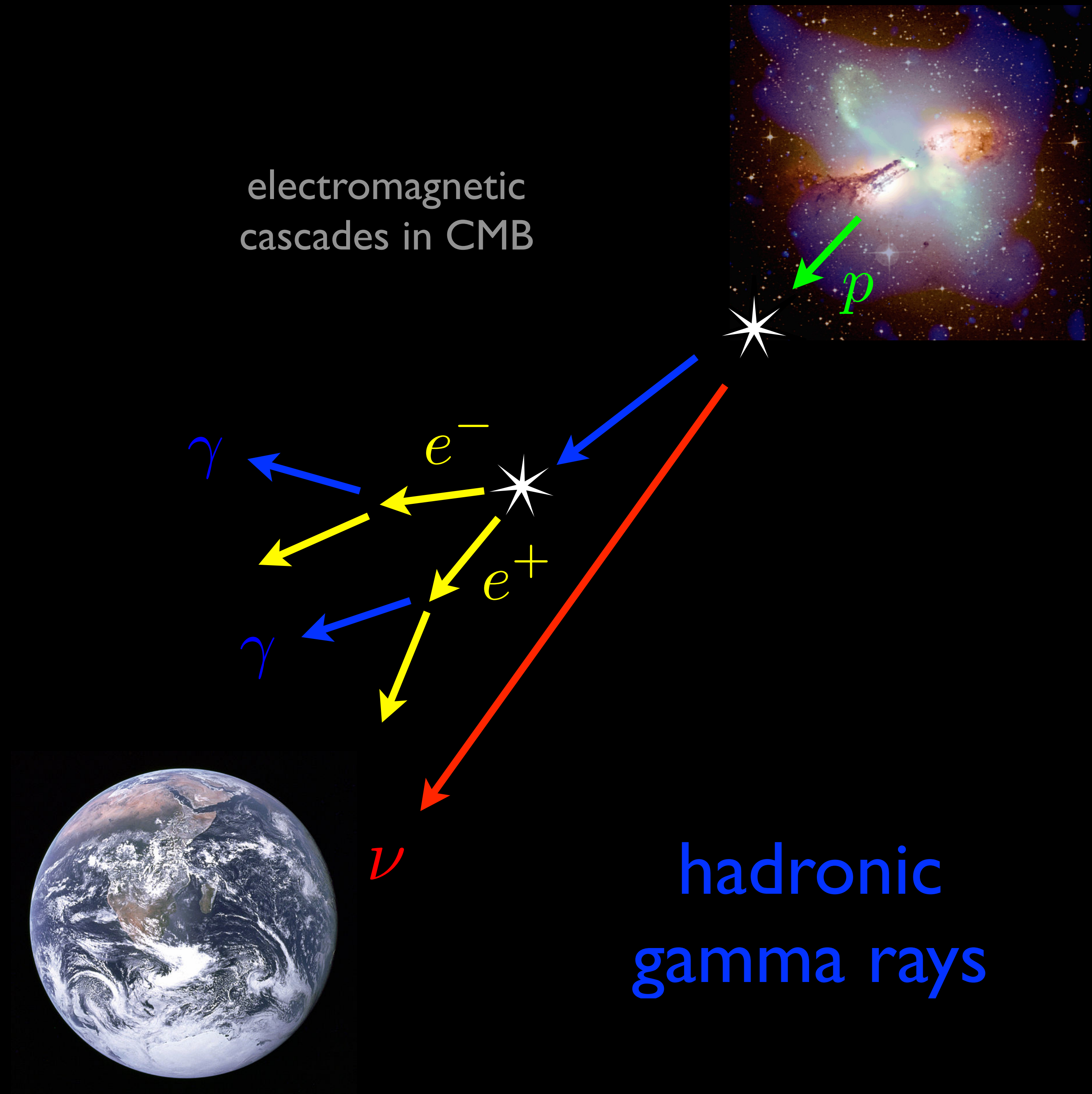
$\rightarrow p + \pi^0$
~ cosmic ray + gamma

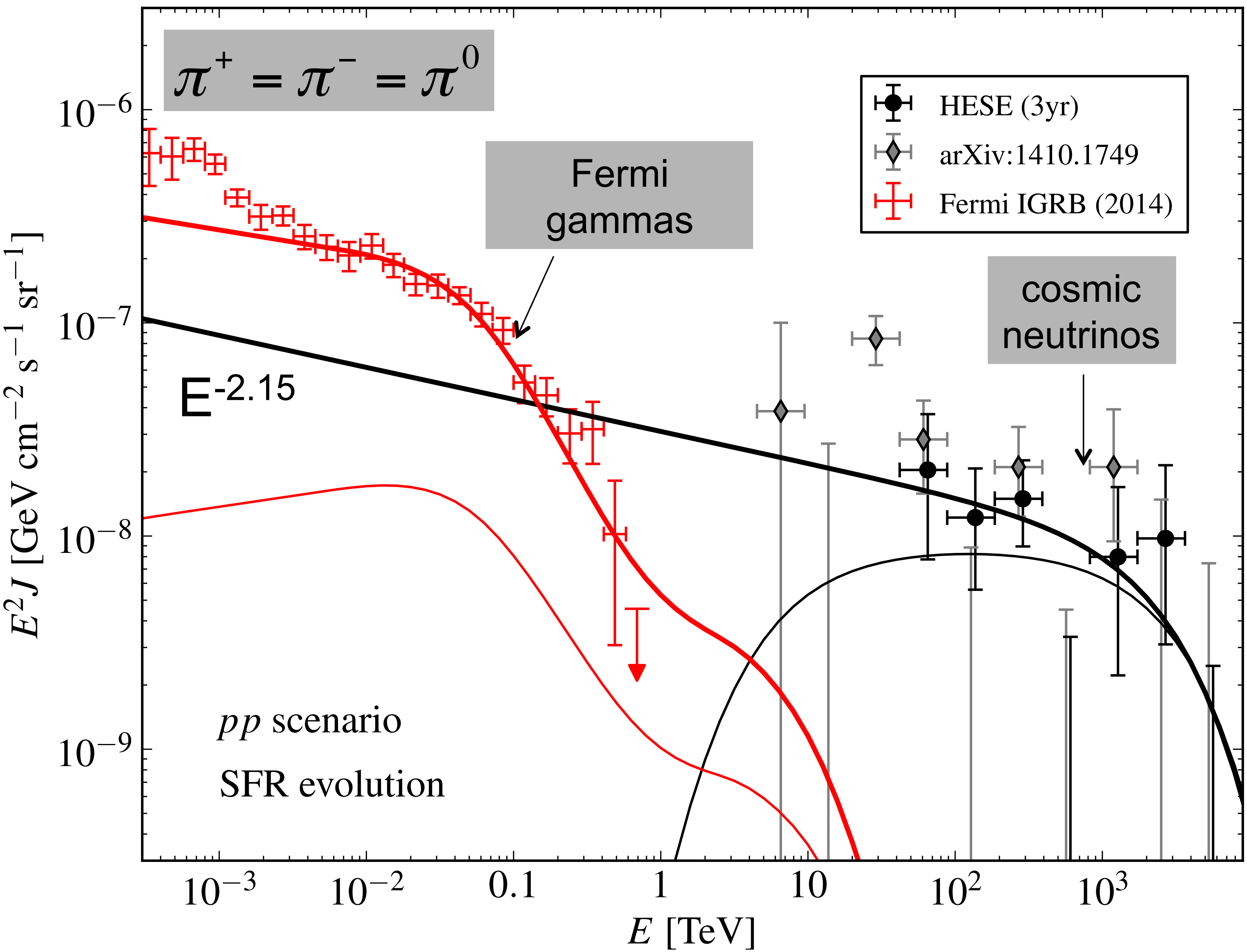
hadronic gamma rays ?

$\pi^+ = \pi^- = \pi^0$



hadronic
gamma rays


electromagnetic
cascades in CMB
p
e−
e+
γ
γ
ν
hadronic
gamma rays



$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
E^-2.15
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

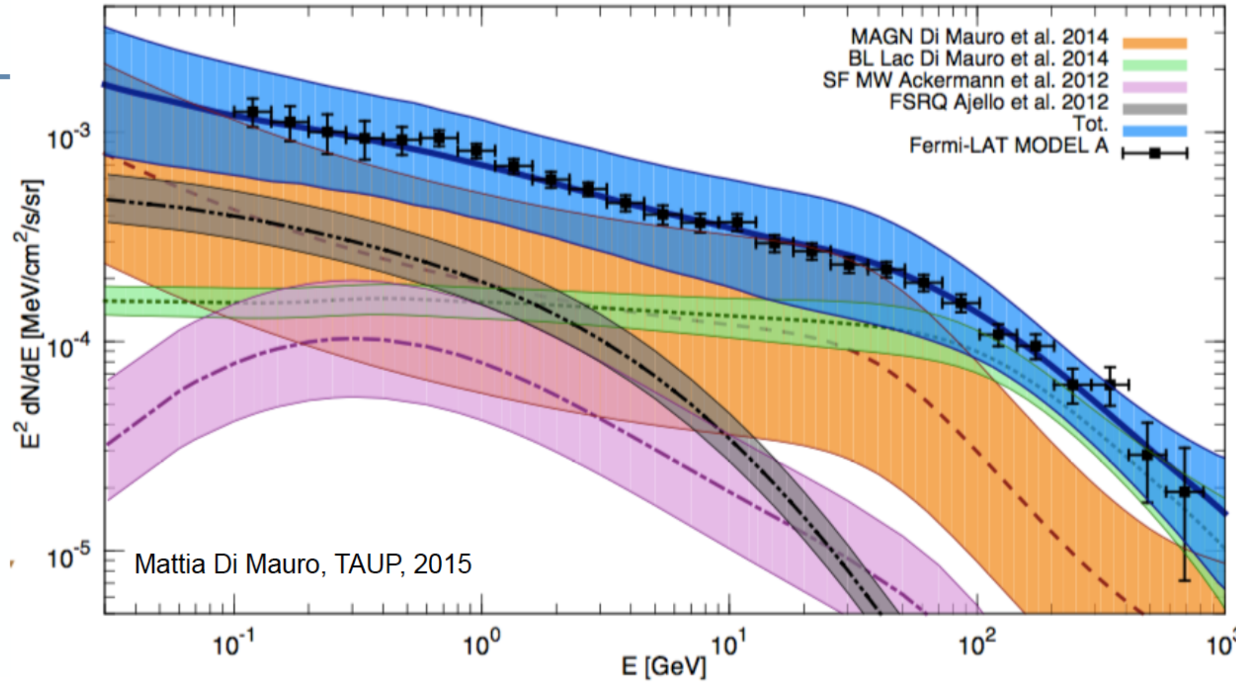
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

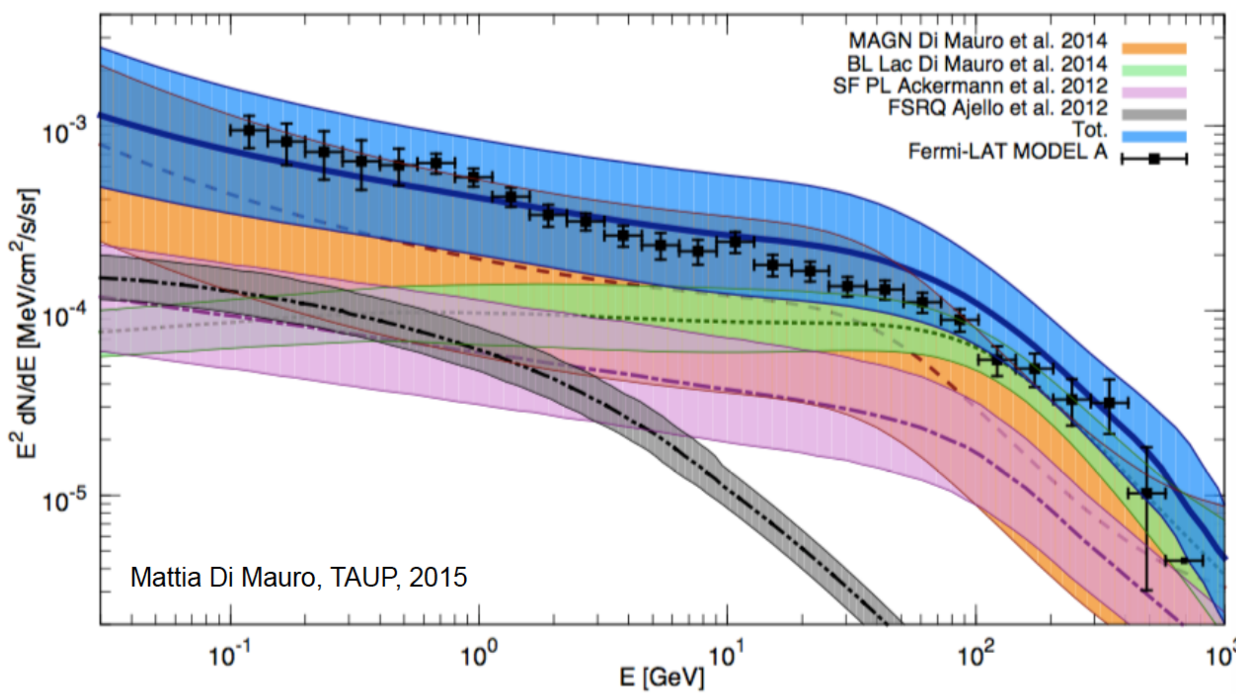
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)

- at some level common Fermi-IceCube sources?

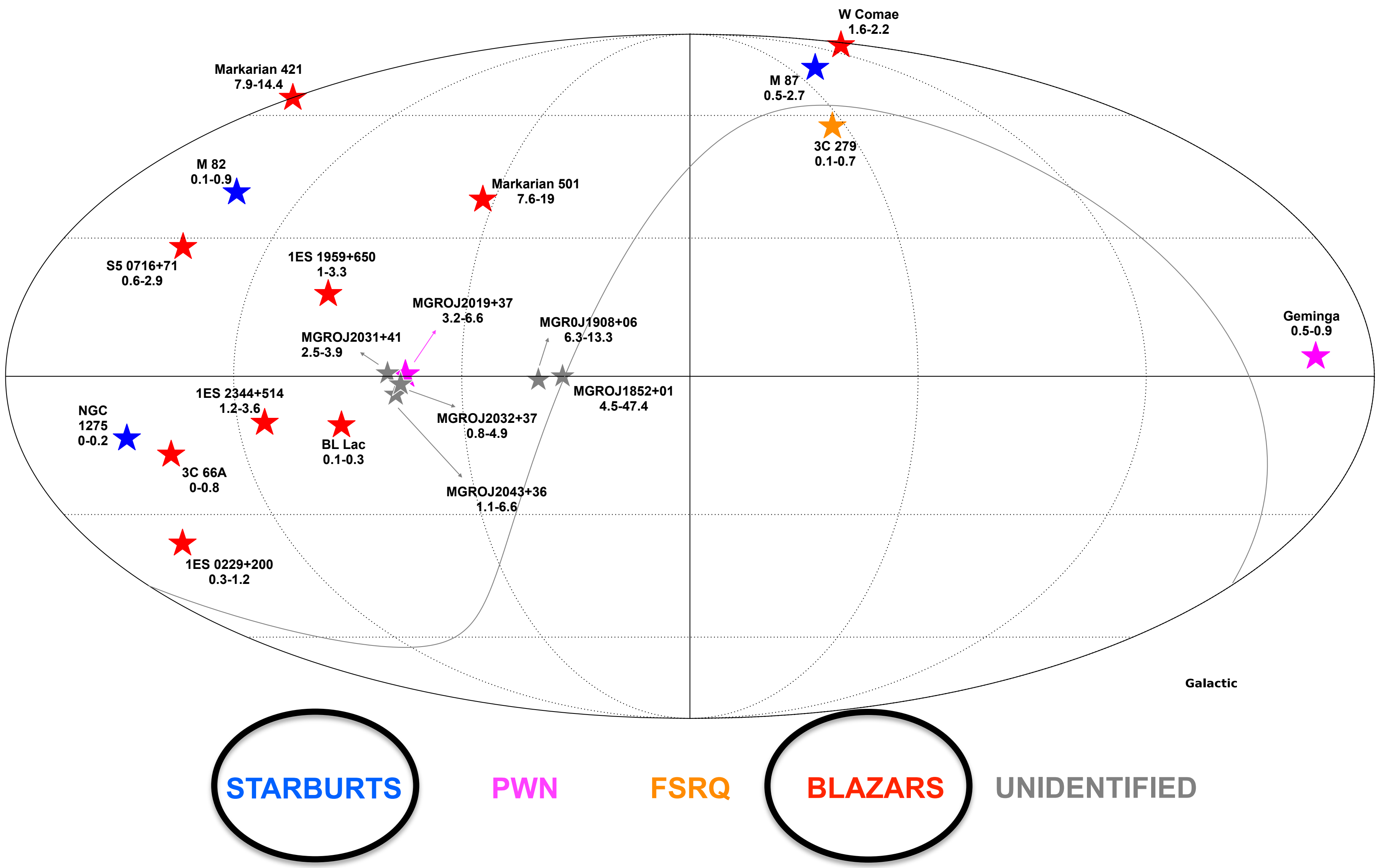
A census

- BL Lac class of Blazars dominates the high-energy gamma-ray emission
  - 86% (+16%/-14%) above 50 GeV
- Large uncertainties in radio-galaxy and star-forming galaxy contributions
- Real diffuse contributions must be small
  - UHECR interactions
  - WIMP annihilation
  - etc.



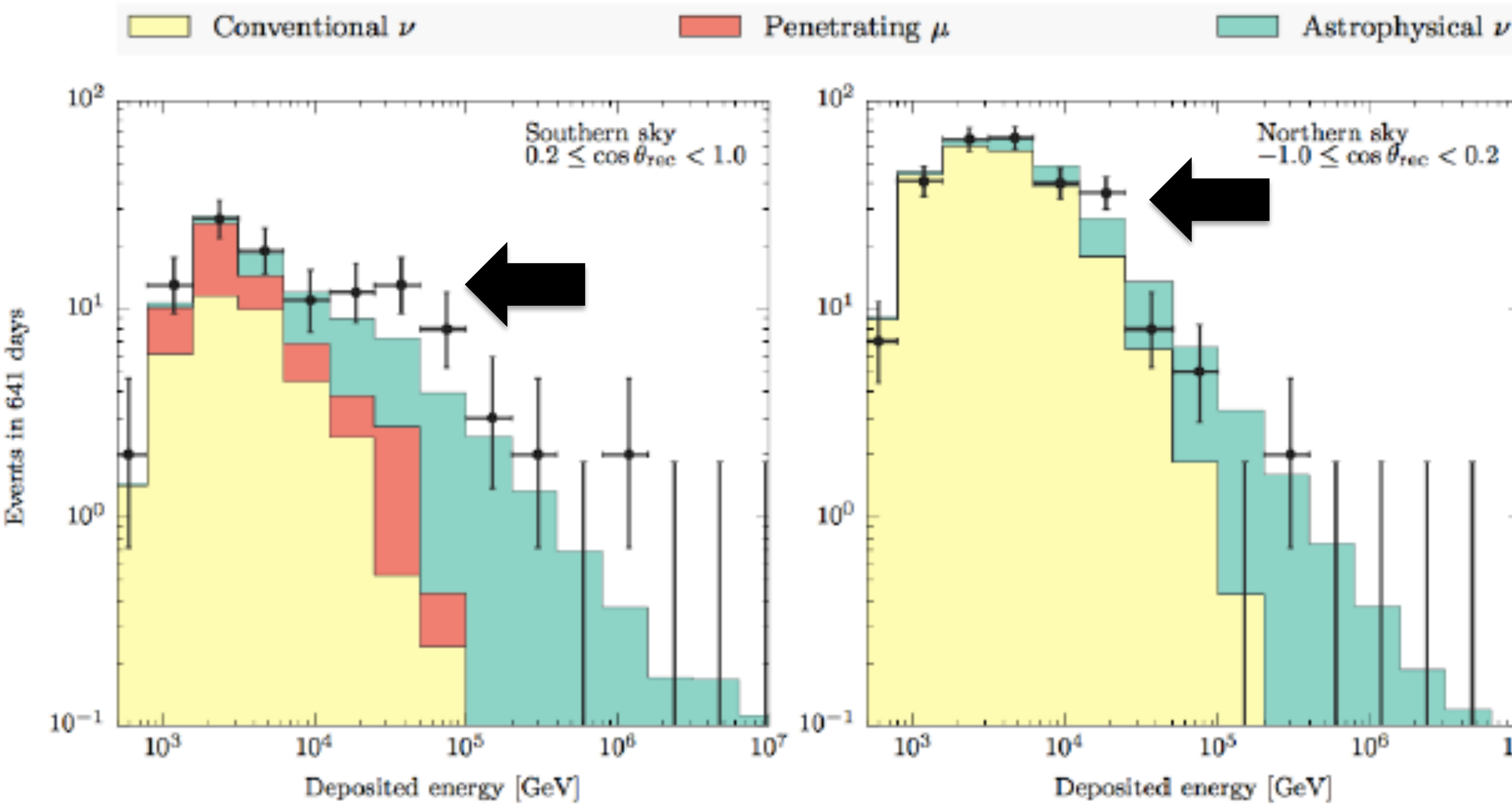


photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters



- there is more

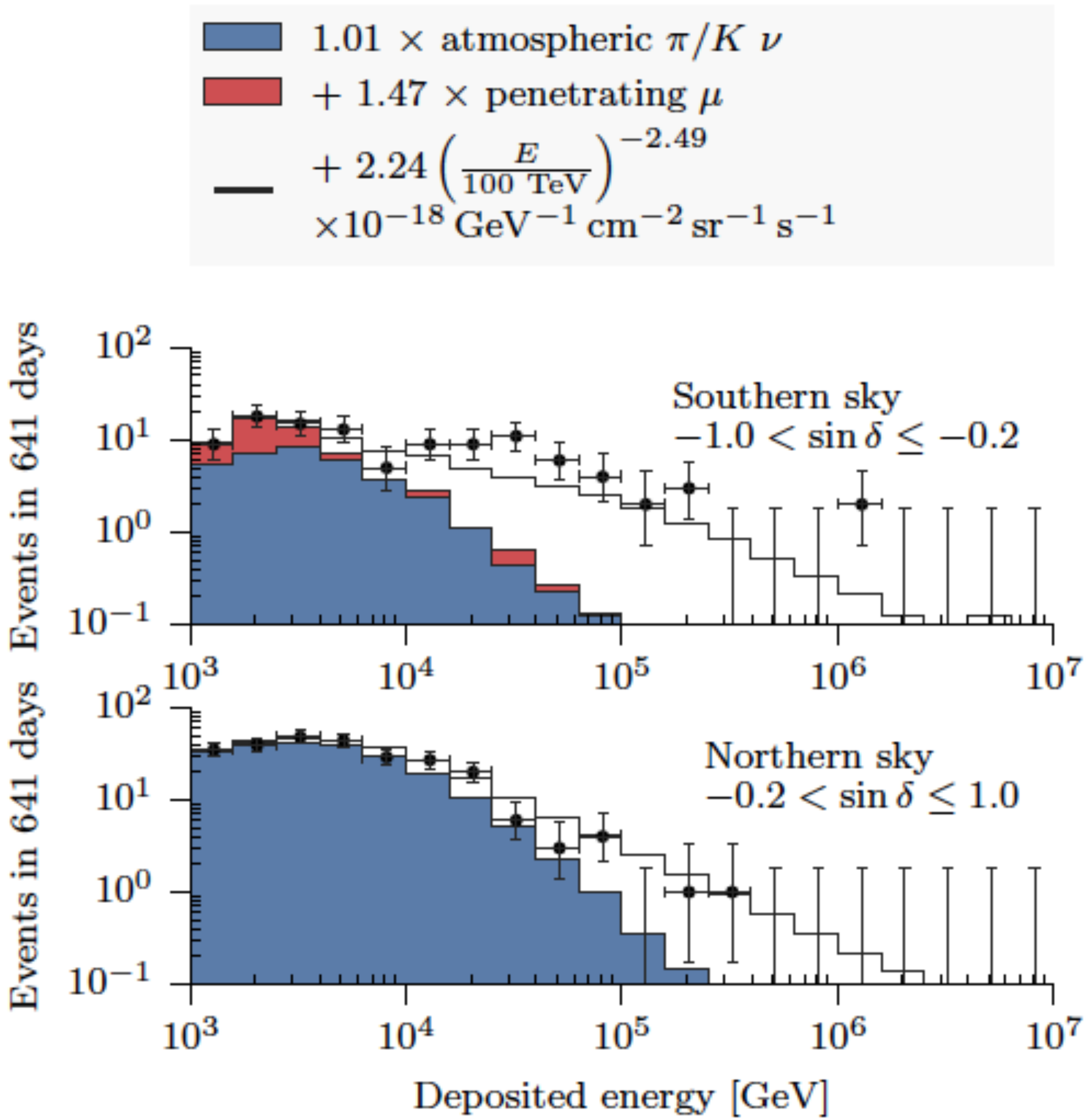
towards lower energies: a second component?



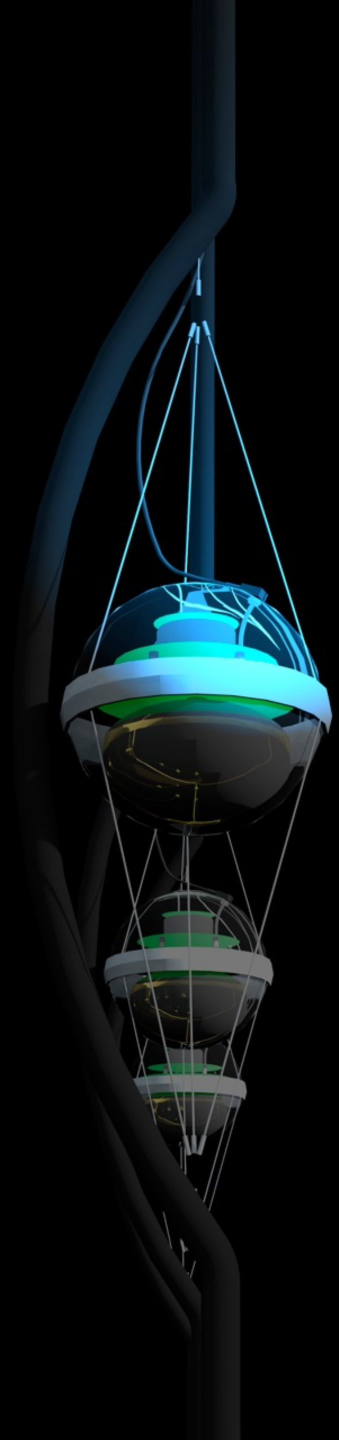
warning:

- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth



1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
+ 2.24 (E / 100 TeV)^−2.49 ×10^−18 GeV^−1 cm^−2 sr^−1 s^−1
Events in 641 days
Southern sky
−1.0 < sin δ ≤ −0.2
Northern sky
−0.2 < sin δ ≤ 1.0
Deposited energy [GeV]



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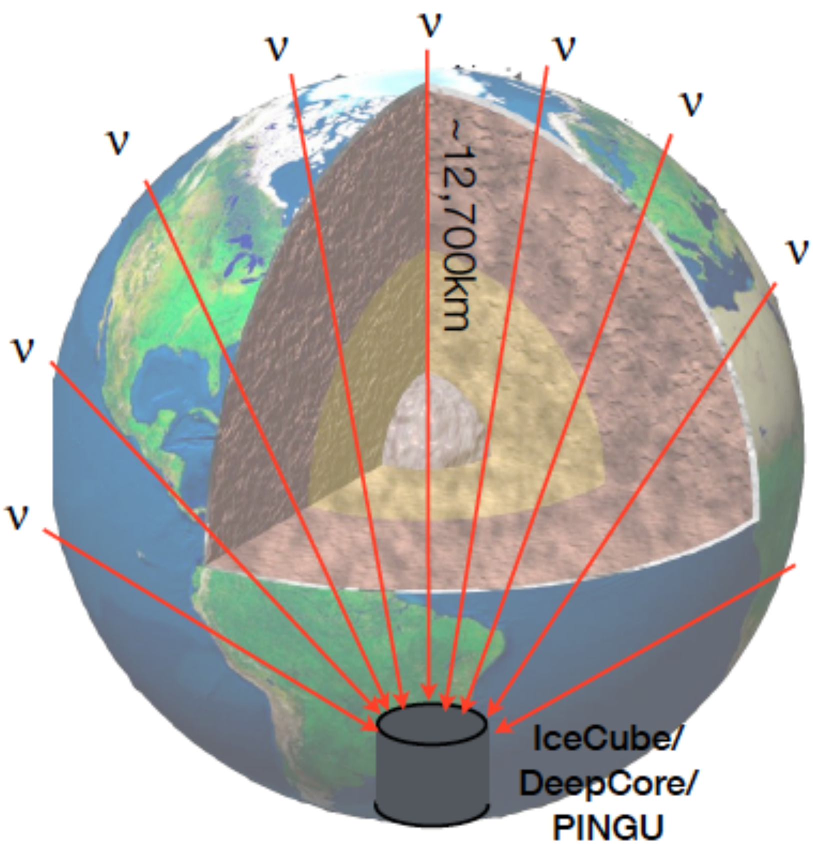
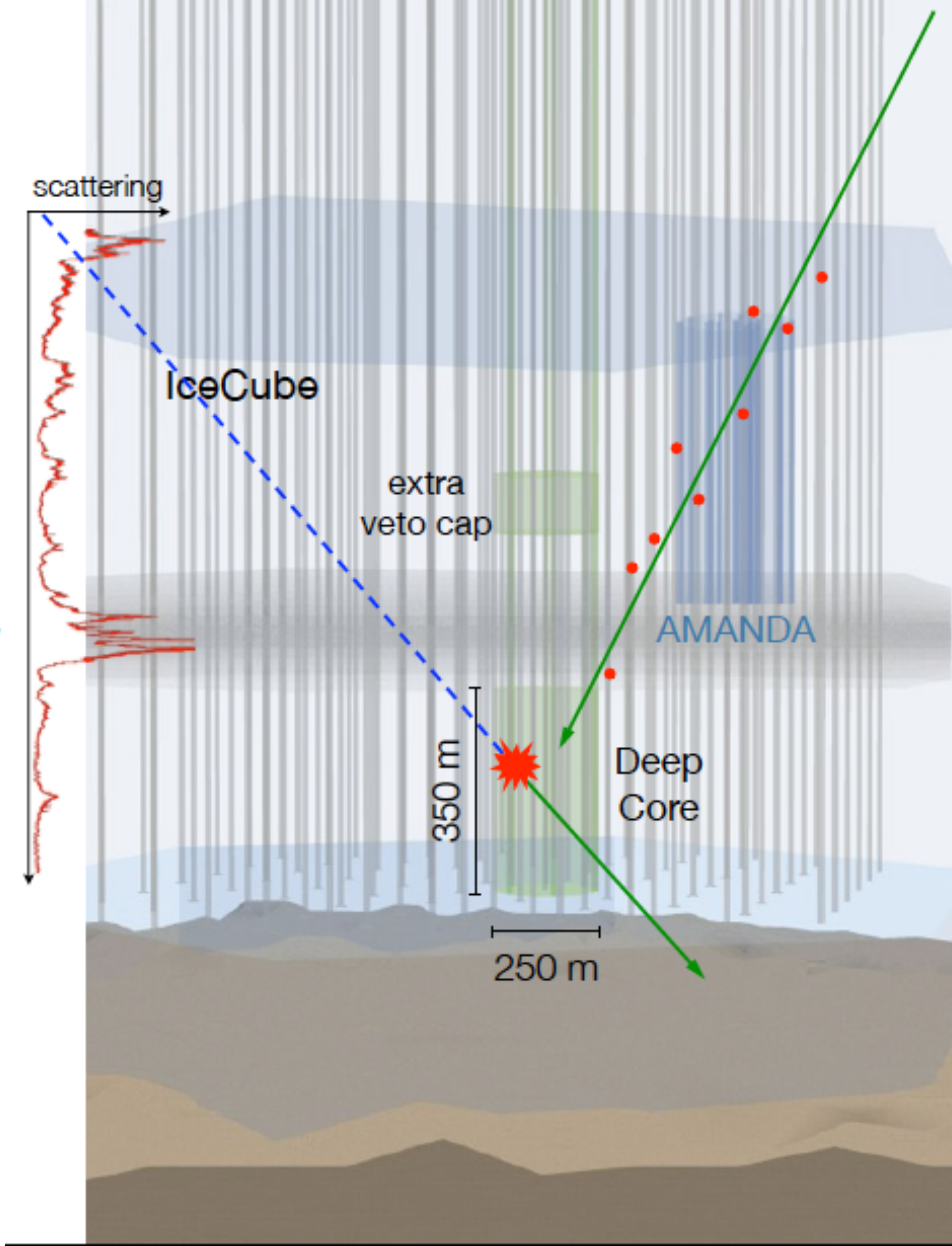
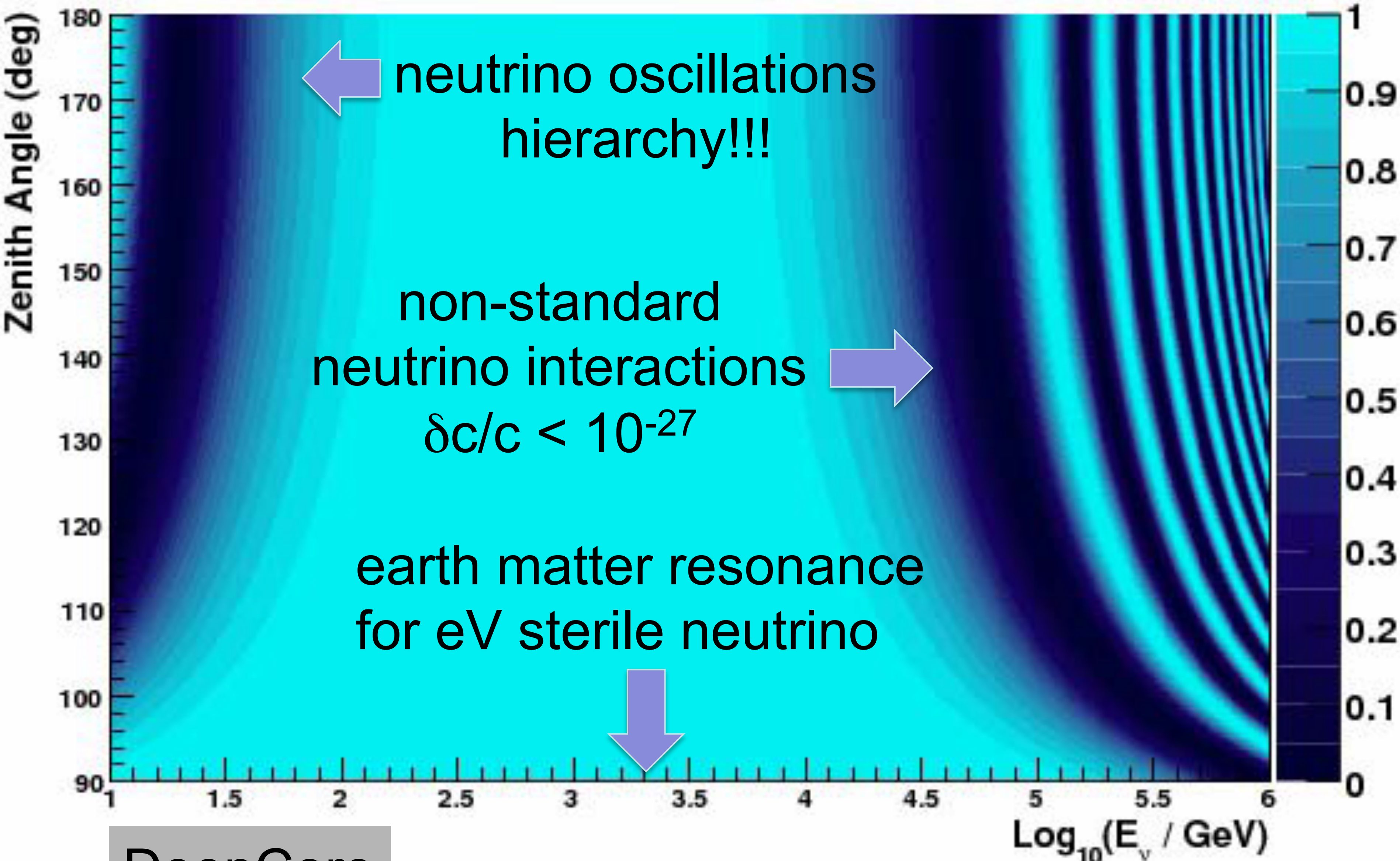
one half million atmospheric neutrinos…

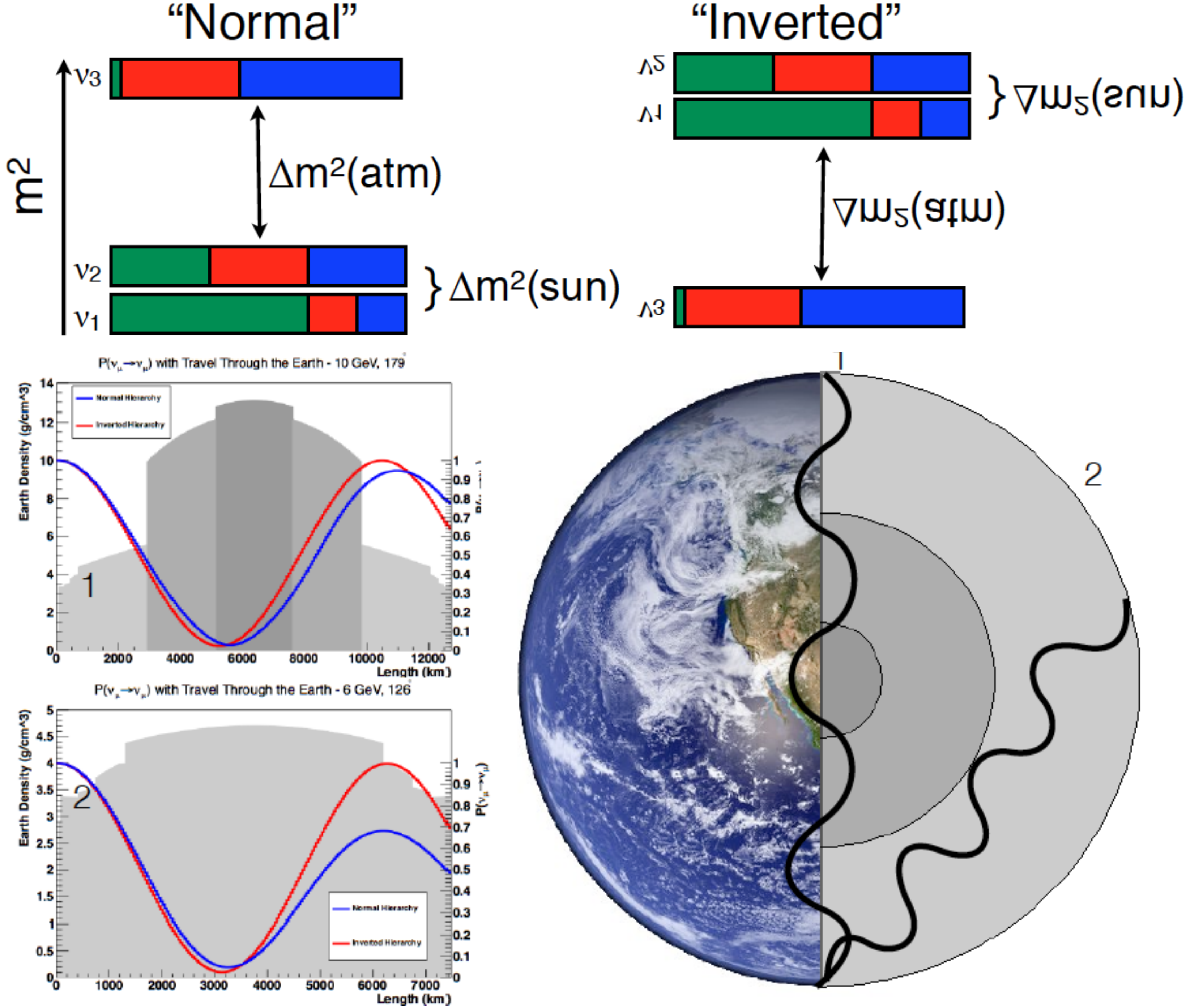




one half million atmospheric neutrinos…



DeepCore

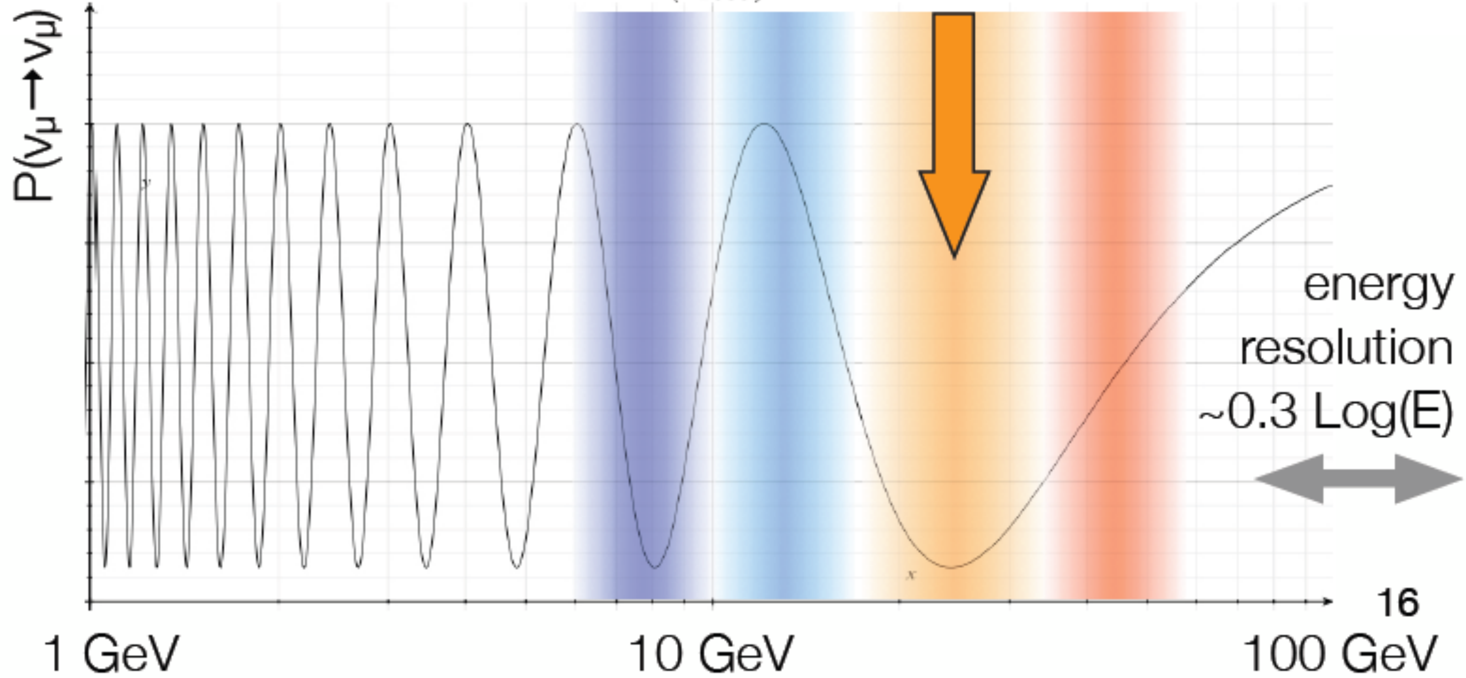


"Normal"
"Inverted"
m²
ν3
ν2
ν1
Δm²(atm)
Δm²(sun)
P(νμ→νμ) with Travel Through the Earth - 10 GeV, 179°
Normal Hierarchy
Inverted Hierarchy
Earth Density (g/cm^3)
Length (km)
1
P(νμ→νμ) with Travel Through the Earth - 6 GeV, 126°
P(νμ→νμ)
2

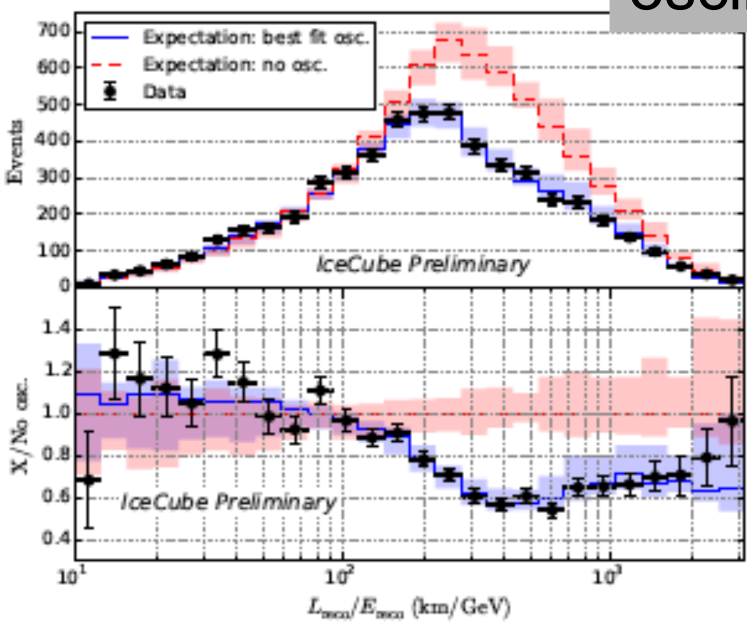
IceCube

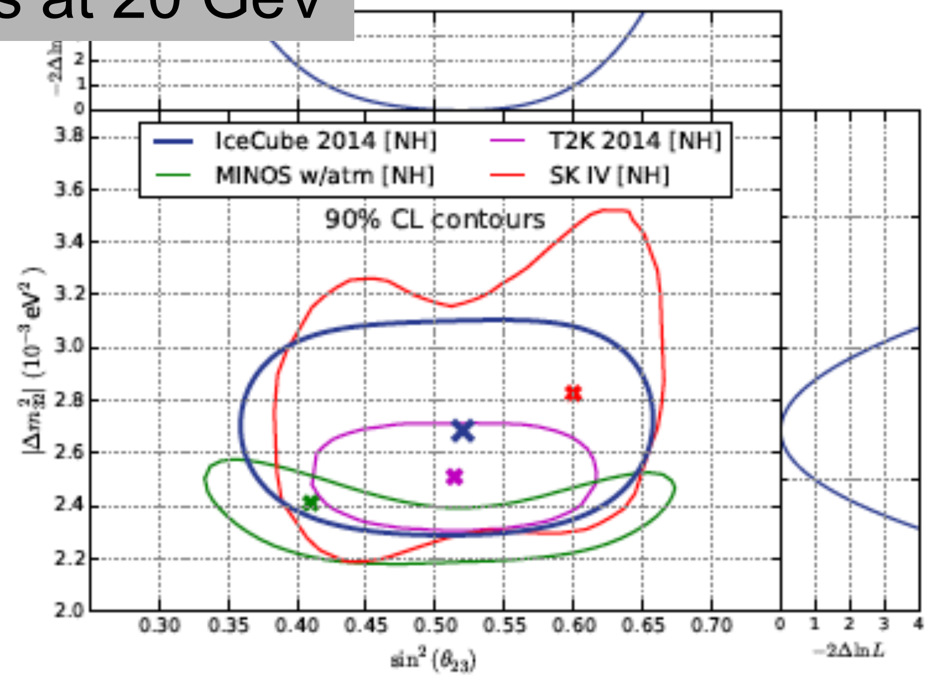
DeepCore

PINGU



oscillations at 20 GeV

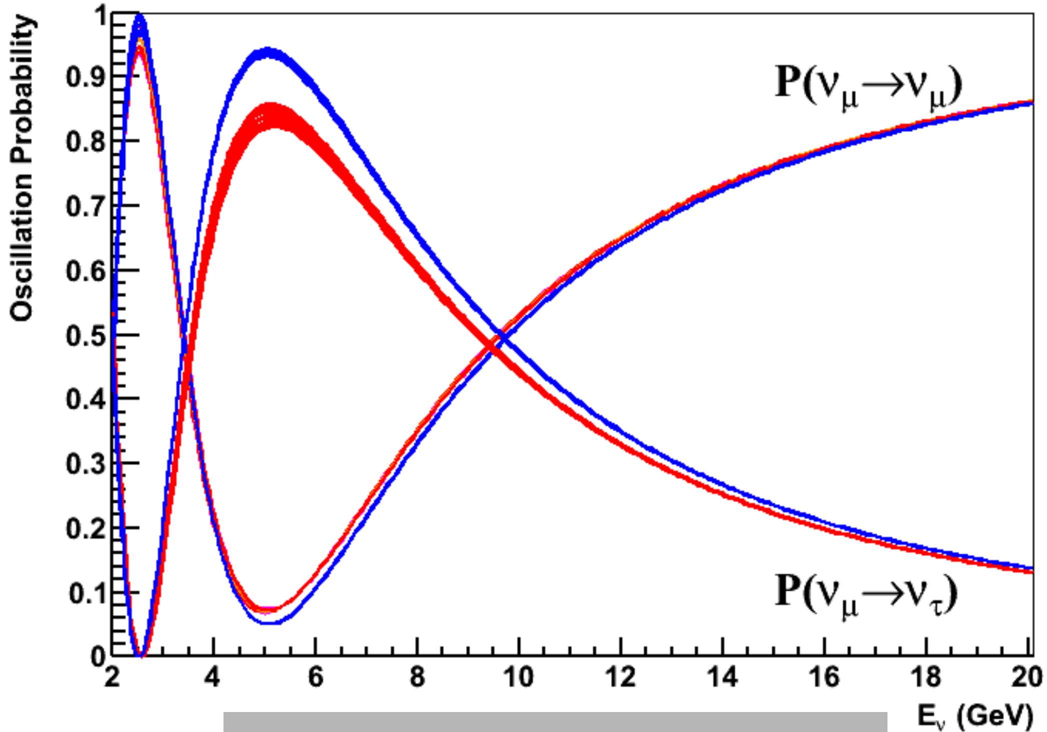




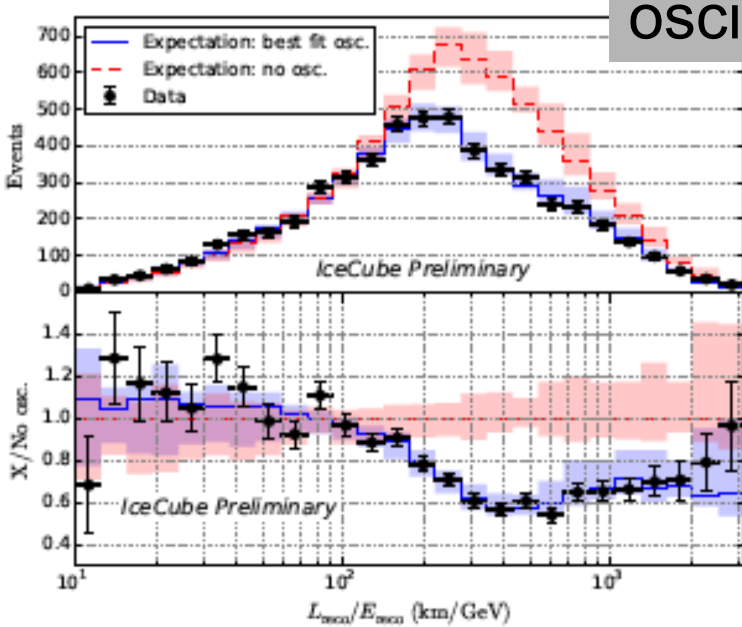
IceCube

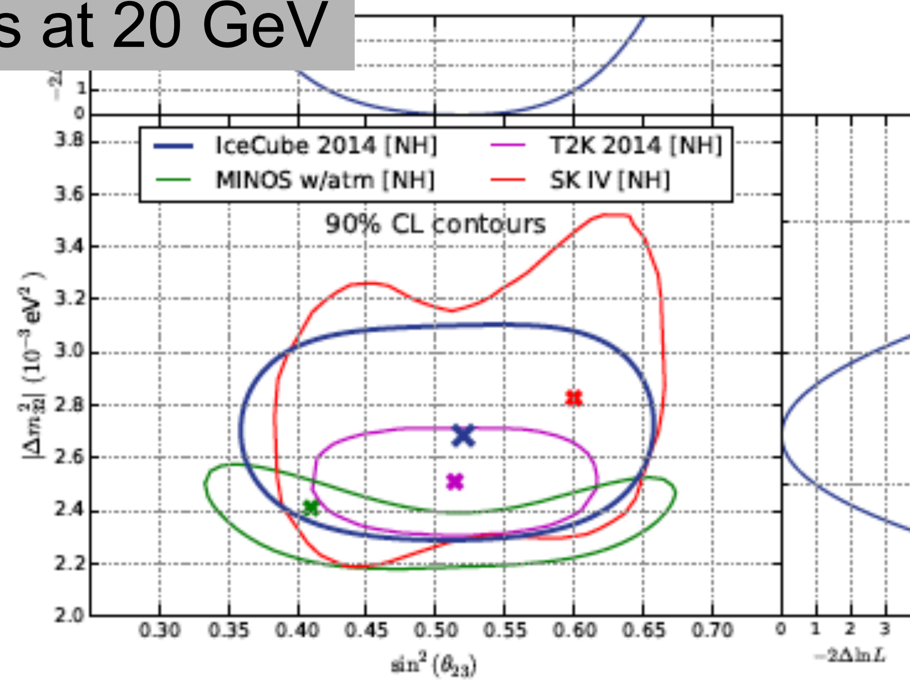
DeepCore

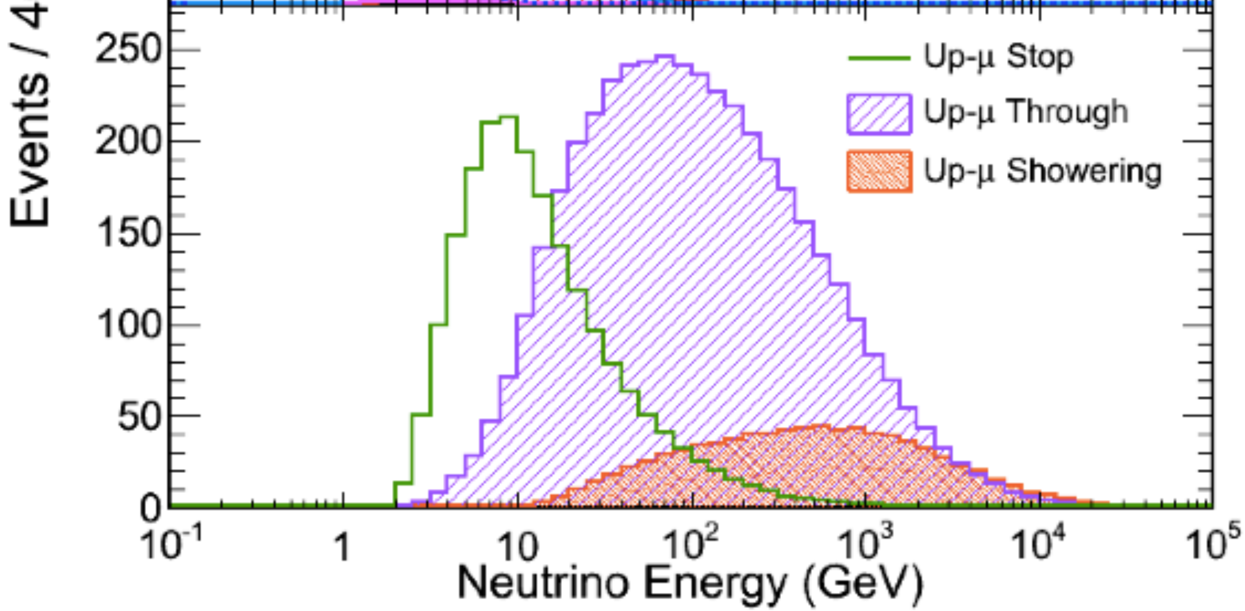
PINGU



oscillations at 20 GeV







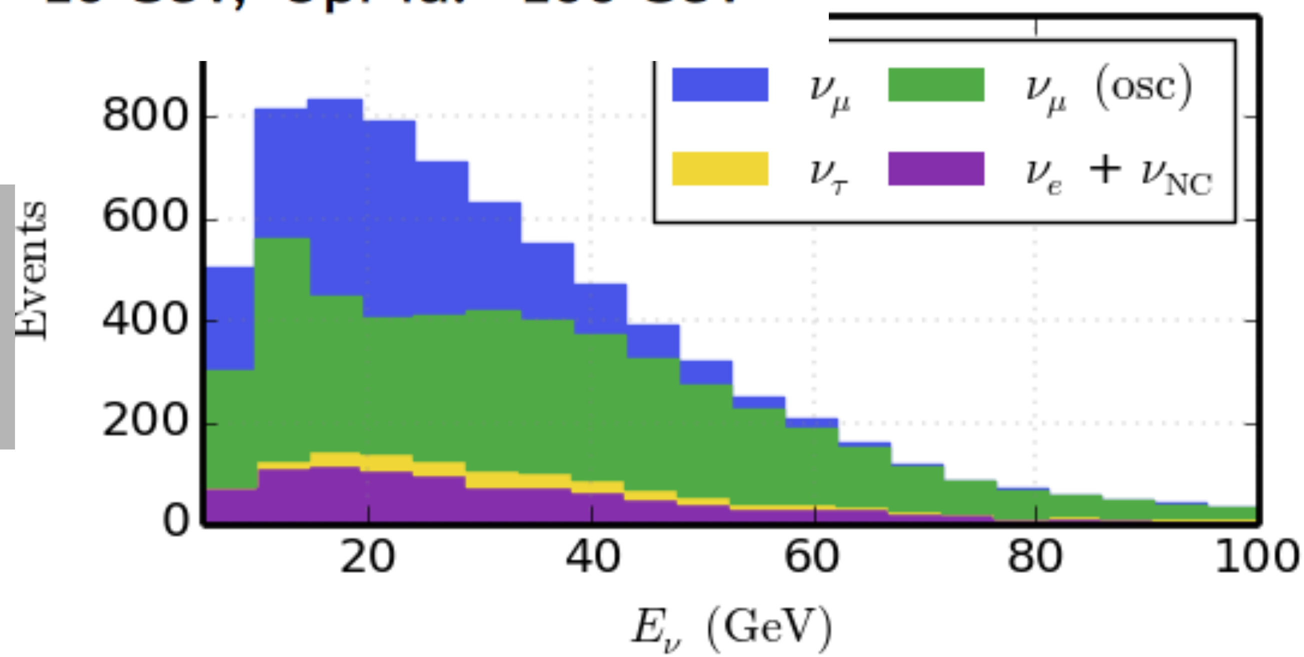
SuperK

~ 1 GeV

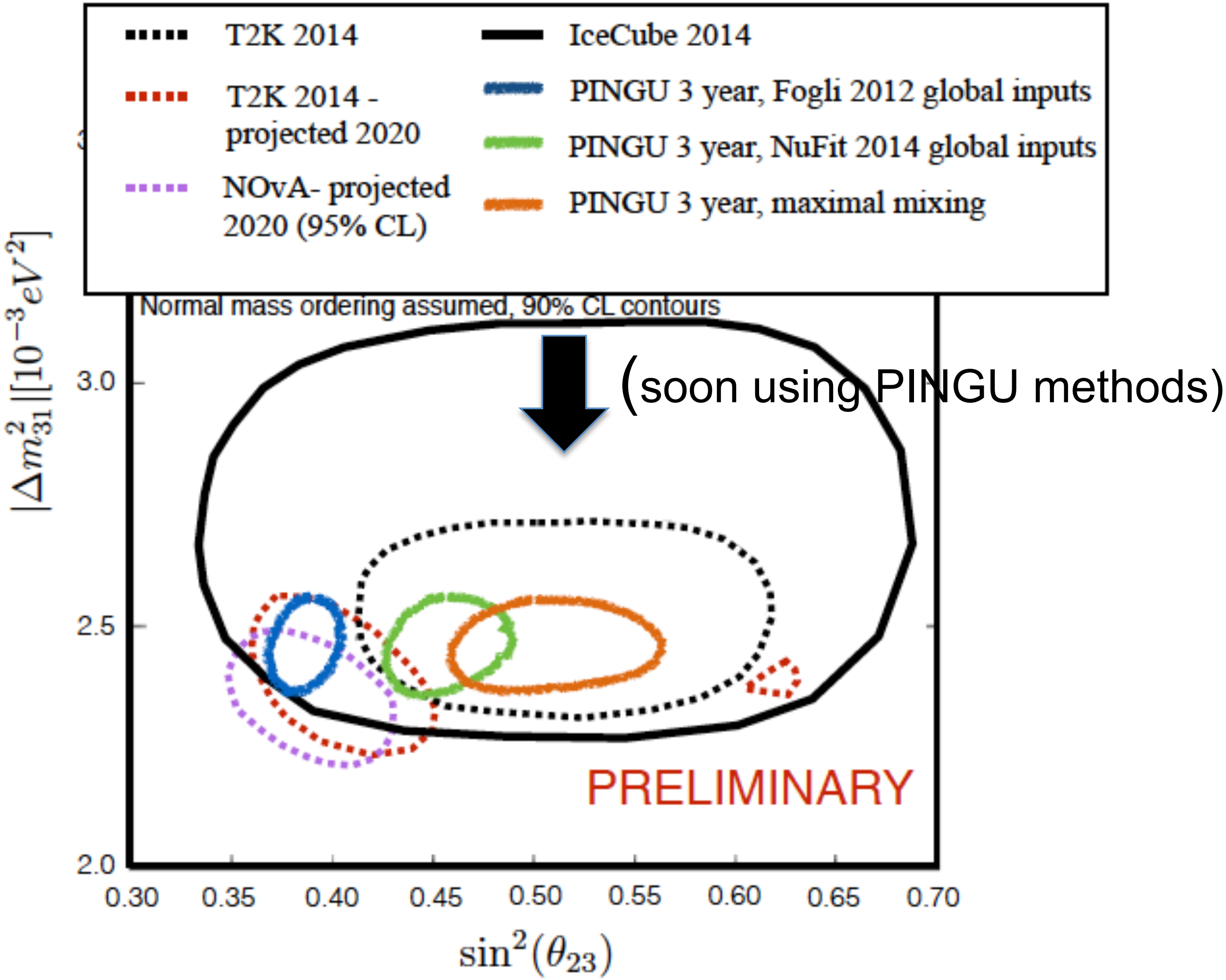
- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

IceCube

6 GeV < E_{reco} < 56 GeV



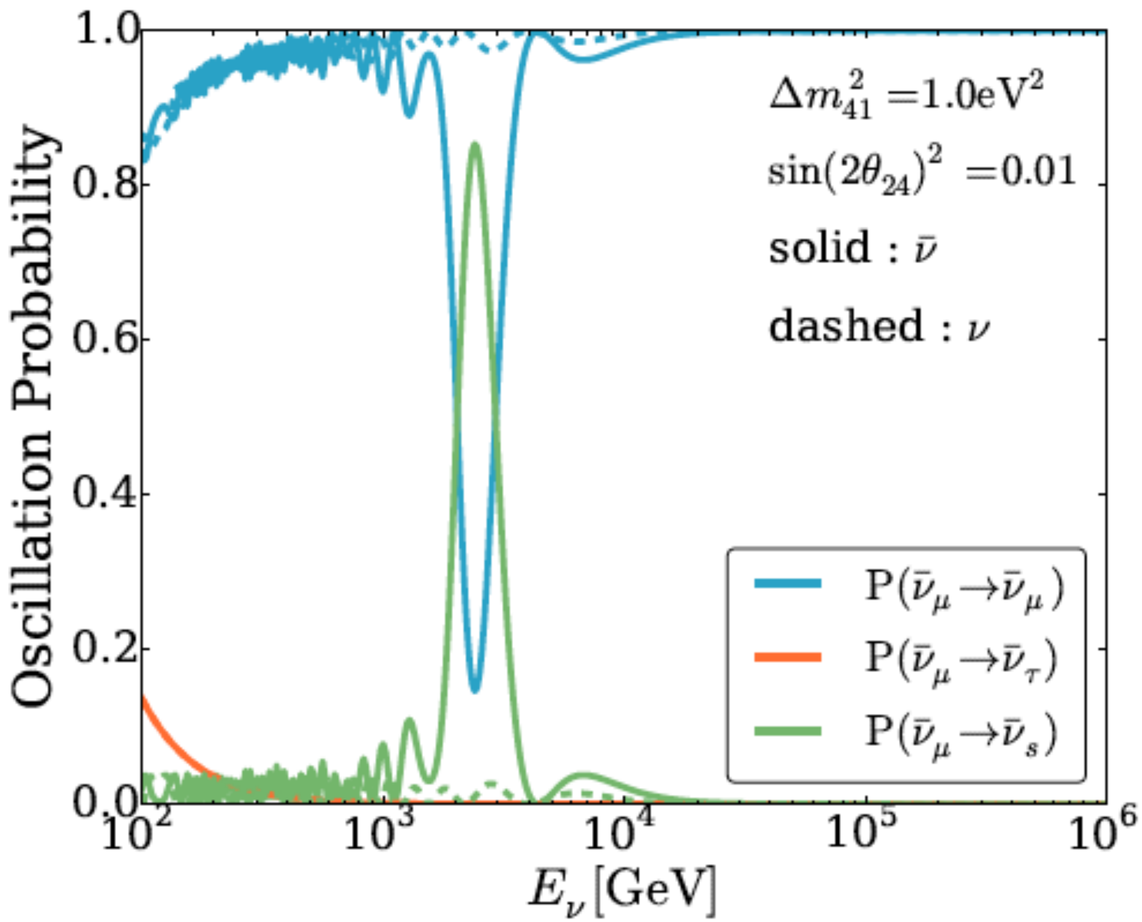
and with PINGU…



eV sterile neutrino → Earth MSW resonance for TeV neutrinos

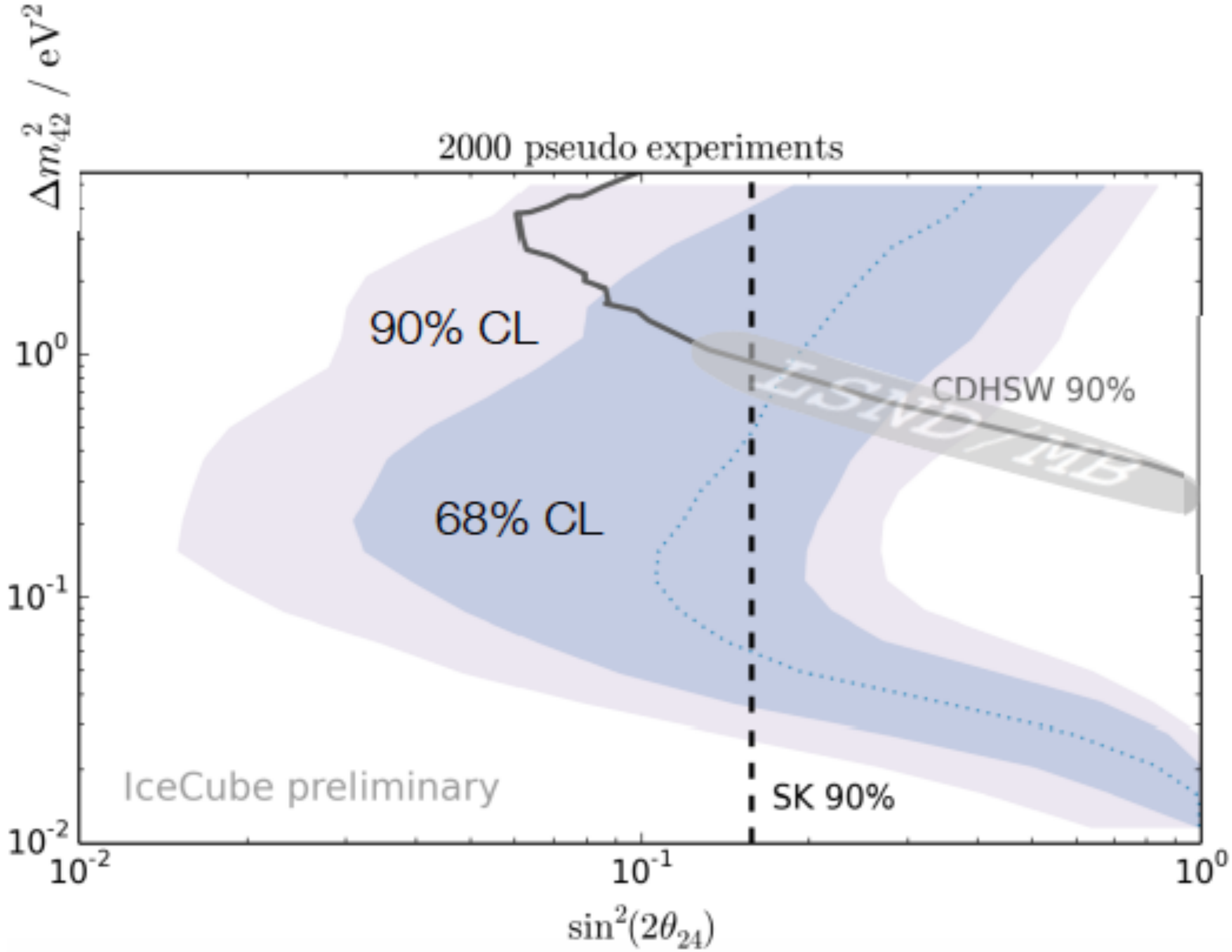
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

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

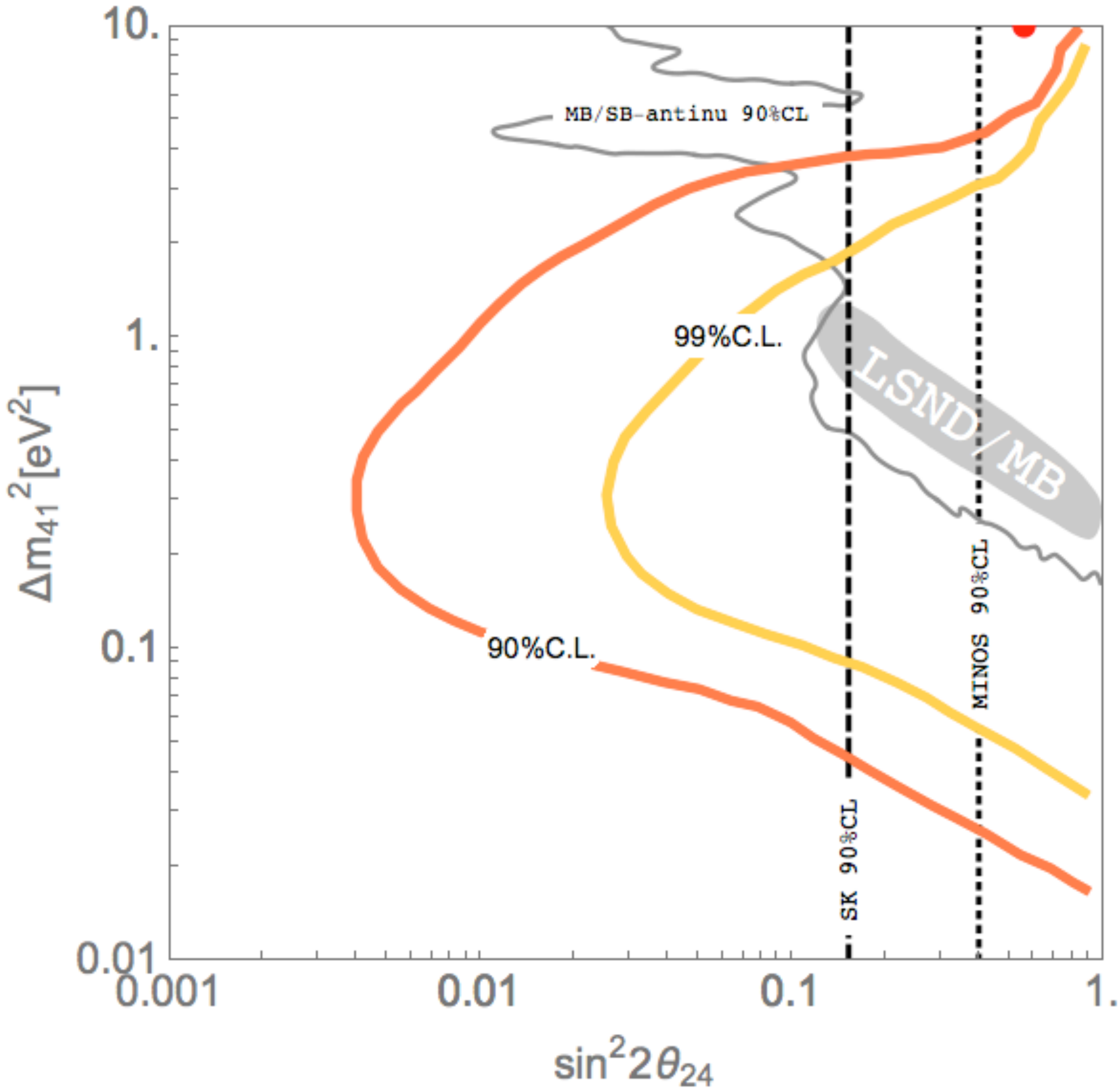


IceCube sensitivity– one year only

Neff=3.15 +/- 0.23
Planck

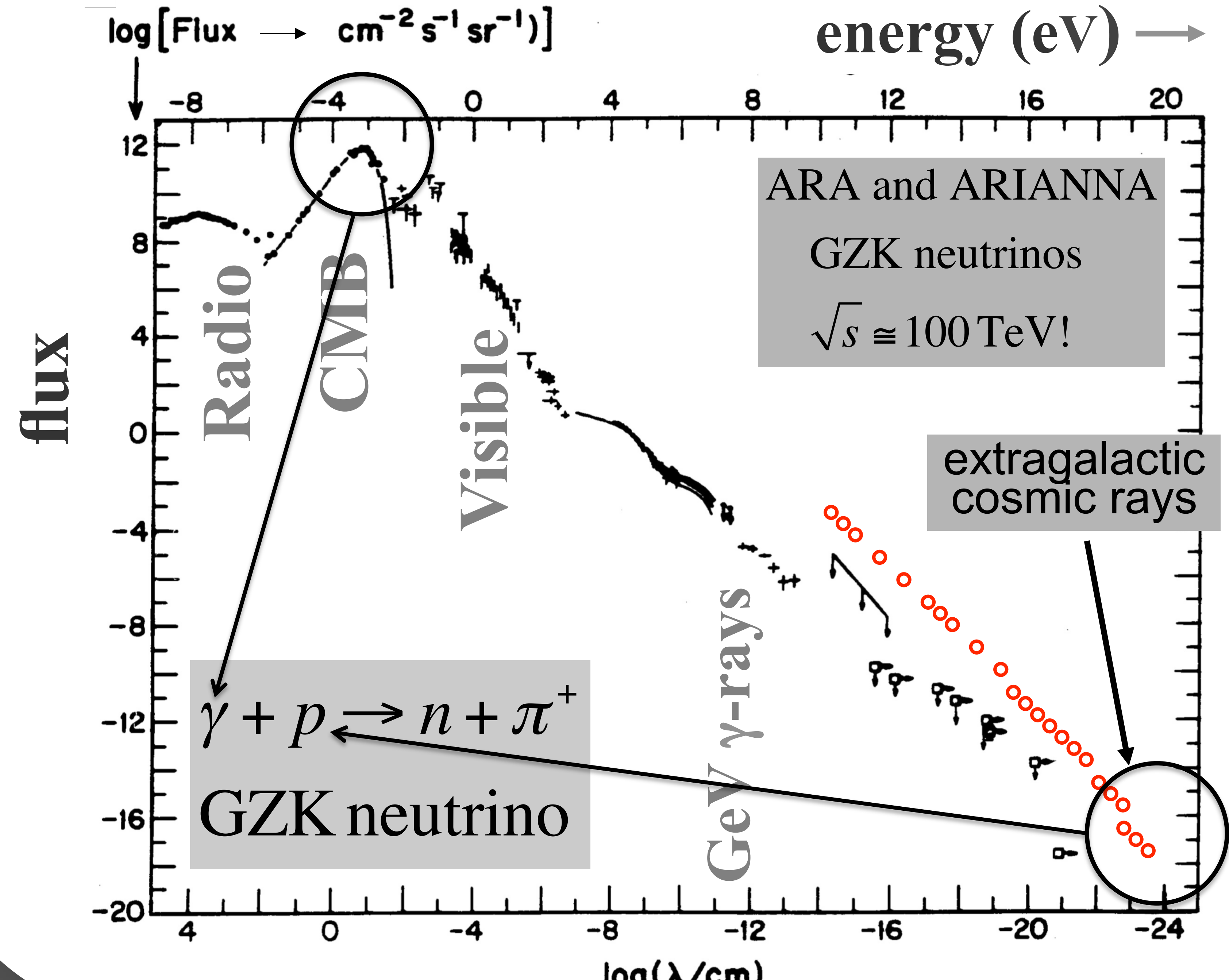


short baseline, reactor, radioactive sources…

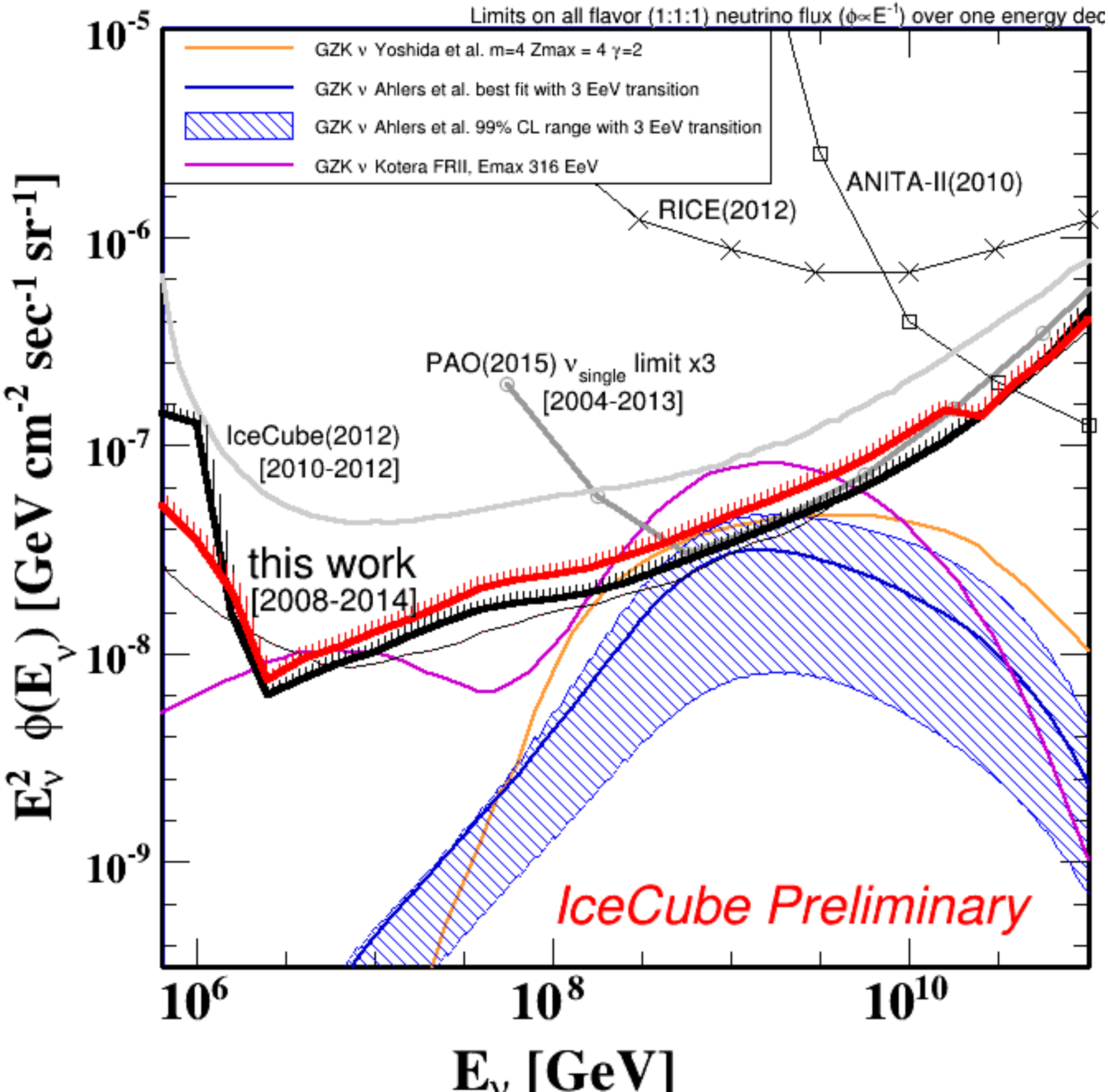


MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL
10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}{}^2$[eV^2]
$\sin^2 2\theta_{24}$

- there is even more

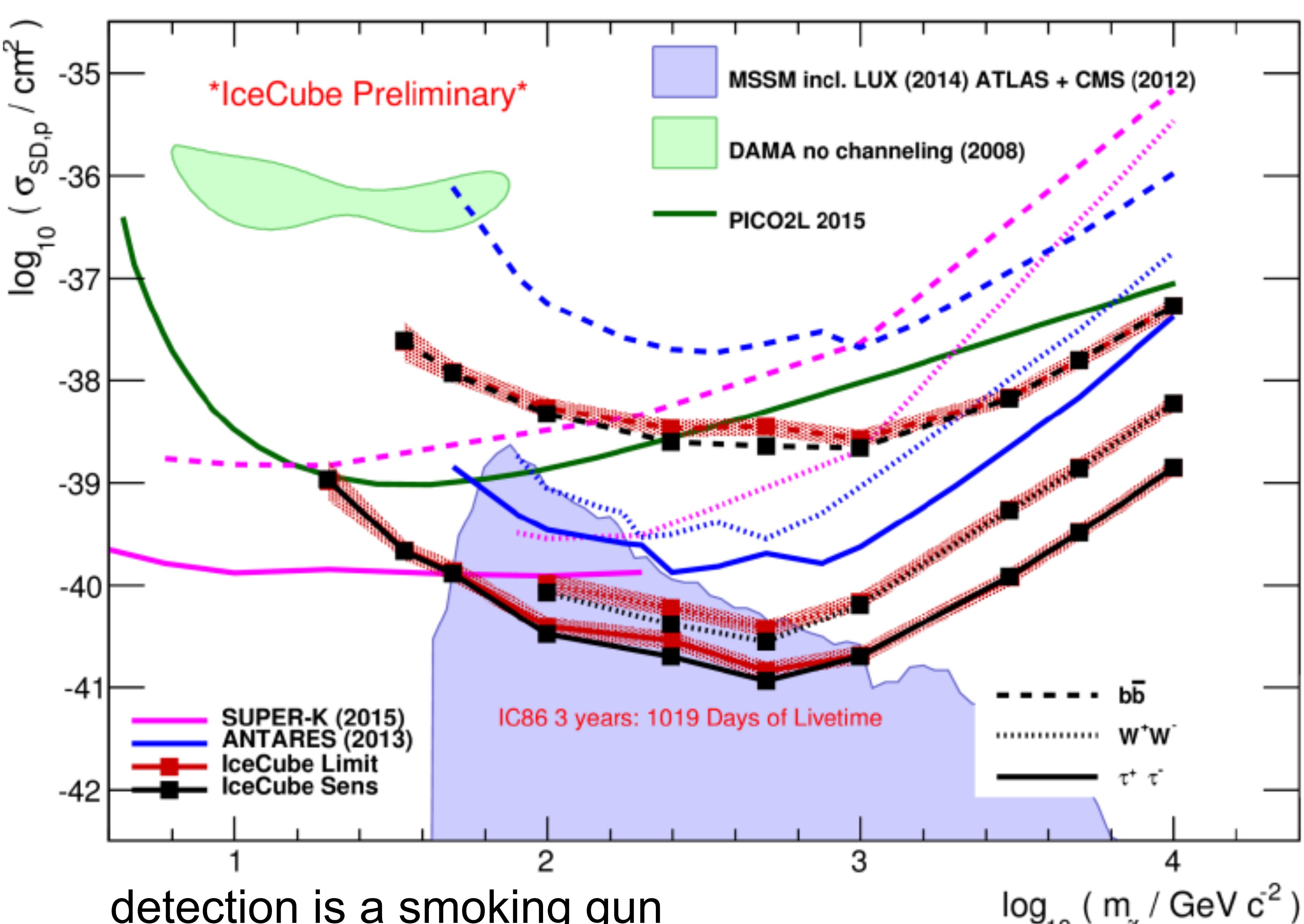


log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV) →
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ARA and ARIANNA
GZK neutrinos
$\sqrt{s} \cong 100\,\mathrm{TeV}!$
extragalactic
cosmic rays
$\gamma + p \rightarrow n + \pi^{+}$
GZK neutrino
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

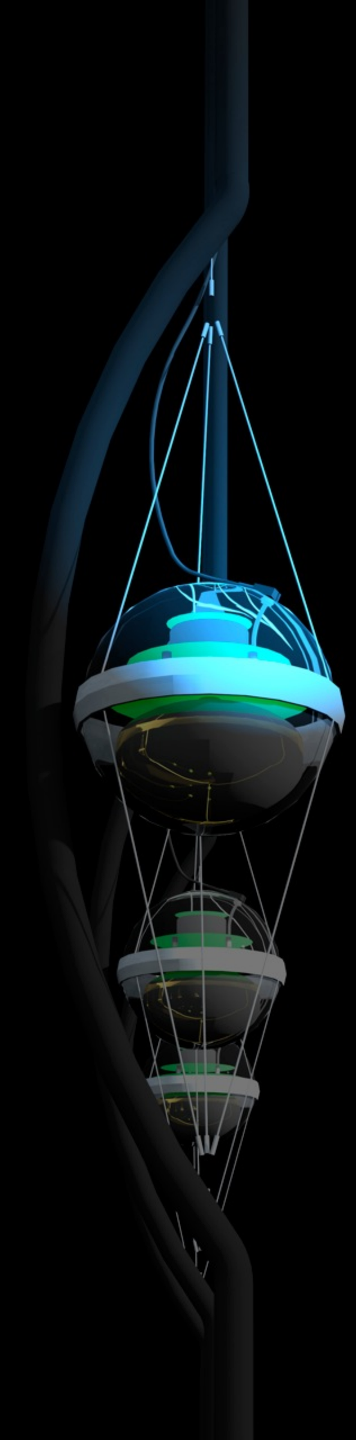


Limits on all flavor (1:1:1) neutrino flux (φ∝E^-1) over one energy dec
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
$E_\nu^2\ \phi(E_\nu)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
E_ν [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{6}
10^{8}
10^{10}

neutrinos as a tool to search for (spin-dependent) dark matter



detection is a smoking gun



IceCube Science
francis halzen

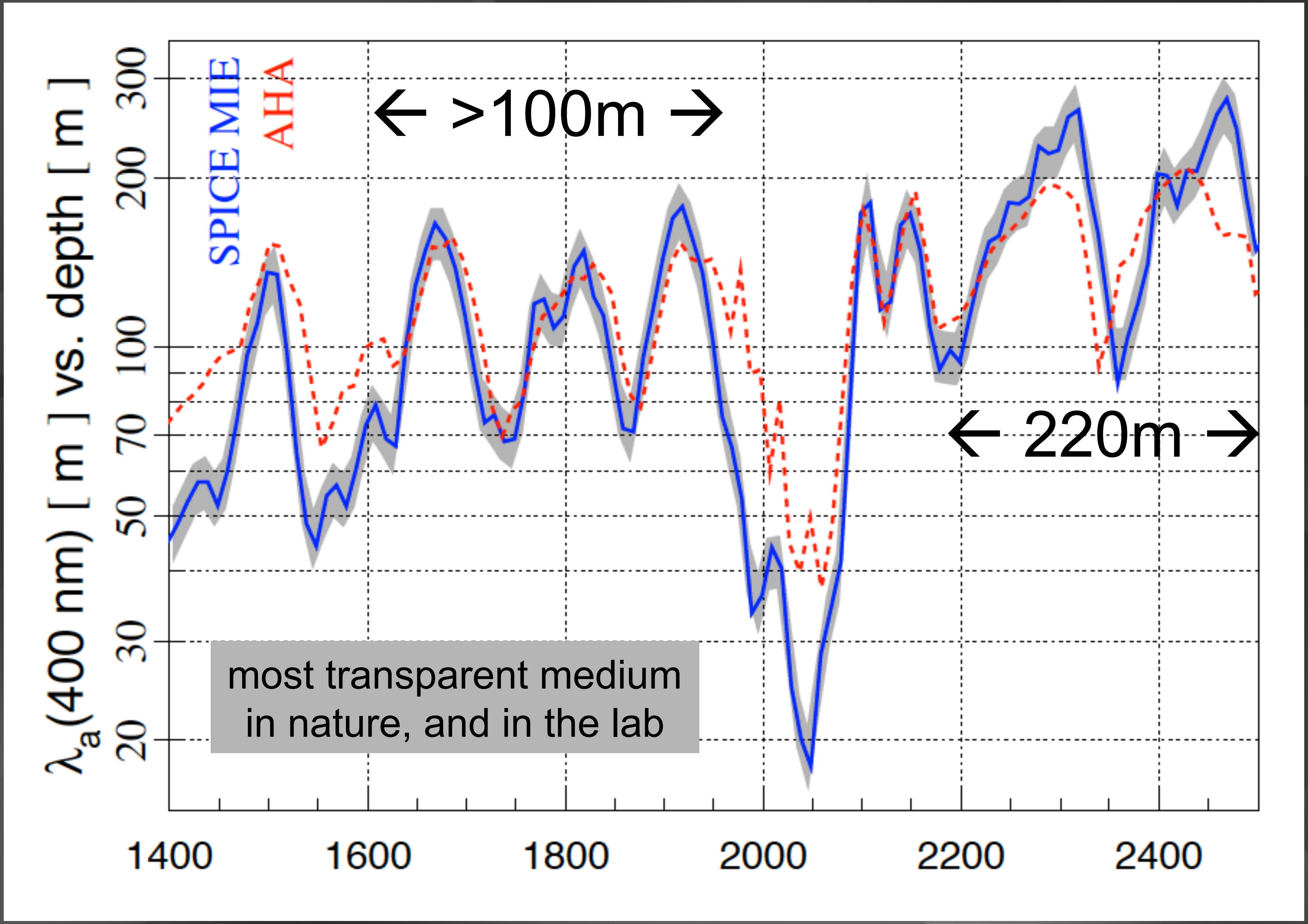
- cosmic neutrinos: discovery and confirmation
- the origin of cosmic neutrinos
- from PeV to GeV: neutrino physics with IceCube
- what next?

IceCube.wisc.edu

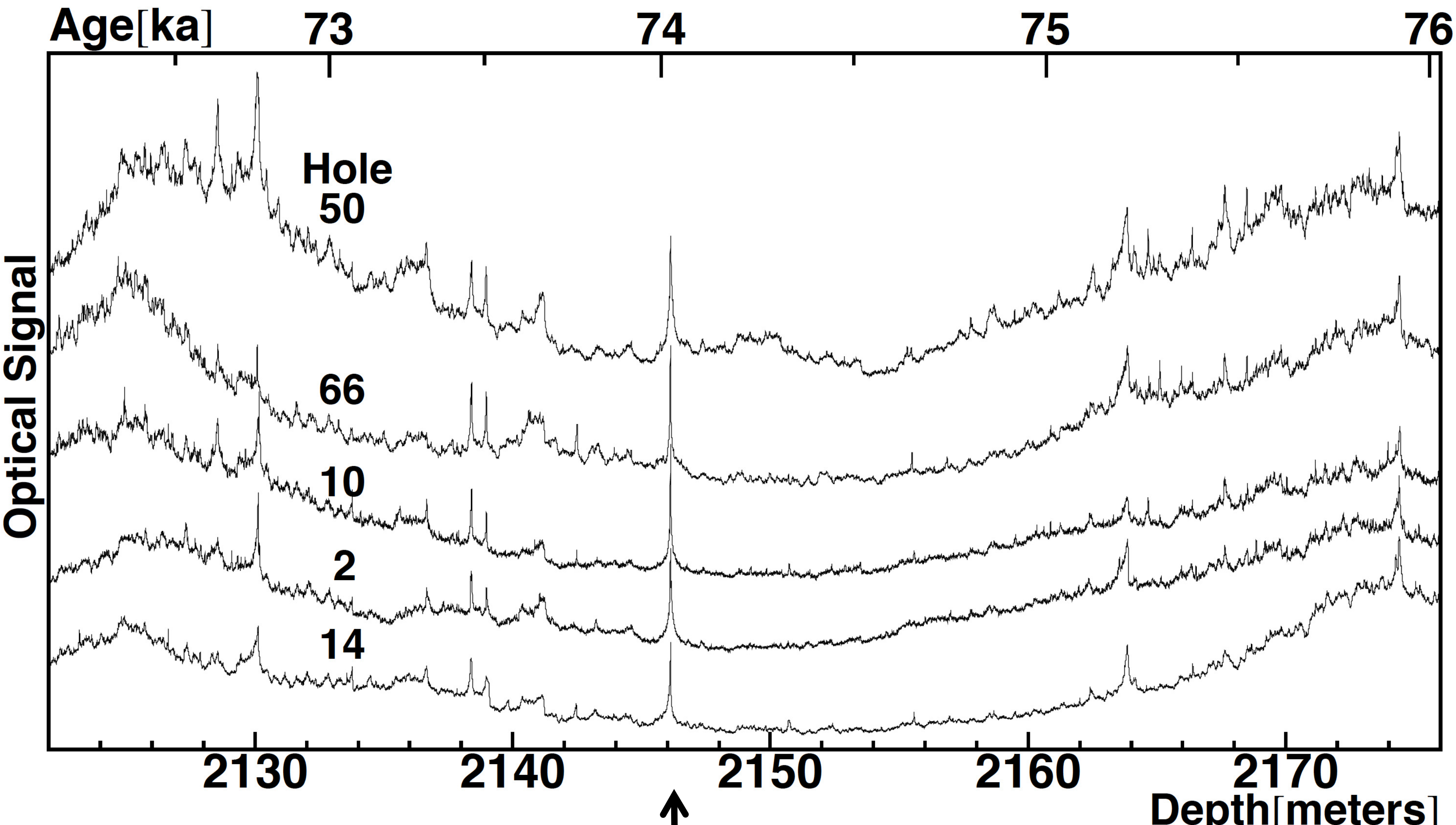
What next?

- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years
- need 1,000 events versus 100 now
- discovery instrument → astronomical telescope

absorption length of Cherenkov light



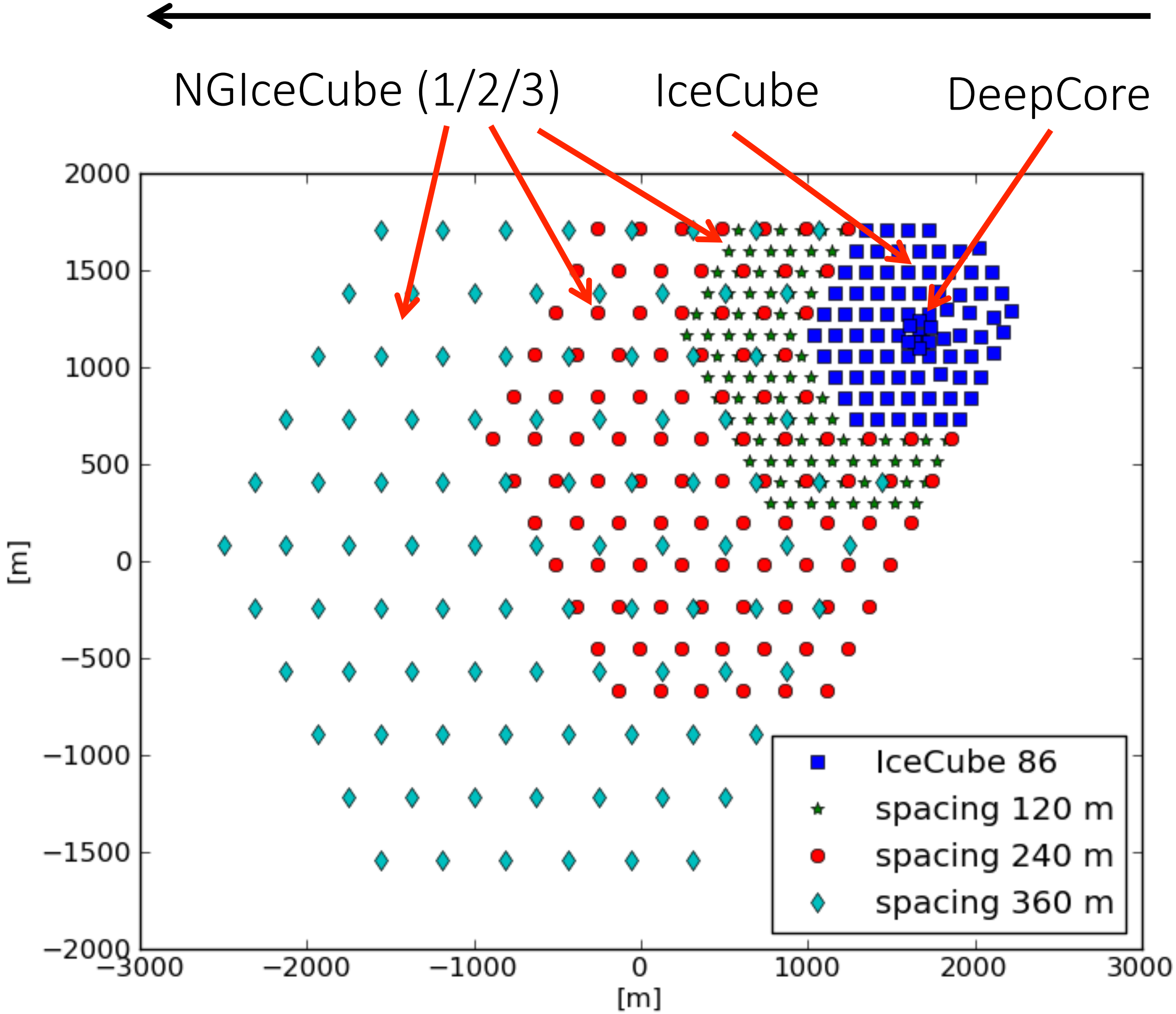
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

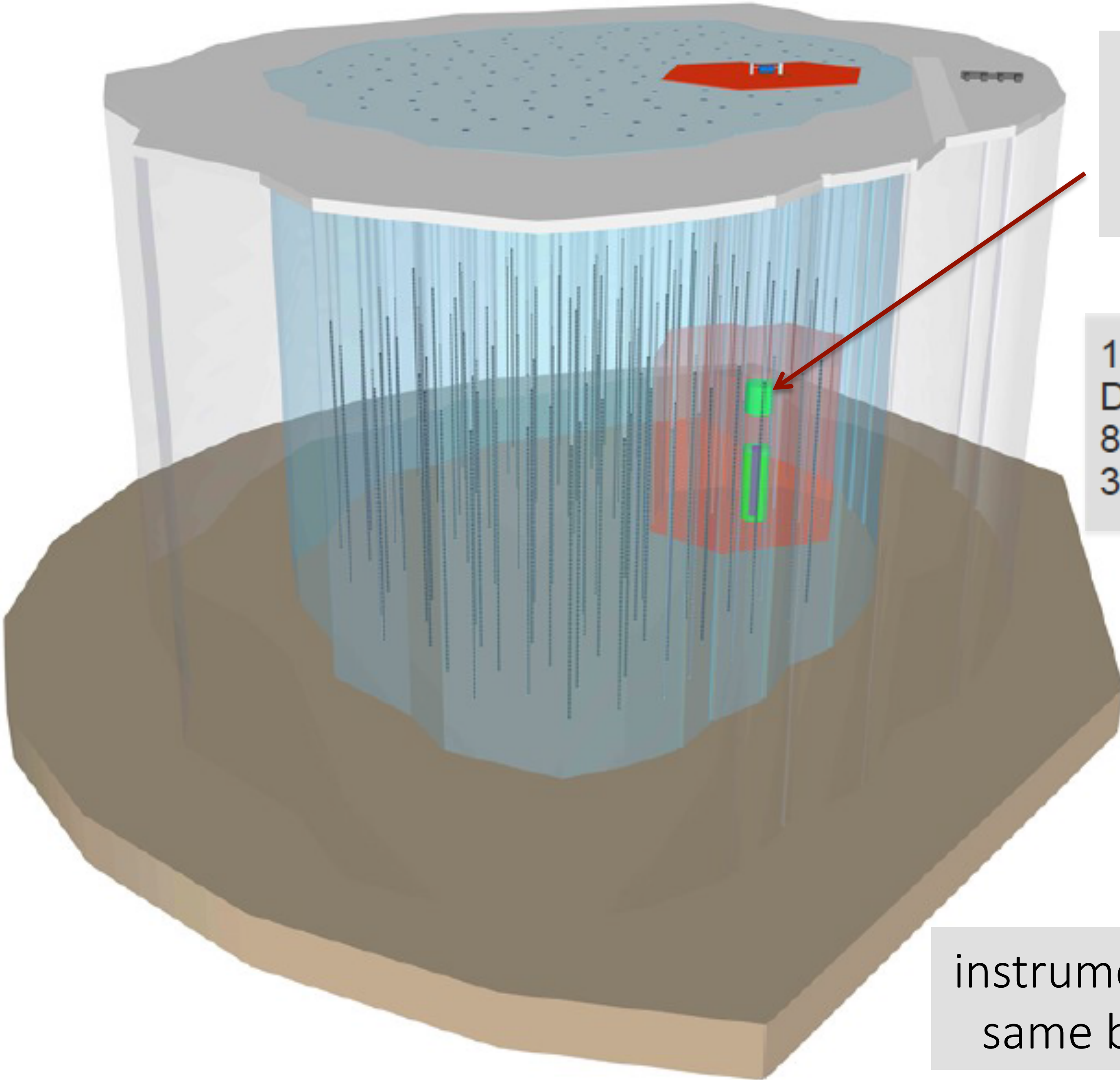
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3



PINGU infill
40 strings
GeV threshold

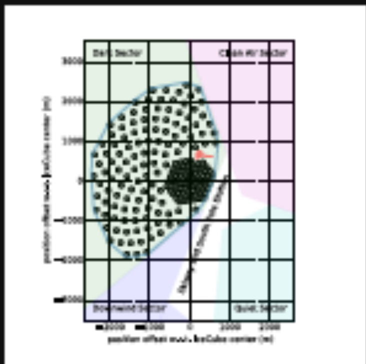
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

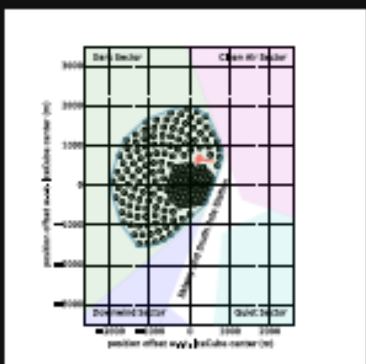
instrumented volume: x 10
same budget as IceCube

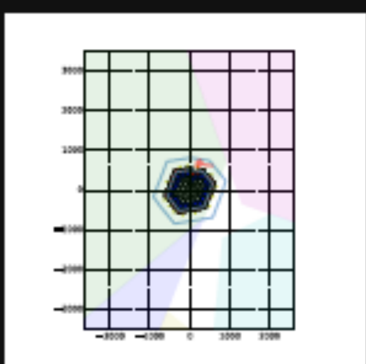
Glashow resonance events per year:

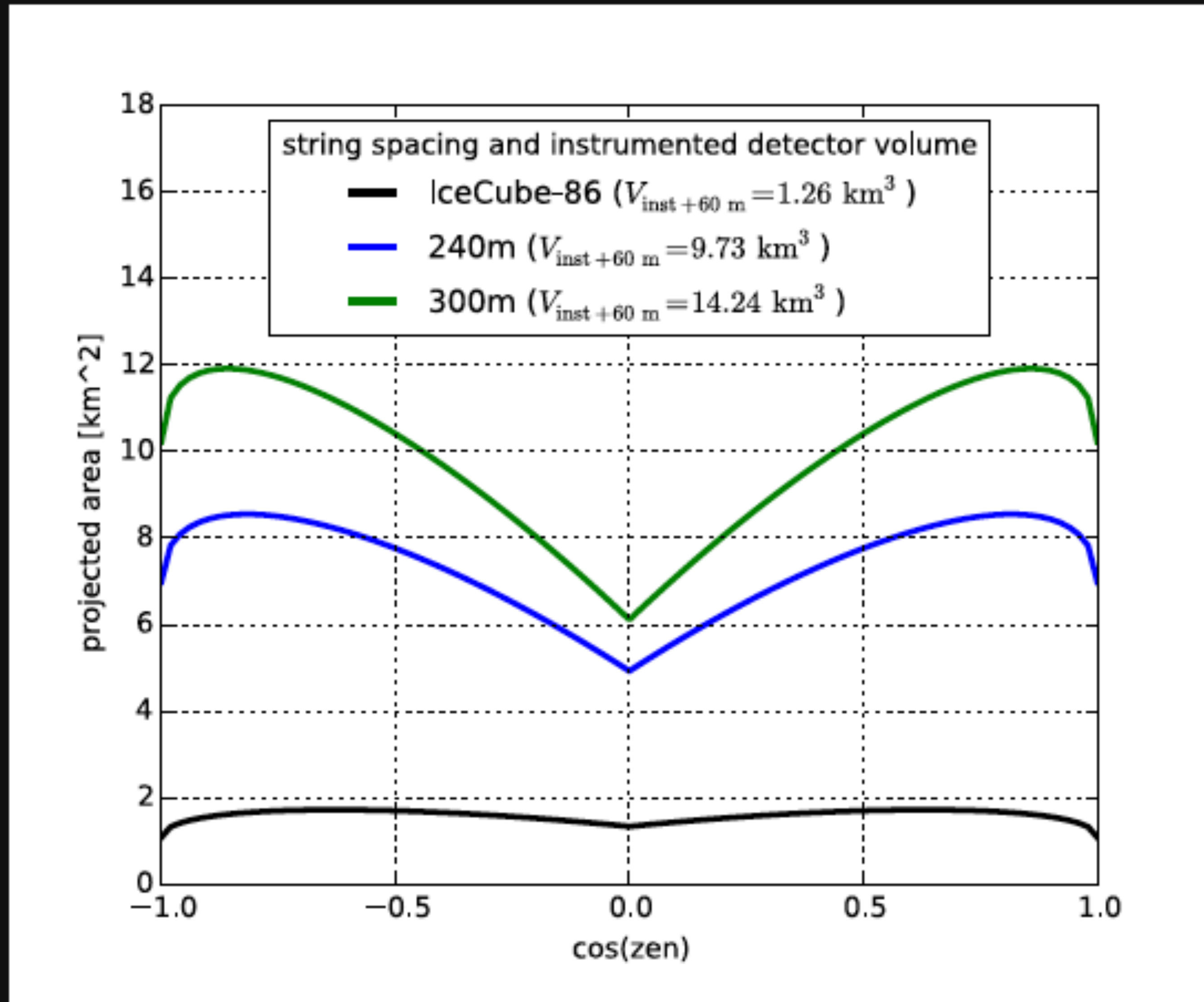
Φ_{ν_e} $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	interaction type	pp source IC-86	240m	360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$	GR	0.12	0.9	2.1
	DIS	0.01	0.1	0.2

$$\bar{\nu}_e + e^- \rightarrow W$$



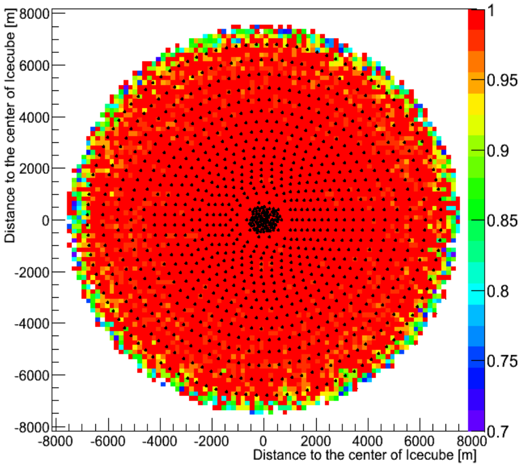





string spacing and instrumented detector volume
IceCube-86 ($V_{\mathrm{inst+60\ m}} = 1.26\ \mathrm{km}^3$)
240m ($V_{\mathrm{inst+60\ m}} = 9.73\ \mathrm{km}^3$)
300m ($V_{\mathrm{inst+60\ m}} = 14.24\ \mathrm{km}^3$)
projected area [km^2]
cos(zen)
0
2
4
6
8
10
12
14
16
18
−1.0
−0.5
0.0
0.5
1.0

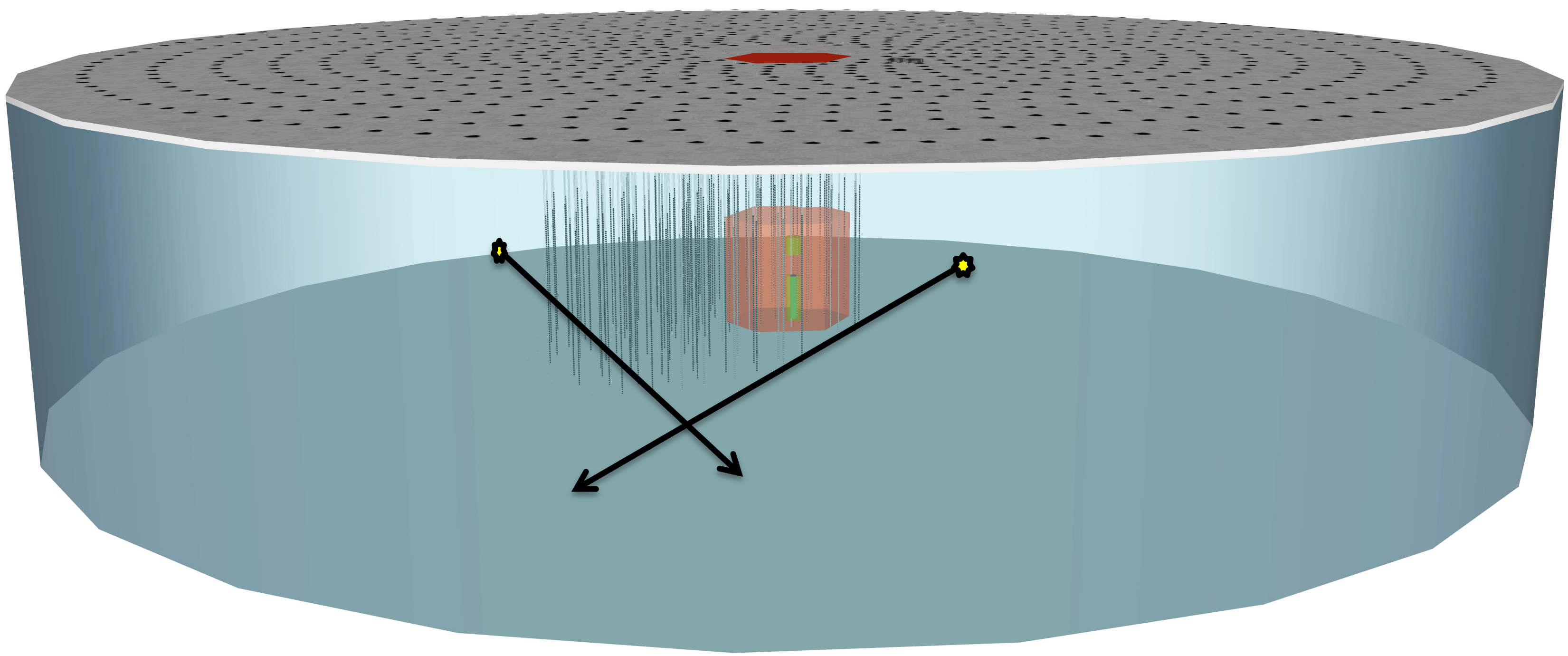
extended surface veto detector

use the large neutrino target volume outside the instrumented volume?



1000 modules?
10000 ?

Air shower veto array



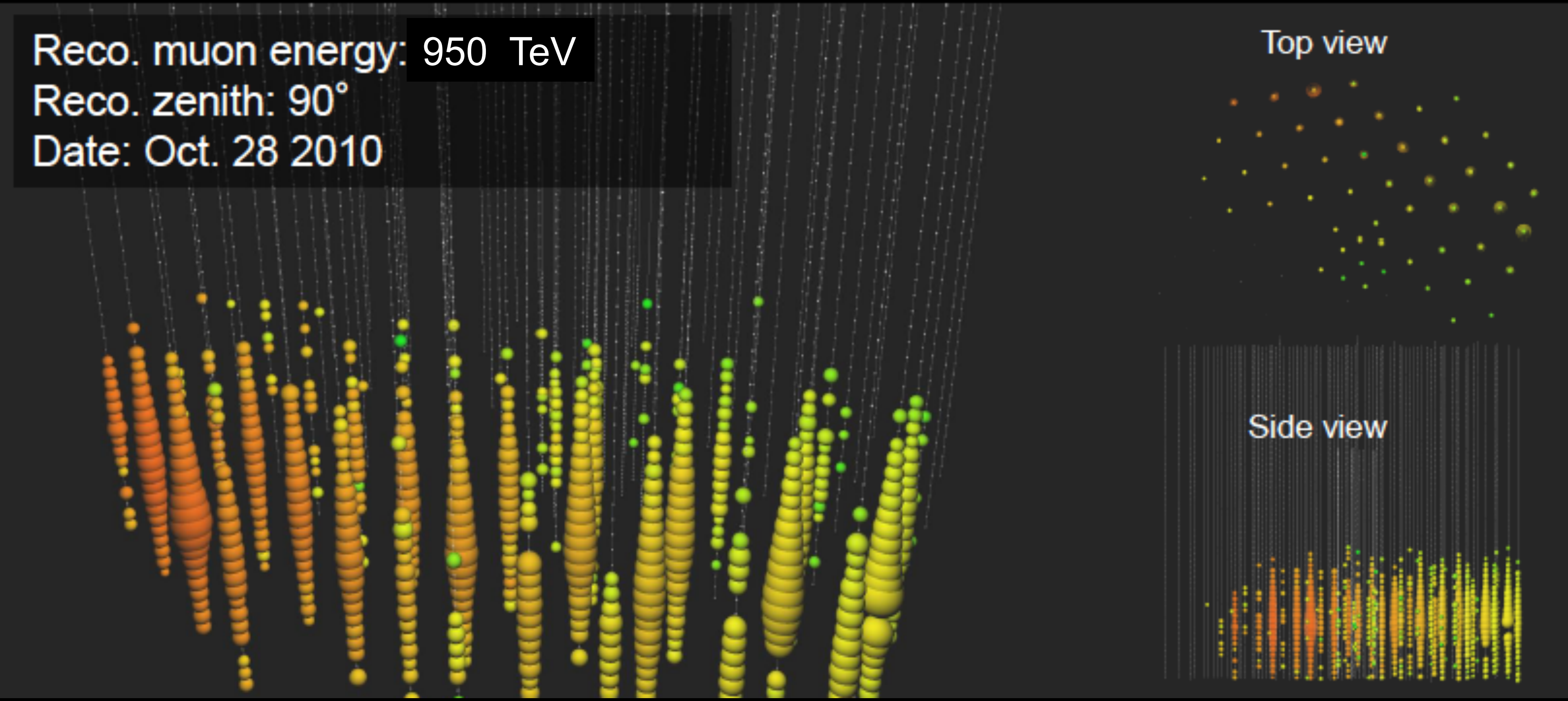
Conclusions

- capitalize on discovery: many analyses have not exploited more than one year of data
- analysis are not in the square root of time regime
- neutrino physics at (relatively) low cost and on short timescales → PINGU
- potential for discovery
- need next-generation detector for astronomy
- neutrinos are never boring!

ANTARES → ORCA and KM3NeT

overflow slides

6 years → 6 σ


Reco. muon energy: 950 TeV
Reco. zenith: 90°
Date: Oct. 28 2010
Top view
Side view

cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

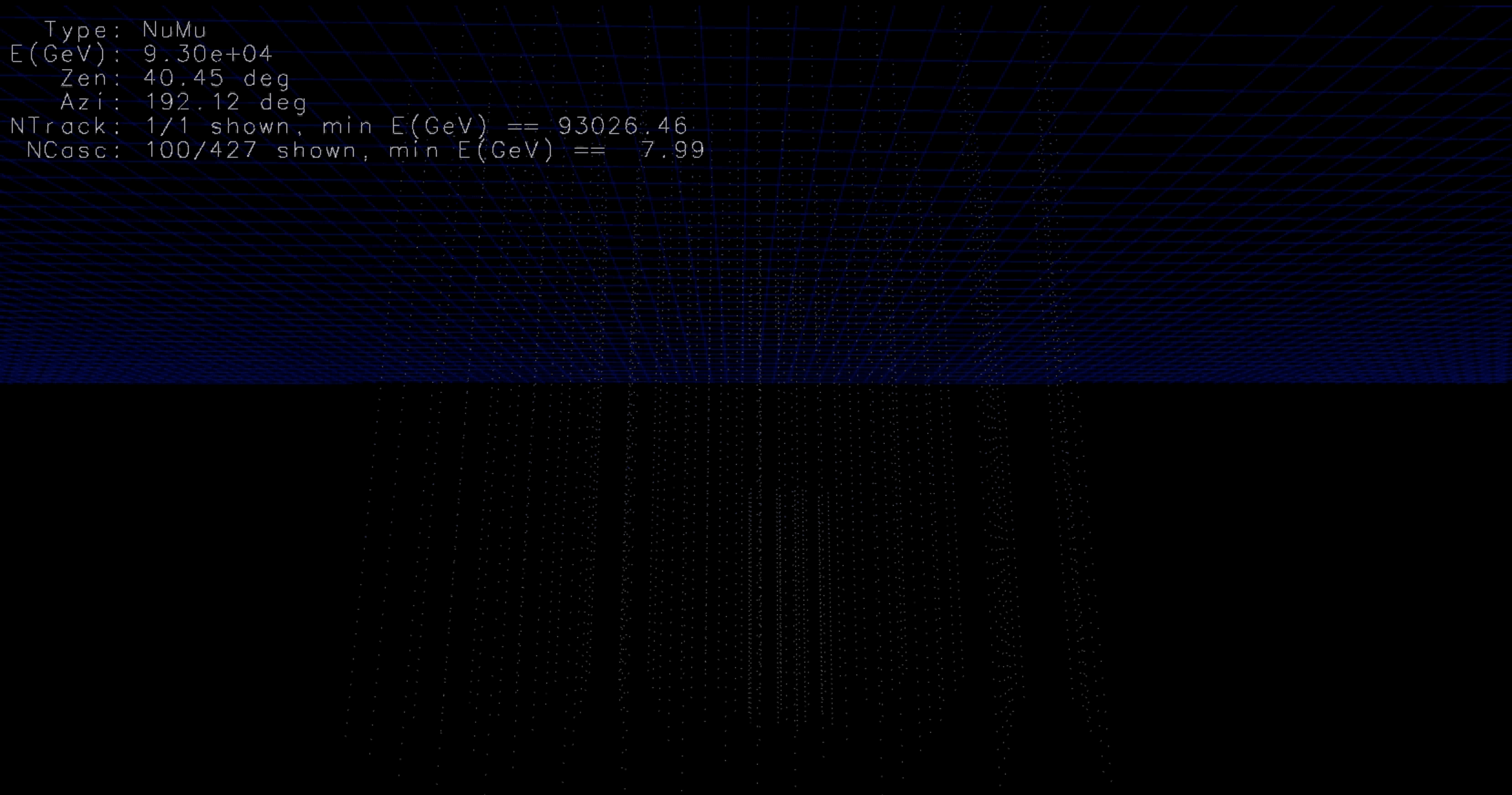
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

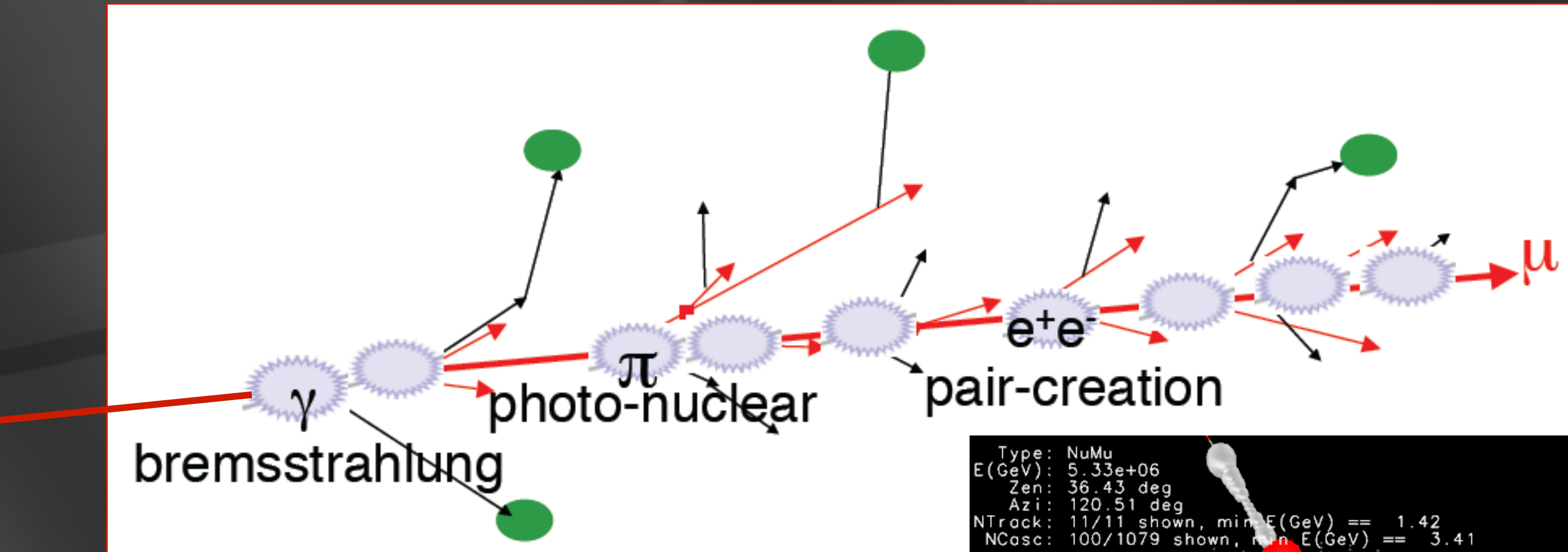
1 event per cubic kilometer per year

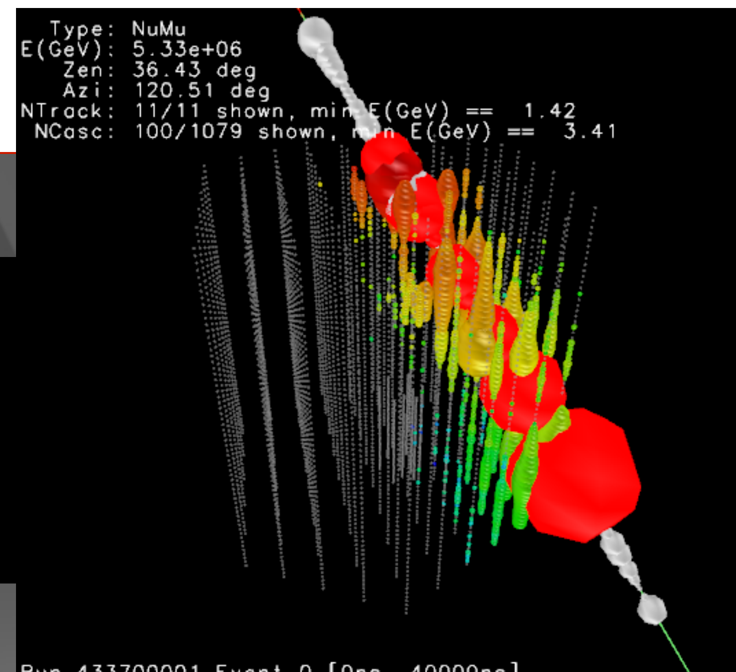
...but it points at its source!

93 TeV muon: light ~ energy

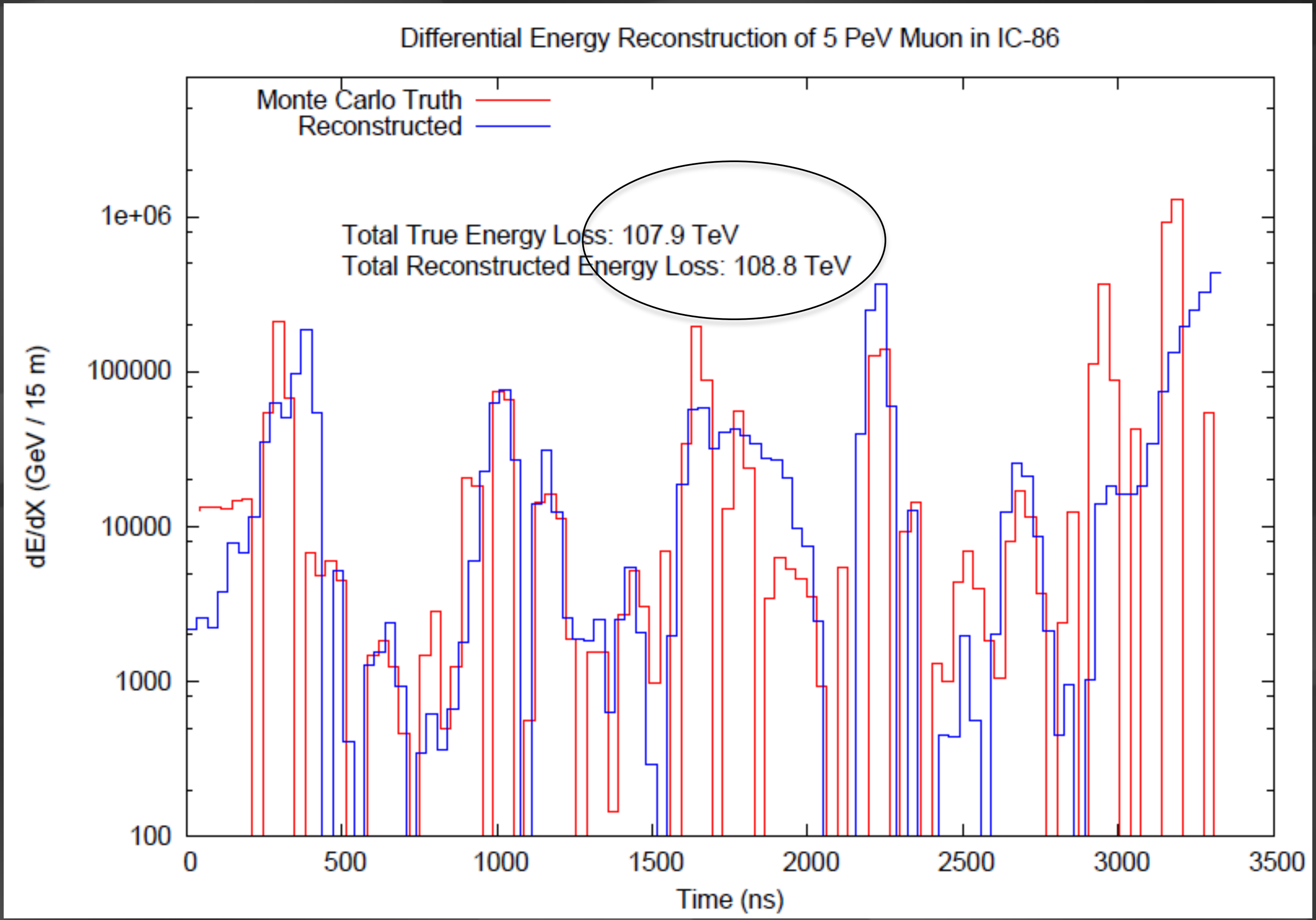


energy measurement (> 1 TeV)



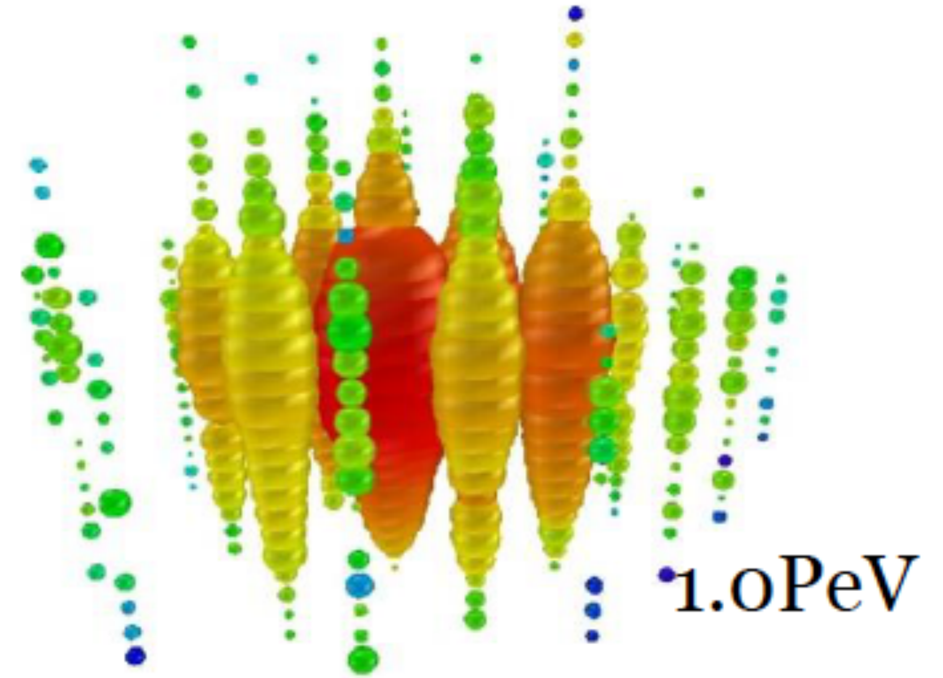


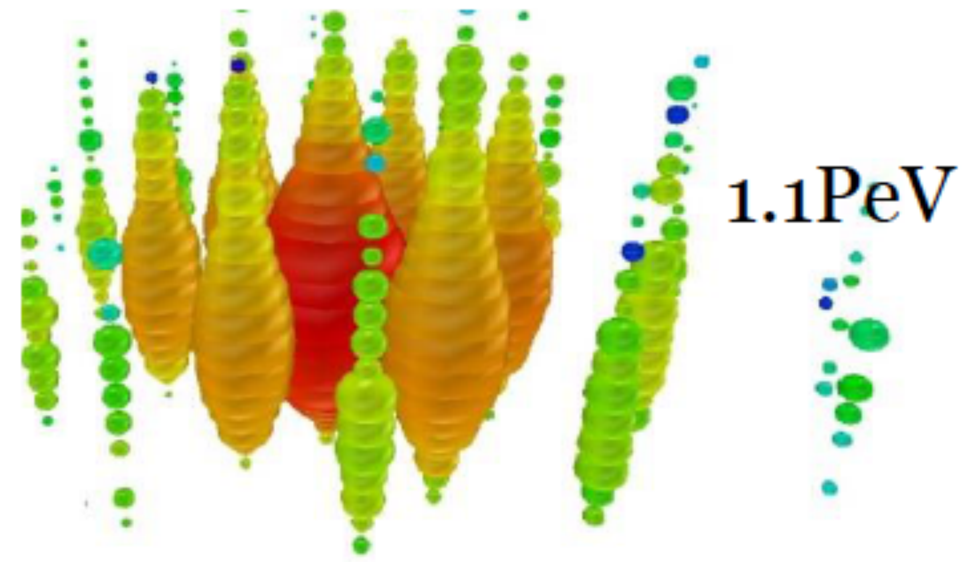
convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



1.1 km

improving angular and energy resolution



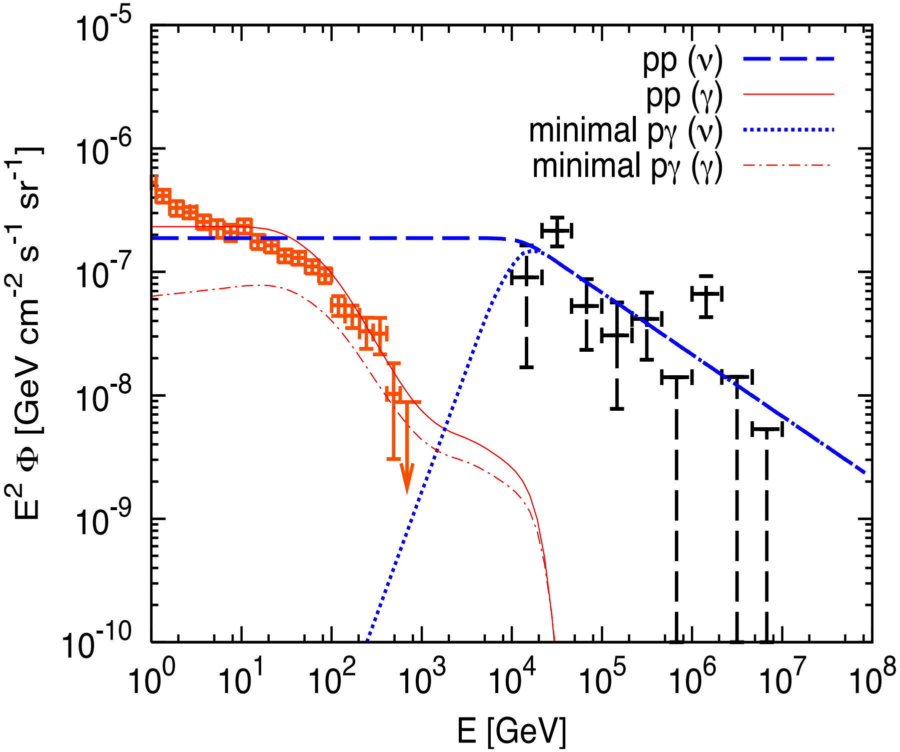


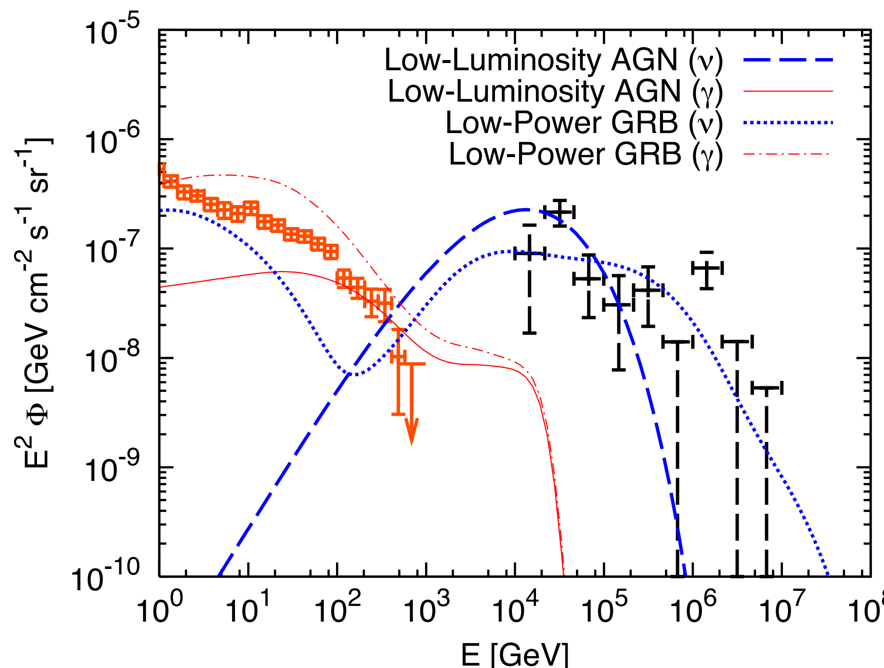
- energy

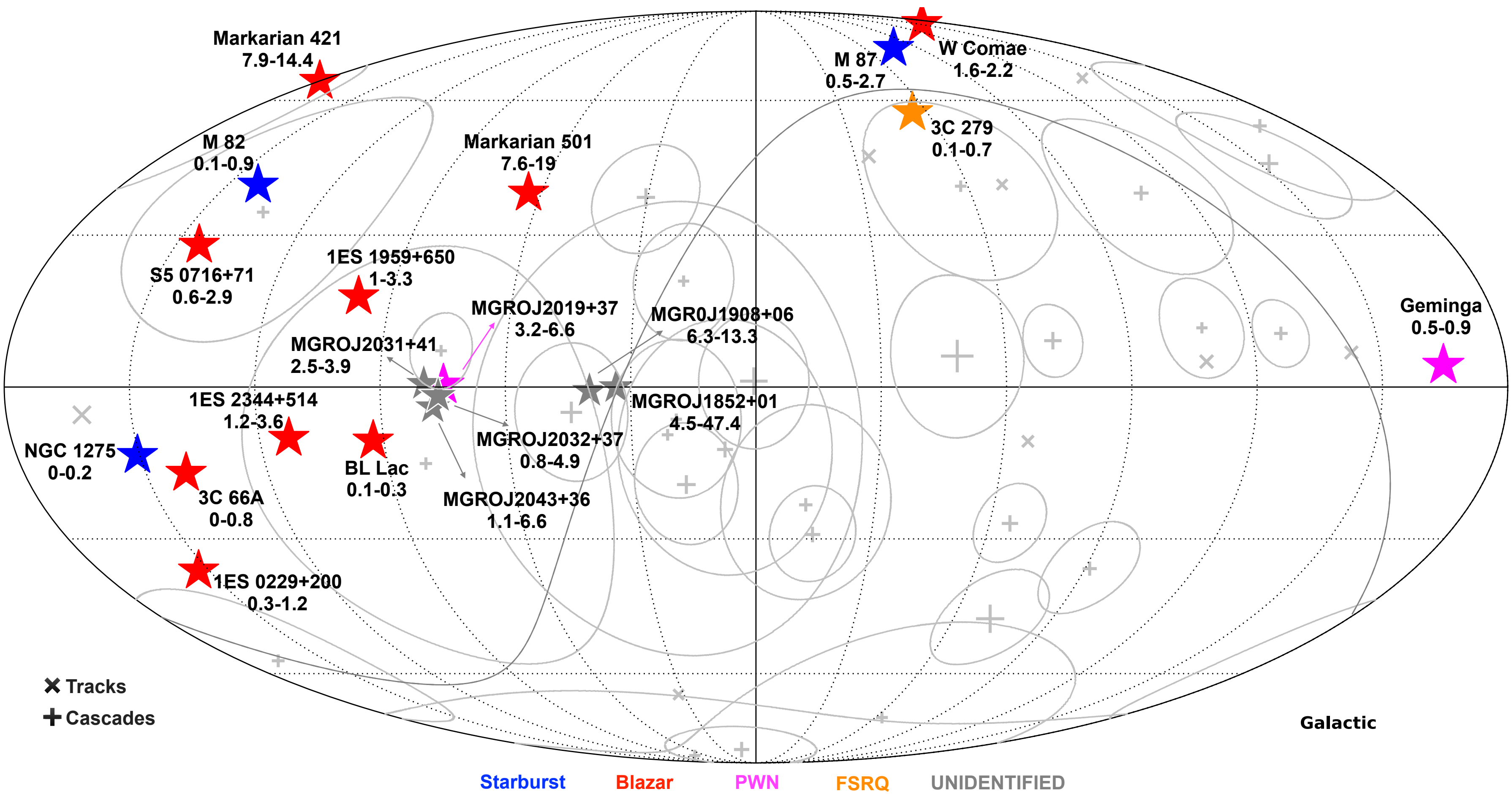
1,041 TeV
1,141 TeV
(15% resolution)

- not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ flux at present level of diffuse limit


pp (ν)
pp (γ)
minimal pγ (ν)
minimal pγ (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]


Low-Luminosity AGN (ν)
Low-Luminosity AGN (γ)
Low-Power GRB (ν)
Low-Power GRB (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]

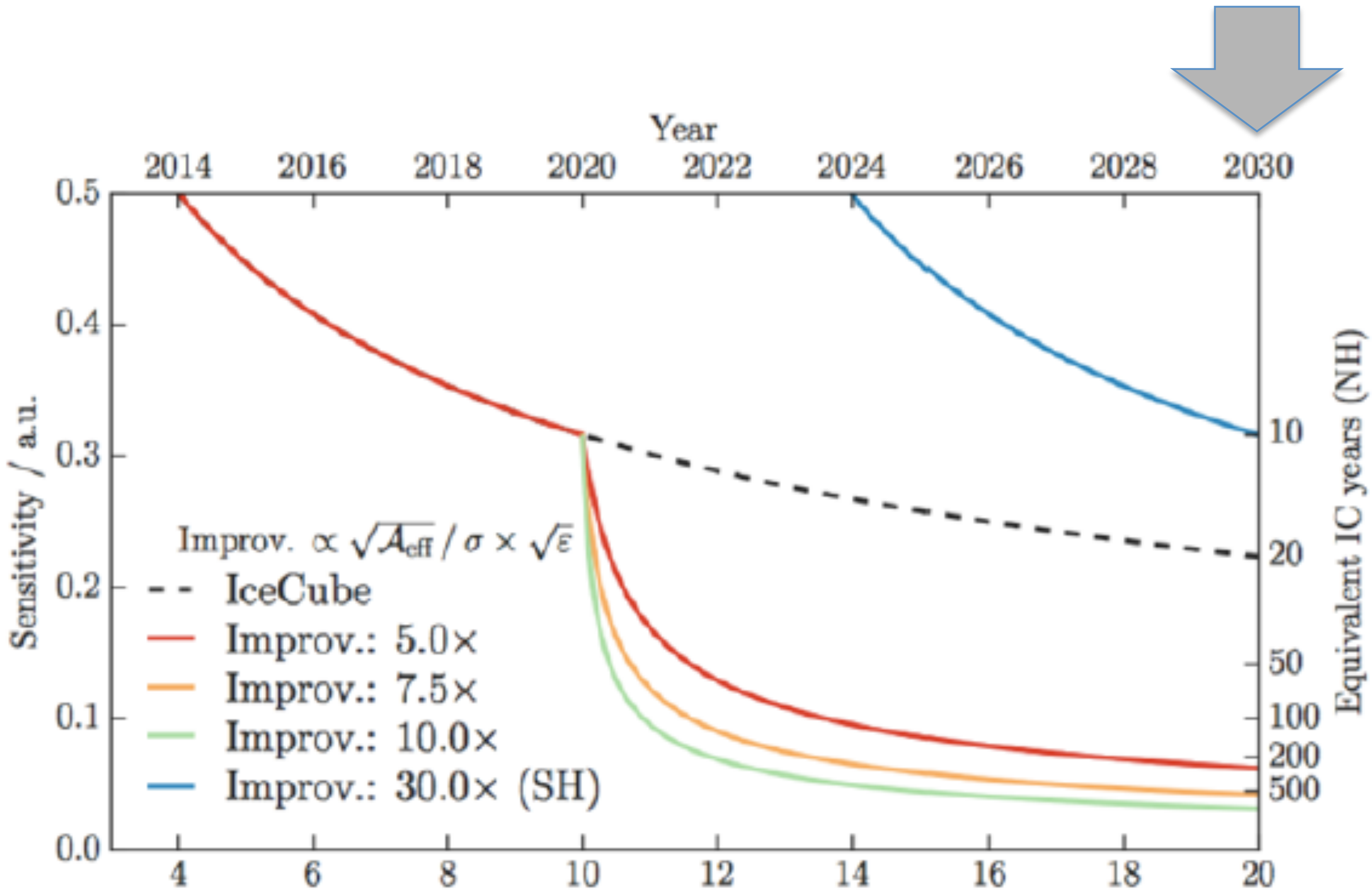


Markarian 421
7.9-14.4
M 82
0.1-0.9
S5 0716+71
0.6-2.9
1ES 1959+650
1-3.3
Markarian 501
7.6-19
MGROJ2019+37
3.2-6.6
MGROJ2031+41
2.5-3.9
MGR0J1908+06
6.3-13.3
MGROJ1852+01
4.5-47.4
1ES 2344+514
1.2-3.6
MGROJ2032+37
0.8-4.9
NGC 1275
0-0.2
BL Lac
0.1-0.3
3C 66A
0-0.8
MGROJ2043+36
1.1-6.6
1ES 0229+200
0.3-1.2
M 87
0.5-2.7
W Comae
1.6-2.2
3C 279
0.1-0.7
Geminga
0.5-0.9
Tracks
Cascades
Galactic
Starburst
Blazar
PWN
FSRQ
UNIDENTIFIED

	Type	Origin	Flux Seen by	Min #Events	Max #Events	flux ratio	Integration bound [TeV]	cut off
MGRO J2031+41	UNID	Galactic	MILAGRO	2.5	3.9	-	$1\text{-}10^3$	✓
MGRO J2019+37	PWN	Galactic	MILAGRO	3.2	6.6	-	$1\text{-}10^3$	✓
MGRO J1908+06	UNID	Galactic	MILAGRO	6.3	13.3	-	$1\text{-}10^3$	✓
MGRO J1852+01	UNID	Galactic	MILAGRO	4.5	47.4	-	$1\text{-}10^3$	✓
MGRO J2032+37	UNID	Galactic	MILAGRO	0.8	4.9	-	$1\text{-}10^3$	✓
MGRO J2043+36	UNID	Galactic	MILAGRO	1.1	6.6	-	$1\text{-}10^3$	✓
Markarian 421	Blazar	Extragalactic	MAGIC	7.9	14.4	2.1	$0.25\text{-}10^3$	✓
M 87	Starburst	Extragalactic	MAGIC	0.5	2.7	0.13	0.1-Infinity	-
Geminga	PWN	Galactic	MILAGRO	0.5	0.9	0.08	17.5-Infinity	-
S5 0716+71	Blazar	Extragalactic	MAGIC	0.6	2.9	0.3	0.2-Infinity	-
1ES 1959+650	Blazar	Extragalactic	MAGIC	1.0	3.3	0.4	0.3-Infinity	-
1ES 2344+514	Blazar	Extragalactic	VERITAS/MAGIC	1.2	3.6	0.8	0.175-Infinity	-
3C 66A	Blazar	Extragalactic	MAGIC	0	0.8	0.4	0.1-Infinity	-
BL Lac	Blazar	Extragalactic	MAGIC	0.1	0.3	0.2	0.1-Infinity	-
W Comae	Blazar	Extragalactic	VERITAS	1.6	2.2	1.9	0.2-Infinity	-
Markarian 501	Blazar	Extragalactic	AGRO	7.6	19	1.7	0.15-Infinity	-
3C 279	FSRQ	Extragalactic	MAGIC	0.1	0.7	1.5	0.25-Infinity	-
1ES 0229+200	Blazar	Extragalactic	HESS	0.3	1.2	0.1	0.58-Infinity	-
M 82	Starburst	Extragalactic	VERITAS	0.1	0.9	0.02	0.35-Infinity	-
NGC 1257	Starburst	Extragalactic	MAGIC	0	0.2	0.18	0.1-Infinity	-

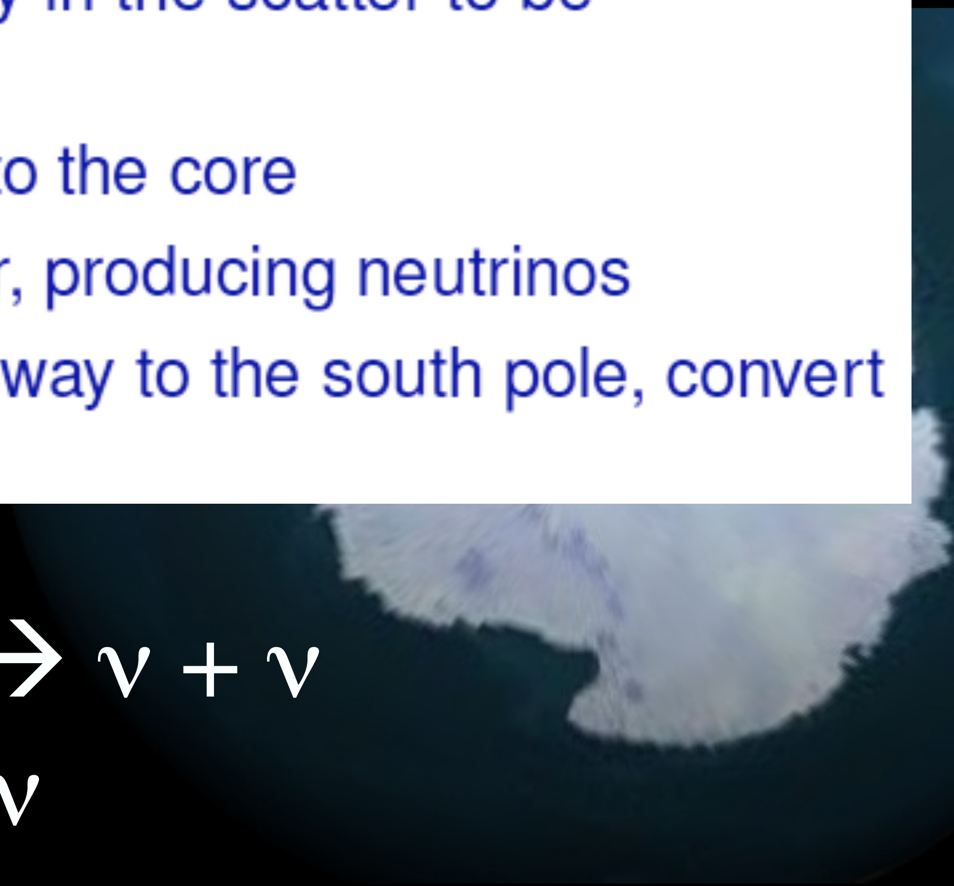
The minimum and maximum expected number of events from interesting sources in 5 years of IC86. The neutrino fluxes are estimated from Gamma ray flux assuming pp interaction at the source. The flux ratio is Integrated Gamma ray flux above threshold energy divided by 90% confidence level neutrino flux limit from 4-year point search of IceCube with a factor 2. The flux used for the W Comae is based on the fitted flux of the flares in different years.

point source sensitivity: equivalent IceCube years



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

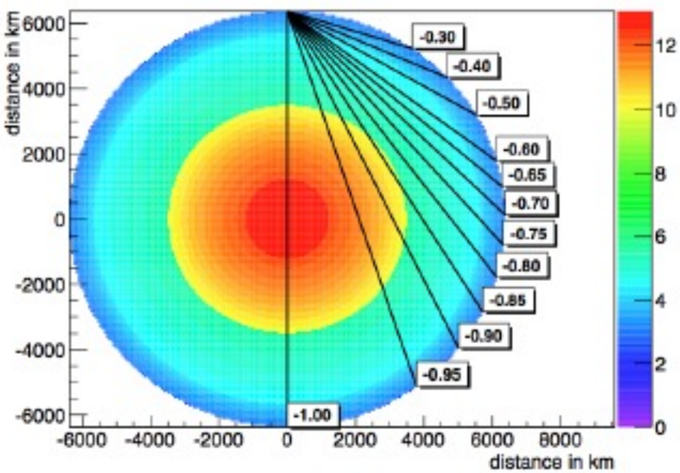


$$\chi + \chi \rightarrow W^{+} + W^{-} \rightarrow \nu + \nu$$

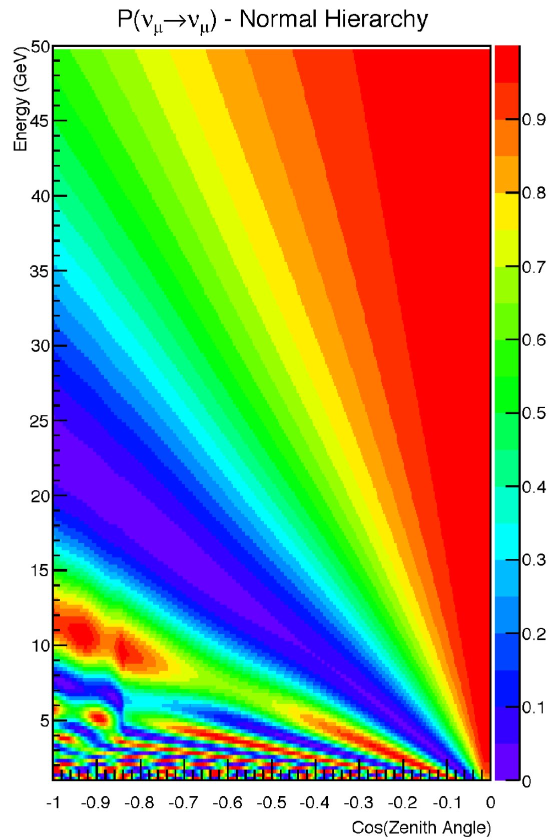
$$b + b \rightarrow \nu + \nu$$

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

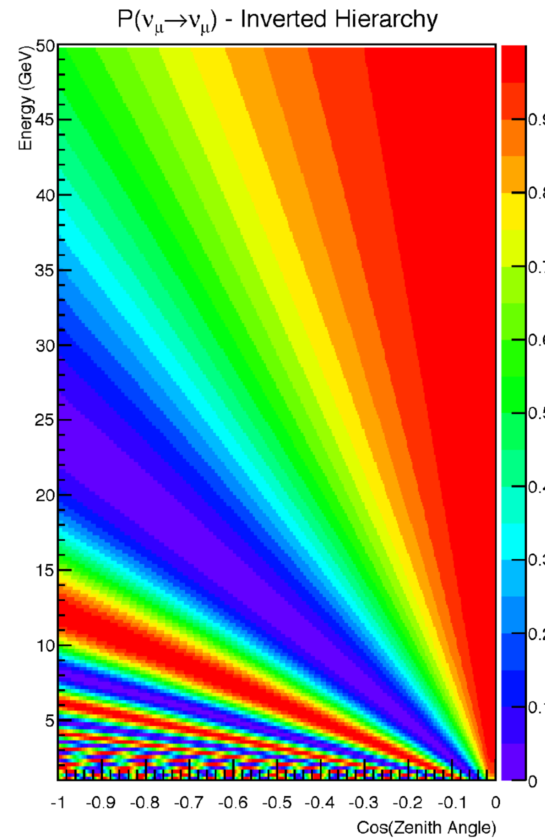
- Map upward ν flux in bins of (E,$\cos\theta$);
- $\cos\theta$= -1 L~12000 Km;



Normal Hierarchy



Inverted Hierarchy



Letter of Intent PINGU- arXiV:1401.2046

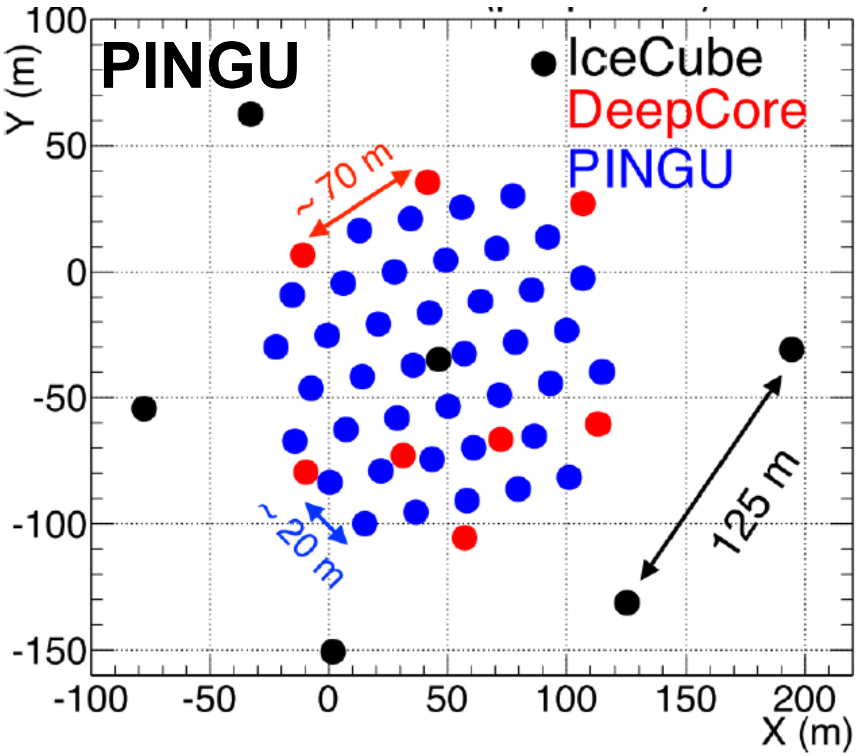
~ 10 GeV : hierarchy revealed by "large" matter effects in the Earth

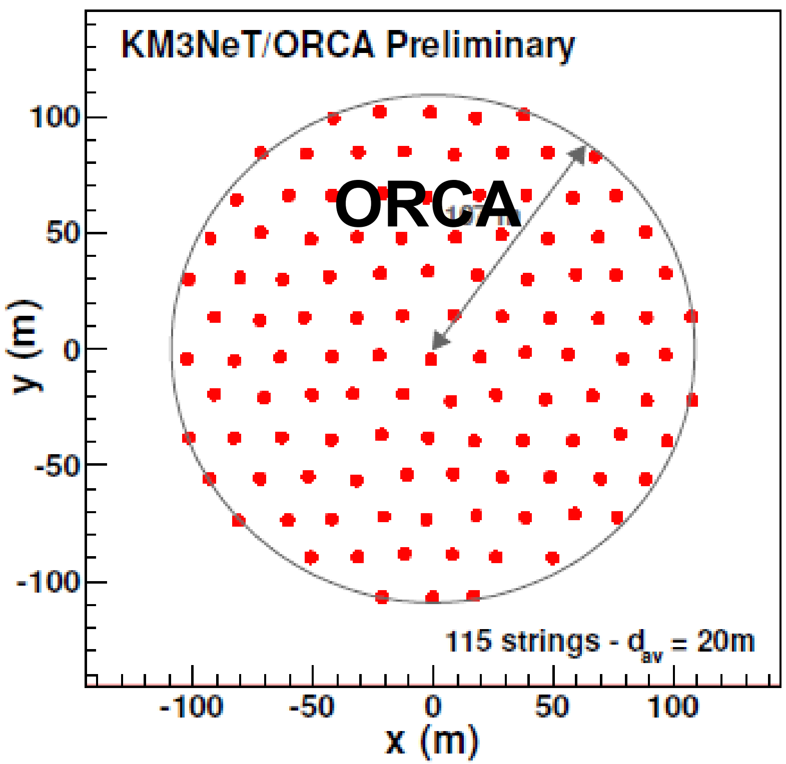
$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2} G_F n_e}{\Delta_{13}}\right]}$$

(mostly) neutrino + antineutrino -

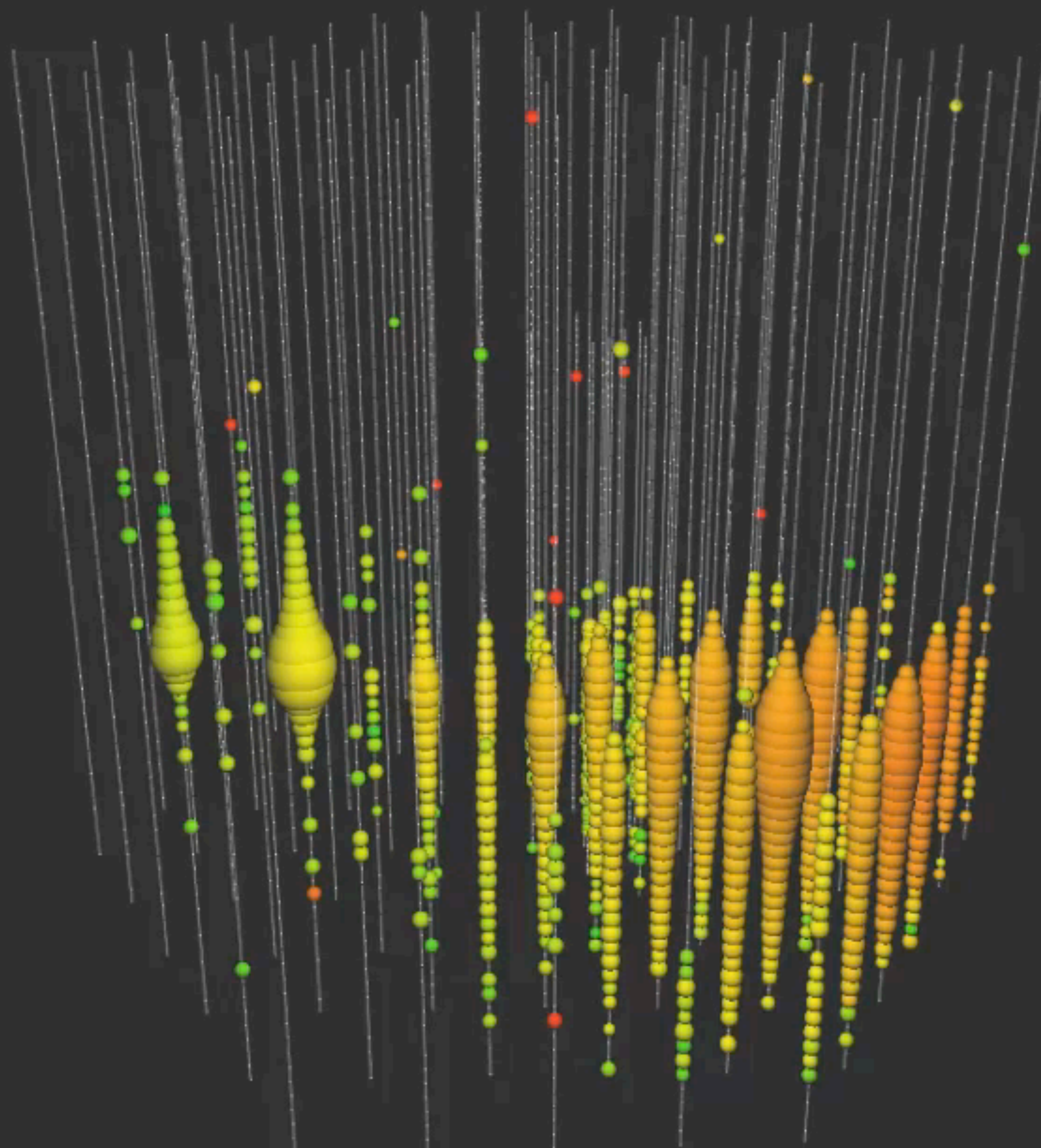
sign Δ_{13} : hierarchy !

- megatons of ice (PINGU) or seawater (ORCA)
- finer granularity than IceCube and KM3NeT

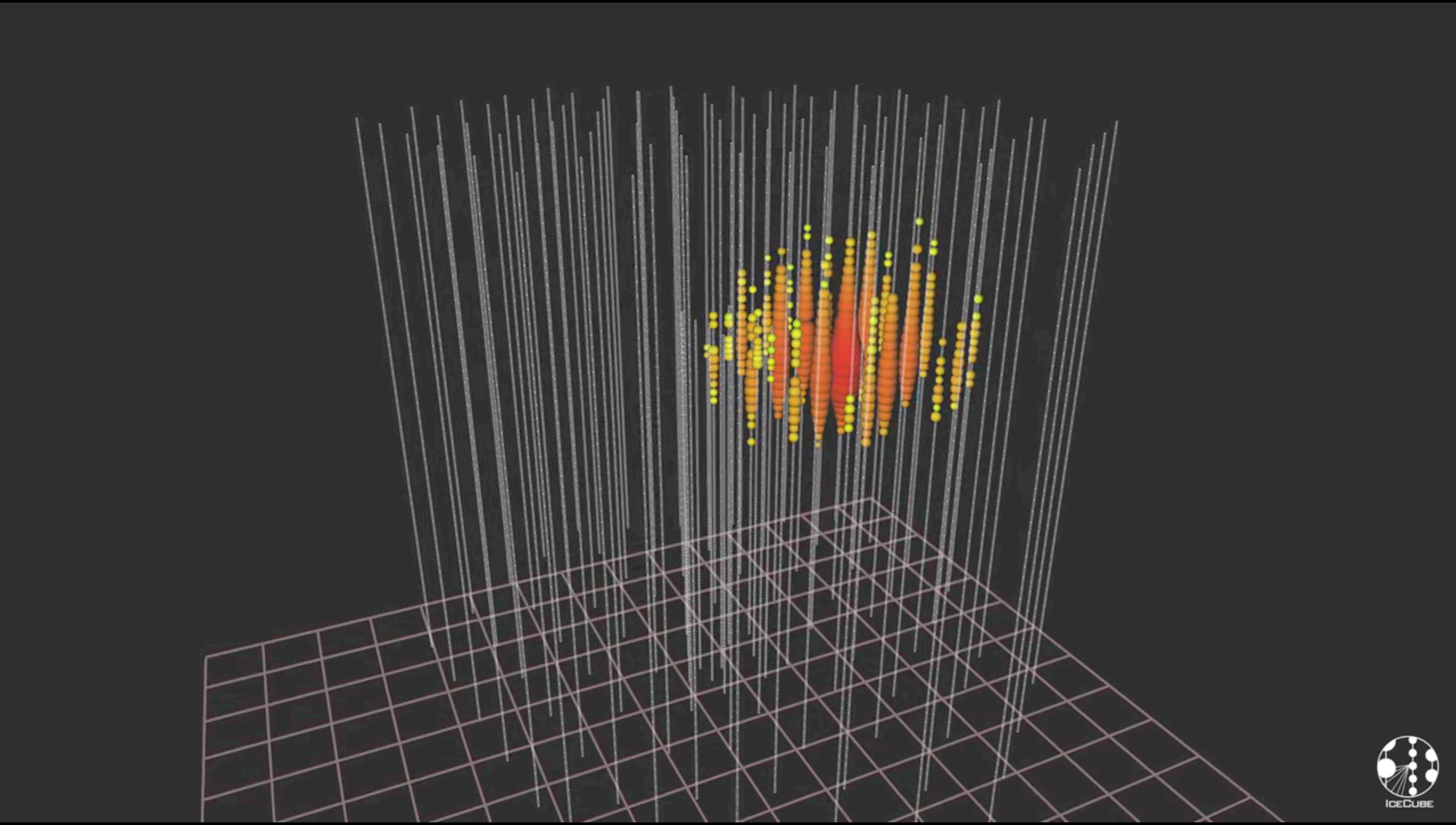


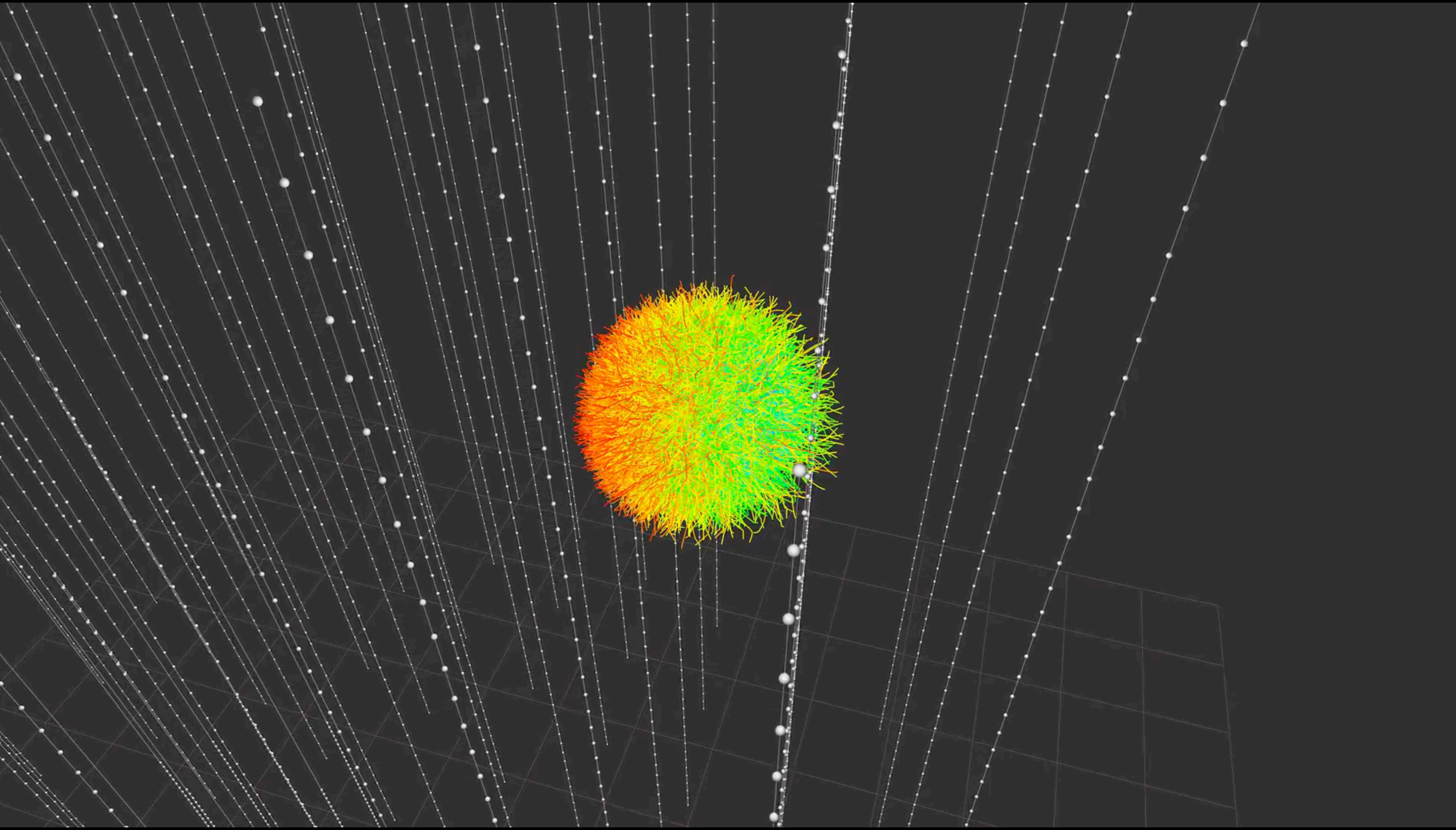


..or alternatively use a magnetized detector distinguishing neutrinos from anti-neutrinos (INO project), or measure oscillating reactor neutrinos over a 60 km baseline (Juno)



GZK neutrino search: two neutrinos with > 1,000 TeV





size = energy

color = time = direction