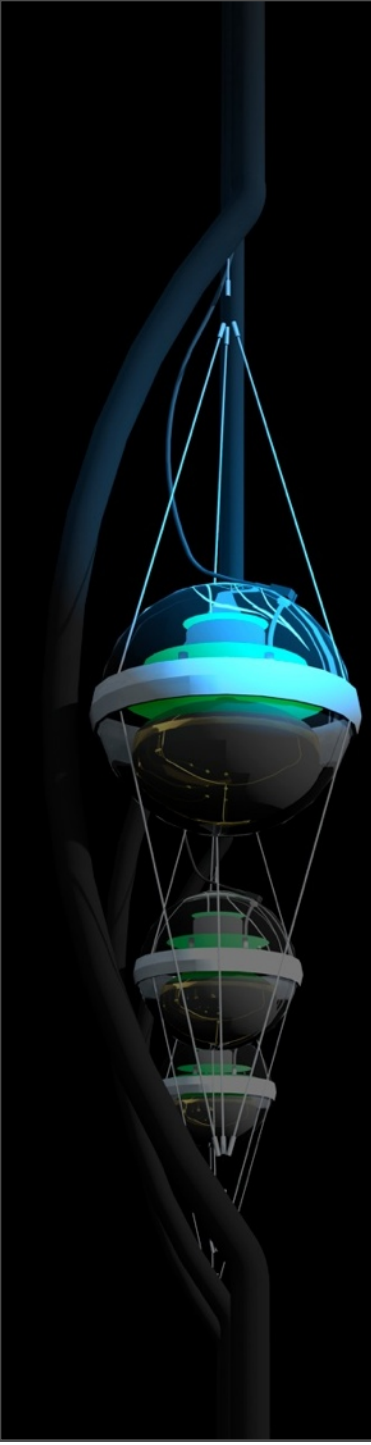
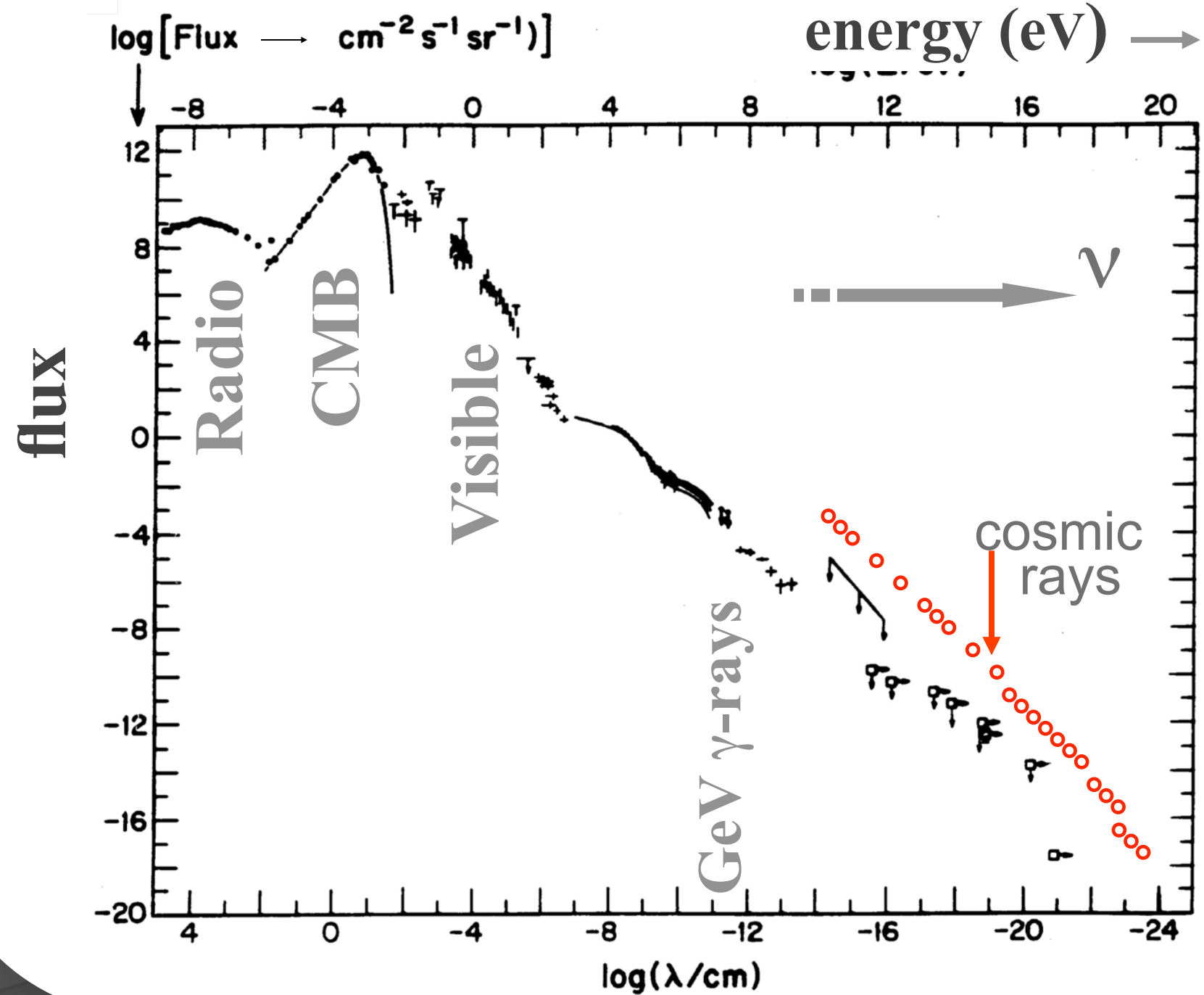


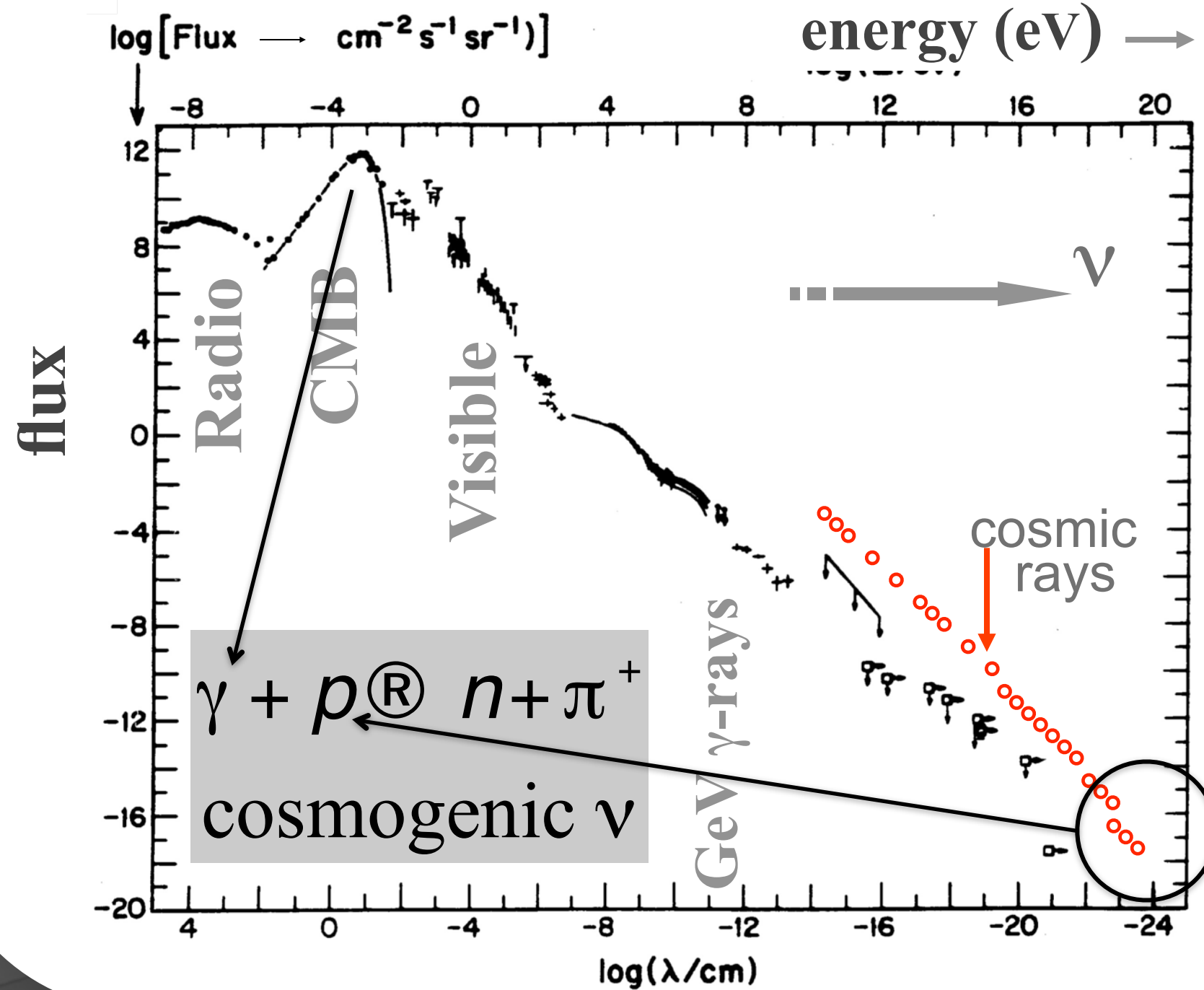
neutrino astronomy

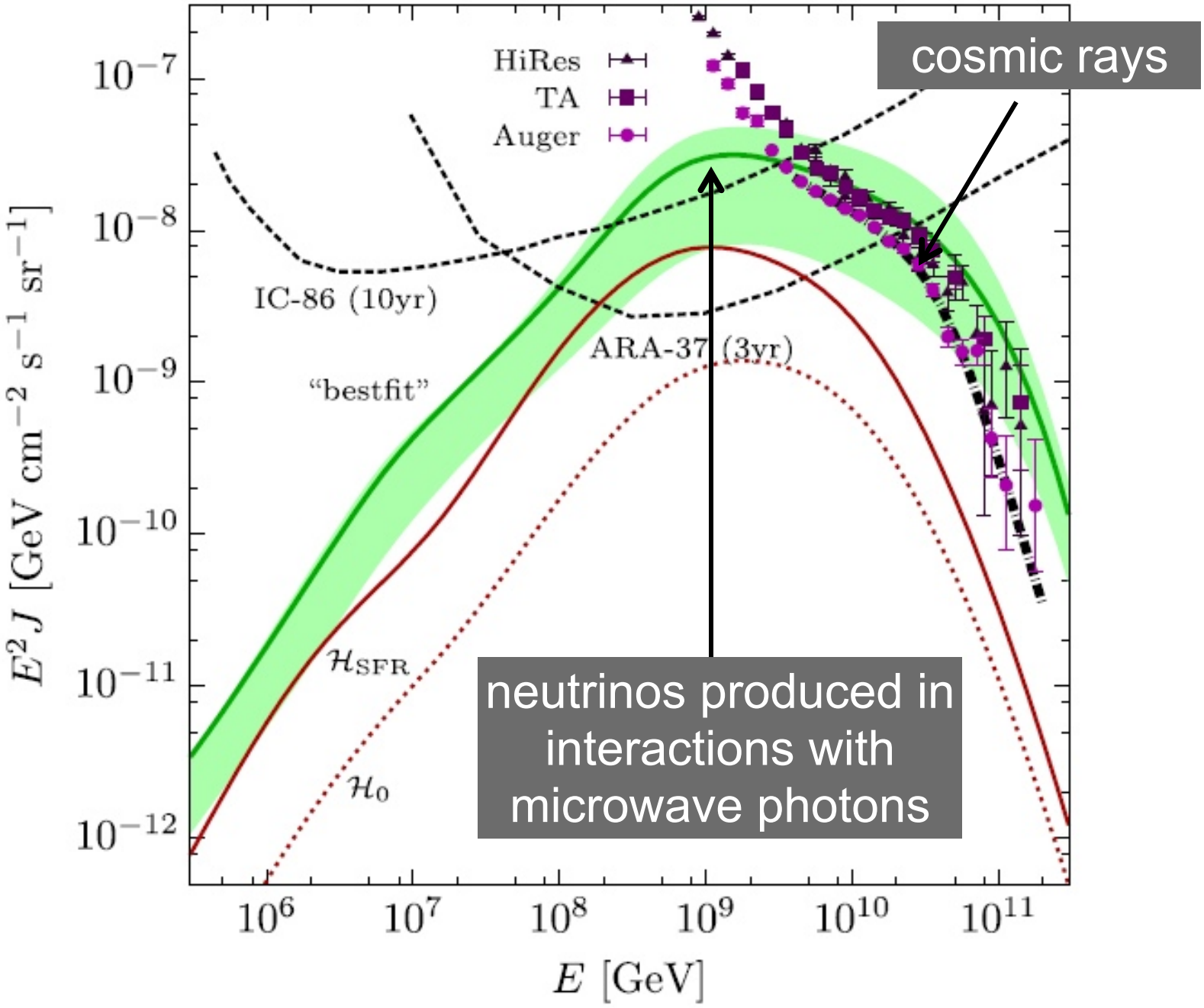
francis halzen

- cosmogenic, supernova and GRB neutrinos
- IceCube
- evidence for cosmic neutrino
- outlook

IceCube.wisc.edu


log[Flux ⟶ cm⁻² s⁻¹ sr⁻¹)]
energy (eV) ⟶
flux
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
log(λ/cm)

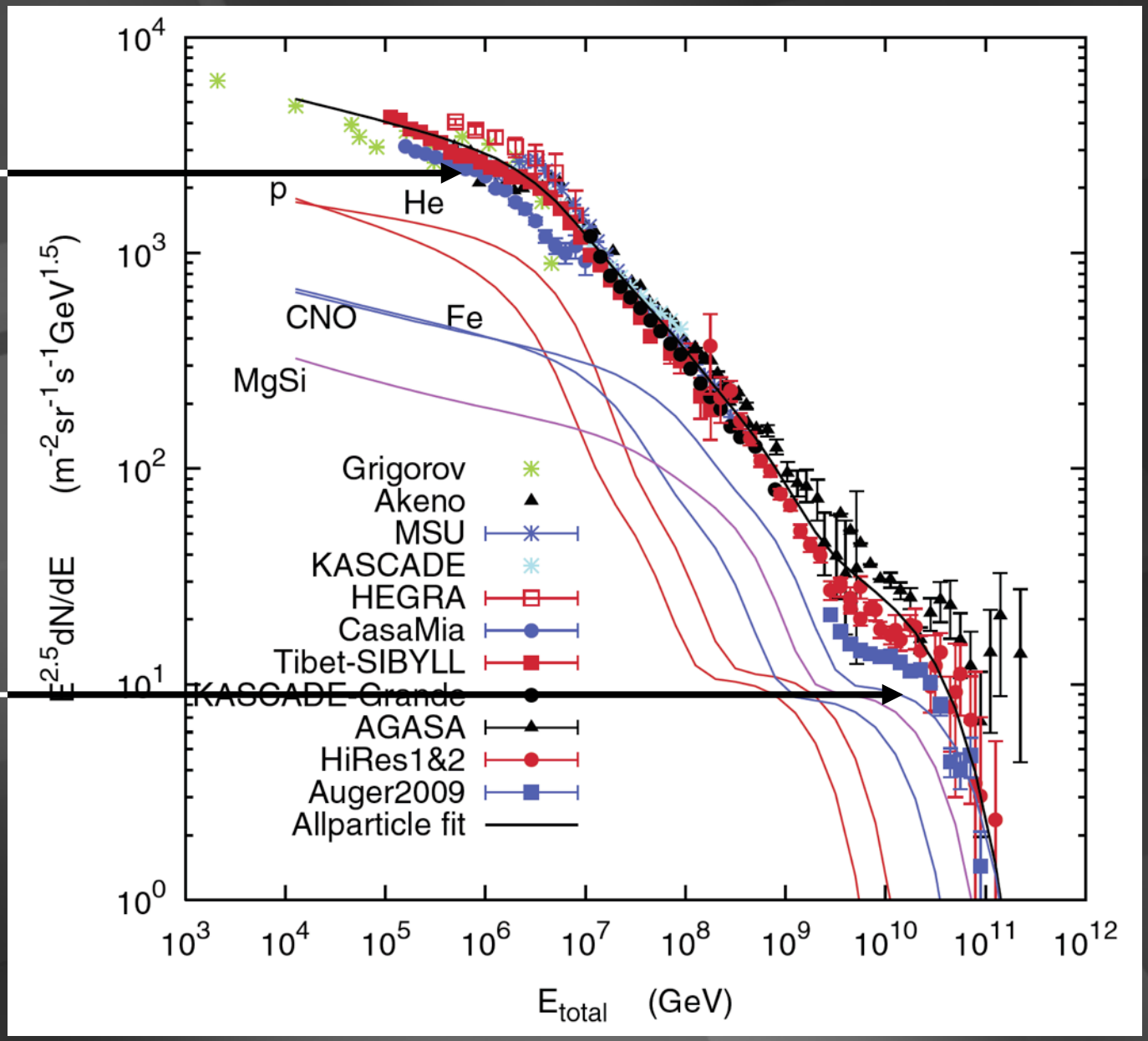

log[Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
γ + p® n+π⁺
cosmogenic ν
log(λ/cm)

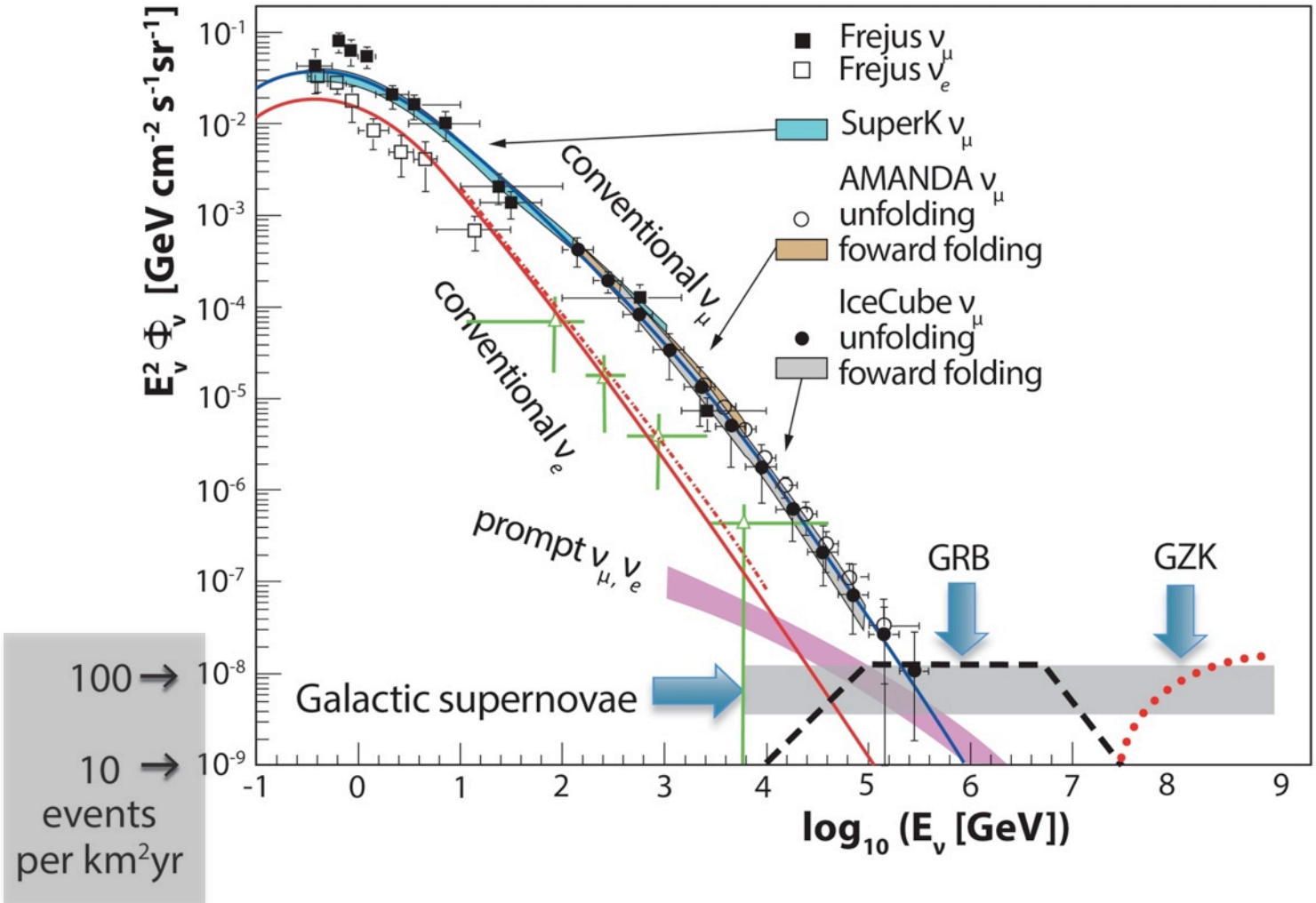

cosmic rays
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
neutrinos produced in interactions with microwave photons
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^6
10^7
10^8
10^9
10^{10}
10^{11}

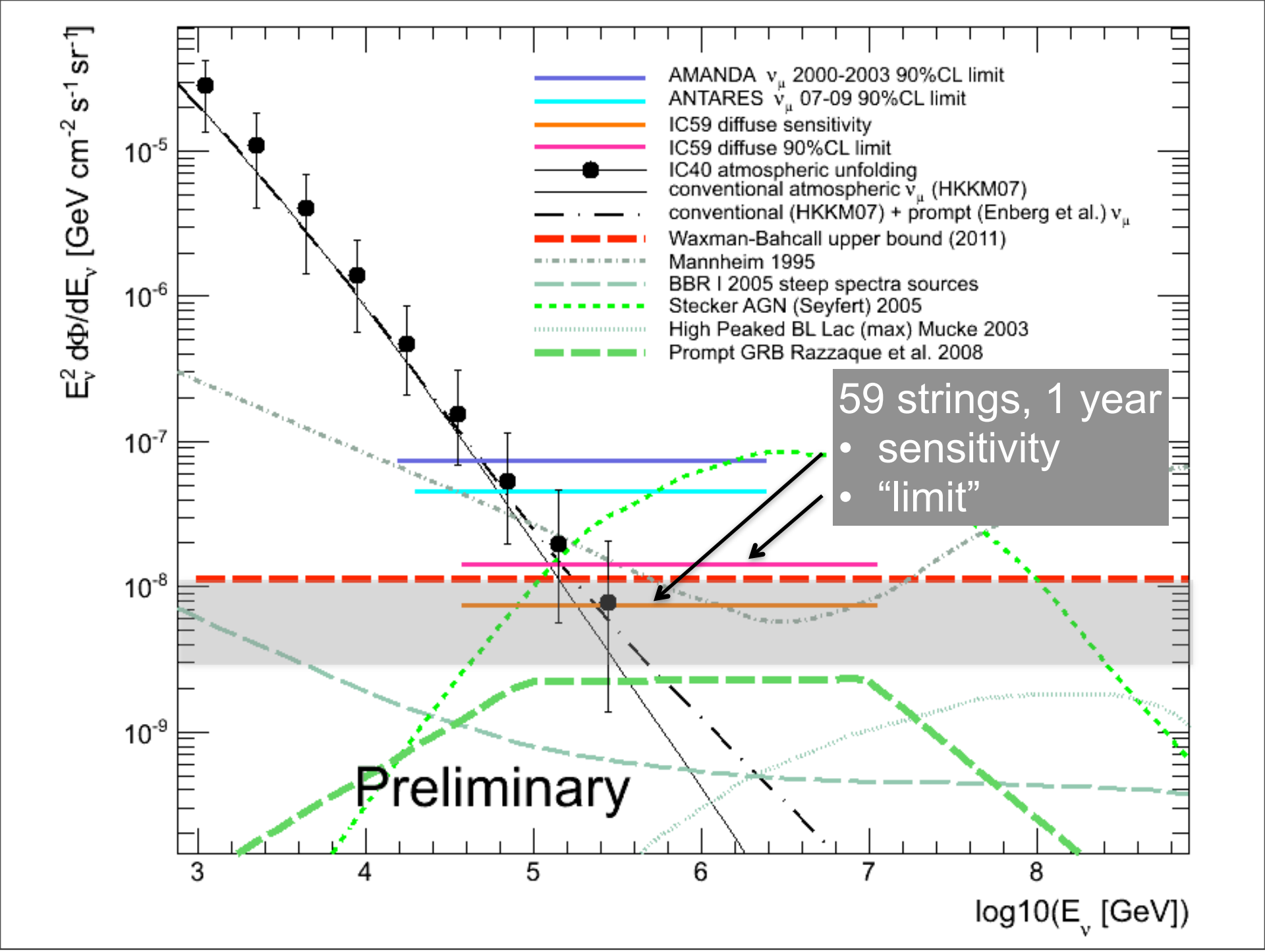
sources accommodating the observed energy budget

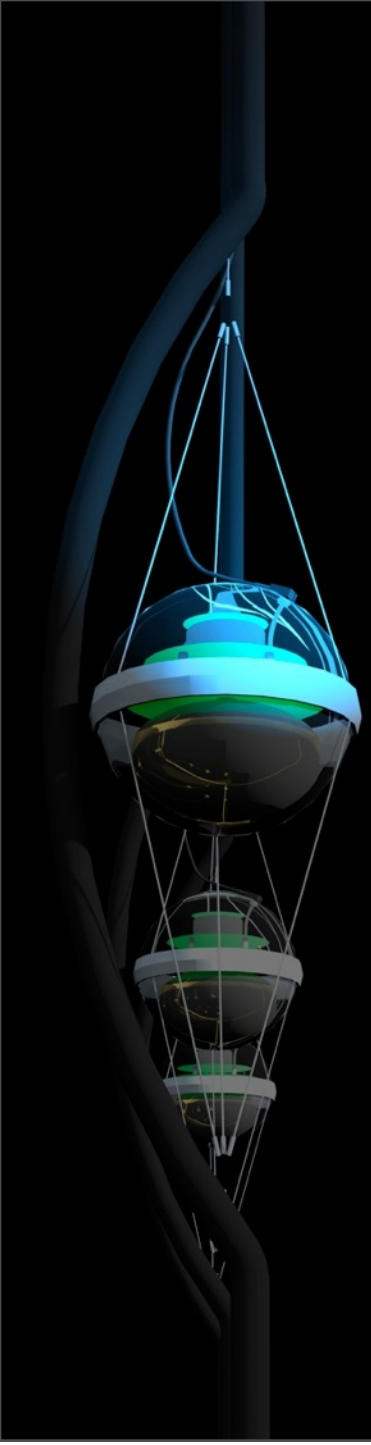
Galactic: supernova remnants?

extragalactic:
- gamma ray bursts?
- active galaxies?




$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1}sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-1
0
1
2
3
4
5
6
7
8
9
$\log_{10}(E_\nu$ [GeV])
Frejus ν_μ
Frejus ν_e
SuperK ν_μ
AMANDA ν_μ
unfolding
foward folding
IceCube ν_μ
unfolding
foward folding
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
GRB
GZK
Galactic supernovae
100 →
10 →
events
per km^{2}yr


AMANDA ν_μ 2000-2003 90%CL limit
ANTARES ν_μ 07-09 90%CL limit
IC59 diffuse sensitivity
IC59 diffuse 90%CL limit
IC40 atmospheric unfolding
conventional atmospheric ν_μ (HKKM07)
conventional (HKKM07) + prompt (Enberg et al.) ν_μ
Waxman-Bahcall upper bound (2011)
Mannheim 1995
BBR I 2005 steep spectra sources
Stecker AGN (Seyfert) 2005
High Peaked BL Lac (max) Mucke 2003
Prompt GRB Razzaque et al. 2008
59 strings, 1 year
• sensitivity
• "limit"
Preliminary
$E_\nu^2\, d\Phi/dE_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
log10(E_ν [GeV])



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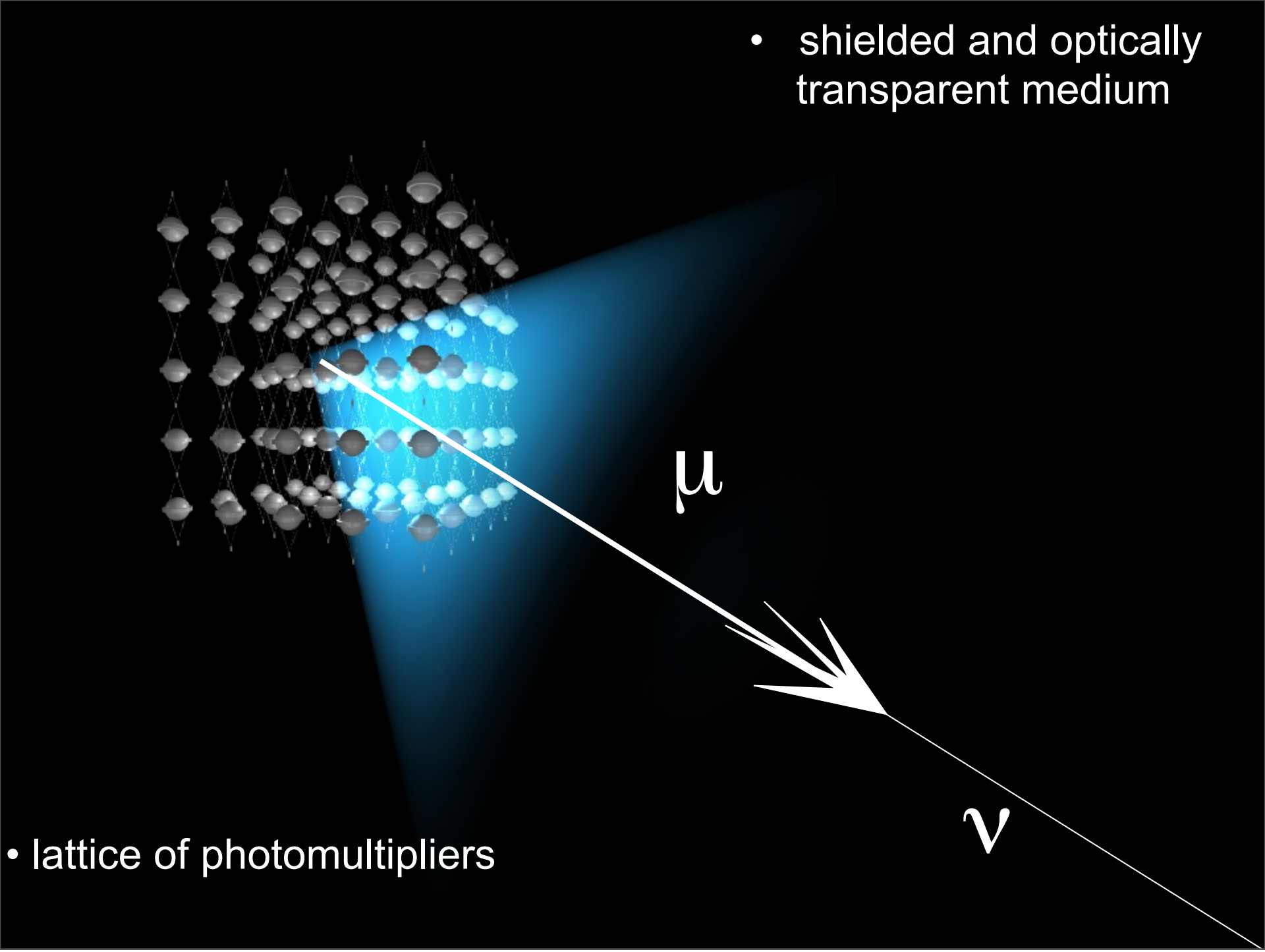
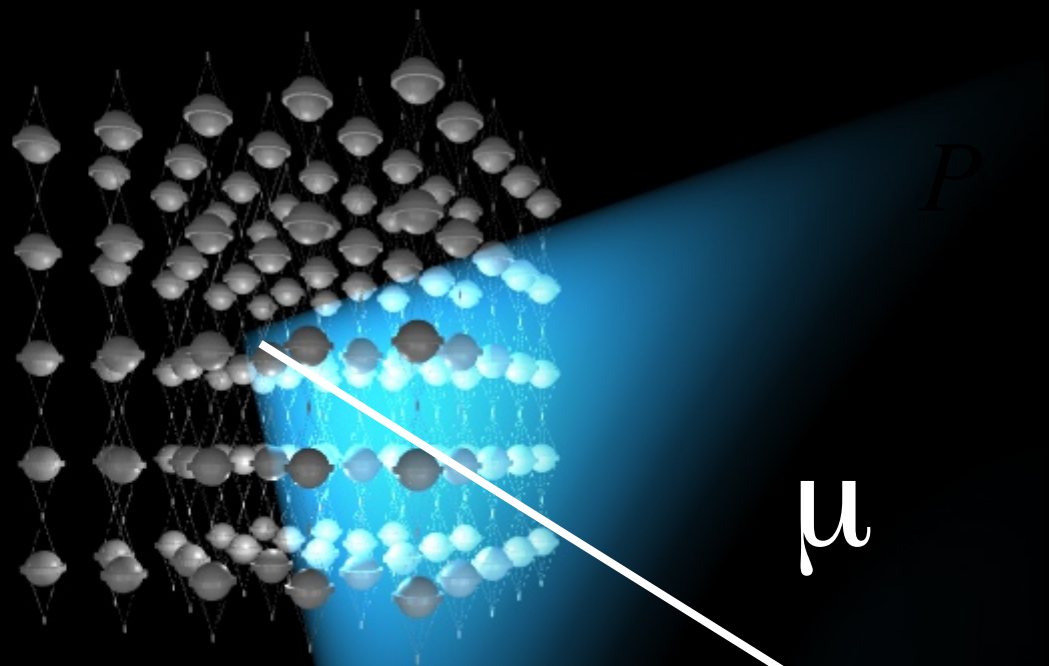
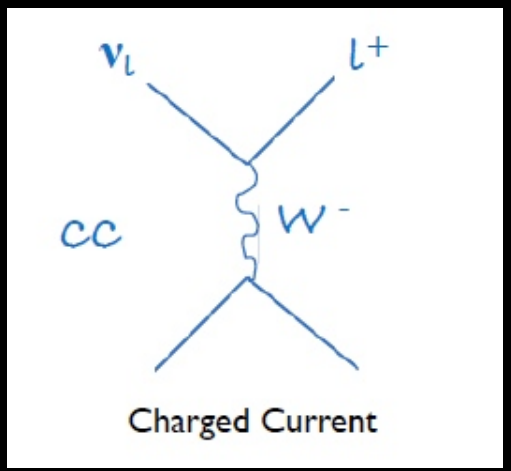

• shielded and optically transparent medium
μ
ν
• lattice of photomultipliers

- shielded and optically transparent medium



μ

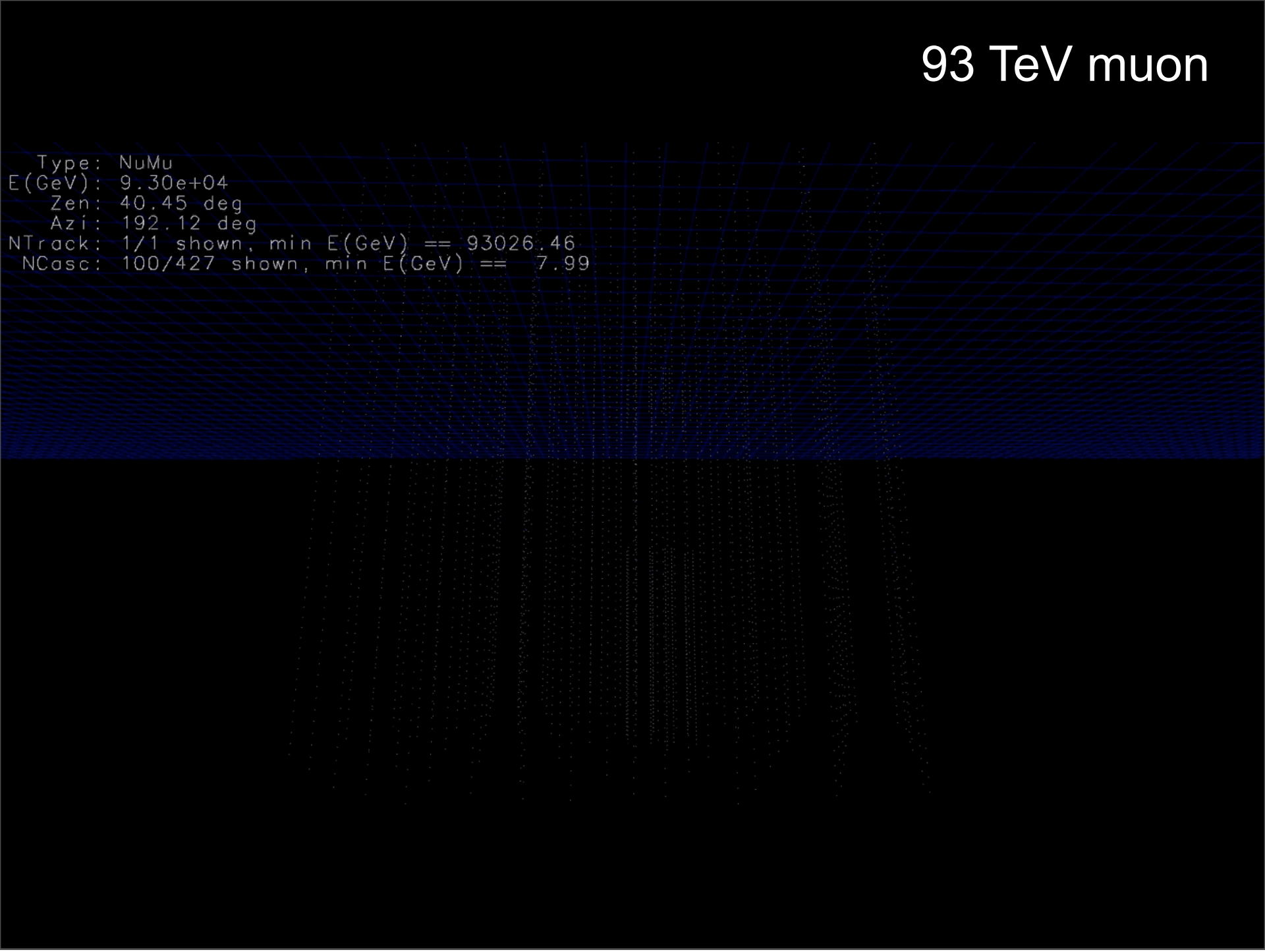


ν

- lattice of photomultipliers

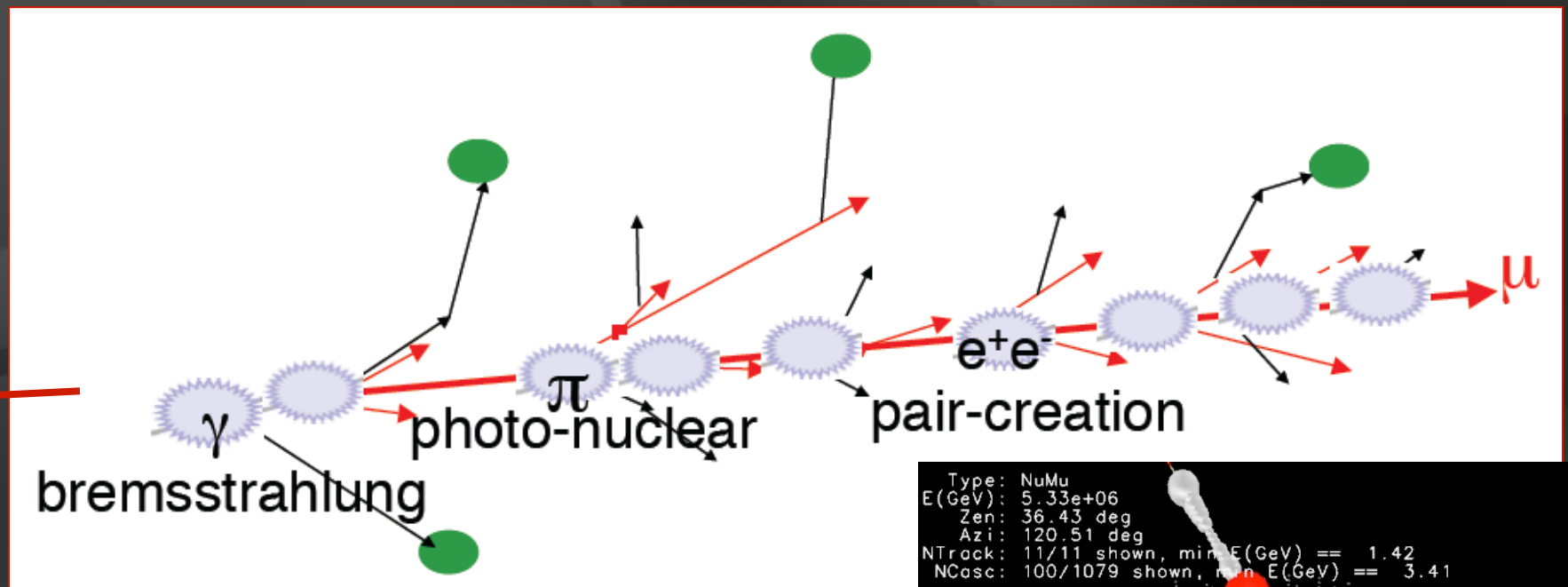
93 TeV muon

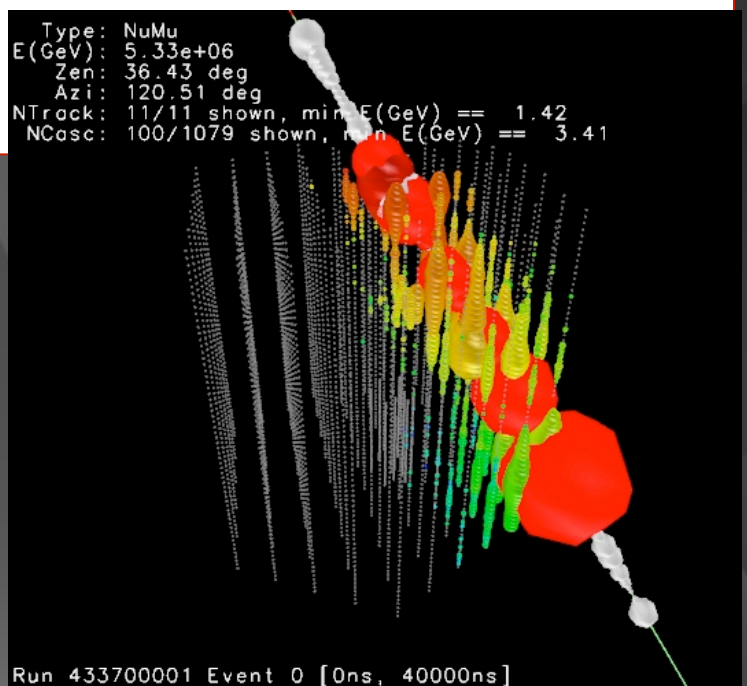
93 TeV muon


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

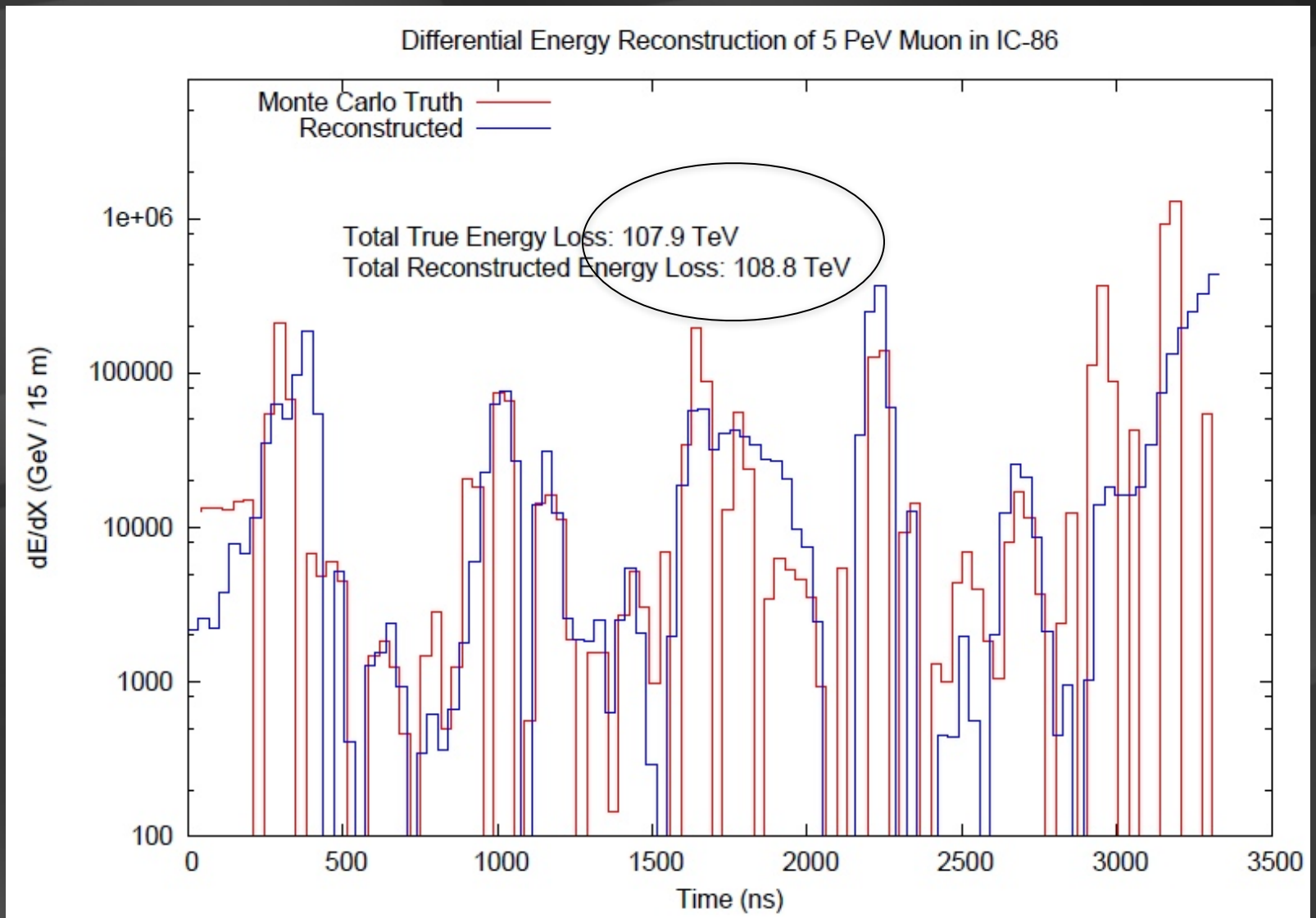
93 TeV muon

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, …)

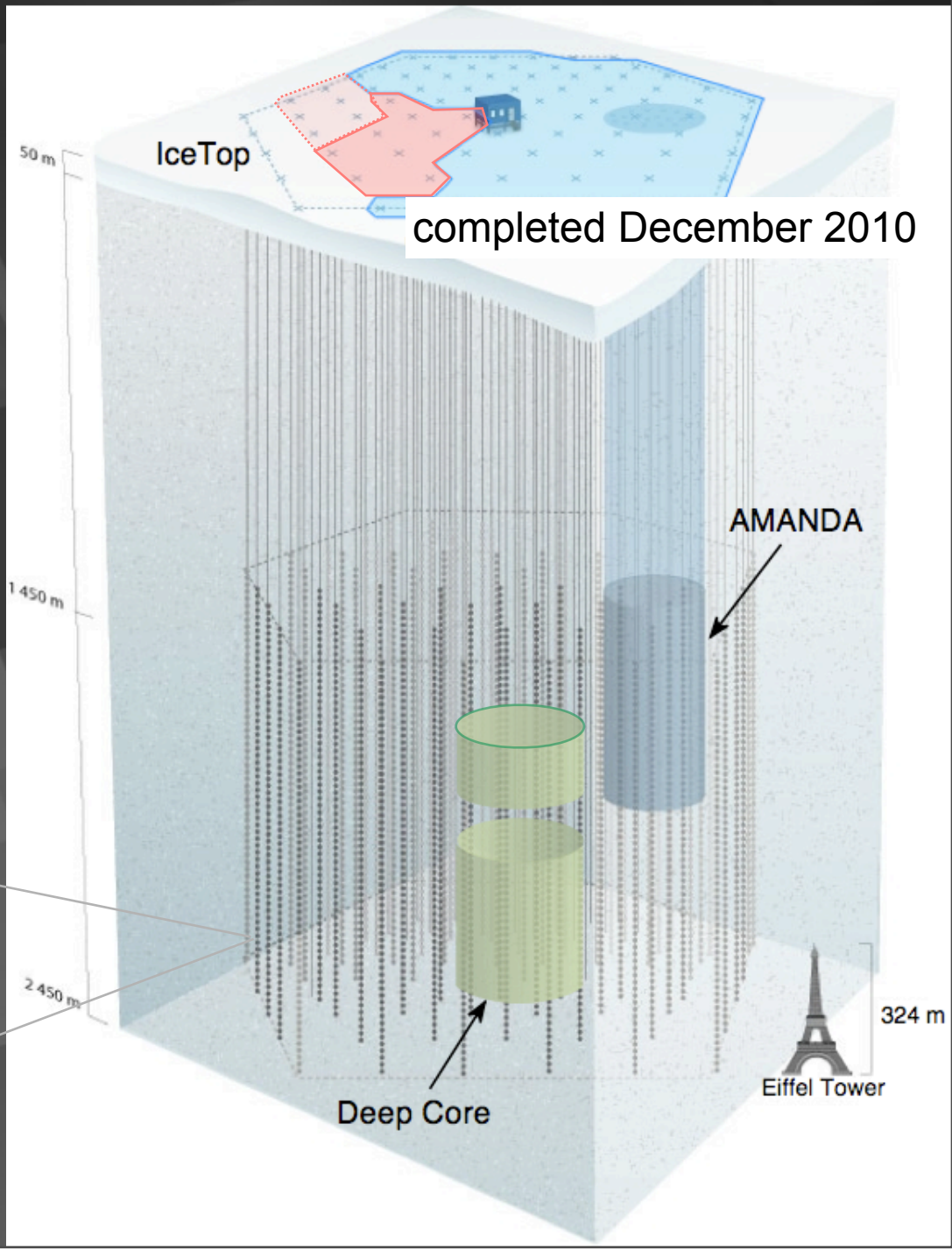


improving angular and energy resolution

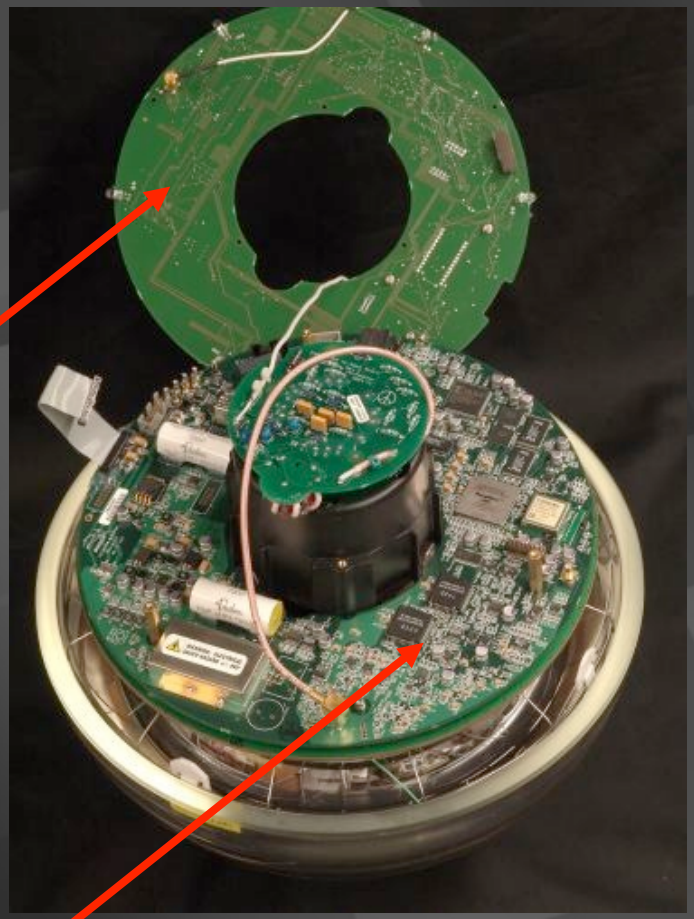
IceCube / Deep Core

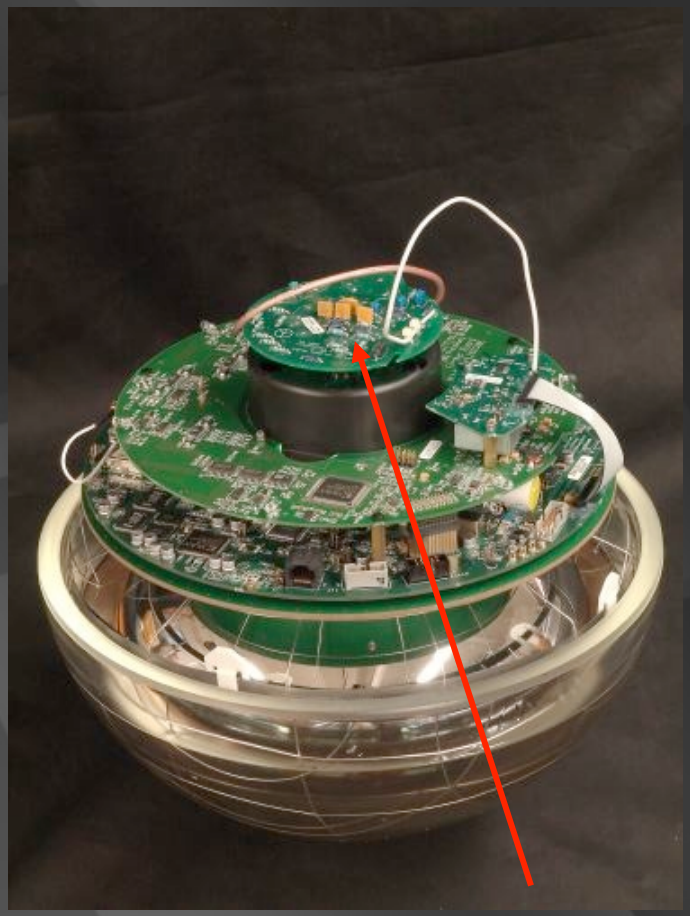
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
  < 0.3 degree off line
  for m
  (10~1 degrees
  showers)
- < 15% energy resolution

Digital Optical Module (DOM)



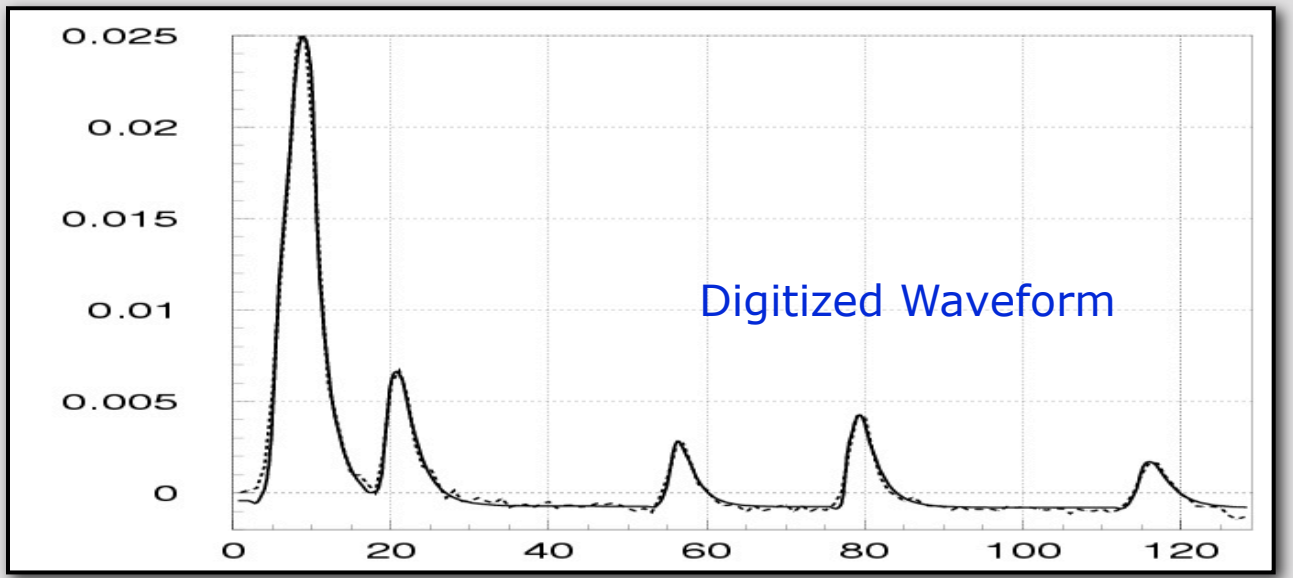
architecture of independent DOMs



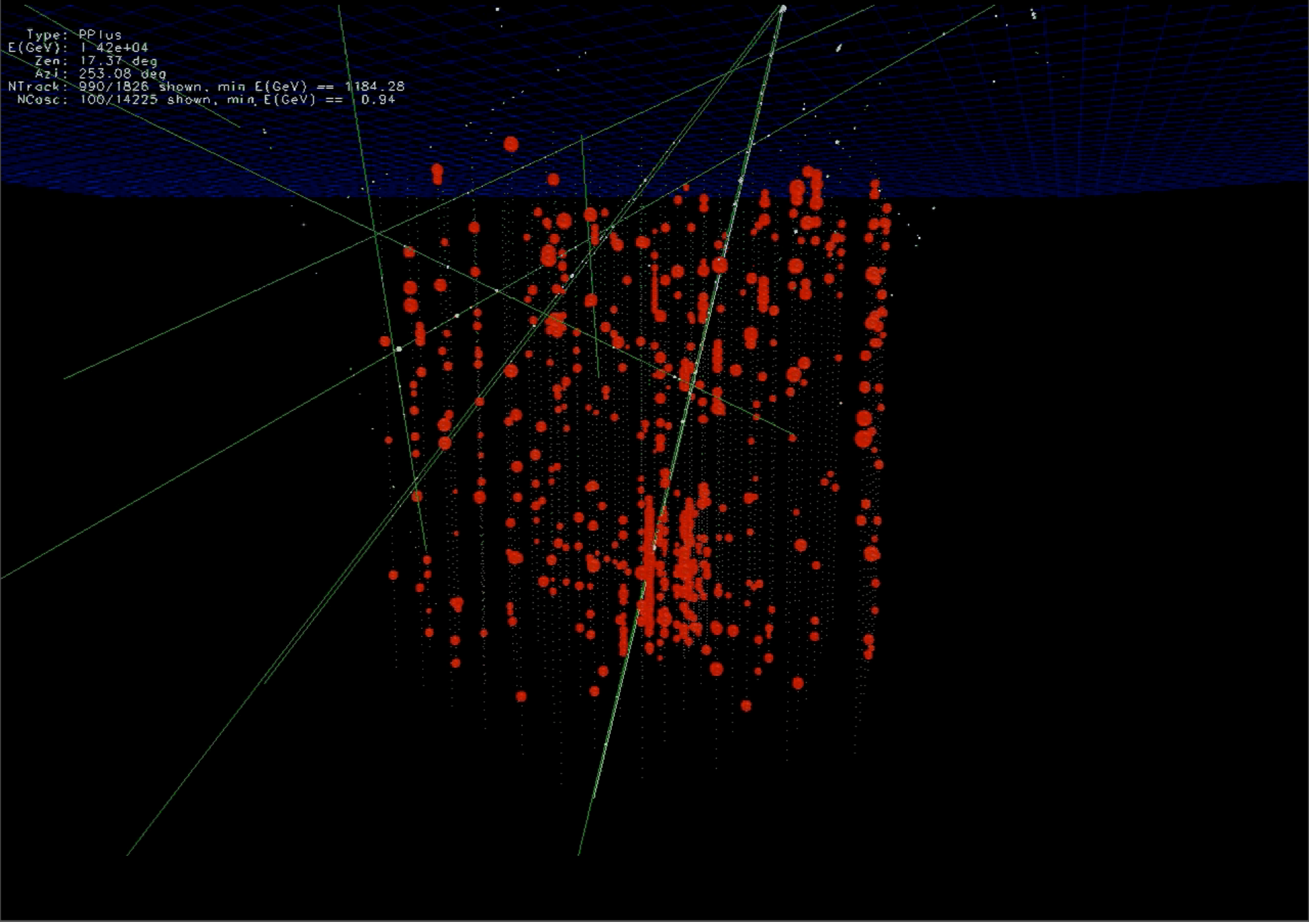


Digital Optical Module (DOM)

… each DOM independently collects light signals like this…



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


Type: PPlus
E(GeV): 1.42e+04
Zen: 17.37 deg
Azi: 253.08 deg
NTrack: 990/1826 shown, min E(GeV) == 1184.28
NCasc: 100/14225 shown, min E(GeV) == 0.94

… 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

Neutrino Skymaps

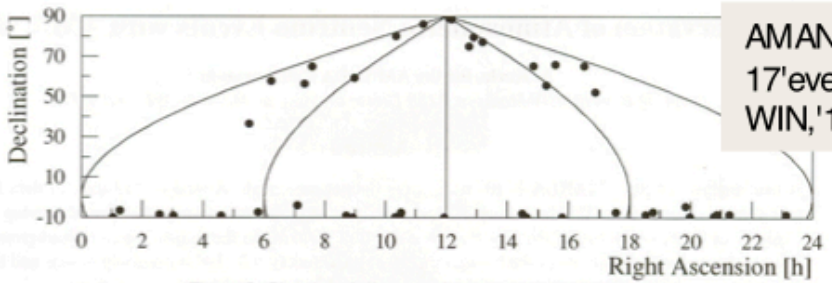


Figure 2: Sky plot of all events that pass level 4 quality cuts.

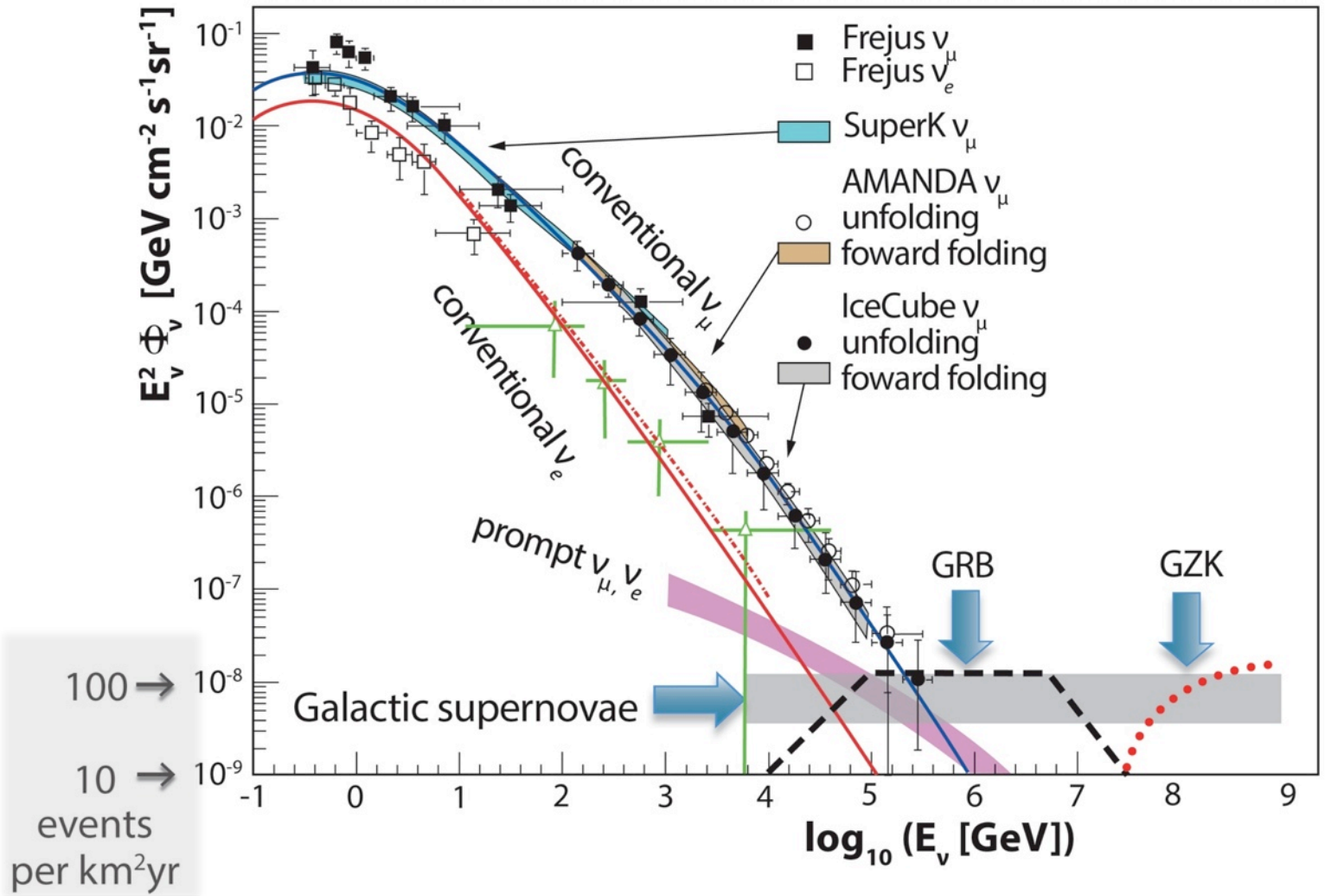
AMANDA-B10
17 events
WIN, 1999

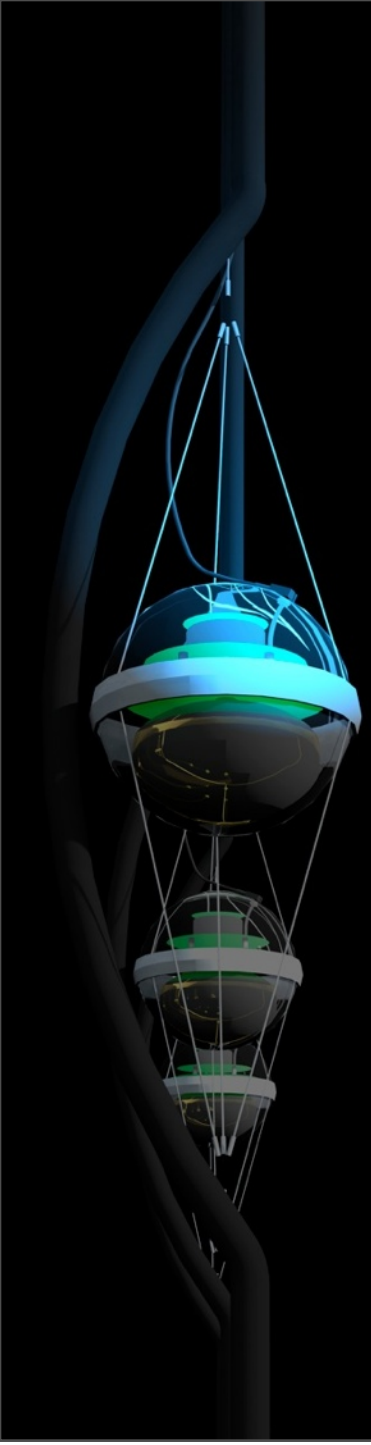
AMANDA-B10
178 events
nature, 2001

AMANDA-II
7 years
6995 events
2006

28 events

IceCube 40+59
60000 events
2012


$E^2_\nu \Phi_\nu$ [GeV cm^{-2} s^{-1}sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-1
0
1
2
3
4
5
6
7
8
9
$\log_{10}(E_\nu$ [GeV])
Frejus ν_μ
Frejus ν_e
SuperK ν_μ
AMANDA ν_μ
unfolding
foward folding
IceCube ν_μ
unfolding
foward folding
conventional ν_μ
conventional ν_e
prompt $\nu_{\mu,}$ ν_e
GRB
GZK
Galactic supernovae
100 →
10 →
events
per km^{2}yr



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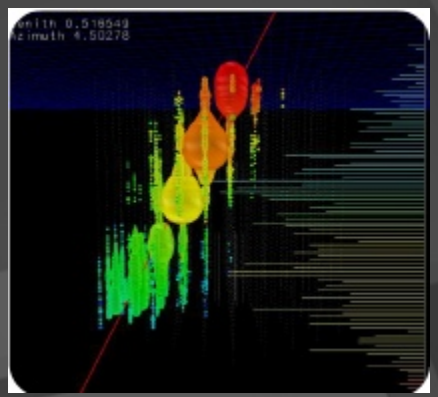
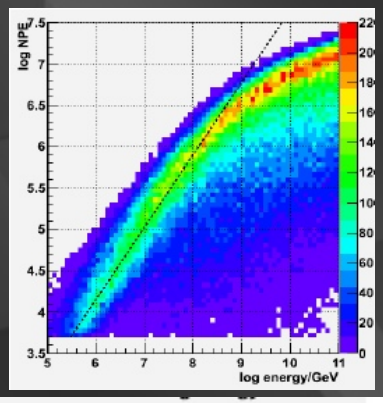
GZK neutrinos: > 41,000 photons near the horizon

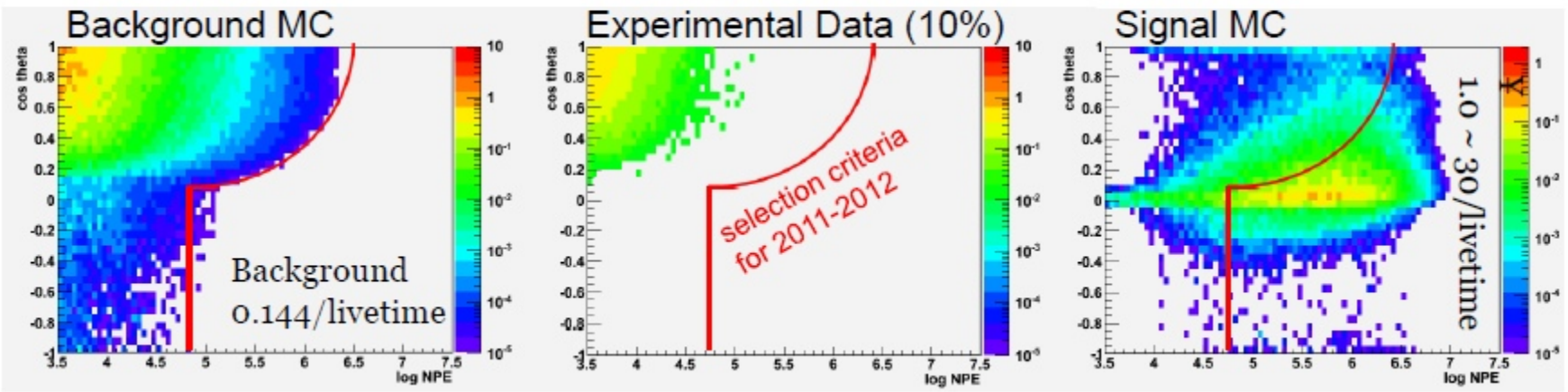


number of channels > 300

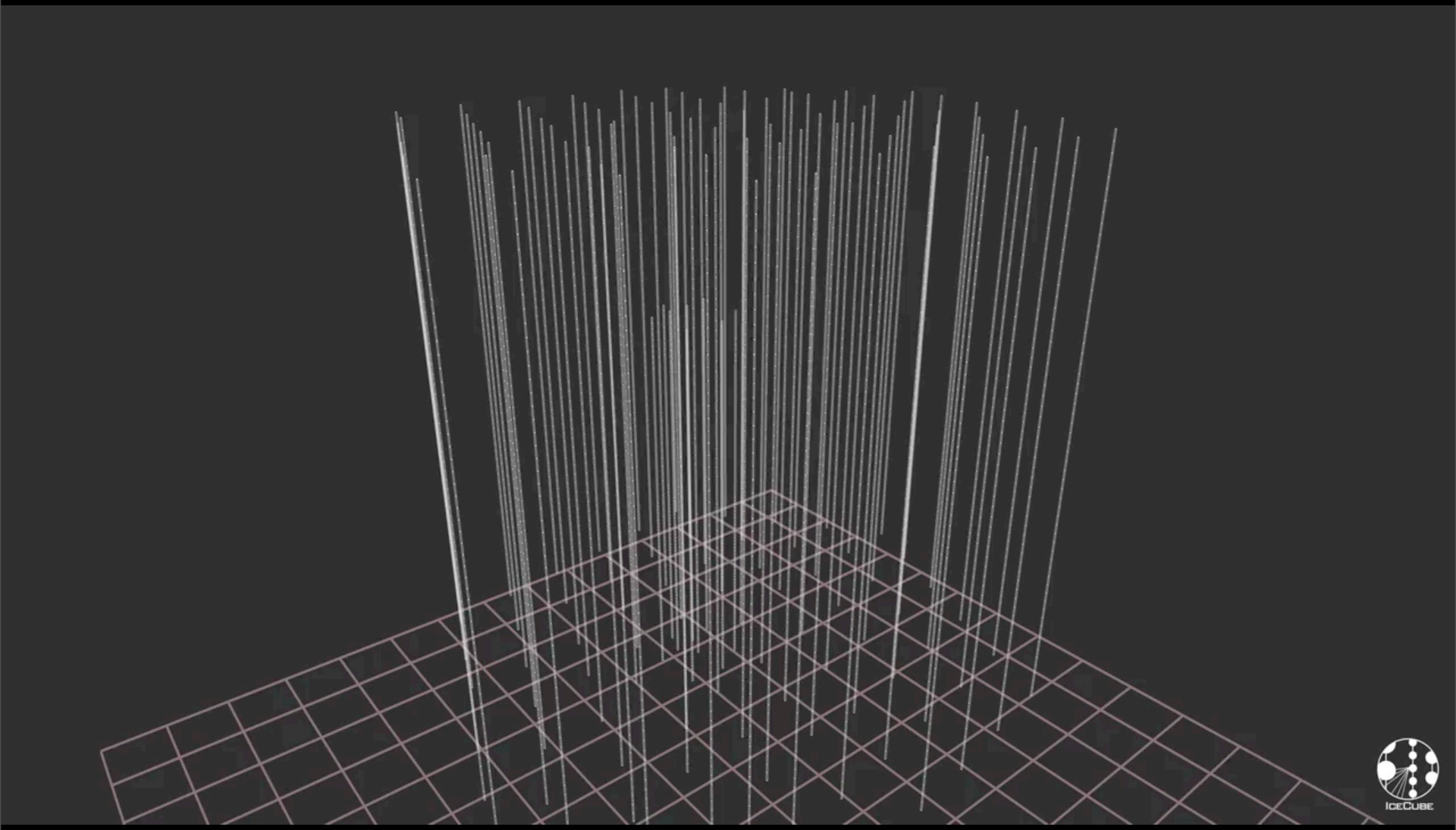


Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

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

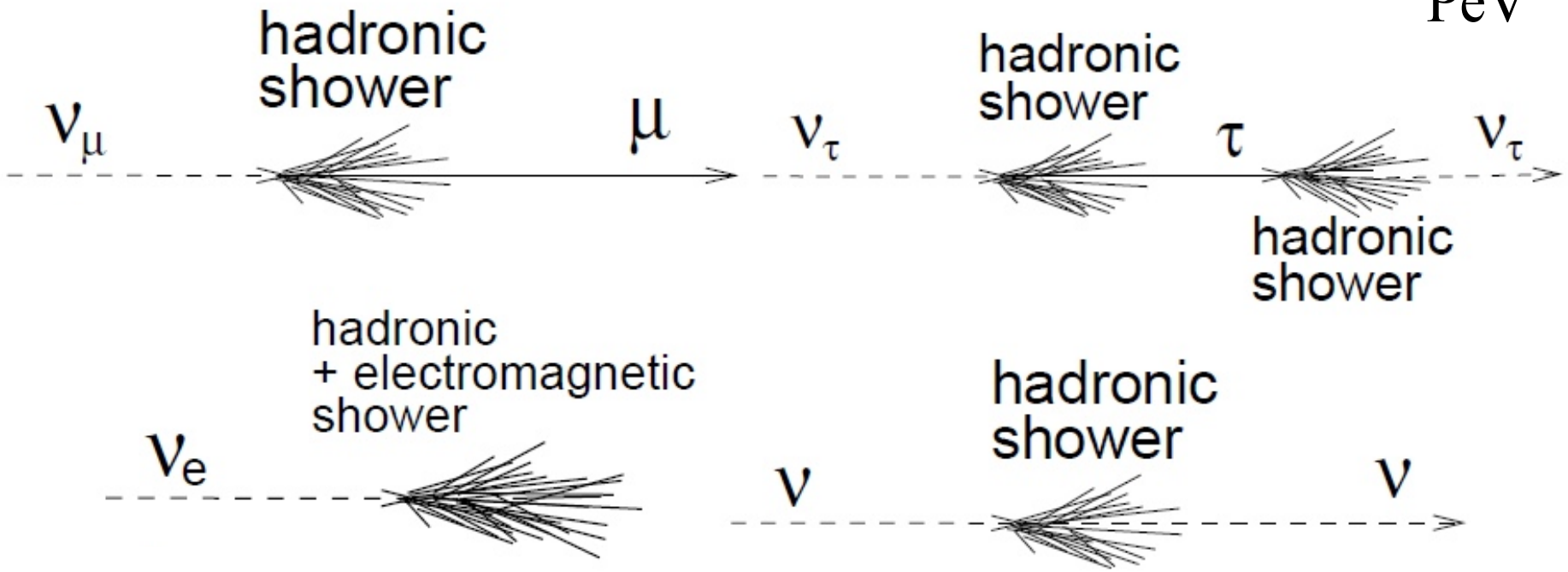


unblinding: 2 events in the signal region

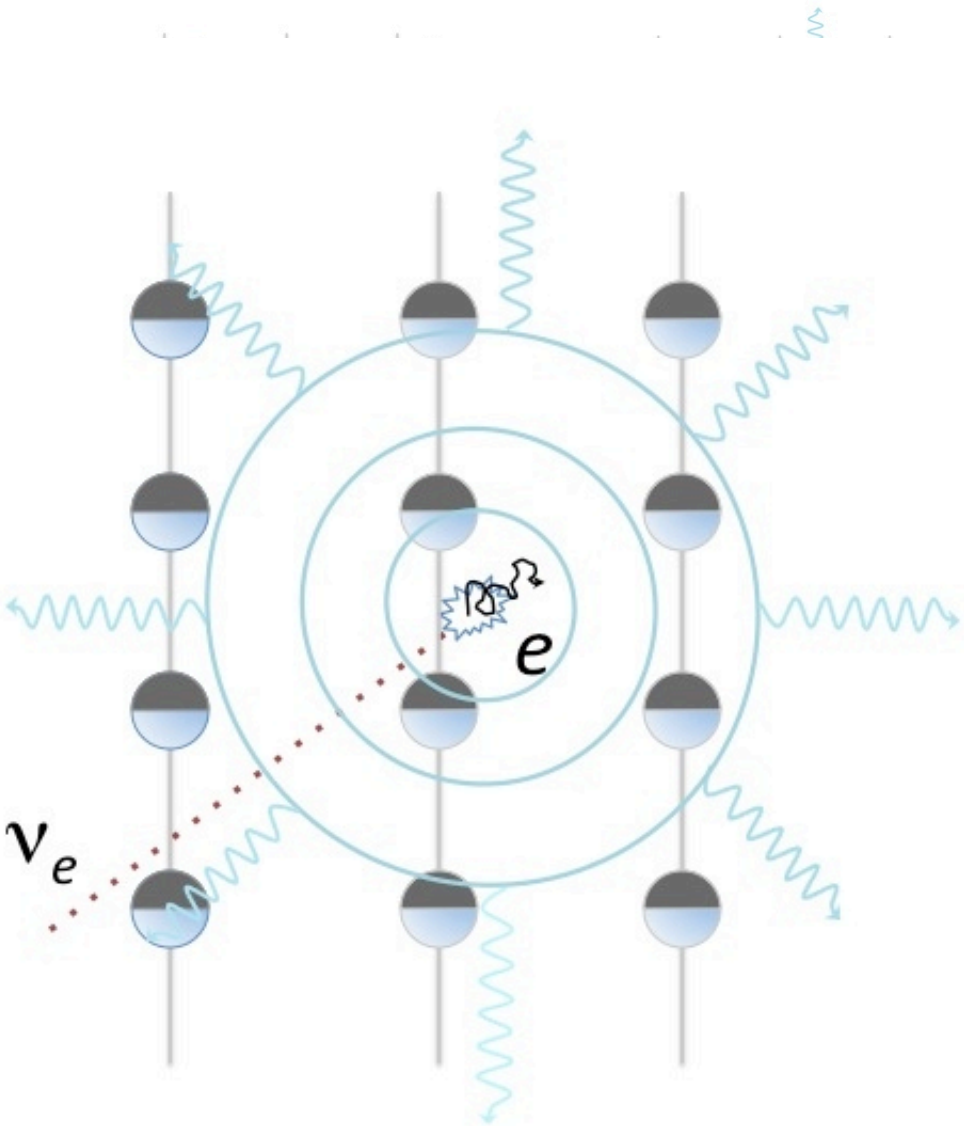

IceCube

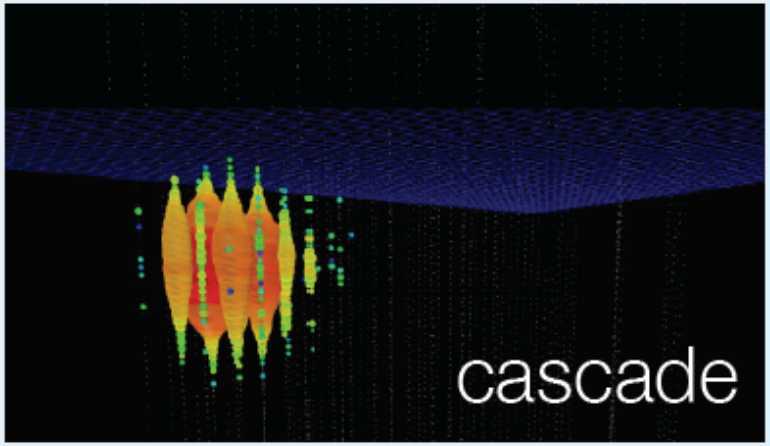
neutrino flavors

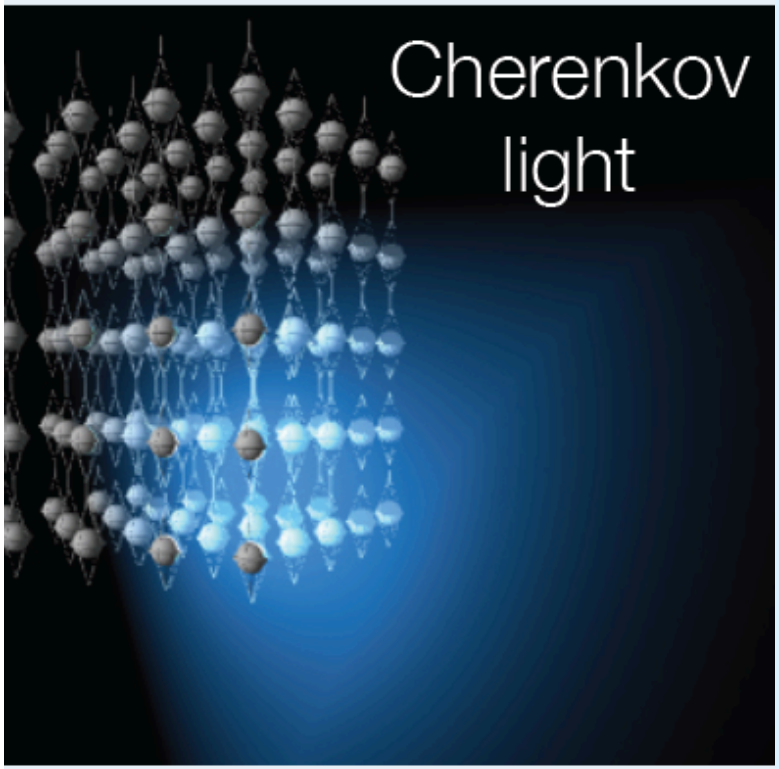
$$\text{length of } \tau \text{ track} = 50\text{m} \times \frac{E_\nu}{\text{PeV}}$$



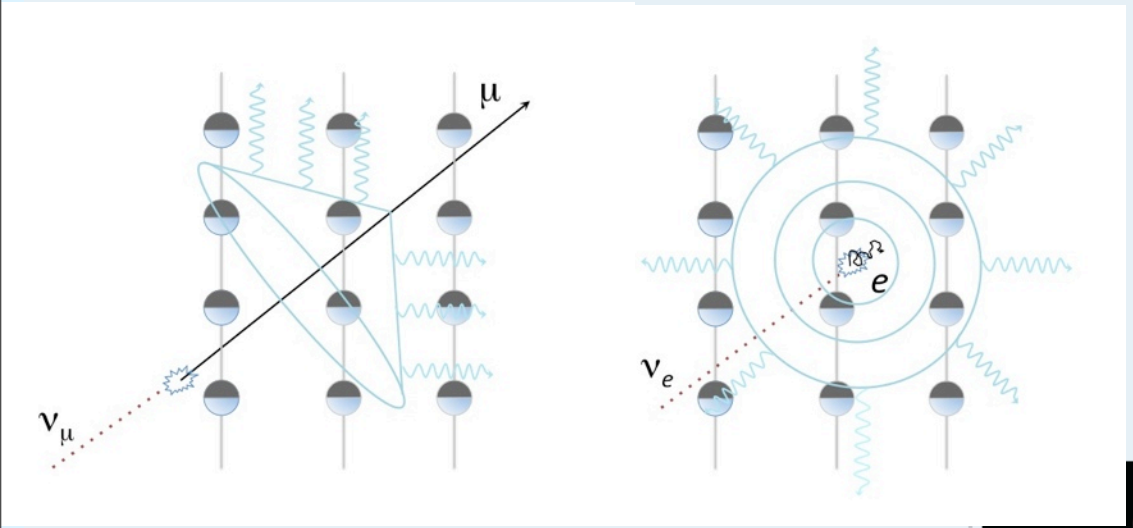
tracks and showers

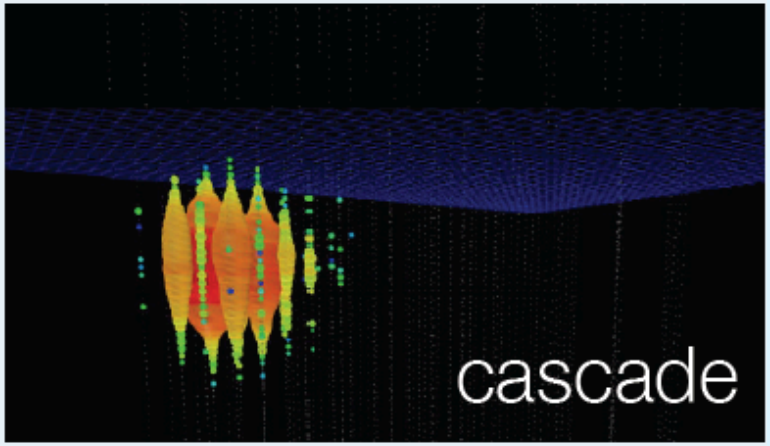


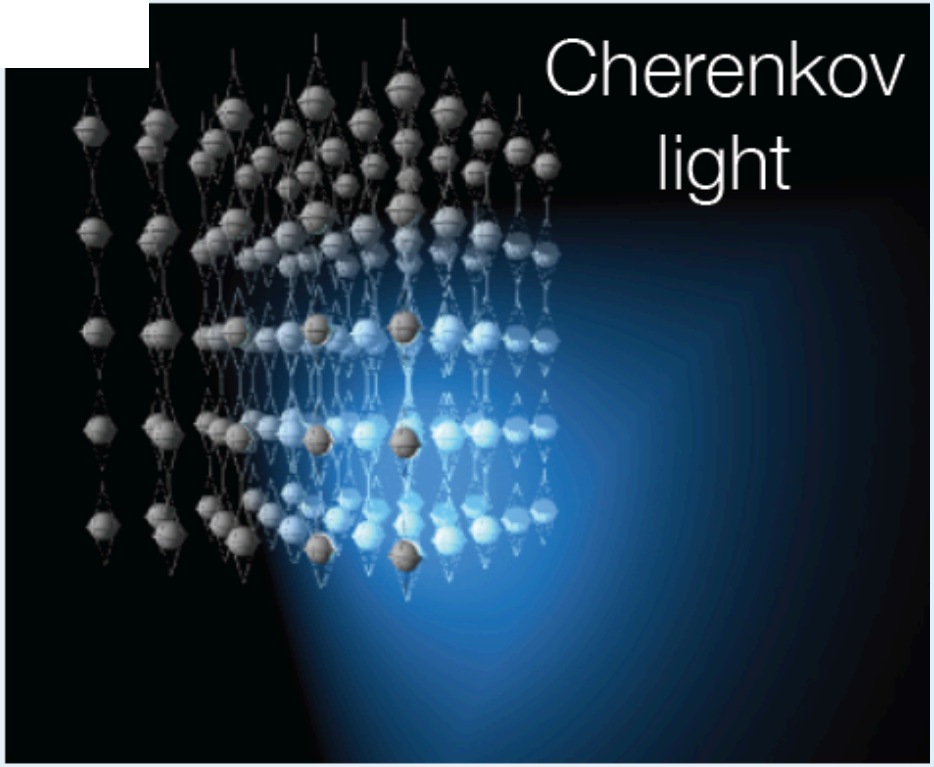


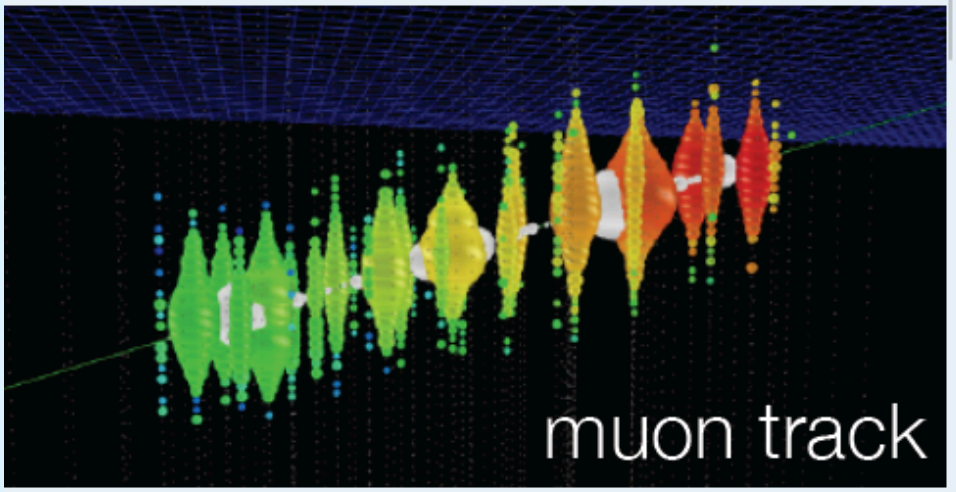


tracks and showers

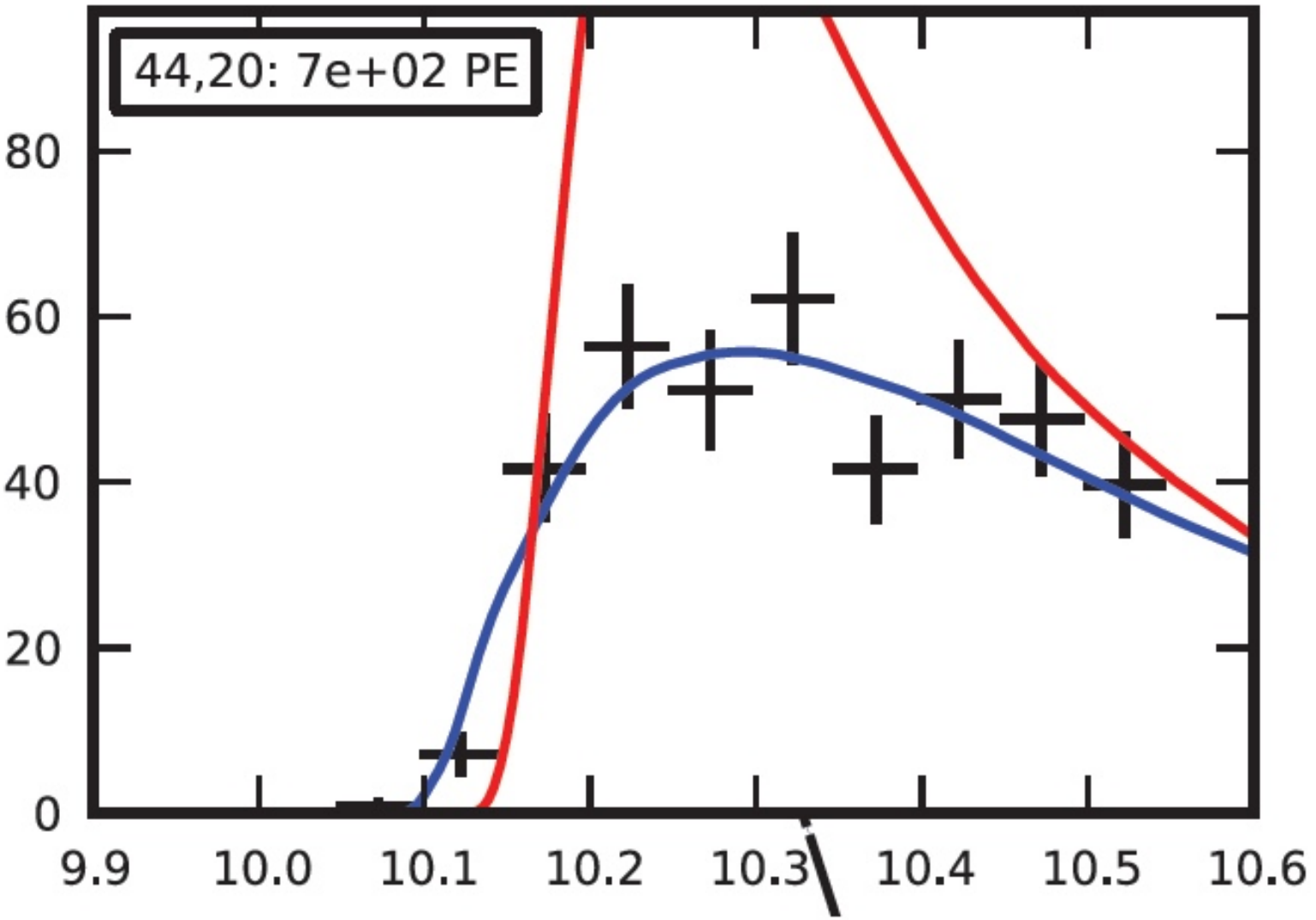




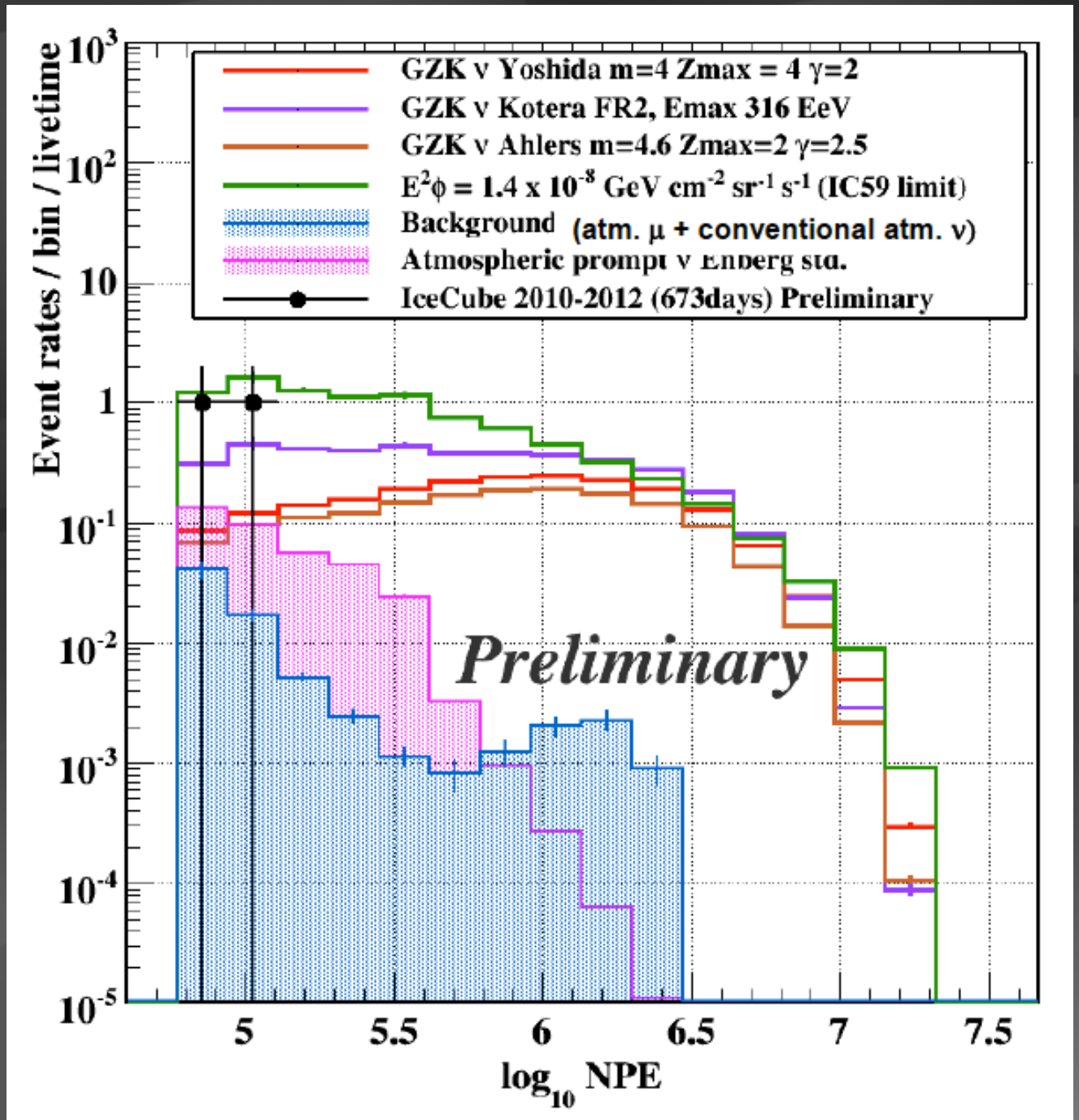




digital optical module 44 on string 20 only



Blue: best-fit direction, red: reversed direction



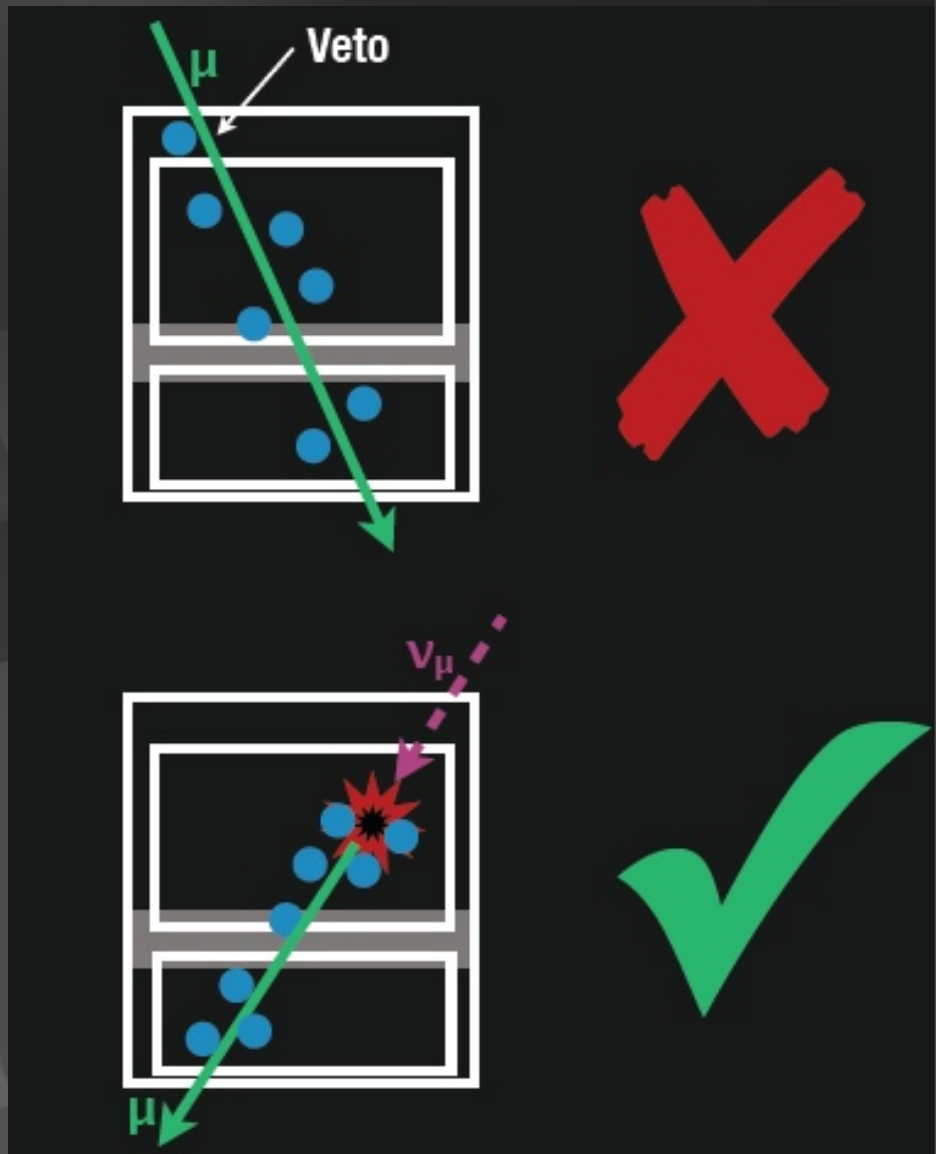
- energy

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

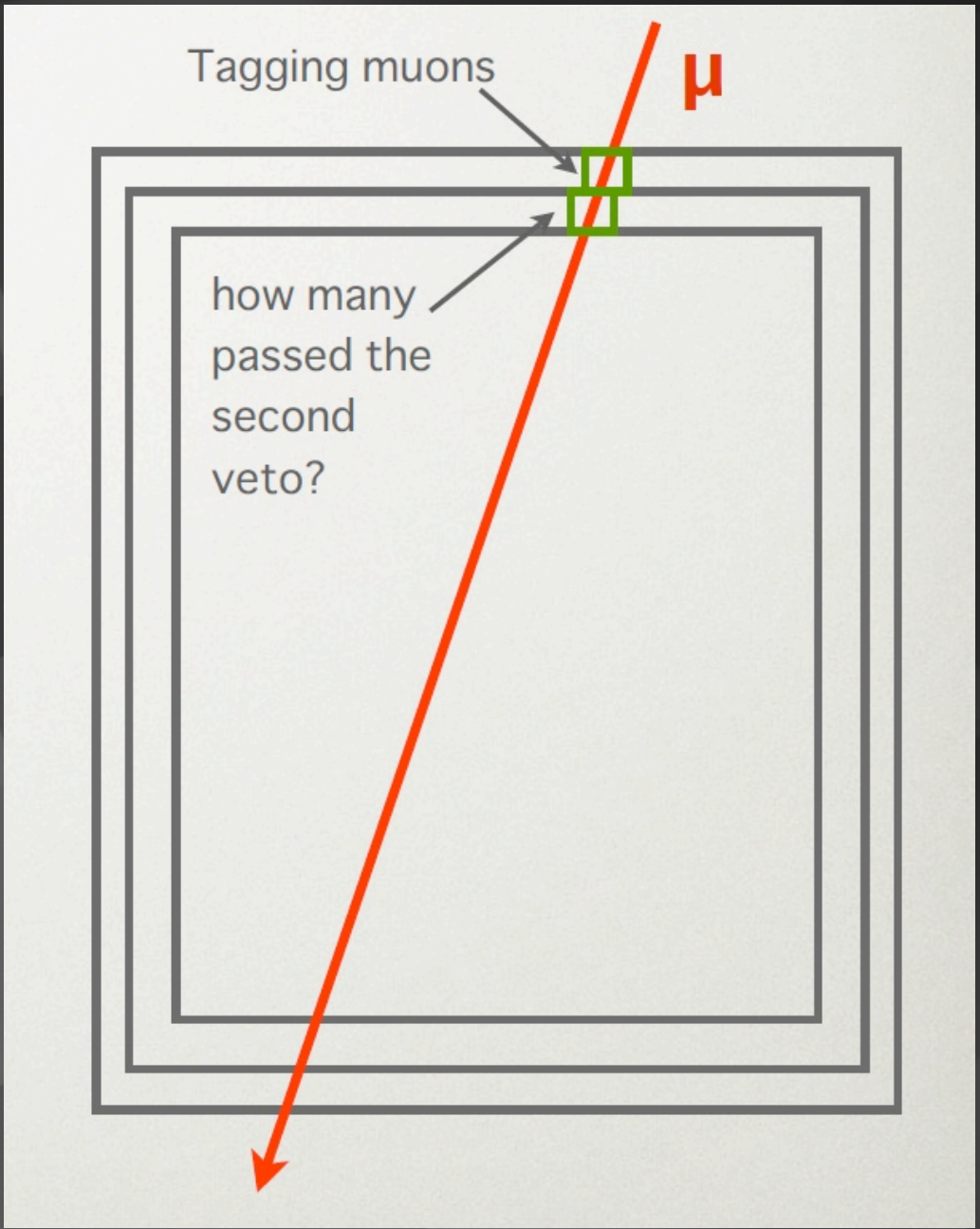
- find more contained events (420 Mton)
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

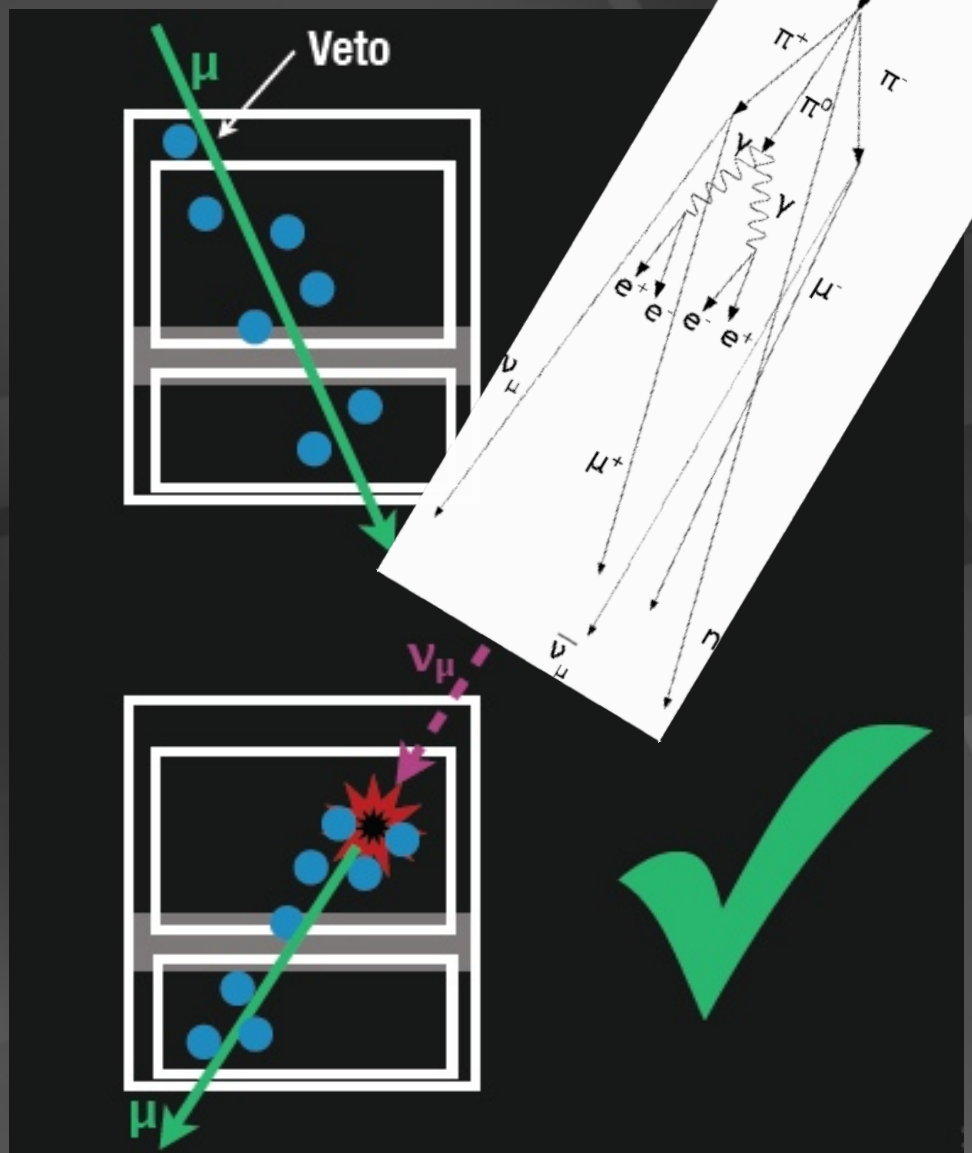


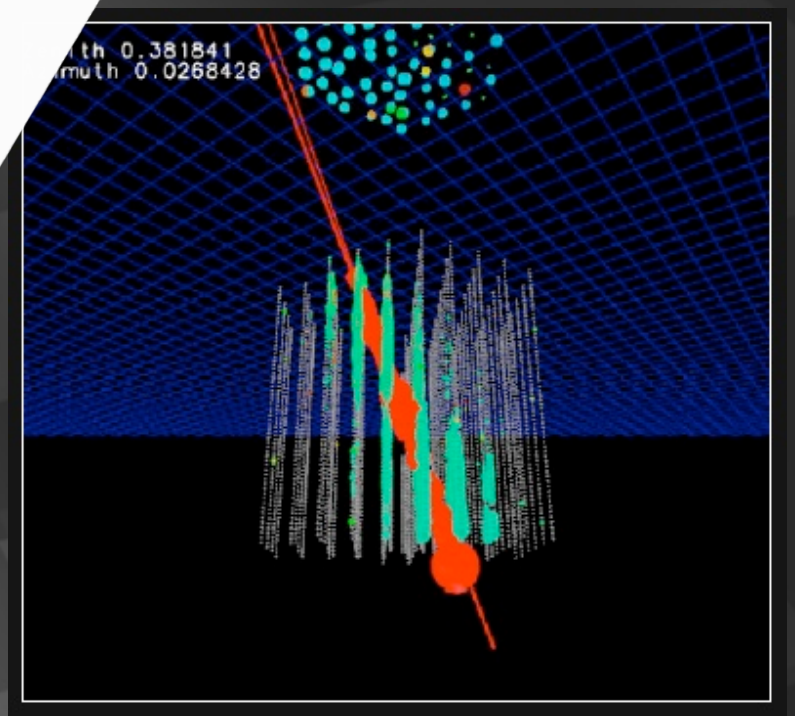
loss in statistics is compensated by event definition

veto efficiency by two layer anticoincidence measurement:

tag muons in the veto region and see what fraction is vetoed by the layer of detectors below; *no simulation*



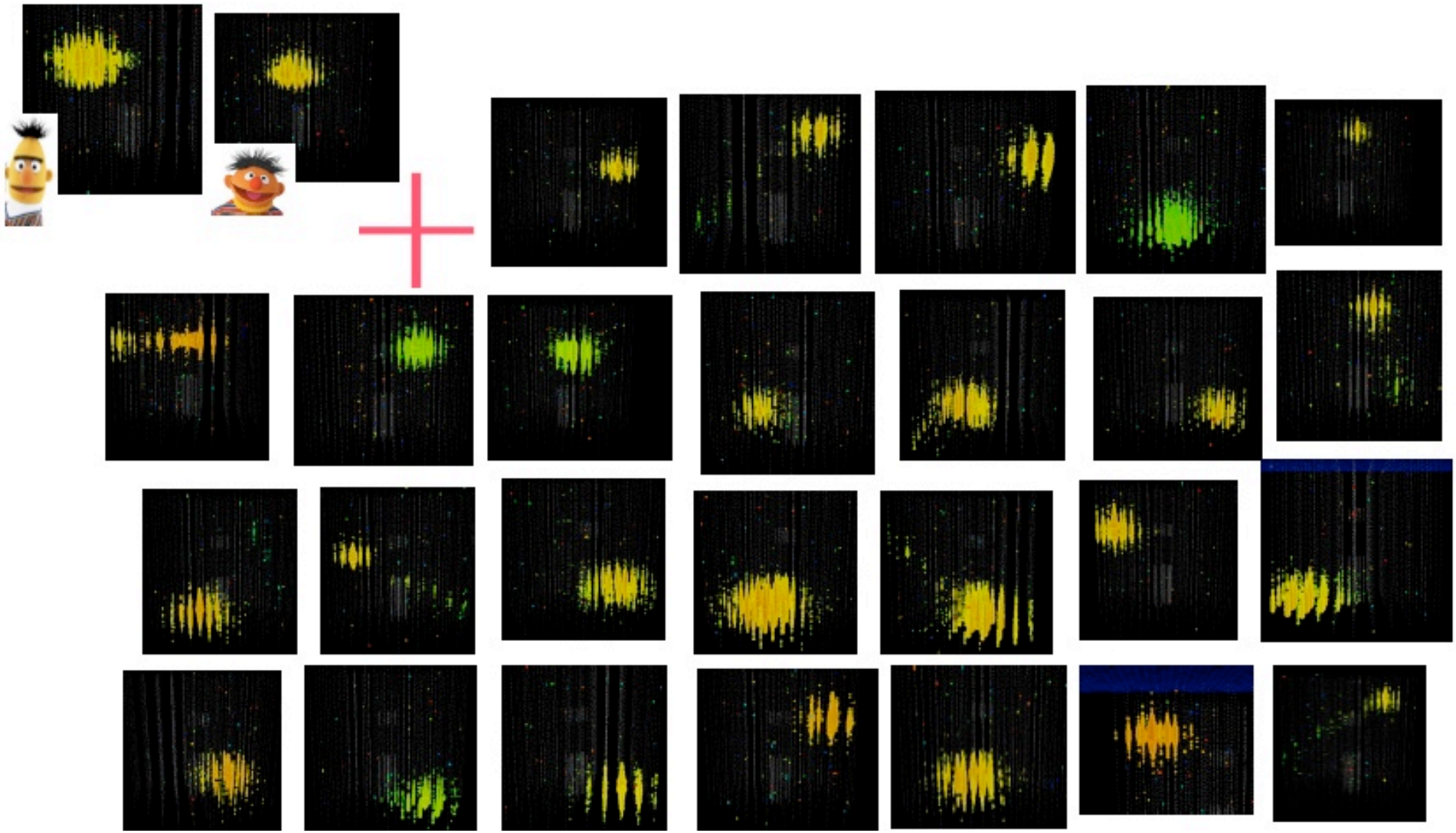




atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

(no signals in IceTop)

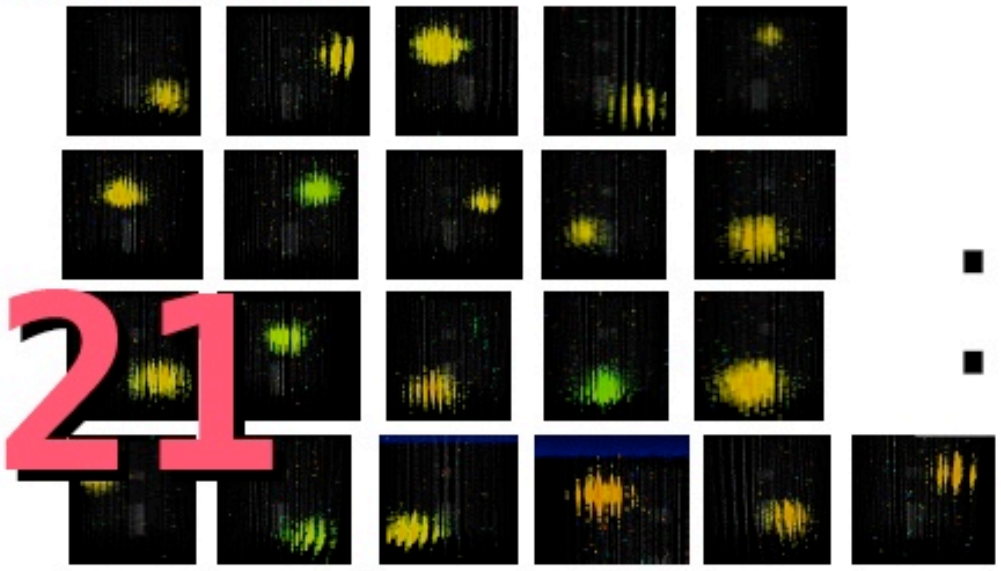
what we found



showers from the South

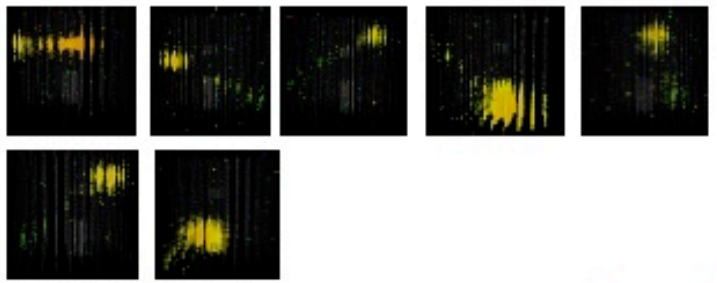
tracks

Showers



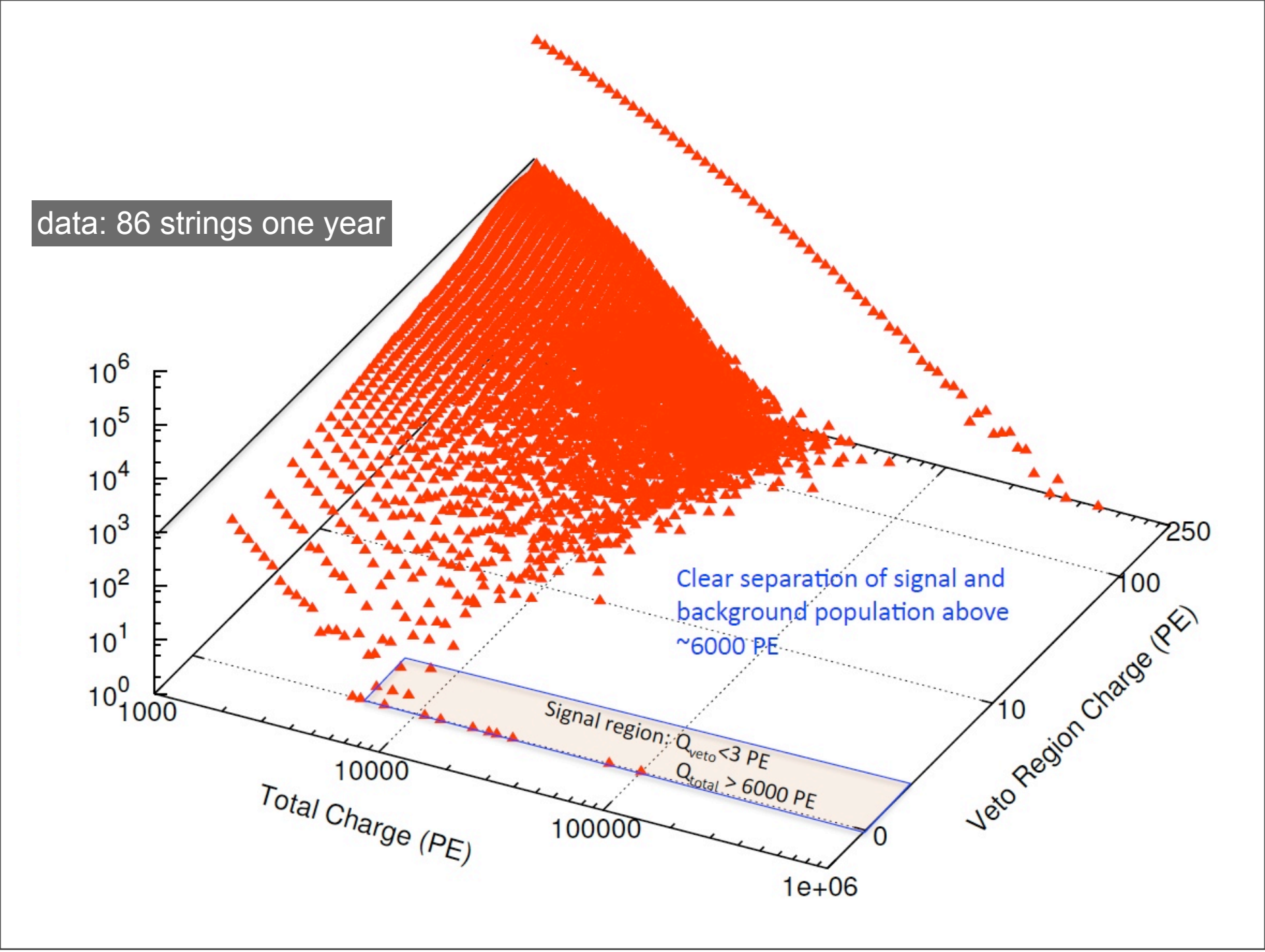
21

Tracks

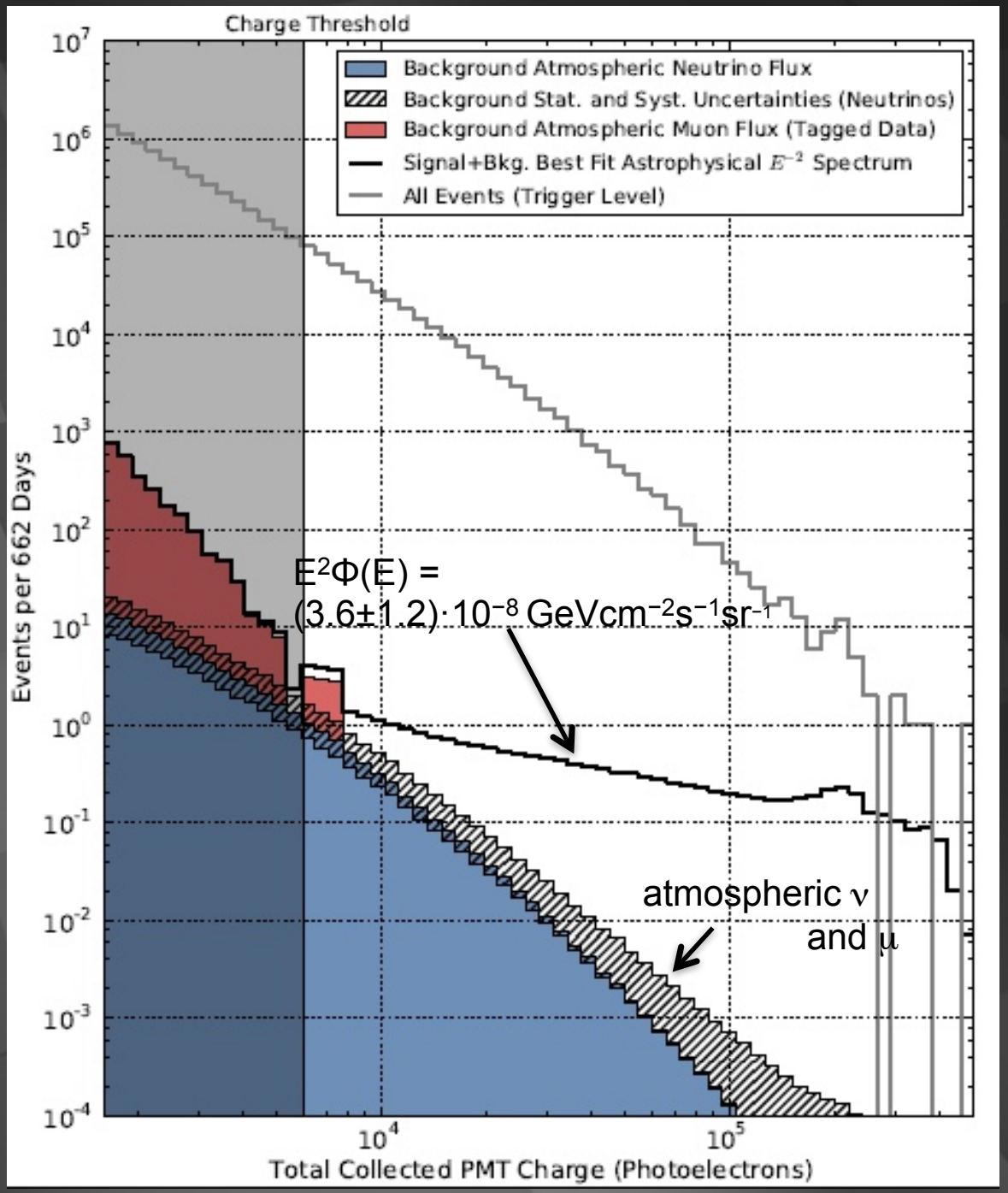


(4 tracks show characteristics of atmospheric muon background)

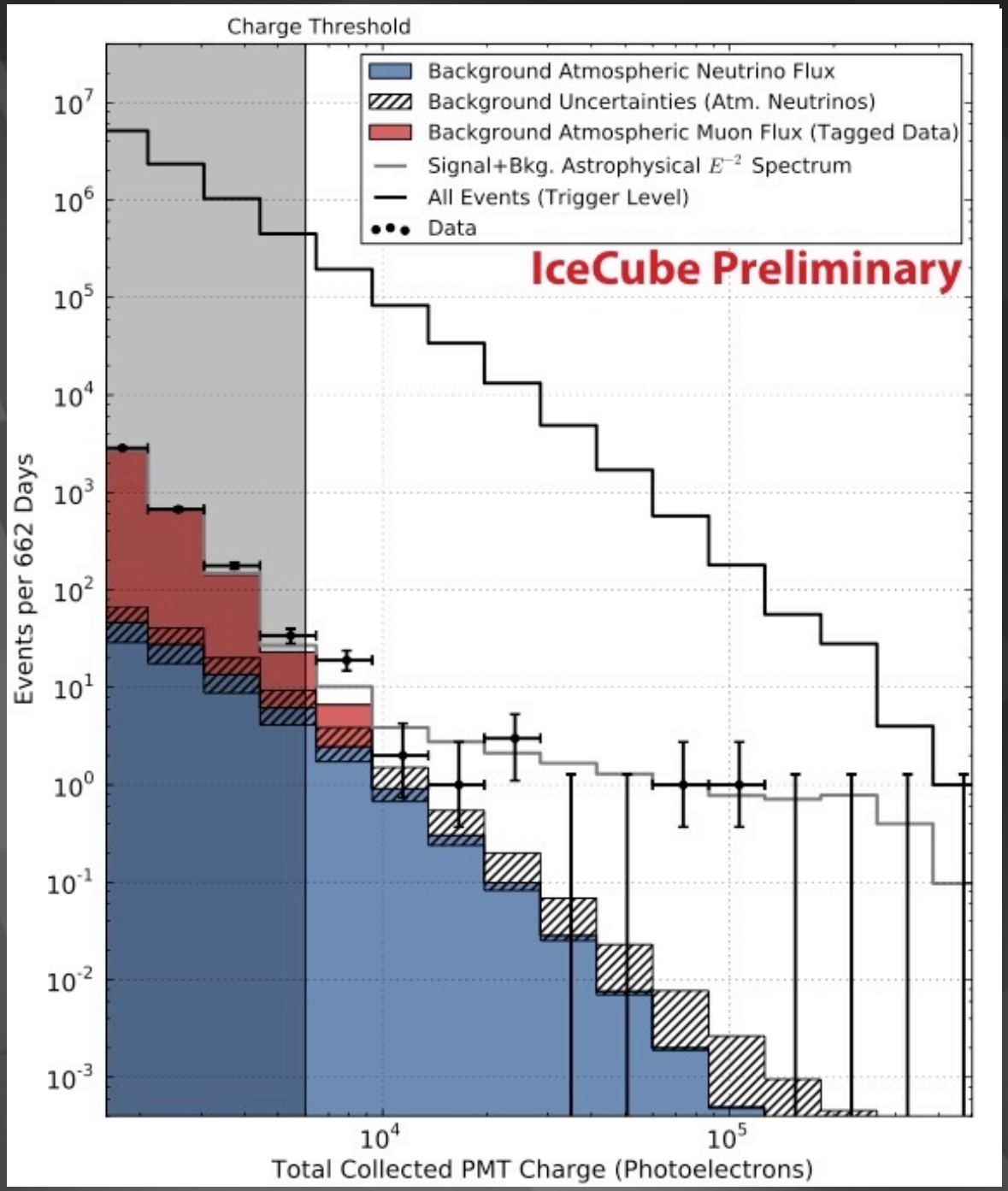
7

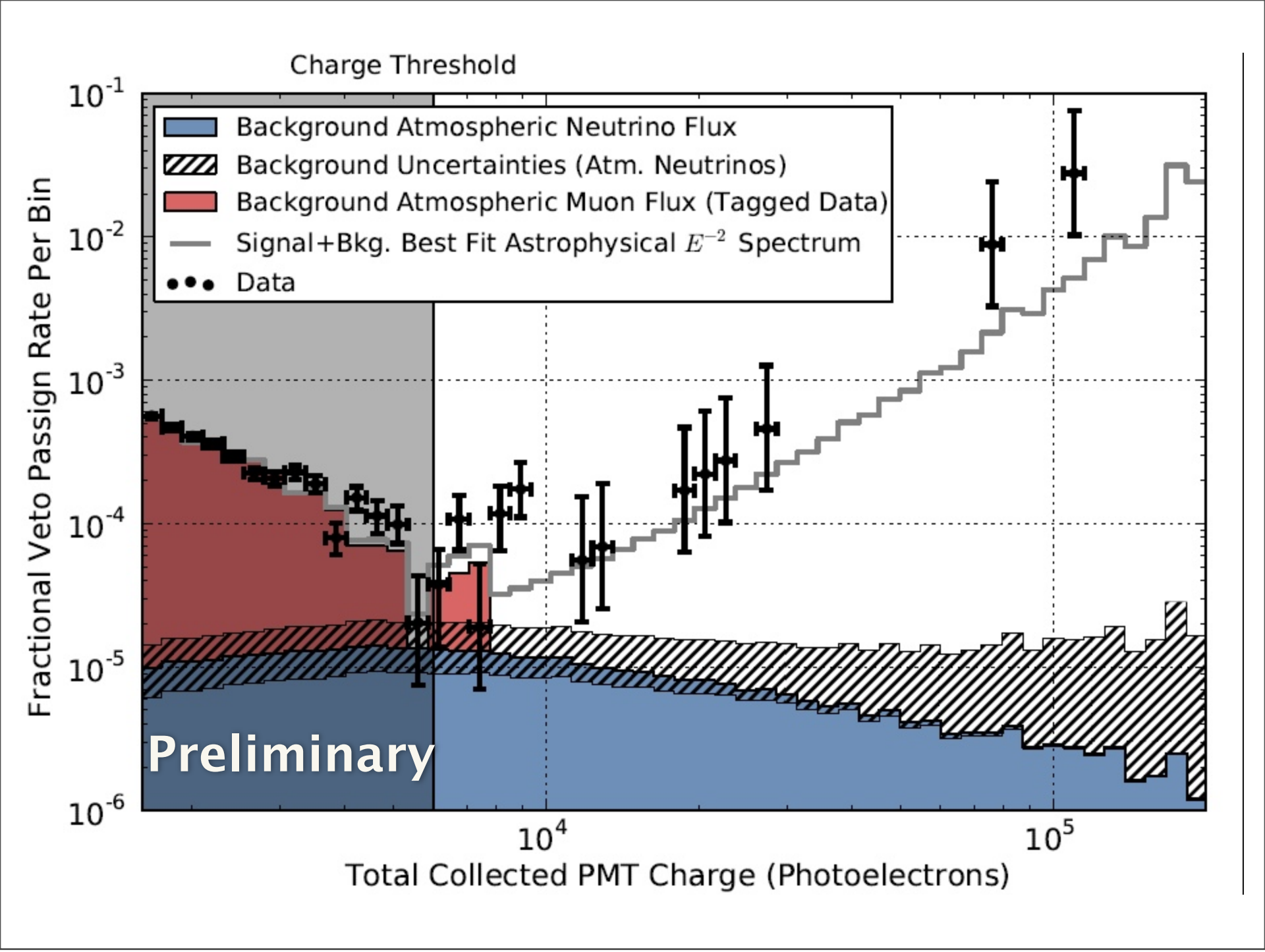

data: 86 strings one year
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1000
10000
100000
1e+06
Total Charge (PE)
250
100
10
0
Veto Region Charge (PE)
Clear separation of signal and background population above ~6000 PE
Signal region: Q_{veto} <3 PE
Q_{total} > 6000 PE

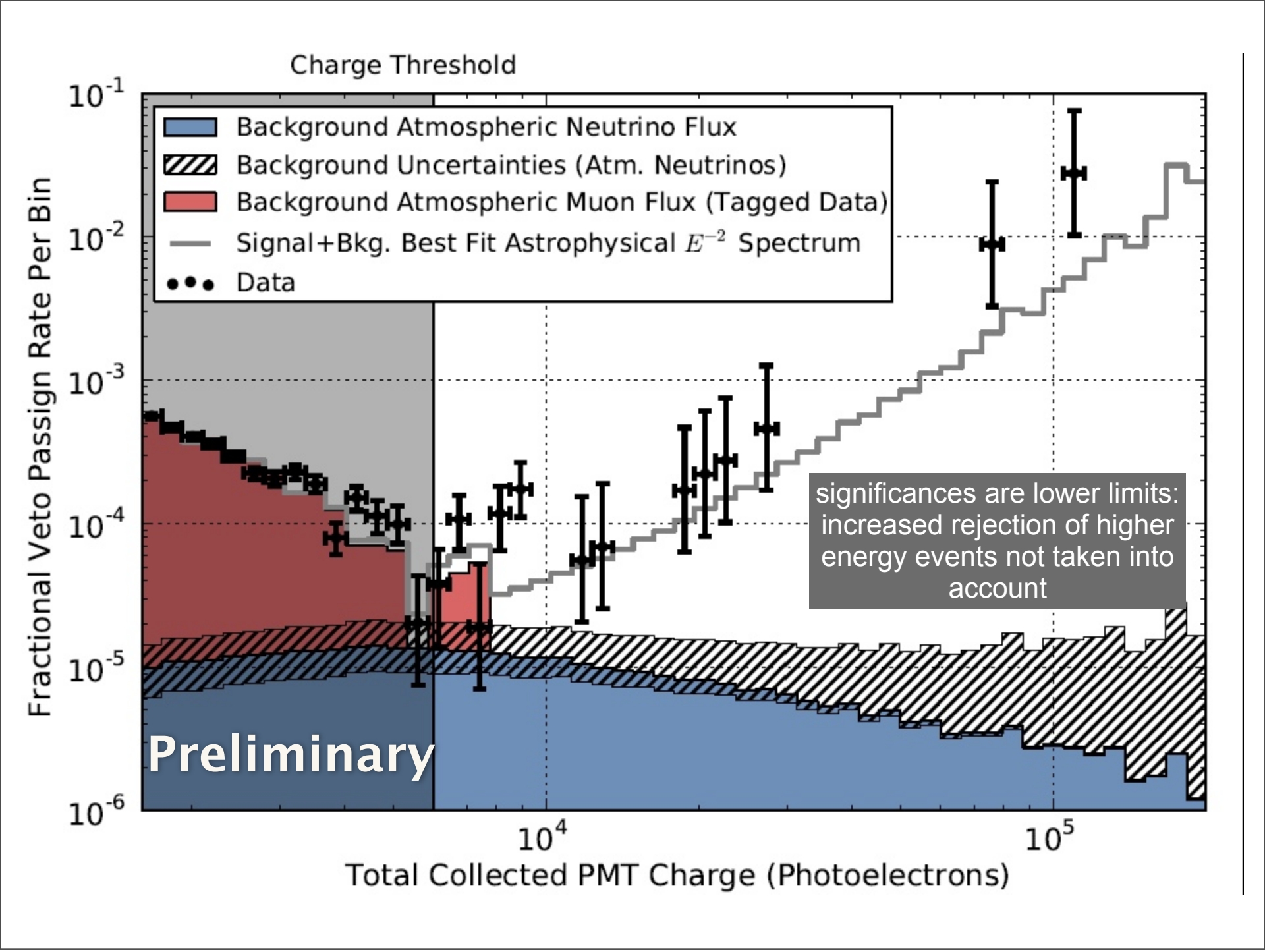
total charge collected by PMTs of events with interaction inside the detector



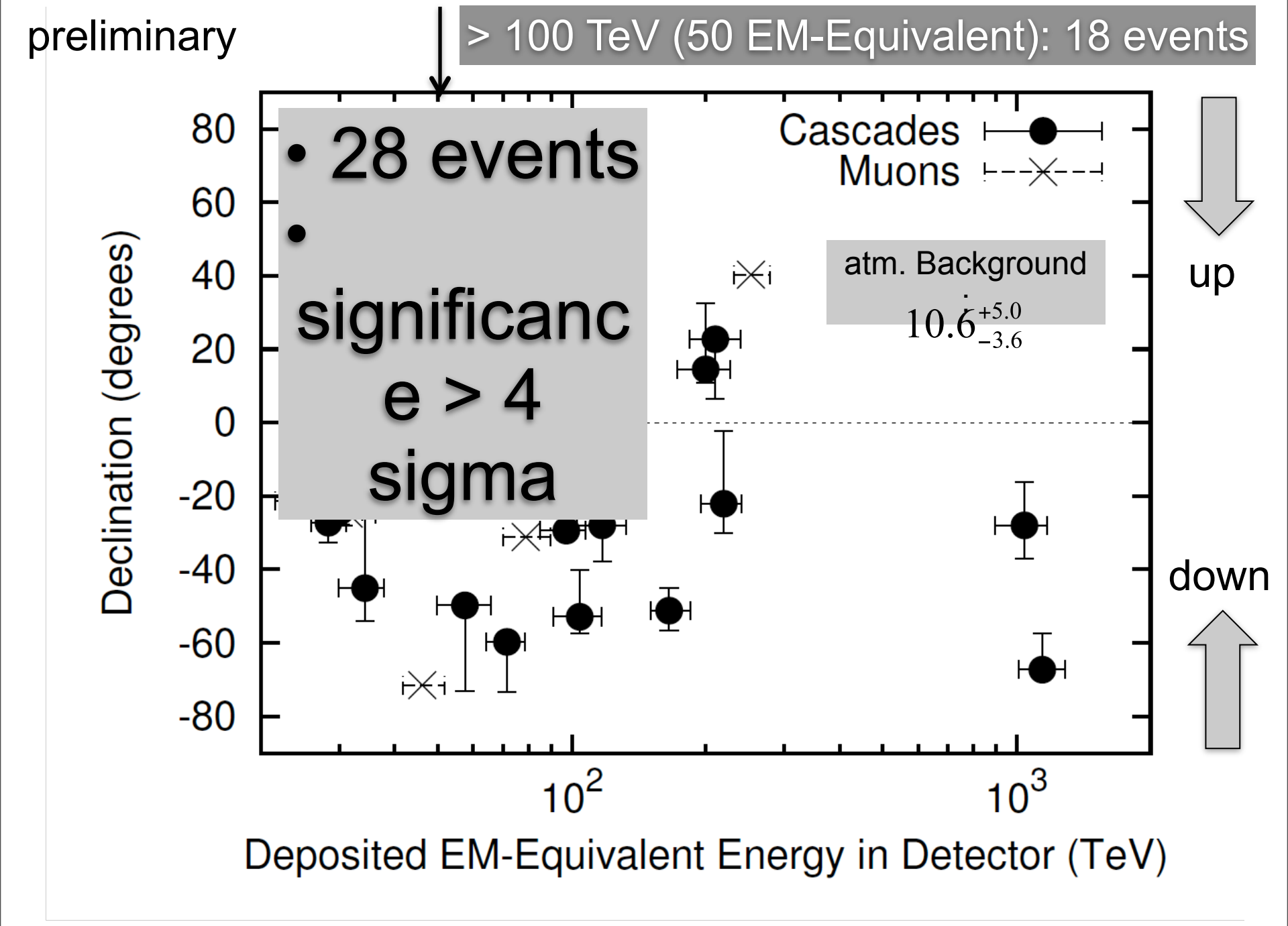
total charge collected by PMTs of events with interaction inside the detector




Charge Threshold
Background Atmospheric Neutrino Flux
Background Uncertainties (Atm. Neutrinos)
Background Atmospheric Muon Flux (Tagged Data)
Signal+Bkg. Best Fit Astrophysical E^{-2} Spectrum
Data
Preliminary
Fractional Veto Passign Rate Per Bin
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{4}
10^{5}
Total Collected PMT Charge (Photoelectrons)


Charge Threshold
Background Atmospheric Neutrino Flux
Background Uncertainties (Atm. Neutrinos)
Background Atmospheric Muon Flux (Tagged Data)
Signal+Bkg. Best Fit Astrophysical E^{-2} Spectrum
Data
significances are lower limits: increased rejection of higher energy events not taken into account
Preliminary
Fractional Veto Passign Rate Per Bin
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{4}
10^{5}
Total Collected PMT Charge (Photoelectrons)

preliminary



itemization of background

- downgoing muons*: 6 ± 3.4
- atmospheric neutrinos**: $4.6 + 3.7 - 2$
- combined: $10.6 + 5 - 3.6$

* 4 observed

** charm included (< 3.4 events at 1 σ : IceCube limit obtained with 59 strings)

events have properties of a cosmic flux

atmospheric background:

- mostly from North (through the Earth, insufficient target to produce neutrinos from the South)
- mostly muons (neutrinos and cosmic ray muons)

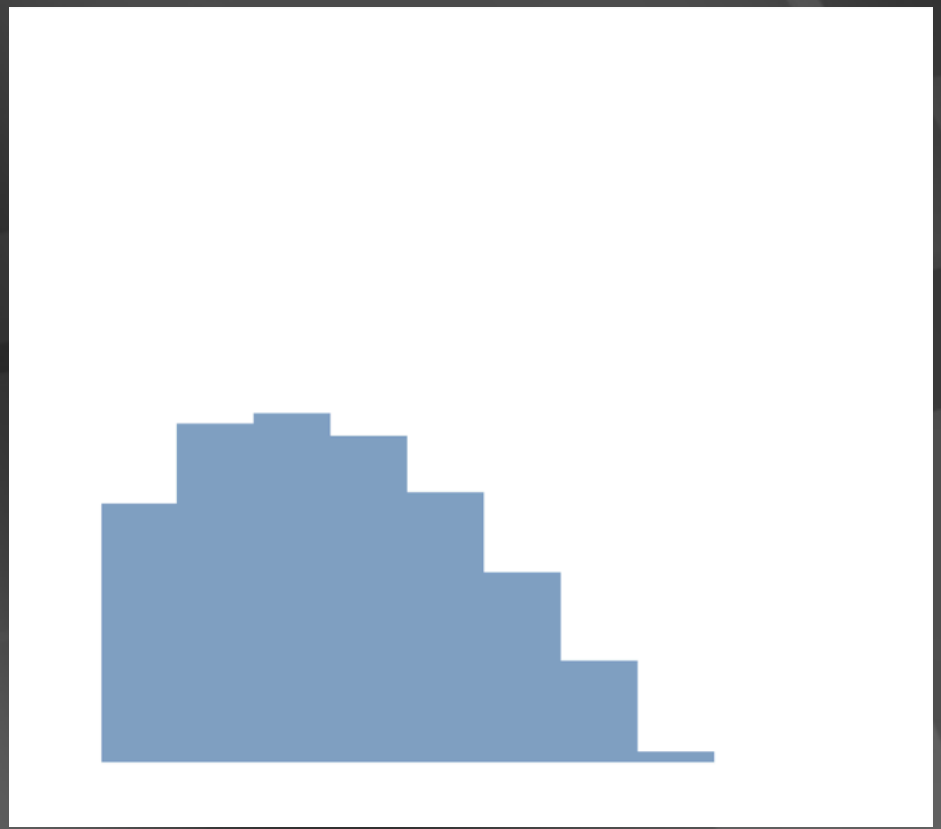
cosmic flux:

- mostly from the South (PeV neutrinos absorbed by the Earth)
- mostly showers (1:1:1 flavor composition and only CC muon neutrinos produce a track)

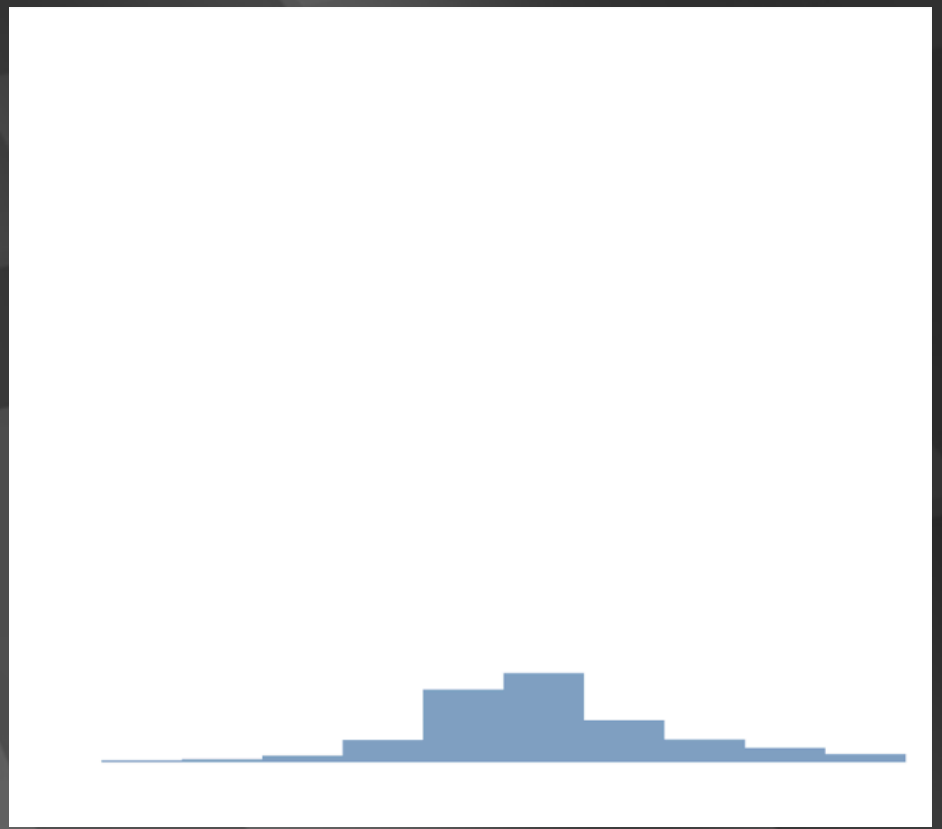
not neutrinos from production and prompt decay of charmed particles in the atmosphere

- IceCube data do not fit the energy dependence required by a charm signal.
- same for the zenith angle dependence.
- rate required to explain the data exceeds our own experimental limit by more than a factor of 2.
- level of charm background allowed by the data (actually, no evidence yet) is consistent with expectations.
- no evidence for the air shower that would have produced the charmed particle (no muons!).

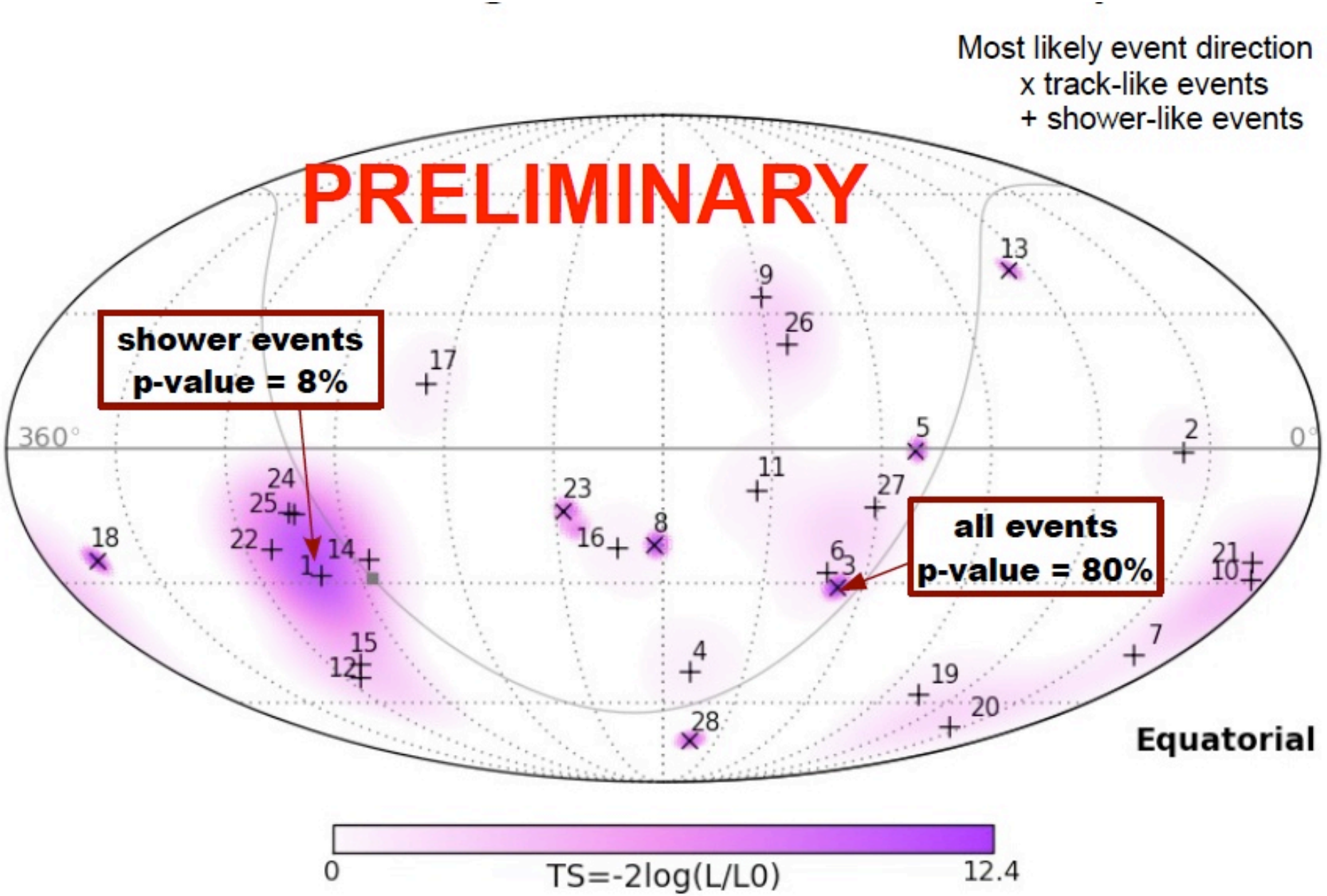
atmospheric muon (blue) + neutrino (red) background
+ astrophysical $E^2\Phi(E) = (3.6 \pm 1.2) \cdot 10^{-8}\ \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$

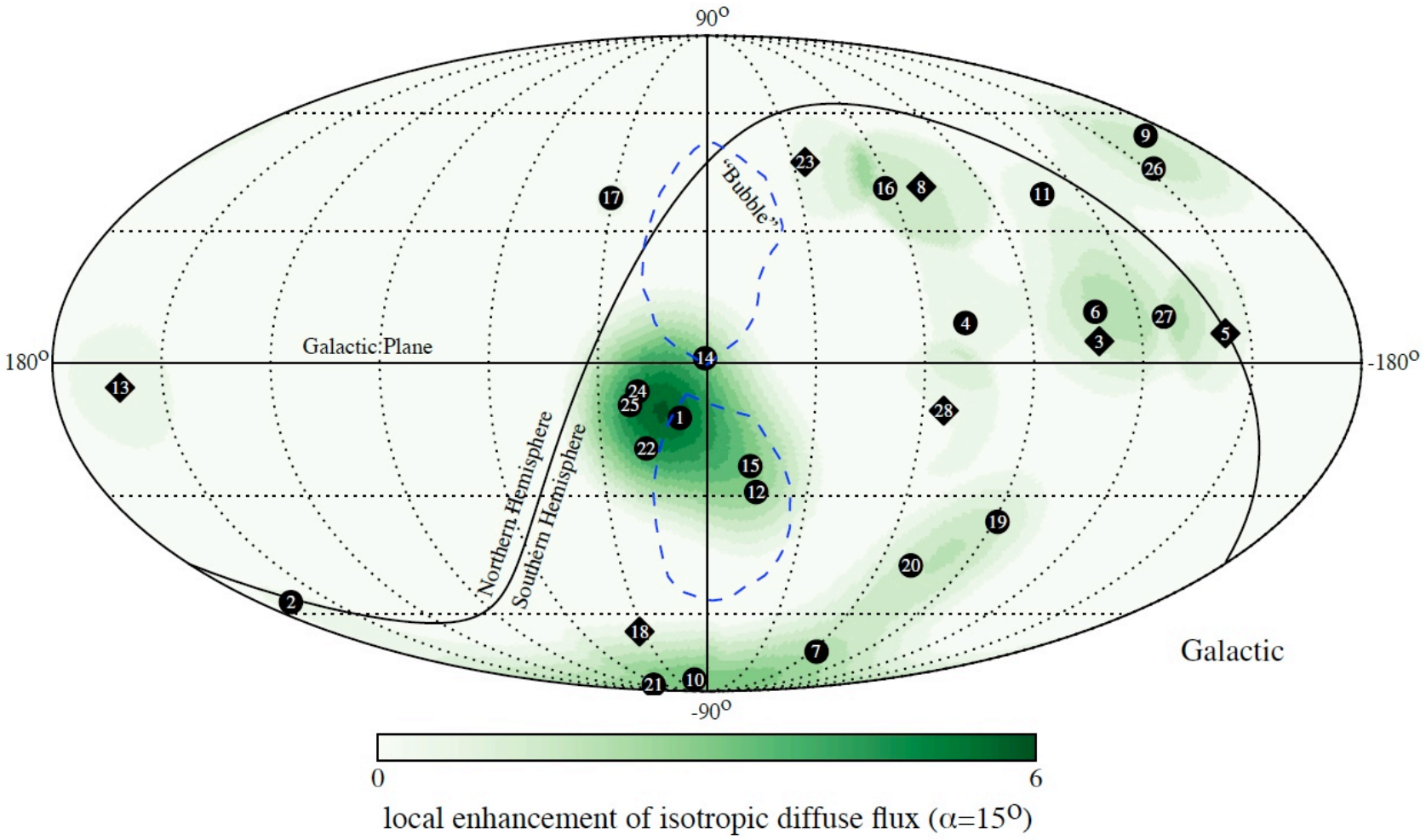


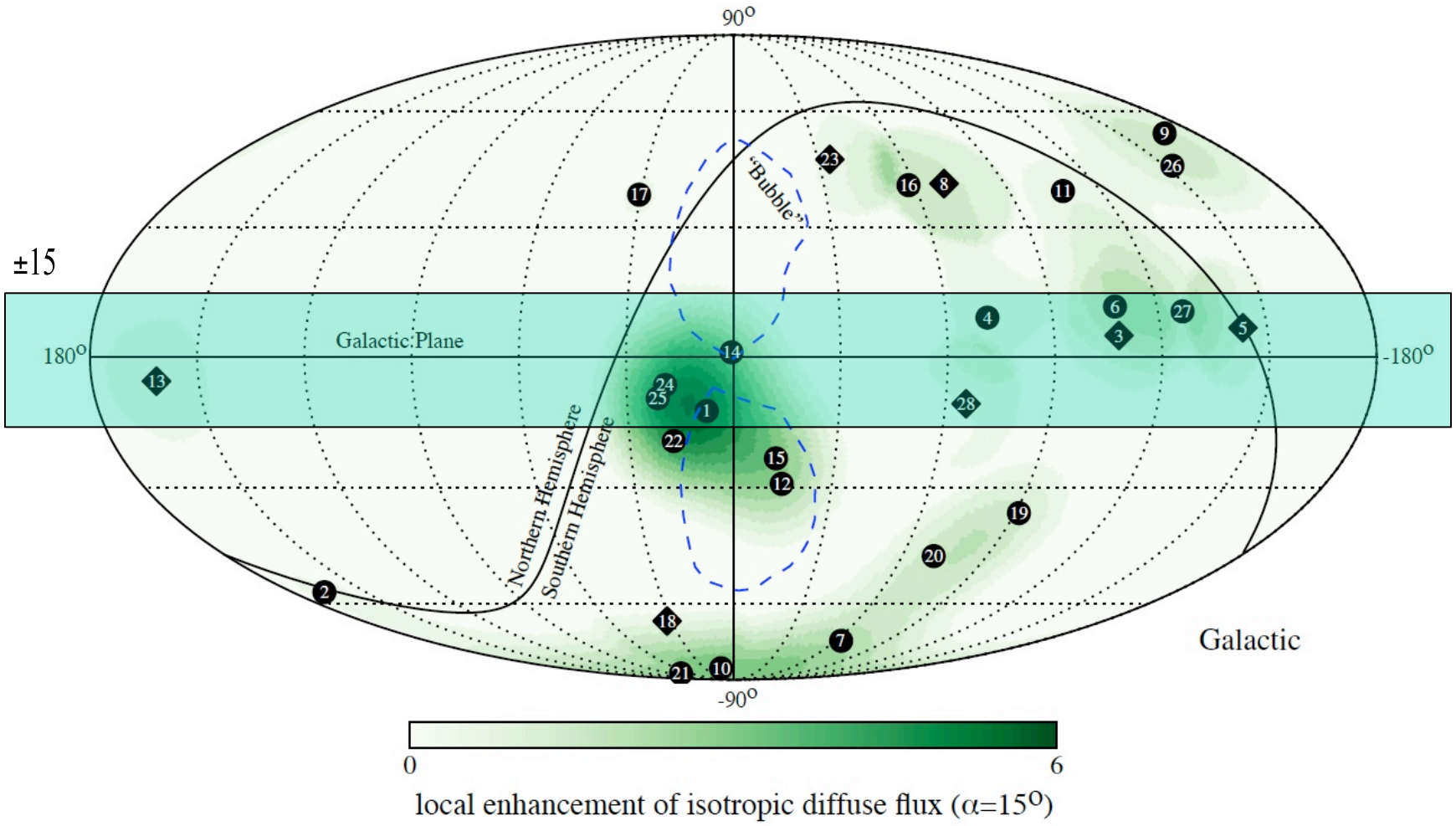
energy deposited in the detector



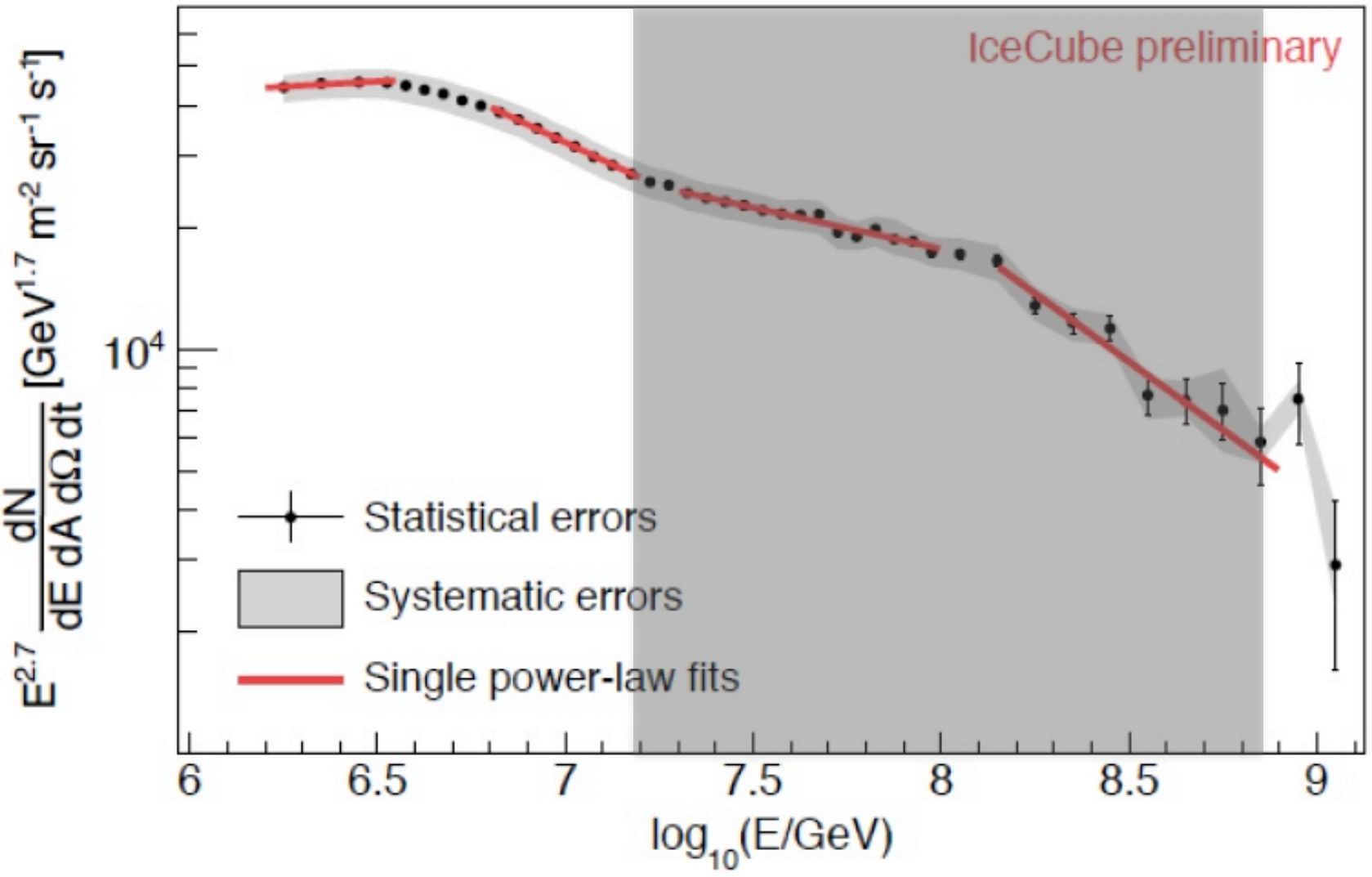
zenith angle


Most likely event direction
x track-like events
+ shower-like events
PRELIMINARY
shower events
p-value = 8%
all events
p-value = 80%
360°
0°
Equatorial
0
TS=-2log(L/L0)
12.4

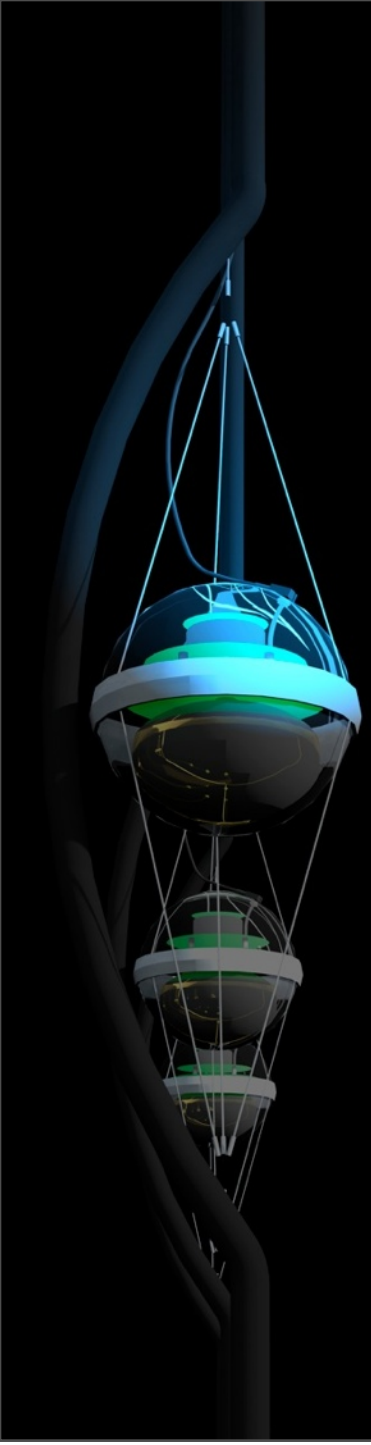

90°
180°
-180°
-90°
Galactic Plane
"Bubble"
Northern Hemisphere
Southern Hemisphere
Galactic
0
6
local enhancement of isotropic diffuse flux (α=15°)


90°
-90°
180°
-180°
±15
Galactic Plane
"Bubble"
Northern Hemisphere
Southern Hemisphere
Galactic
0
6
local enhancement of isotropic diffuse flux (α=15°)

the relevant energy range of cosmic rays producing PeV neutrinos



Galactic or

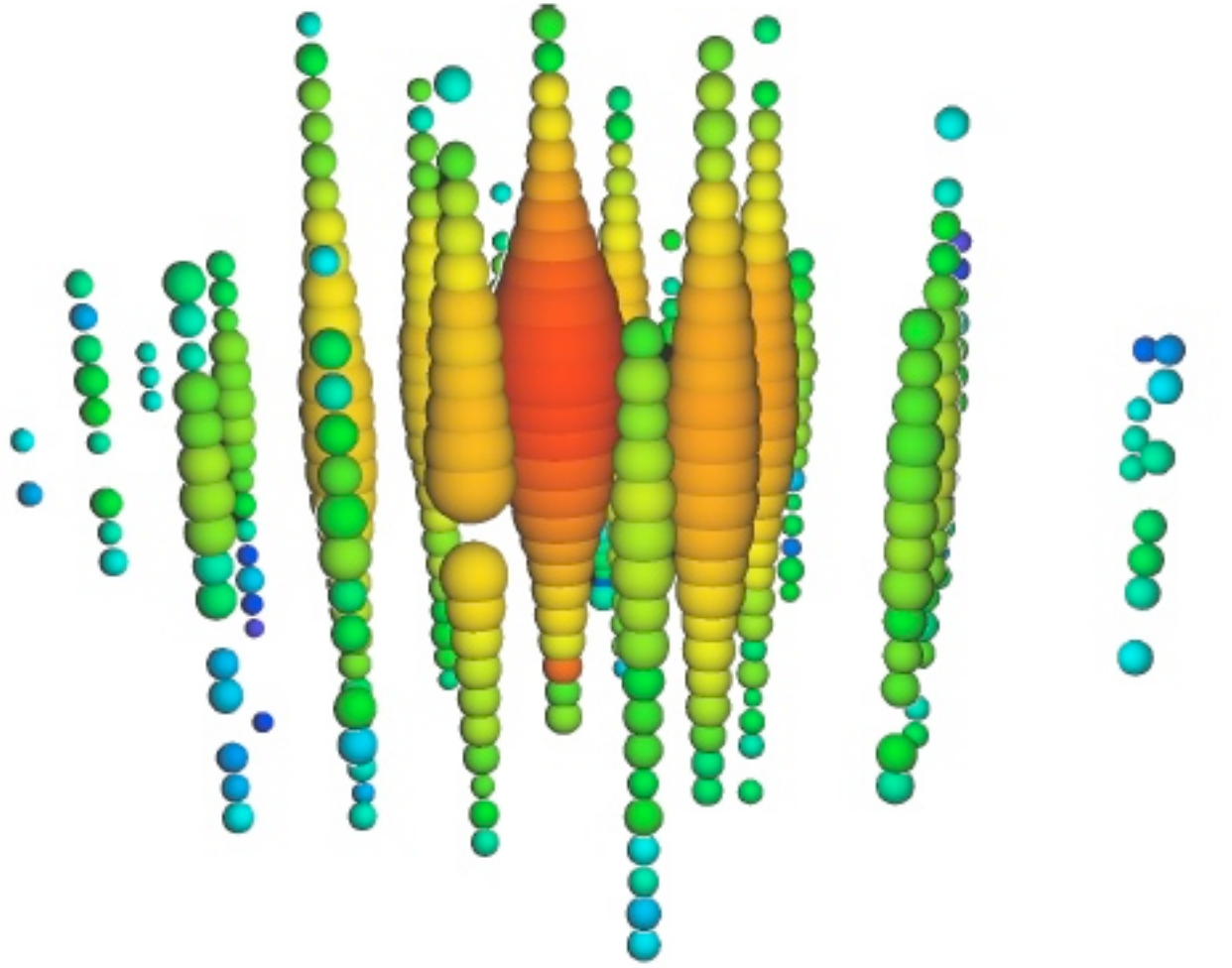


conclusions

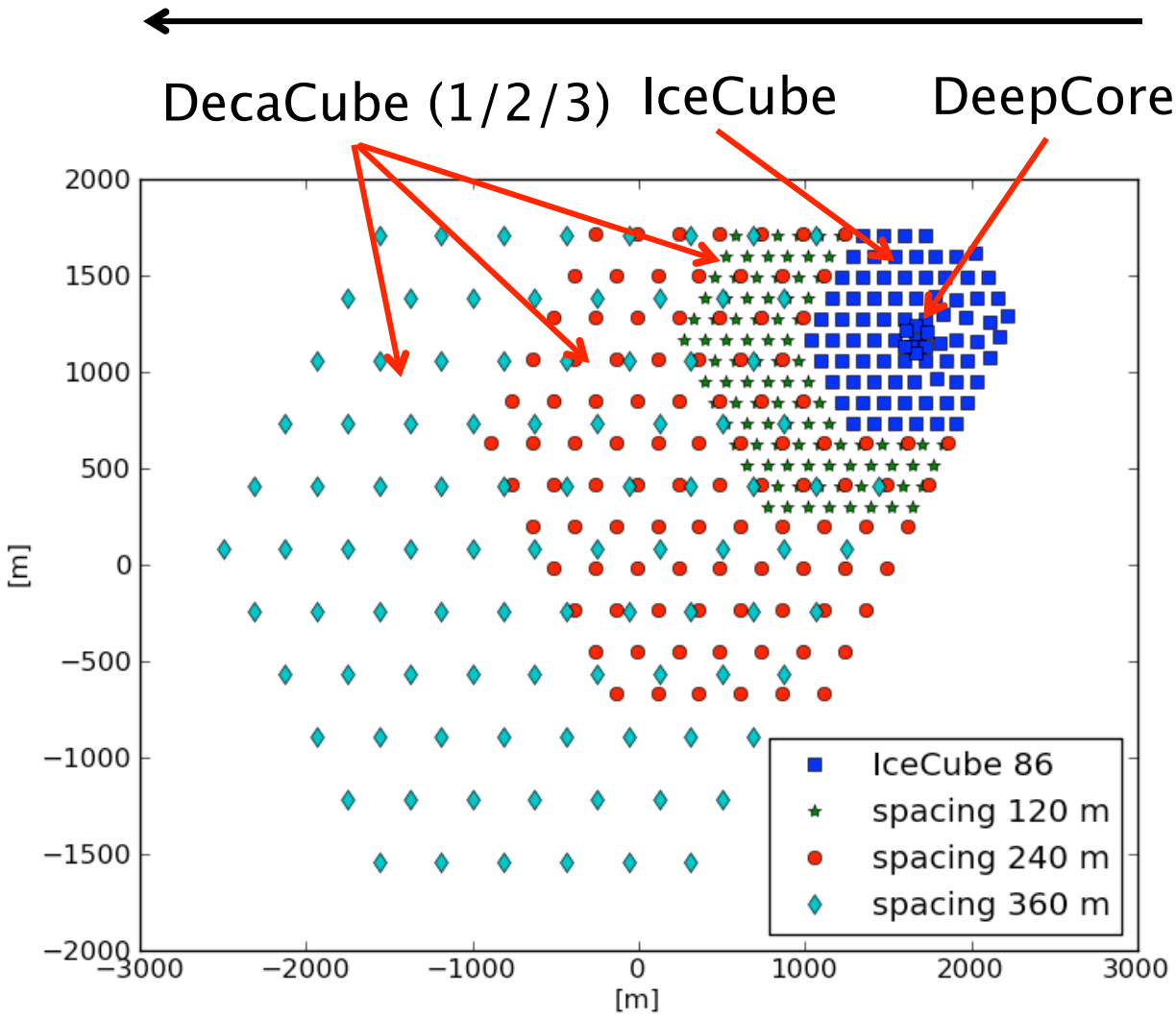
- first evidence for (→ observation of) cosmic neutrinos
- origin not revealed (yet), several analyses in progress to identify sources– muons are the key
- one more year of data ready for unblinding, more being taken

IceCube.wisc.edu

10% of data taken during year 2 of IceCube unblinded



increase in threshold not important
(in the region 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

IceCube & PINGU collaborations

Collaborating Organizations

Chiba University
Clark Atlanta University
DESY-Zeuthen
Ecole Polytechnique Fédérale de Lausanne
FAU Erlangen-Nürnberg
Georgia Institute of Technology
HU Berlin
JGU Mainz
Lawrence Berkeley National Laboratory
Niels Bohr Institute
Ohio State University
Pennsylvania State University
RU Bochum
RWTH Aachen
Southern University and A&M College
Stockholms universitet
Stony Brook University
Sungkyunkwan University
TU Dortmund
TU München
Universität Bonn
Universität Wuppertal
Université libre de Bruxelles
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