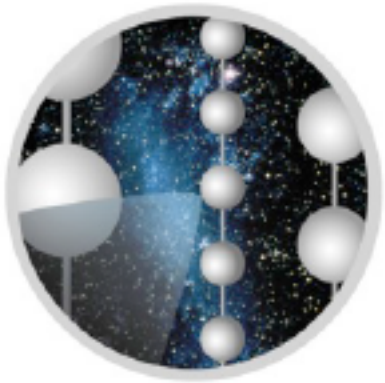


IceCube

francis halzen

- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

IceCube.wisc.edu

IceCube has observed a flux of neutrinos from the cosmos of PeV (1,000 TeV) neutrinos that is “at the level” of the astronomical gamma ray flux. We thus established that neutrinos play a role similar to photons in the high-energy non-thermal universe.

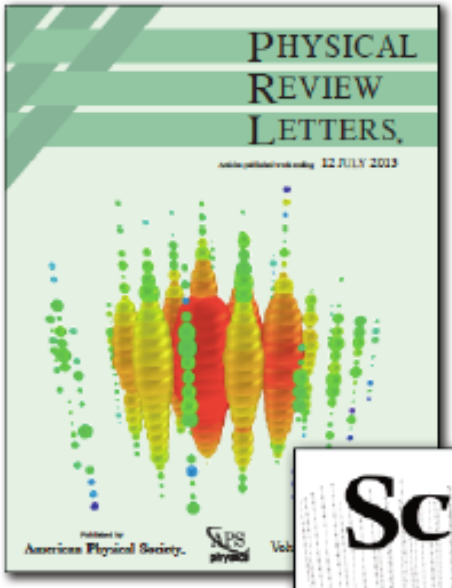
Ann.Rev.Nucl.Sci 10 (1960) 63

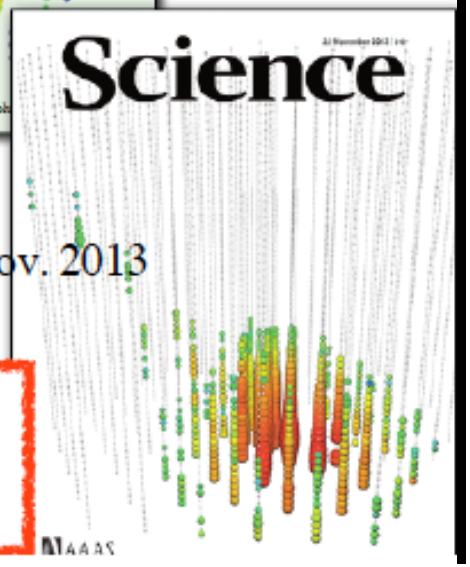
COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

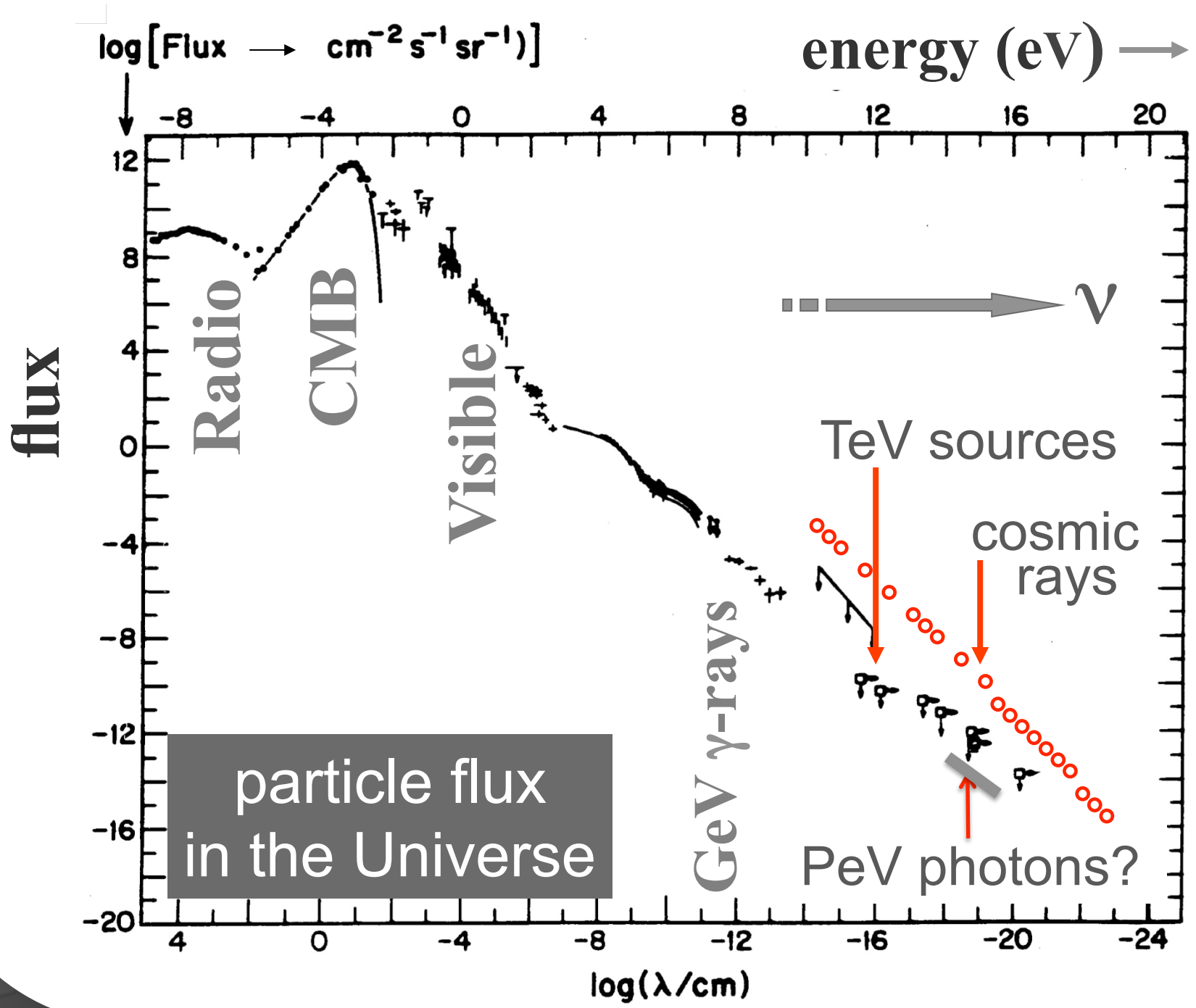
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

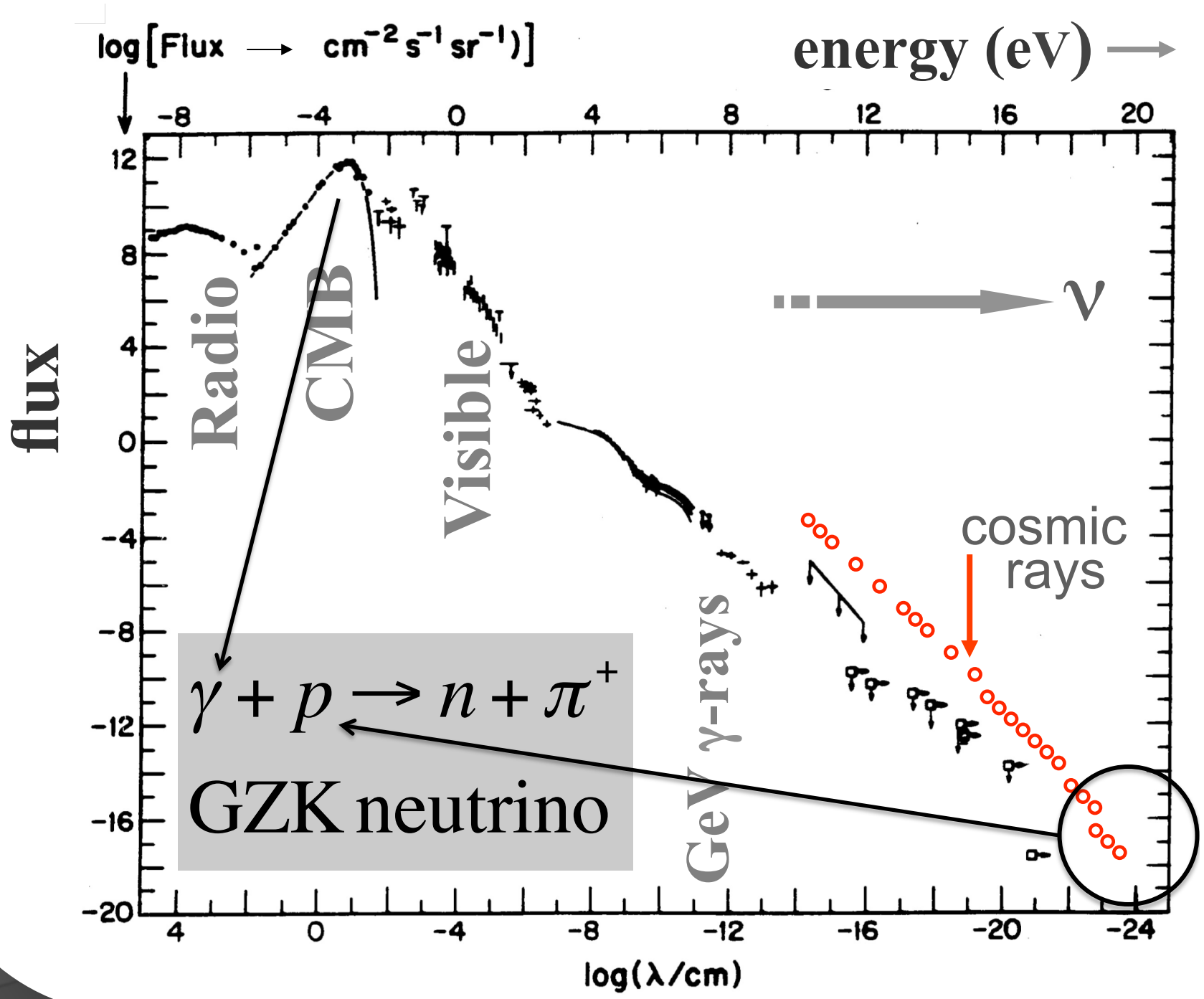




Science 342, Nov. 2013

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources
cosmic rays
PeV photons?
particle flux in the Universe
log(λ/cm)


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

cosmic rays interact with the microwave background

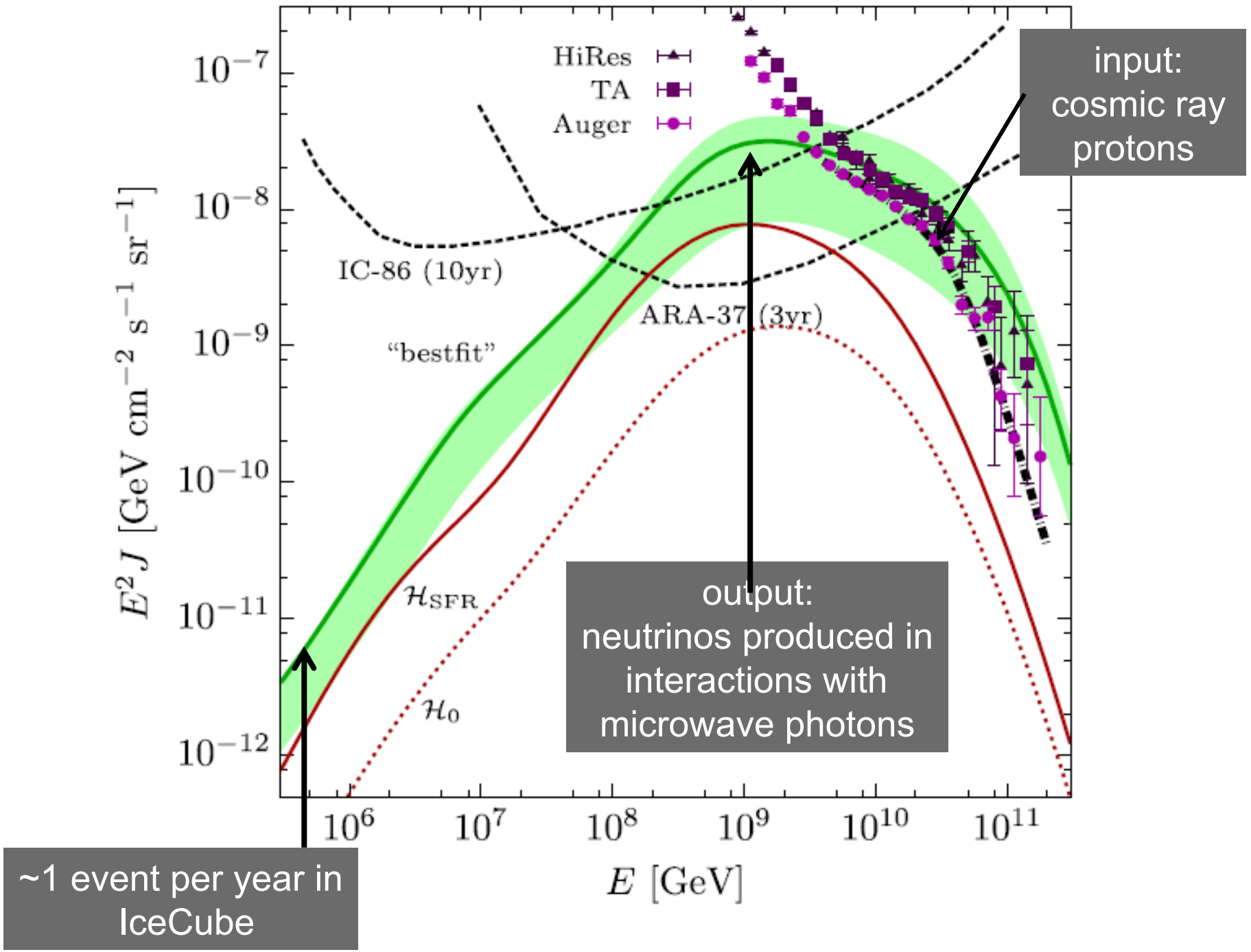
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

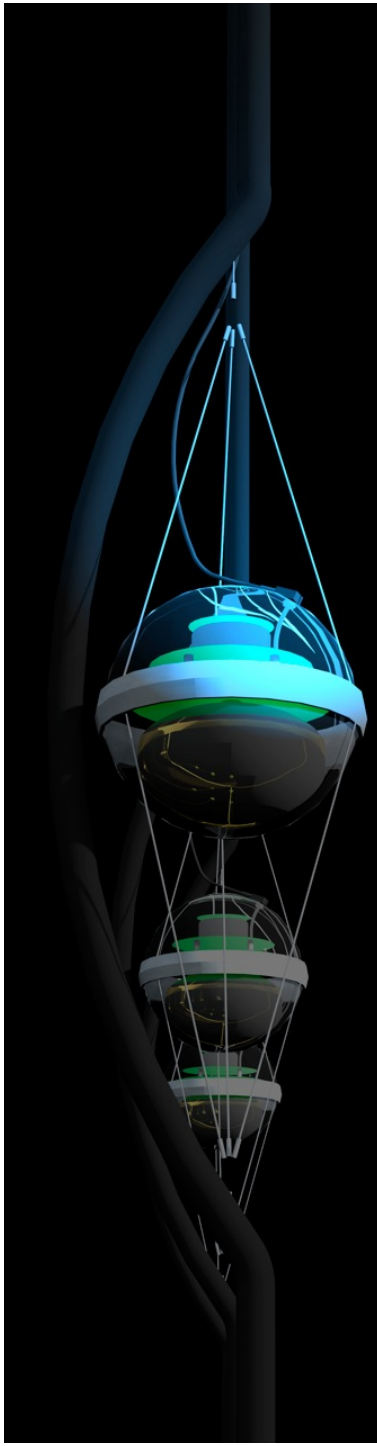
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!


HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
$E^2 J$ [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
~1 event per year in IceCube



IceCube

francis halzen

- cosmogenic neutrinos
- the energetics of cosmic ray sources
- neutrinos associated with cosmic rays
- a cubic kilometer detector
- evidence for extraterrestrial neutrinos
- conclusions

IceCube.wisc.edu

Hillas formula :

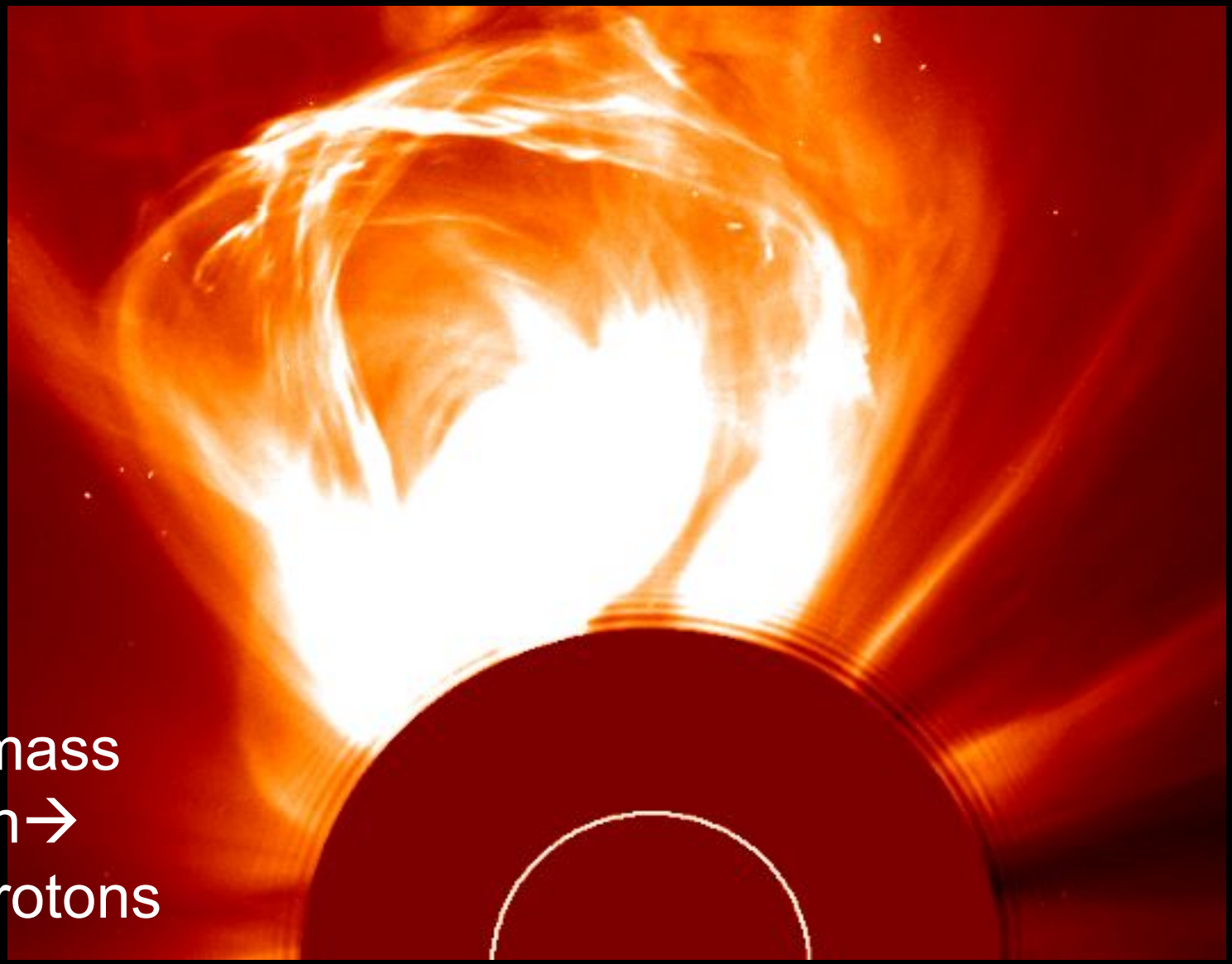
- accelerator must contain the particles

$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

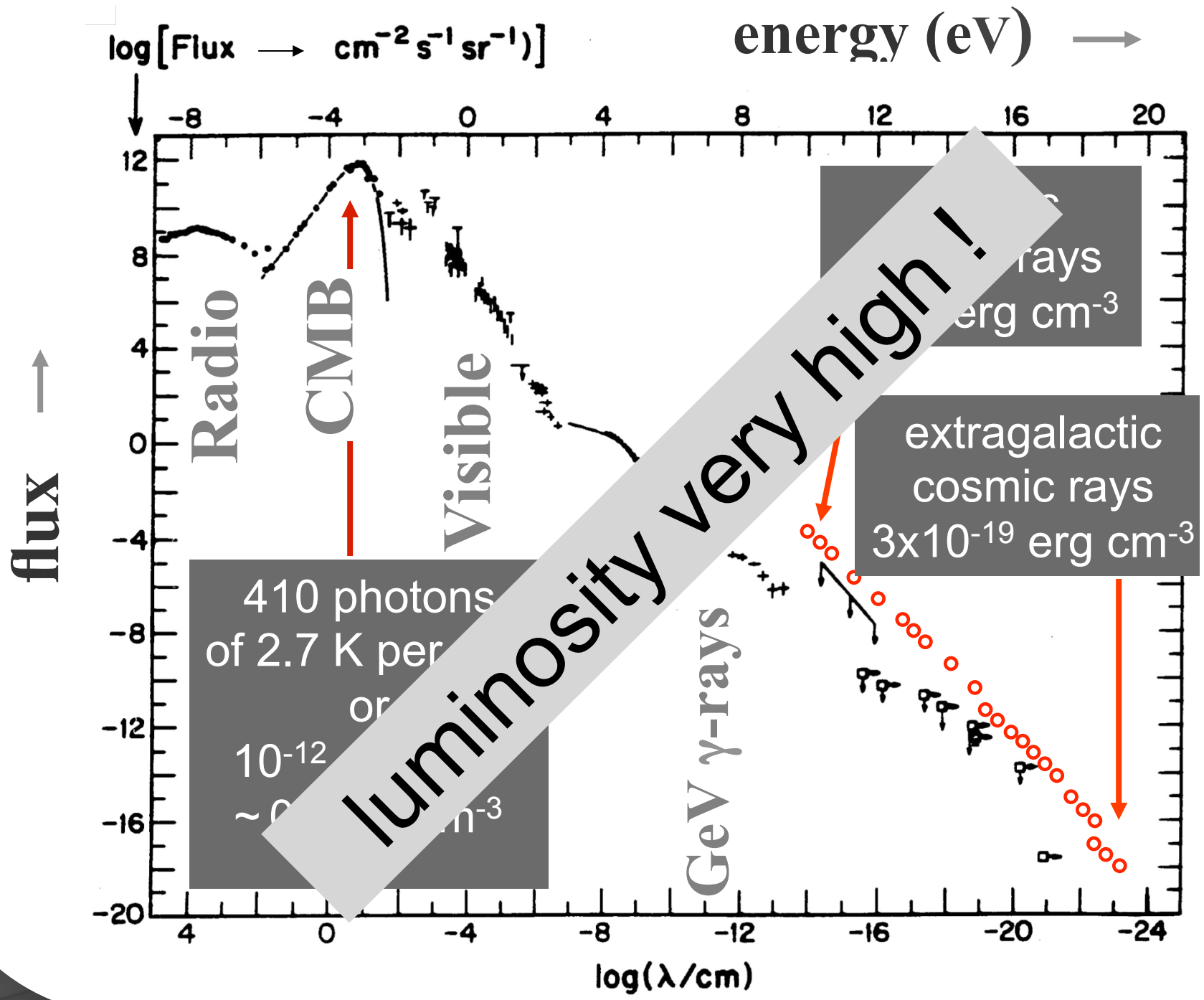
$$E \leq \mathrm{v}\, qBR$$

- dimensional analysis, difficult to satisfy

the sun constructs an accelerator

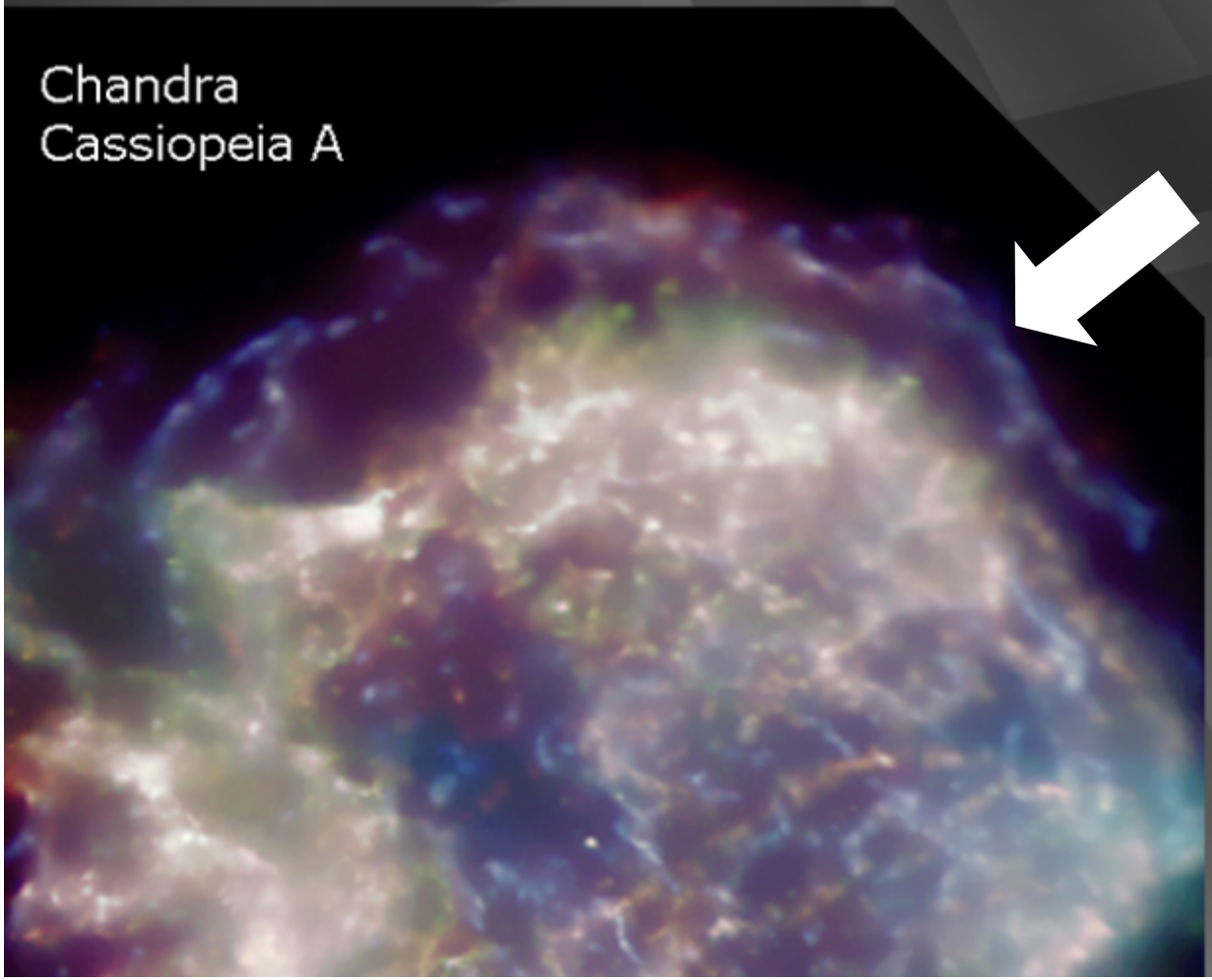


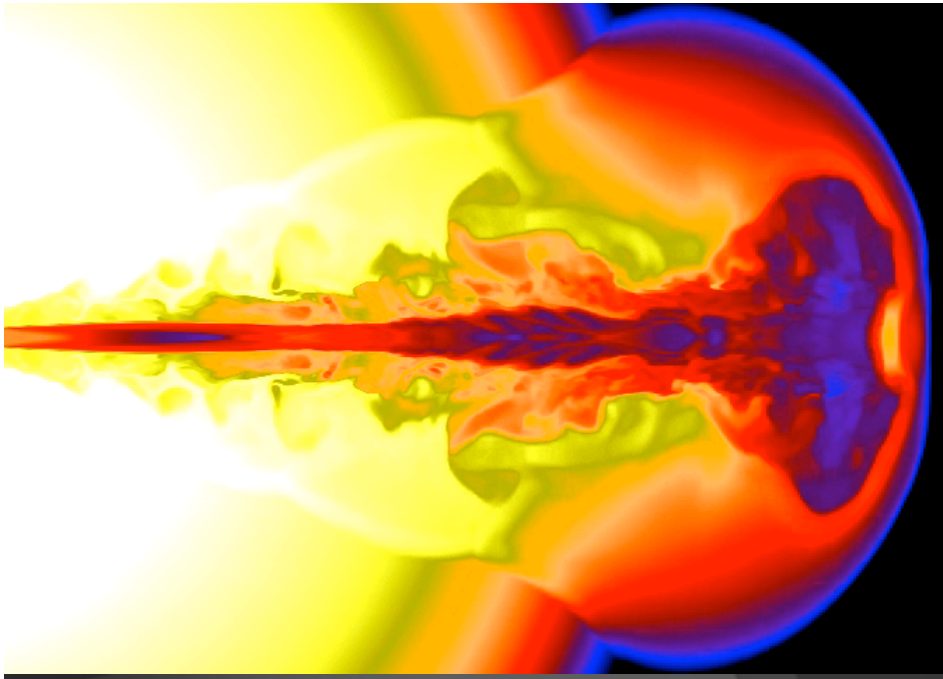
coronal mass ejection→ 10 GeV protons


energy (eV)
log [Flux → cm⁻² s⁻¹ sr⁻¹)]
flux
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
410 photons
of 2.7 K per
or
10⁻¹²
rays
erg cm⁻³
extragalactic
cosmic rays
3x10⁻¹⁹ erg cm⁻³
luminosity very high !

supernova remnants

HESS





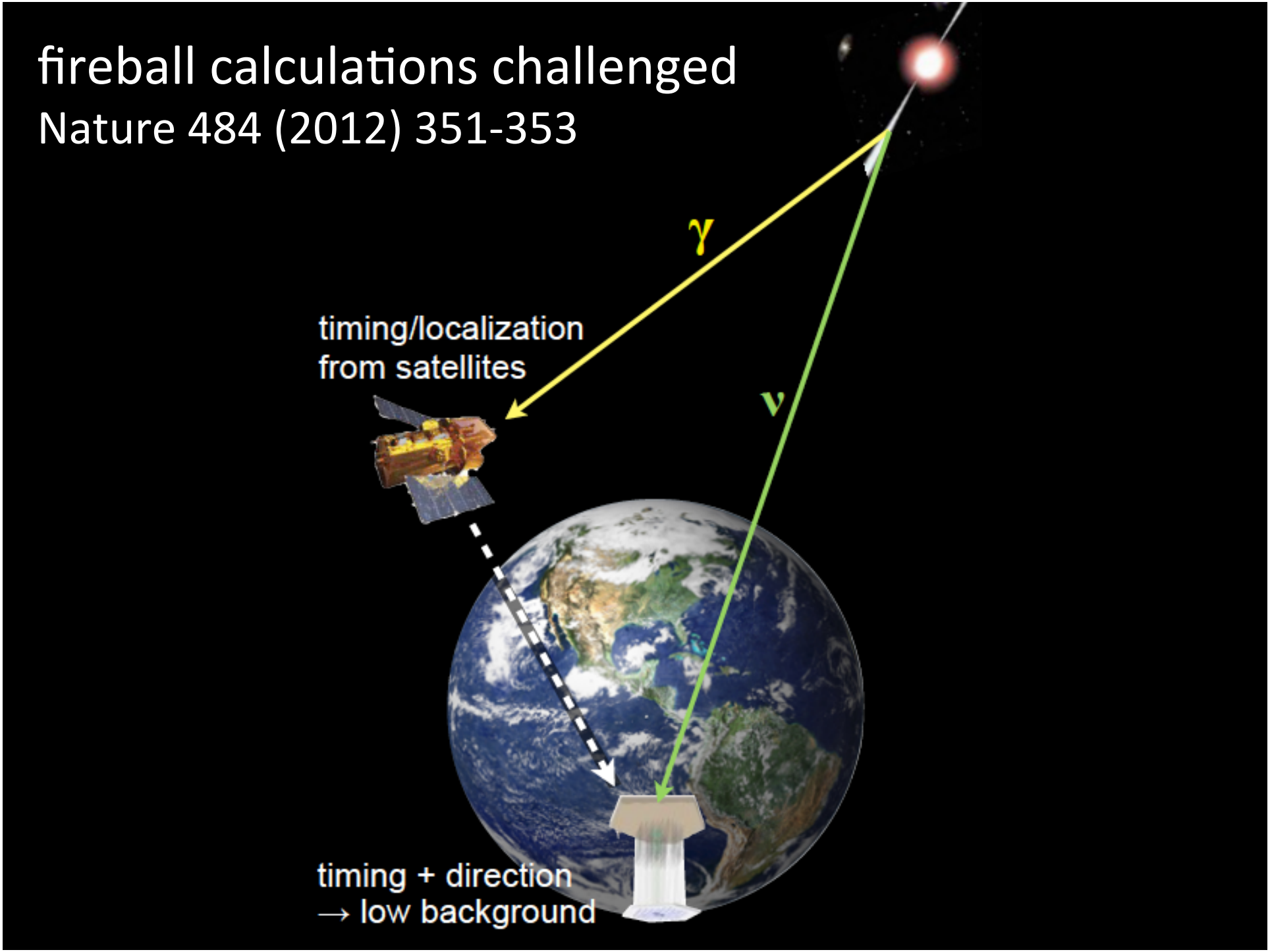
…and if the star collapses to a black hole…

gamma ray burst

- ✓ happens in seconds not thousands of year
- ✓ beamed along the spin axis of the black hole
- ✓ simulation not image
- ✓ ? IceCube, Nature 2011

fireball calculations challenged

Nature 484 (2012) 351-353



neutrinos and neutrons are produced in the interactions of fireball protons with synchrotron photons

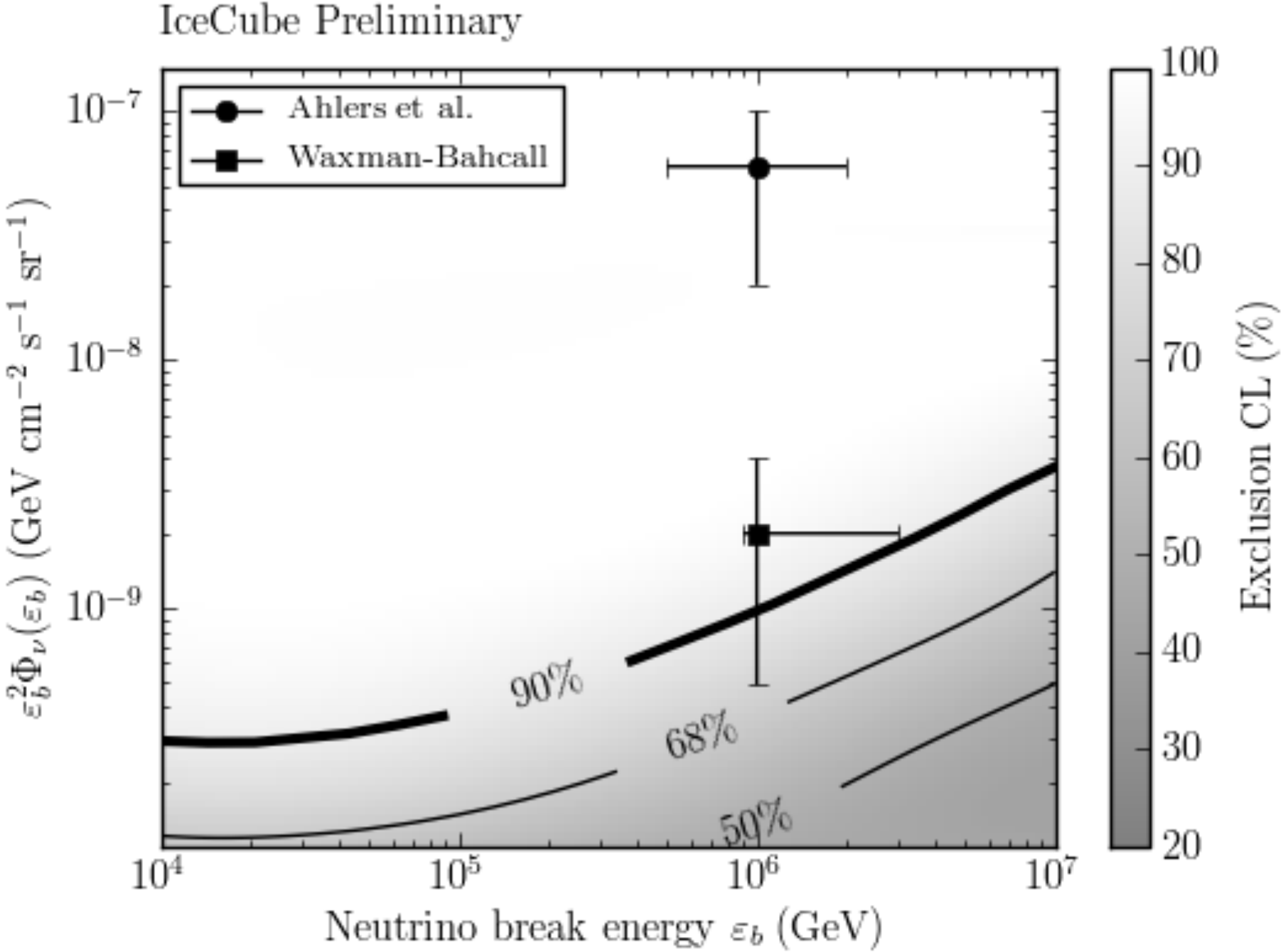
decays to a PeV neutrino

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

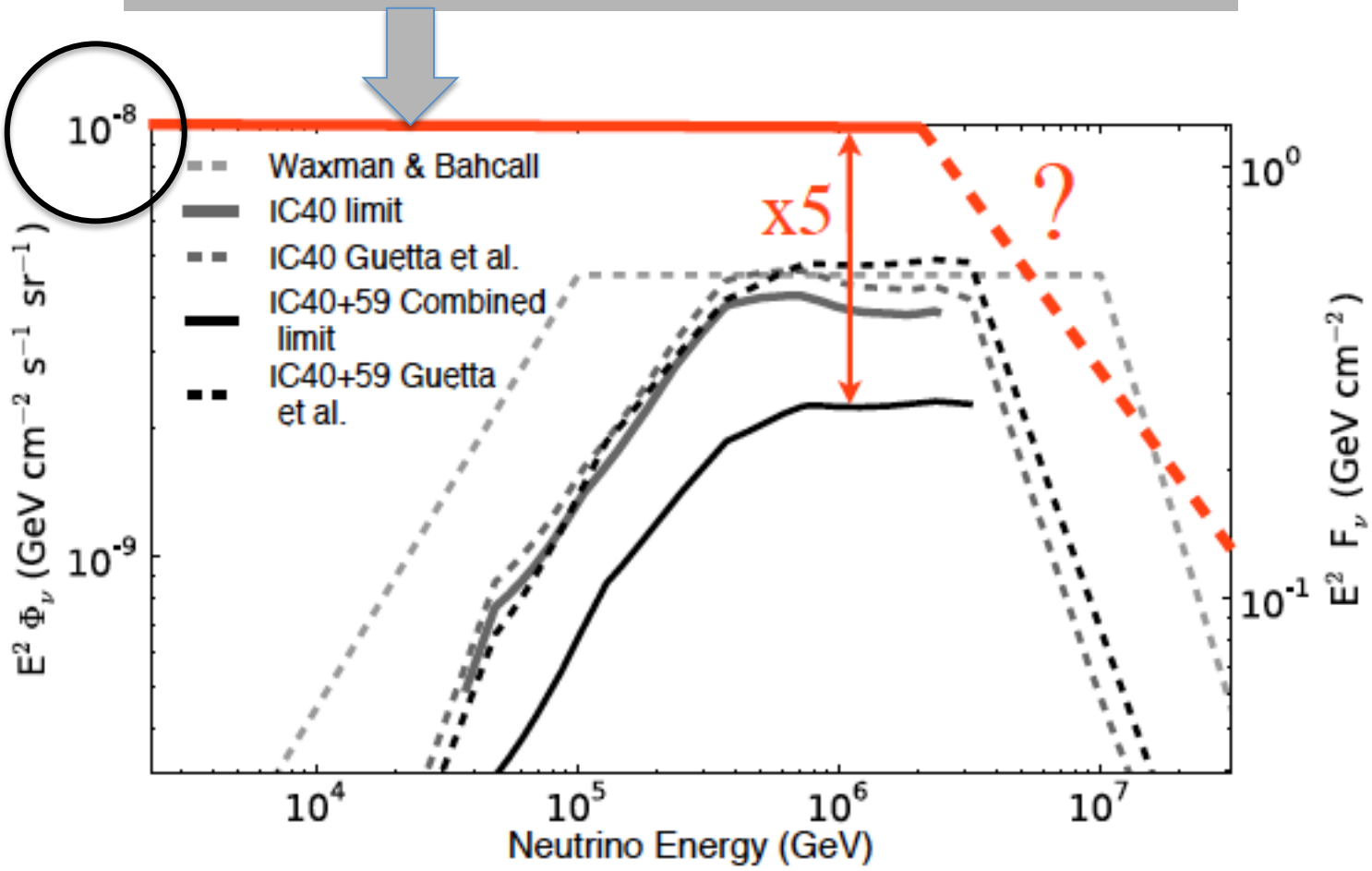
protons are trapped in the expanding fire-ball and lose energy

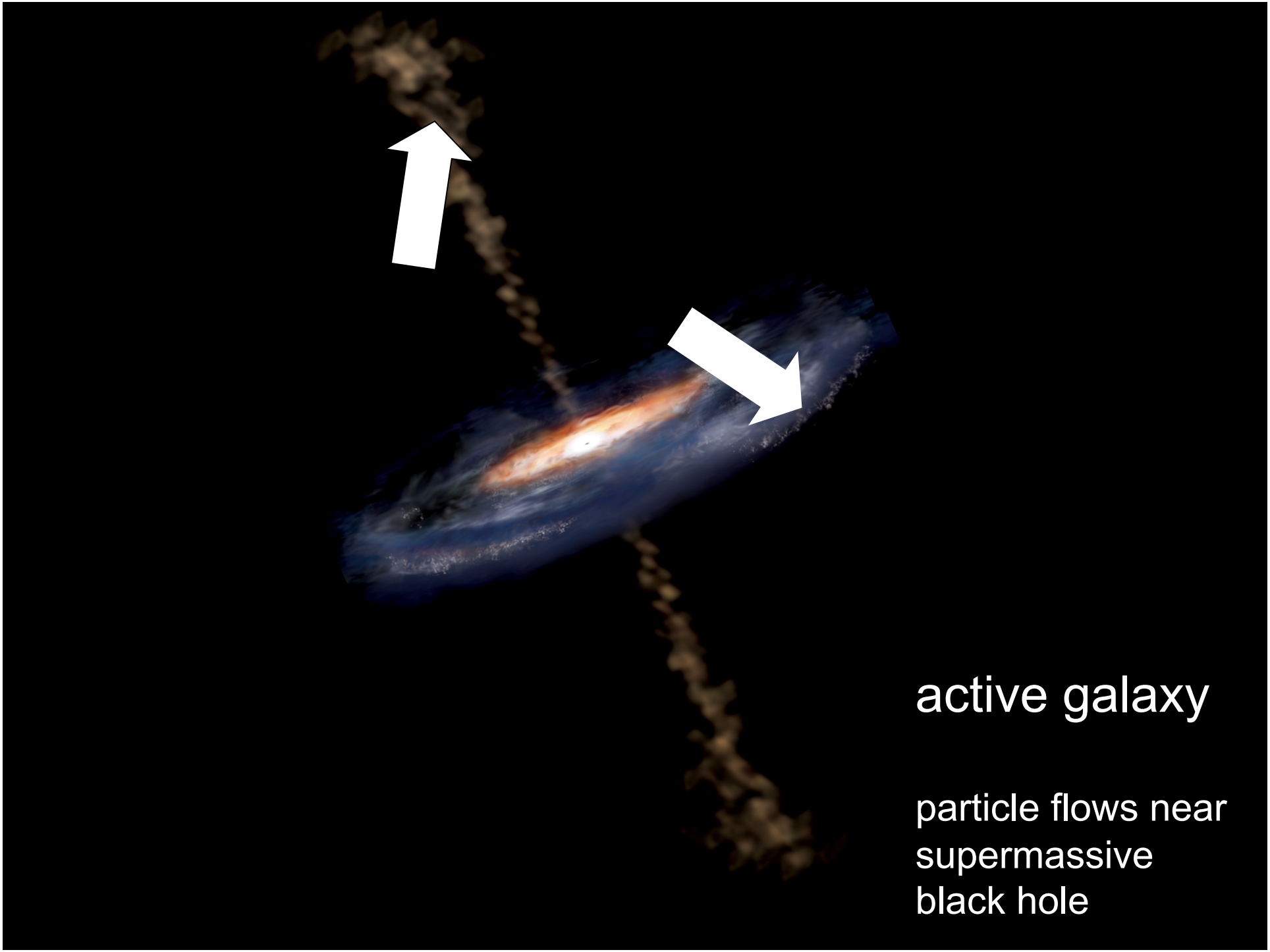
decays to cosmic ray

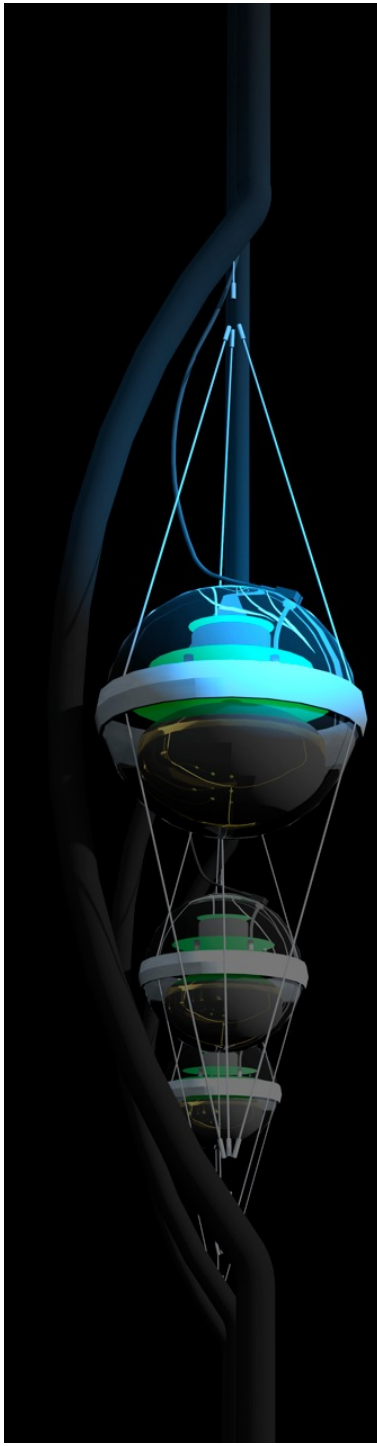
GRB: one neutrino per cosmic ray observed
→ ruled out by IceCube


IceCube Preliminary
Ahlers et al.
Waxman-Bahcall
90%
68%
50%
10^{-7}
10^{-8}
10^{-9}
$\varepsilon_b^2 \Phi_\nu(\varepsilon_b)$ (GeV cm^{-2} s^{-1} sr^{-1})
10^4
10^5
10^6
10^7
Neutrino break energy ε_b (GeV)
100
90
80
70
60
50
40
30
20
Exclusion CL (%)

gamma ray burst are not the origin of the cosmic neutrinos observed by IceCube




active galaxy
particle flows near
supermassive
black hole



IceCube

francis halzen

- cosmogenic neutrinos
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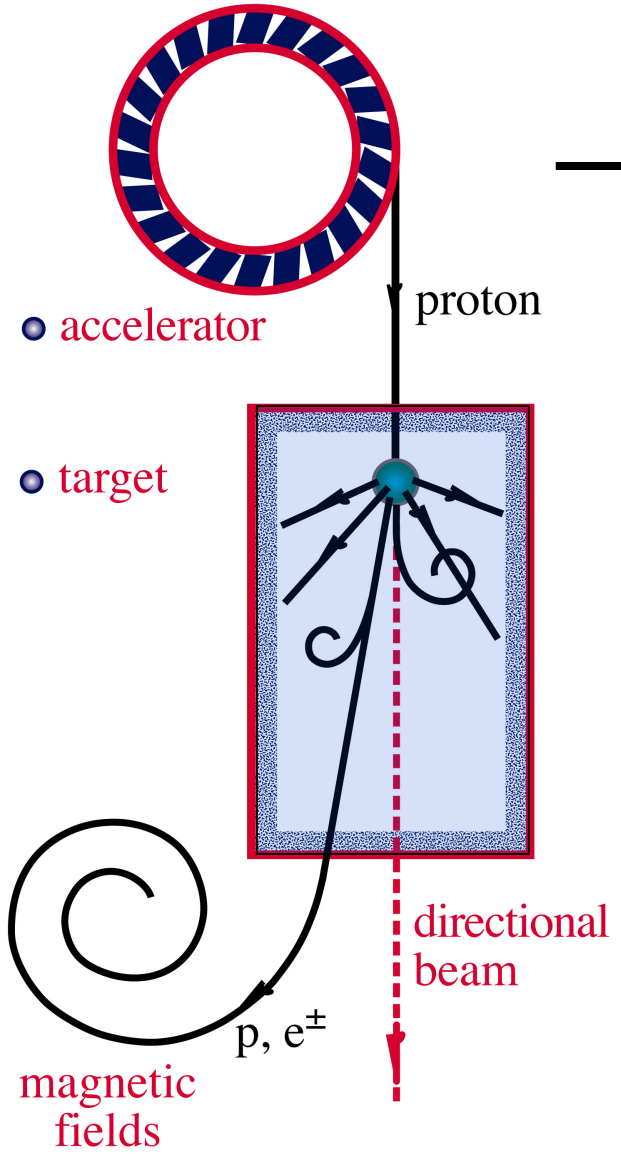
- conclusions

IceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

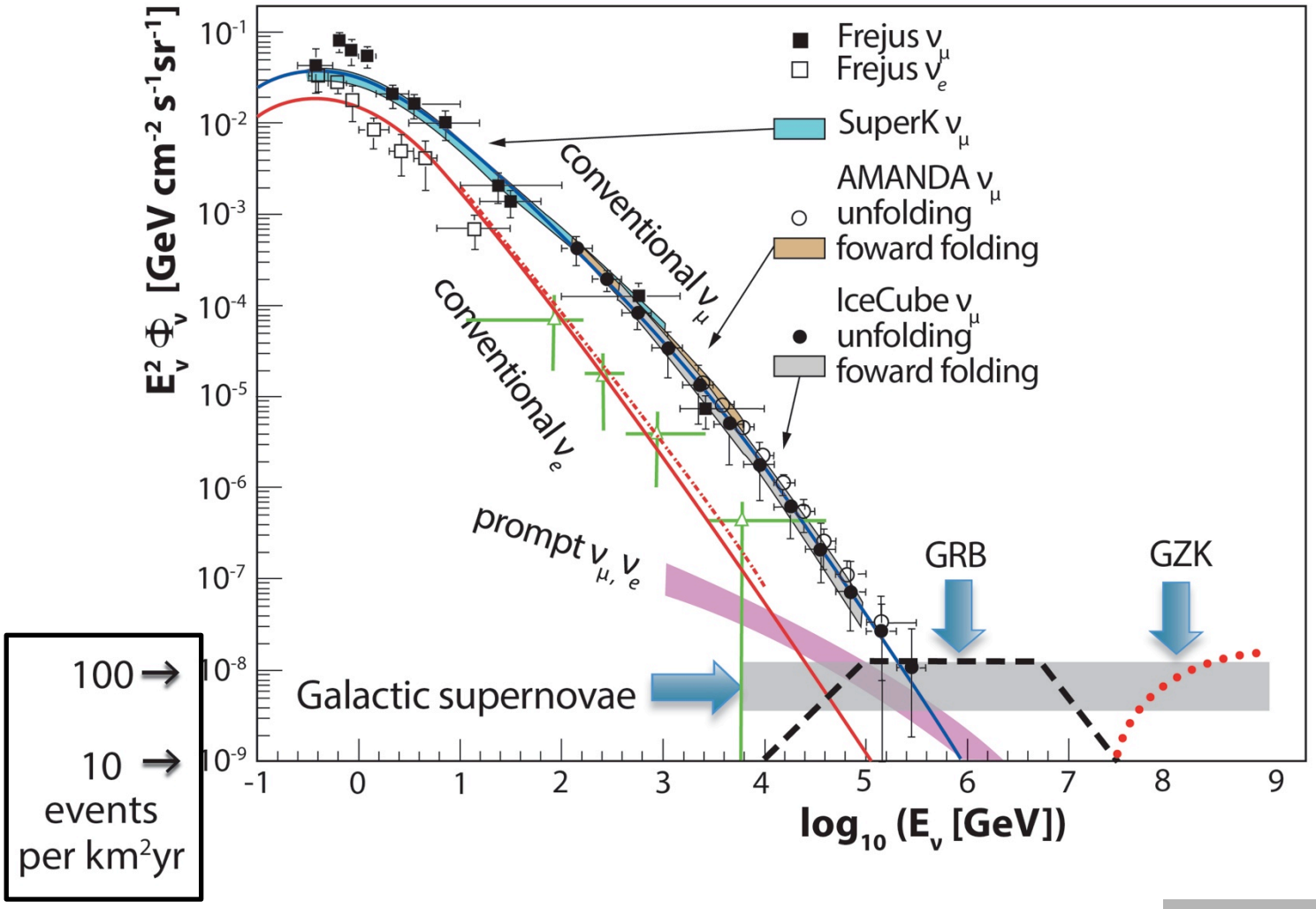
radiation
and dust

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

~ cosmic ray + neutrino

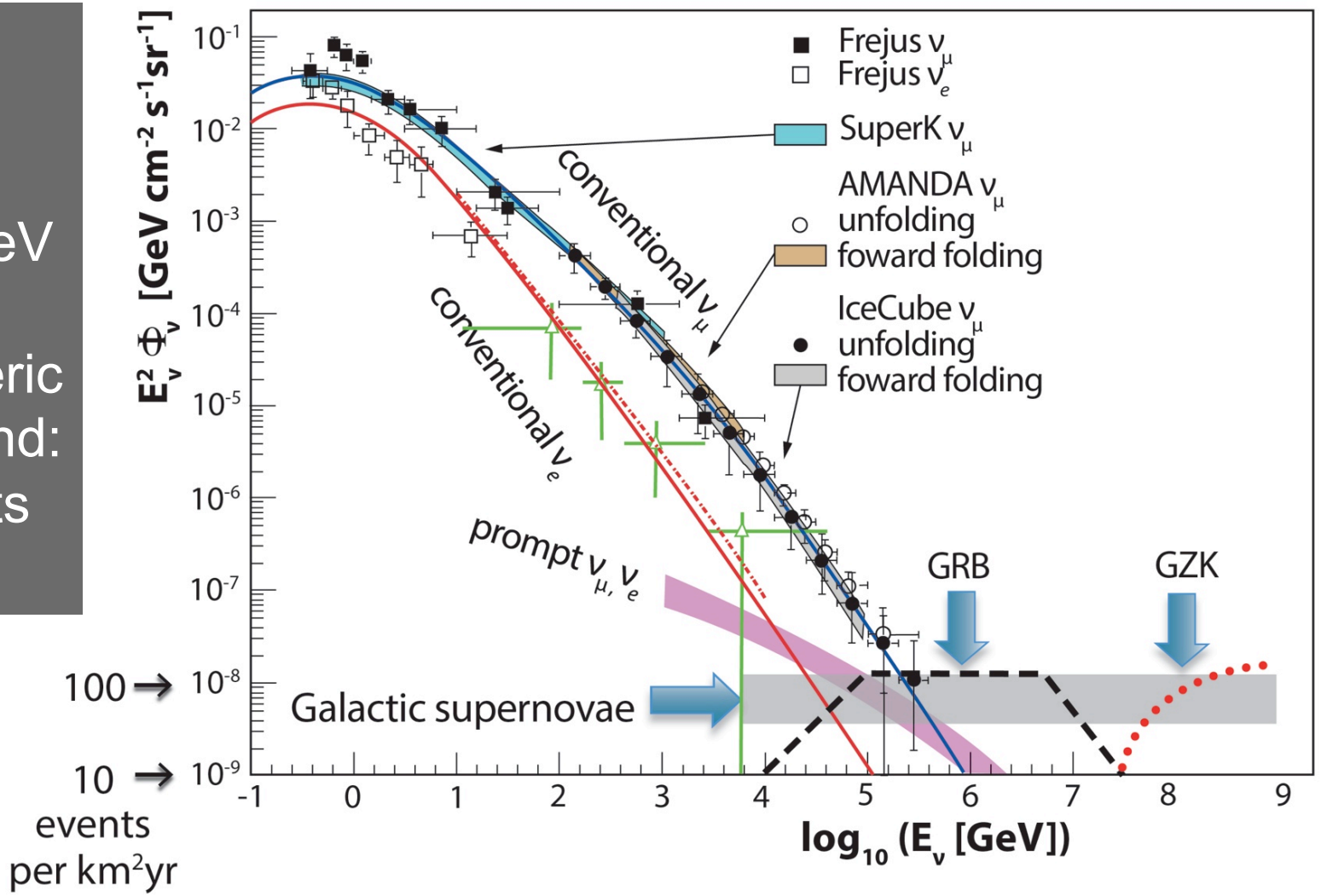
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

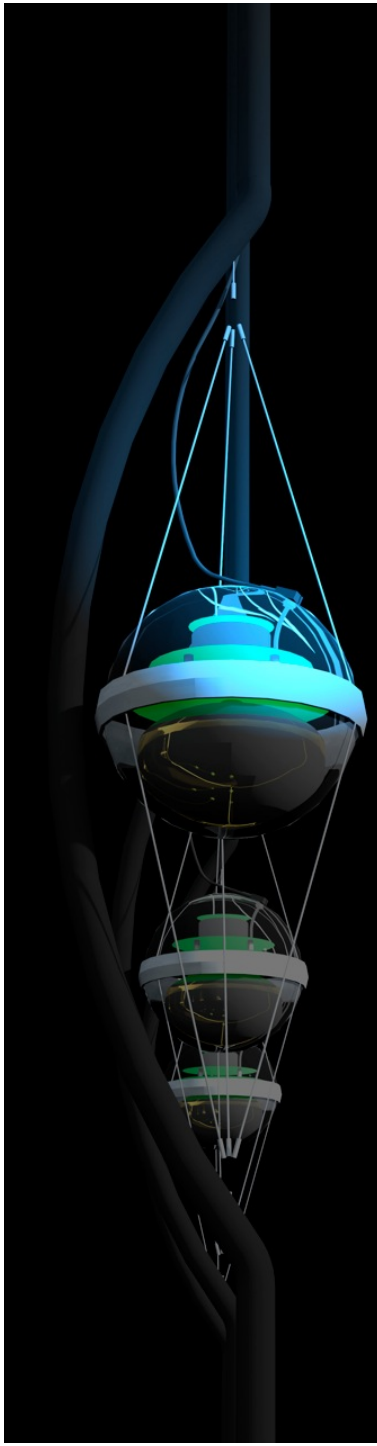


$$\Phi_\nu \equiv \frac{dN}{dE} \approx \frac{1}{E^2}$$

- cosmic neutrinos: energy
  > 60 TeV
- atmospheric background: 1~2 events per year



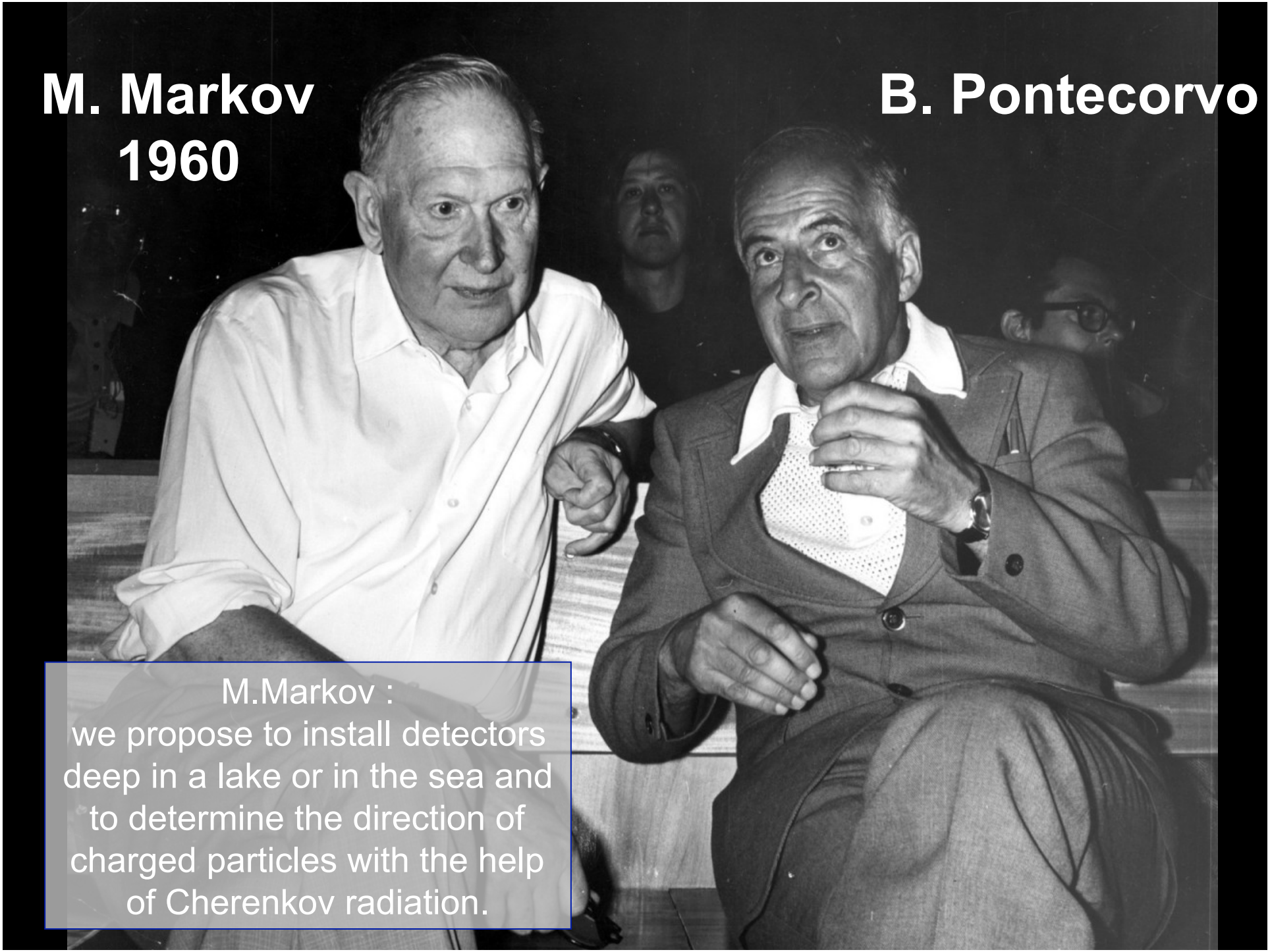
atmospheric ⇑ cosmic



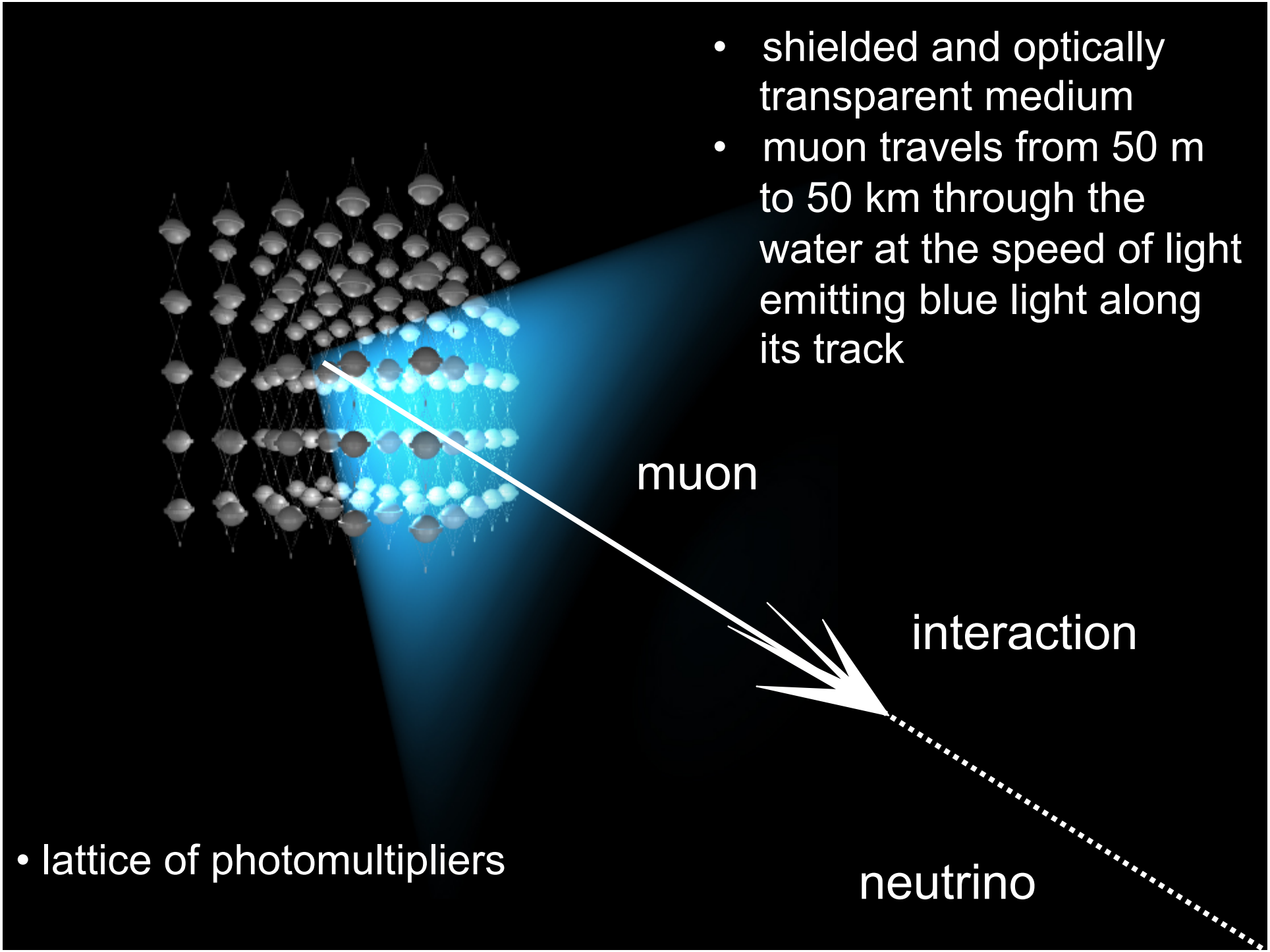
IceCube

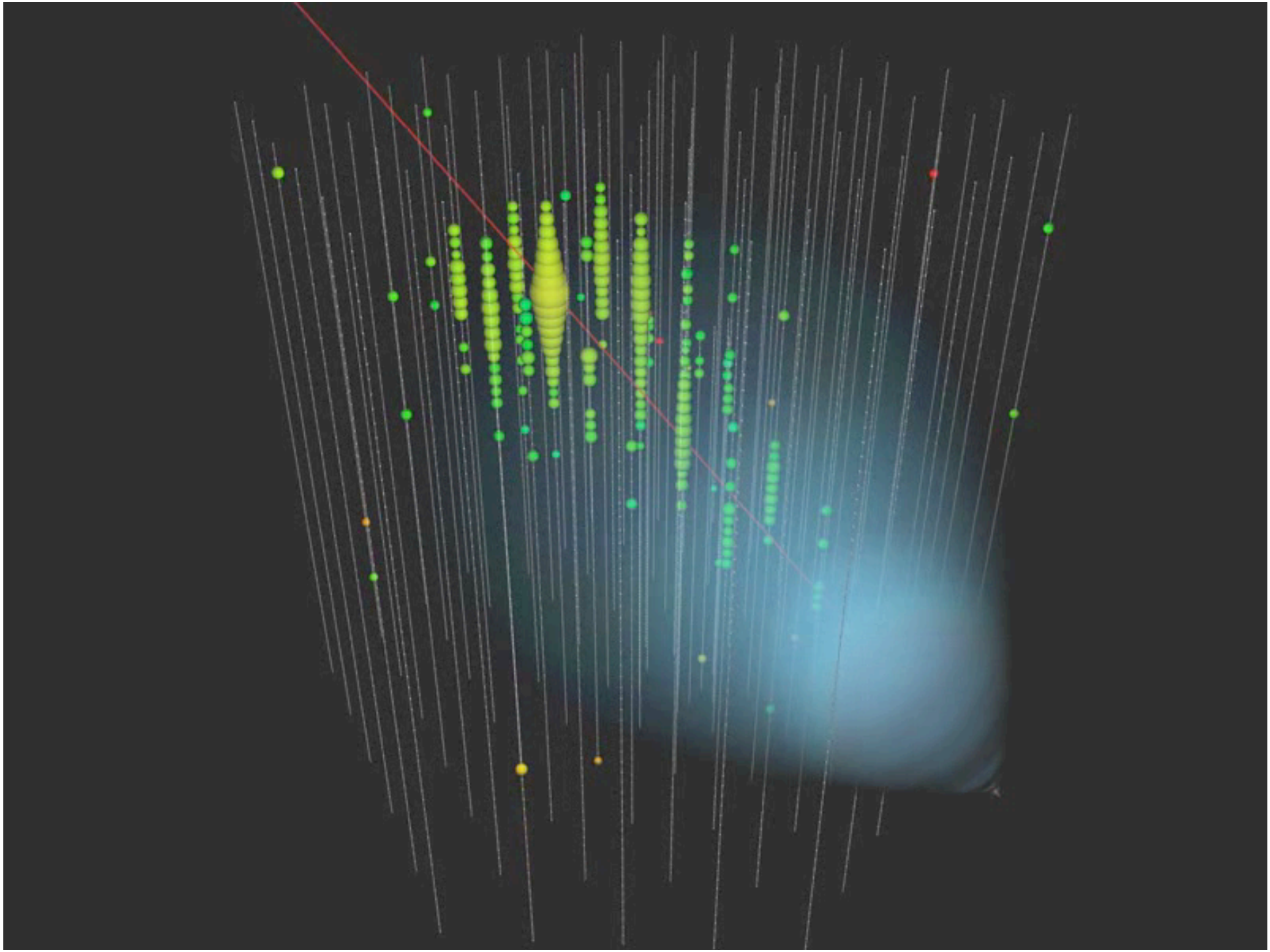
francis halzen

- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

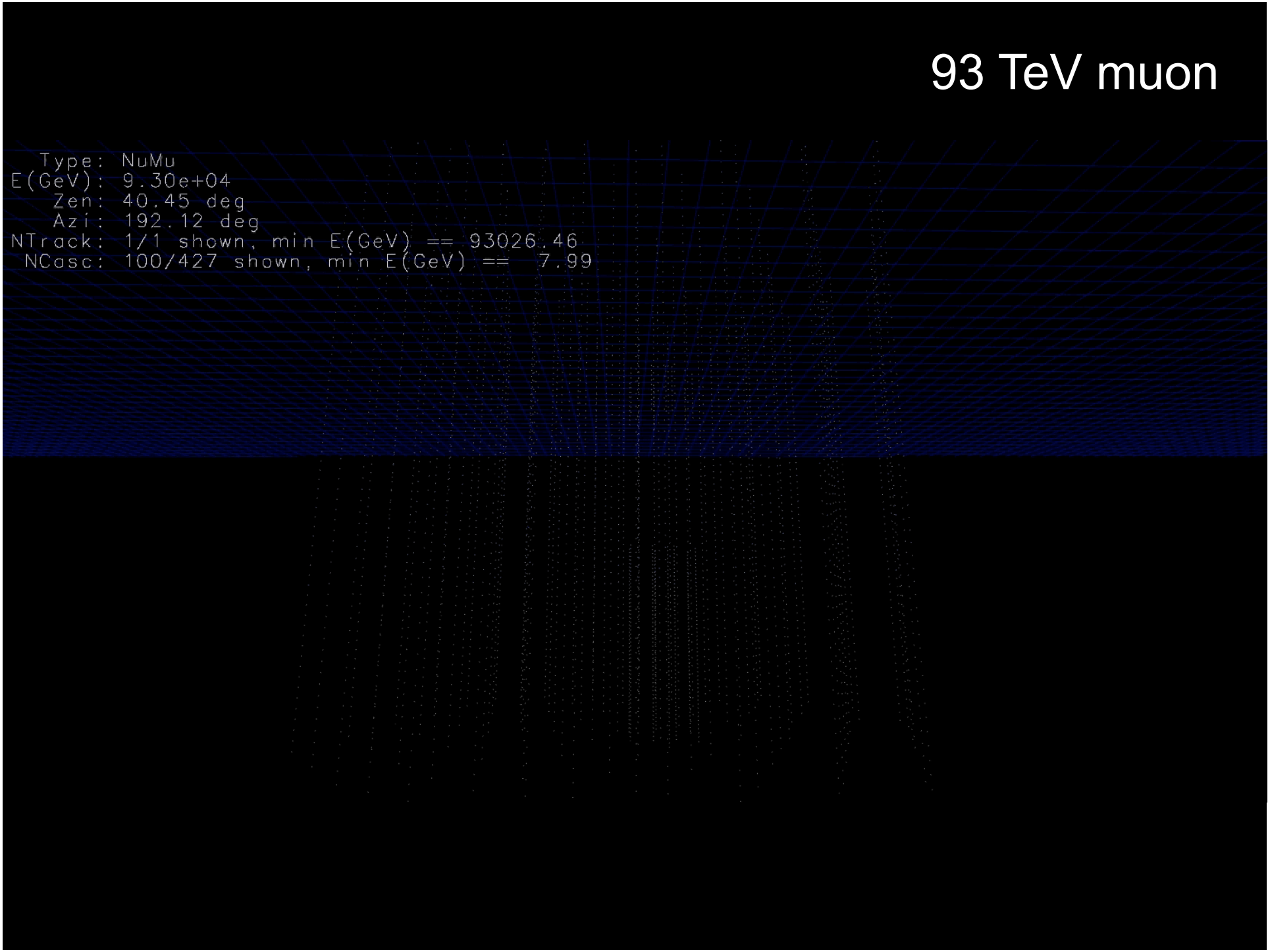


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

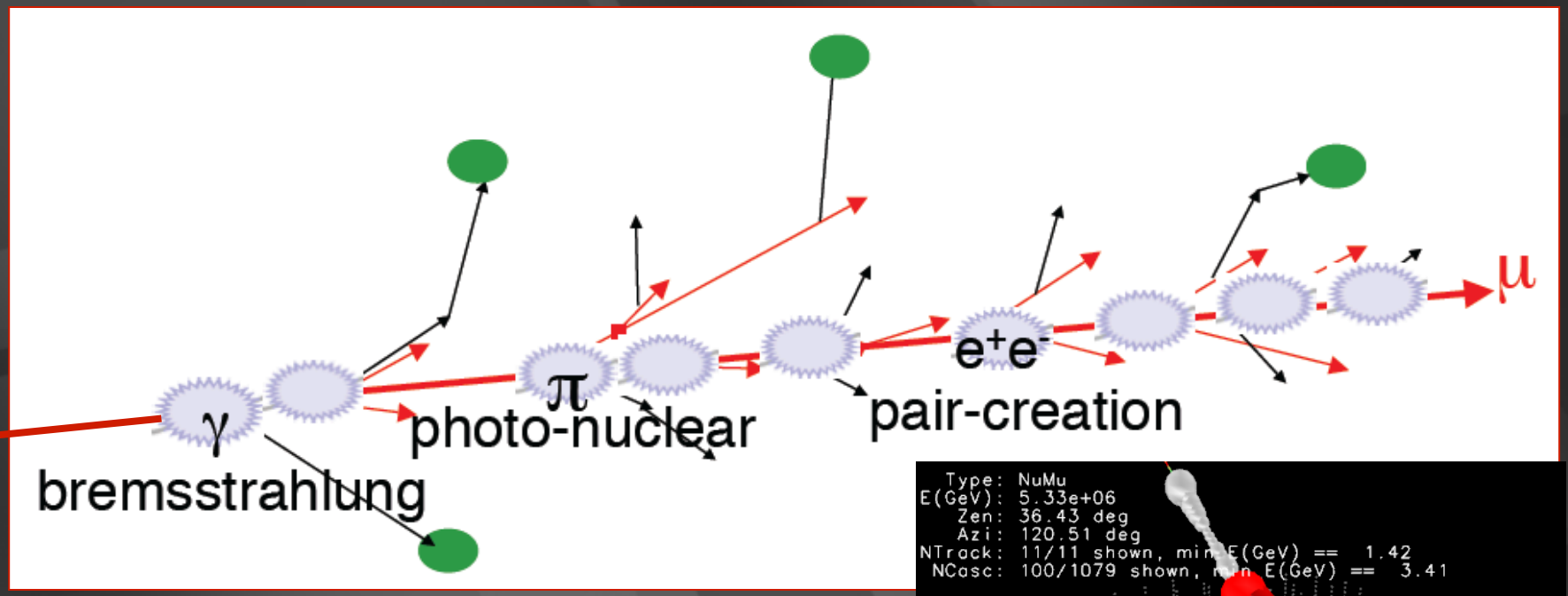

• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
• lattice of photomultipliers
neutrino

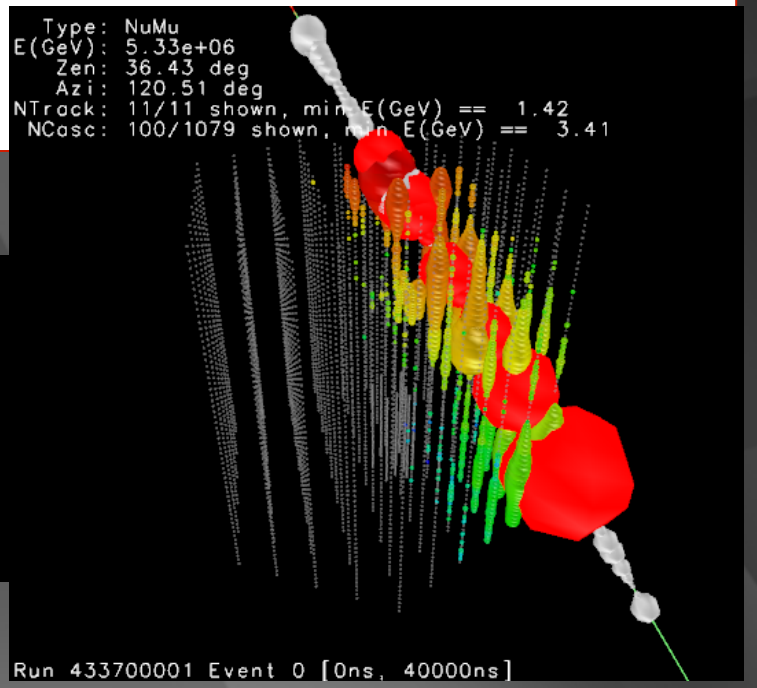


93 TeV muon

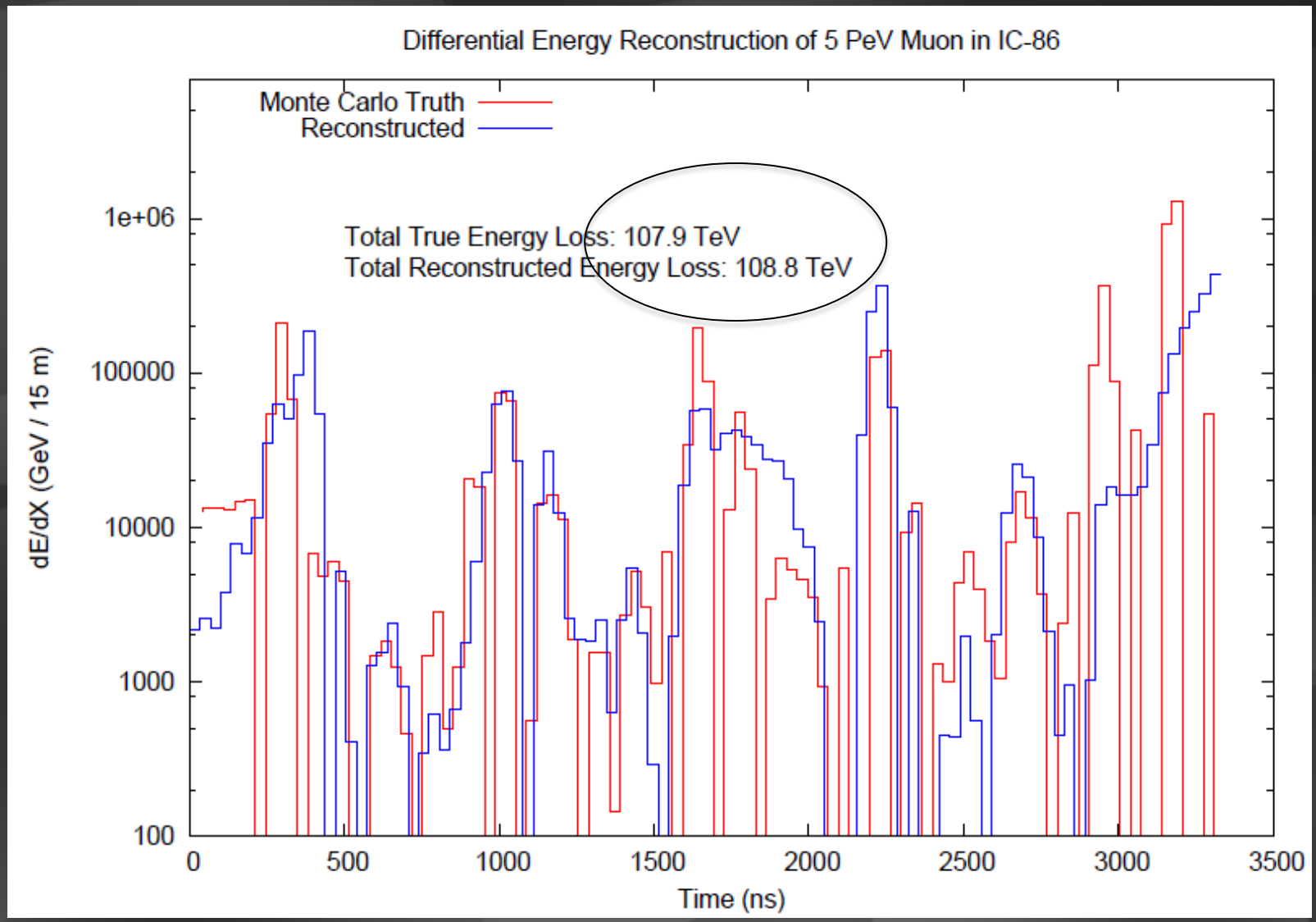

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)

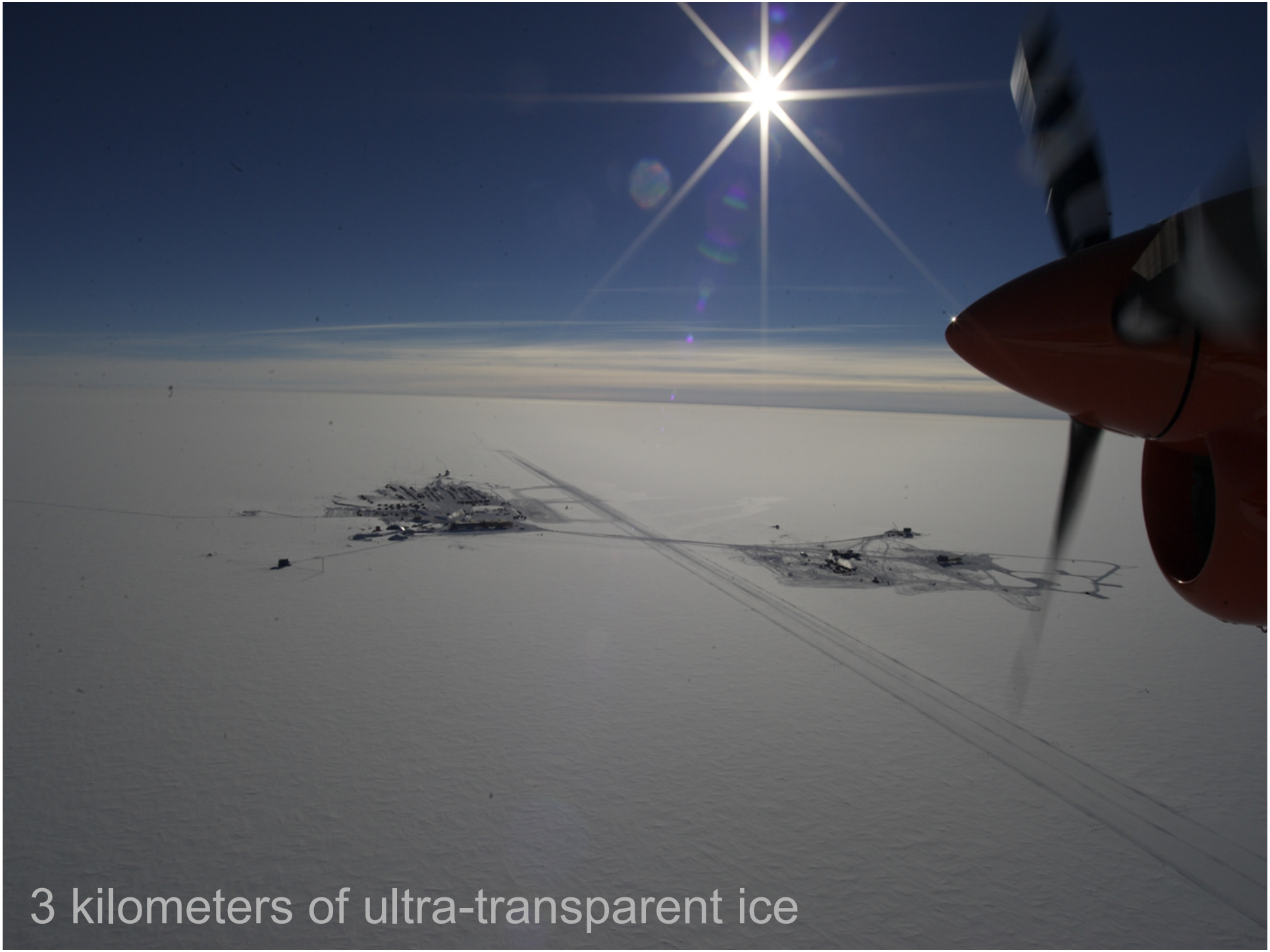




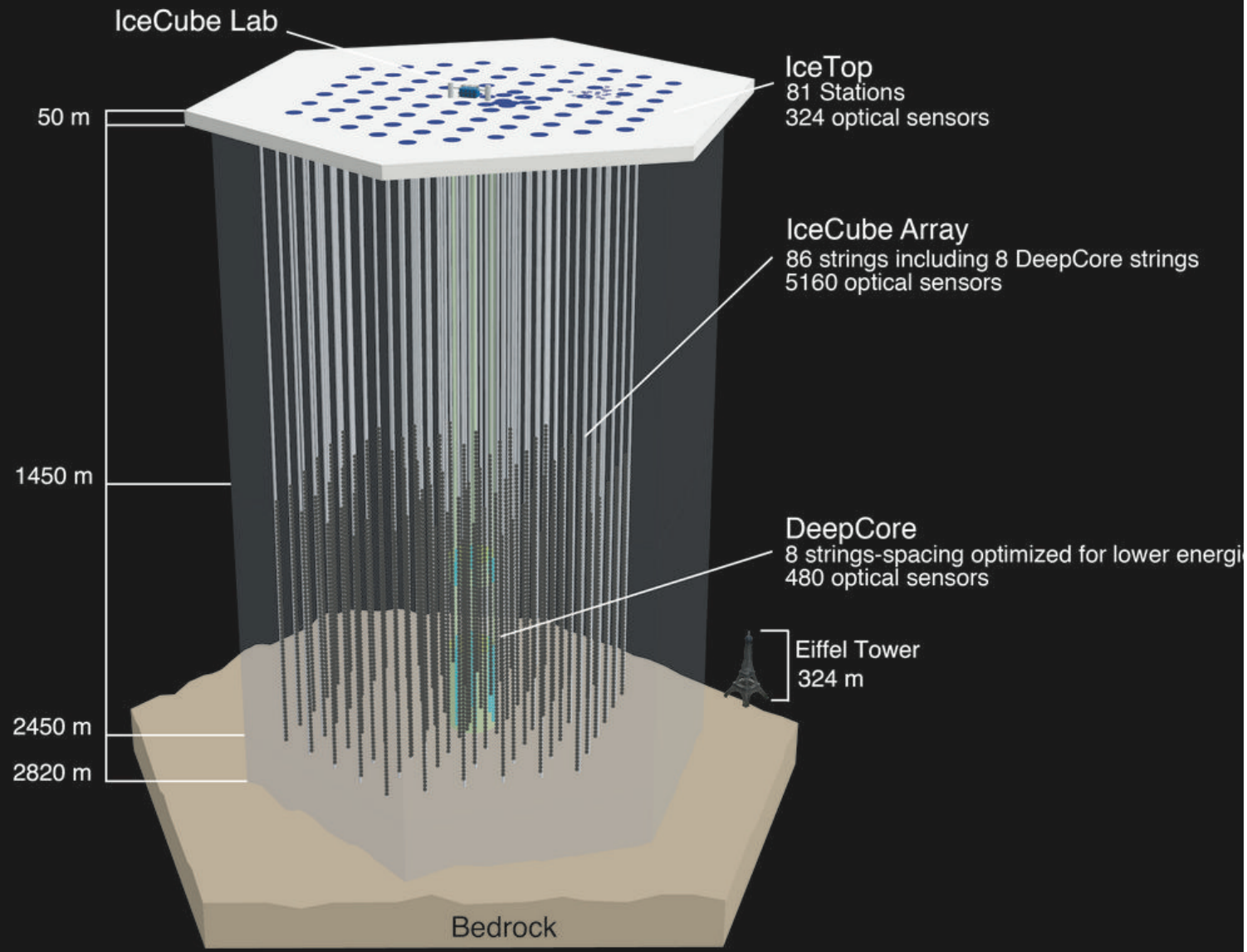
convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



improving angular and energy resolution

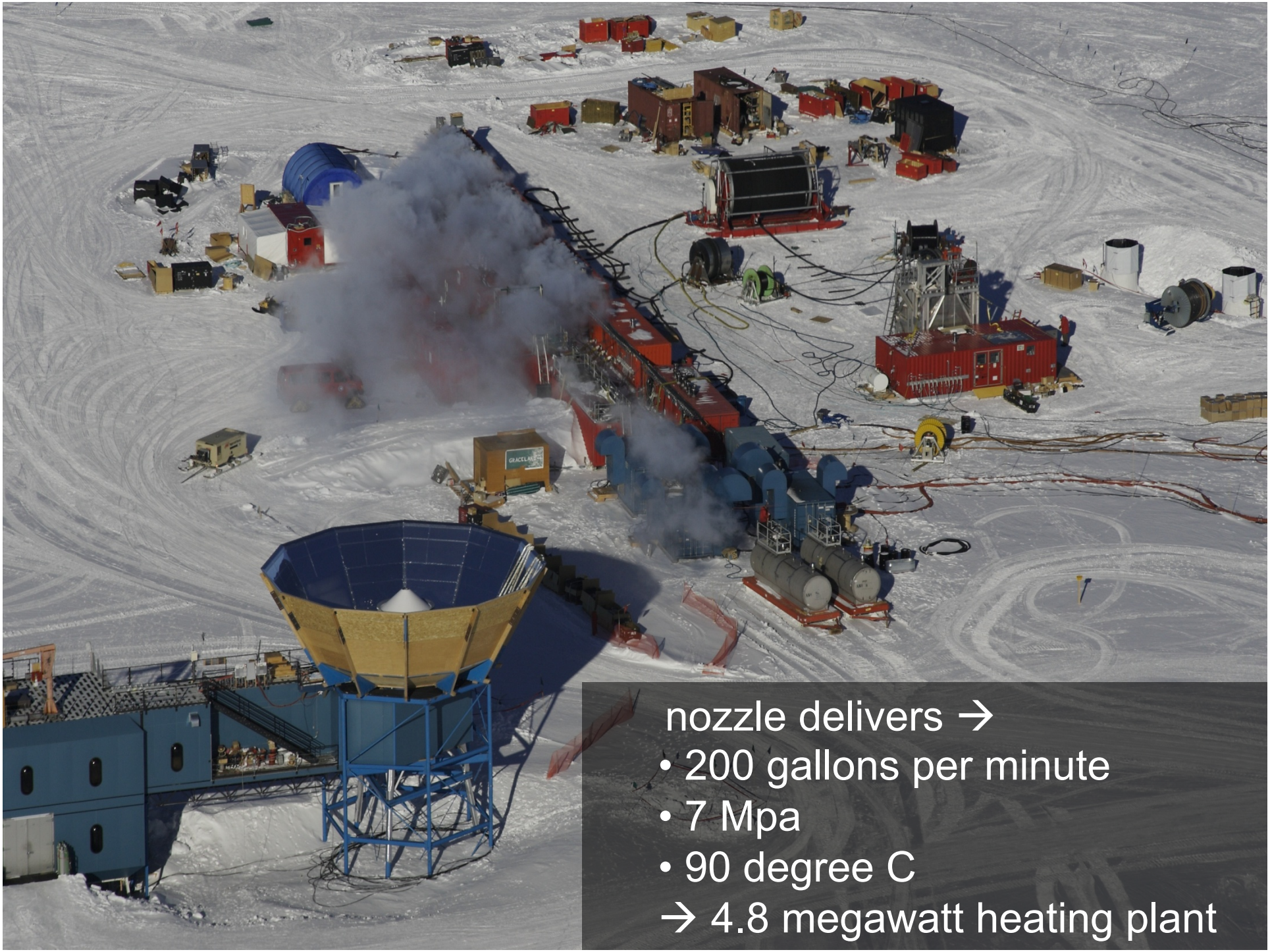

3 kilometers of ultra-transparent ice

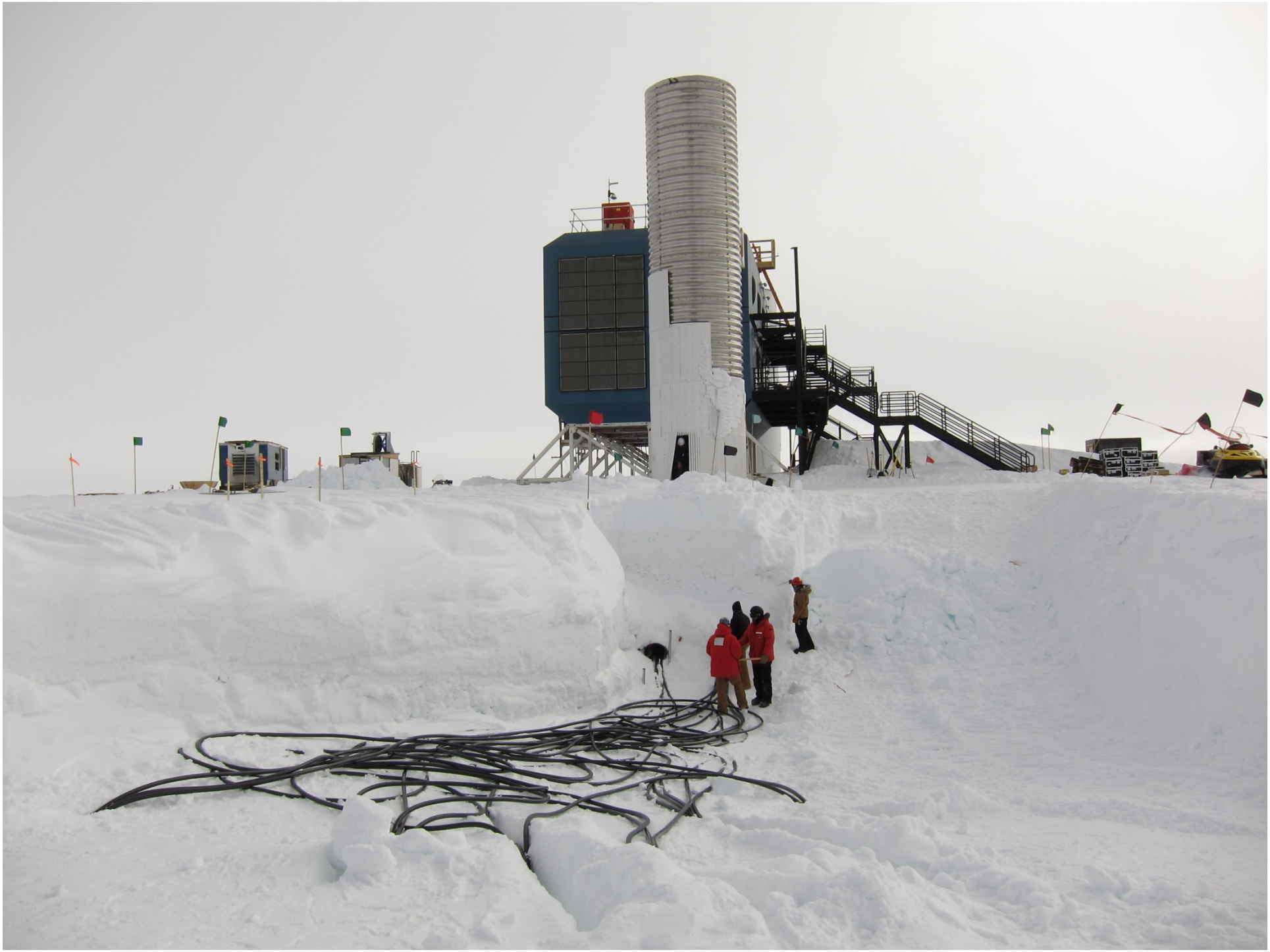
IceCube: transforms 1 km3 of natural Antarctic ice into a Cherenkov detector



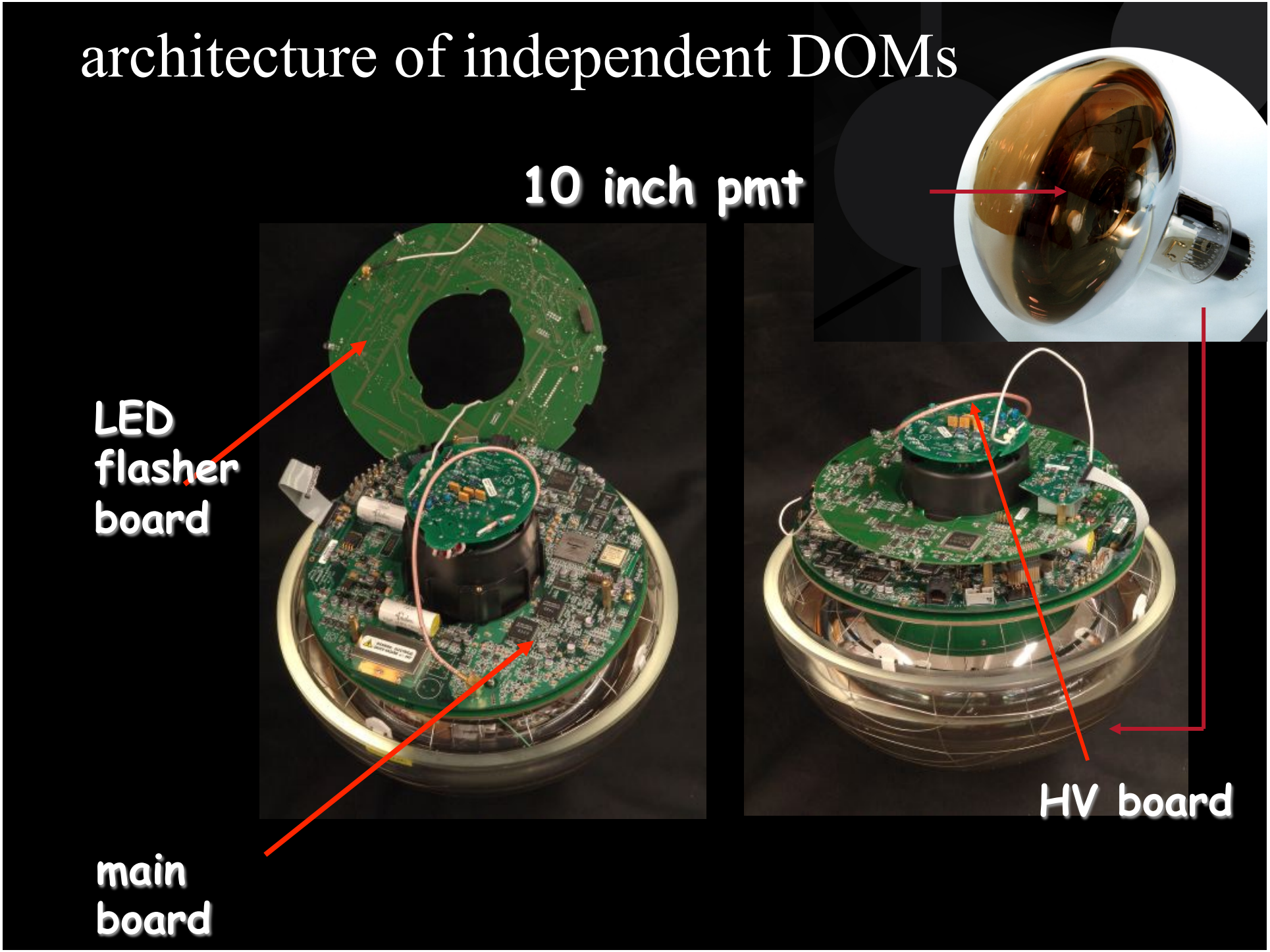
drilling and deployment

2 days per hole
3.5 cm/second

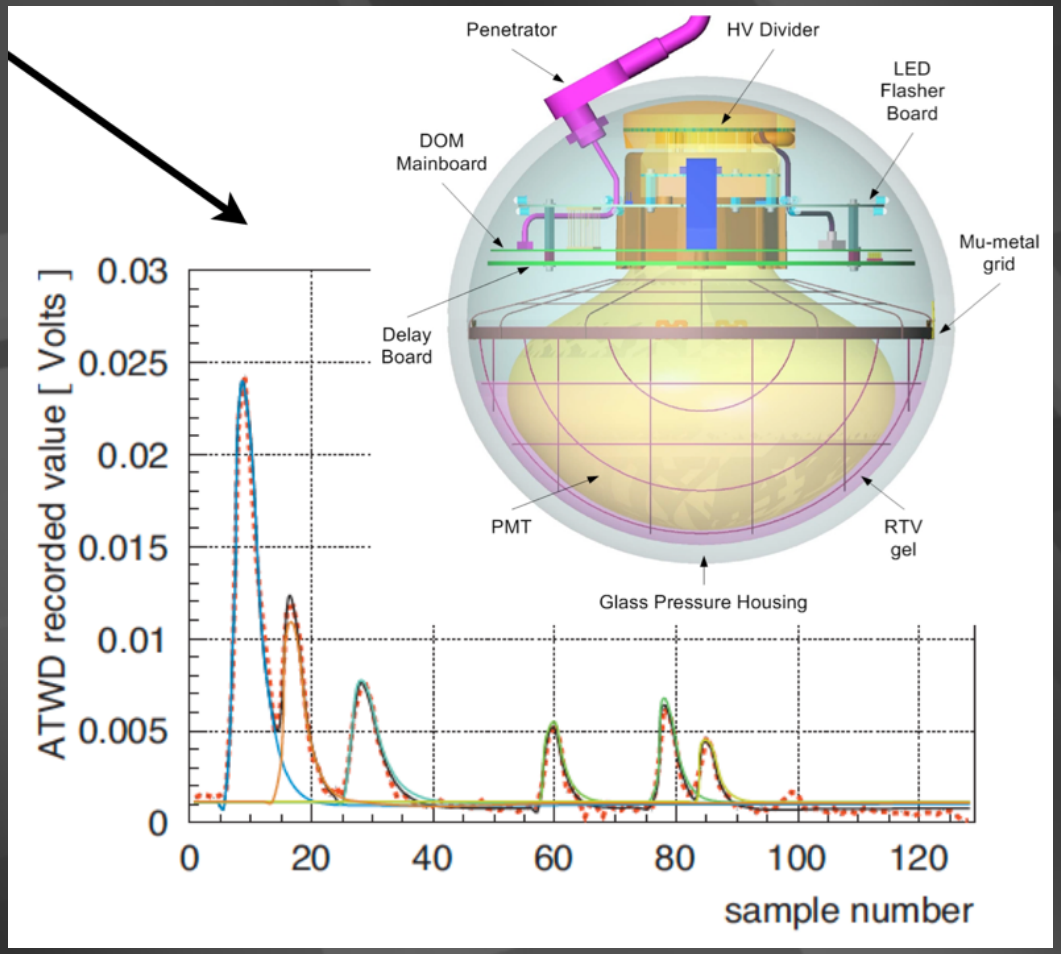

nozzle delivers →
• 200 gallons per minute
• 7 Mpa
• 90 degree C
→ 4.8 megawatt heating plant



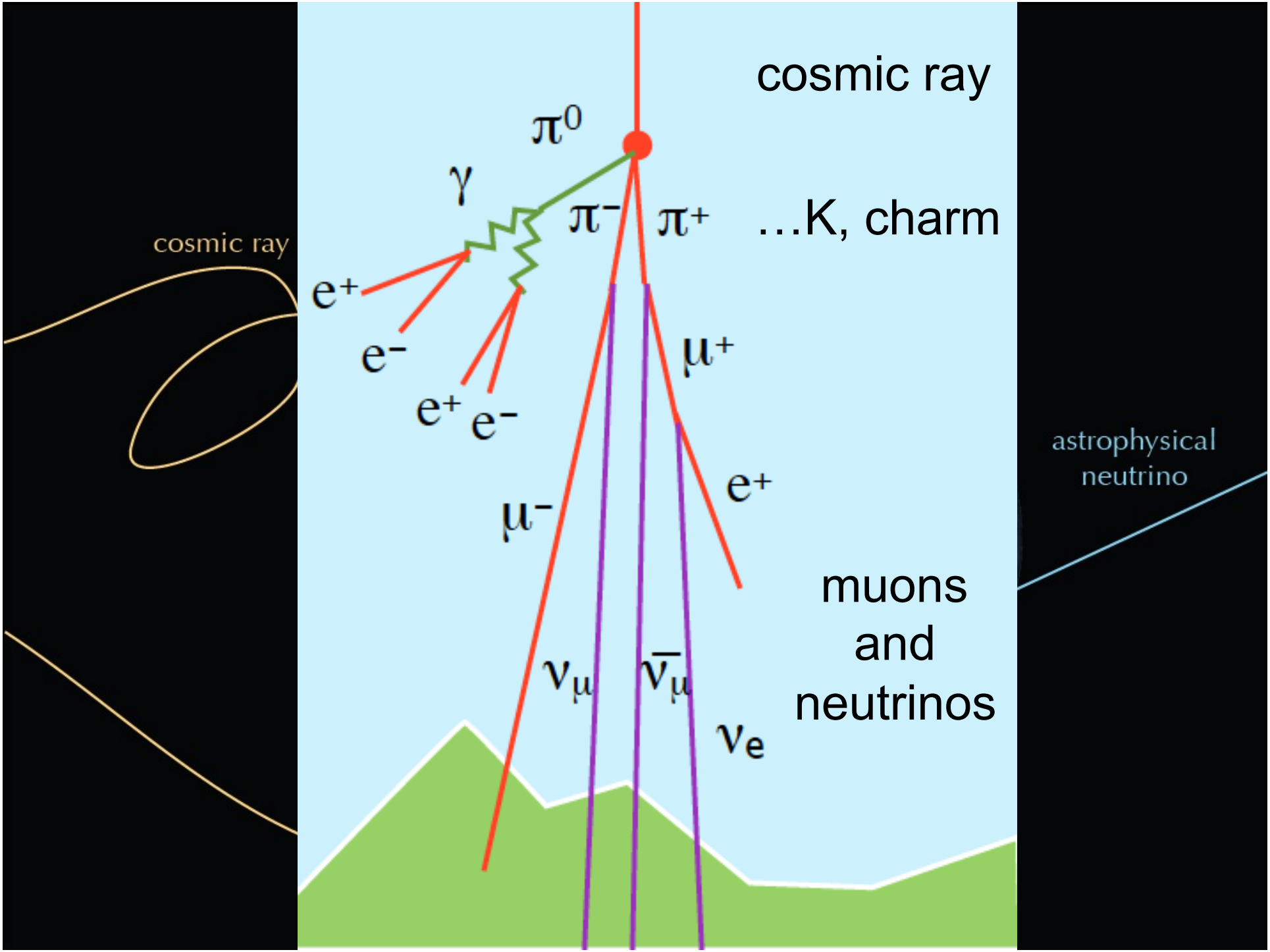
architecture of independent DOMs

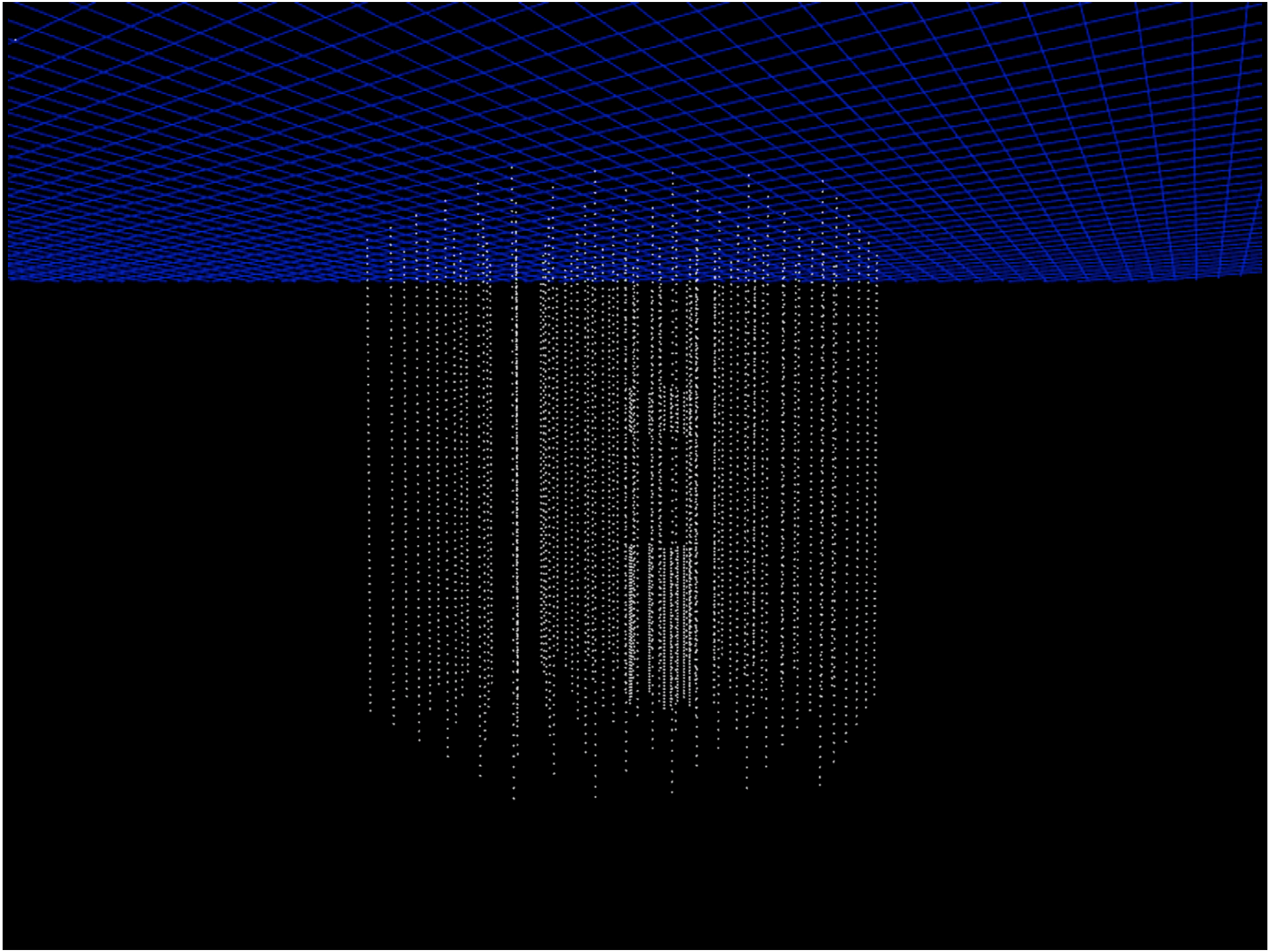


… each Digital Optical Module independently collects light signals like this, digitizes them,



…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…


cosmic ray
cosmic ray
π^0
γ
π^-
π^+
…K, charm
e^+
e^-
e^+
e^-
μ^+
e^+
μ^-
muons
and
neutrinos
ν_μ
$\bar{\nu}_\mu$
ν_e
astrophysical
neutrino

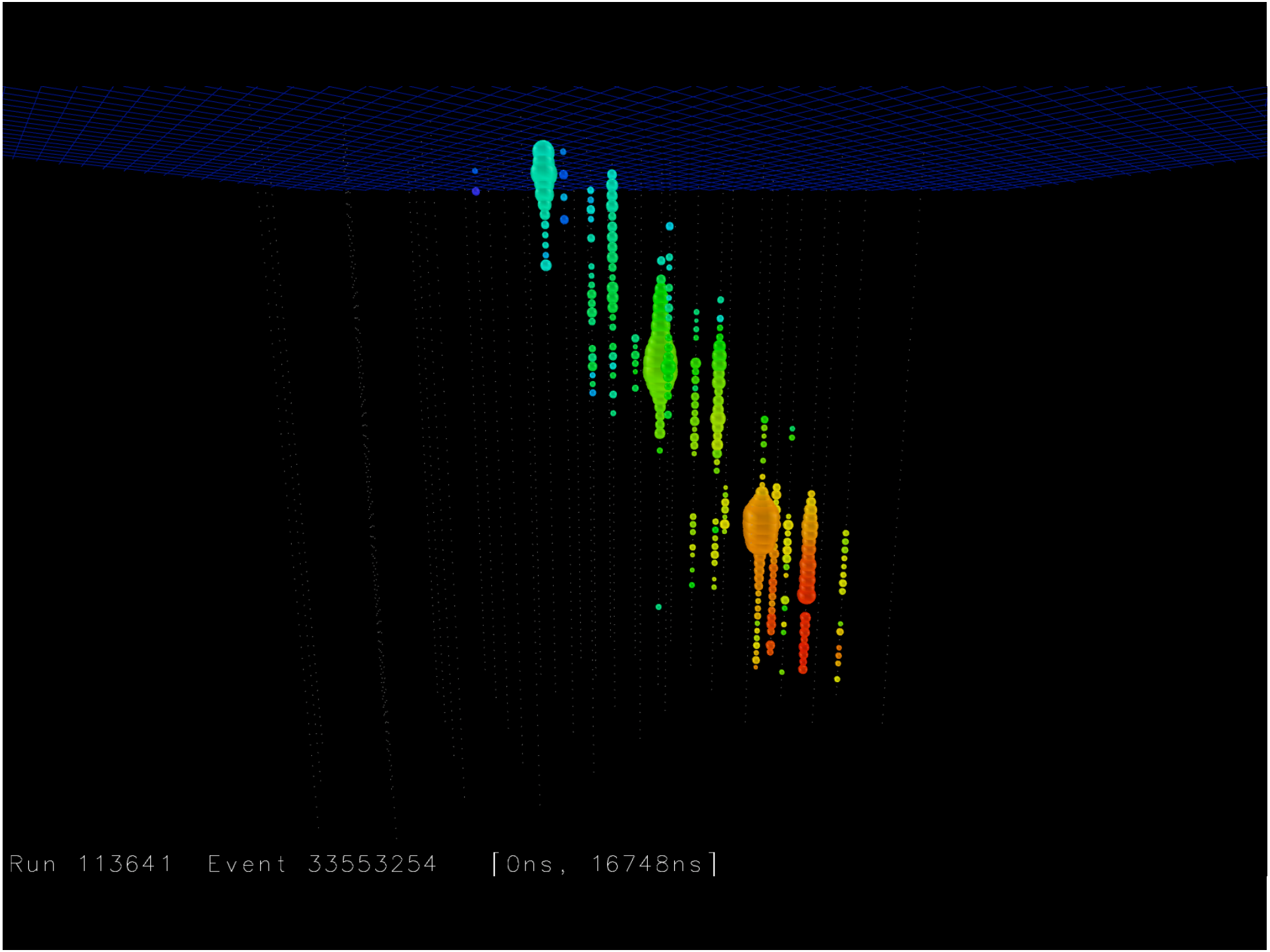


… you looked at 10msec of data !

muons detected per year:

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

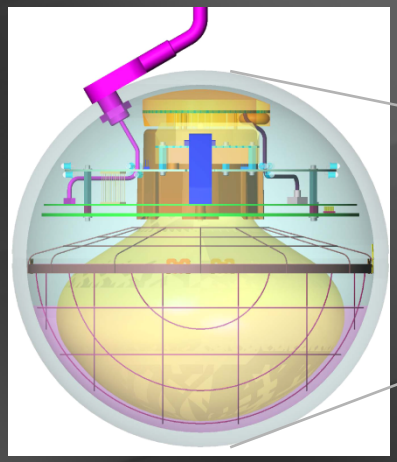
* 2700 per second ** 1 every 6 minutes


Run 113641 Event 33553254 [0ns, 16748ns]

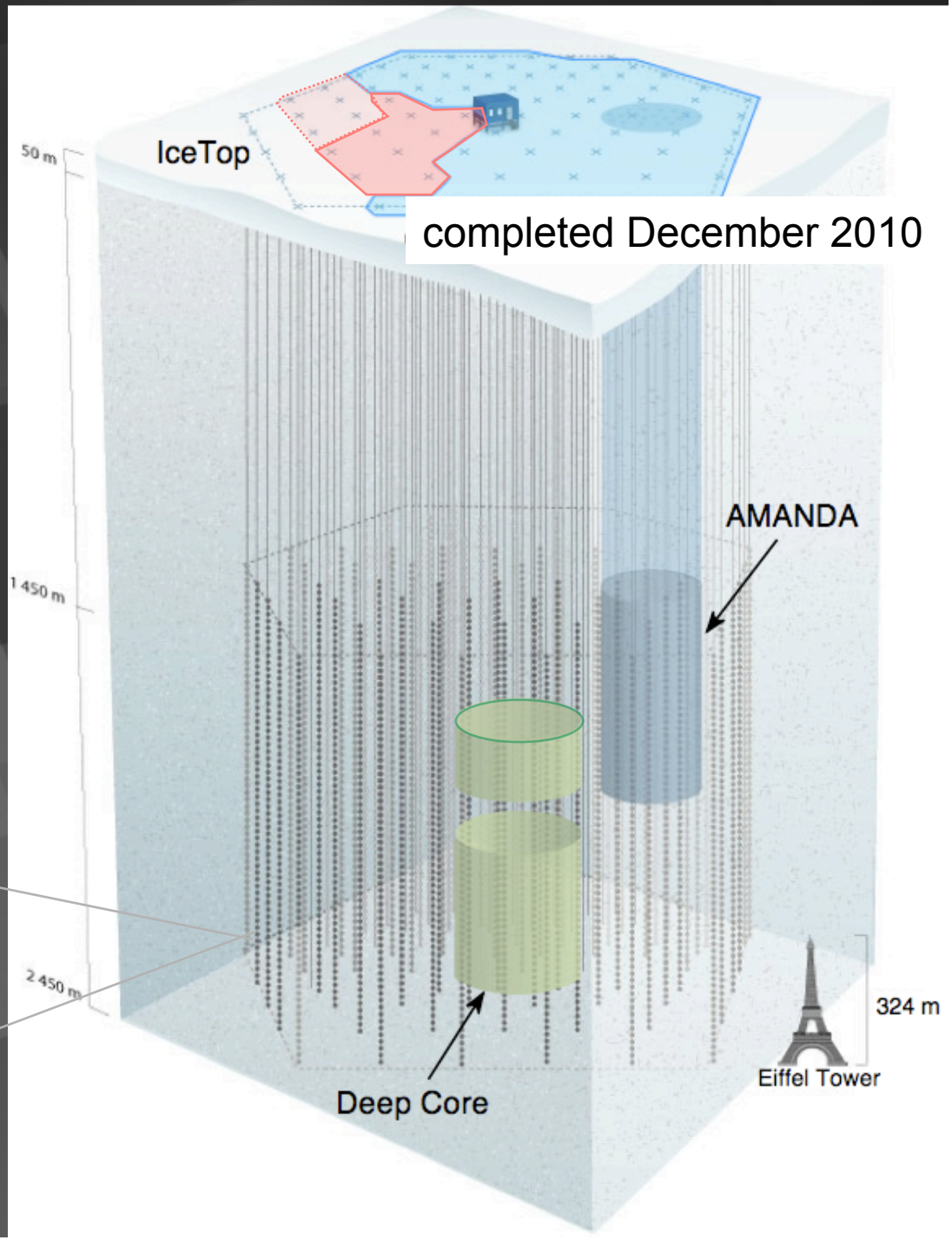
… for science and for the experimental accomplishment of building IceCube …

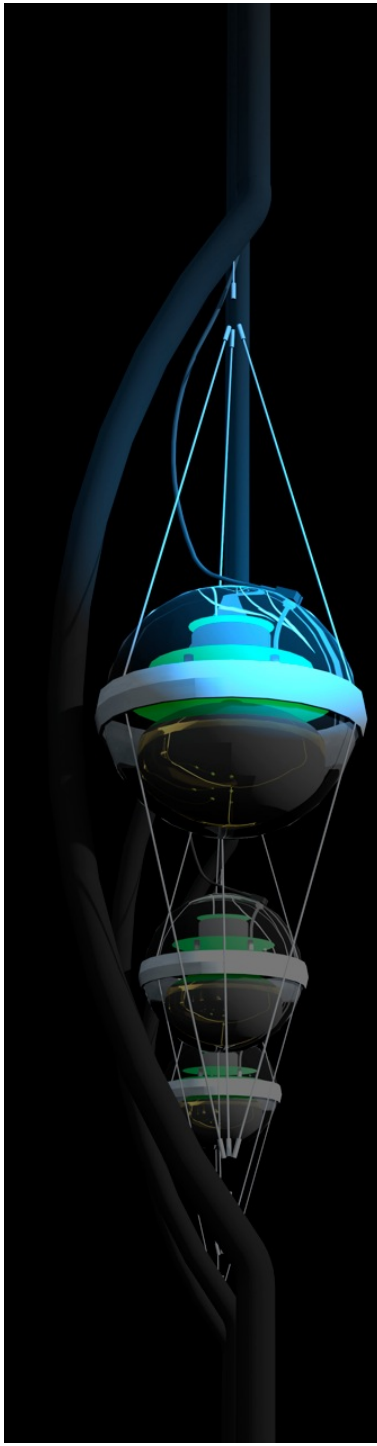
IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
  < 0.3 degree off line
  for muons
  (10~15 degrees for showers)
- < 15% energy resolution



Digital Optical Module (DOM)





IceCube

francis halzen

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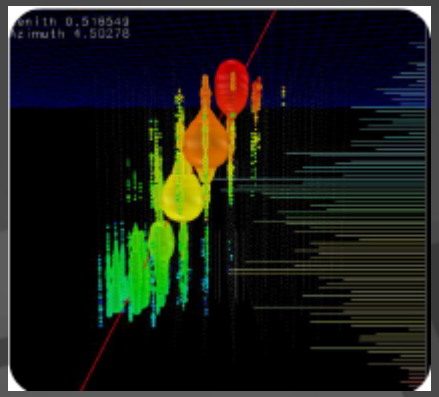
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

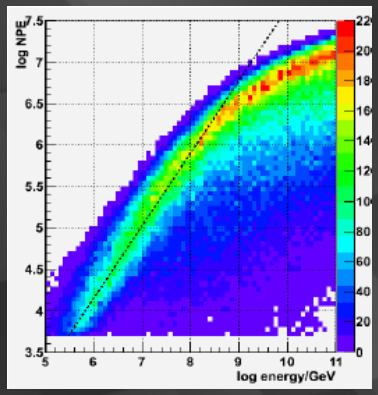
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source!

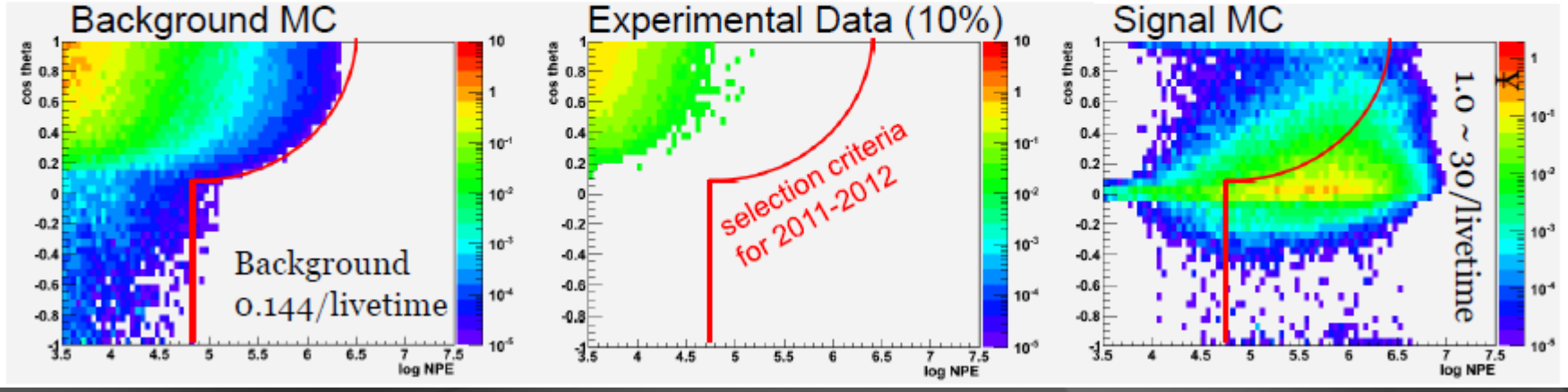
GZK neutrinos: > 41,000 photons near the horizon
> 300 channels



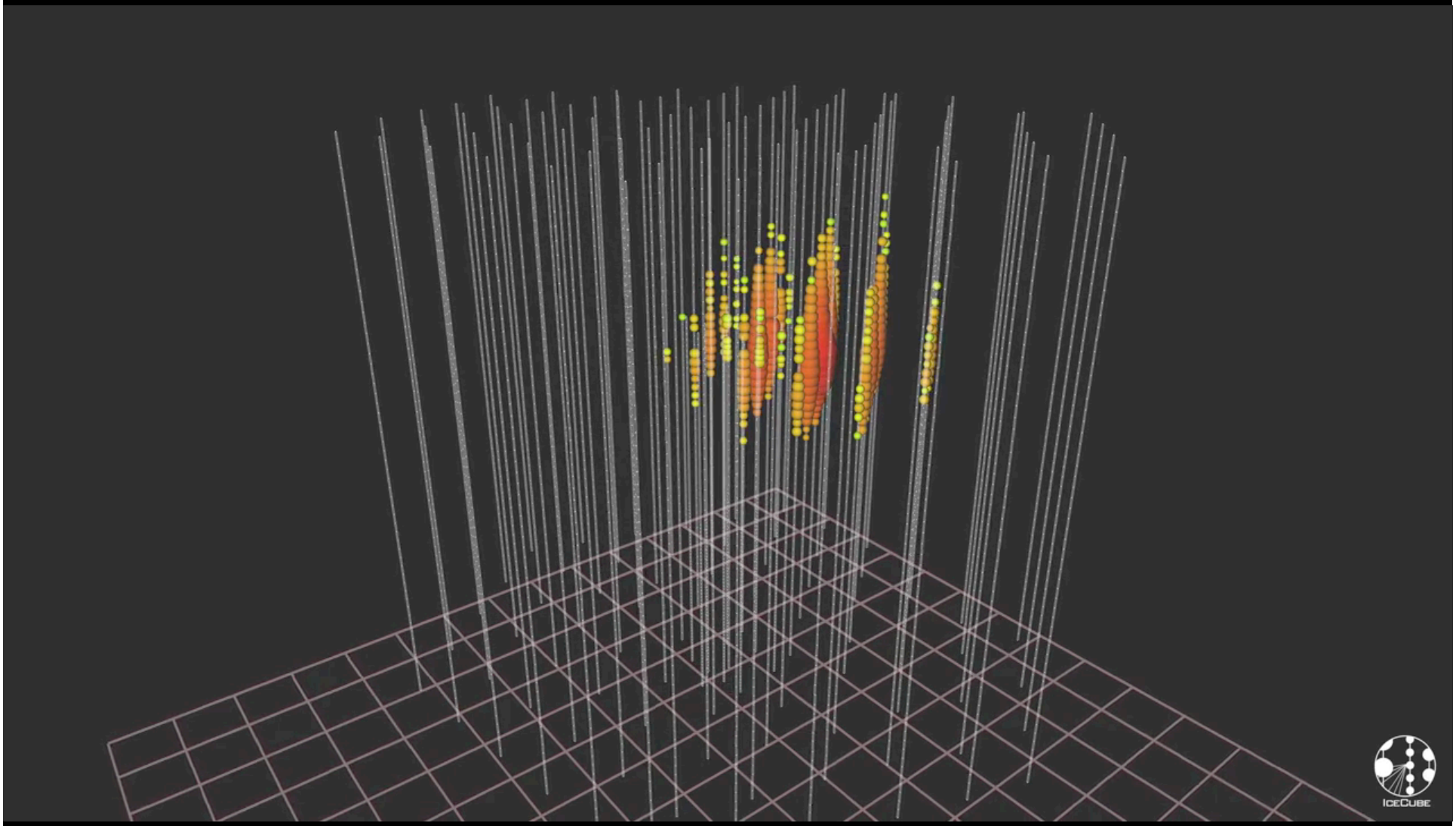


Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

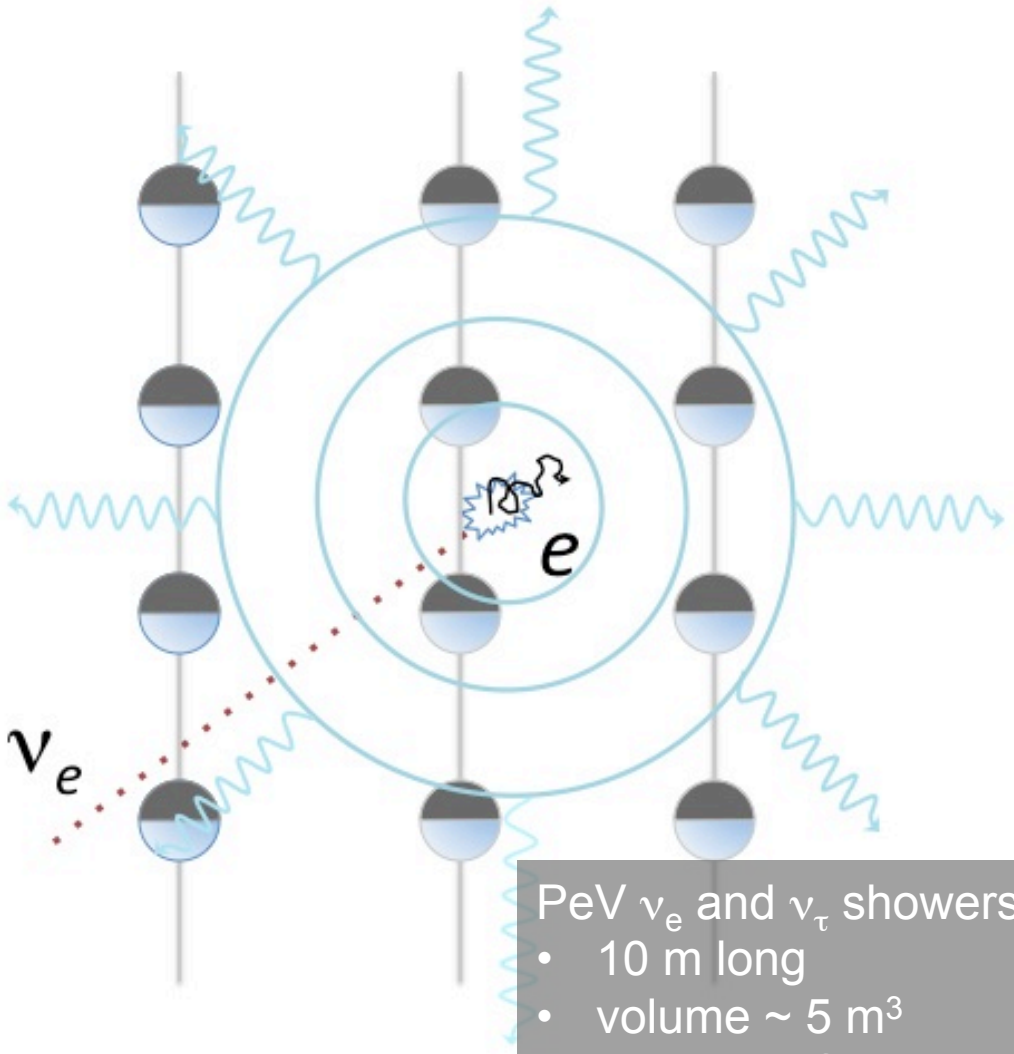
- Optimization based MC and MC verification based on 10% experimental 'burn' sample



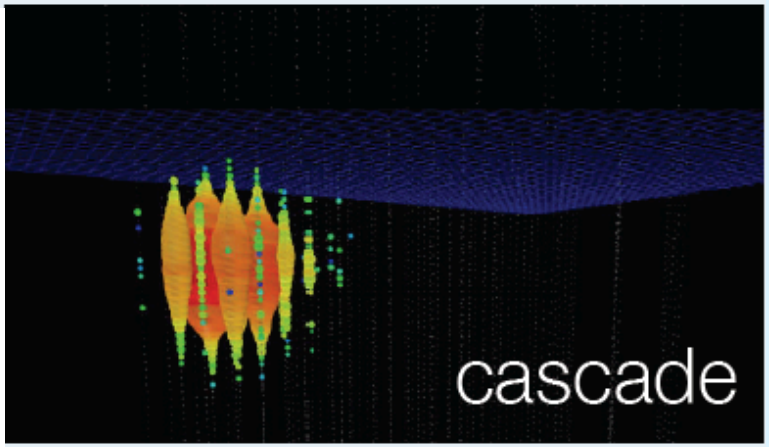
unblinding: 2 events in the signal region

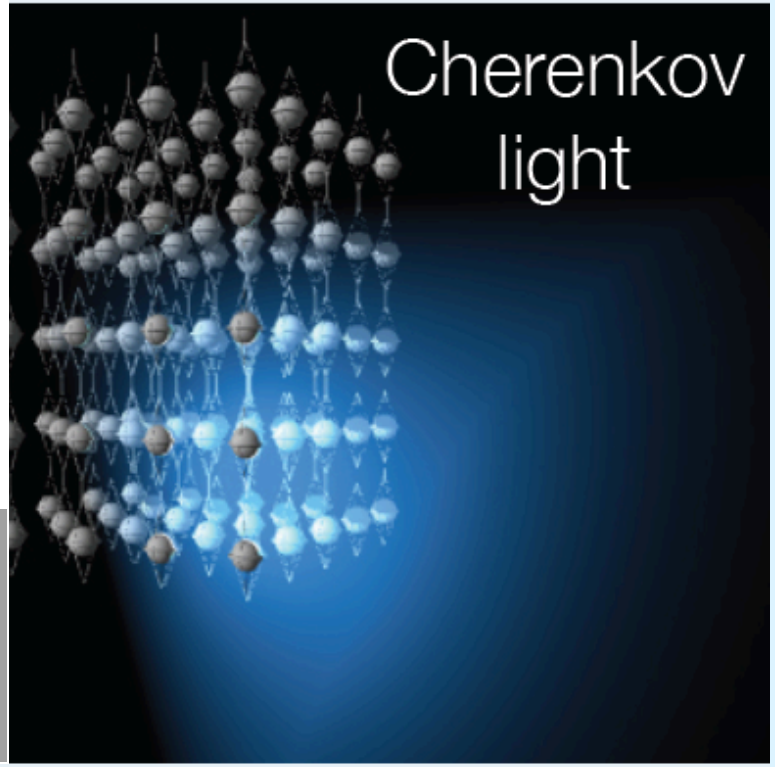

IceCube

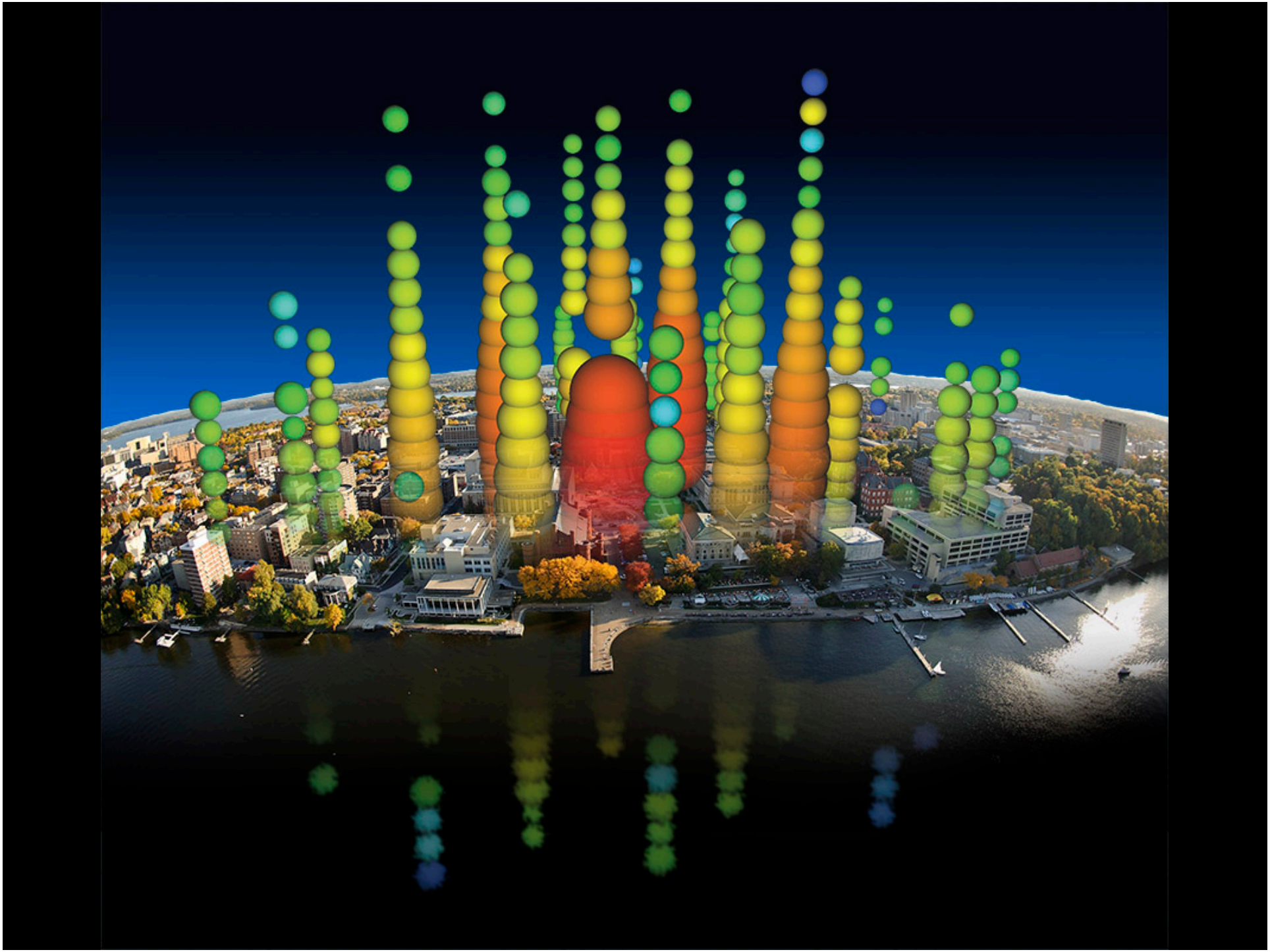
tracks and showers

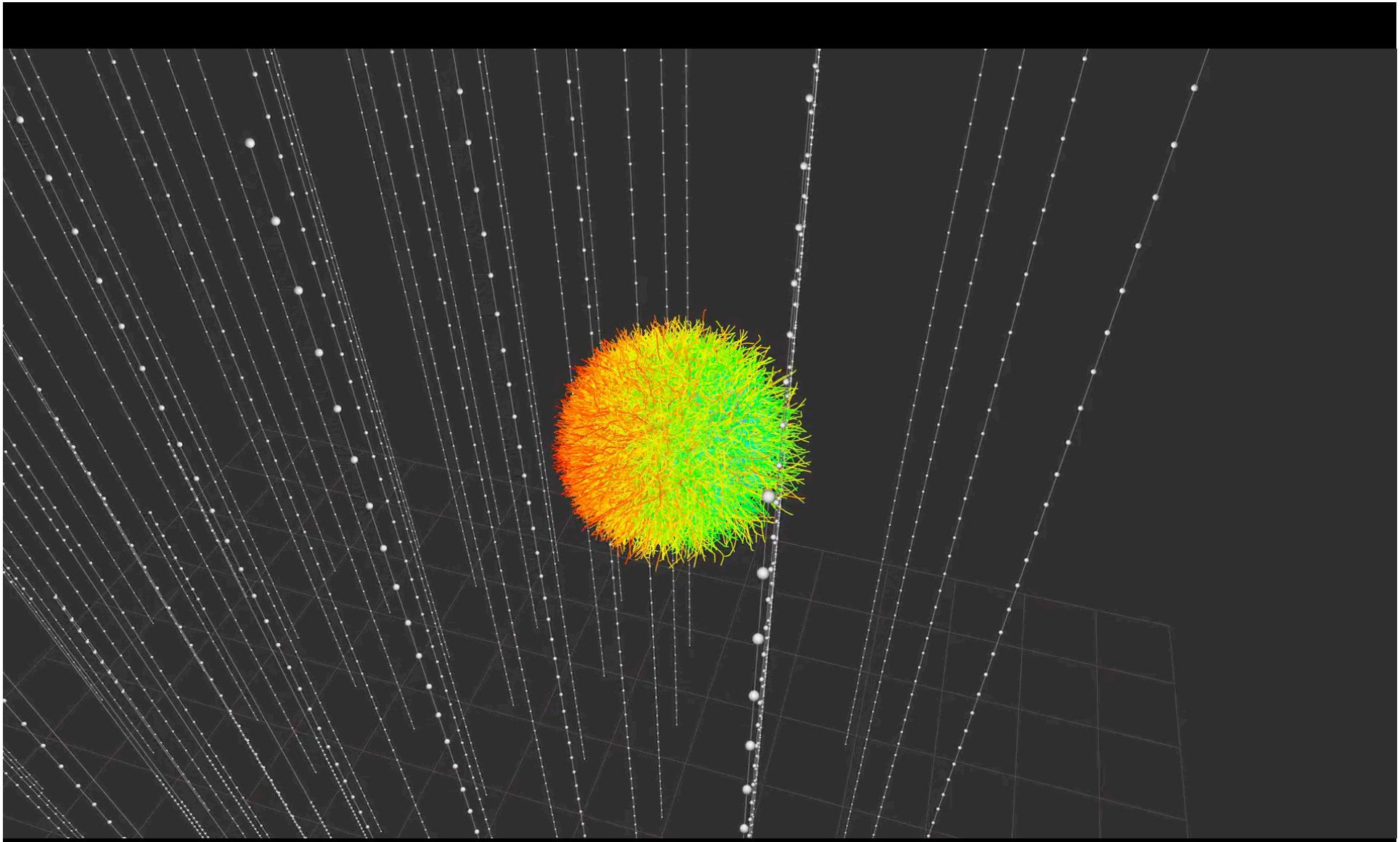


PeV ν_e and ν_τ showers:
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



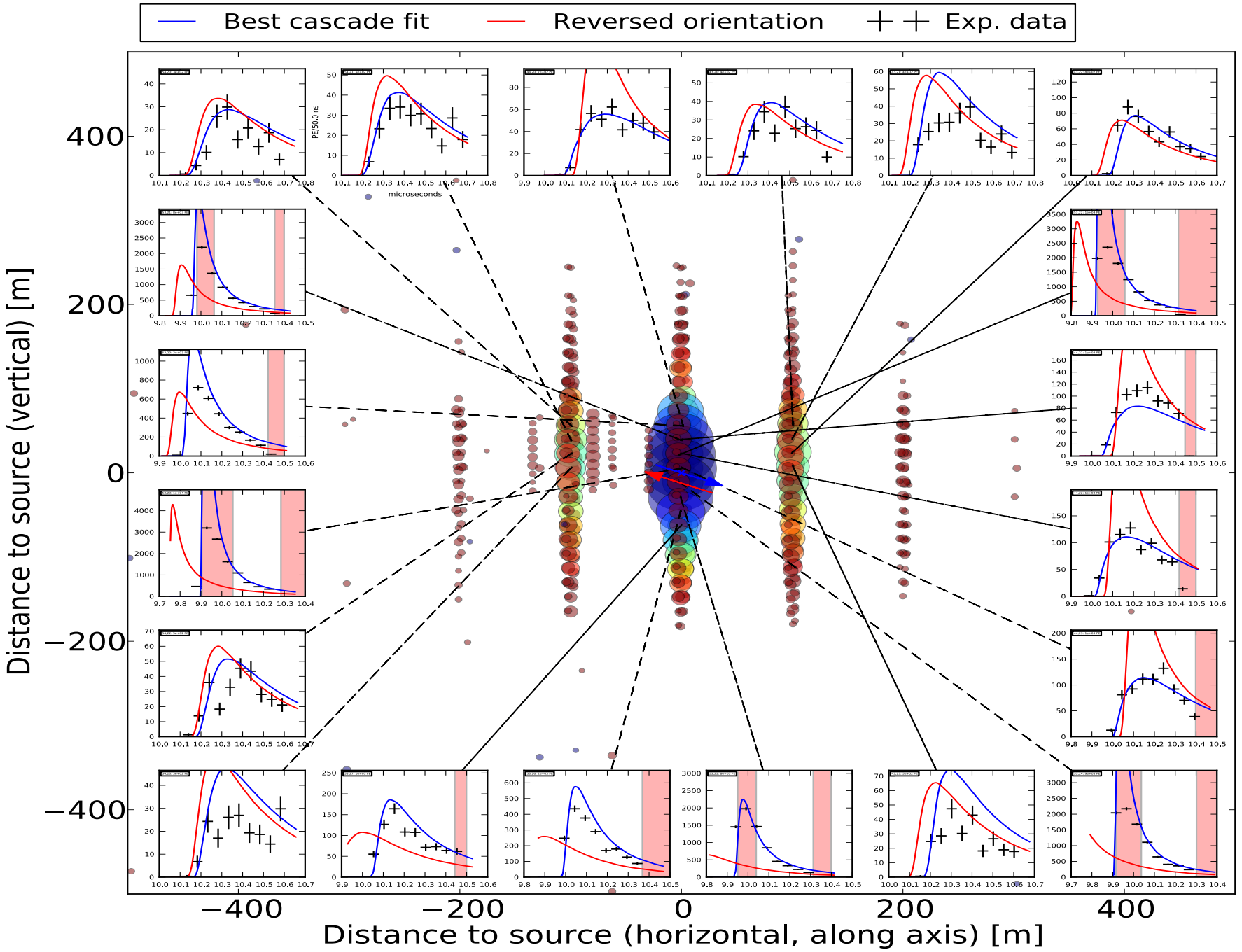




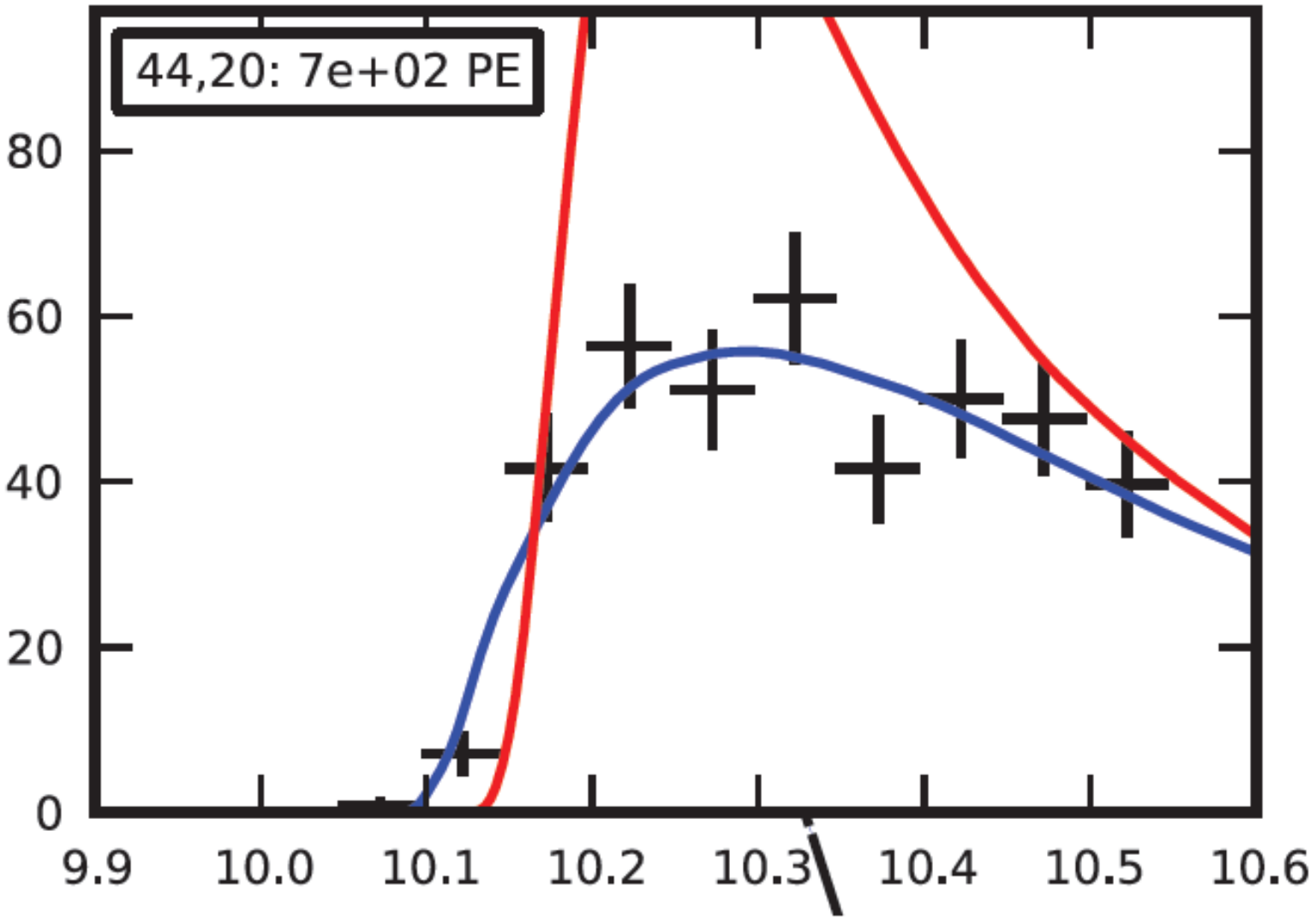


size = energy

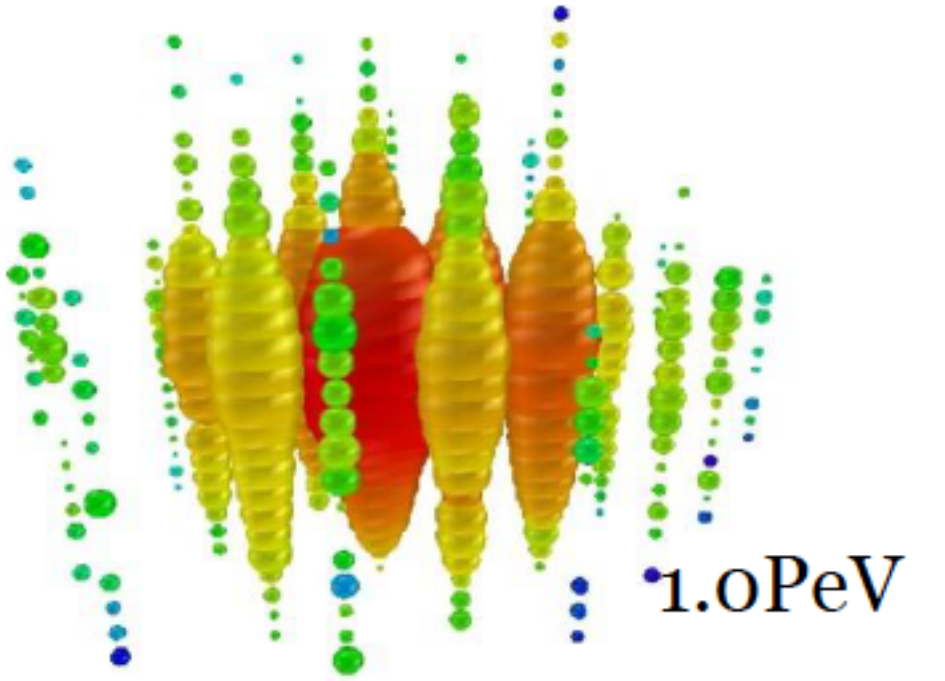
color = time = direction

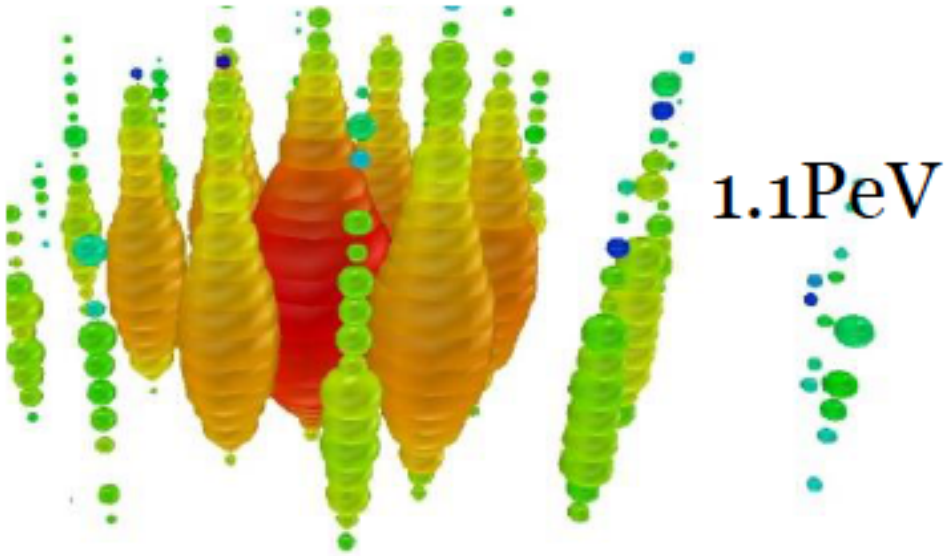

Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400
PE/50.0 ns
microseconds

digital optical module 44 on string 20 only



Blue: best-fit direction, red: reversed direction





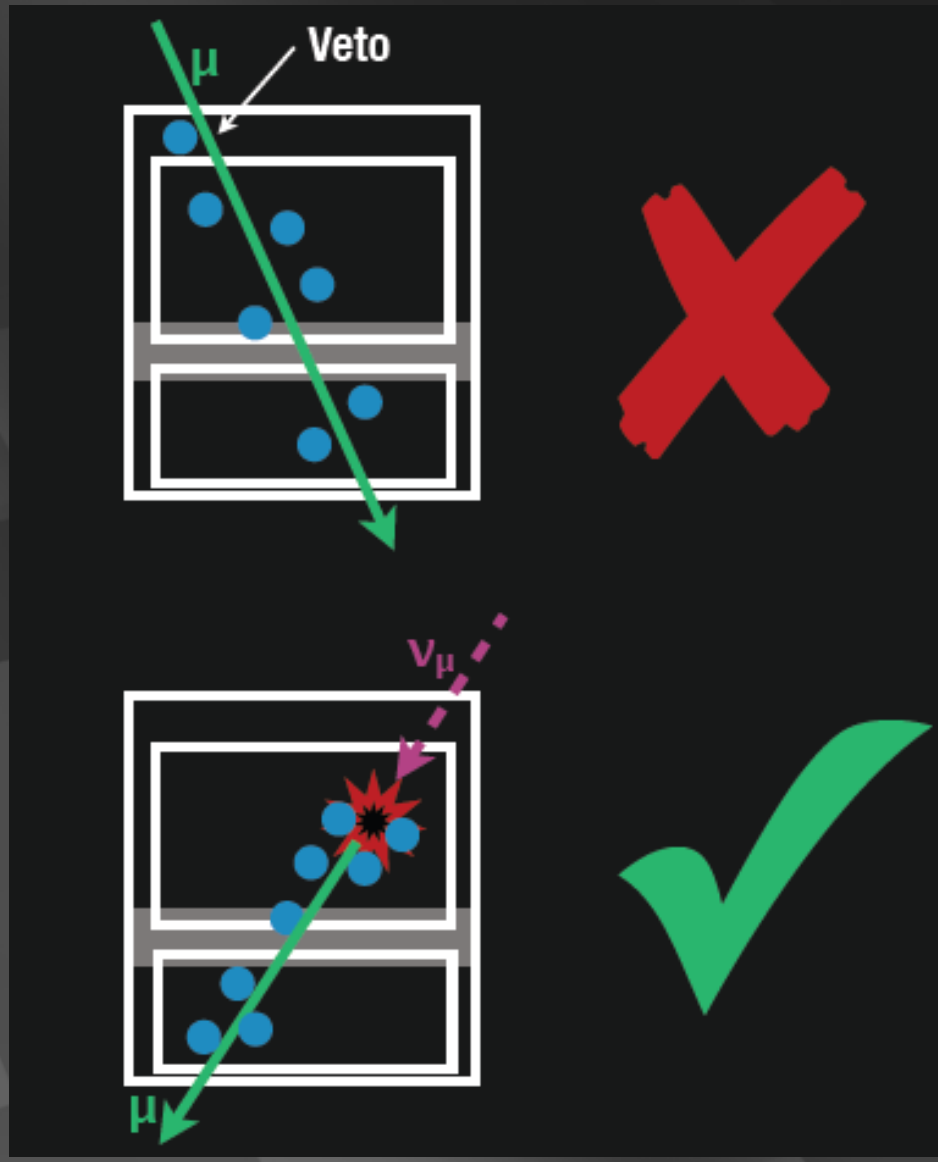
• energy

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

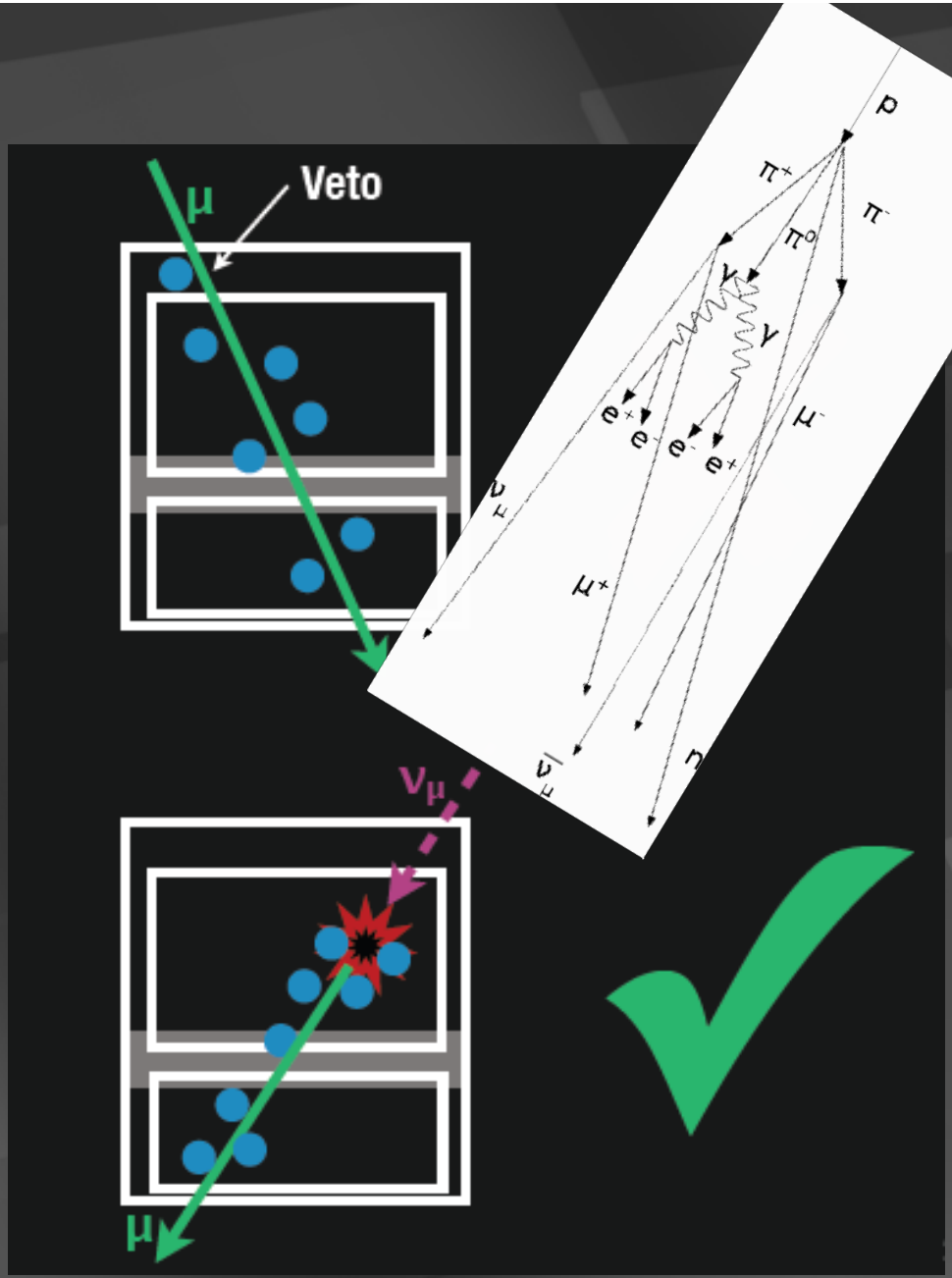
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

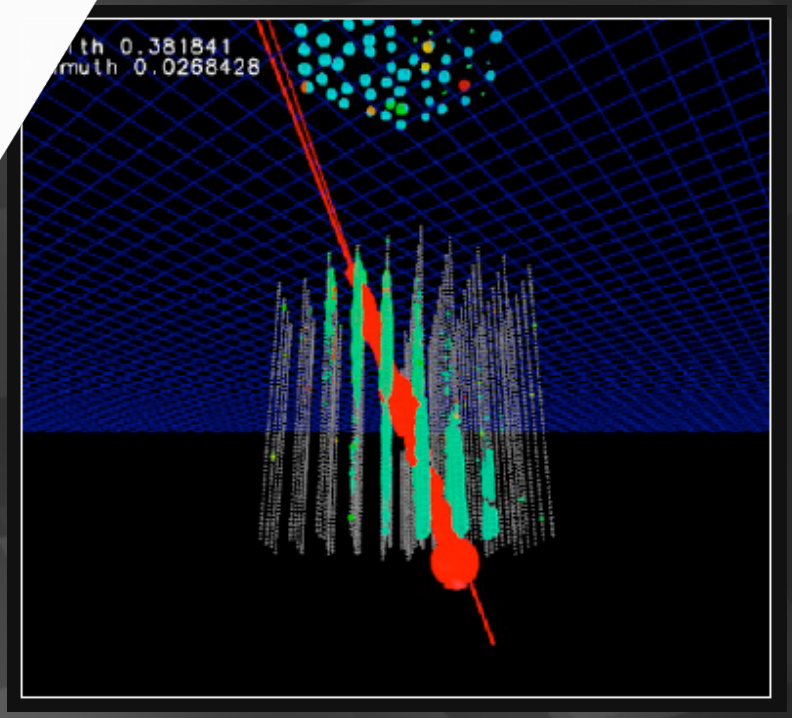
→ flux at present level of diffuse limit

- find more contained events (420 Mton)
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



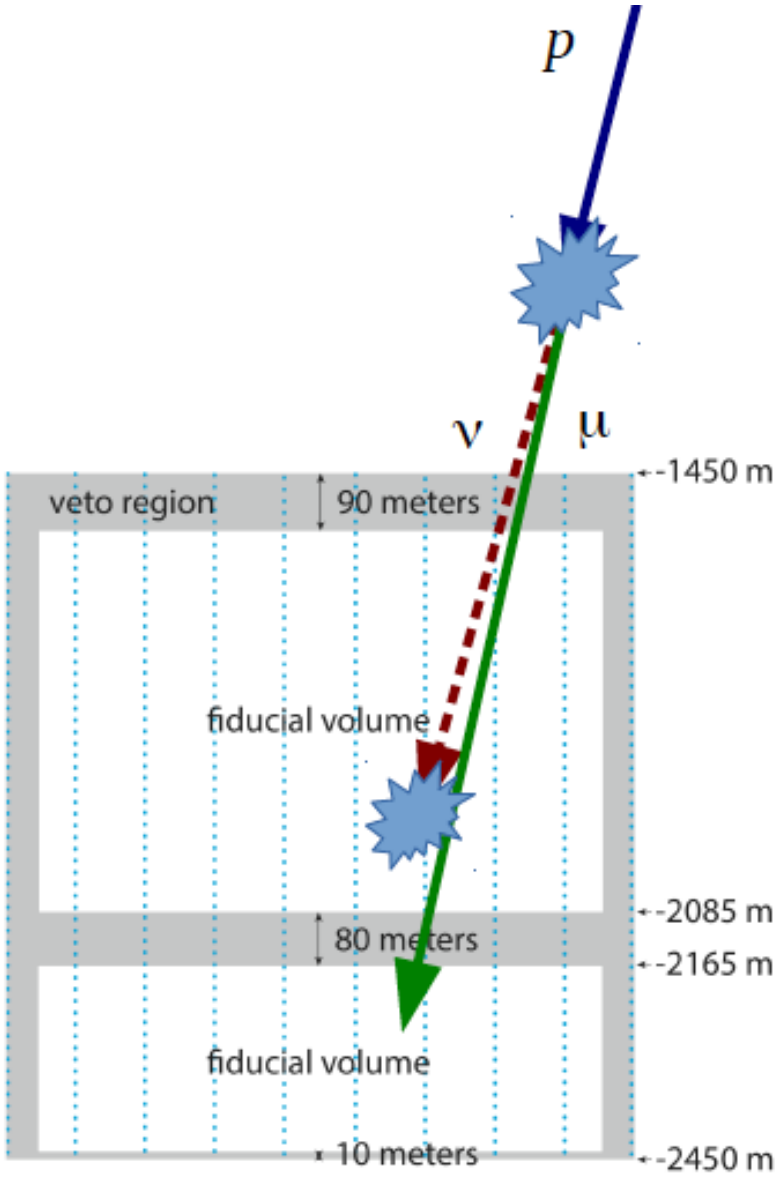
loss in statistics is compensated by event definition



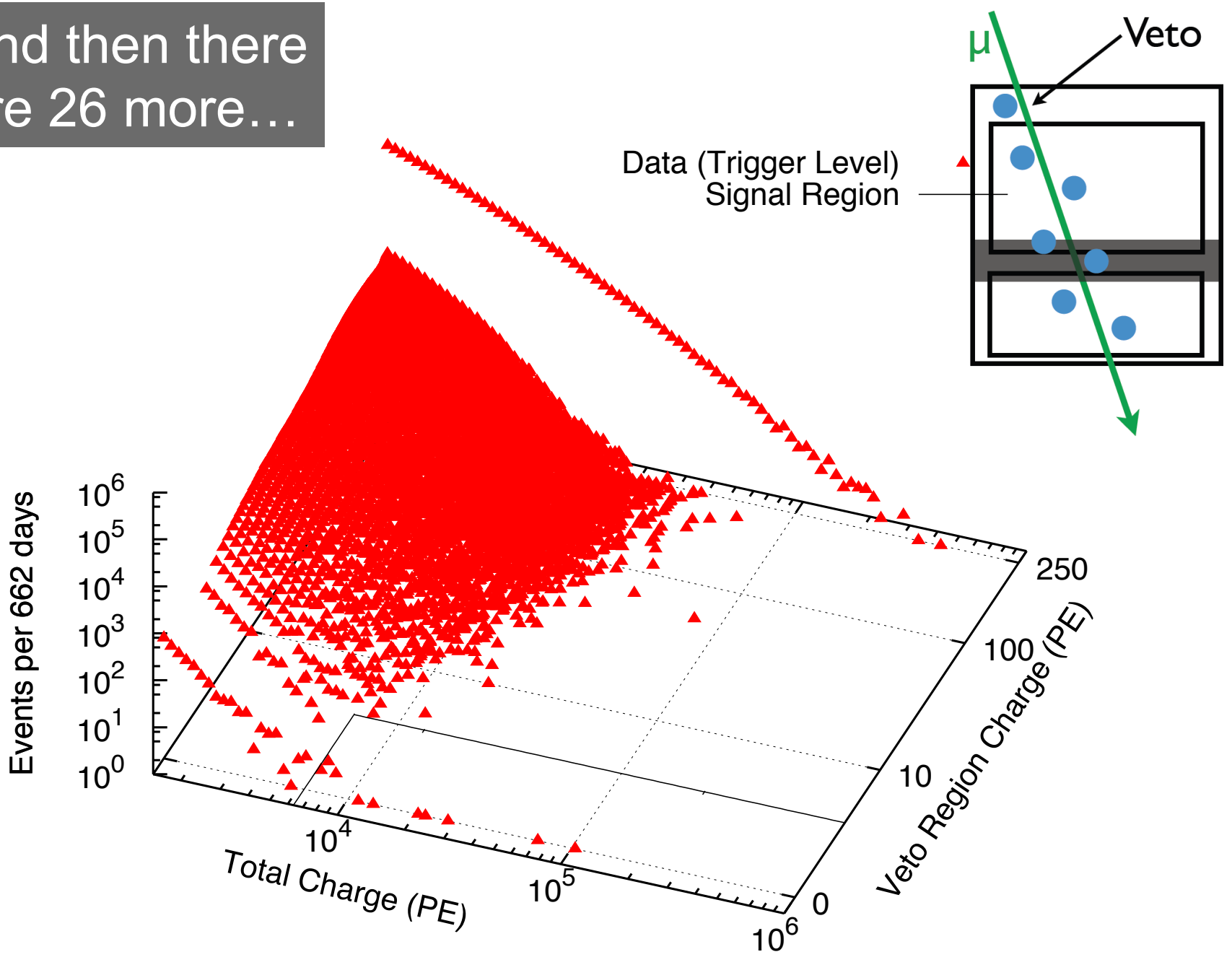


atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

(also, no signals in IceTop)

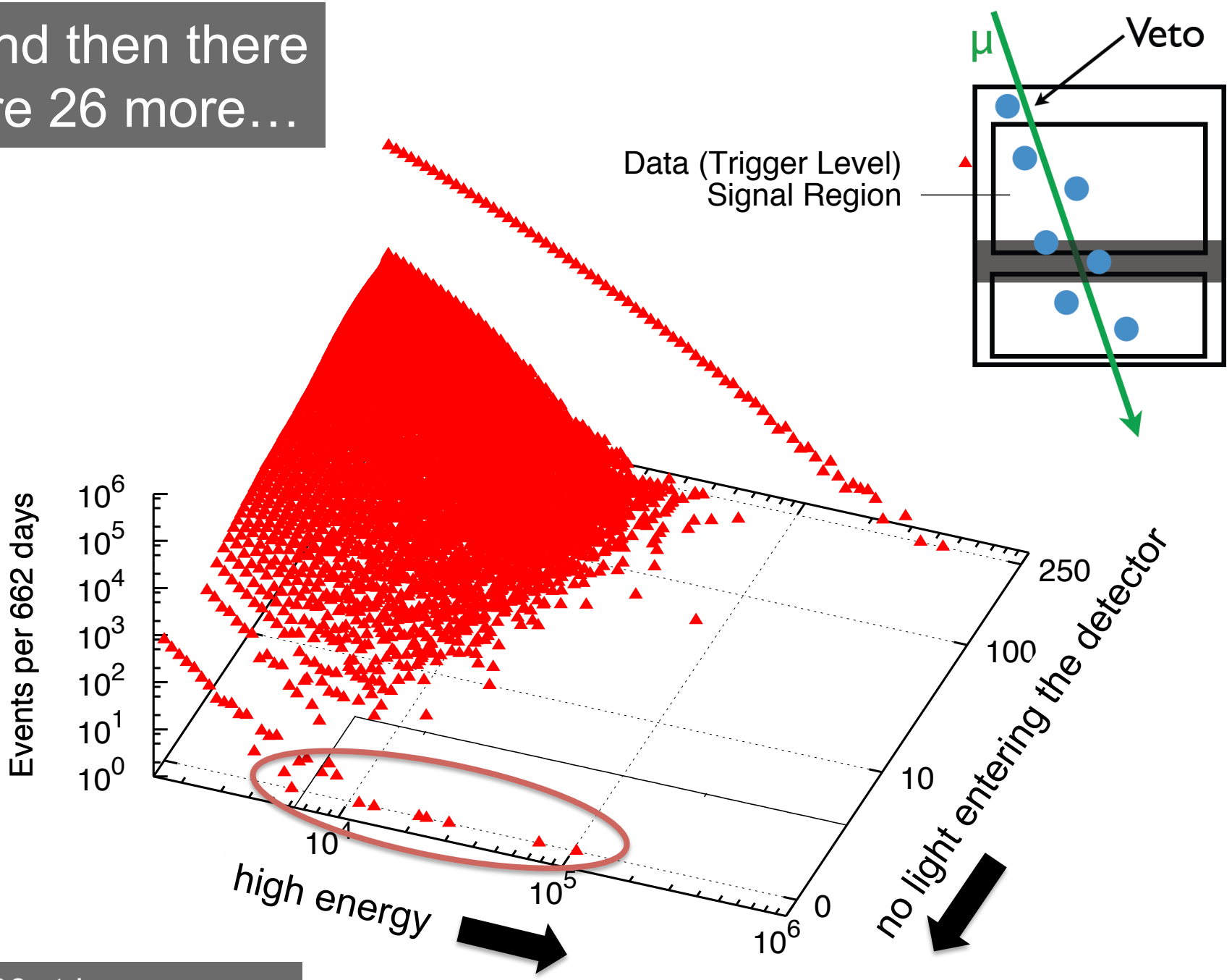

p
ν
μ
veto region
90 meters
-1450 m
fiducial volume
-2085 m
80 meters
-2165 m
fiducial volume
10 meters
-2450 m

…and then there were 26 more…



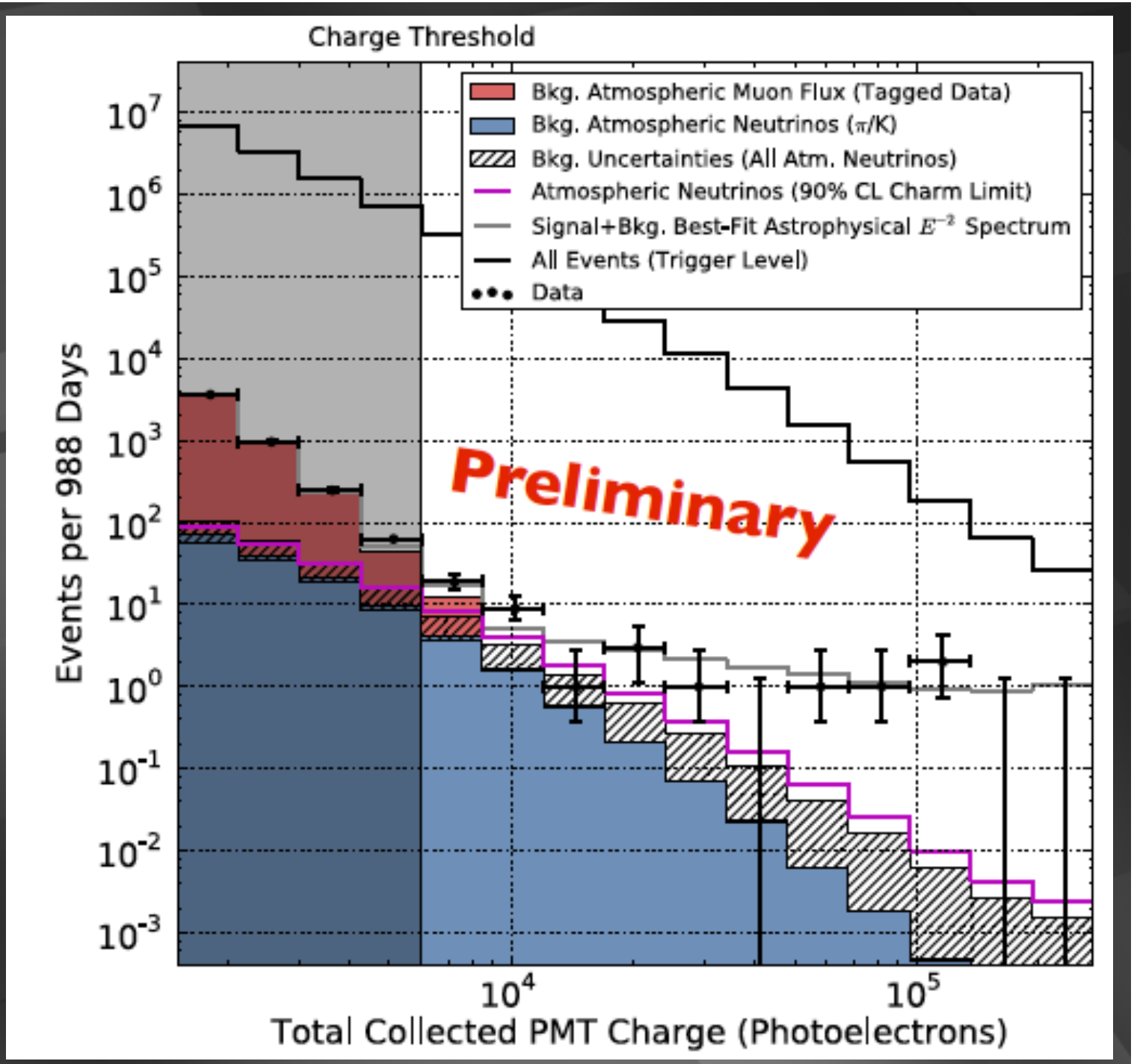
data: 86 strings one year

…and then there were 26 more…

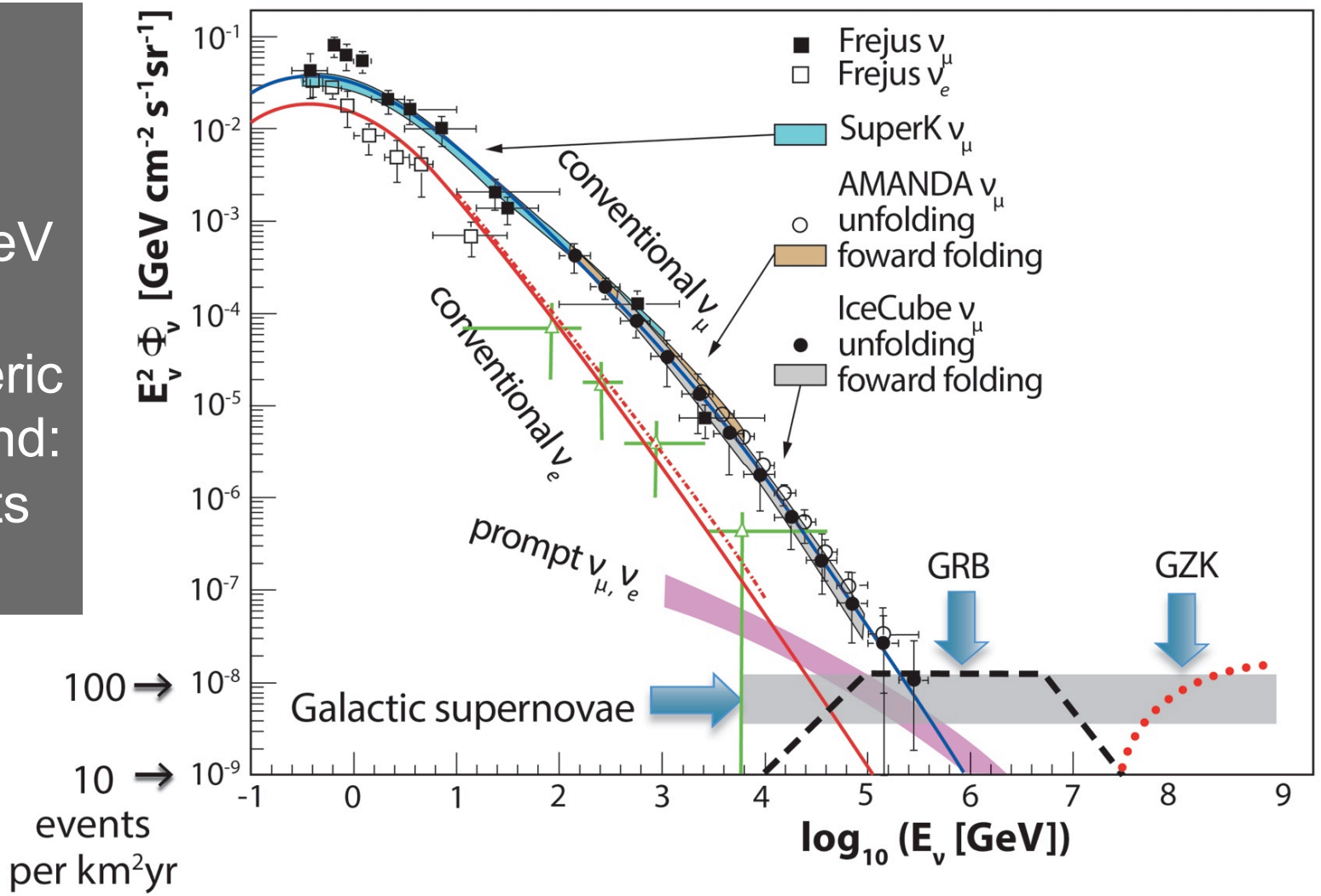


data: 86 strings one year

total charge collected by PMTs of events with interaction inside the detector

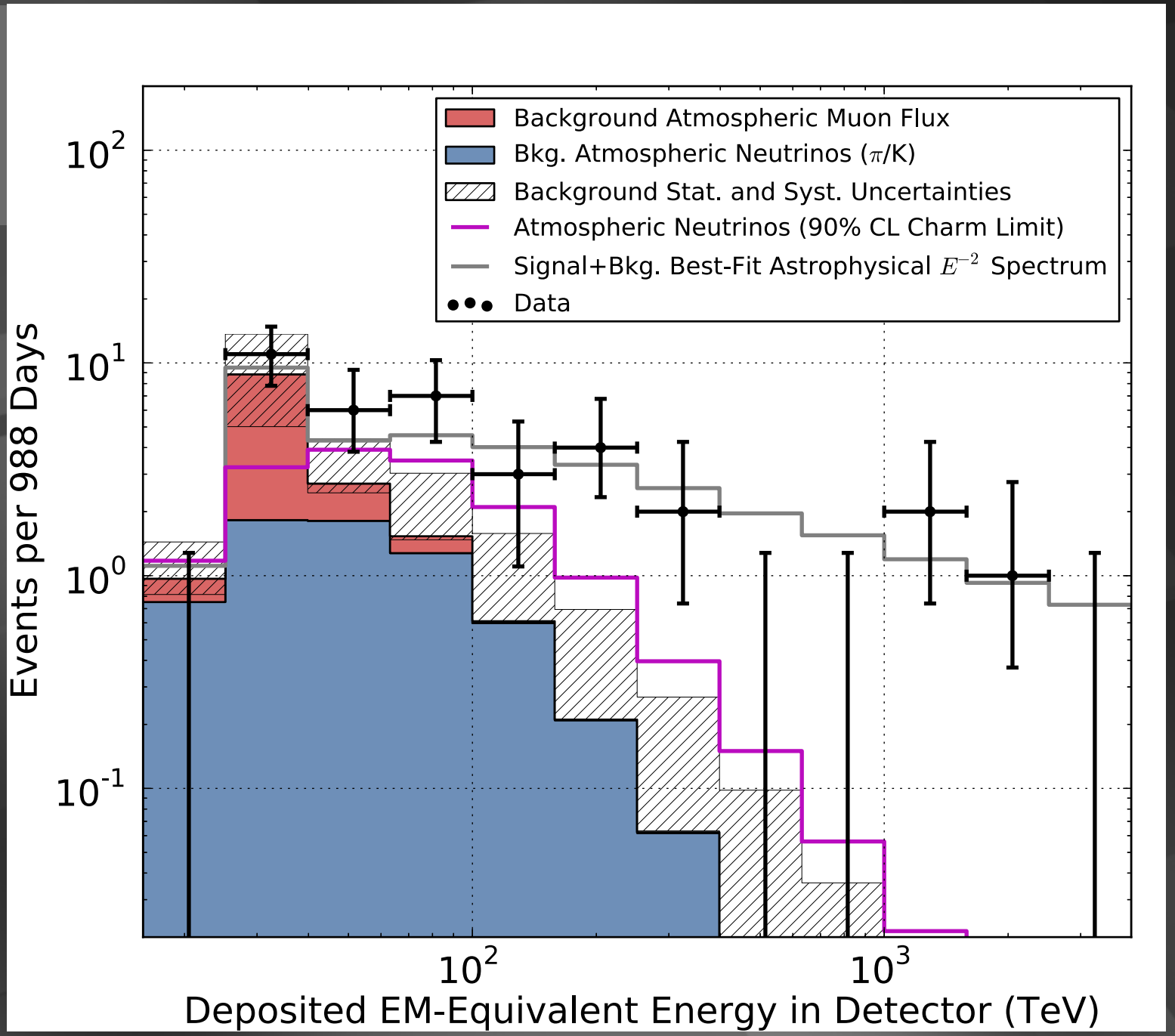


- cosmic neutrinos: energy
  > 60 TeV
- atmospheric background: 1~2 events per year

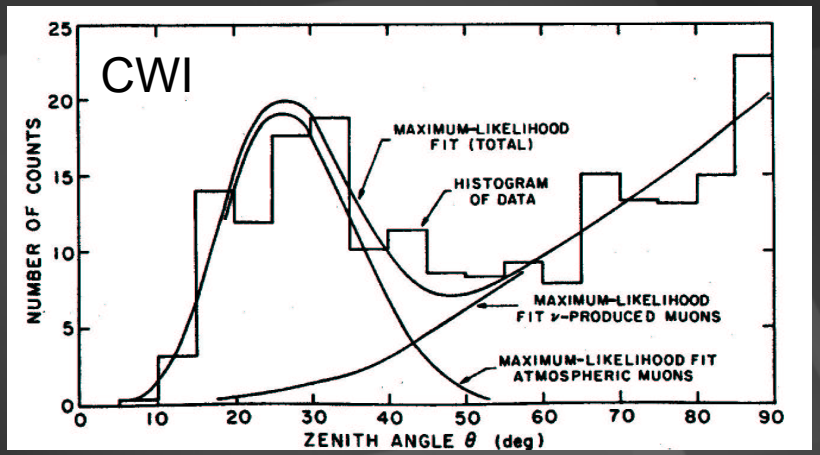


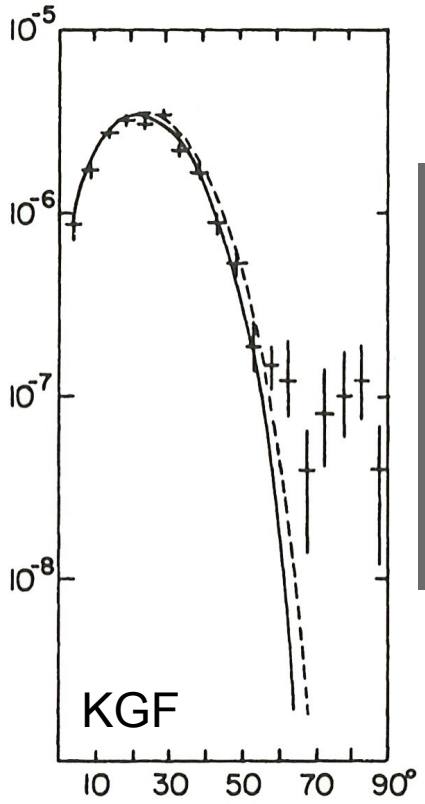
atmospheric ⇑ cosmic

3 years
astro-ph
1405.5303



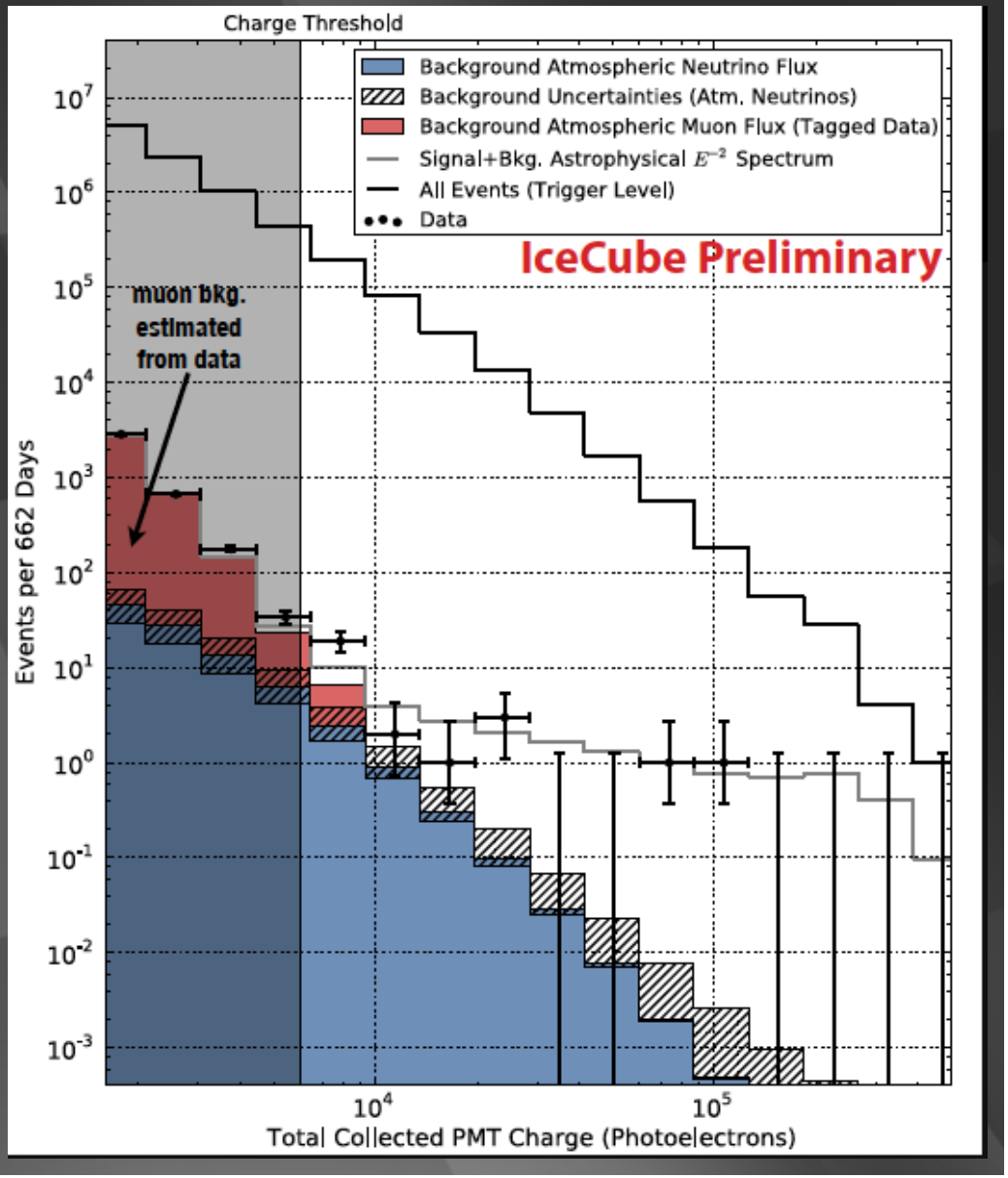
2013 atmospheric and cosmic neutrinos

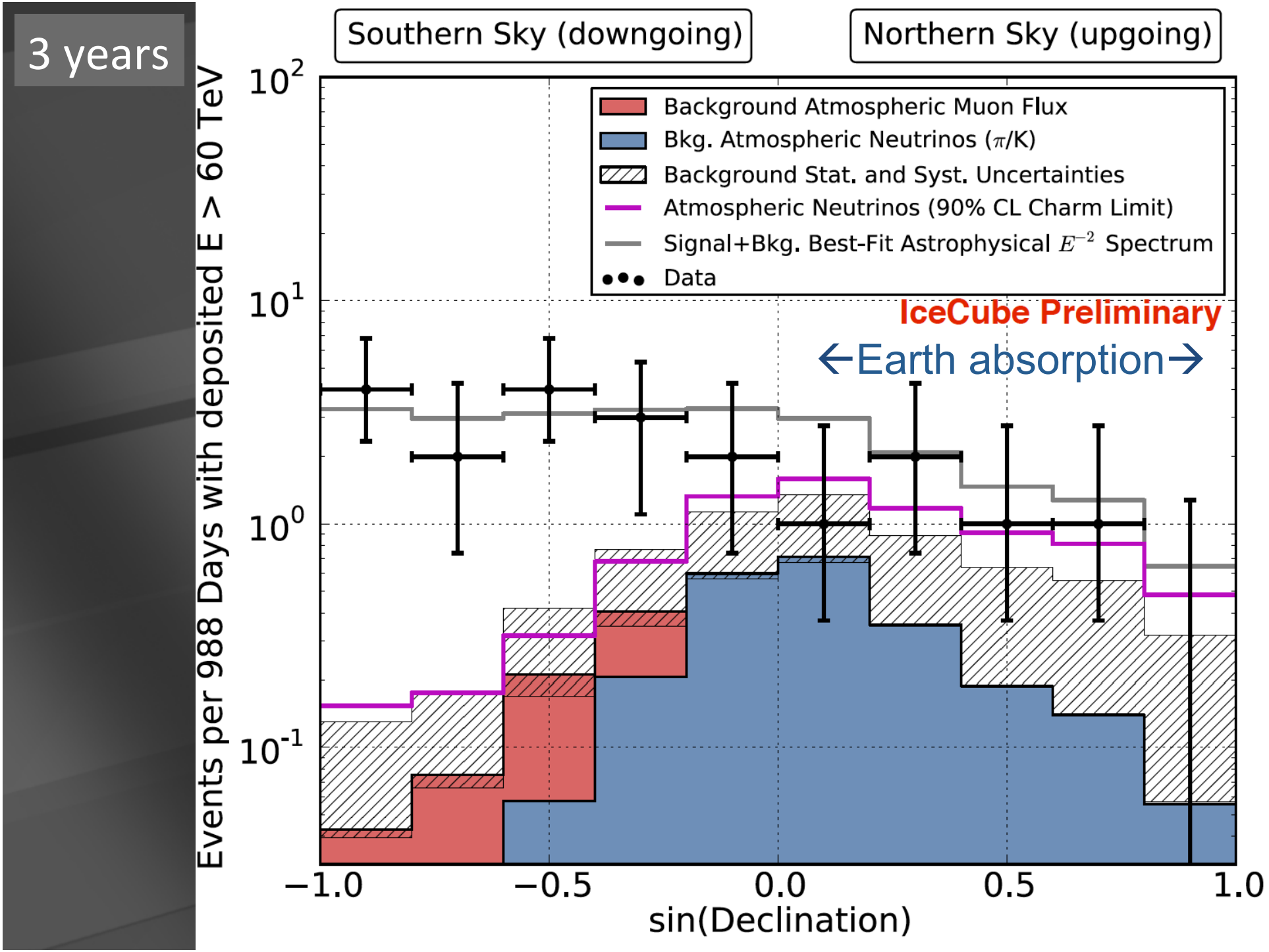


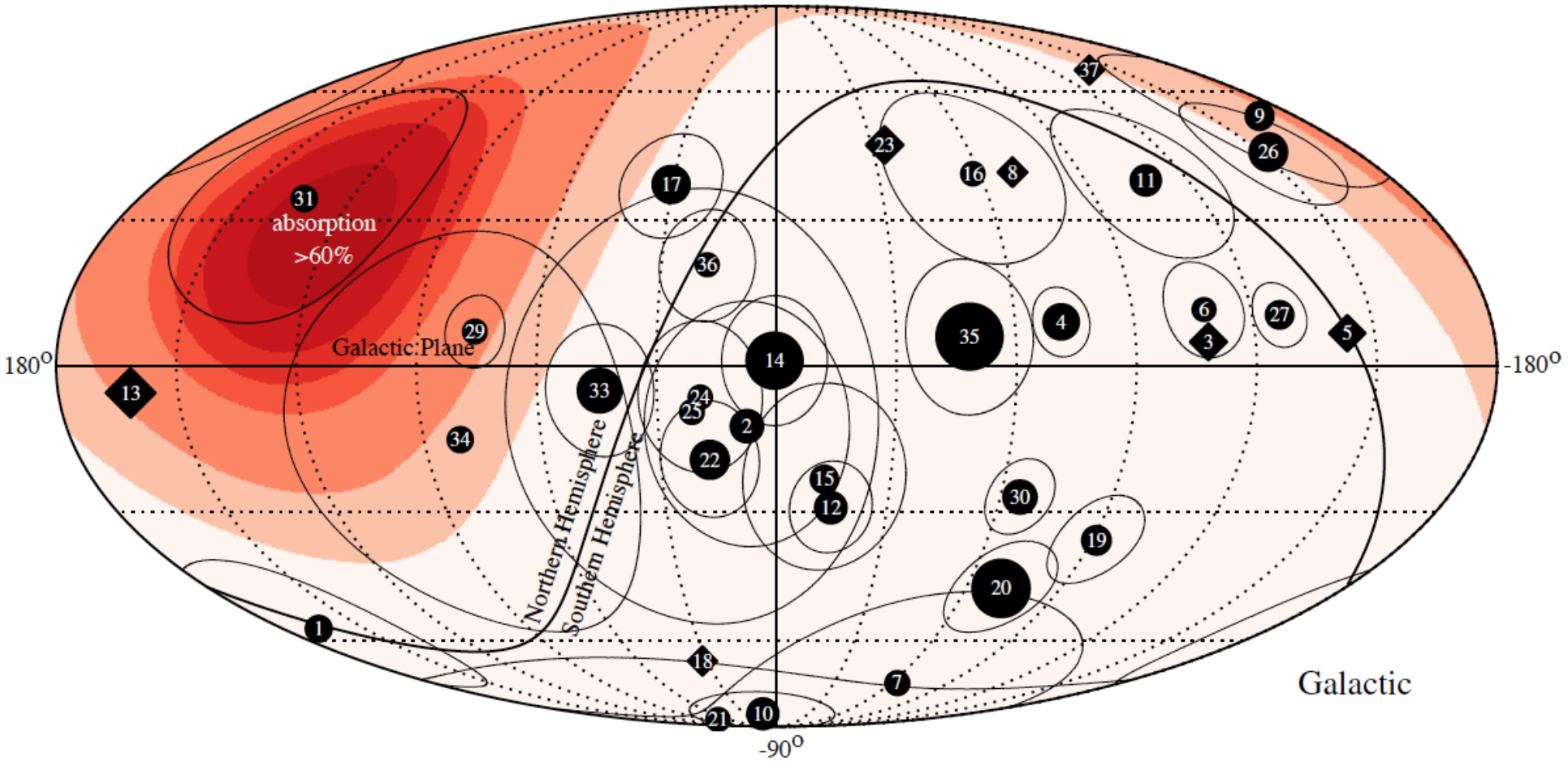


1965

cosmic ray muons and atmospheric neutrinos




3 years
Southern Sky (downgoing)
Northern Sky (upgoing)
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
IceCube Preliminary
←Earth absorption→
Events per 988 Days with deposited E > 60 TeV
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)



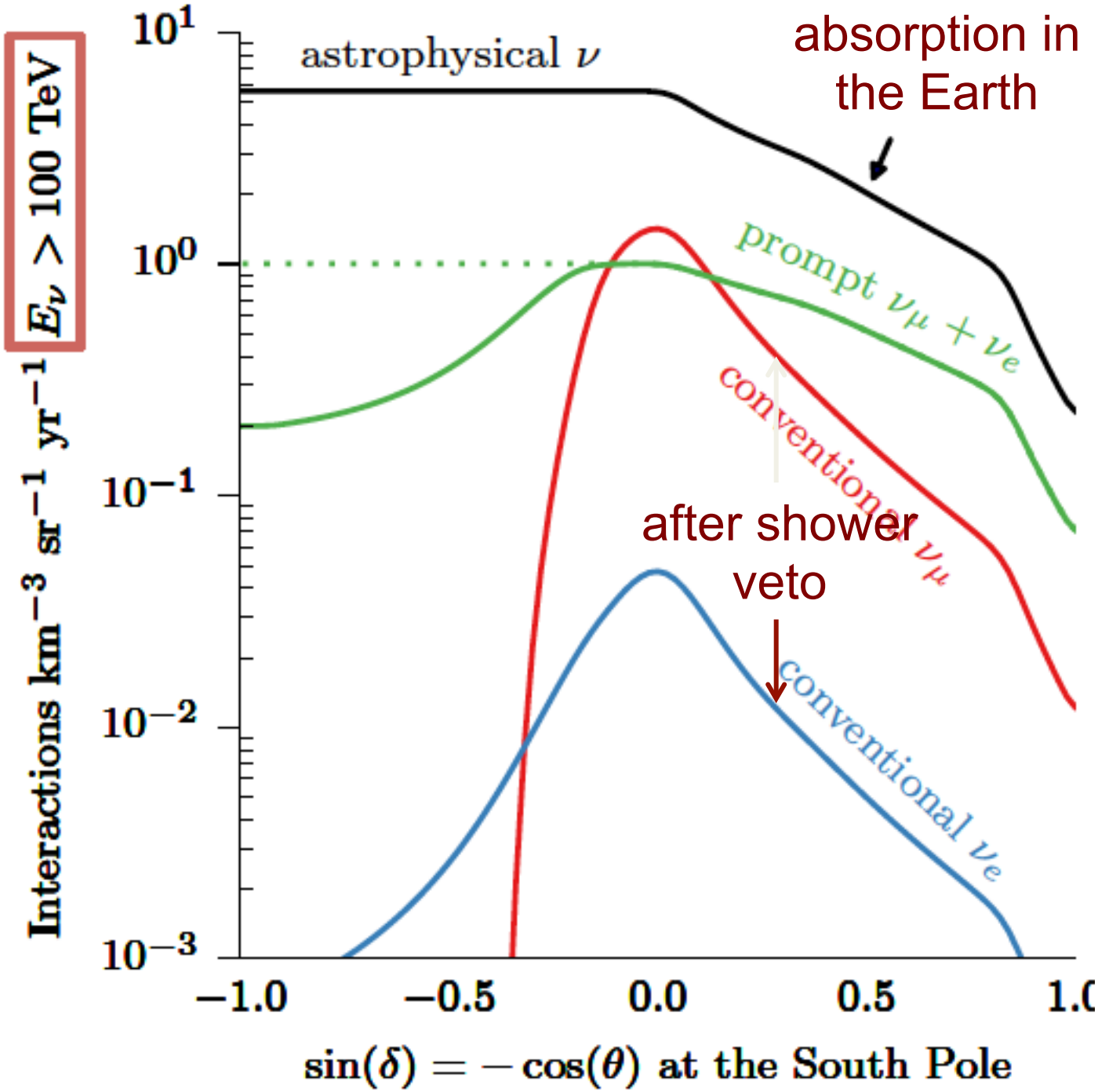
diamonds: muon tracks (0.4 degree resolution)

circles : electromagnetic showers

: energy

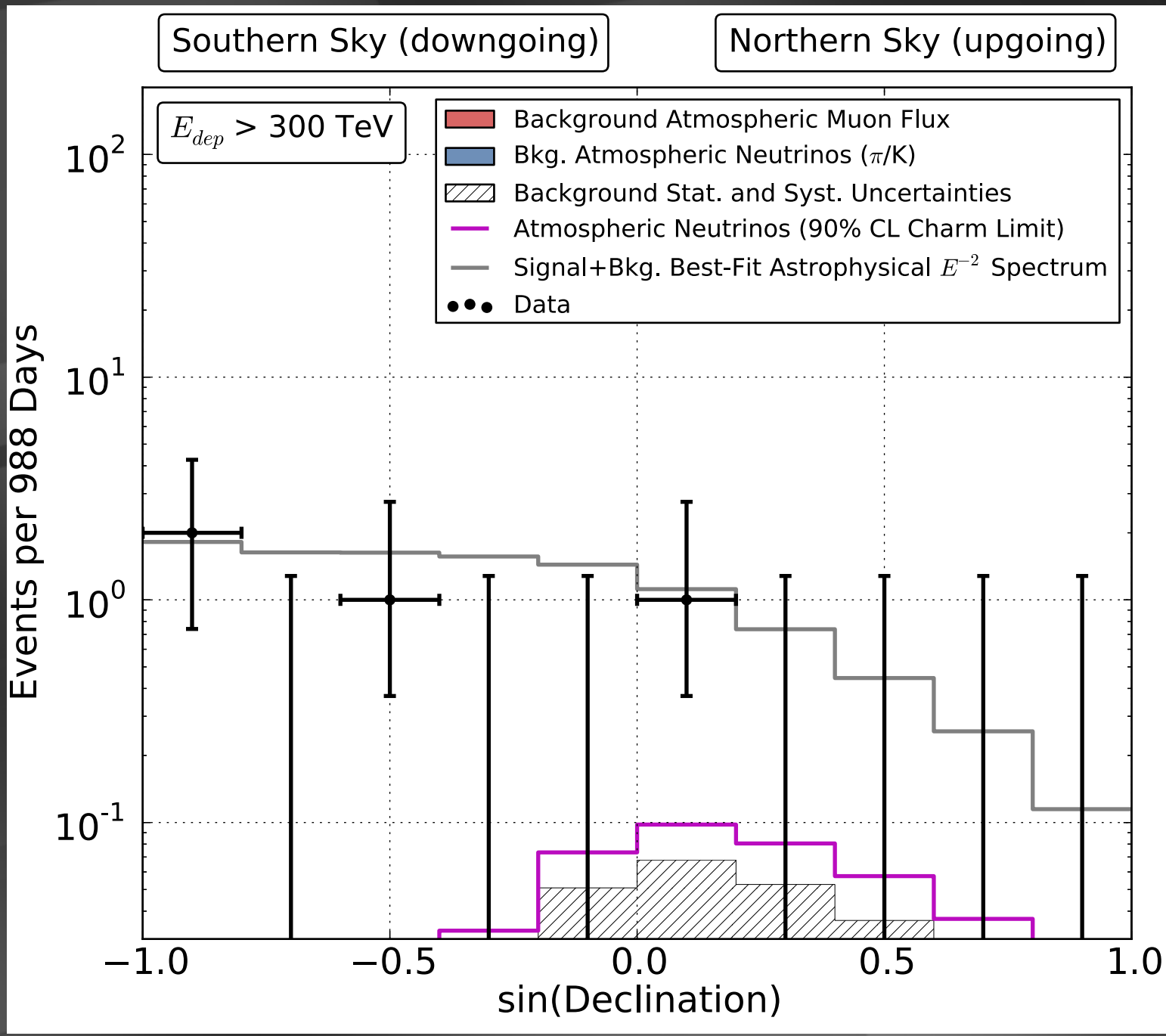
: angular resolution

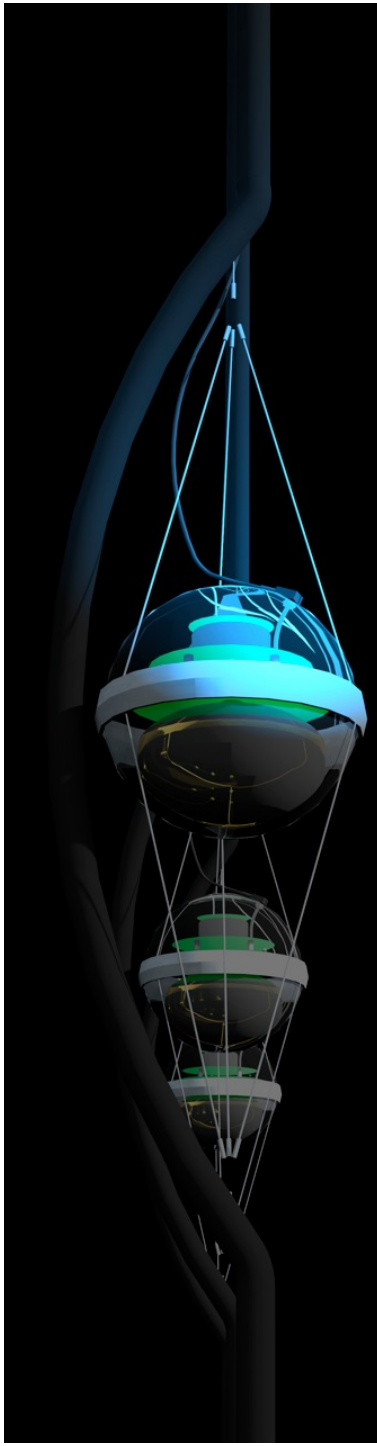
agrees with signal, not background



same plot animated:

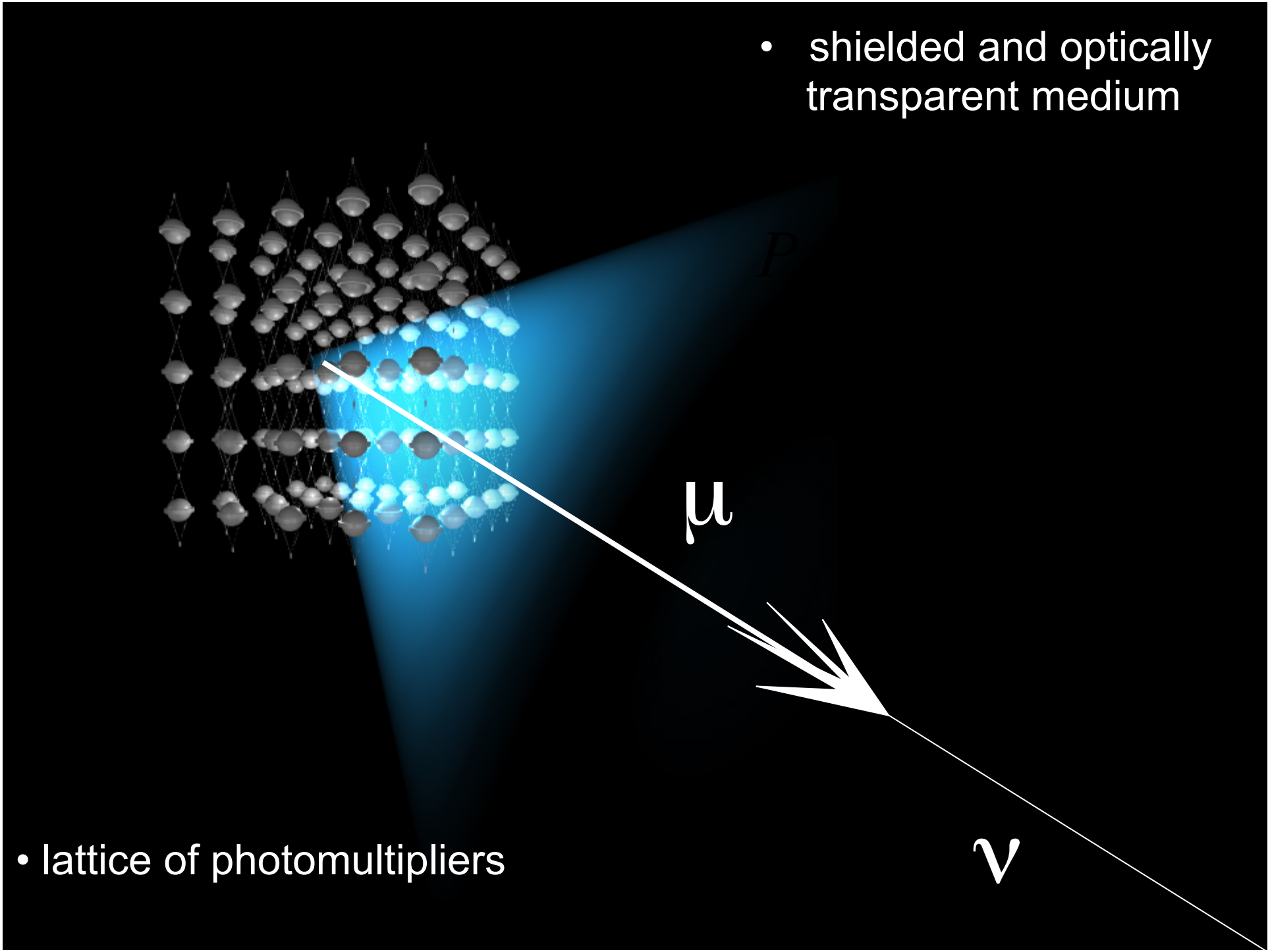
- events versus background as a function of energy
- cuts from > 30 TeV (all events) to until only PeV events remain
- background disappears ~ 60 TeV


Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 300 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

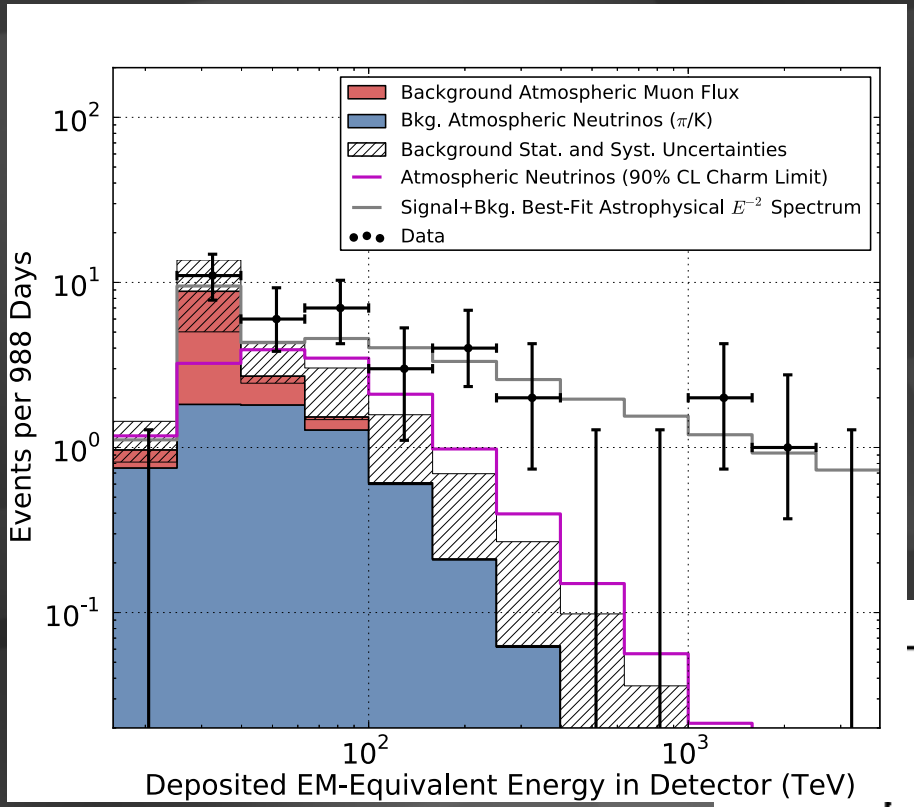


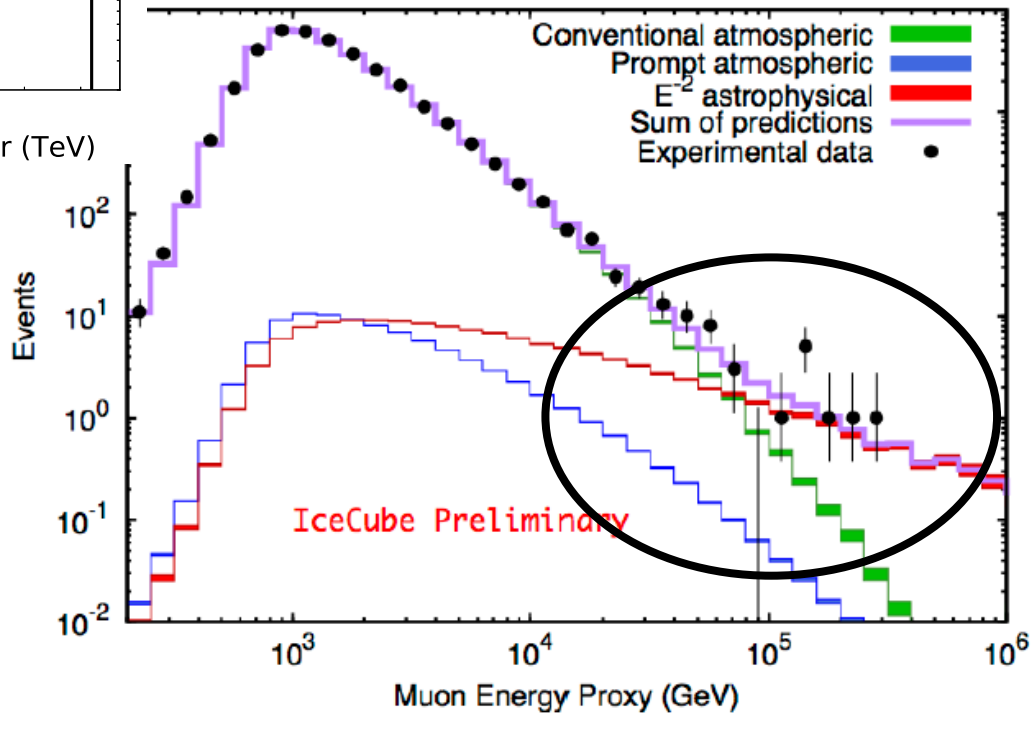
icebound neutrinos

- confirmation ?


• shielded and optically transparent medium
μ
ν
• lattice of photomultipliers

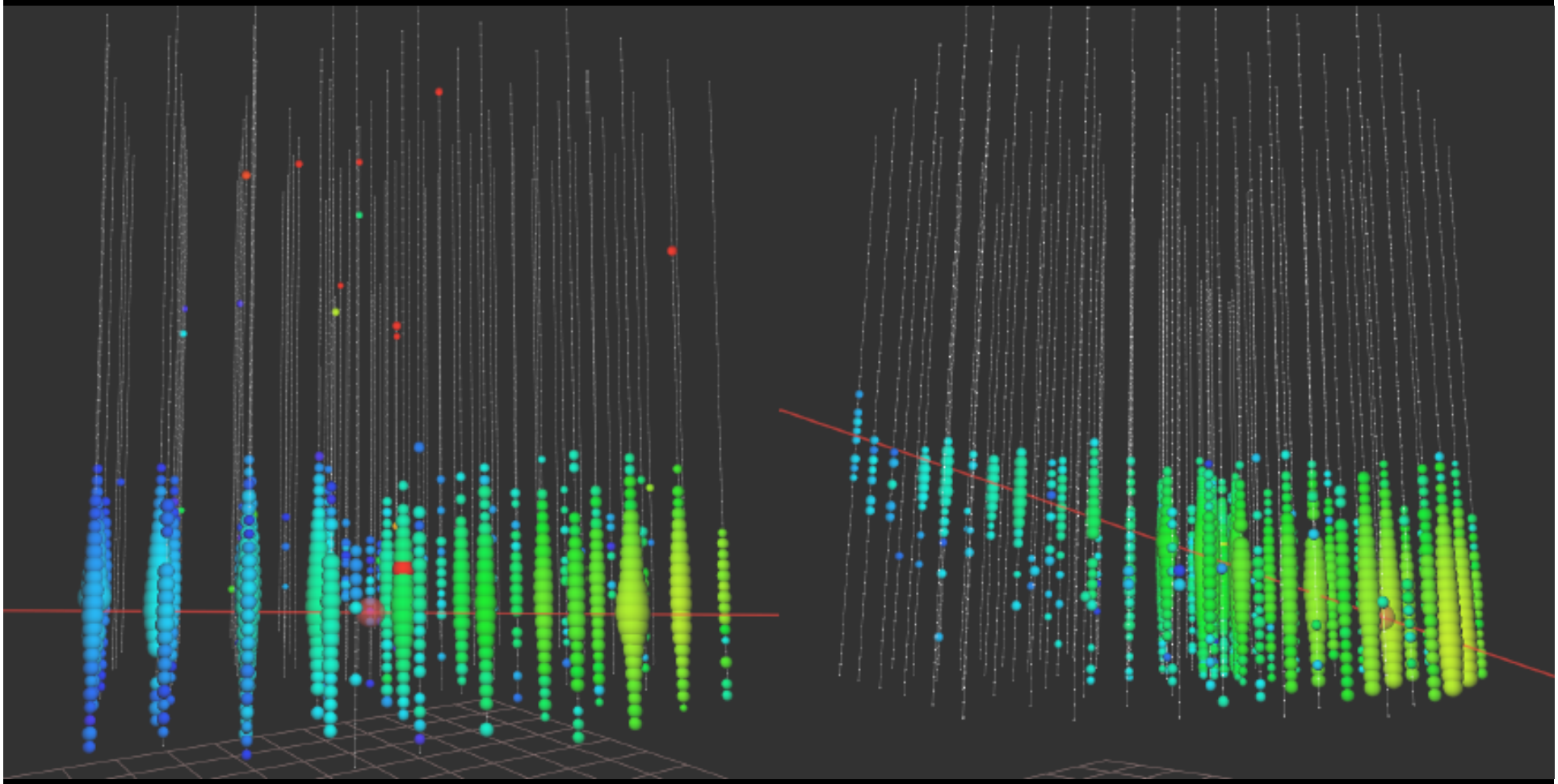
confirmation!
flux of muon neutrinos
through the Earth



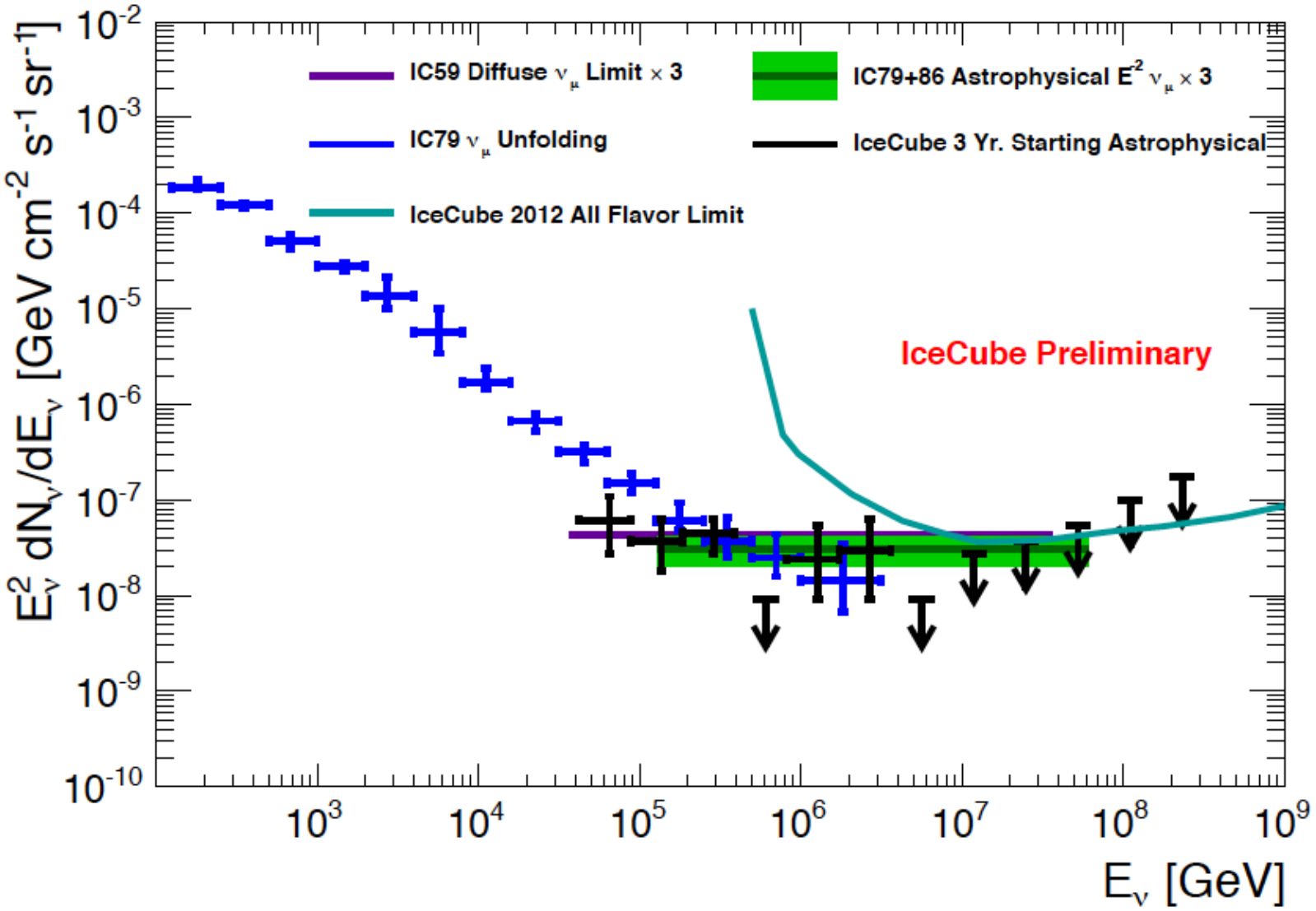


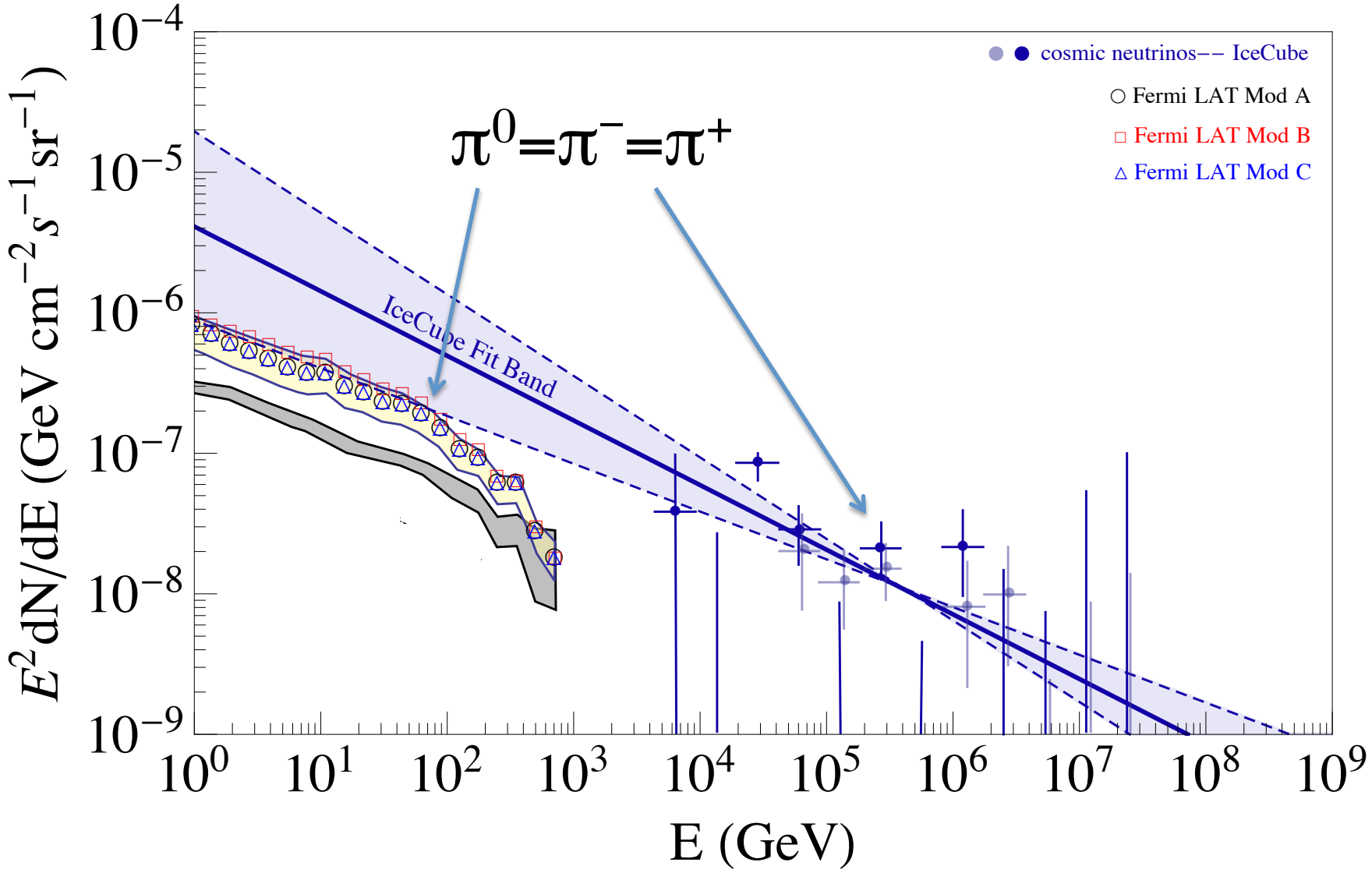
neutrinos of all flavors
interacting inside
IceCube

highest energy muon energy observed: 560 TeV
→ PeV energy neutrino



the high energy neutrino flux: atmospheric and cosmic

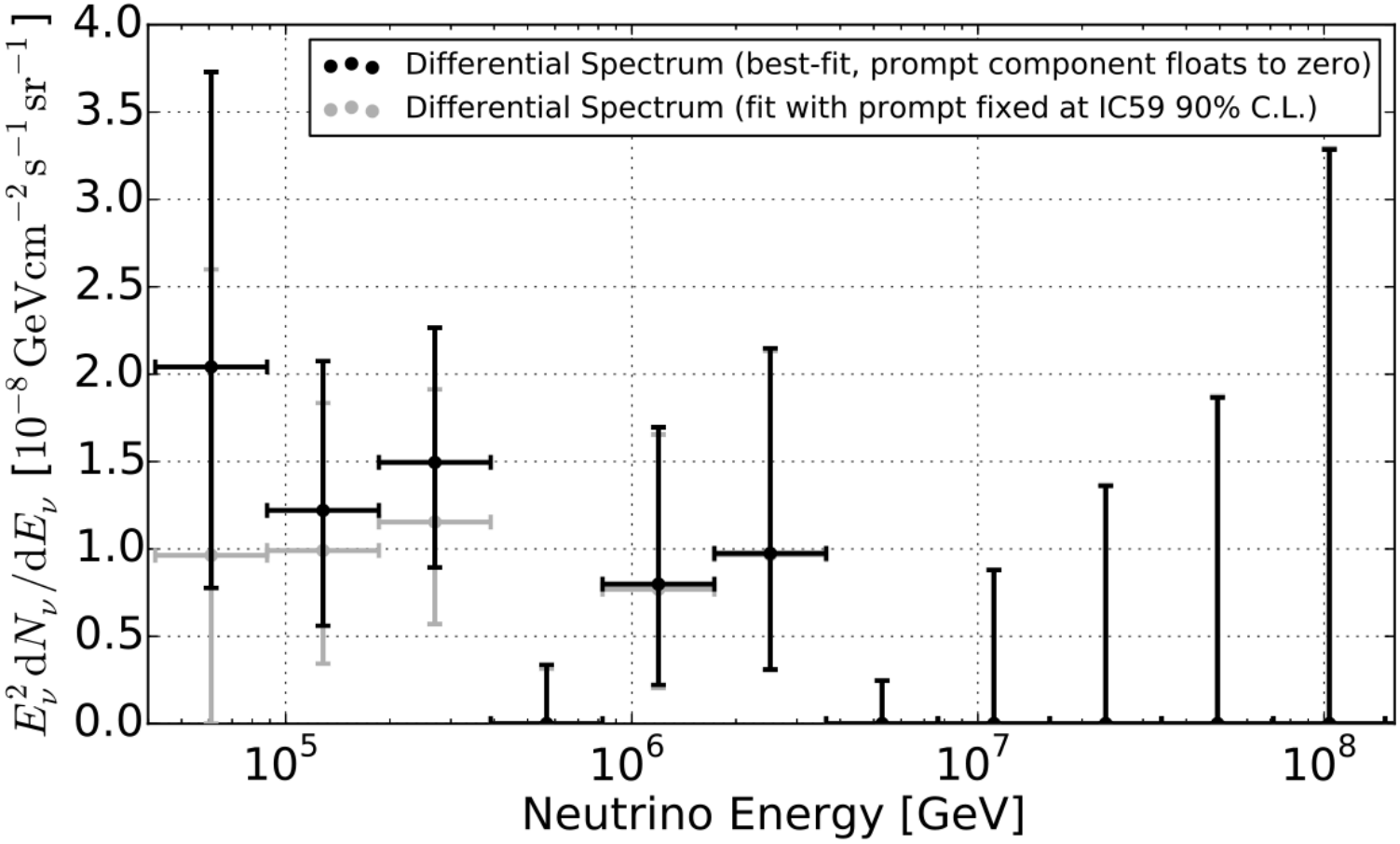



cosmic neutrinos-- IceCube
Fermi LAT Mod A
Fermi LAT Mod B
Fermi LAT Mod C
$\pi^0=\pi^-=\pi^+$
IceCube Fit Band
E^2dN/dE (GeV cm$^{-2}s^{-1}$sr^{-1})
E (GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

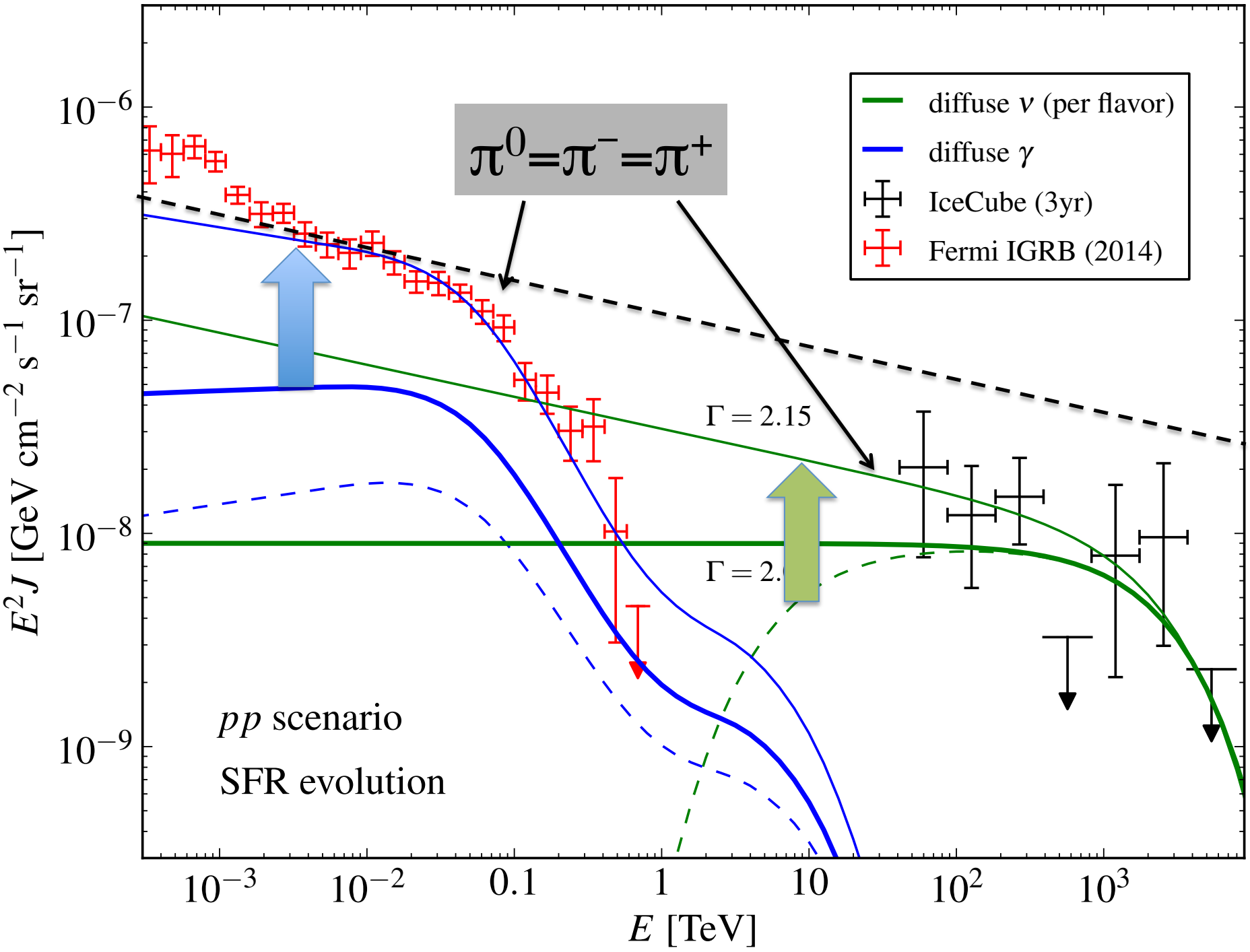
the spectrum

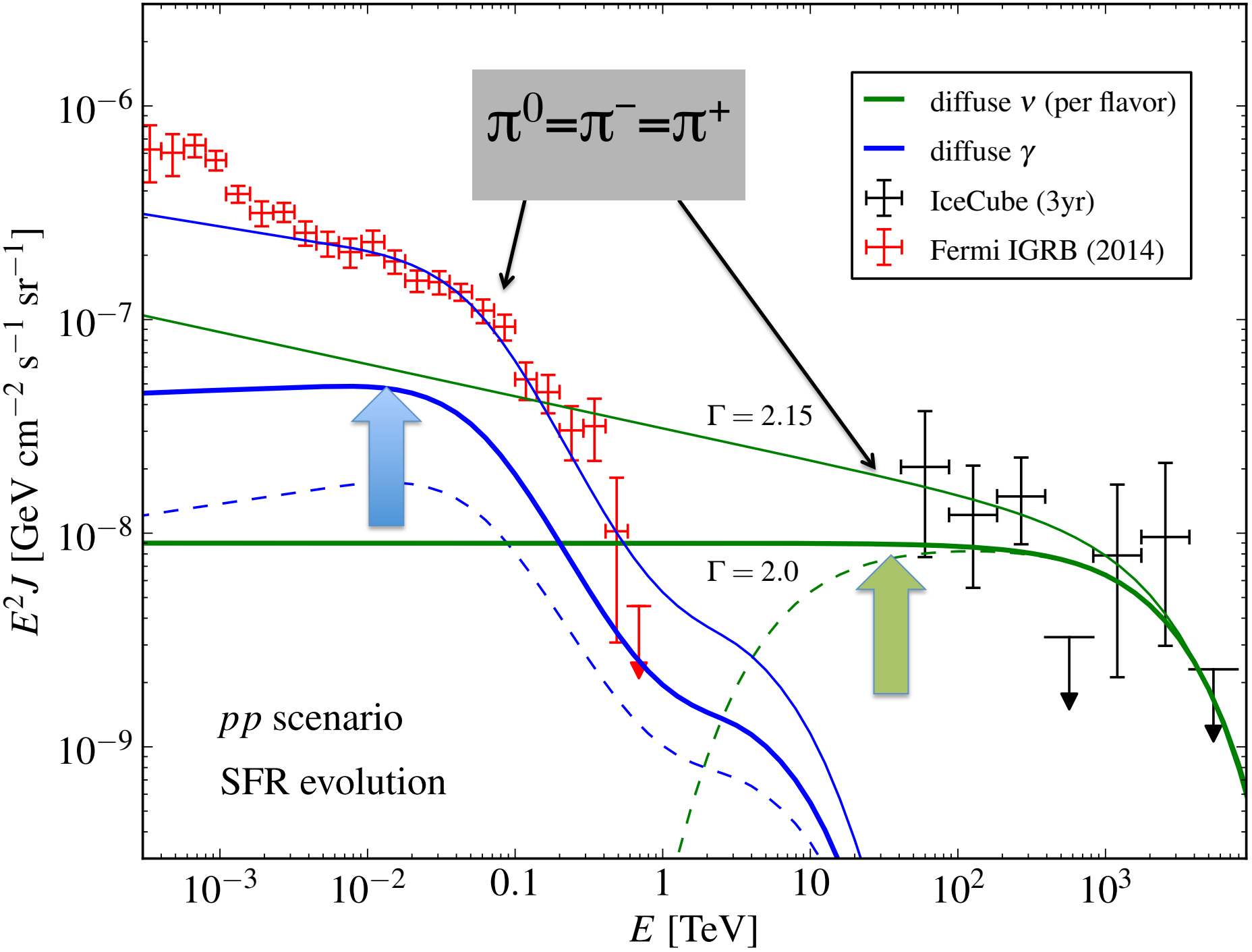
Γ=2.3±0.3
inc. prompt

IceCube
1405.5303



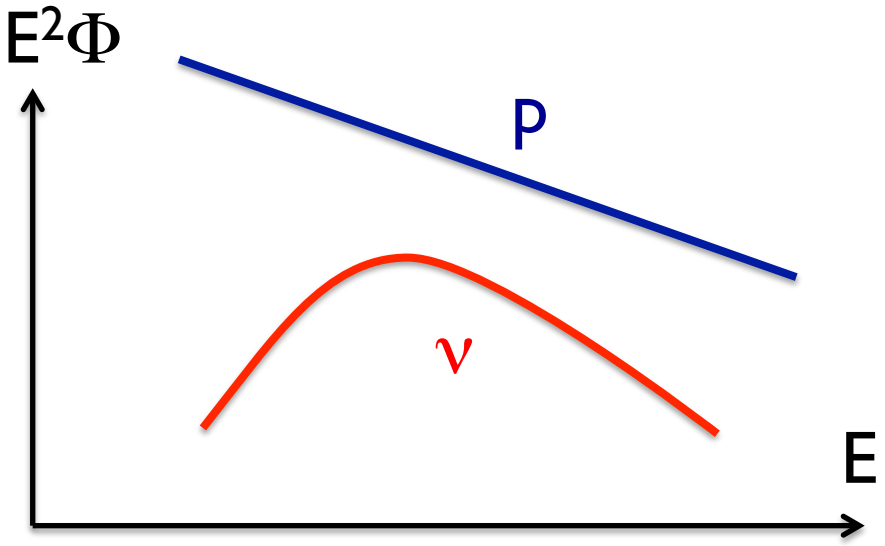
$$E^2\phi(E) = 1.5 \times 10^{-8}(E/100\,\mathrm{TeV})^{-0.3}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$


$\pi^0=\pi^-=\pi^+$
diffuse ν (per flavor)
diffuse γ
IceCube (3yr)
Fermi IGRB (2014)
$\Gamma = 2.15$
$\Gamma = 2.$
pp scenario
SFR evolution
E^2J [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


$\pi^0=\pi^-=\pi^+$
diffuse ν (per flavor)
diffuse γ
IceCube (3yr)
Fermi IGRB (2014)
$\Gamma = 2.15$
$\Gamma = 2.0$
pp scenario
SFR evolution
E^2J [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

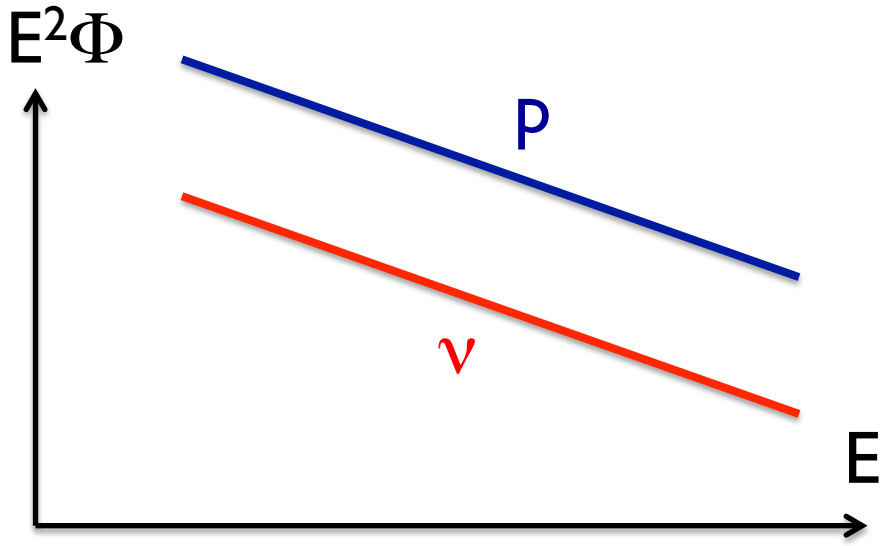
pγ vs pp

$$p + \gamma \rightarrow N\pi + X$$

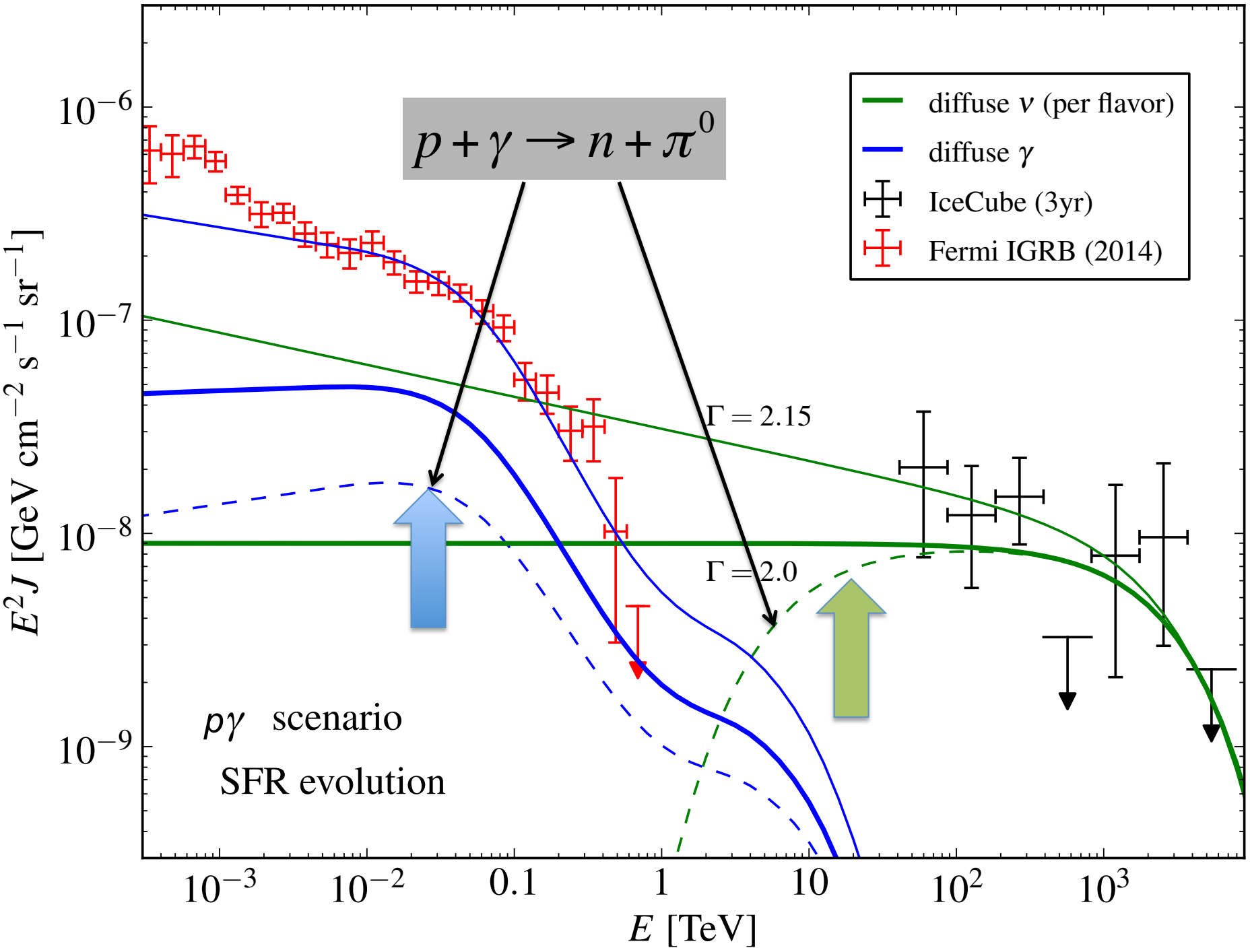


tracks photon target spectrum

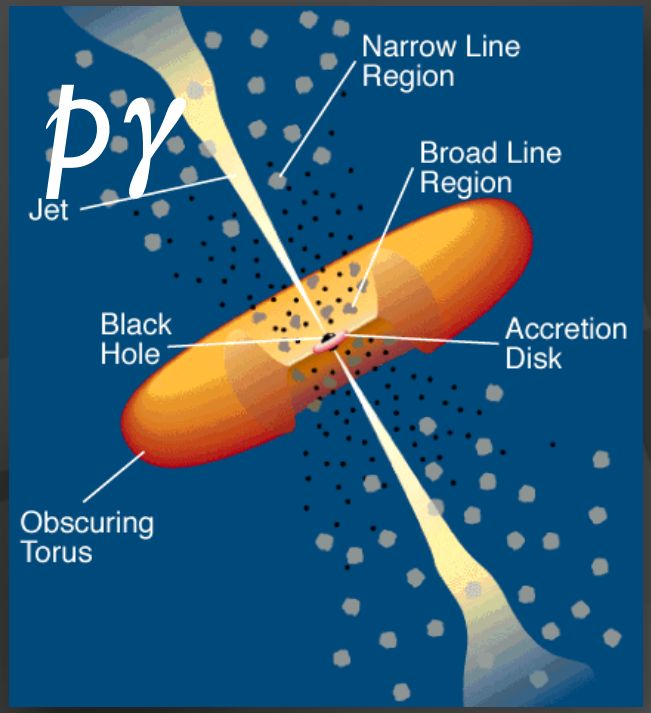
$$p + p \rightarrow N\pi + X$$



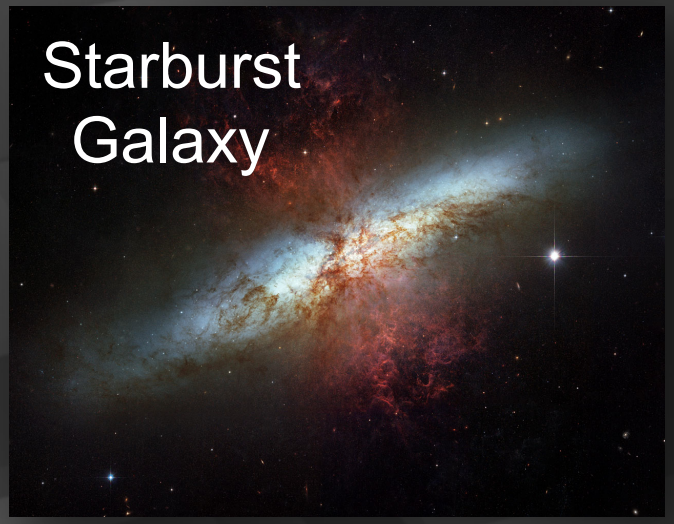
tracks cosmic ray spectrum

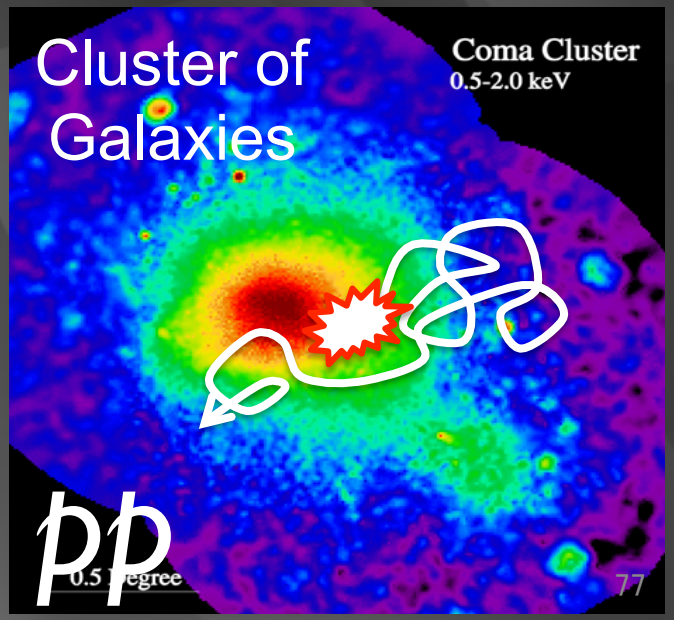

$p+\gamma \rightarrow n+\pi^0$
diffuse ν (per flavor)
diffuse γ
IceCube (3yr)
Fermi IGRB (2014)
$\Gamma = 2.15$
$\Gamma = 2.0$
$p\gamma$ scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

external shocks versus cosmic ray reservoirs



target density too low





nearest star forming region in Cygnus

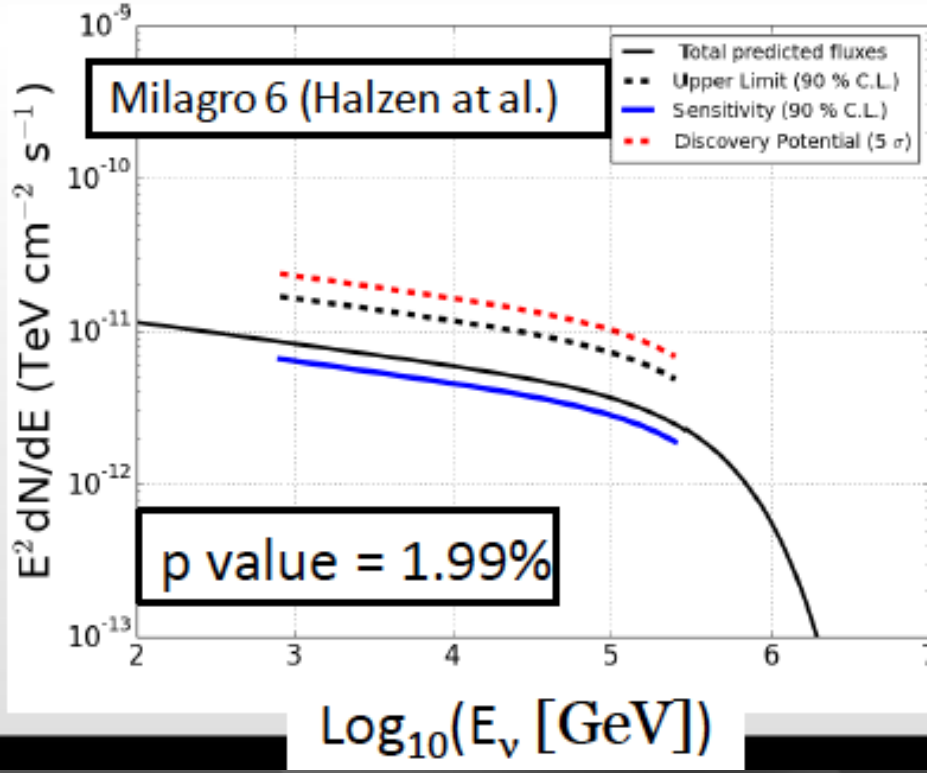
Most interesting result: "Milagro 6":

- 6 sources of TeV photons with SNR Associations Reported by Milagro Collaboration. 5 detections, 1 excess. (arXiv:0705.0707)

p value	: 1.99%
n_s fitted	: 51
γ fitted	: 3.95

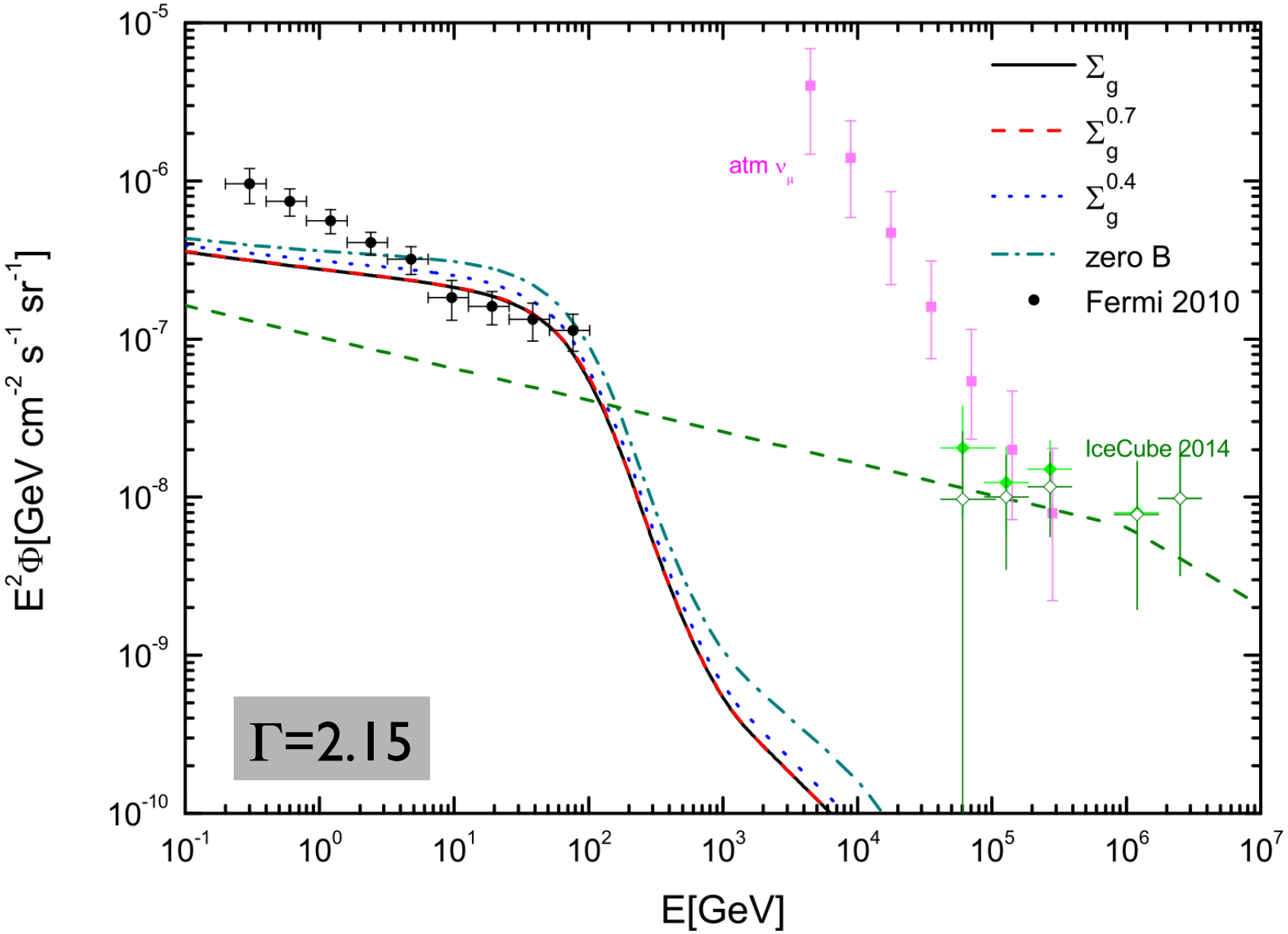
Significance Evolving over time

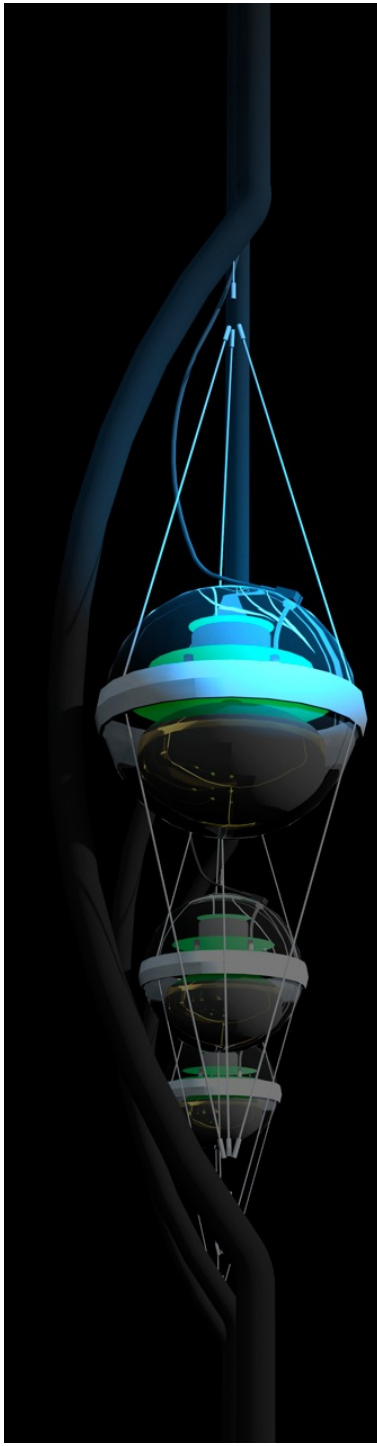
IC40	: 2% (a posteriori)
IC59	: >= 50%
IC79+59	: 20.4%
IC86-1 + 79 + 59	: 1.99%



also, 8-year AMANDA data: 2.3 sigma

the non-thermal Universe is hadronic !



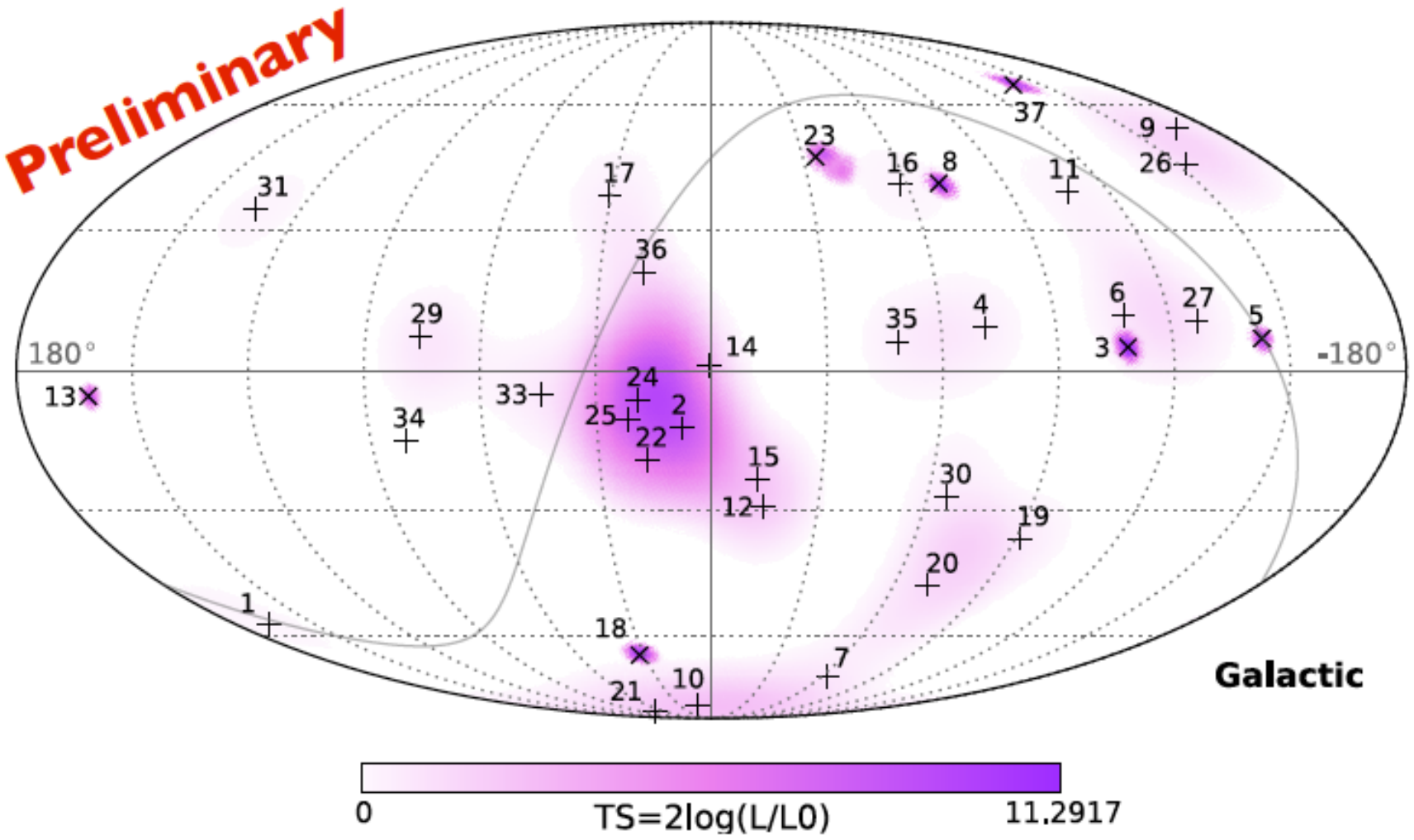


IceCube: the discovery of cosmic neutrinos

francis halzen

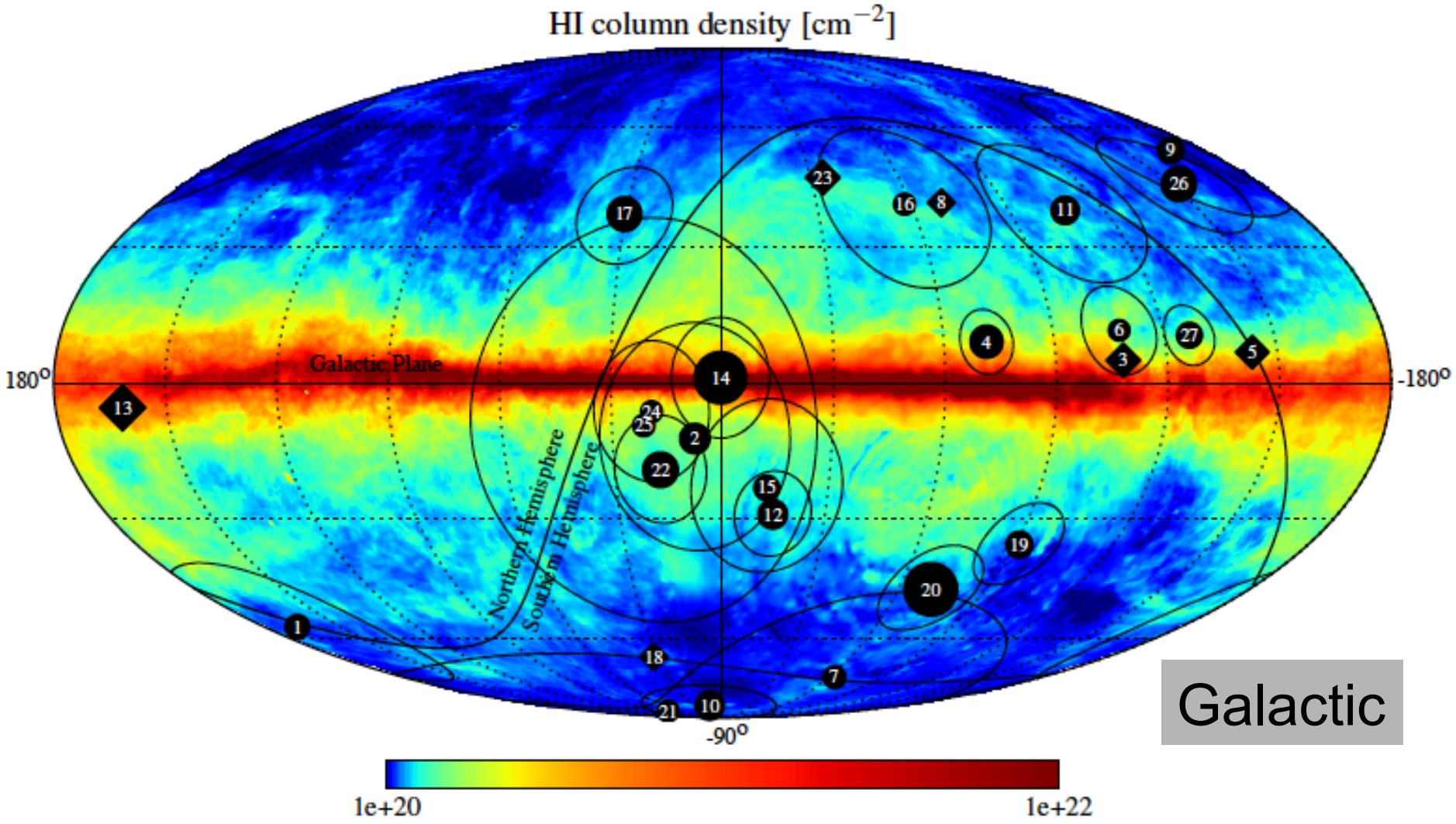
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

where do they come from (3 year data)?



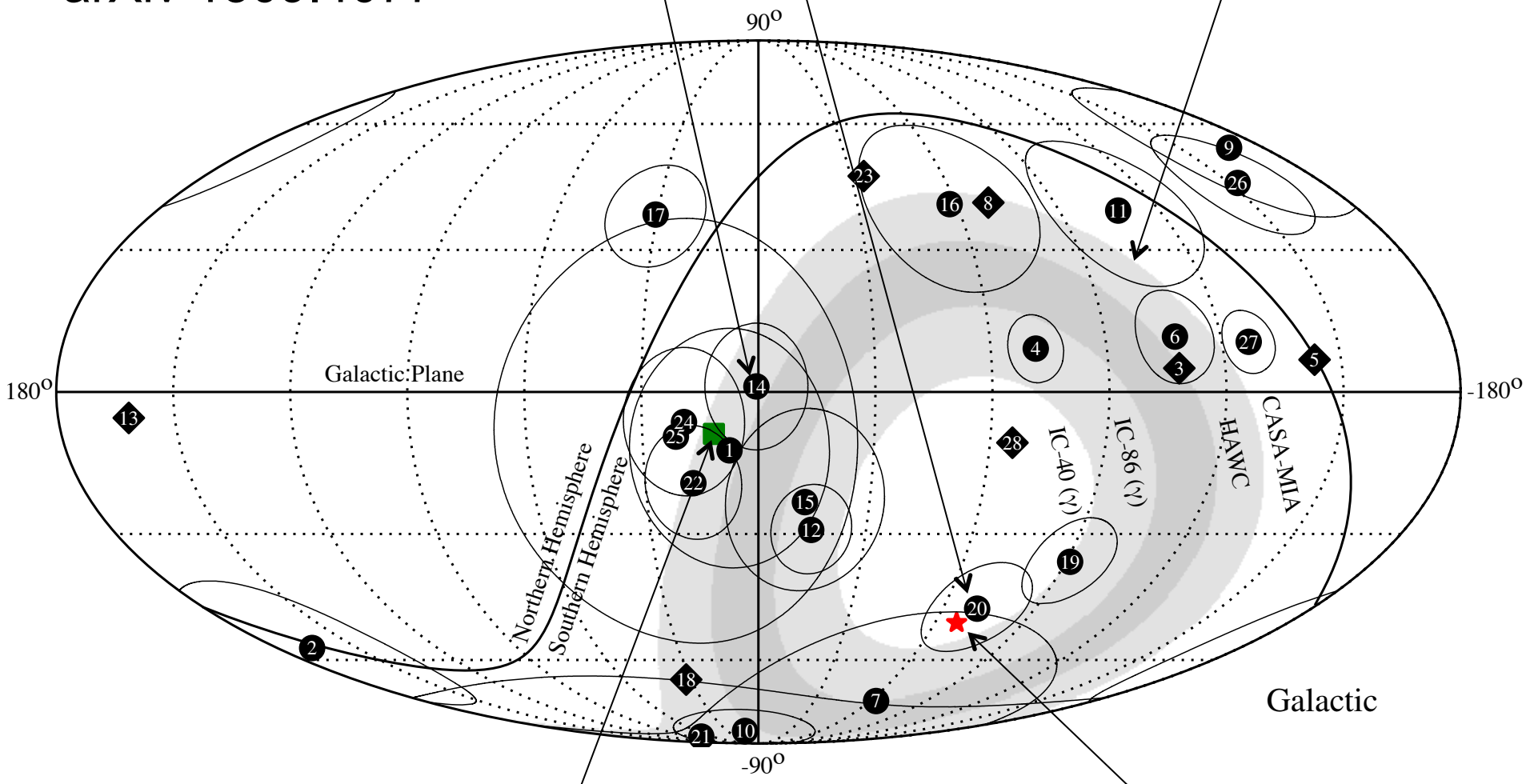
hottest spot 7.2%: consistent with diffuse flux with fllavor 1:1:1?

correlation with Galactic plane: TS of 2.8% for a width of 7.5



Galactic

Galactic coordinates
arXiv 1309.4077



Galactic vs cosmological ?

~ 10kpc Galactic sources are NOT likely the main origin

$$F \propto \int d^3x \frac{n(r)}{4\pi r^2} \sim nR$$

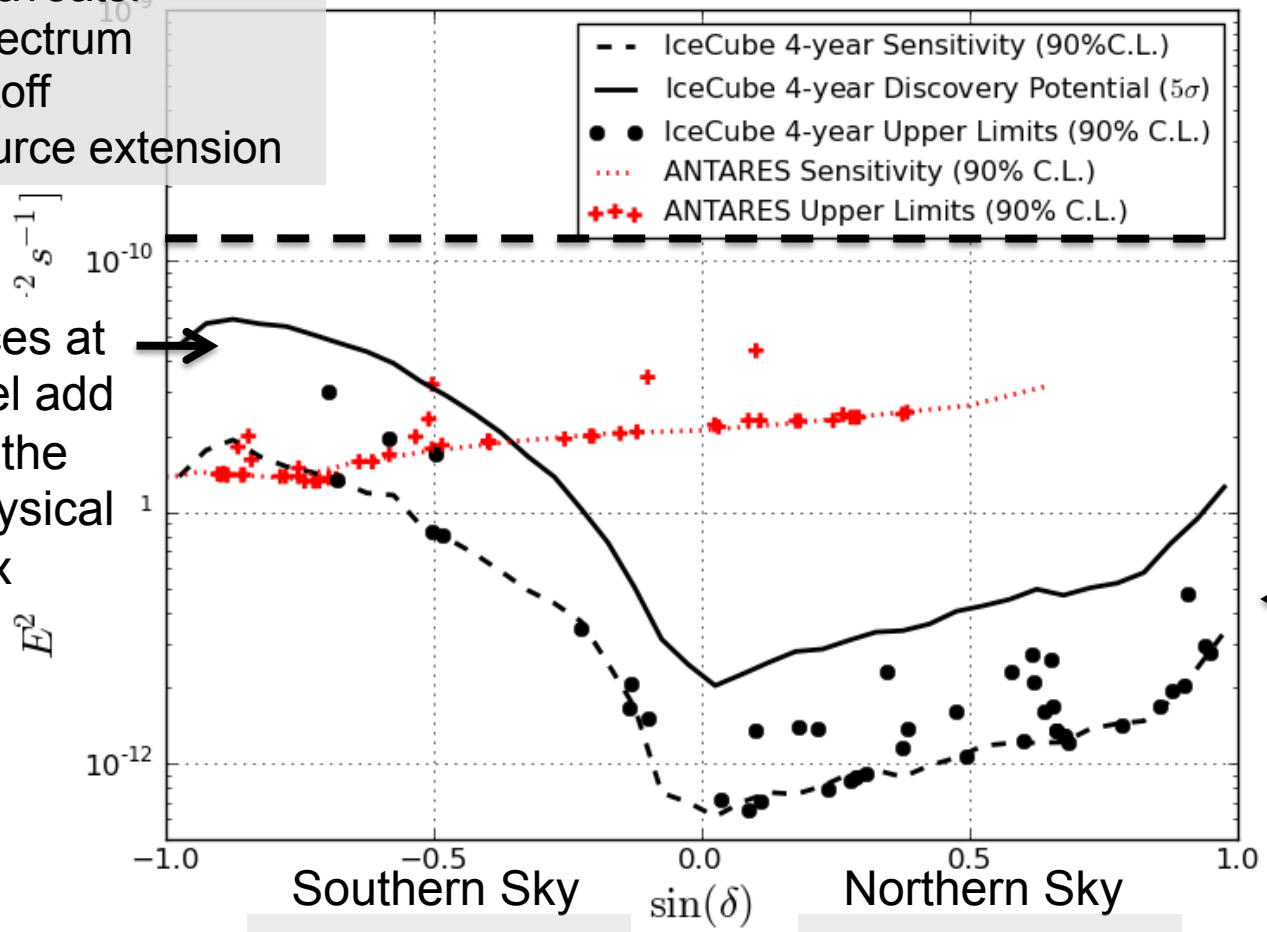
$$\frac{F_{\rm Gal}}{F_{\rm Cos}} = \frac{n_{\rm Gal}}{\bar{n}} \frac{R_{\rm Gal}}{R_{\rm H}} = \left(\frac{\ell_{\rm gal}}{R_{\rm Gal}}\right)^3 \frac{R_{\rm Gal}}{R_{\rm H}}$$

$$\sim 100 \left(\frac{\ell_{\rm gal}}{3\,{\rm Mpc}}\right)^3 \left(\frac{R_{\rm Gal}}{10\,{\rm kpc}}\right)^{-2} \left(\frac{R_{\rm H}}{3\,{\rm Gpc}}\right)^{-1}$$

If sources were Galactic, they should dominate the cosmological

combining the cosmic flux measurement with point source upper limits constrains the source population

many caveats!
- E^{-2} spectrum
- no cutoff
- no source extension



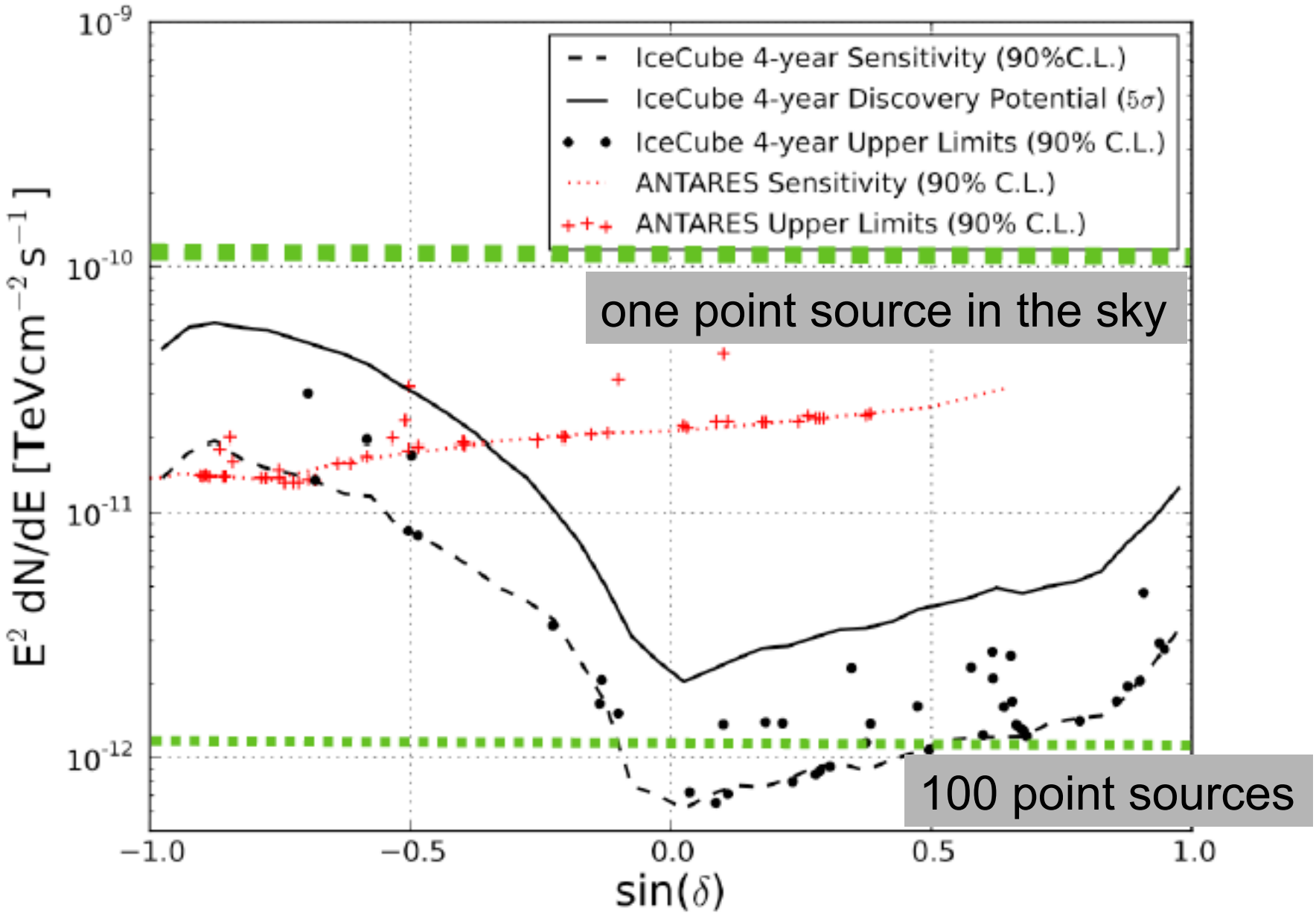
2 sources at this level add up to the astrophysical flux

Astrophysical flux (high-energy contained events)

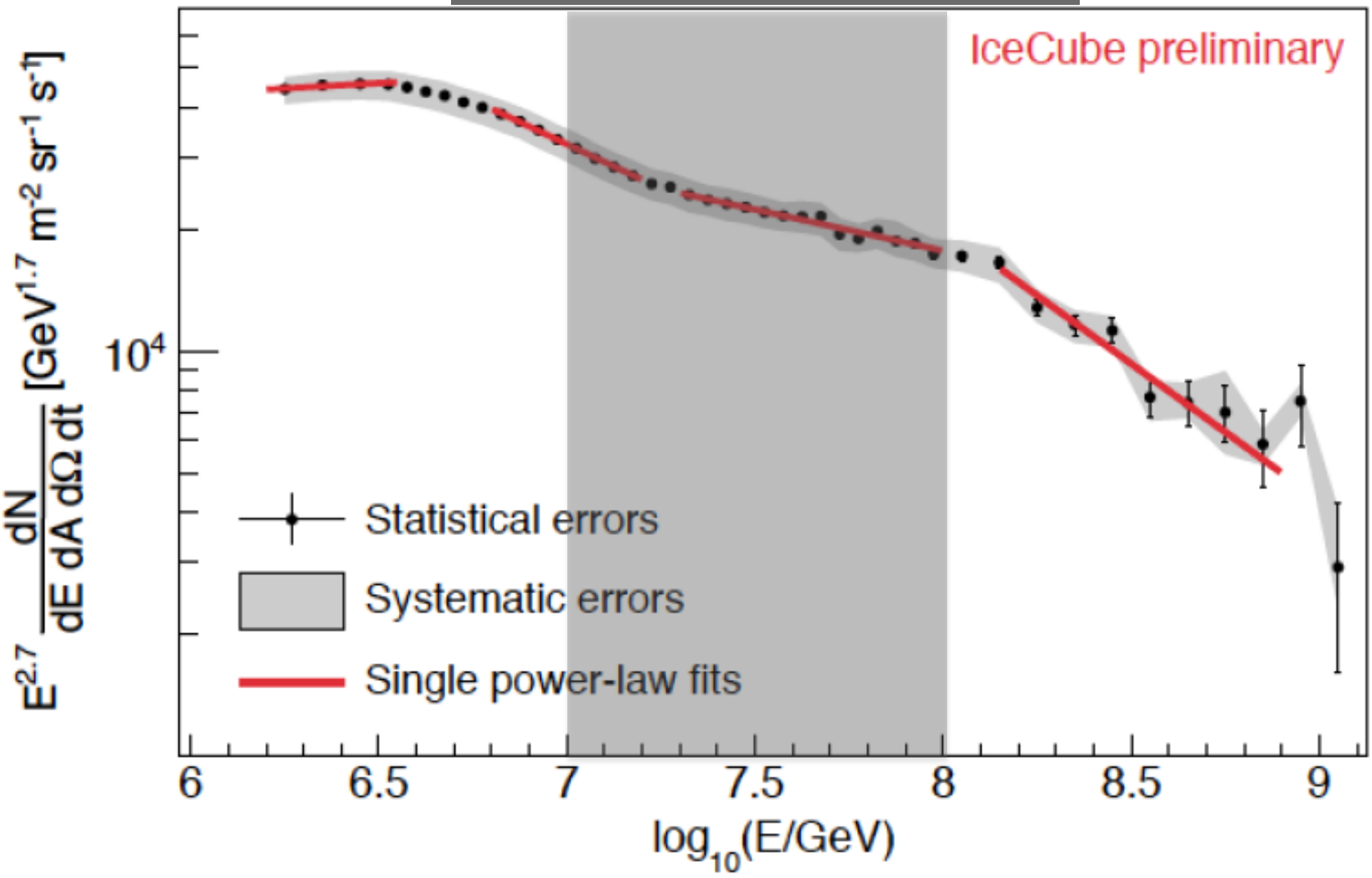
20 sources at this level add up to the astrophysical flux

Southern Sky
PeV - EeV

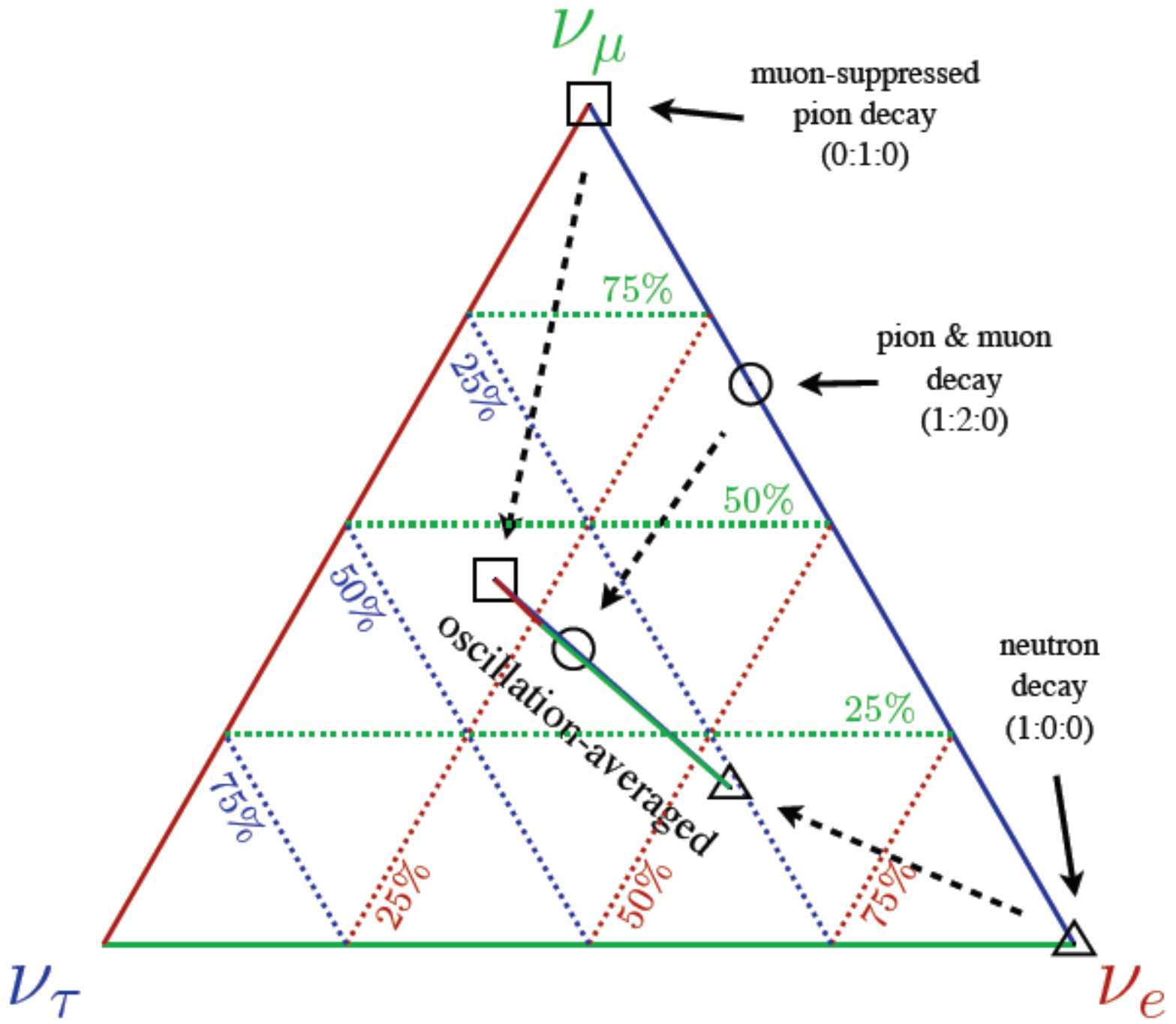
Northern Sky
TeV - PeV


IceCube 4-year Sensitivity (90%C.L.)
IceCube 4-year Discovery Potential (5σ)
IceCube 4-year Upper Limits (90% C.L.)
ANTARES Sensitivity (90% C.L.)
ANTARES Upper Limits (90% C.L.)
one point source in the sky
100 point sources
E² dN/dE [TeVcm⁻² s⁻¹]
sin(δ)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
−1.0
−0.5
0.0
0.5
1.0

the energy range of cosmic accelerators producing PeV neutrinos



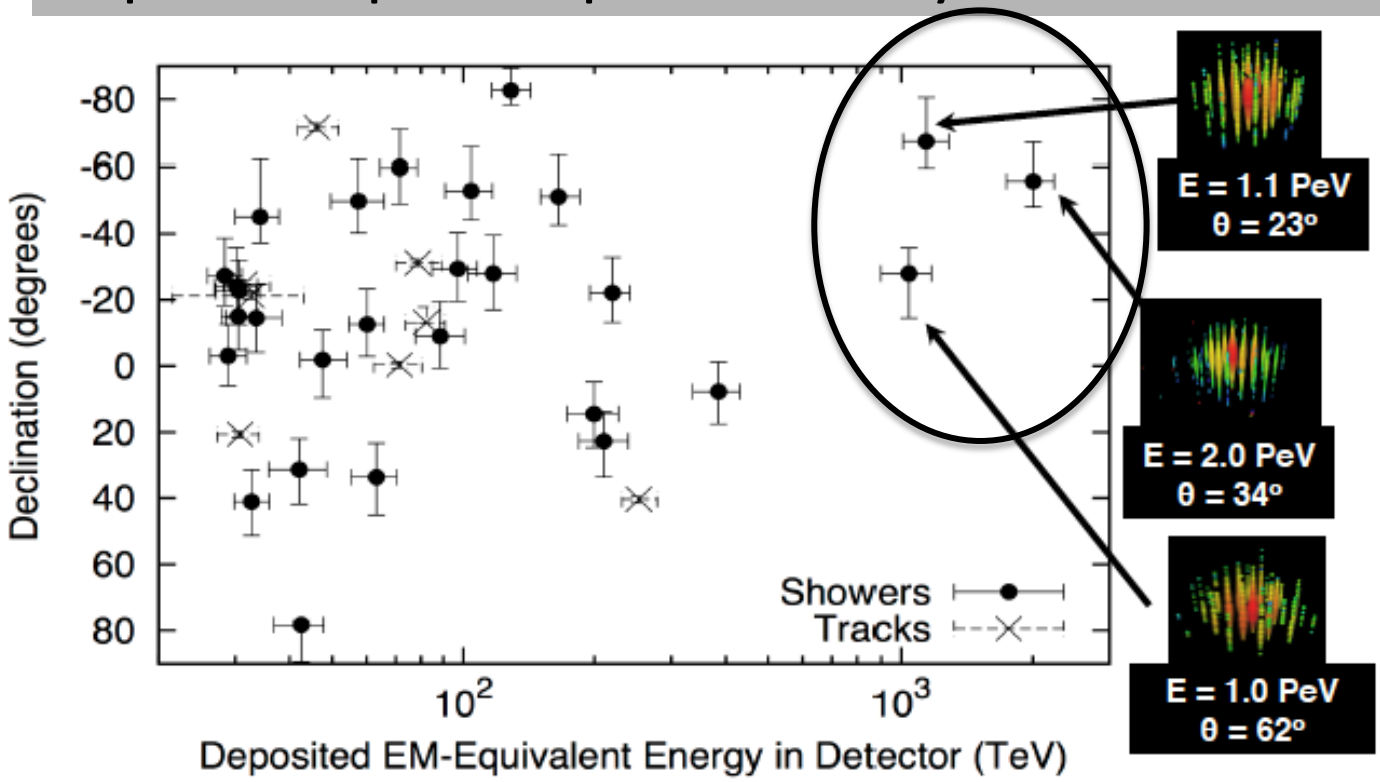
Galactic or extragalactic?


ν_μ
muon-suppressed
pion decay
(0:1:0)
75%
25%
pion & muon
decay
(1:2:0)
50%
50%
oscillation-averaged
neutron
decay
(1:0:0)
25%
75%
25%
50%
75%
ν_τ
ν_e

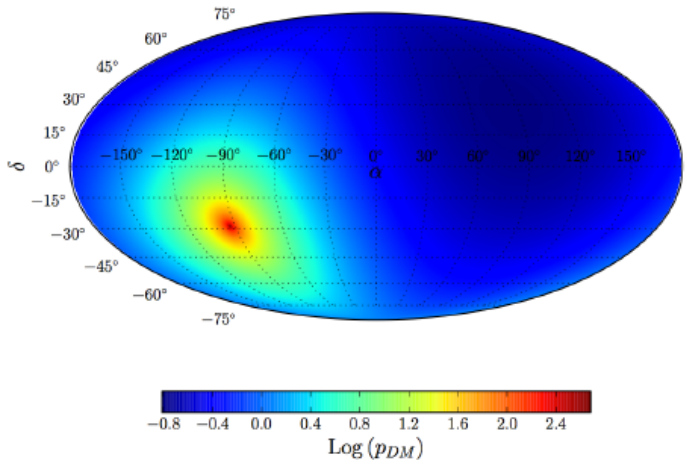
where do they come from?

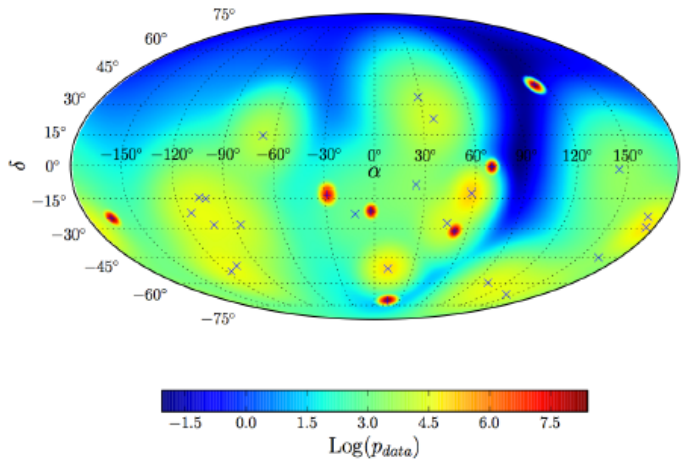
- not all Galactic
- where are the PeV photons?
- we may be surprised, it happened before
- need more events: no SCO-X1, more like Martin Ryle's radio stars

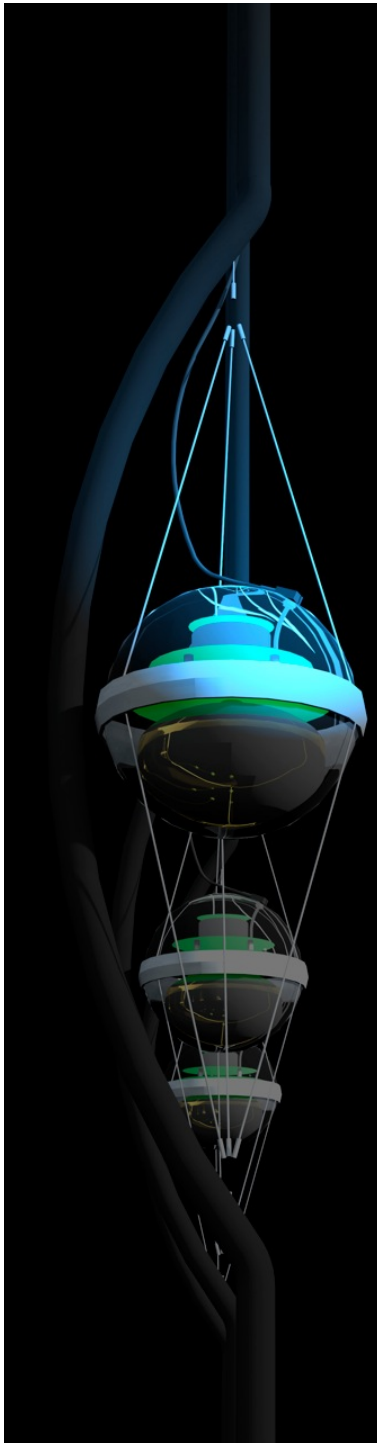
expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle







IceCube

francis halzen

- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

IceCube.wisc.edu

what if ???

a next-generation IceCube with a volume of 10 km^3 and an angular resolution of 0.3 degrees will identify the sources of a “diffuse” flux in several years and guarantee astronomy

discovery instrument → astronomical telescope

auto correlation: multiple neutrinos from the same source

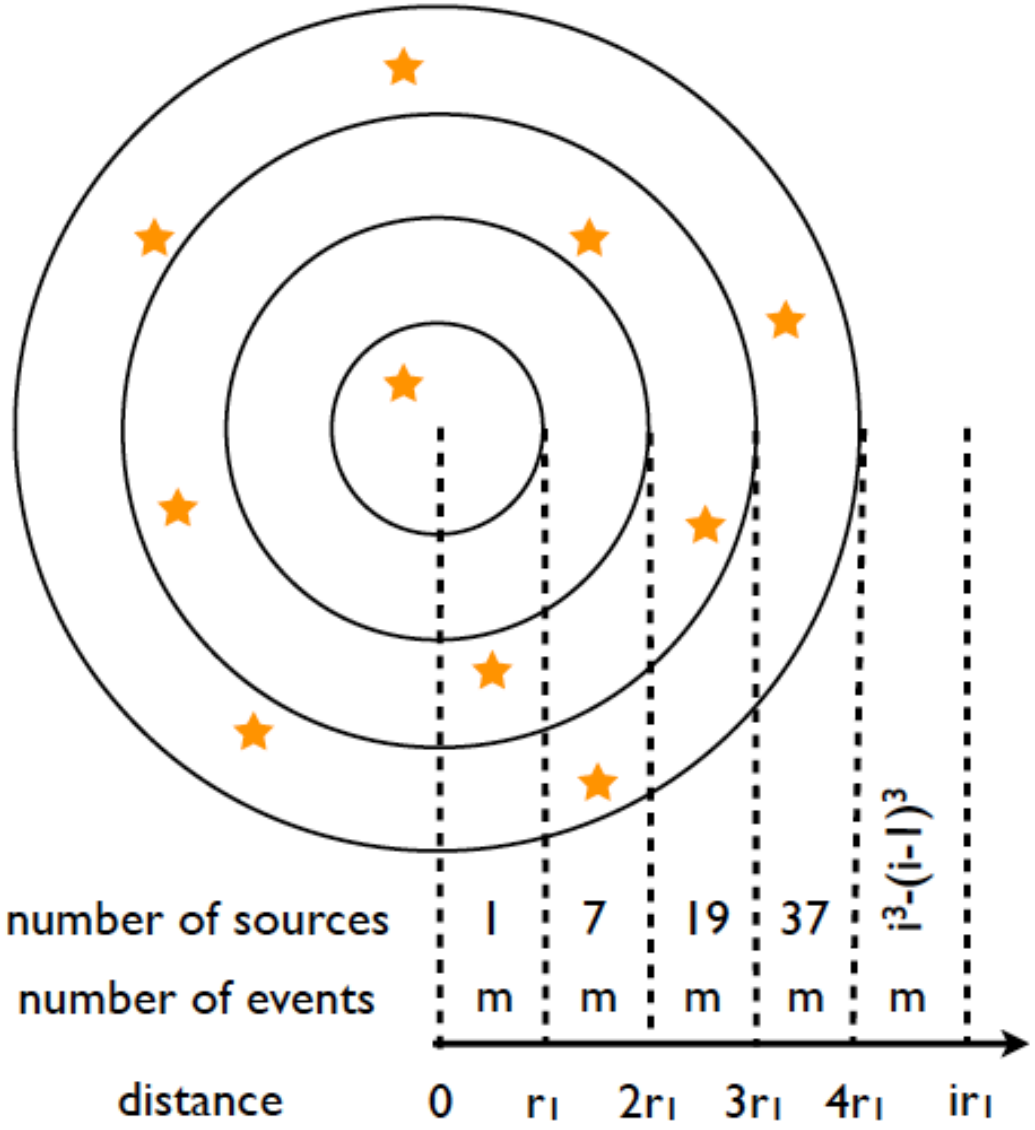
total number of events required to observe
n-events multiplets from the closest sources is

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

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**



- total number of sources

$$n_s \simeq 10^6 - 10^7$$

- total number of "slices"

$$n_{\text{slice}} \simeq (n_s)^{\frac{1}{3}}$$

- total number of events

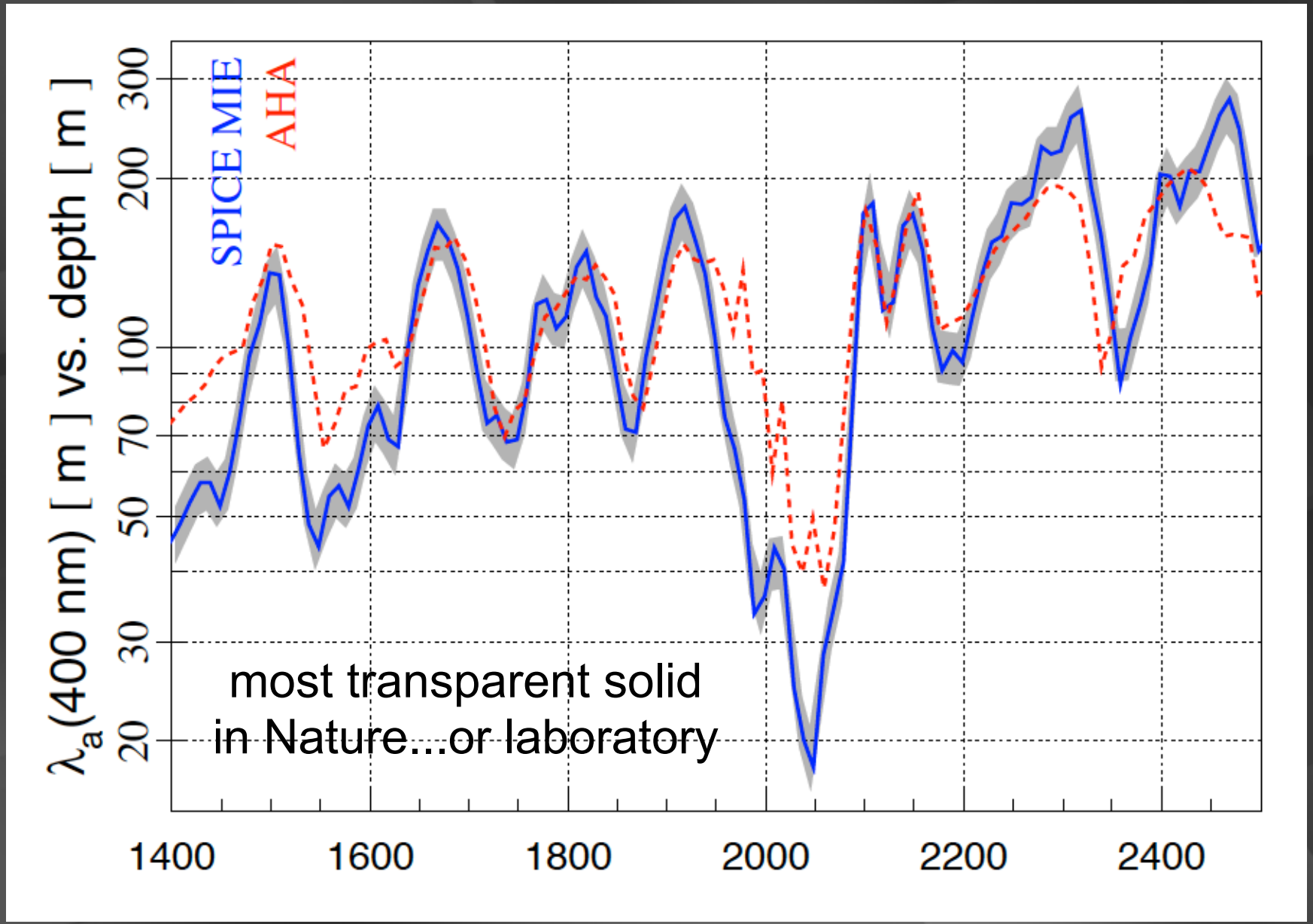
$$\bar{N} \simeq m \times n_{\text{slice}} = m \times (n_s)^{\frac{1}{3}}$$

✔ required number of events to see a doublet ($m = 2$)

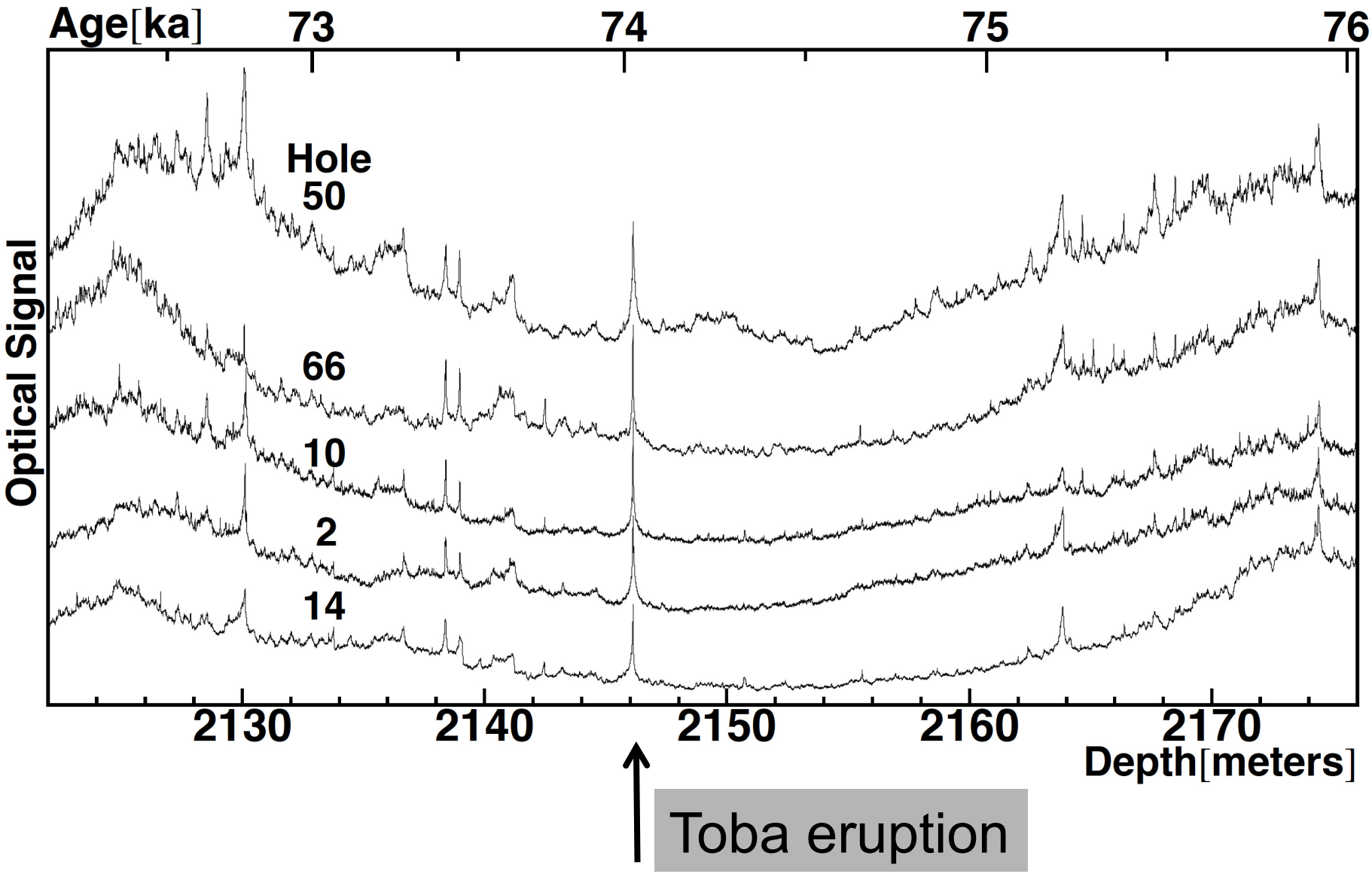
$$\bar{N} \simeq 200 - 500$$

✘ random clusters are very likely with bad angular resolusion!

absorption length ← 220m →

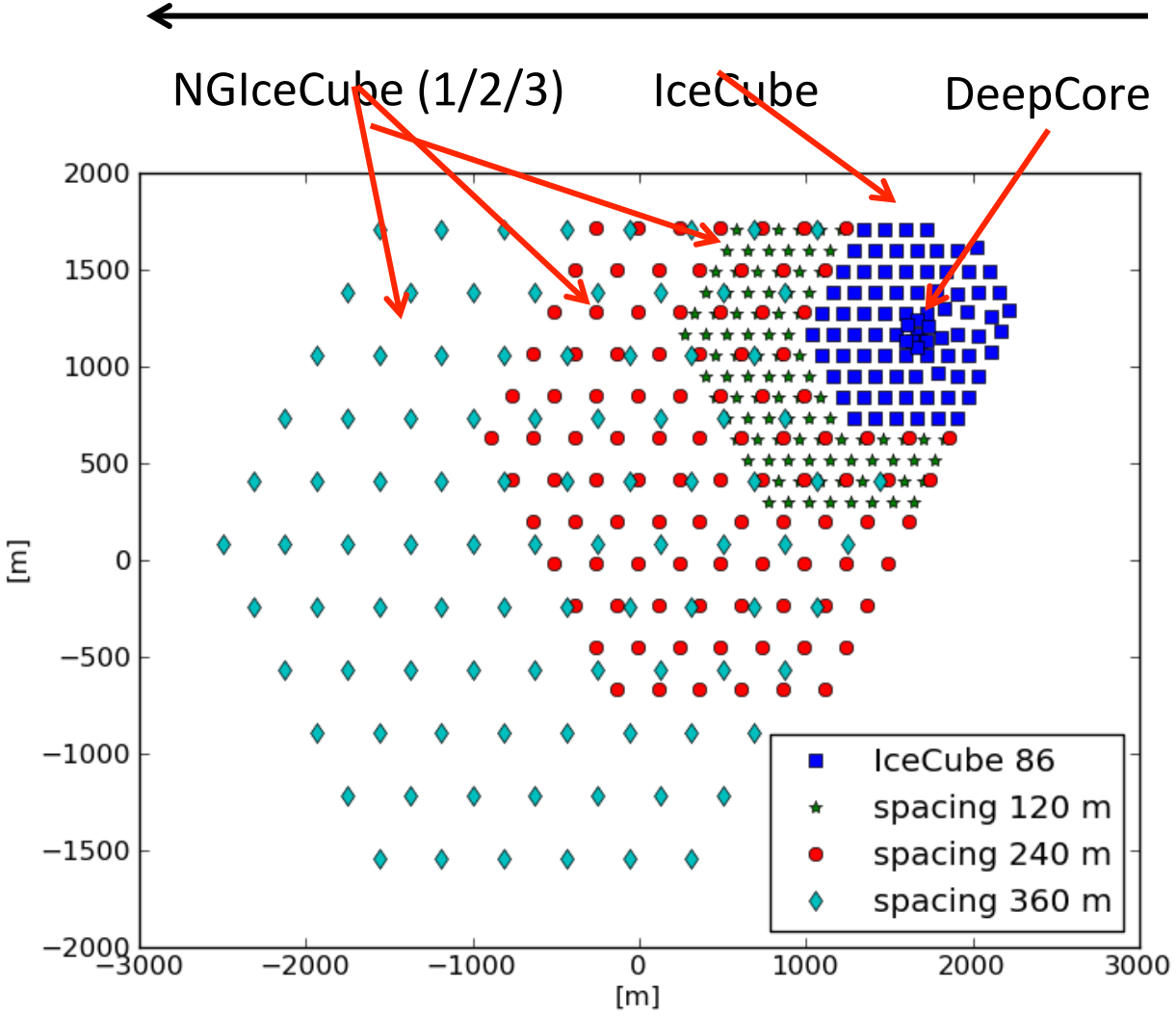


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where 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

Bert:
Energy 1 PeV

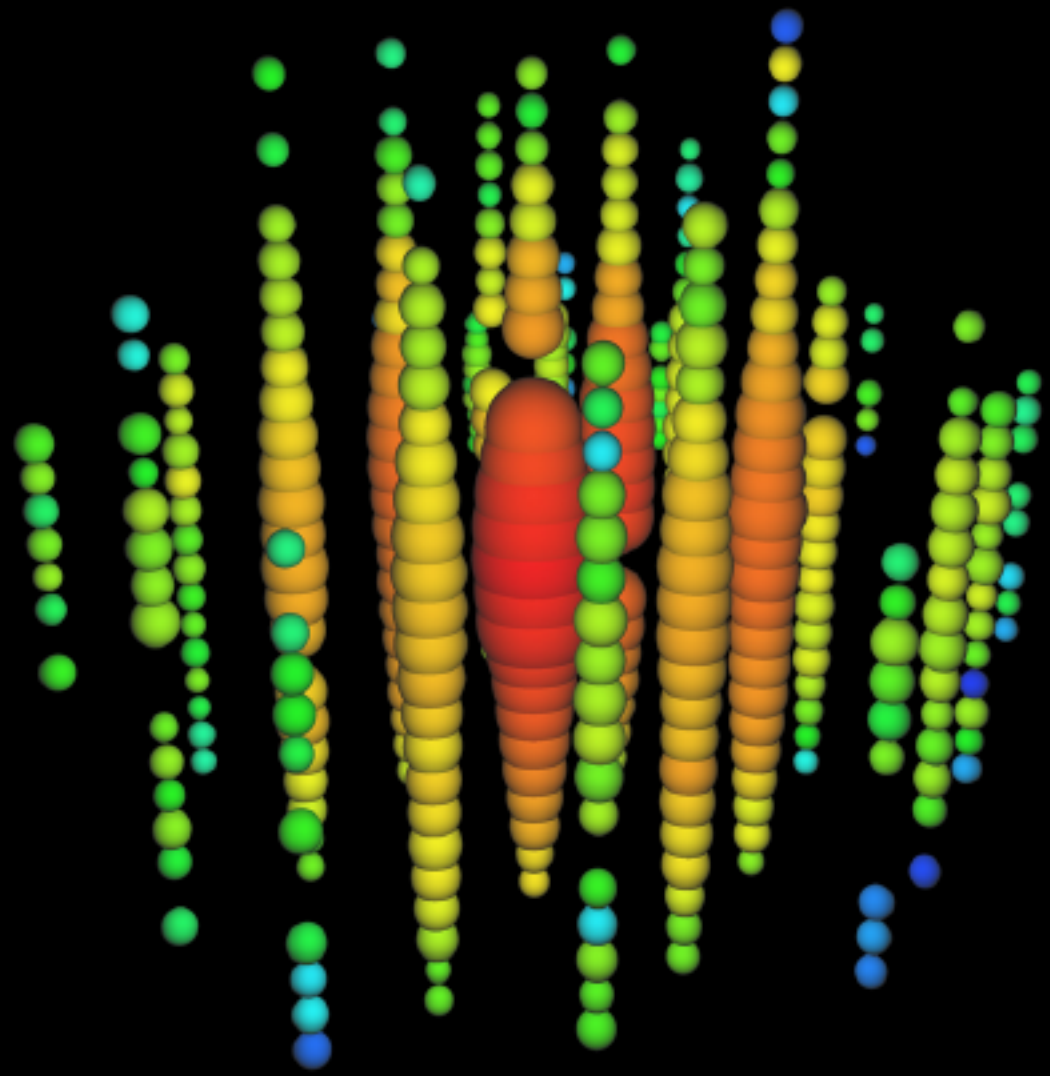
How well could we reconstruct this event with fewer strings?

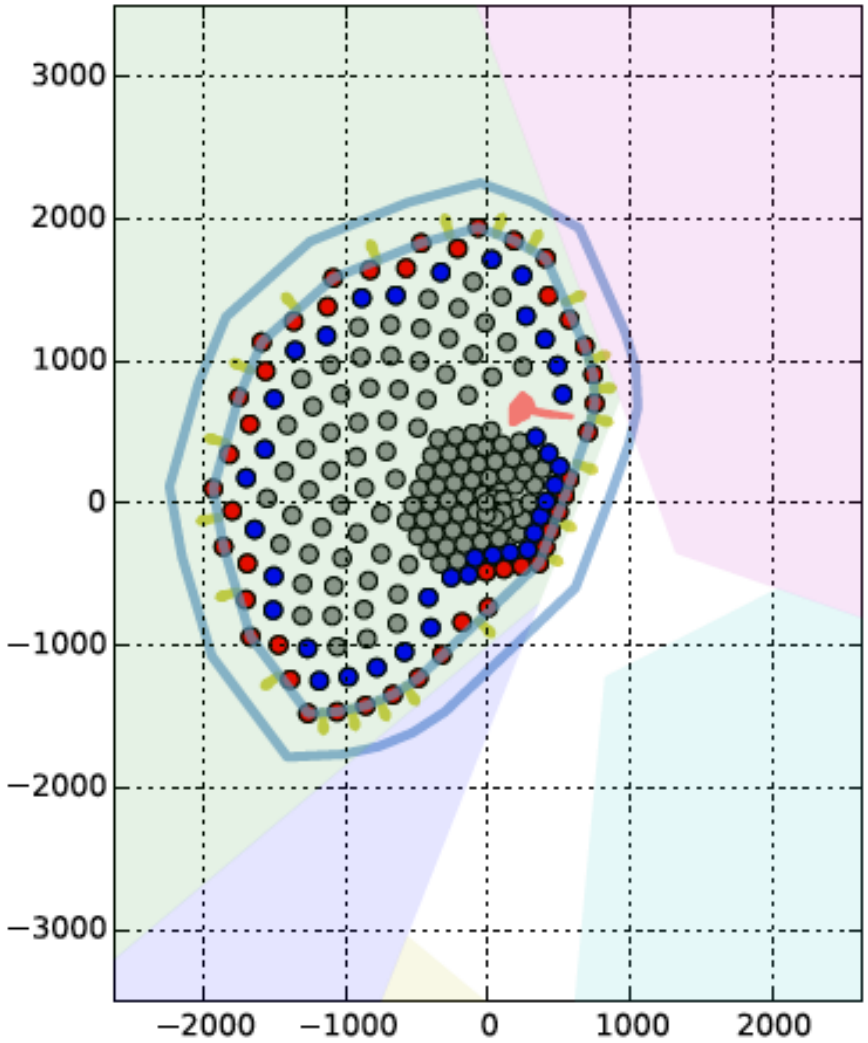
Analyzed event using only subsets of 20 IceCube strings spaced at 250m.

Result:
Vertex reconstruction:~ 12m
Angular resolution: ~30°
Energy resolution: 10%

Same result for Ernie, the other PeV event.

→ Don't need 100,000 photoelectrons to measure energy to 10%.

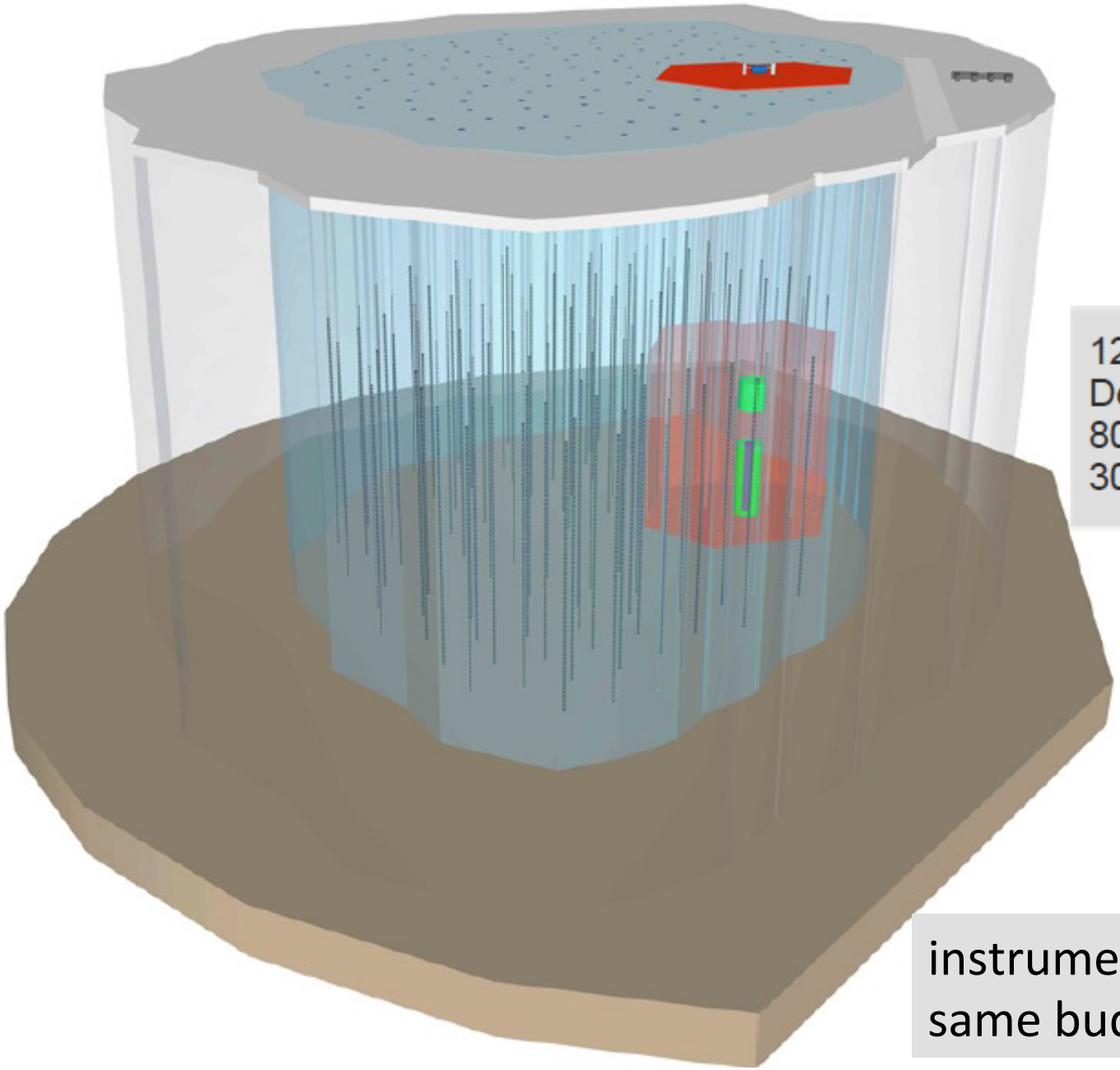




“Sunflower 120”

top area (instrumented+60m border): 7.0 km^2

strings: IC86+96 | string spacing: ~240m



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

instrumented volume: x 10
same budget as IceCube

- more cosmogenic neutrinos; coincidences with ARA?
- more double-bang tau neutrinos
- better flavor measurements
- better sensitivity to new neutrino physics
- ……

Next-Generation IceCube

- capitalize on discovery
- astronomy guaranteed
- ~ 120 strings: more sensors per string with higher quantum efficiency
- proven techniques, low risk
- flexibility of deployment per seasons: optimization
- cost similar to original detector

from discovery to astronomical telescopes:

parallel development in the Mediterranean

ANTARES → KM3NeT

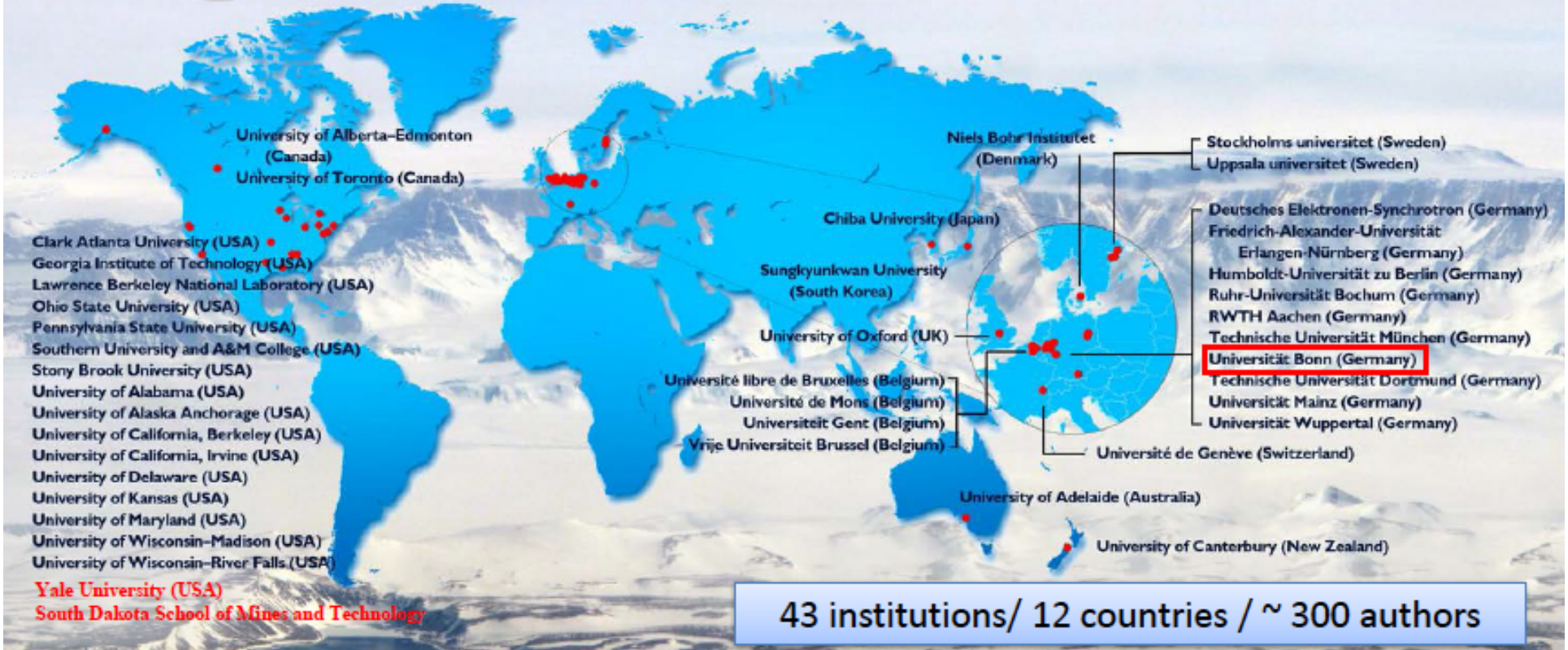
IceCube has observed a flux of neutrinos from the cosmos of PeV (1,000 TeV) neutrinos that is at the level of the astronomical gamma ray flux. We thus established that neutrinos play a role similar to photons in the high-energy non-thermal universe.

from discovery to astronomical telescopes:

parallel development in the Mediterranean

ANTARES → KM3NeT

The IceCube Collaboration



43 institutions/ 12 countries / ~ 300 authors

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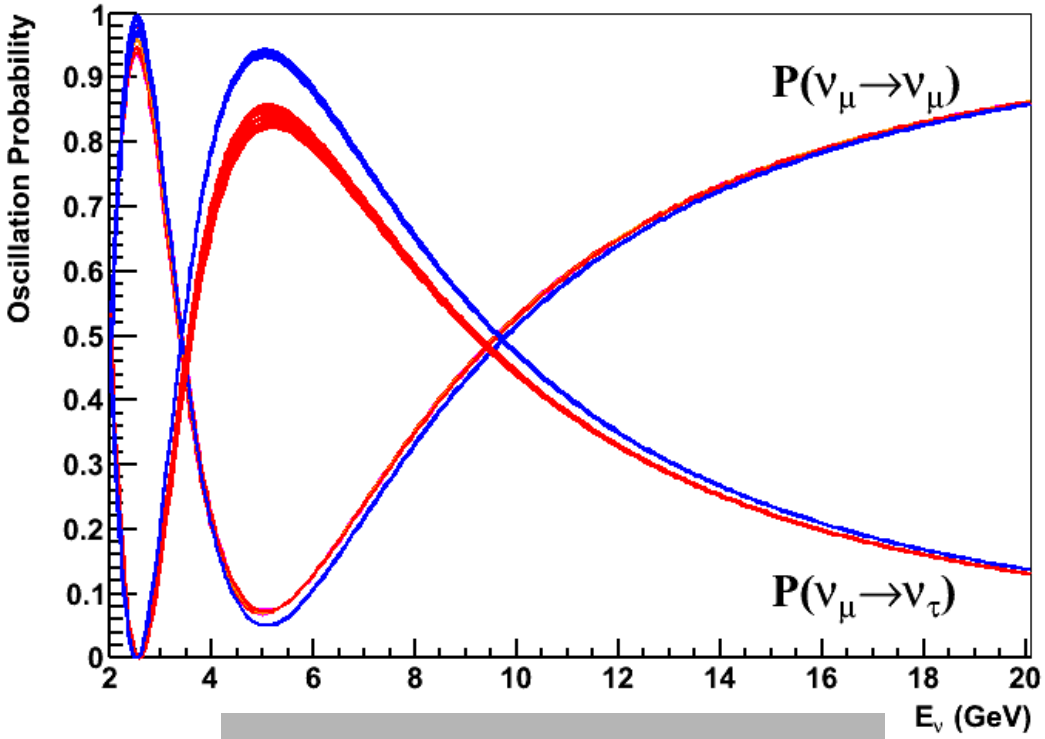
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube

DeepCore

PINGU



oscillations at 20 GeV