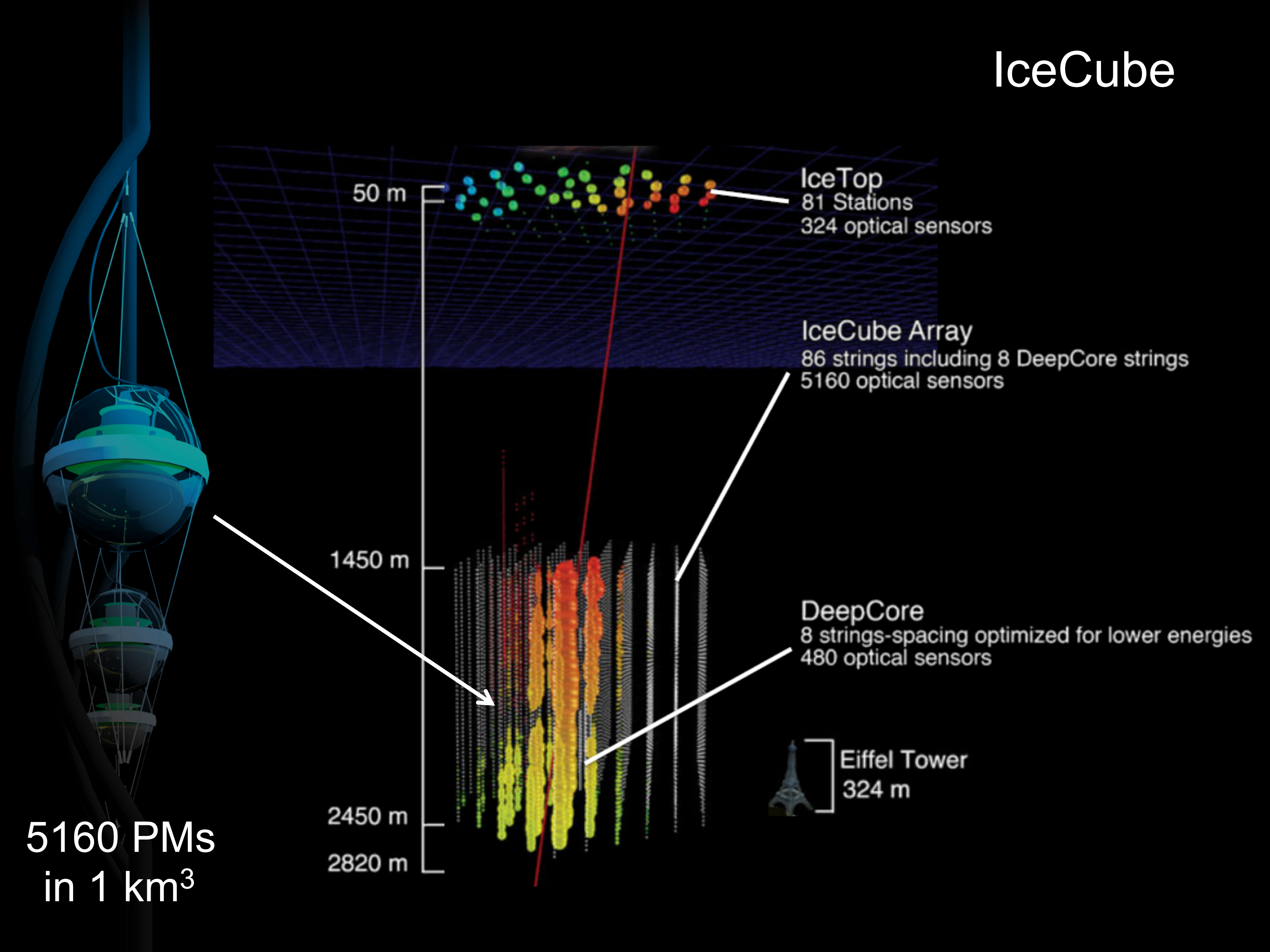
IceCube Gen2

Francis Halzen

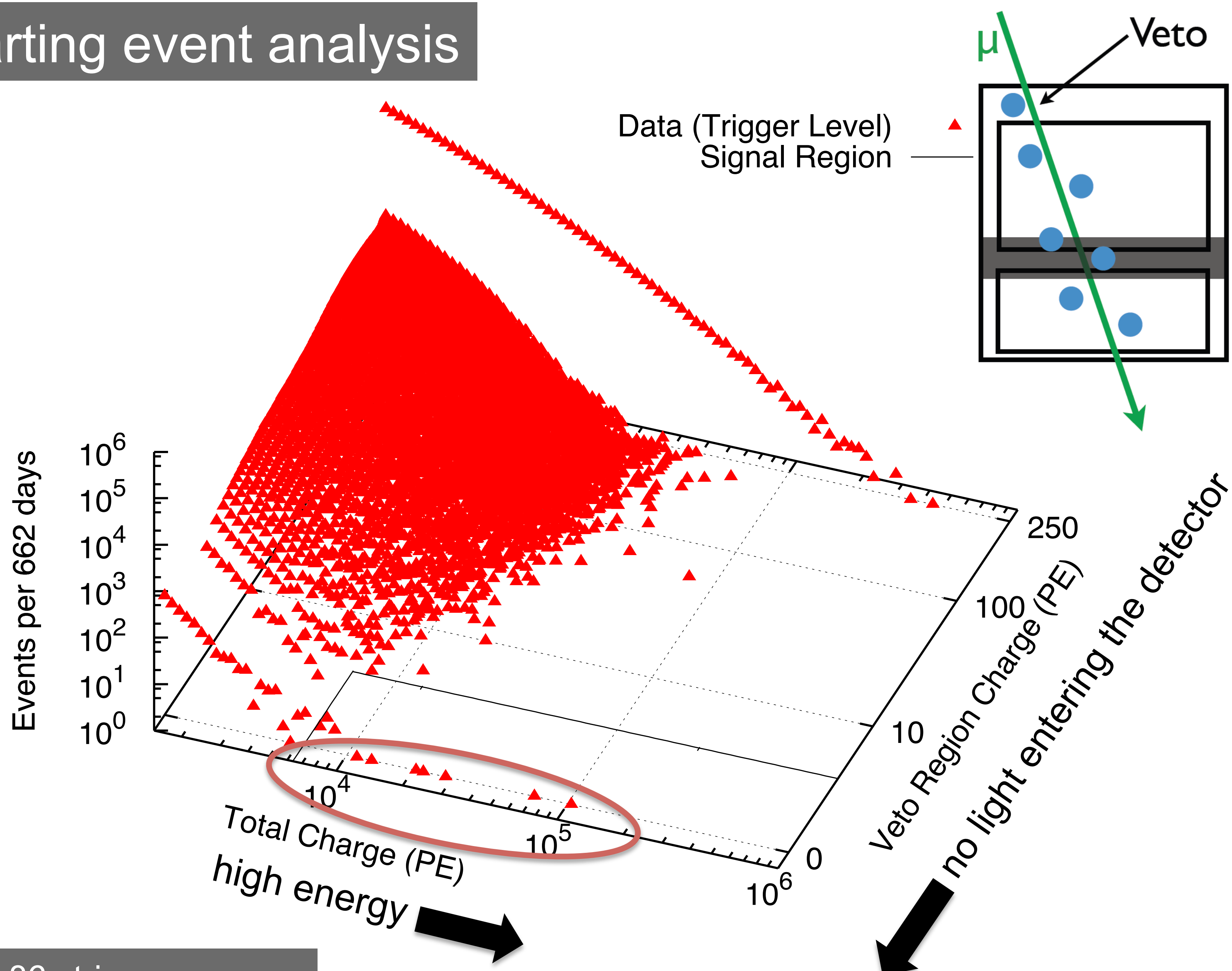
- build on discovery
- incredible dynamic (wavelength) range:
  2 GeV – 2000 TeV and MeV for bursts
- do astronomy (guaranteed?)
  - extragalactic sources
  - GZK neutrinos
  - Galactic sources (Cygnus)
- high precision atmospheric oscillations (hierarchy?)

IceCube

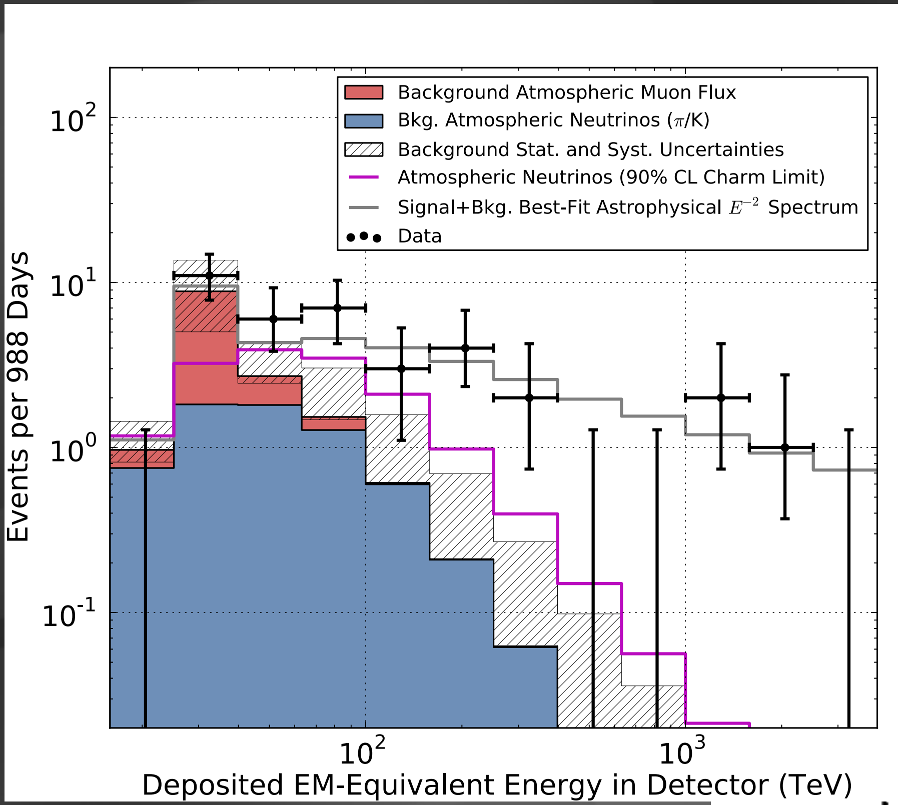


5160 PMs in 1 km^3

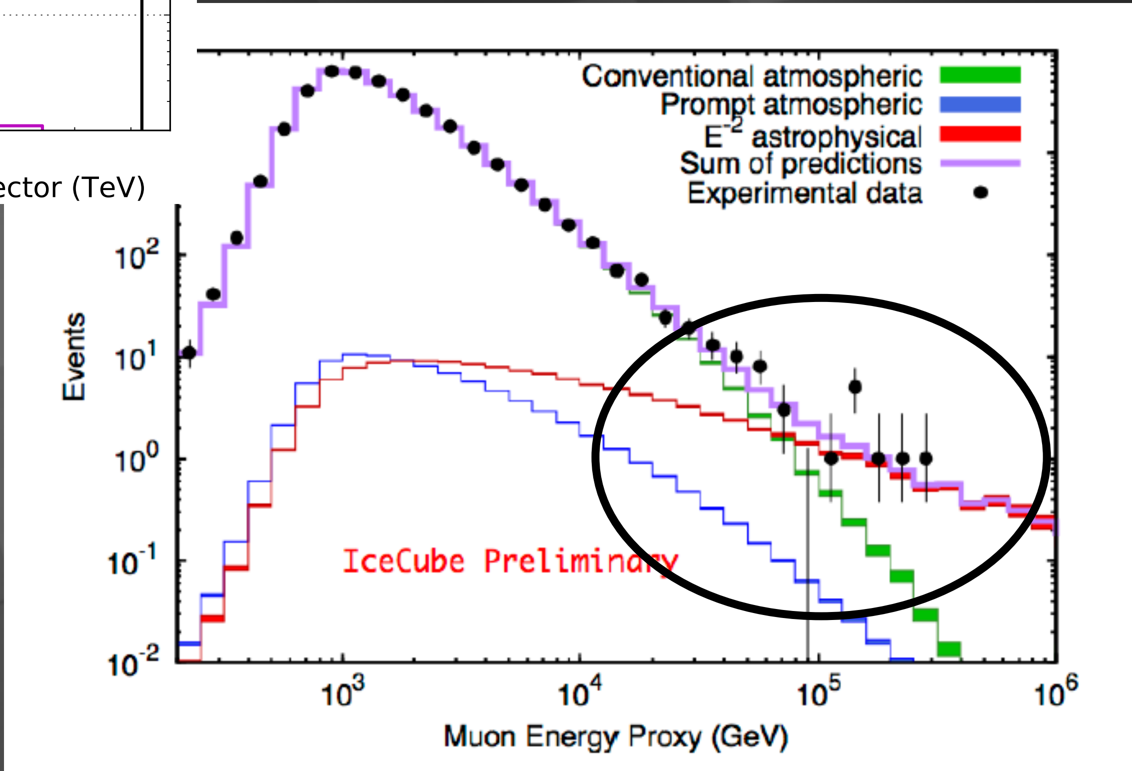
starting event analysis



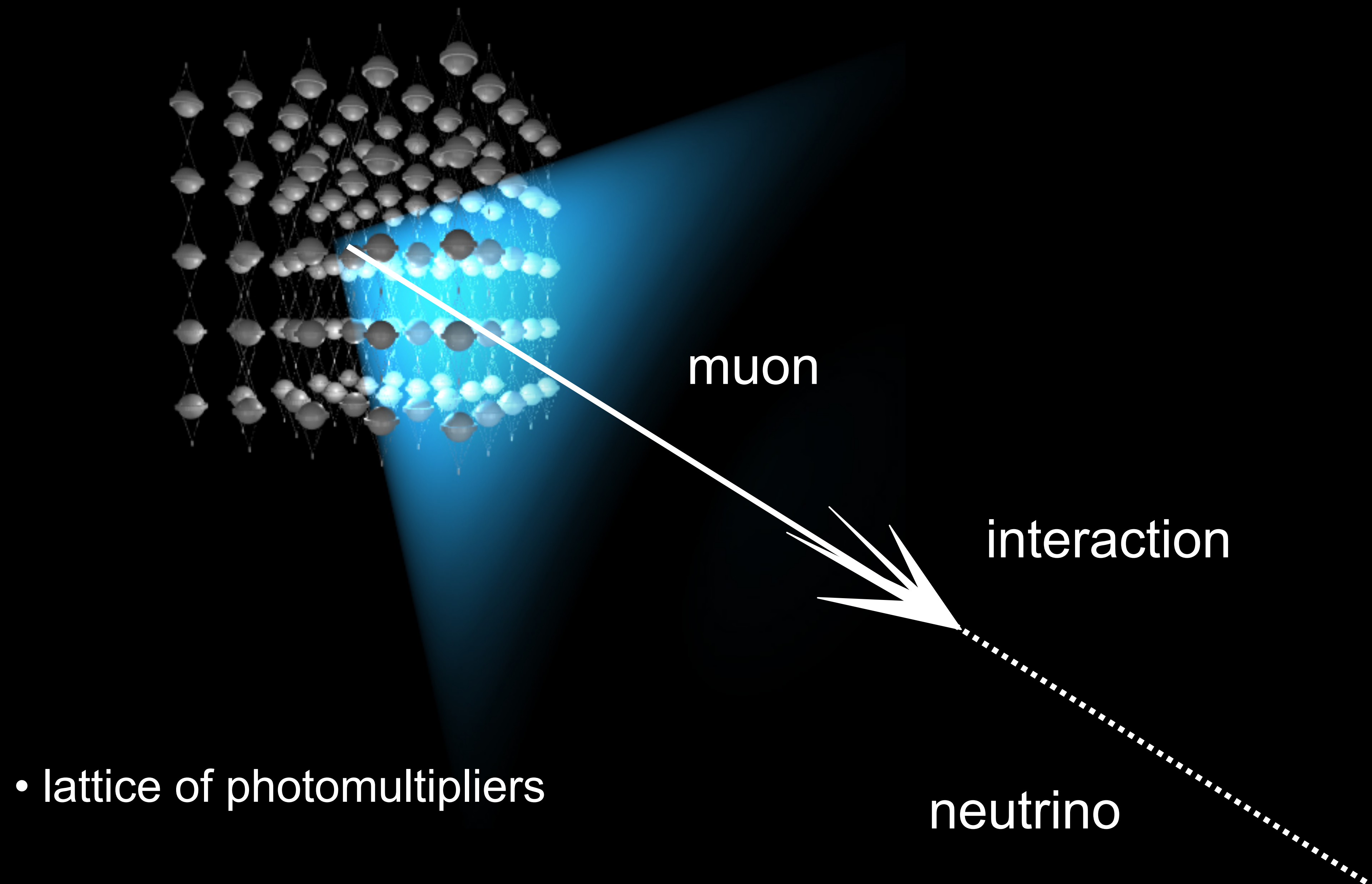
data: 86 strings one year



confirmation!
flux of muon neutrinos
through the Earth

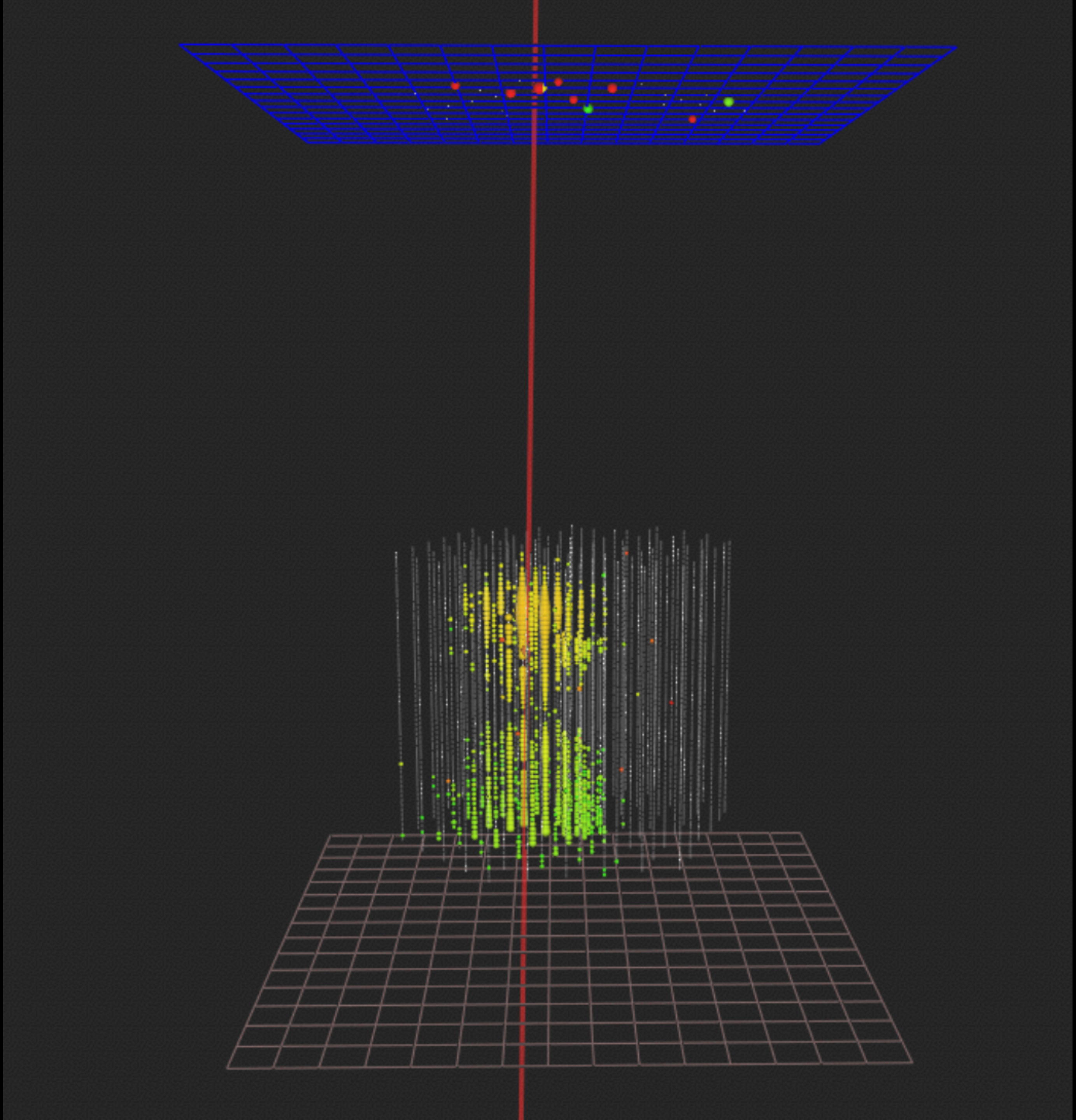


neutrinos of all flavors
interacting inside
IceCube


muon
interaction
neutrino
• lattice of photomultipliers

430 TeV

1 event:
5 sigma
discovery?

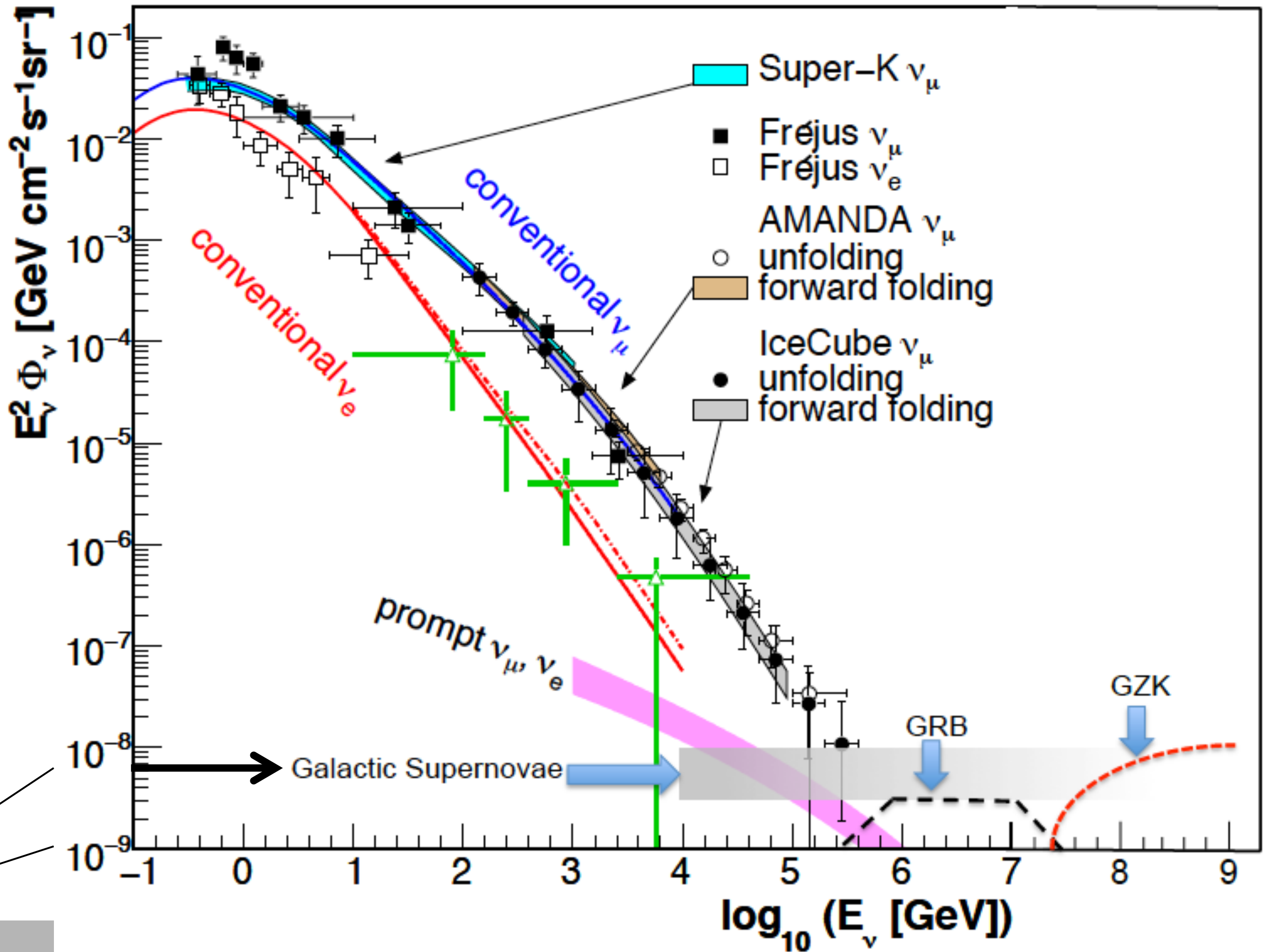


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

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

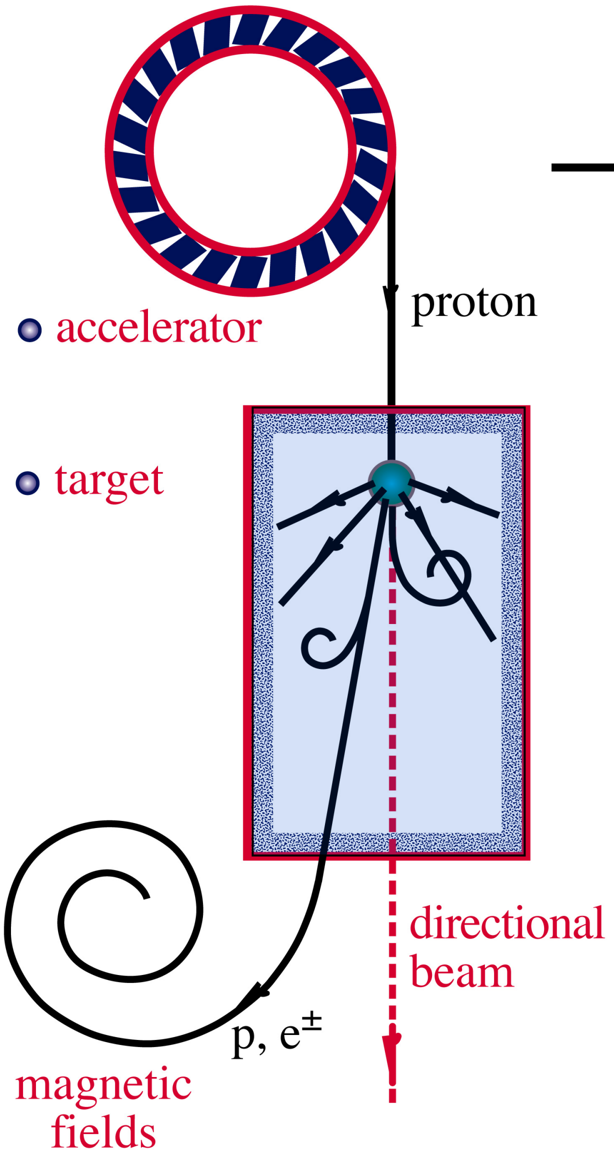


atmospheric

cosmic

100 TeV

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

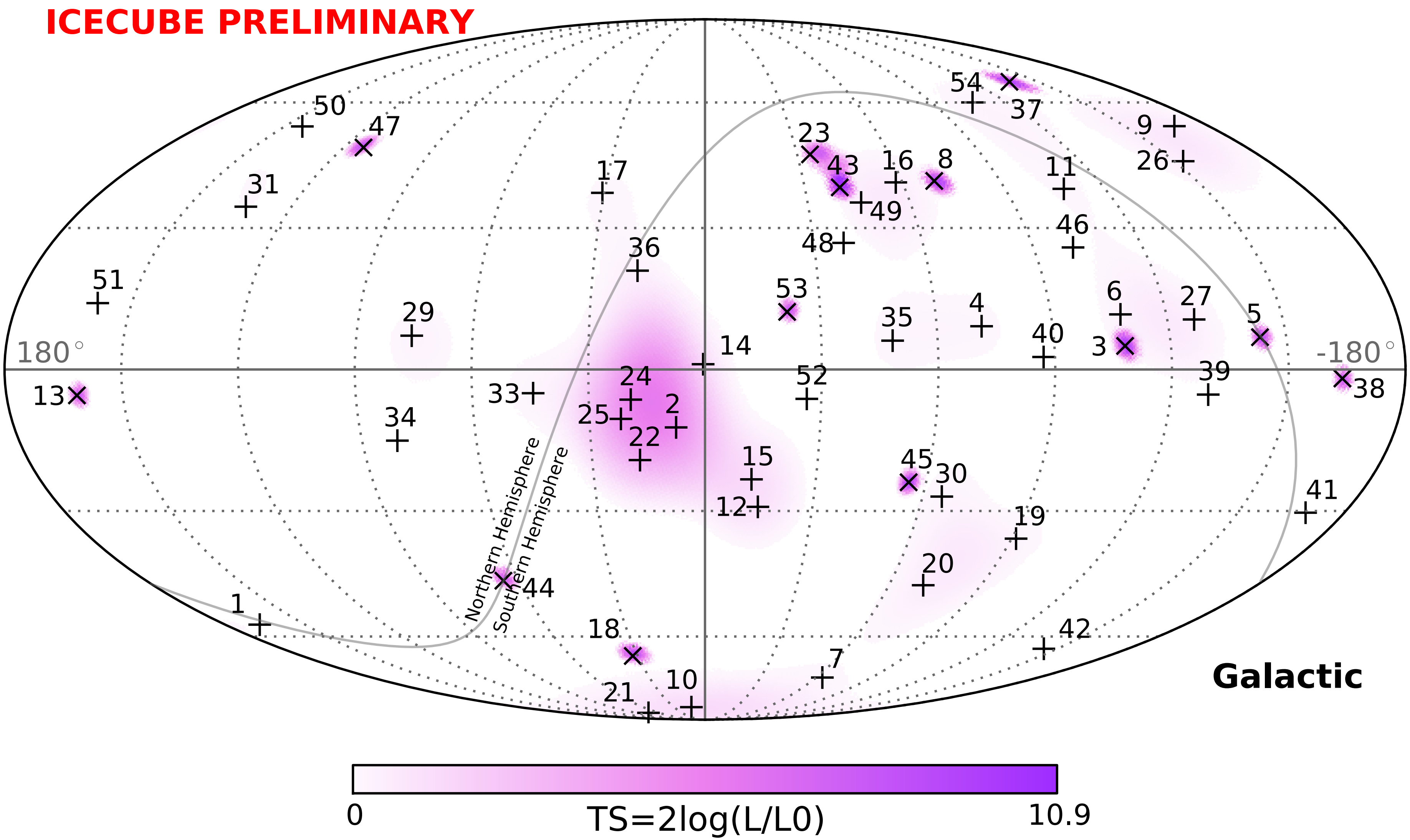
black hole
neutron star

radiation and dust

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

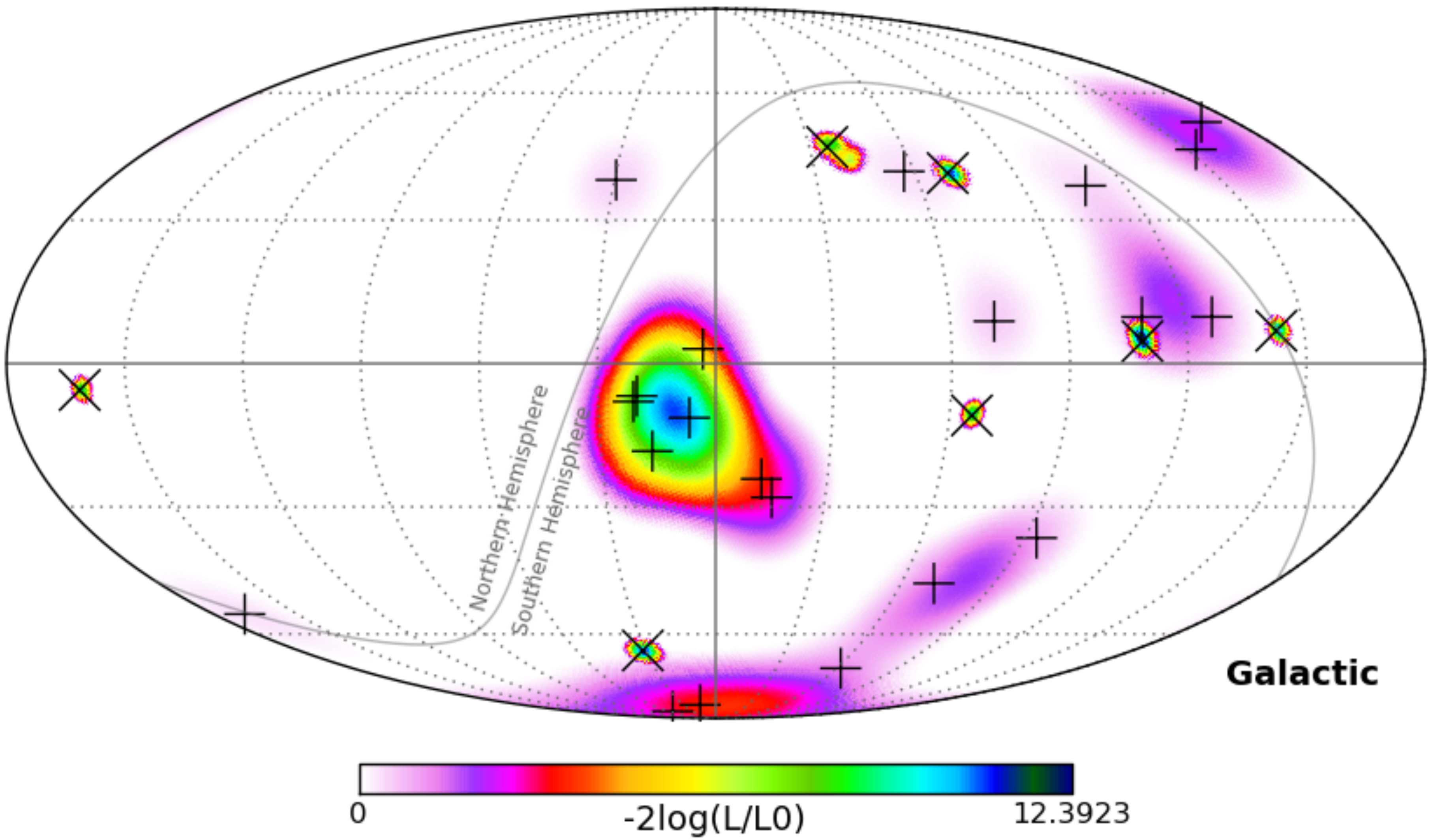
$\rightarrow p + \pi^0$
~ cosmic ray + gamma

4 year HESE



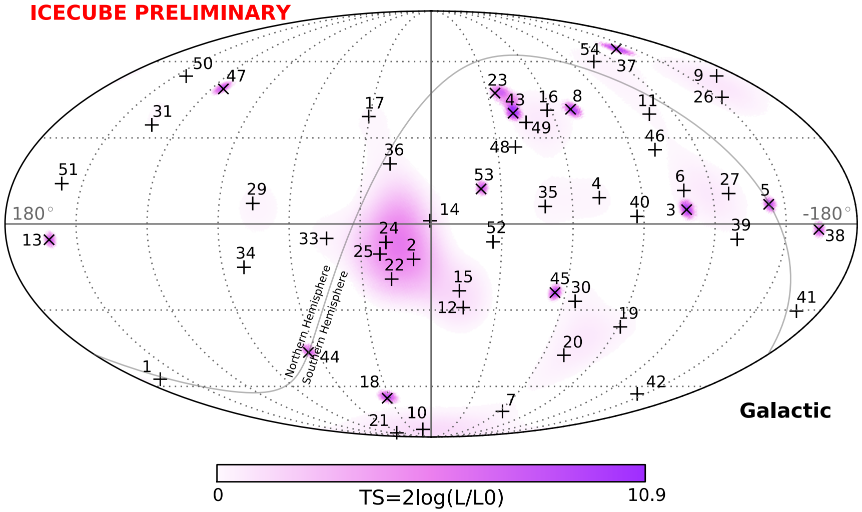
where do they come from?

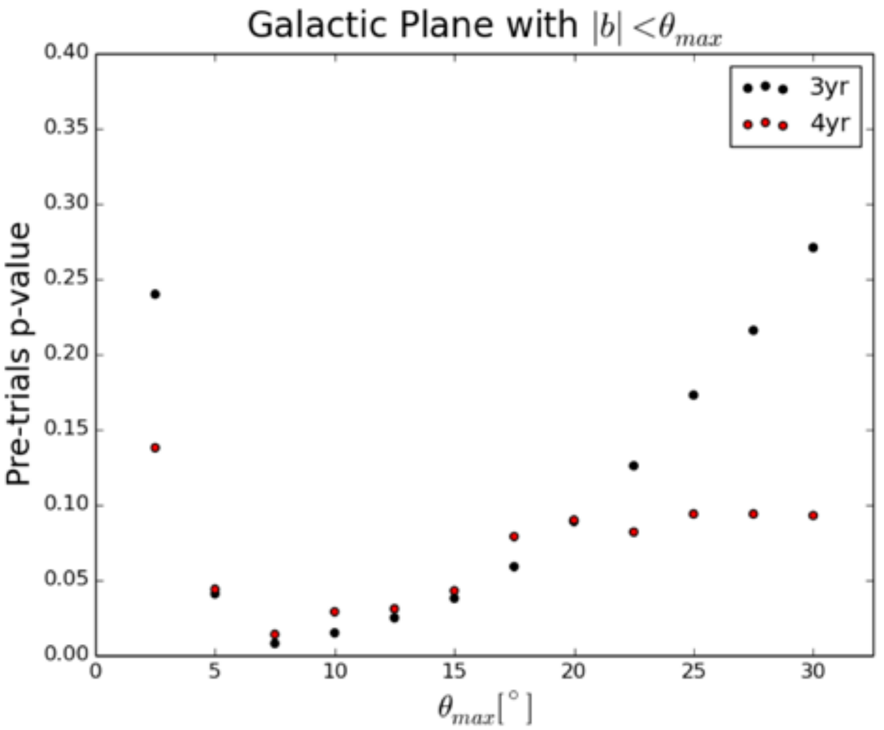
2 year HESE


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

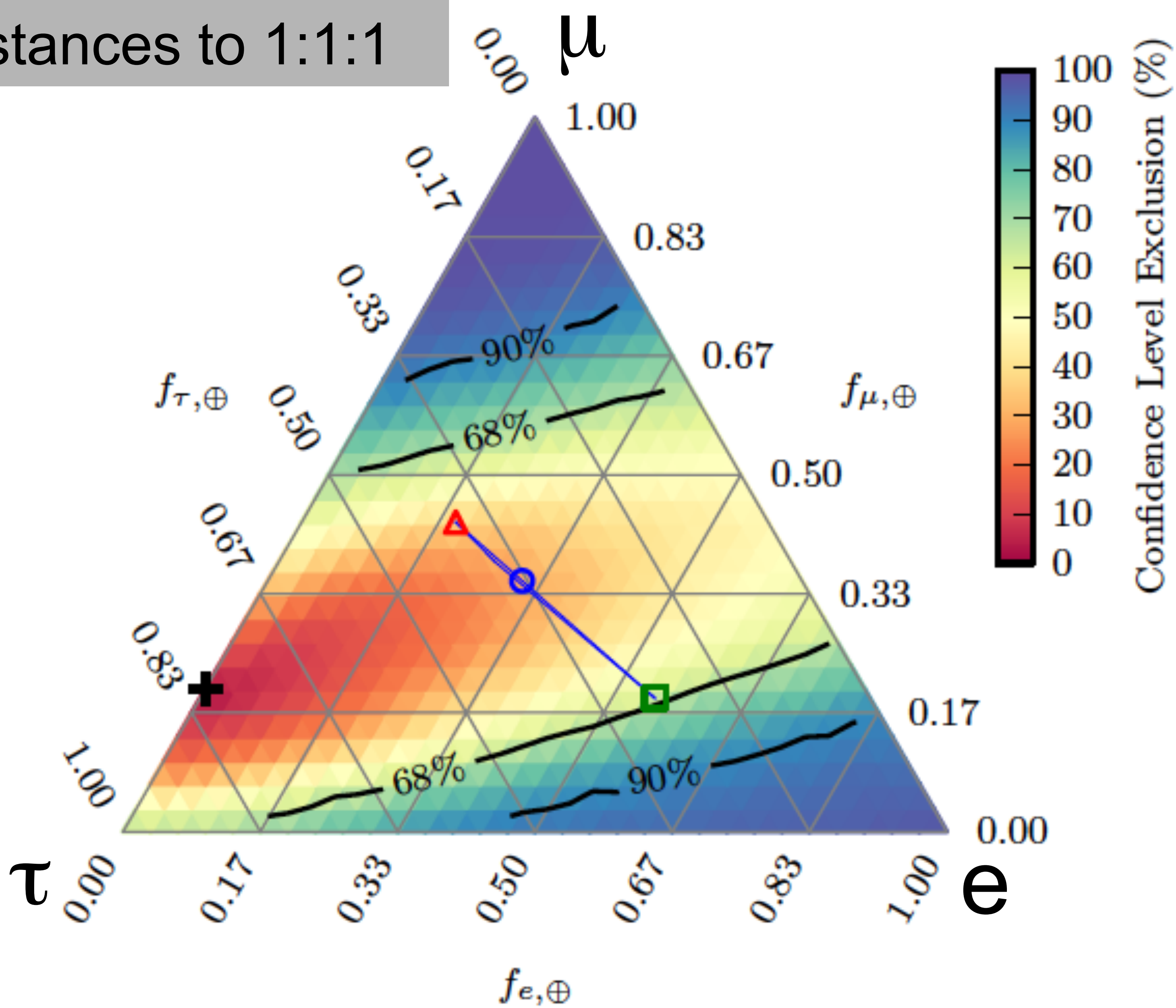
Galactic Plane Width Scan with 5000 trials each

Post trial
- 3 year: 2.8%
- 4 year: 3.3%



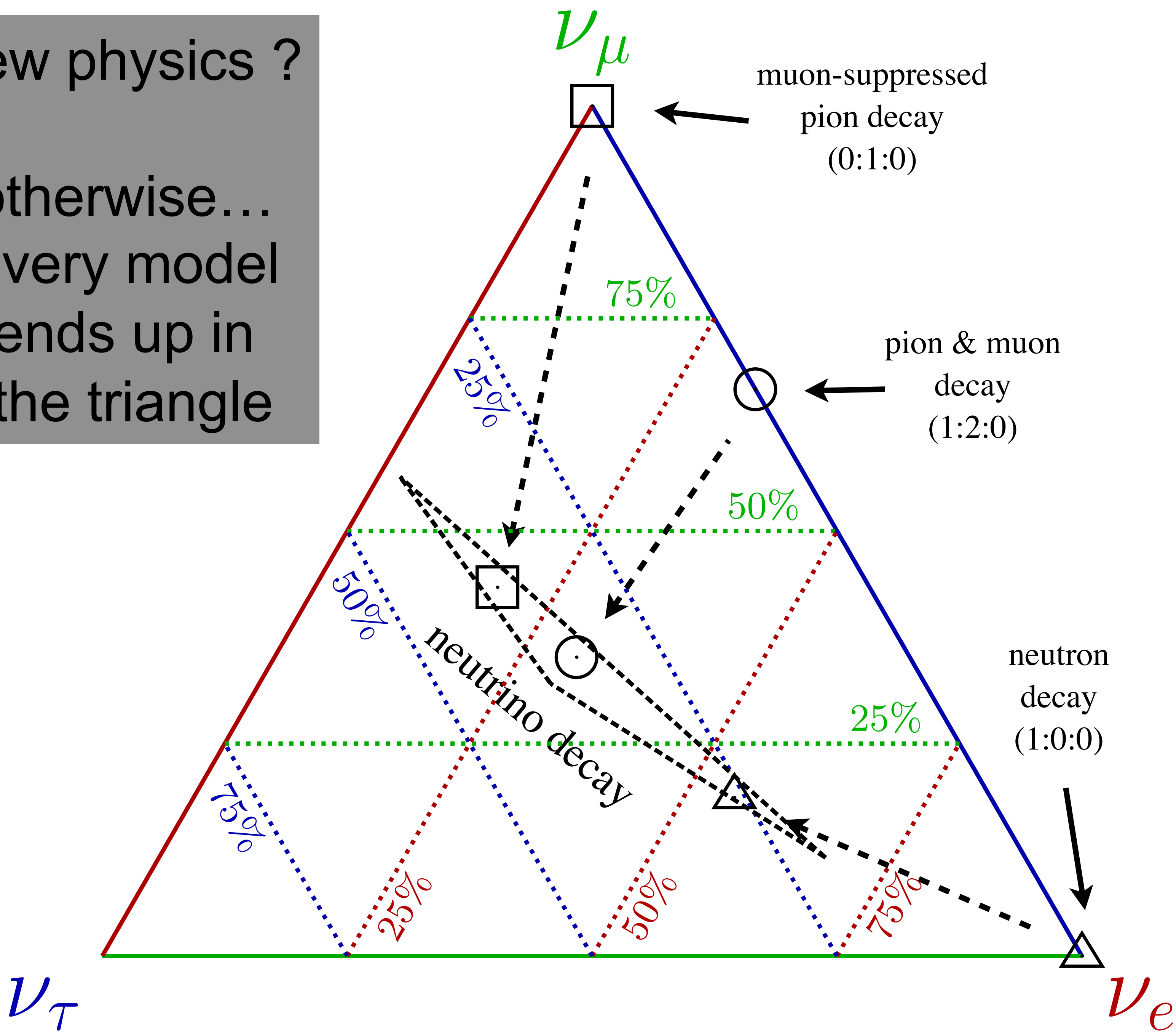


oscillate over cosmic distances to 1:1:1

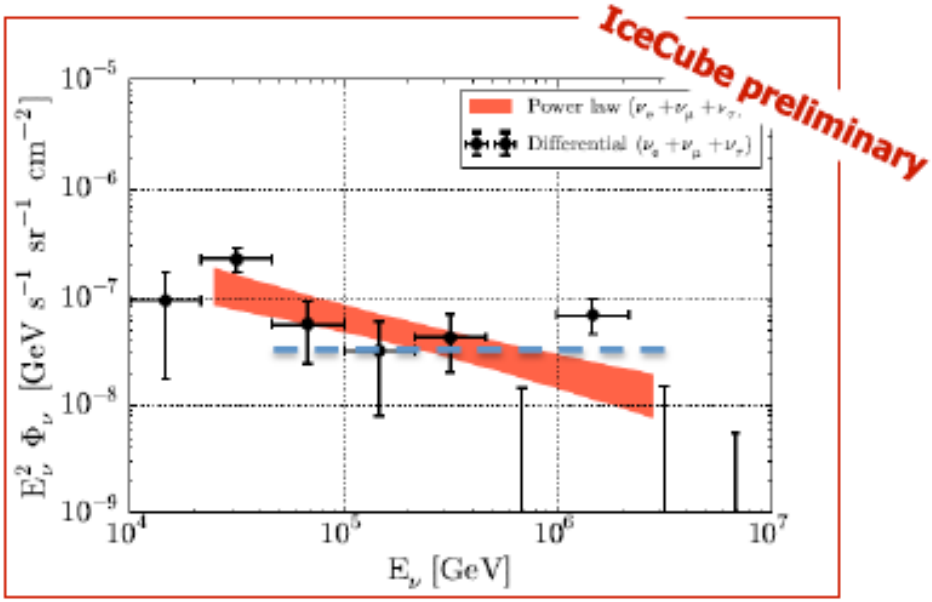


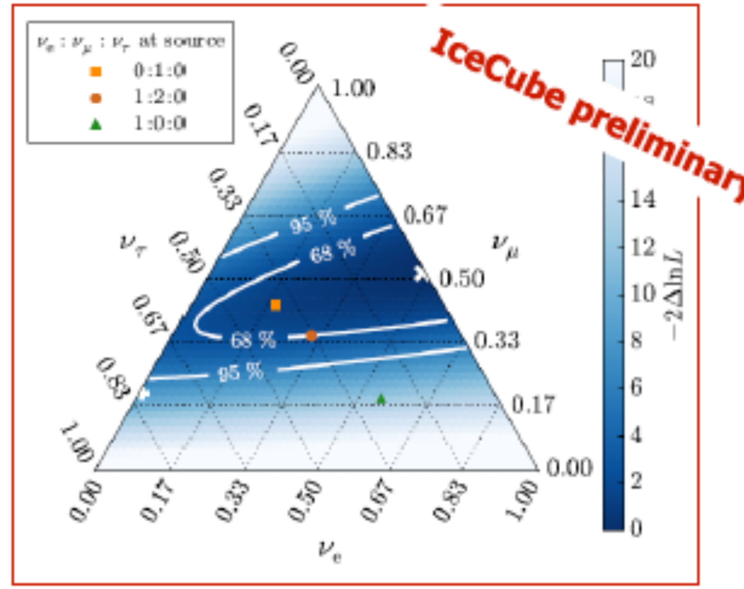
new physics ?

otherwise…
every model
ends up in
the triangle



- 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



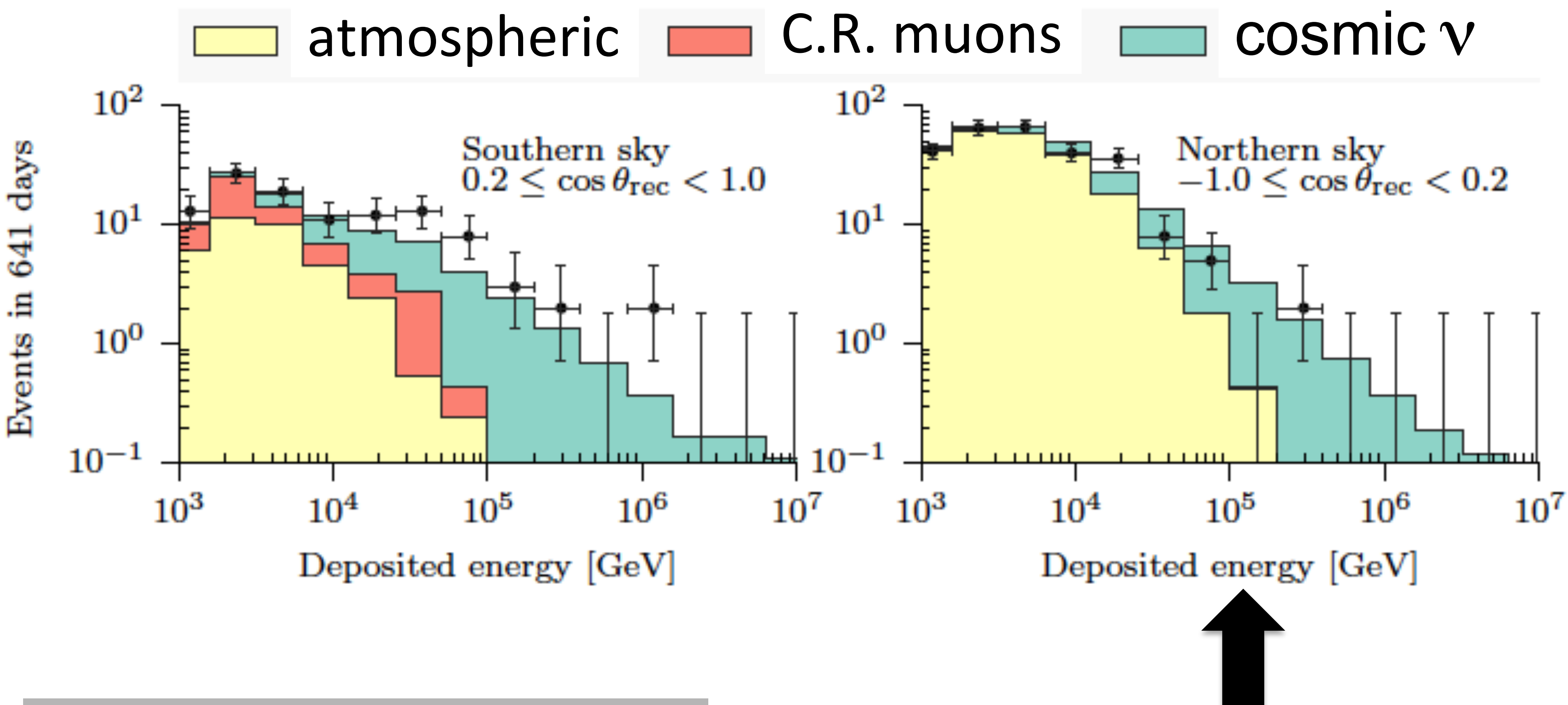


assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 at Earth →

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 ± 1.2)x10^{-18} (GeV · cm^2 · s · sr)$^{-1}$	

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

starting events; towards lower energies: a power?



warning:

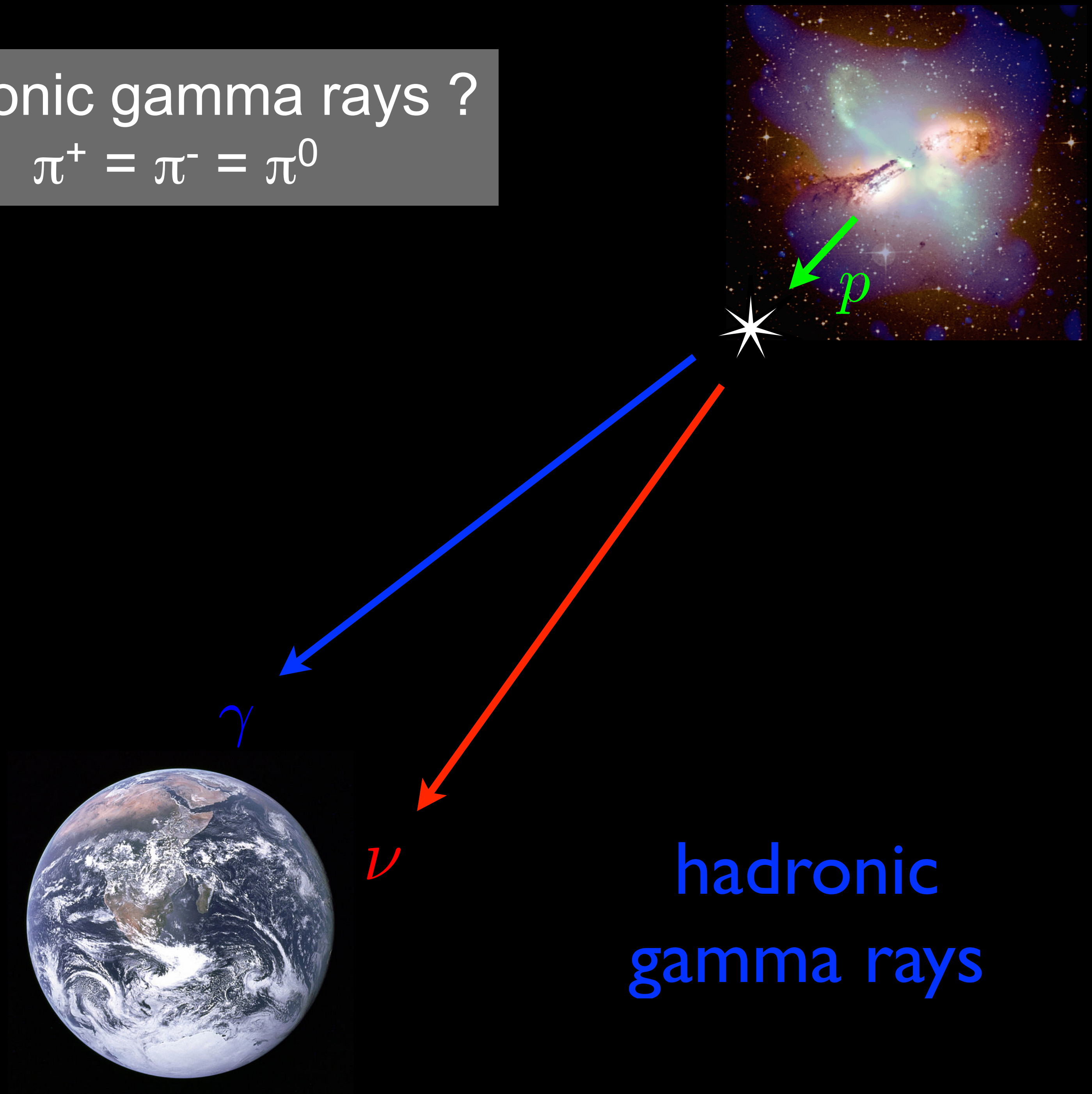
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

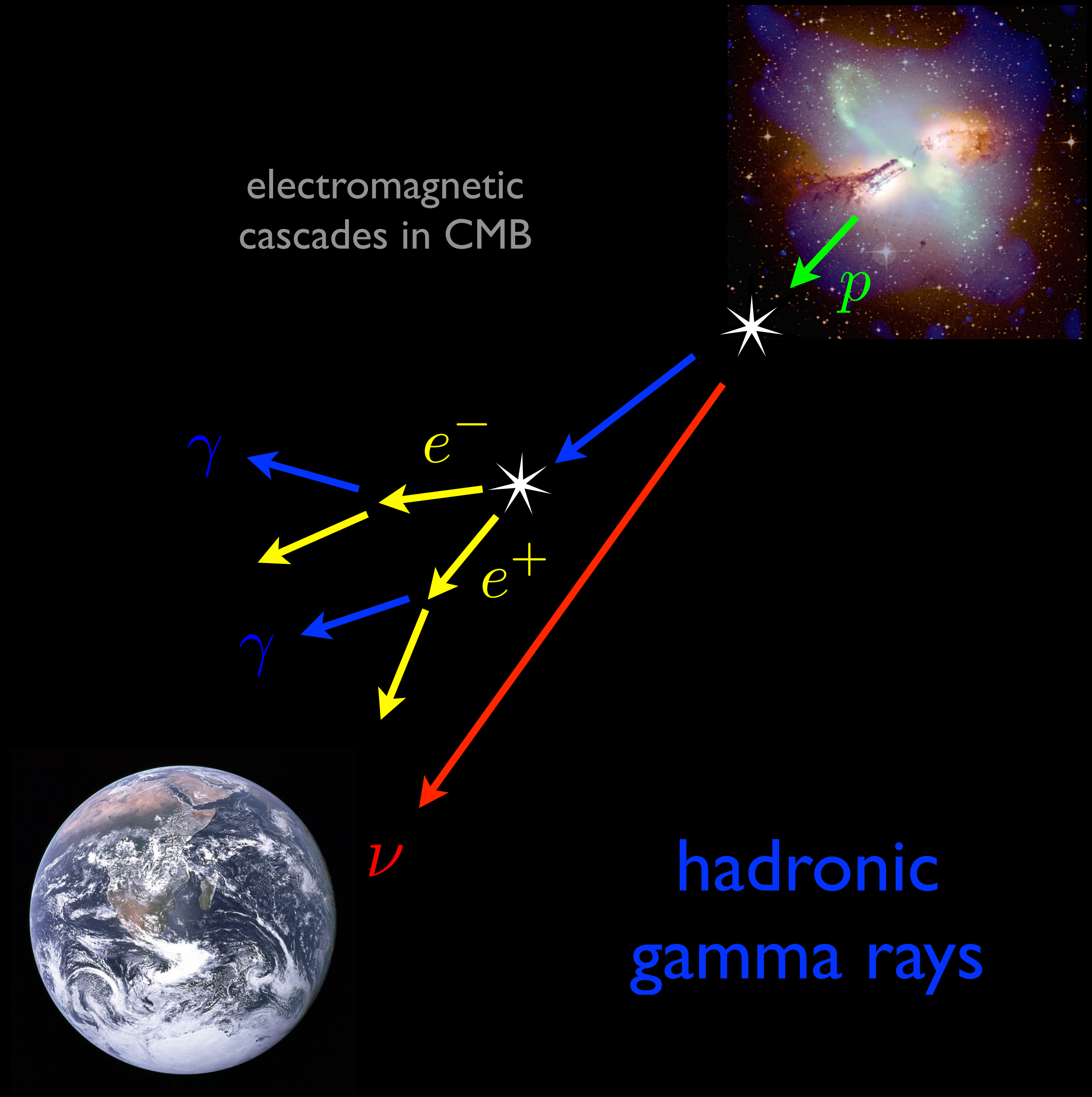
- we observe a diffuse extragalactic flux as expected, neutrinos have no horizon unlike cosmic rays and gamma rays that are absorbed on extragalactic background light
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

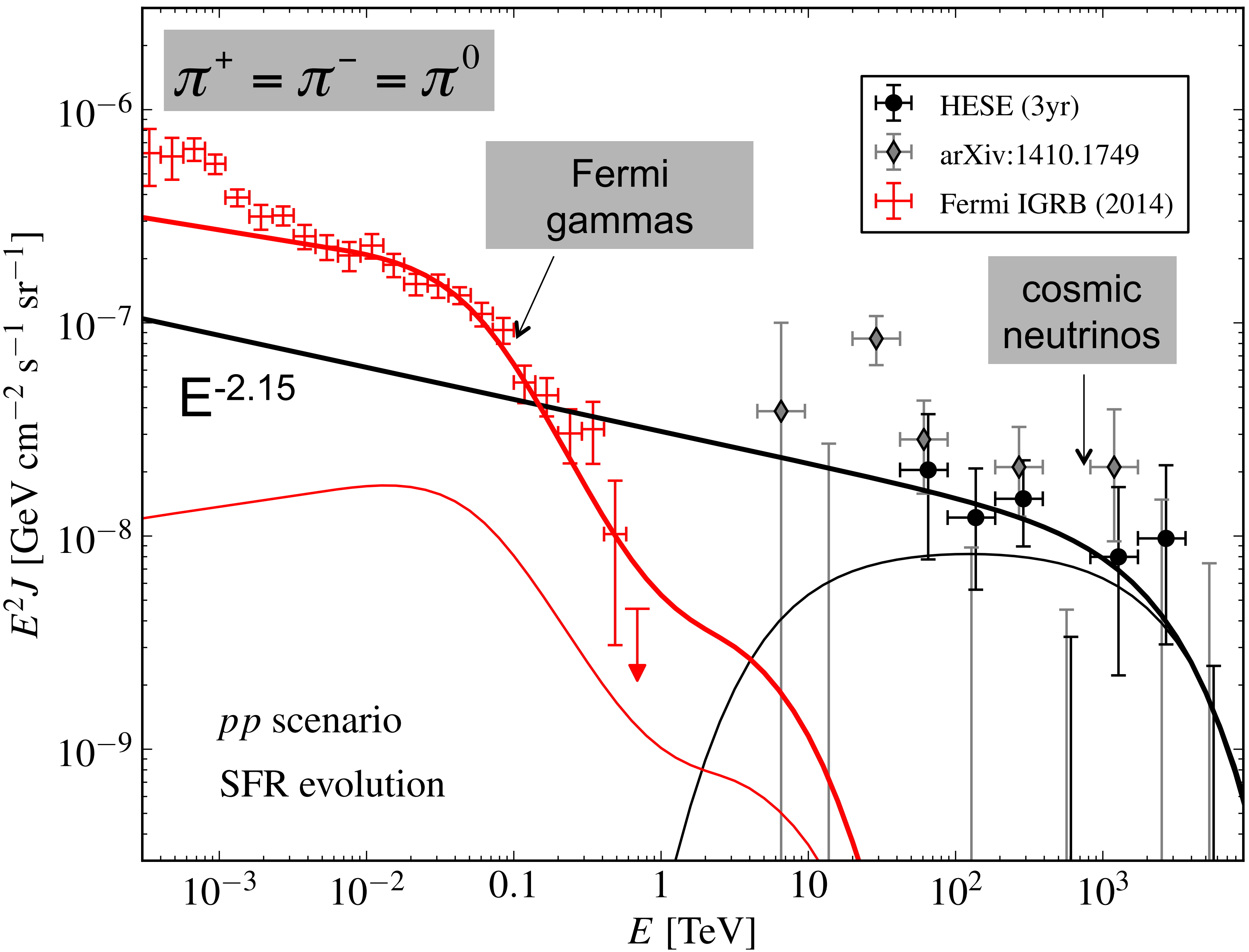
hadronic gamma rays ?

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



hadronic
gamma rays


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



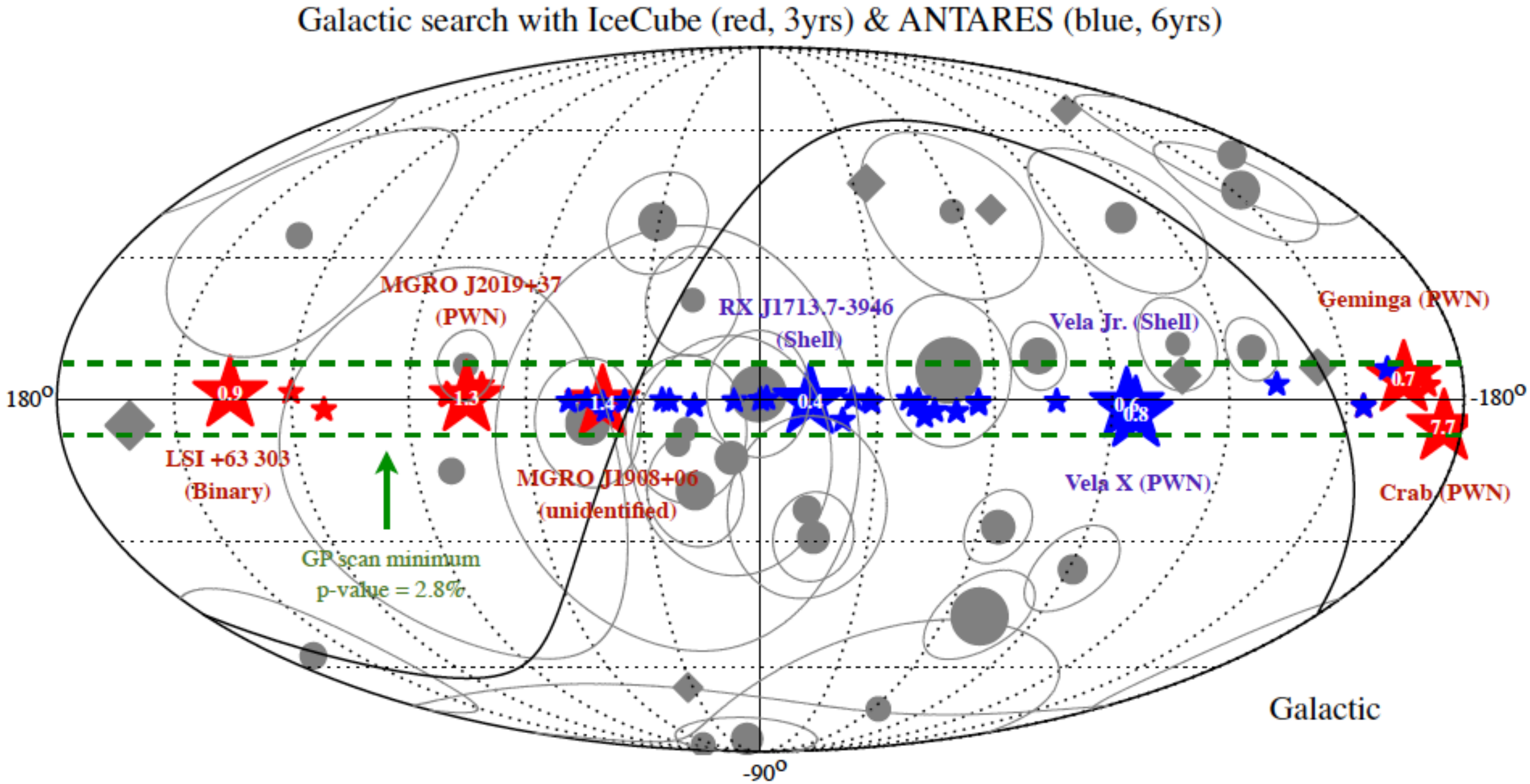
$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]

- we have observed a flux of 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

- hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

- gamma ray sources: predict neutrinos. We are close to identifying point sources.

neutrino event rates from gamma ray sources



as some (all?) gamma ray sources produce neutrinos, we are close to detecting neutrinos from known high energy gamma ray emitters (one neutrino per photon)

- we observe a diffuse extragalactic flux as expected, neutrinos have no horizon unlike cosmic rays and gamma rays that are absorbed on extragalactic background light
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?
- active galaxies, most likely blazars, or starburst galaxies?
- correlation to catalogues should confirm this

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  - GZK neutrinos
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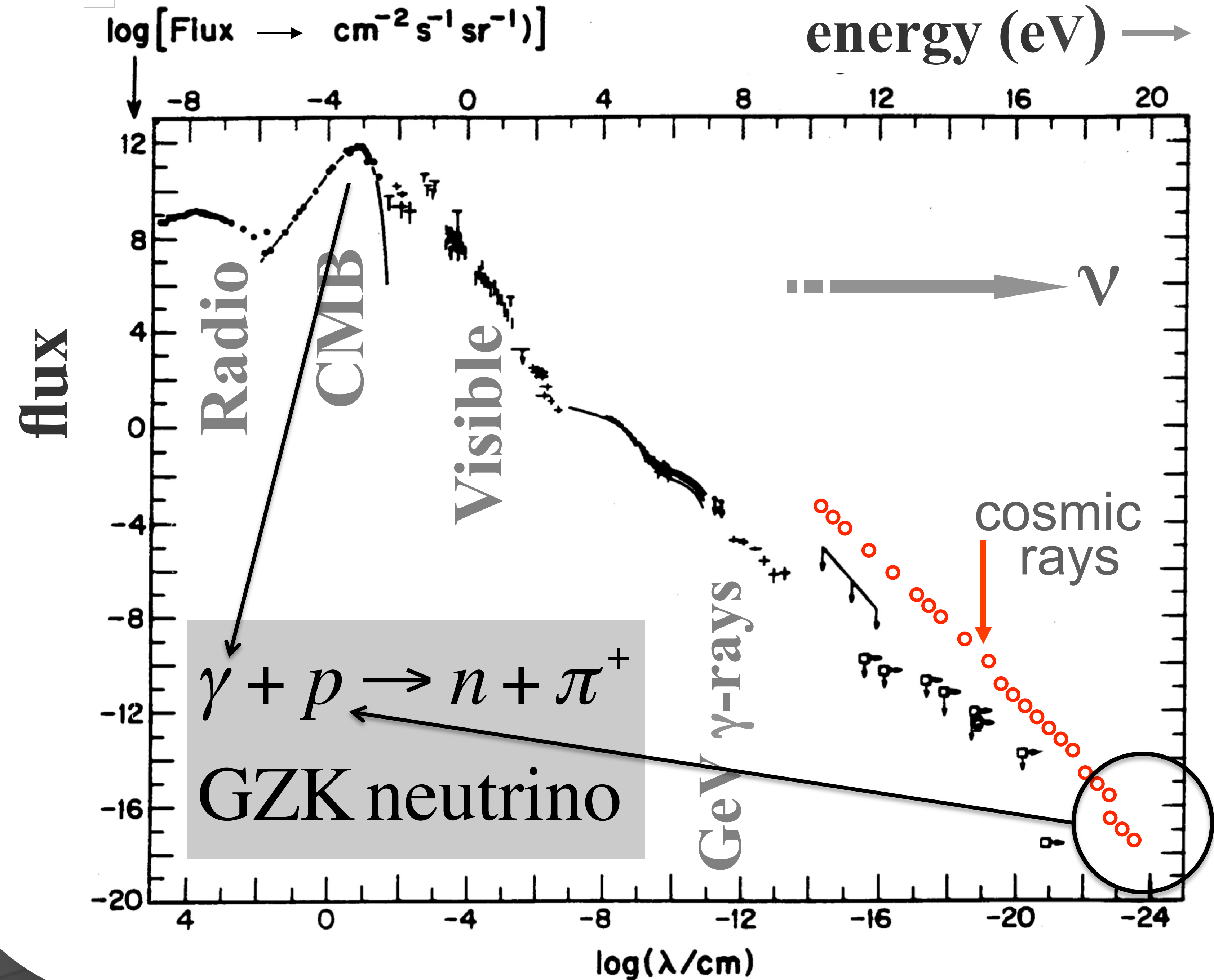
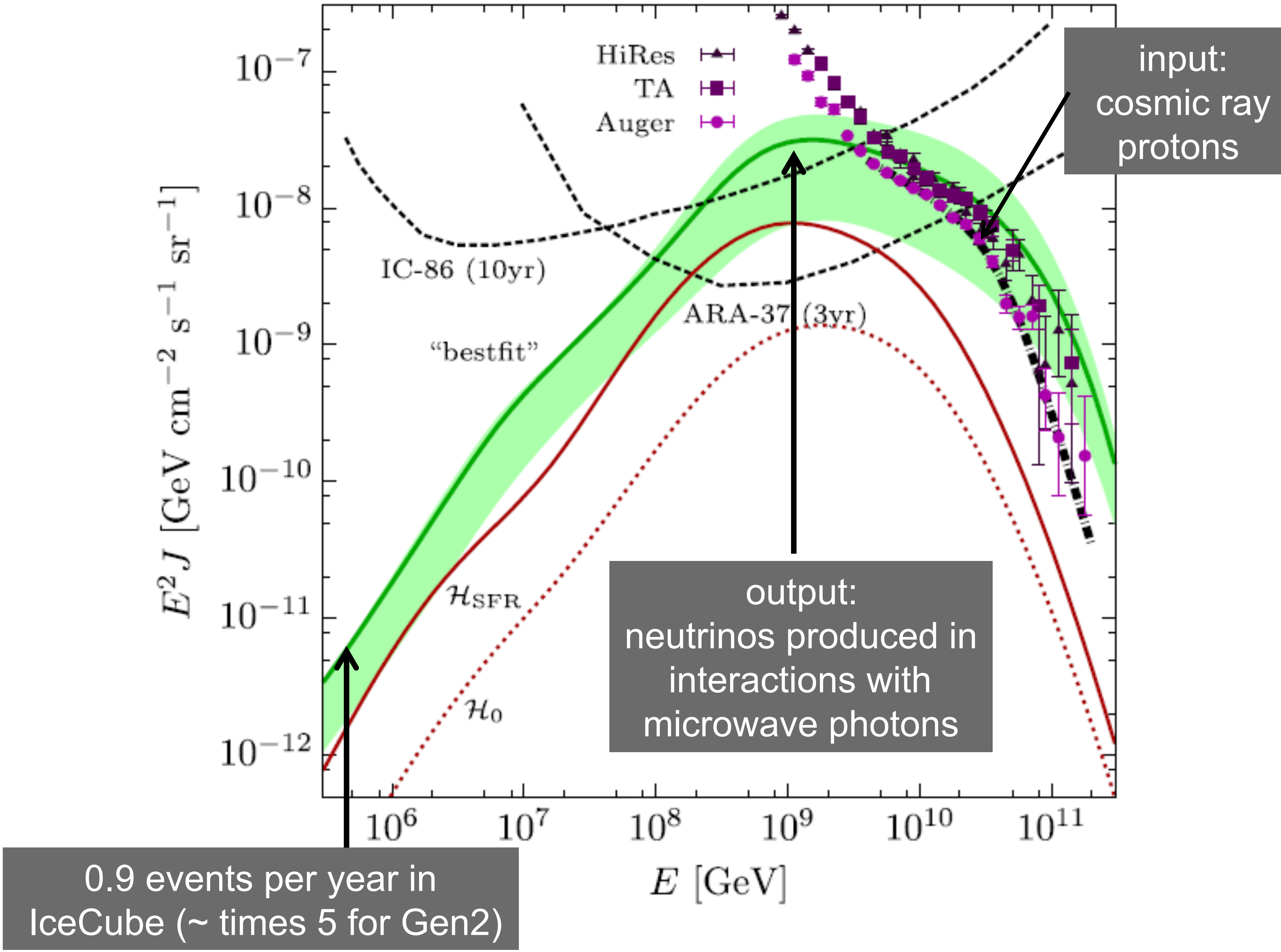
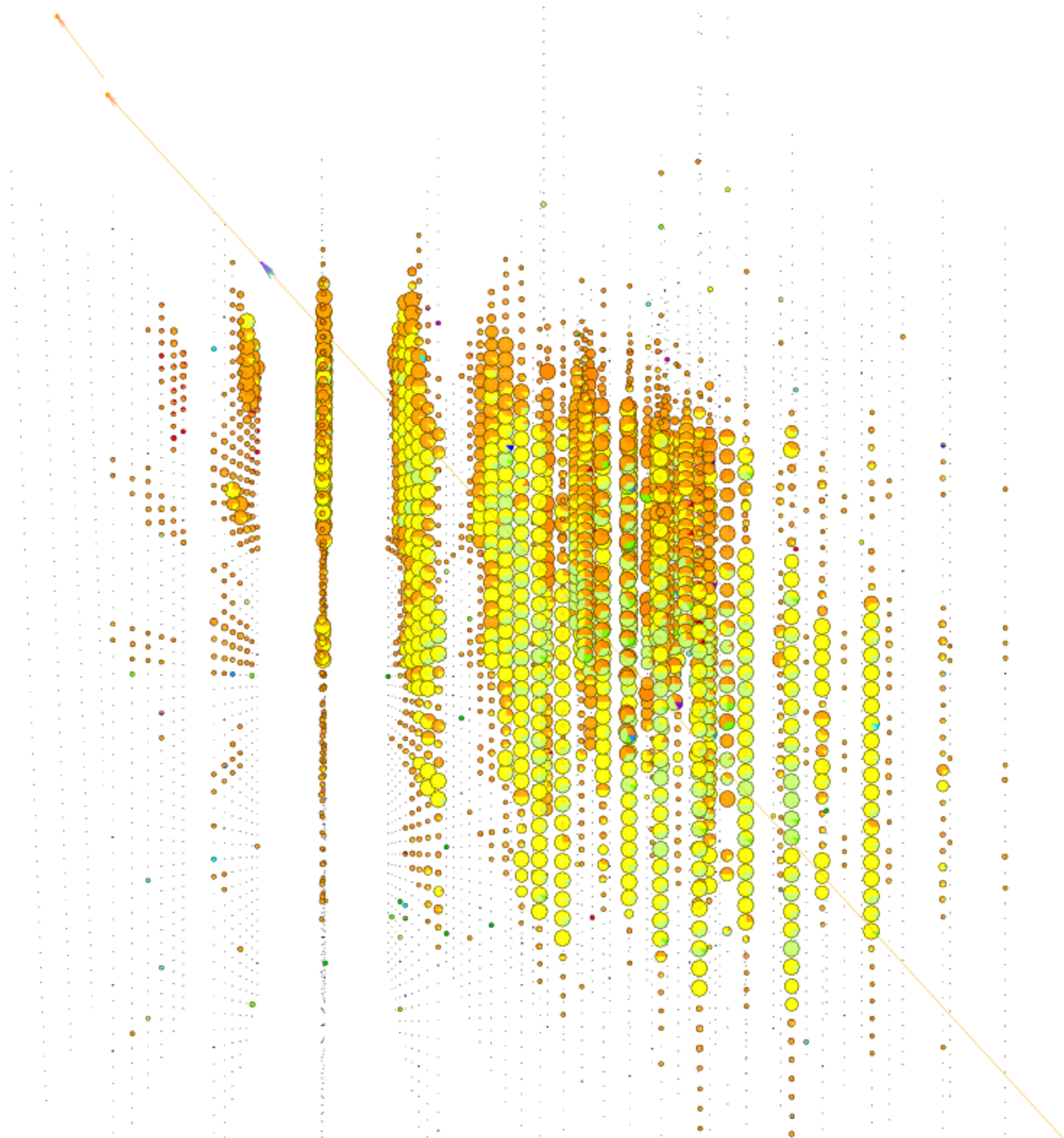


log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV) →
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
$\gamma + p \rightarrow n + \pi^+$
GZK neutrino
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^6
10^7
10^8
10^9
10^{10}
10^{11}
input: cosmic ray protons
output: neutrinos produced in interactions with microwave photons
0.9 events per year in IceCube (~ times 5 for Gen2)

GZK neutrinos: an event



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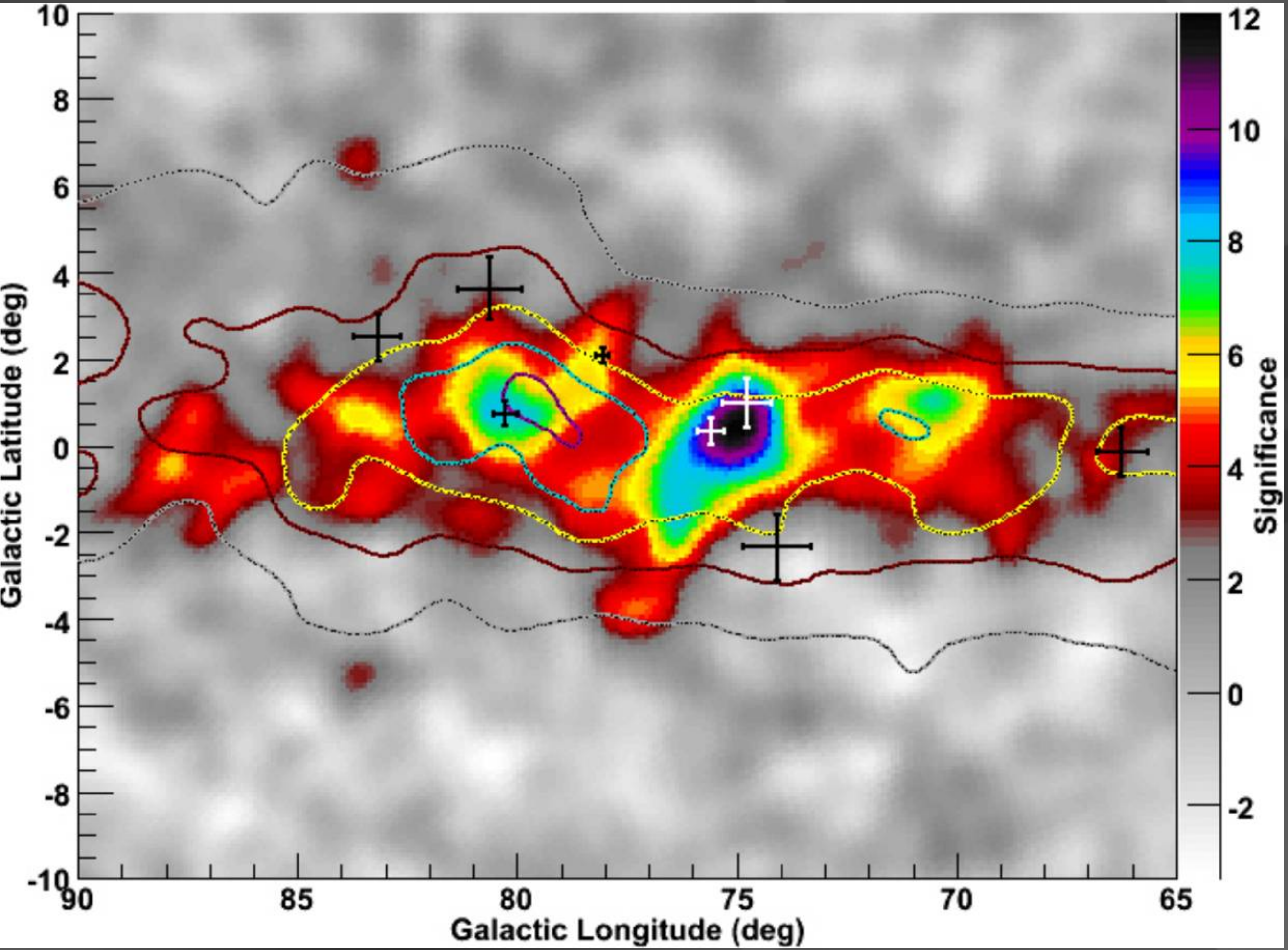
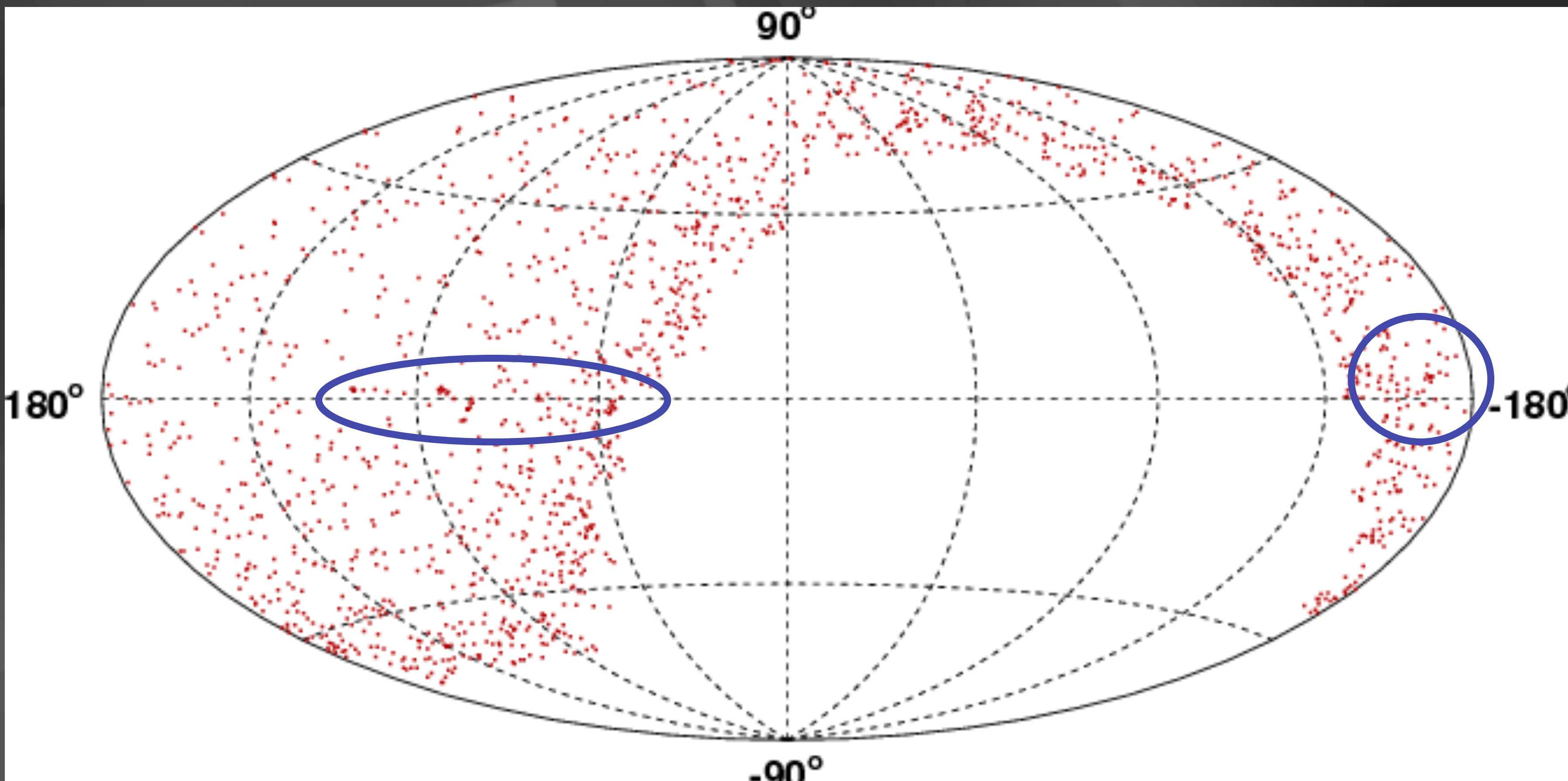
Cygnus region at ~ 1kpc : Milagro



translation of TeV gamma rays into TeV neutrinos yields:

3 ± 1 ν per year in IceCube per source

5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV



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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

auto correlation: multiple neutrinos from the same source

total number of events required to observe
n-events multiplets from the closest sources is

$$740 \times \left[\frac{n}{2}\right] \times \left[\frac{\rho_0}{10^{-5}}\right]^{\frac{1}{3}} \text{ events}$$

for a observed diffuse cosmic flux and 0.4 degrees angular resolution

examples of local source densities (per Mpc^3):

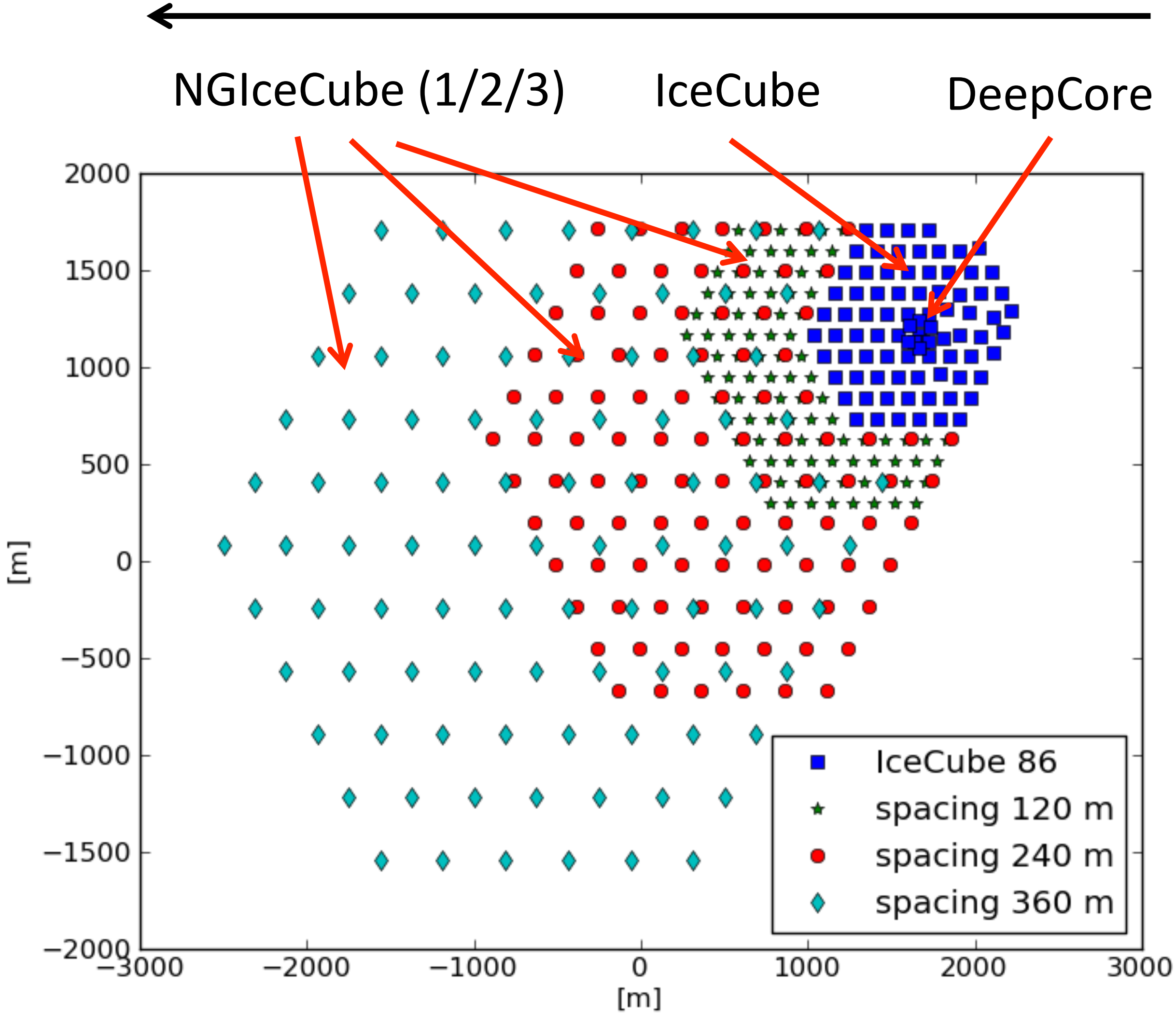
- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

Seeing nearby sources in a diffuse flux

- low source density is good
- flaring sources is good
- catalogues is even better
- Fermi catalogues is exactly what we need

measured optical properties → twice the string spacing

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

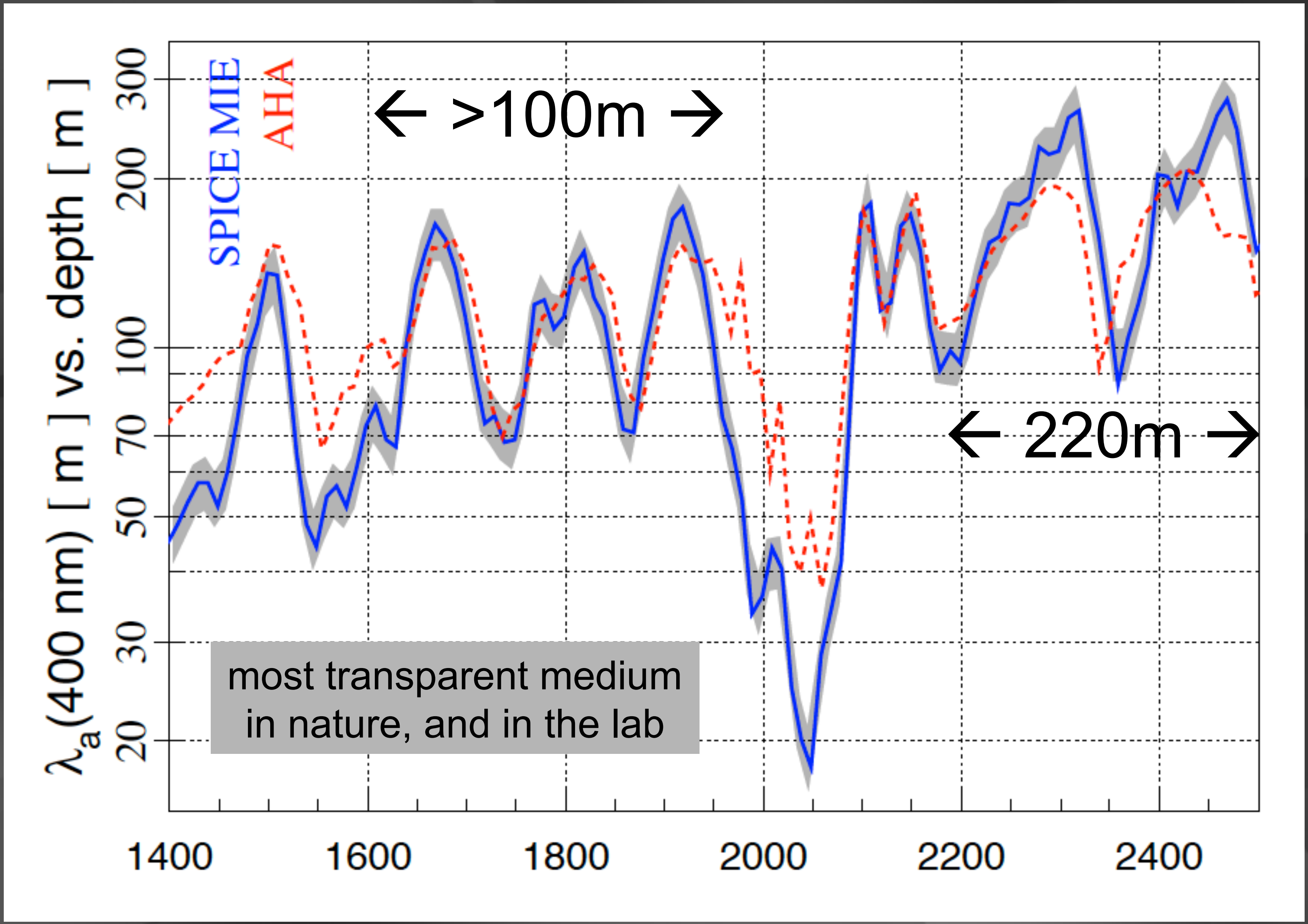


Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

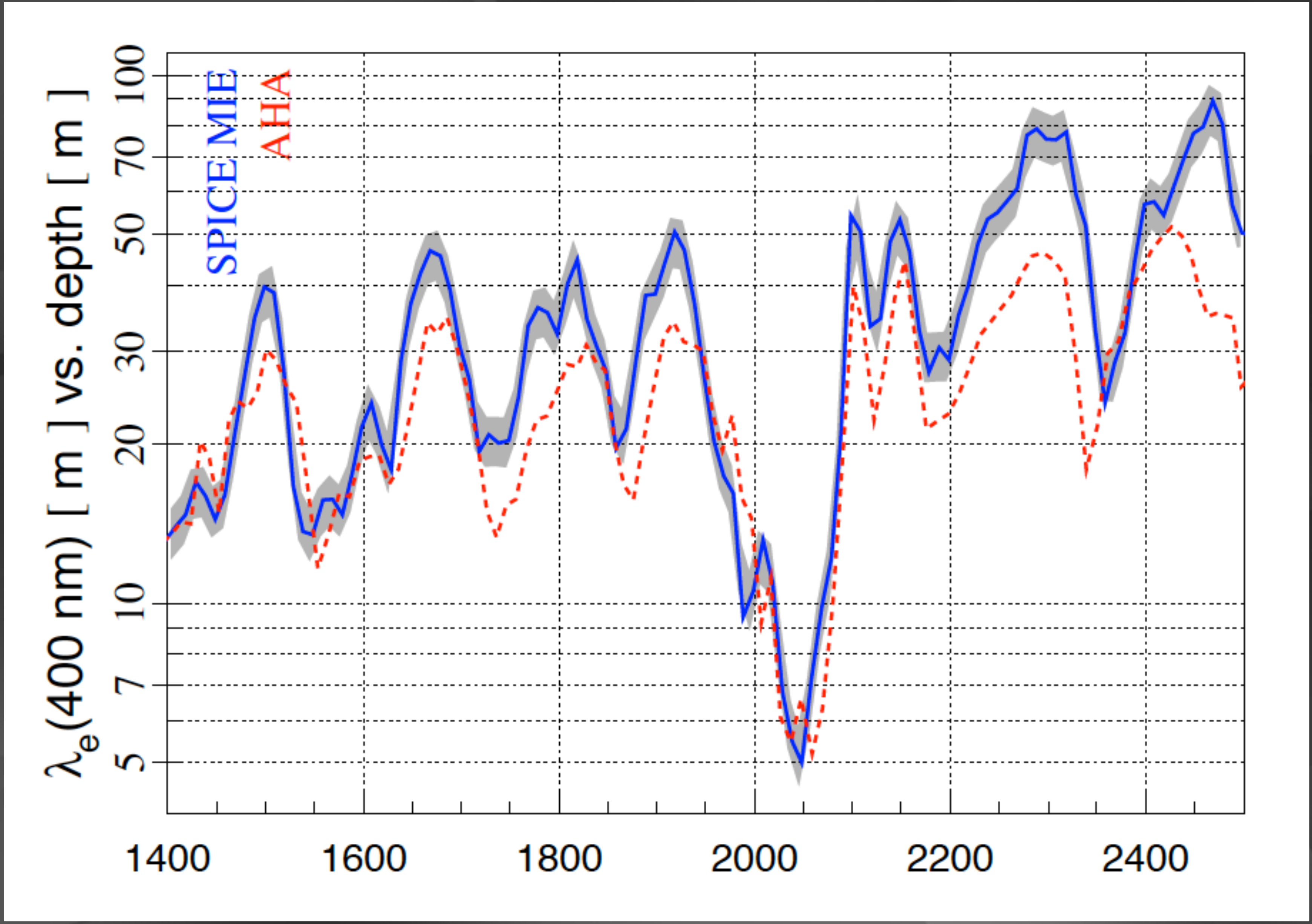
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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

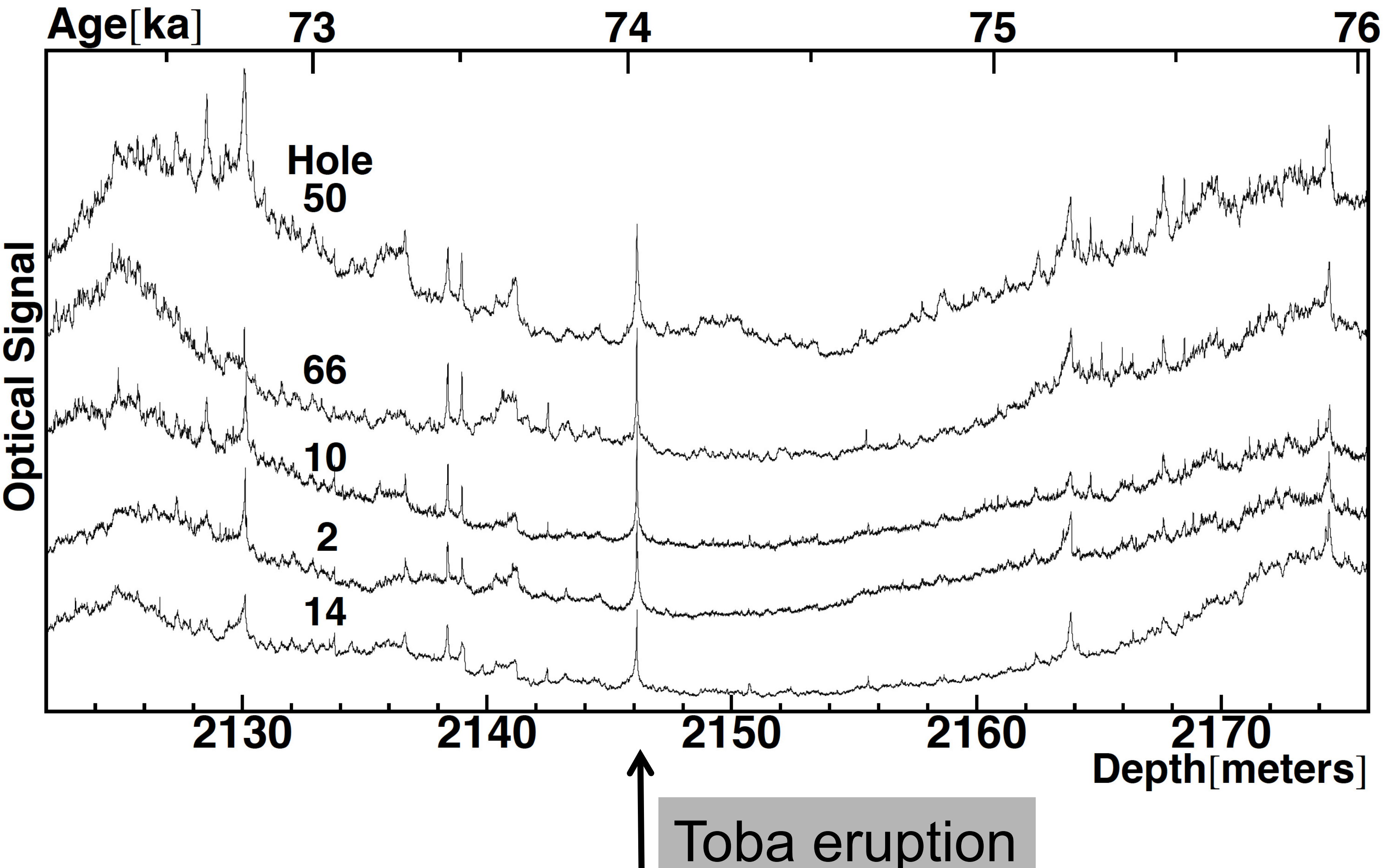
absorption length of Cherenkov light



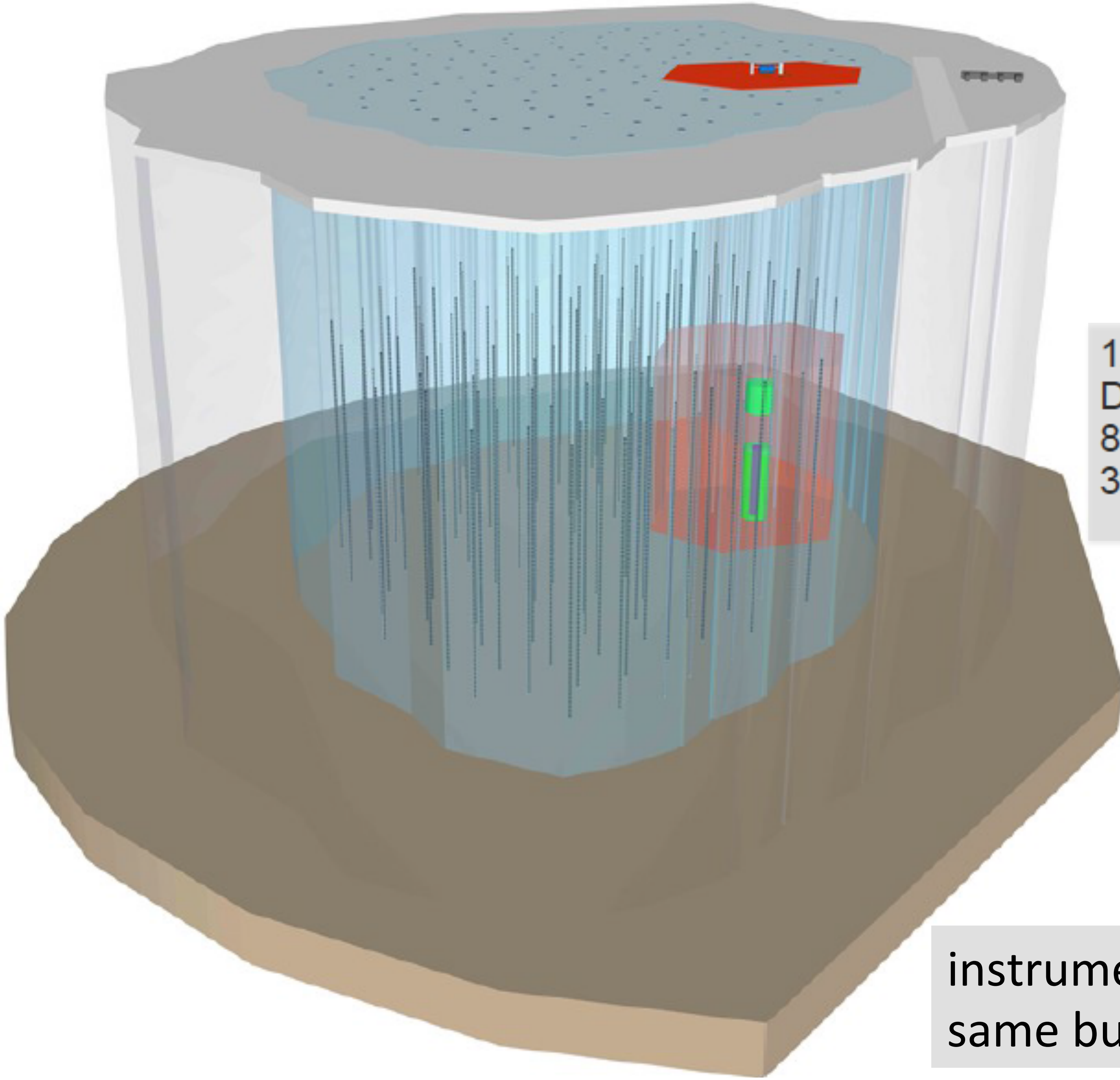
scattering length ← 47m →



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



Toba eruption



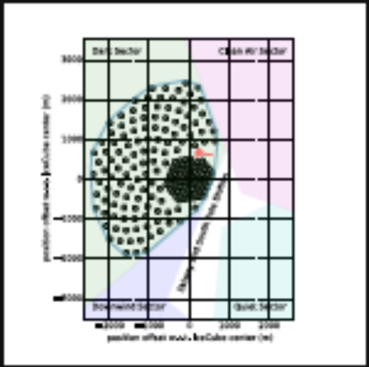
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

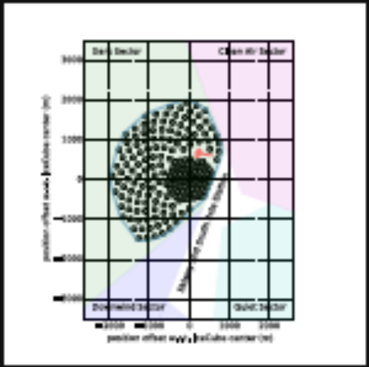
instrumented volume: x 10
same budget as IceCube

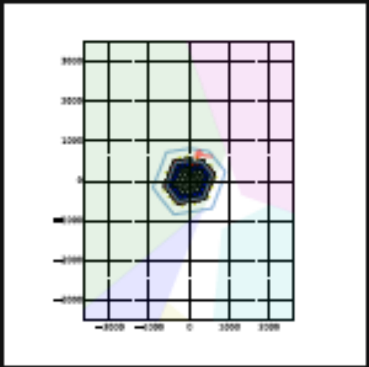
Glashow resonance events per year:

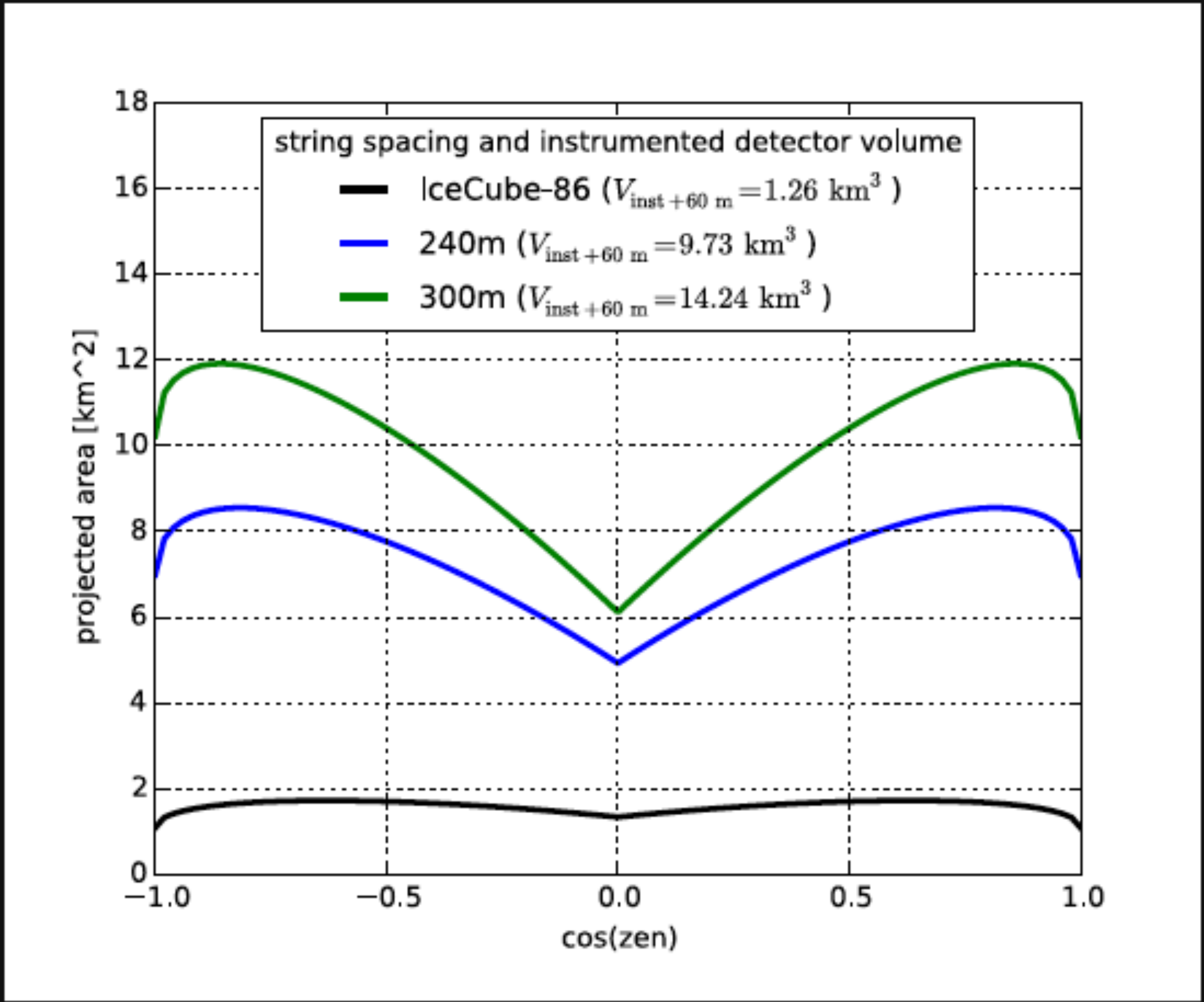
Φ_{ν_e} $[\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}]$	interaction type	pp source IC-86	pp source 240m	pp source 360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$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

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

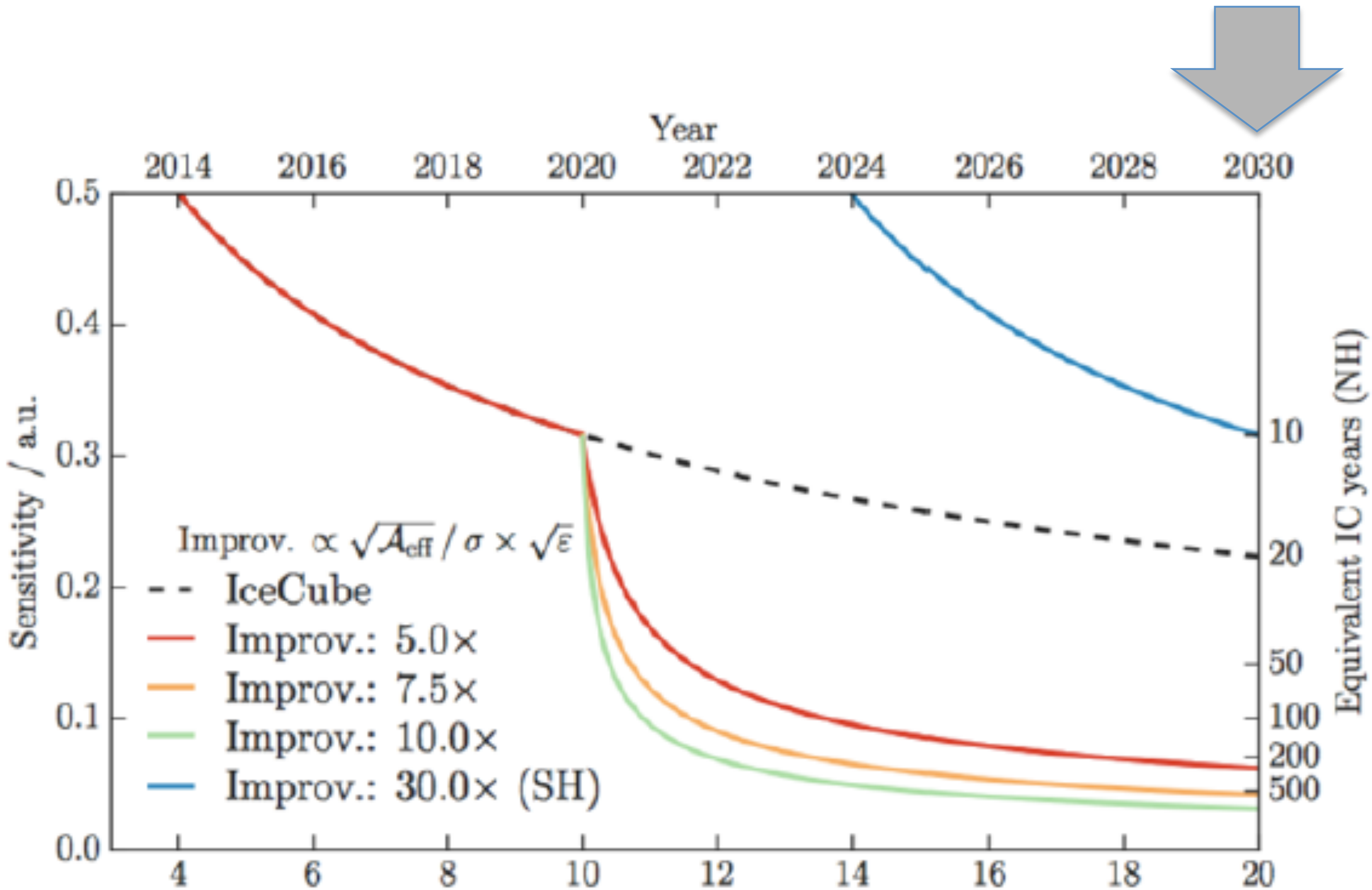






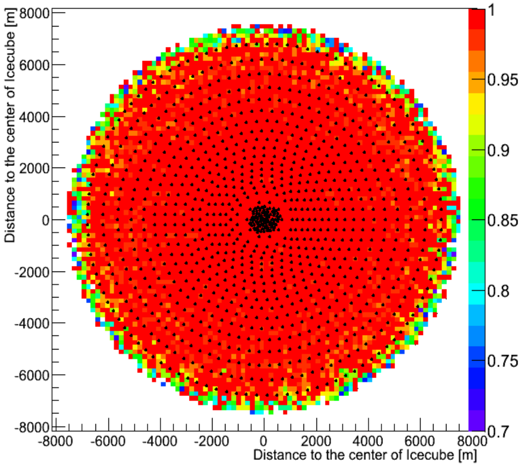

string spacing and instrumented detector volume
IceCube-86 ($V_{\mathrm{inst+60\ m}}=1.26\ \mathrm{km}^3$)
240m ($V_{\mathrm{inst+60\ m}}=9.73\ \mathrm{km}^3$)
300m ($V_{\mathrm{inst+60\ m}}=14.24\ \mathrm{km}^3$)
projected area [km^2]
cos(zen)
0
2
4
6
8
10
12
14
16
18
−1.0
−0.5
0.0
0.5
1.0

point source sensitivity: equivalent IceCube years



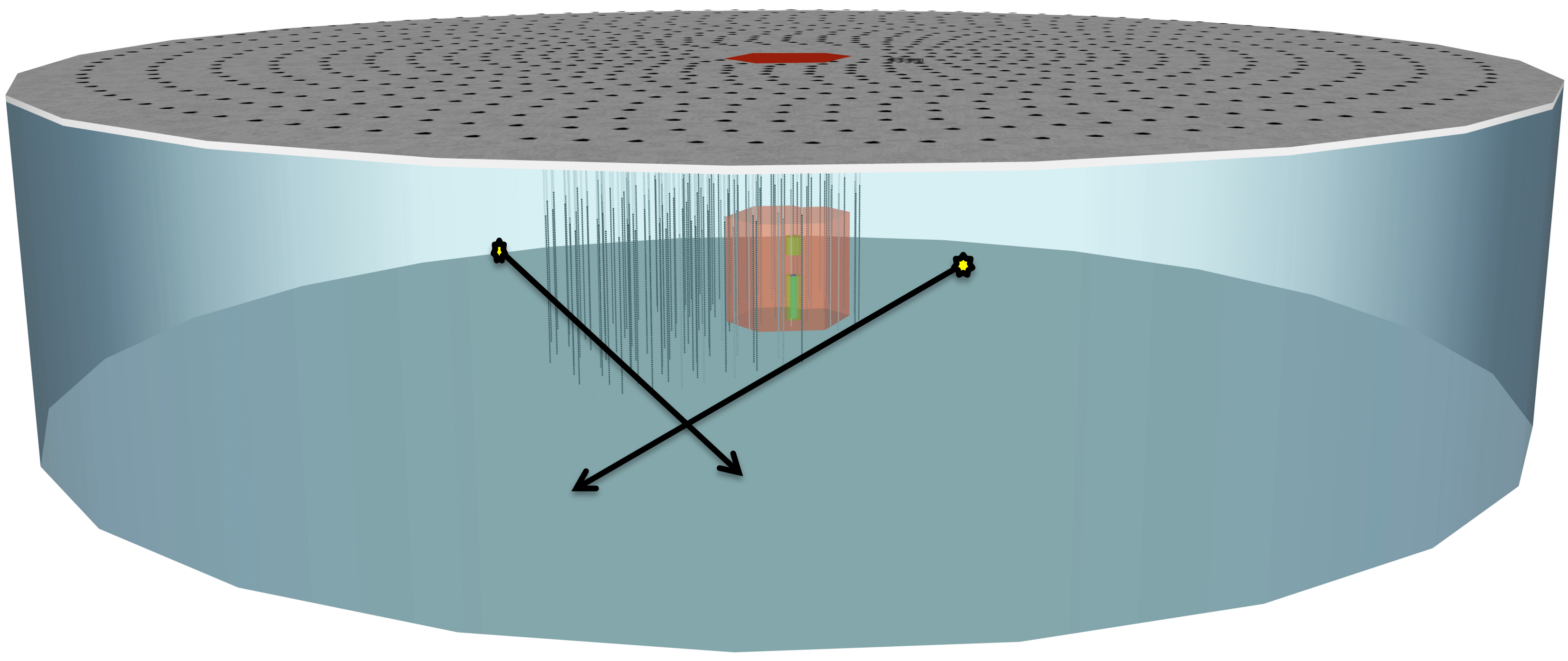
extended surface veto detector

use the large neutrino target volume outside the instrumented volume?



1000 modules?
10000 ?

Air shower veto array



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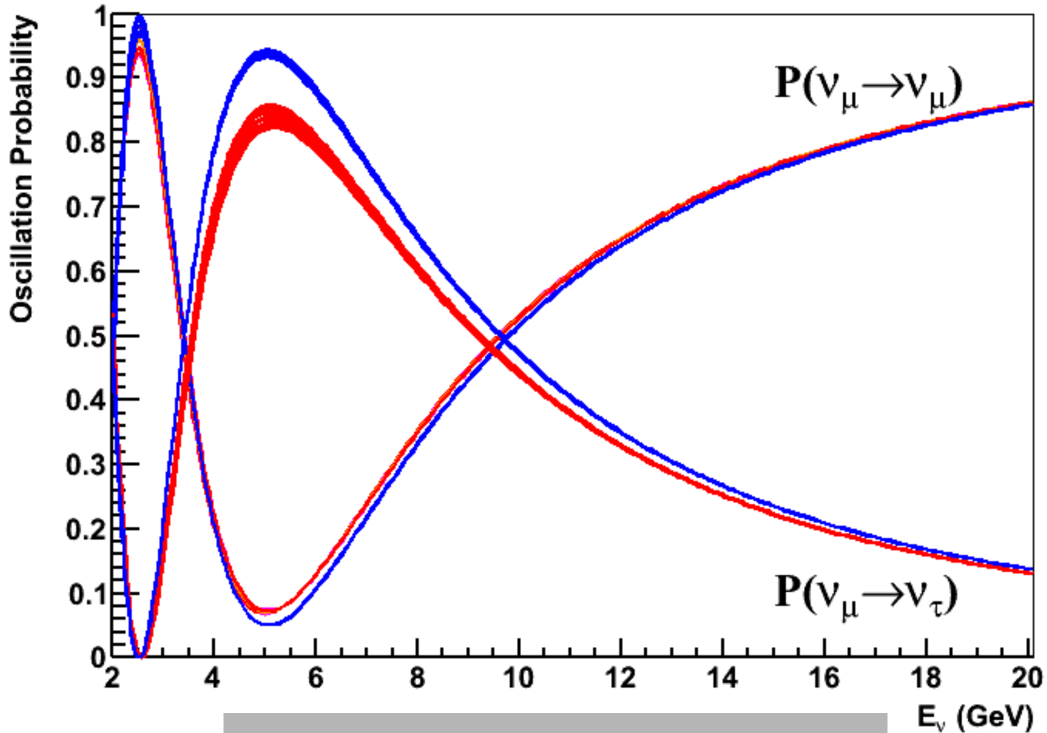
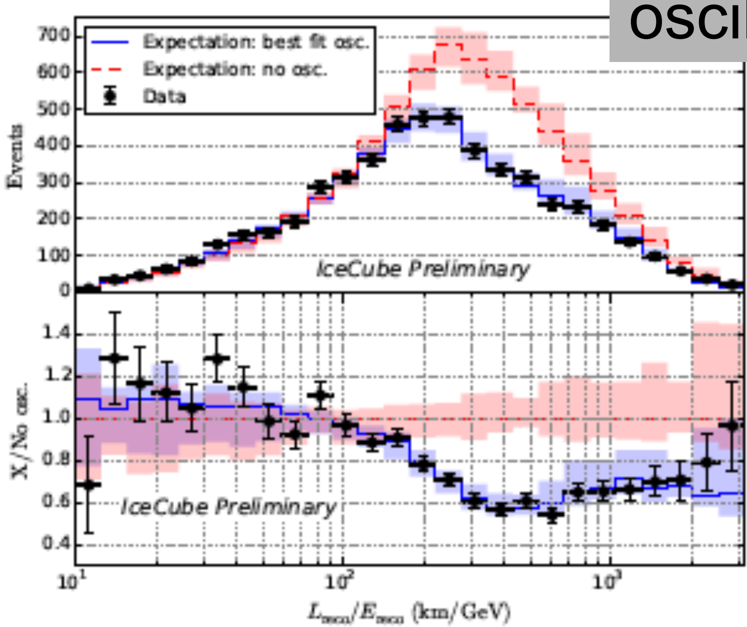
IceCube

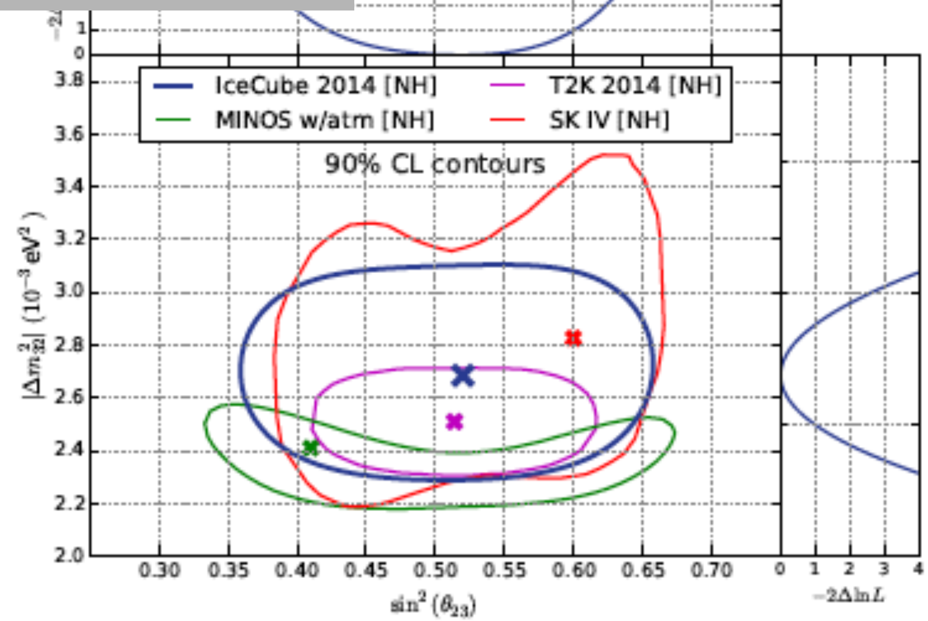
DeepCore

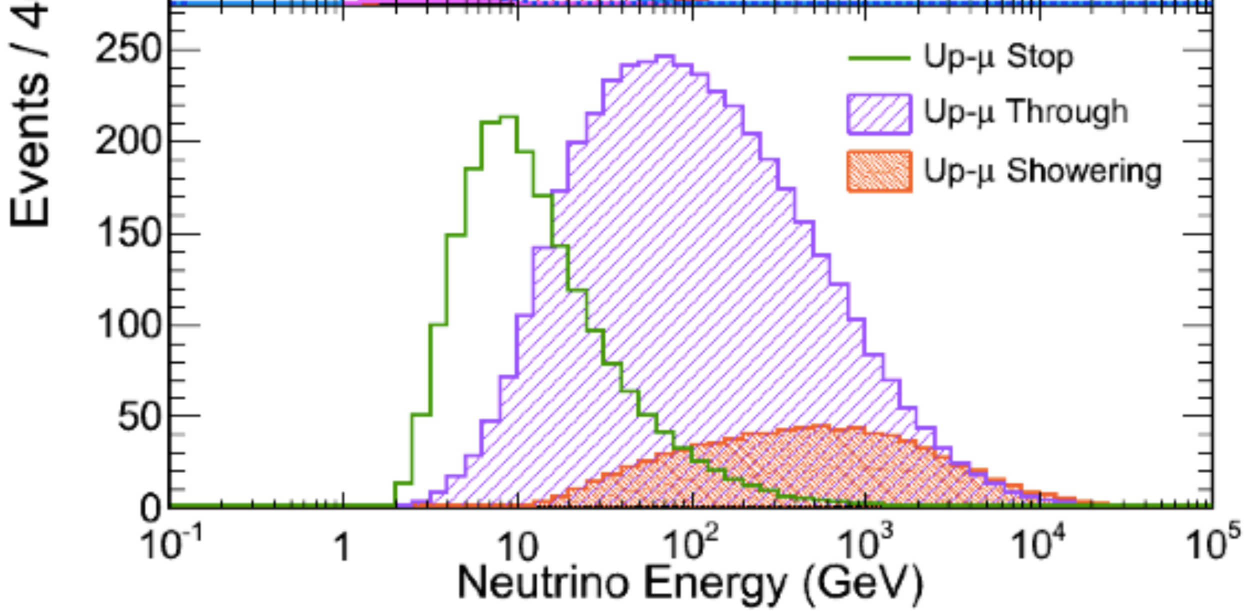
PINGU



oscillations at 10 GeV



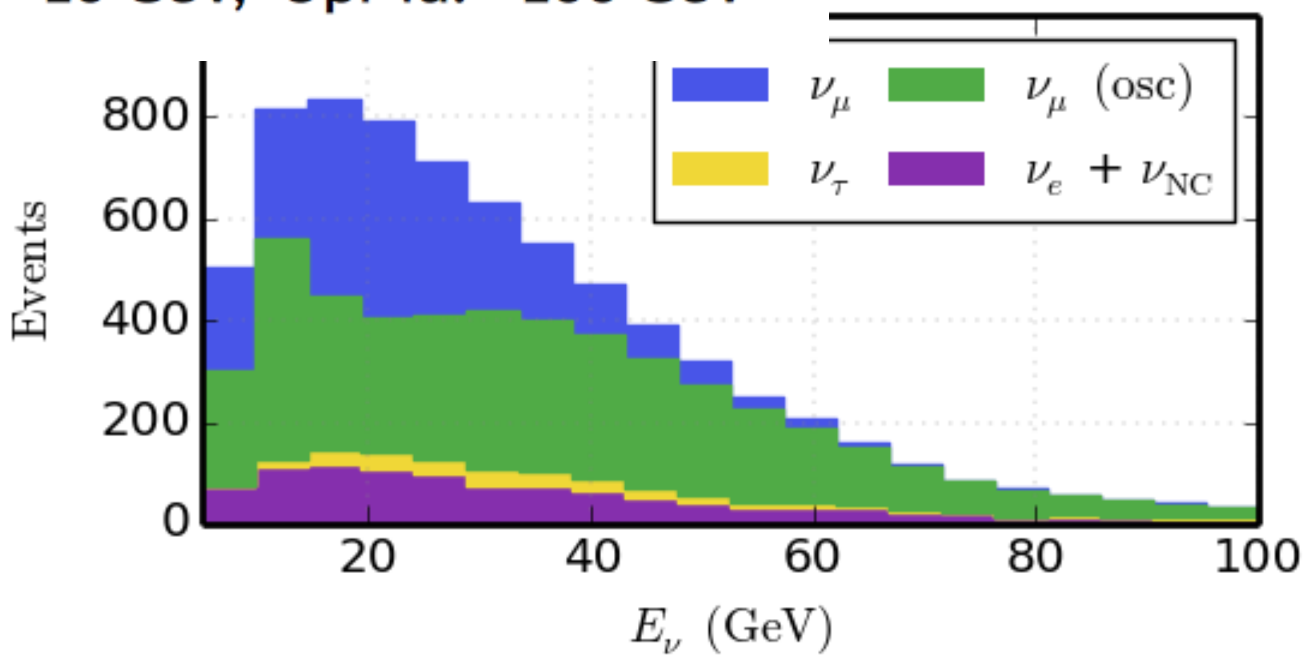




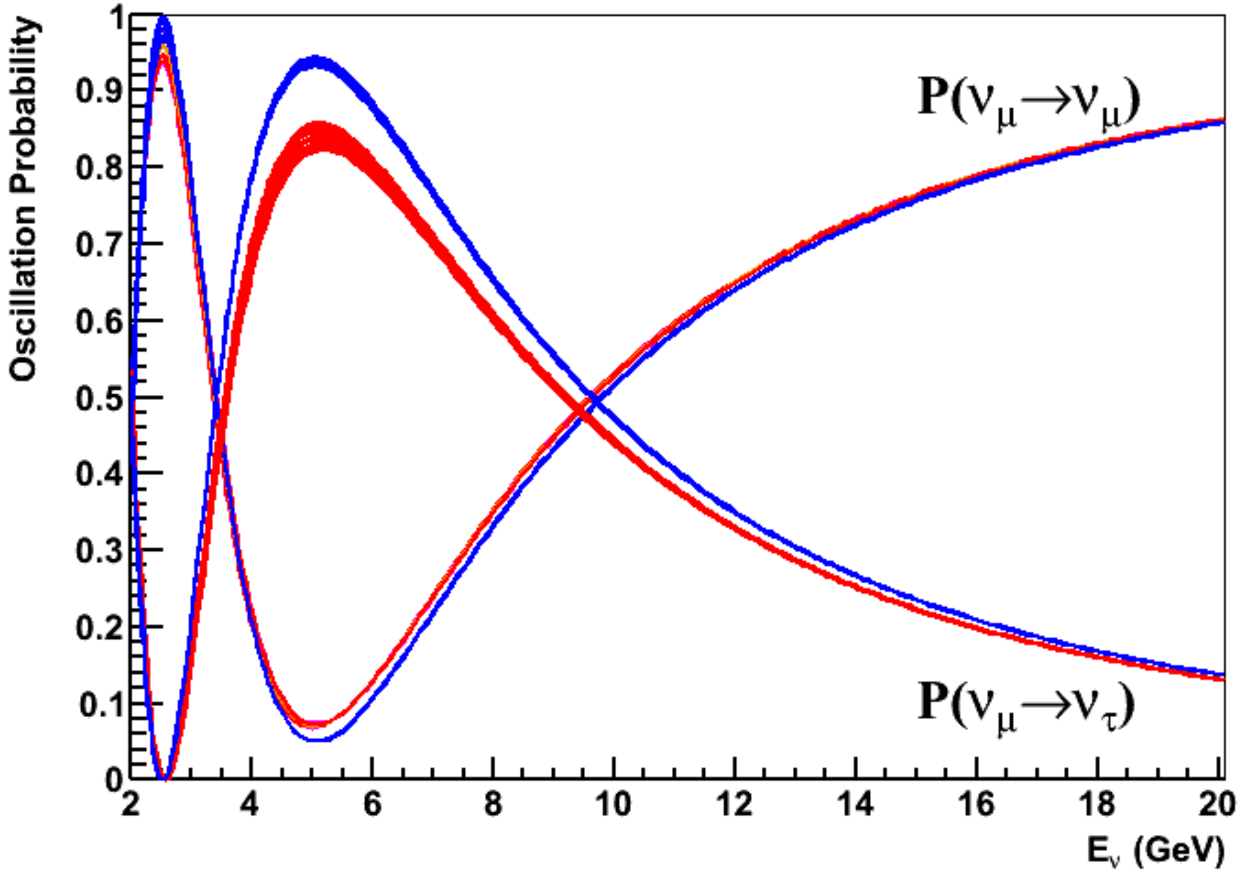
SuperK

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

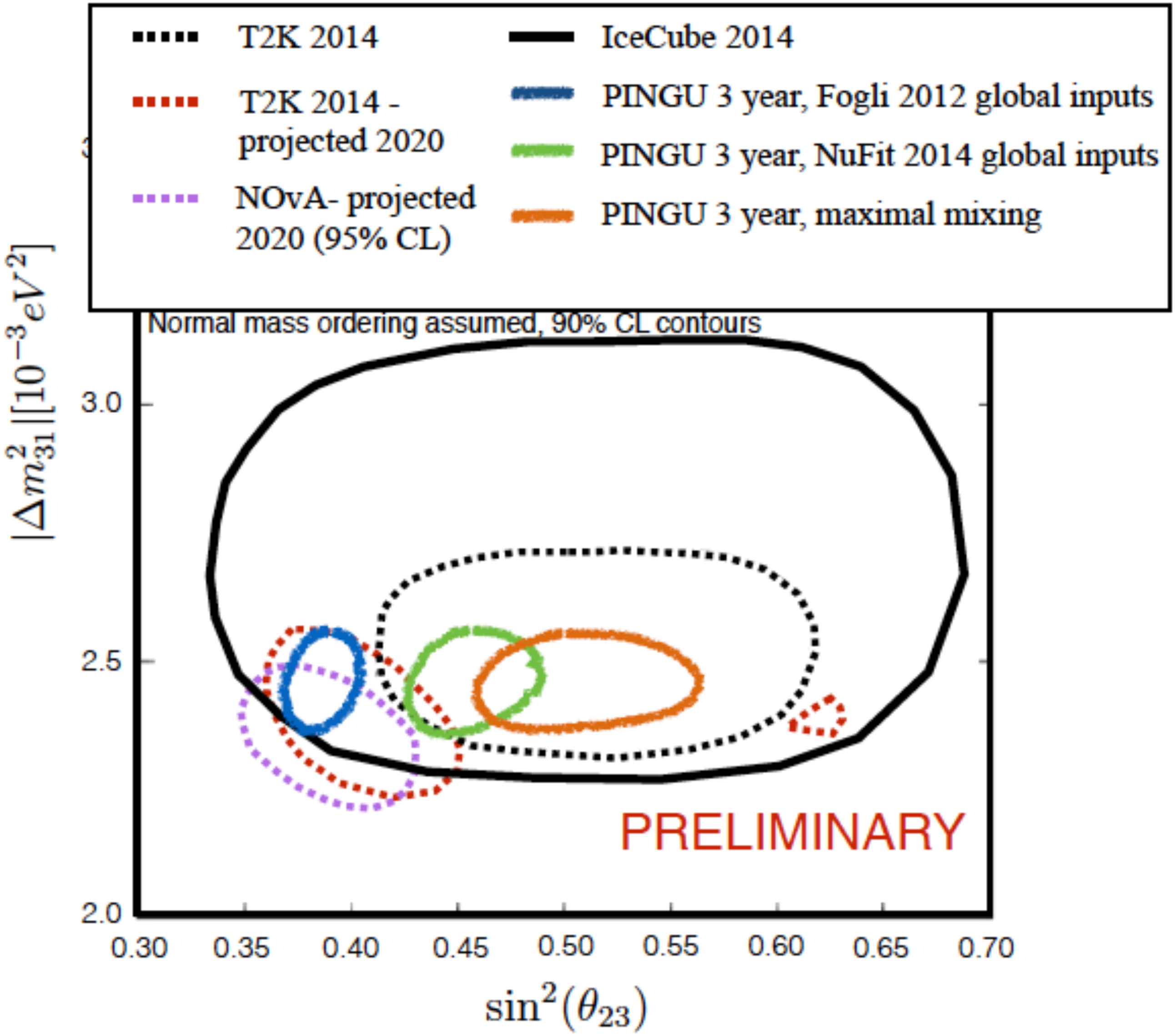
IceCube



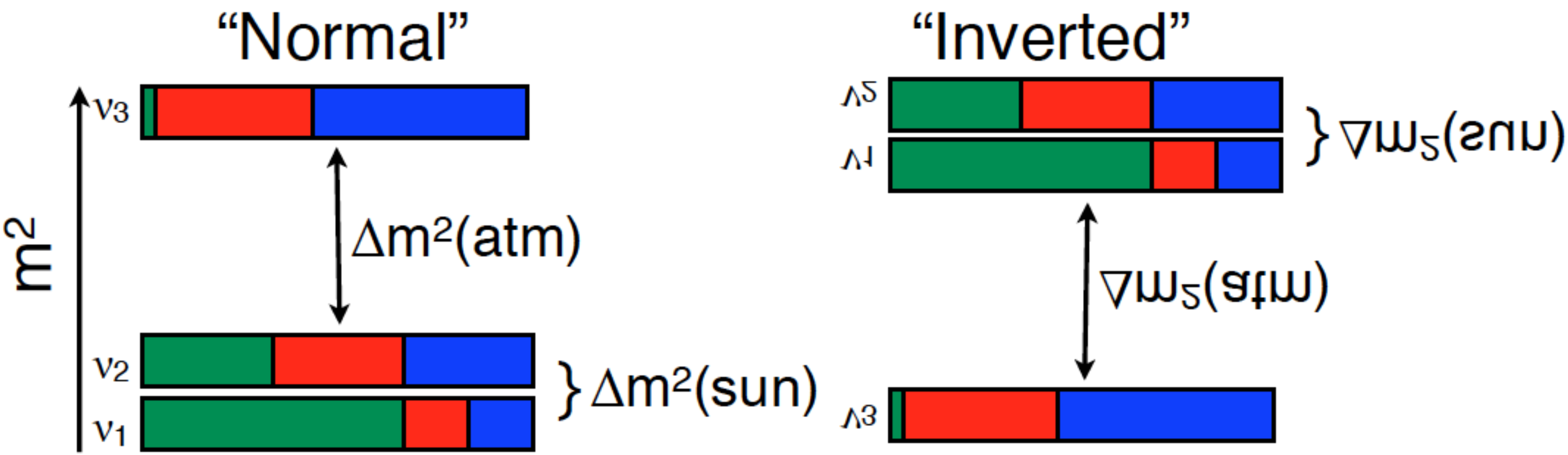
- oscillations at 10 GeV energy and above
- same oscillation parameters measured in a new energy range.



and with PINGU



neutrino mass hierarchy ?



did not talk about:

- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos

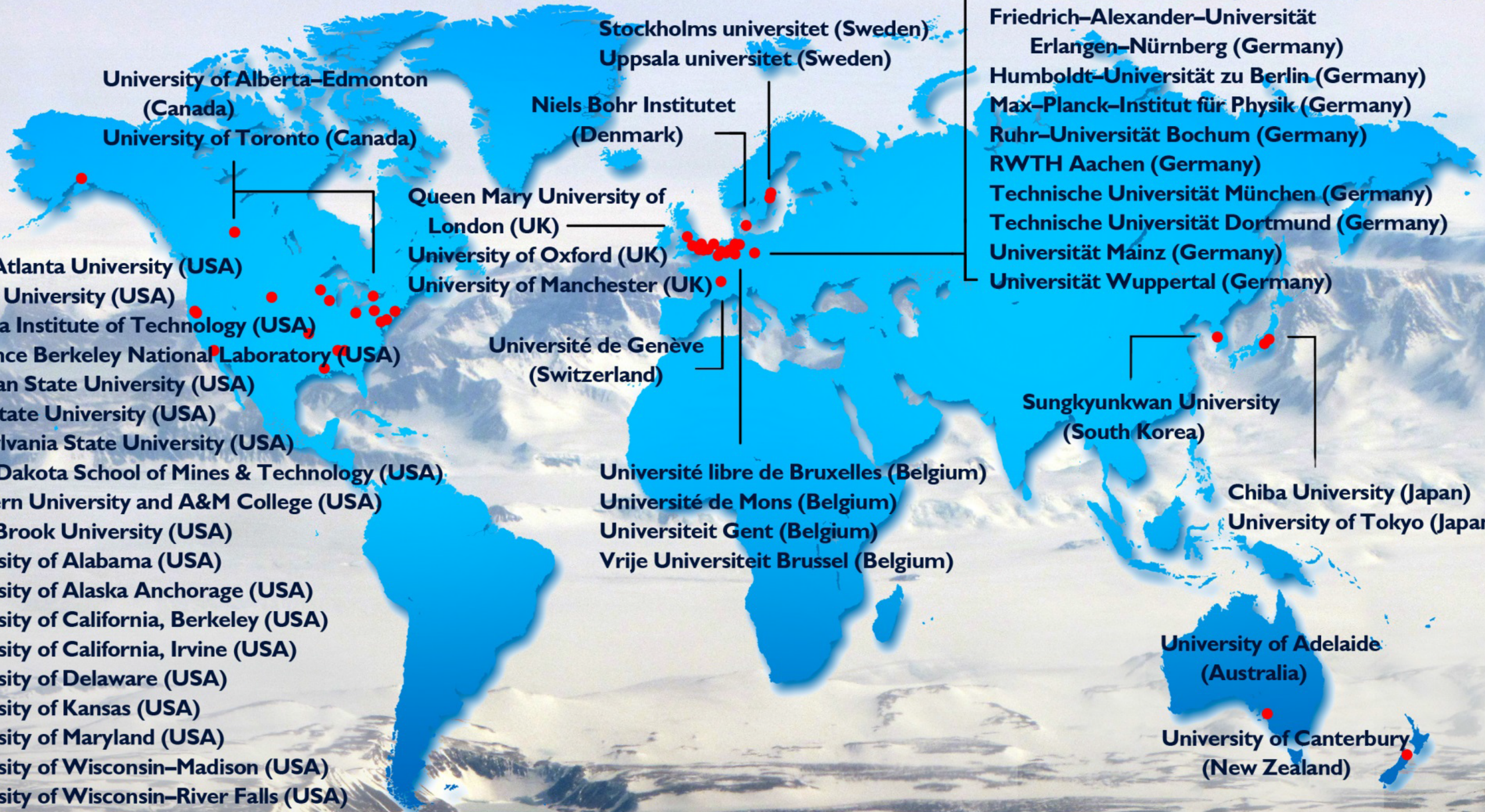
….

- **PINGU** (**P**recision **I**ceCube **N**ext **G**eneration **U**pgrade)—a component with 40 strings, 20 m surface spacing, and 60 Gen2 DOMs/string for low energy (≥ 1 GeV) studies including neutrino mass hierarchy and dark matter searches.
- **IceCube-Gen2 High Energy Array (HEA)**—a ~10-km^3 deep detector with 120 strings, ~250 m surface spacing, and 80 Gen2 DOMs/string neutrino astronomy.

Less well defined: surface detector components:

- **IceCube-Gen2 Cosmic Ray Veto Array**—a ~100-km^2 surface detector for veto for cosmic rays background
- **IceCube-Gen2 Radio Array (RA)**—a 100 to ~300-km^2 scale detector for extremely high energy (≥ 10^{18} eV) cosmogenic neutrinos.
- AND, of course, existing **IceCube-86 (IceTop and DeepCore)**

The IceCube–PINGU Collaboration



International Funding Agencies

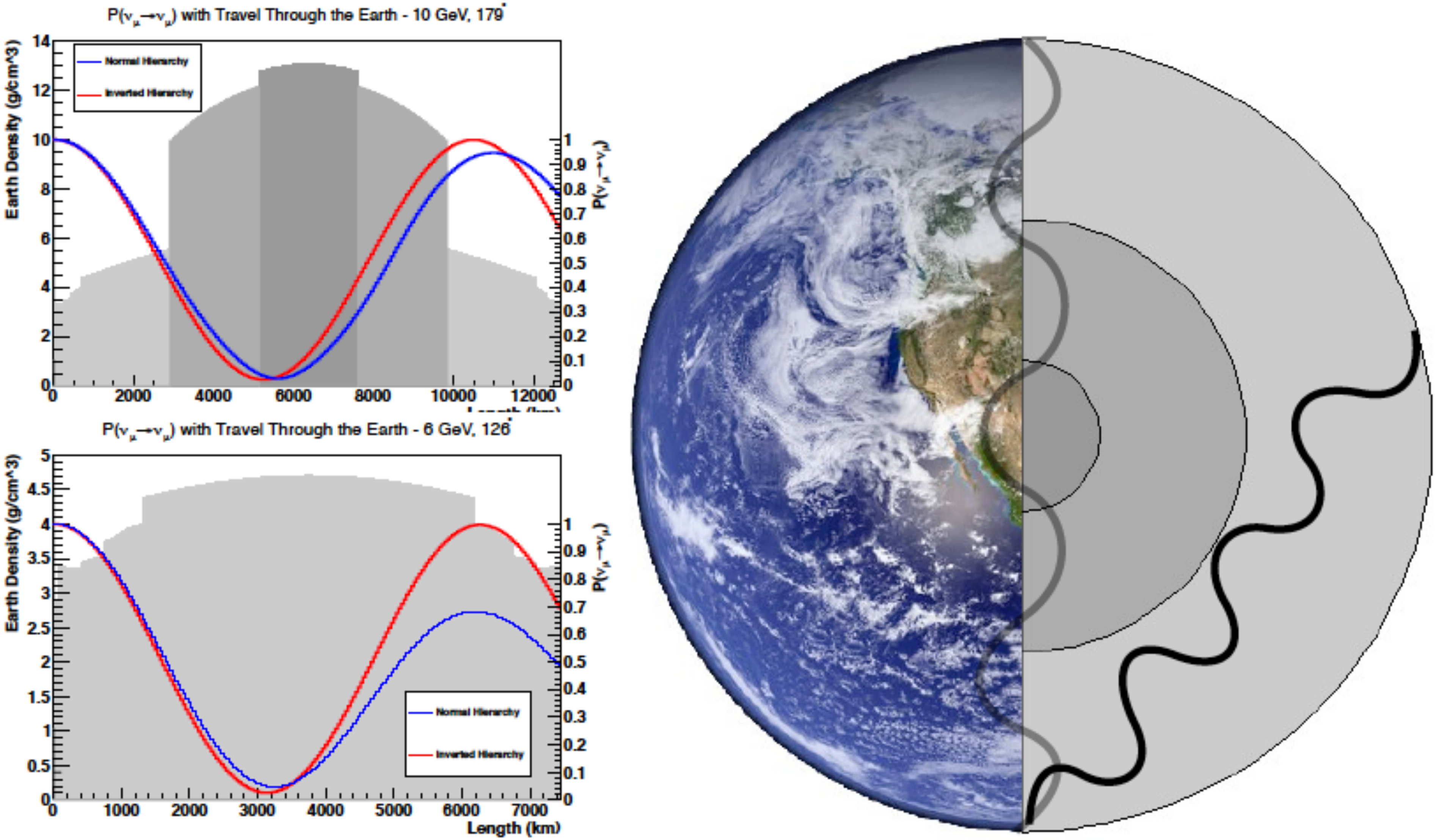
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation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

~ 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 !


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°
Earth Density (g/cm^3)
P(ν_μ→ν_μ)
Normal Hierarchy
Inverted Hierarchy
0
1000
2000
3000
4000
5000
6000
7000
Length (km)