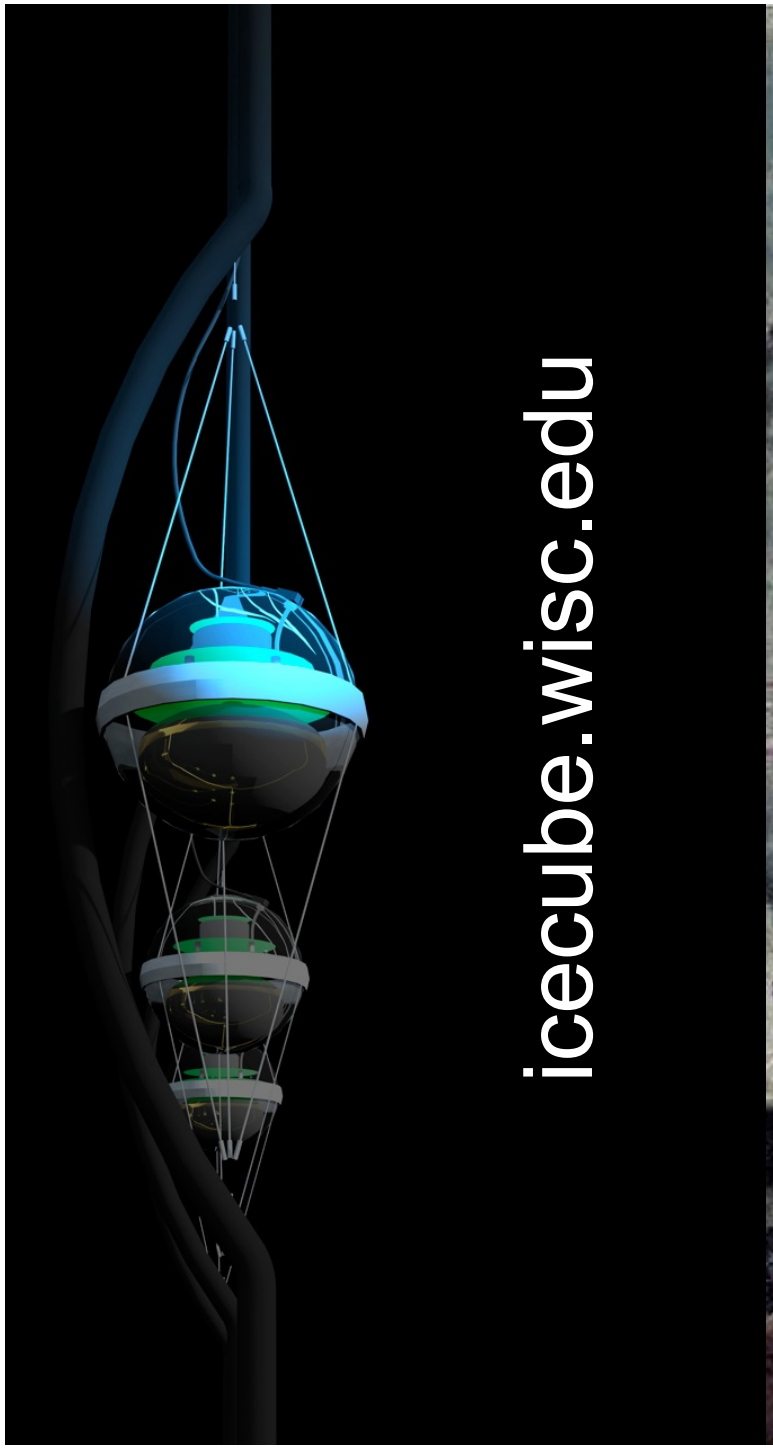
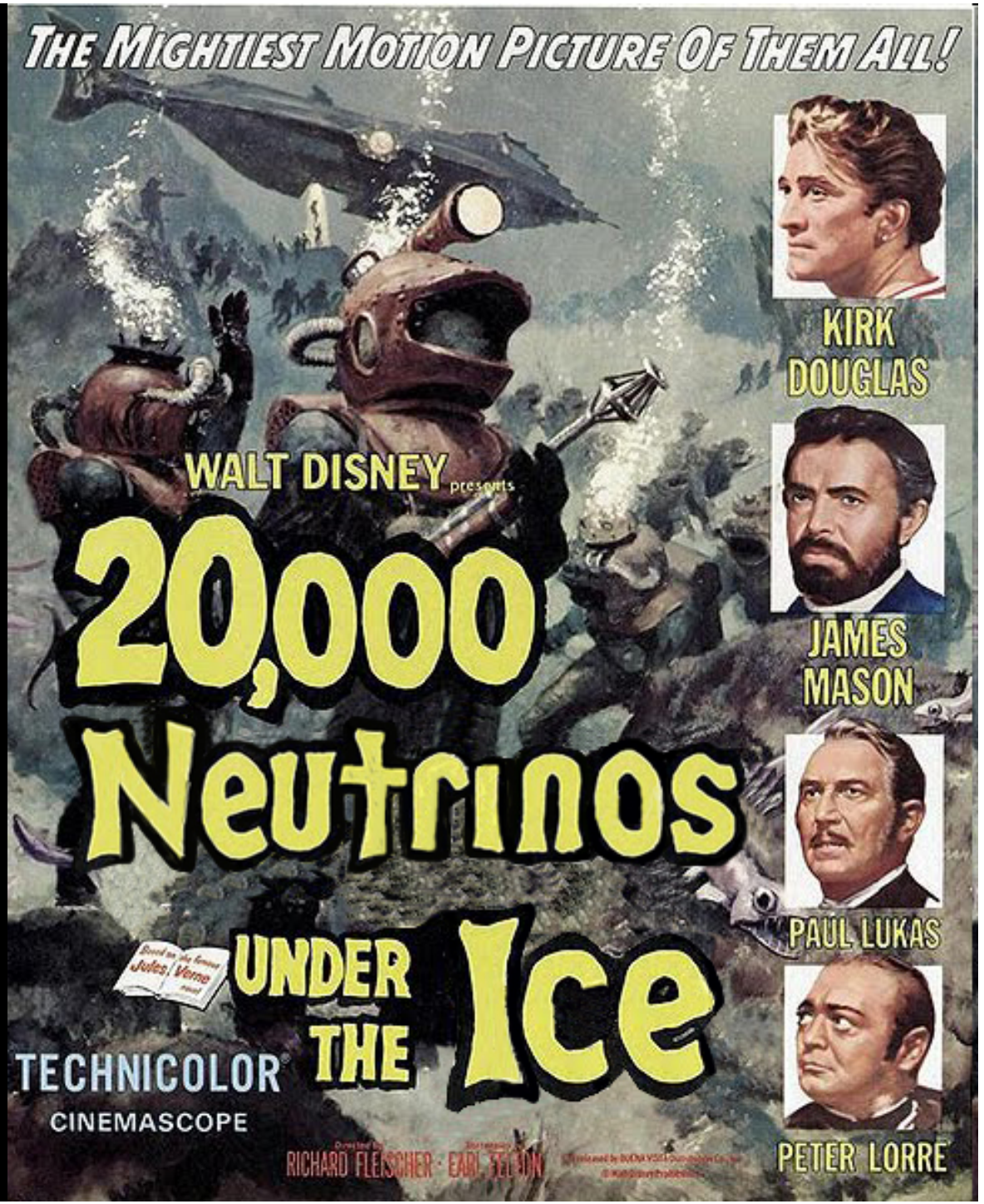
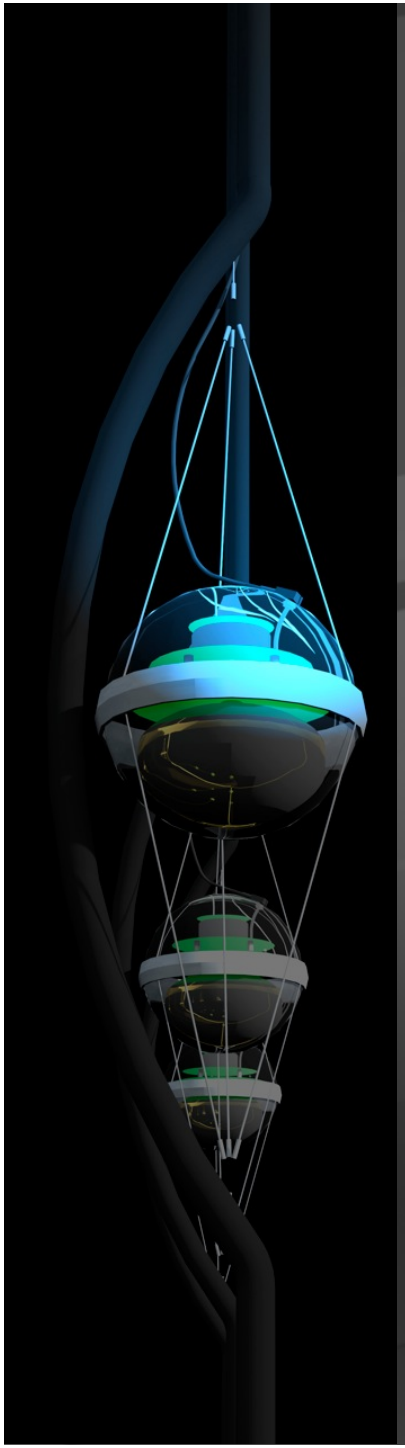


icecube.wisc.edu





- we built a km^3 neutrino detector → 3 challenges:
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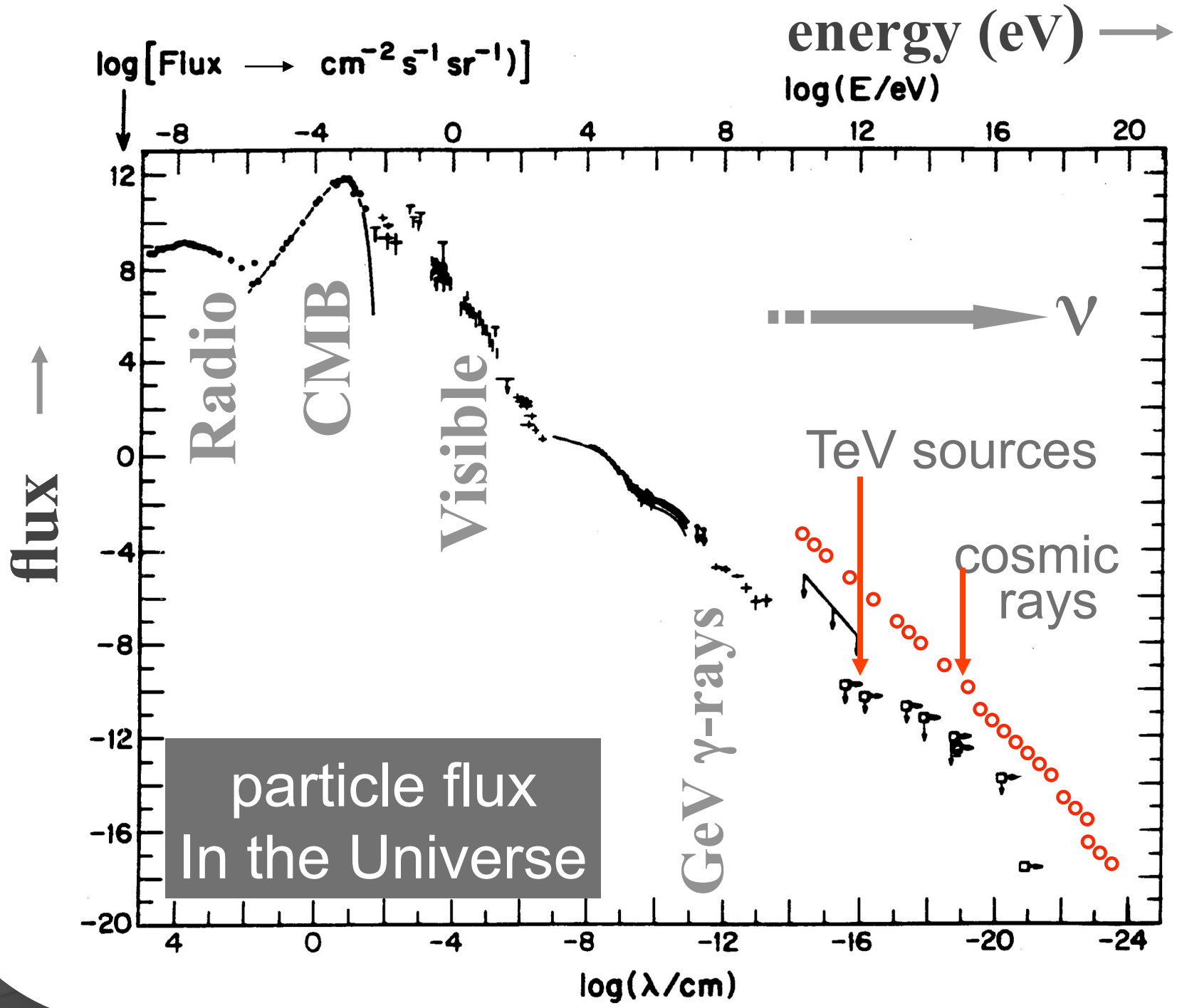
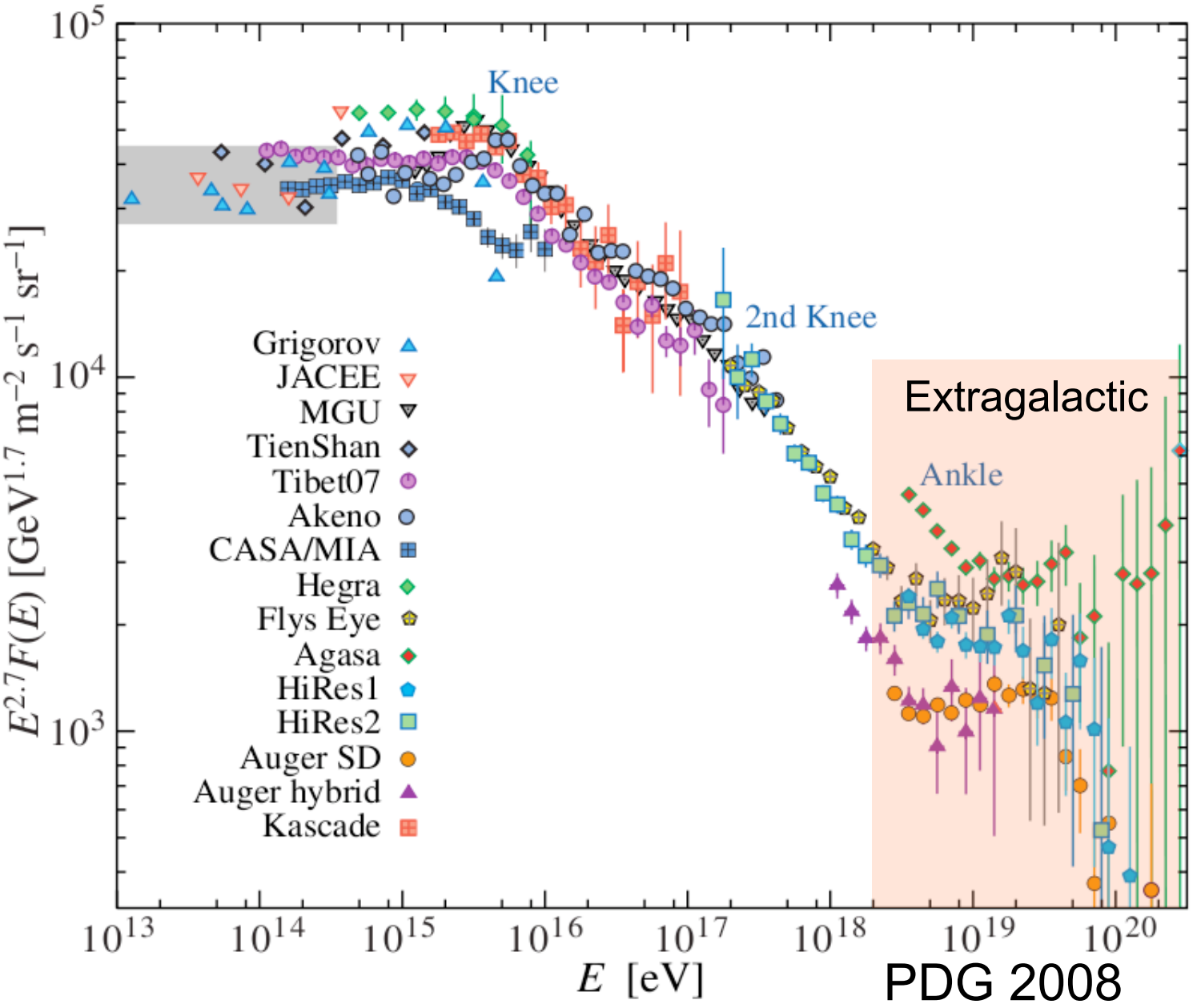
IceCube.wisc.edu


energy (eV)
log[Flux → cm⁻² s⁻¹ sr⁻¹)]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources
cosmic rays
particle flux
In the Universe
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

cosmic rays



PDG 2008

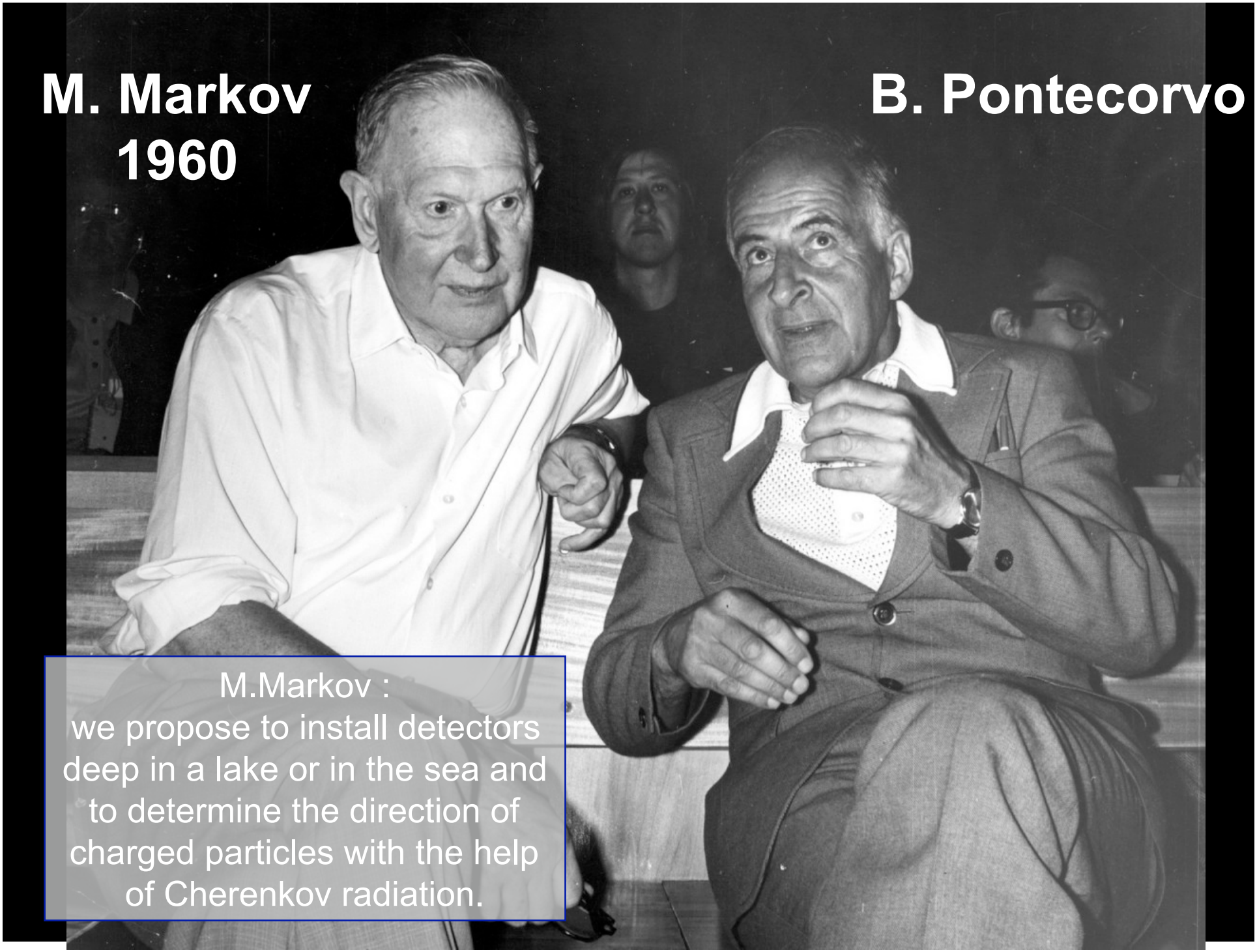
cosmic rays interact with the microwave background

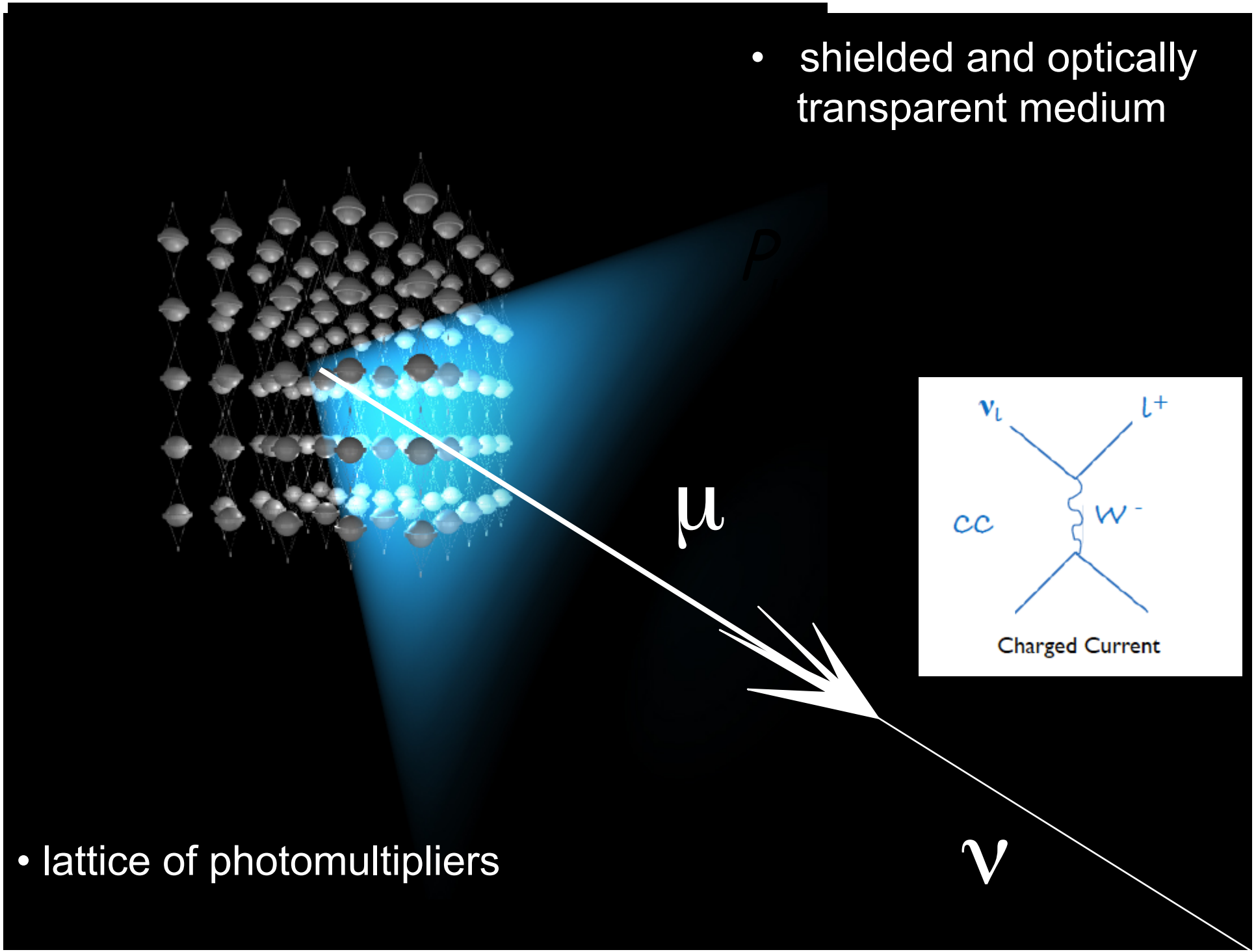
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

cosmic rays disappear, neutrinos appear

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

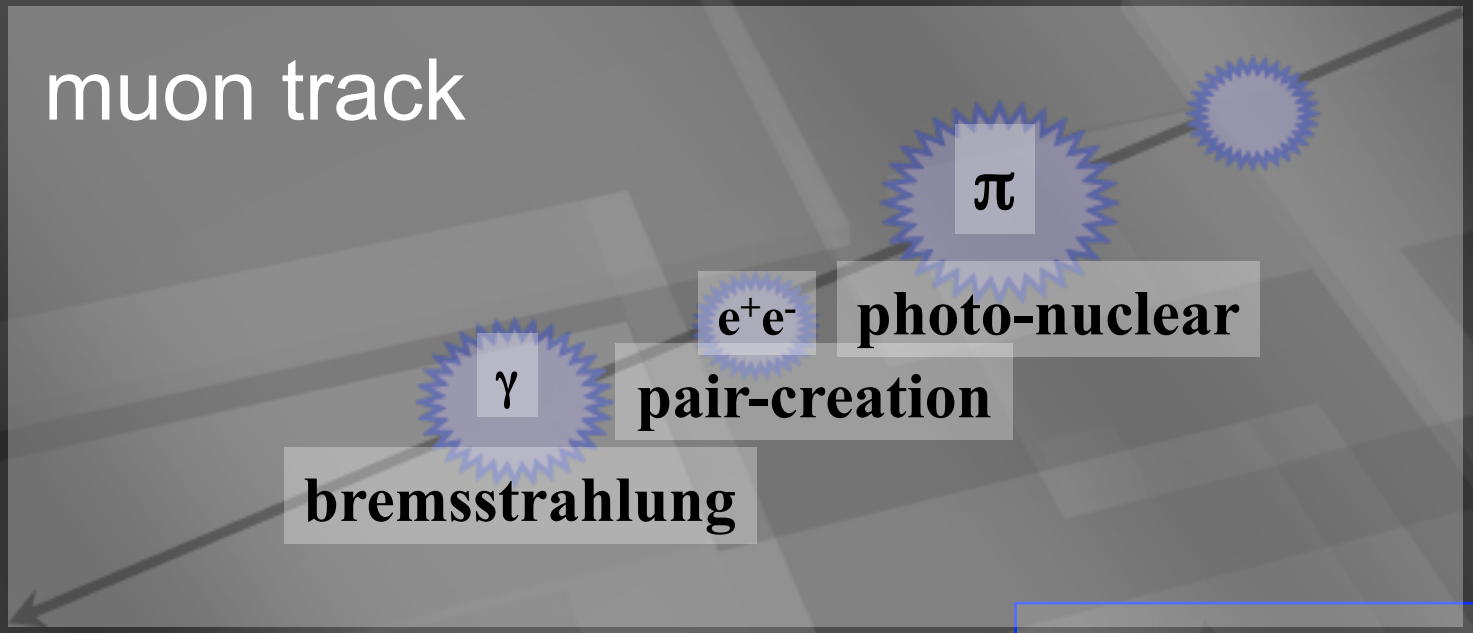
~ 1 GZK event per kilometer cube per year


M. Markov
1960
B. Pontecorvo
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.

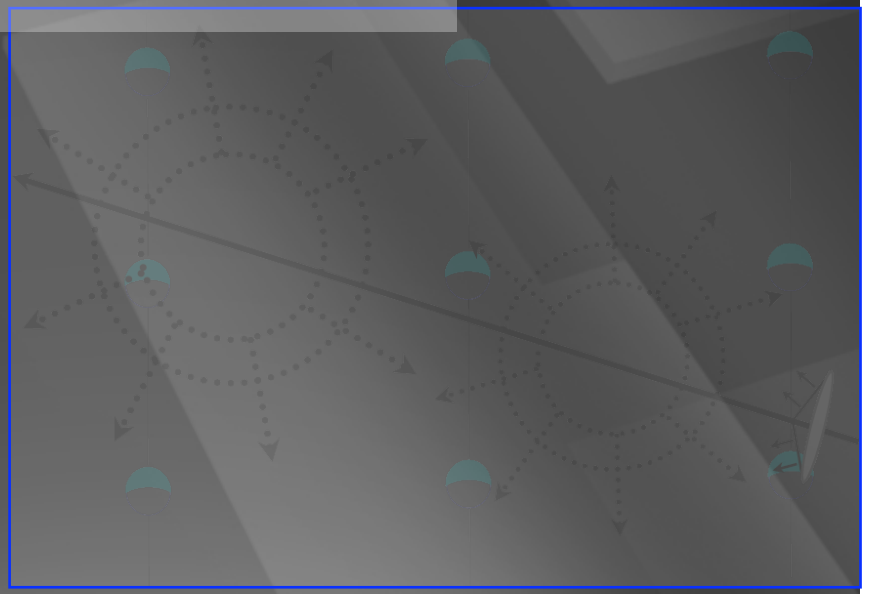

• shielded and optically transparent medium
p
μ
ν
• lattice of photomultipliers
ν_l
l^+
cc
W^-
Charged Current

photomultiplier tube

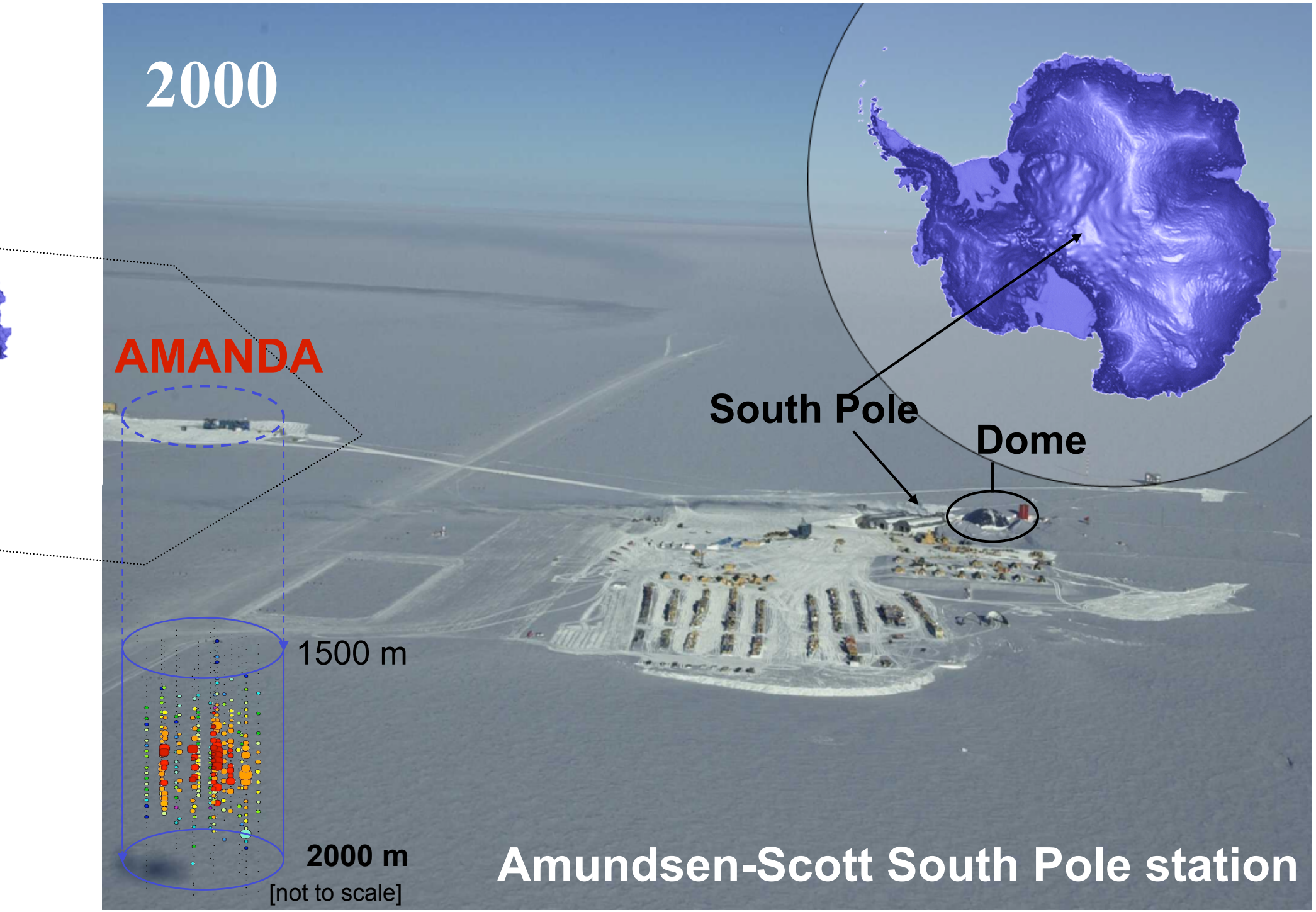
energy measurement (> 1 TeV)



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

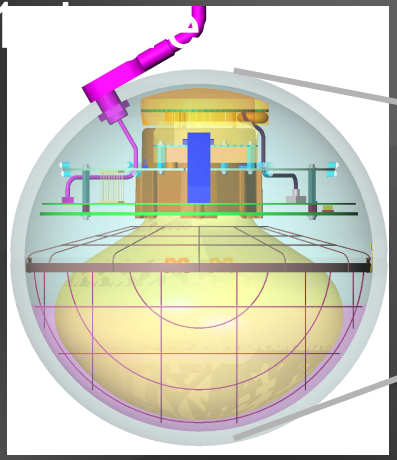



why did it take so long ?

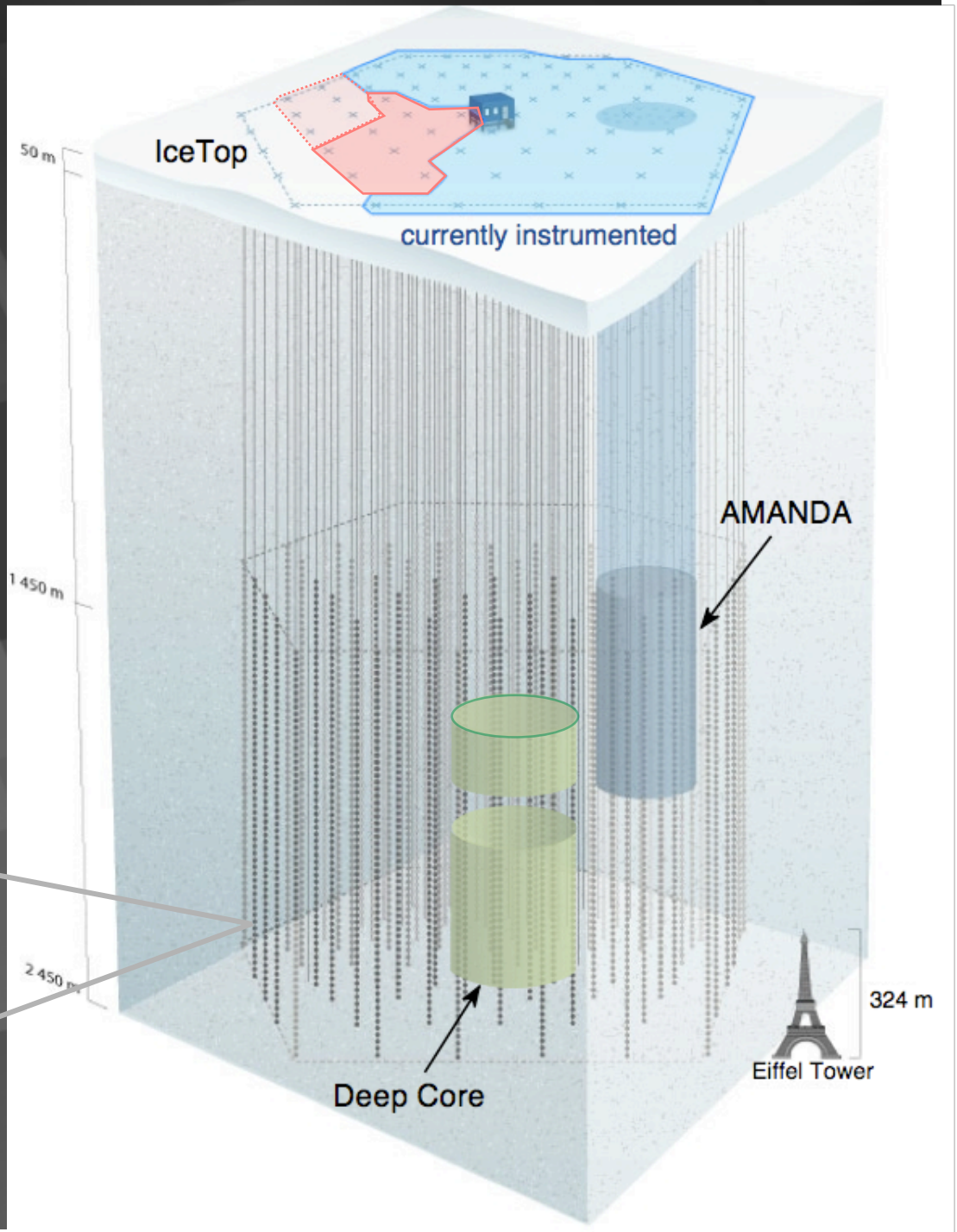

2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

IceCube / Deep Core

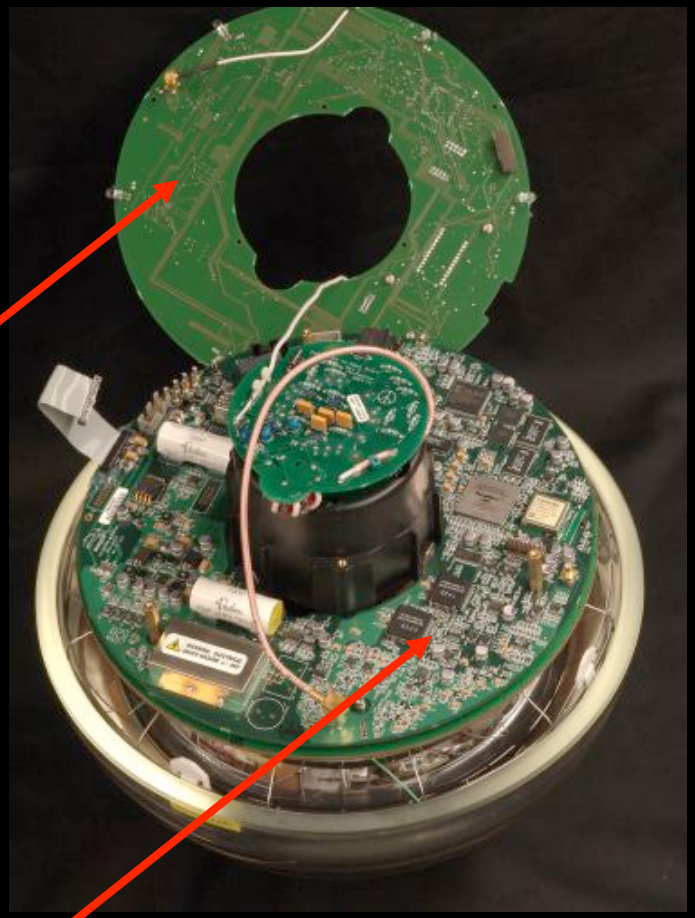
- detects Cherenkov light from showers and muon tracks initiated by neutrinos
- detects ~220 neutrinos and 1.7x10^8 muons per day
- threshold 10 GeV
- angular resolution 0.4~1

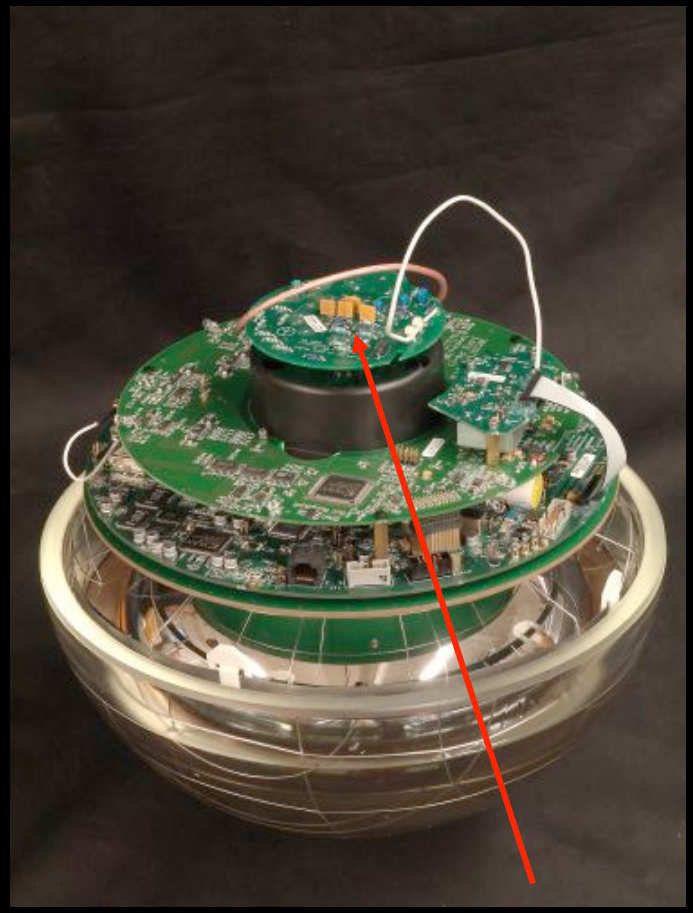


5320 Digital Optical Modules (DOM)

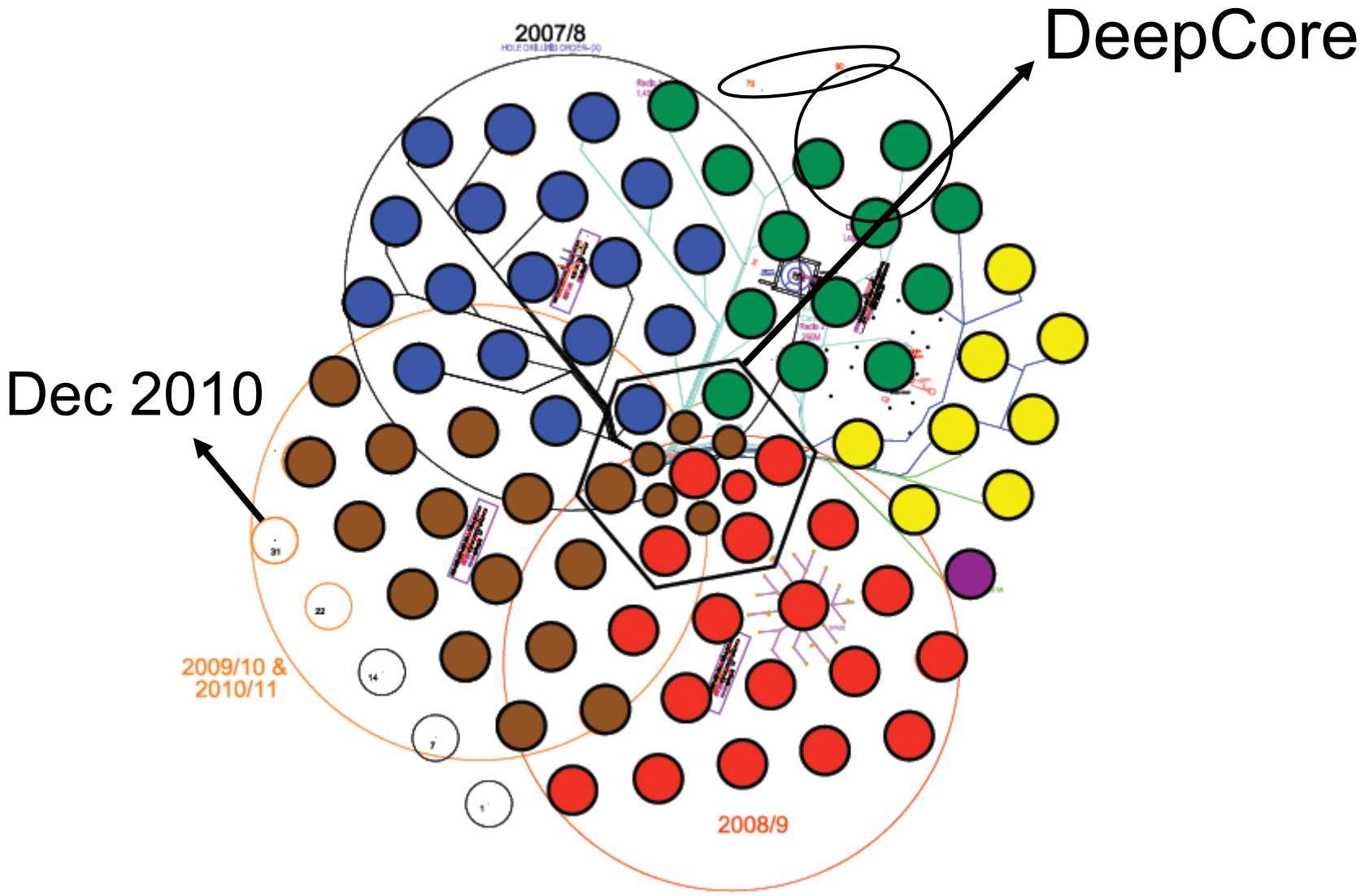


architecture of independent DOMs

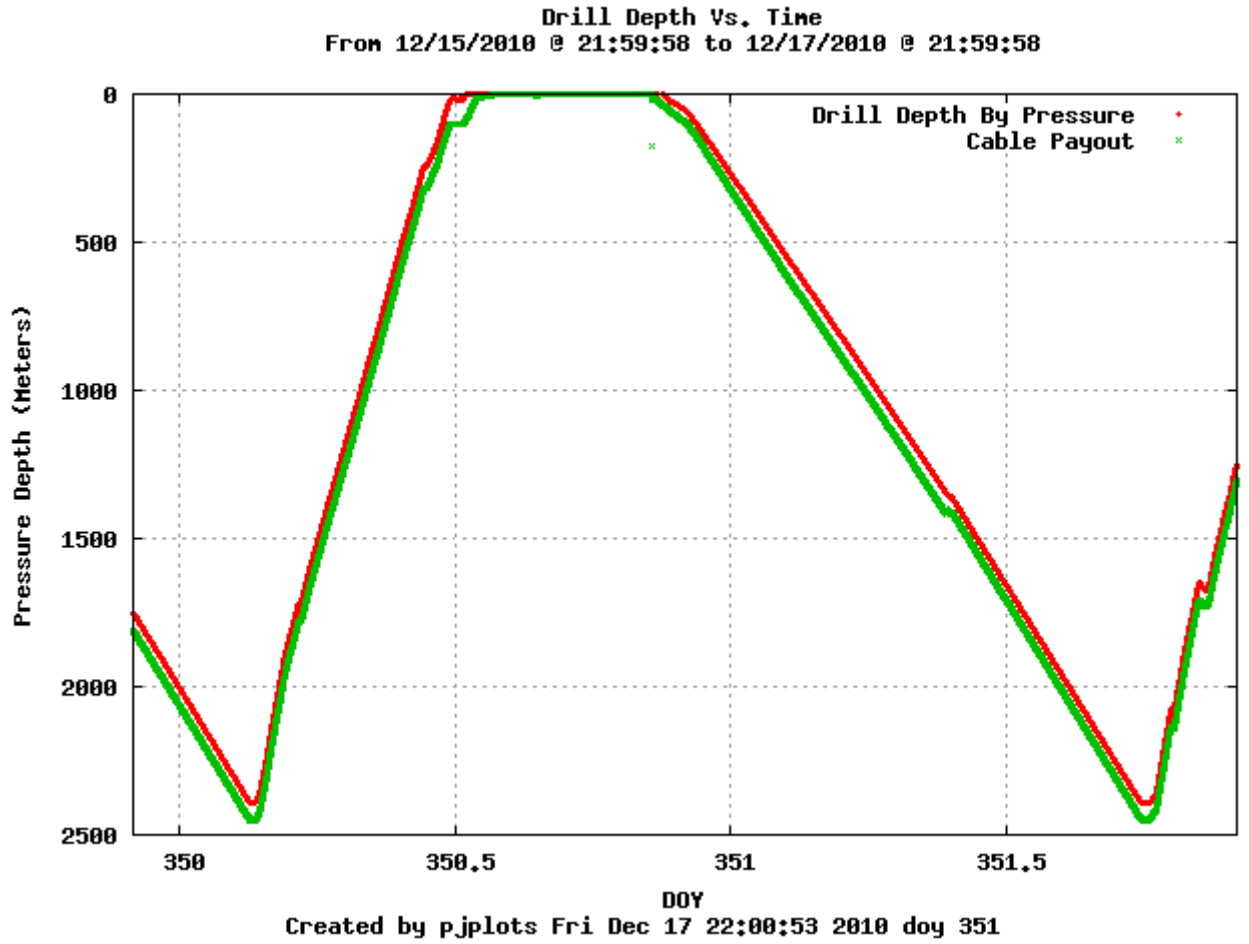


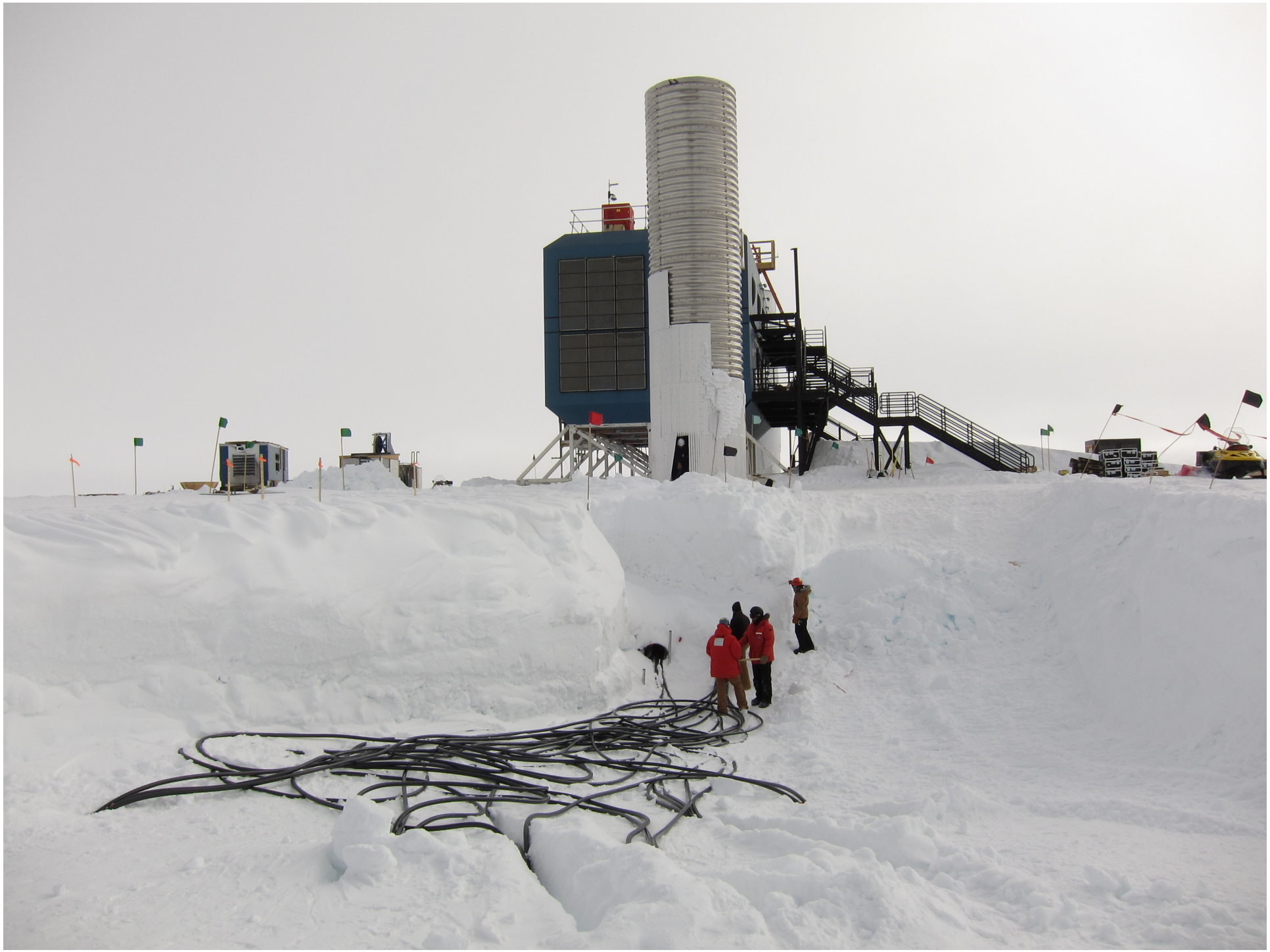


January 20, 2010

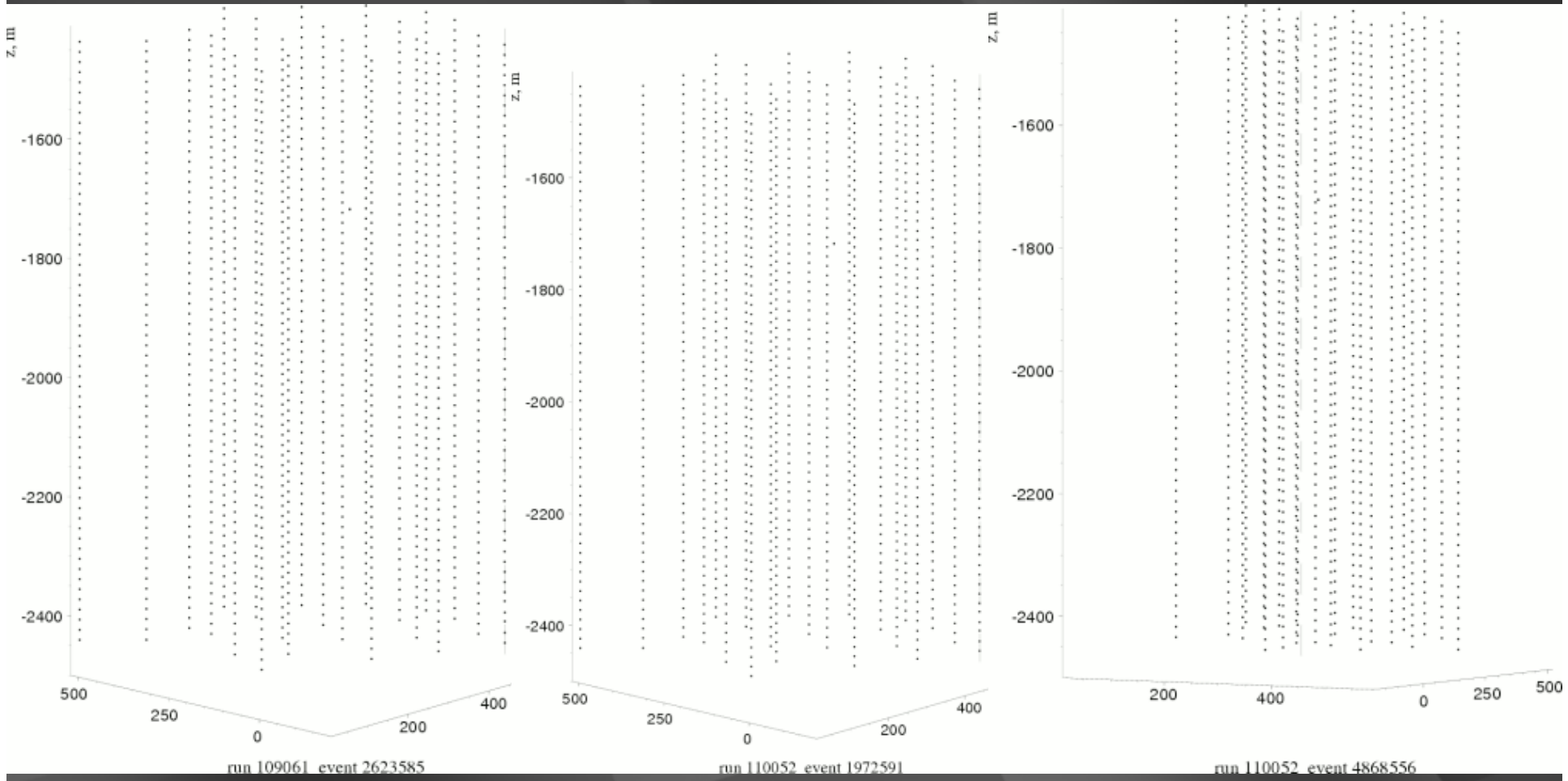


10:39 this morning

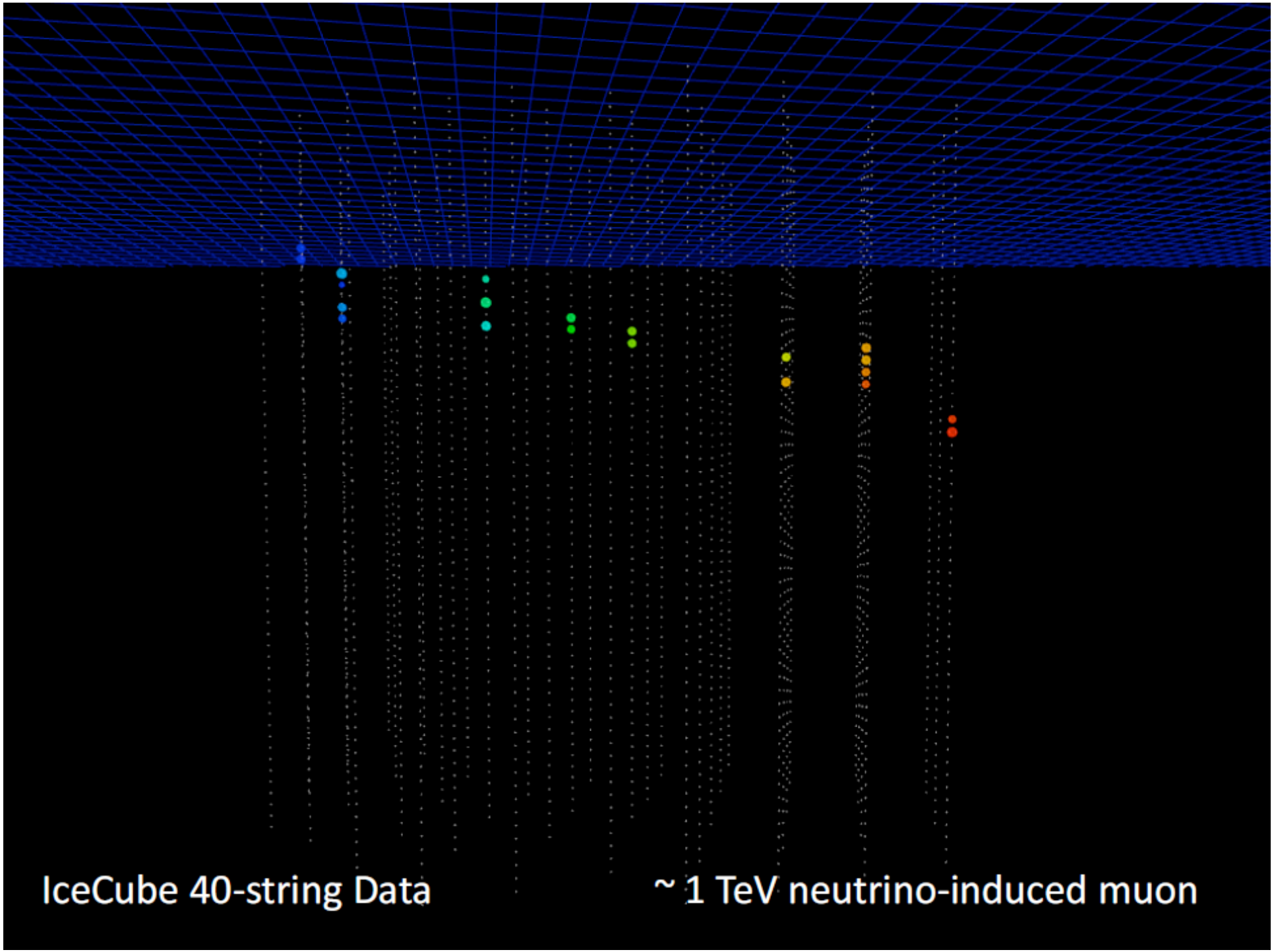


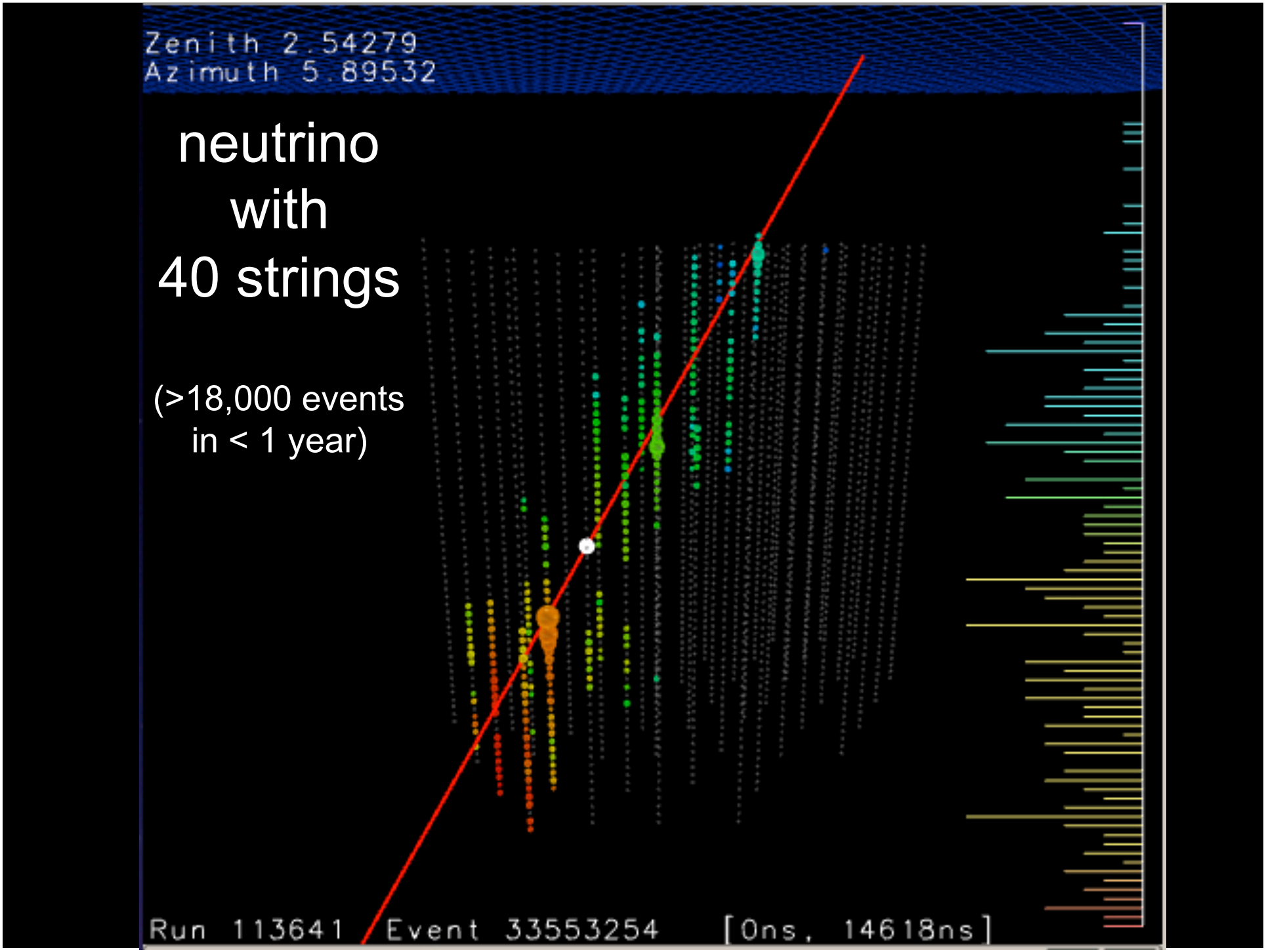


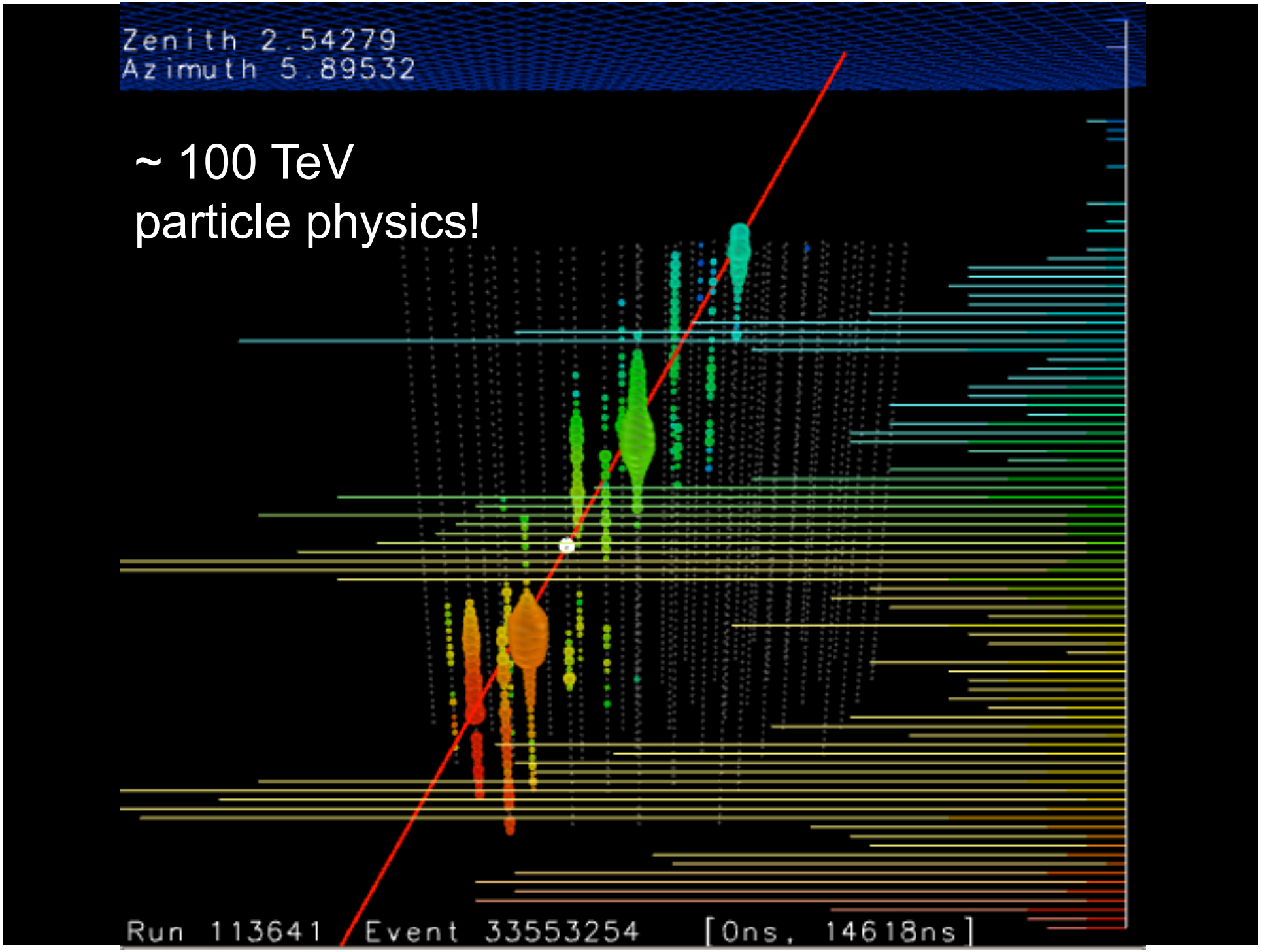
IceCube neutrinos (40 out of 80 strings)

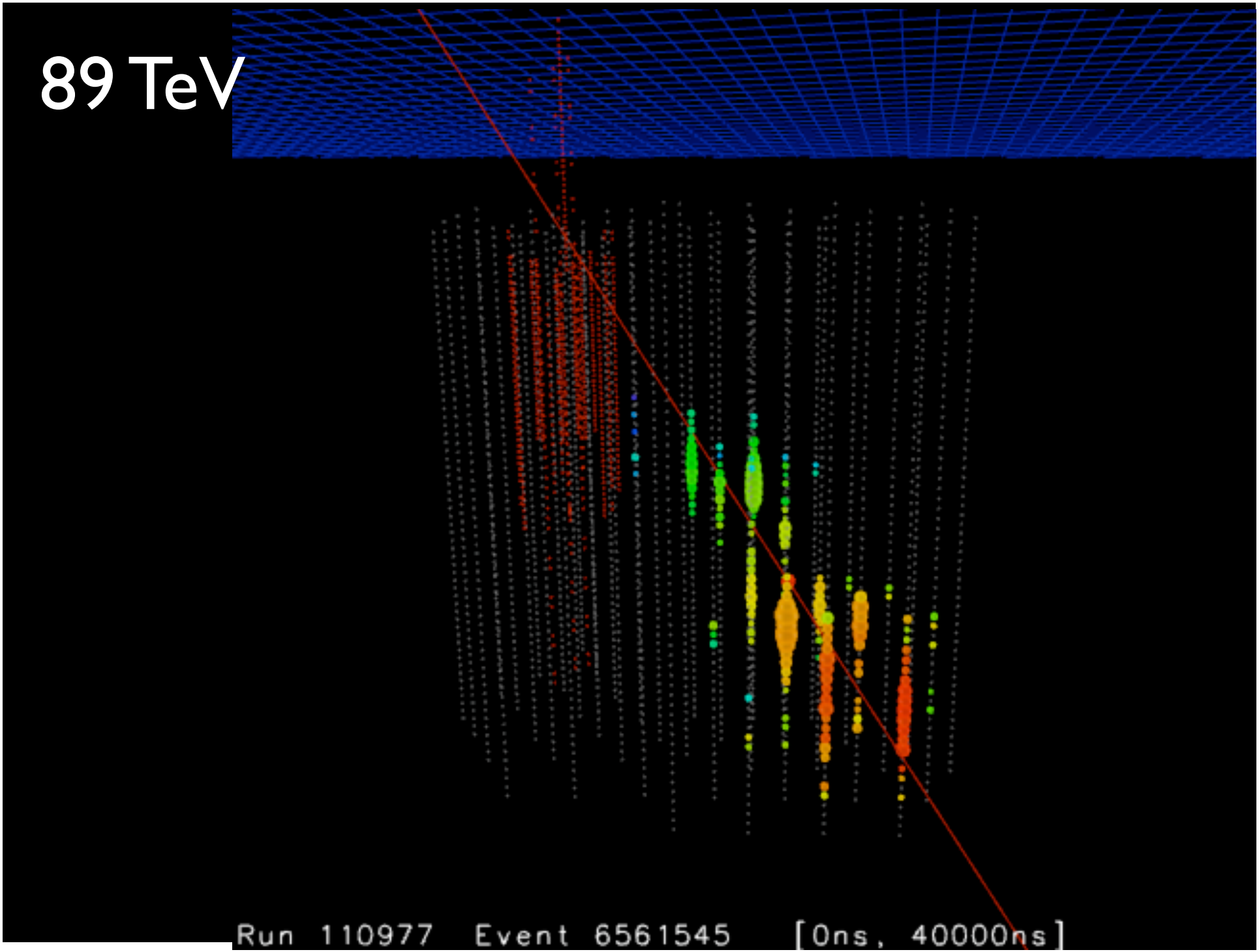


→ operated for 276 days → collected > 18,000 ν's

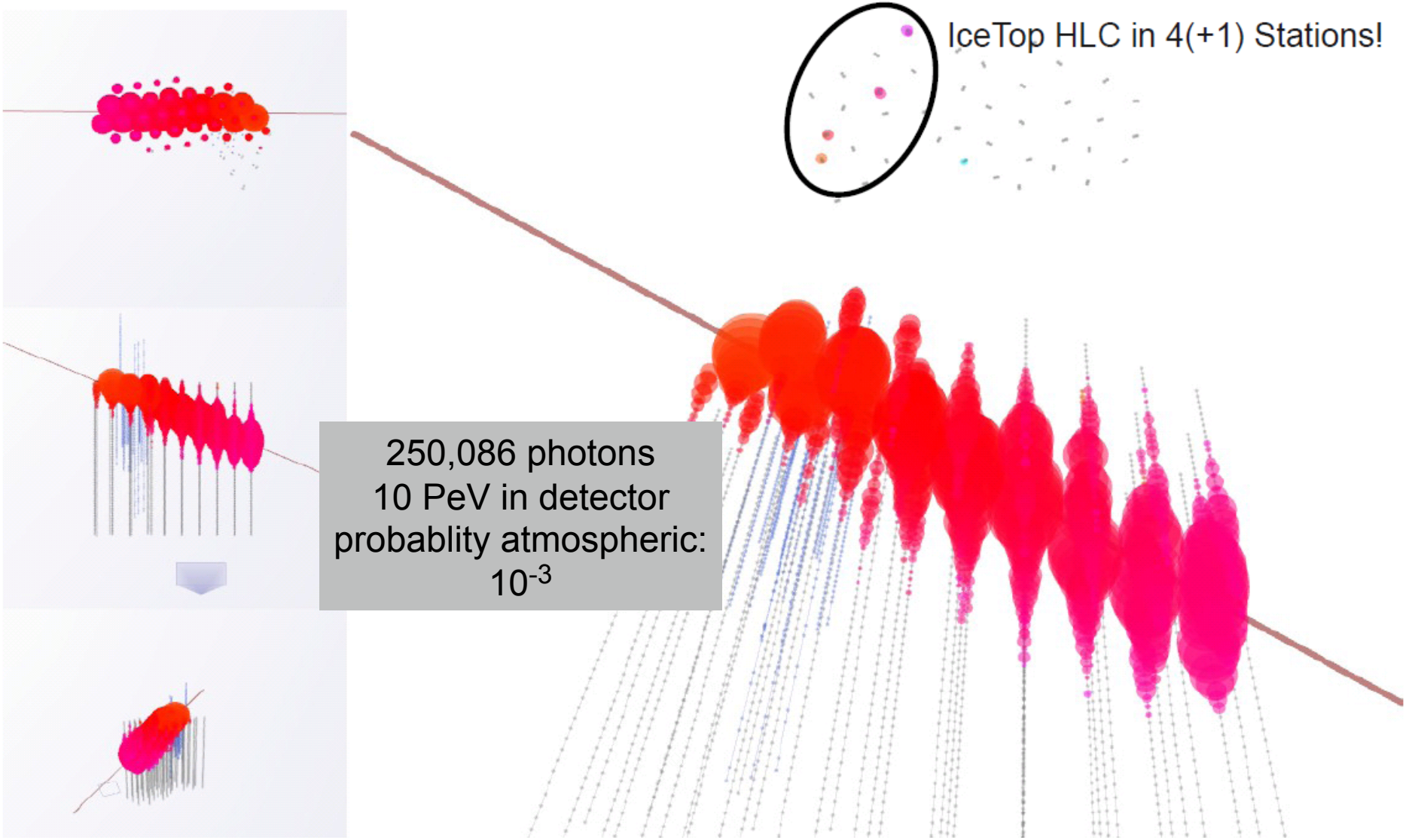

IceCube 40-string Data
~ 1 TeV neutrino-induced muon


Zenith 2.54279
Azimuth 5.89532
neutrino
with
40 strings
(>18,000 events
in < 1 year)
Run 113641 Event 33553254 [0ns, 14618ns]

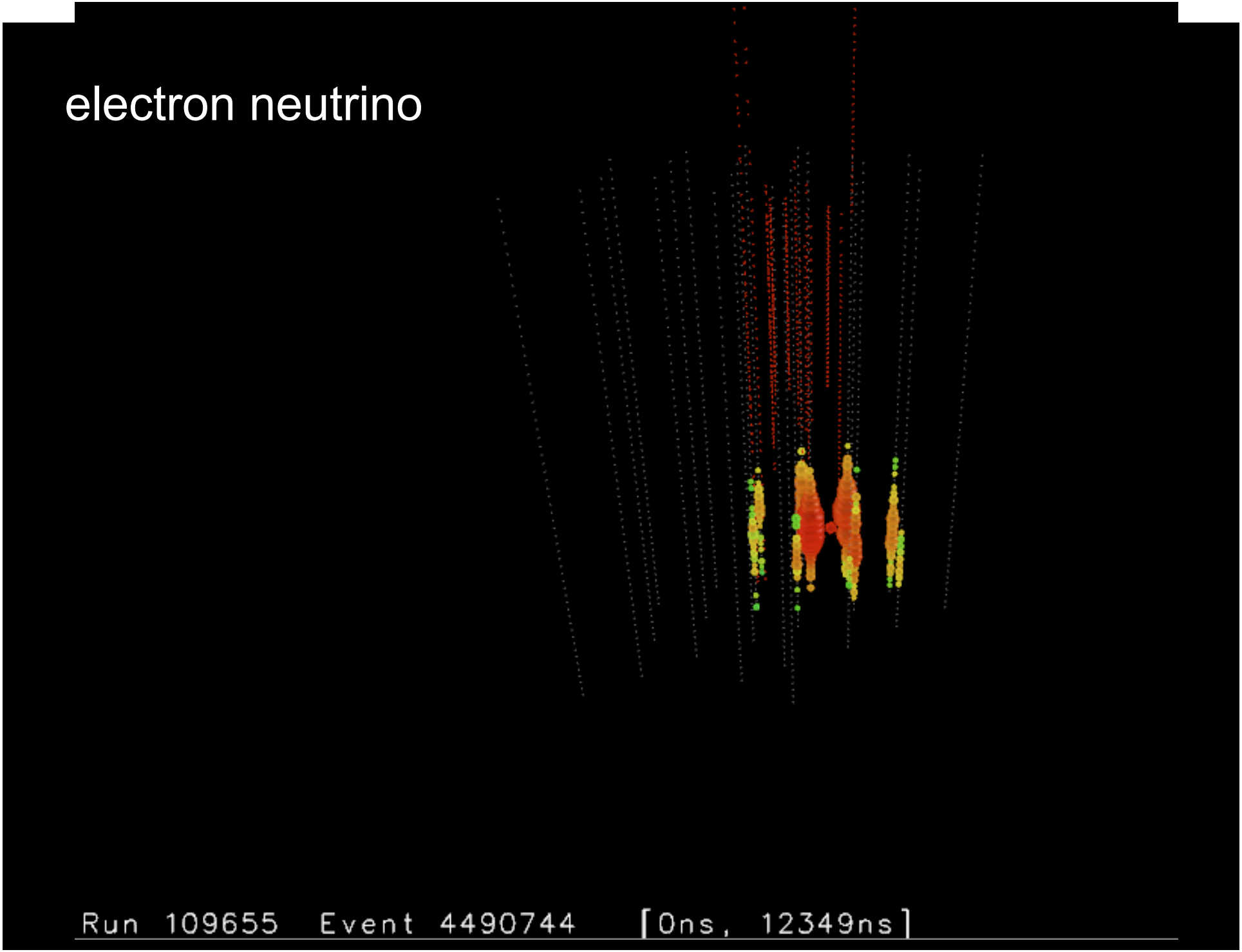

Zenith 2.54279
Azimuth 5.89532
~ 100 TeV
particle physics!
Run 113641 Event 33553254 [0ns, 14618ns]

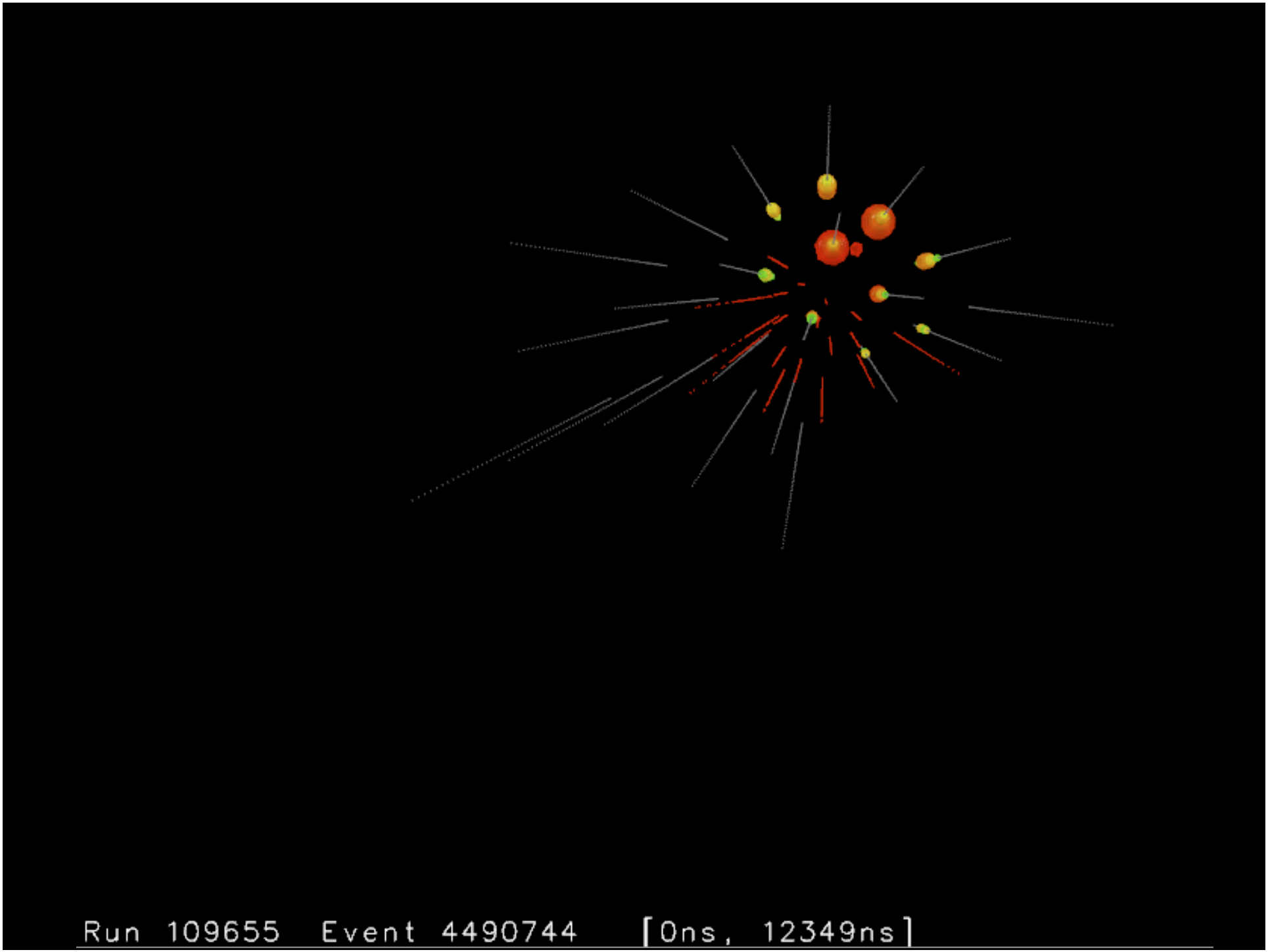

89 TeV
Run 110977 Event 6561545 [0ns, 40000ns]

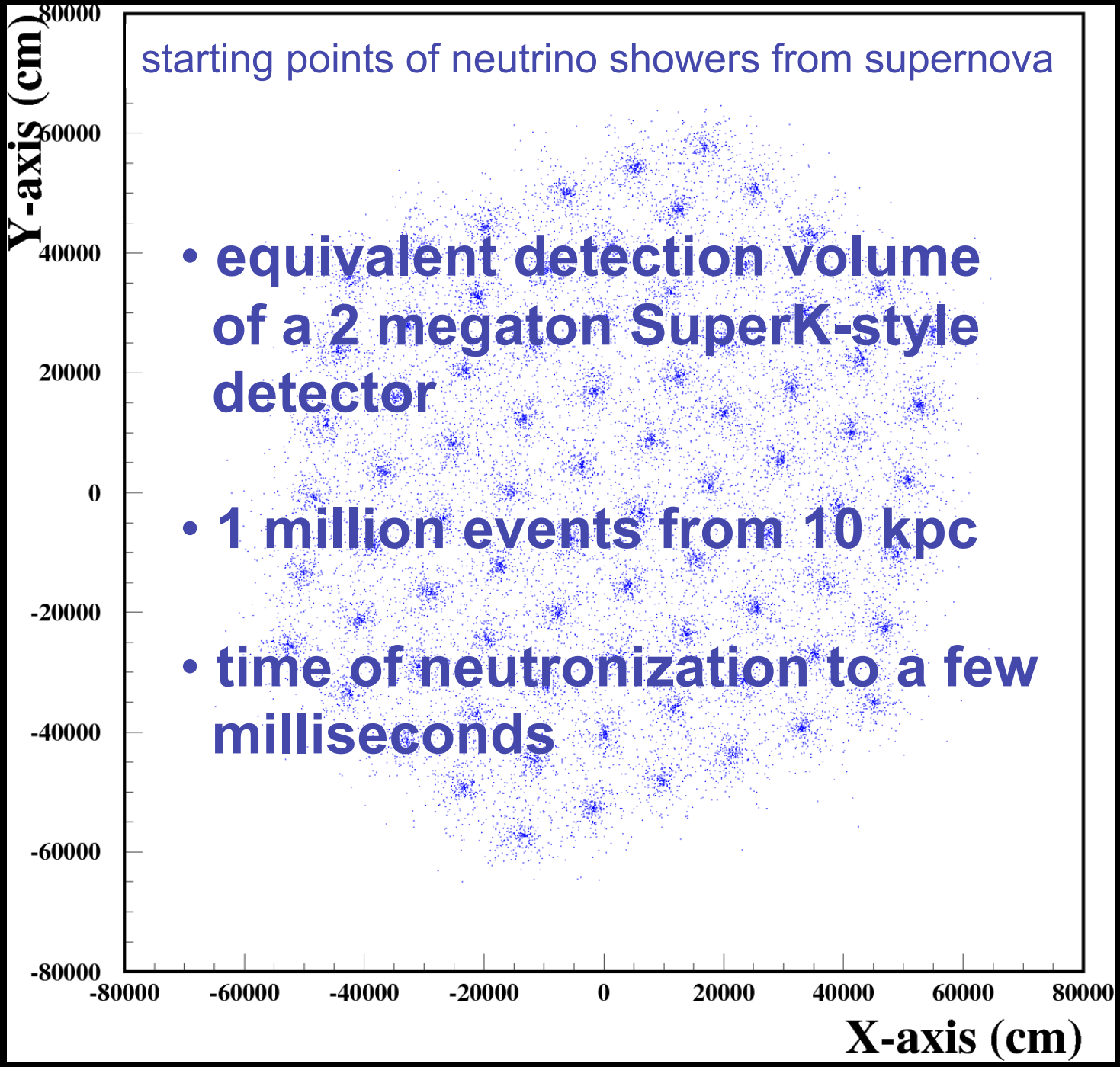
Biggest Shower in IC40 EHE Analysis

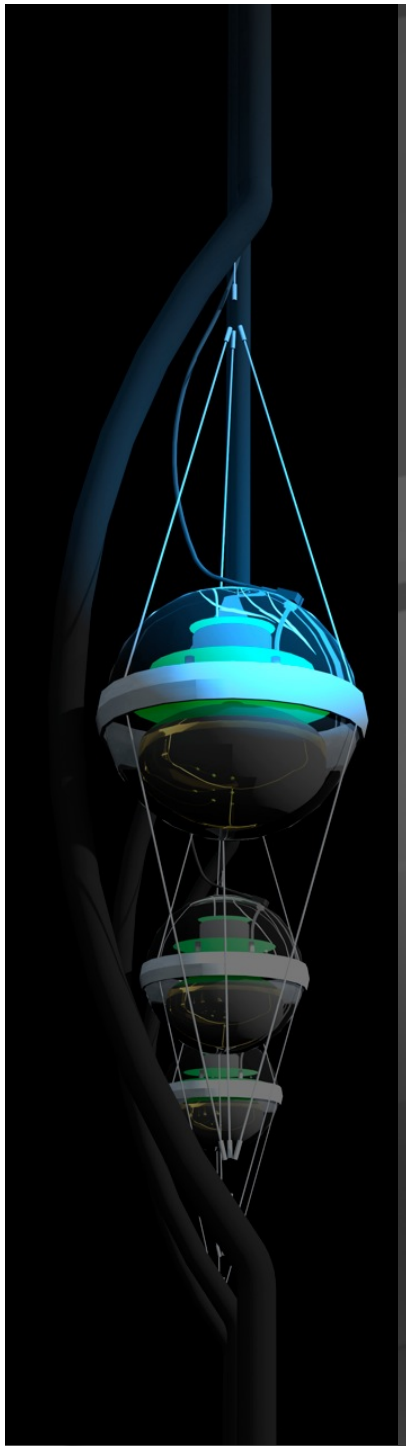


electron neutrino




Run 109655 Event 4490744 [0ns, 12349ns]


starting points of neutrino showers from supernova
• equivalent detection volume of a 2 megaton SuperK-style detector
• 1 million events from 10 kpc
• time of neutronization to a few milliseconds
Y-axis (cm)
80000
60000
40000
20000
0
-20000
-40000
-60000
-80000
-80000
-60000
-40000
-20000
0
20000
40000
60000
80000
X-axis (cm)



- we built a km^3 neutrino detector → 3 challenges:
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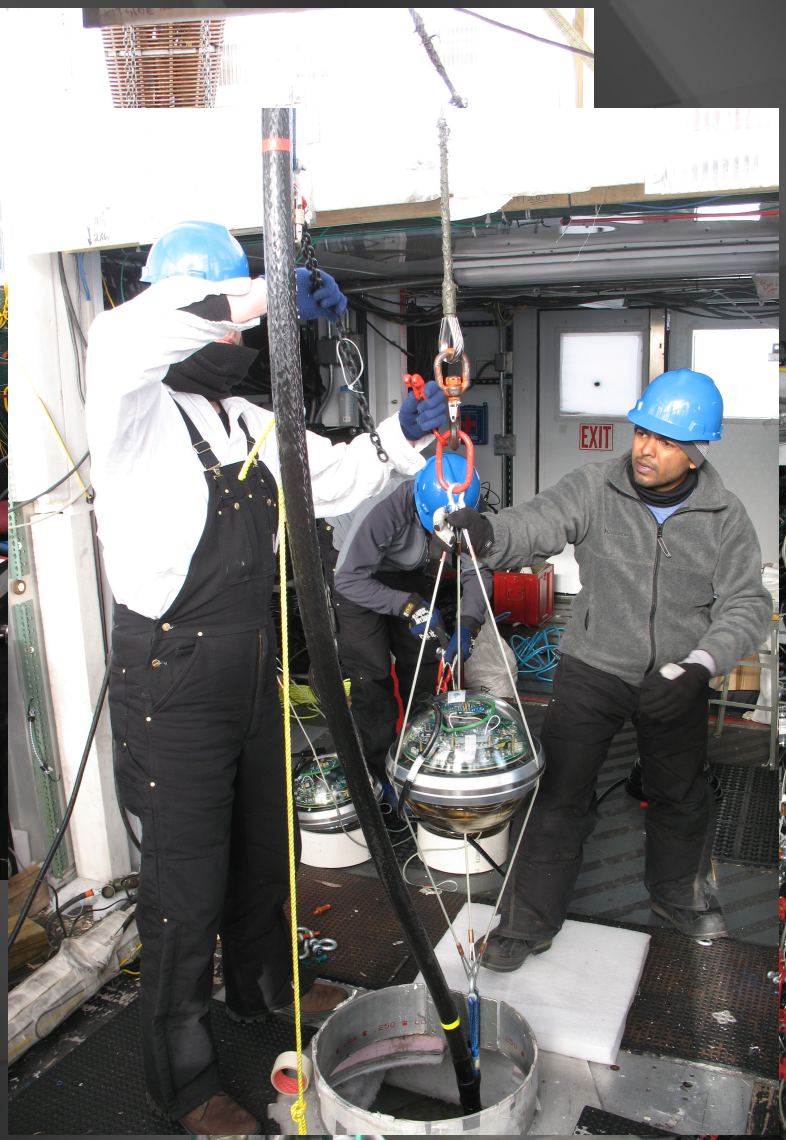
  - optics of ice
  - atmospheric muons
- atmospheric neutrino spectrum
- atmospheric muon spectrum: first surprise
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - GZK neutrinos
  - a multi-wavelength story
- search for dark matter

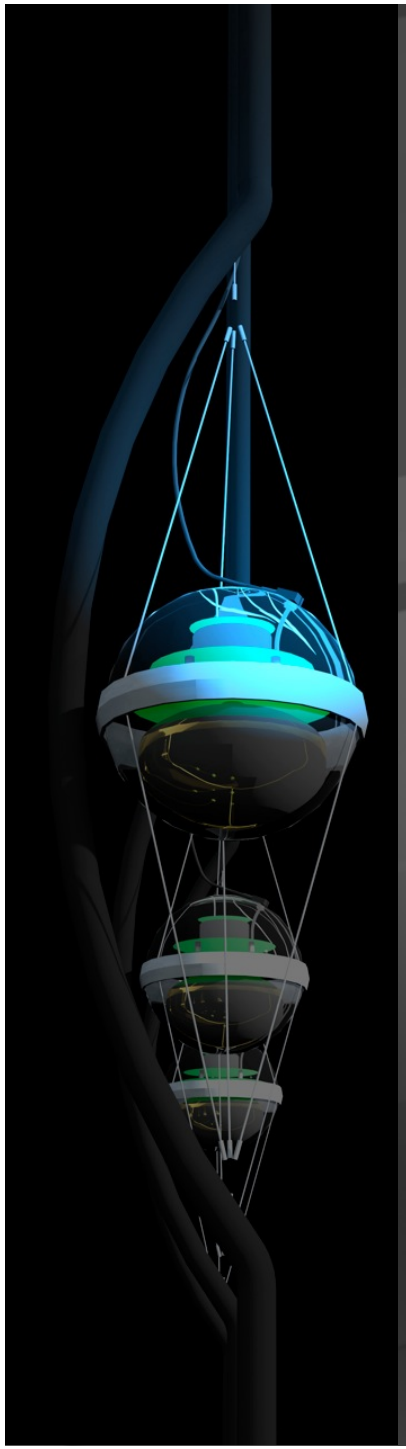
IceCube.wisc.edu


5 megawatt power plant

drilling and deployment



to 2500 m in
less than
2 days →
3.5 cm/second



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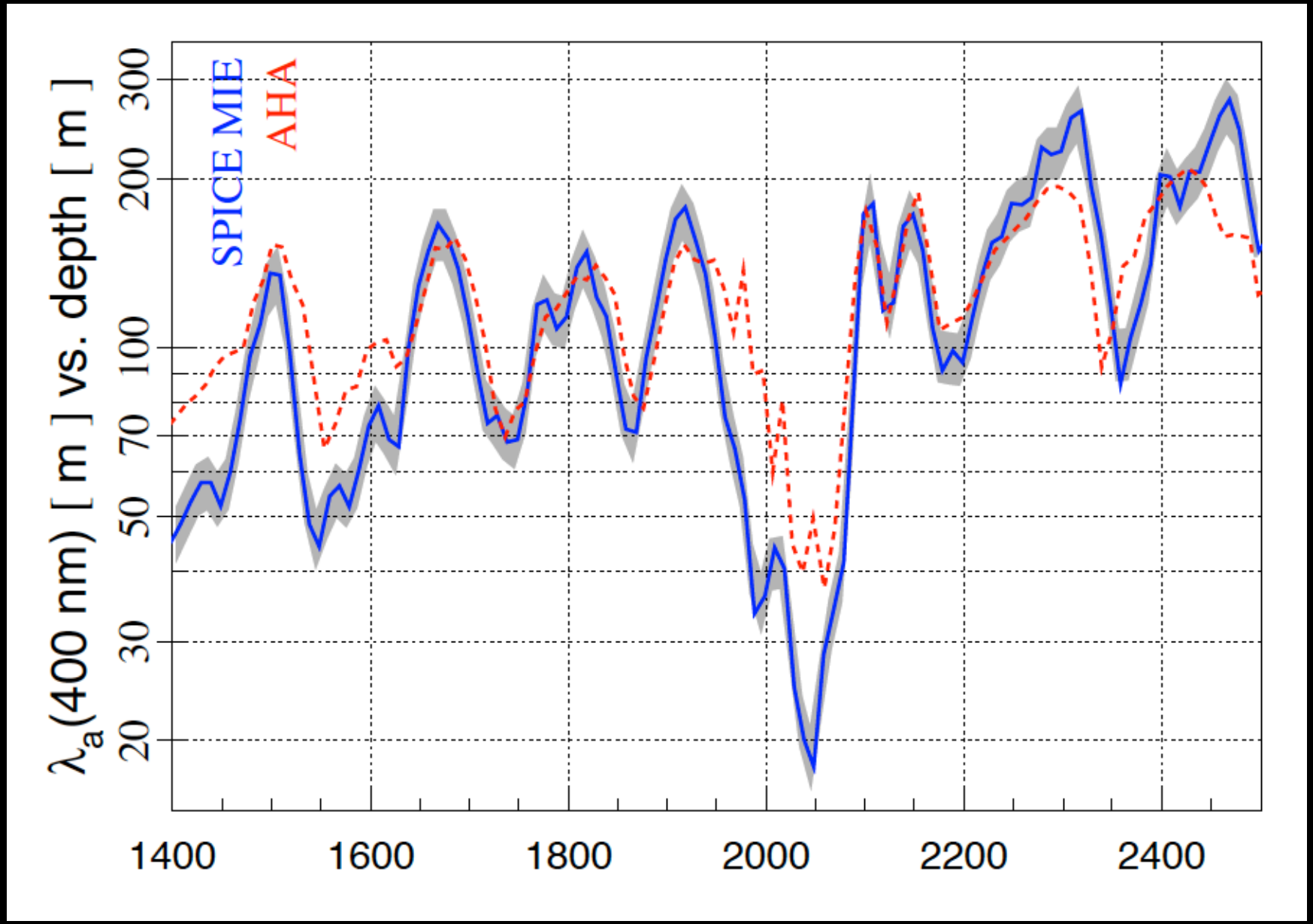
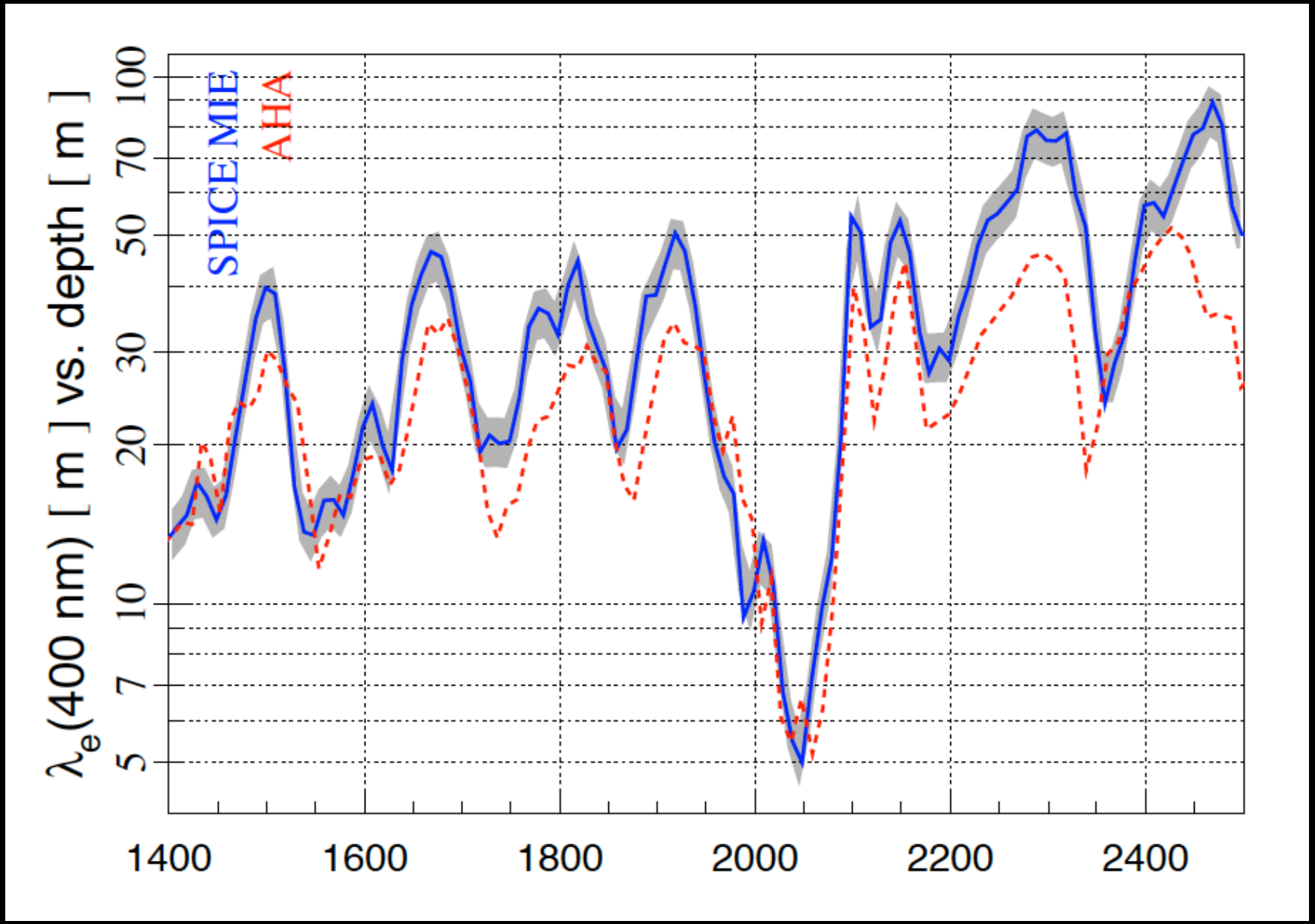
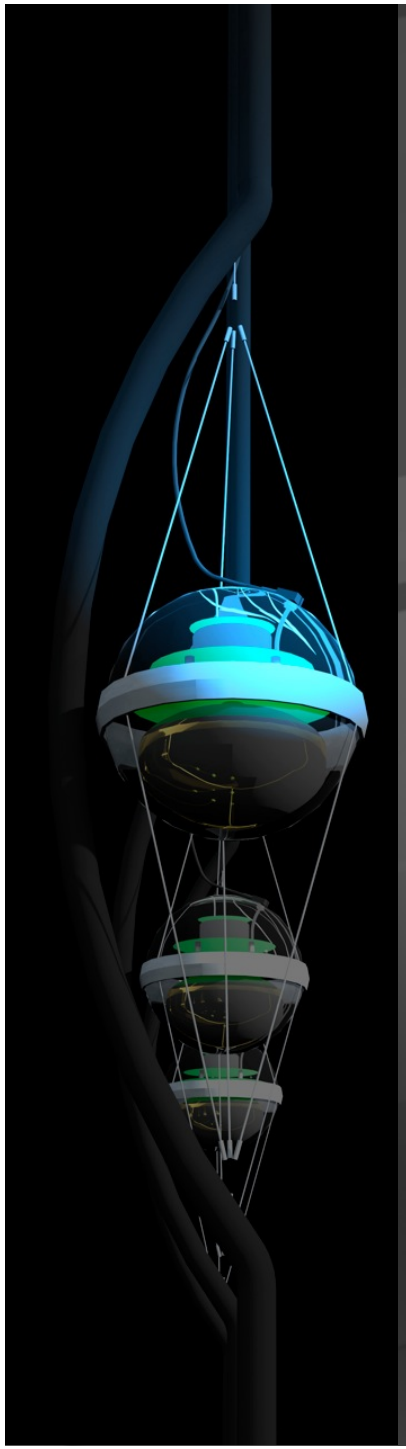
absorption length



scattering length





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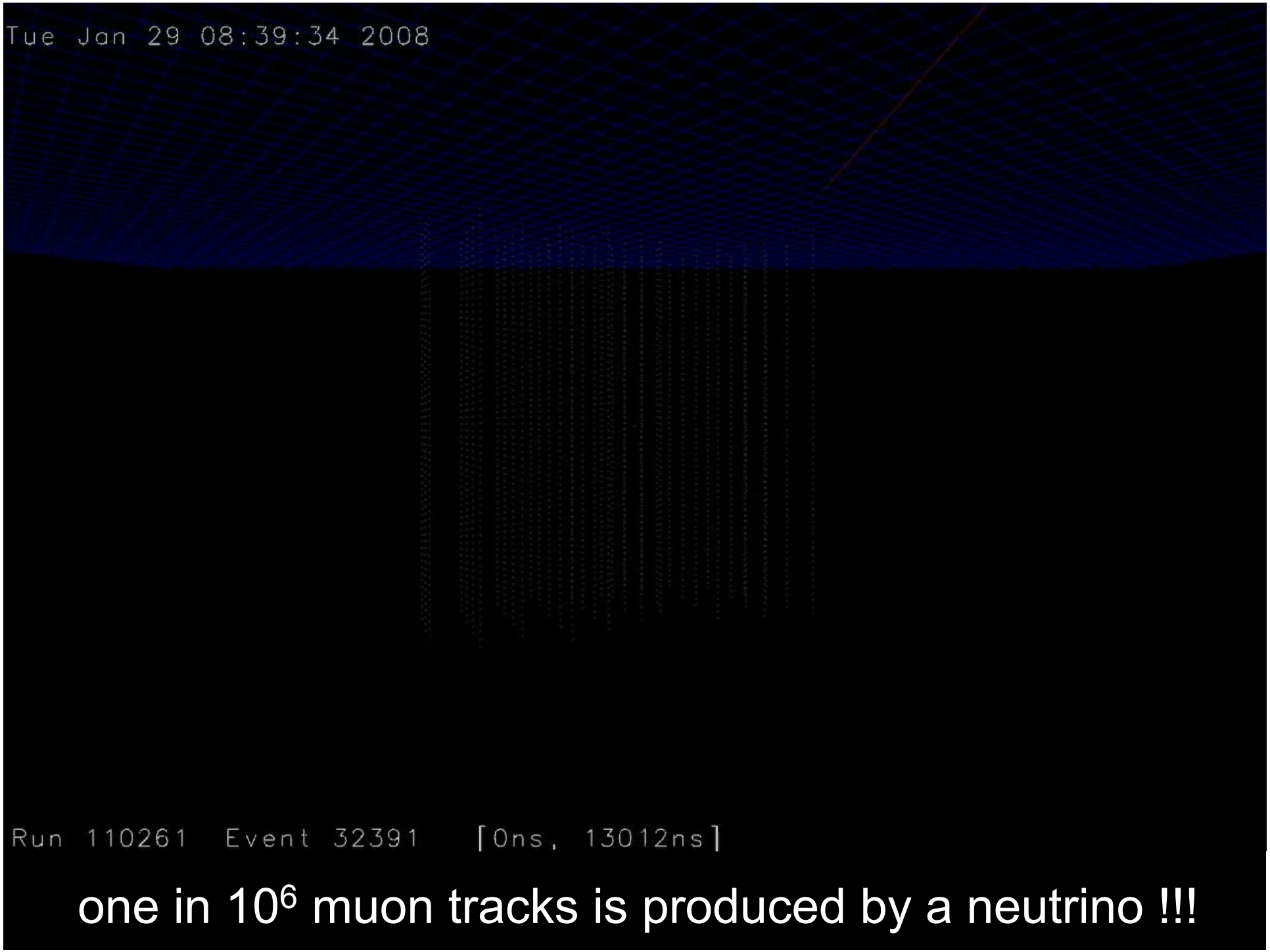
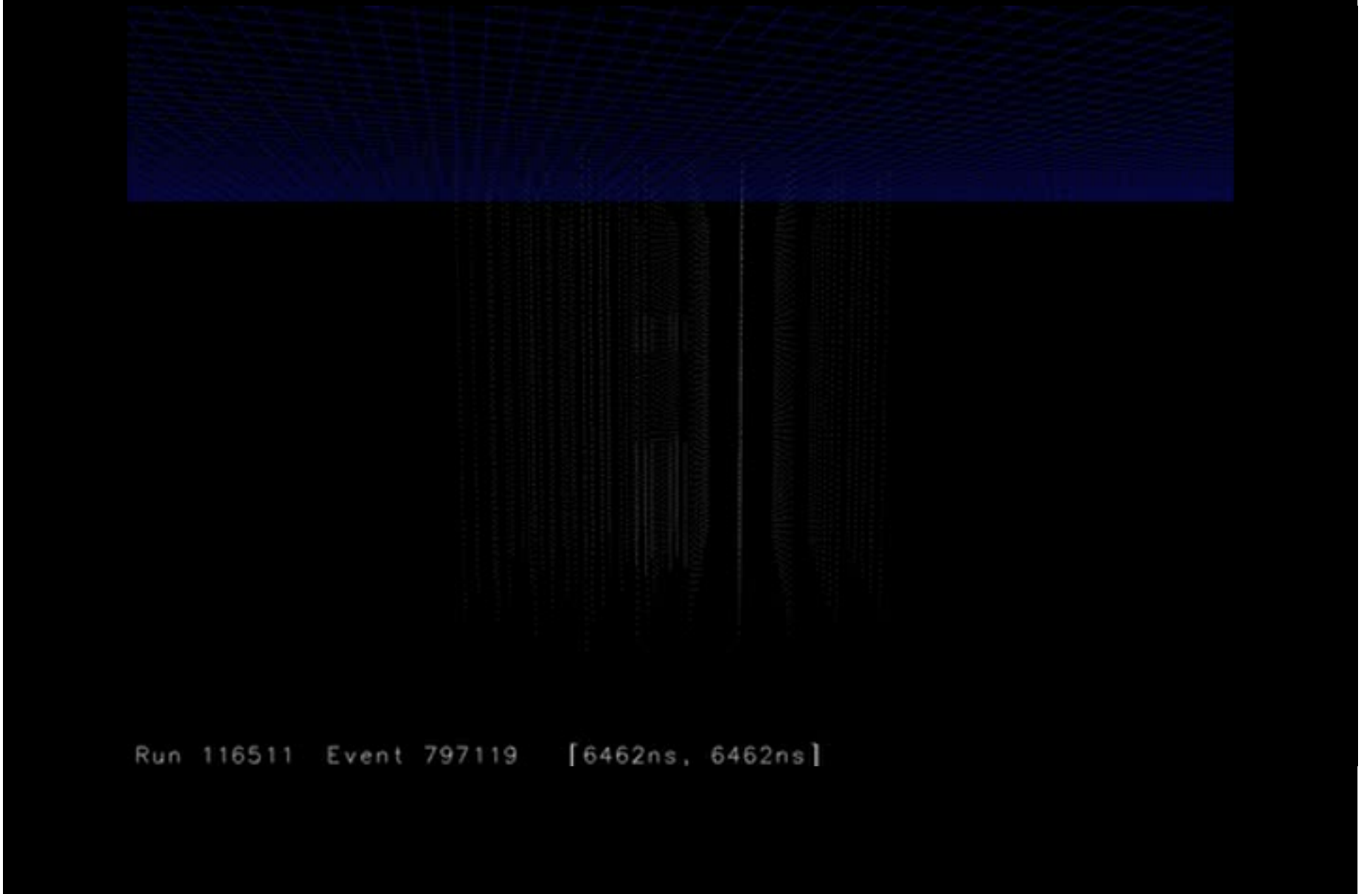
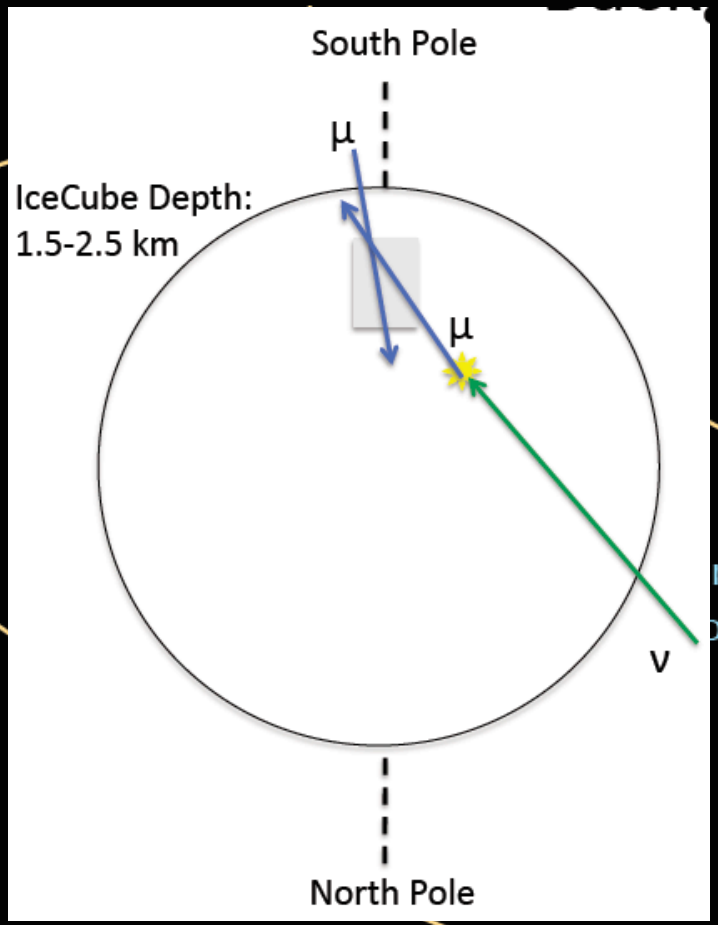


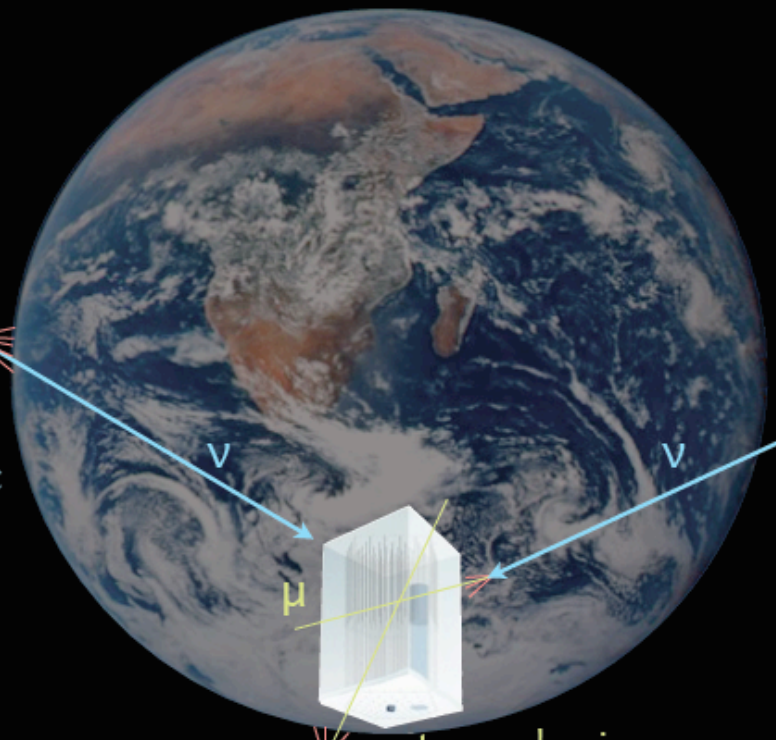
one in 10^6 muon tracks is produced by a neutrino !!!

muon passing DeepCore



Signals and Backgrounds





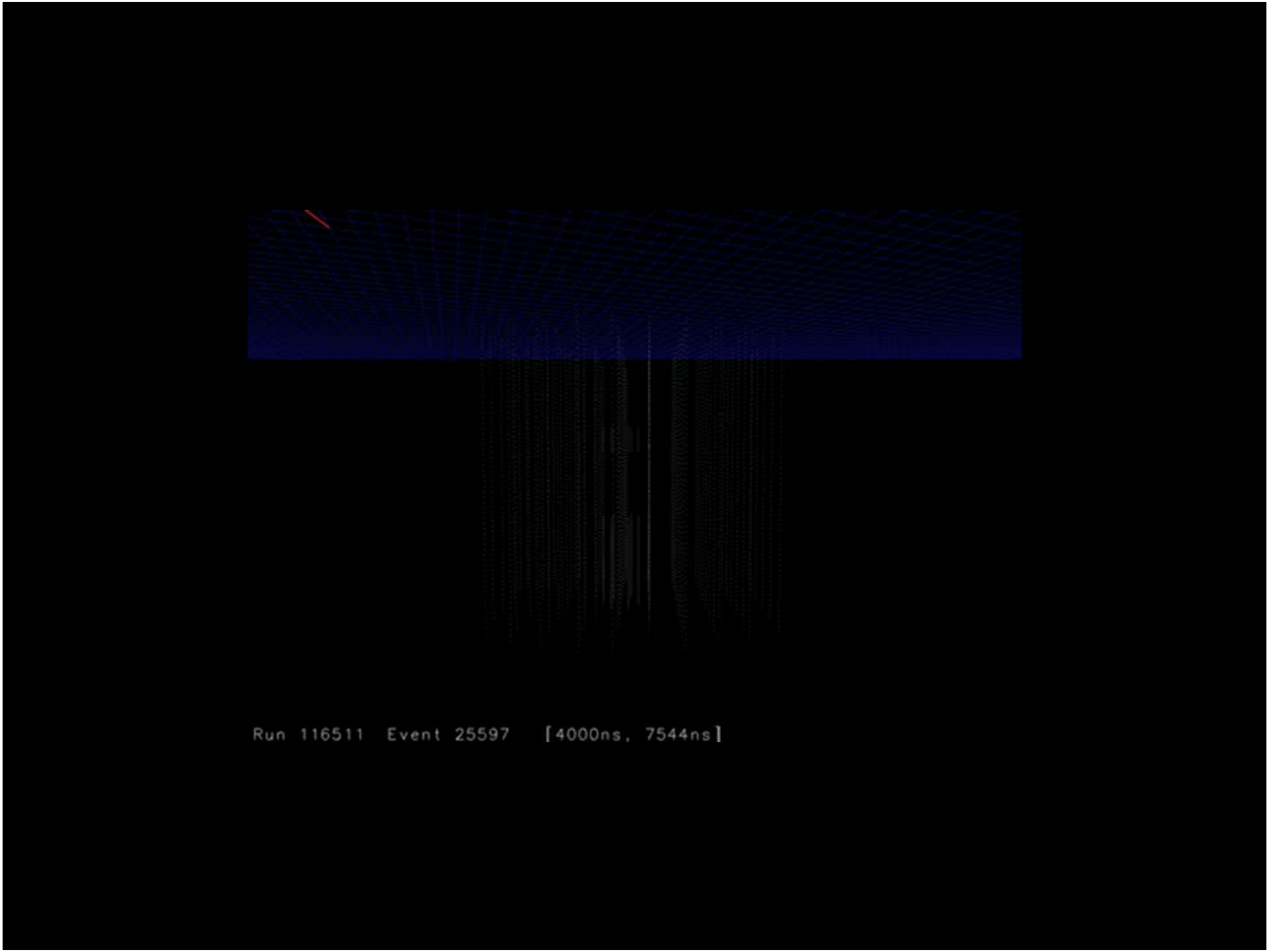
astrophysical
neutrino

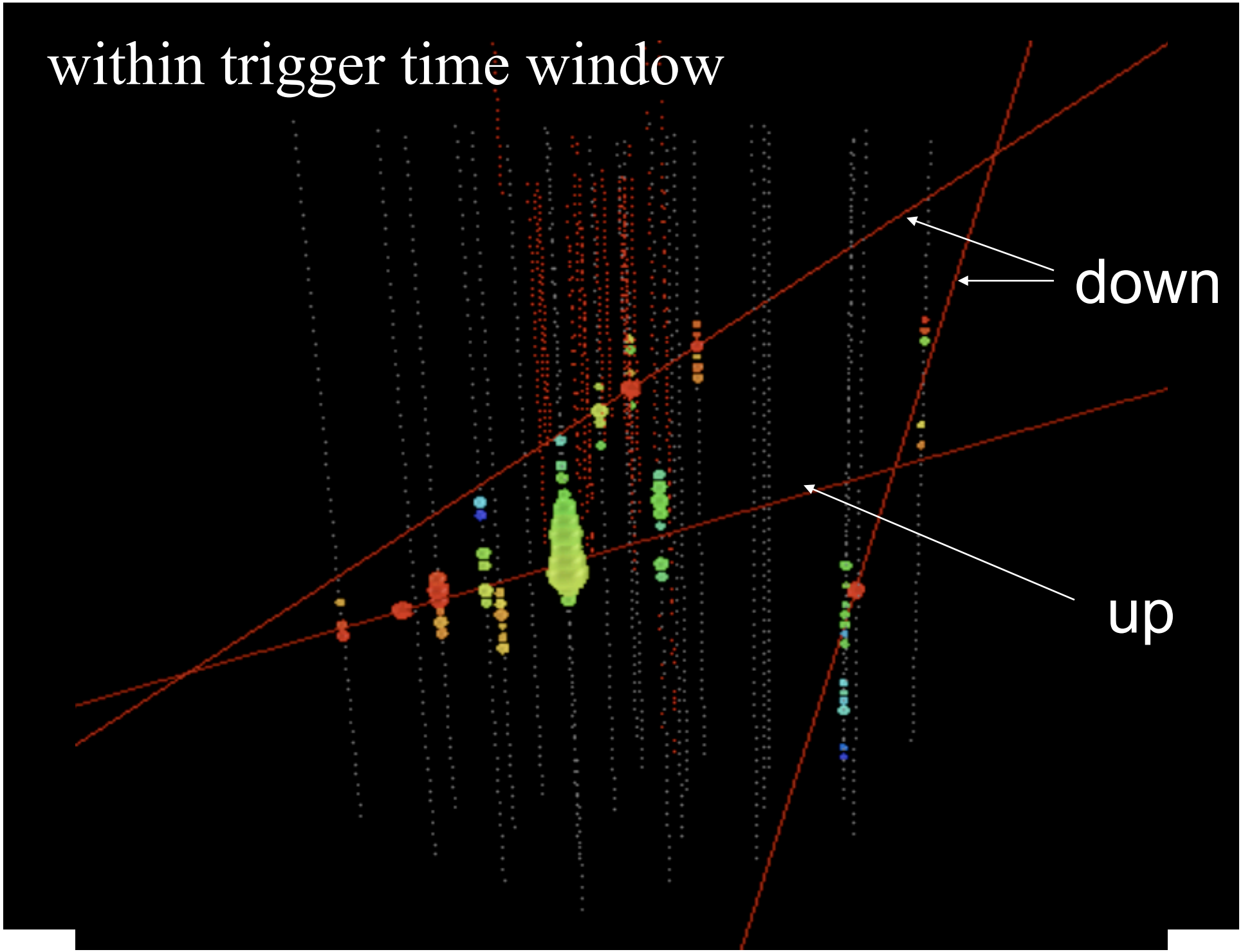
atmospheric
muon

muons detected per year:

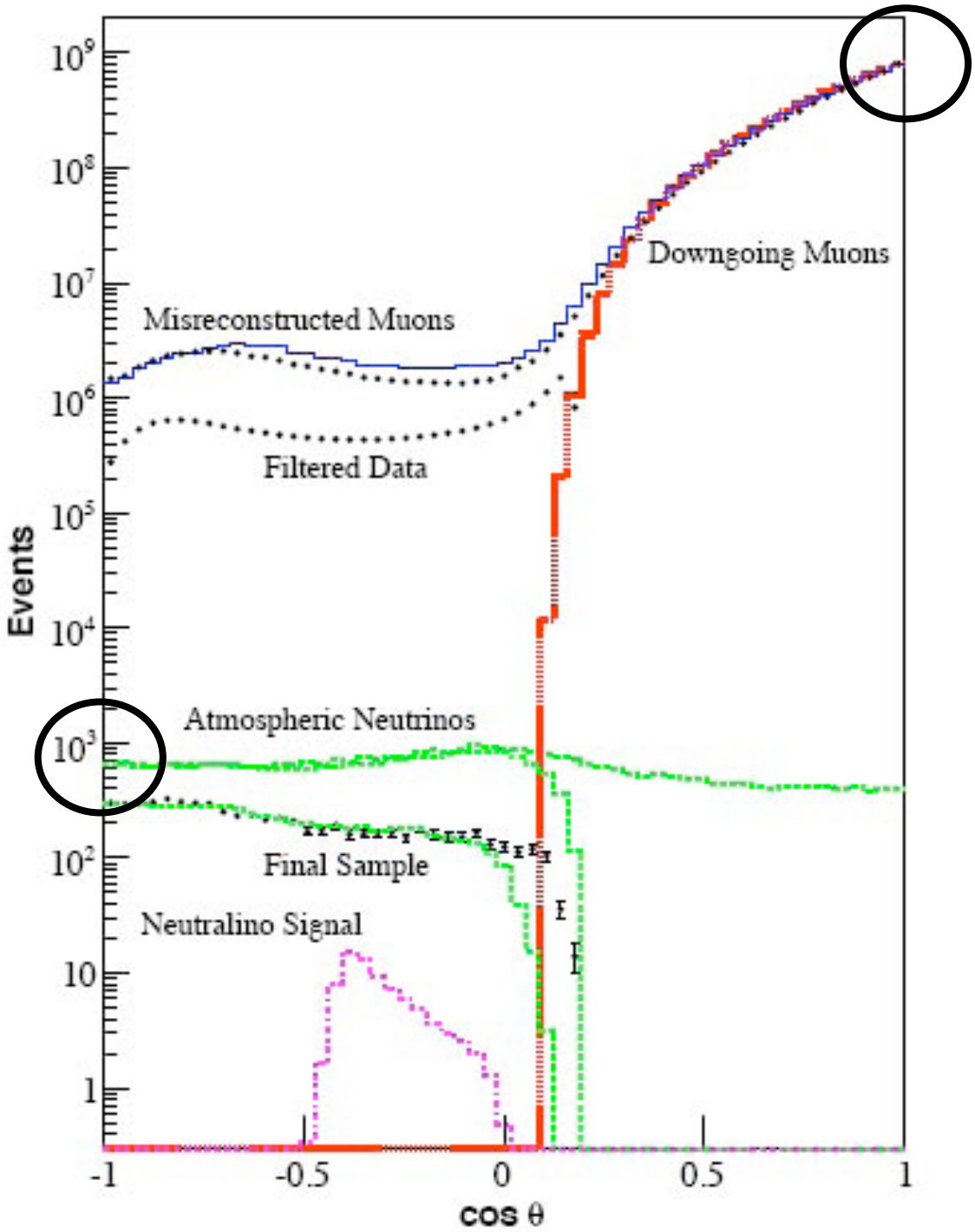
- atmospheric μ 7×10^{10}
- atmospheric $\nu \rightarrow \mu$ $> 4 \times 10^{4}$
- cosmic $\nu \rightarrow \mu$ ~ 10

muon passing DeepCore


Run 116511 Event 25597 [4000ns, 7544ns]


within trigger time window
down
up


Sep 7 03:19:17 2010
5 muons in 40 μs
116511 Event 424890 [8000ns, 9047ns]

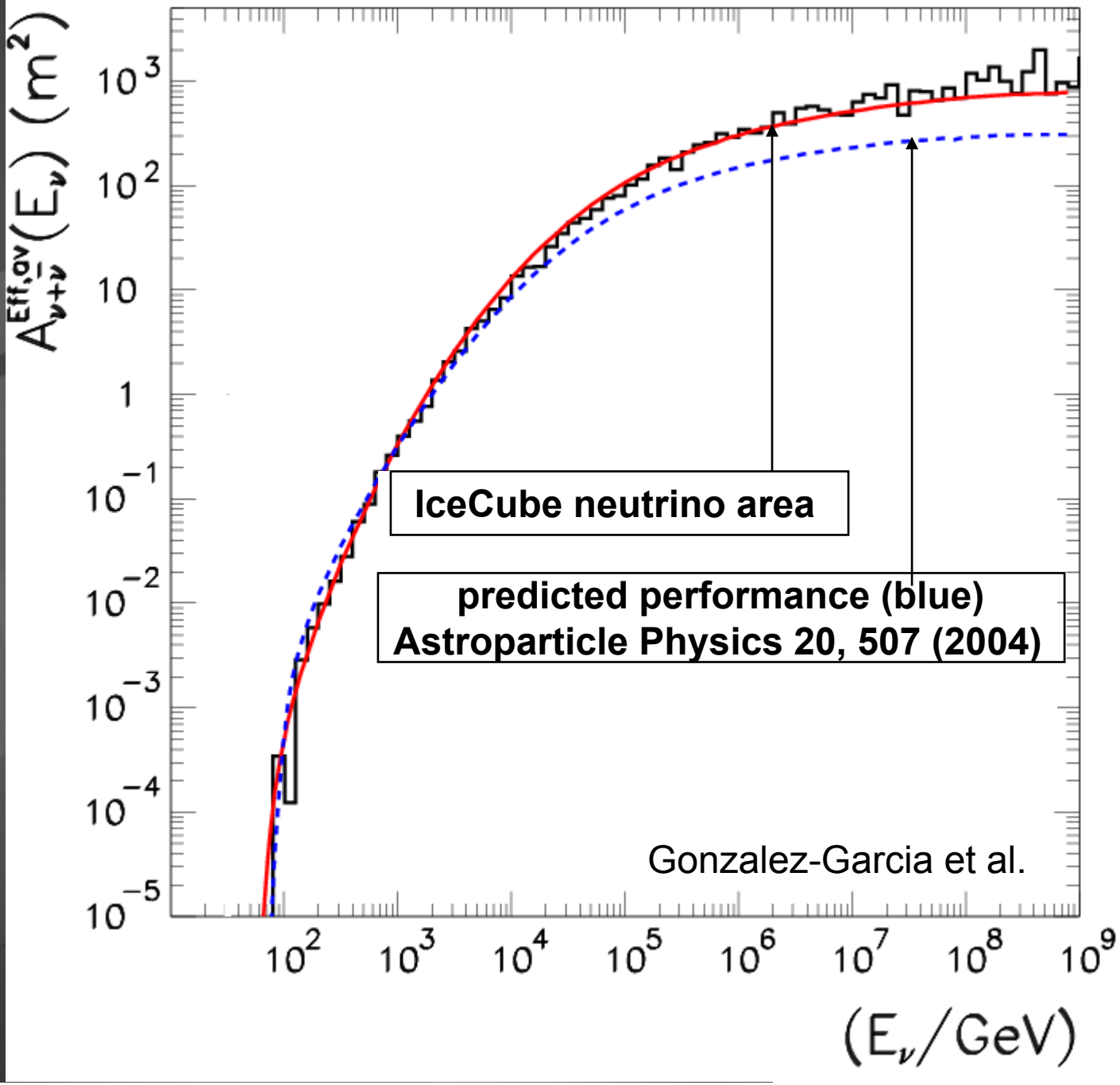

Events
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Misreconstructed Muons
Downgoing Muons
Filtered Data
Atmospheric Neutrinos
Final Sample
Neutralino Signal
-1
-0.5
0
0.5
1
cos θ

IceCube performance

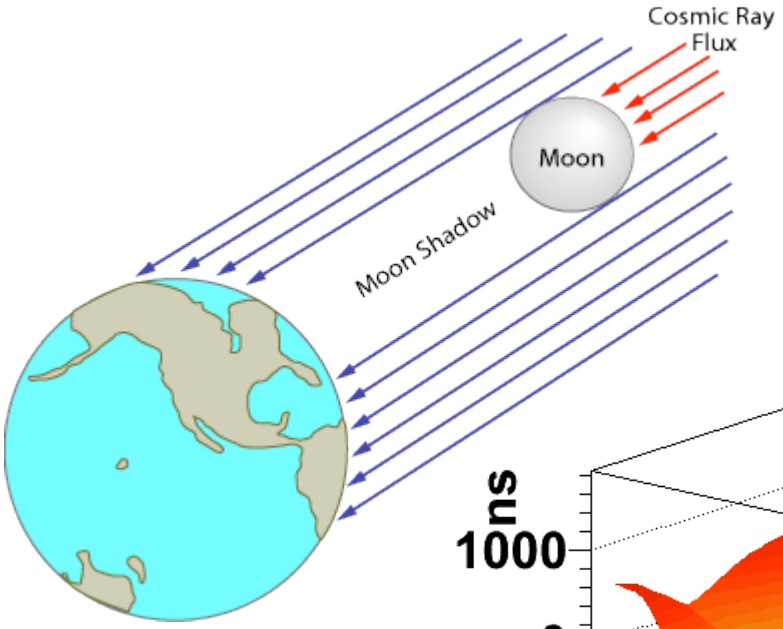
then
and
now

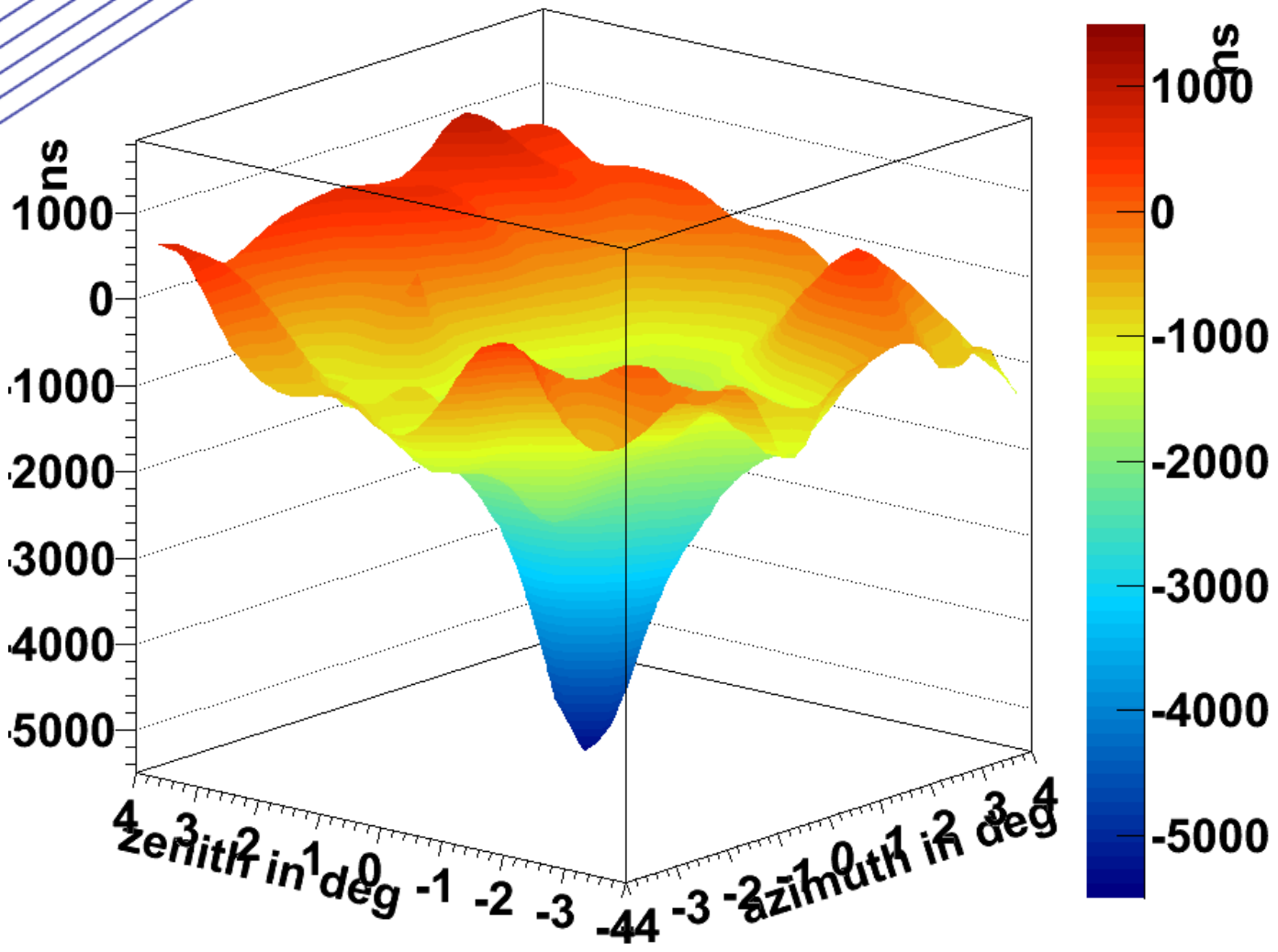
PeV: x2
EeV: x3

neutrino
"mirror"
area



moon shadow

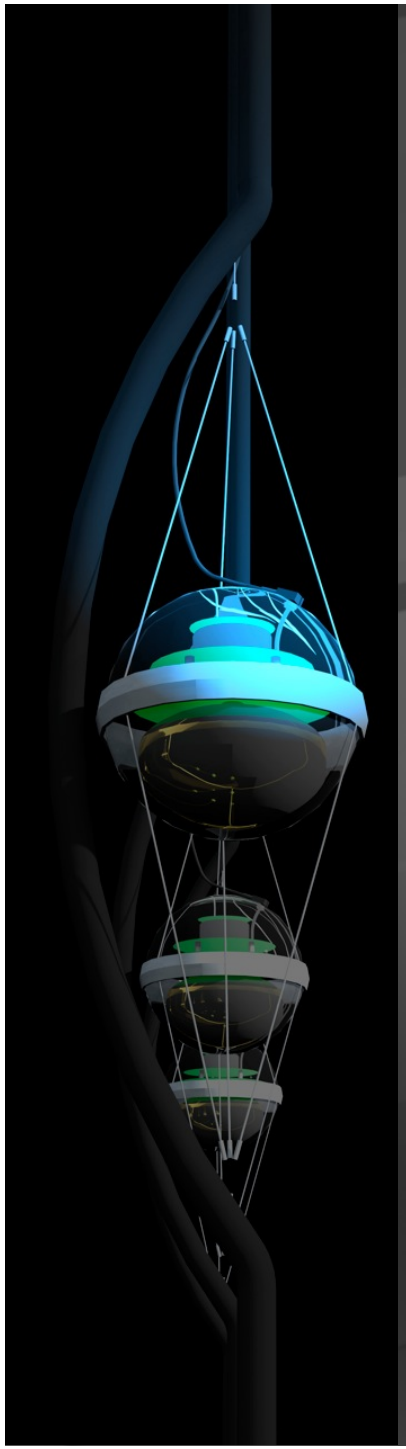




> 10σ
< 1 deg

IceCube science

we measure the flux of atmospheric muons and neutrinos at higher energies and with better statistics than previous experiments. Any deviations from what is expected is new neutrino physics or new astrophysics. We just look for surprises.



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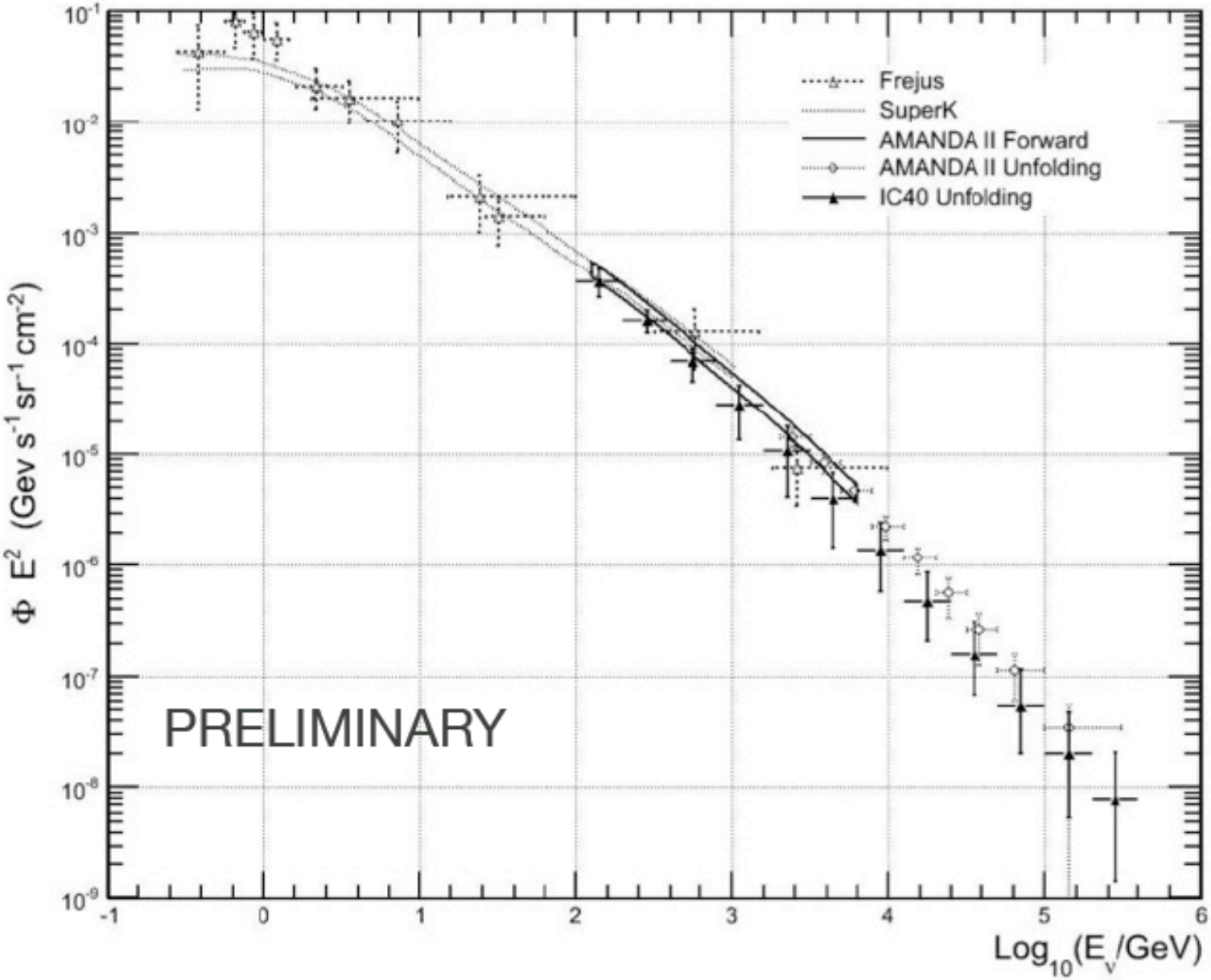
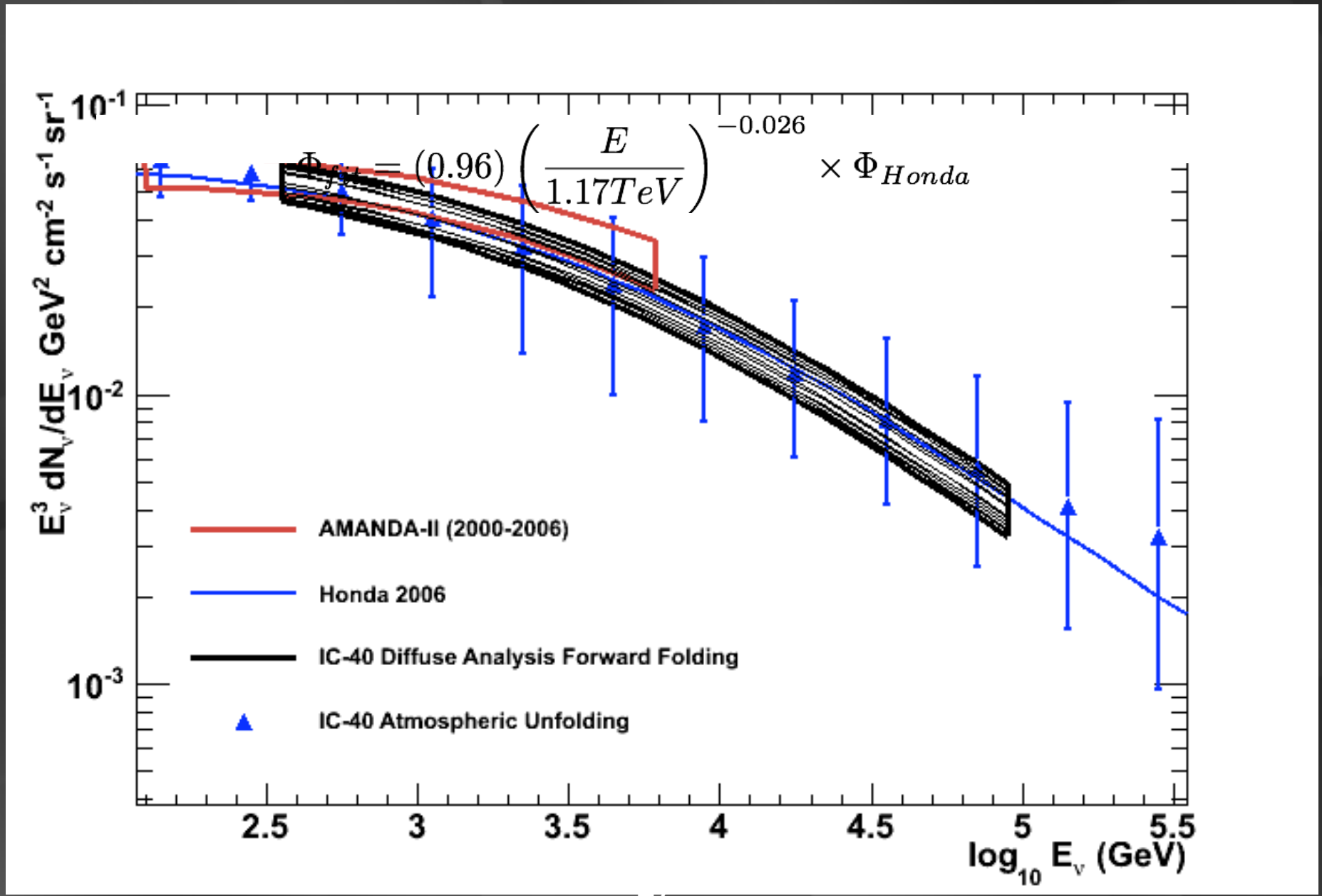
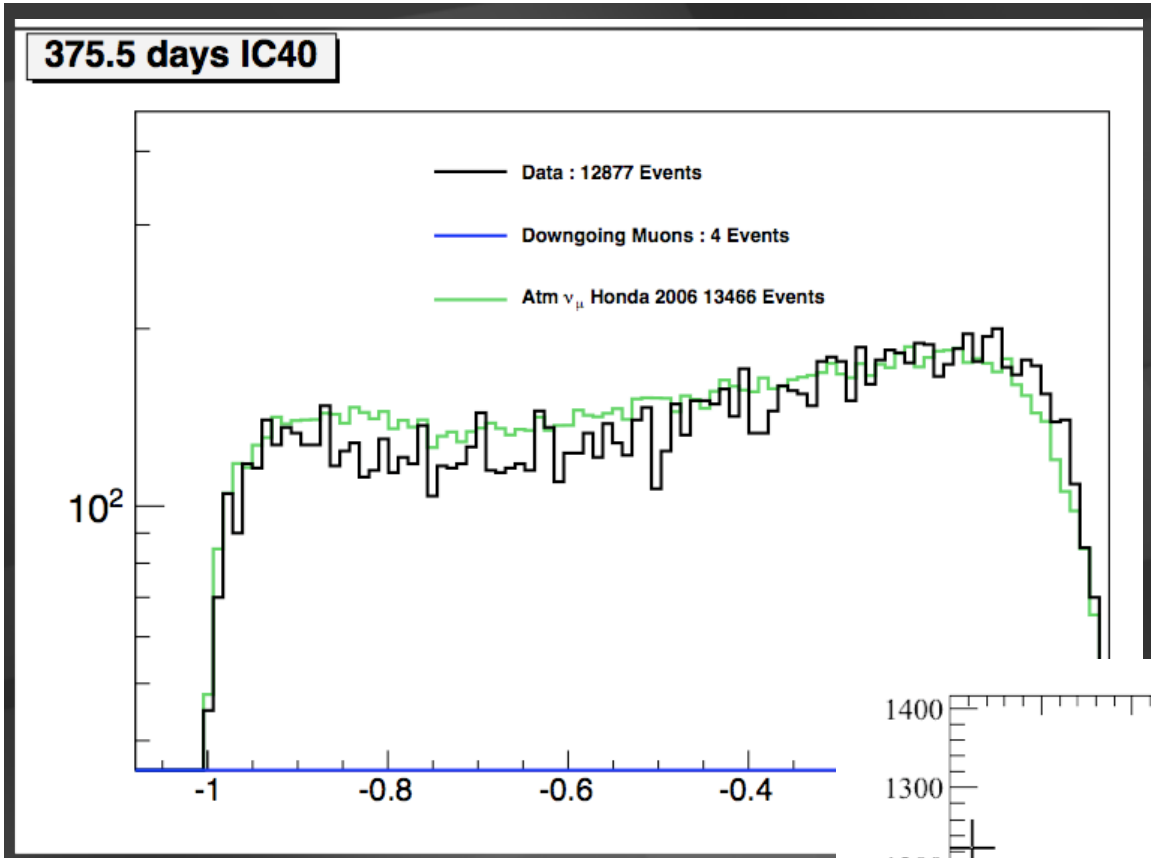
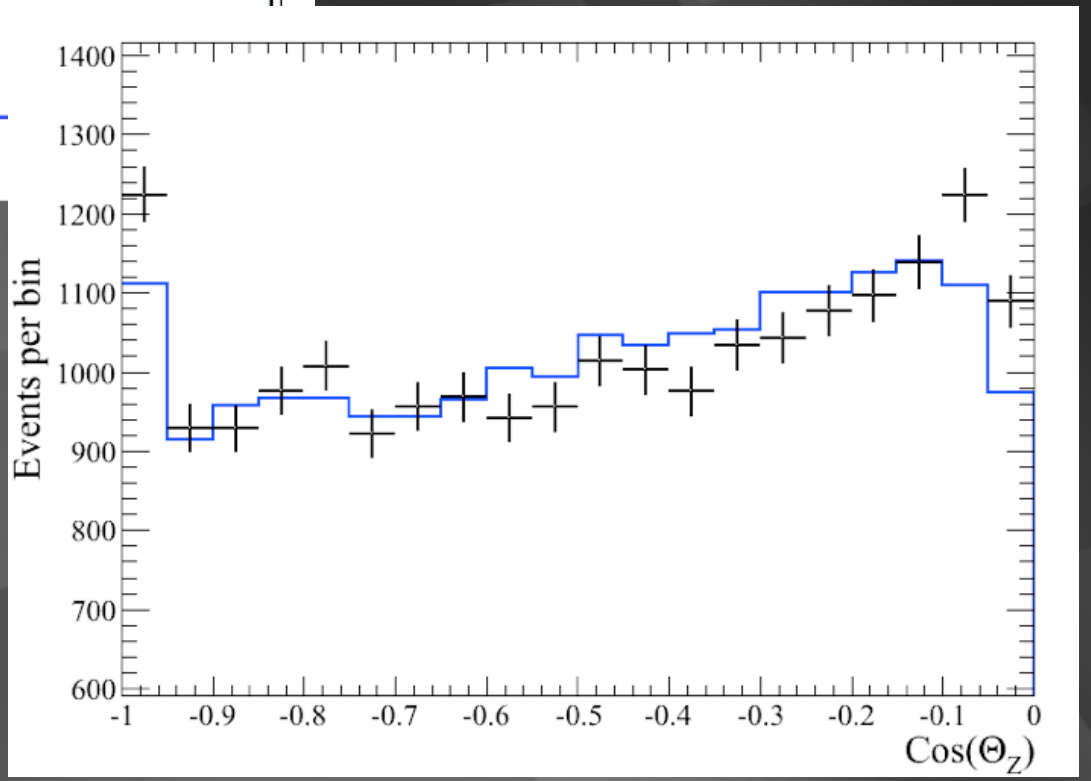

Frejus
SuperK
AMANDA II Forward
AMANDA II Unfolding
IC40 Unfolding
PRELIMINARY
Φ E² (Gev s⁻¹ sr⁻¹ cm⁻²)
Log10(Eν/GeV)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
-1
0
1
2
3
4
5
6

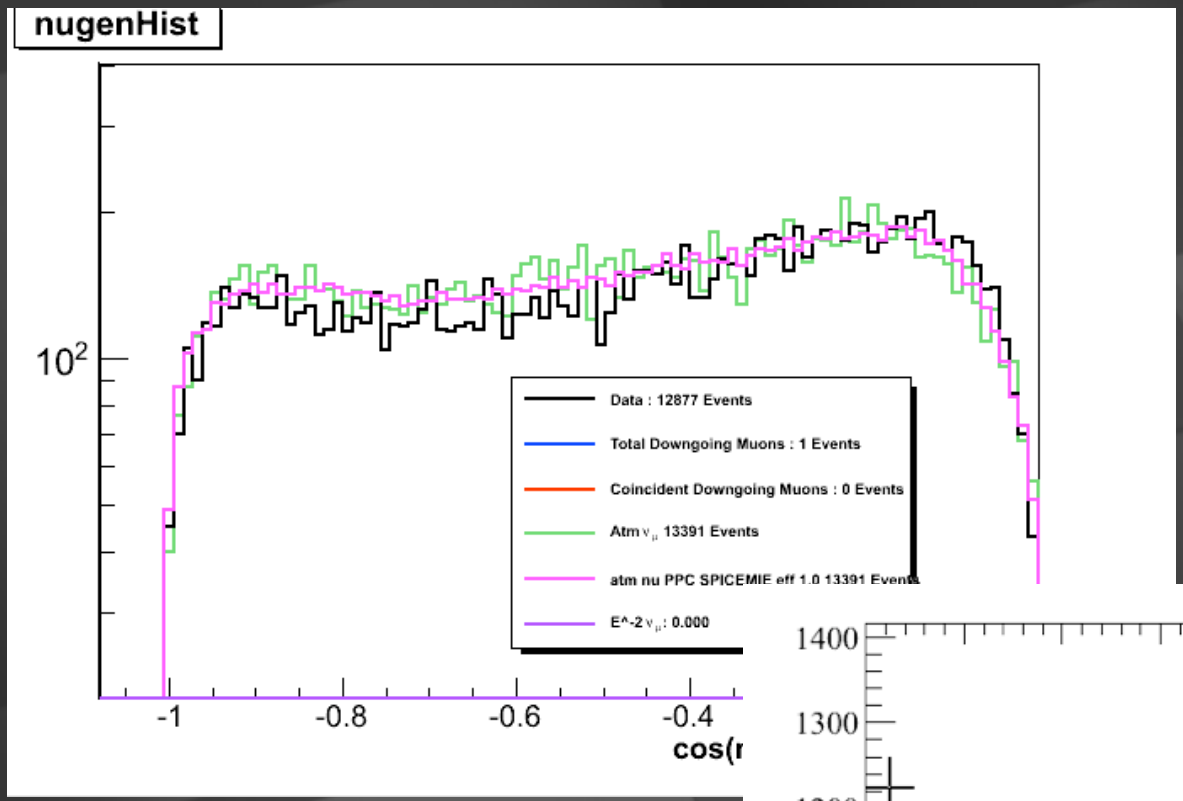
measured atmospheric neutrino spectrum



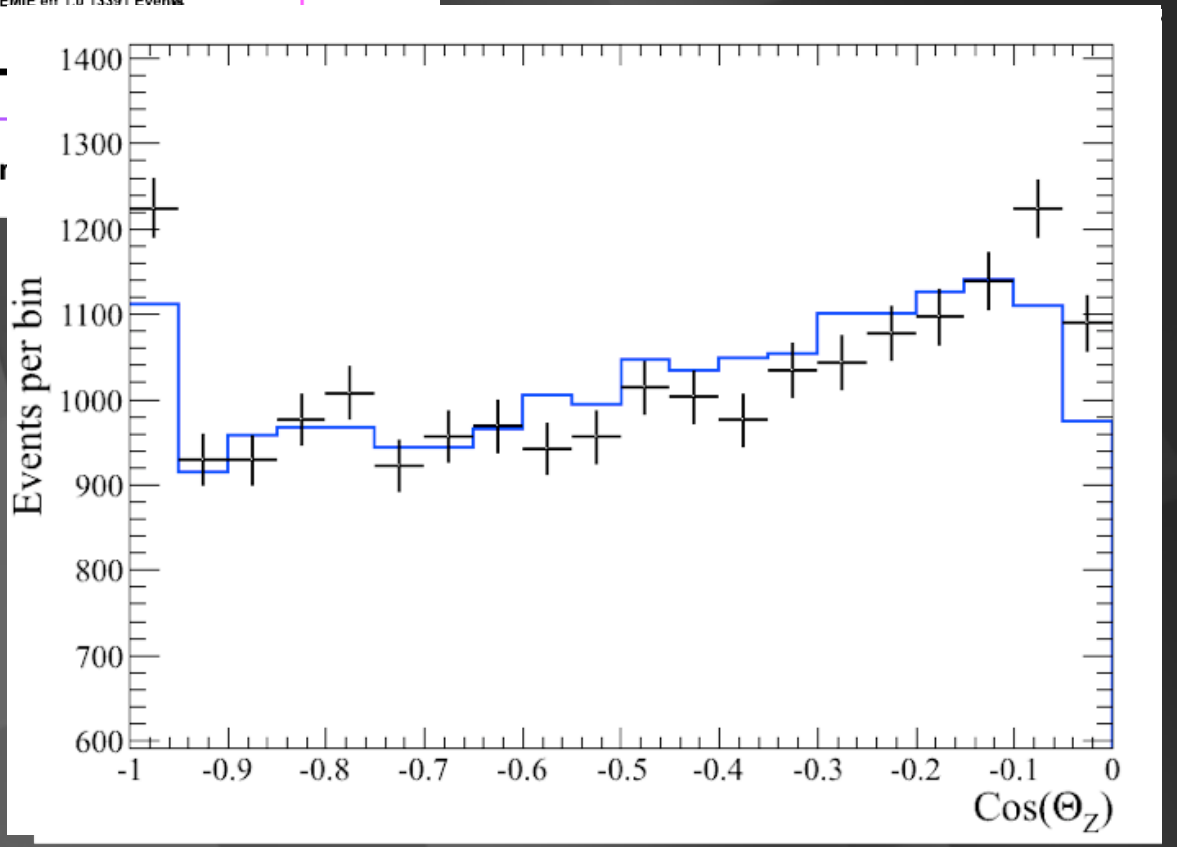


zenith angle
two analyses





zenith angle
two analyses



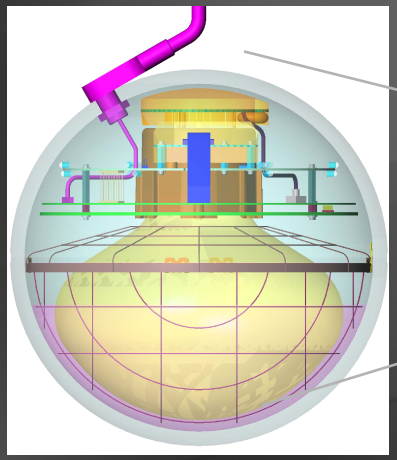
systematics !

- K/π ratio
- zenith acceptance of modules
- ice

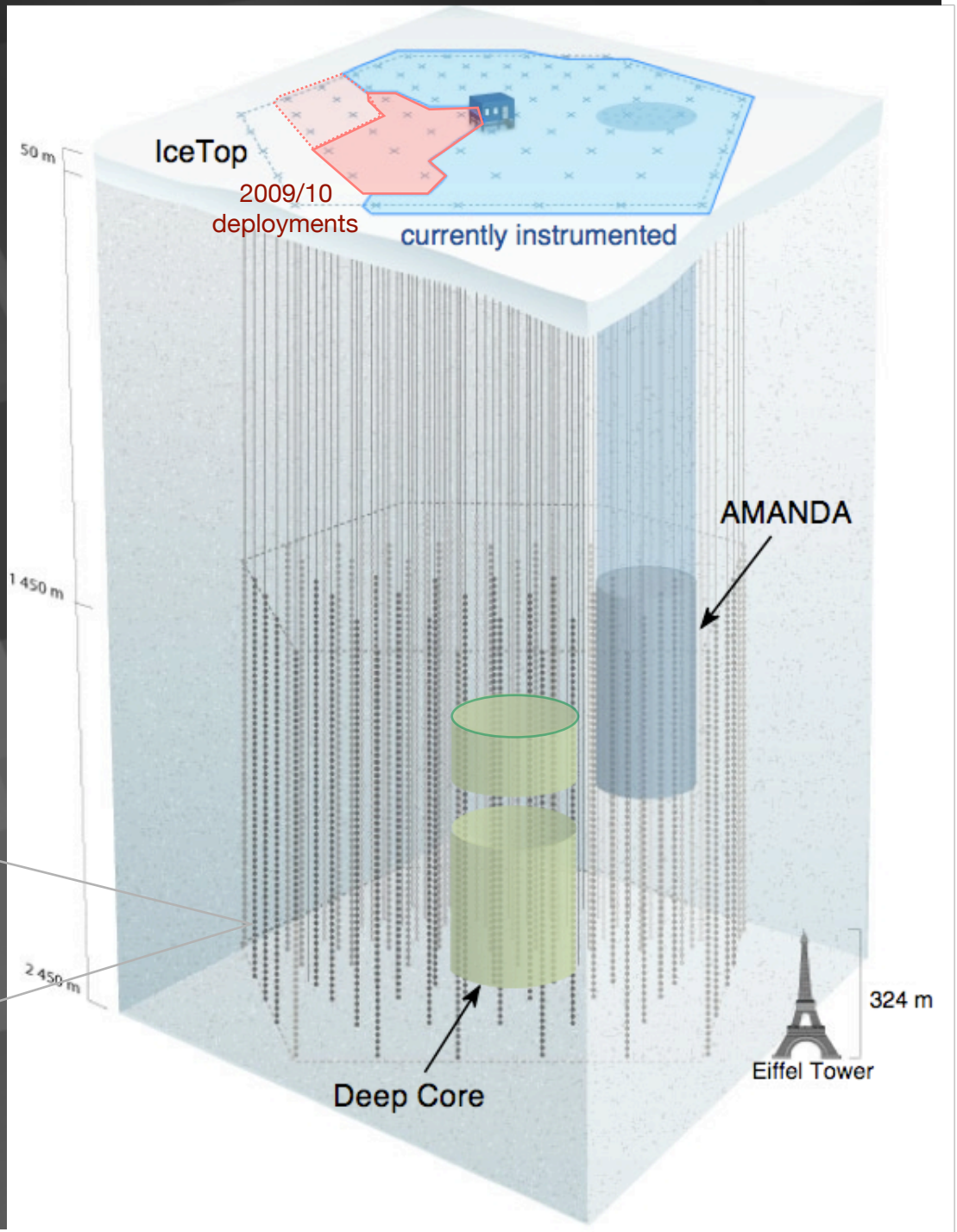
IceCube Deep Core

- extends capabilities of IceCube into the ~10 GeV to ~300 GeV (ν_μ) energy range

- several ten thousand atmospheric neutrinos per year

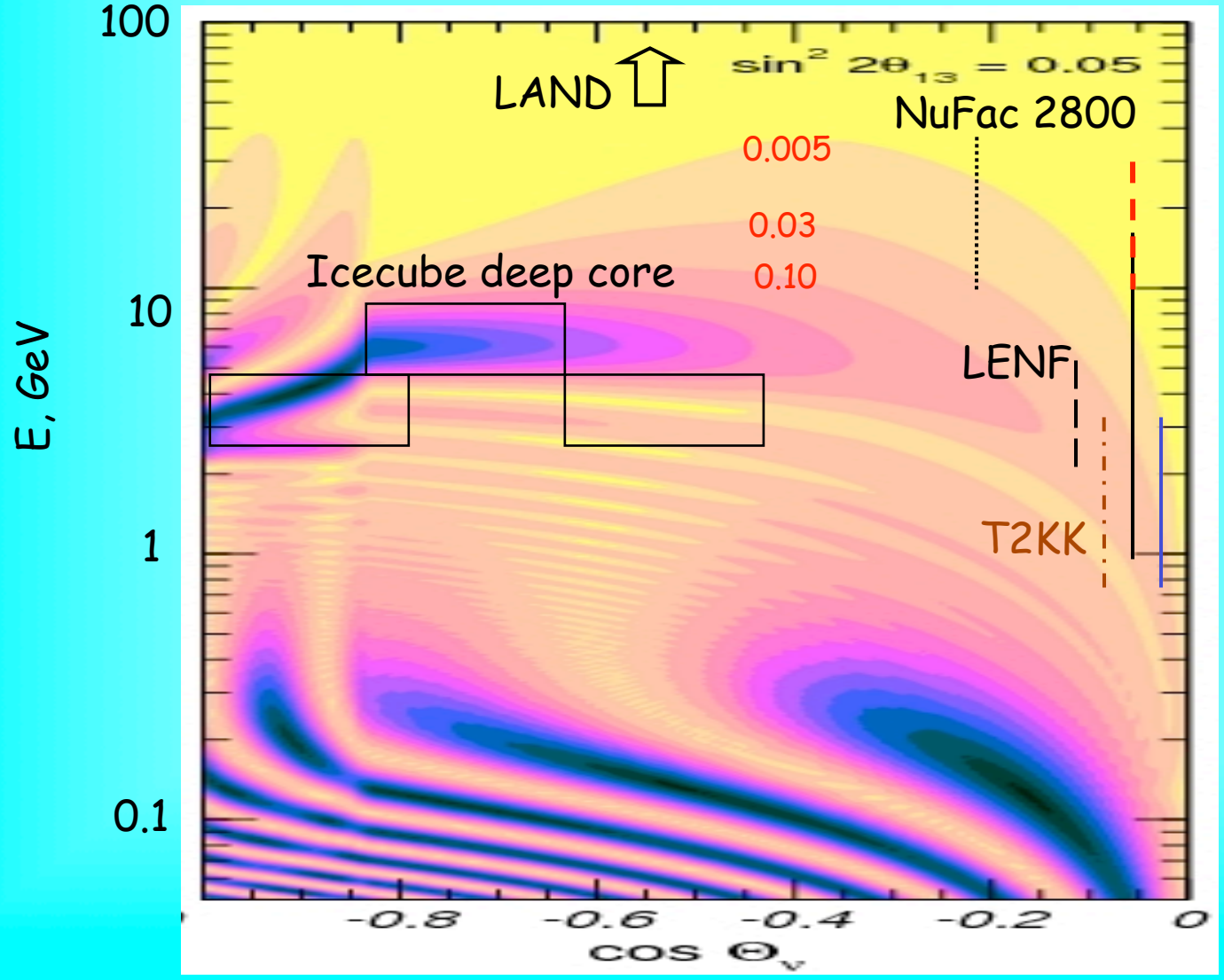


Digital Optical Module (DOM)



Smirnov, Erice 2010

Large atmospheric neutrino detectors

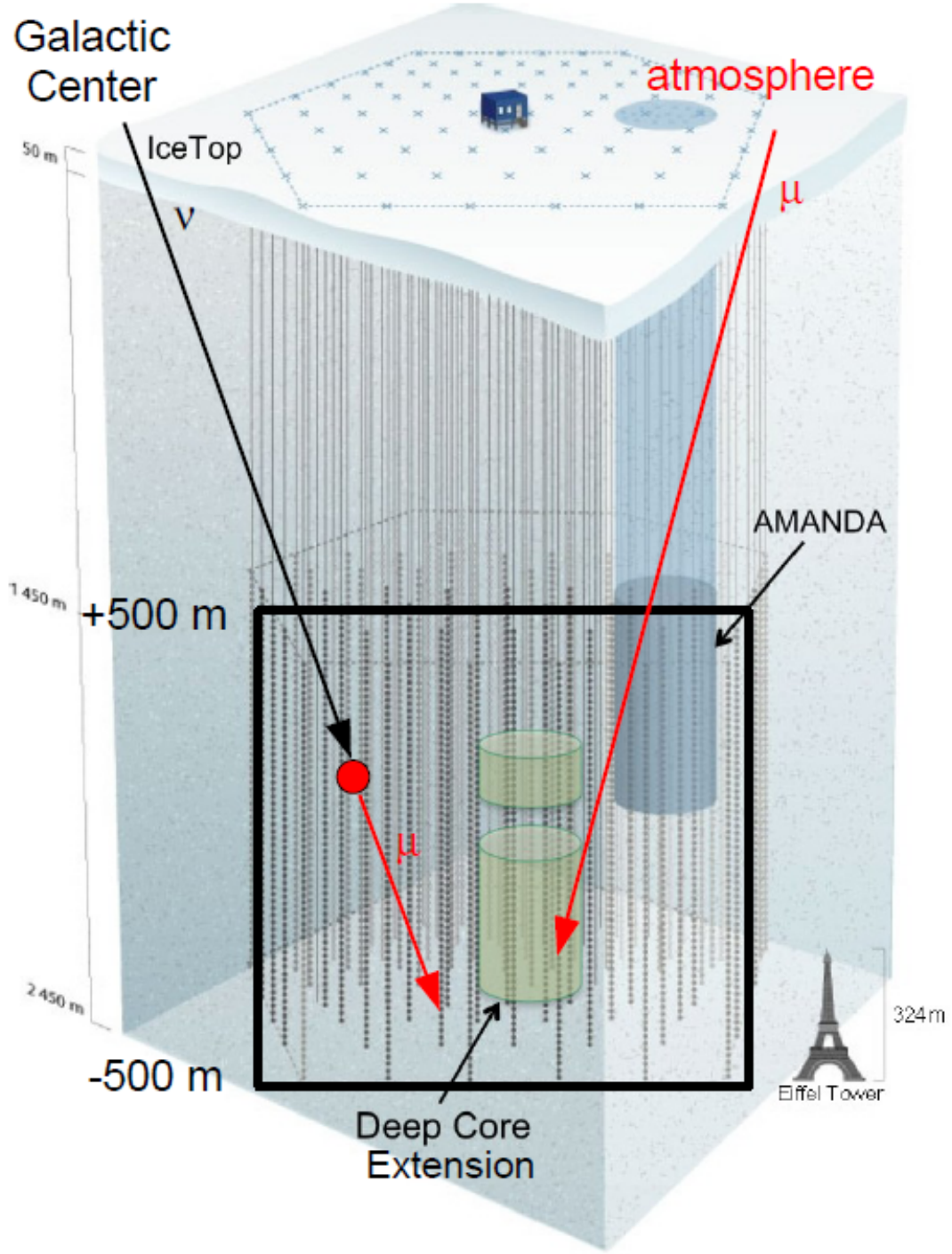


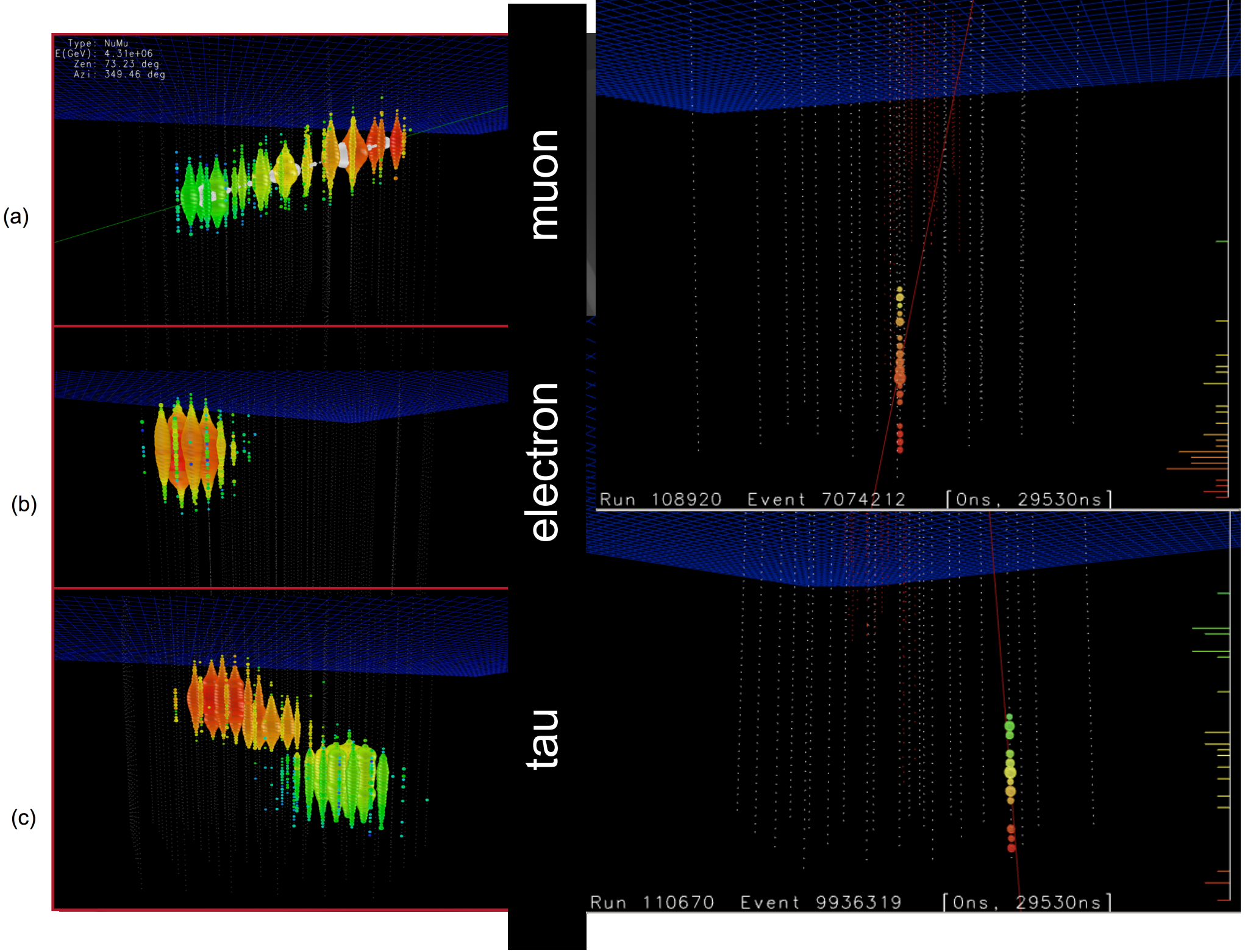
CNGS

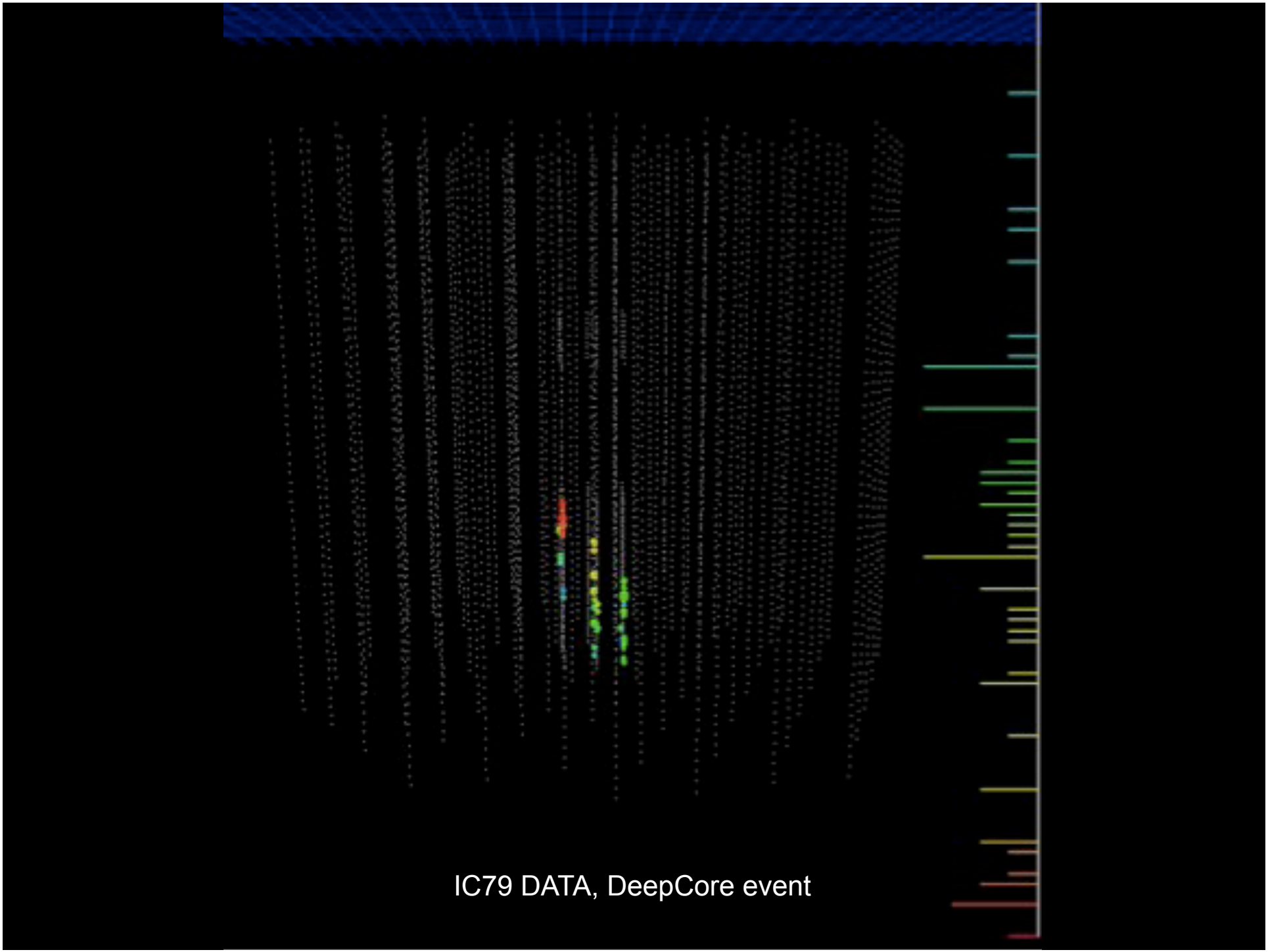
MINOS

T2K

Degeneracy of parameters

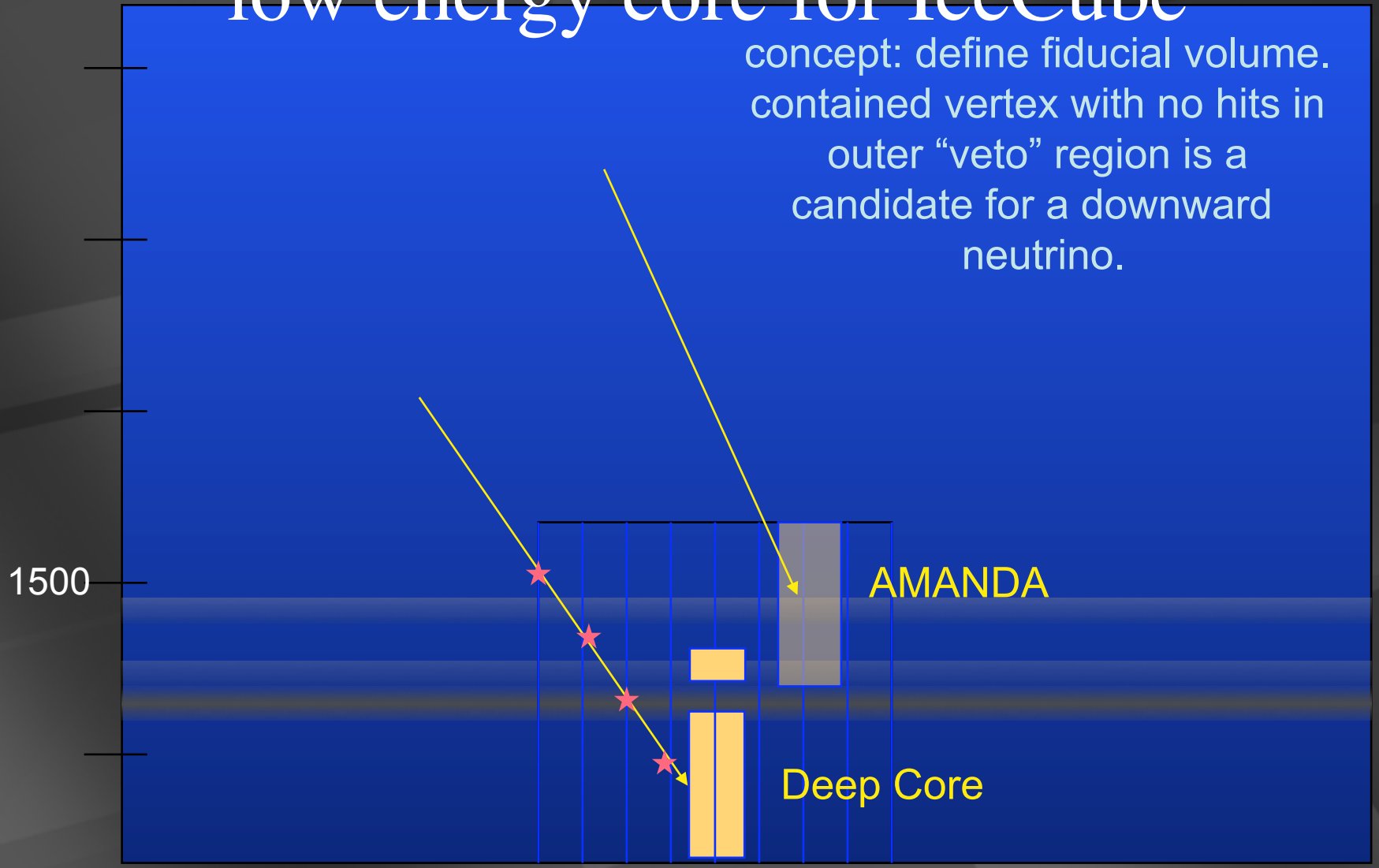

Galactic
Center
IceTop
atmosphere
ν
μ
50 m
1 450 m
2 450 m
+500 m
-500 m
AMANDA
μ
Deep Core
Extension
324 m
Eiffel Tower


Type: NuMu
E(GeV): 4.31e+06
Zen: 73.23 deg
Azi: 349.46 deg
(a)
(b)
(c)
muon
electron
tau
Run 108920 Event 7074212 [0ns, 29530ns]
Run 110670 Event 9936319 [0ns, 29530ns]


IC79 DATA, DeepCore event

low energy core for IceCube

concept: define fiducial volume. contained vertex with no hits in outer "veto" region is a candidate for a downward neutrino.



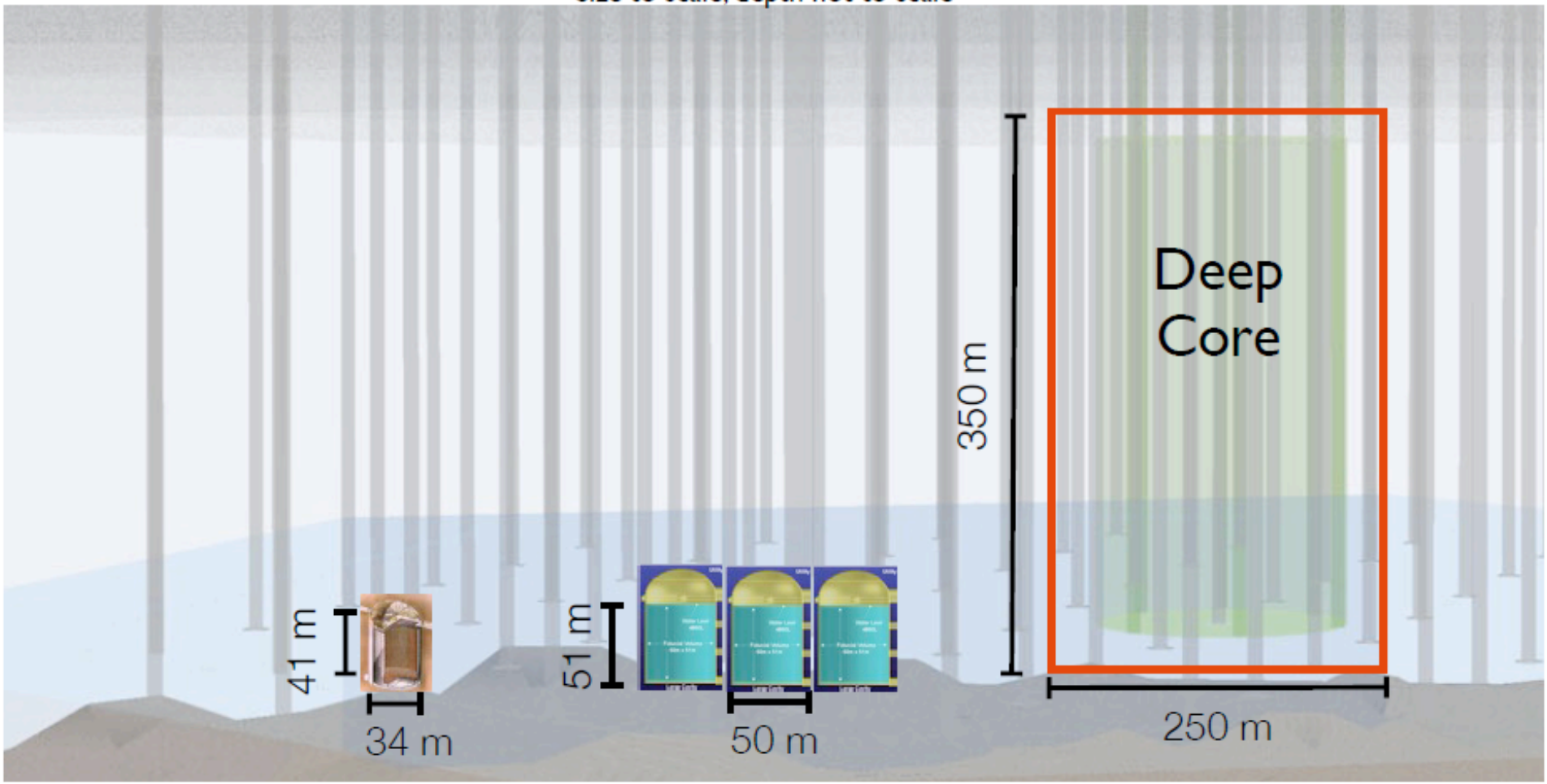
$$n_{strings} \times height \times \left(\pi\ \lambda^2_{scatt}\right) \approx ten\ Mton$$

DeepCore: 15,000 kton

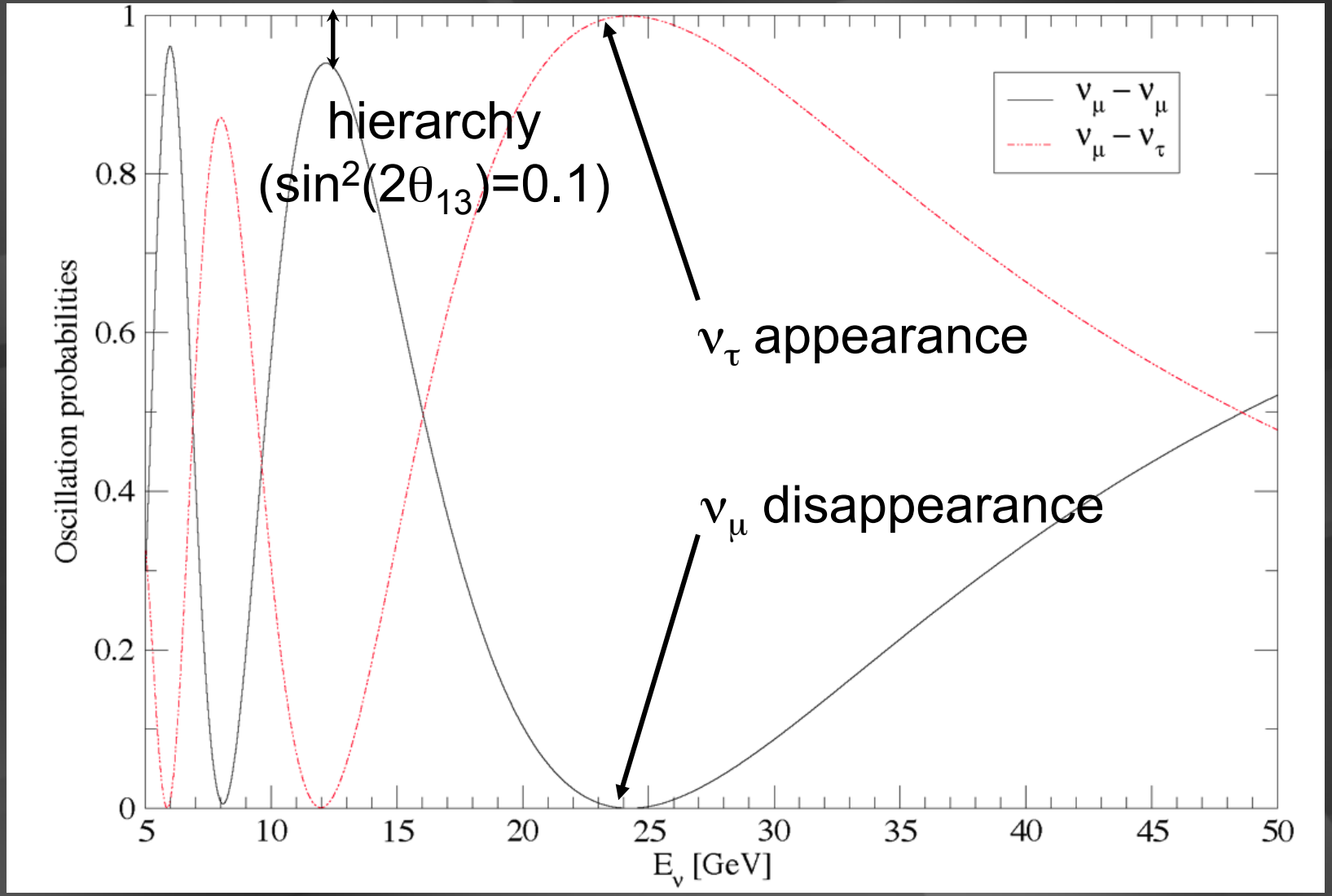
LBNE (DUSEL Water Cherenkov) 3 x100 kton

Super K 50 kton

Size to scale, depth not to scale



neutrino oscillations in Deep Core



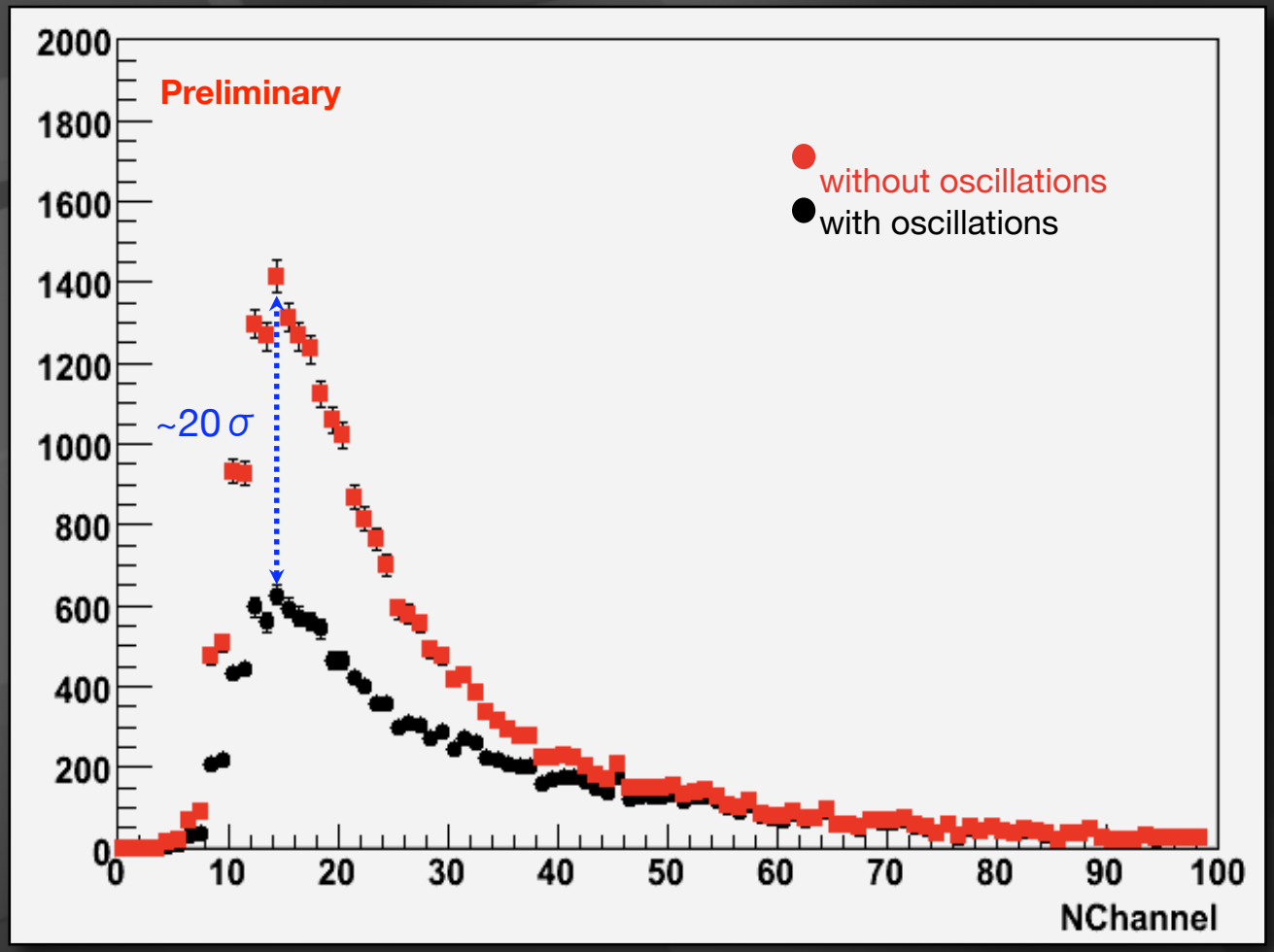
resonance in effective θ_{13} angle traversing the Earth diameter at 10 GeV

muon neutrino disappearance

full detector simulation of 3-flavor oscillations

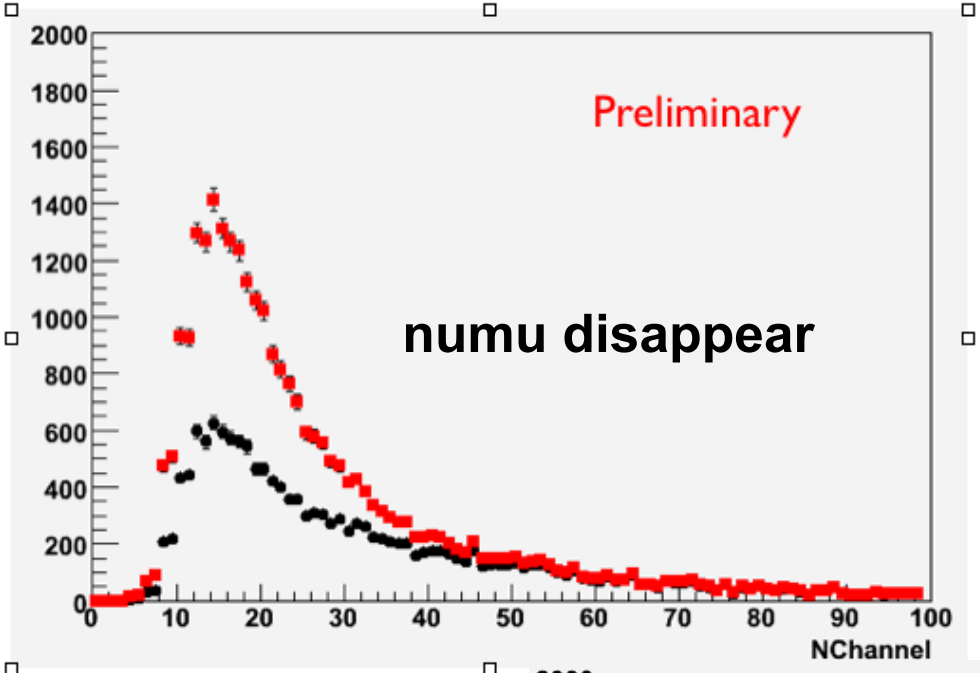
- 1 year DC
  - noo bg assumed
  - cos(θ) < -0.6

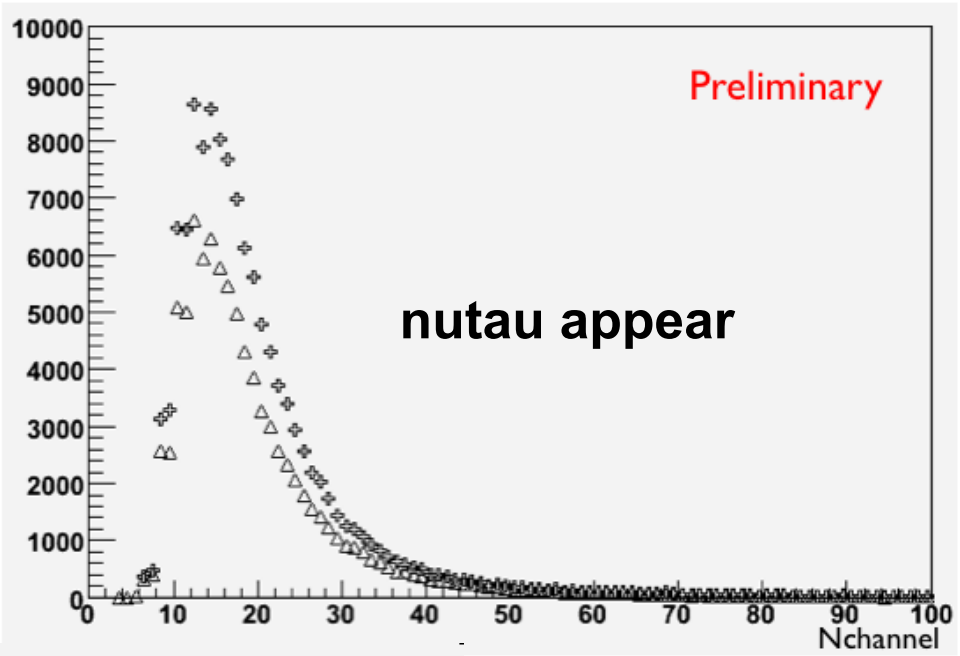
number of hit DOM used as simple energy estimator

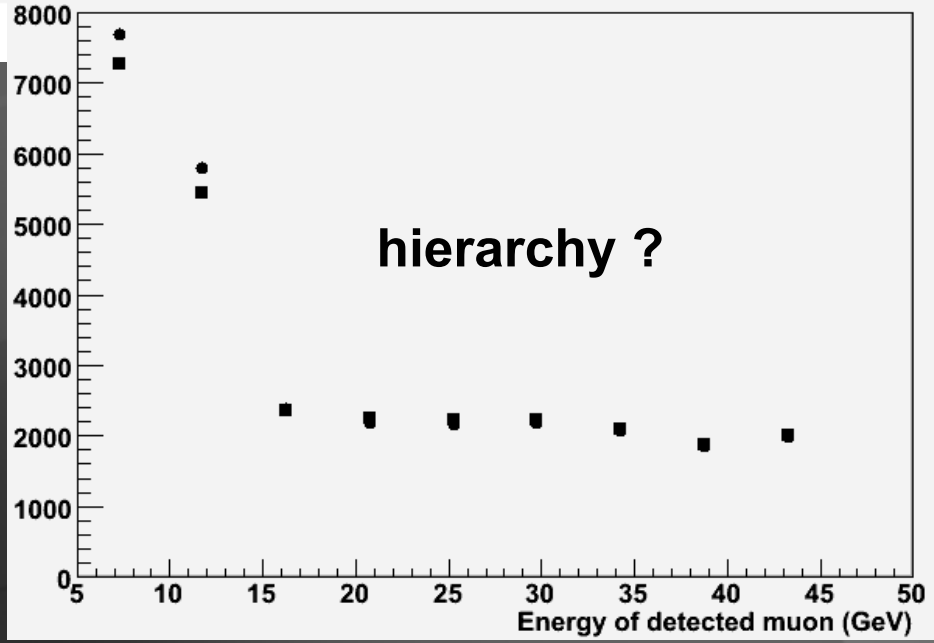


r of

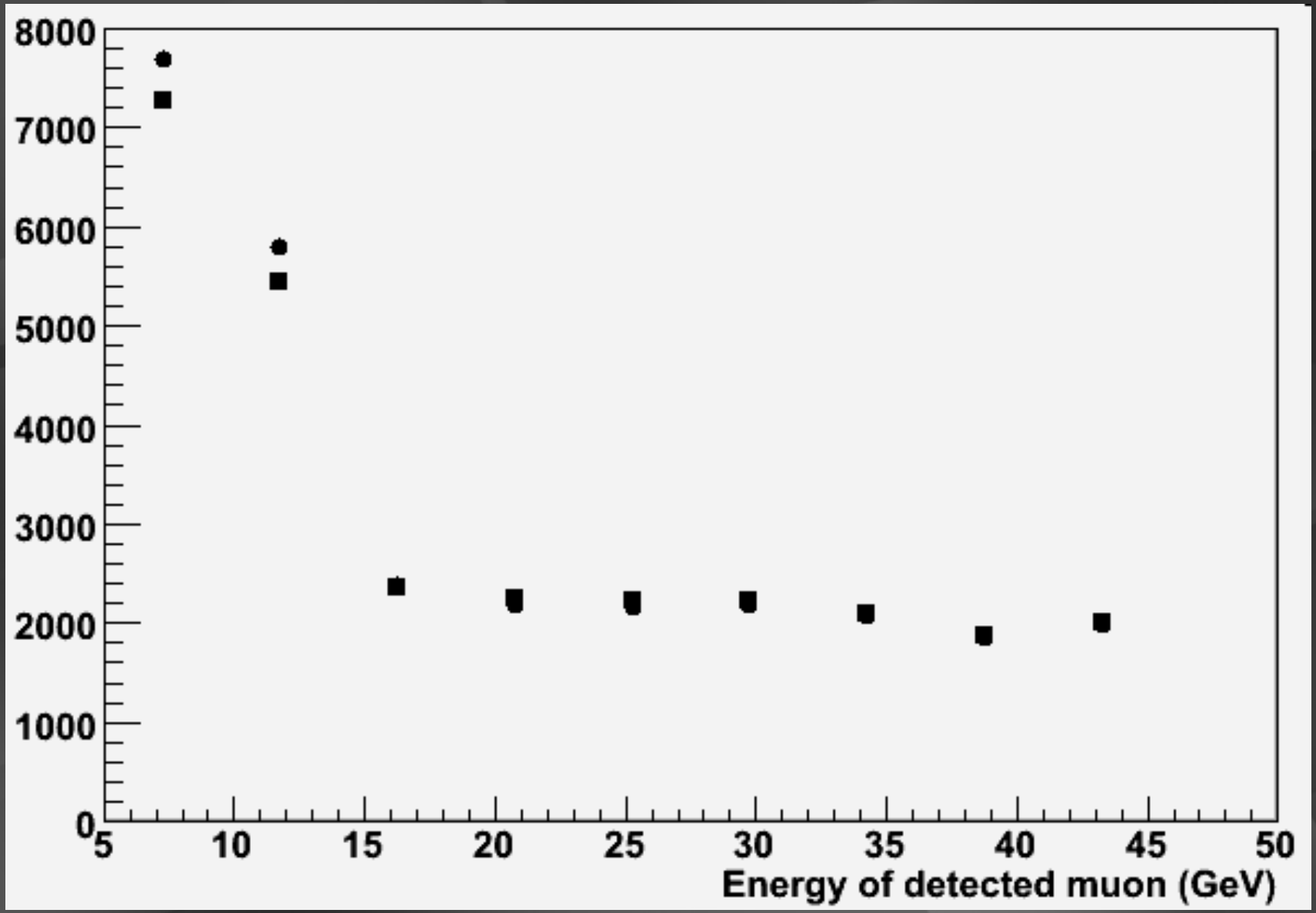
< -0.6
rrors
σ







hierarchy by statistics?



~ 10 GeV : hierarchy from matter effects in the Earth near first absorption dip

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(\cos 2\theta_{13} \pm \frac{\sqrt{2G_F}N_e}{\Delta_{13}} \right)^2}$$

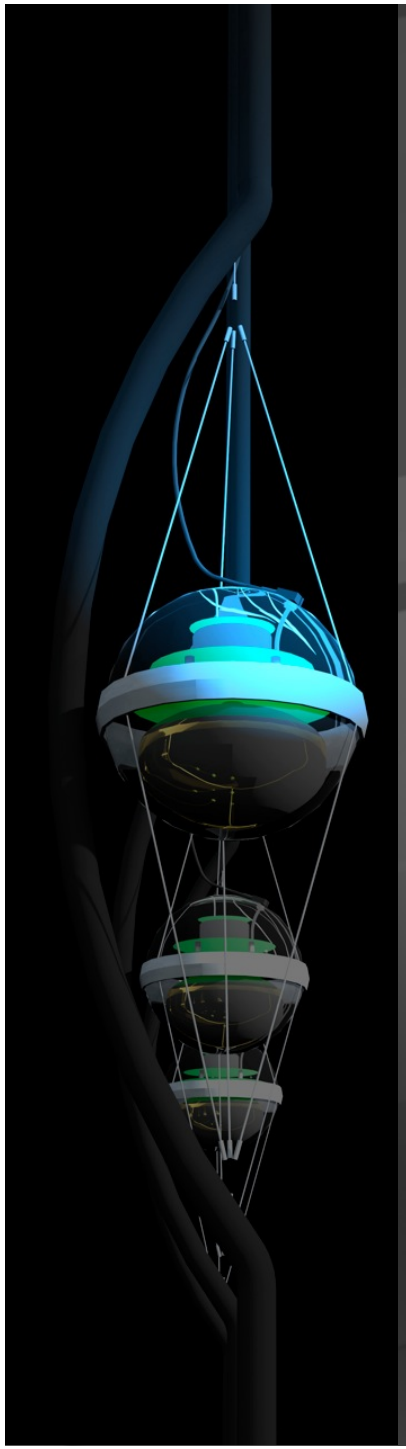
(mostly) neutrino + antineutrino -

sign Δ_{13} : hierarchy !

neutrinos with 40 strings

We have measured the atmospheric neutrino spectrum to an energy of 400 TeV. The data is consistent with the predicted energy dependence. IceCube can therefore search for cosmic neutrinos by (high) energy (and not just clustering), i.e. by looking for neutrinos with an energy that is not compatible with atmospheric origin.

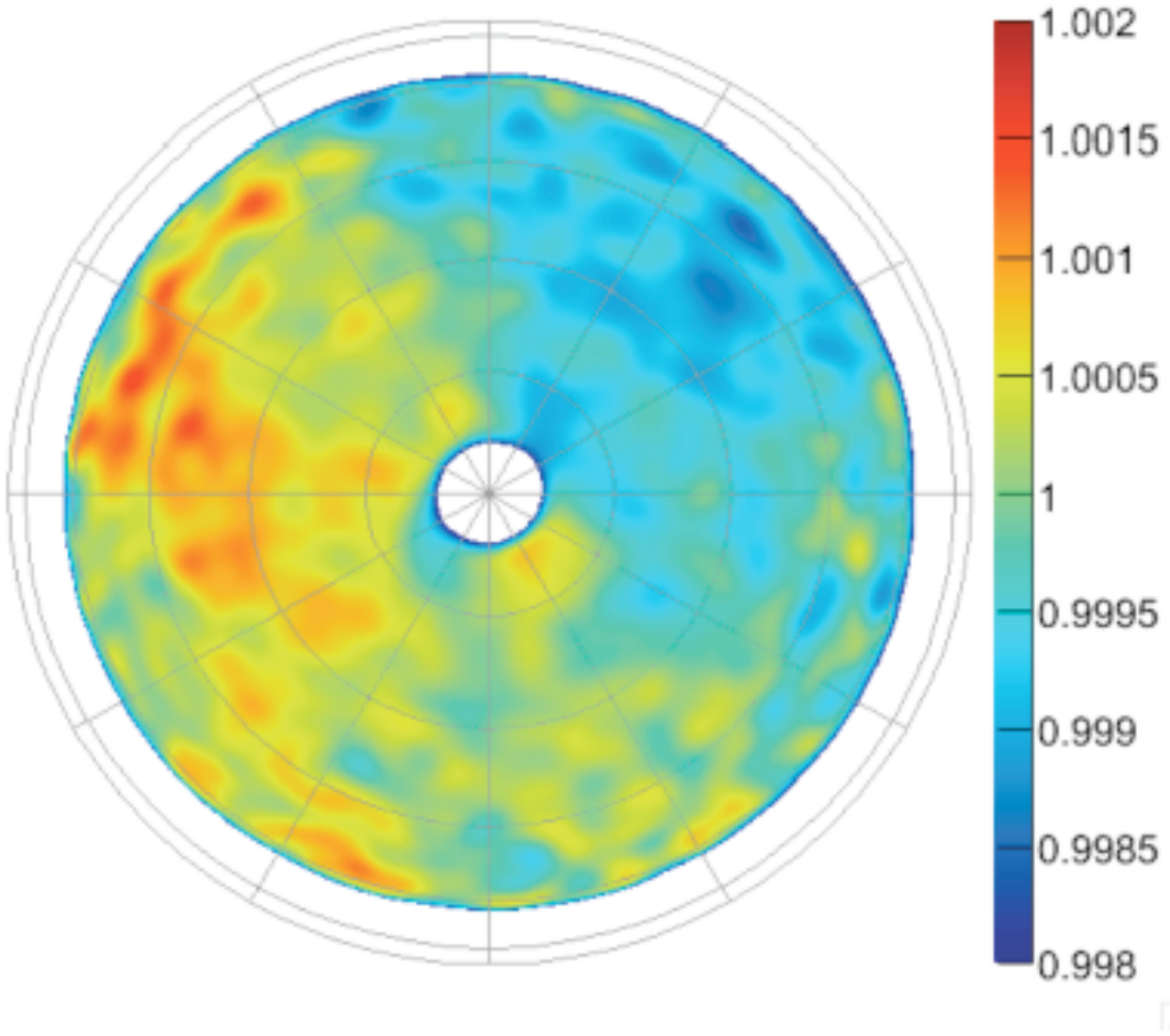
No evidence for a significant charm component.

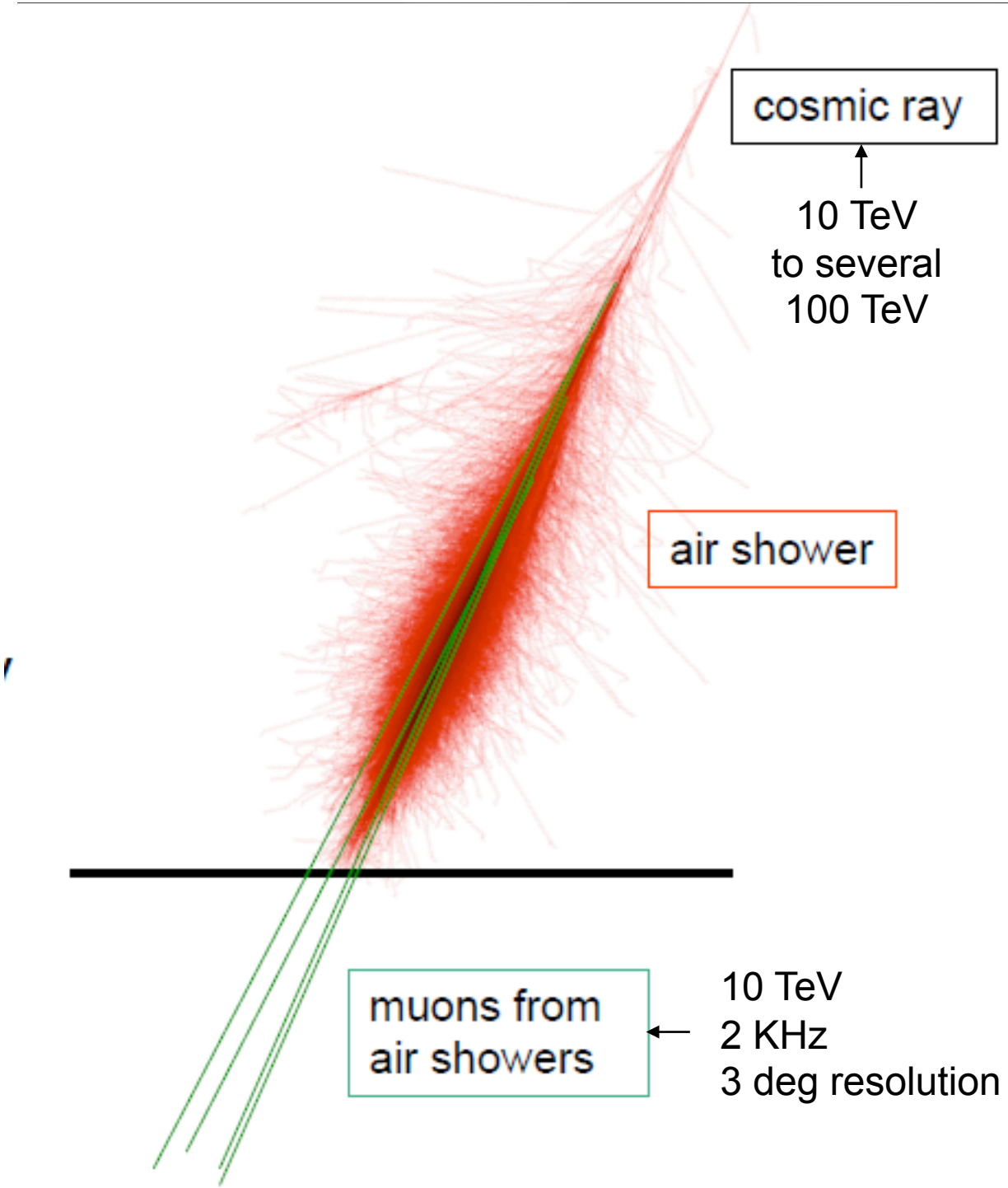


- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- atmospheric neutrino spectrum
- atmospheric muon spectrum: first surprise
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - GZK neutrinos
  - a multi-wavelength story
- search for dark matter

IceCube.wisc.edu

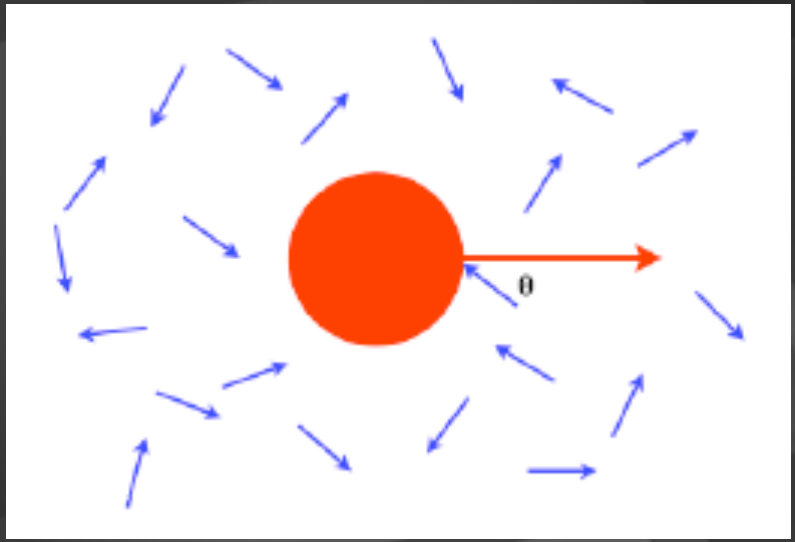
Orthonormal Projection





cosmic rays in IceCube

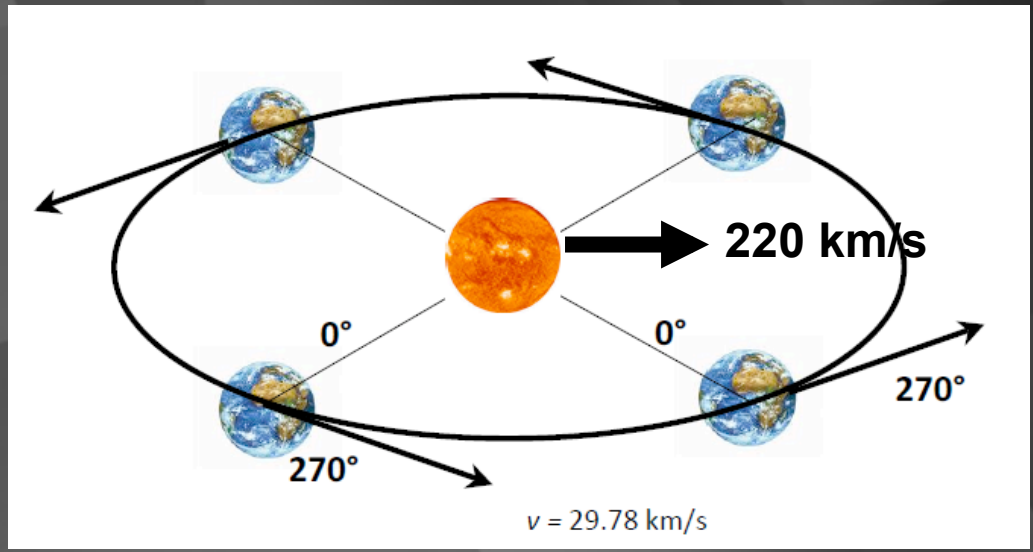
- galactic
- not solar
- highest energies approach the “knee”
- gyroradius < 1 pc in microgauss field
- closest sources > 100 pc



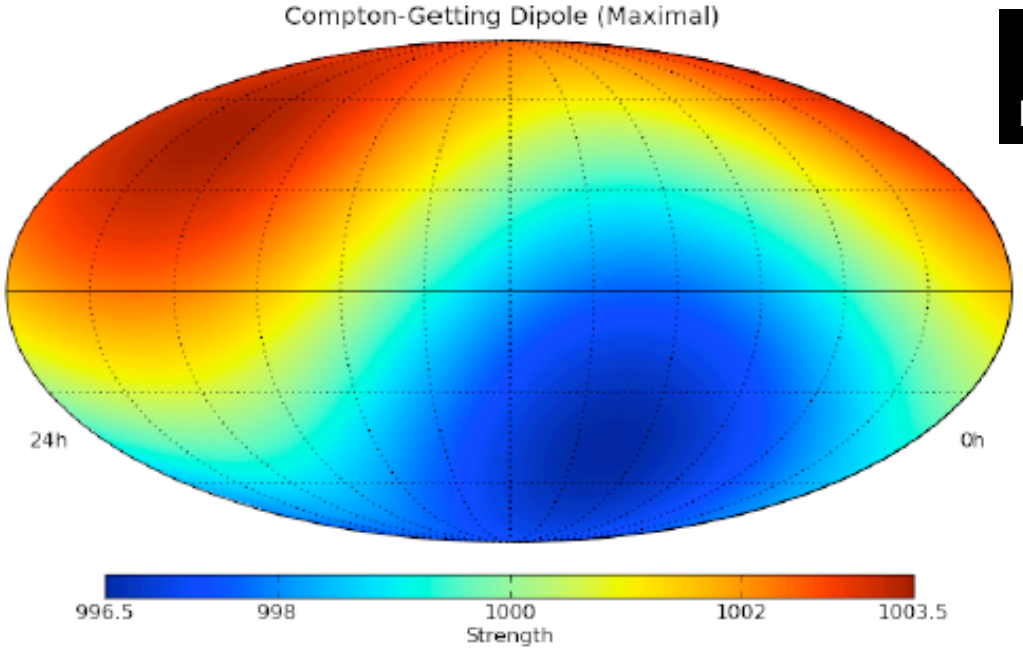
dipole anisotropies

motion of the Earth in the frame of the cosmic rays

- solar dipole: motion of the Earth around the sun
- motion of the Sun relative to the Galaxy (Compton-Getting)



Compton-Getting effect



equatorial coordinates:
right ascention and declination

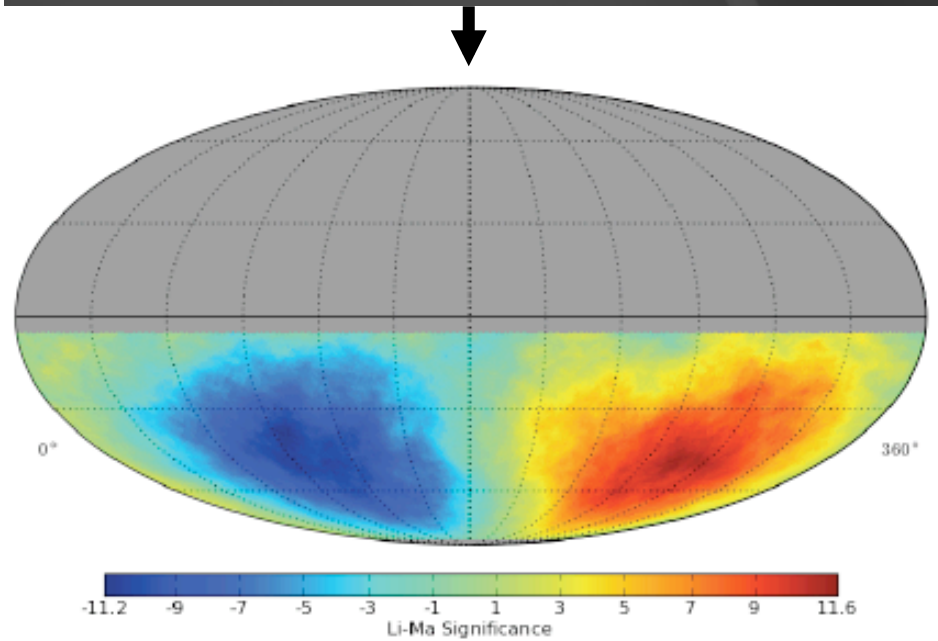
$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\,\frac{v}{c}\,\cos\vartheta$$

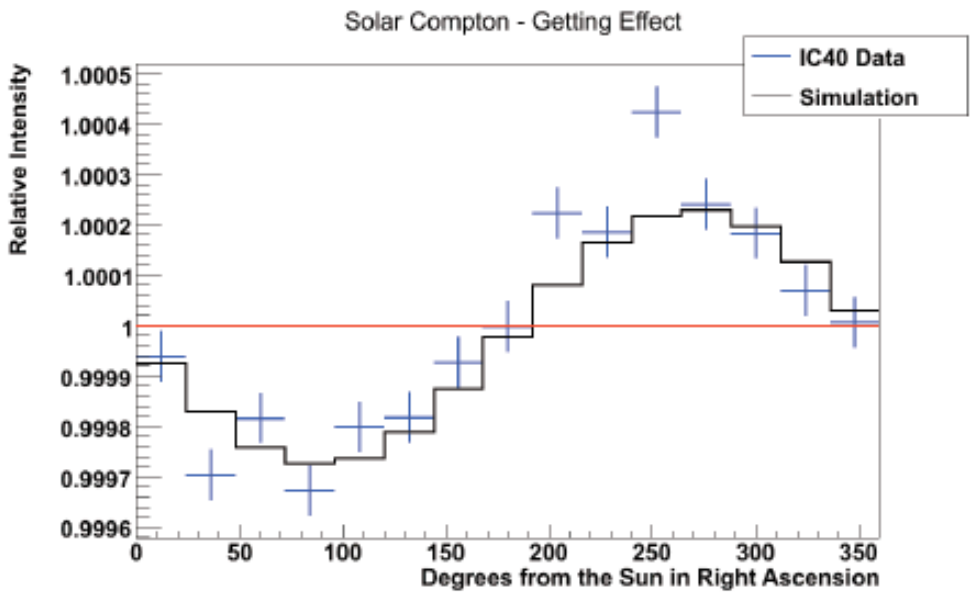
$\gamma = 2.7$ cosmic ray spectral index

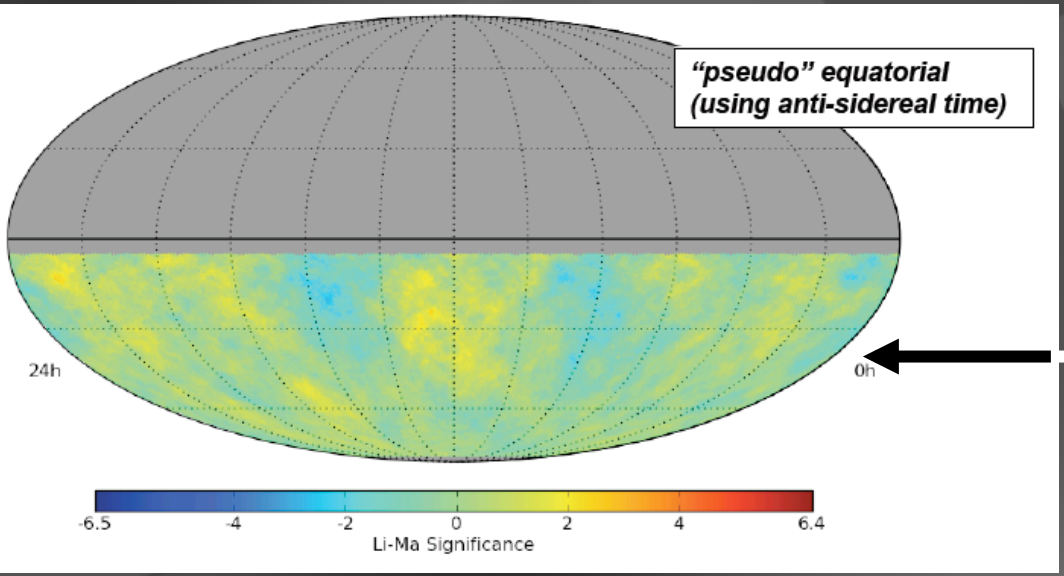
$v = 220$ km/s speed

- 0.35% effect (if frame of the CR is the Galaxy)
- inclined relative to the equatorial plane
- easy !
- not seen

universal (solar) time

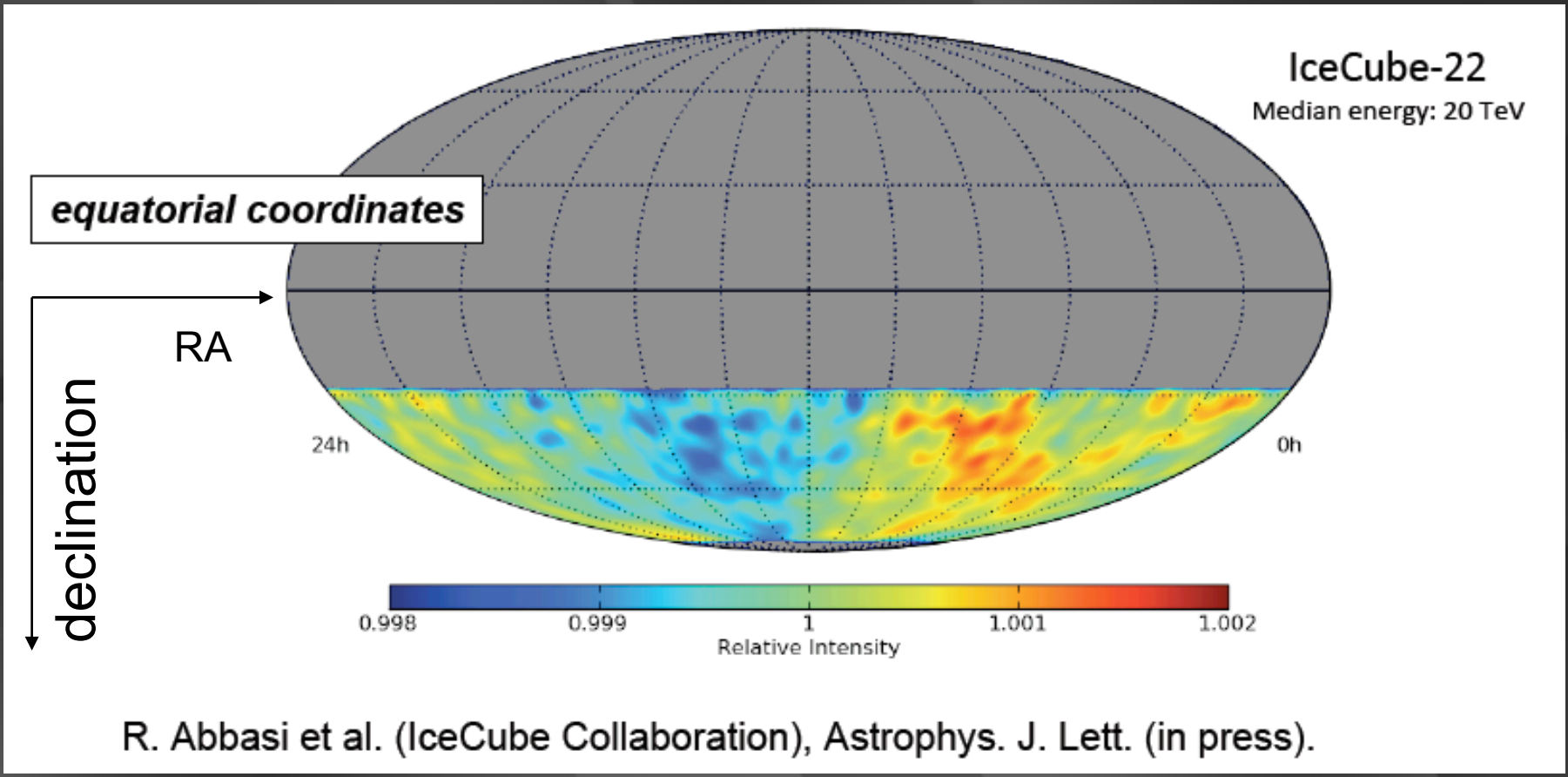






- will not affect maps in siderial time (RA-dec)
- systematics test → map in anti-siderial time (unphysical)

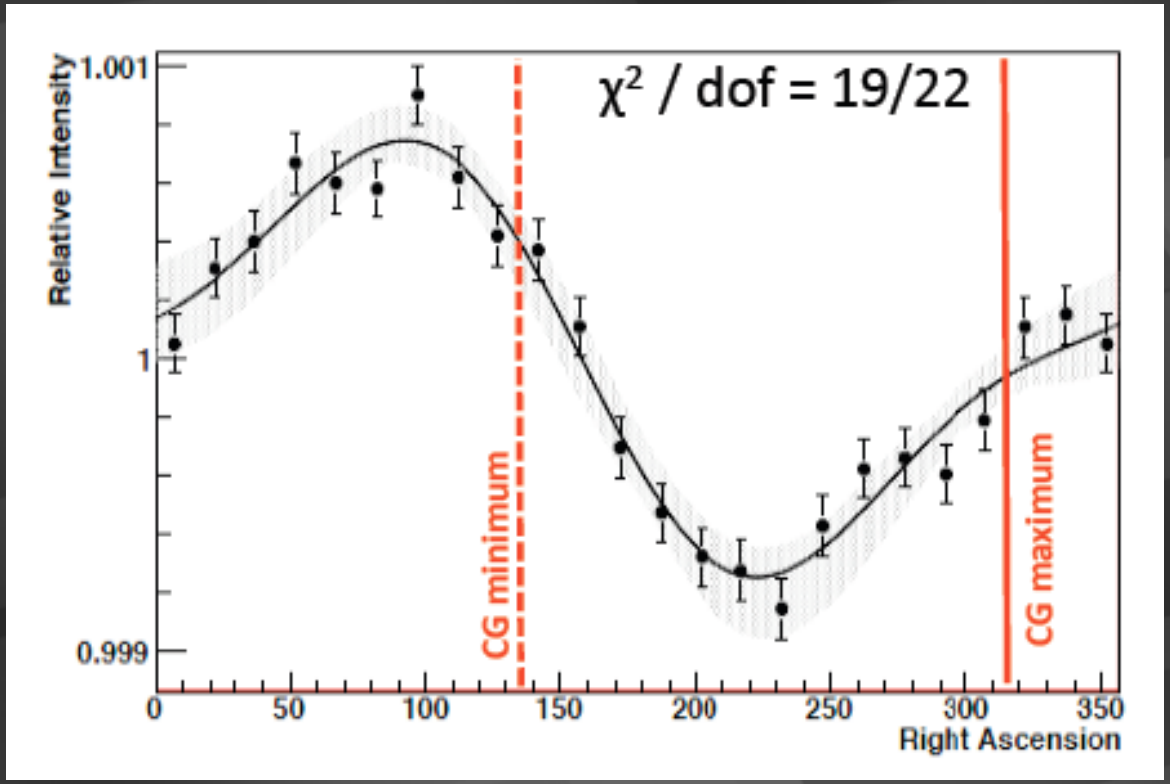
IceCube-22 string result



R. Abbasi et al. (IceCube Collaboration), Astrophys. J. Lett. (in press).

relative intensity in equatorial coordinates :

for each declination belt of width 3 degrees the map shows the number of events relative to the average in the belt



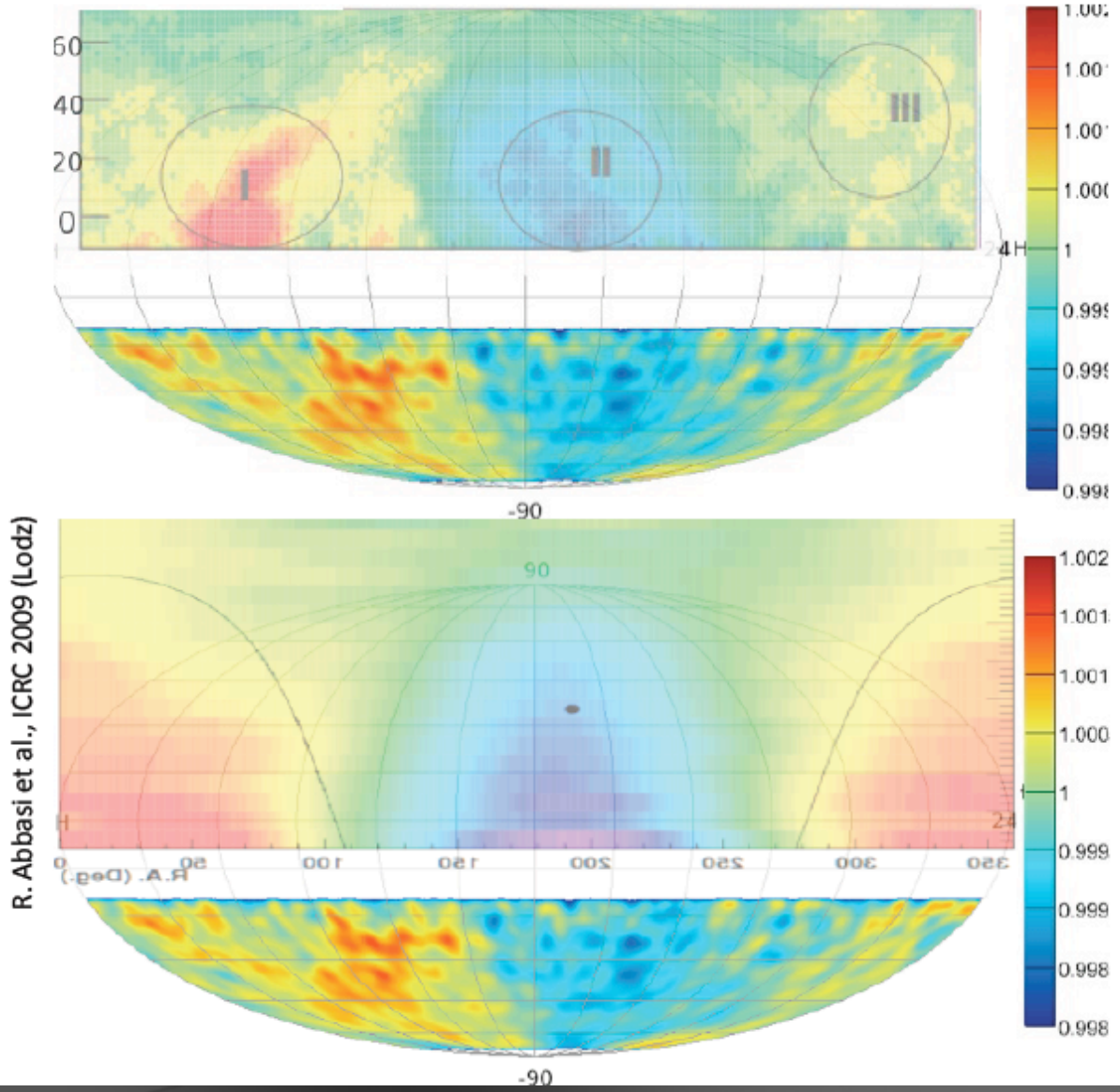
not a dipole

wrong phase for Compton-Getting

$$\sum_{i=1}^{2} A_i \cos(i(\alpha - \phi_i)) + B$$

$$A_1 = (6.4 \pm 0.2 \pm 0.8) \times 10^{-4}$$
$$A_2 = (2.1 \pm 0.3 \pm 0.5) \times 10^{-4}$$
$$\varphi_1 = 66.4^\circ \pm 2.6^\circ \pm 3.8^\circ$$
$$\varphi_2 = -65.6^\circ \pm 4.0^\circ \pm 7.5^\circ$$

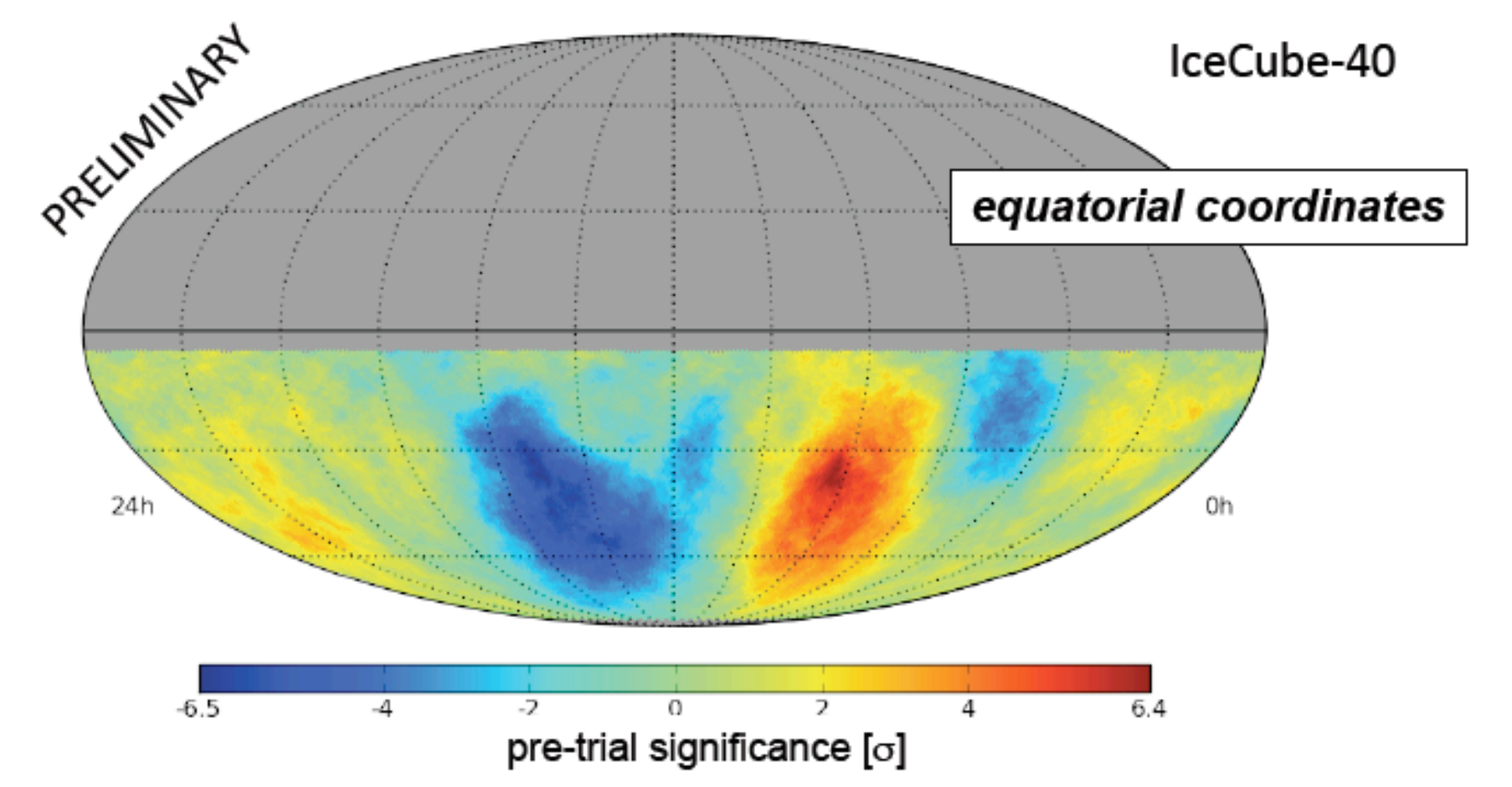
Comparison to Northern Hemisphere



IceCube & Tibet Array

IceCube & Milagro

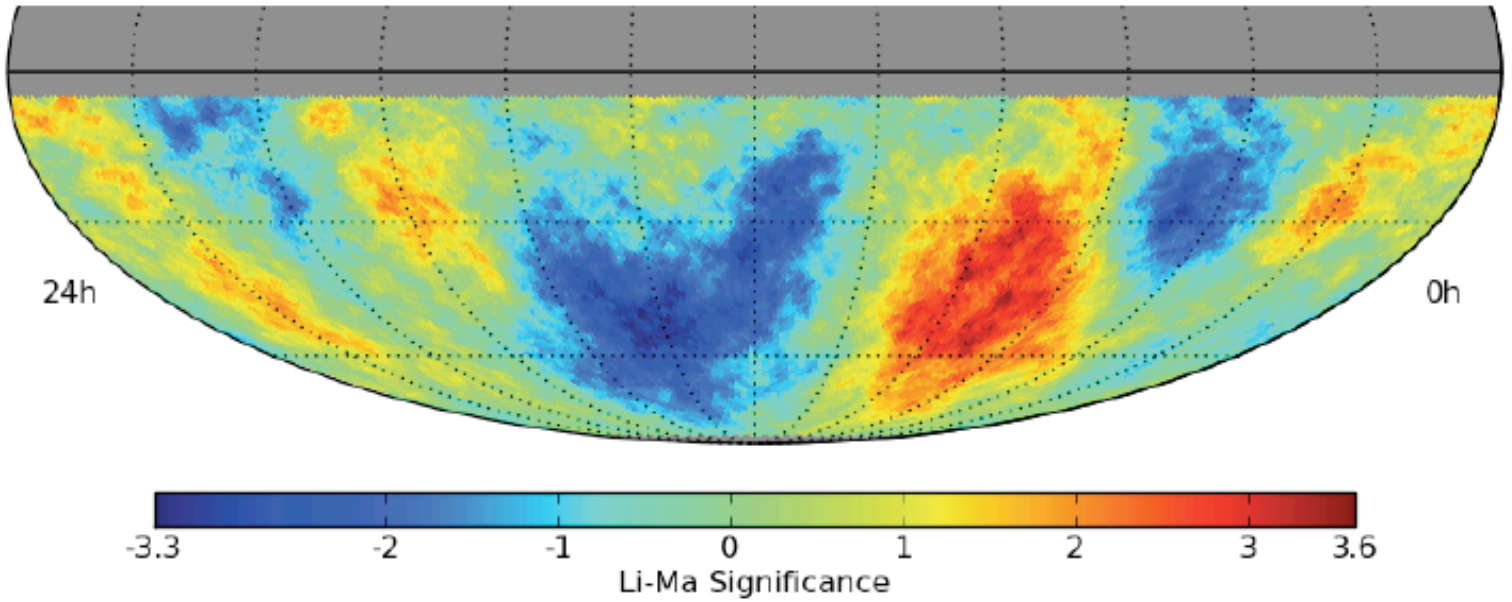
IceCube skymap



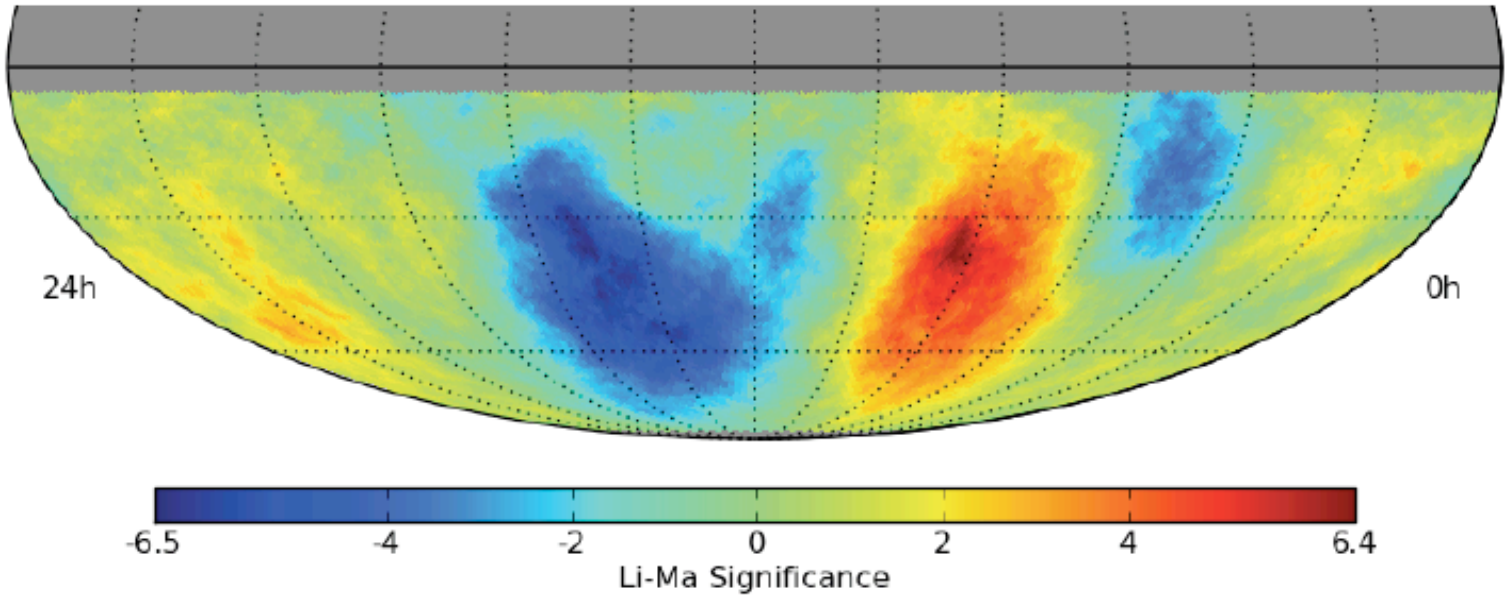
map is smoothed over 20 degrees (or 4 hours)
will be tested a priori with 59 strings
also search for smaller structures

IceCube with 22 and 24 strings : different detector, different year

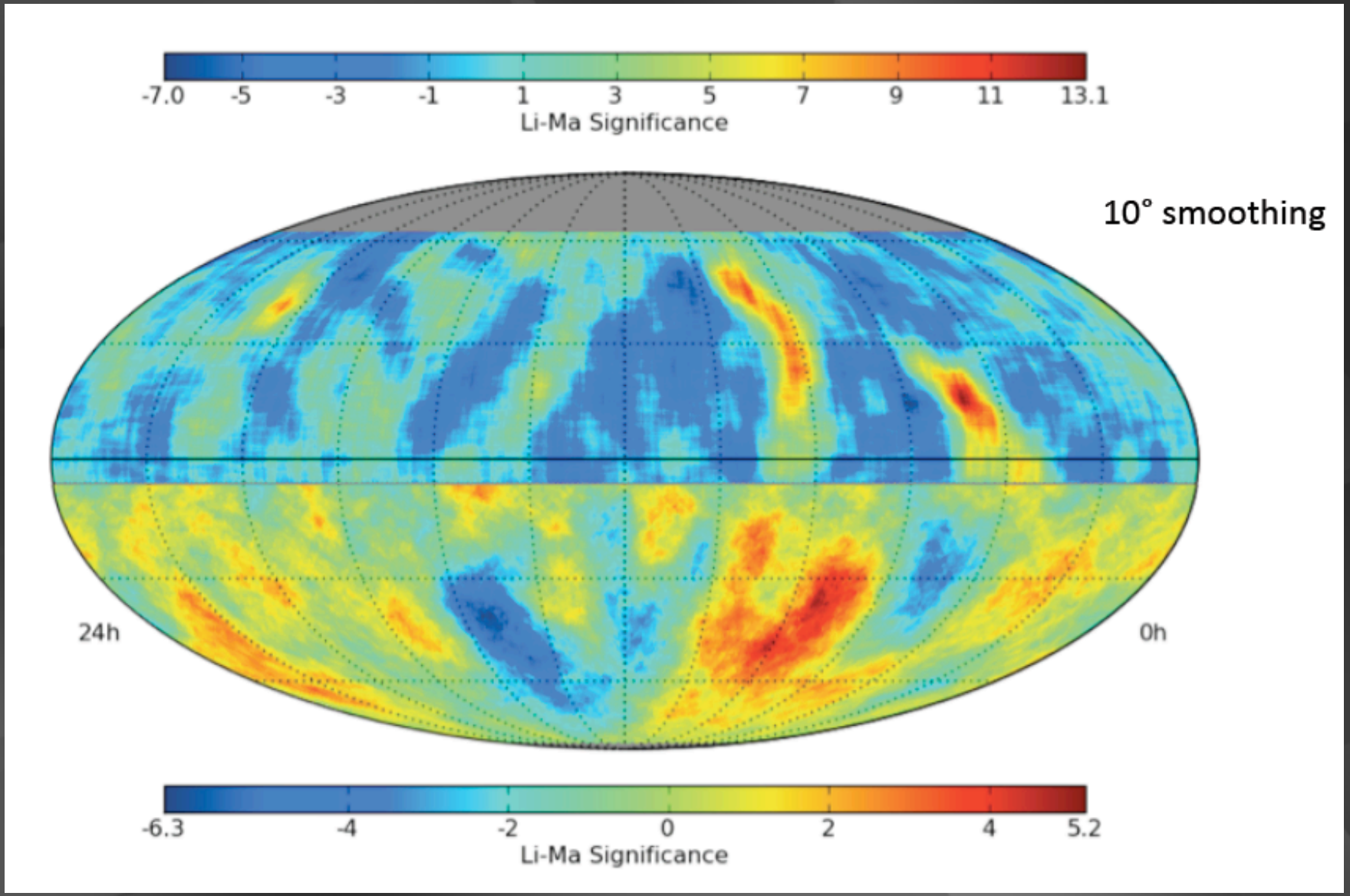
IC22



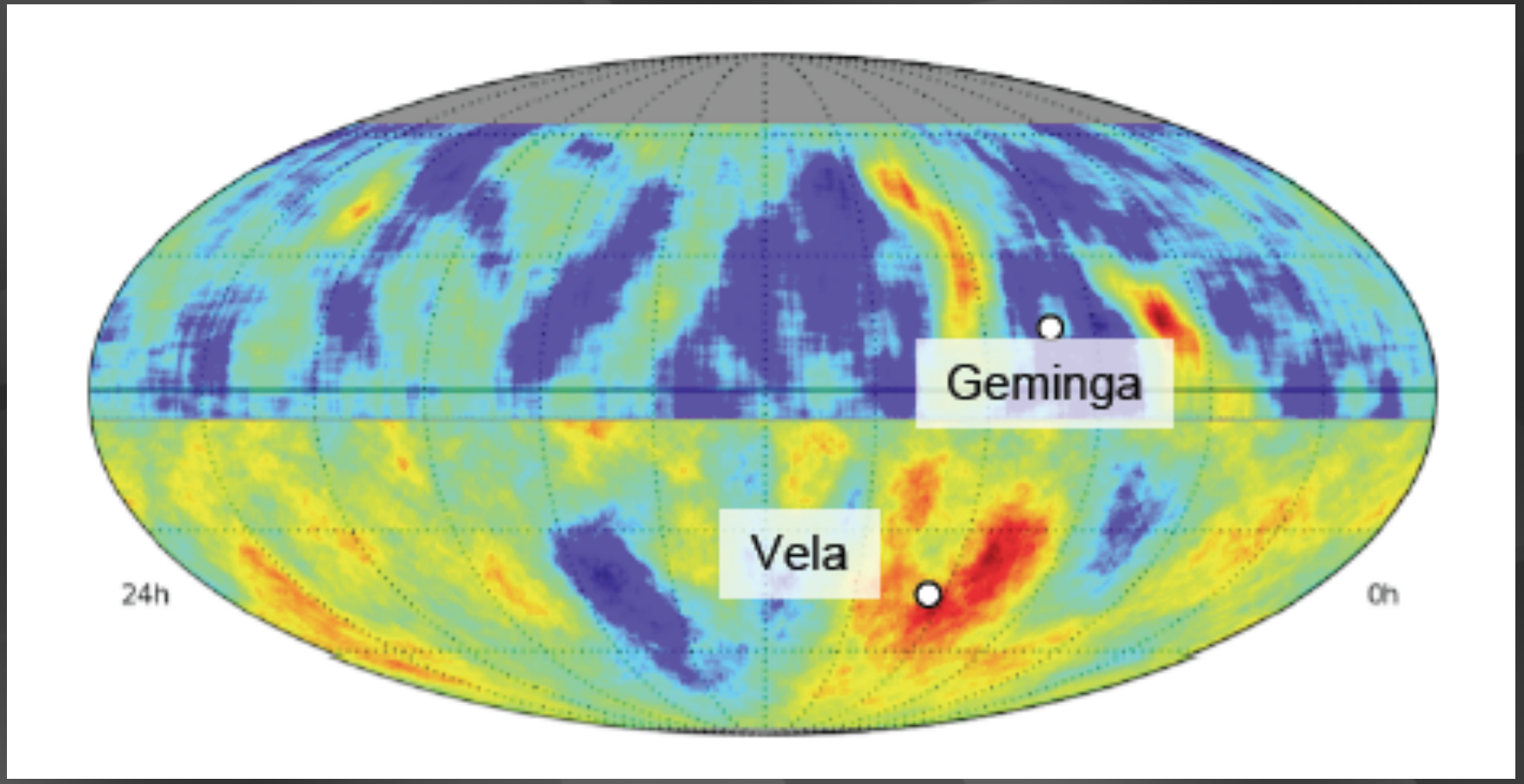
IC40



IceCube (20 TeV) and Milagro (10 TeV)

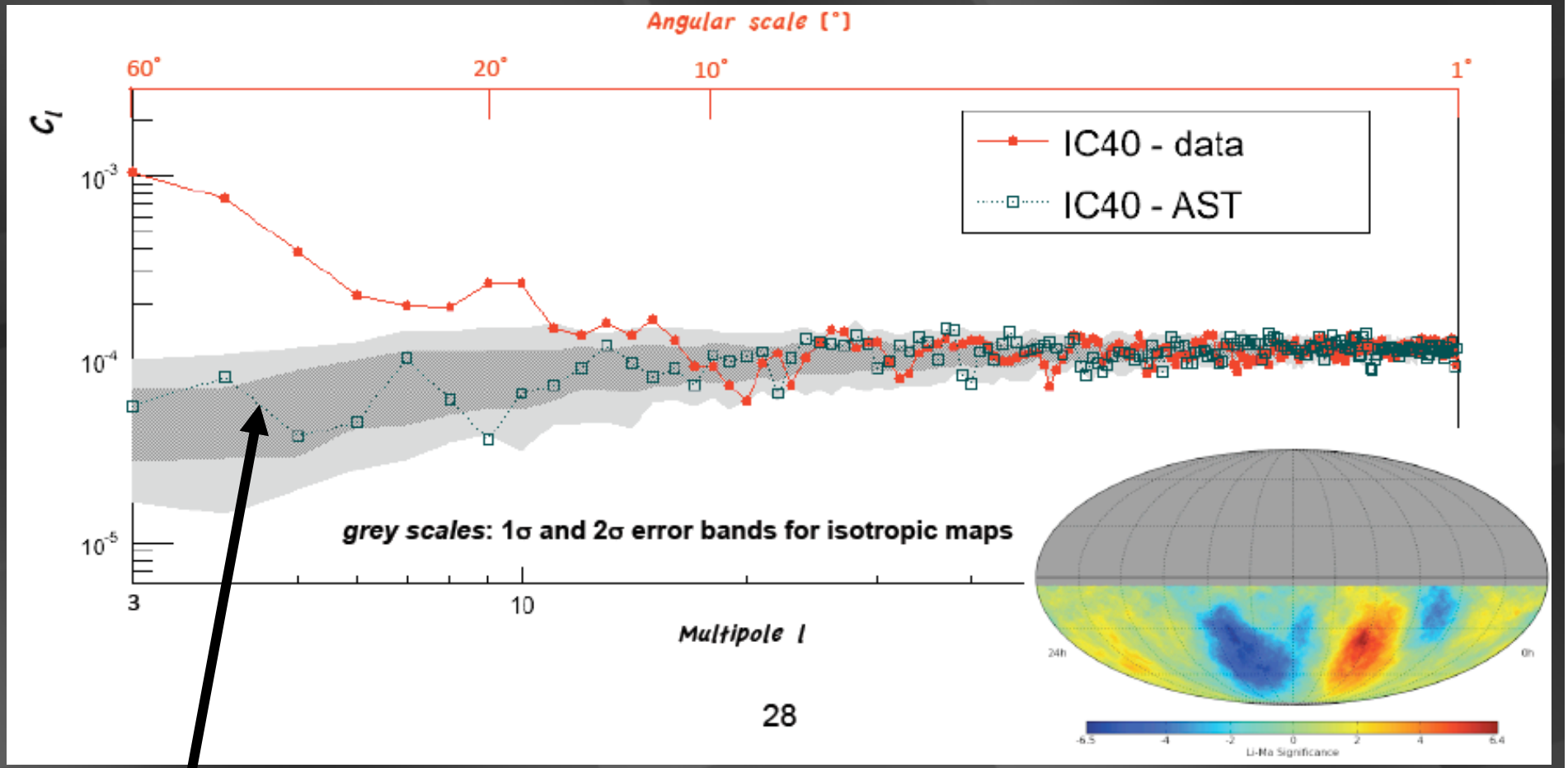


did we finally detect supernova remnants ?



- arrival of 100 TeV CR consistent with the age of Vela and… we do not understand diffusion
- something else

angular power spectrum (red)



same for anti(!)-siderial map as a check

muon (!) astronomy

We have established that the arrival directions of the highest energy Galactic cosmic rays are not uniformly distributed in the sky. We find a large excess in the direction of Vela, the strongest gamma ray source in the sky.

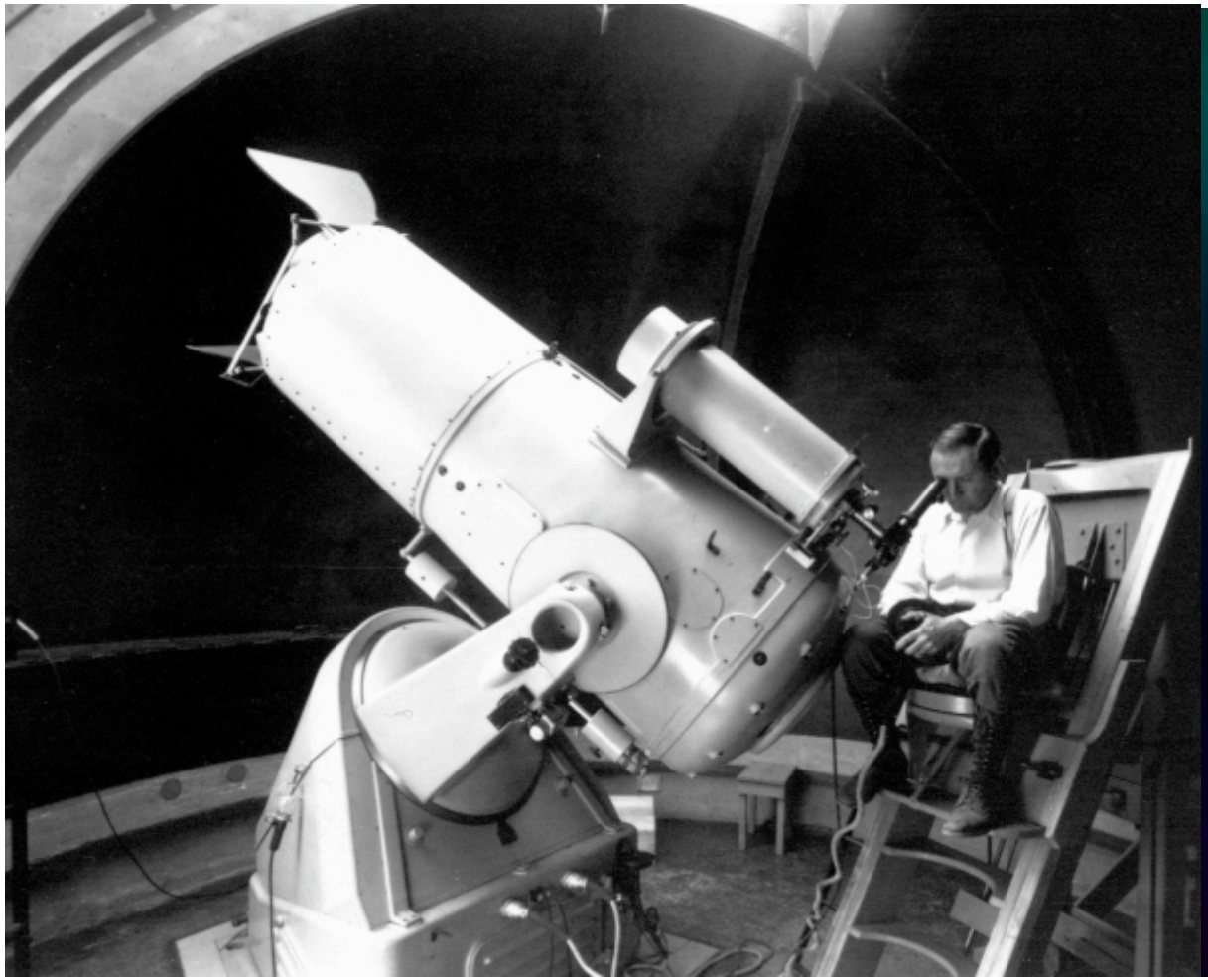
Note: muons with energy in excess of 20 TeV have a gyroradius of less than 0.1 pc. The Vela pulsar is at ~300 pc.

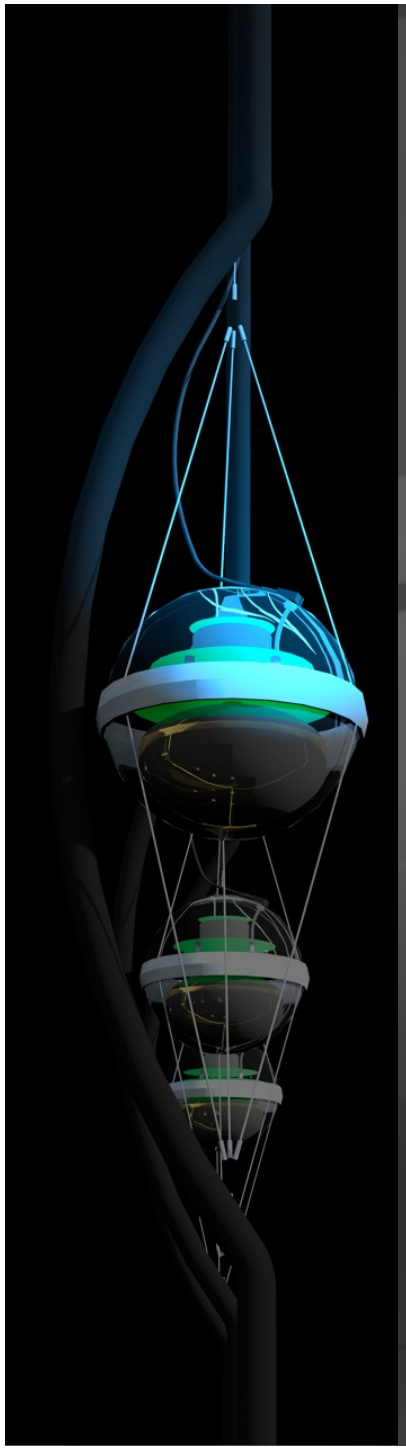
ON SUPER-NOVAE

By W. Baade and F. Zwicky

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

Communicated March 19, 1934





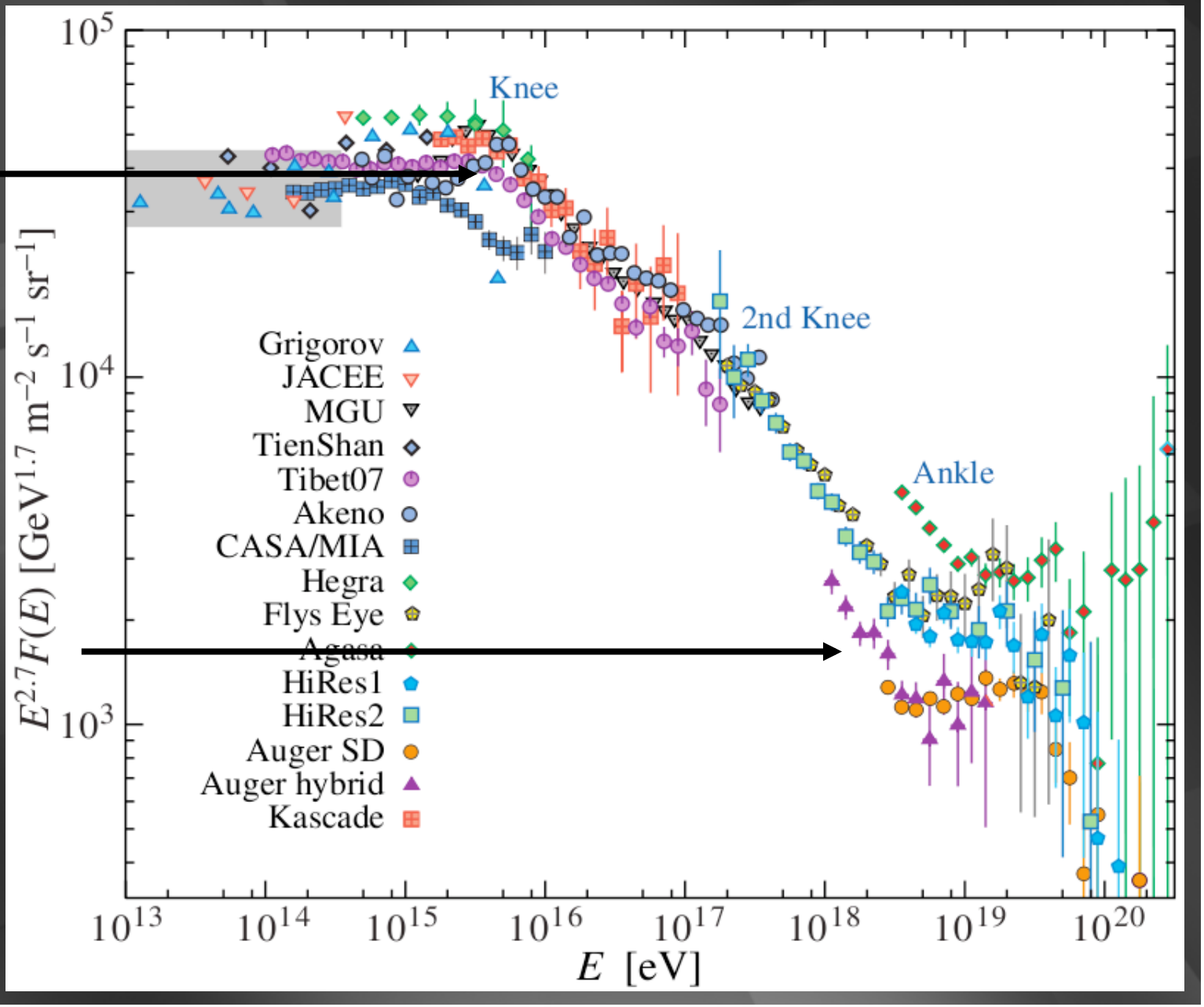
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- atmospheric neutrino spectrum
- atmospheric muon spectrum: first surprise
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - GZK neutrinos
  - a multi-wavelength story
- search for dark matter

IceCube.wisc.edu

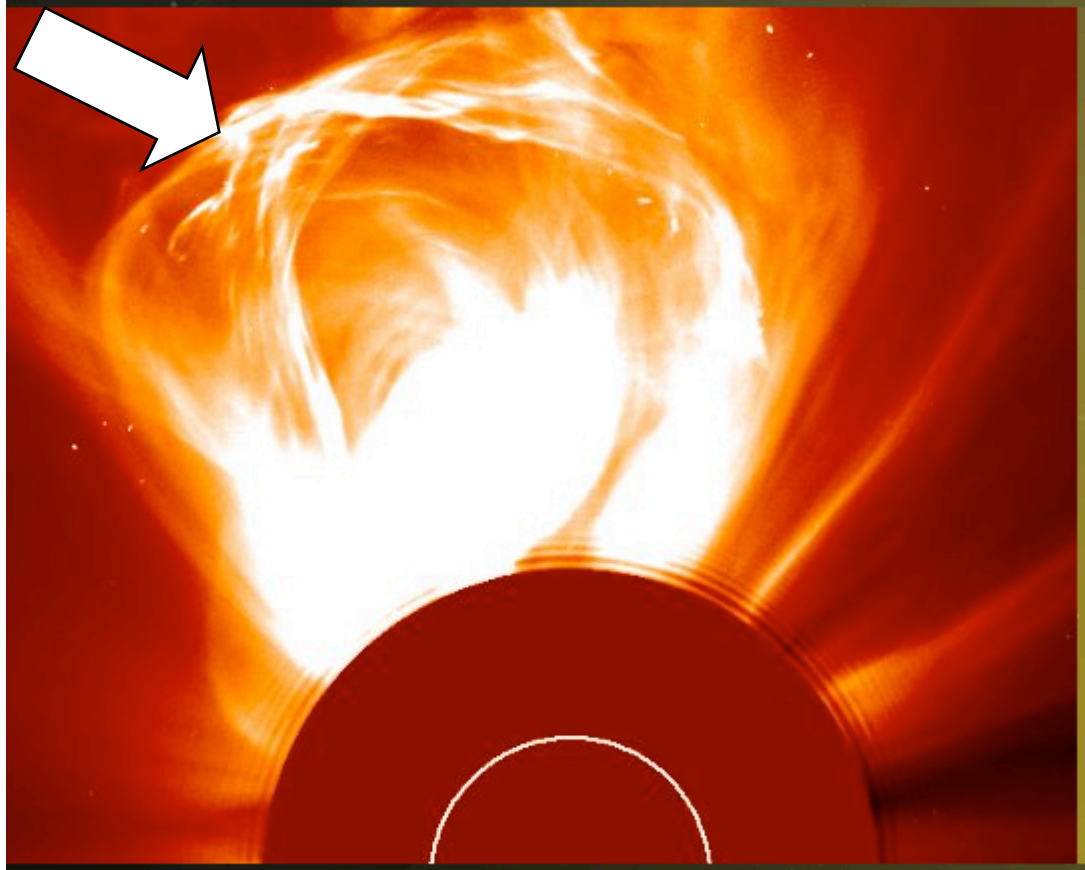
… often wrong, but never in doubt …

Galactic: supernova remnants?

extragalactic: gamma ray bursts?



shock acceleration (solar flare)



coronal
mass
ejection
→
10 GeV
particles

flows of charged particles result in large B-fields

Hillas formula :

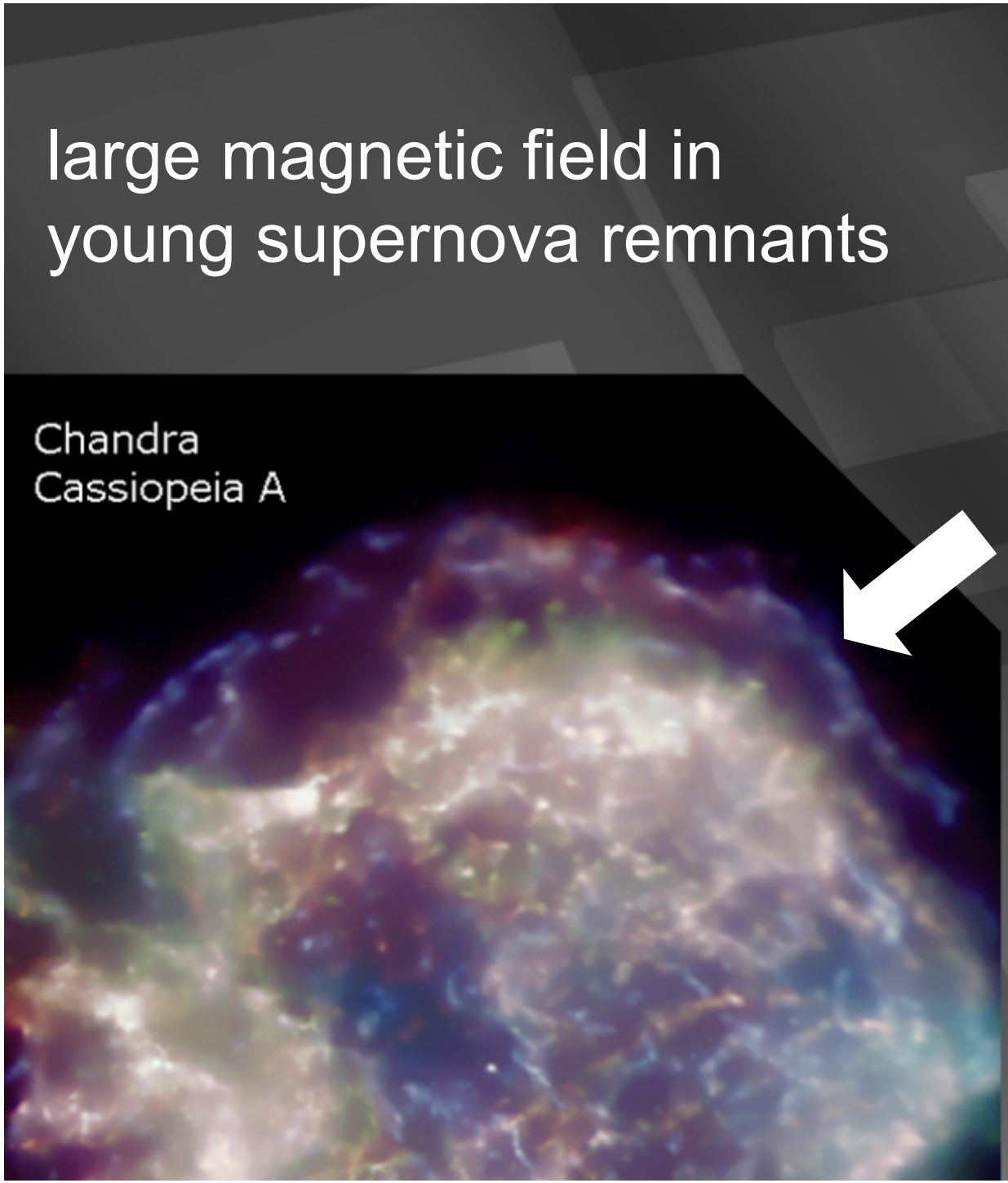
- accelerator must contain the particles

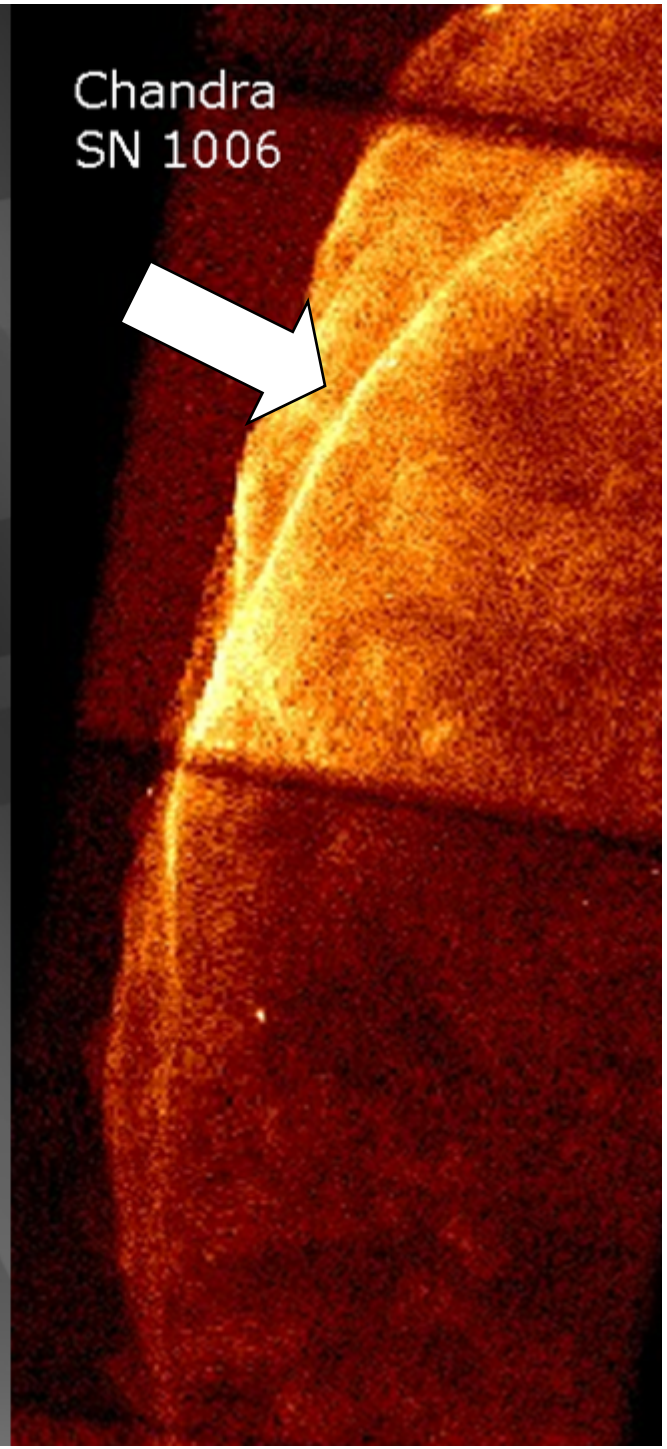
$$R_{gyro}\left(=\frac{E}{cqB}\right) \leq R$$

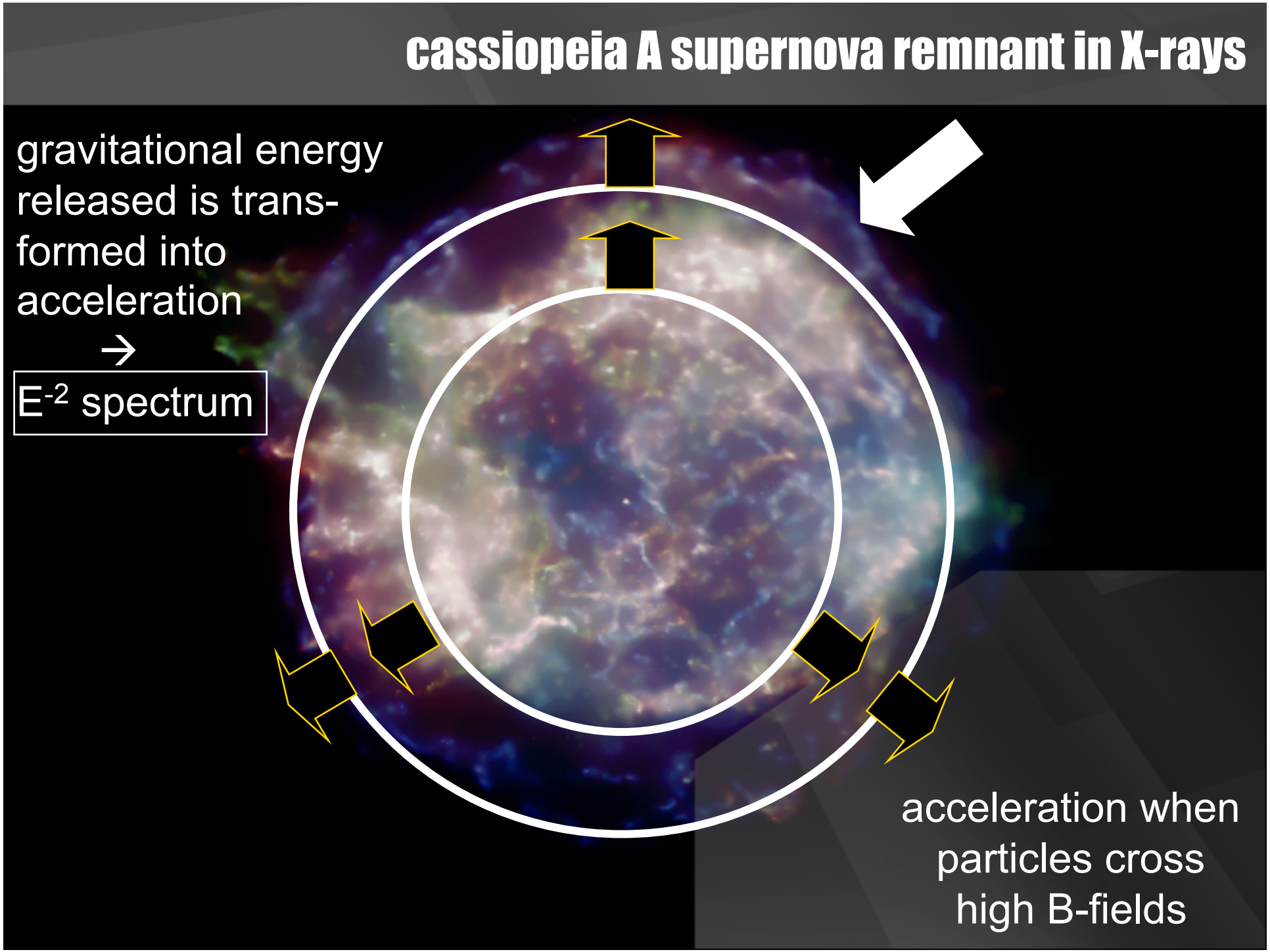
$$\boxed{E \leq c\, qBR}$$

- dimensional analysis, difficult to satisfy

large magnetic field in young supernova remnants



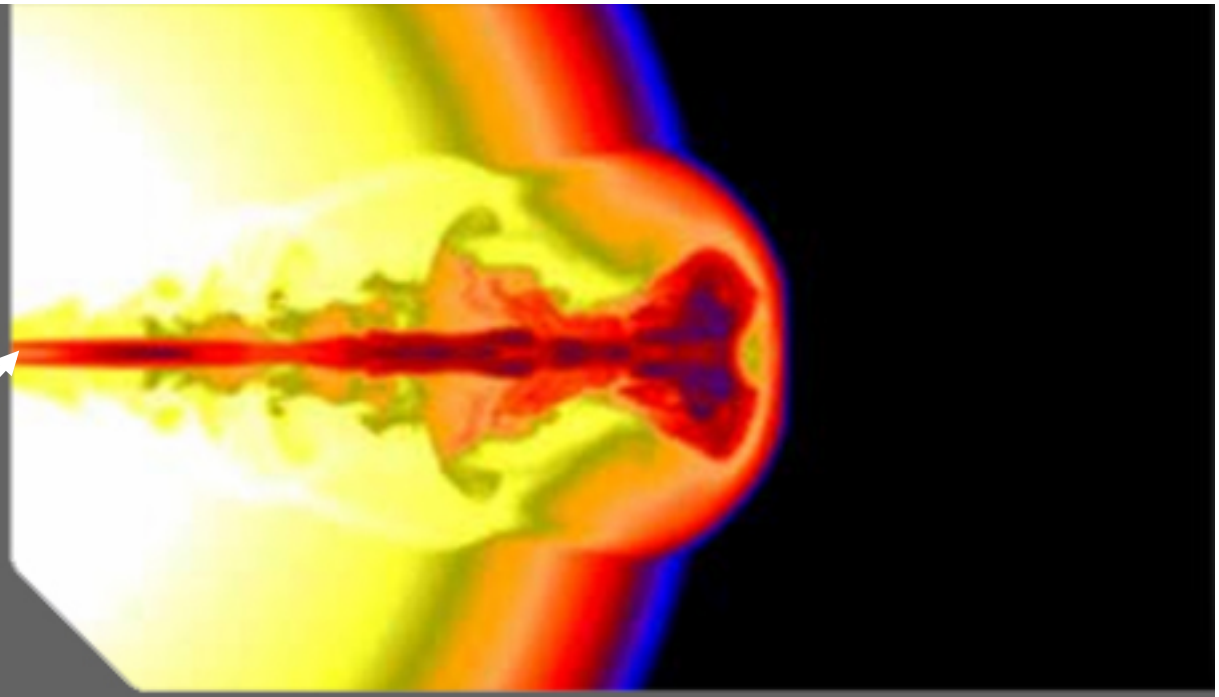



cassiopeia A supernova remnant in X-rays
gravitational energy released is trans-formed into acceleration
→
E^{-2} spectrum
acceleration when particles cross high B-fields

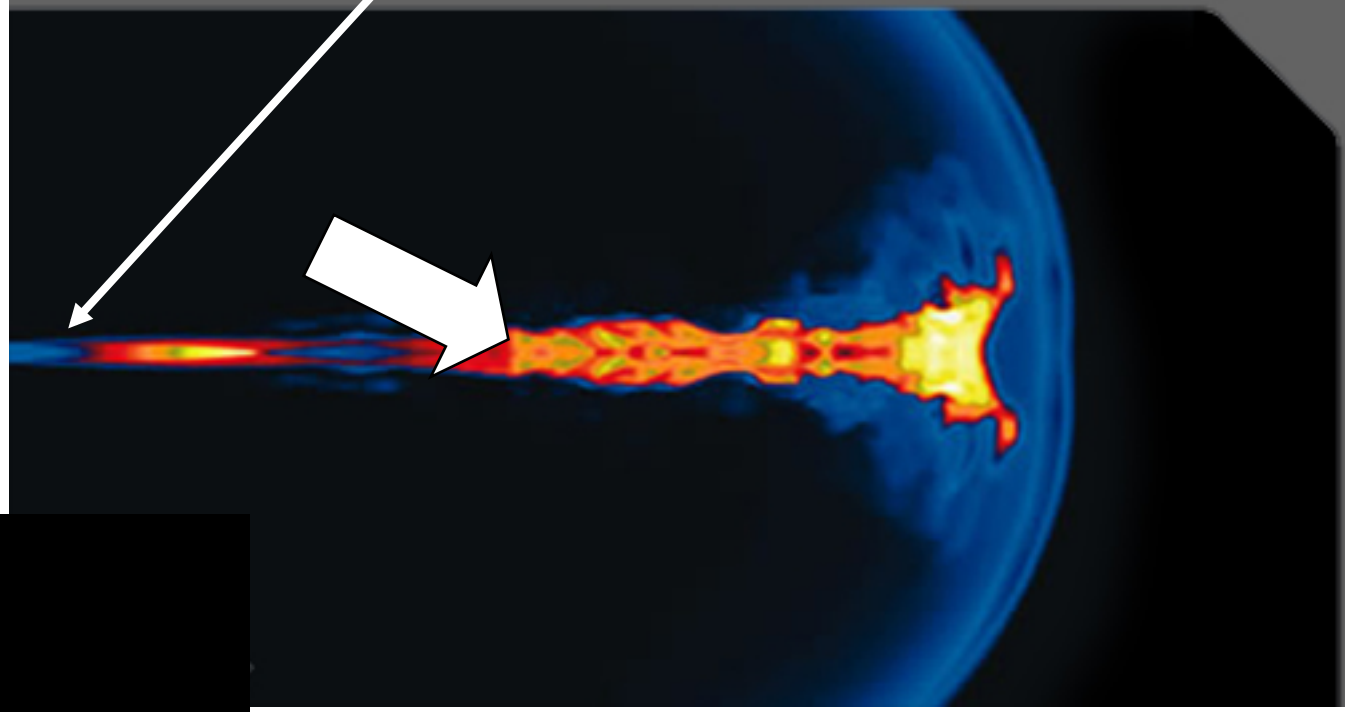
and if the star collapses to a black hole …

collapse of massive star produces a

gamma ray burst



spinning black hole

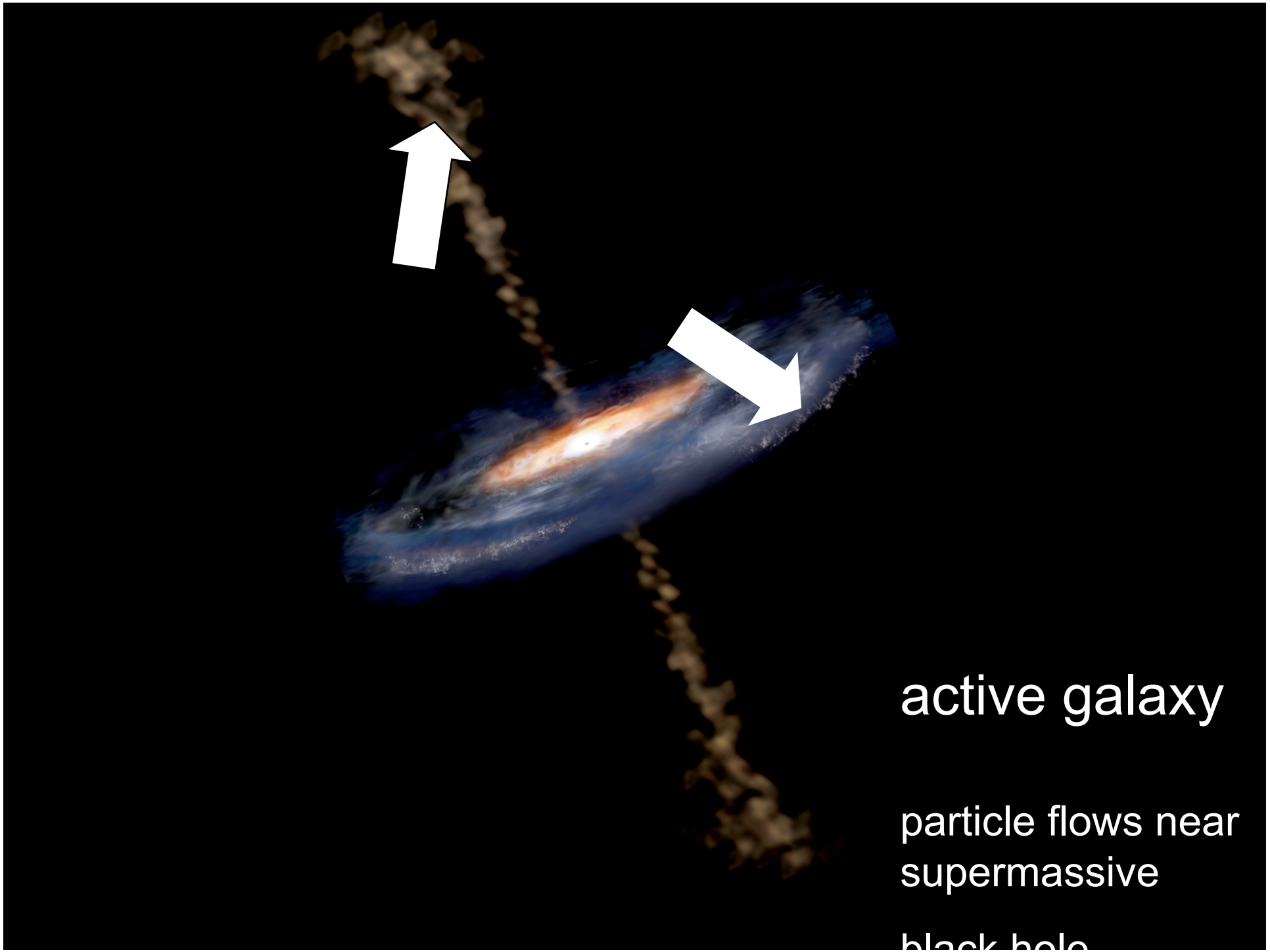


shocks produced in the outflow of the spinning black hole:

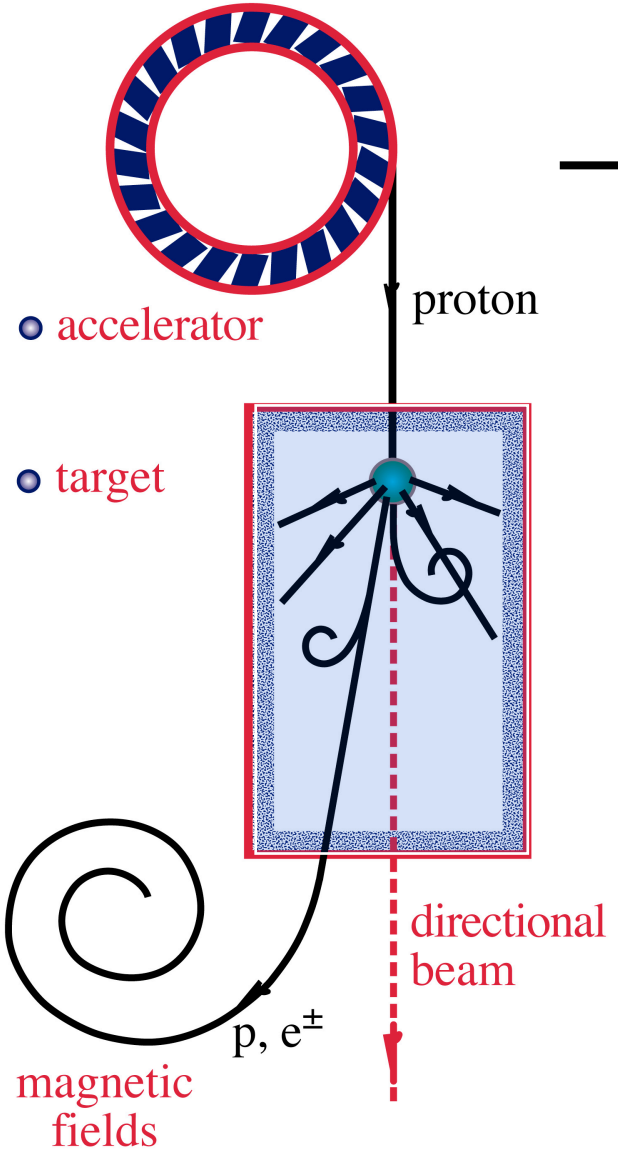
electrons

and

protons ?


active galaxy
particle flows near supermassive
black hole

ν and γ beams : heaven and earth



black hole

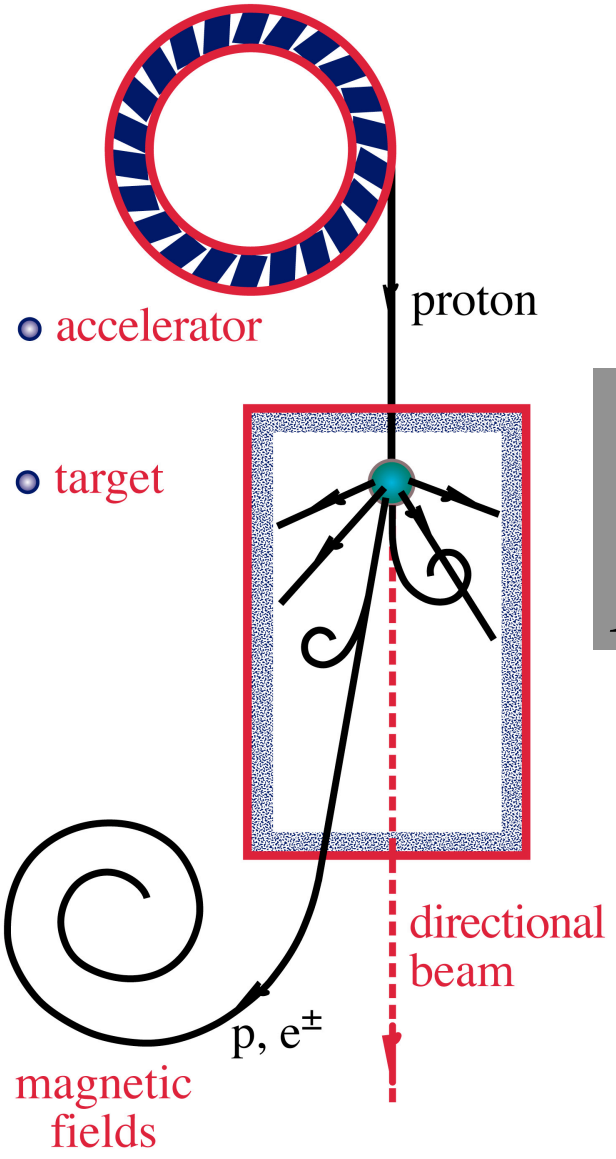
radiation and dust

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

~ cosmic ray + neutrino

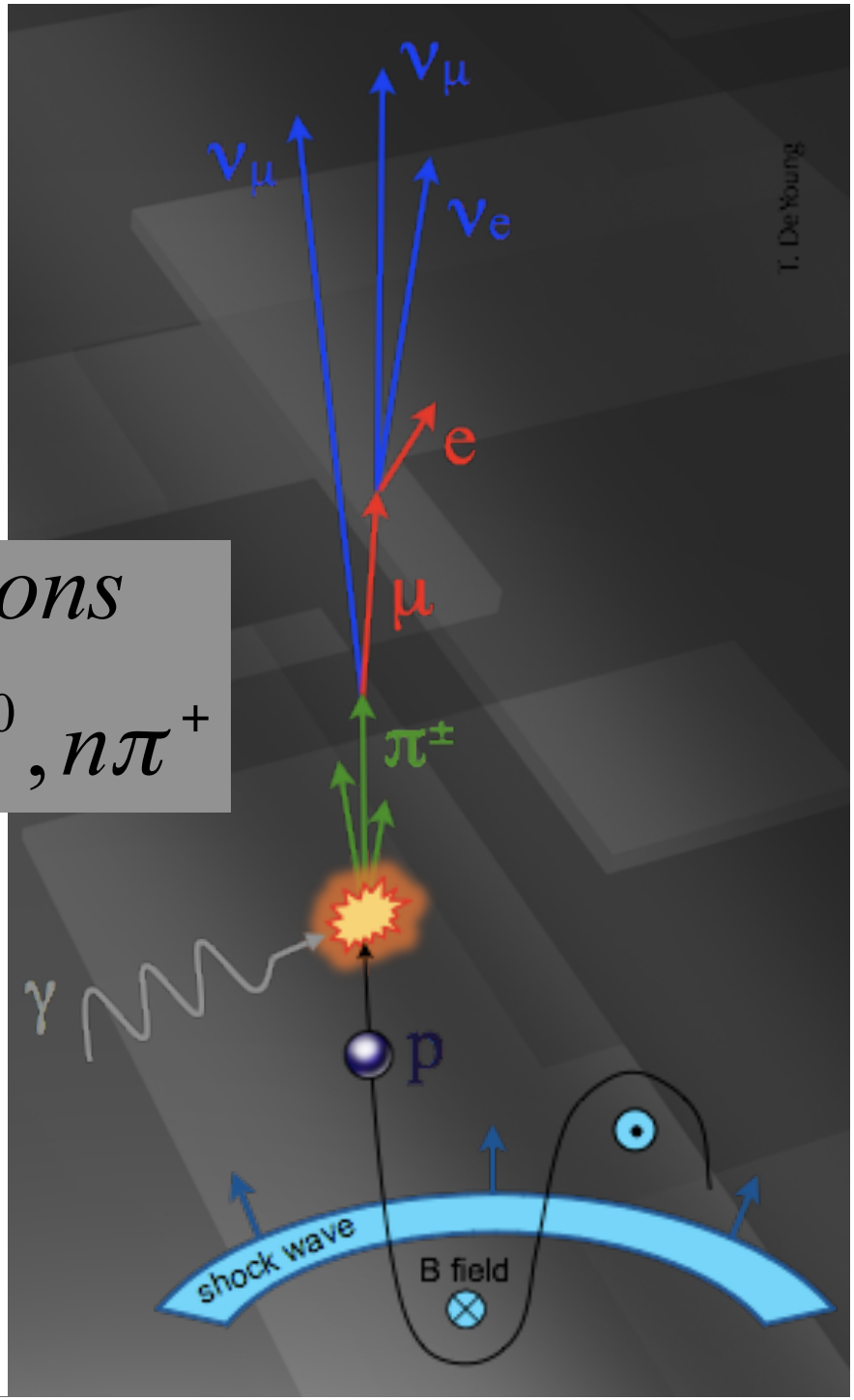
$\rightarrow p + \pi^0$

~ cosmic ray + gamma



$$pp \rightarrow pions$$

$$p\gamma \rightarrow p\pi^0, n\pi^+$$



neutral pions

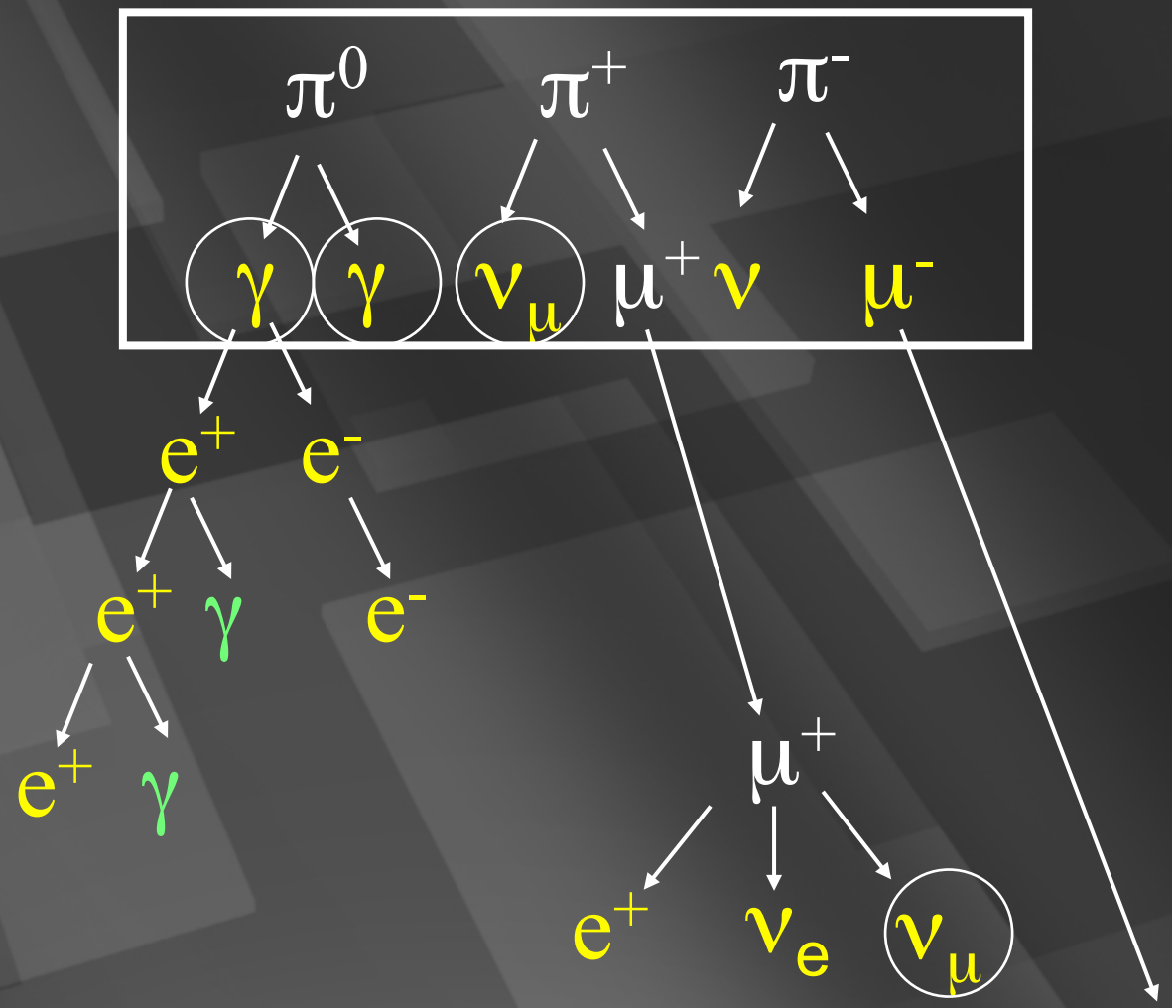
are observed as

gamma rays

charged pions

are observed as

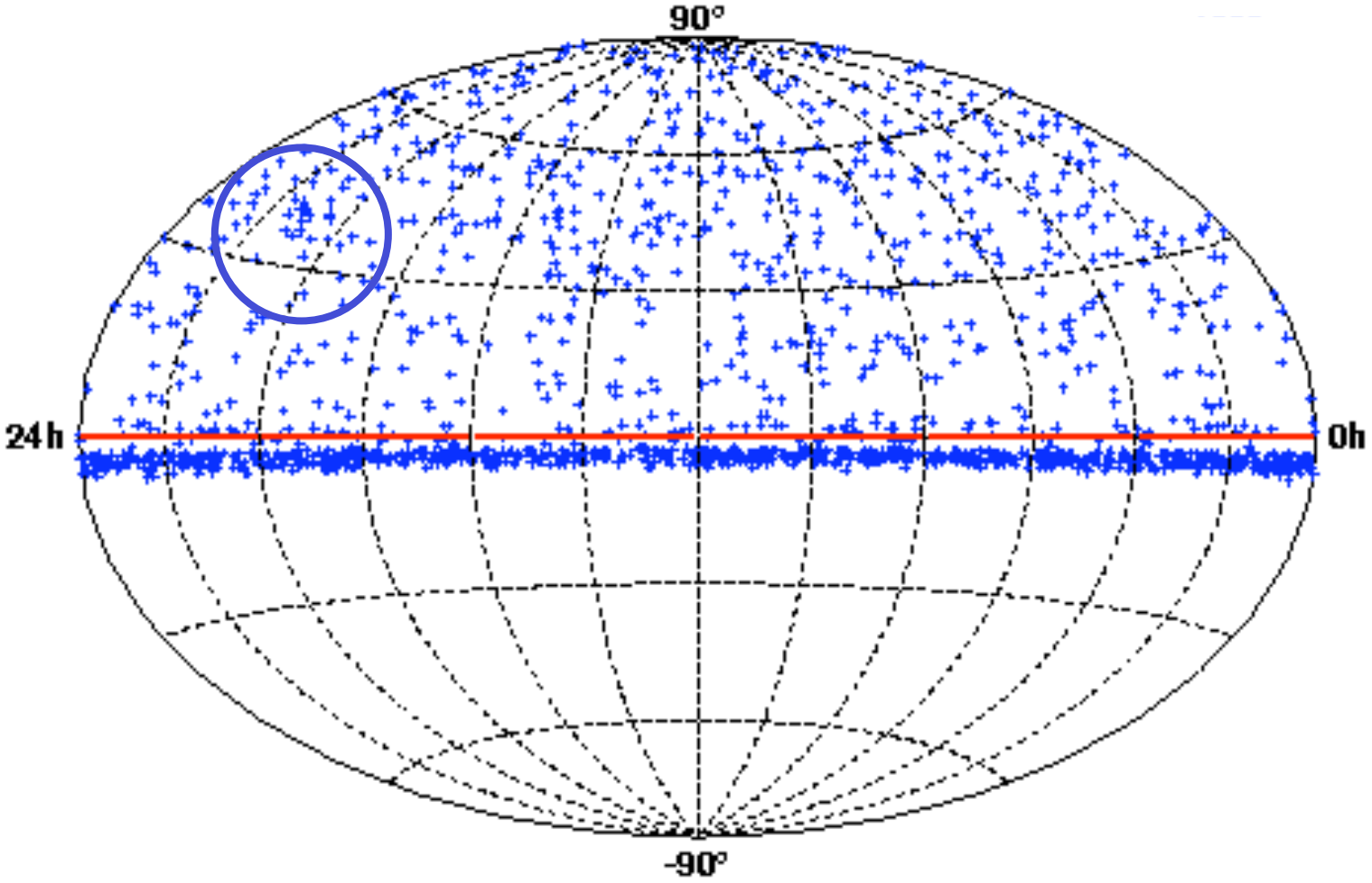
neutrinos



$$\nu_\mu + \nu_\mu = \gamma + \gamma$$

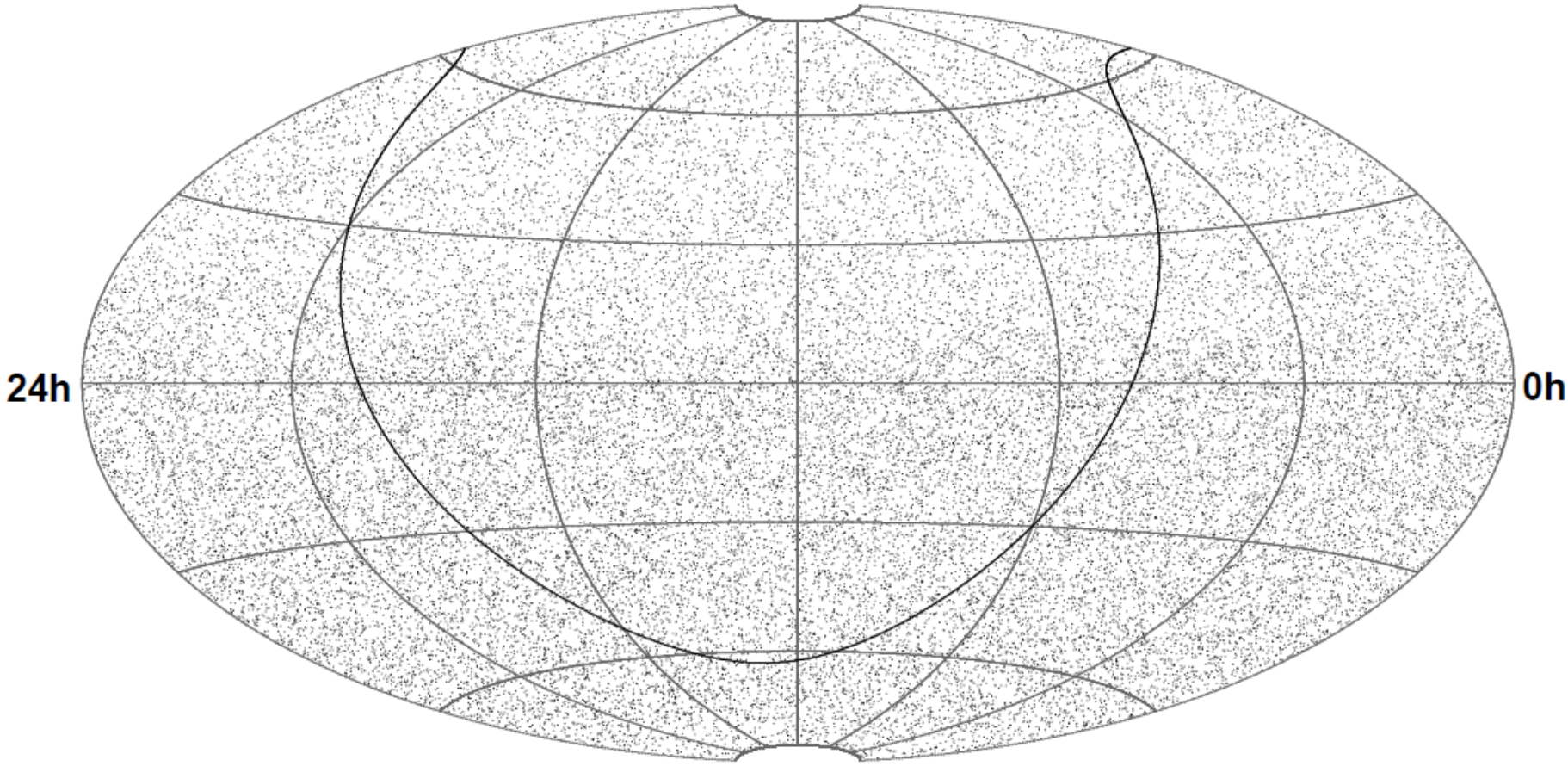
AMANDA II 2000

directions of ~ 600 neutrinos



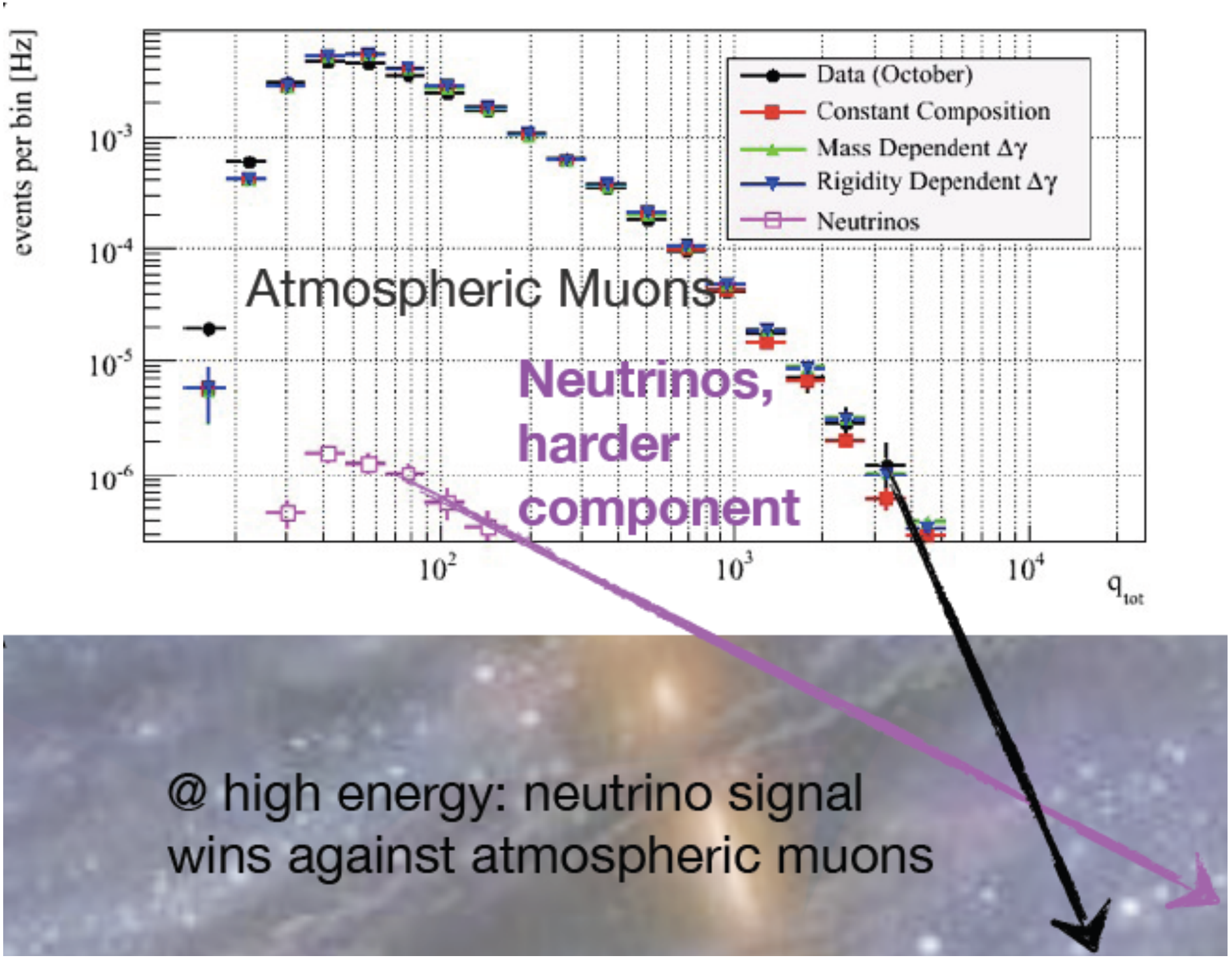
IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos

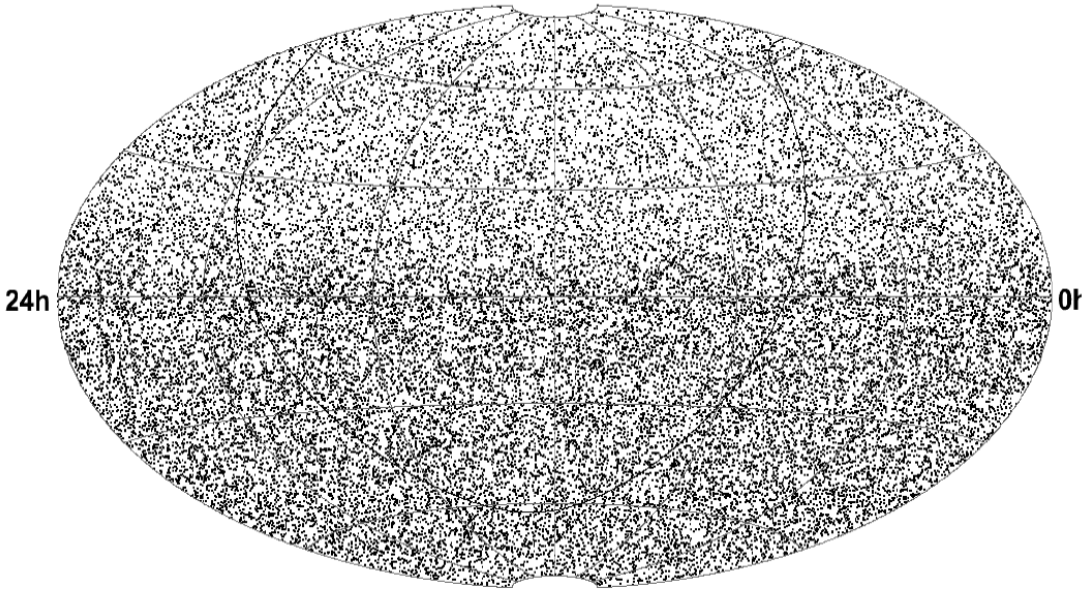


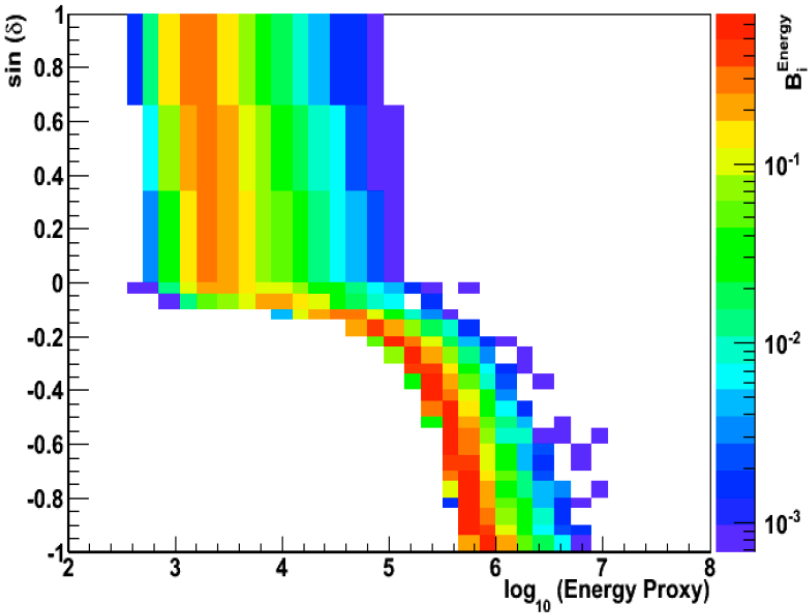
search for
- **clustering**
- **high energy**

southern sky: 23151 muons


events per bin [Hz]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{2}
10^{3}
10^{4}
q_{tot}
Data (October)
Constant Composition
Mass Dependent Δγ
Rigidity Dependent Δγ
Neutrinos
Atmospheric Muons
Neutrinos, harder component
@ high energy: neutrino signal wins against atmospheric muons

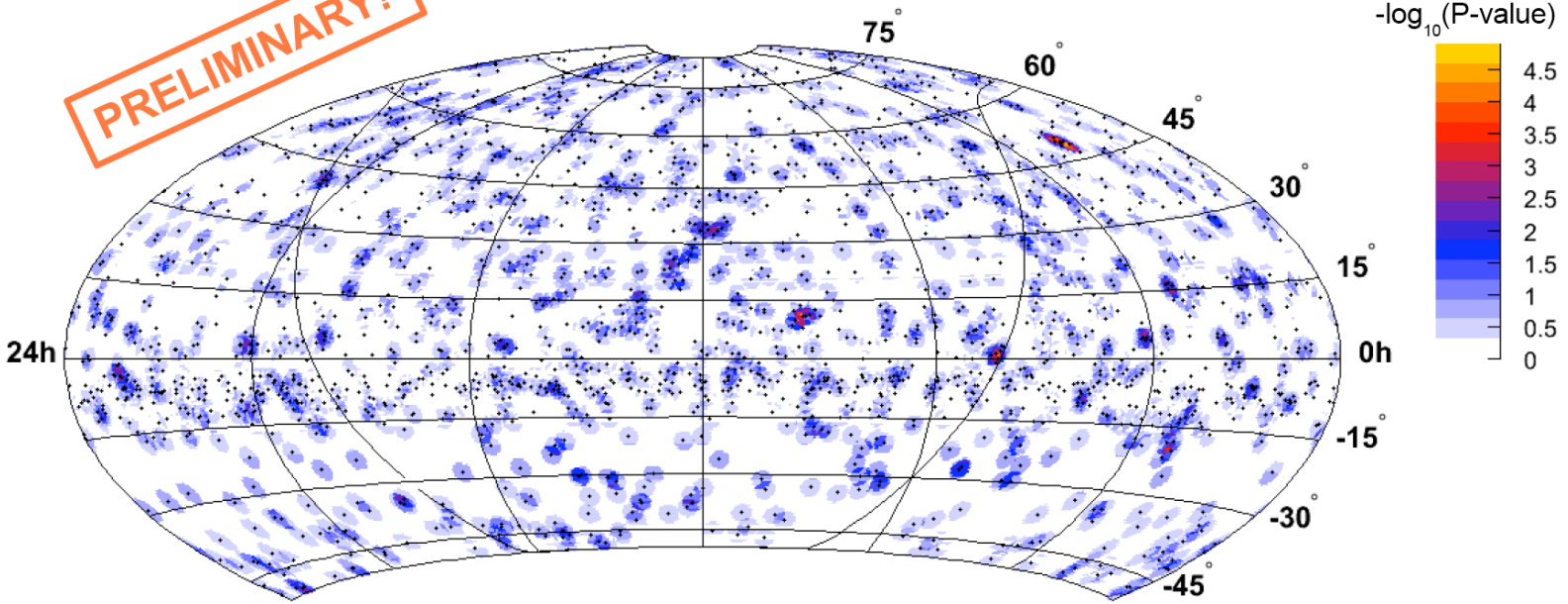
Northern Hemisphere





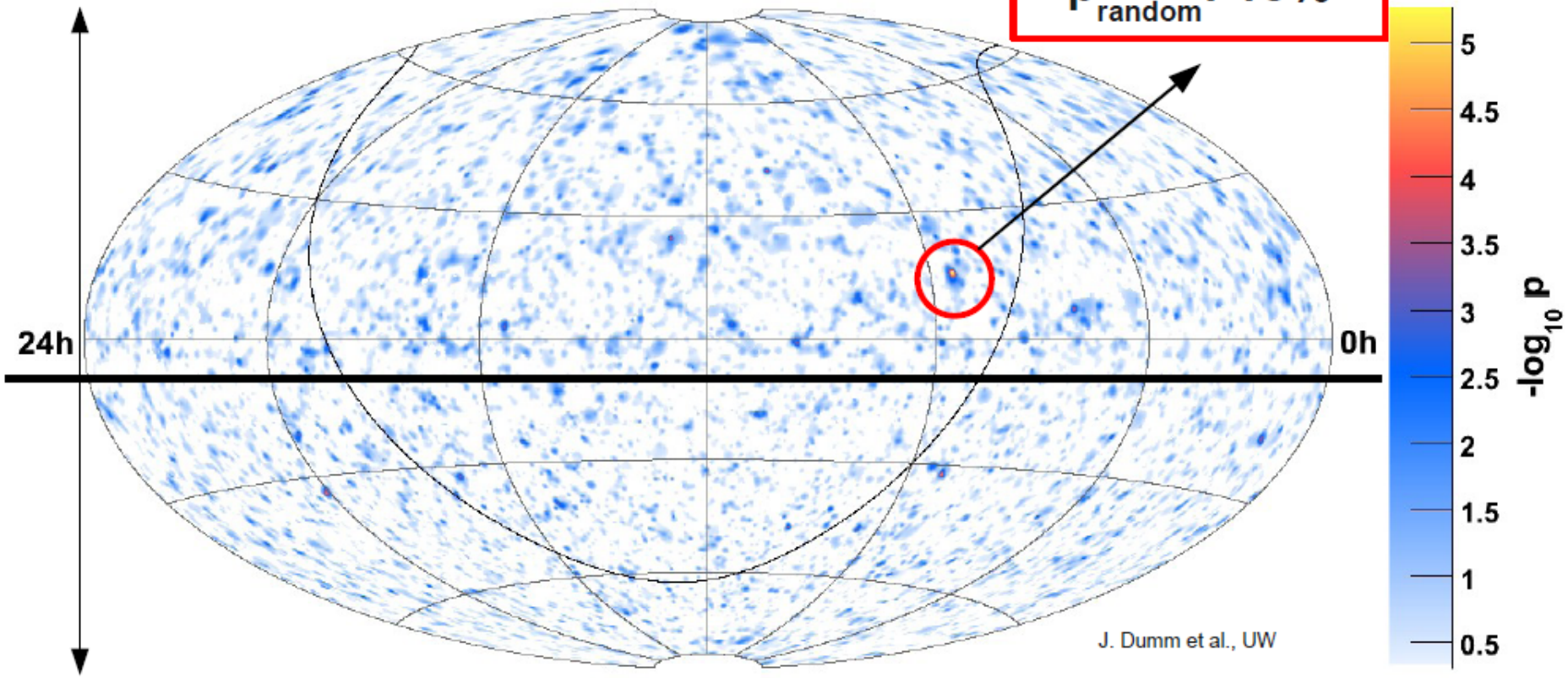
Southern Hemisphere

PRELIMINARY!

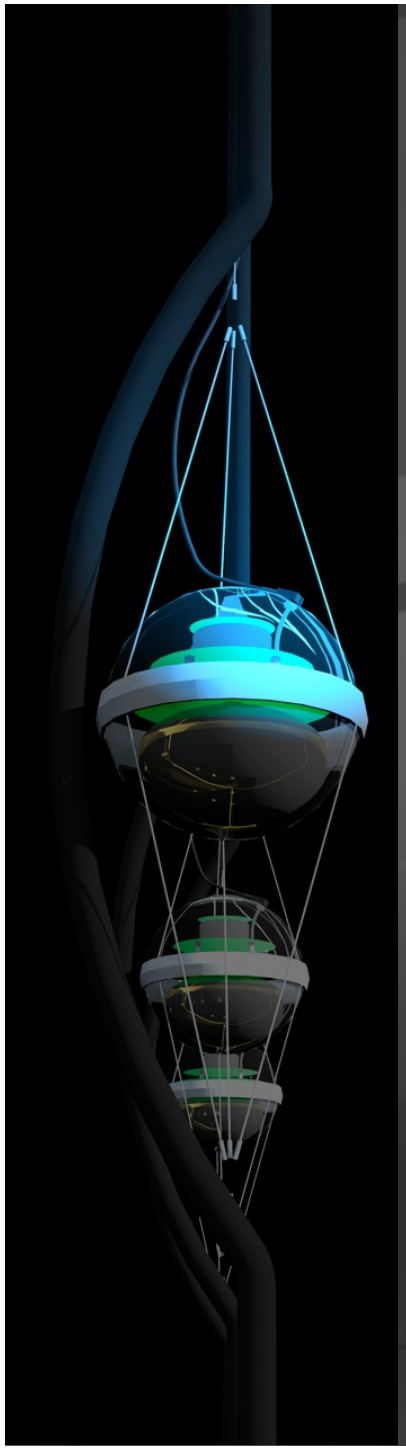


IC40 Point Source Search

Below Horizon:
Data dominated by atmospheric **Neutrinos**
Energy Range 10s-100s of TeV



Above Horizon:
Data dominated by atmospheric **Muons**
Energy Range >PeV, increasing with angle



- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- atmospheric neutrino spectrum
- atmospheric muon spectrum: first surprise
- search for the sources of the Galactic cosmic rays
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  - gamma ray bursts
  - GZK neutrinos
  - a multi-wavelength story
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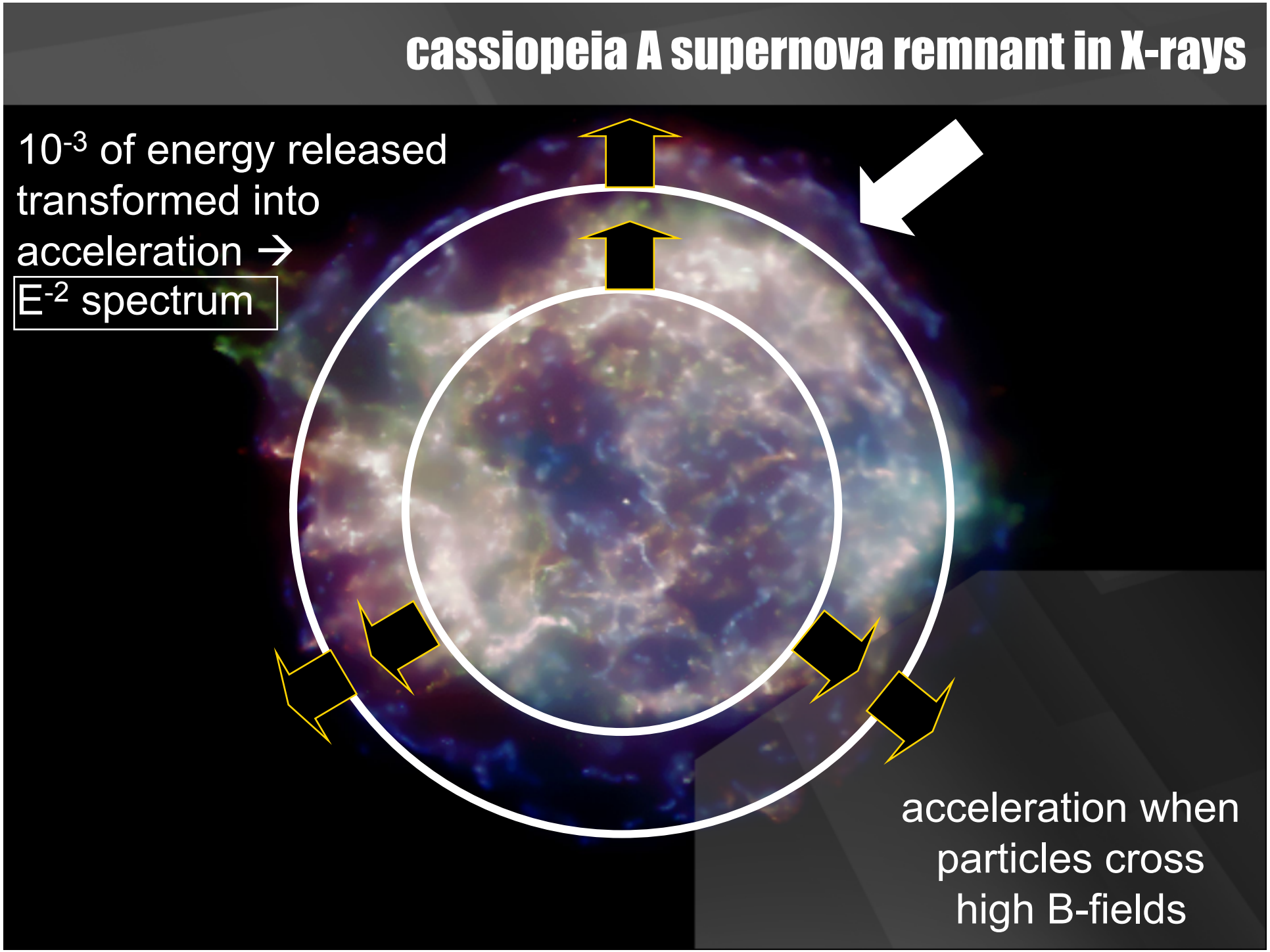
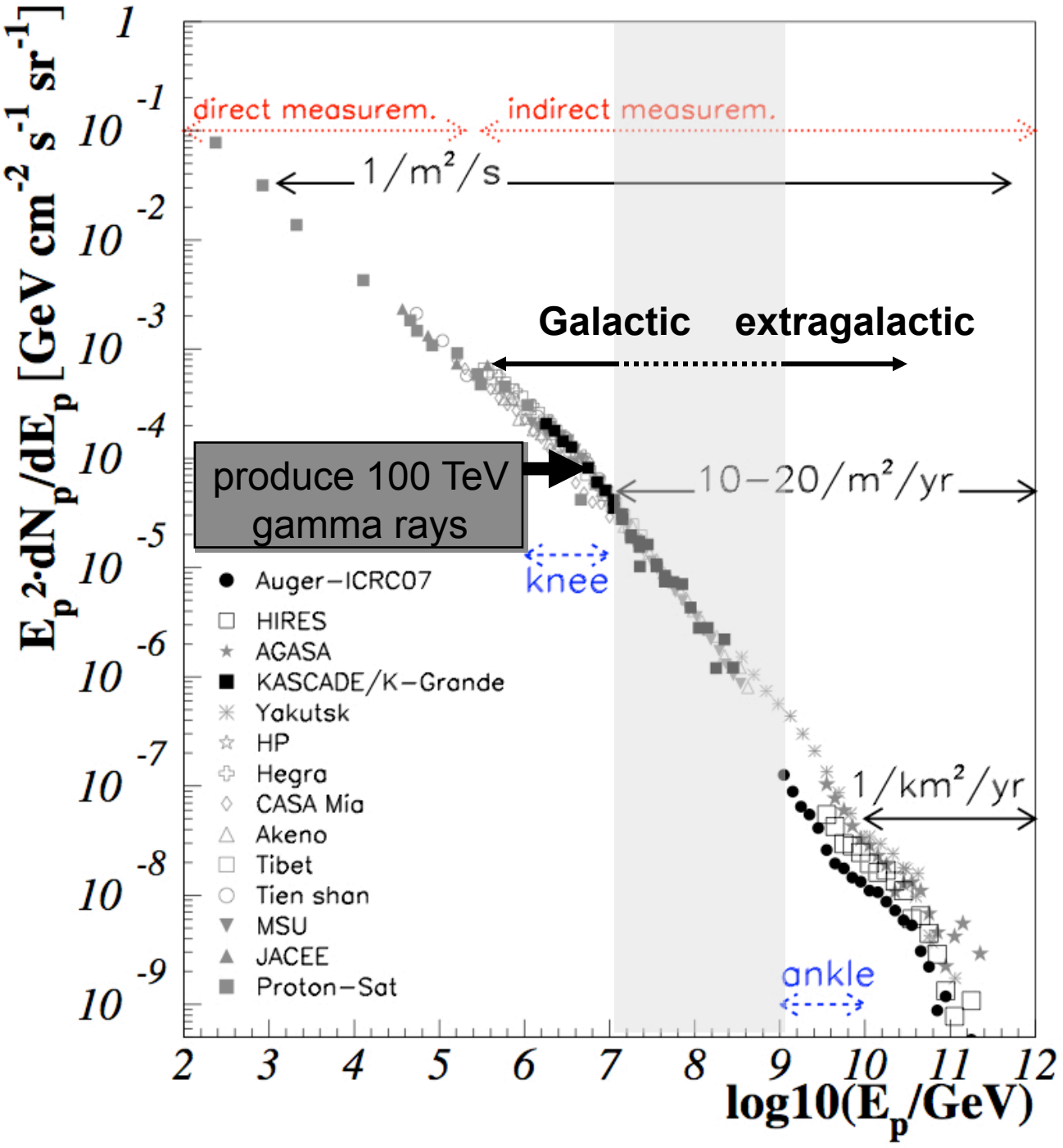
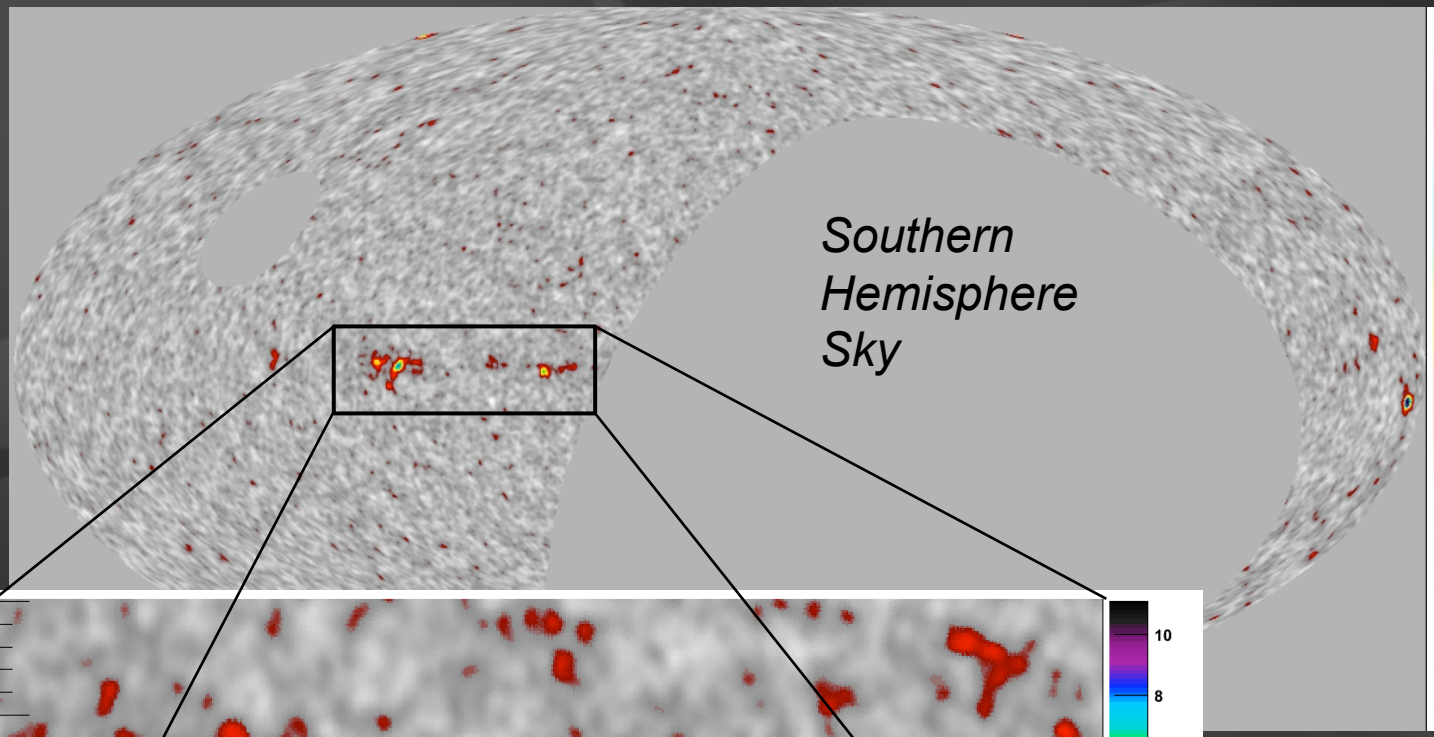
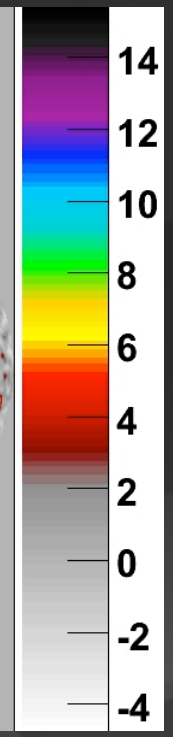

cassiopeia A supernova remnant in X-rays
10^{-3} of energy released transformed into acceleration →
E^{-2} spectrum
acceleration when particles cross high B-fields

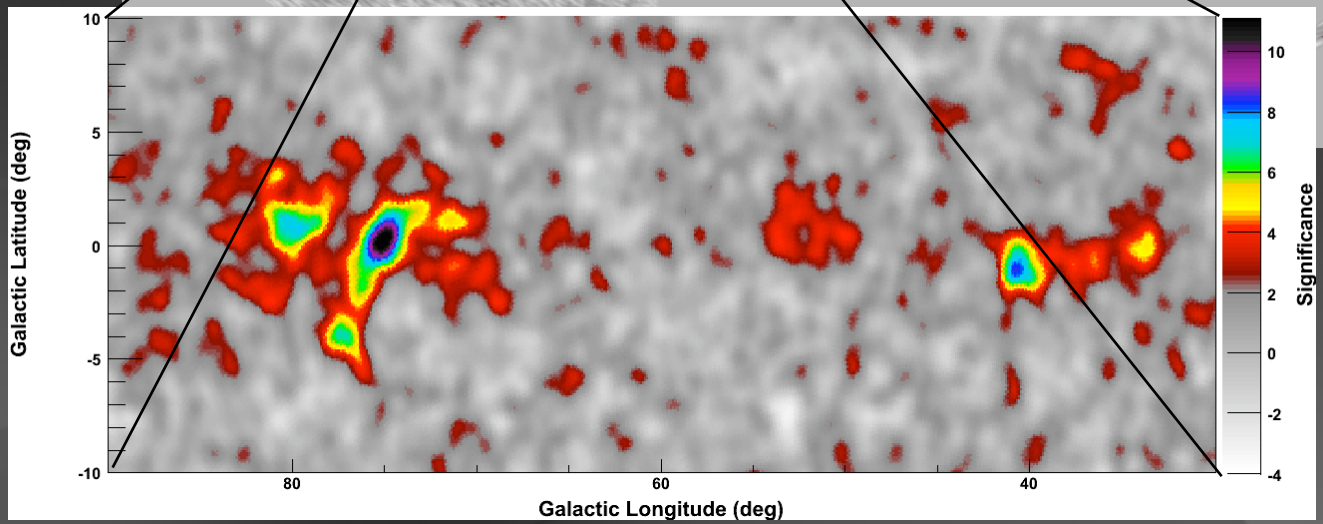
Galactic cosmic rays

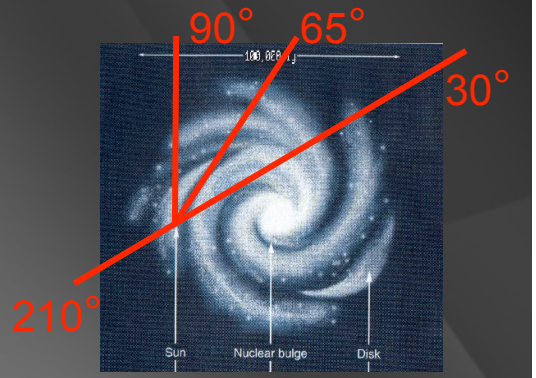


galactic plane in 10 TeV gamma rays :
supernova remnants in star forming regions



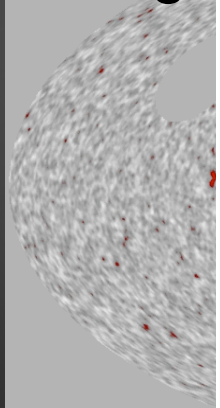




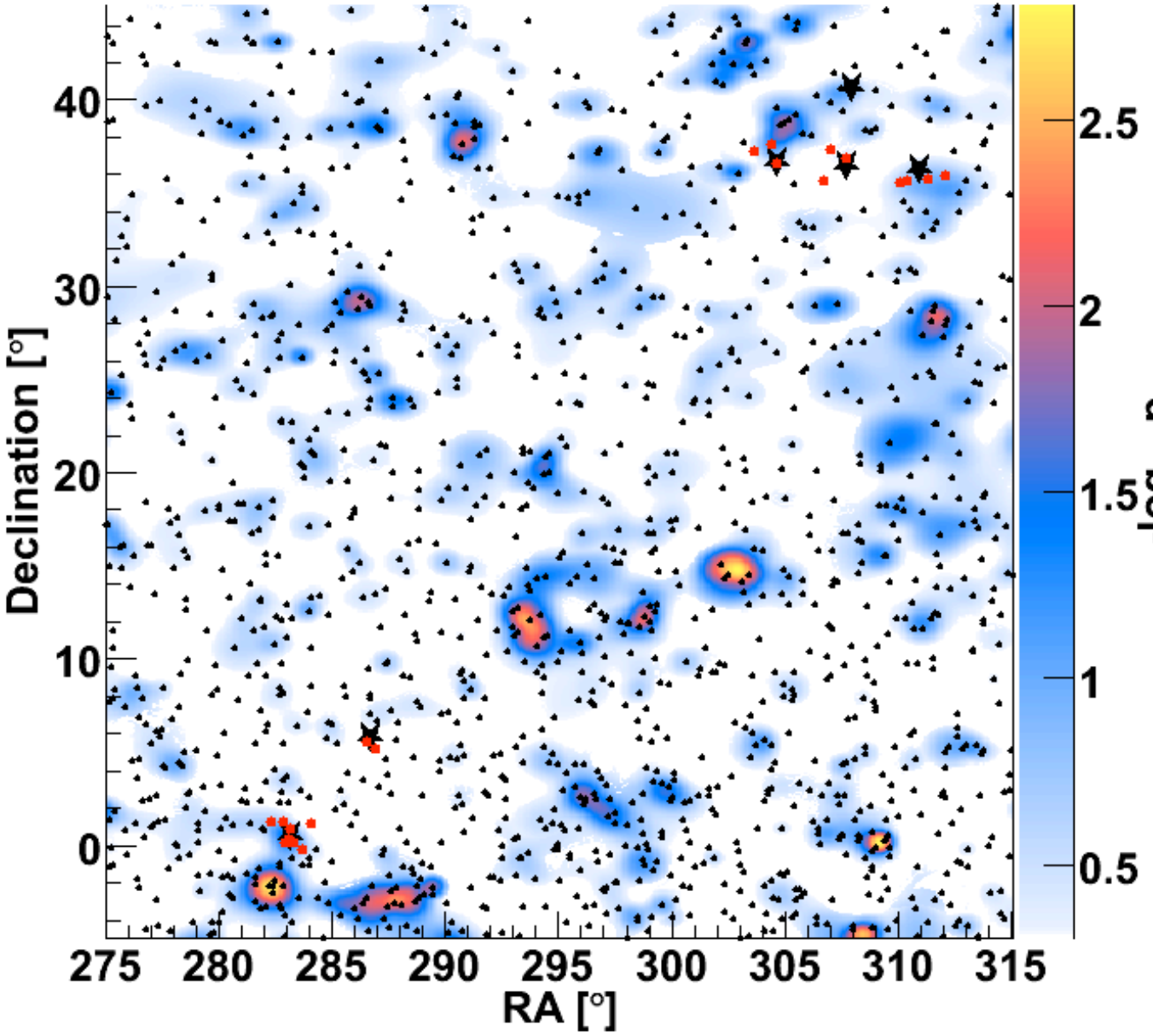


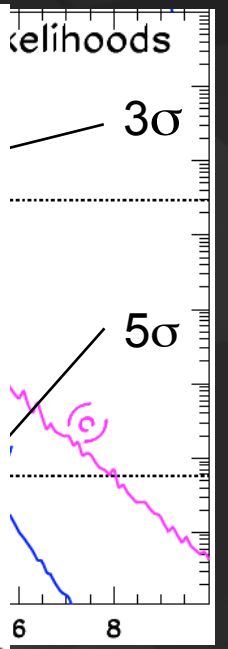
milagro

Milagr

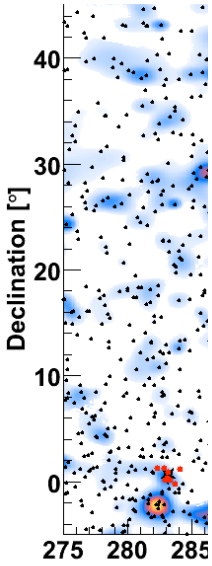


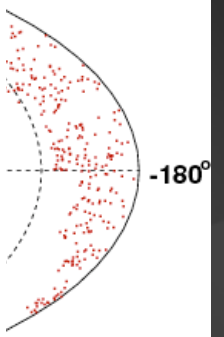
preliminary



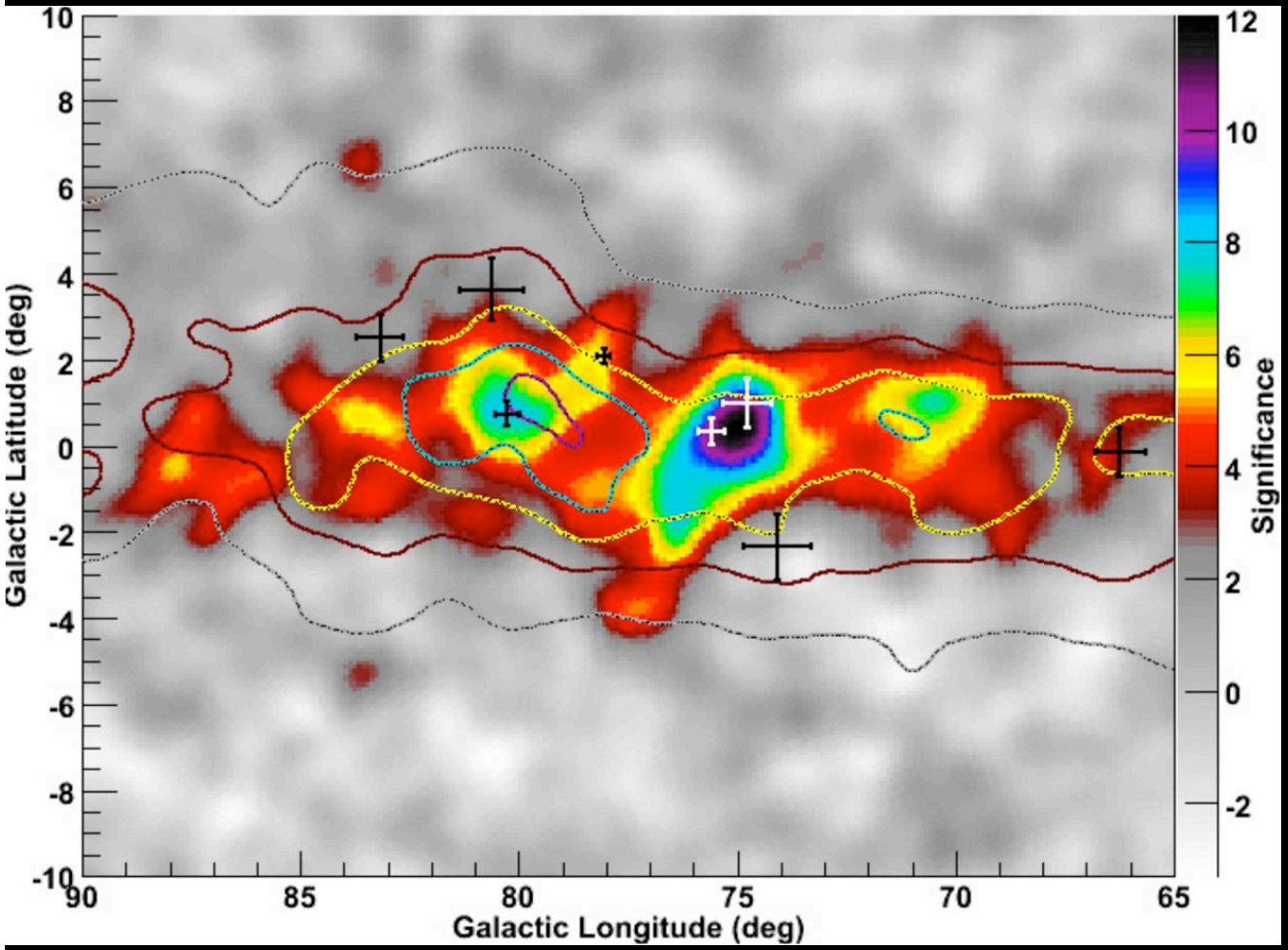


years





cygnus region : Milagro

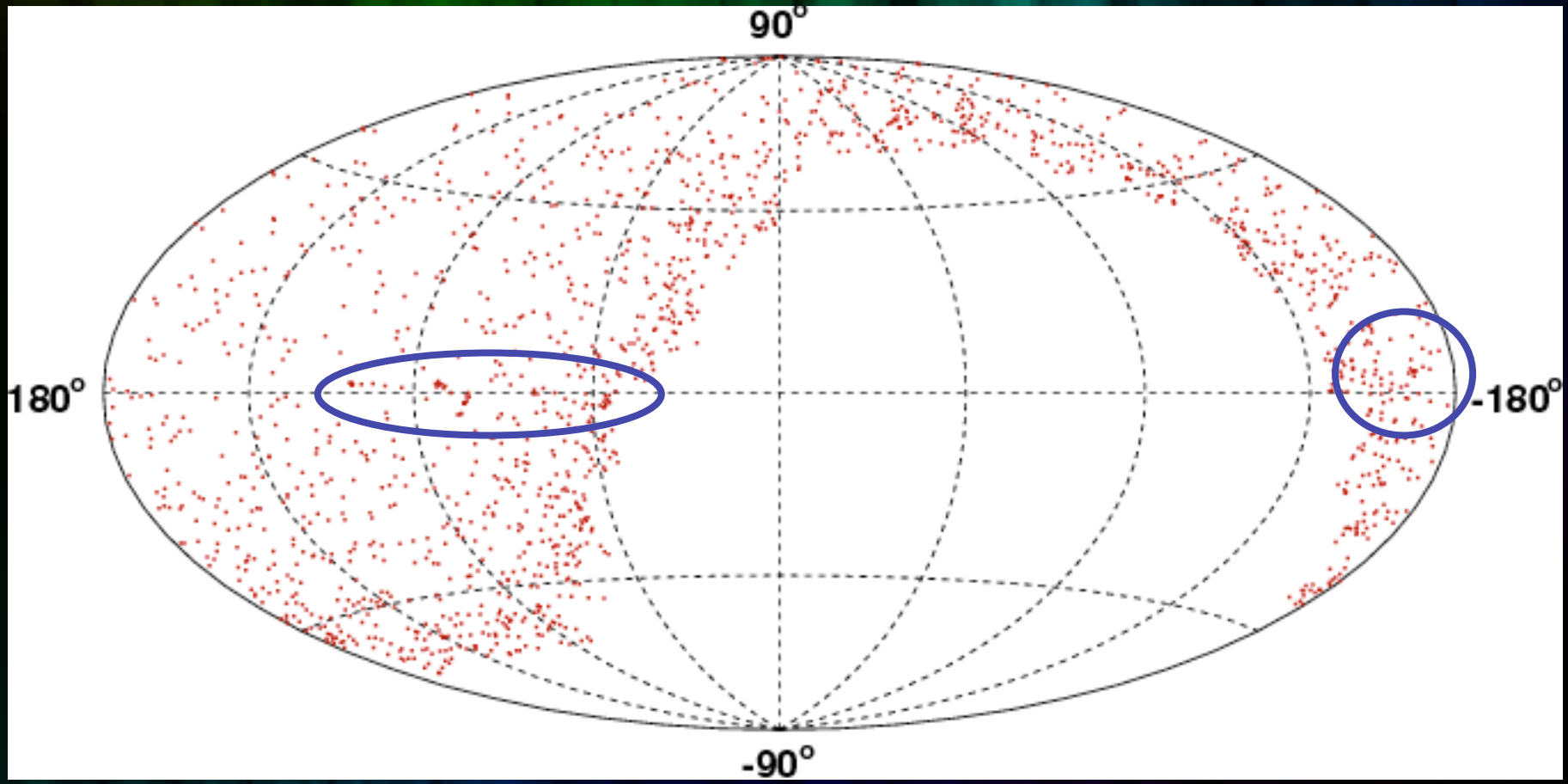


Milagro

translation of
TeV gamma rays
into
TeV neutrinos

3 ± 1 ν per year in IceCube per source

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



20,000 atmospheric neutrinos later …

STACKING 6 MILAGRO SNR

Preliminary

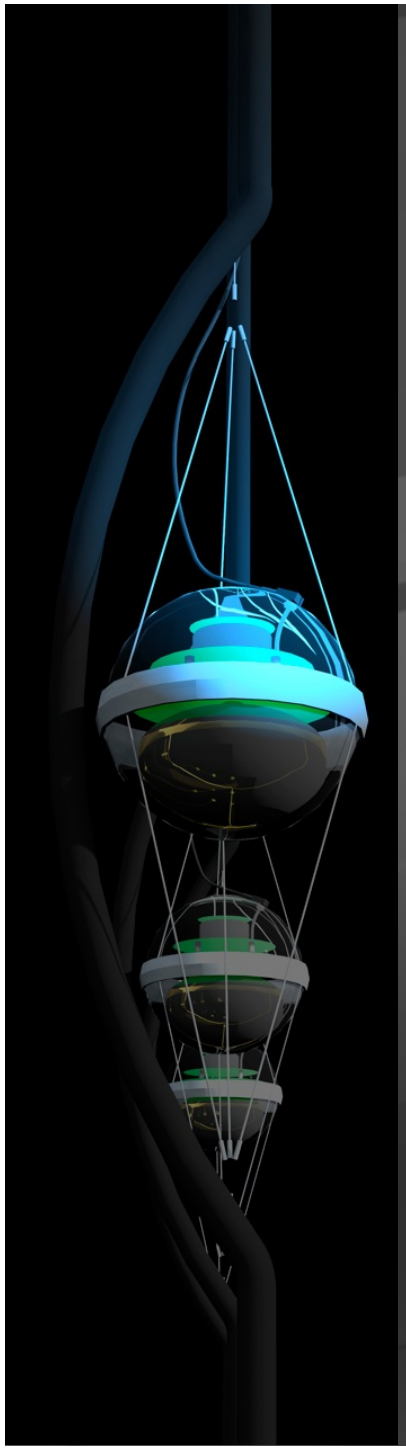
IC40 Stacking Search	Med. Sensitivity	90% Upper Limit
Milagro 6 SNR	2.05 * prediction	5.50 * prediction

3.0 events in IC40 predicted by flux from Halzen, Kappes, O'Murchadha (2008)

p-values of 6 Milagro SNR stacked searches:

AMANDA 7-yr	22-strings	40-strings
20%	27%	2.3%

(a posteriori)



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  - atmospheric muons
- atmospheric neutrino spectrum
- atmospheric muon spectrum: first surprise
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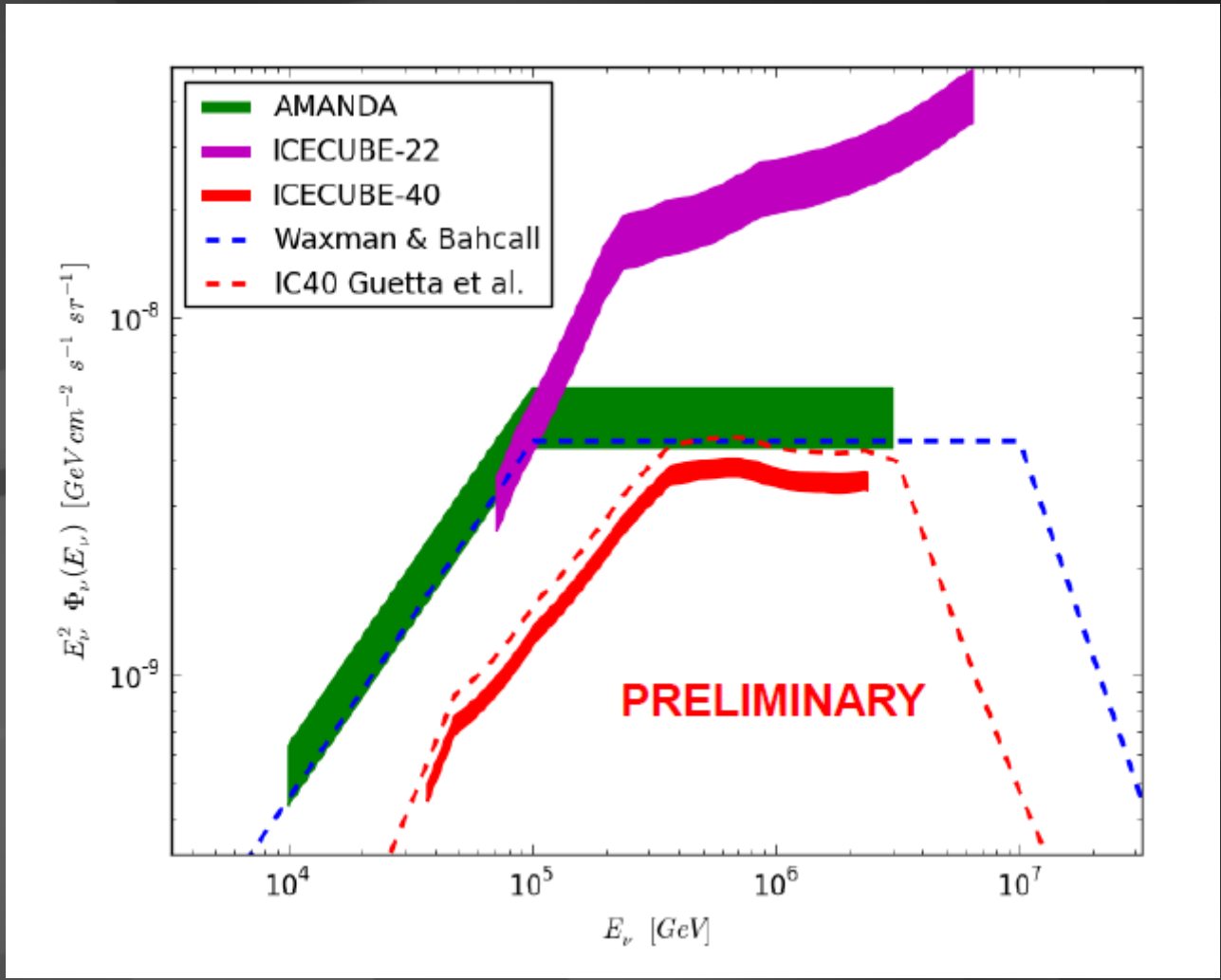
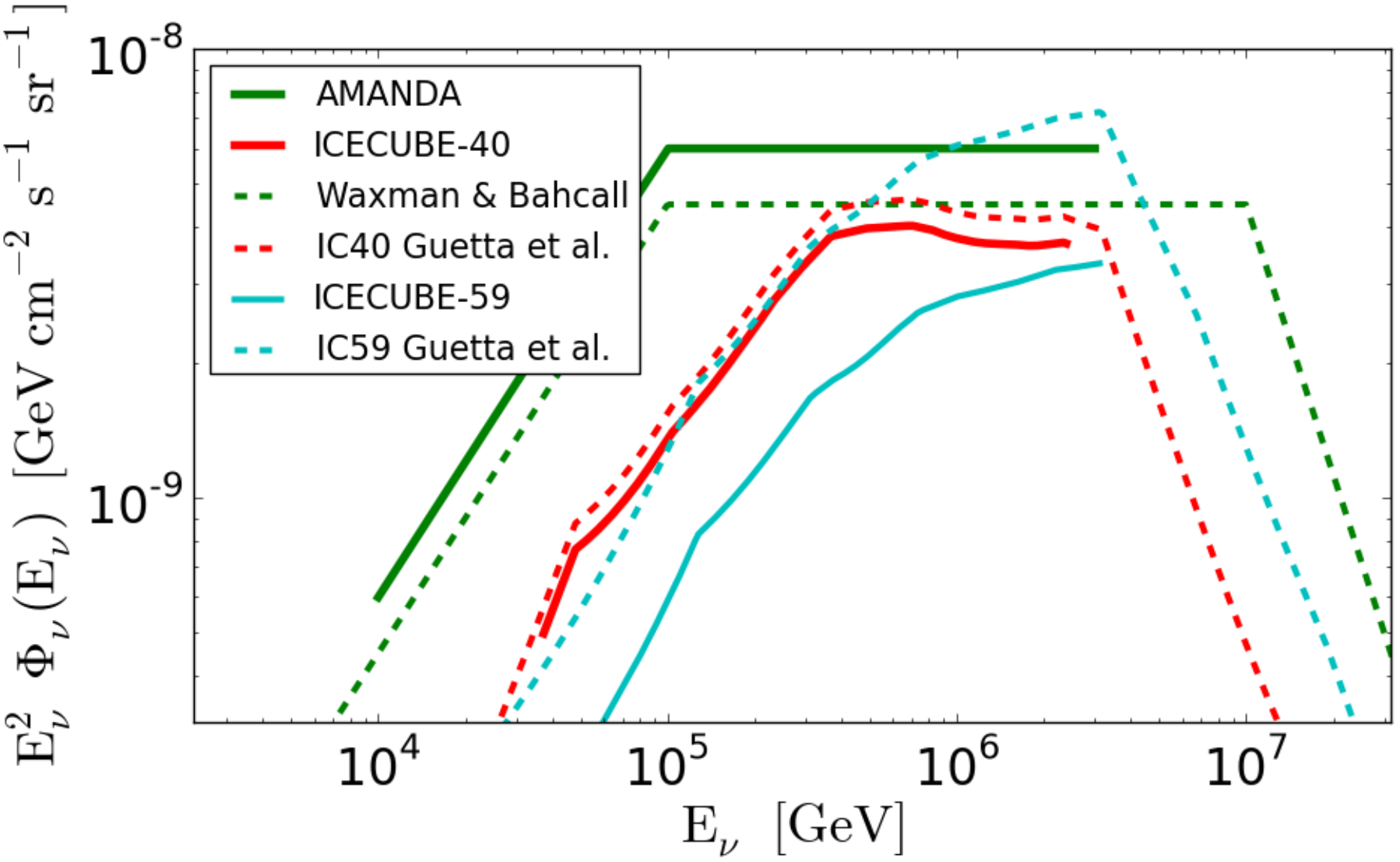
GRB

protons and photons co-exist in the fireball →

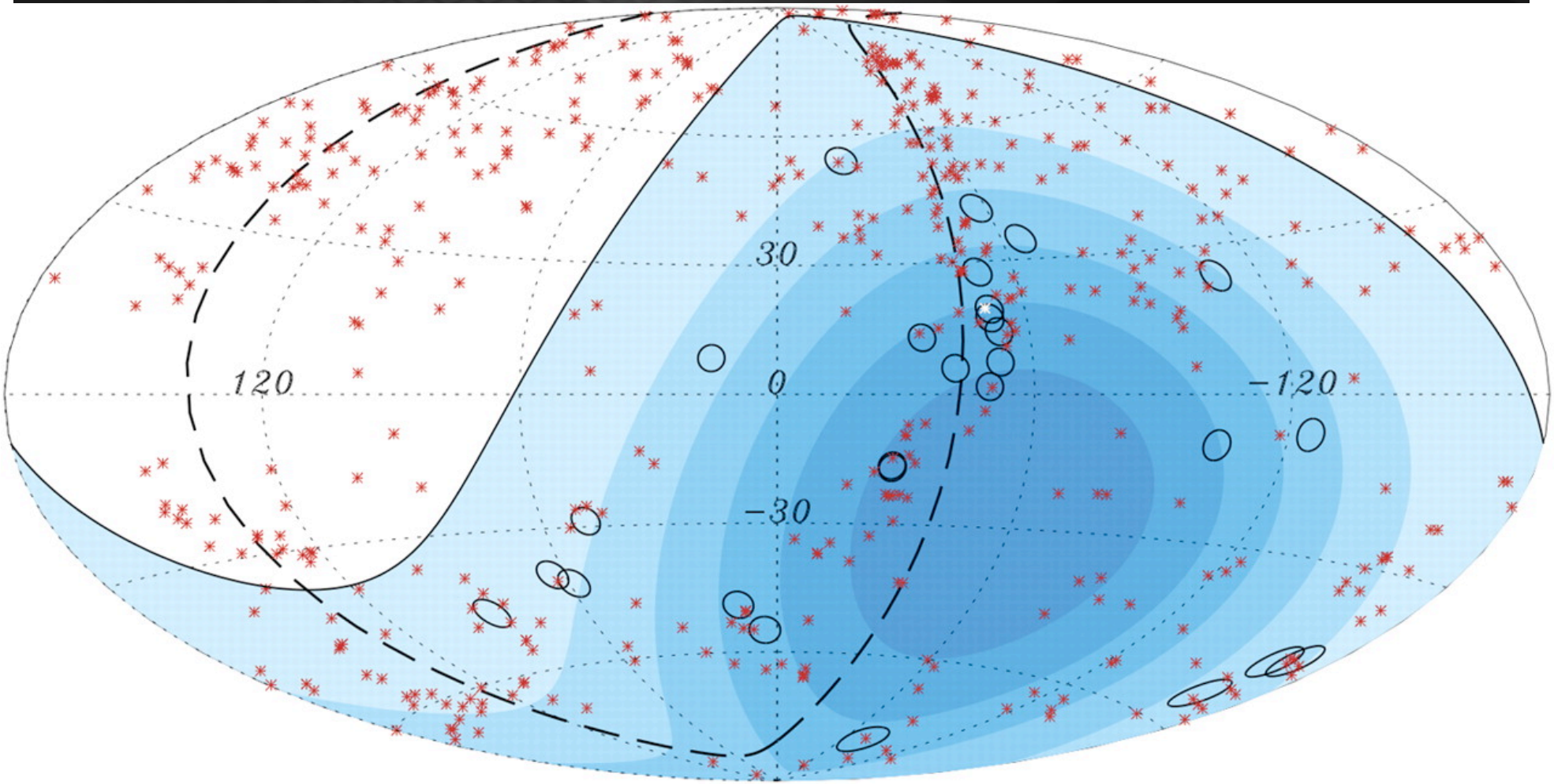
ν production



- proton flux = observed cosmic ray flux (WB)
- observation of 117 burst with IceCube-40 strings
- 4 events expected, none seen

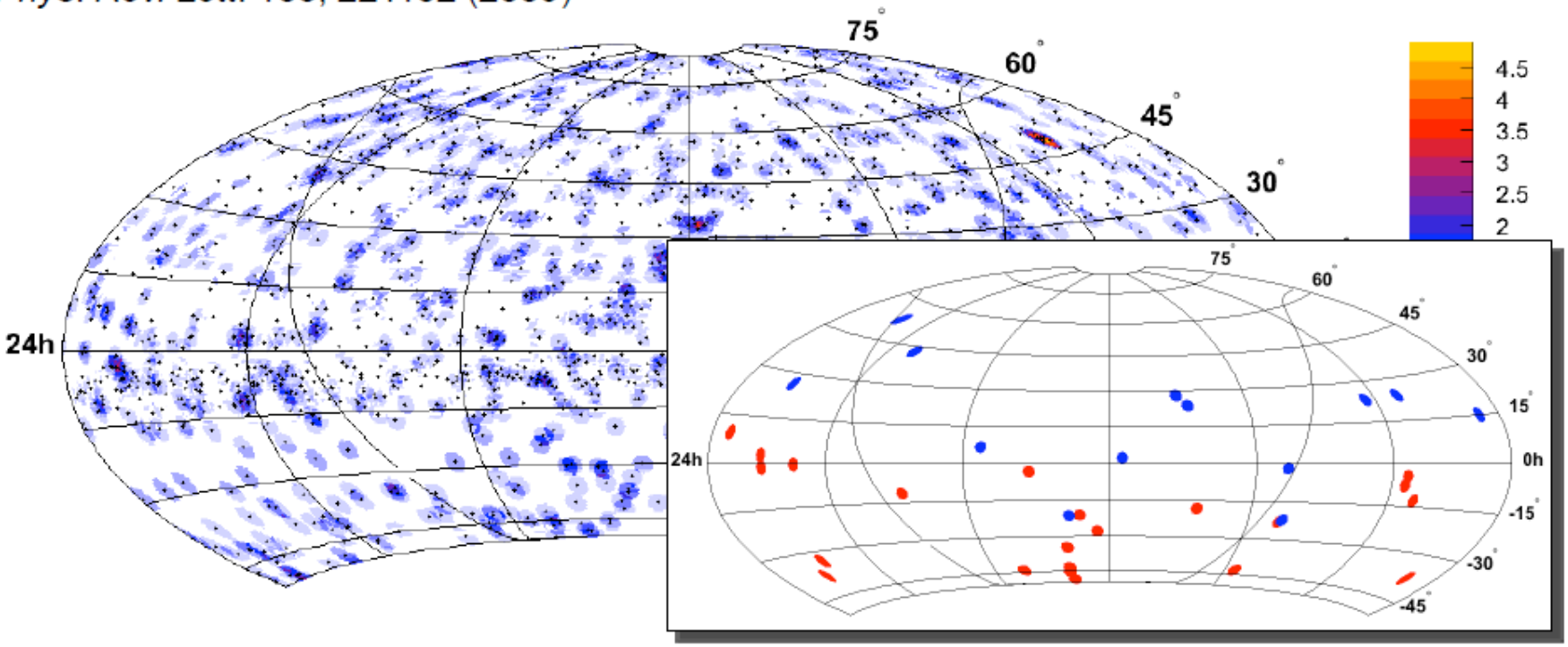

AMANDA
ICECUBE-40
Waxman & Bahcall
IC40 Guetta et al.
ICECUBE-59
IC59 Guetta et al.
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
E_ν [GeV]
$E_\nu^2\ \Phi_\nu(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]

Auger : the sources revealed ?



correlation of arrival directions with active galaxies

Phys. Rev. Lett. 103, 221102 (2009)

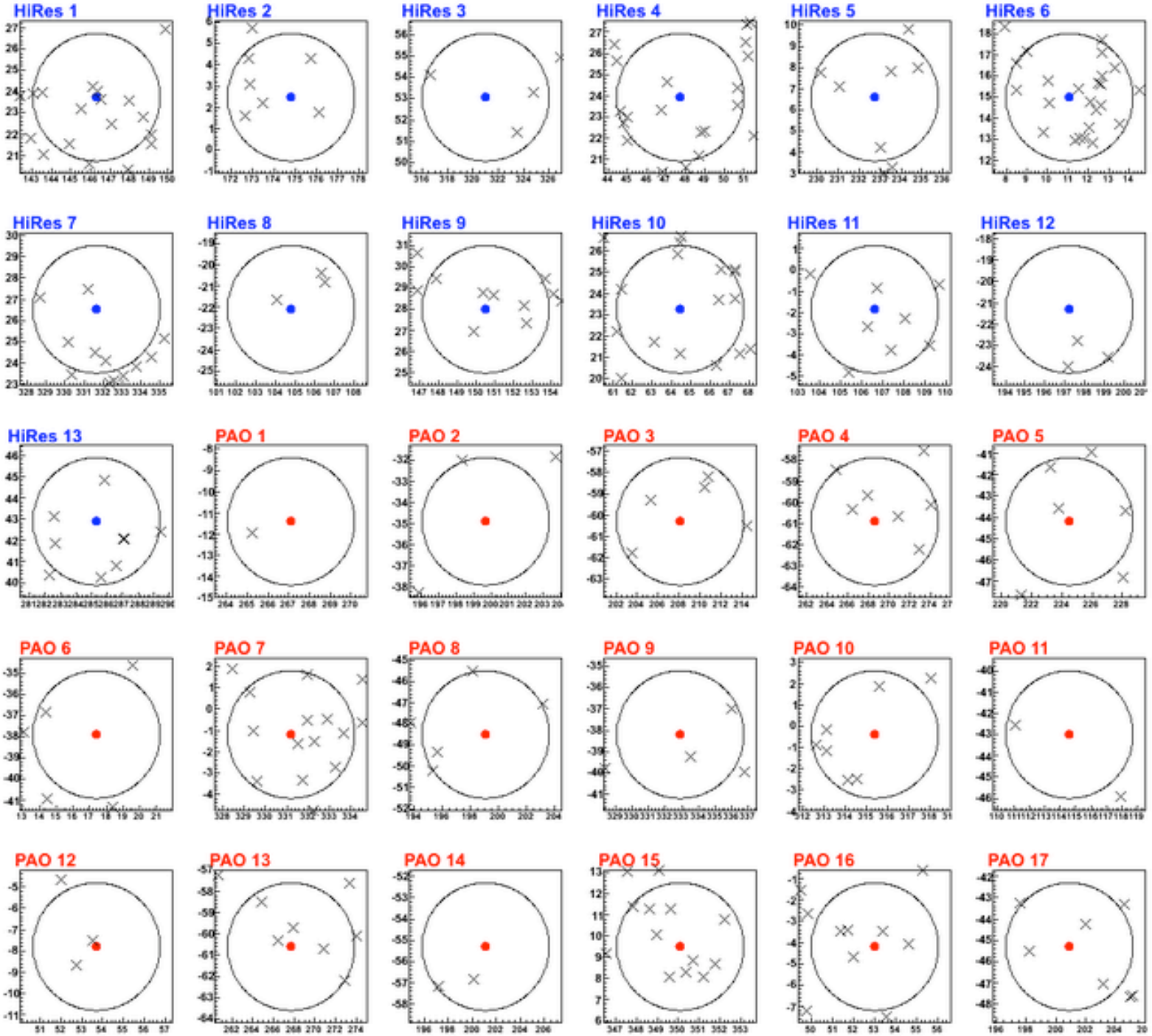


Look for neutrinos from entire sky by demanding high energies (~PeV)

- Reduces data to 1,877 events; max *p*-value 37.4% – not significant

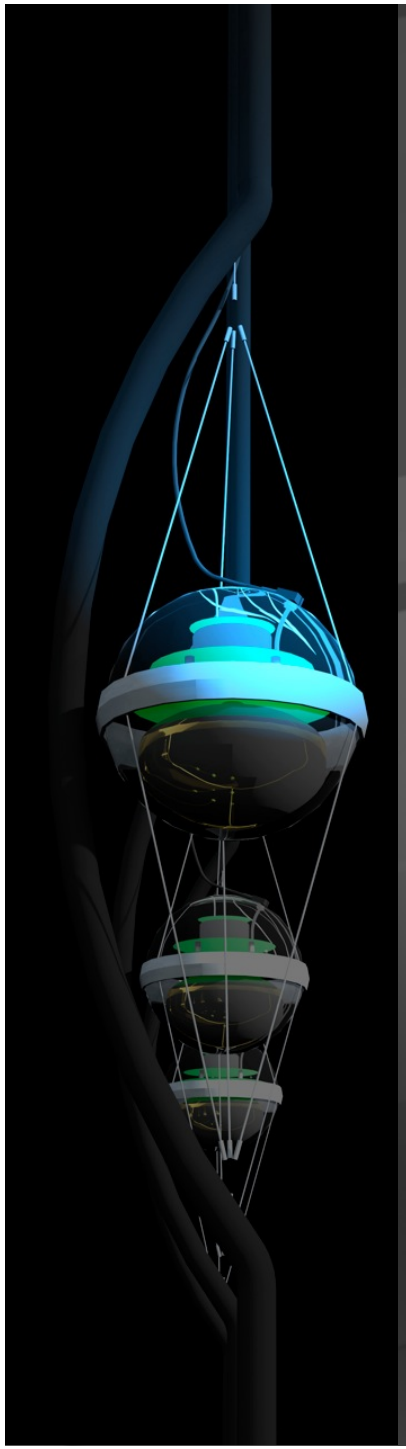
Also search for correlations with Auger, HiRes UHE events within 3º radius

- Observe 60 events, 43.7 expected → *p*-value 0.98%, 2.33σ (preliminary)


HiRes 1
HiRes 2
HiRes 3
HiRes 4
HiRes 5
HiRes 6
HiRes 7
HiRes 8
HiRes 9
HiRes 10
HiRes 11
HiRes 12
HiRes 13
PAO 1
PAO 2
PAO 3
PAO 4
PAO 5
PAO 6
PAO 7
PAO 8
PAO 9
PAO 10
PAO 11
PAO 12
PAO 13
PAO 14
PAO 15
PAO 16
PAO 17

	IC-40 results	IC-22 results
HiRes 4		
events (real/expected)	10 / 6.6	1 / 1.0
pre-trial p-value	0.13	0.73
pre-trial sigma	1.12	-
HiRes 6		
events (real/expected)	21 / 7.7	2 / 1.3
pre-trial p-value	0.000047	0.36
pre-trial sigma	3.91	0.36
PAO 1		
events (real/expected)	1 / 1.2	7 / 2.3
pre-trial p-value	-	0.009
pre-trial sigma	-	2.35

RA 11.07° Dec. 14.99°



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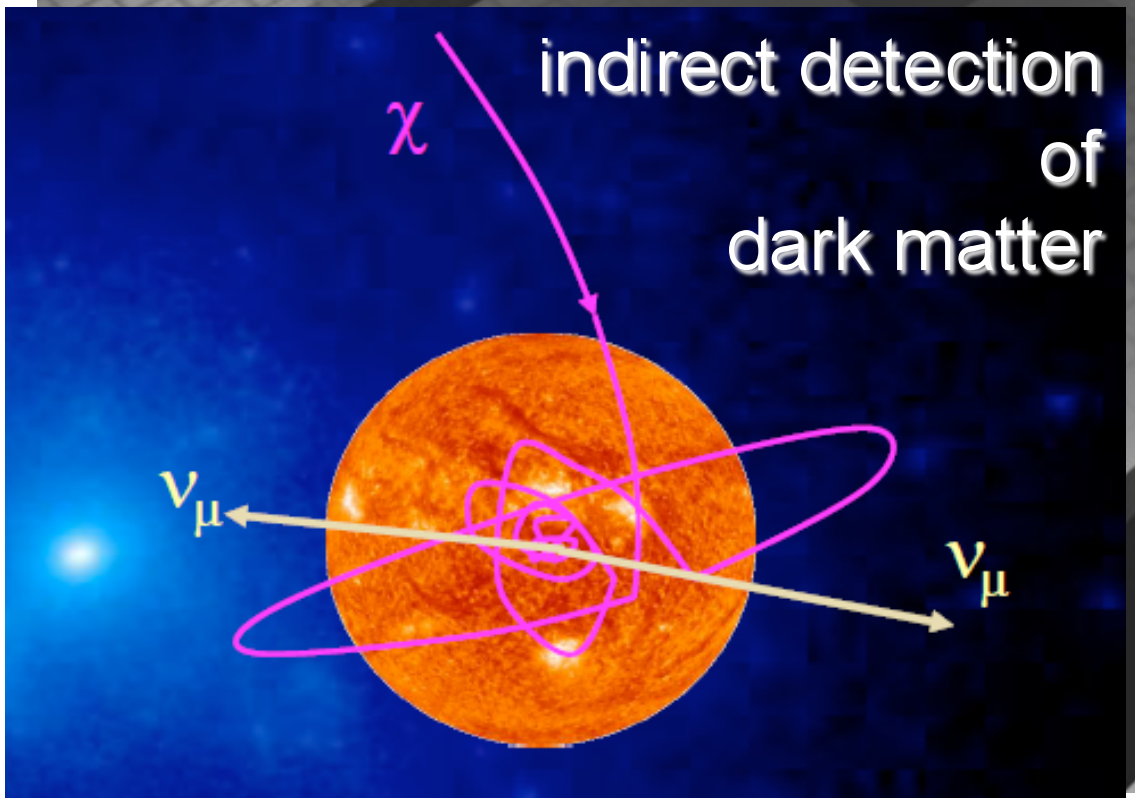
- capture

$$\frac{dN}{dt} = C_{cap} - C_{ann} N^2$$

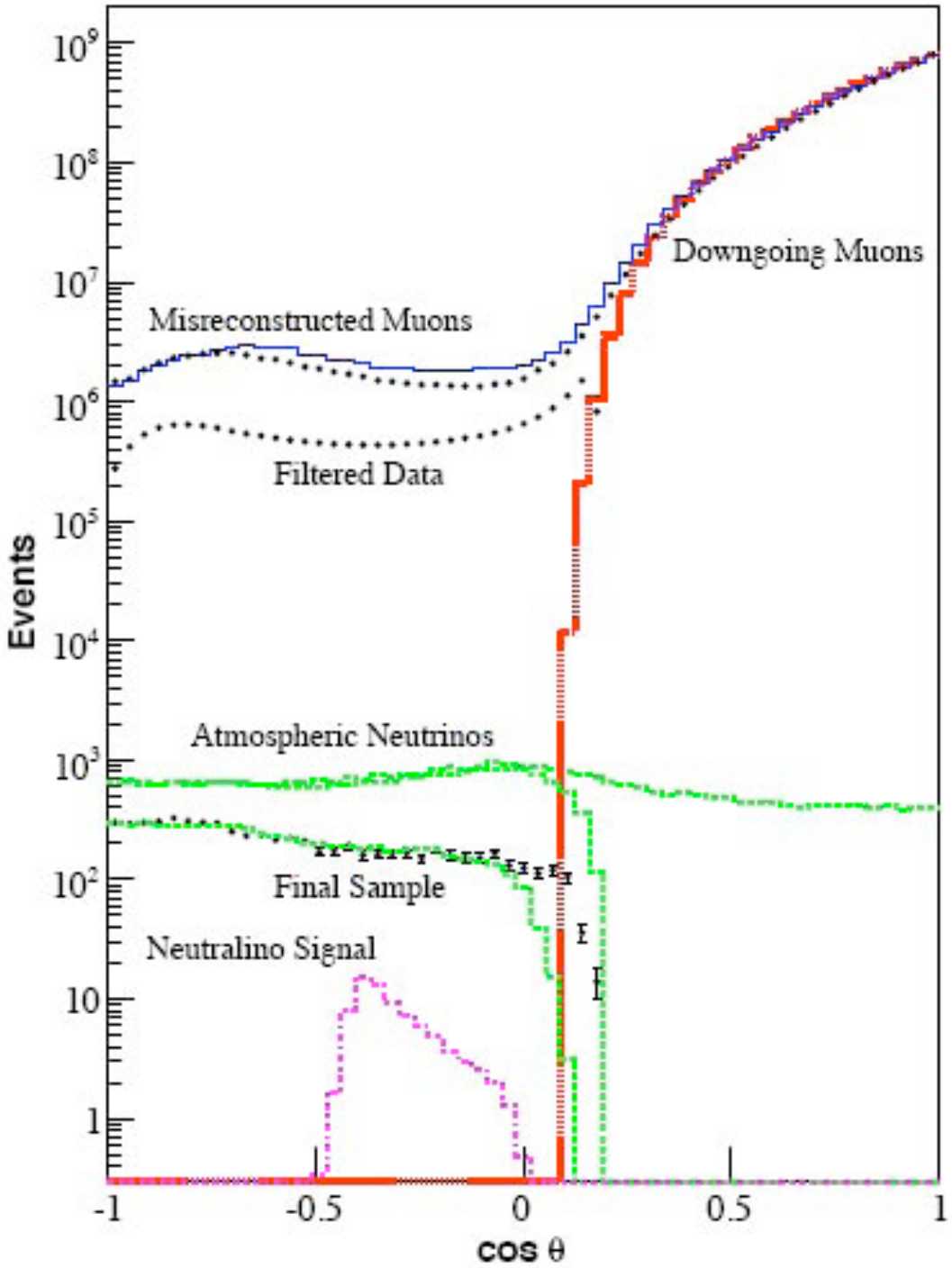
- equilibrium

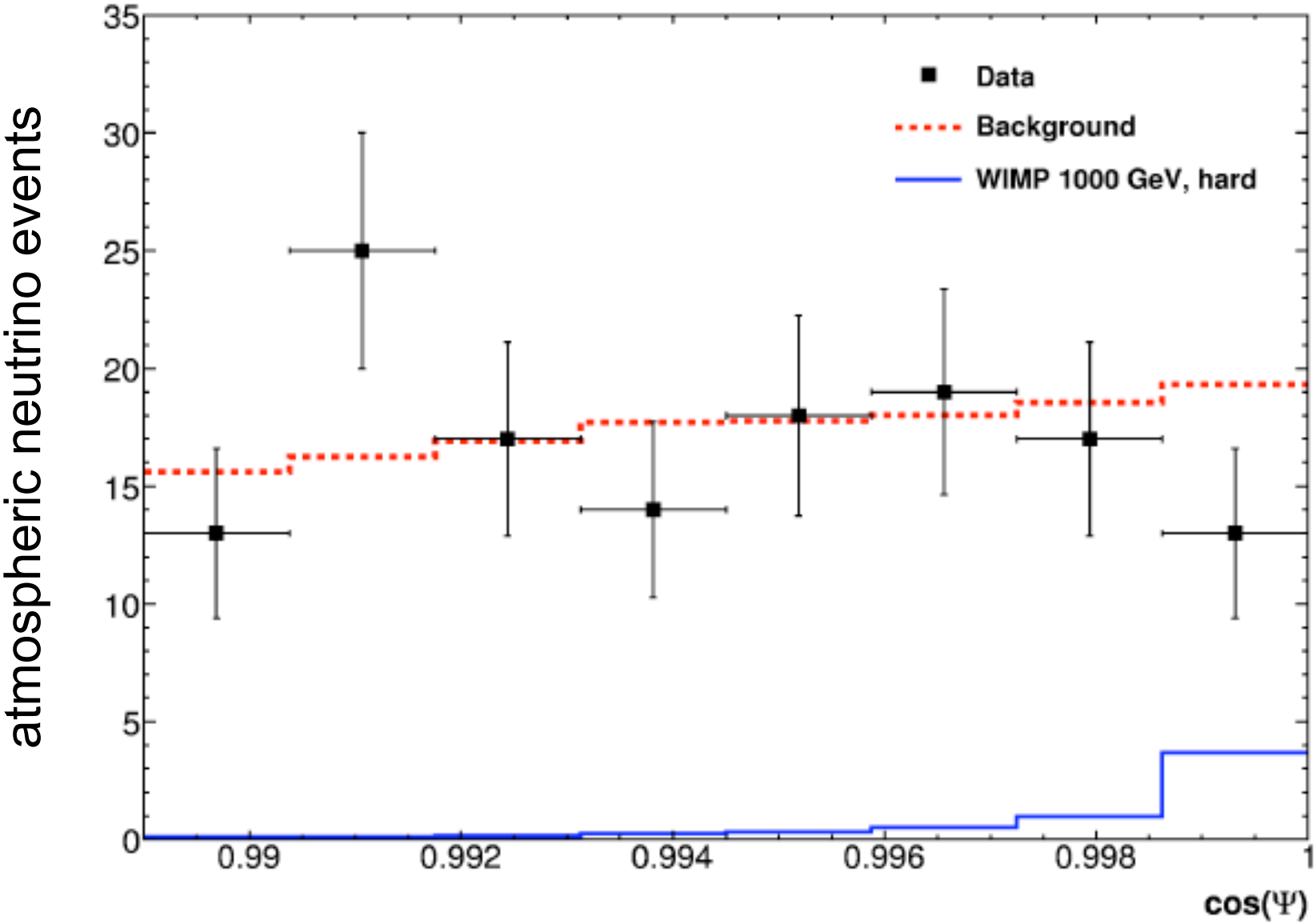
$$\Gamma_{ann} = \frac{1}{2} C_{ann} N^2 = \frac{1}{2} C_{cap}$$



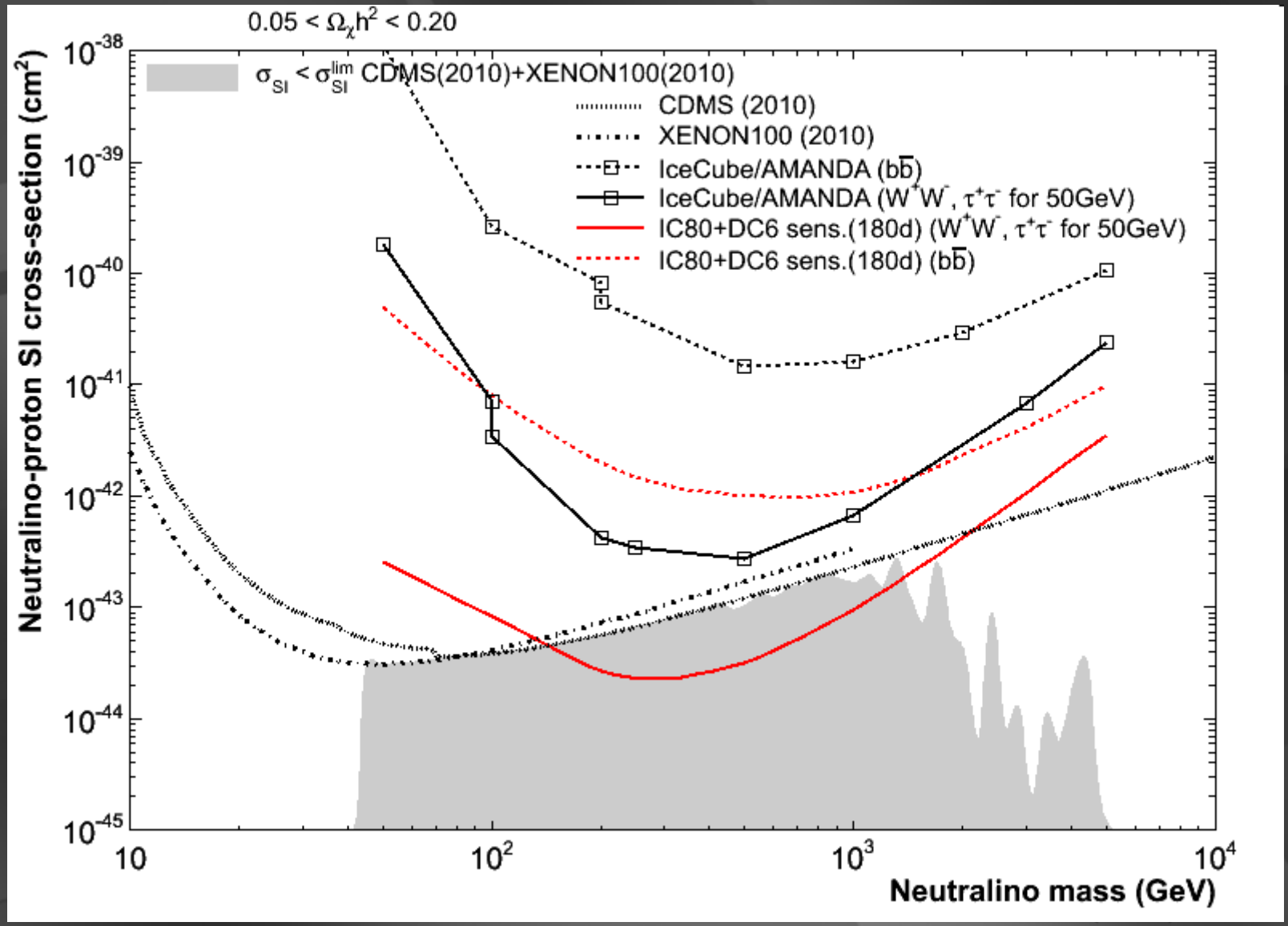
neutrino flux

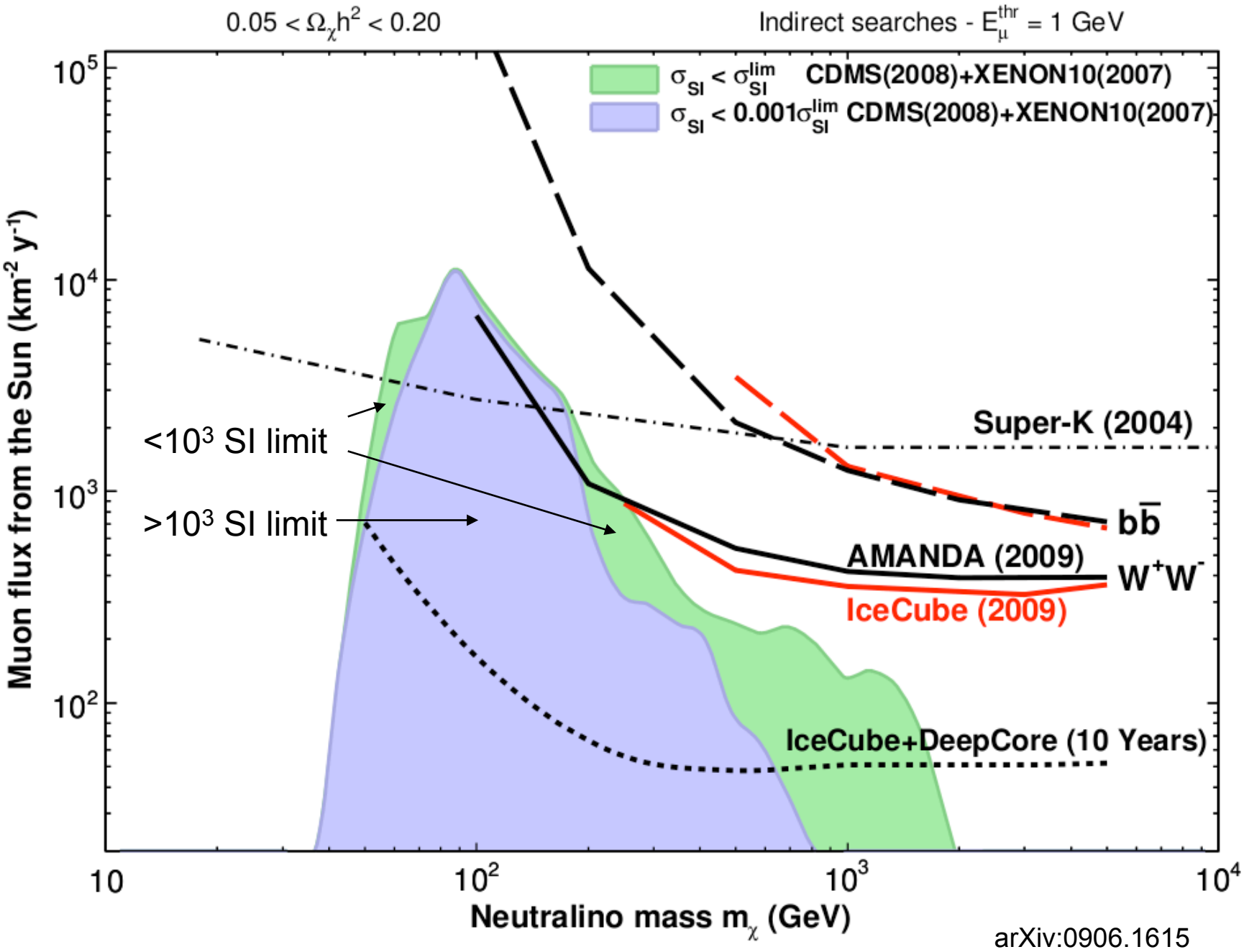
wimp-nucleon cross section


Events
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Misreconstructed Muons
Downgoing Muons
Filtered Data
Atmospheric Neutrinos
Final Sample
Neutralino Signal
-1
-0.5
0
0.5
1
cos θ

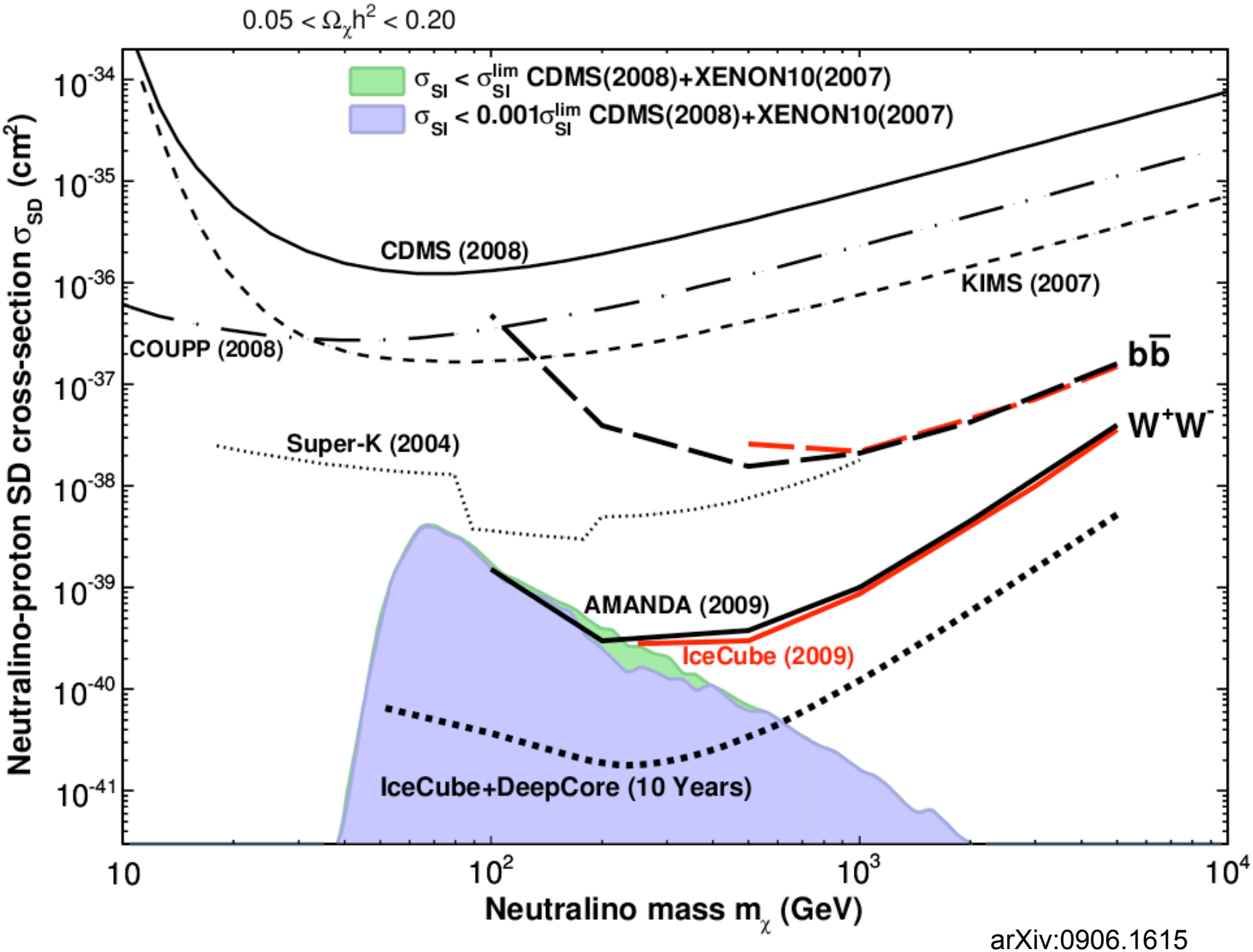

atmospheric neutrino events
35
30
25
20
15
10
5
0
0.99
0.992
0.994
0.996
0.998
1
cos(Ψ)
Data
Background
WIMP 1000 GeV, hard
the sun

sensitivity to wimps with spin-*independent* interactions





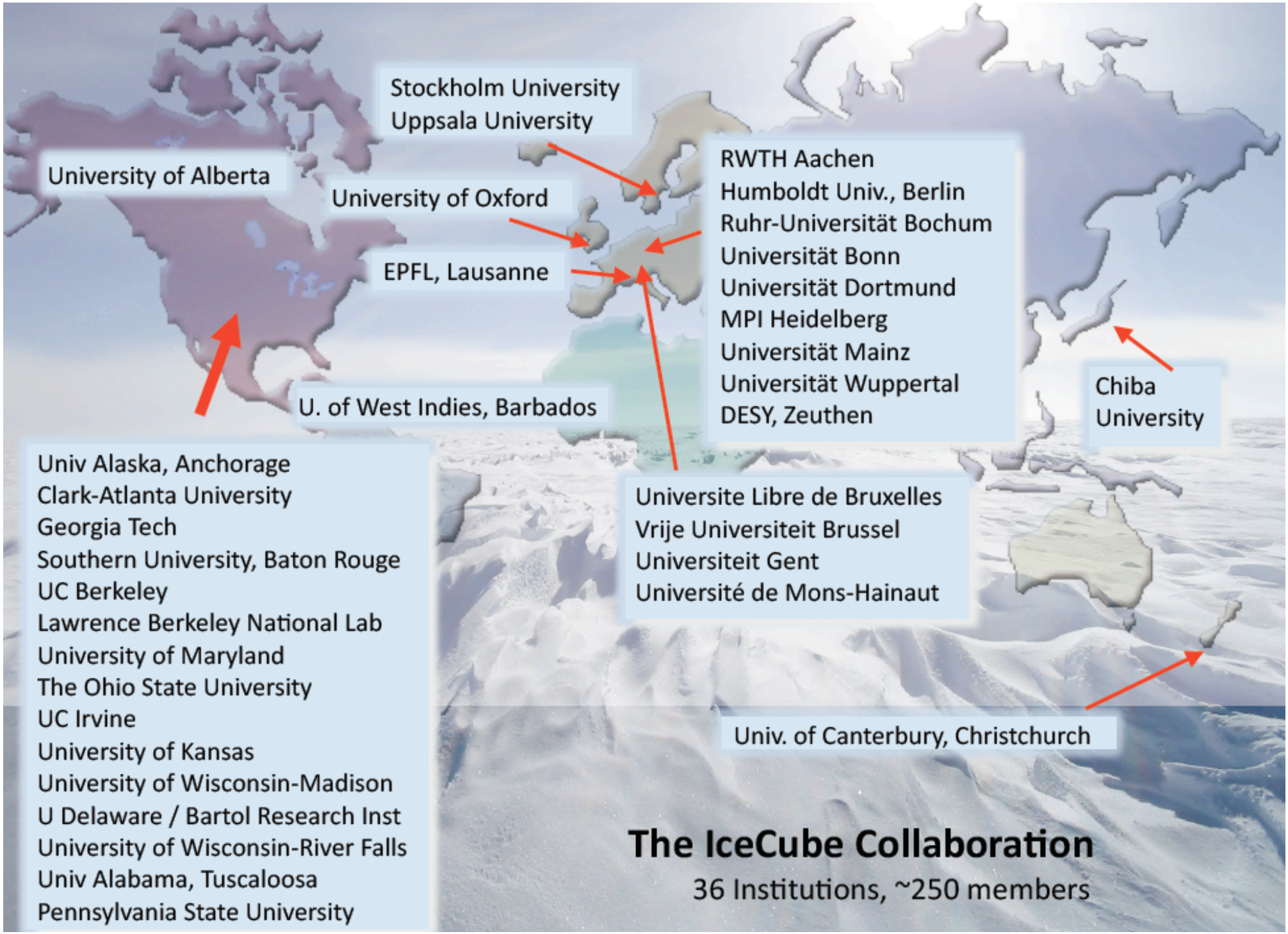
arXiv:0906.1615



arXiv:0906.1615

conclusions

- none yet, but
- the instrumentation is in place
- or almost in place ….


Stockholm University
Uppsala University
University of Alberta
University of Oxford
EPFL, Lausanne
RWTH Aachen
Humboldt Univ., Berlin
Ruhr-Universität Bochum
Universität Bonn
Universität Dortmund
MPI Heidelberg
Universität Mainz
Universität Wuppertal
DESY, Zeuthen
Chiba University
U. of West Indies, Barbados
Univ Alaska, Anchorage
Clark-Atlanta University
Georgia Tech
Southern University, Baton Rouge
UC Berkeley
Lawrence Berkeley National Lab
University of Maryland
The Ohio State University
UC Irvine
University of Kansas
University of Wisconsin-Madison
U Delaware / Bartol Research Inst
University of Wisconsin-River Falls
Univ Alabama, Tuscaloosa
Pennsylvania State University
Universite Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut
Univ. of Canterbury, Christchurch
The IceCube Collaboration
36 Institutions, ~250 members