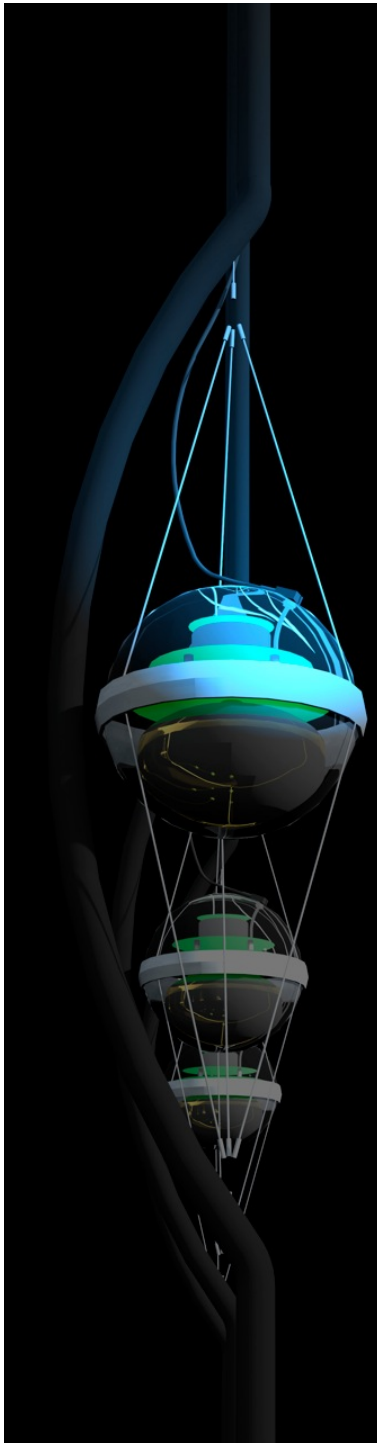

IceCube

francis halzen

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

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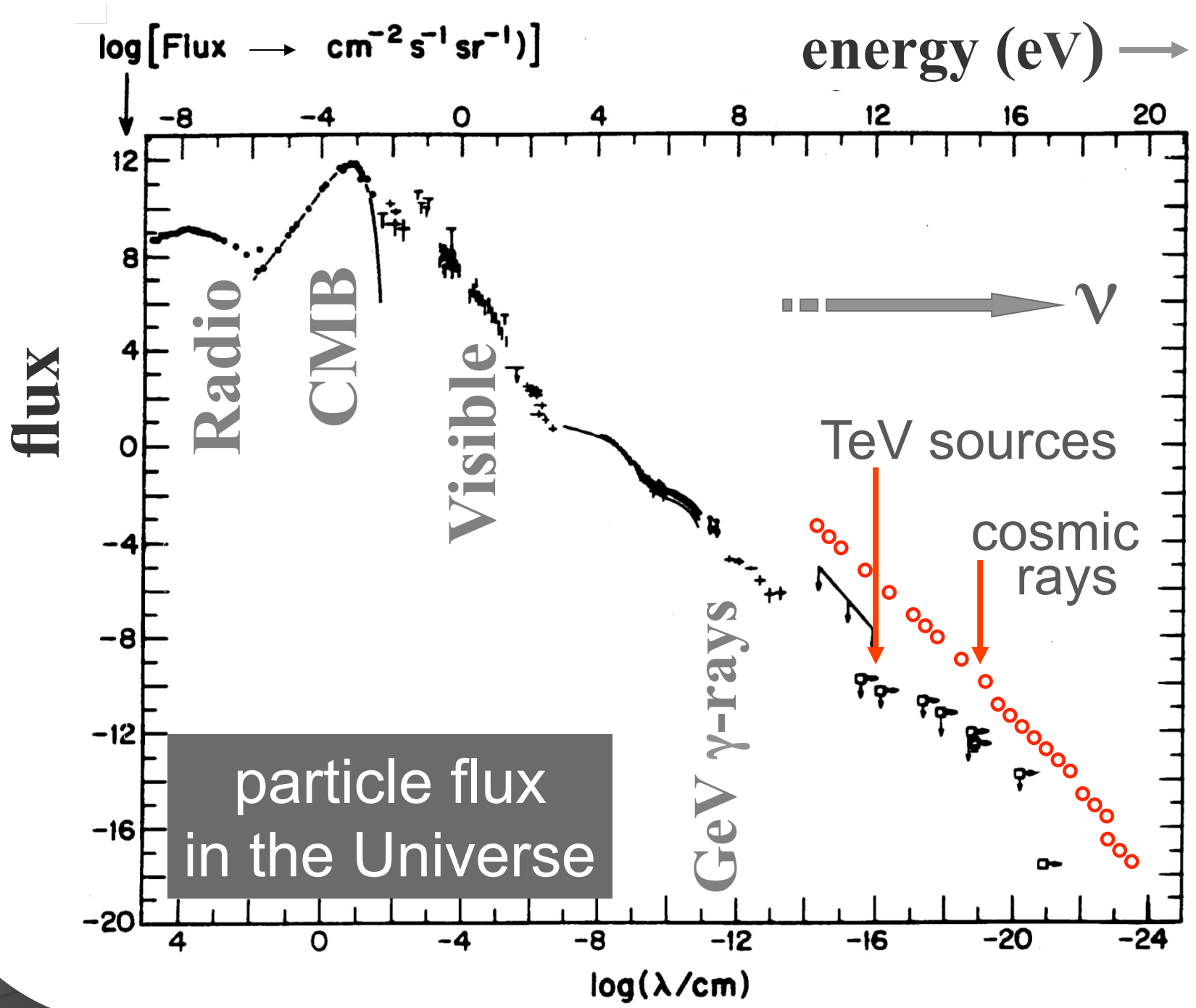
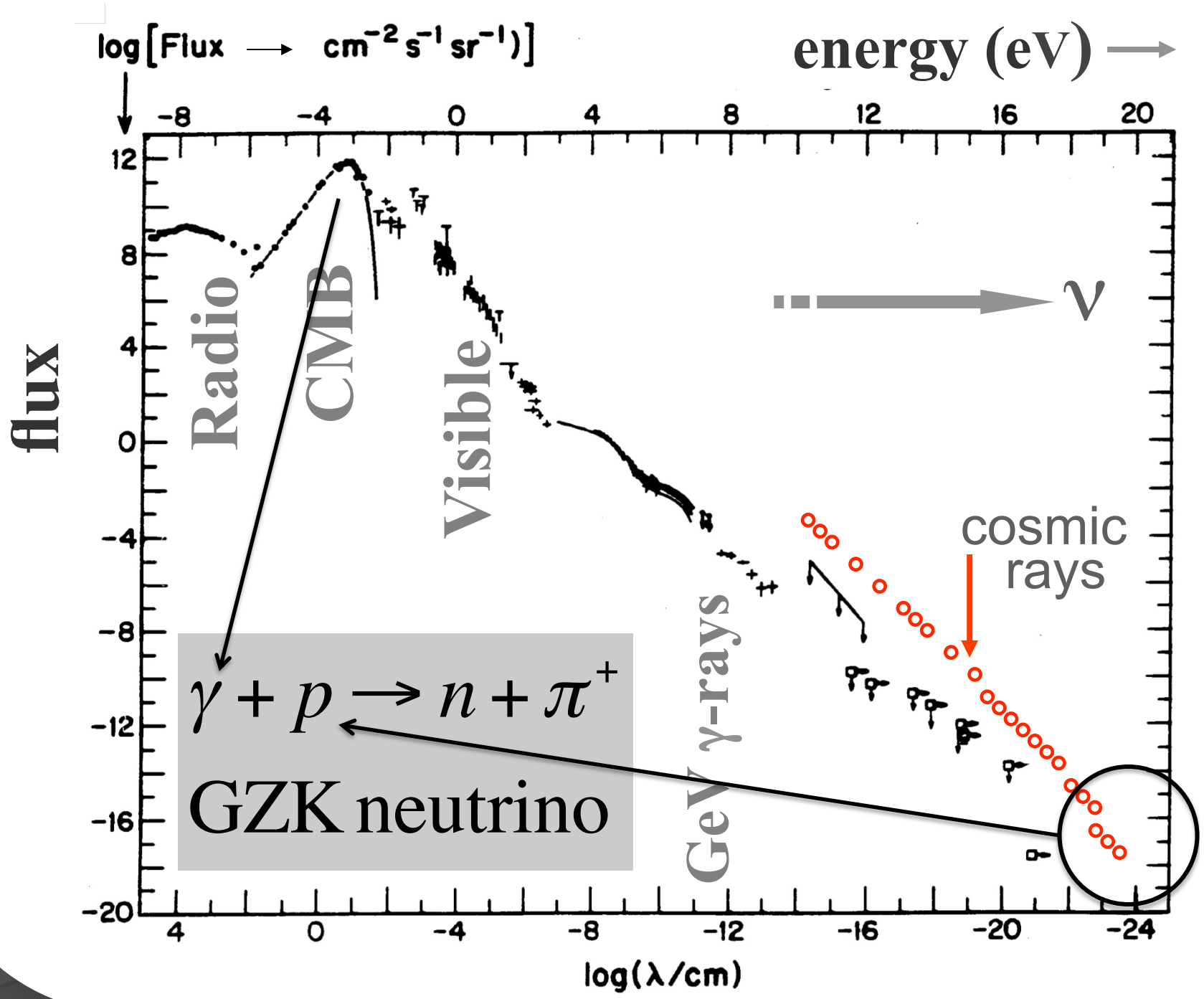

log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources
cosmic rays
log(λ/cm)
particle flux in the Universe

neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

new window on the Universe : discovery instrument


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

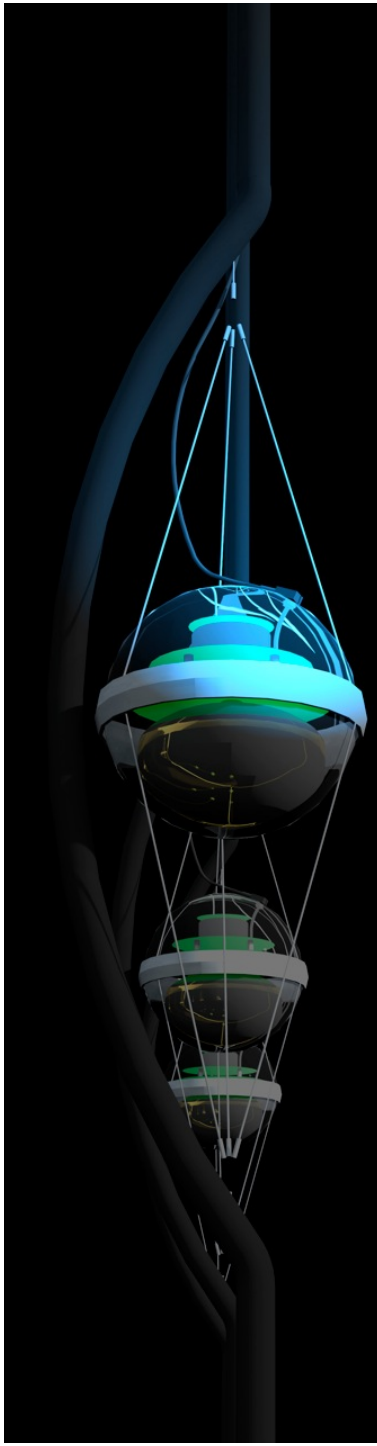
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^{18} eV) 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!



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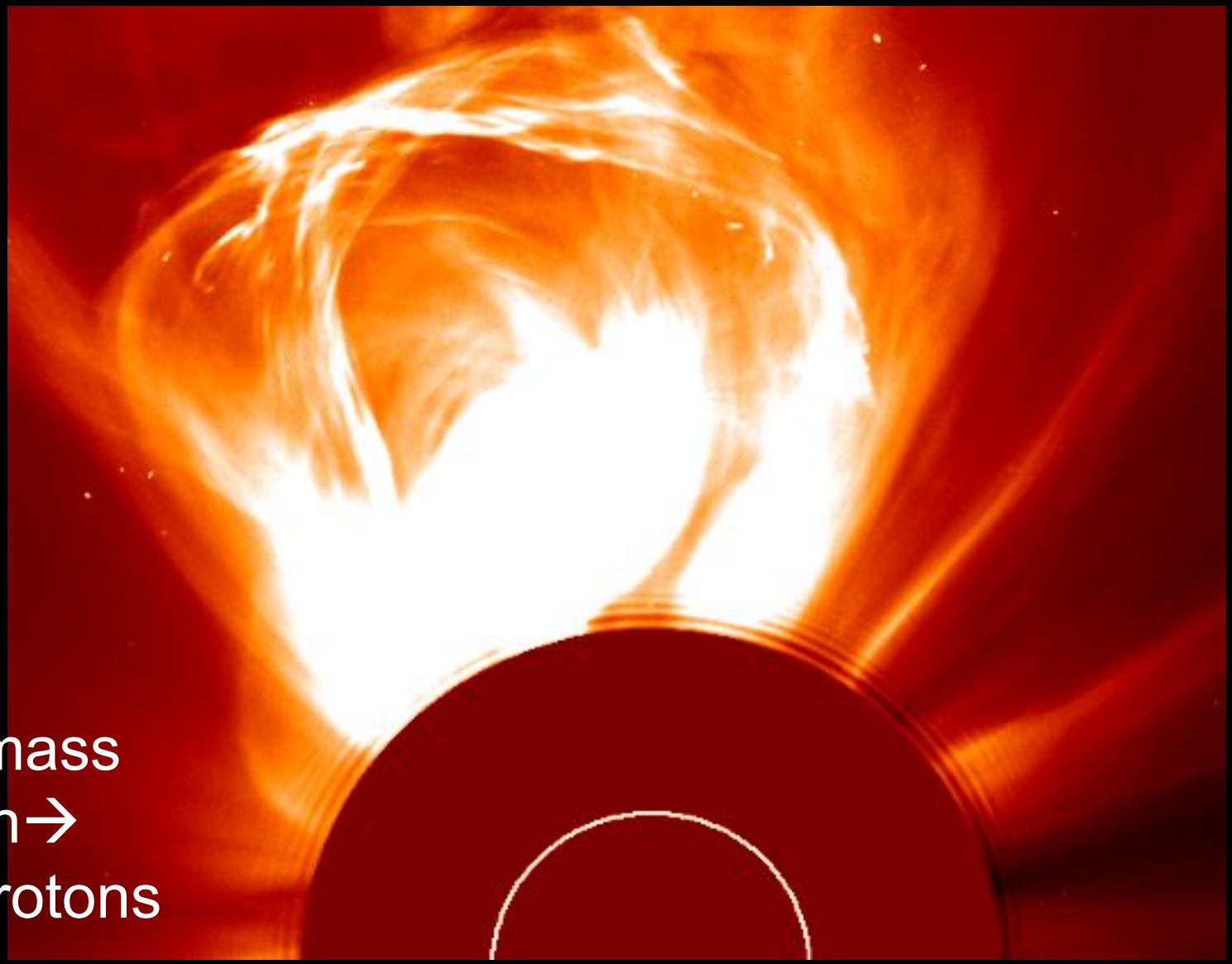
the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

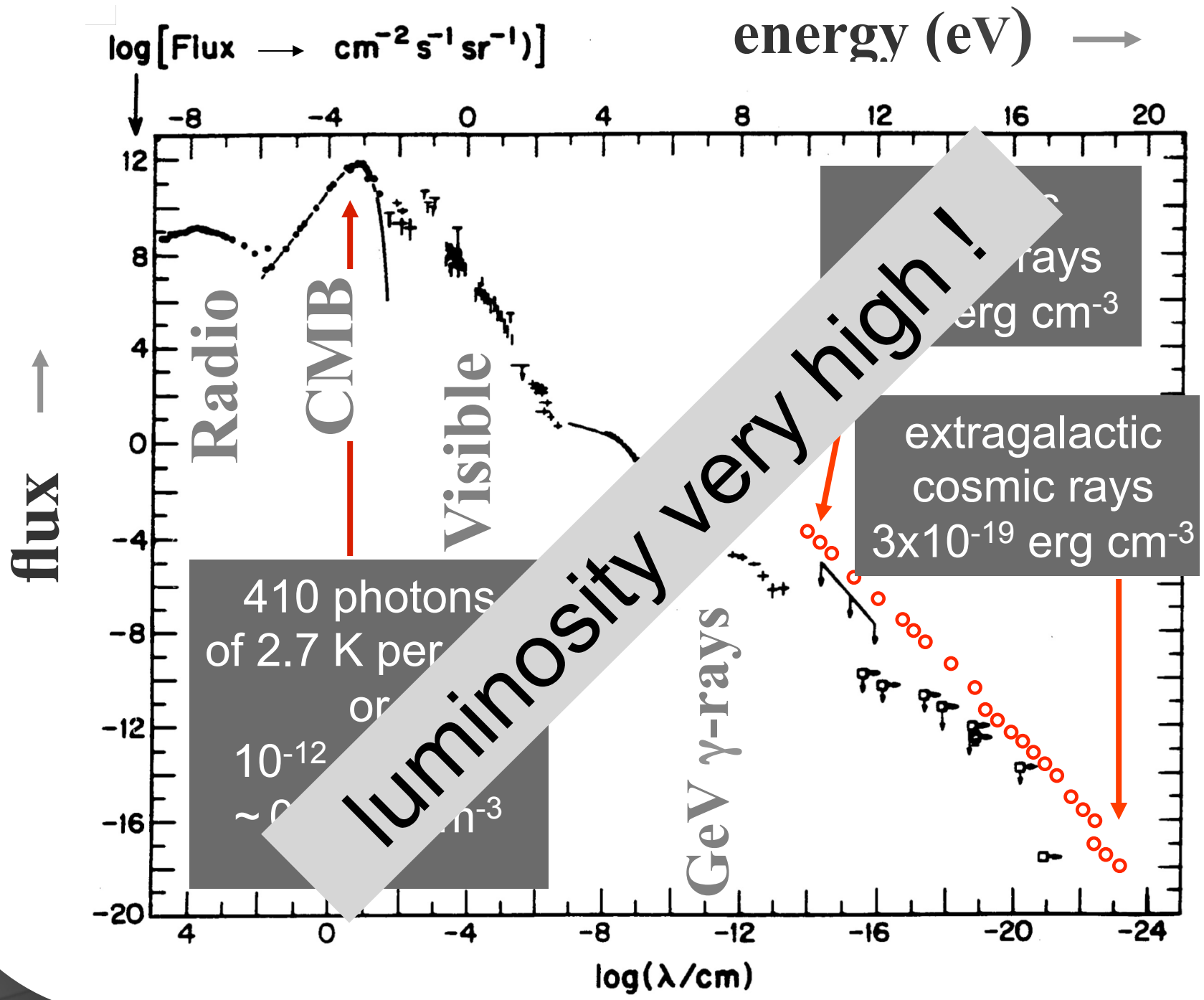
Hillas formula :

- accelerator must contain the particles

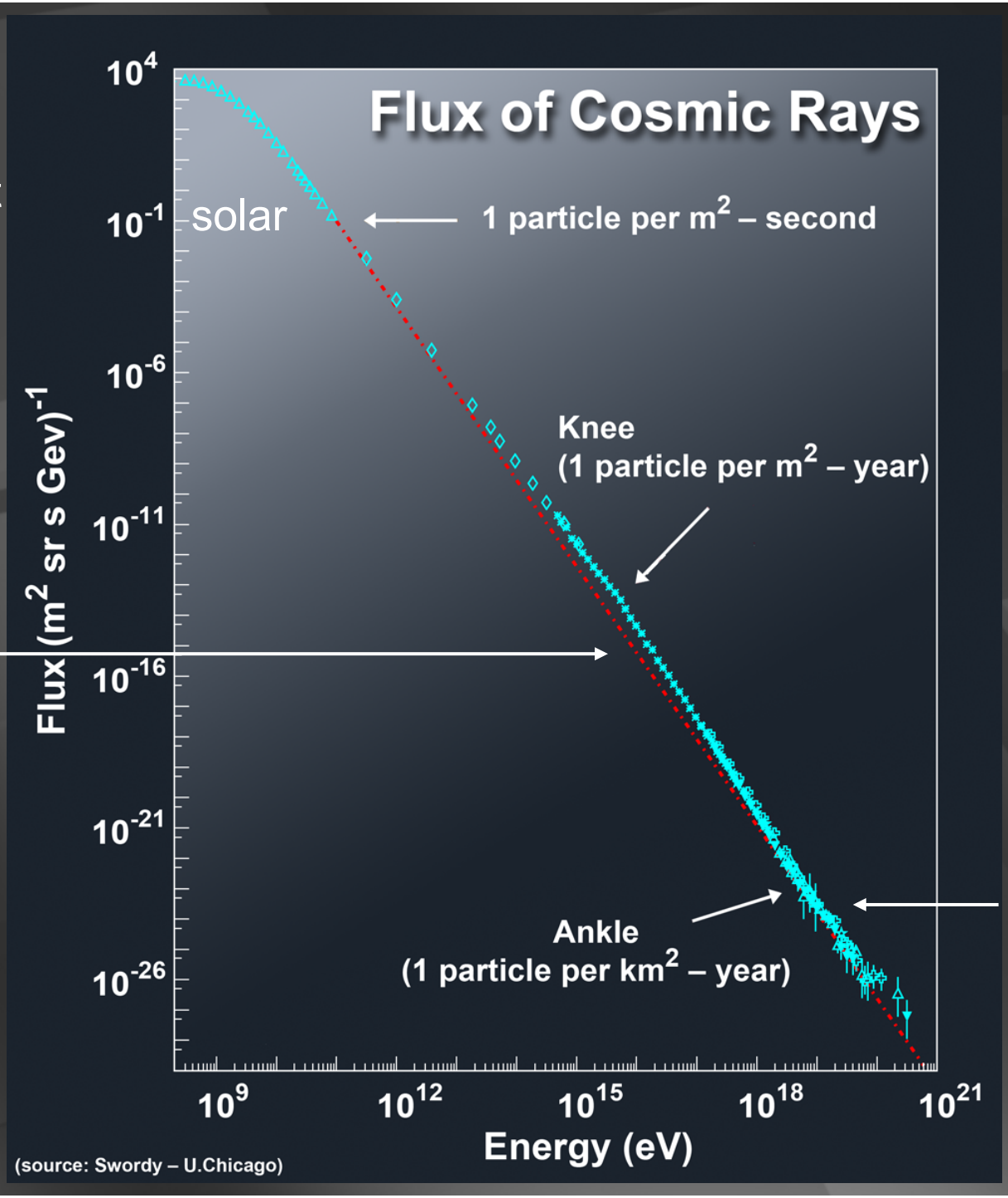
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

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

- dimensional analysis, difficult to satisfy


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 !

sources that accommodate the observed energy budget

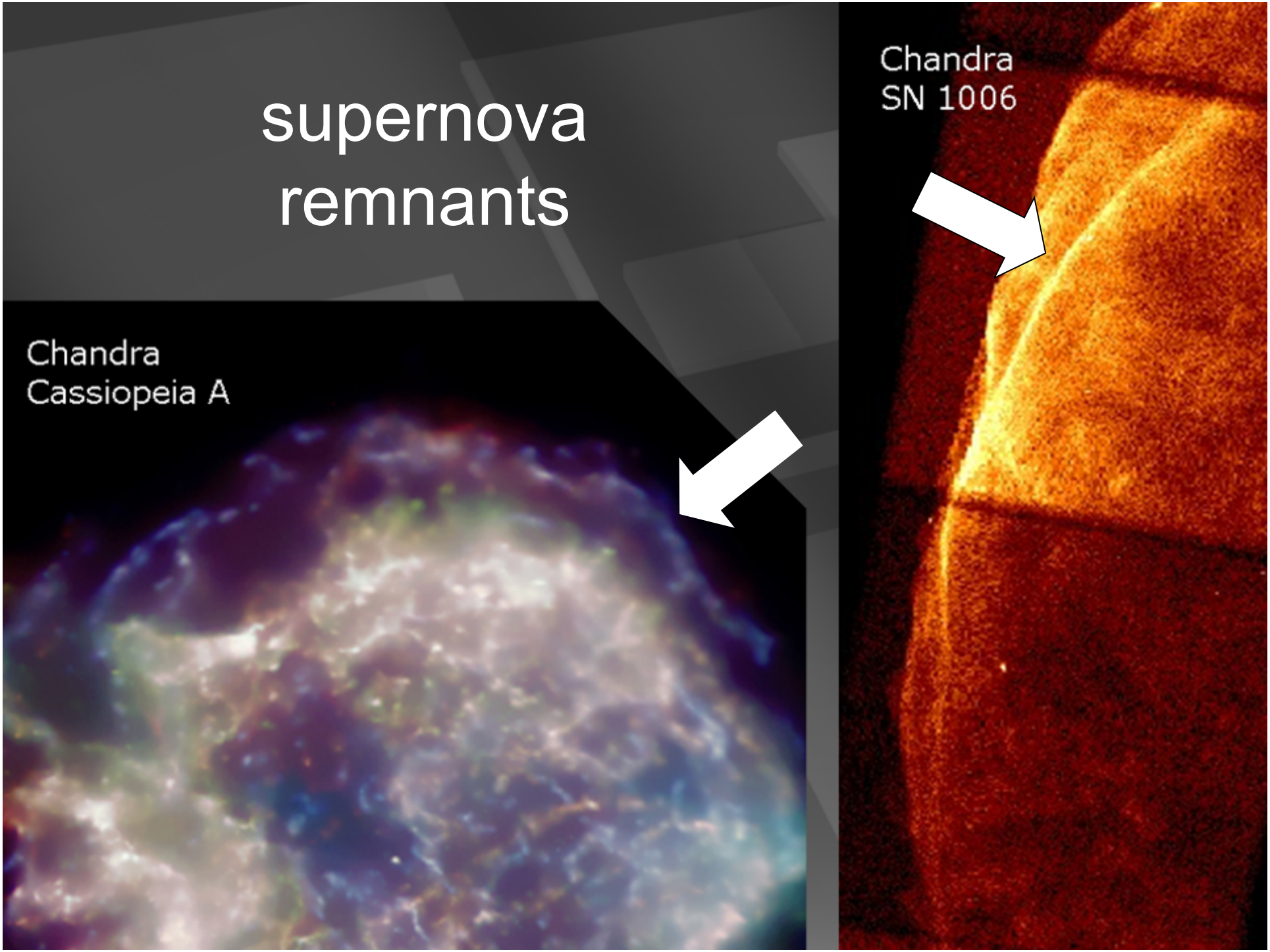


Galactic: supernova remnants?

extragalactic:

- gamma ray bursts??
- active galaxies?

supernova remnants

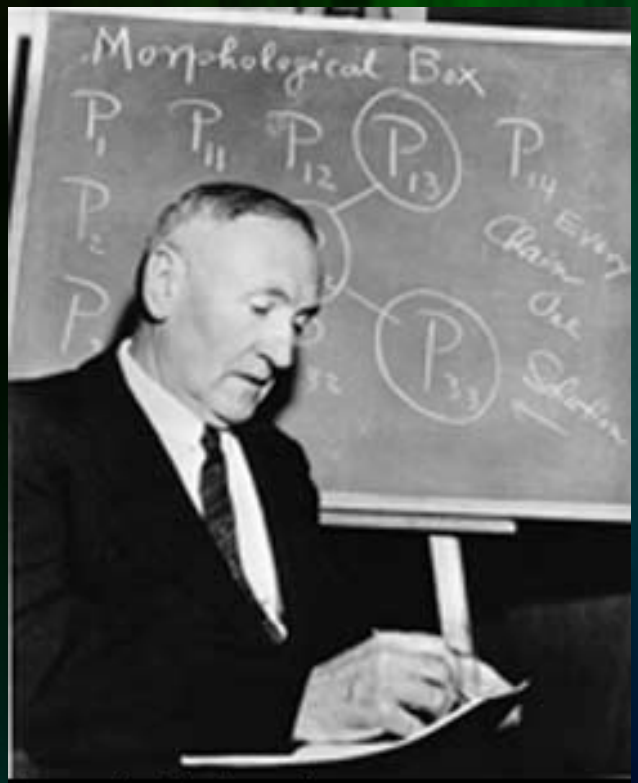


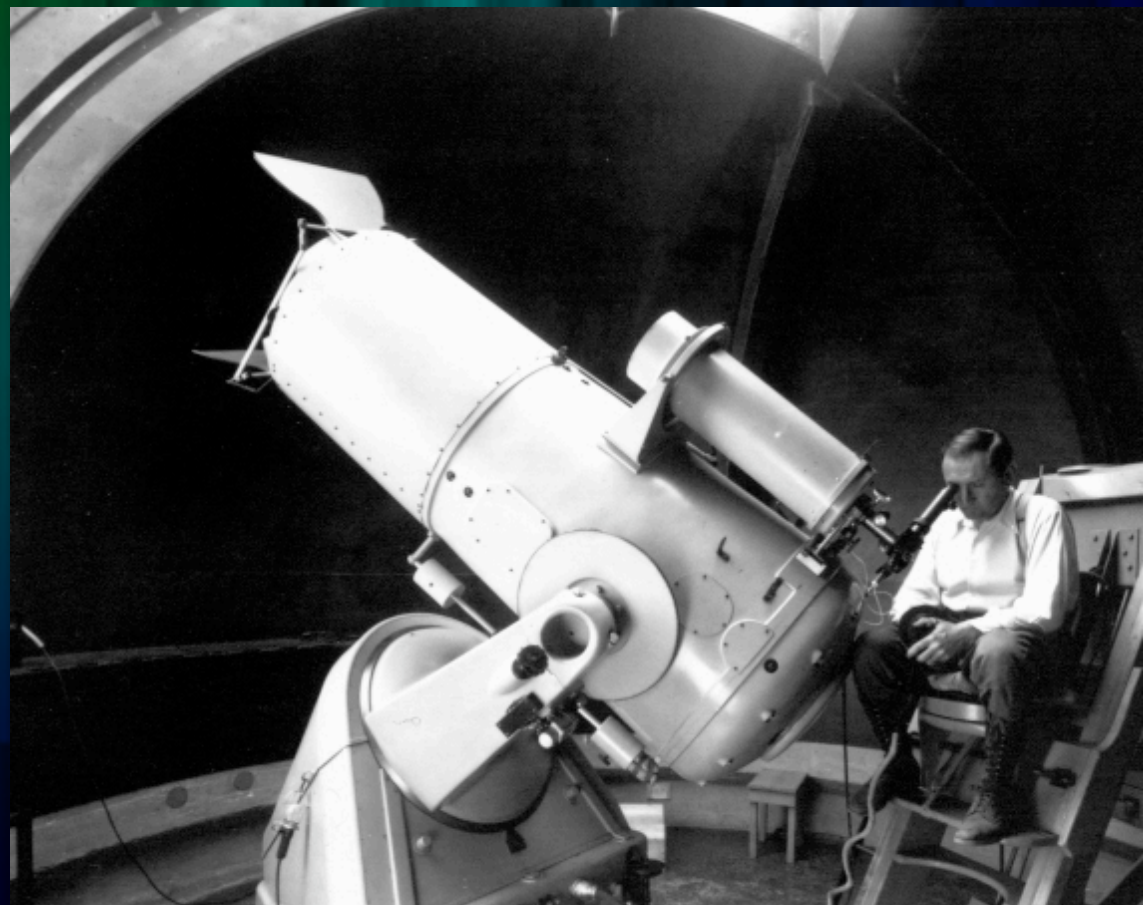
ON SUPER-NOVAE

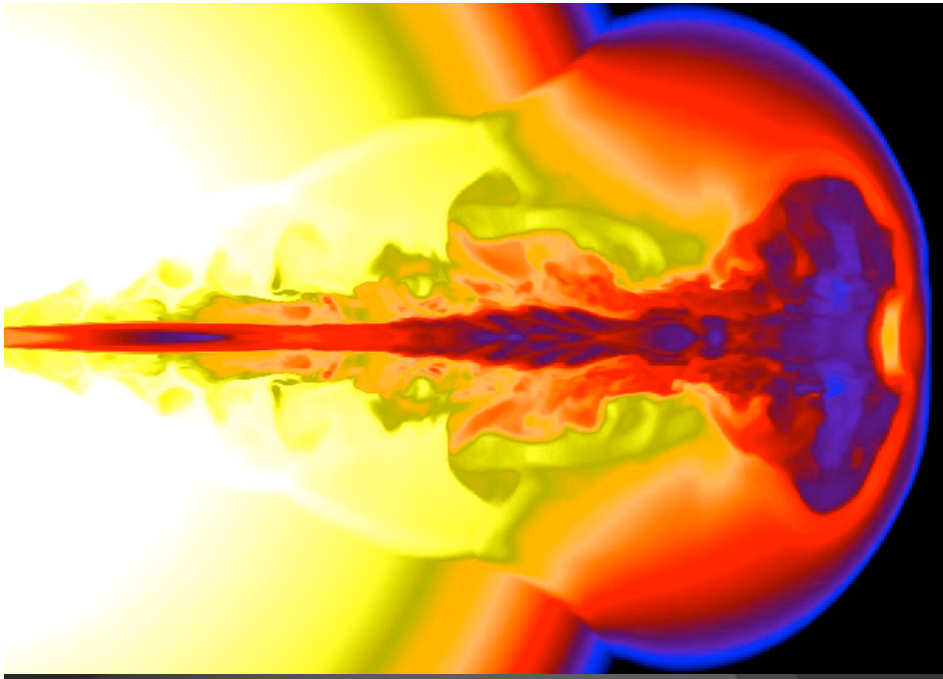
By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934



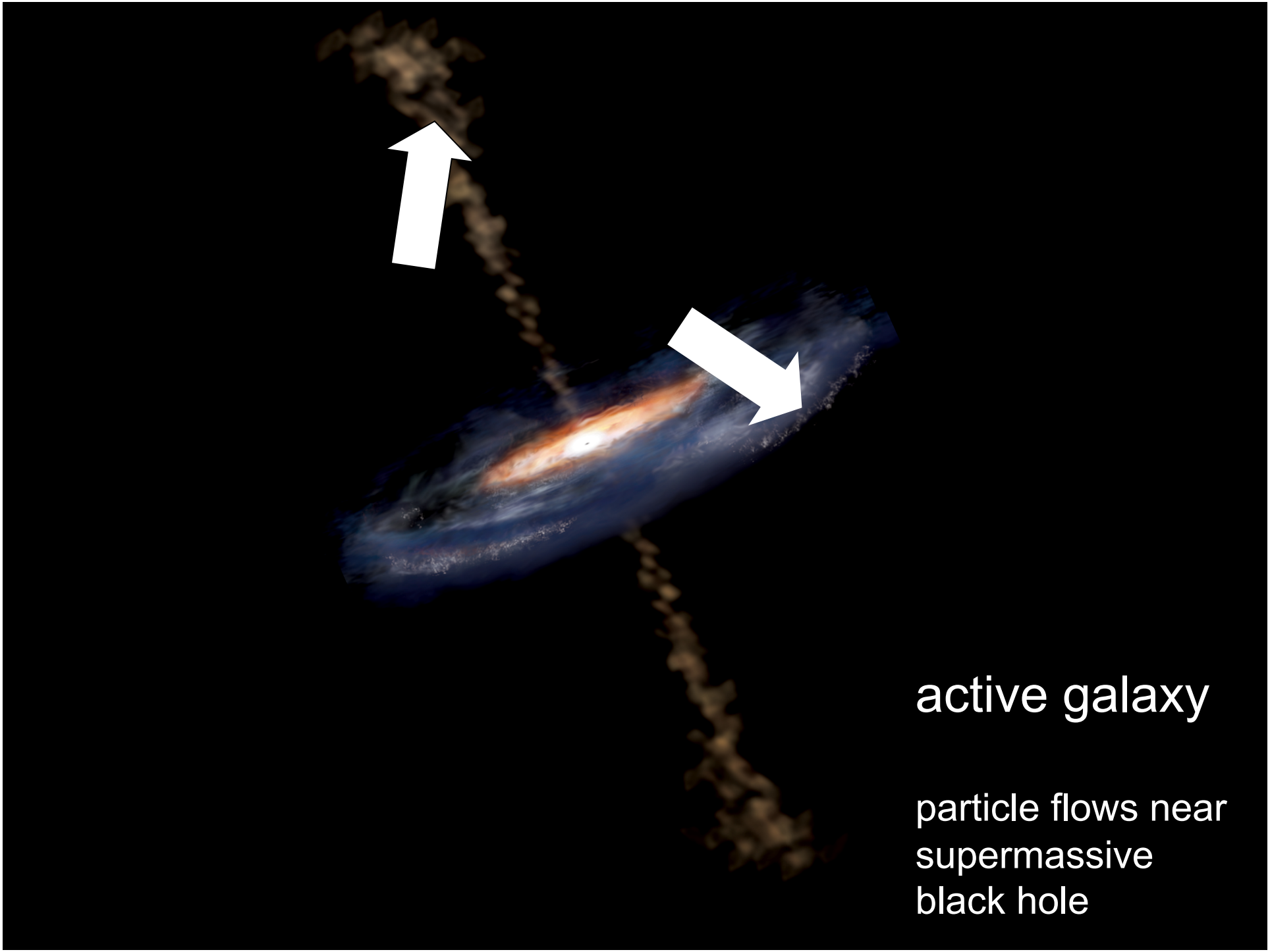


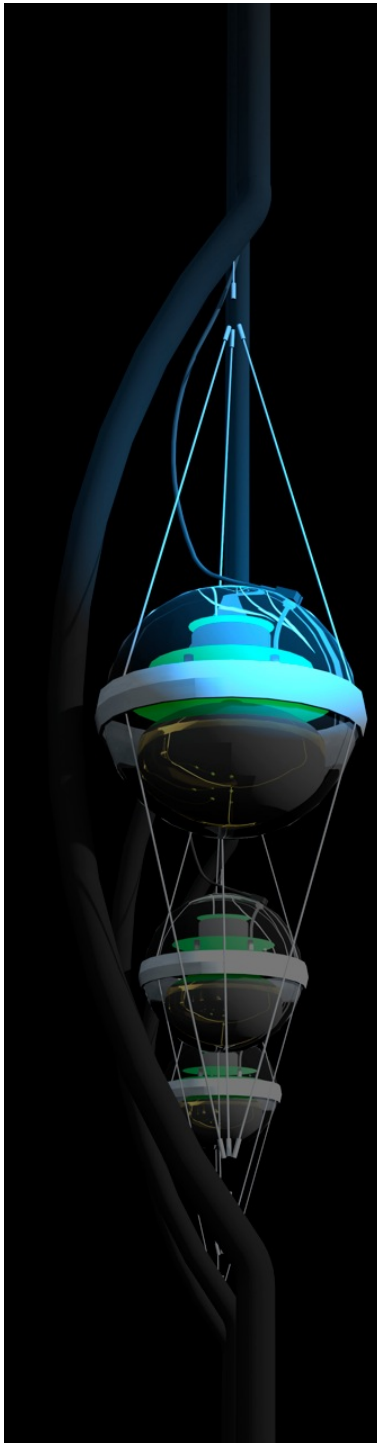


…and if the star collapses to a black hole…

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


active galaxy
particle flows near
supermassive
black hole



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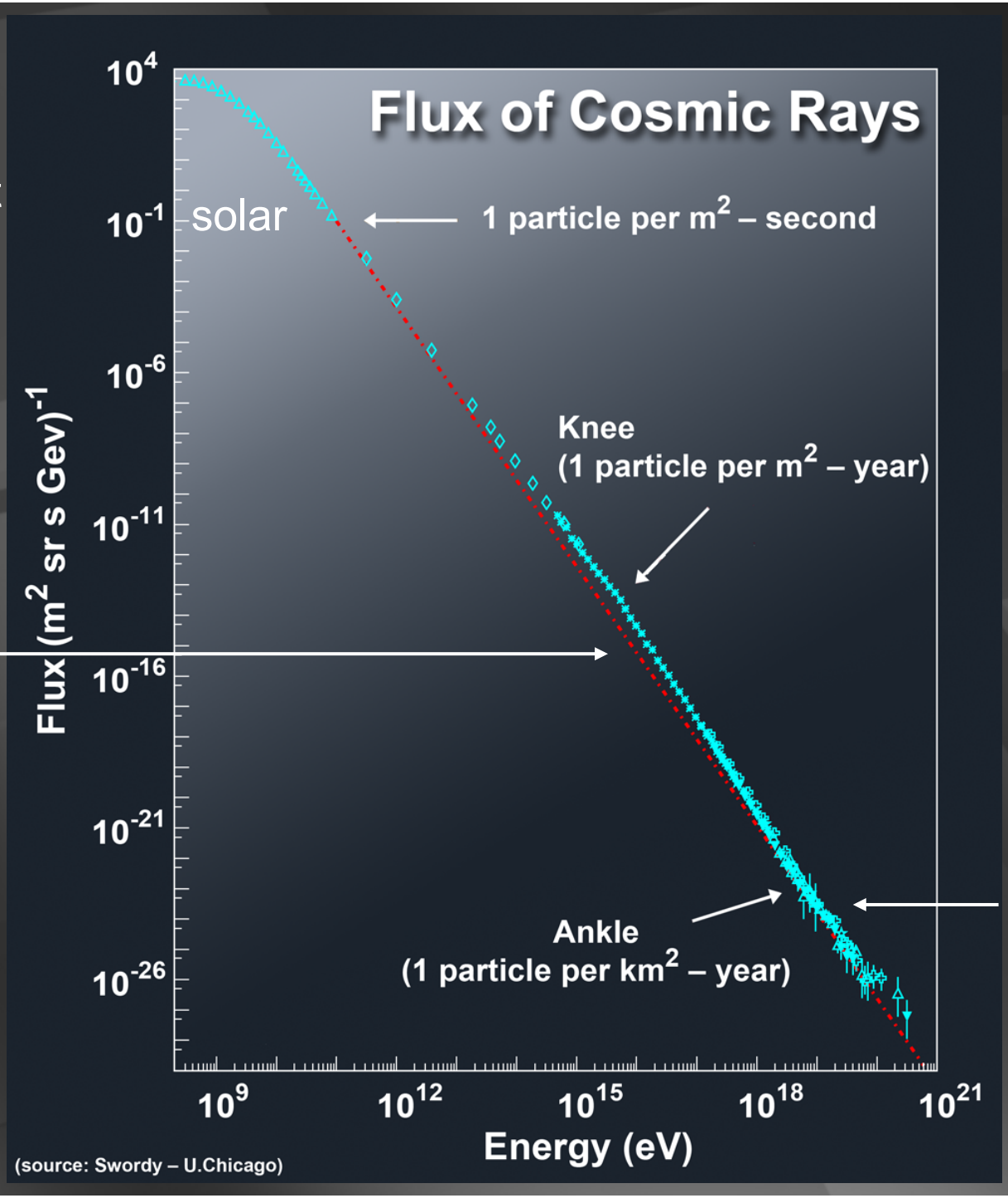
sources that accommodate the observed energy budget

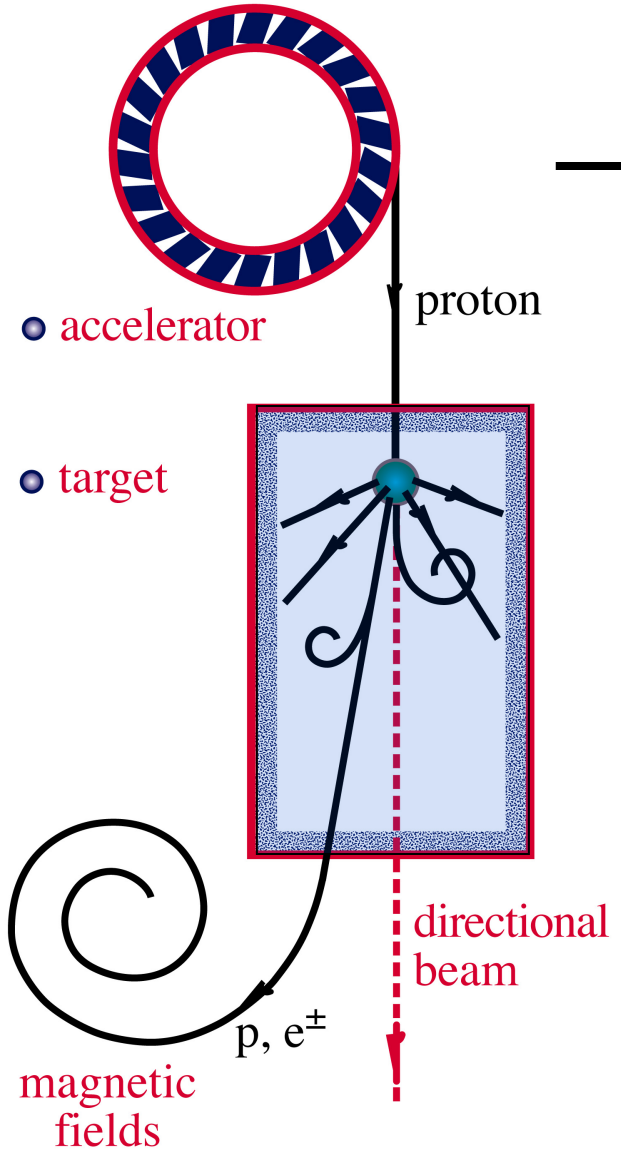


Galactic: supernova remnants?

extragalactic:

- gamma ray bursts??
- active galaxies?

ν and γ beams : heaven and earth



black hole
neutron star

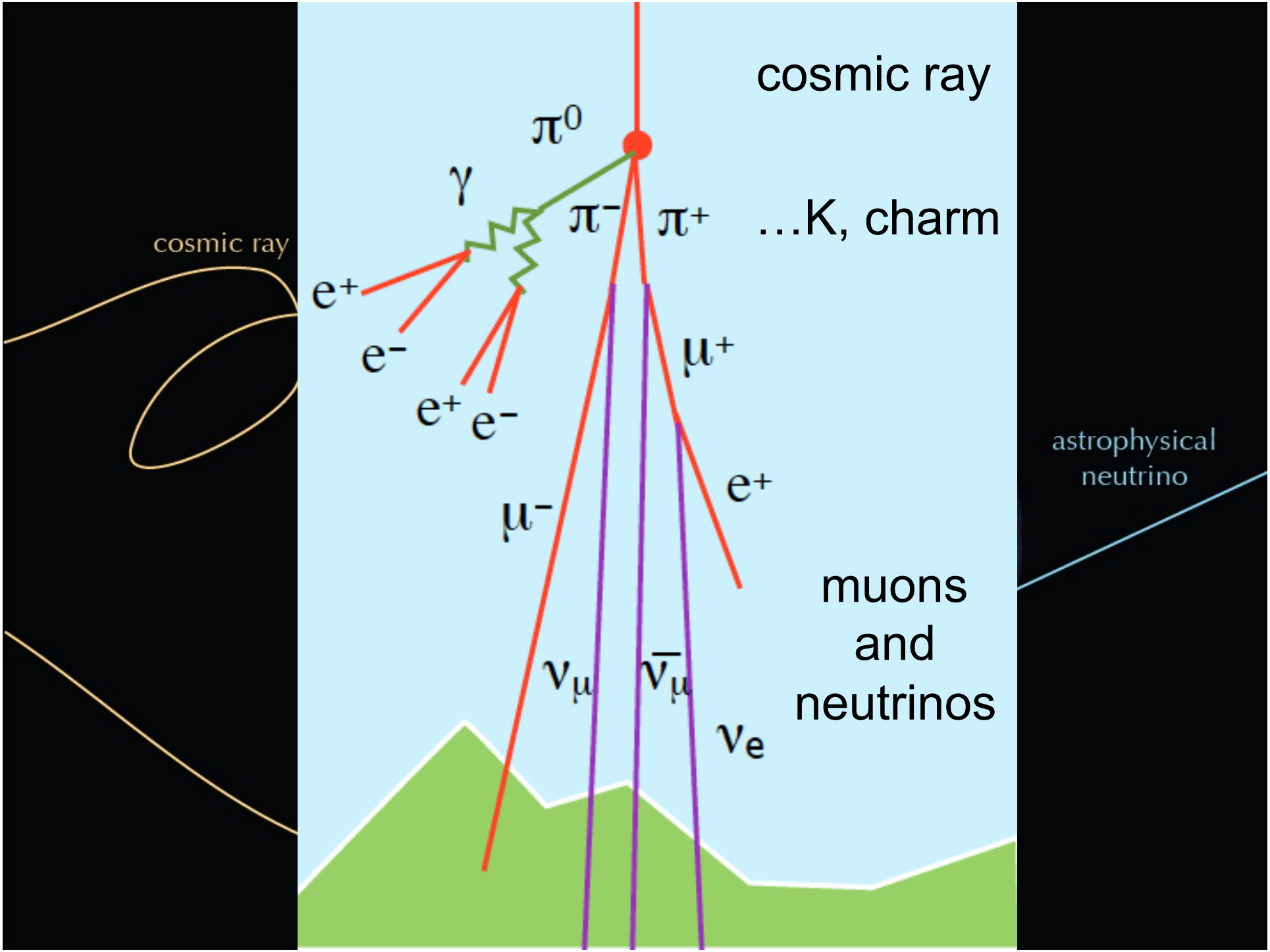
radiation
and dust

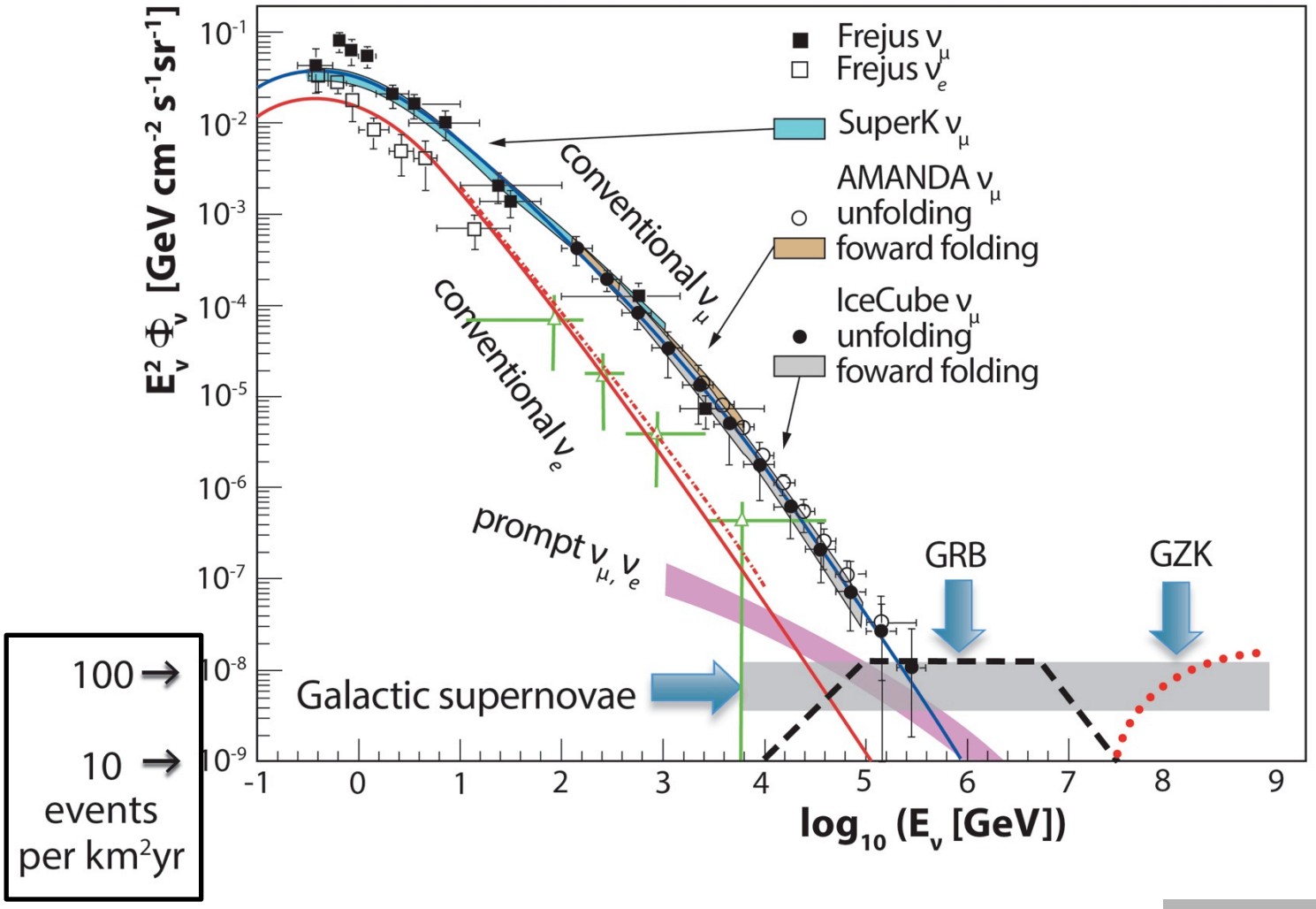
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

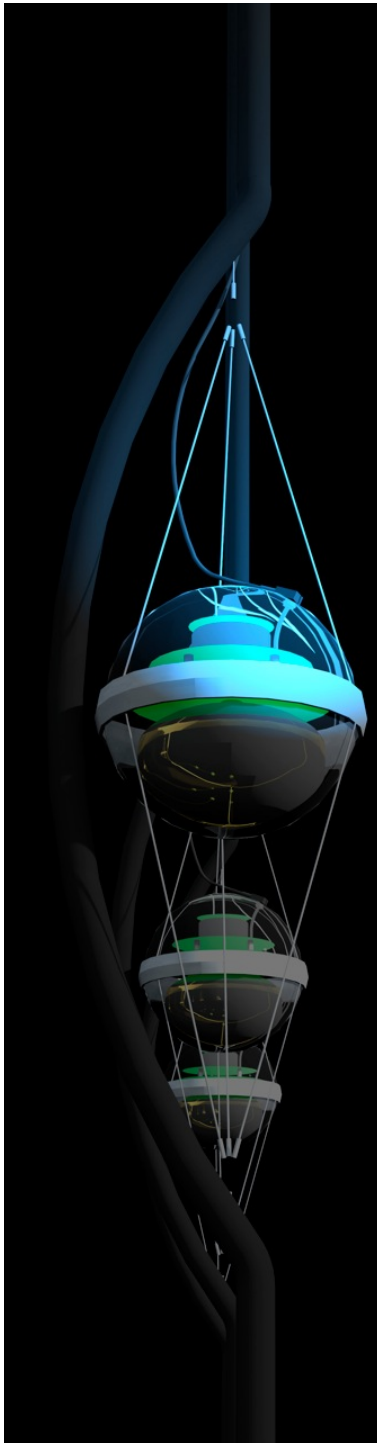
$\rightarrow p + \pi^0$

~ cosmic ray + gamma


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



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



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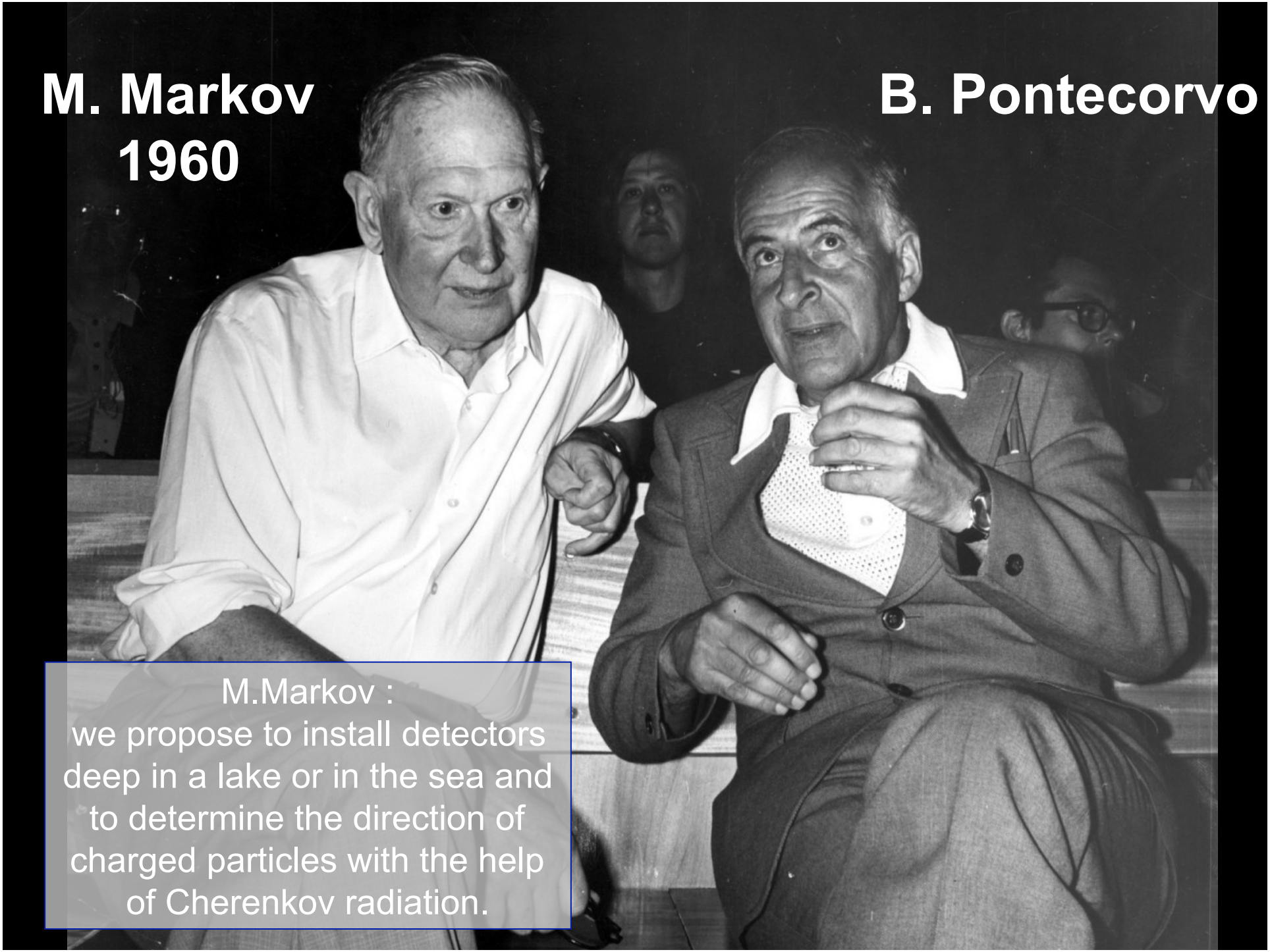
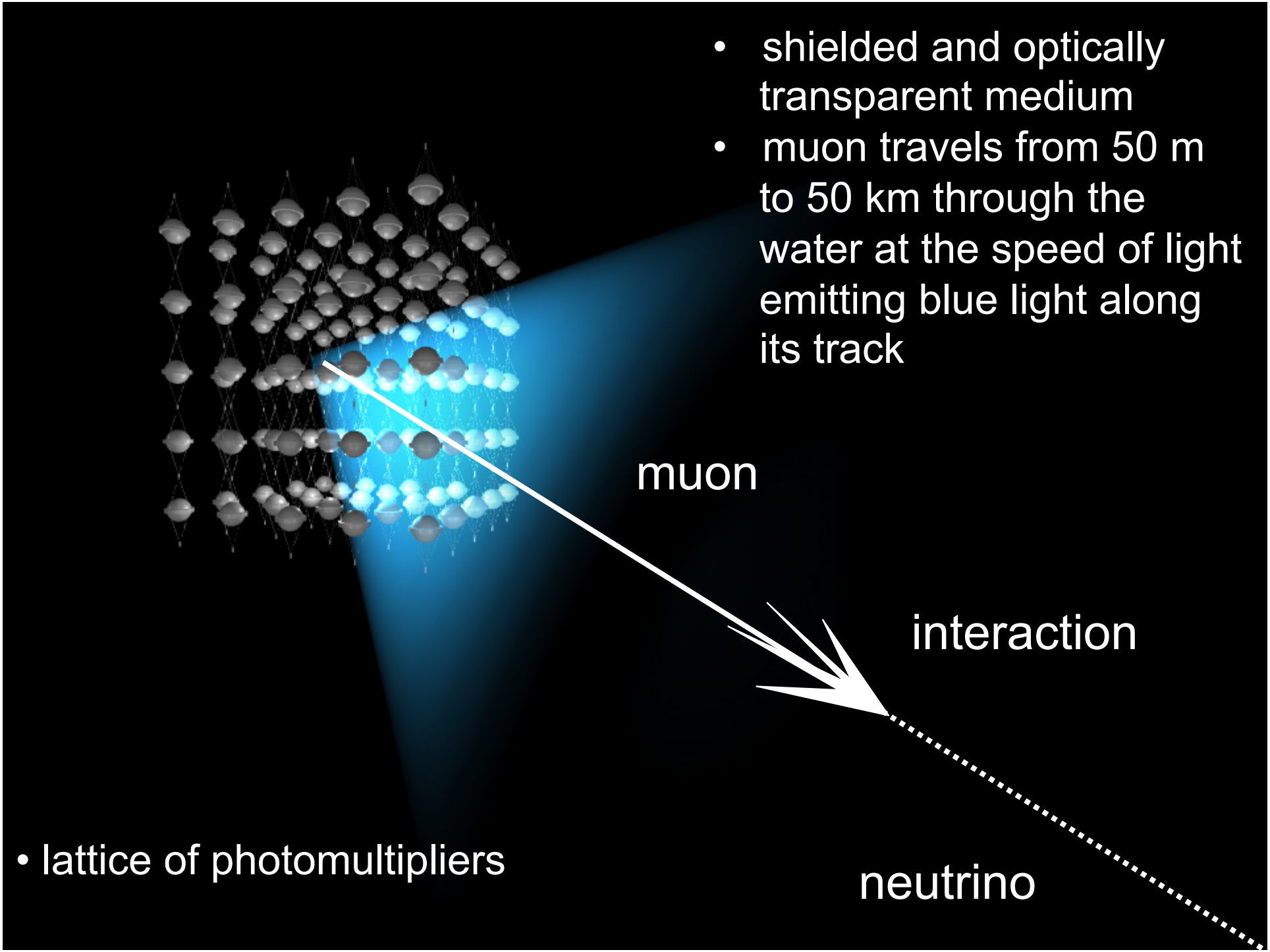
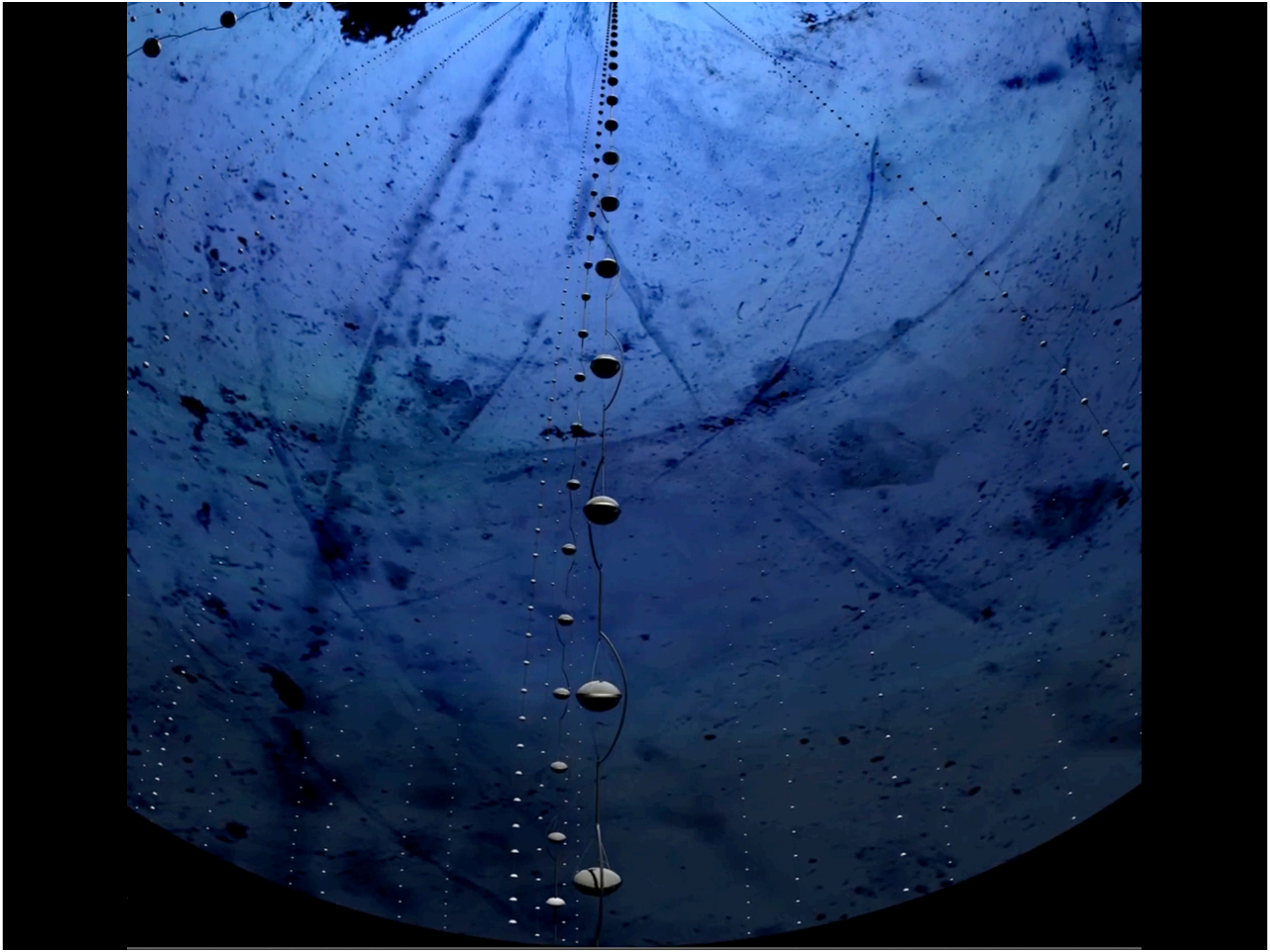
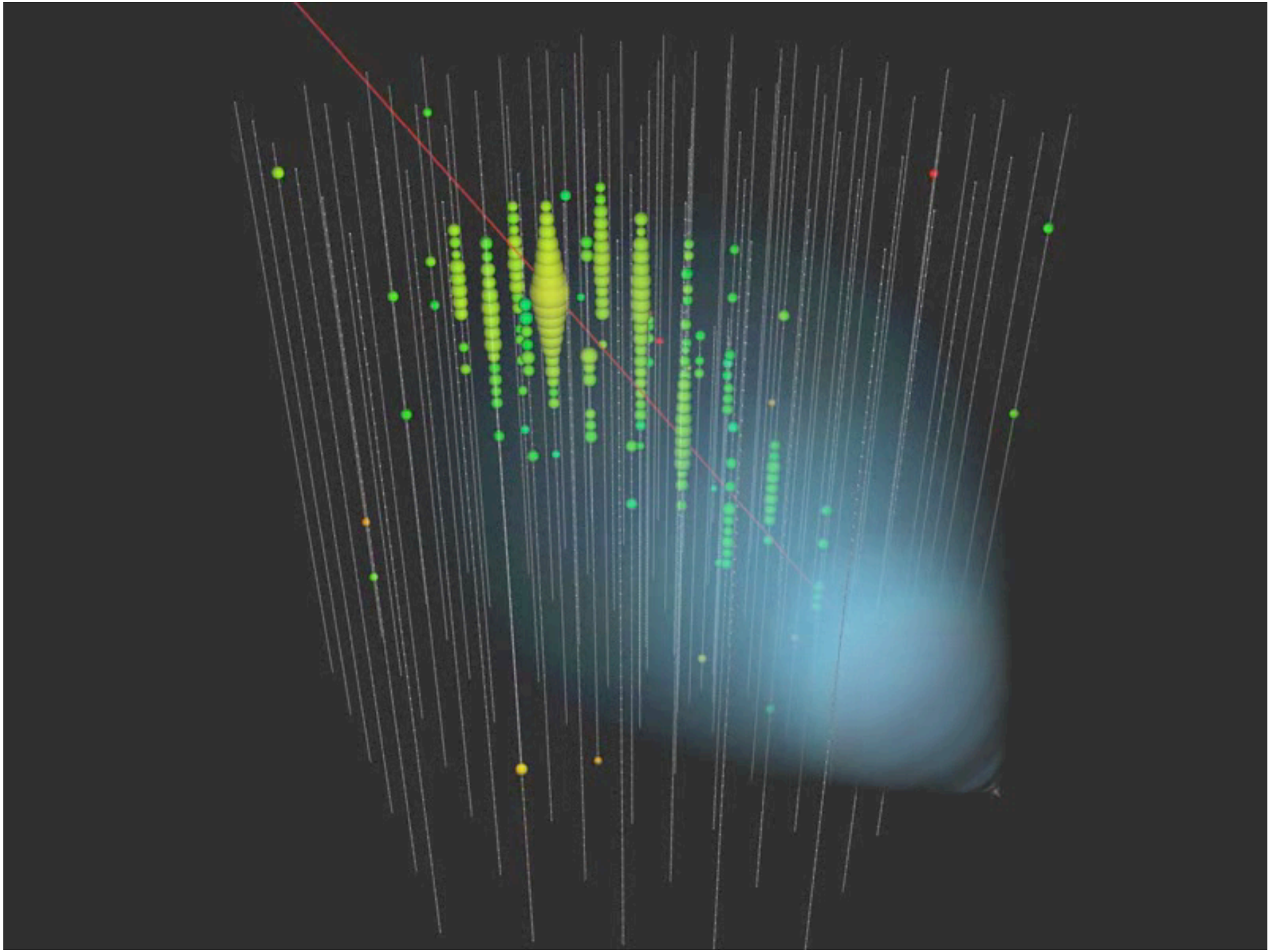


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

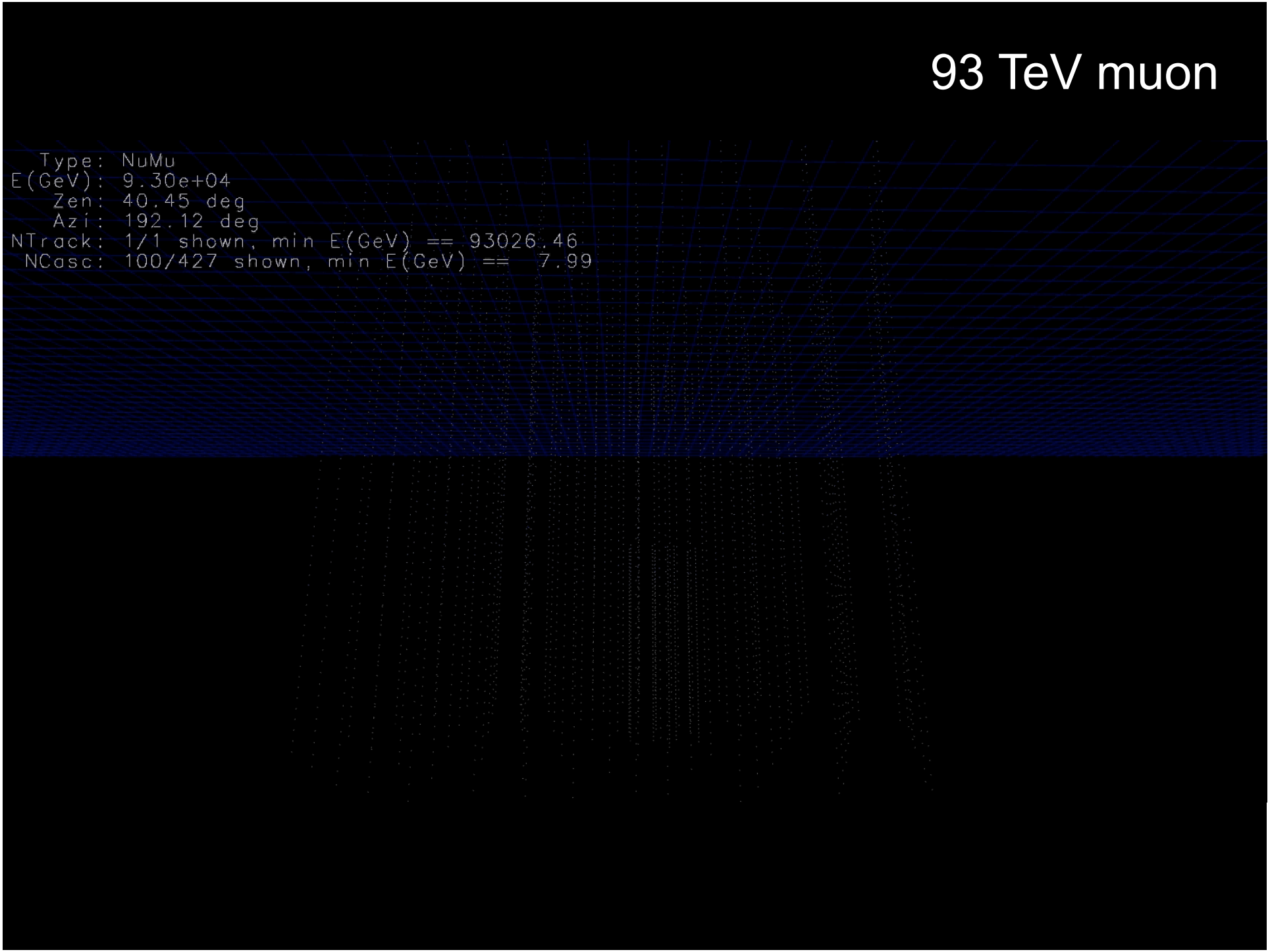

• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
• lattice of photomultipliers
neutrino



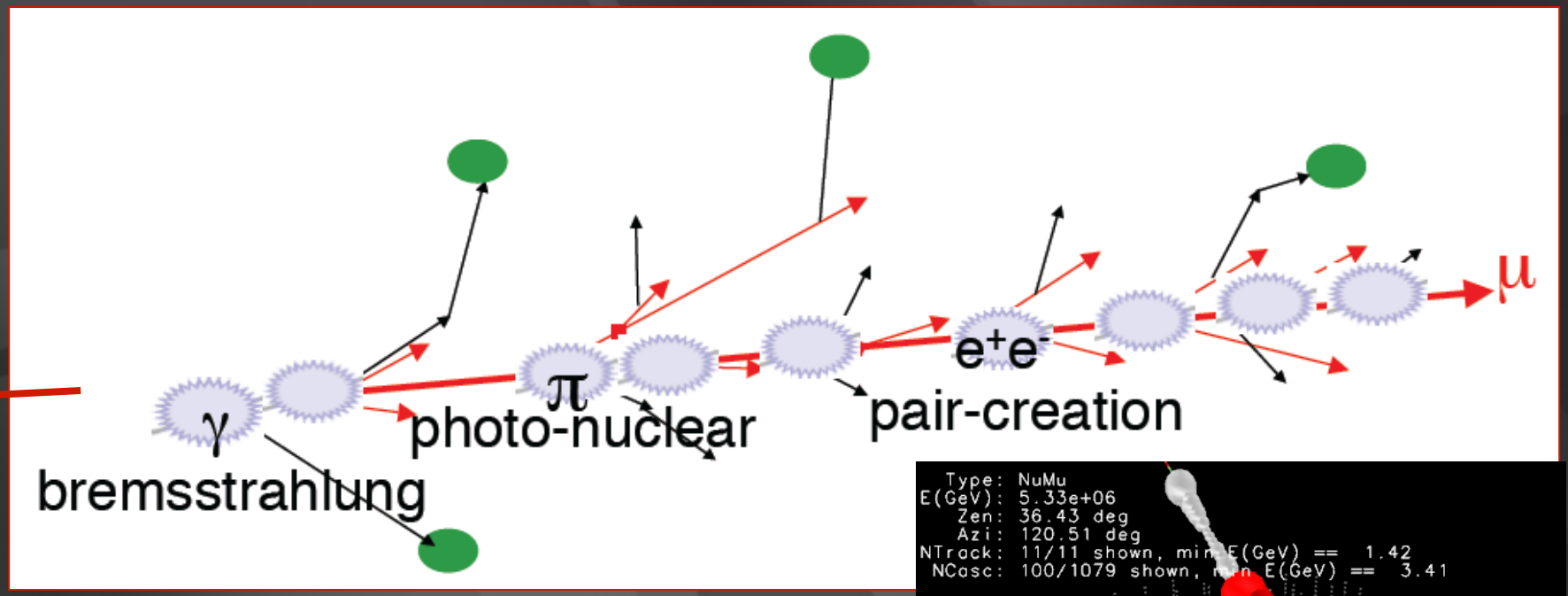
photomultiplier tube -10 inch



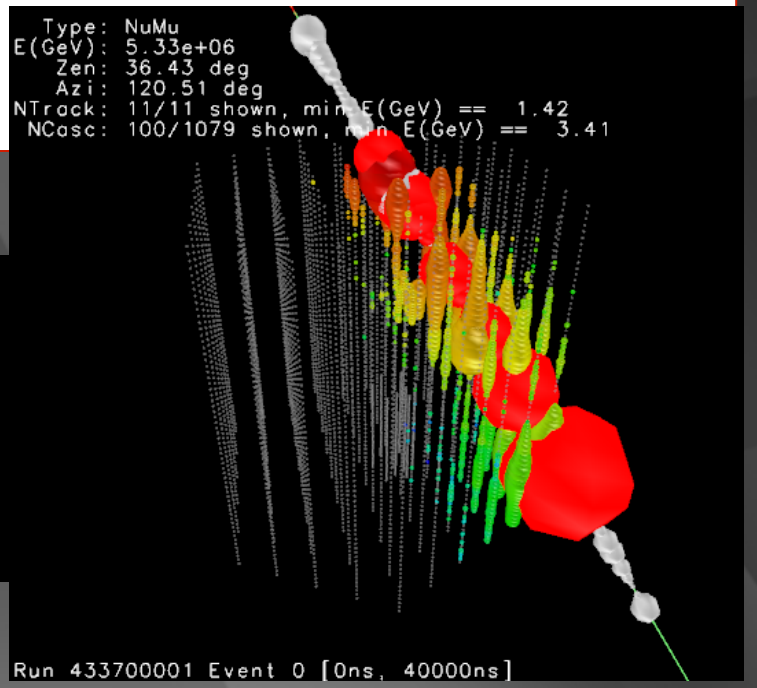
93 TeV muon

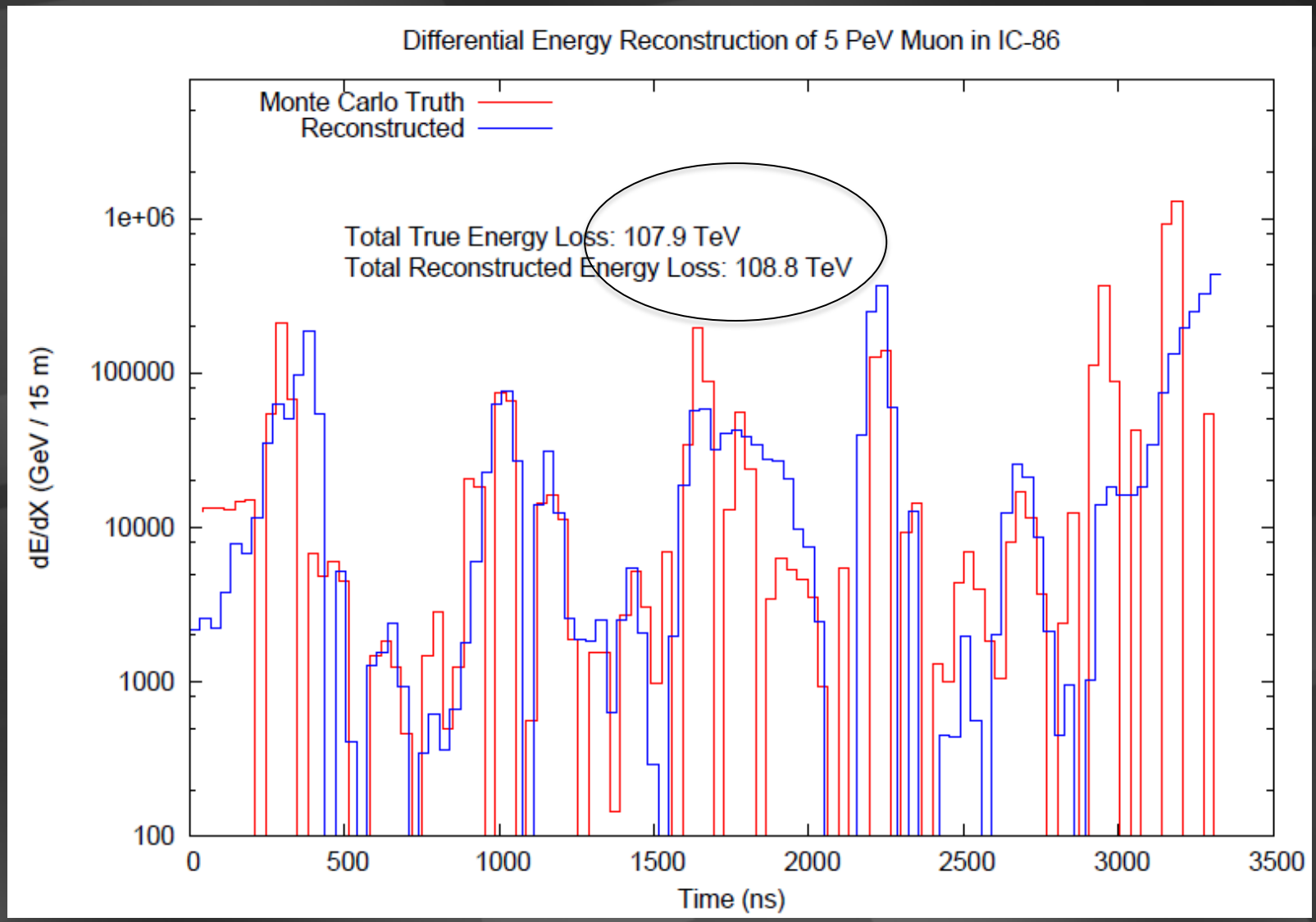

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)

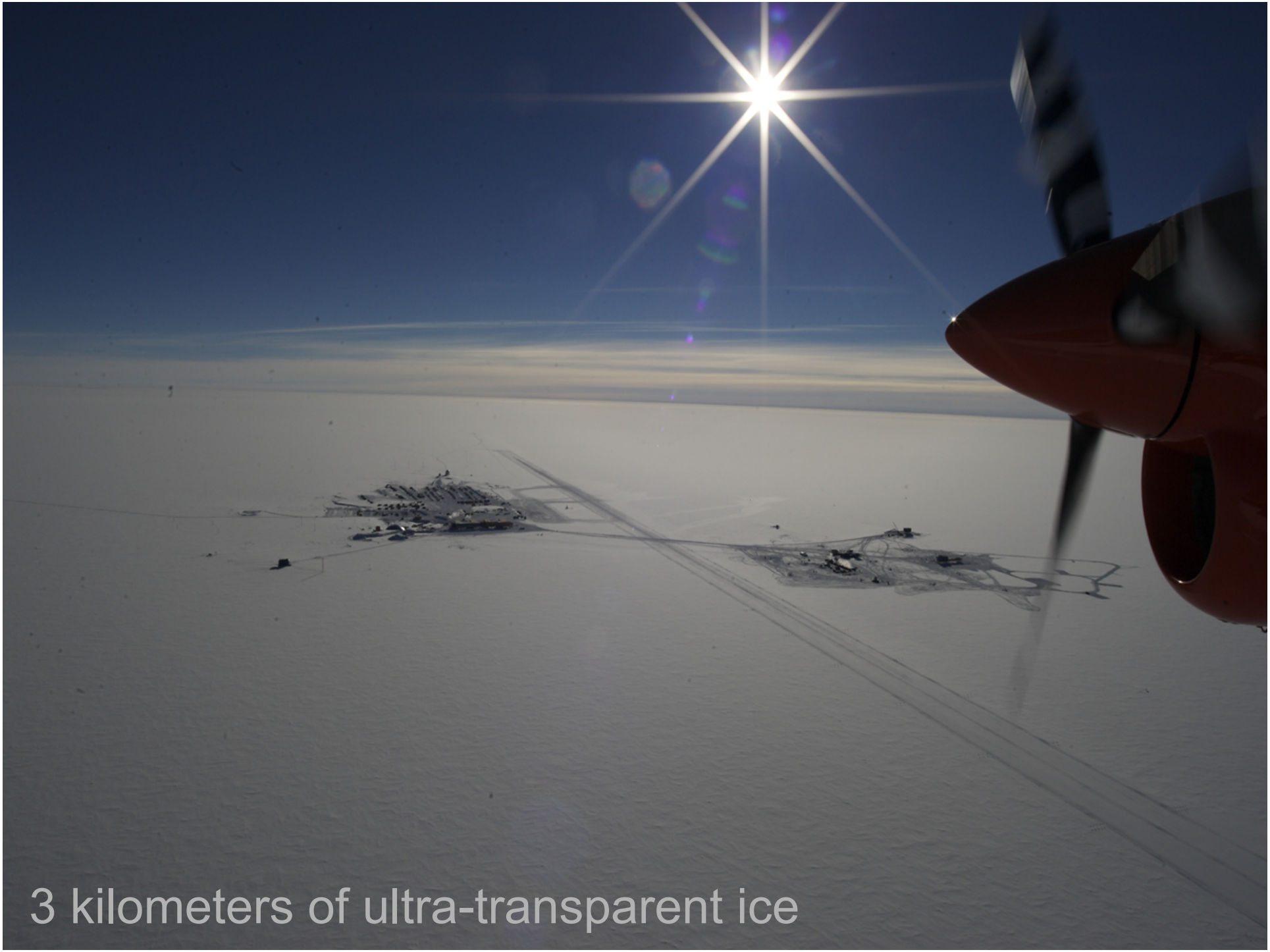


convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)





improving angular and energy resolution

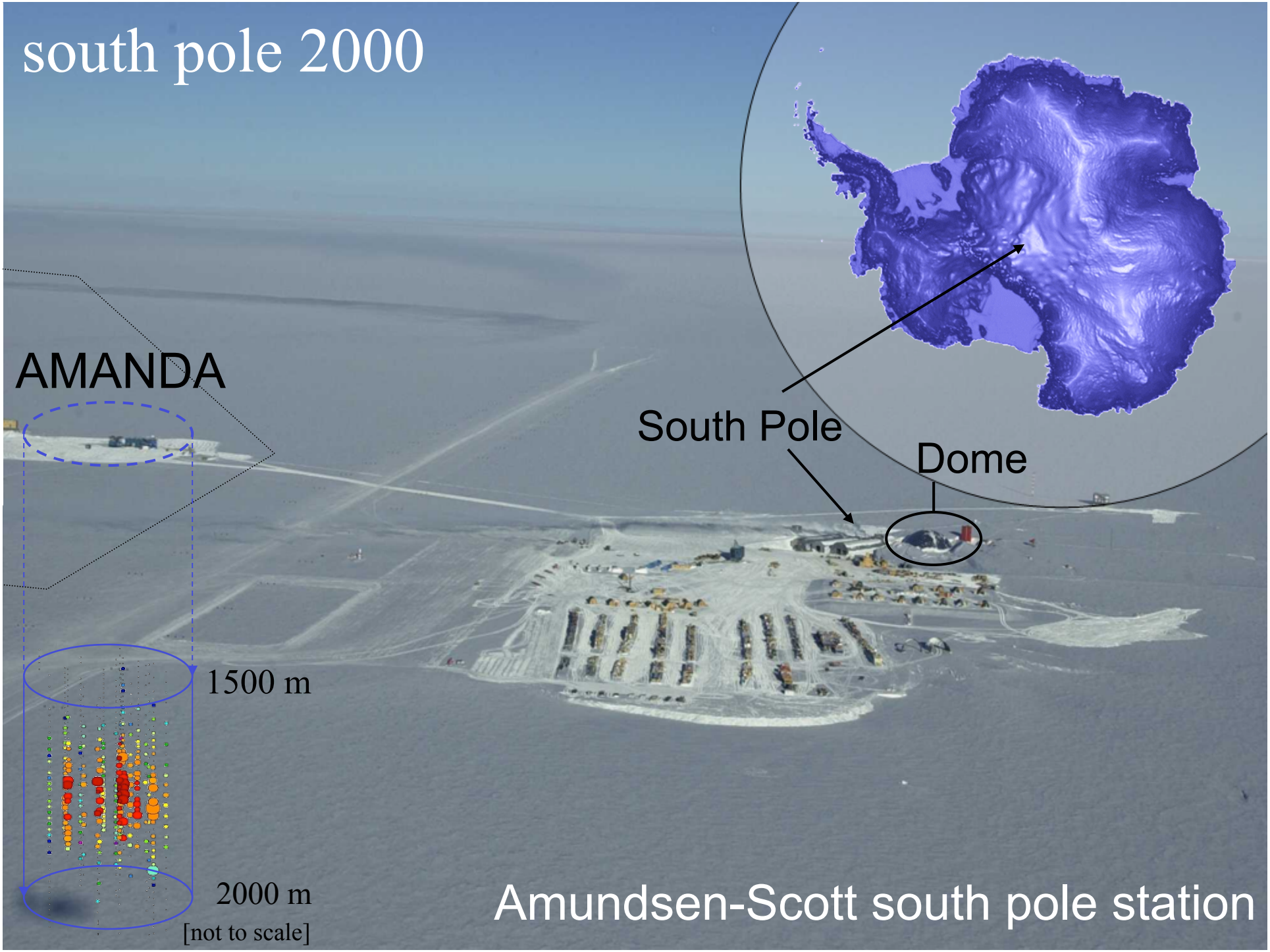

3 kilometers of ultra-transparent ice

Nature 91

Observation of muons using the polar ice cap as a Cerenkov detector

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* Department of Physics, University of California, Berkeley, California 94720, USA
† Department of Physics, University of California, Irvine, California 92717, USA
‡ Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA


south pole 2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott south pole station

Observation of high-energy neutrinos using Čerenkov detectors embedded deep in Antarctic ice

E. Andrés*, P. Askebjer†, X. Bai‡, G. Barouch*, S. W. Barwick§, R. C. Bay‖, K.-H. Becker¶, L. Bergström†, D. Bertrand#, D. Bierenbaum§, A. Biron☆, J. Booth§, O. Botner**, A. Bouchta☆, M. M. Boyce*, S. Carius††, A. Chen*, D. Chirkin‖¶, J. Conrad**, J. Cooley*, C. G. S. Costa#, D. F. Cowen‡‡, J. Dailing§, E. Dalberg†, T. DeYoung*, P. Desiati☆, J.-P. Dewulf#, P. Doksus*, J. Edsjö†, P. Ekström†, B. Erlandsson†, T. Feser§§, M. Gaug☆, A. Goldschmidt‖, A. Goobar†, L. Gray*, H. Haase☆, A. Hallgren**, F. Halzen*, K. Hanson‡‡, R. Hardtke*, Y. D. He‖, M. Hellwig§§, H. Heukenkamp☆, G. C. Hill*, P. O. Hulth†, S. Hundertmark§, J. Jacobsen‖, V. Kandhadai*, A. Karle*, J. Kim§, B. Koci*, L. Köpke§§, M. Kowalski☆, H. Leich☆, M. Leuthold☆, P. Lindahl††, I. Liubarsky*, P. Loaiza**, D. M. Lowder‖, J. Ludvig‖, J. Madsen*, P. Marciniewski**, H. S. Matis‖, A. Mihalyi‡‡, T. Mikolajski☆, T. C. Miller‡, Y. Minaeva†, P. Miočinović‖, P. C. Mock§, R. Morse*, T. Neunhöffer§§, F. M. Newcomer‡‡, P. Niessen☆, D. R. Nygren‖, H. Ögelman*, C. Pérez de los Heros**, R. Porrata§, P. B. Price‖, K. Rawlins*, C. Reed§, W. Rhode¶, A. Richards‖, S. Richter☆, J. Rodríguez Martino†, P. Romenesko*, D. Ross§, H. Rubinstein†, H.-G. Sander§§, T. Scheider§§, T. Schmidt☆, D. Schneider*, E. Schneider§, R. Schwarz*, A. Silvestri¶☆, M. Solarz‖, G. M. Spiczak‡, C. Spiering☆, N. Starinsky*, D. Steele*, P. Steffen☆, R. G. Stokstad‖, O. Streicher☆, Q. Sun†, I. Taboada‡‡, L. Thollander†, T. Thon☆, S. Tilav*, N. Usechak§, M. Vander Donckt#, C. Walck†, C. Weinheimer§§, C. H. Wiebusch☆, R. Wischnewski☆, H. Wissing☆, K. Woschnagg‖, W. Wu§, G. Yodh§ & S. Young§

NATURE 2001

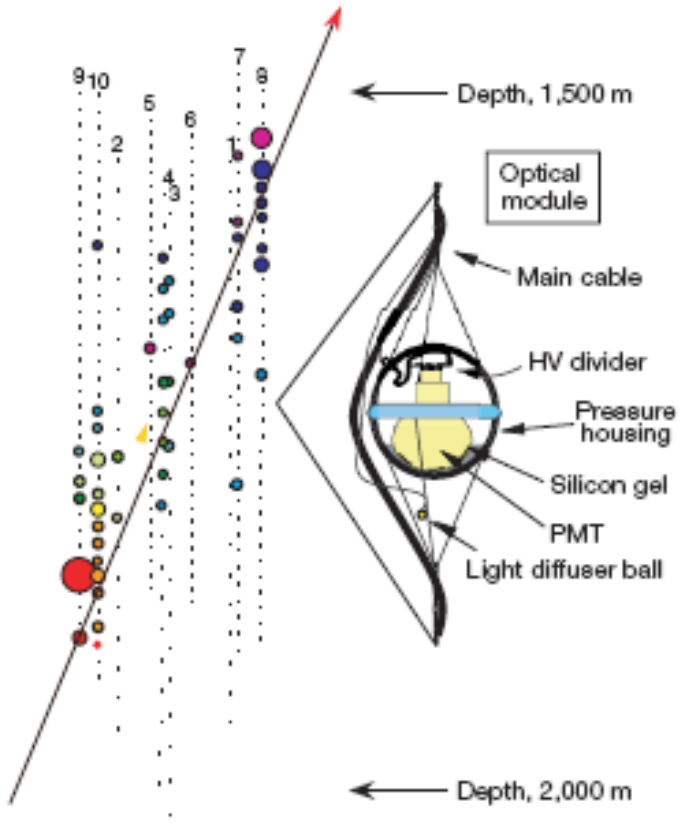
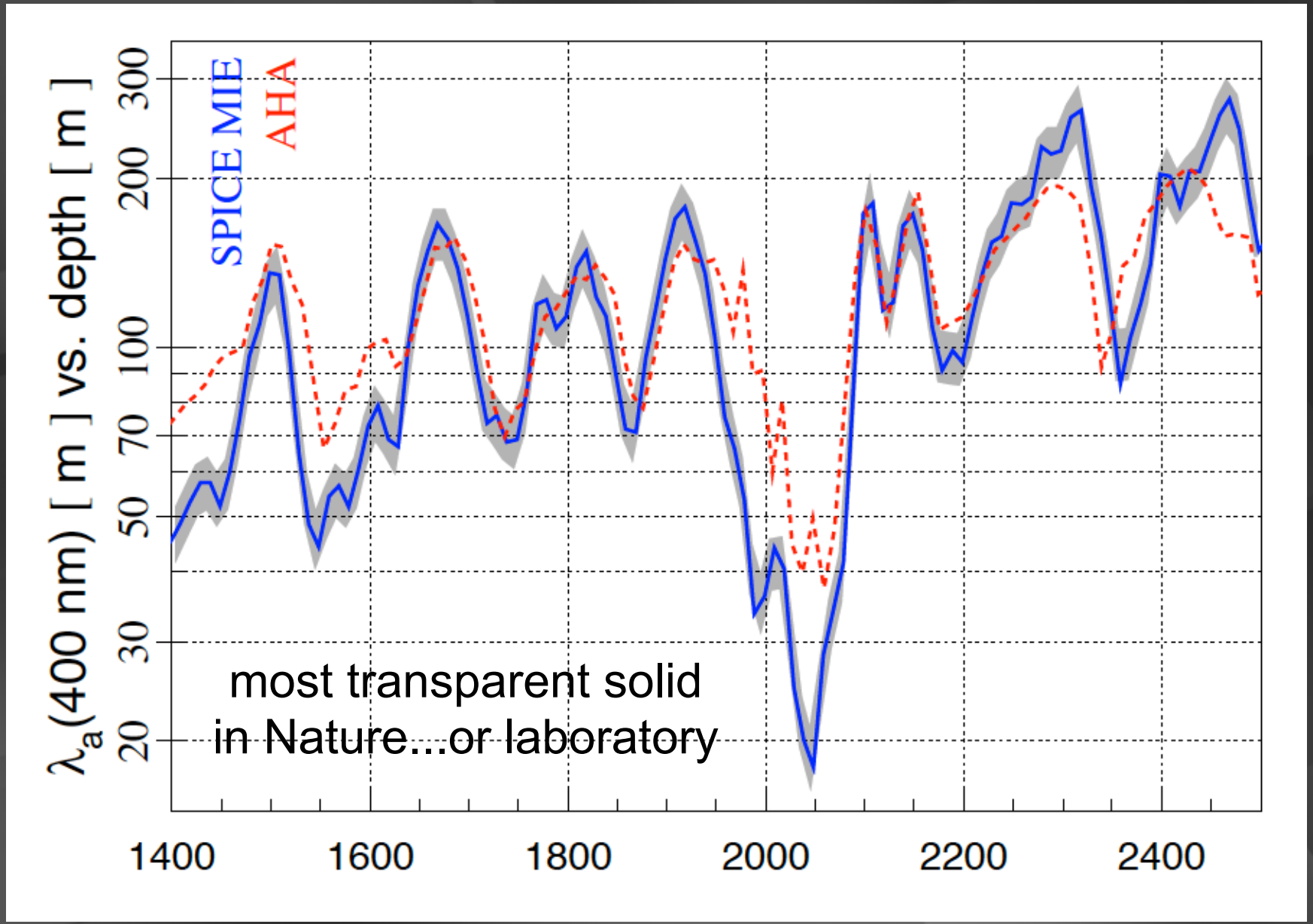
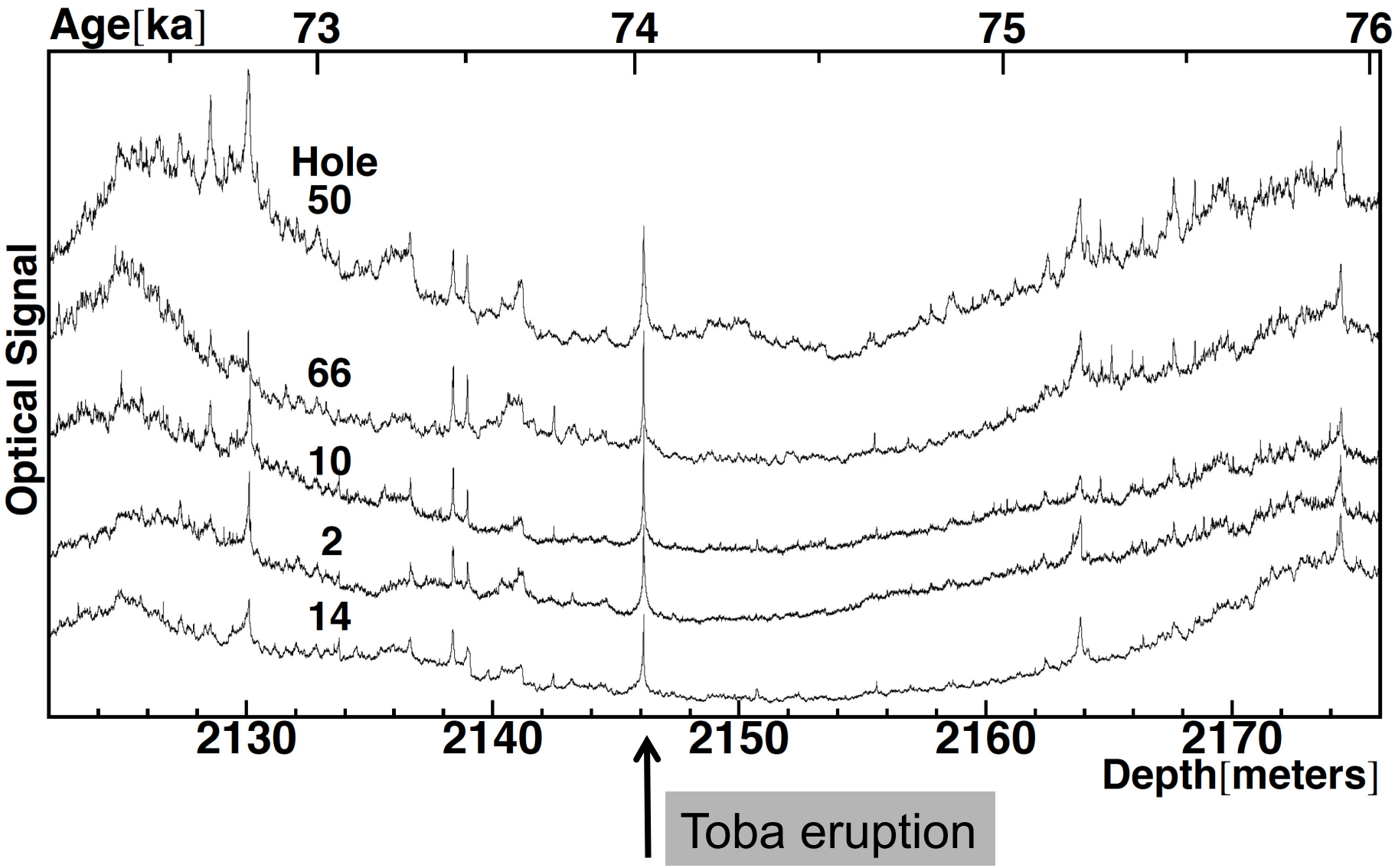


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon.

absorption length ← 220m →

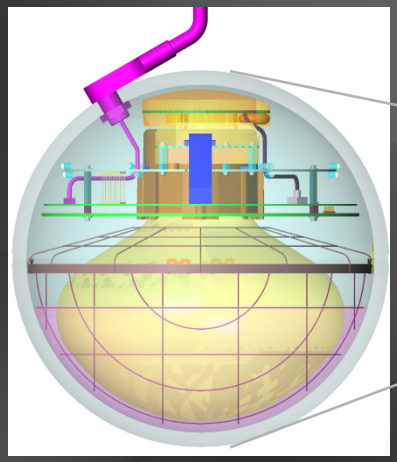


scattering measurement on dust

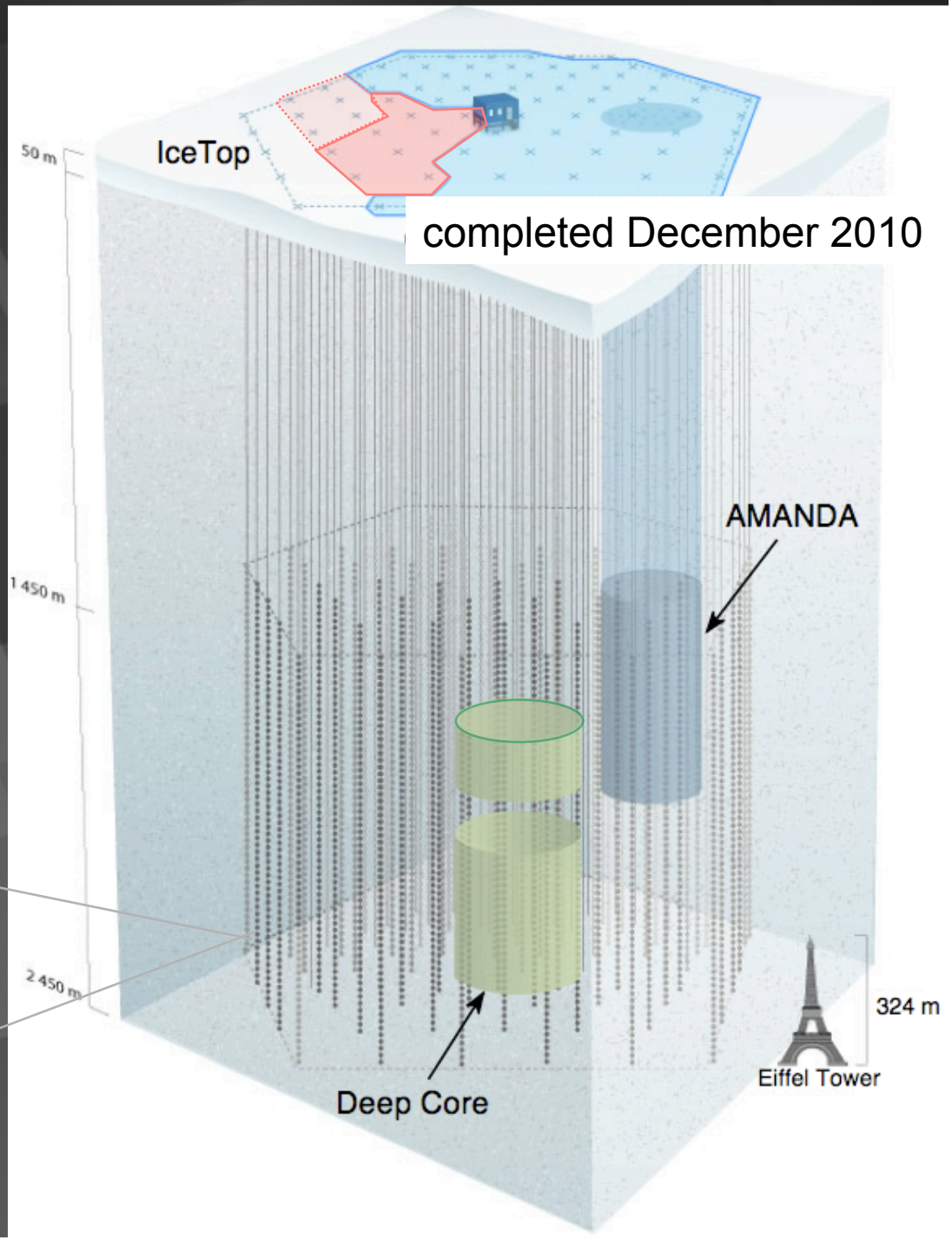


IceCube / Deep Core

- 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

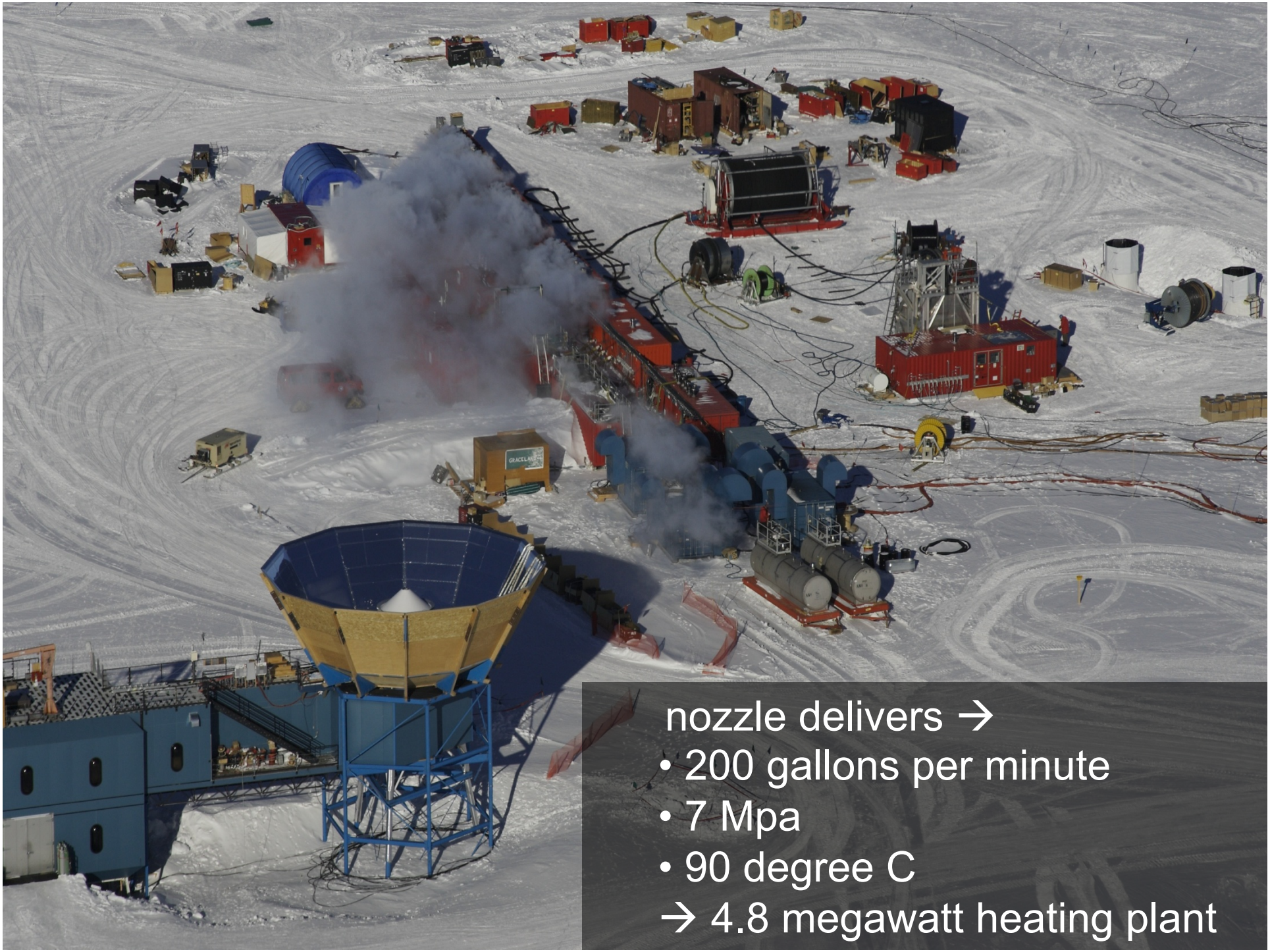


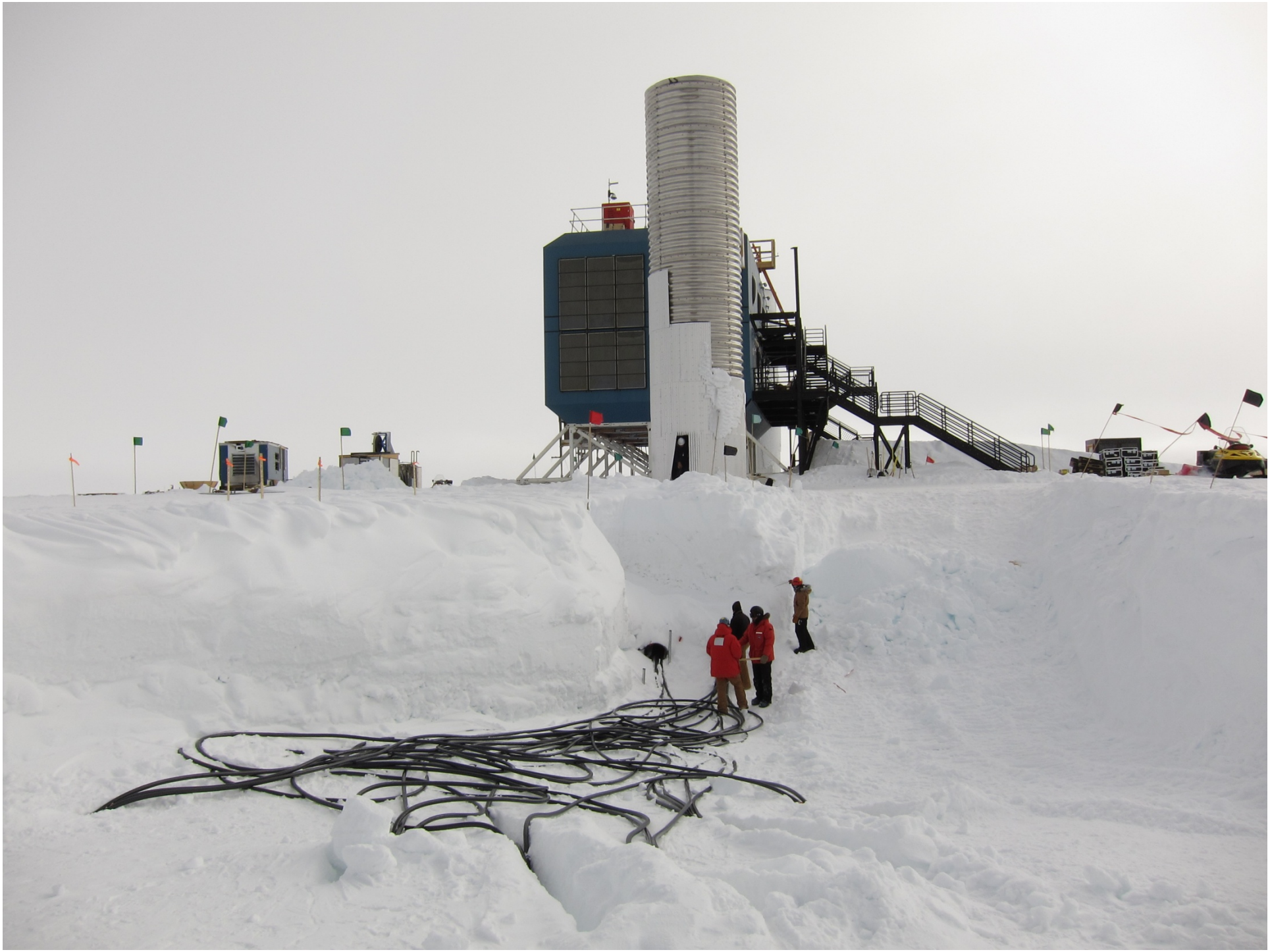
Digital Optical Module (DOM)



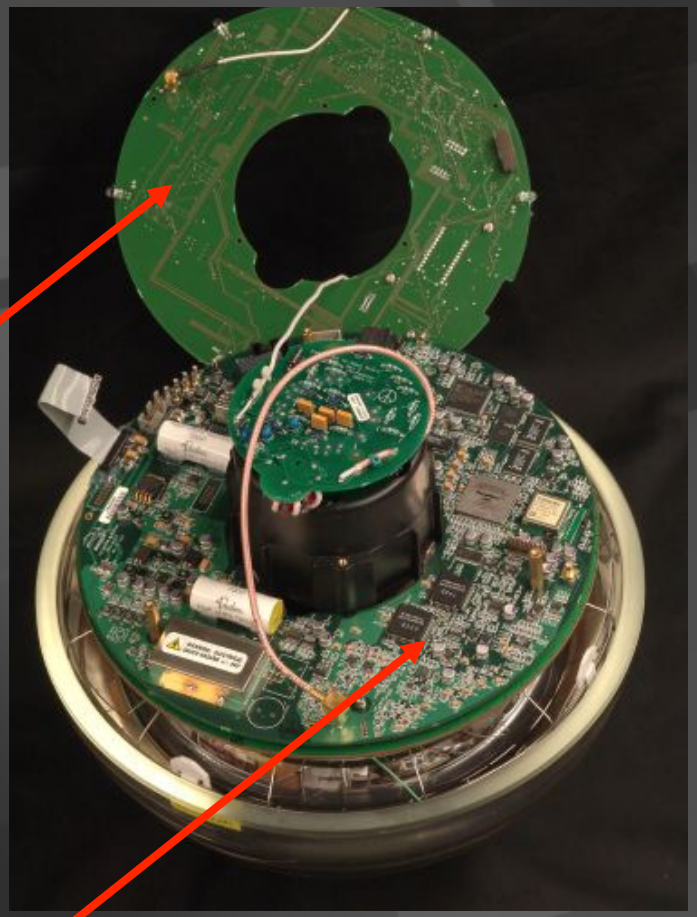
drilling and deployment

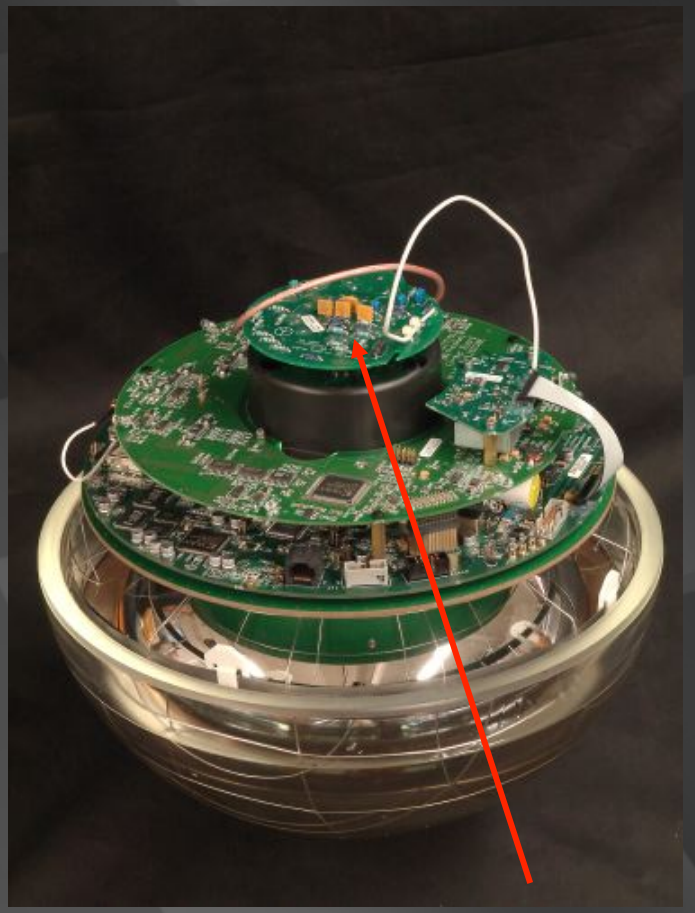
2 days per hole
3.5 cm/second


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



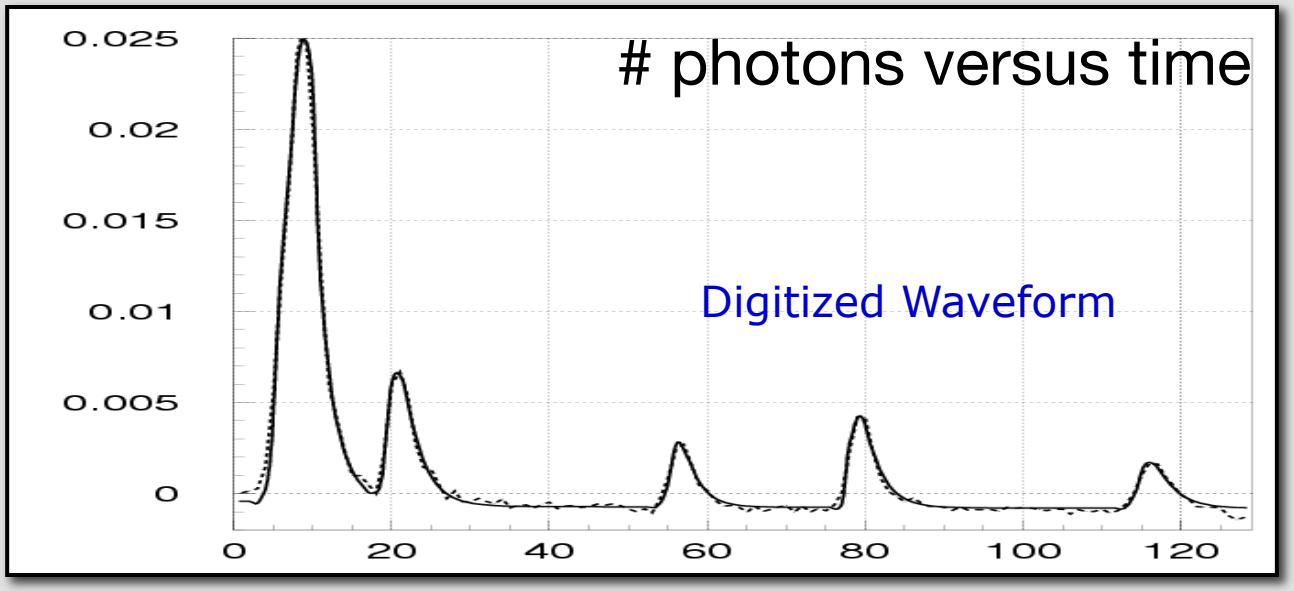
architecture of independent DOMs





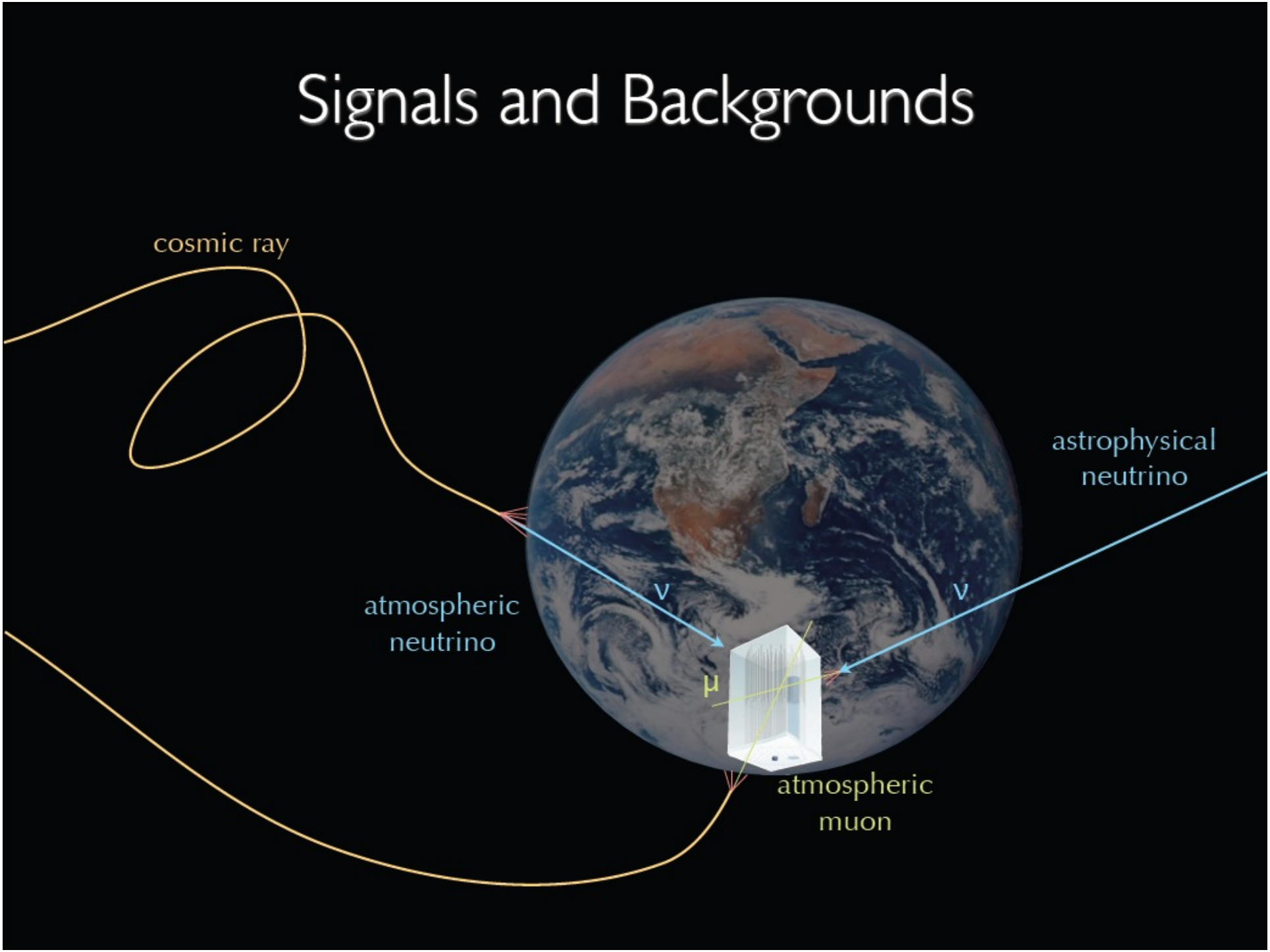
Digital Optical Module (DOM)

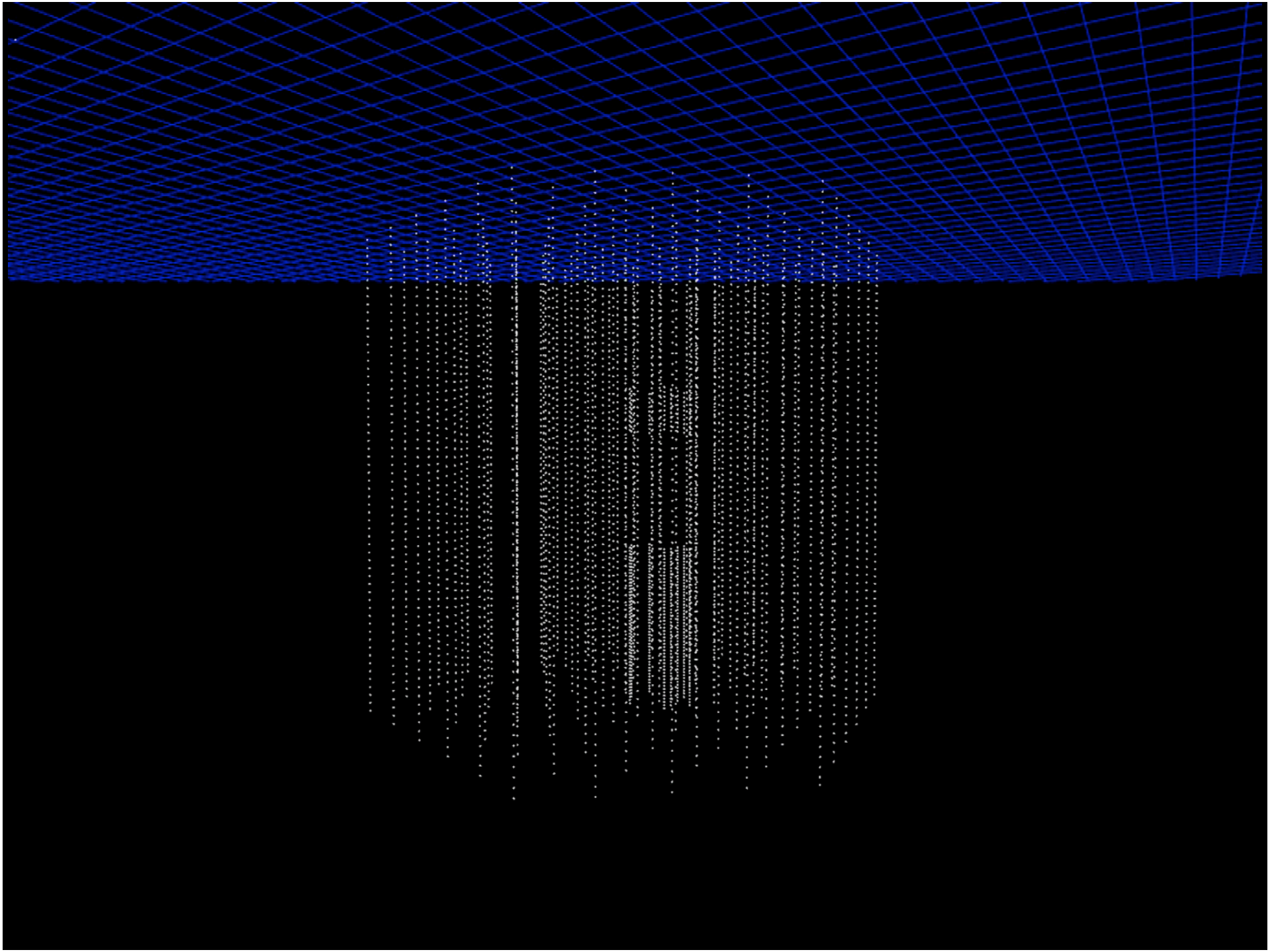
… each DOM independently collects light signals like this…



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

Signals and Backgrounds



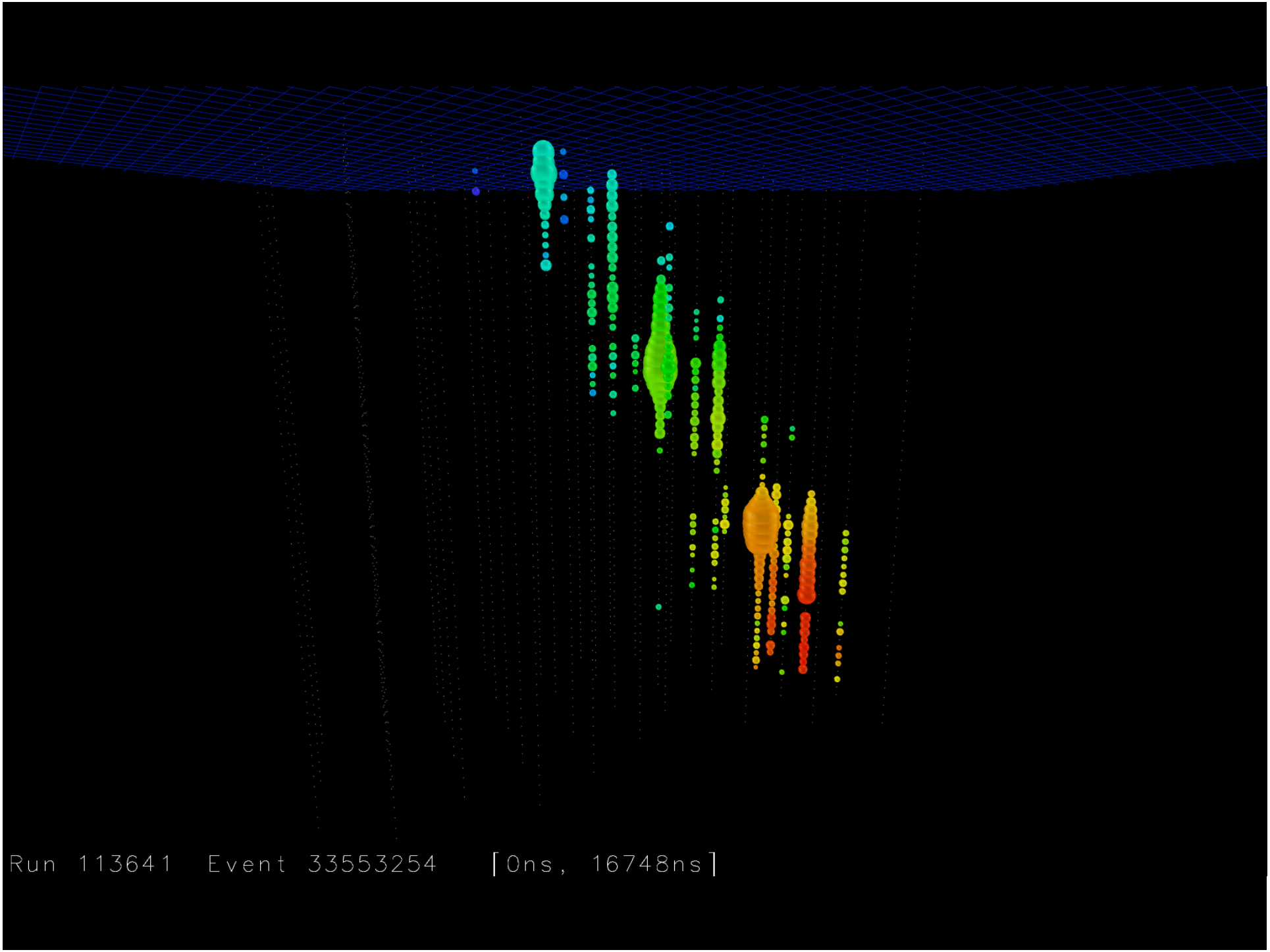


… you looked at 10msec of data !

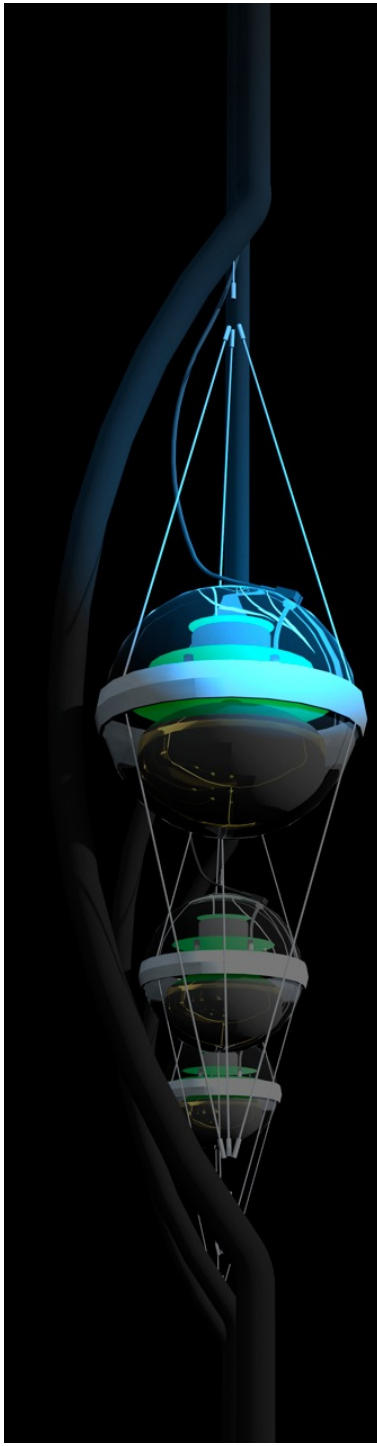
muons detected per year:

- 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

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

cosmic rays interact with the microwave background

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

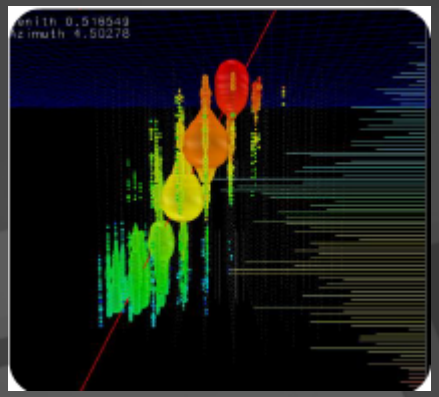
cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

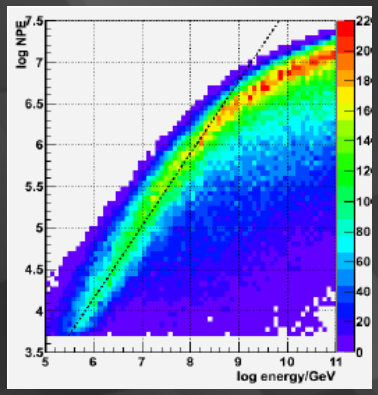
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source

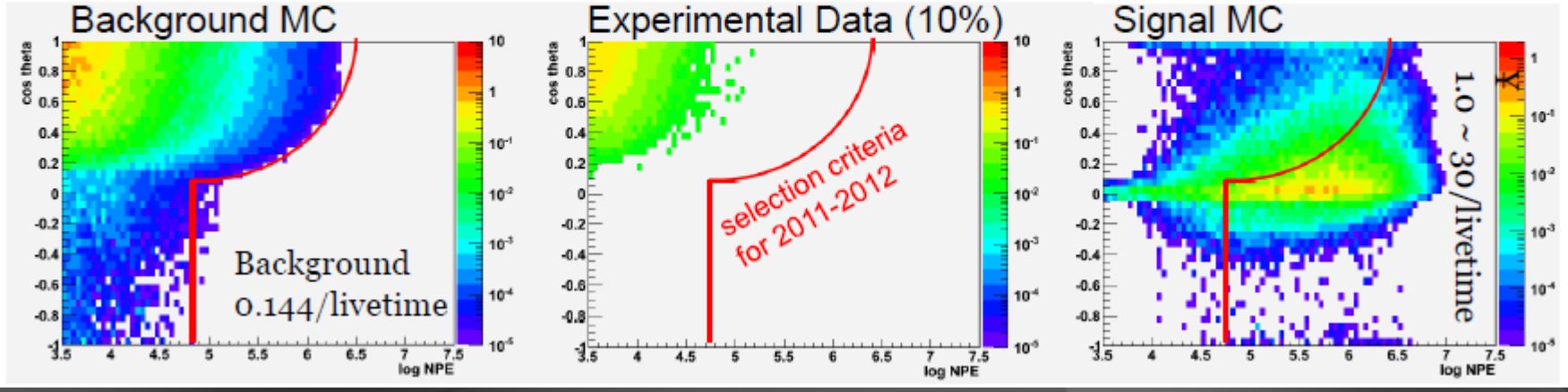
GZK neutrinos: > 41,000 photons near the horizon
> 300 channels



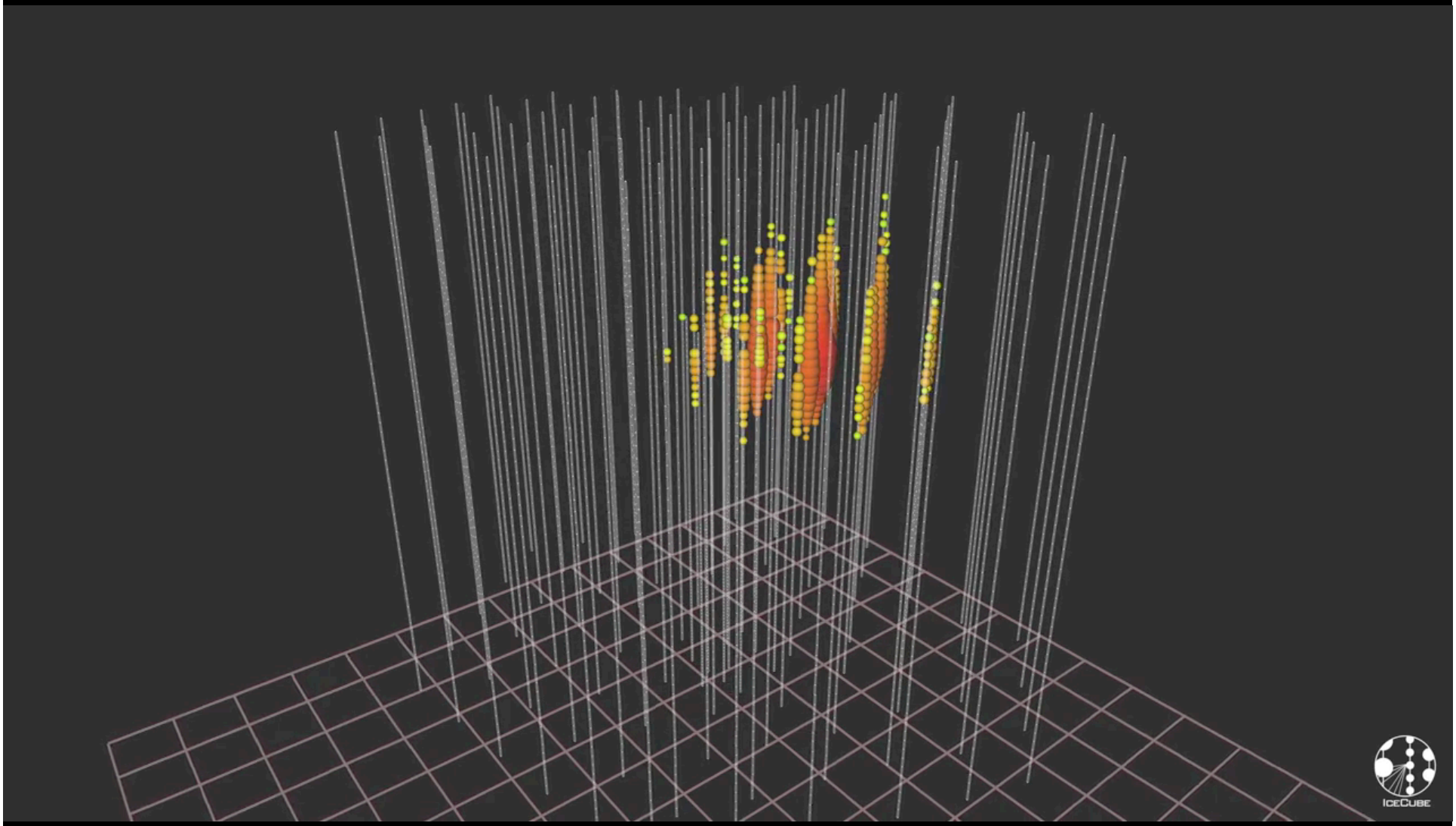


Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

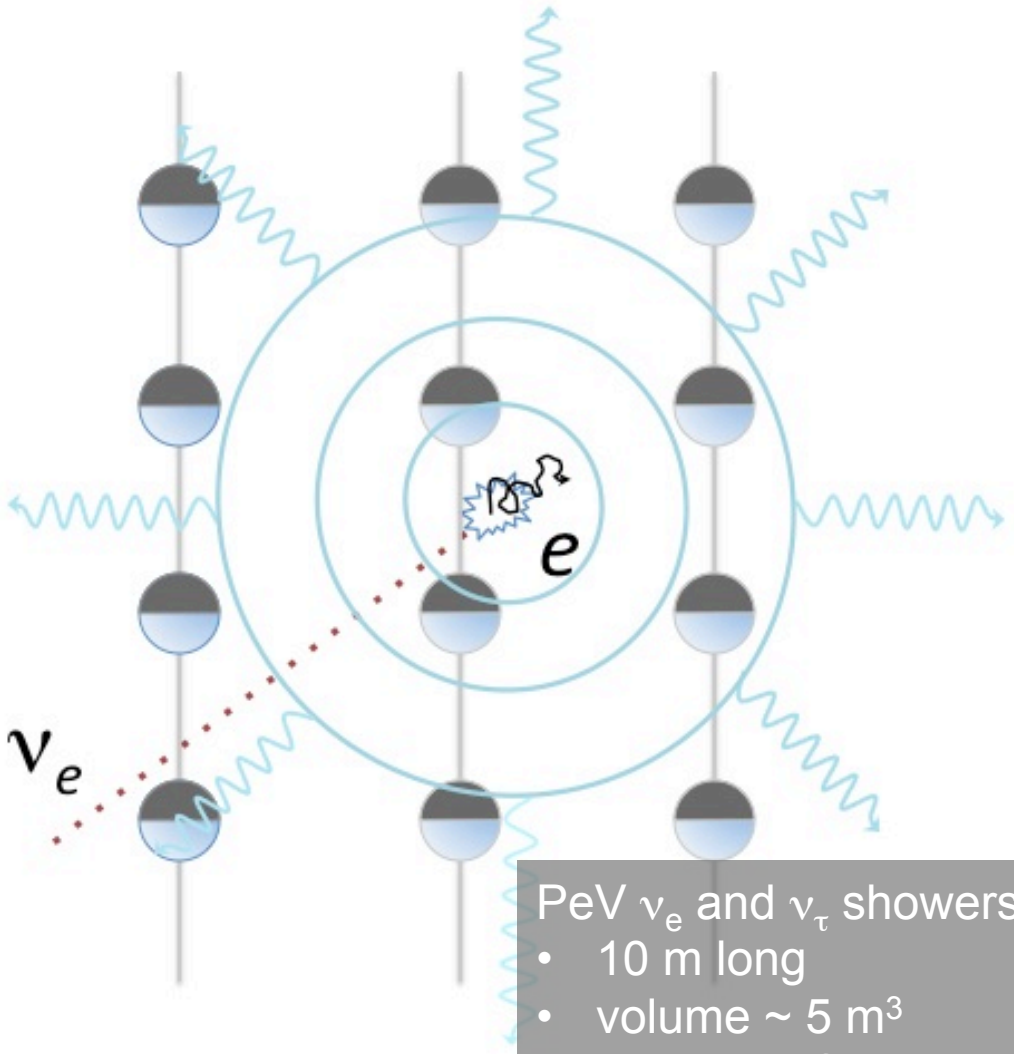
- Optimization based MC and MC verification based on 10% experimental 'burn' sample



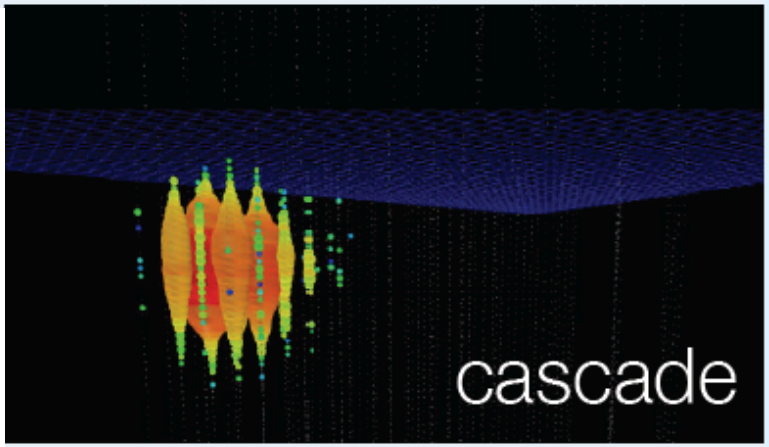
unblinding: 2 events in the signal region

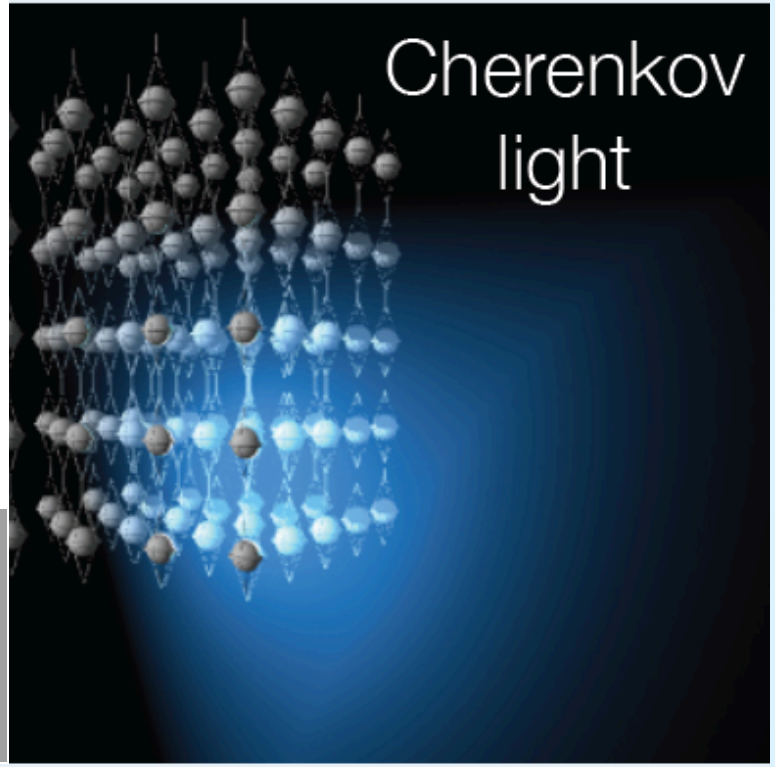

IceCube

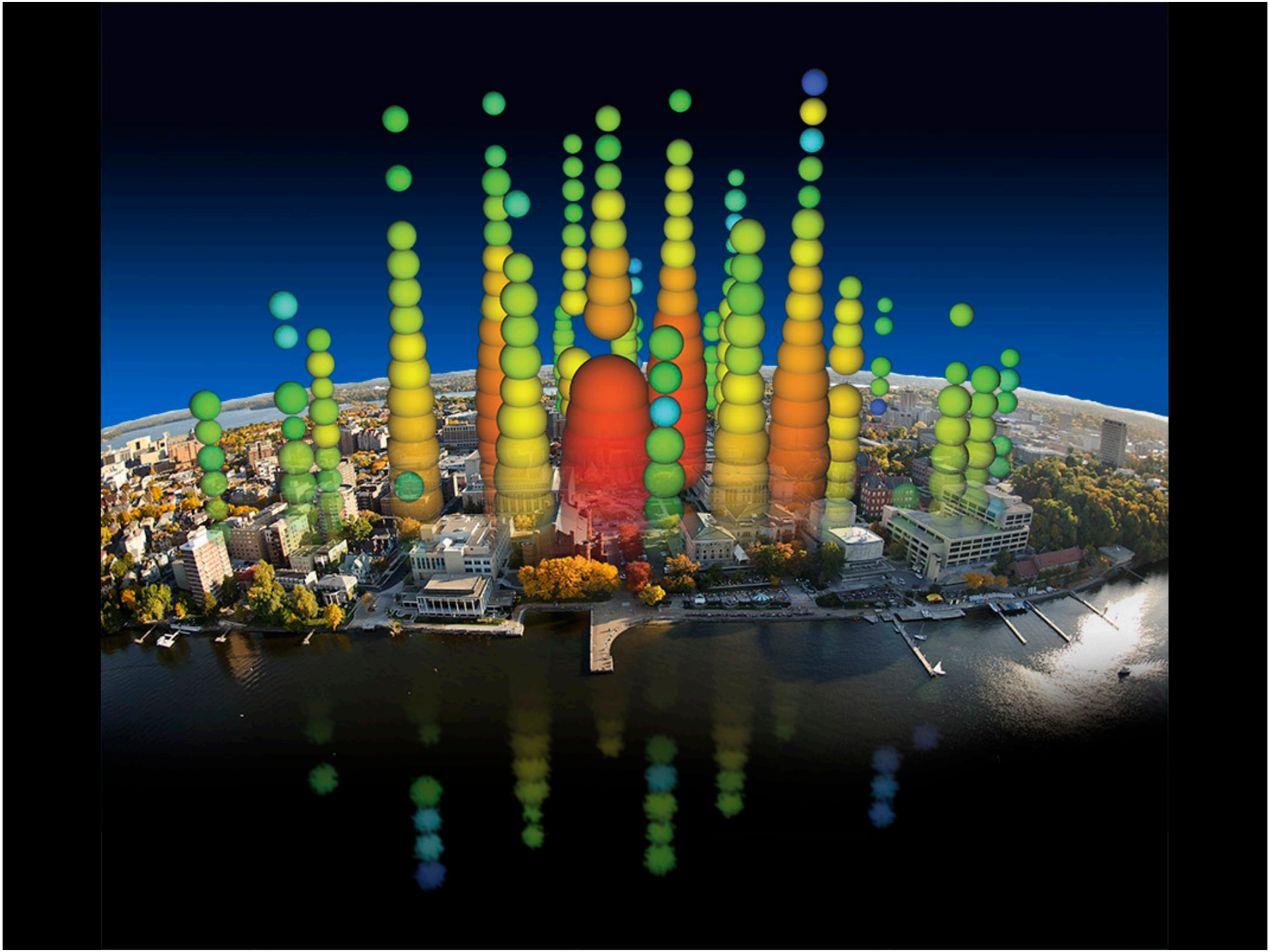
tracks and showers

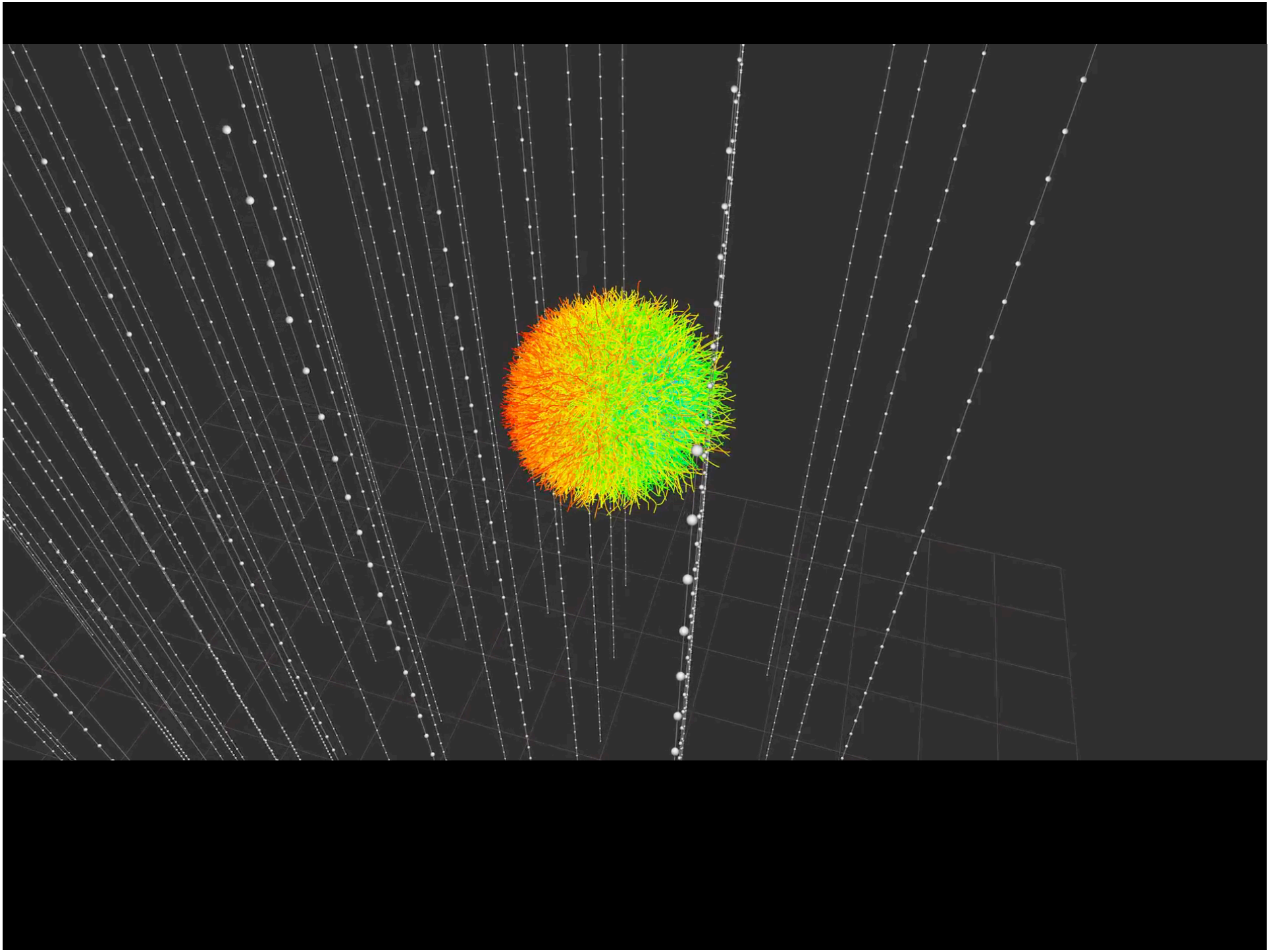


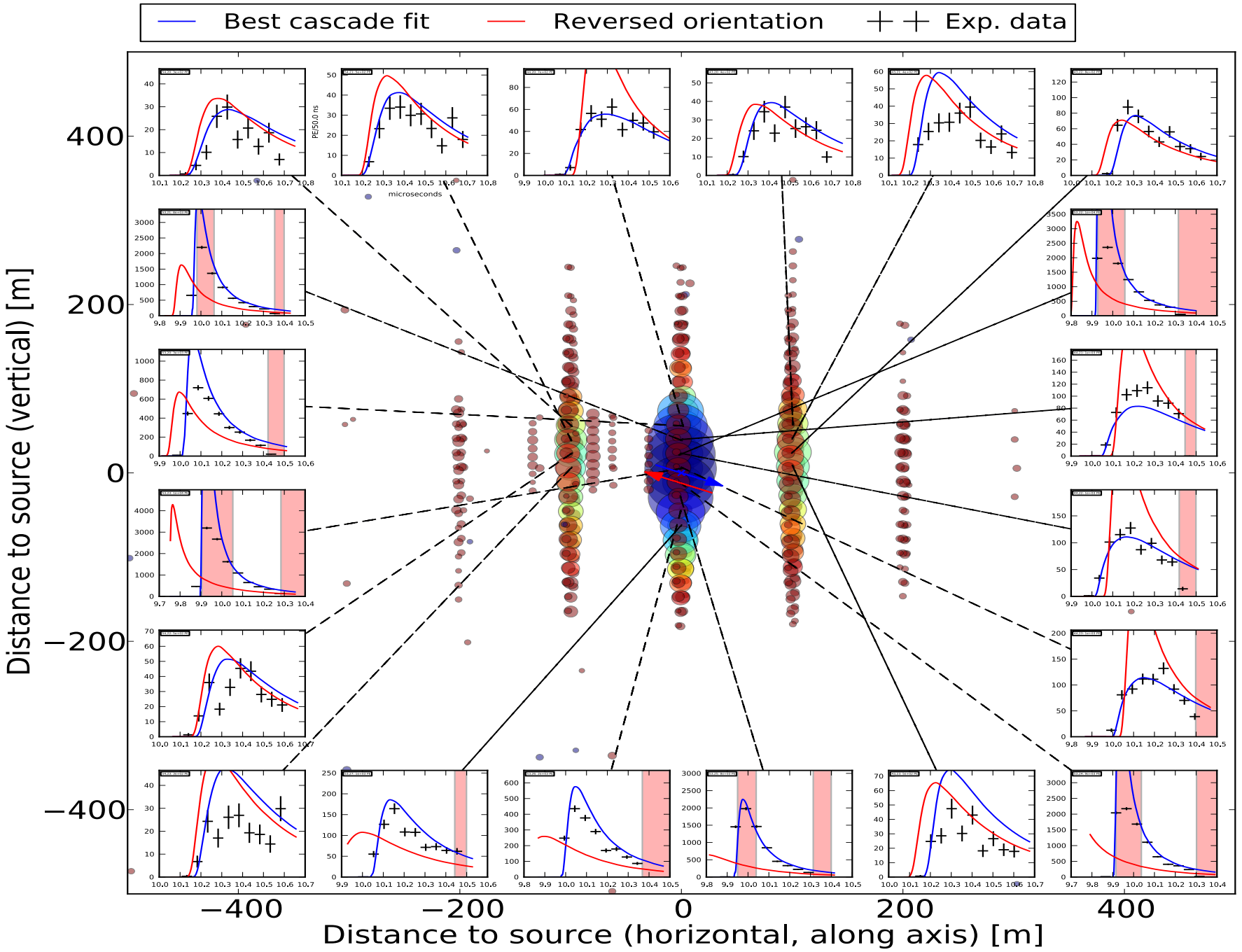
PeV ν_e and ν_τ showers:
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



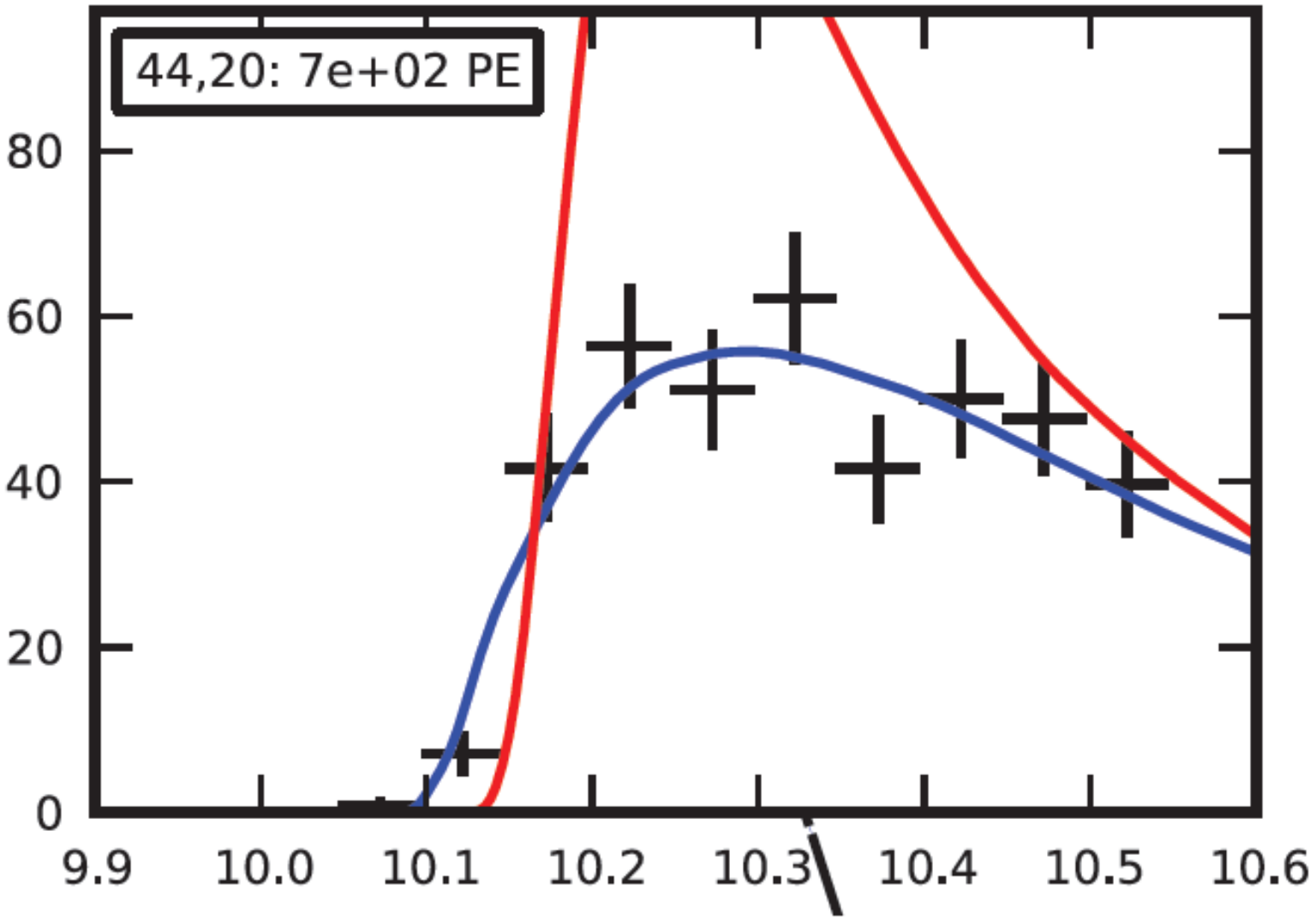




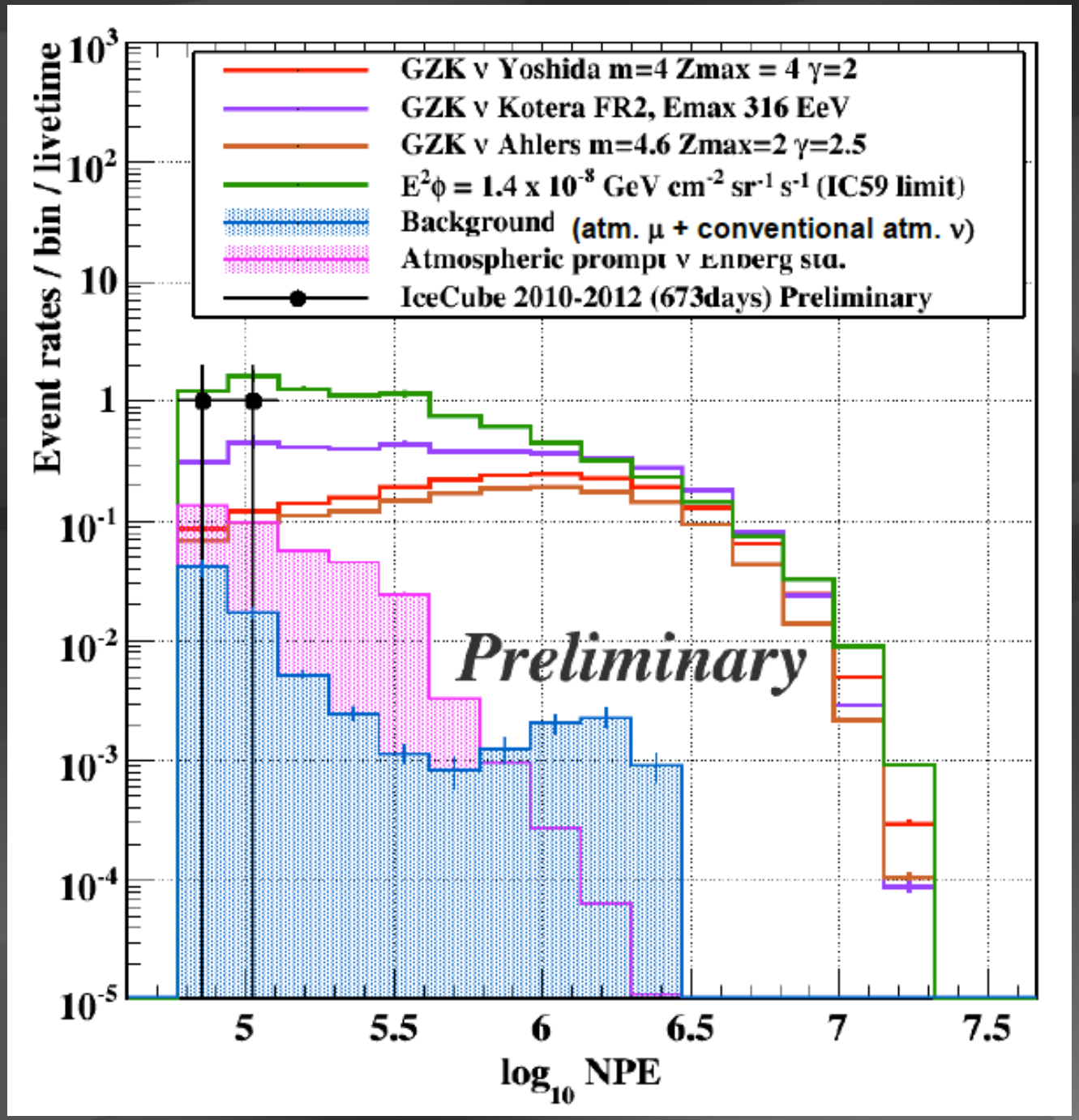



Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400
PE/50.0 ns
microseconds

digital optical module 44 on string 20 only



Blue: best-fit direction, red: reversed direction



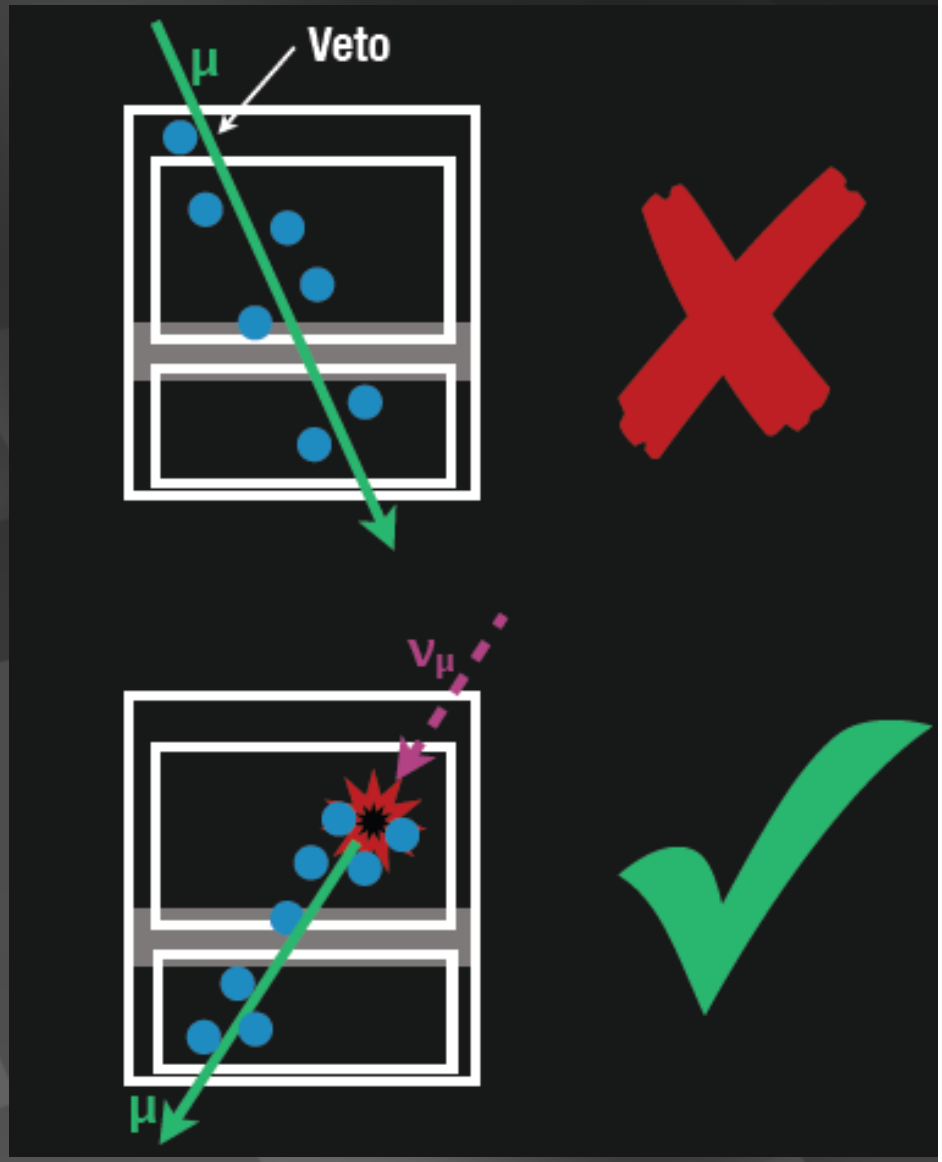
- energy

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

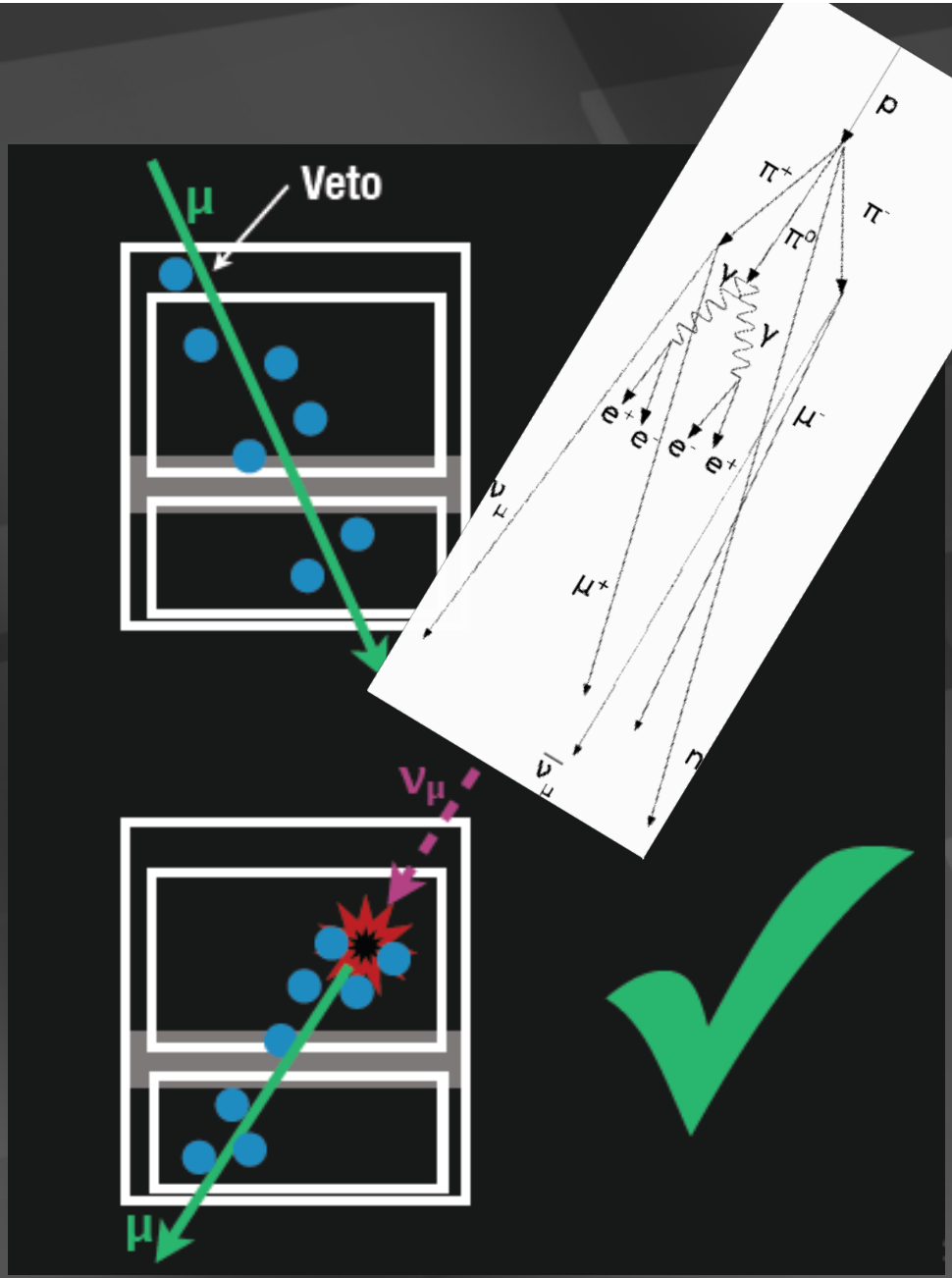
- not atmospheric: probability of no accompanying muon is 10^{-3} per event

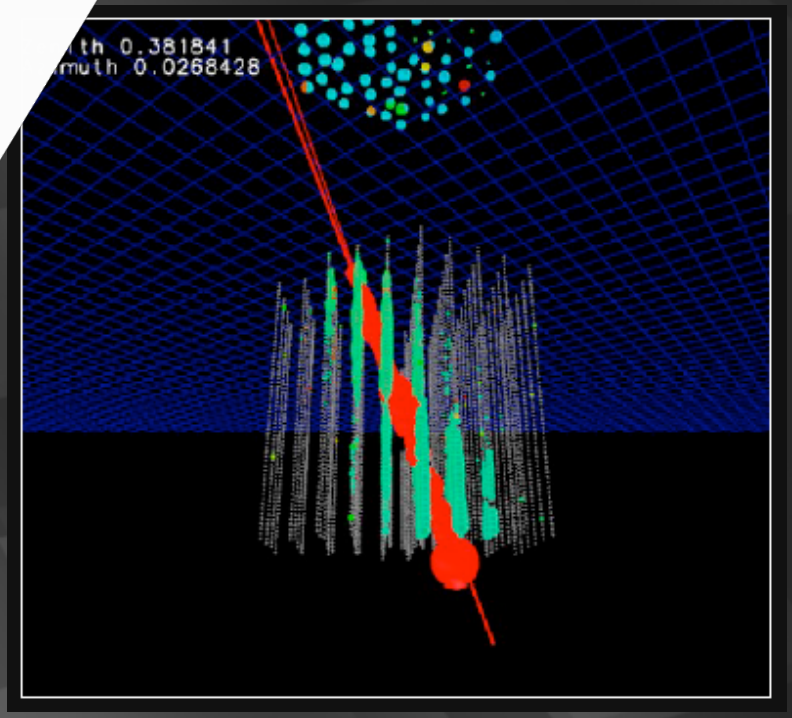
→ flux at present level of diffuse limit

- 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

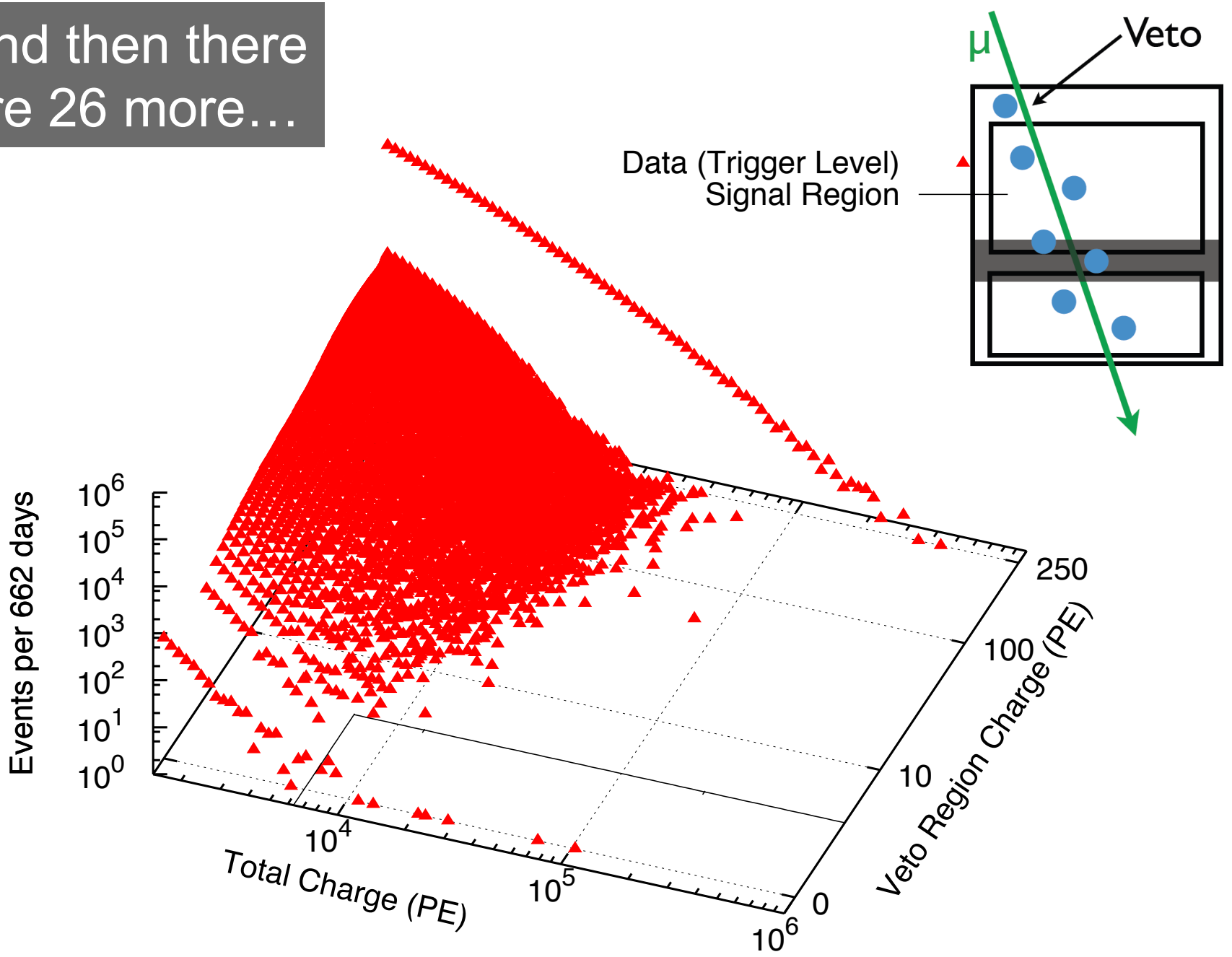




atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

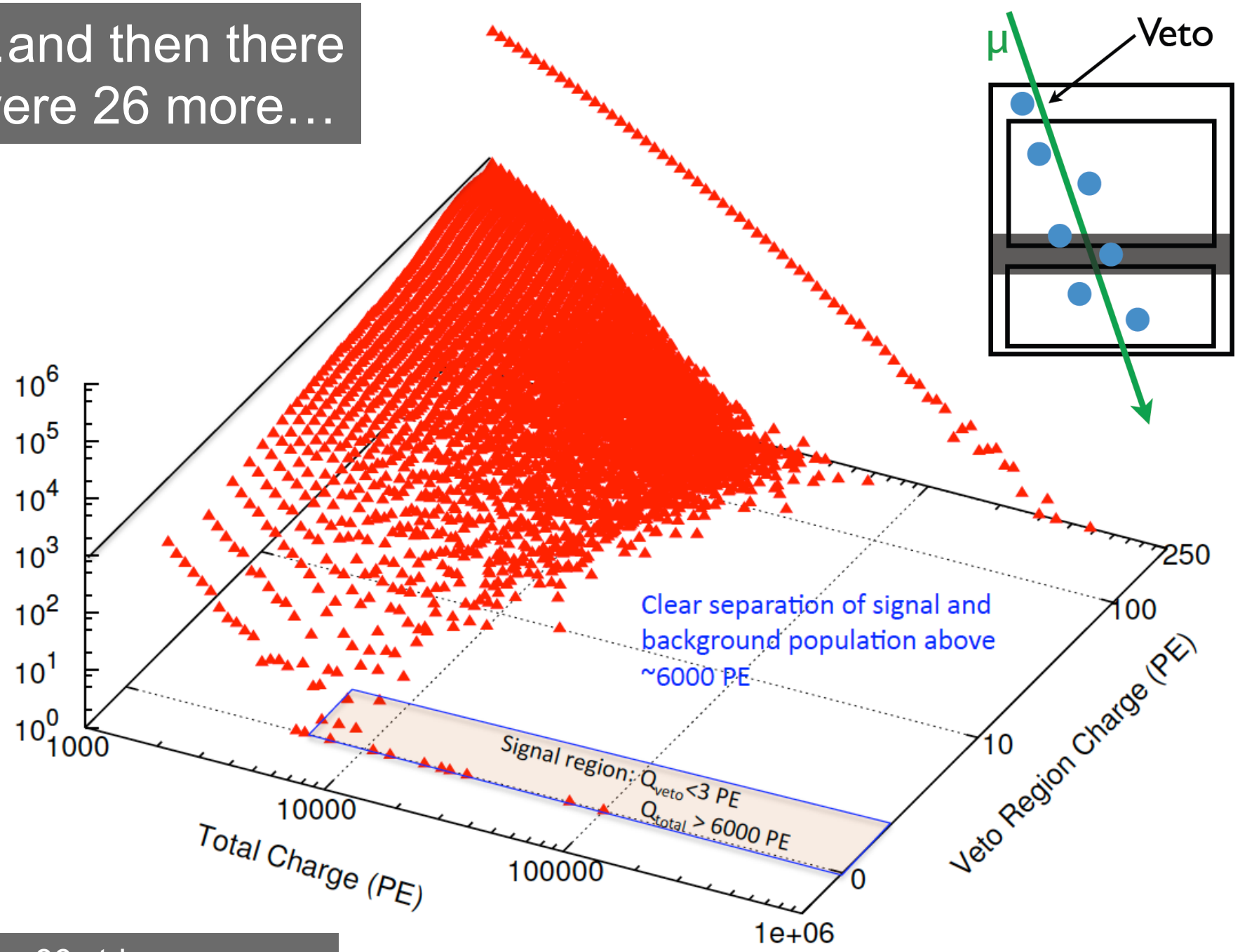
(also, no signals in IceTop)

…and then there were 26 more…



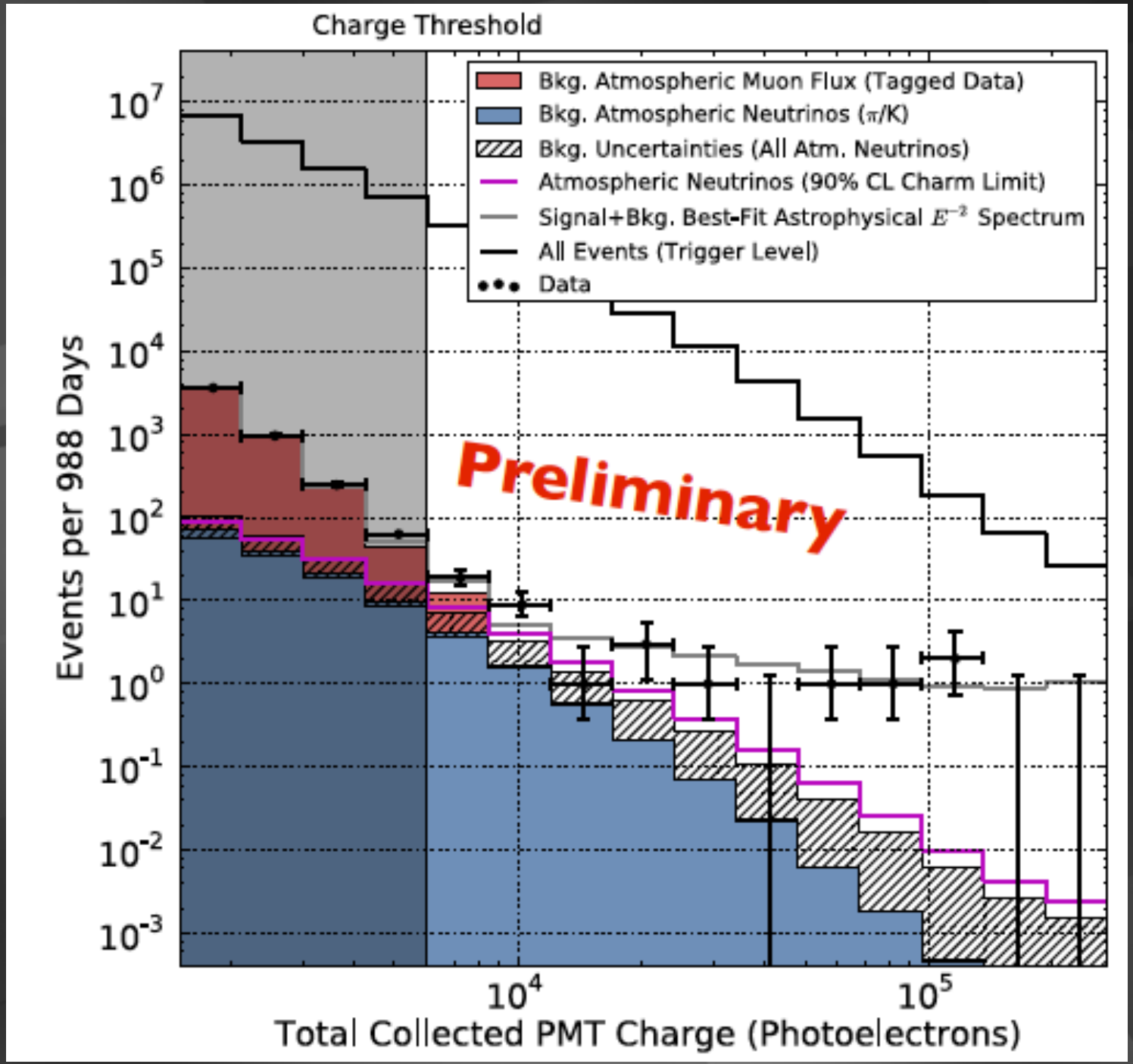
data: 86 strings one year

…and then there were 26 more…

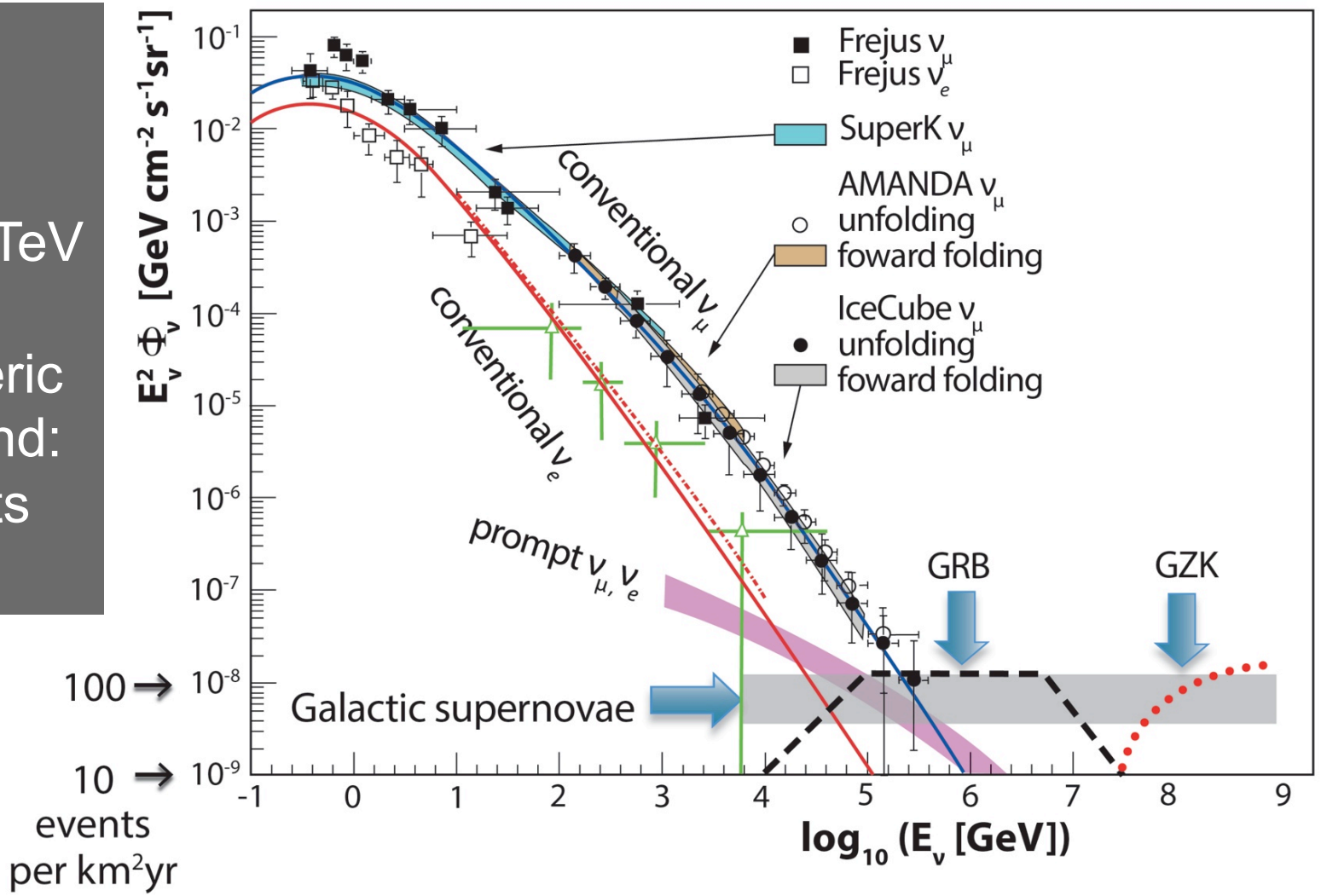


data: 86 strings one year

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

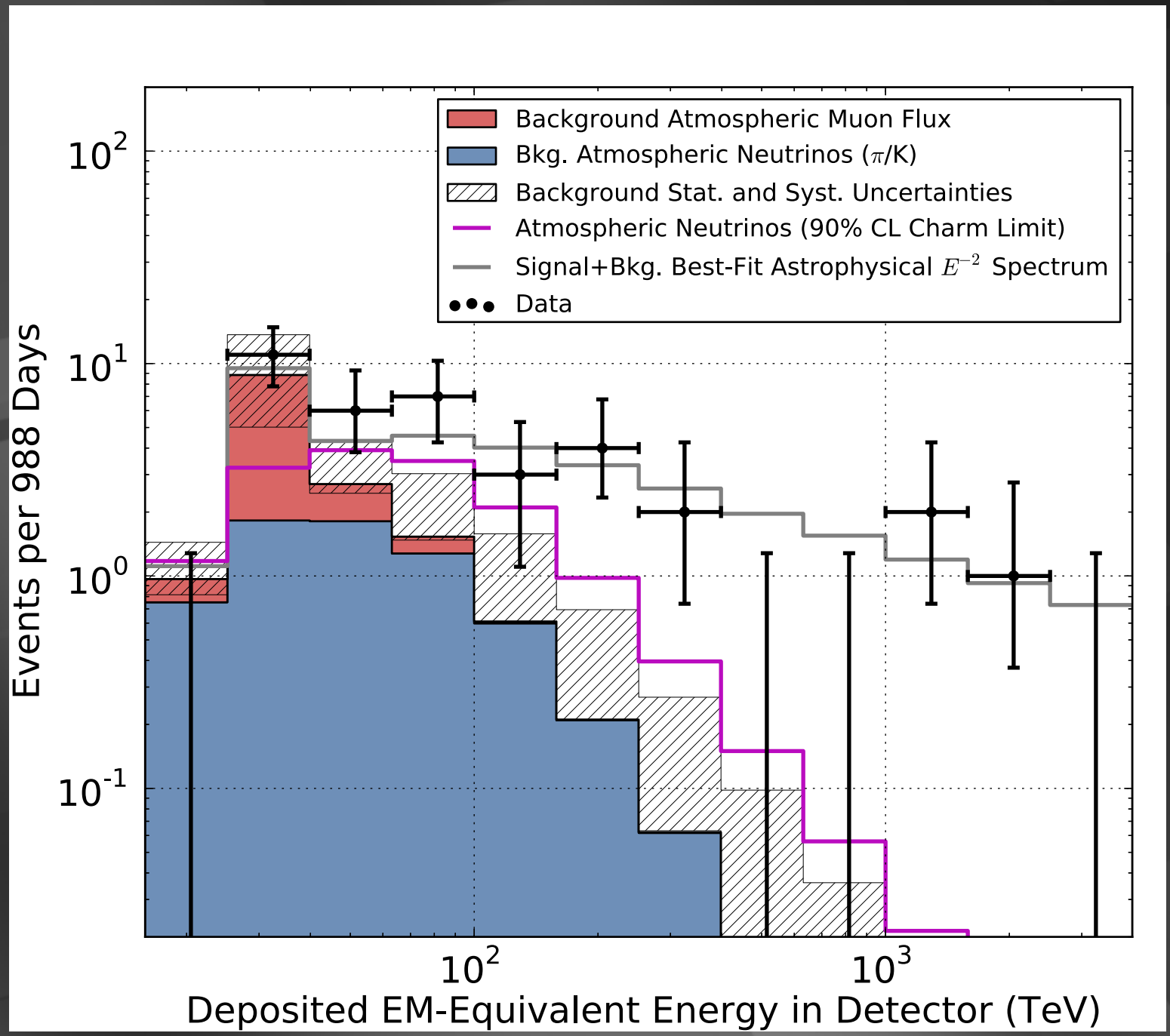


- cosmic neutrinos: energy
  > 100 TeV
- atmospheric background: 1~2 events per year

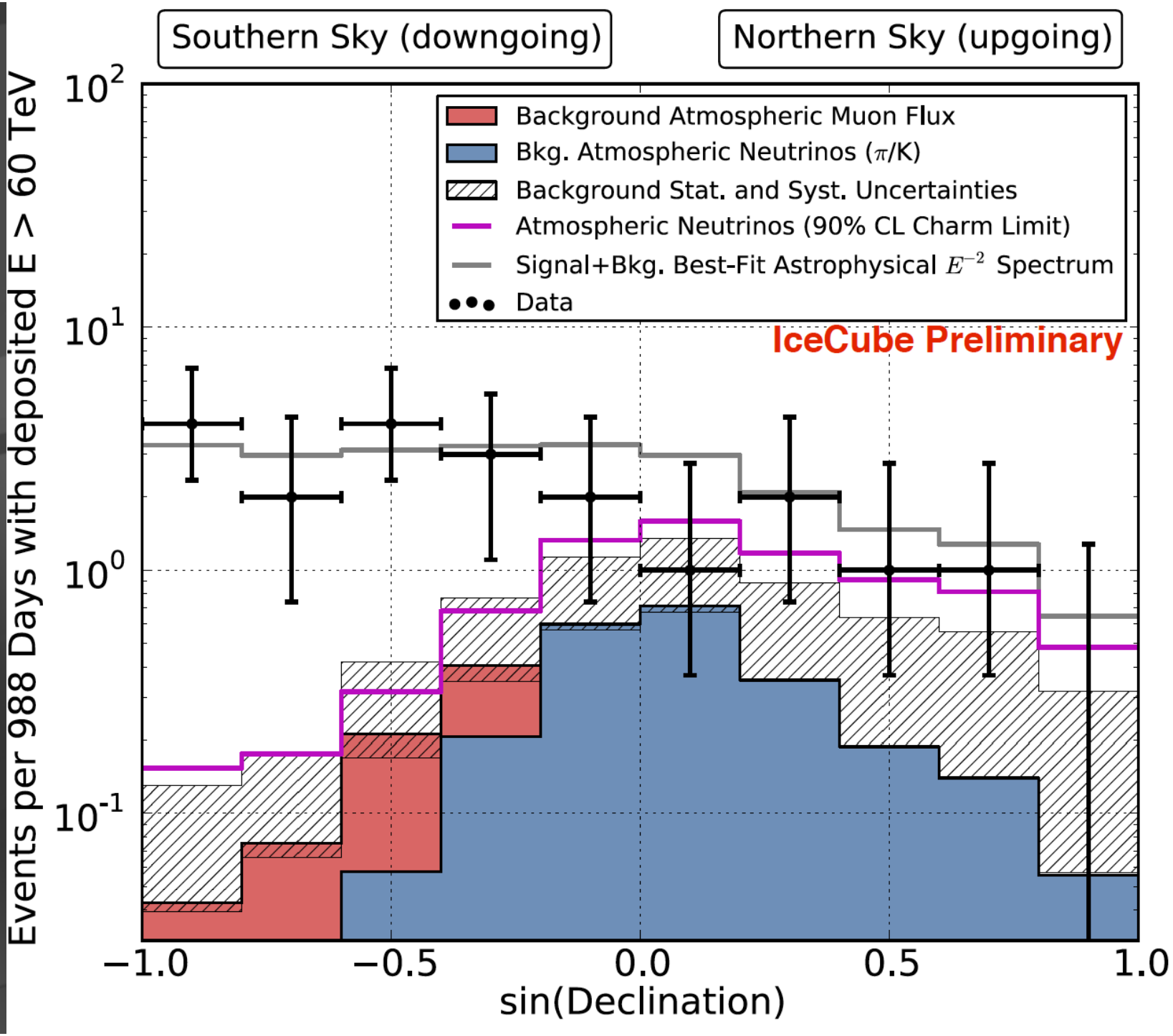


atmospheric ⇑ cosmic

3 years

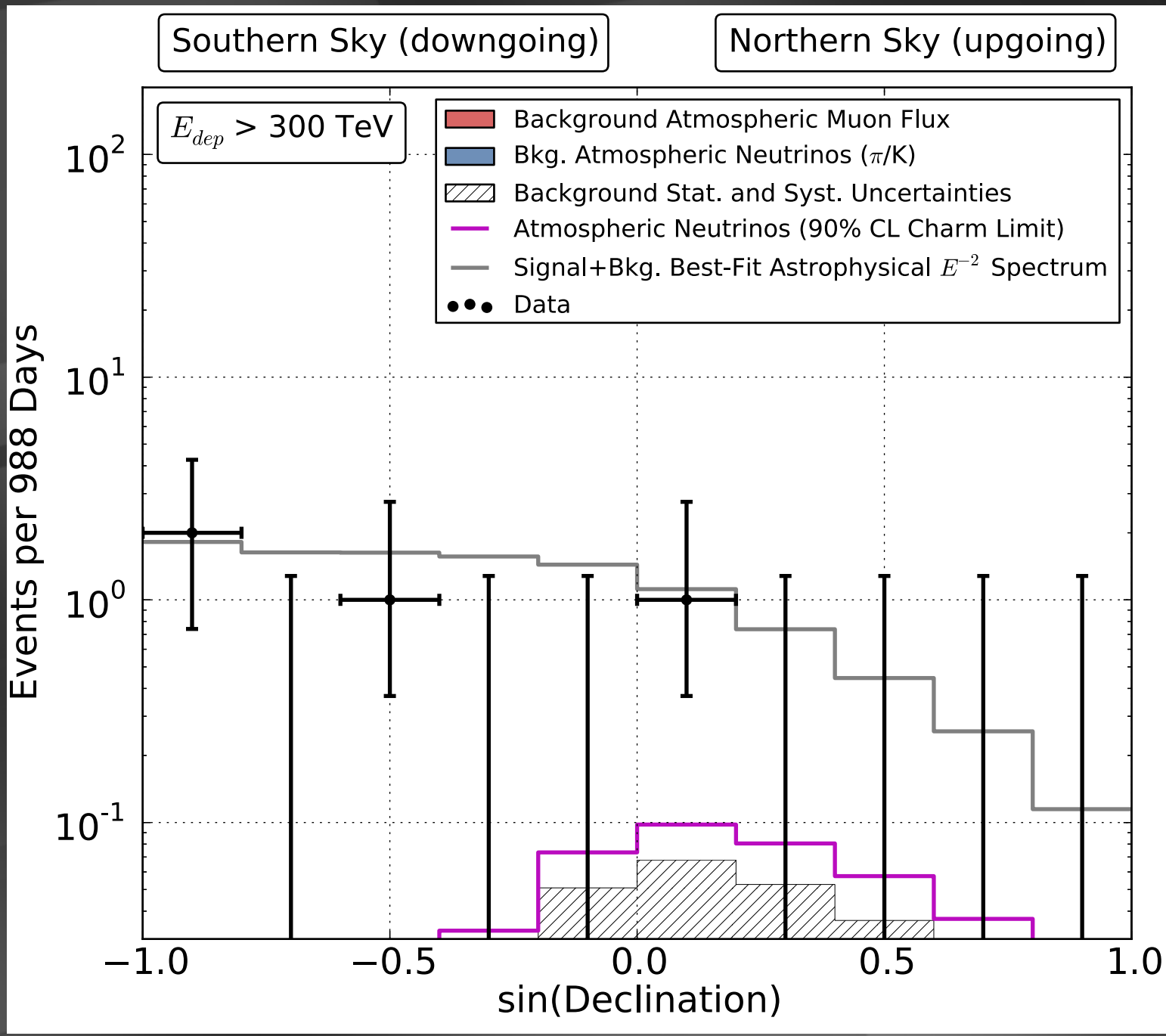

Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

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
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)

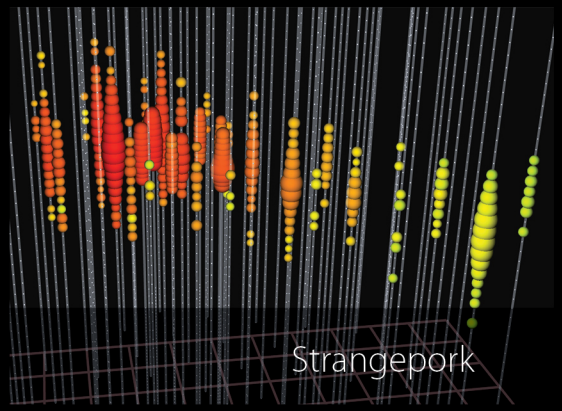
same plot animated:

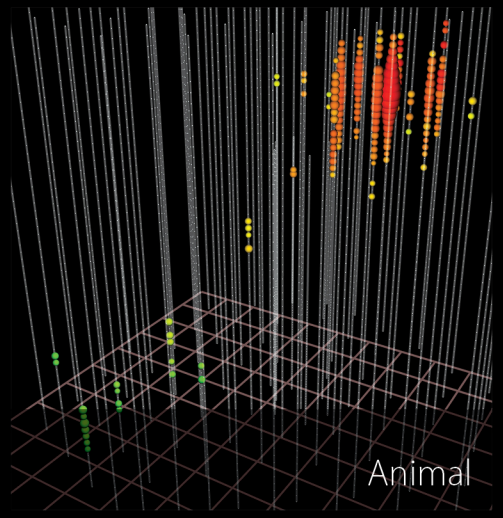
- events versus background as a function of energy
- cuts from > 30 TeV (all events) to until only PeV events remain
- background disappears ~ 60 TeV

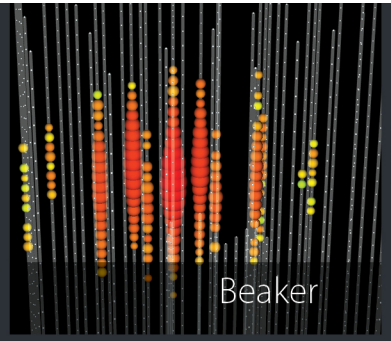

Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 300 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1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

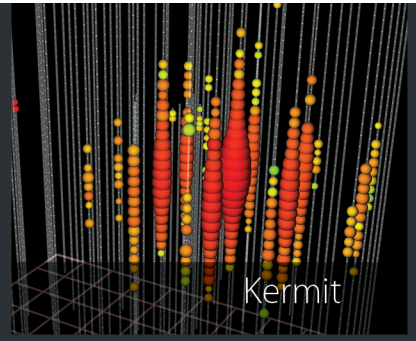
- all features agree with signal, not with background
- each event can be scrutinized

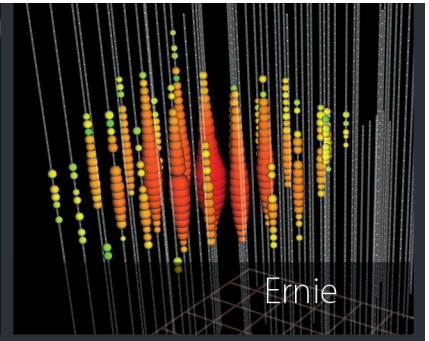
28 High Energy Events

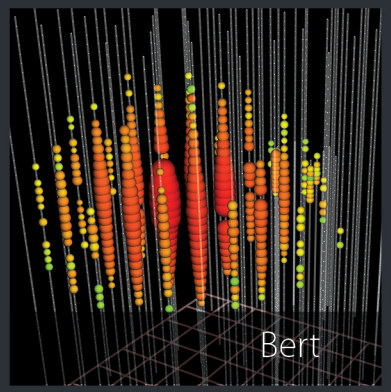


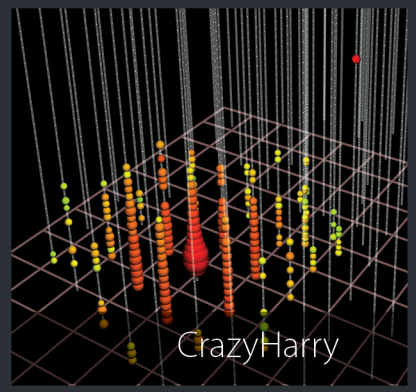


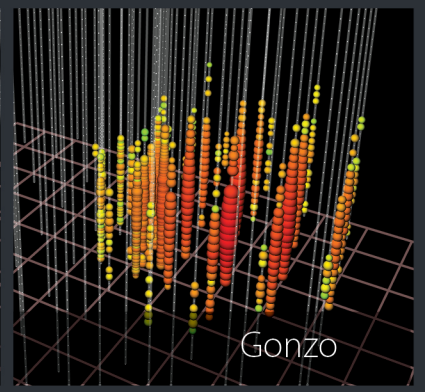


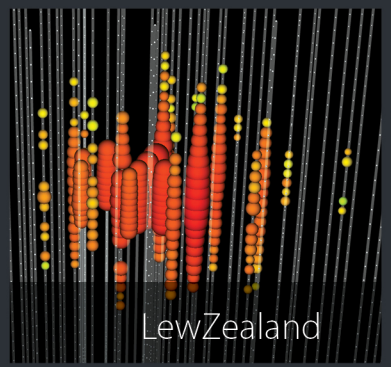


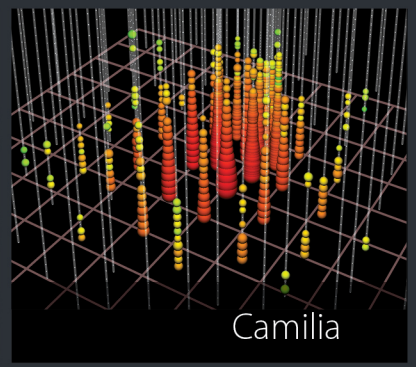


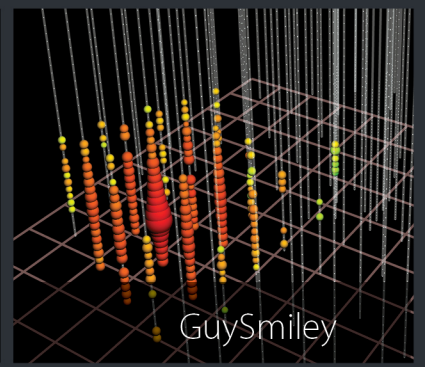


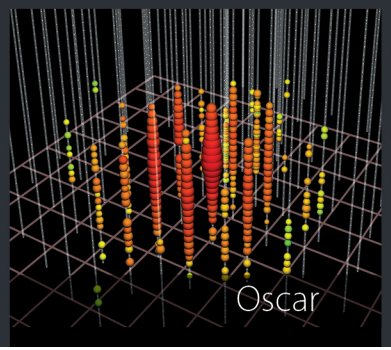


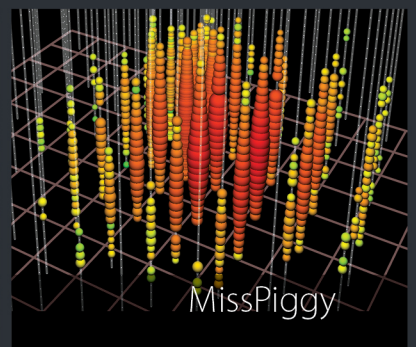


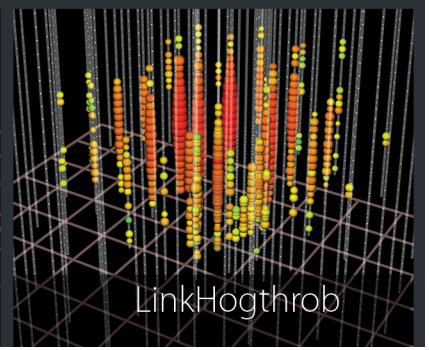




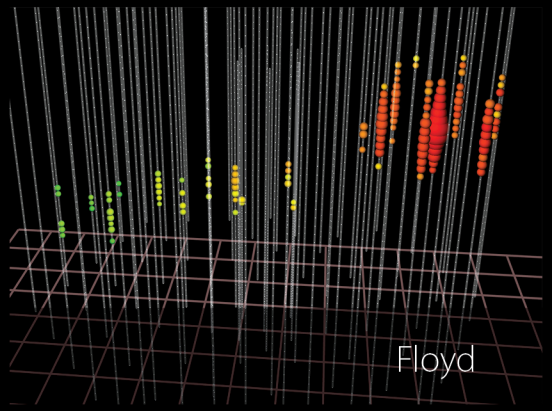


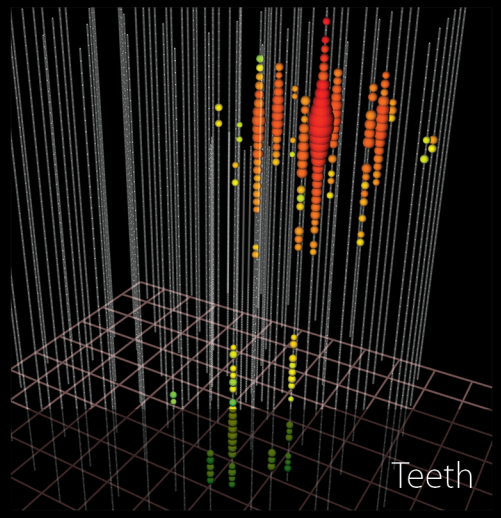


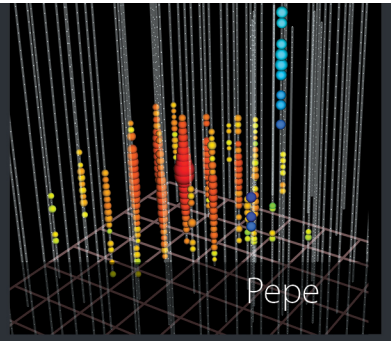


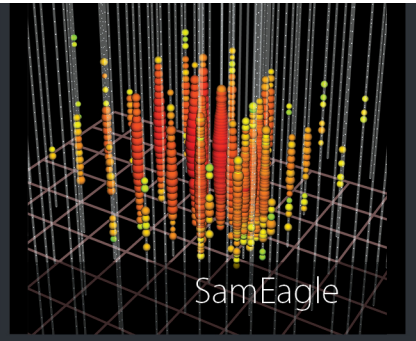


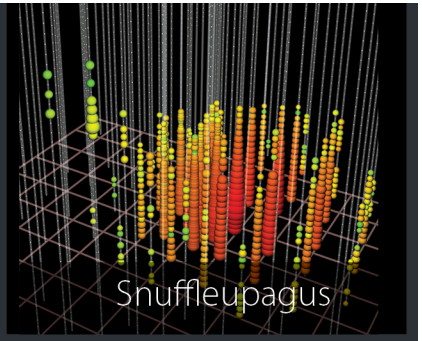
28 High Energy Events

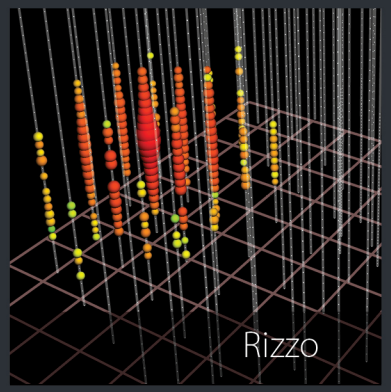


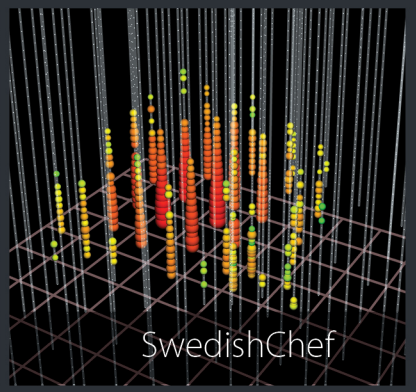


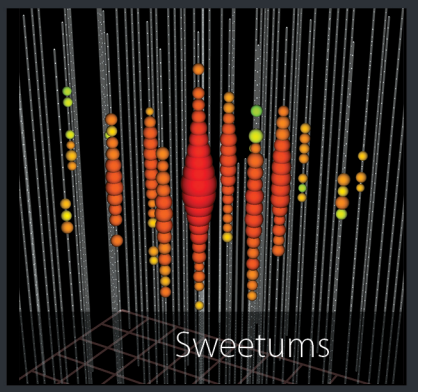


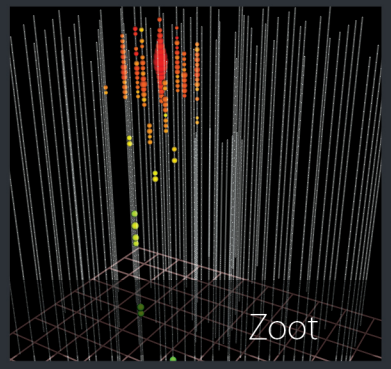


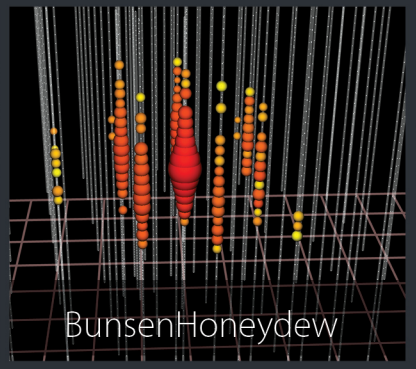


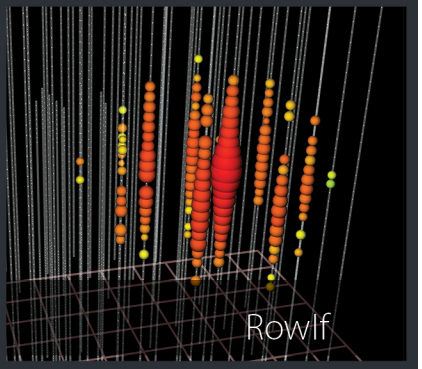


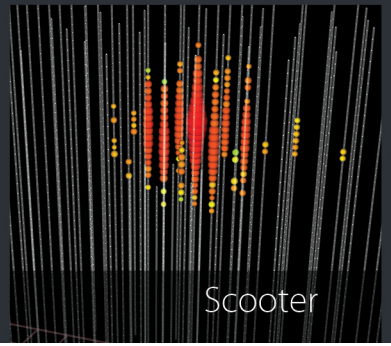


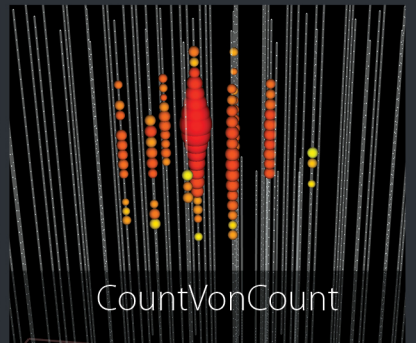


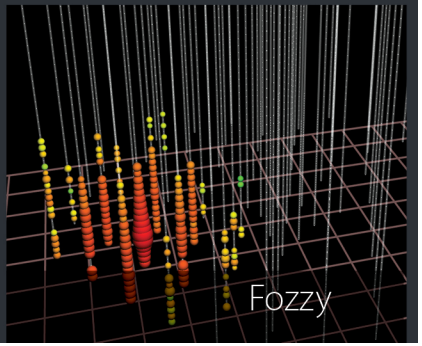




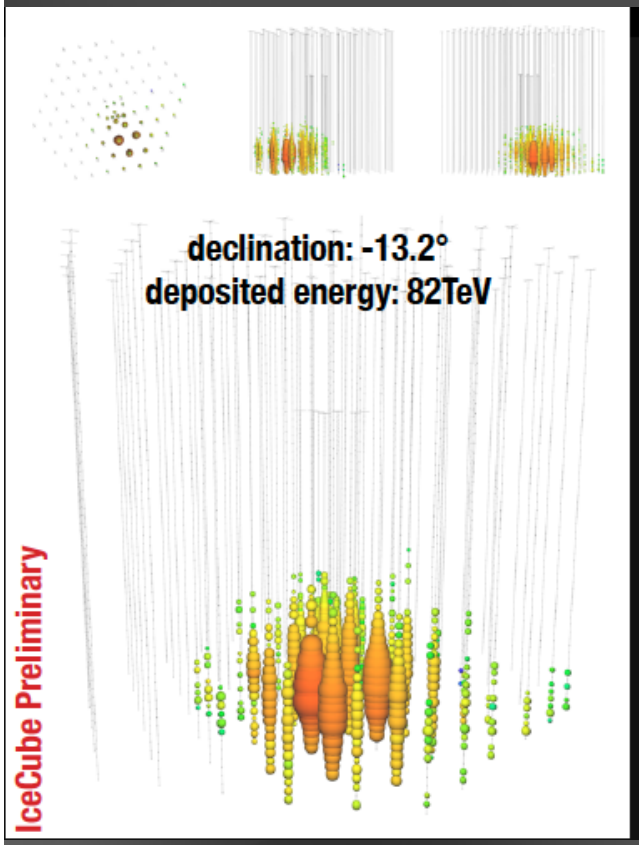


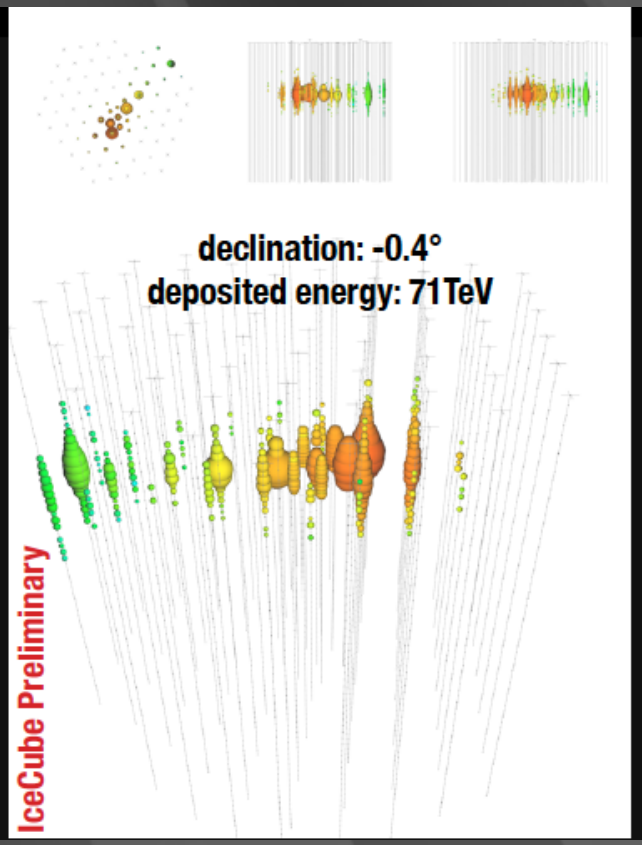


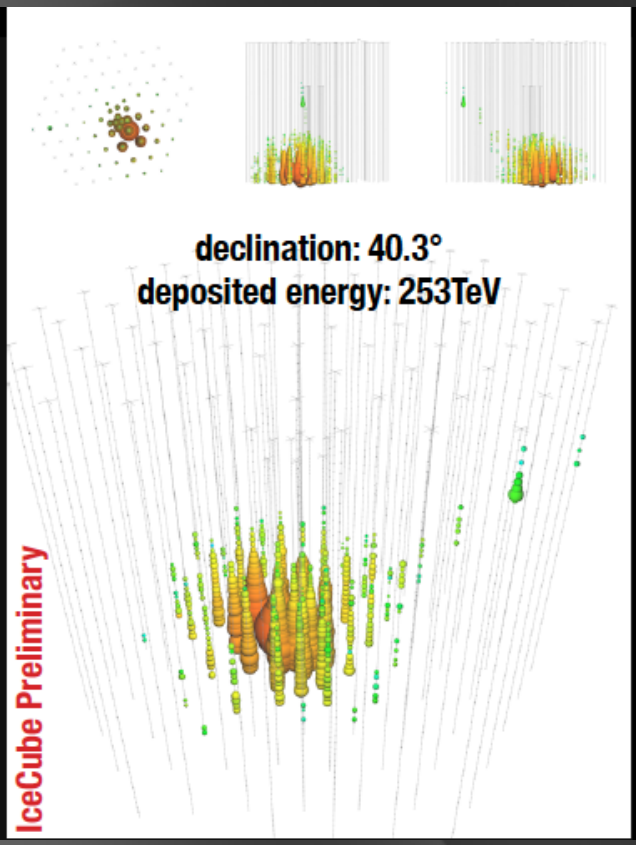


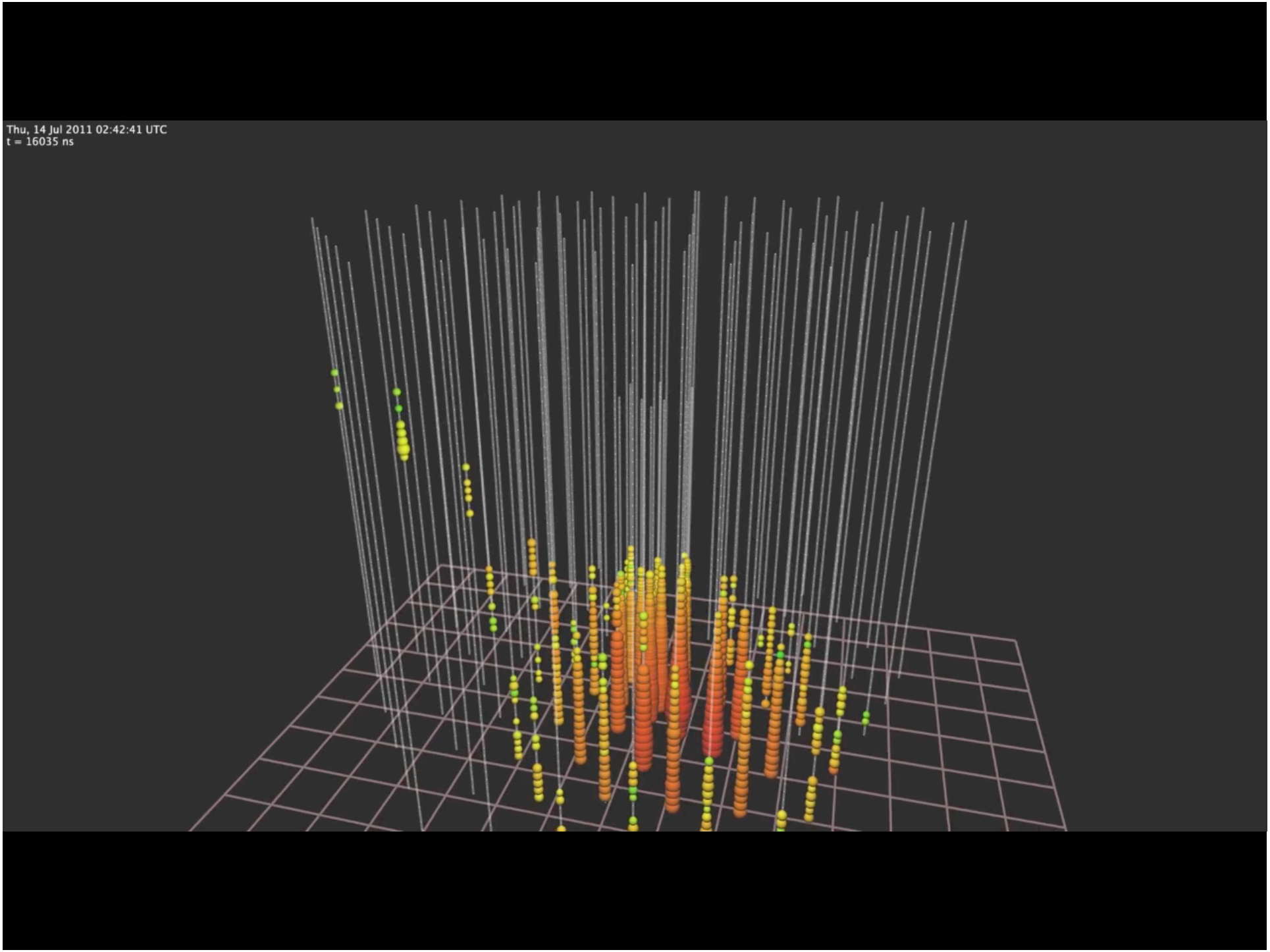


some interesting events

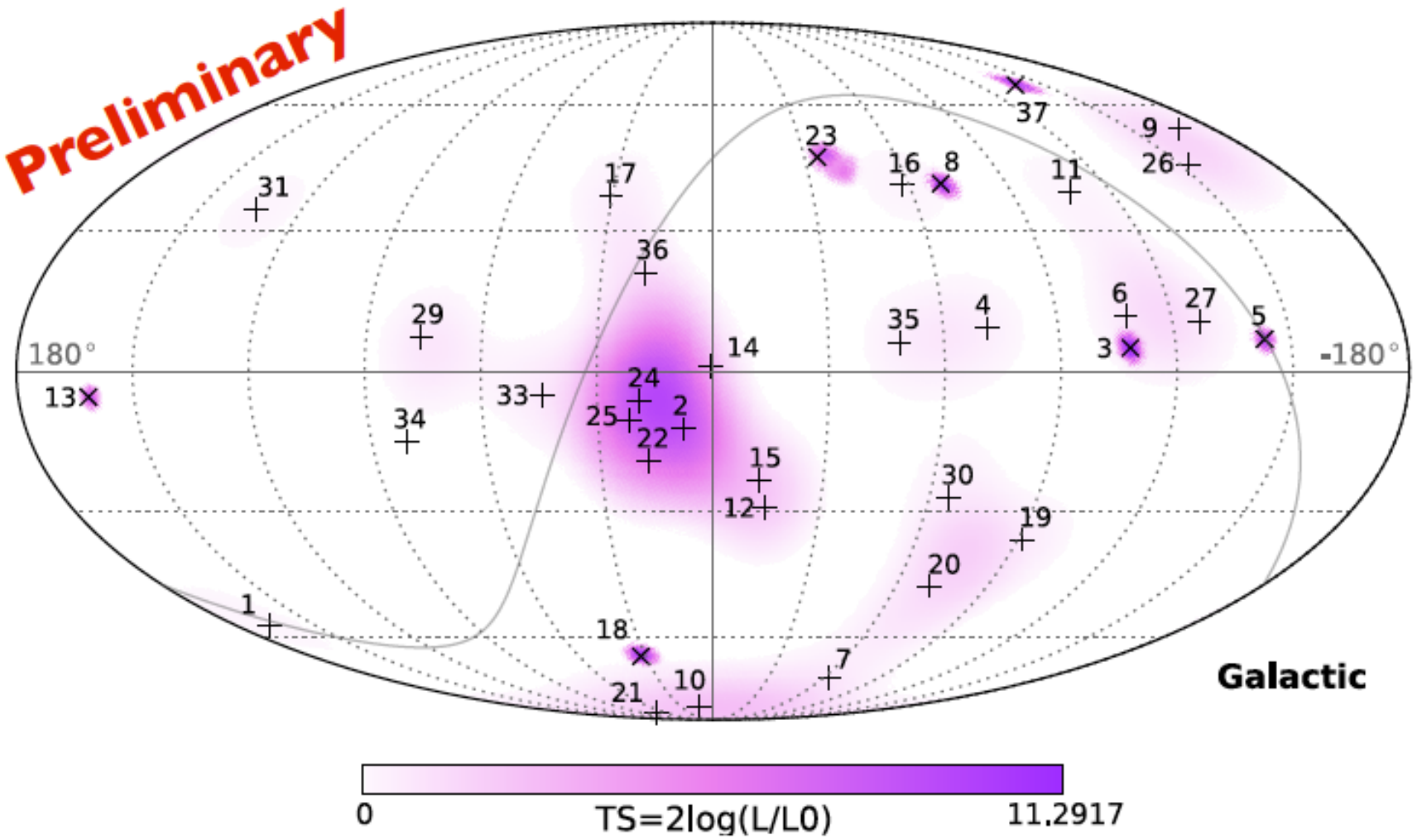


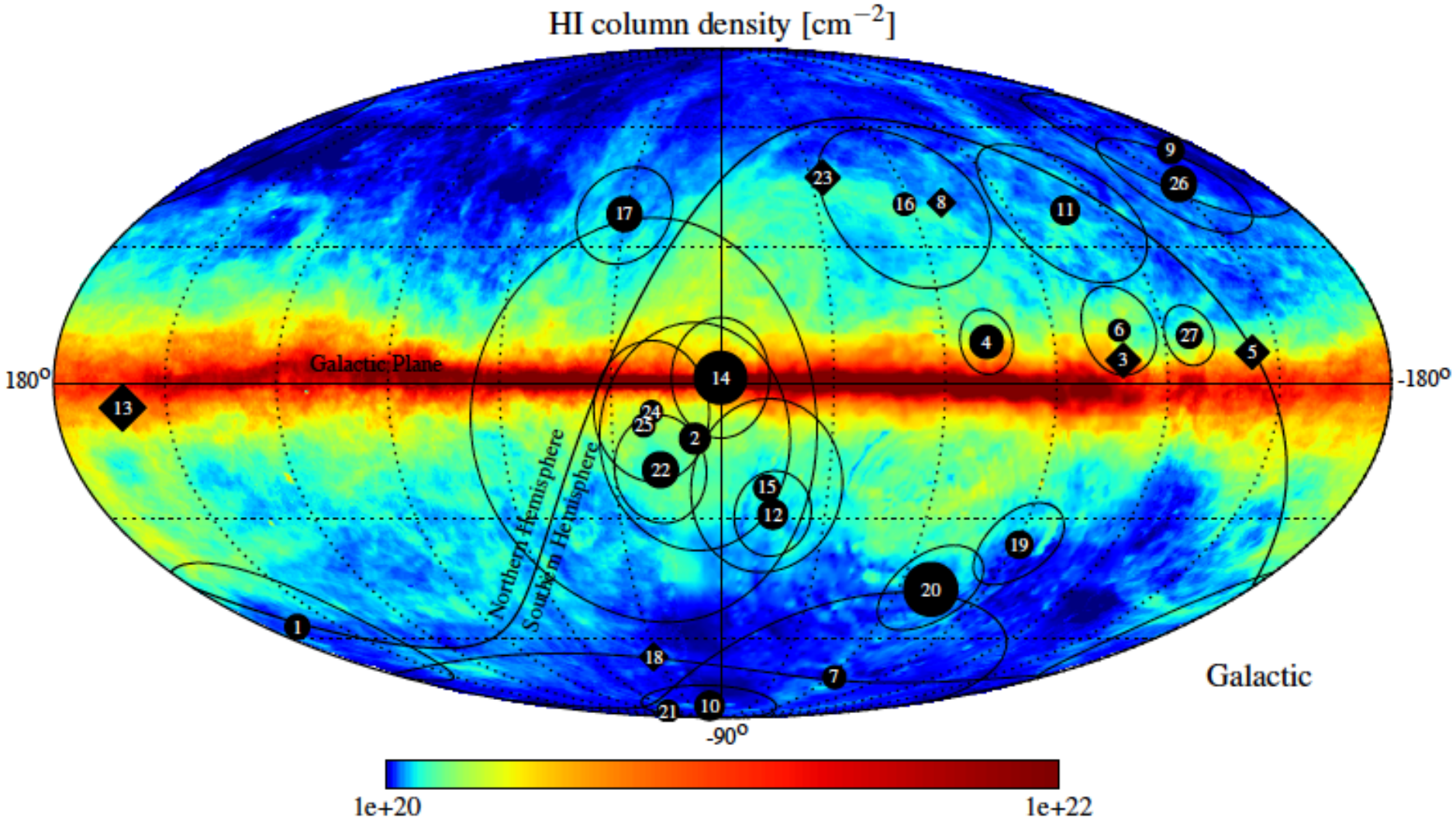





Thu, 14 Jul 2011 02:42:41 UTC
t = 16035 ns

where do they come from (3 year data)?




HI column density [cm^{-2}]
Galactic Plane
180°
-180°
-90°
Northern Hemisphere
Southern Hemisphere
Galactic
1e+20
1e+22
1
2
3
4
5
6
7
8
9
10
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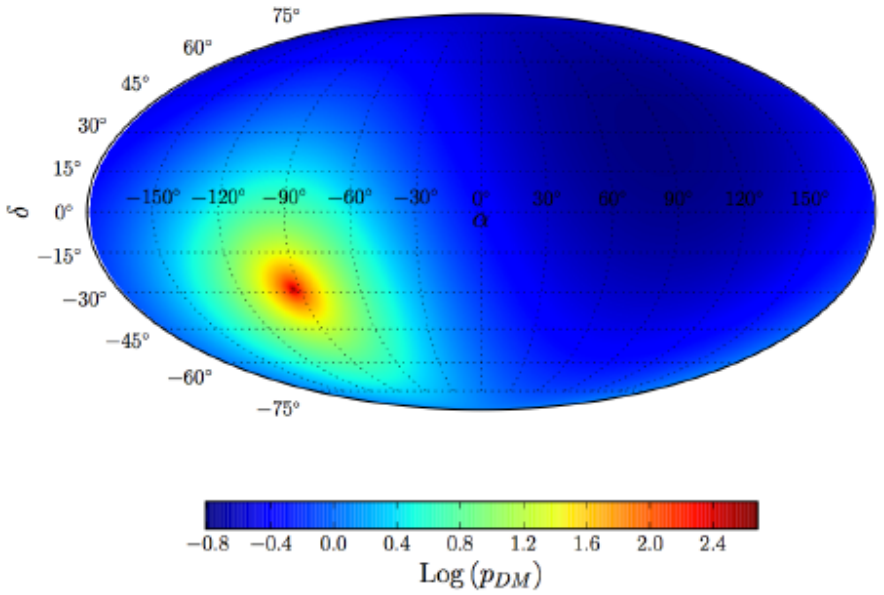
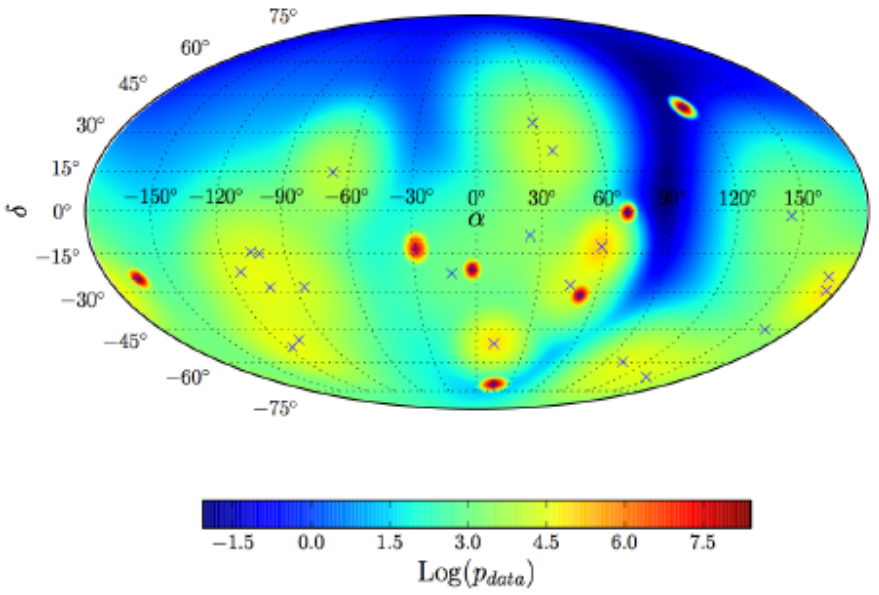
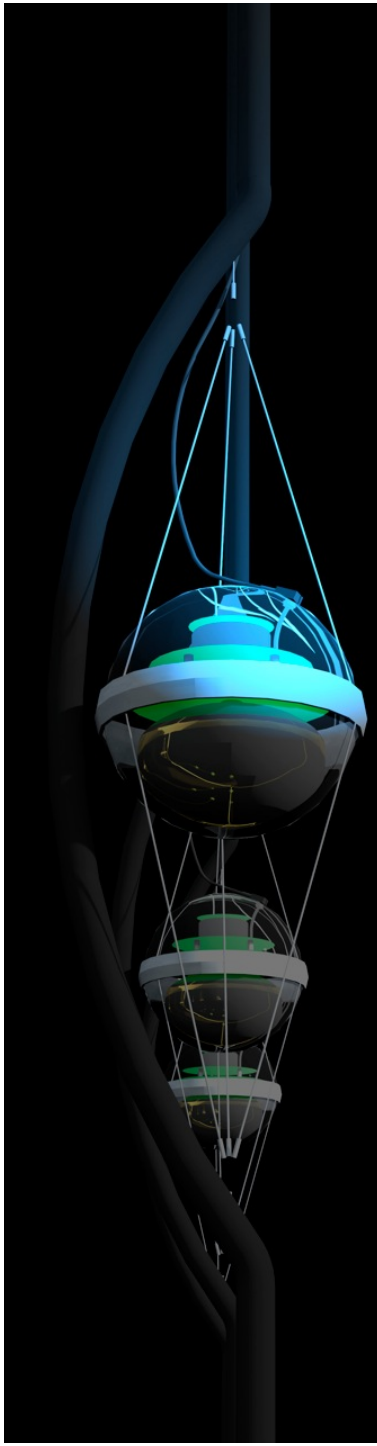
27

expect surprises: produced by Galactic dark matter halo?







conclusions

- first observation of cosmic neutrinos
- origin not revealed yet, but…
- one more year of data by May 15
- better and different analyses soon (well-reconstructed ν_μ)

IceCube.wisc.edu

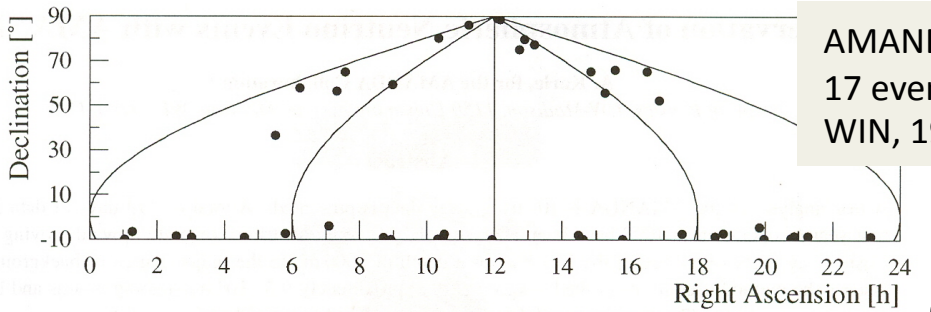
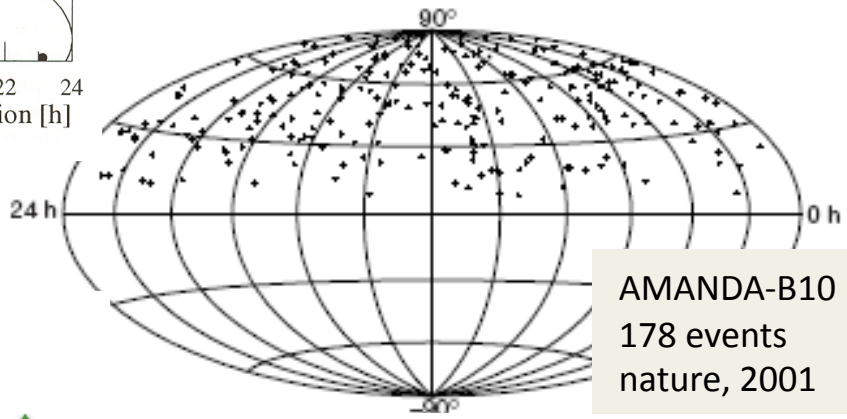
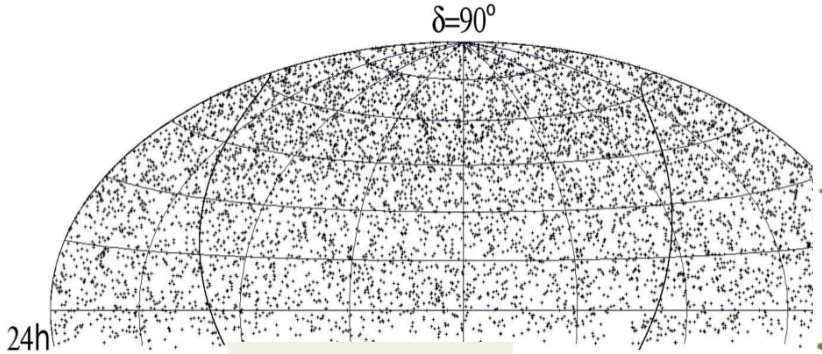


Figure 2: Sky plot of all events that pass level 4 quality cuts.

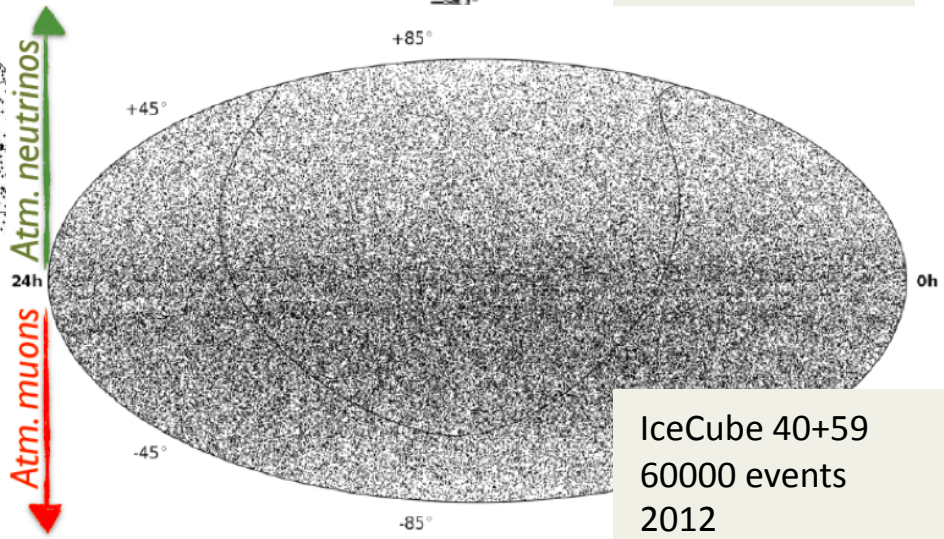
AMANDA-B10
17 events
WIN, 1999



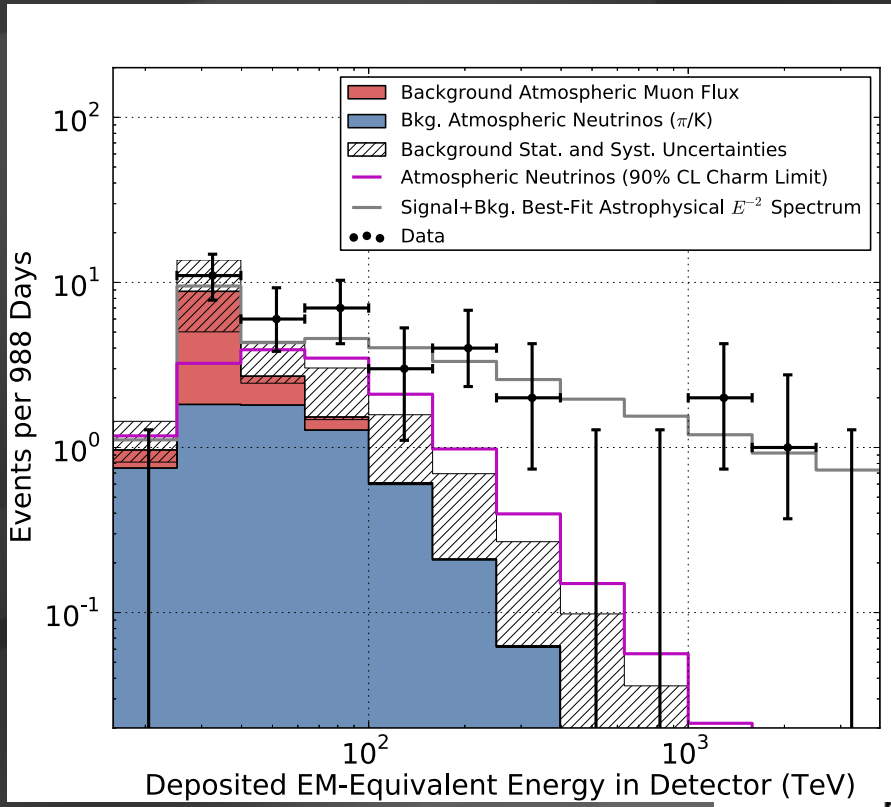
AMANDA-B10
178 events
nature, 2001



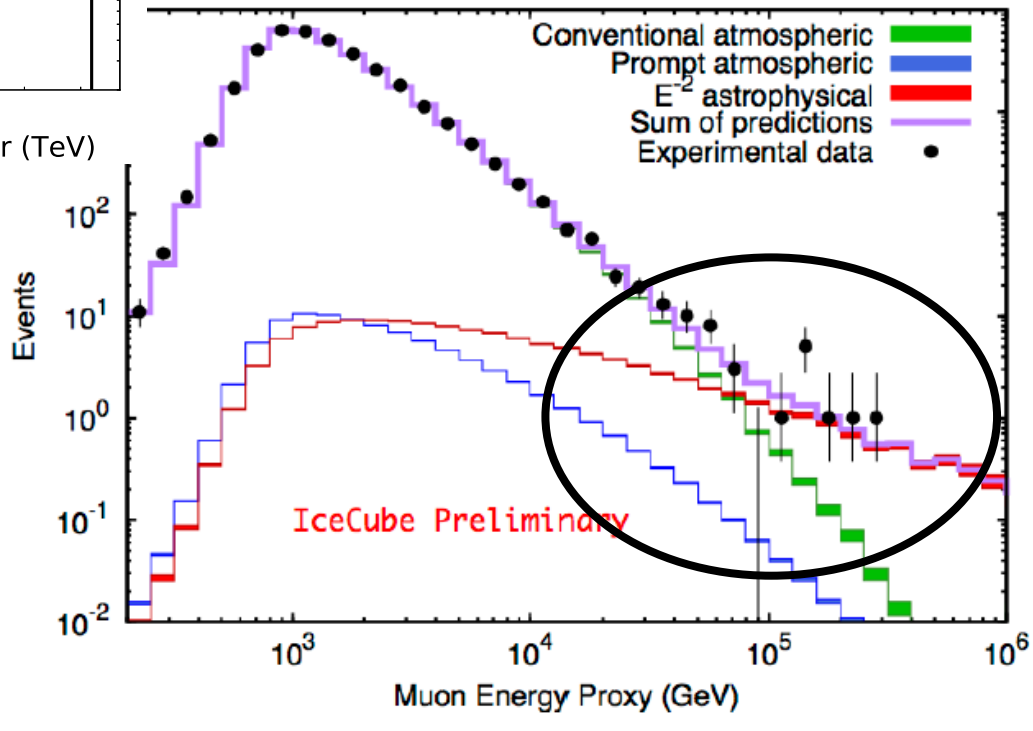
AMANDA-II
7 years
6995 events
2006



IceCube 40+59
60000 events
2012

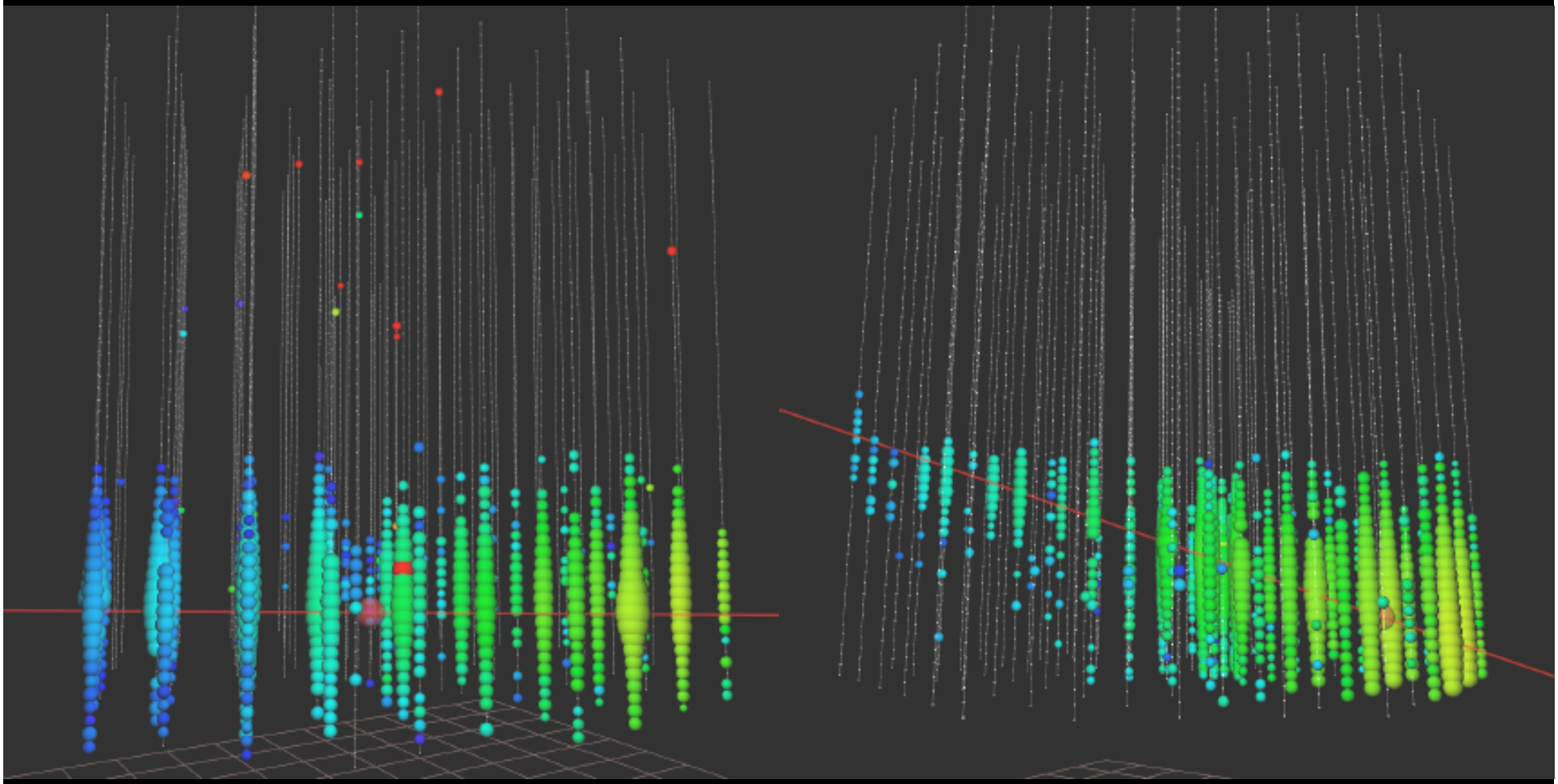


3.9 σ confirmation!
flux of muon neutrinos
through the Earth



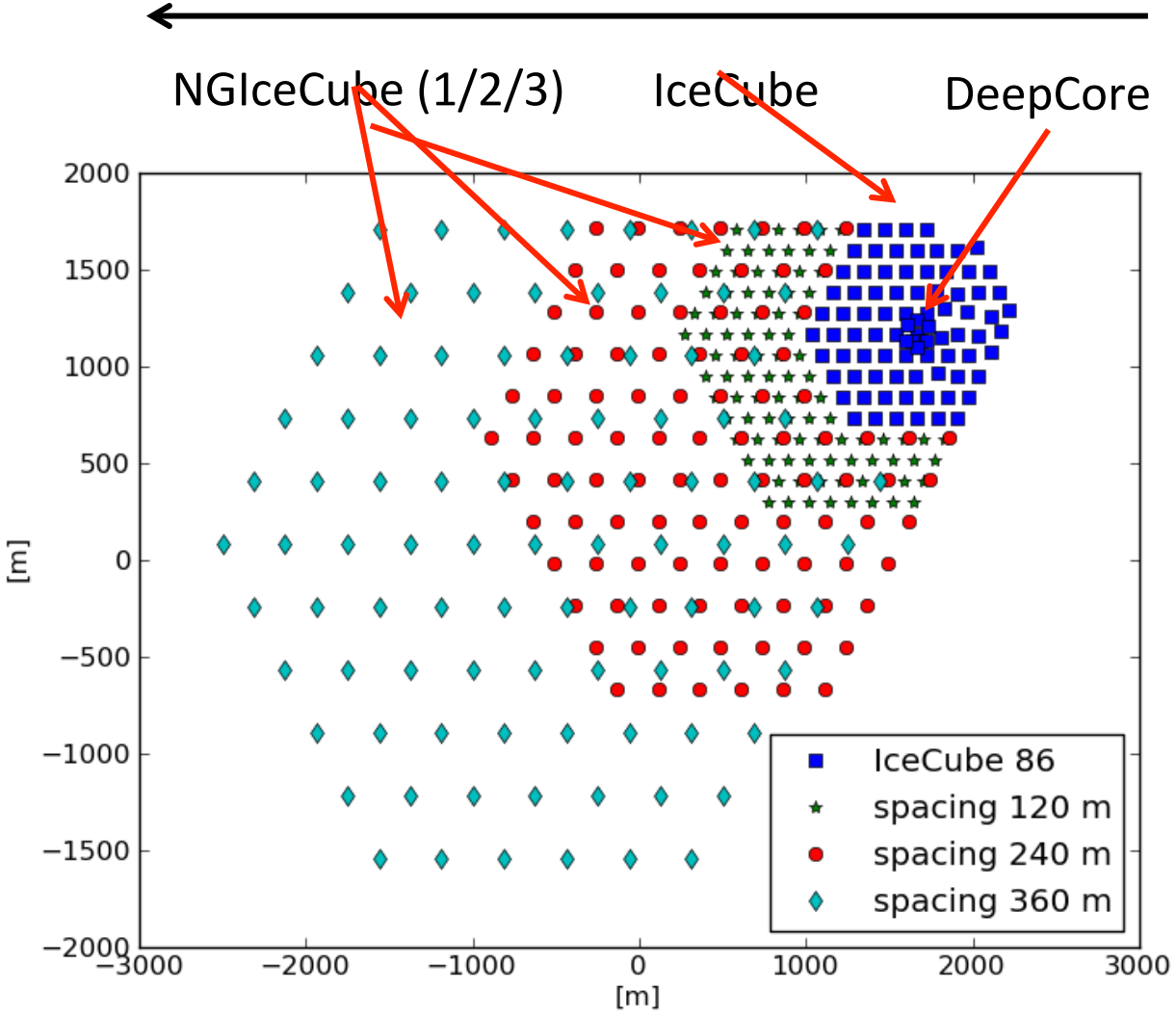
neutrinos of all flavors
interacting inside
IceCube

highest energy muon energy observed: 560 TeV



measured optical properties → twice the string spacing

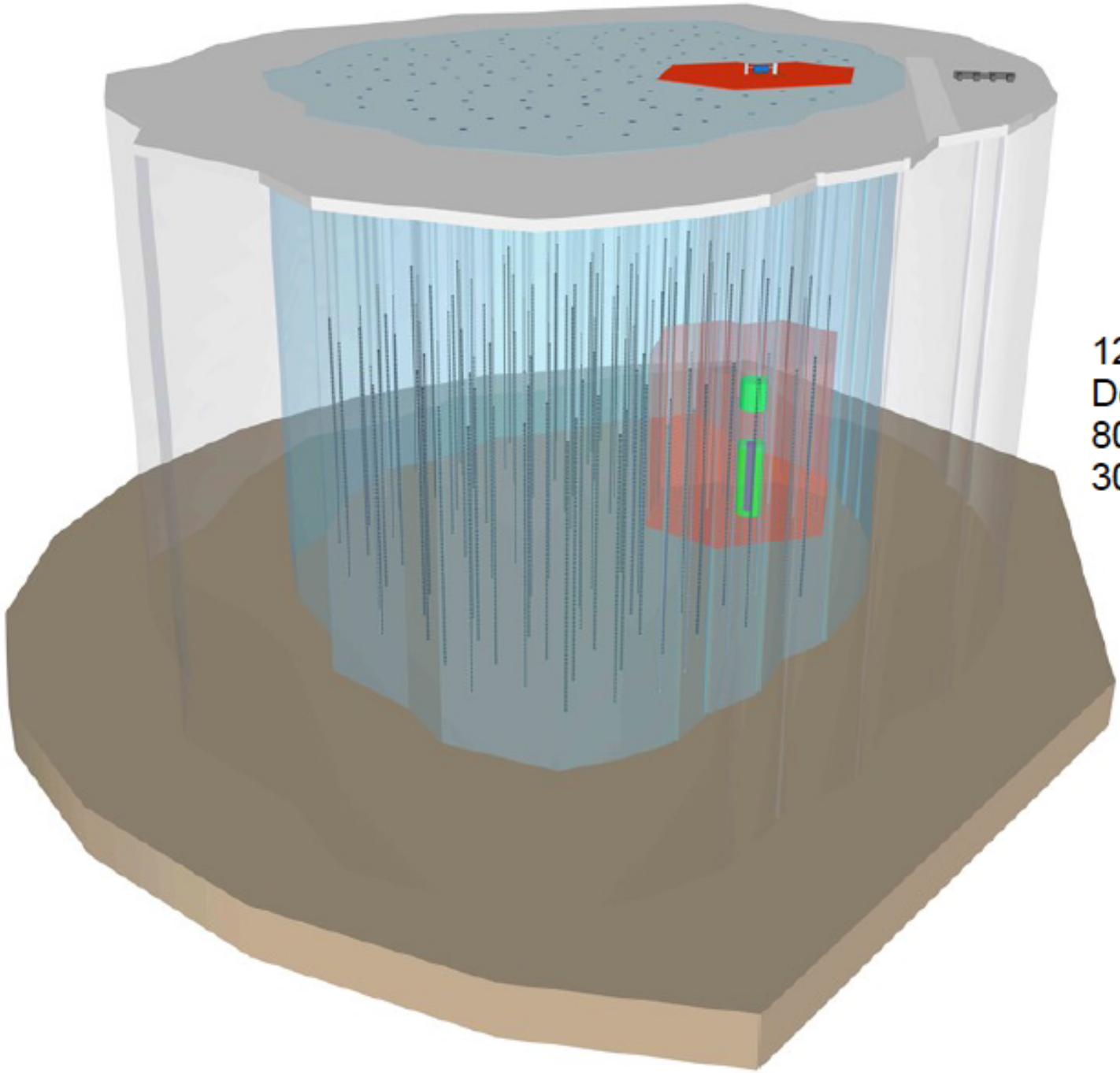
(increase in threshold not important: only eliminates energies where atmospheric background dominates)



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

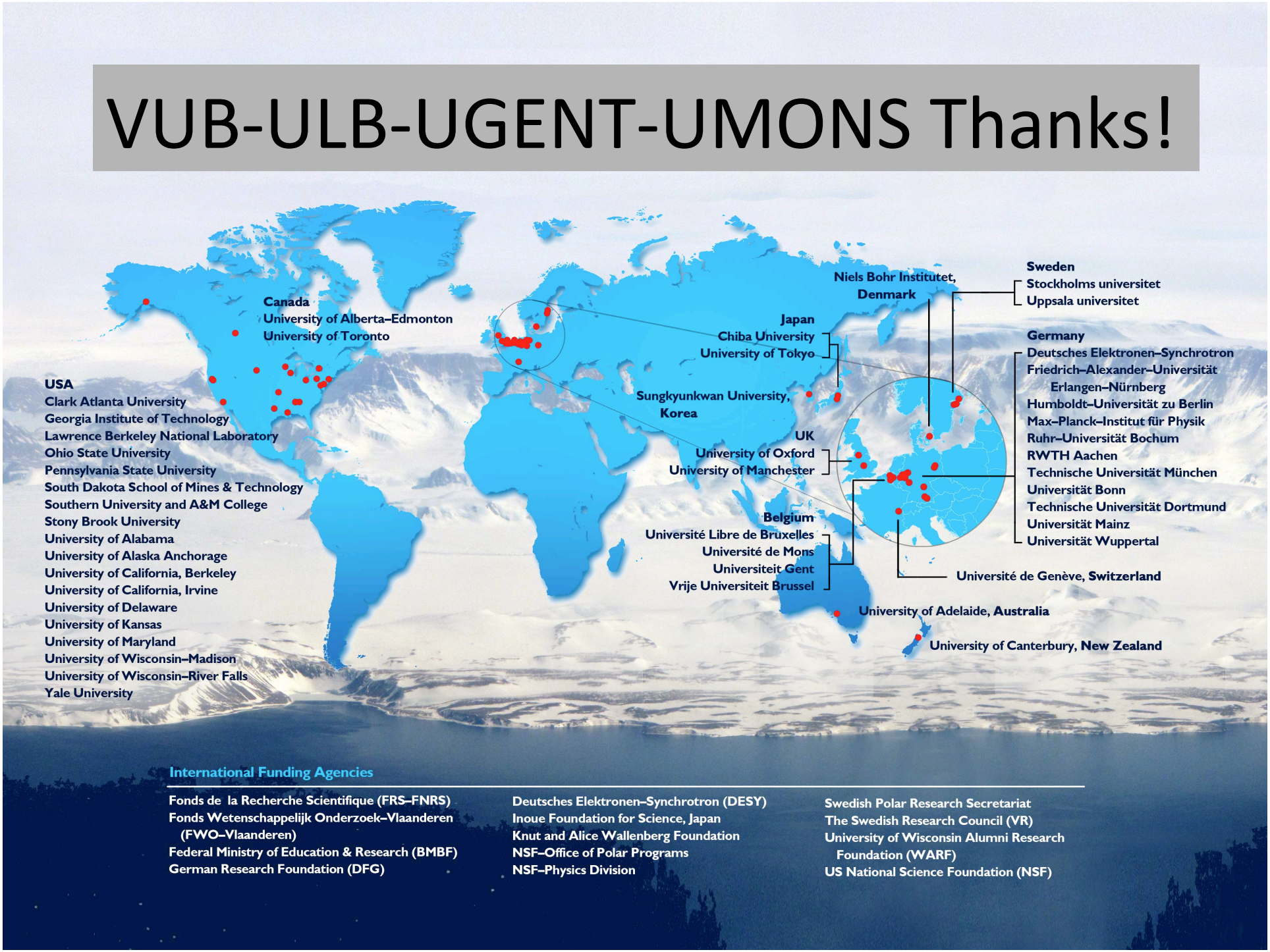
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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



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

VUB-ULB-UGENT-UMONS Thanks!



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