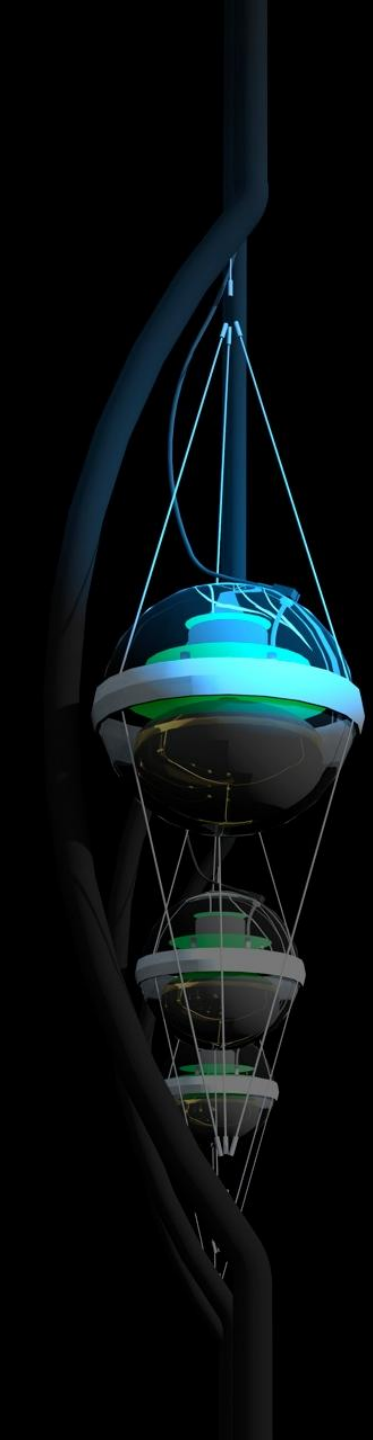
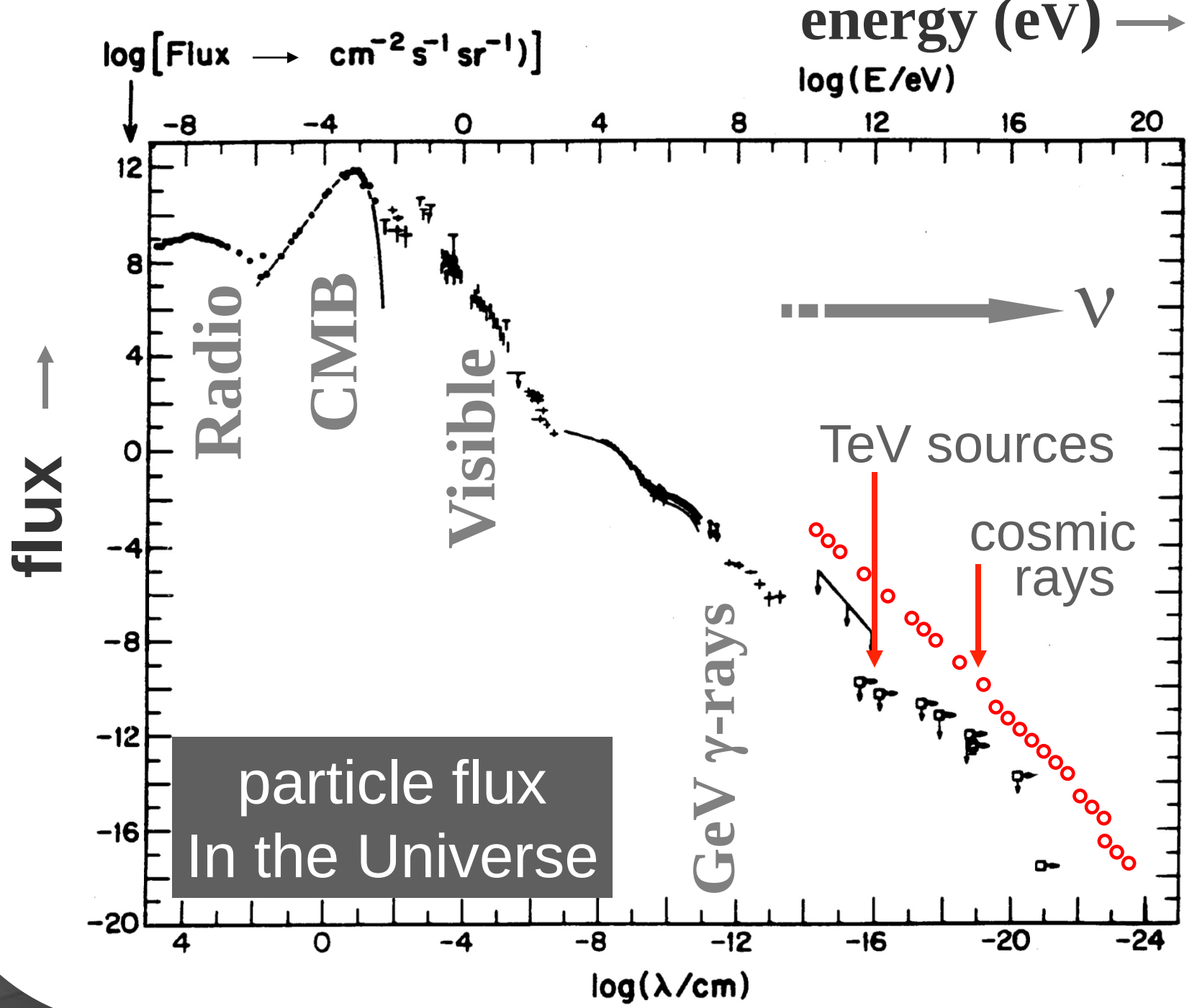
neutrino astronomy

francis halzen
university of wisconsin
http://icecube.wisc.edu



- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies
- particle physics, mostly dark matter

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 interact with the microwave background

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

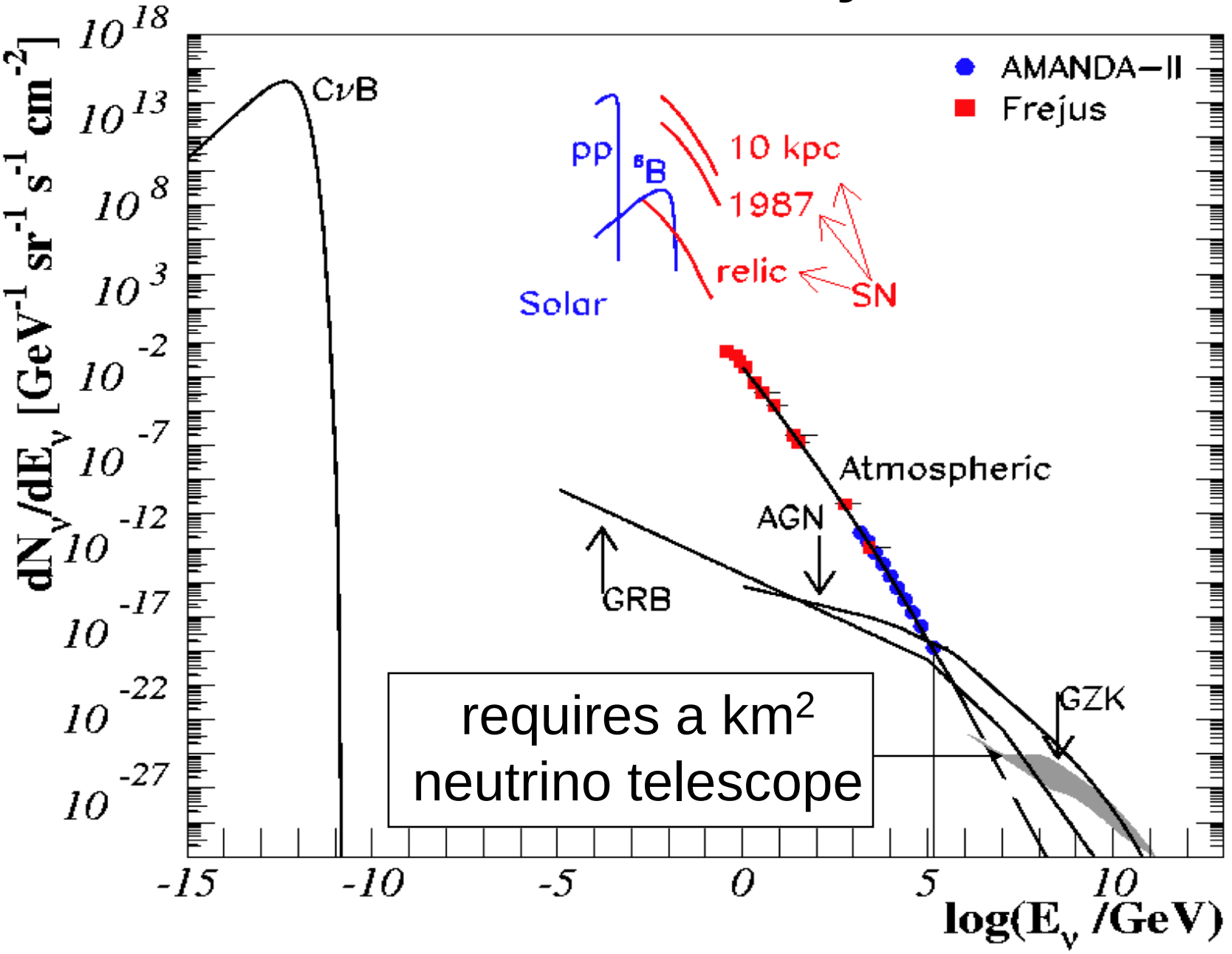
cosmic rays disappear, neutrinos appear

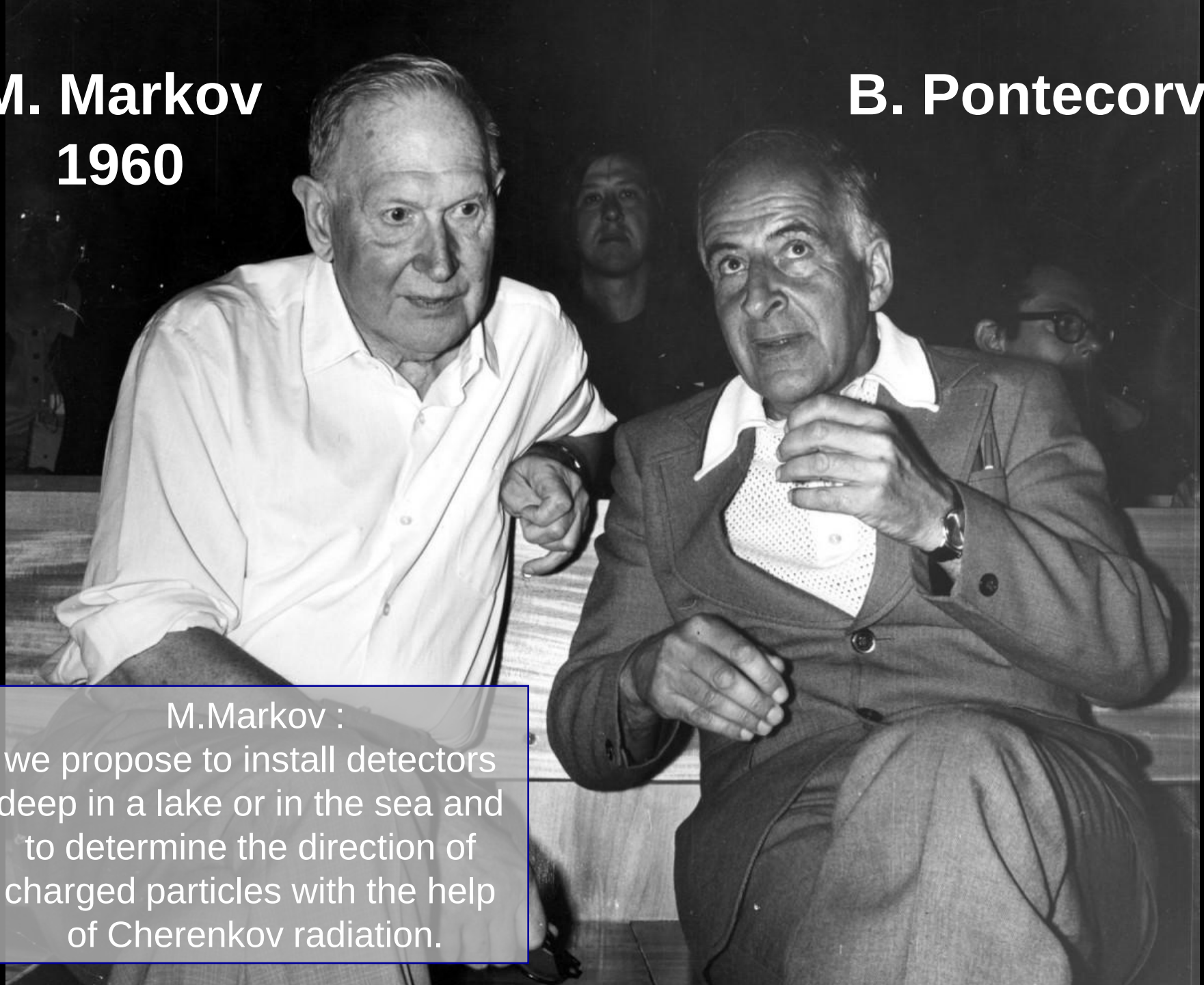
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

$$E_{\upsilon} \geq 2 \times 10^{6} TeV$$

~ 1 GZK event per kilometer cube per year

neutrino sky

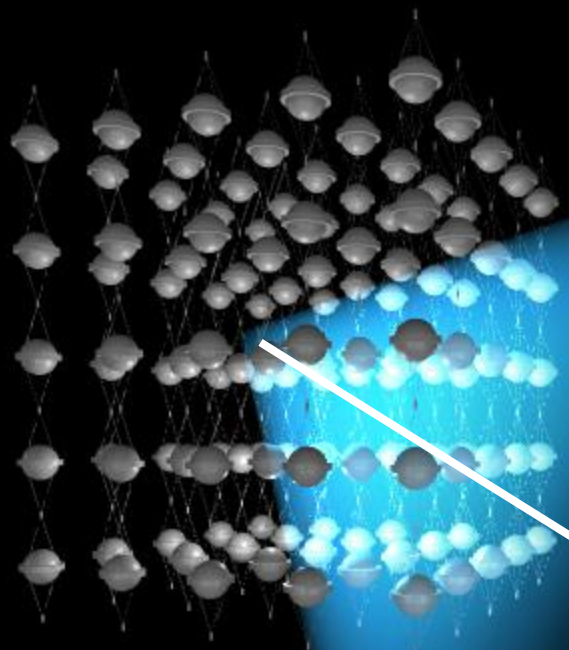




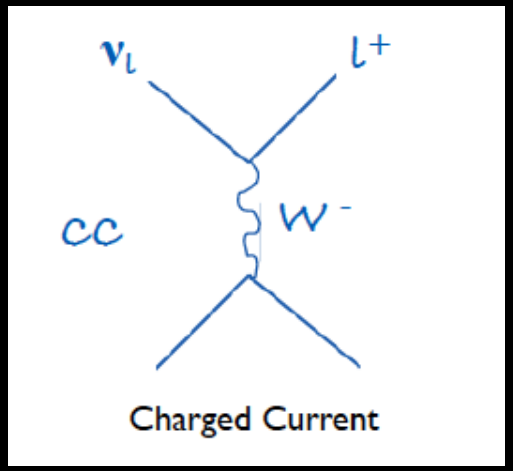
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

- shielded and optically transparent medium

$$P_{\mu\to\nu} = \frac{\lambda_\mu}{\lambda_\nu} = n\sigma_\nu R_\mu$$



μ

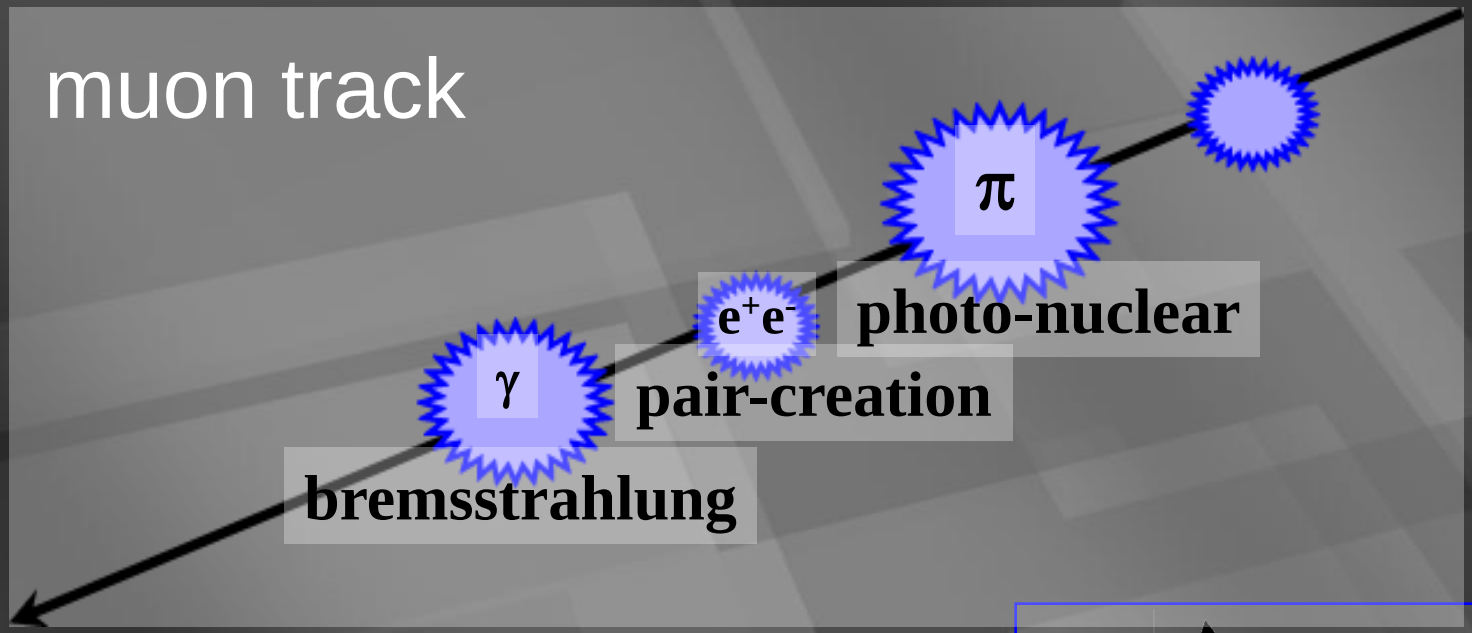


ν

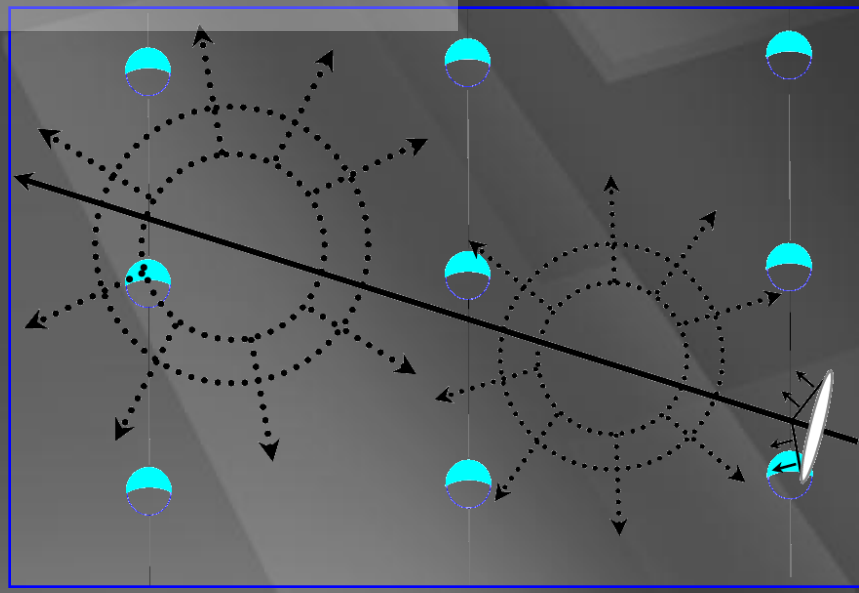
- lattice of photomultipliers

photomultiplier tube

energy measurement (> 1 TeV)

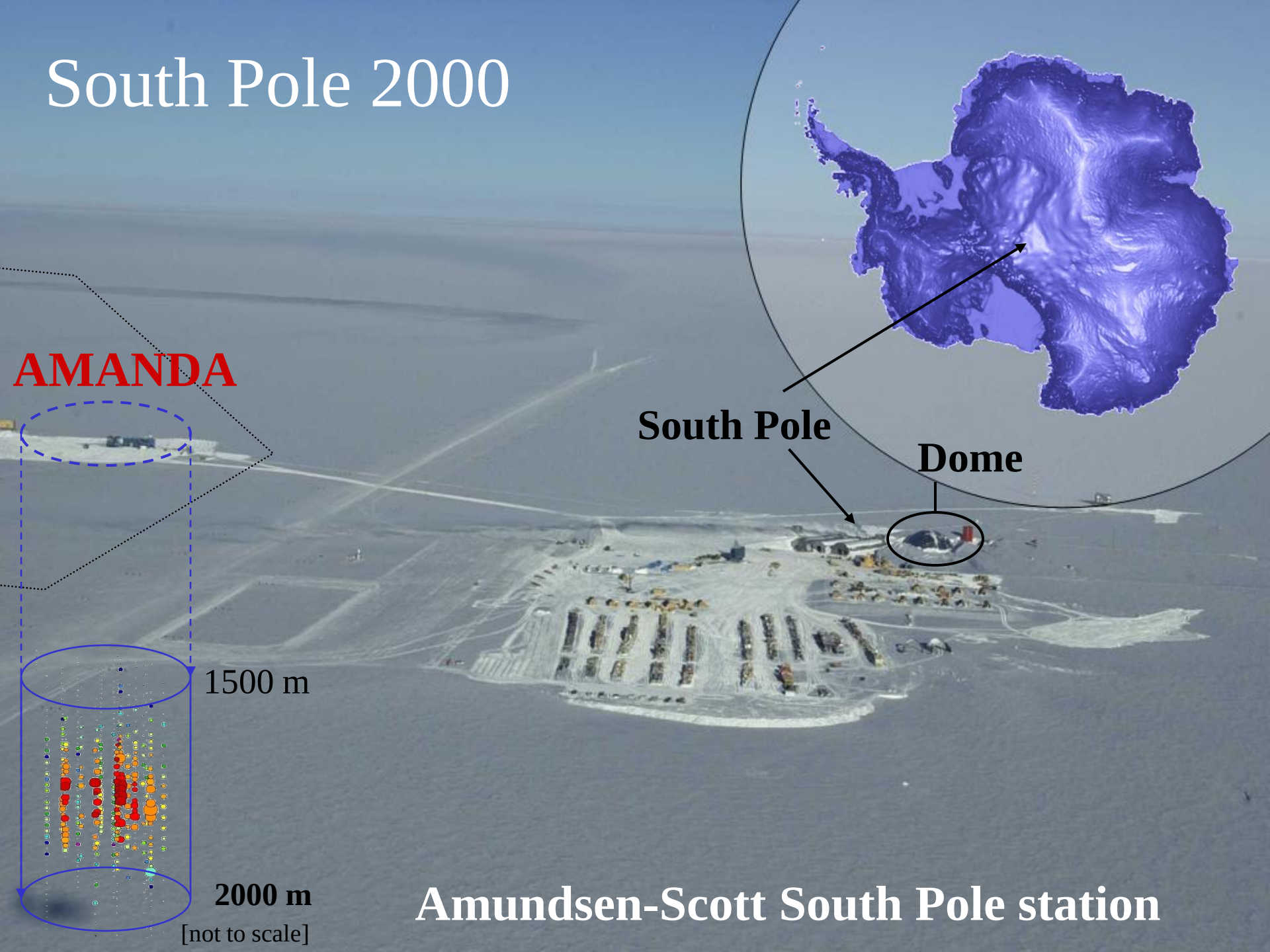


convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



50,000 year old sterile ice instead of water

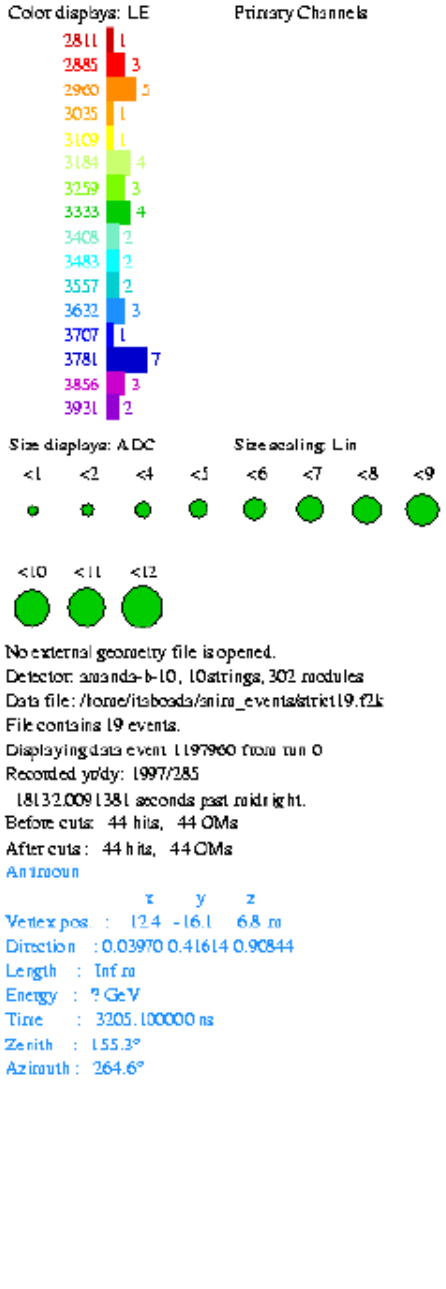
South Pole 2000



AMANDA Event Signatures: Muons

neutrino interaction
$\rightarrow$ muon track

$\nu_\mu + p \rightarrow \mu + \ldots$



ANTARES

neutrinos:
Mediterranean

AMANDA:

- simple
- high voltage supplied via (coax, twisted pair, fibre optic) cable
- analog photomultiplier signal up via same cable
- successful
- photomultiplier pulses after 2 km… not pretty

WHAT DO WE REALLY NEED?

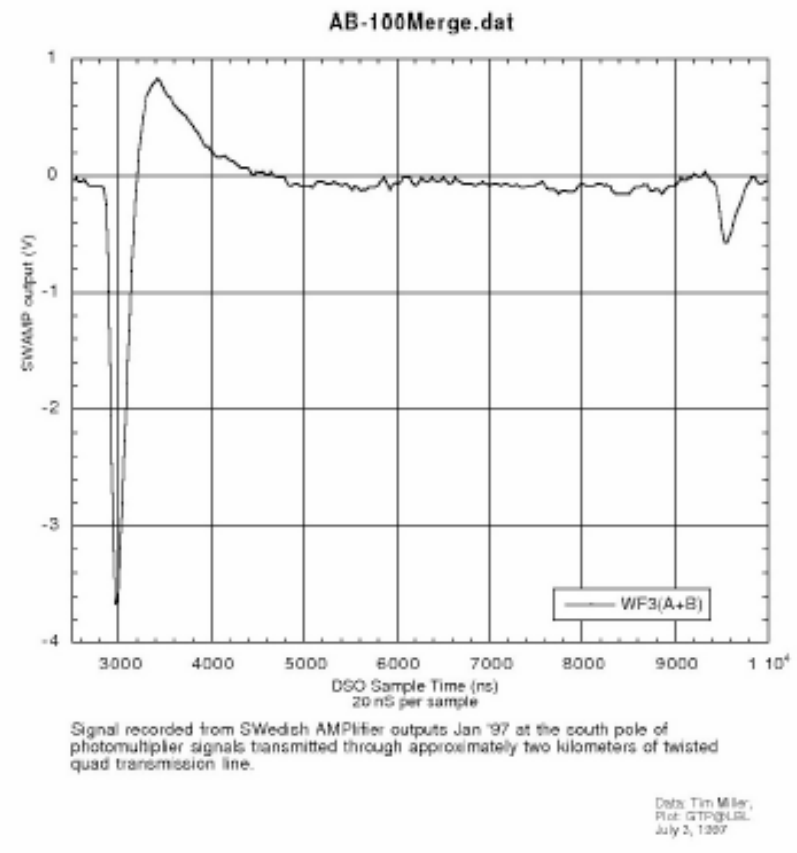
- complex wave form information (scattering in ice)
- large dynamic range; more that 10^6
- low power consumption
- stable operation, easy calibration

ANSWER : ANALOG TO DIGITAL CONVERSION

Each optical module must become a complete semi-autonomous data acquisition platform, linked in an all digital decentralized network

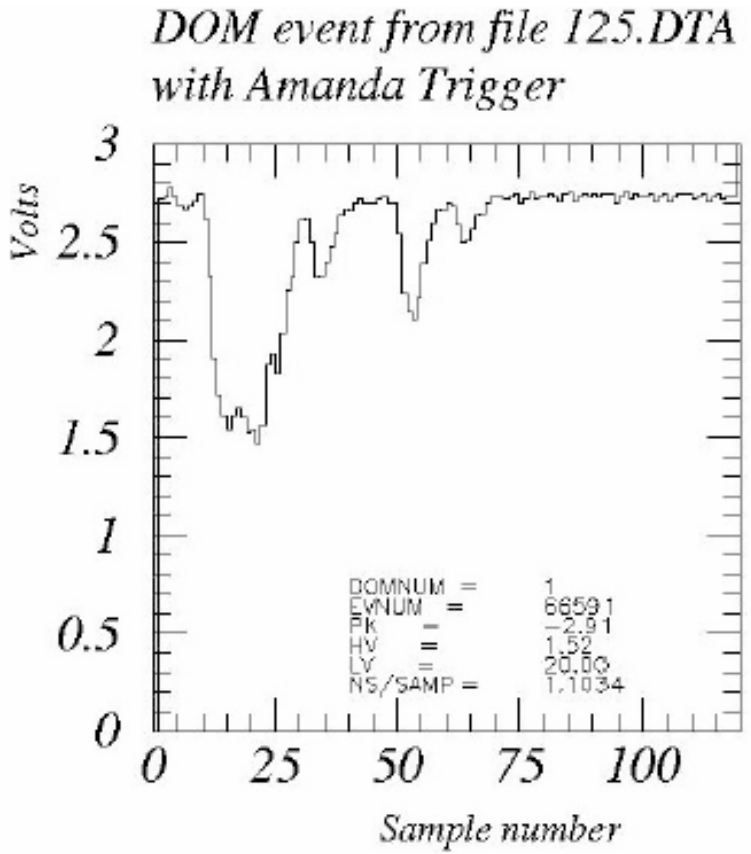
- “Let’s make 5000 complex tethered satellites and bury them forever in ice”
- “Will the cold keep them from working?”
- “Nothing like this has ever been done”
- “What if we make a mistake we can’t fix?”

AMANDA



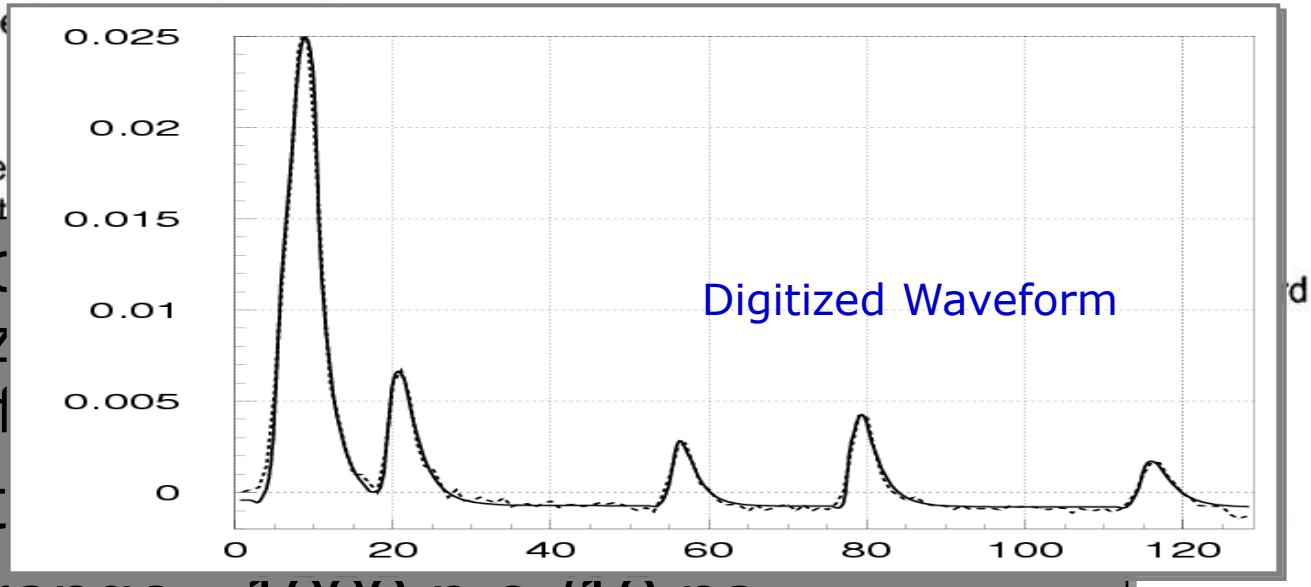
7.5us

DOM



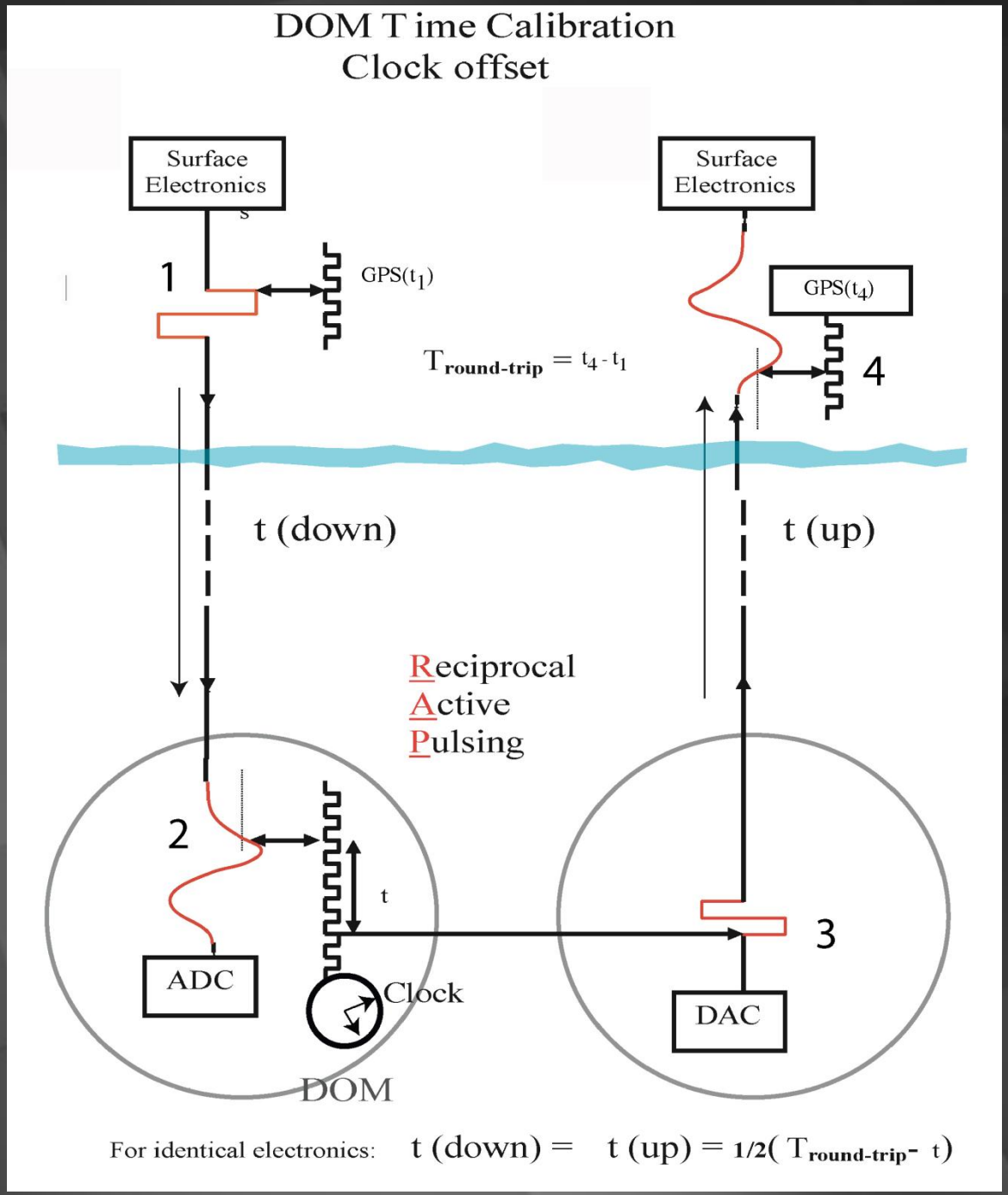
132ns

The Digital Optical Module (DOM)



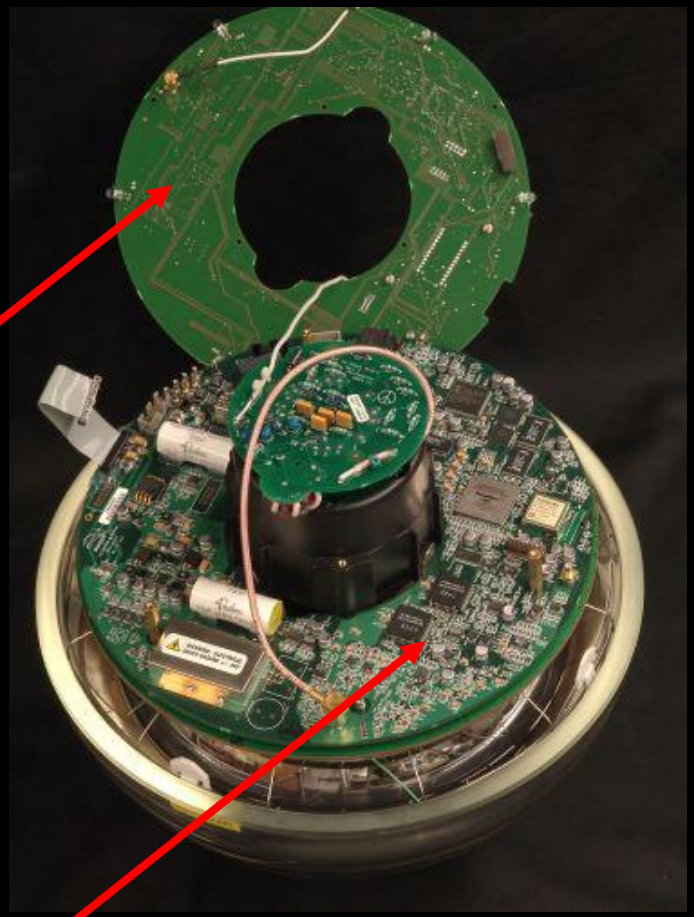
- Onboard c
  - 300 MHz
  - 40 MHz f
- Absolute t
- Dynamic range ~1000 p.e./10 ns
- Deadtime < 1%
- Noise rate ~700 Hz (260 Hz w/ artif. deadtime)
- Failure rate < 1%

2 nanosecond timing across 1 km^3



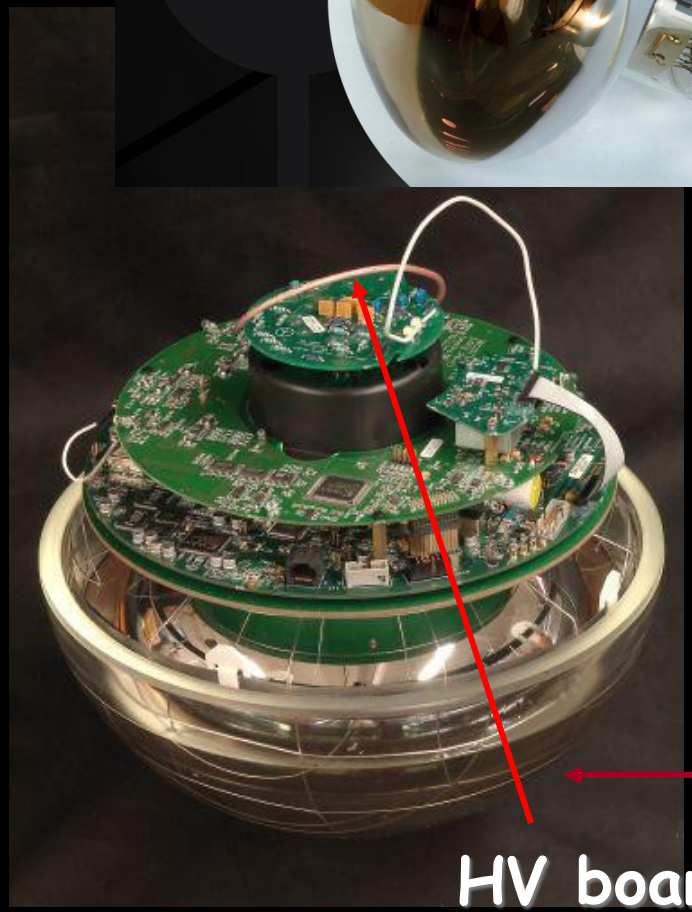
architecture of independent DOMs

10 inch pmt

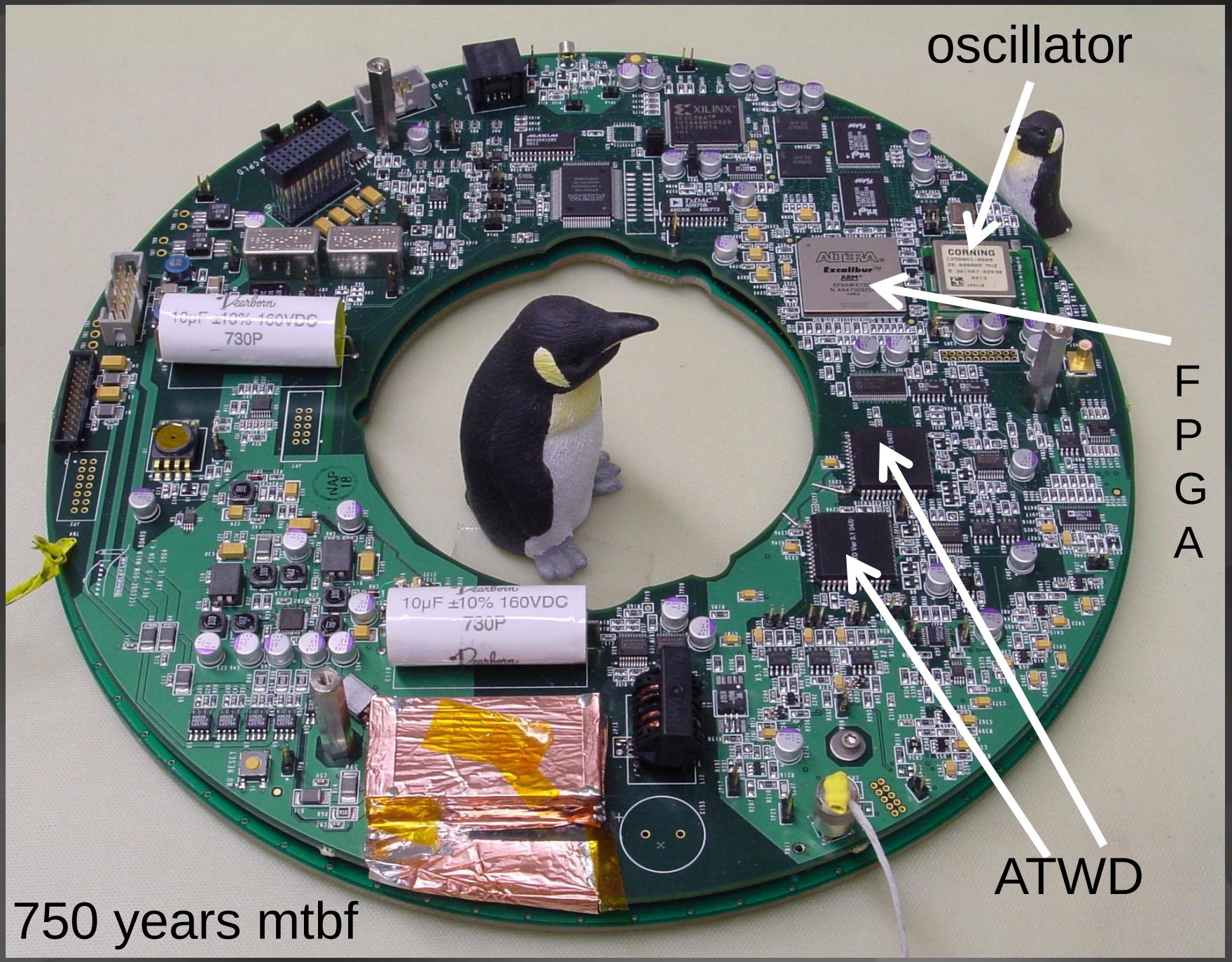


LED flasher board

main board

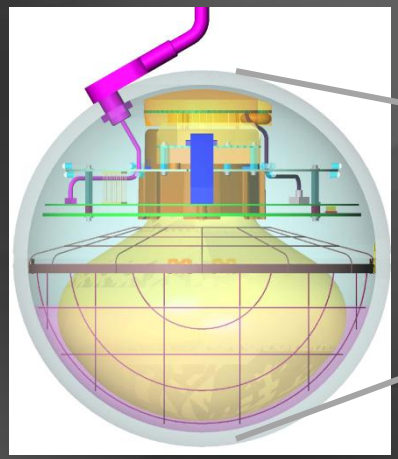


HV board

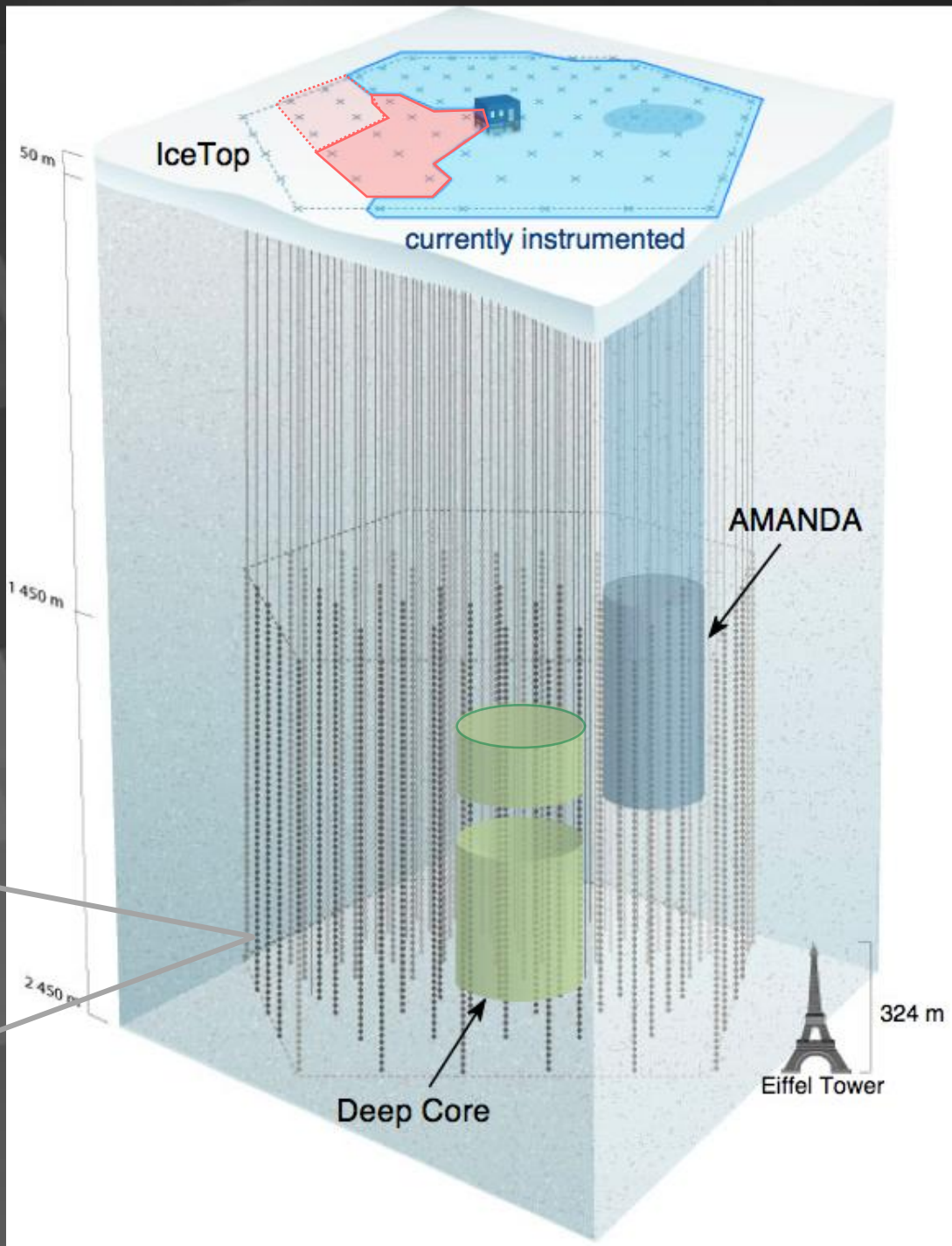

oscillator
FPGA
ATWD
750 years mtbf

IceCube / Deep Core

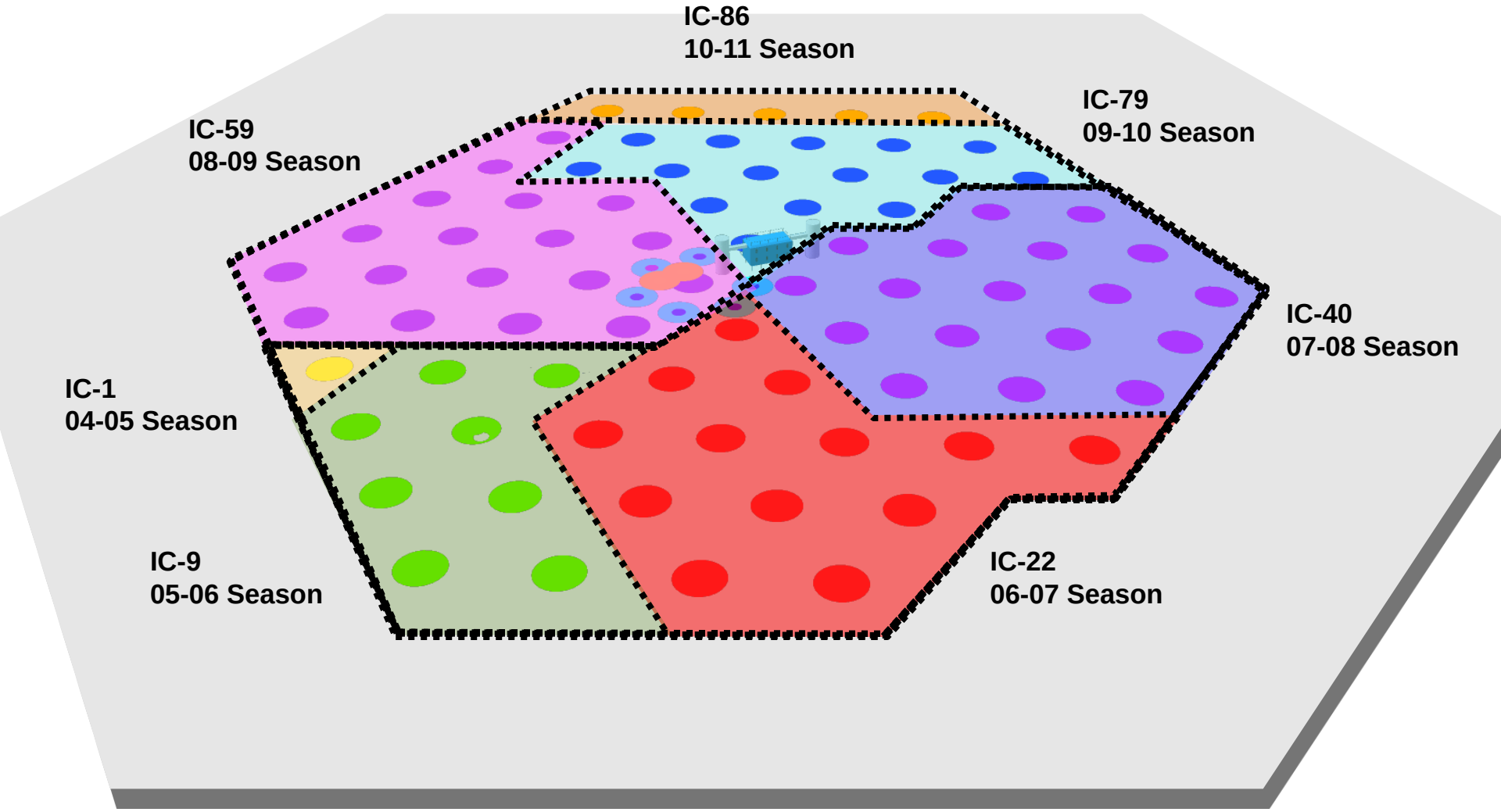
- detects Cherenkov light from showers and muon tracks initiated by neutrinos
- detects ~220 neutrinos and 1.7×10^8 muons per day
- threshold 10 GeV
- angular resolution 0.4~1 degree



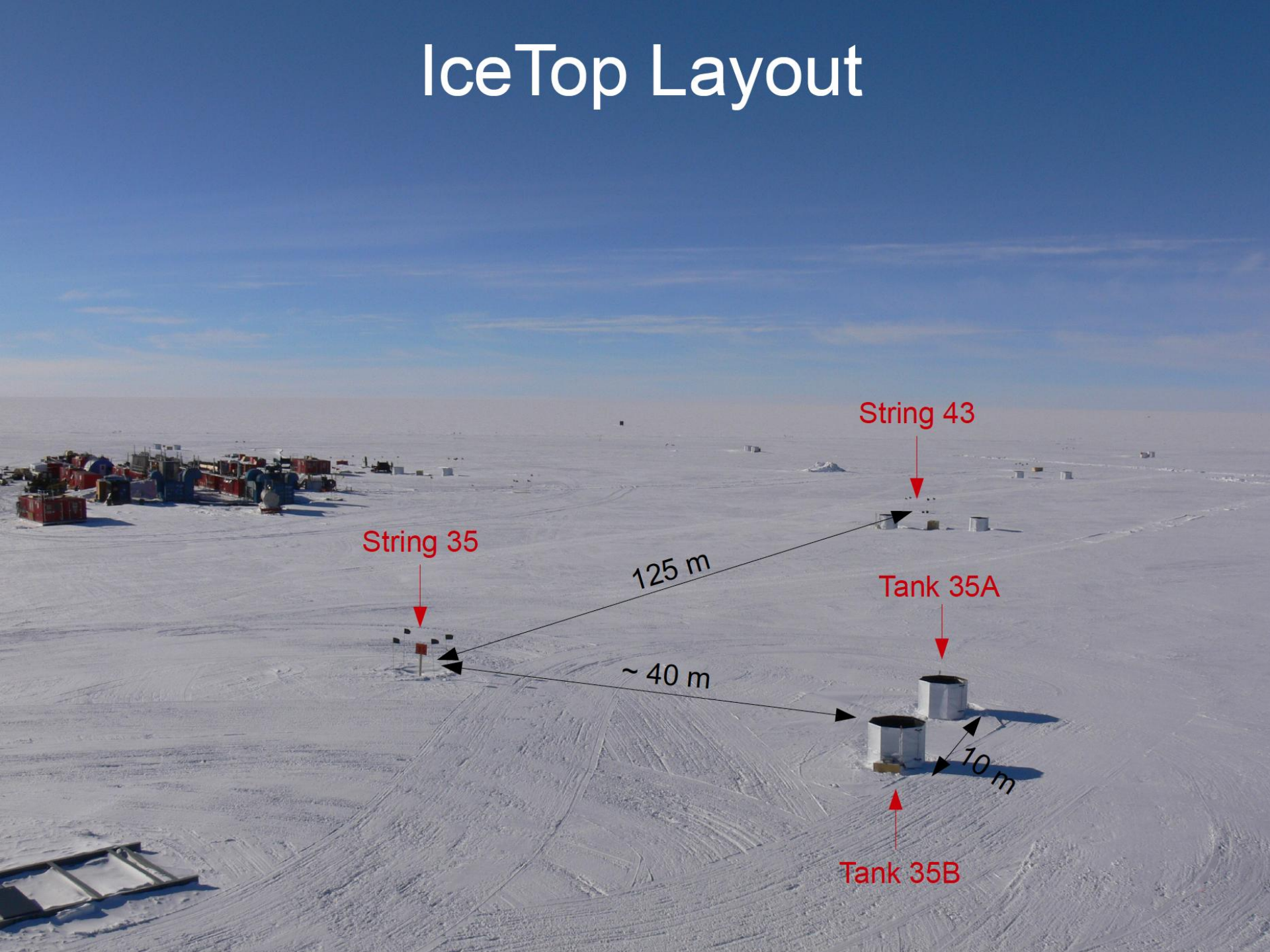
5320 Digital Optical Modules (DOM)

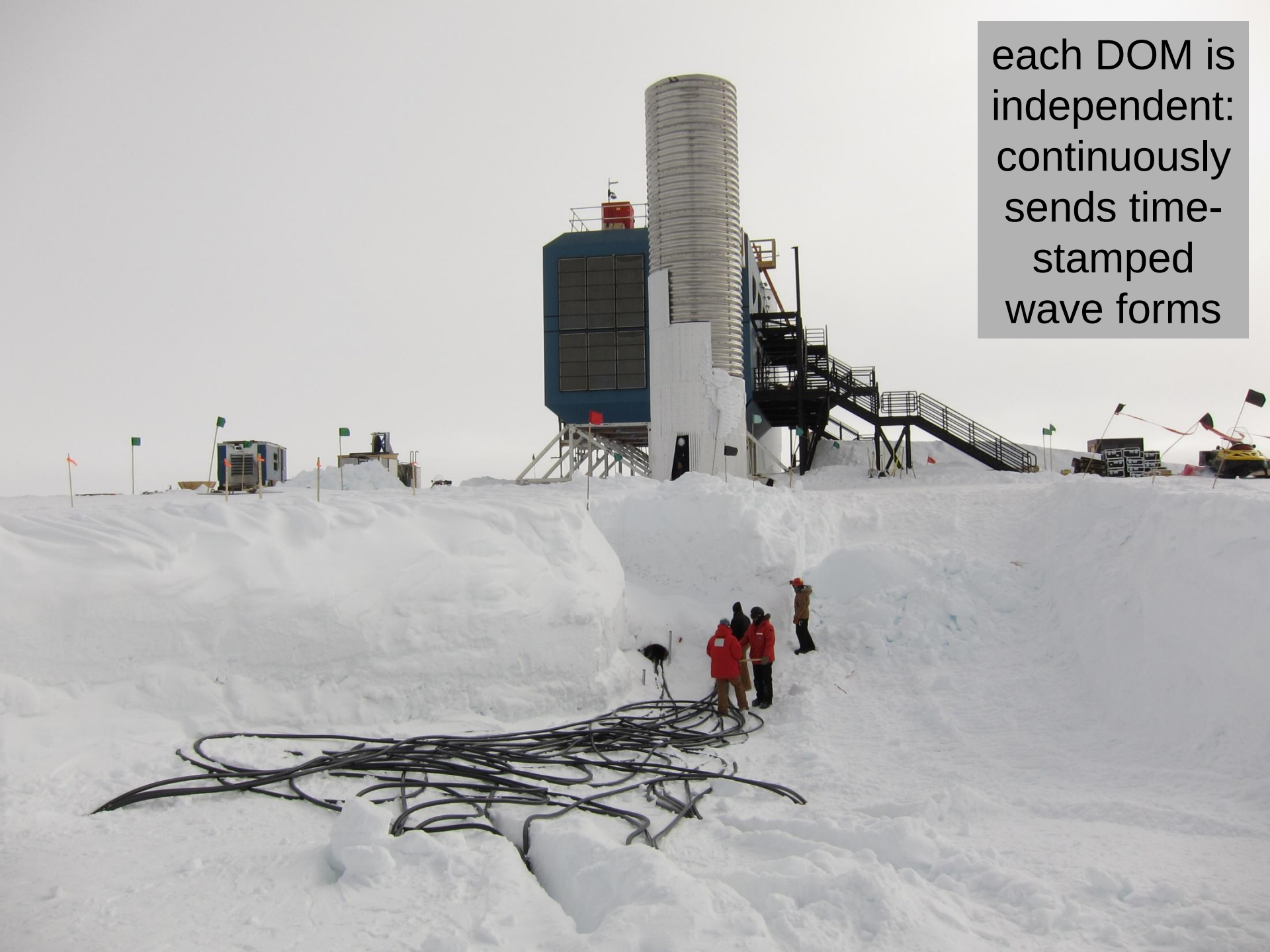


completed December 18, 2010



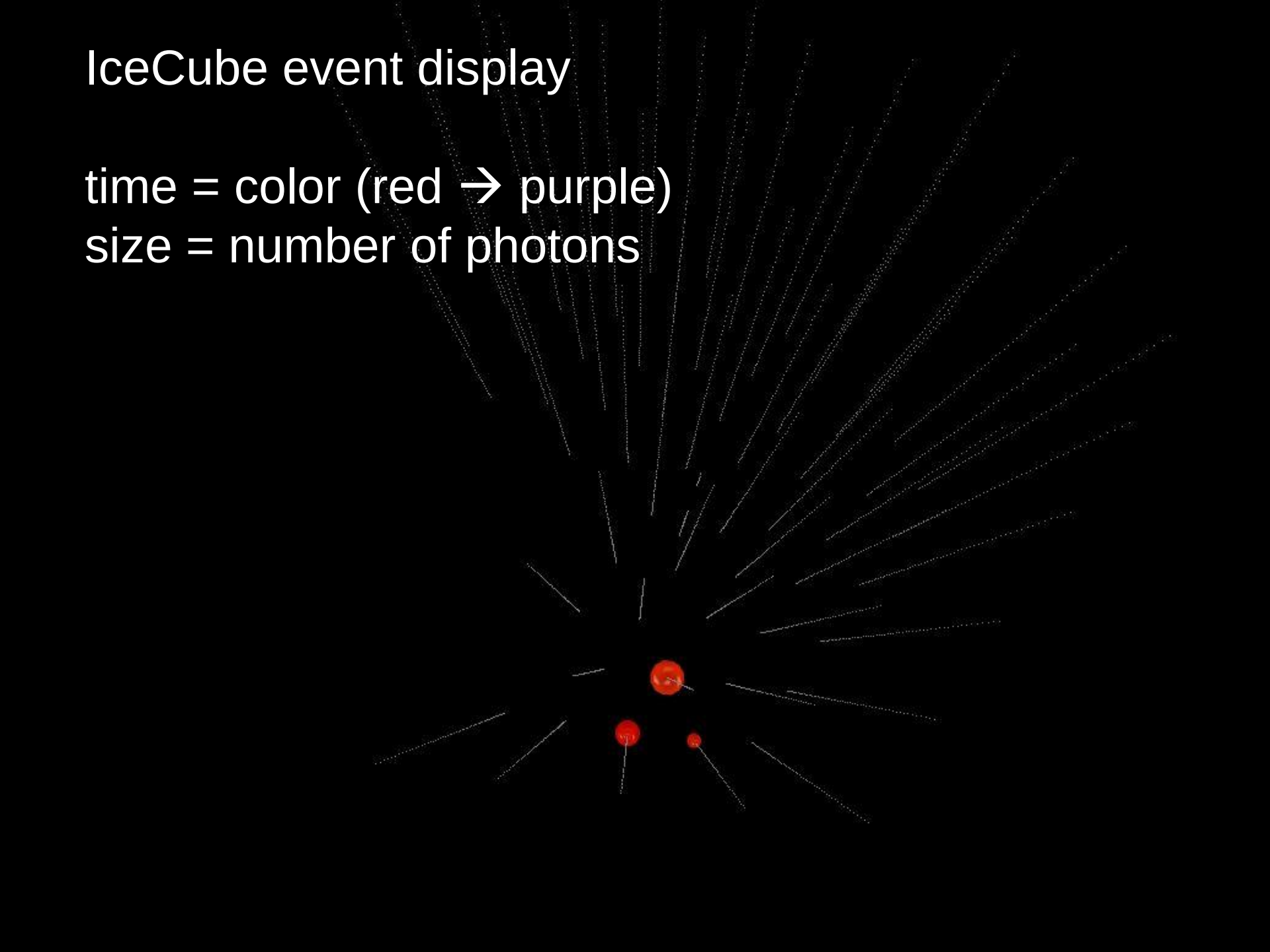
IceTop Layout

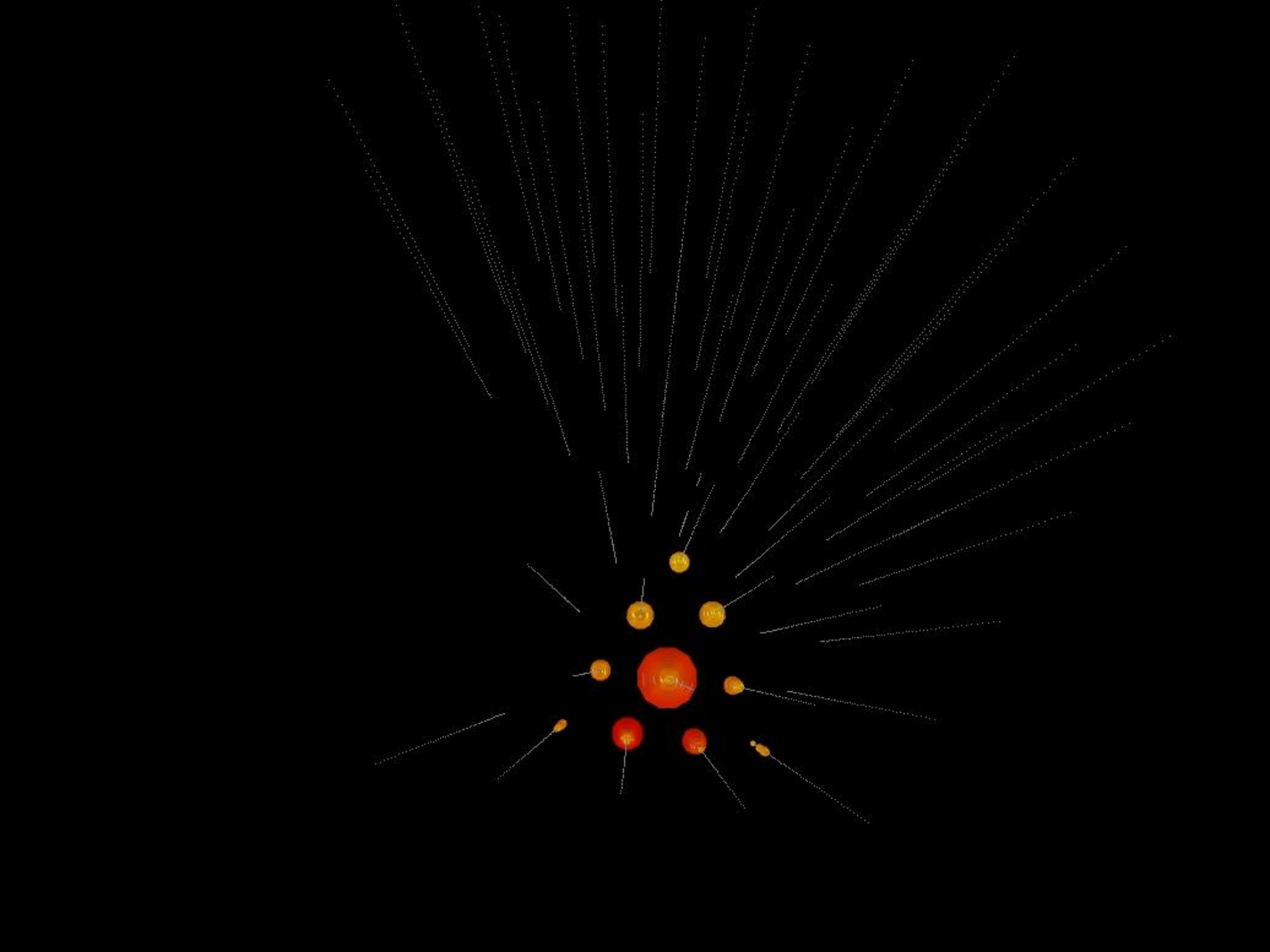


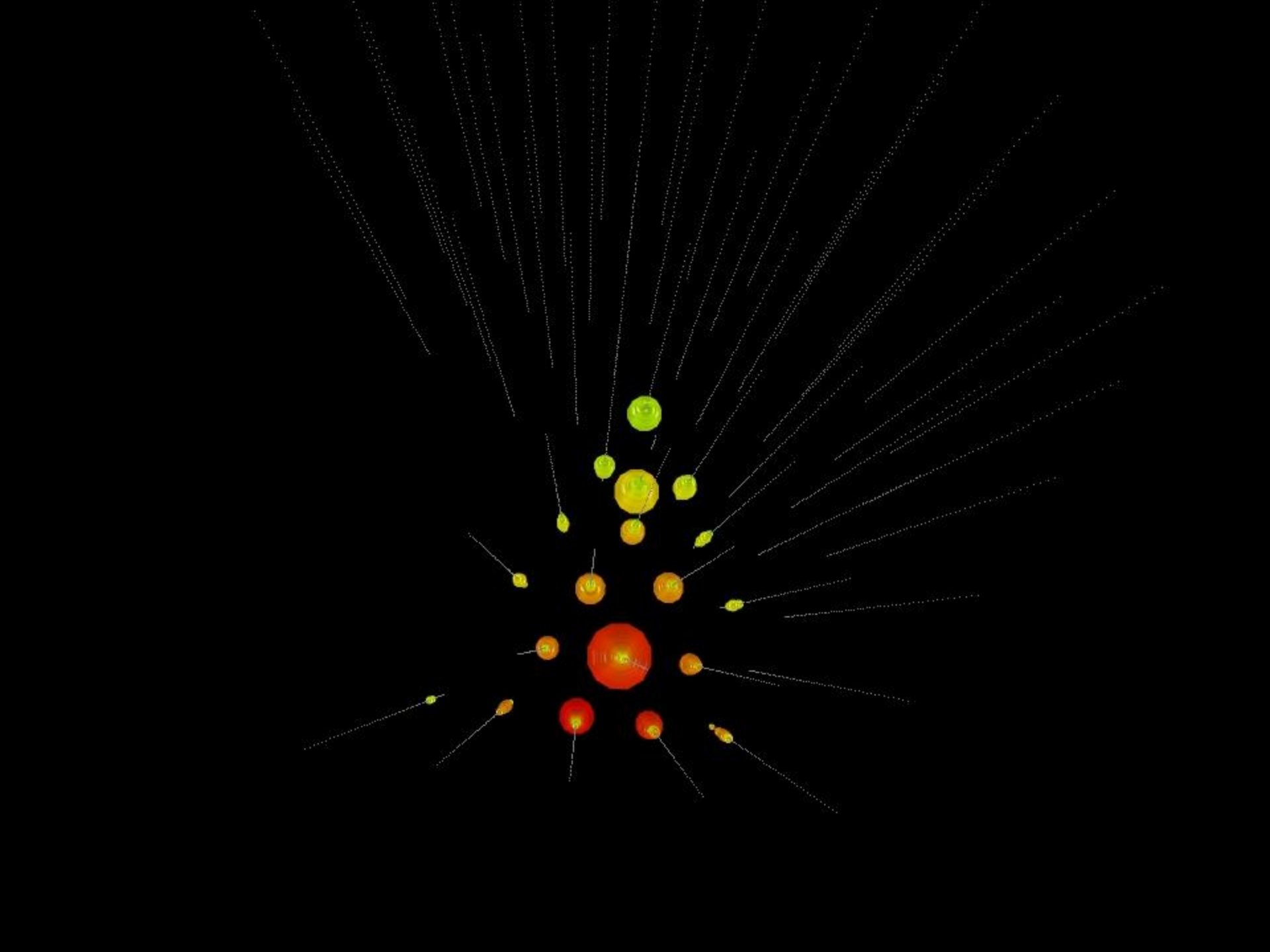

each DOM is independent: continuously sends time-stamped wave forms

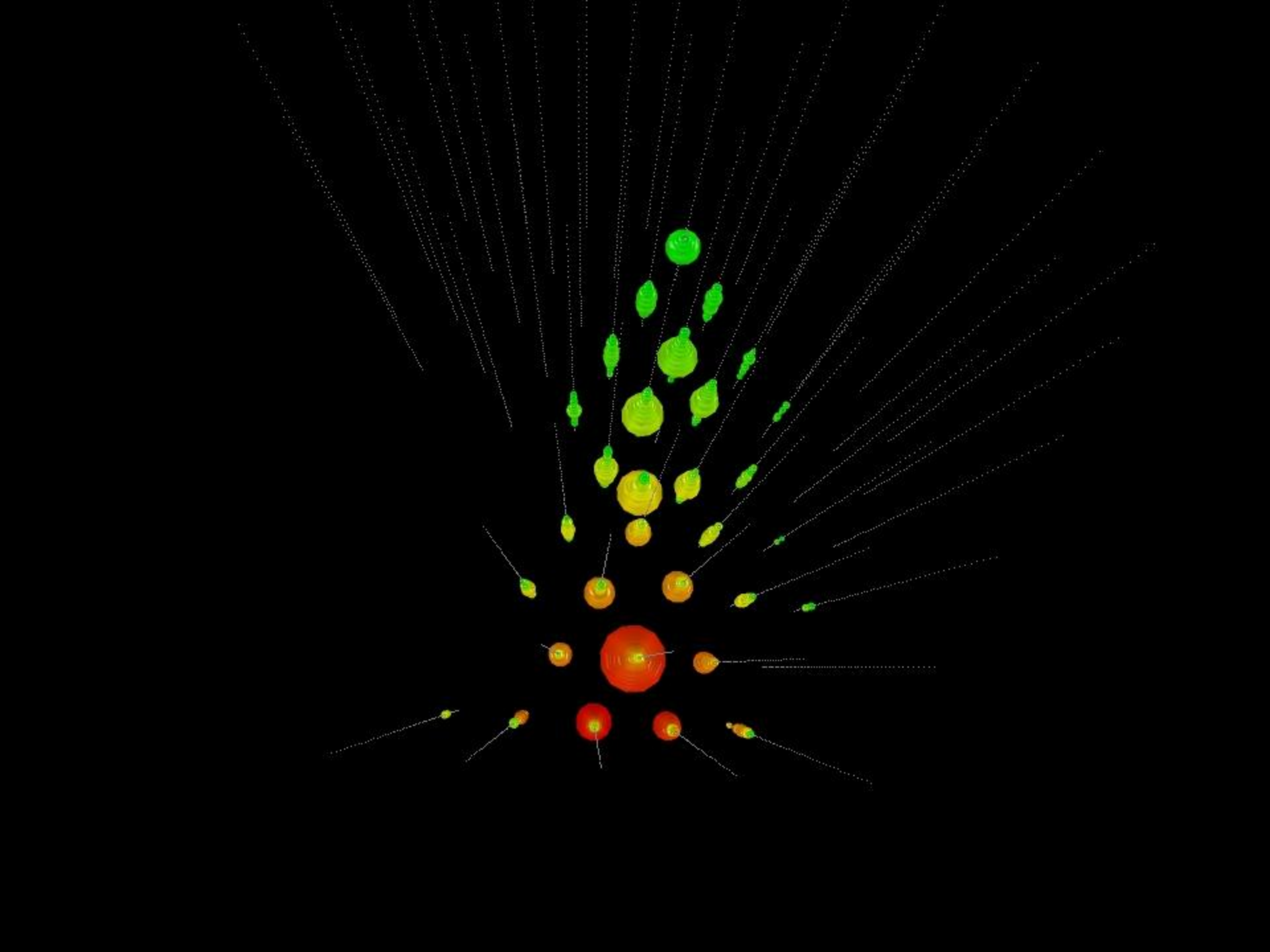
IceCube event display

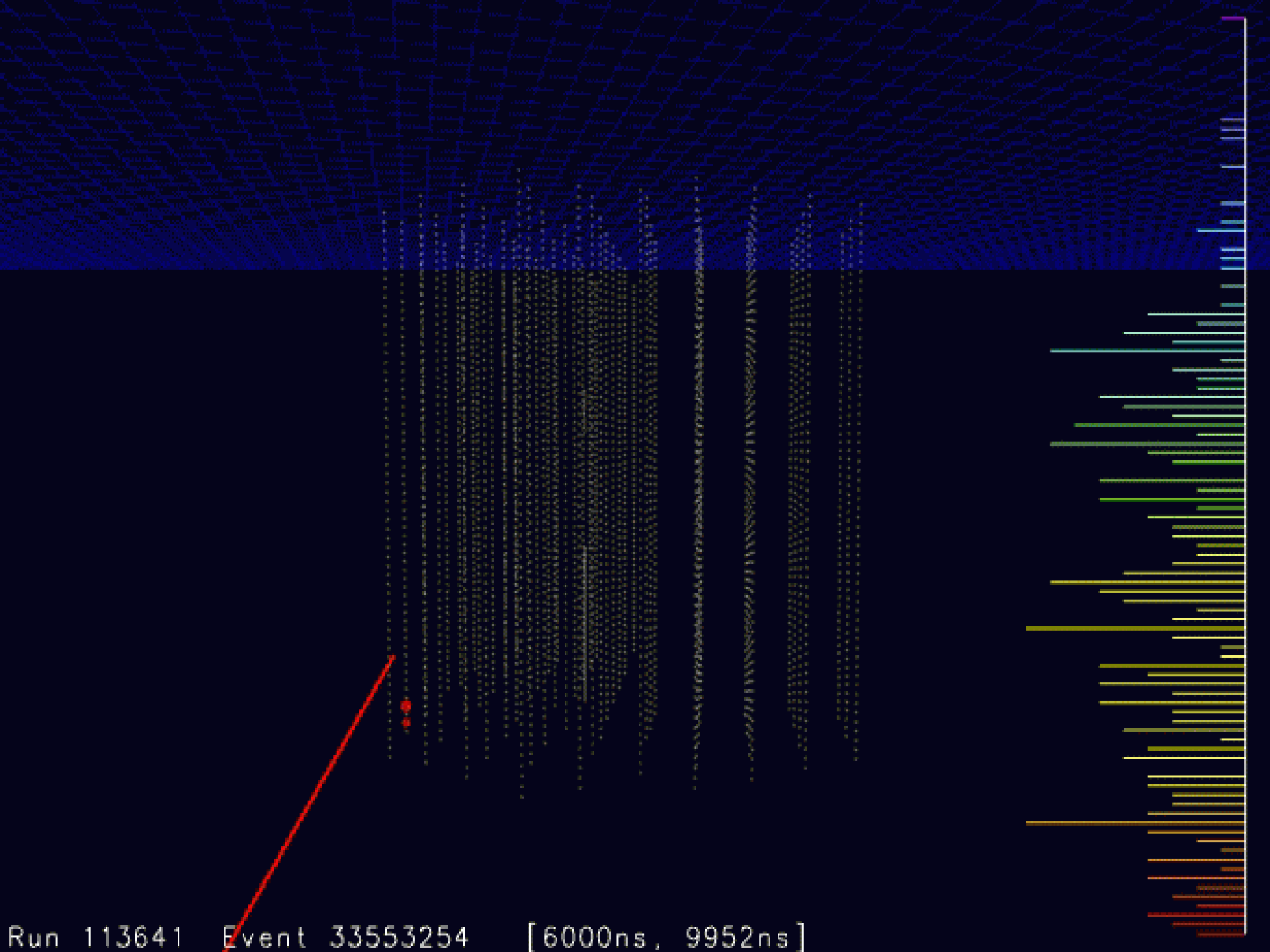
time = color (red → purple)
size = number of photons



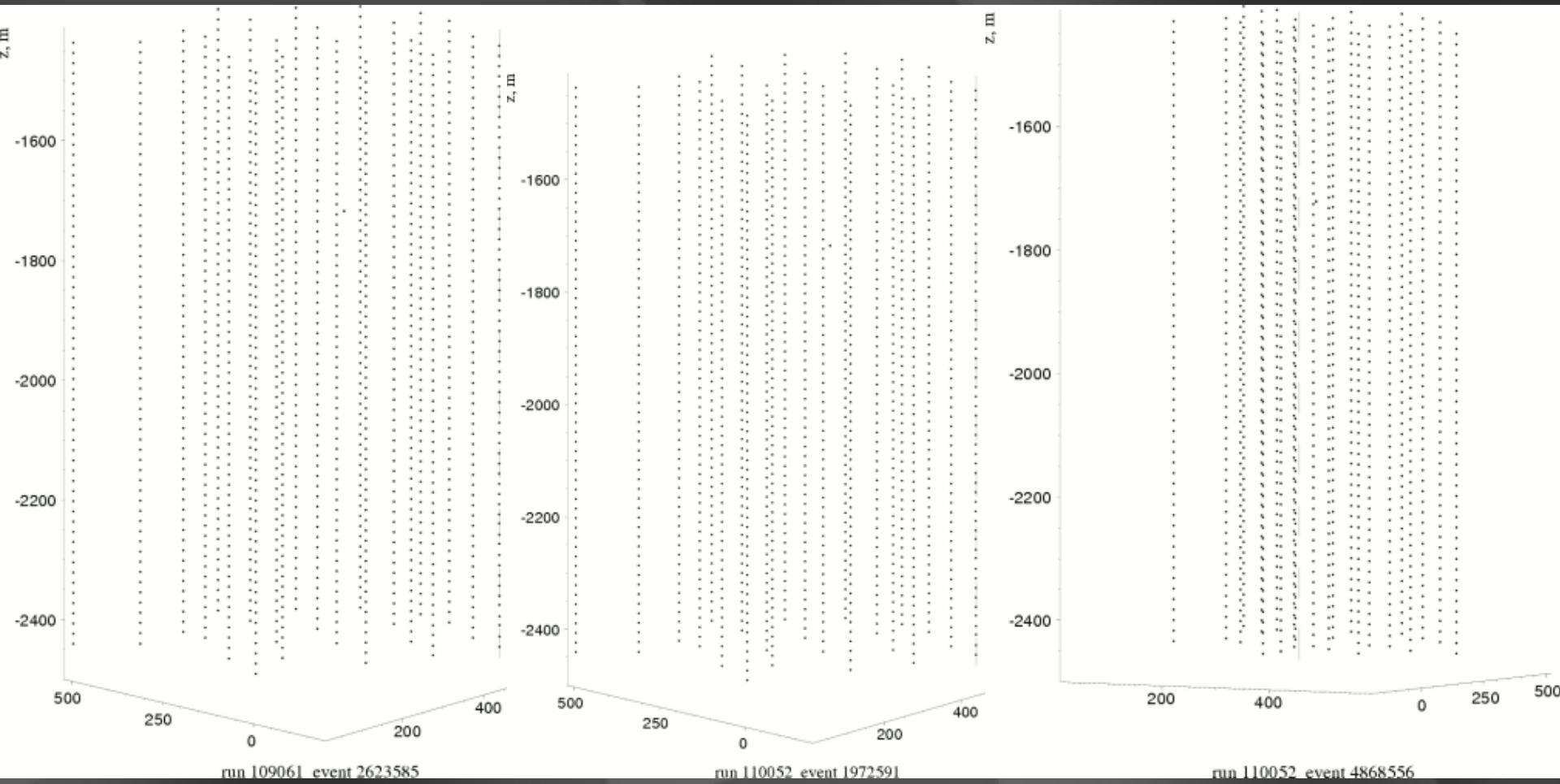




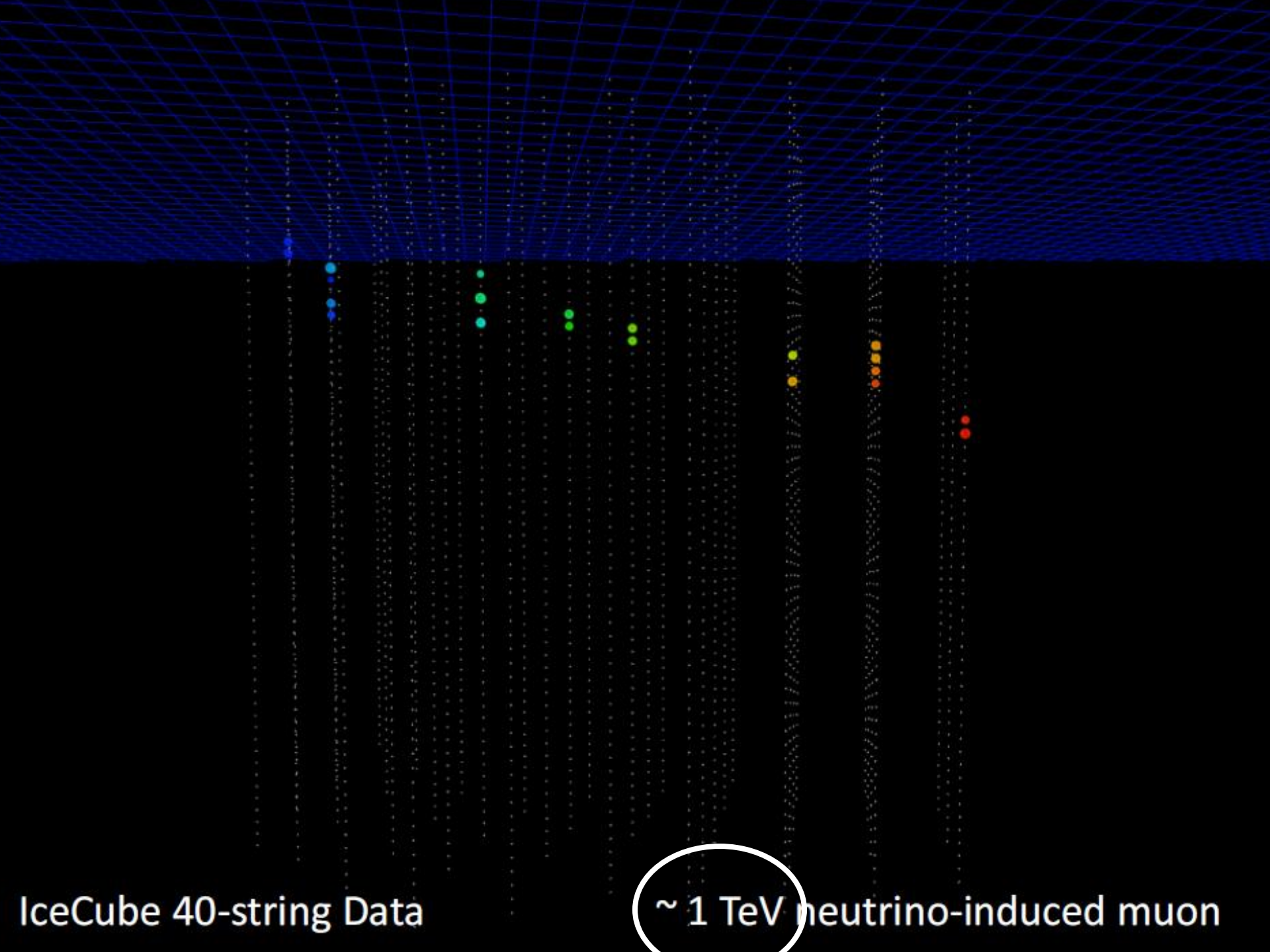



Run 113641 Event 33553254 [6000ns, 9952ns]

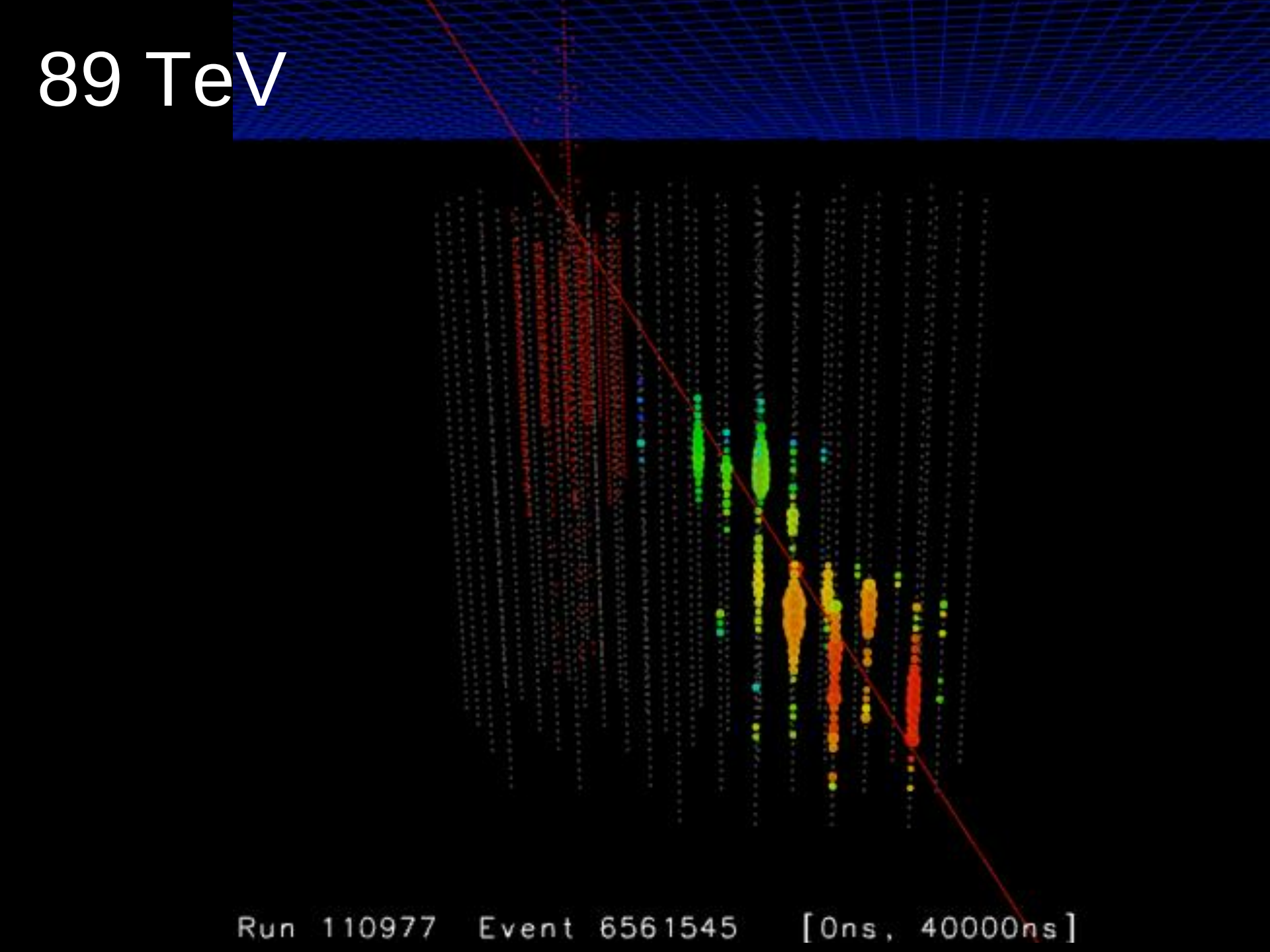
IceCube neutrinos (40 out of 80 strings)



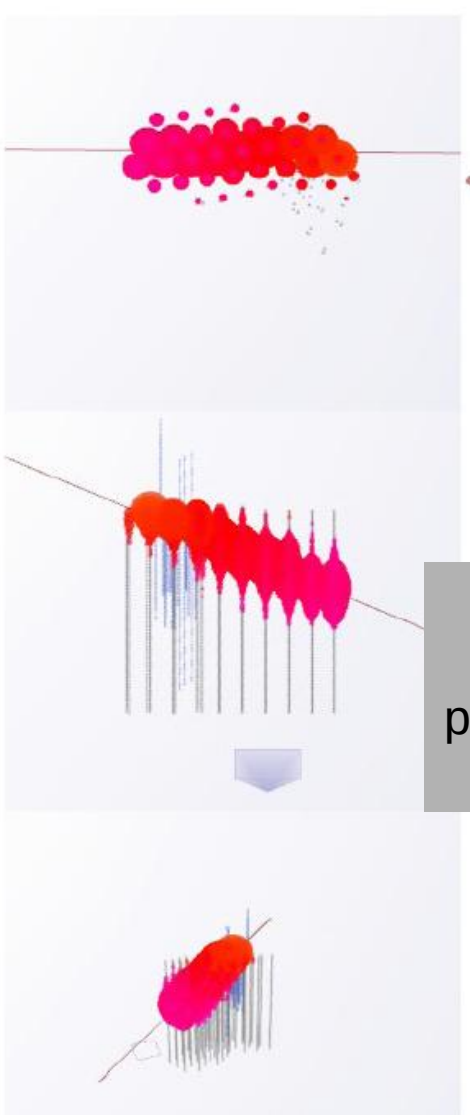
→ operated for 276 days → collected > 18,000 ν's

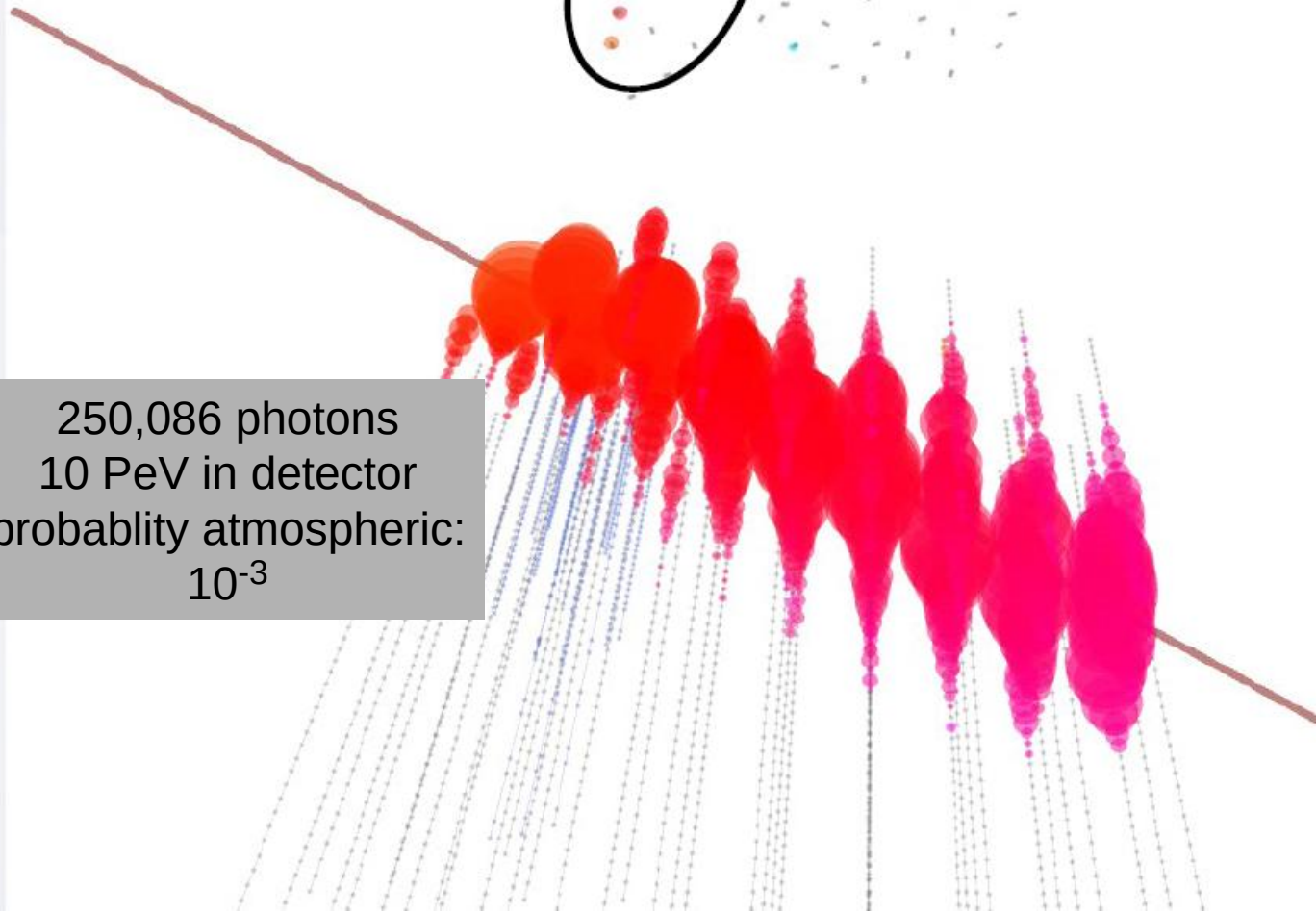

IceCube 40-string Data
~ 1 TeV neutrino-induced muon

89 TeV



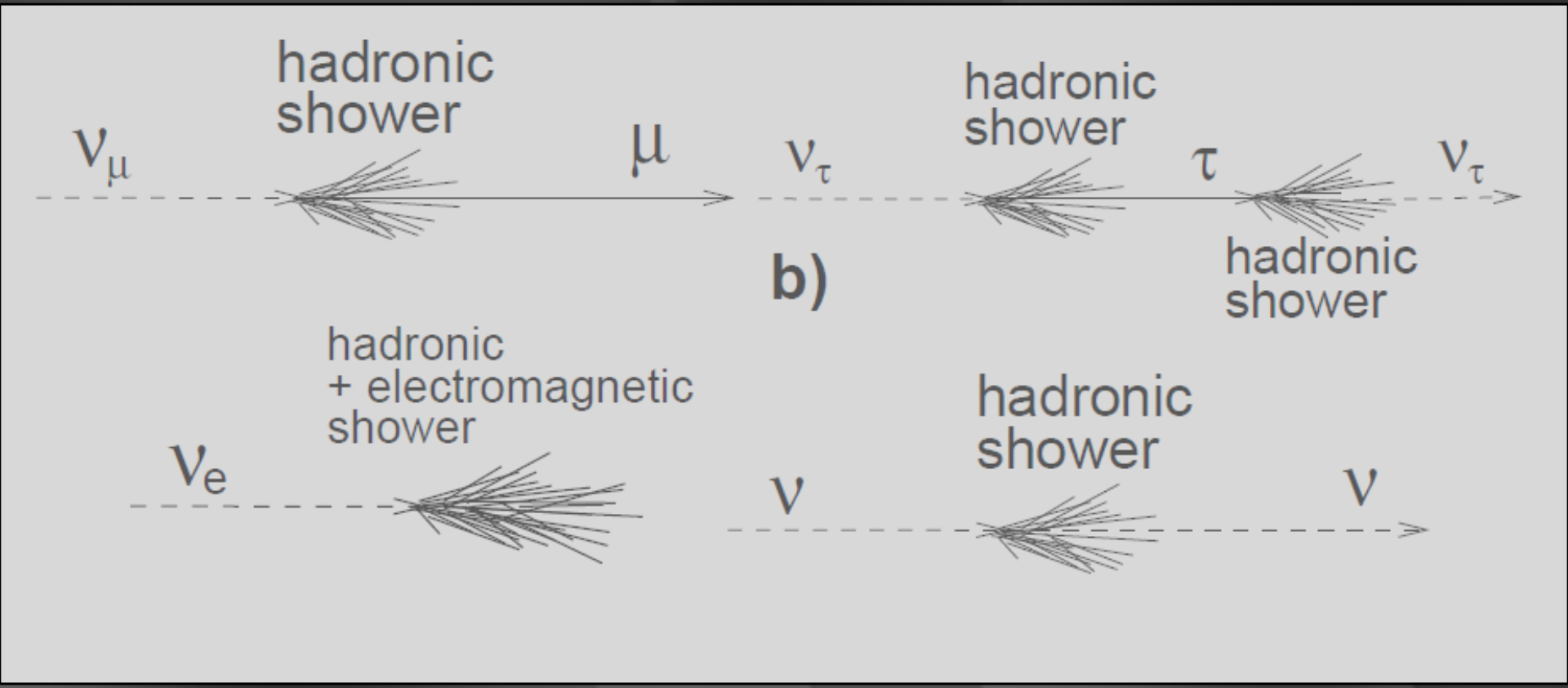
Biggest Shower in IC40 EHE Analysis



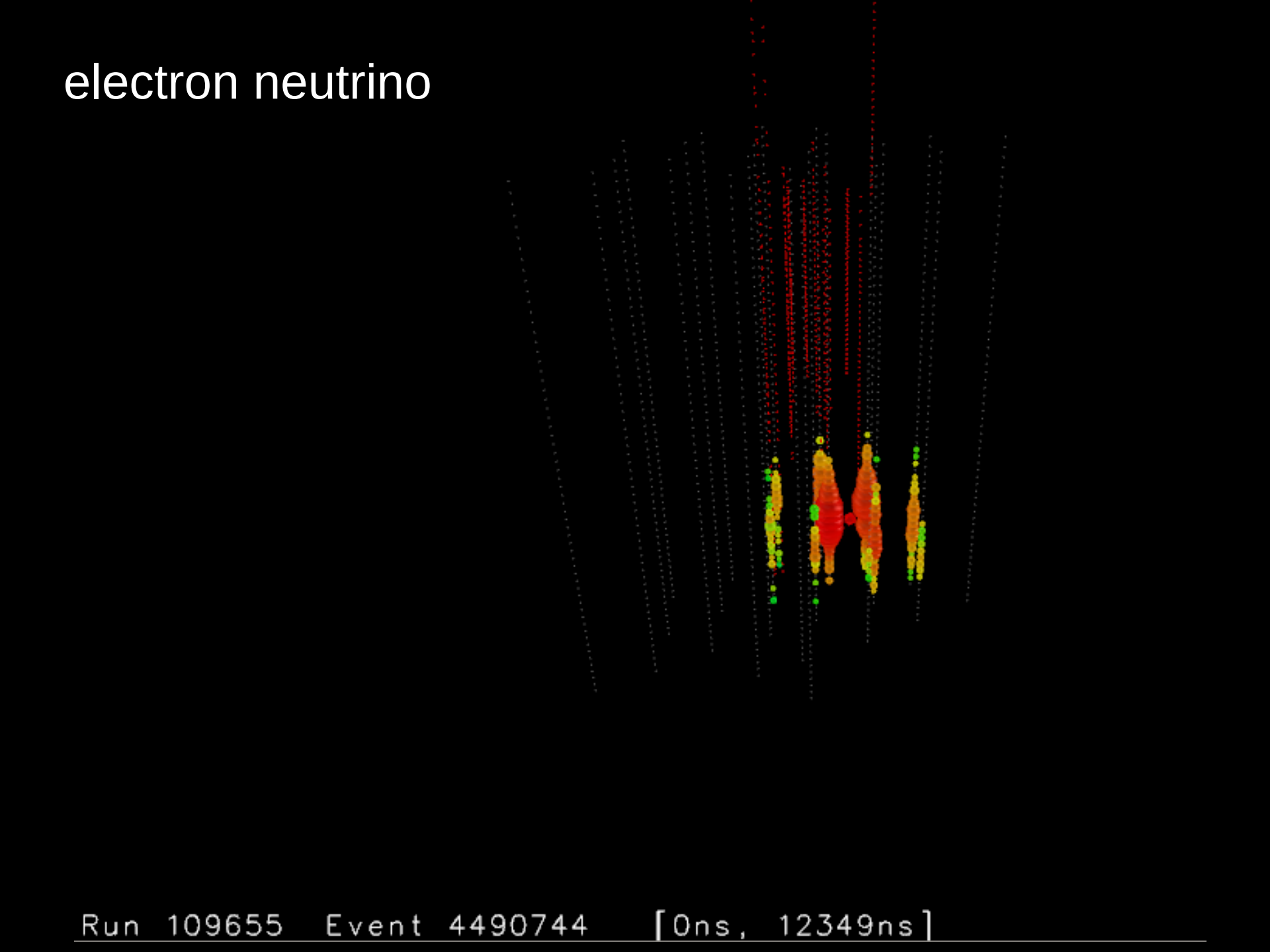


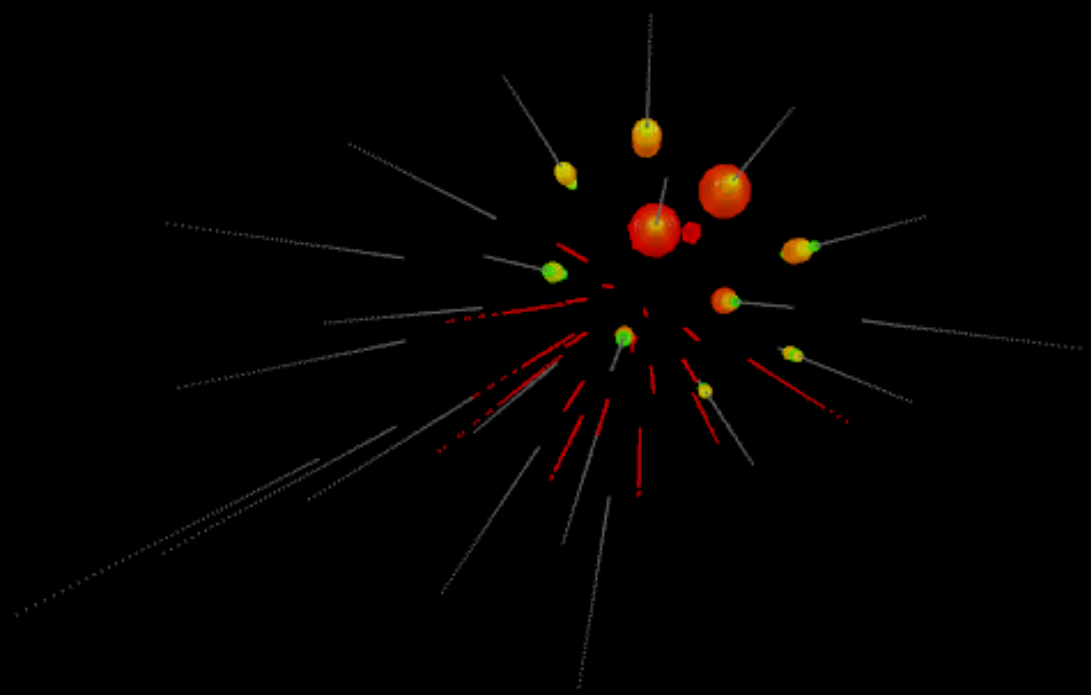
250,086 photons
10 PeV in detector
probablity atmospheric:
10^{-3}

neutrino flavors



electron neutrino

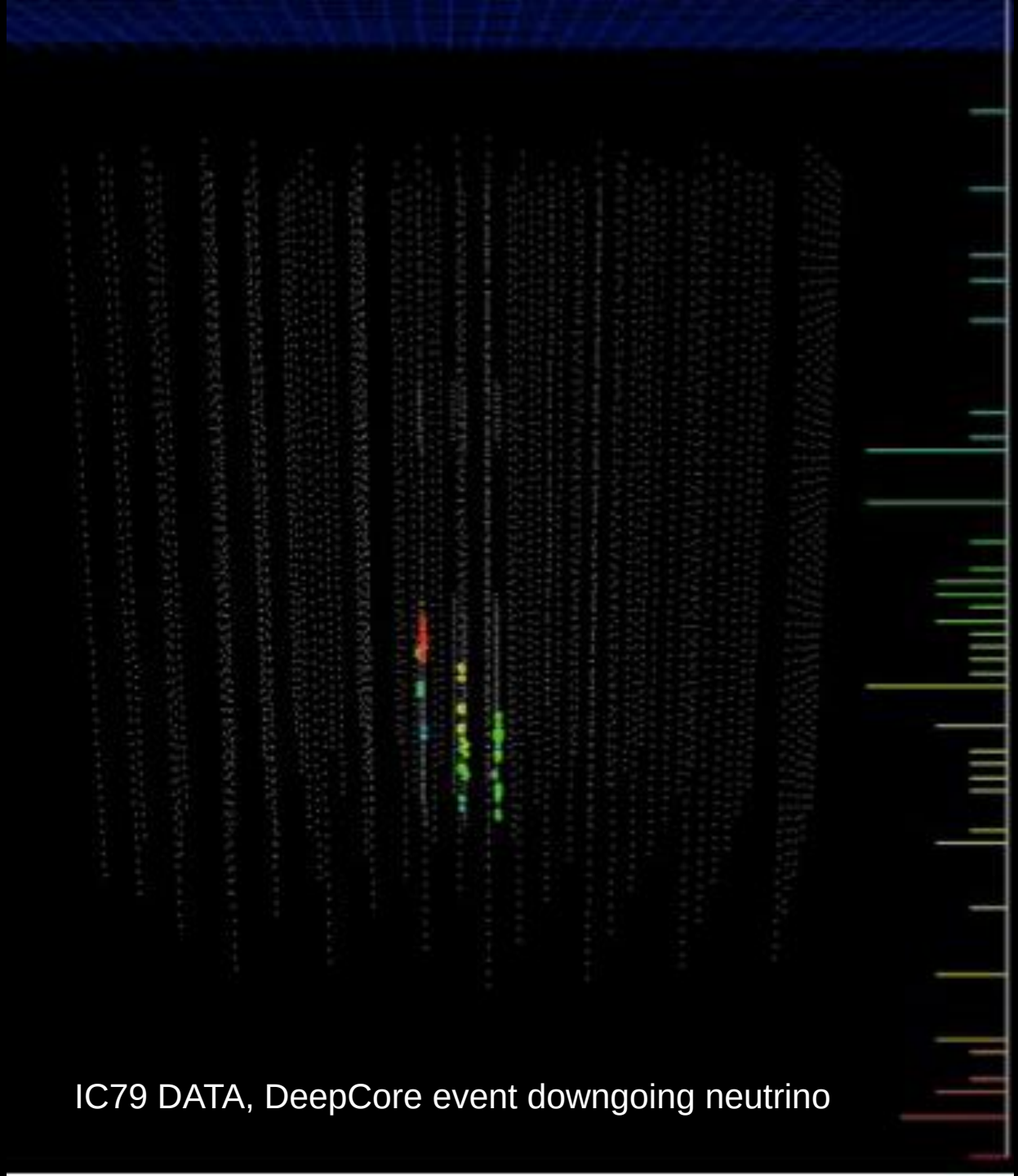




seen: 14 events

predicted: 3 atmospheric and 4 background

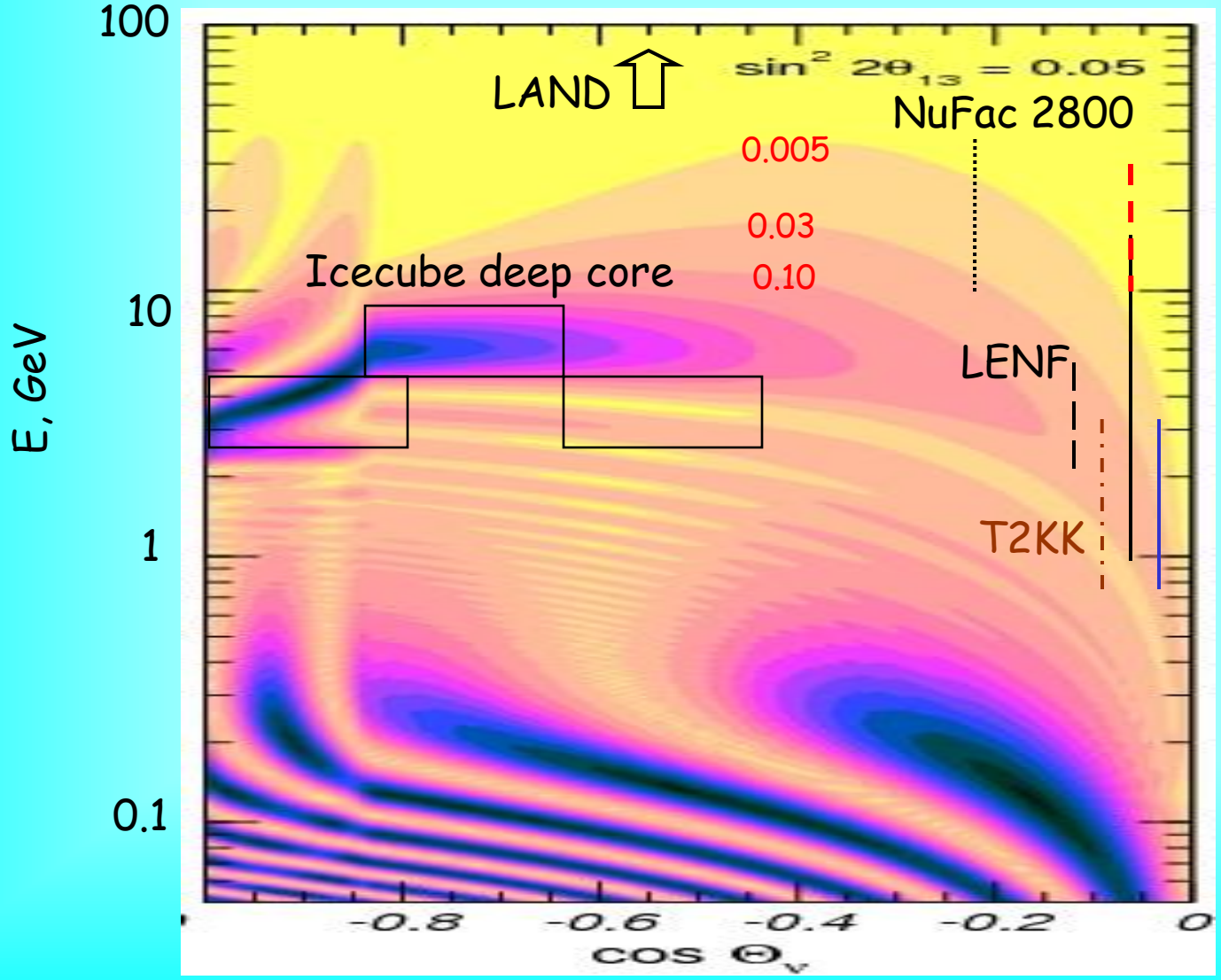
Run 109655 Event 4490744 [0ns, 12349ns]



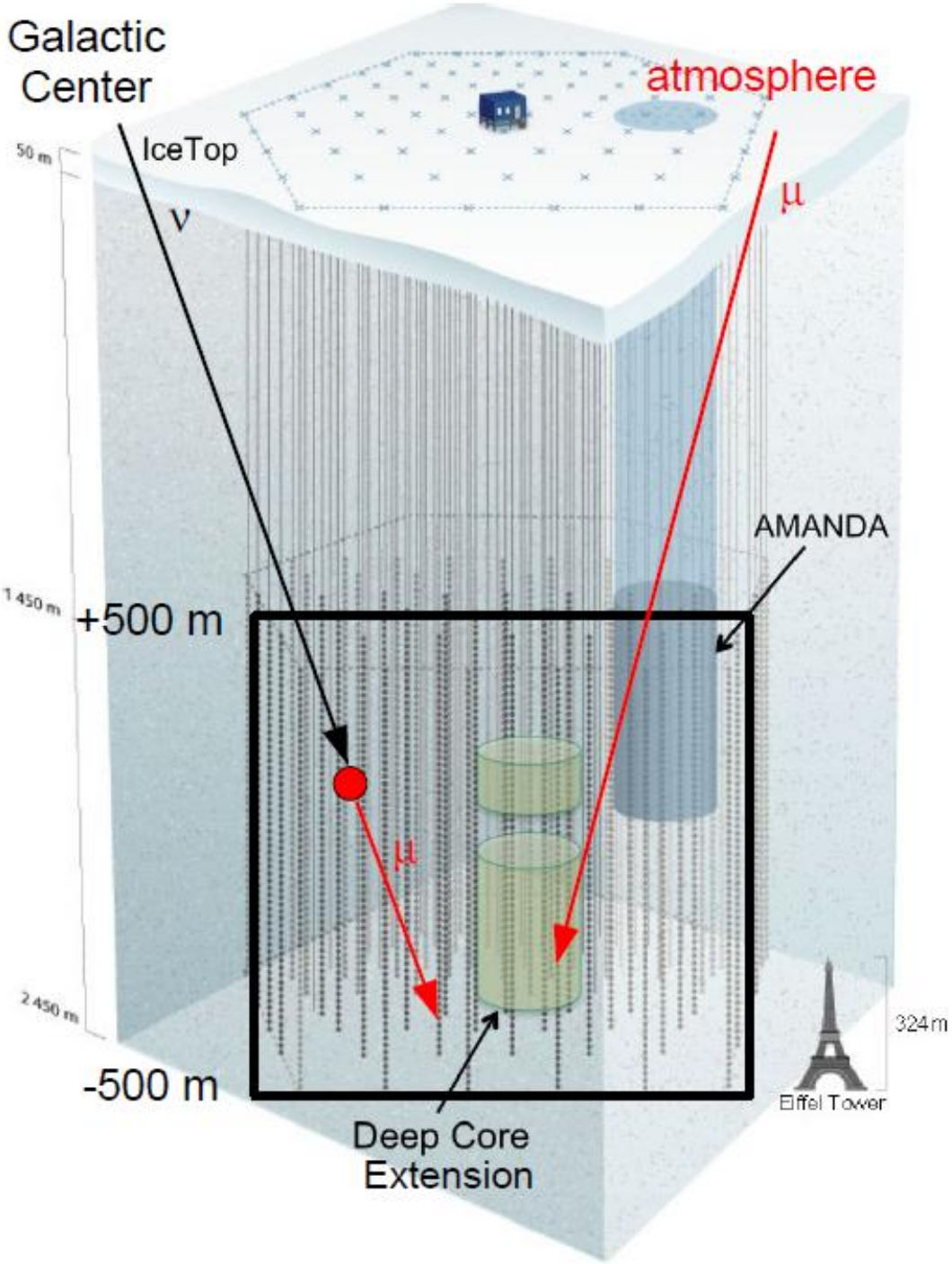
IC79 DATA, DeepCore event downgoing neutrino

Smirnov, Erice 2010

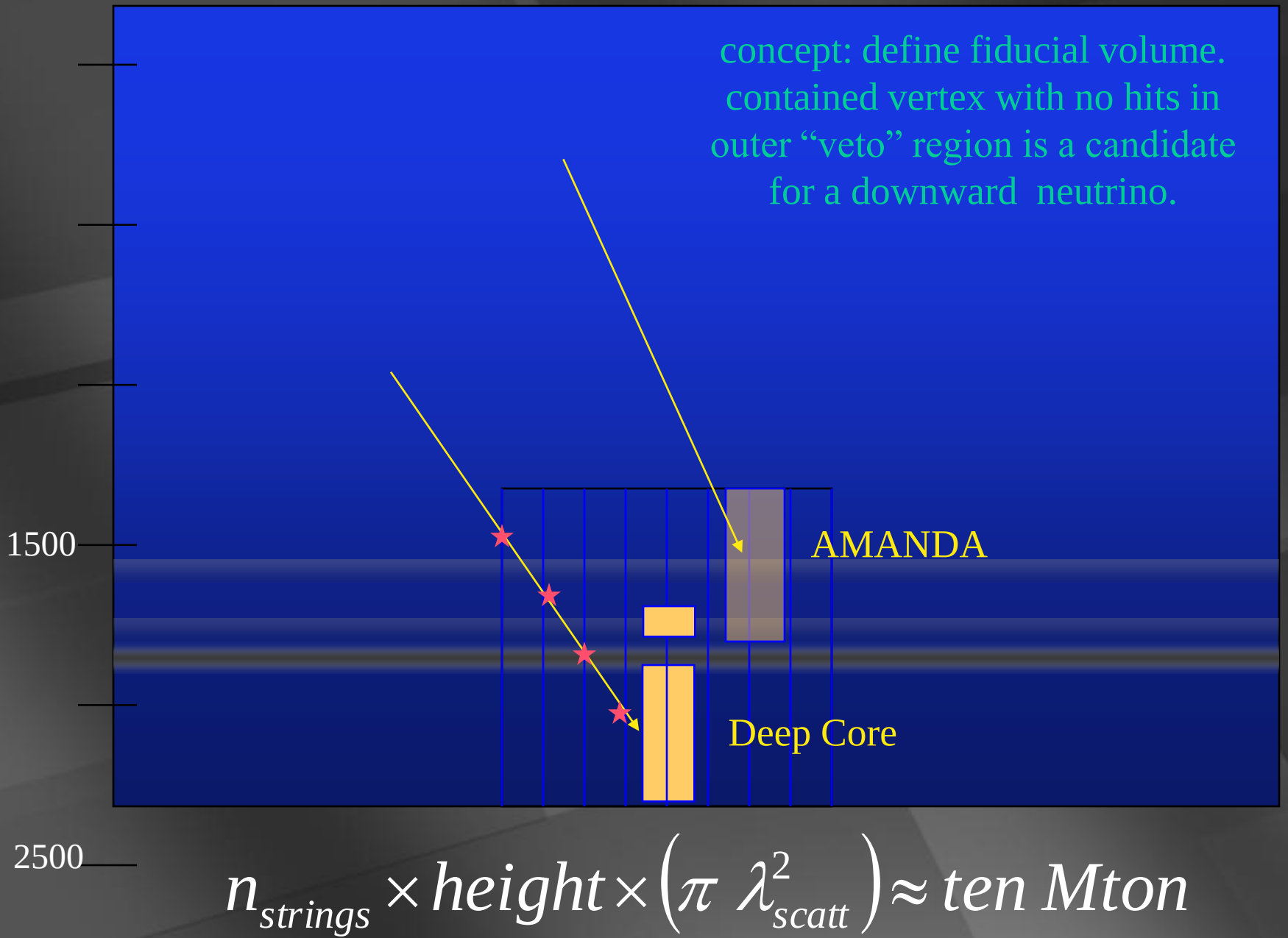
Large atmospheric neutrino detectors



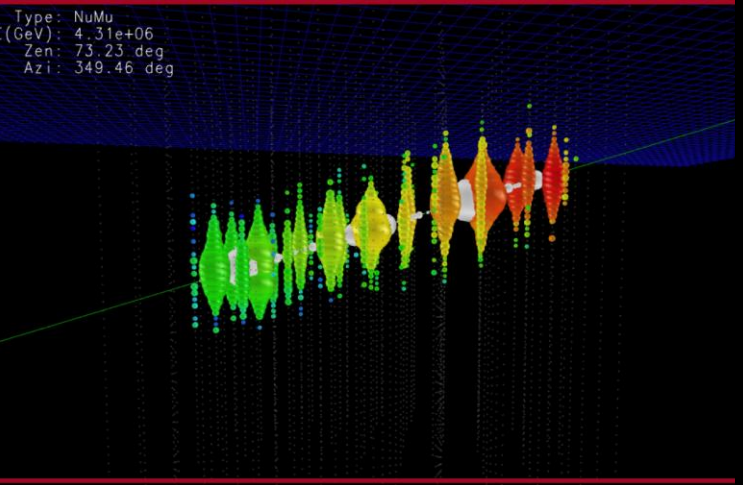
Degeneracy of parameters


Galactic
Center
IceTop
atmosphere
ν
μ
50 m
1450 m
+500 m
AMANDA
μ
2450 m
-500 m
Deep Core
Extension
324 m
Eiffel Tower

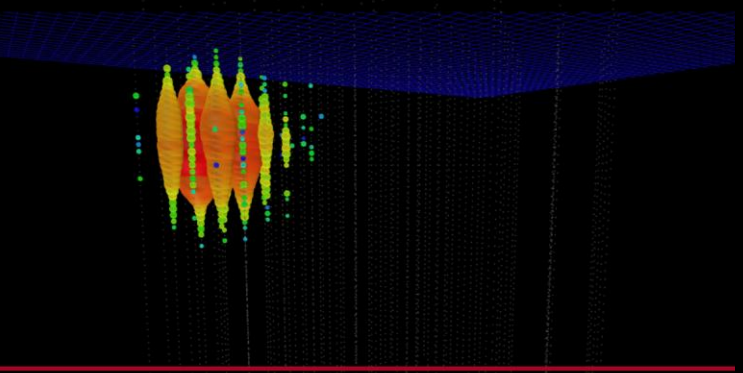
low energy core for IceCube



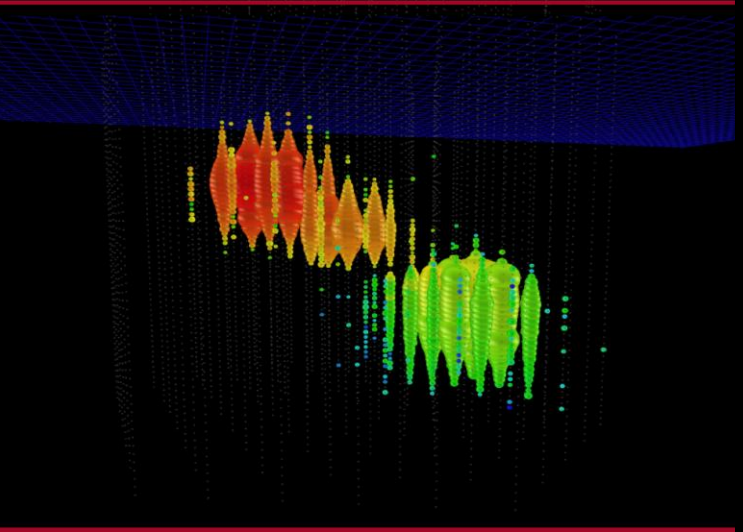
$$n_{strings} \times height \times \left(\pi\ \lambda^2_{scatt}\right) \approx ten\ Mton$$



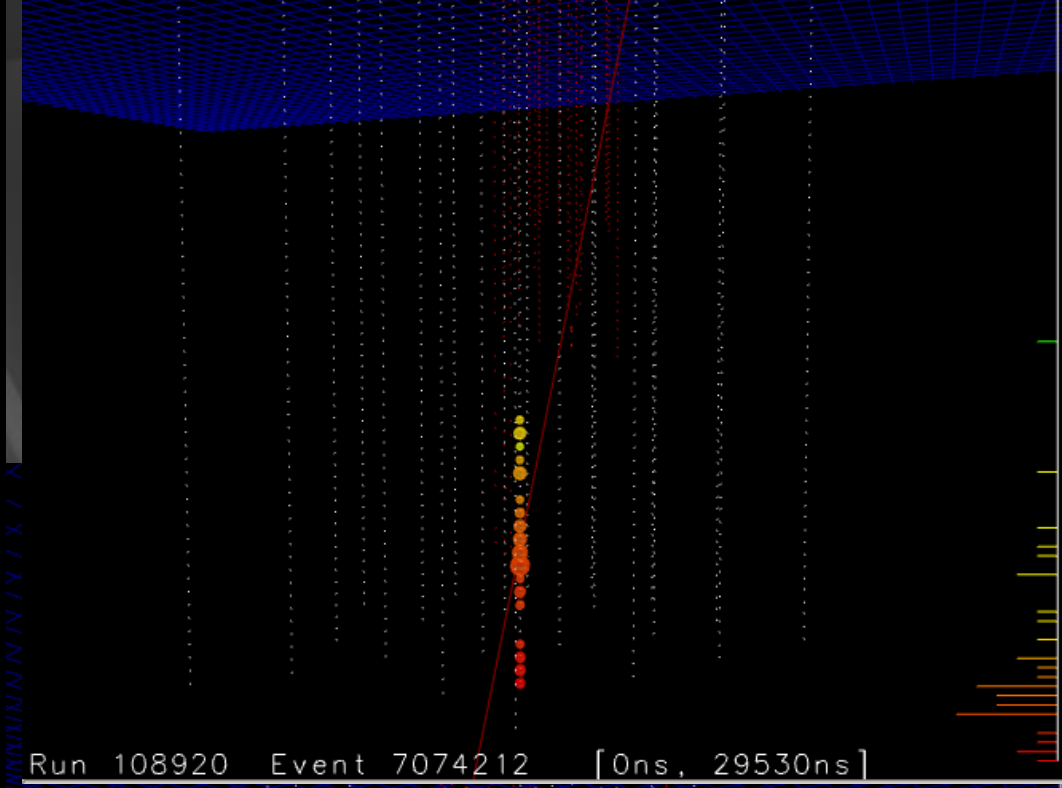
muon

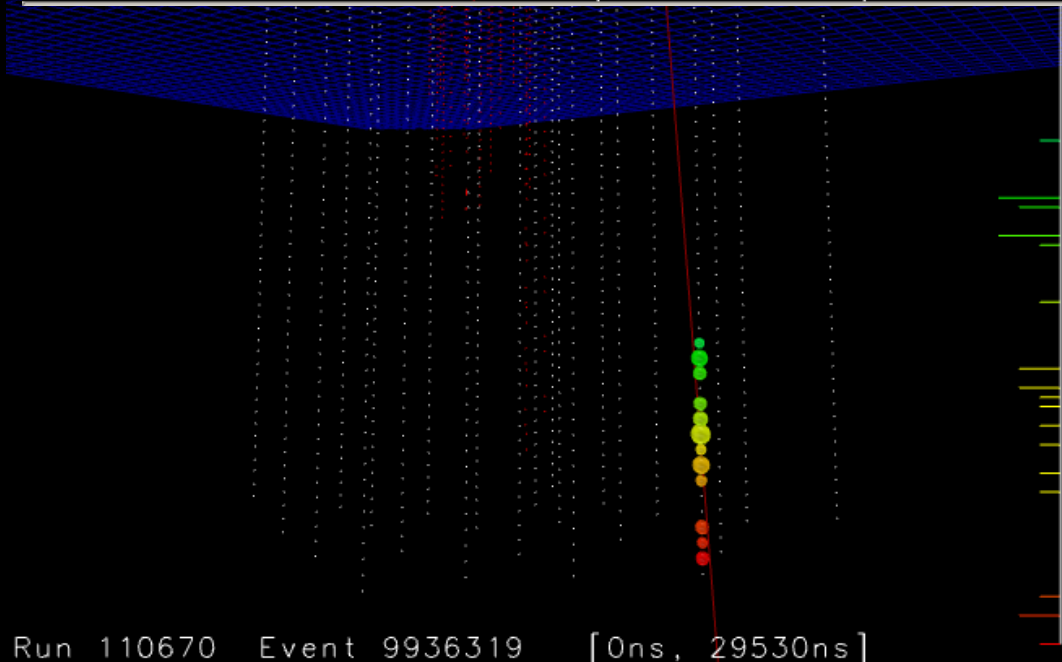


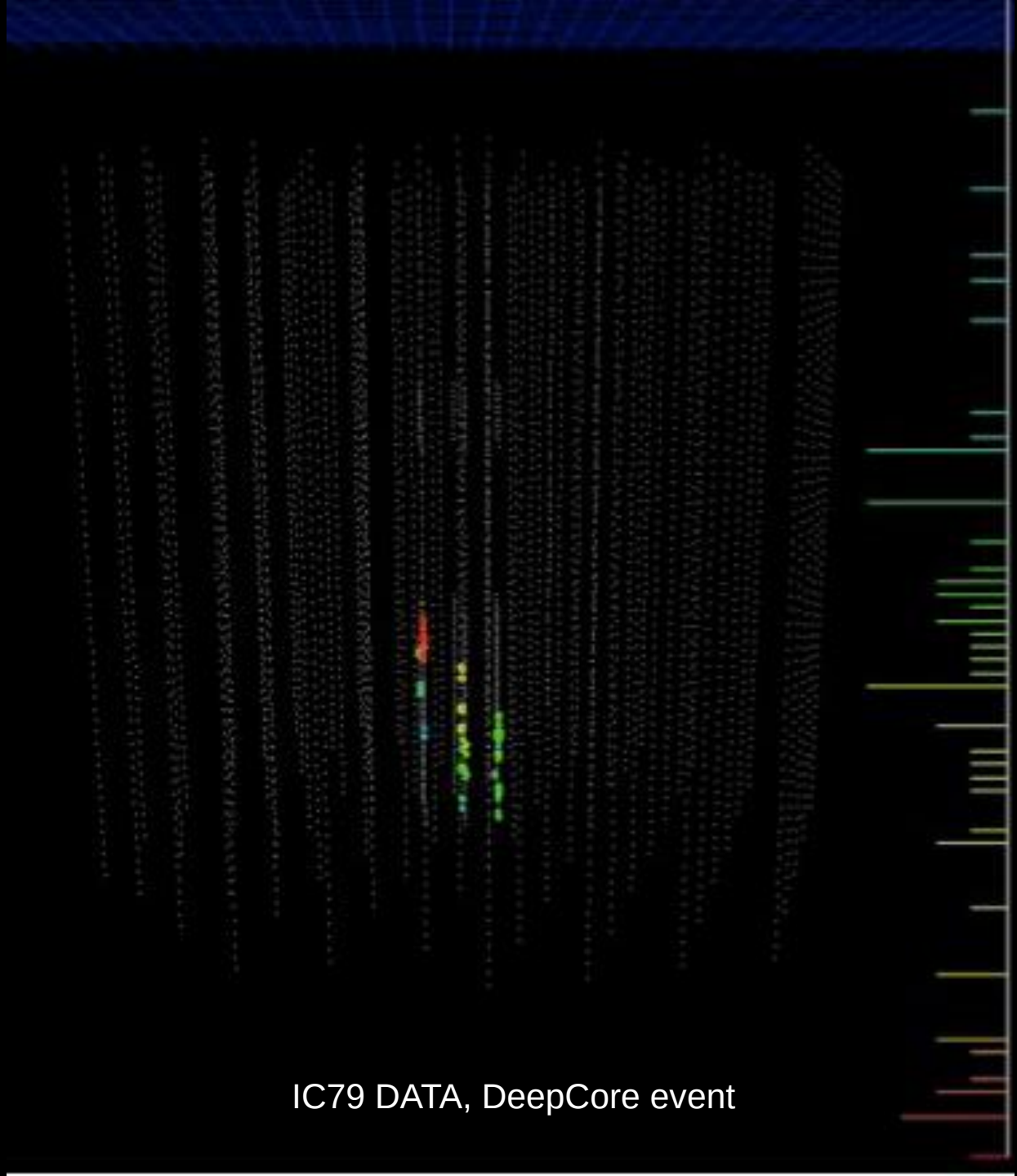
electron



tau

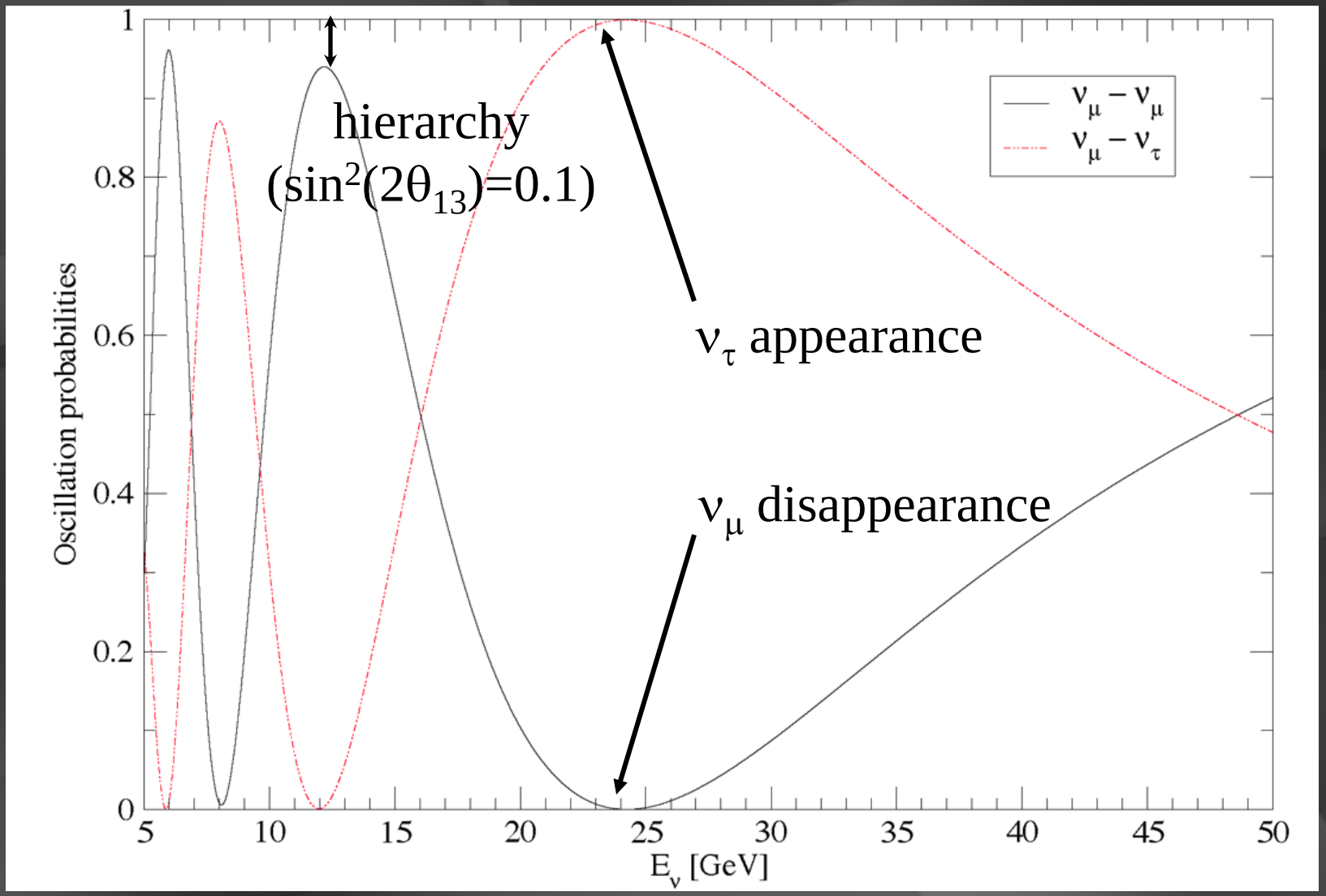






IC79 DATA, DeepCore event

neutrino oscillations in DeepCore



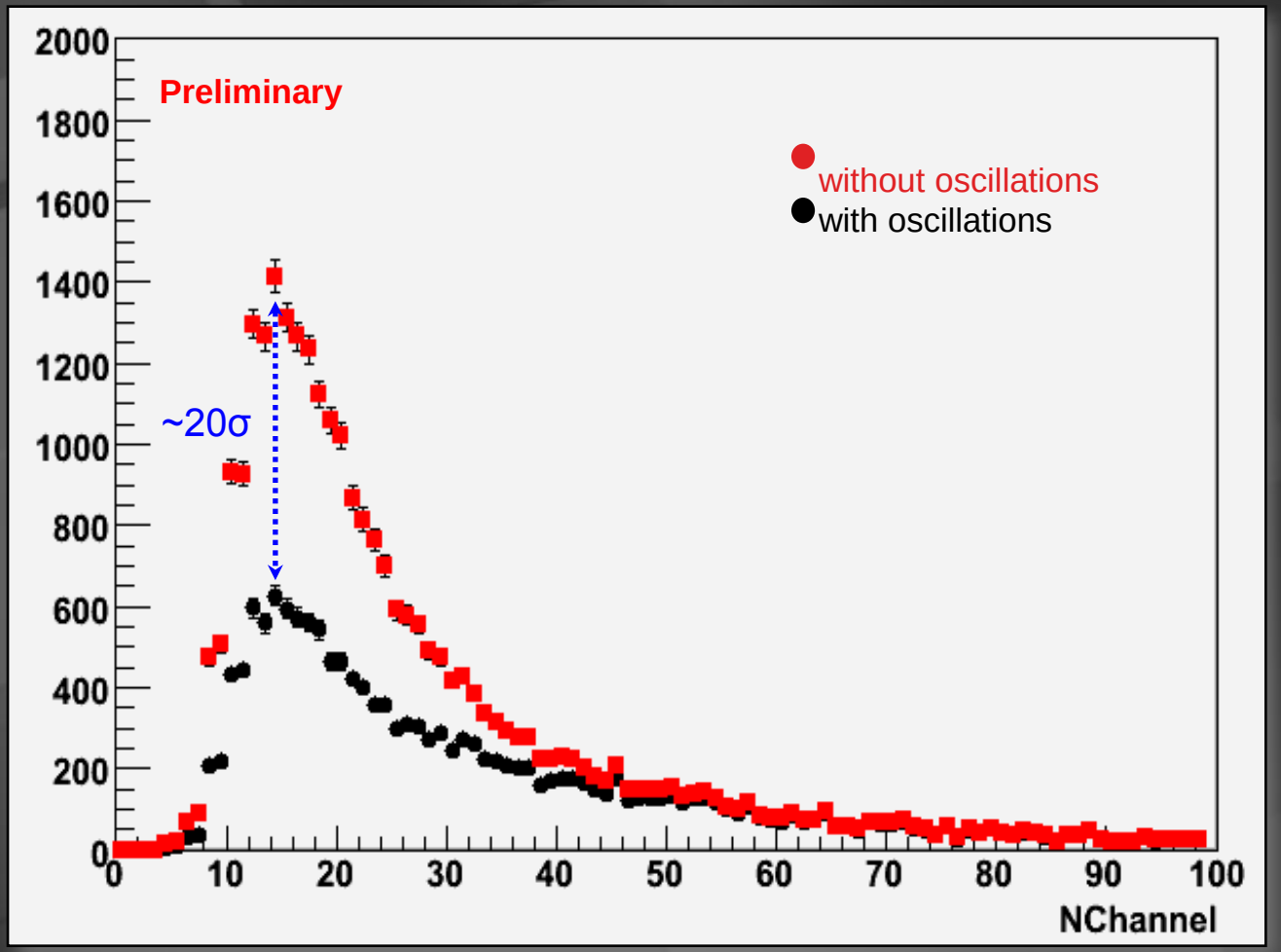
•resonance in effective θ_{13} angle traversing the Earth diameter at 10 GeV

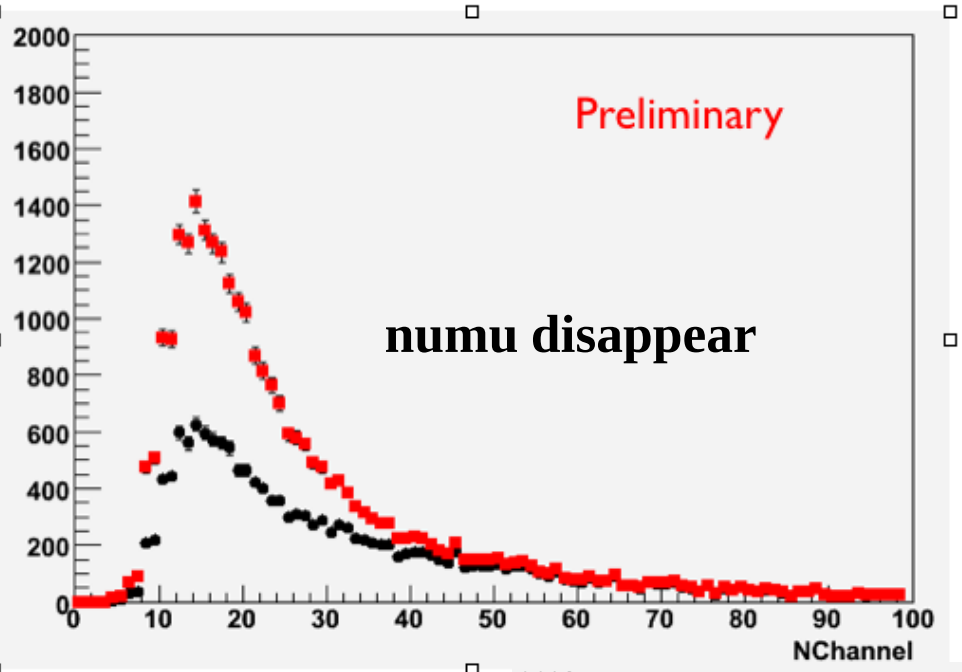
muon neutrino disappearance

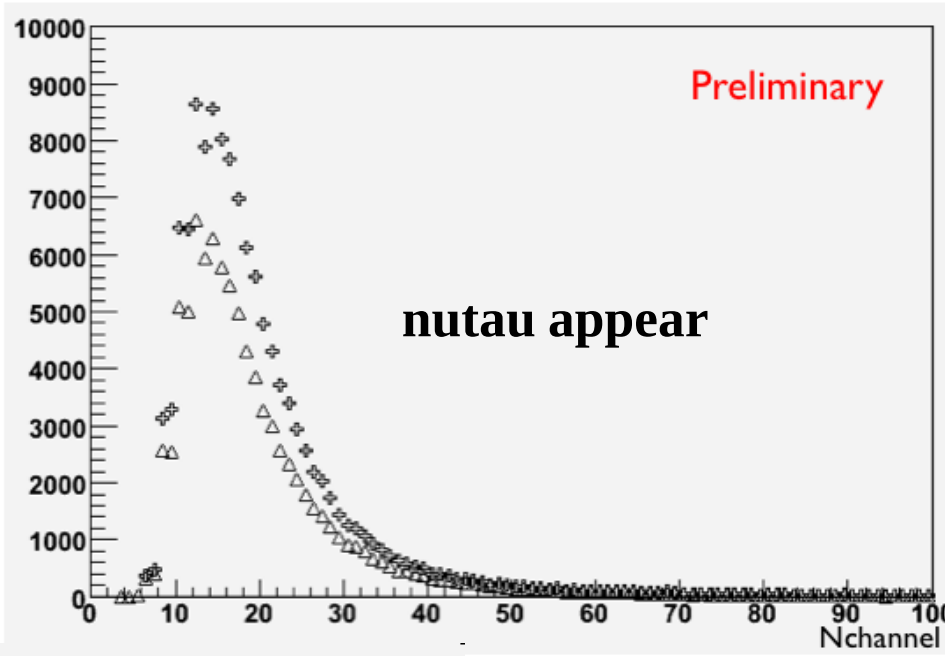
full detector simulation of 3-flavor oscillations

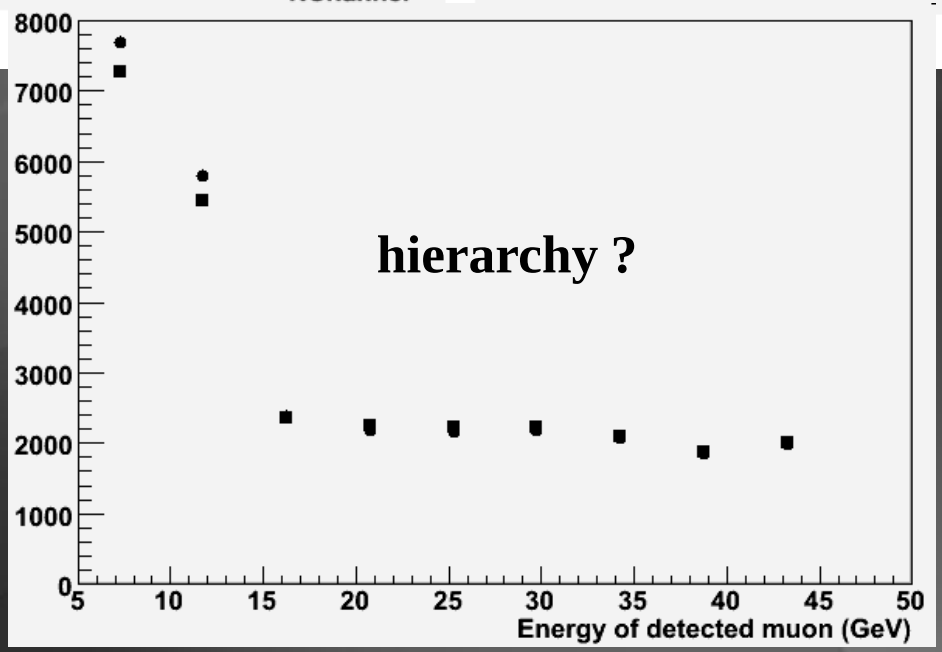
- 1 year DC
  - noo bg assumed
  - $\cos(\theta) < -0.6$

number of hit DOM used as simple energy estimator

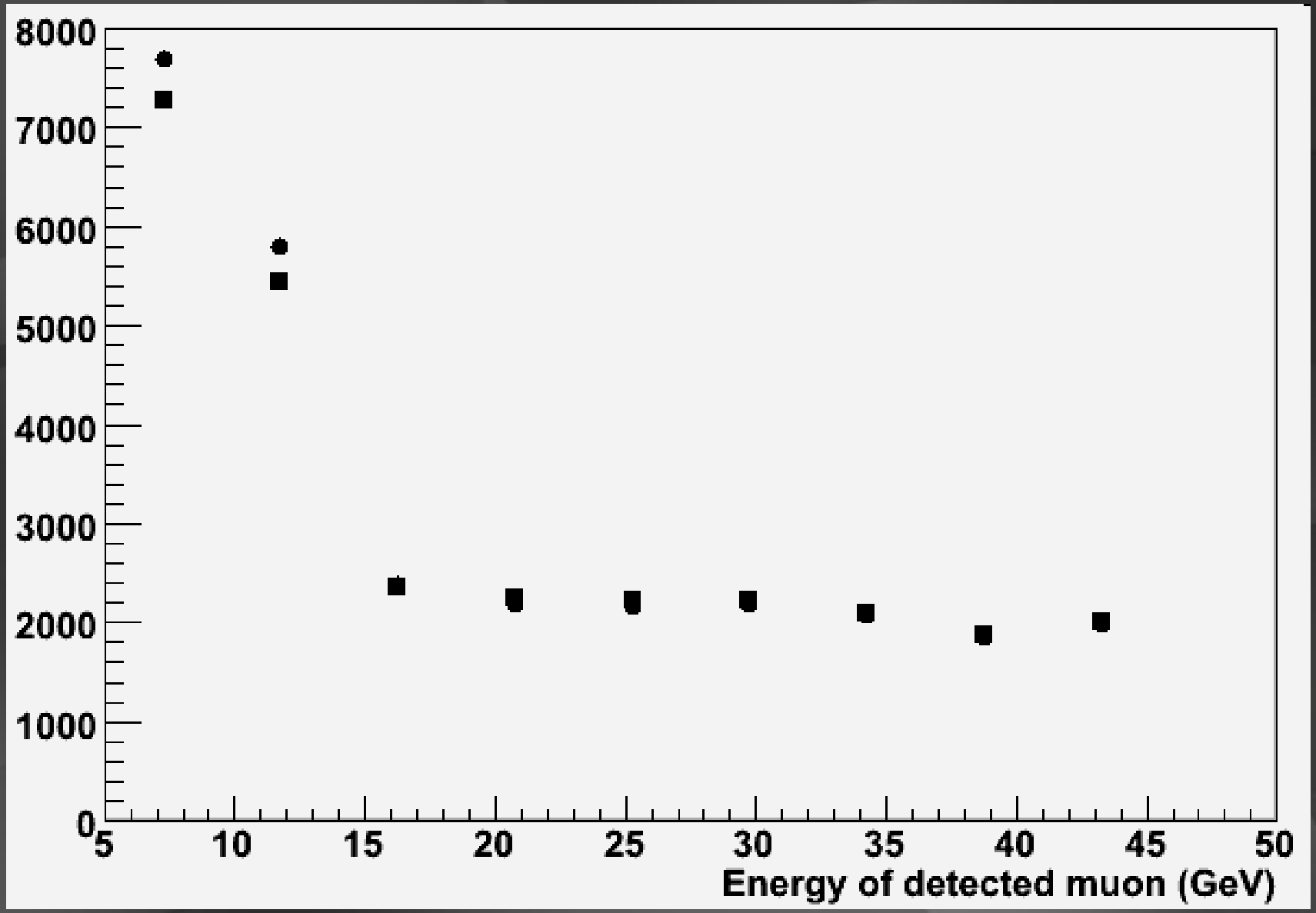



Preliminary
numu disappear
NChannel


Preliminary
nutau appear
Nchannel


hierarchy ?
Energy of detected muon (GeV)

hierarchy by statistics?

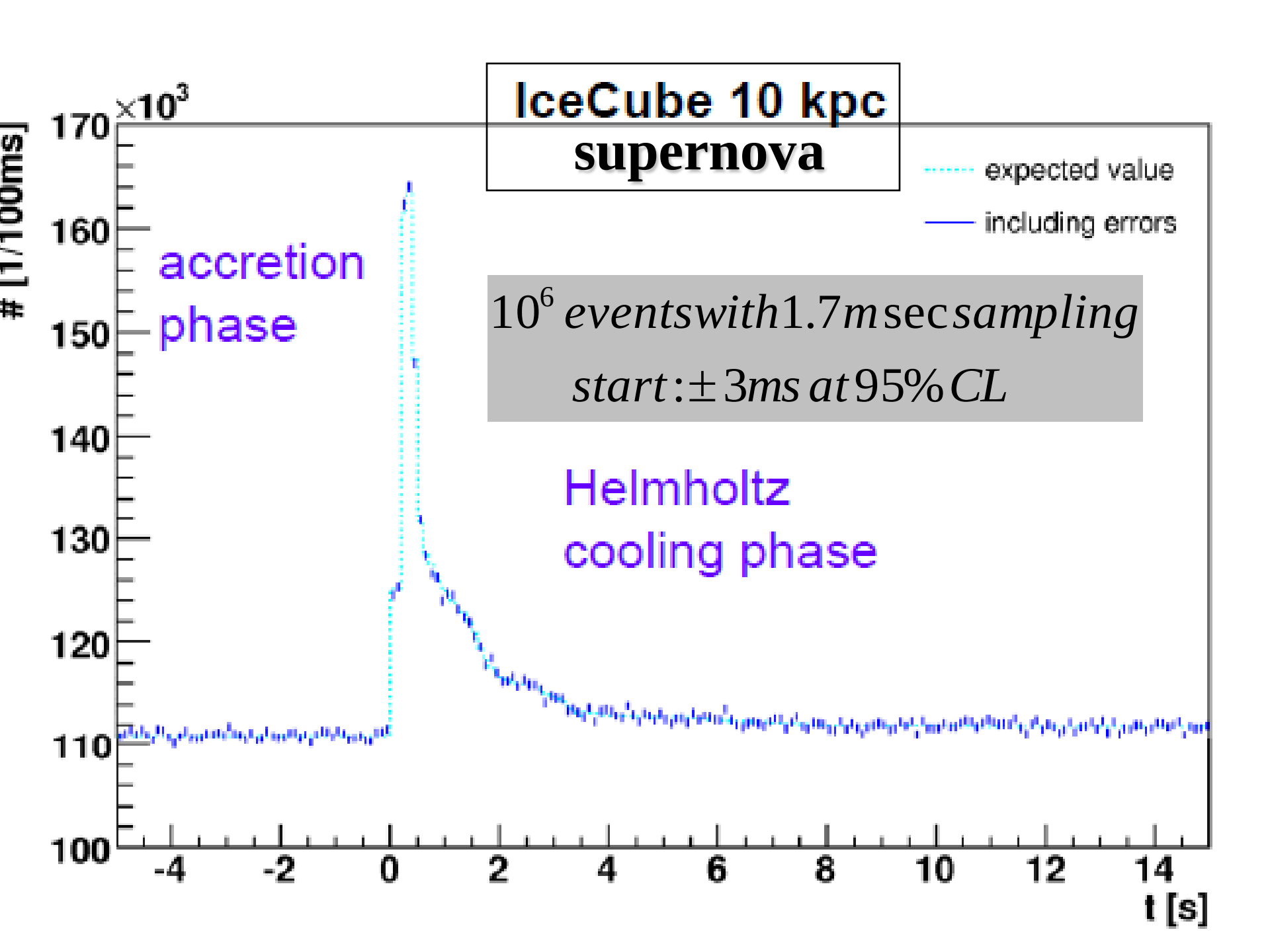


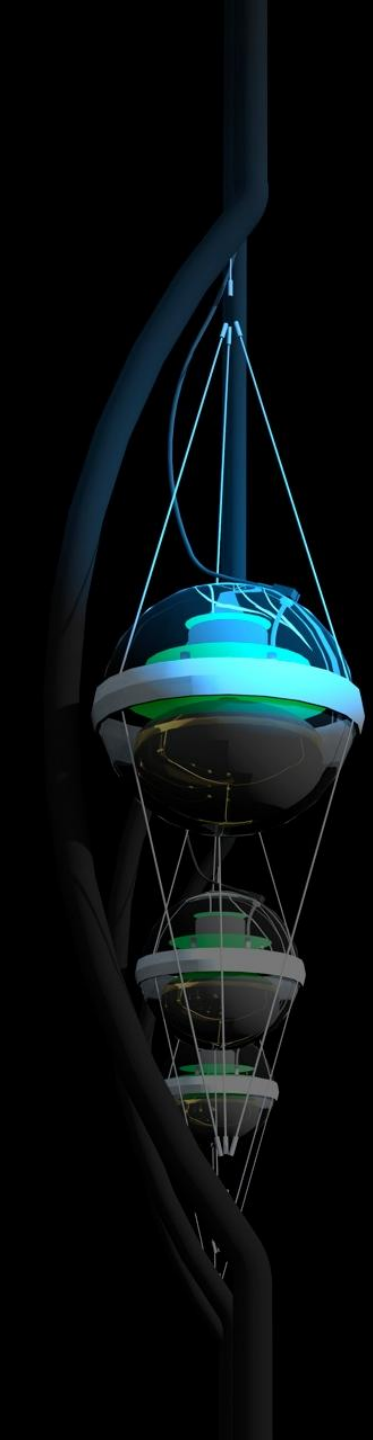
~ 10 GeV : hierarchy from matter effects in the Earth near first absorption dip

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

(mostly) neutrino + antineutrino -

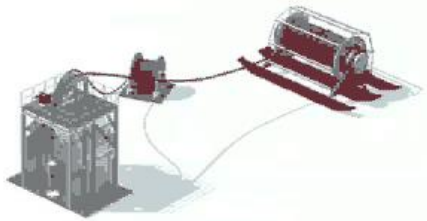
sign Δ_{13} : hierarchy !


IceCube 10 kpc
supernova
expected value
including errors
accretion
phase
10^6 events with 1.7 msec sampling
start : ± 3 ms at 95% CL
Helmholtz
cooling phase
[1/100ms]
×10^3
170
160
150
140
130
120
110
100
-4
-2
0
2
4
6
8
10
12
14
t [s]



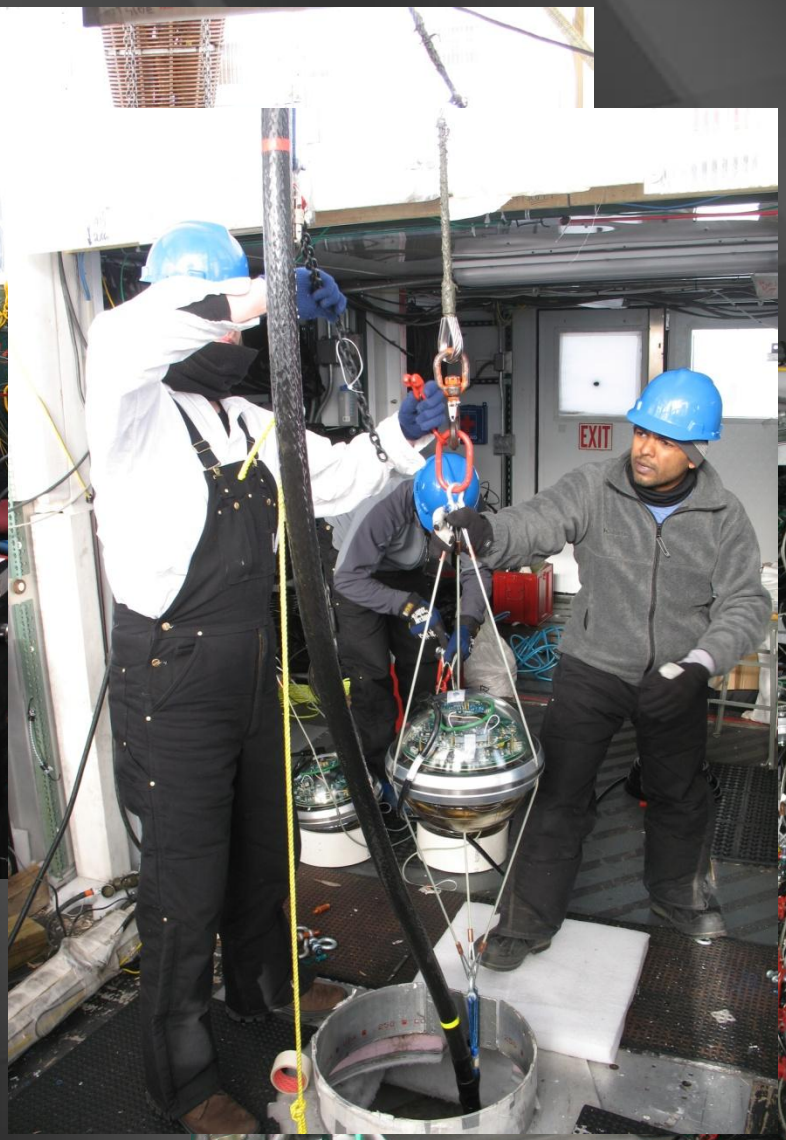
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

IceCube.wisc.edu



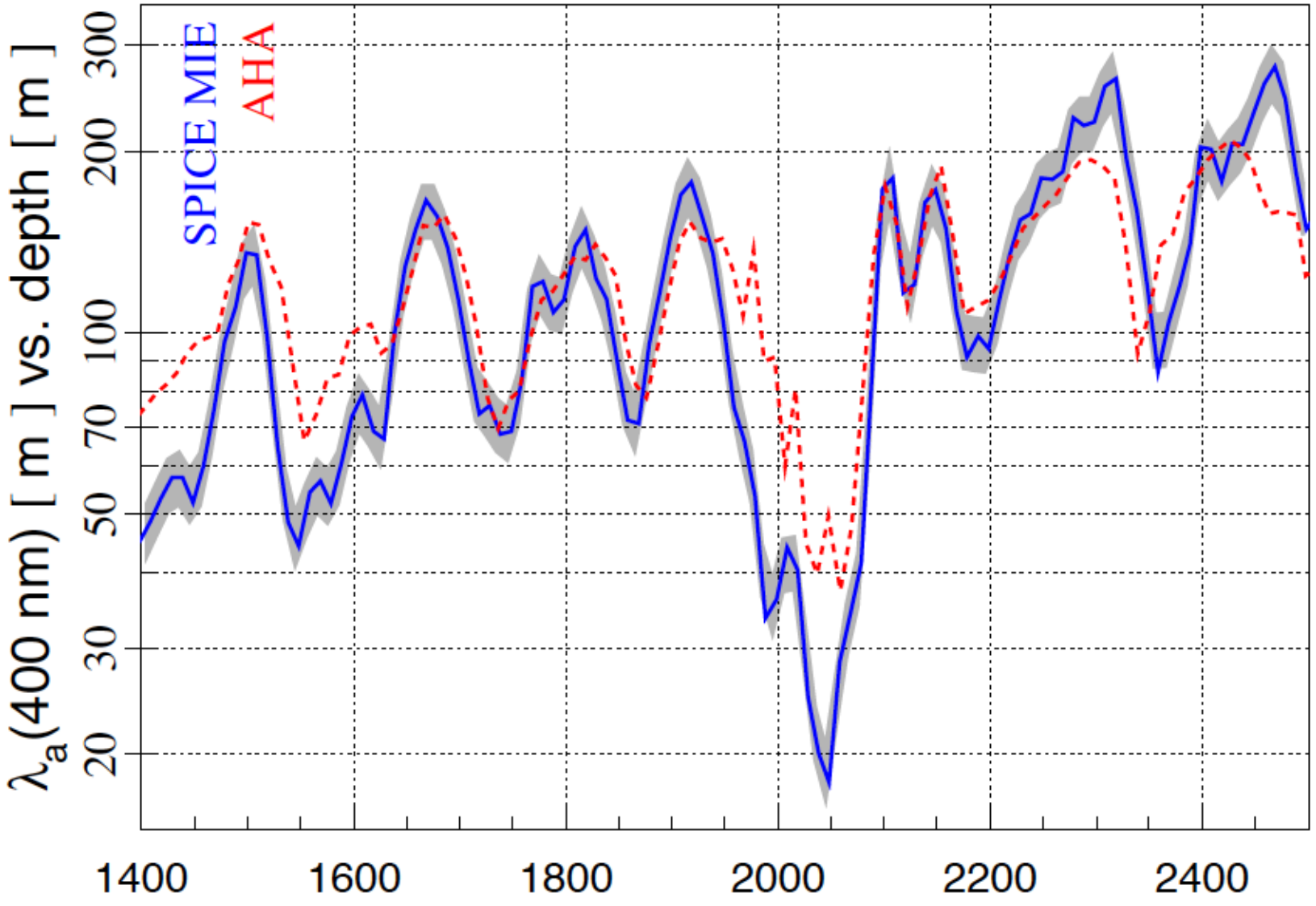

nozzle delivers →
• 200 gallons per minute
• 7 Mpa
• 90 degree C
→ 4.8 megawatt heating plant

drilling and deployment

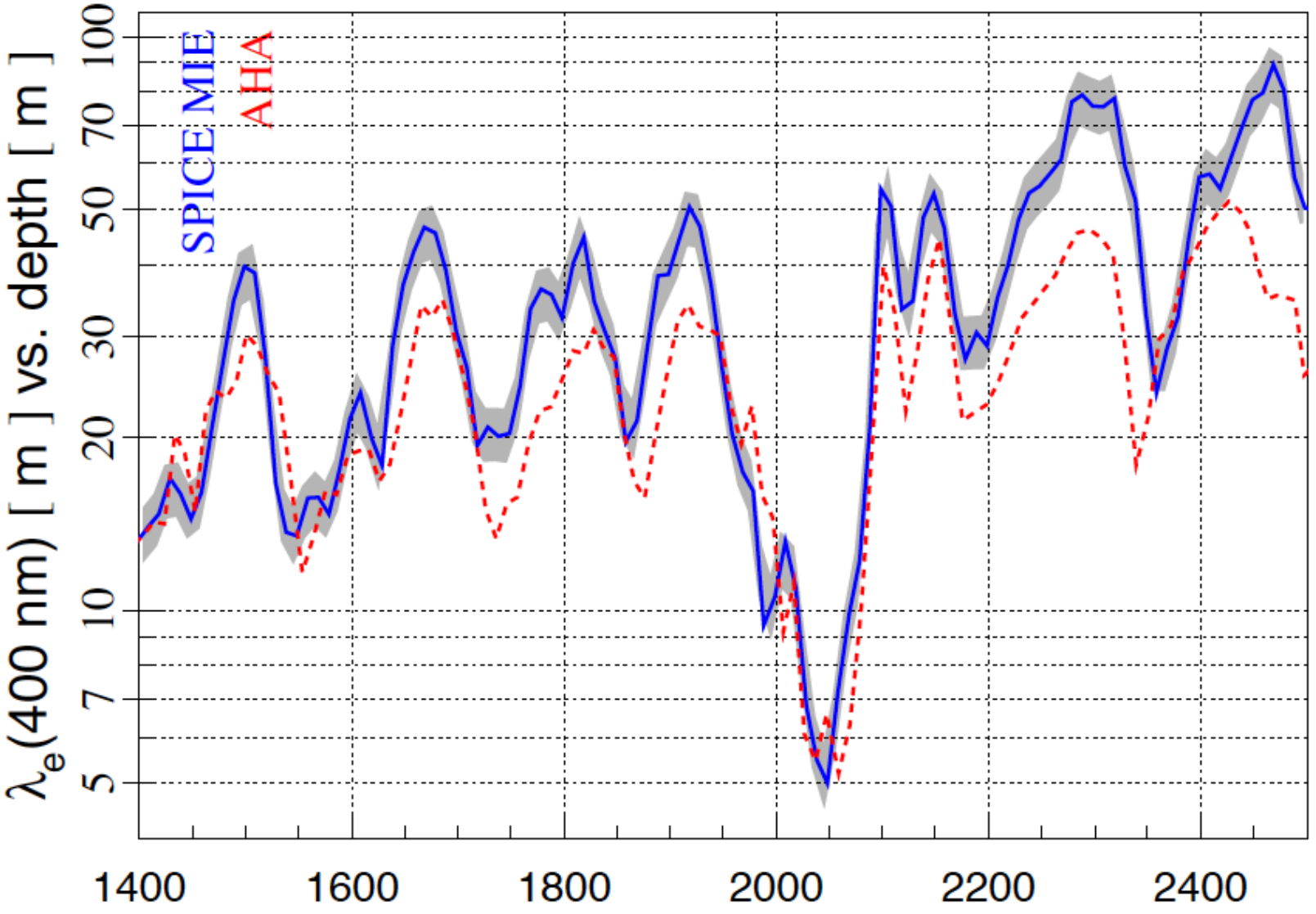


to 2500 m in less than 2 days → 3.5 cm/second

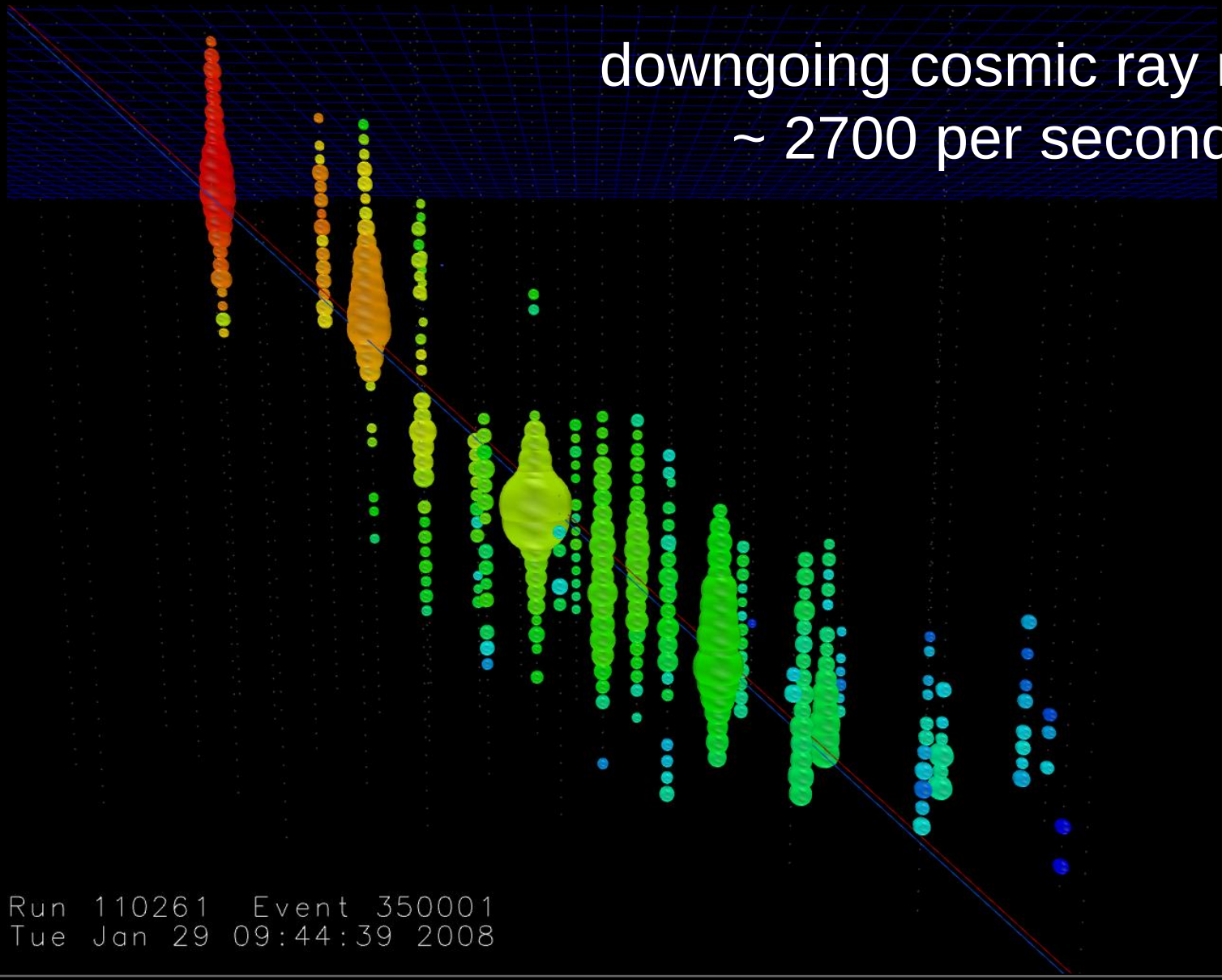
absorption length ← 220m →



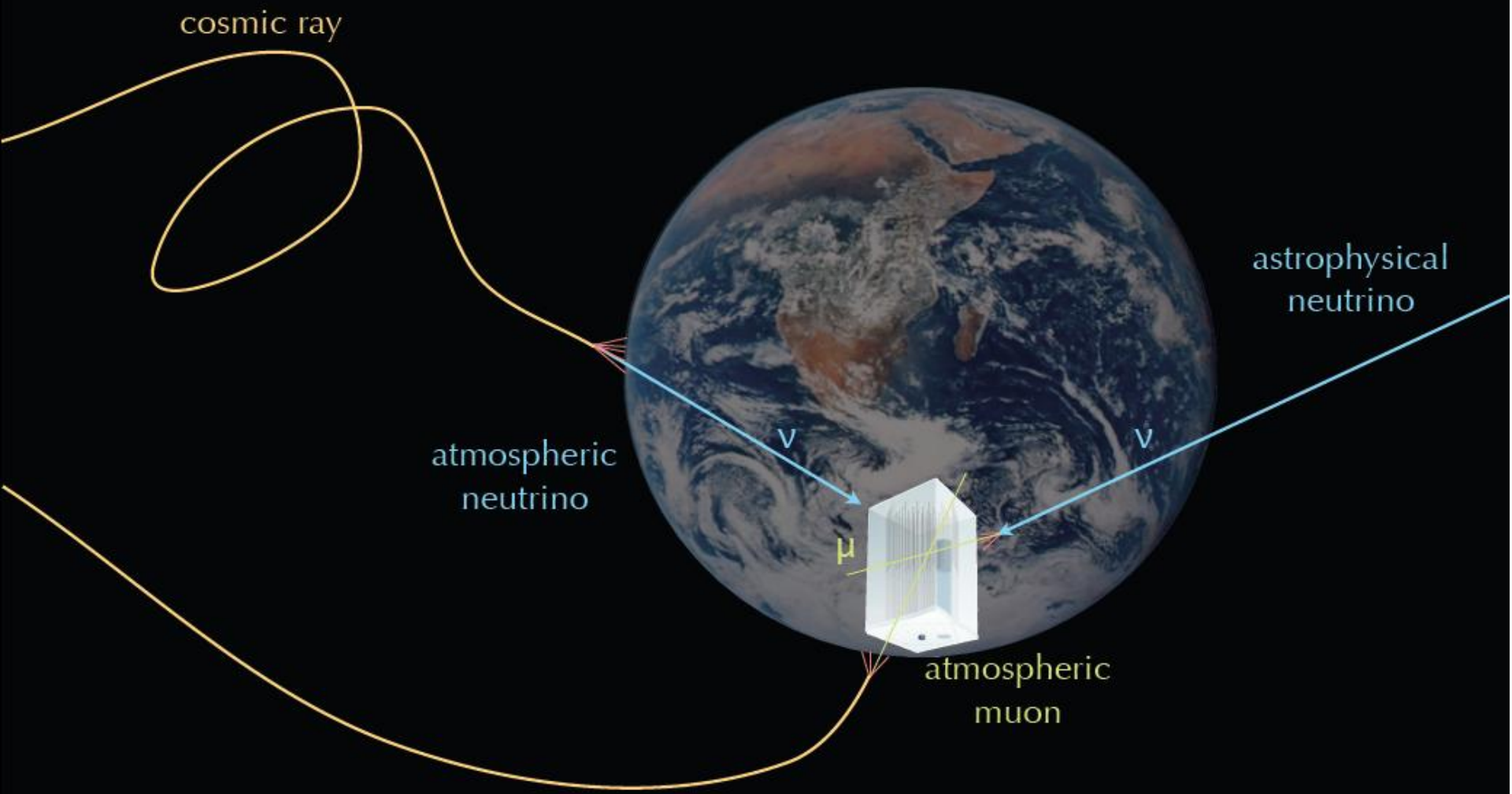
scattering length ← 47m →



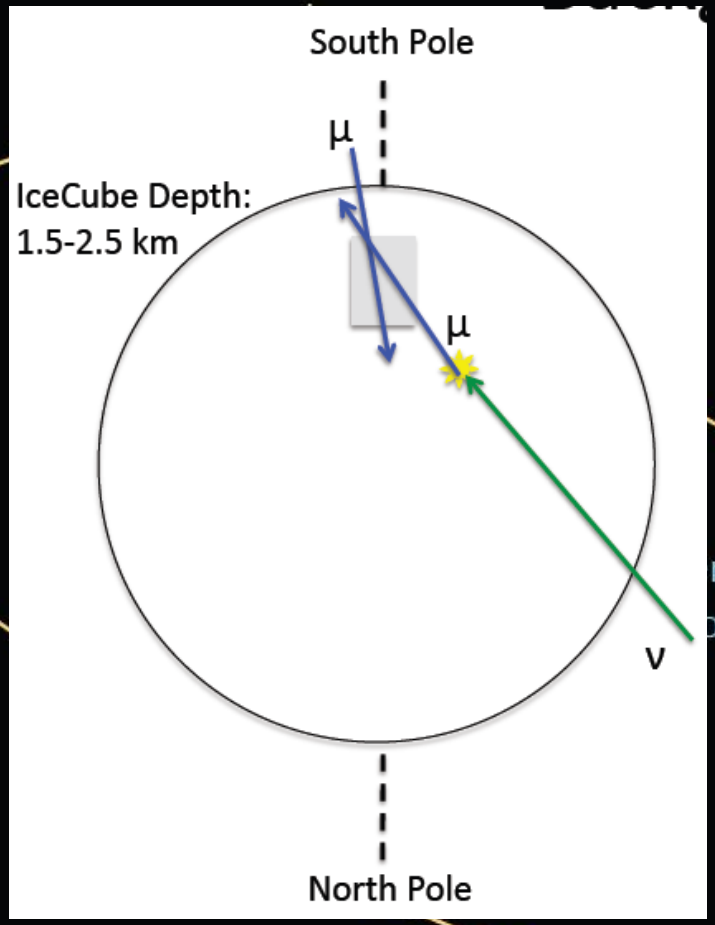
Muon event in IceCube

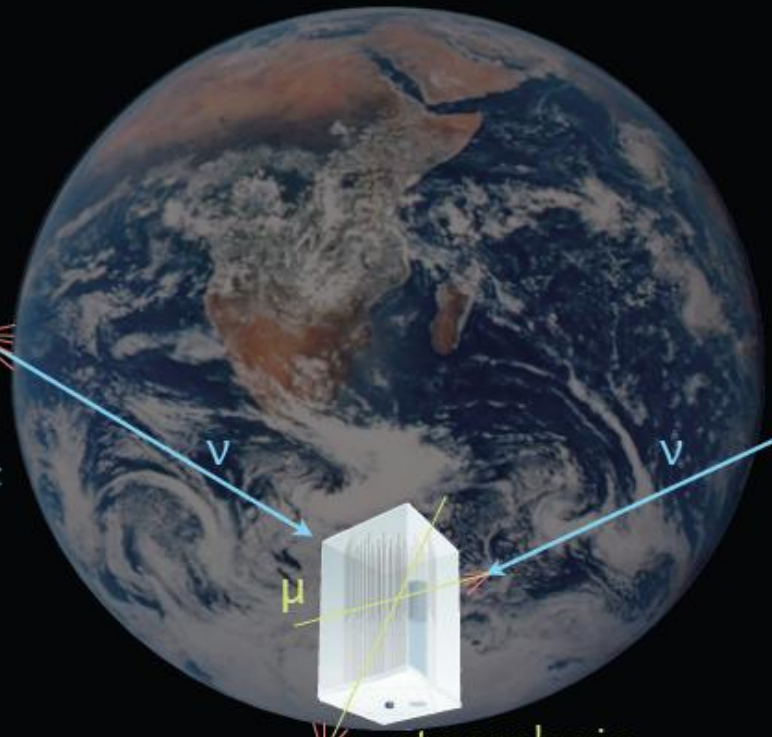


Signals and Backgrounds



Signals and Backgrounds





astrophysical
neutrino

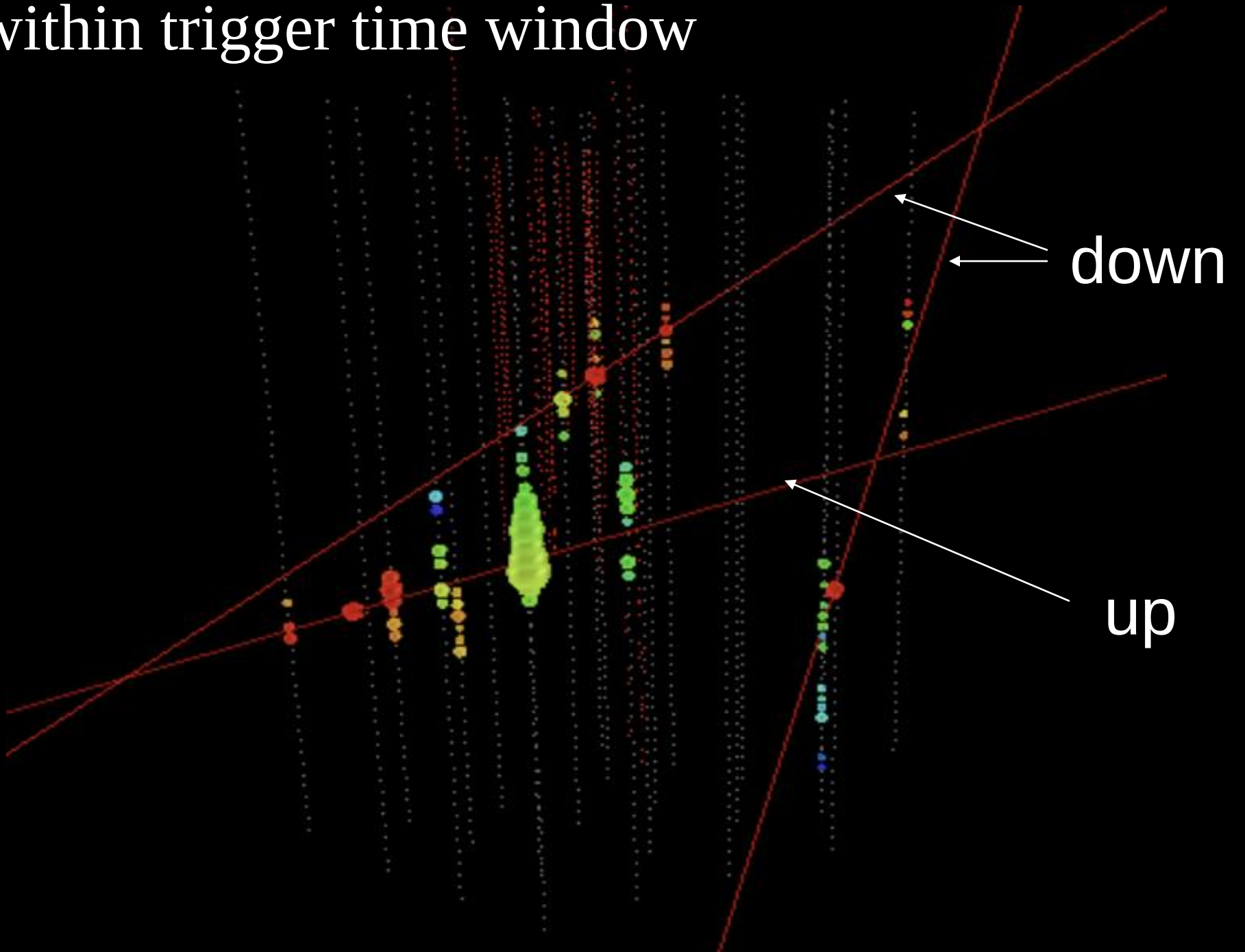
atmospheric
muon

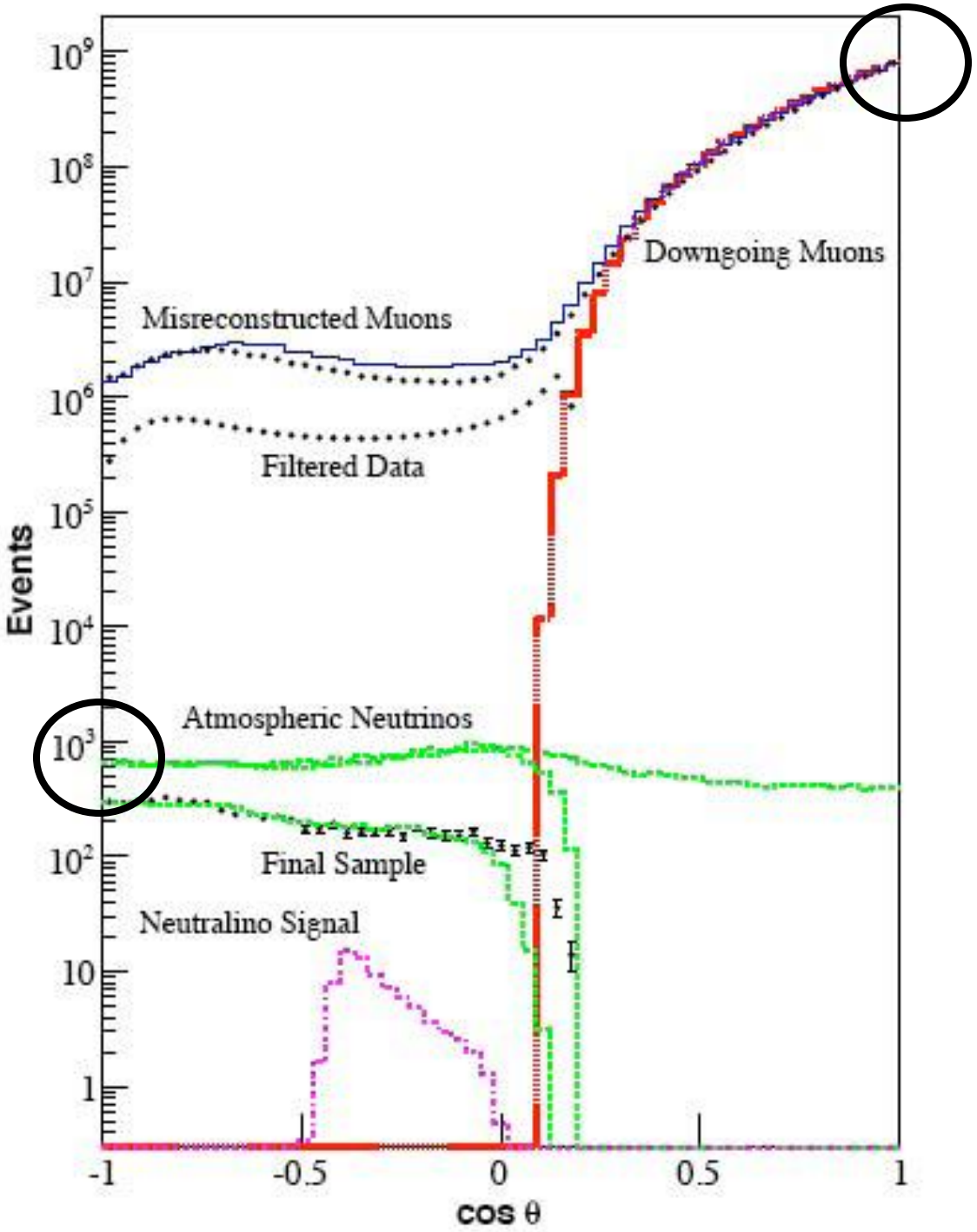
muons detected per year:

- atmospheric* μ 7×10^{10}
- atmospheric $\nu \rightarrow \mu$ $> 8 \times 10^{4}$
- cosmic $\nu \rightarrow \mu$ ~ 10

* > 2000 per second

within trigger time window

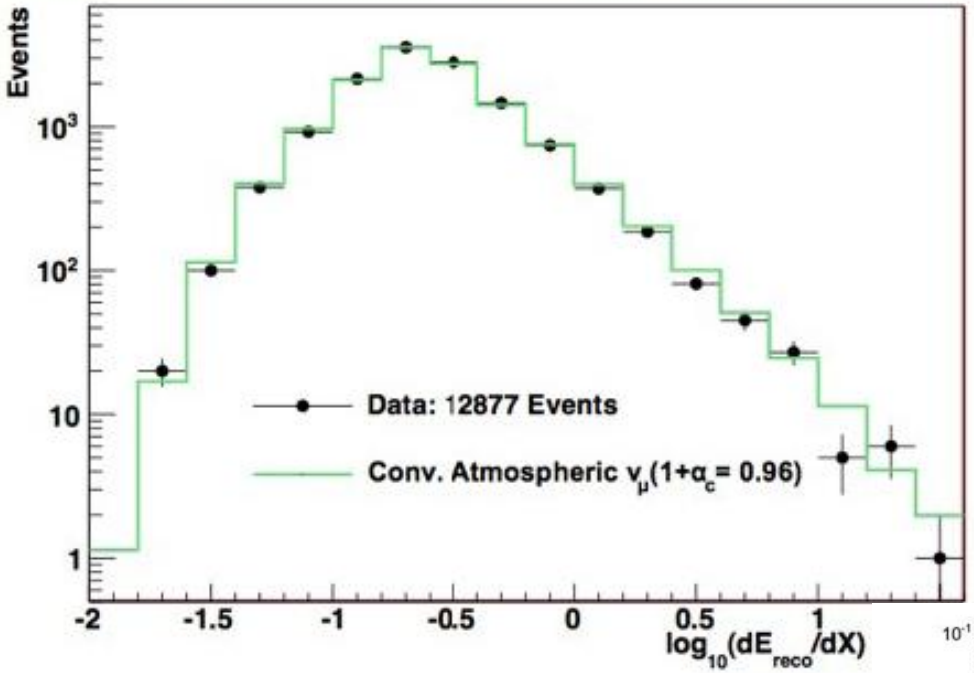


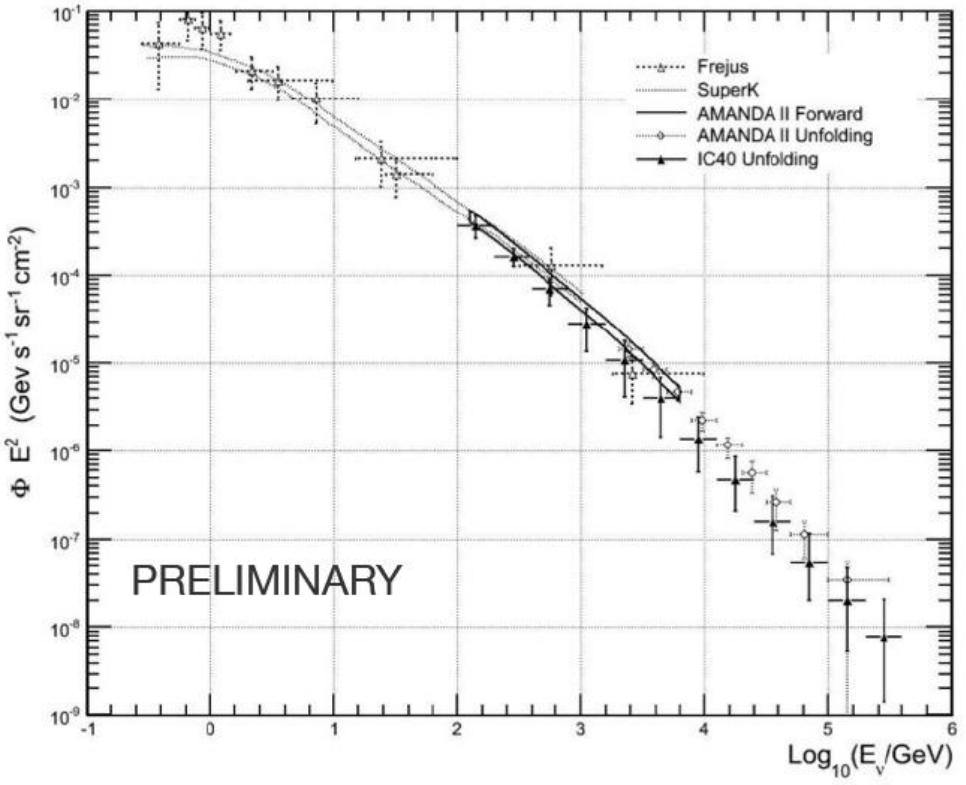

Events
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Misreconstructed Muons
Downgoing Muons
Filtered Data
Atmospheric Neutrinos
Final Sample
Neutralino Signal
-1
-0.5
0
0.5
1
cos θ

… on to 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.

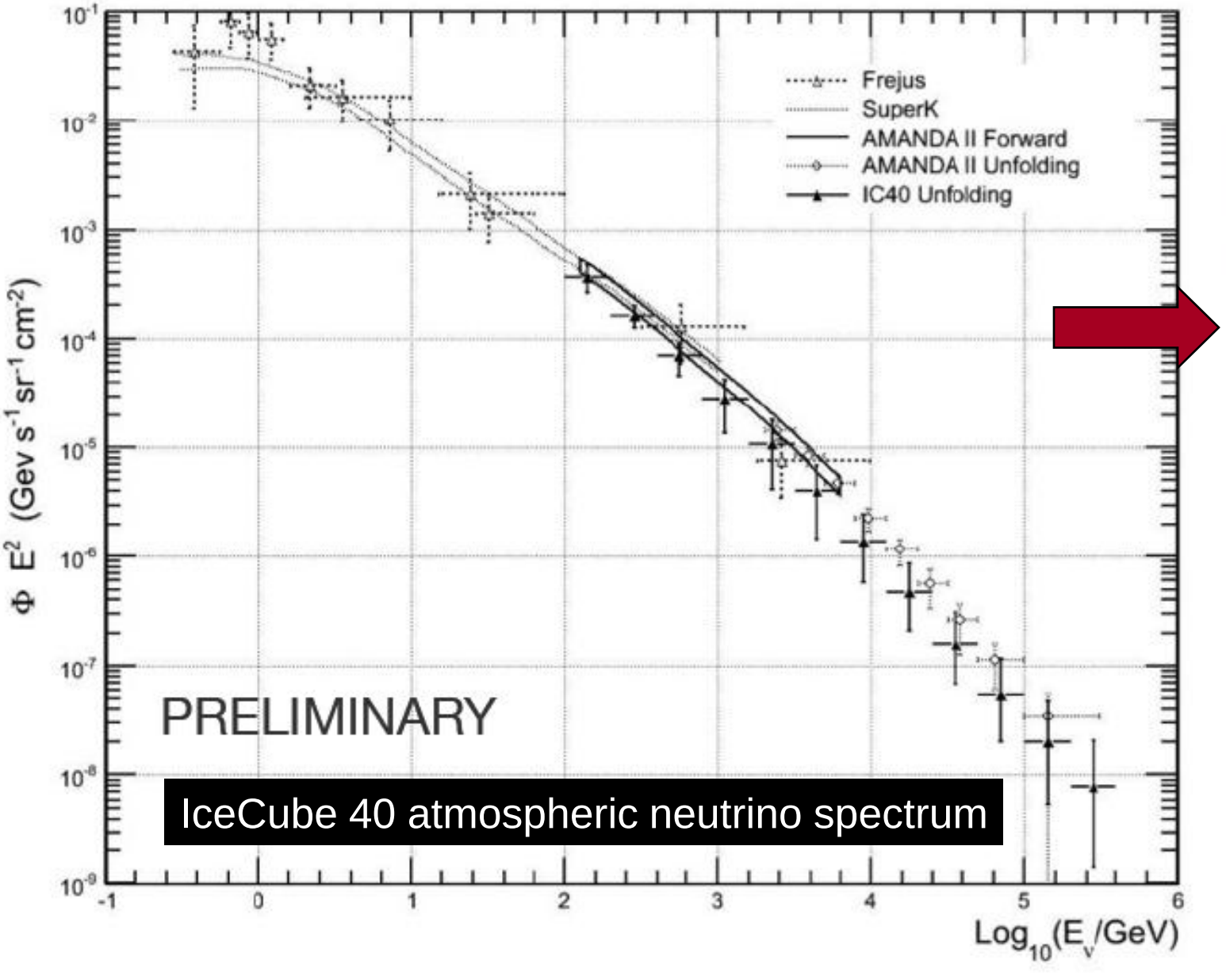
IceCube-40 atmospheric neutrino spectrum

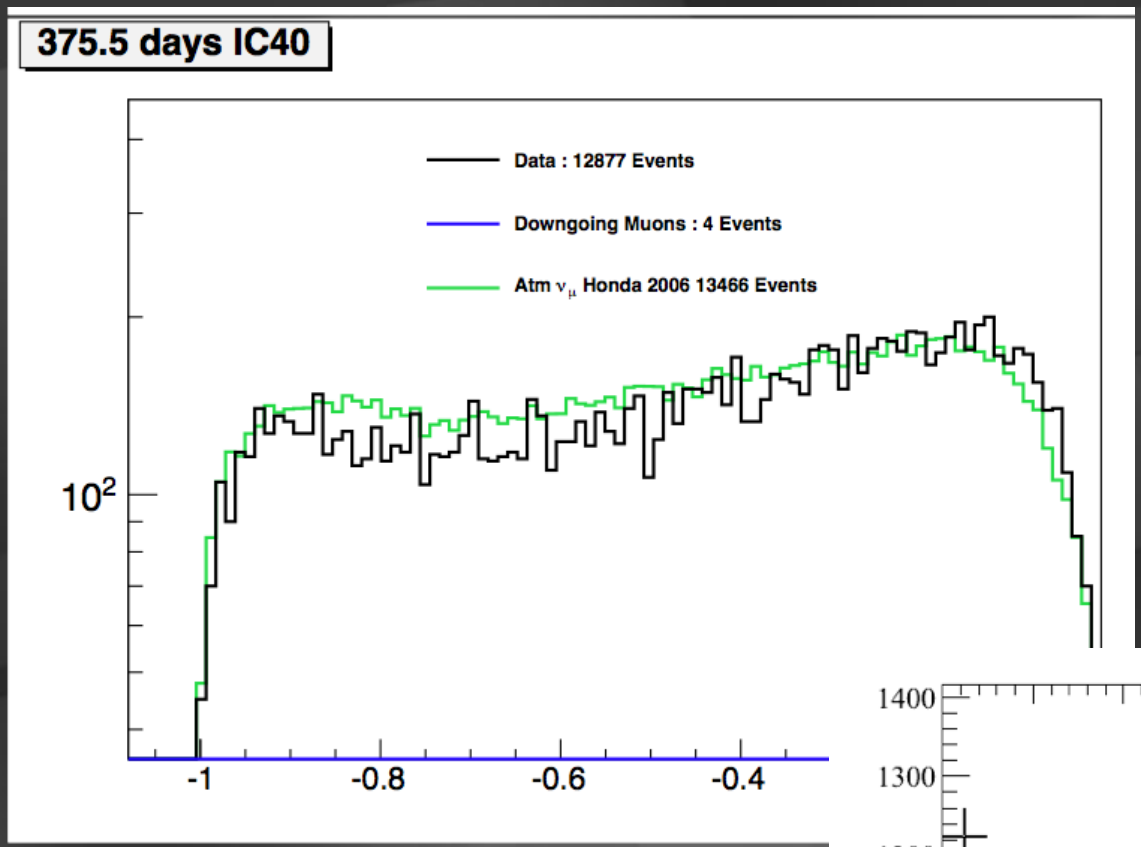




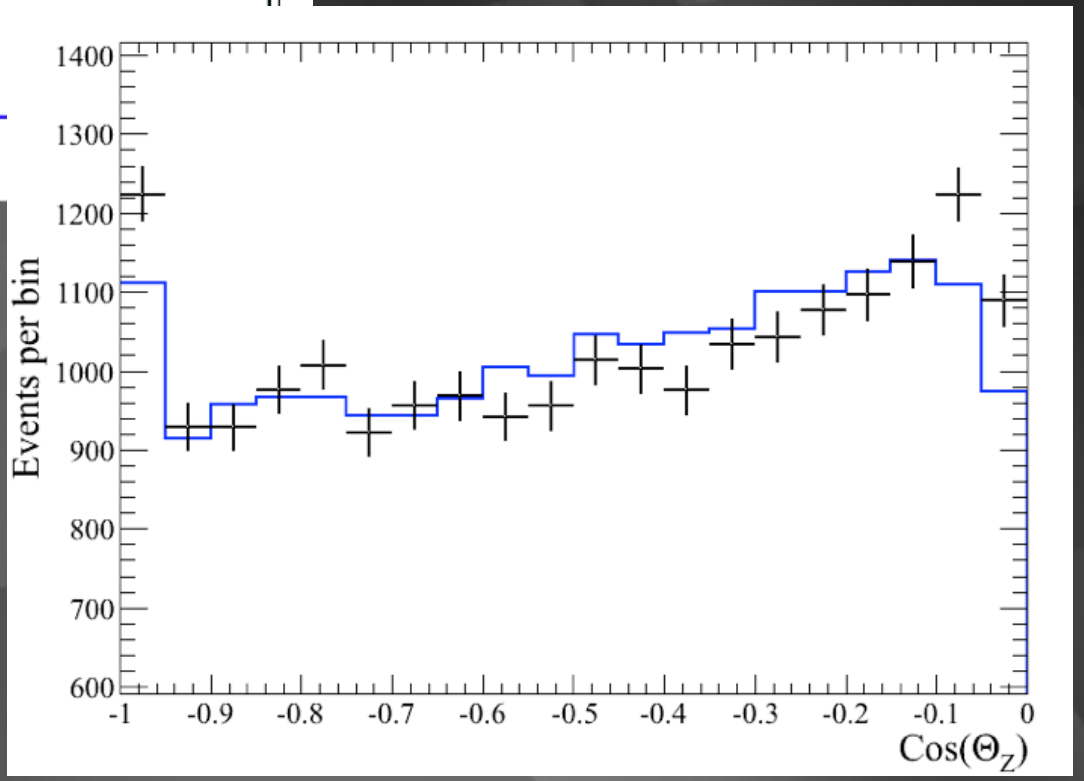
cosmic neutrinos:

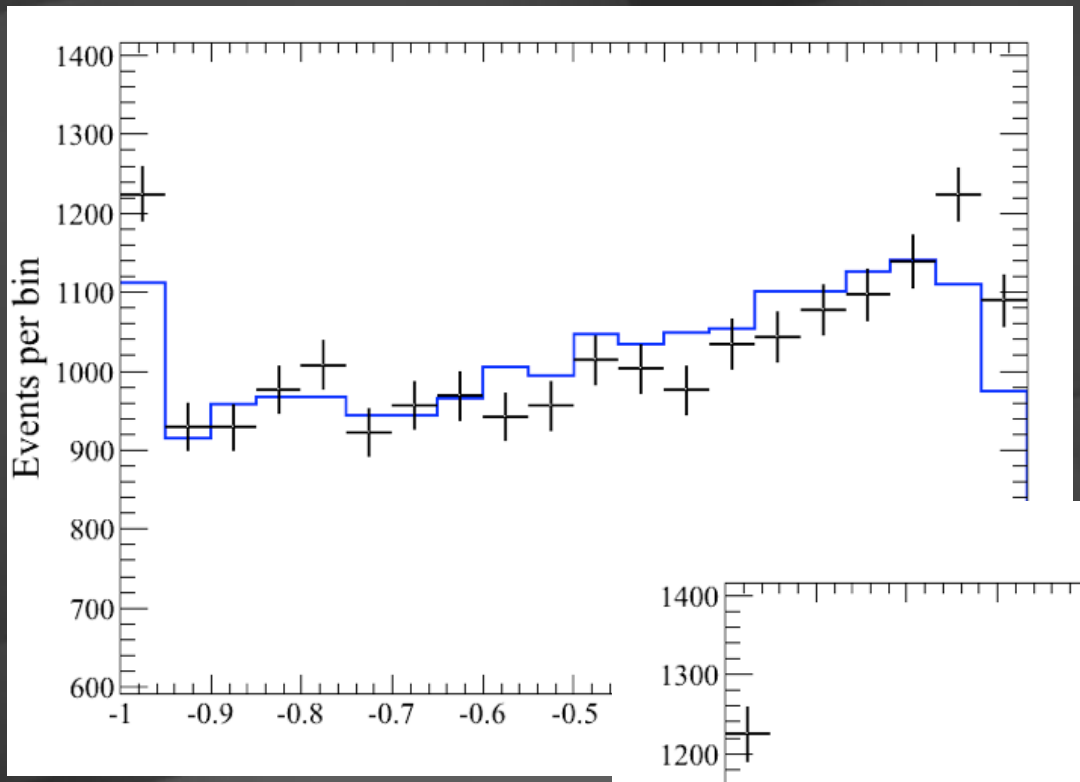
energy: >> 100 TeV





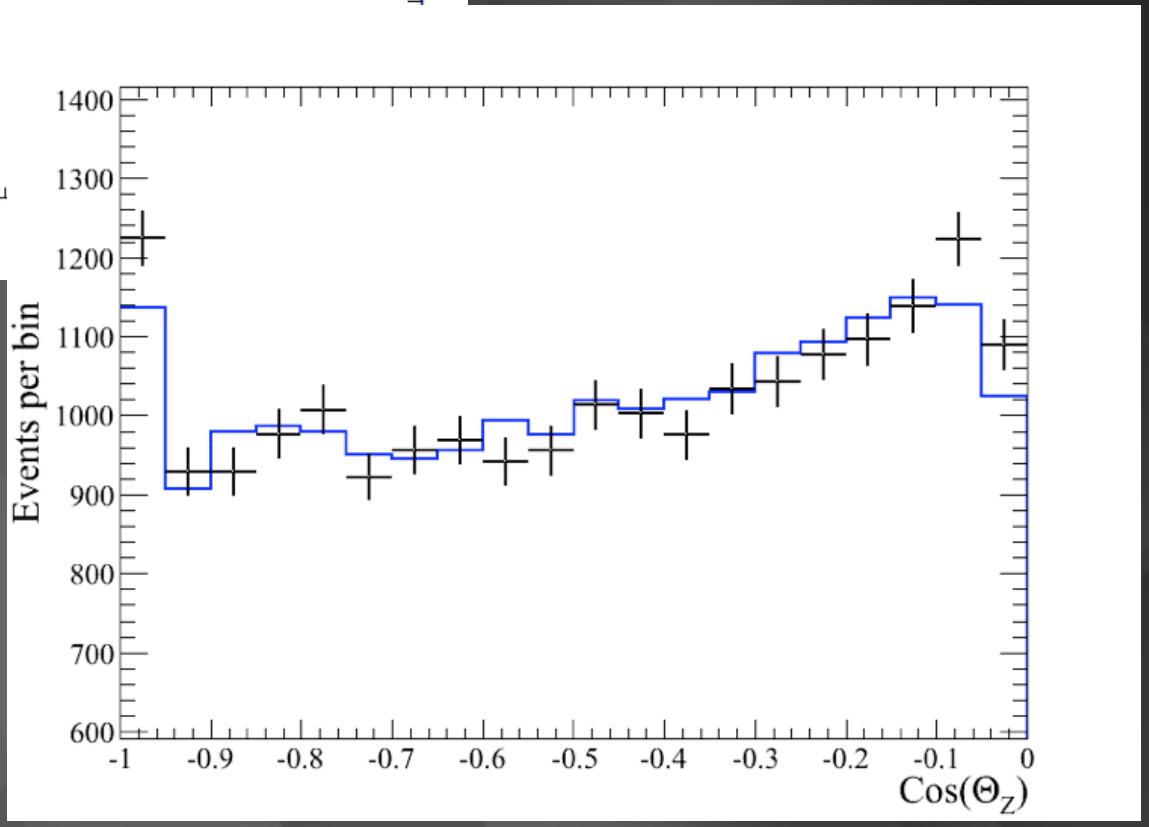
zenith angle
two analyses

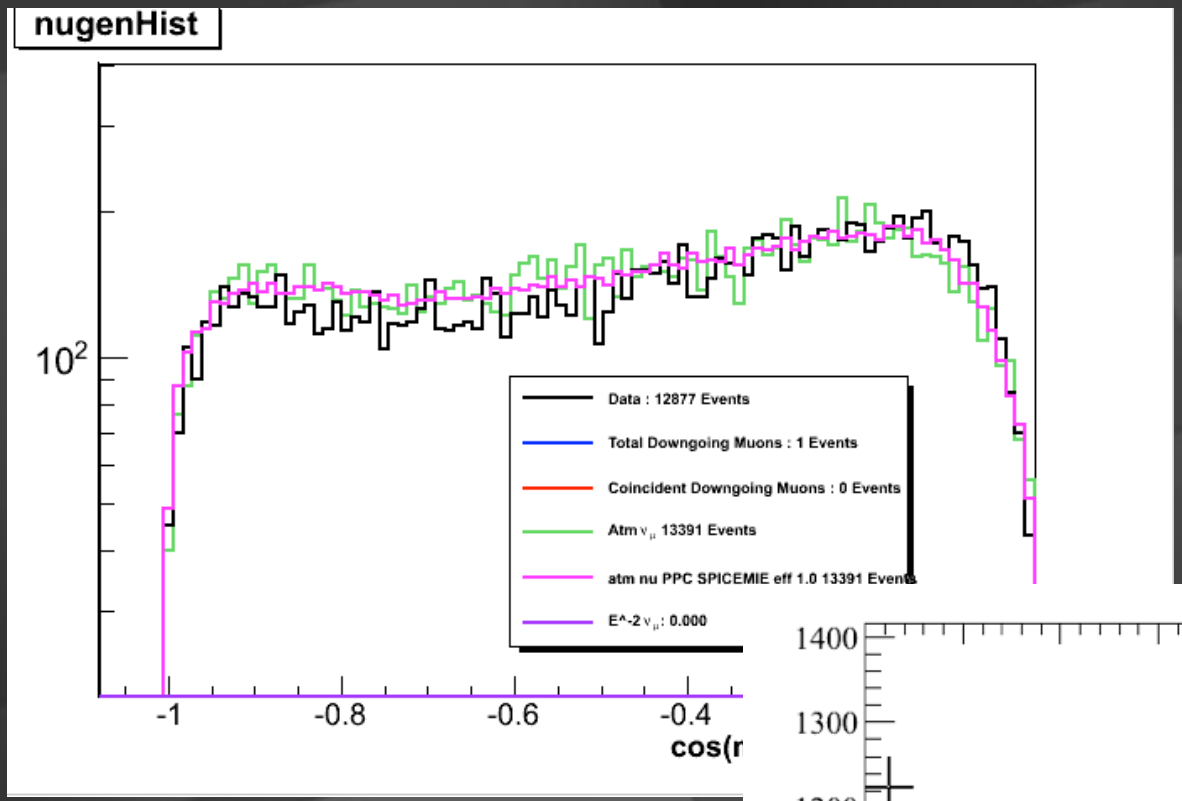



Events per bin
1400
1300
1200
1100
1000
900
800
700
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5

3

3+1

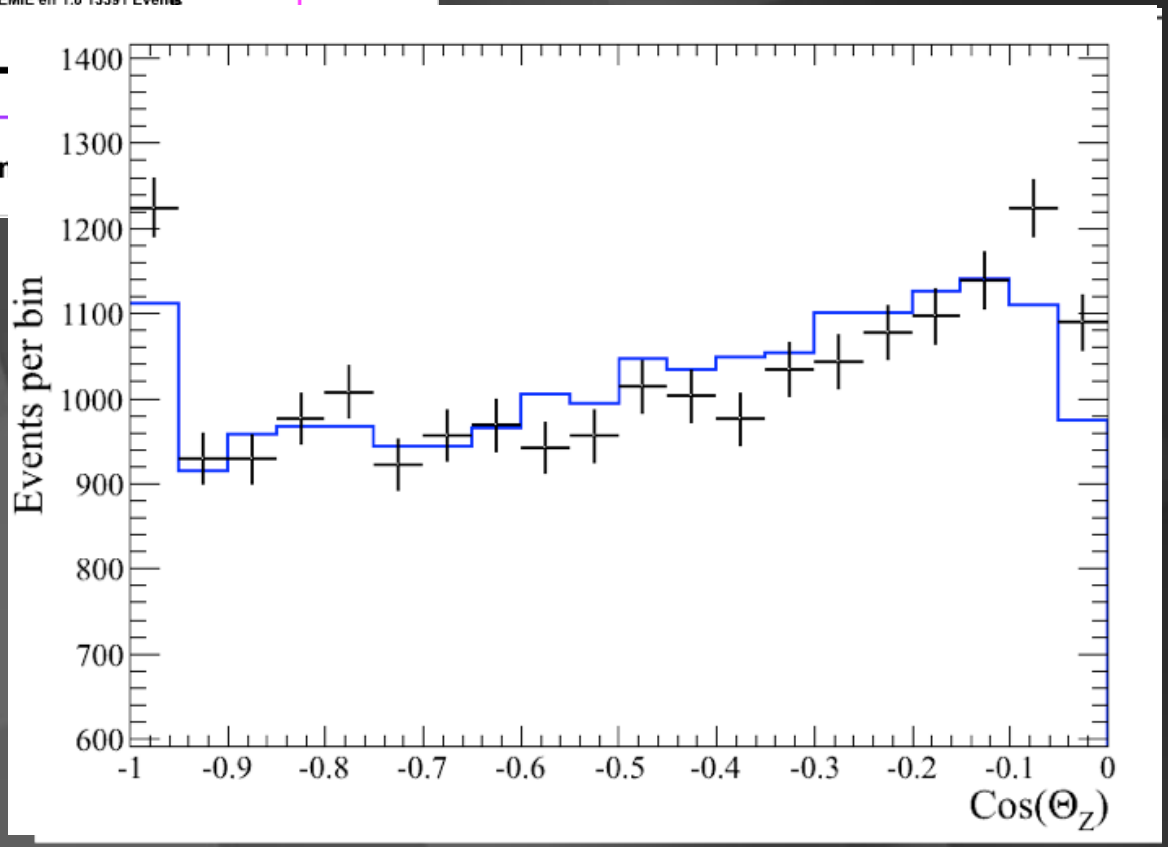

Events per bin
1400
1300
1200
1100
1000
900
800
700
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cos(Θz)



zenith angle
two analyses

systematics !

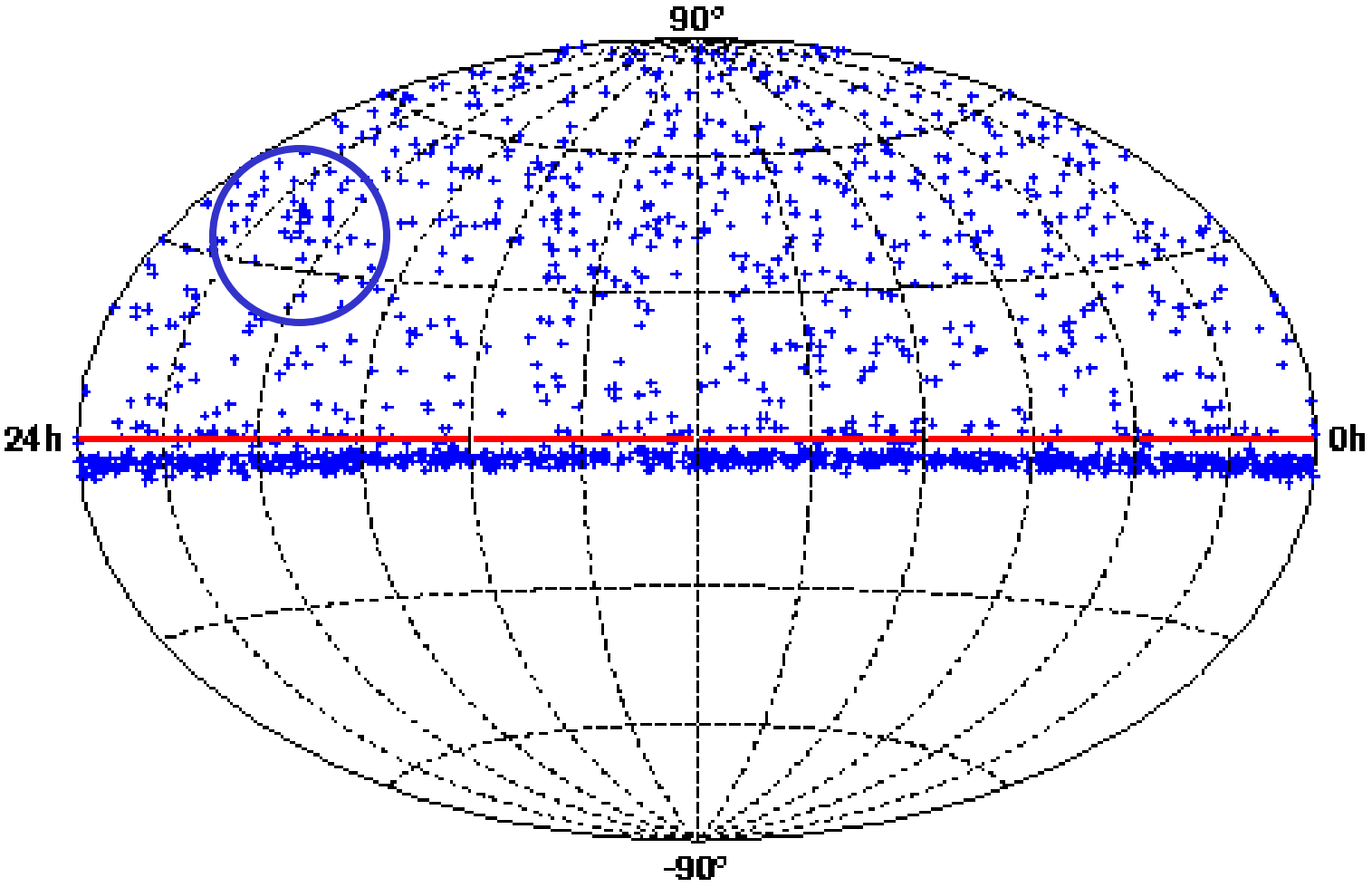
- K/π ratio
- zenith acceptance of modules
- ice



early astronomy

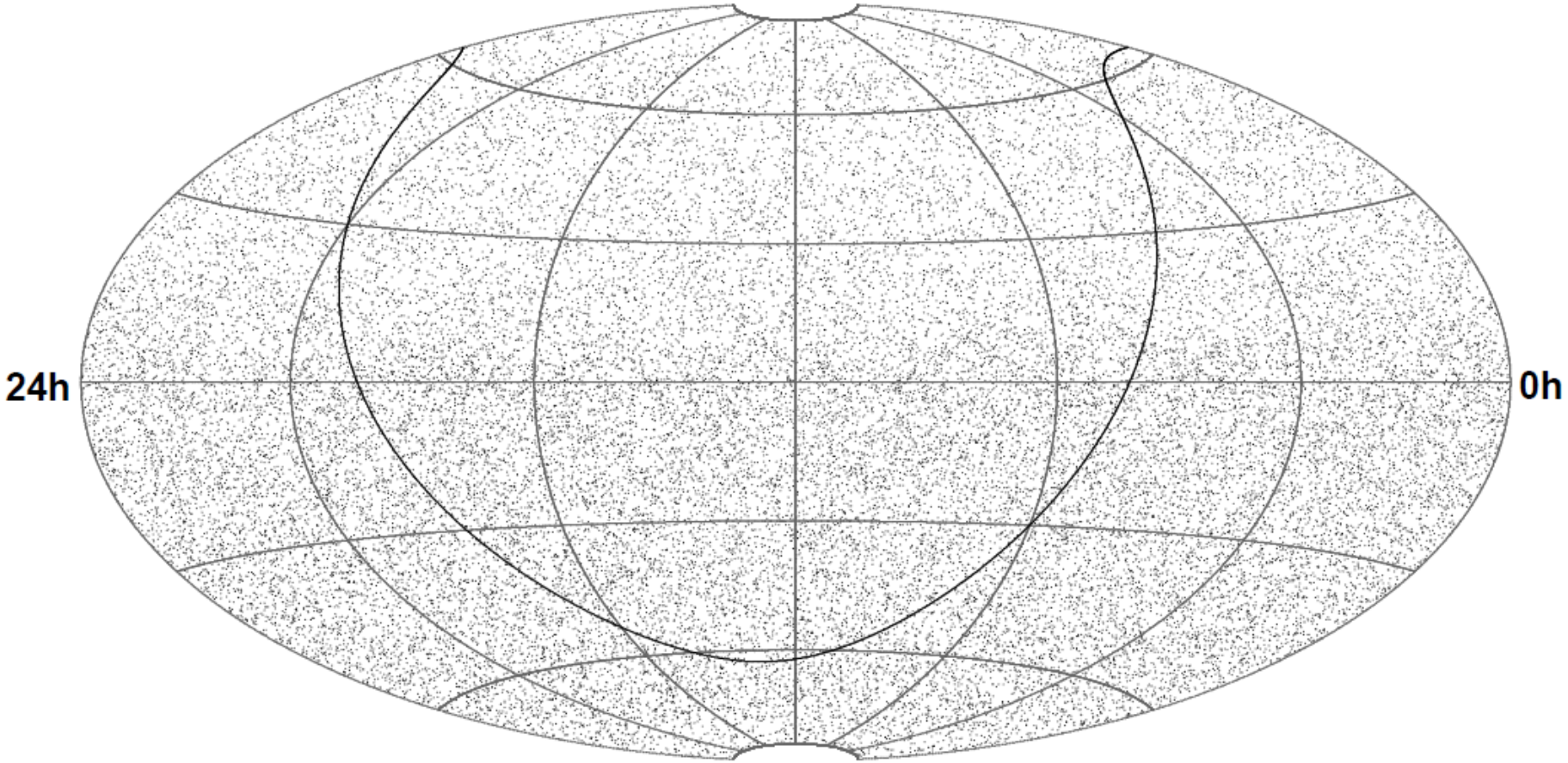
AMANDA 2000

directions of ~ 600 neutrinos



IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos

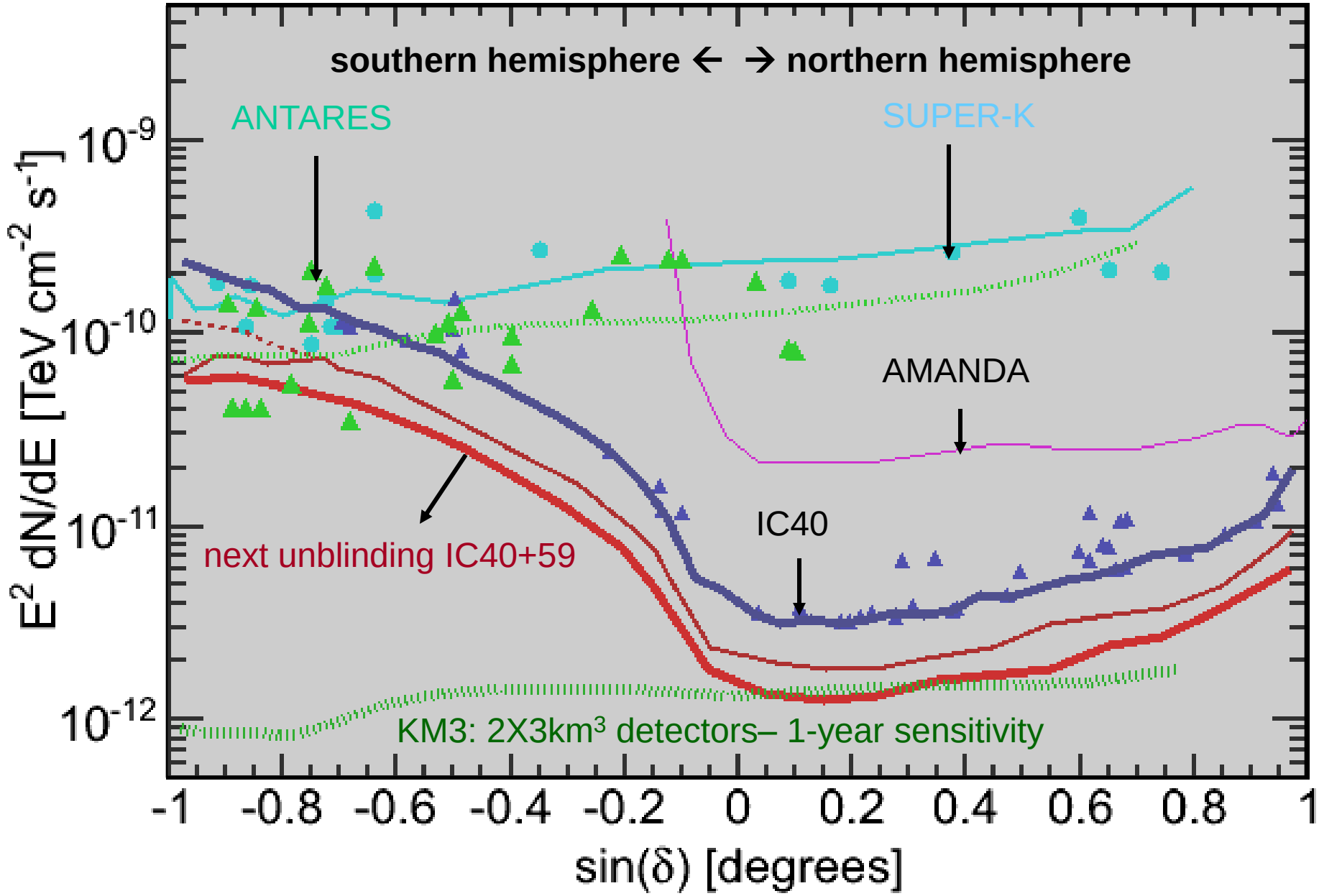


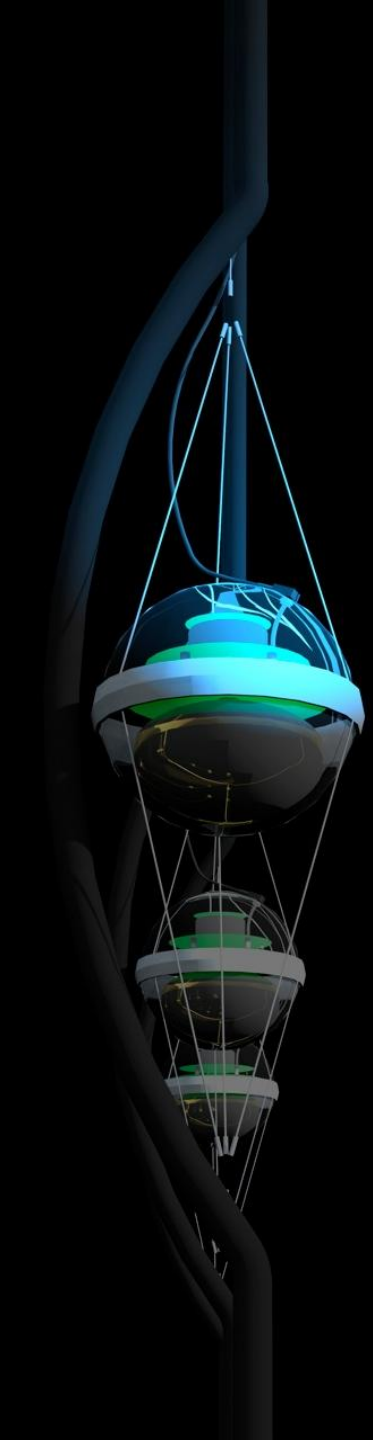
search for
- clustering
- high energy (>> 100 TeV)

southern sky: 23151 muons

- nothing seen
- nothing expected next?

limits (symbols) / sensitivies (lines) to point sources





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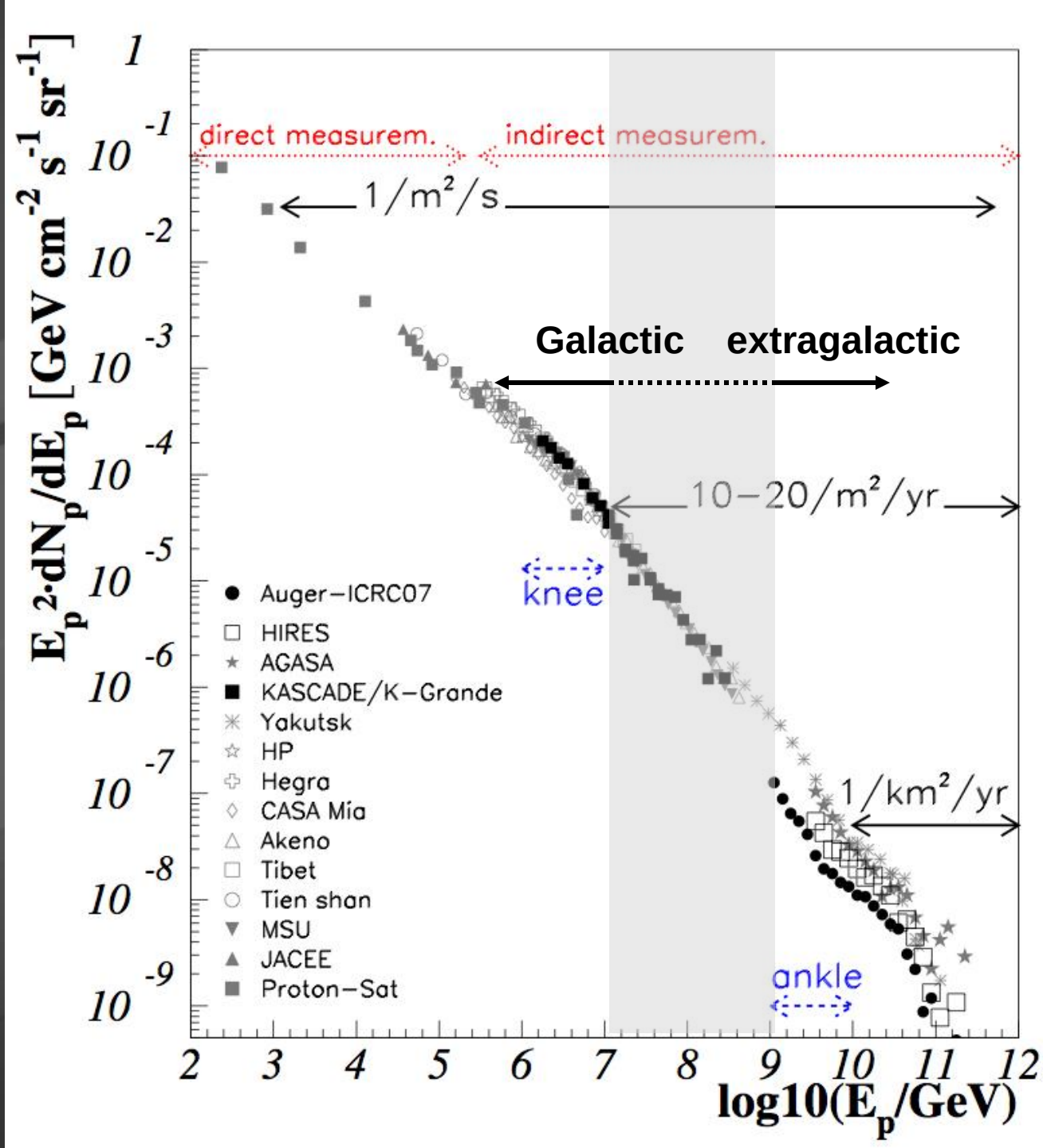
  - active galaxies

IceCube.wisc.edu

Galactic and extragalactic cosmic rays

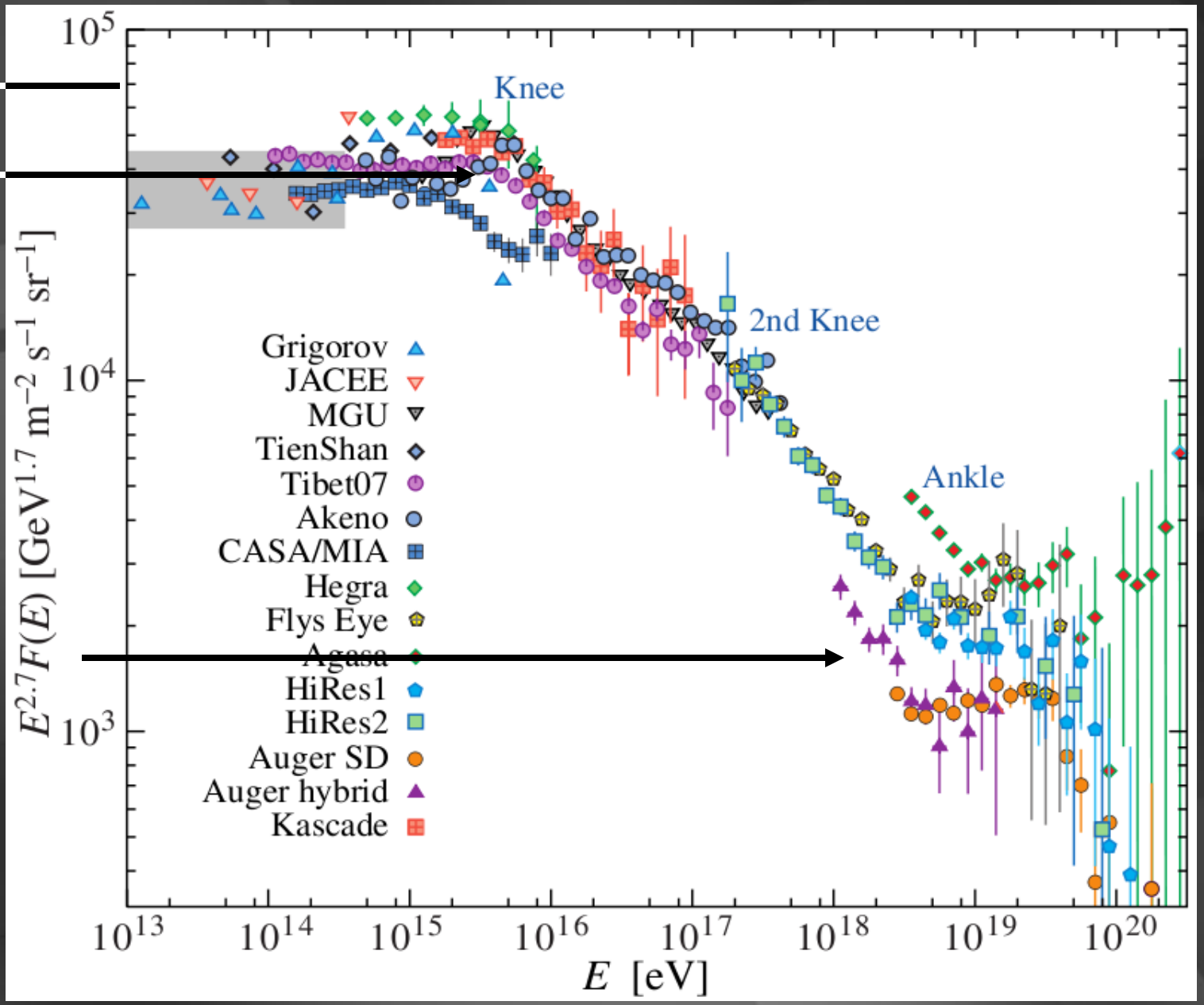


… often wrong, but never in doubt …

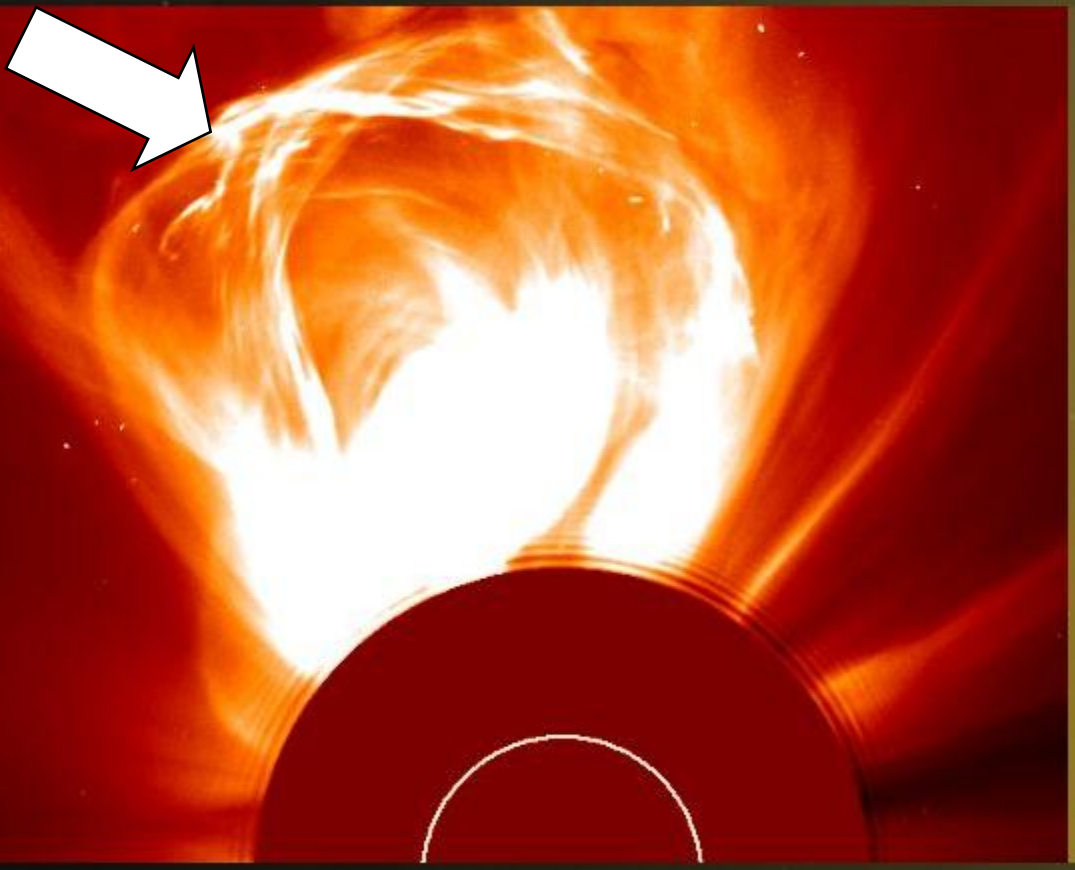
solar cosmic rays

Galactic: supernova remnants?

extragalactic: gamma ray bursts? active galaxies?



particle acceleration in solar flare

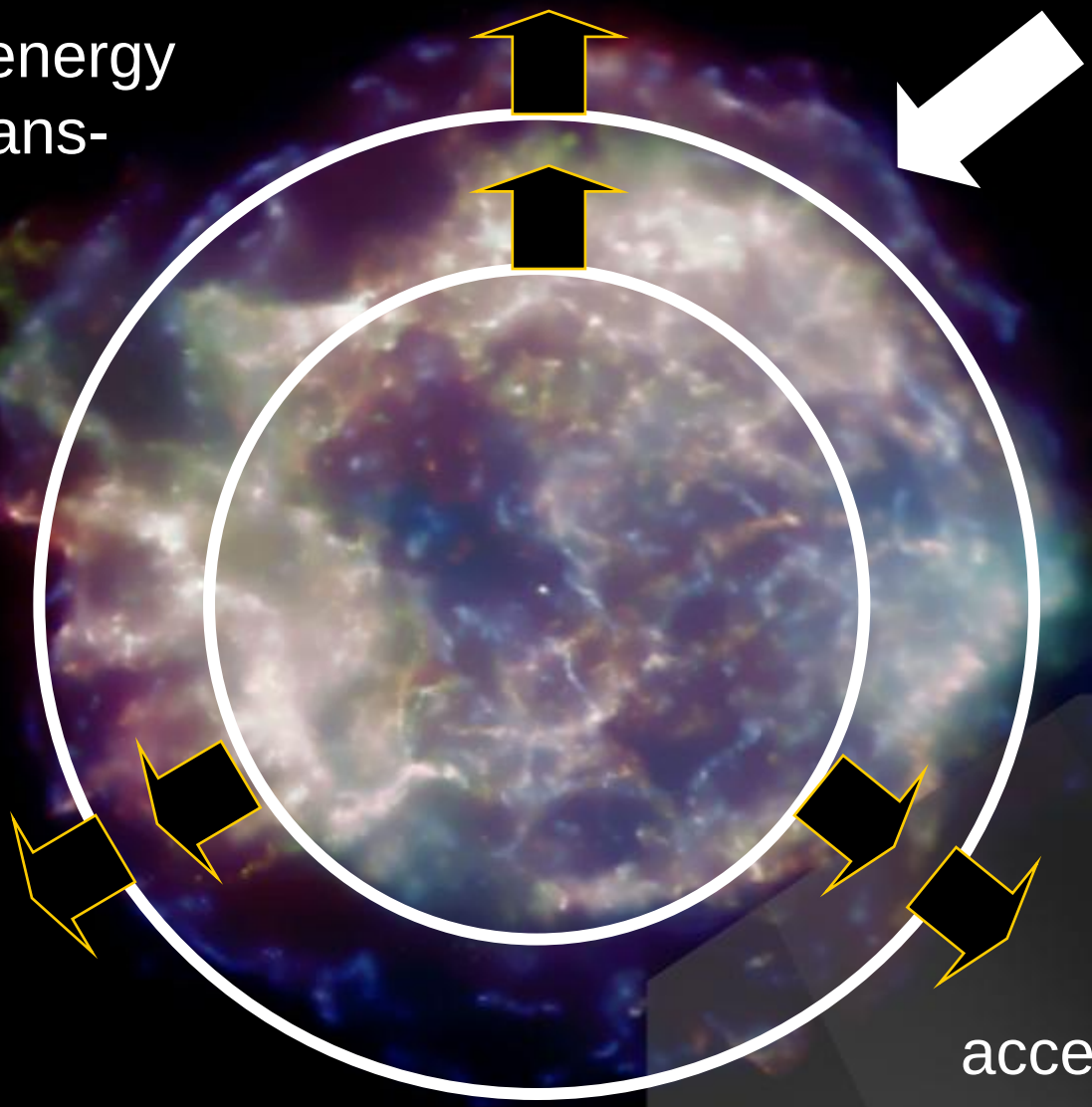


coronal
mass
ejection
→
10 GeV
particles

flows of charged particles result in large B-fields

cassiopeia A supernova remnant in X-rays

gravitational energy released is trans-formed into acceleration



acceleration when particles cross high B-fields

Galactic cosmic rays :

must produce pionic γ-rays in interactions with hydrogen in Galactic plane (1 proton cm^{-3})

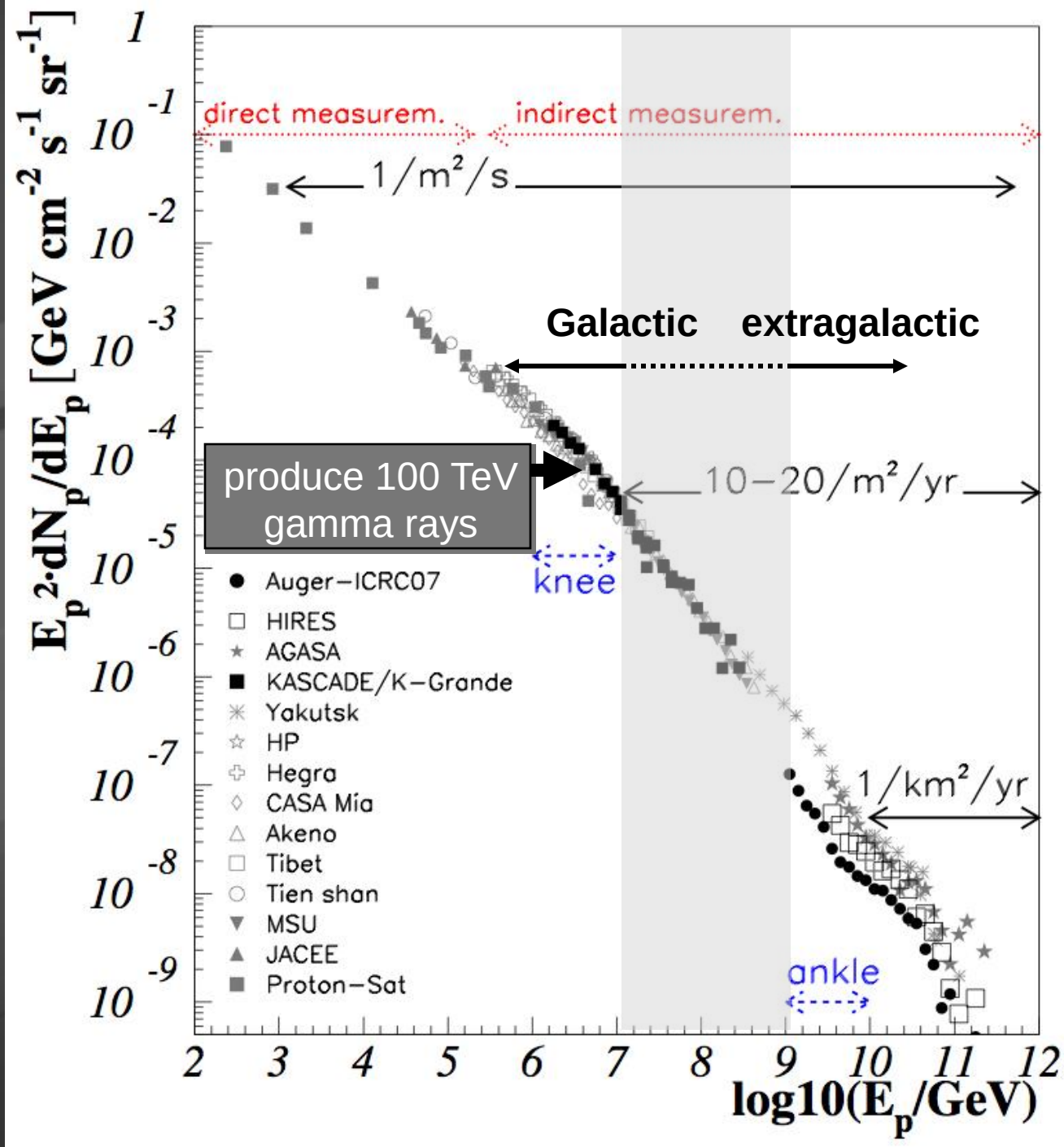
↓

cr + p → pions

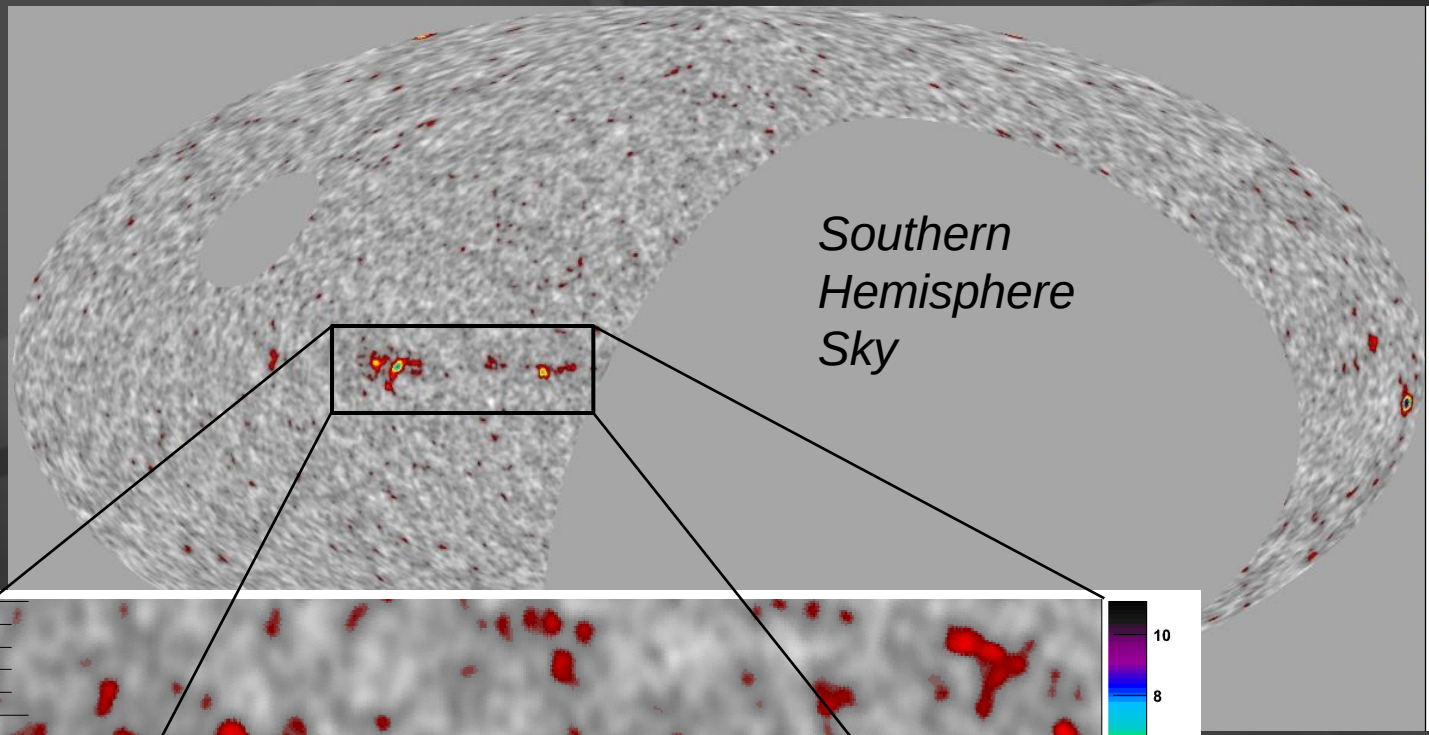
$\pi^0 \rightarrow \gamma\gamma$

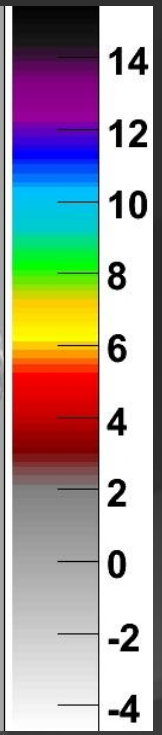
↓

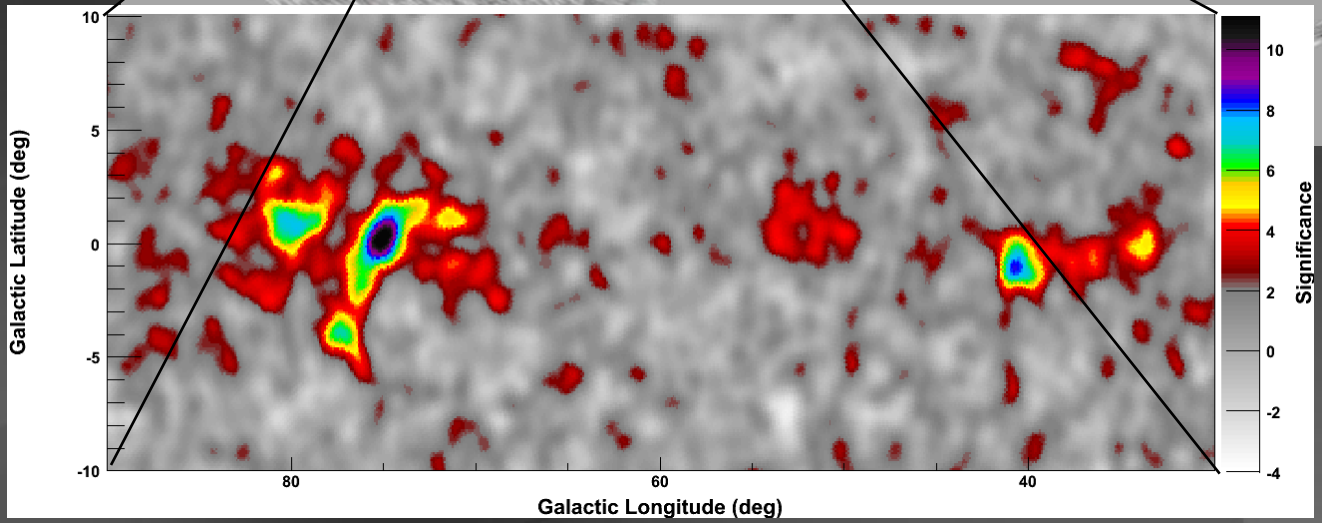
trace cosmic rays

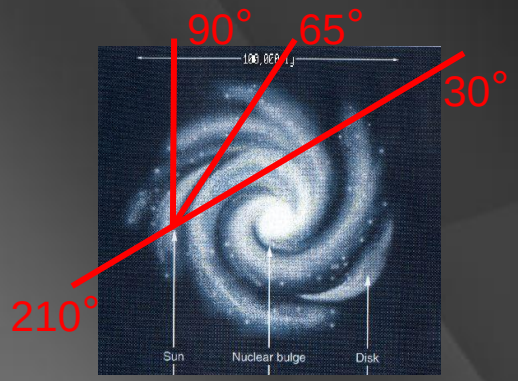


galactic plane in 10 TeV gamma rays :
supernova remnants in star forming regions









milagro

neutral pions

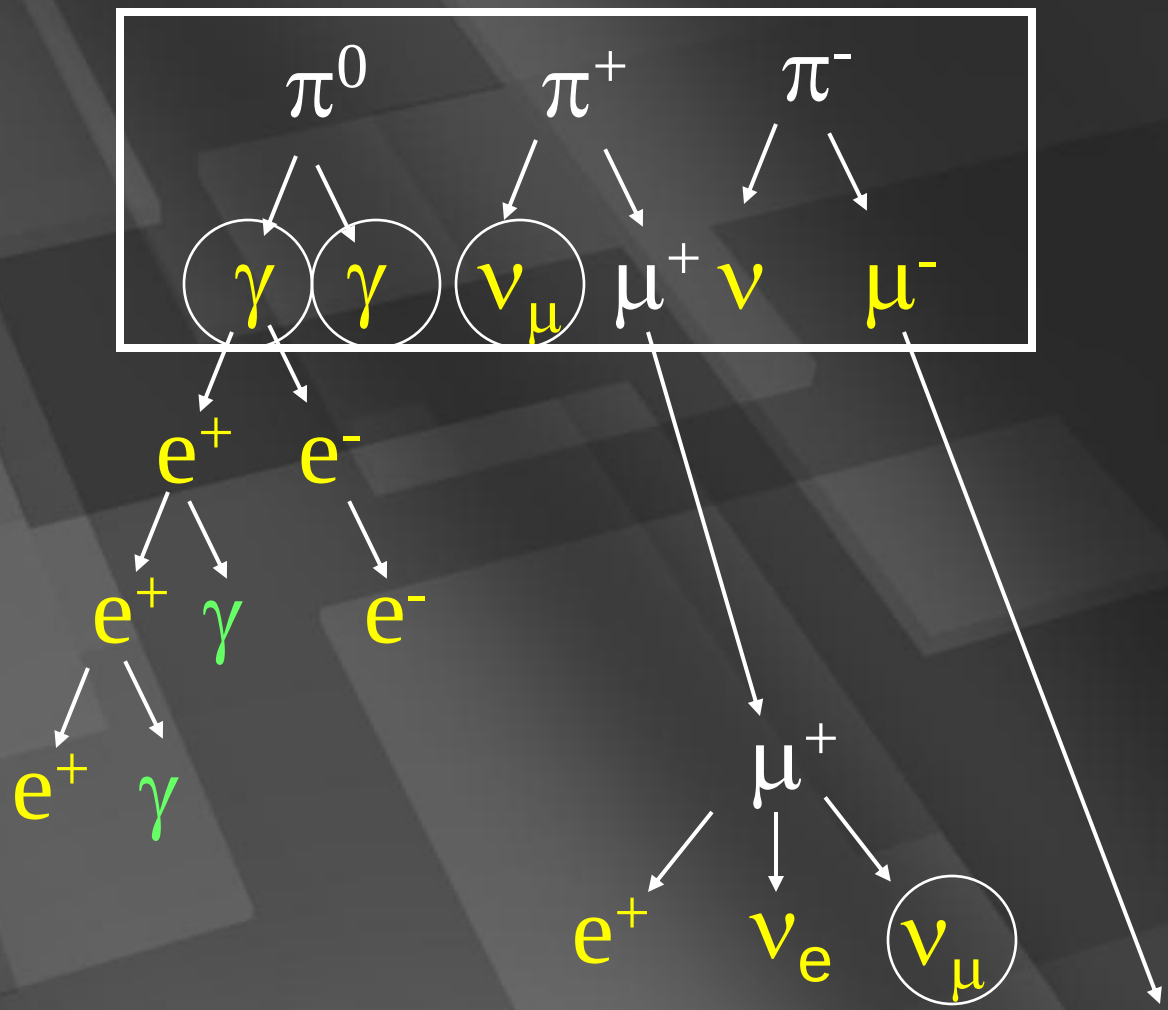
are observed as

gamma rays

charged pions

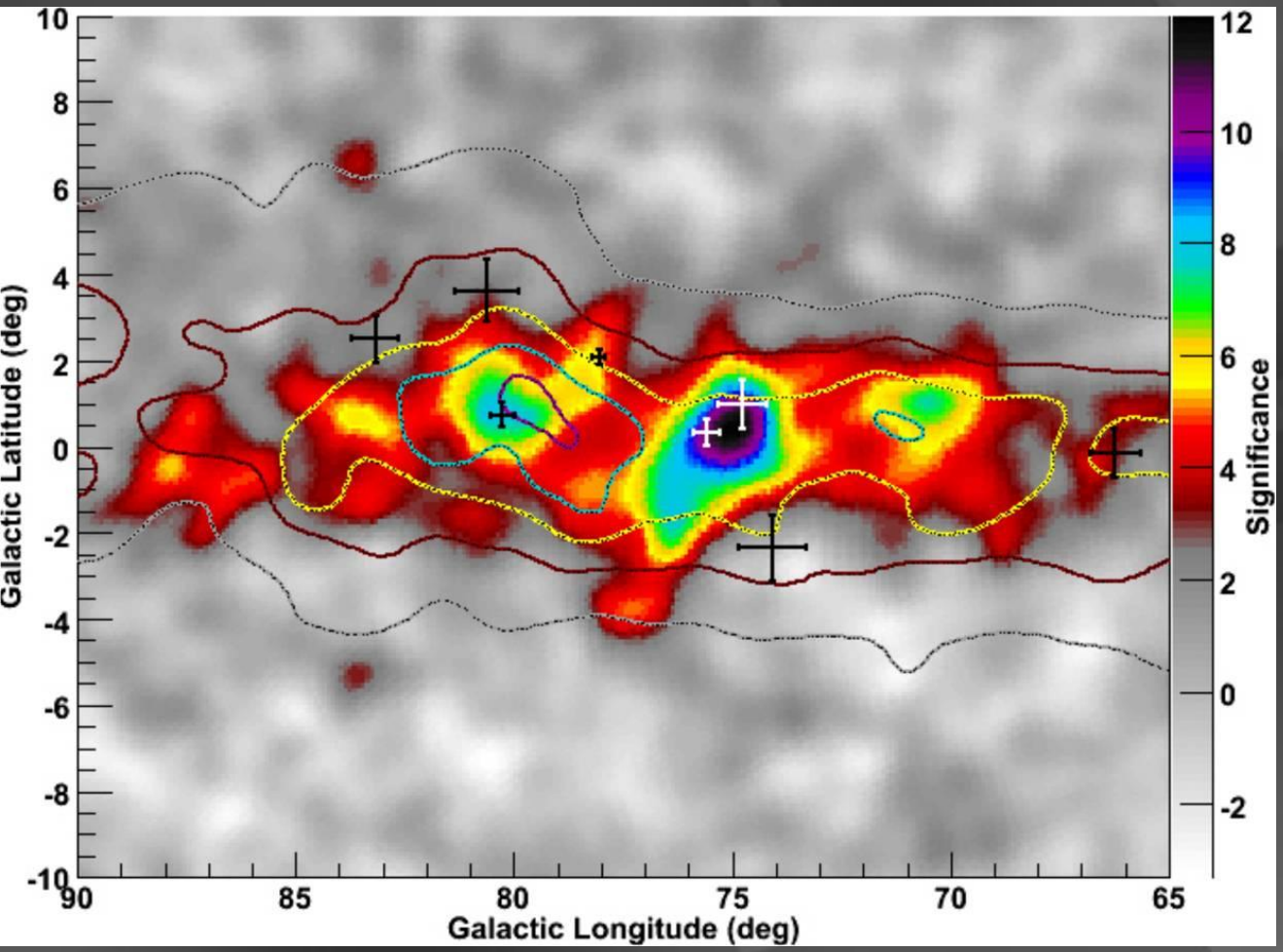
are observed as

neutrinos



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

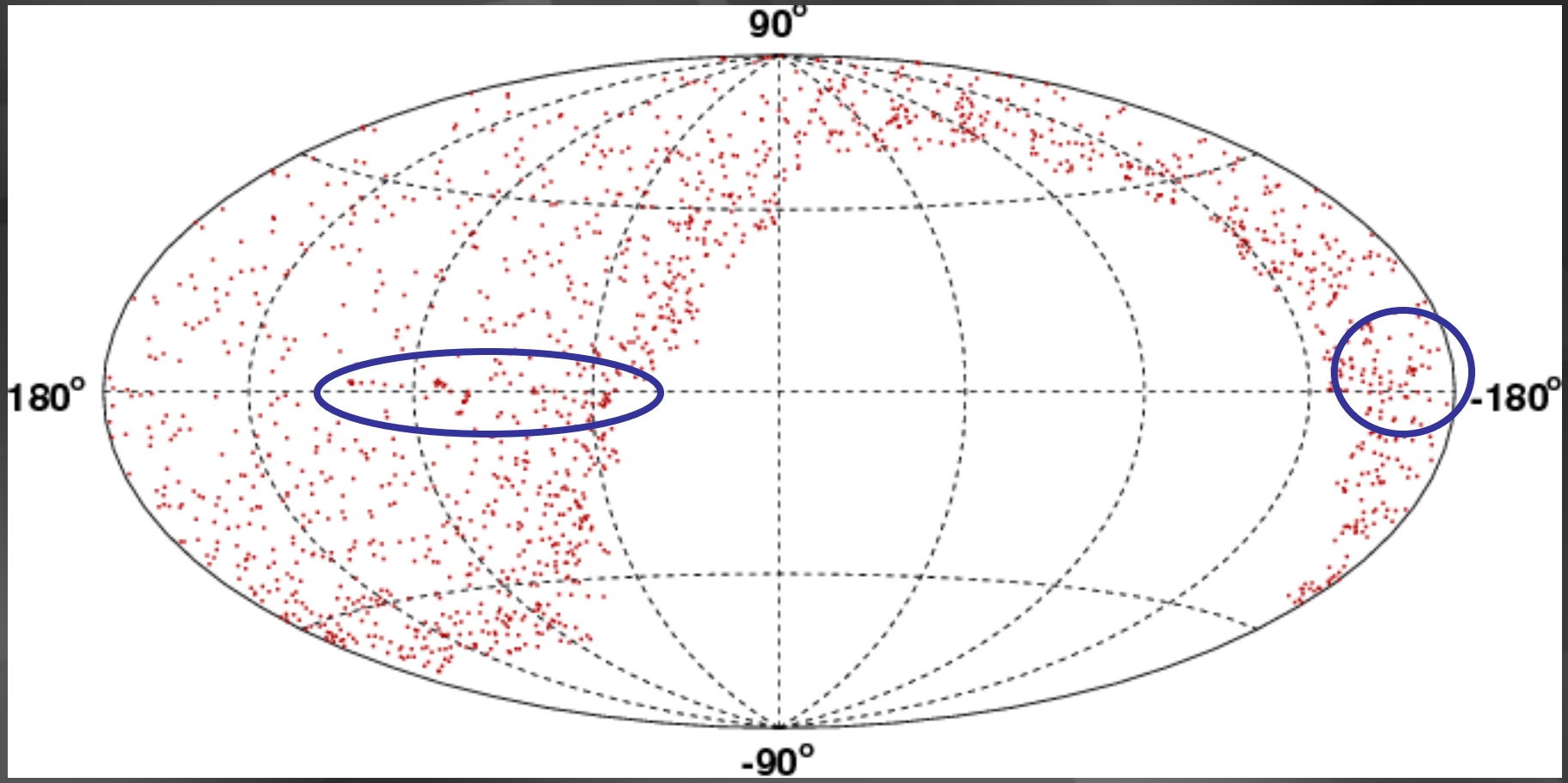
cygnus region : Milagro



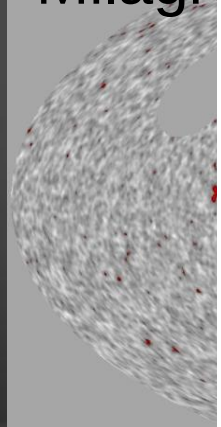
translation of
TeV gamma rays
into
TeV neutrinos :

3 ± 1 ν per year in IceCube per source

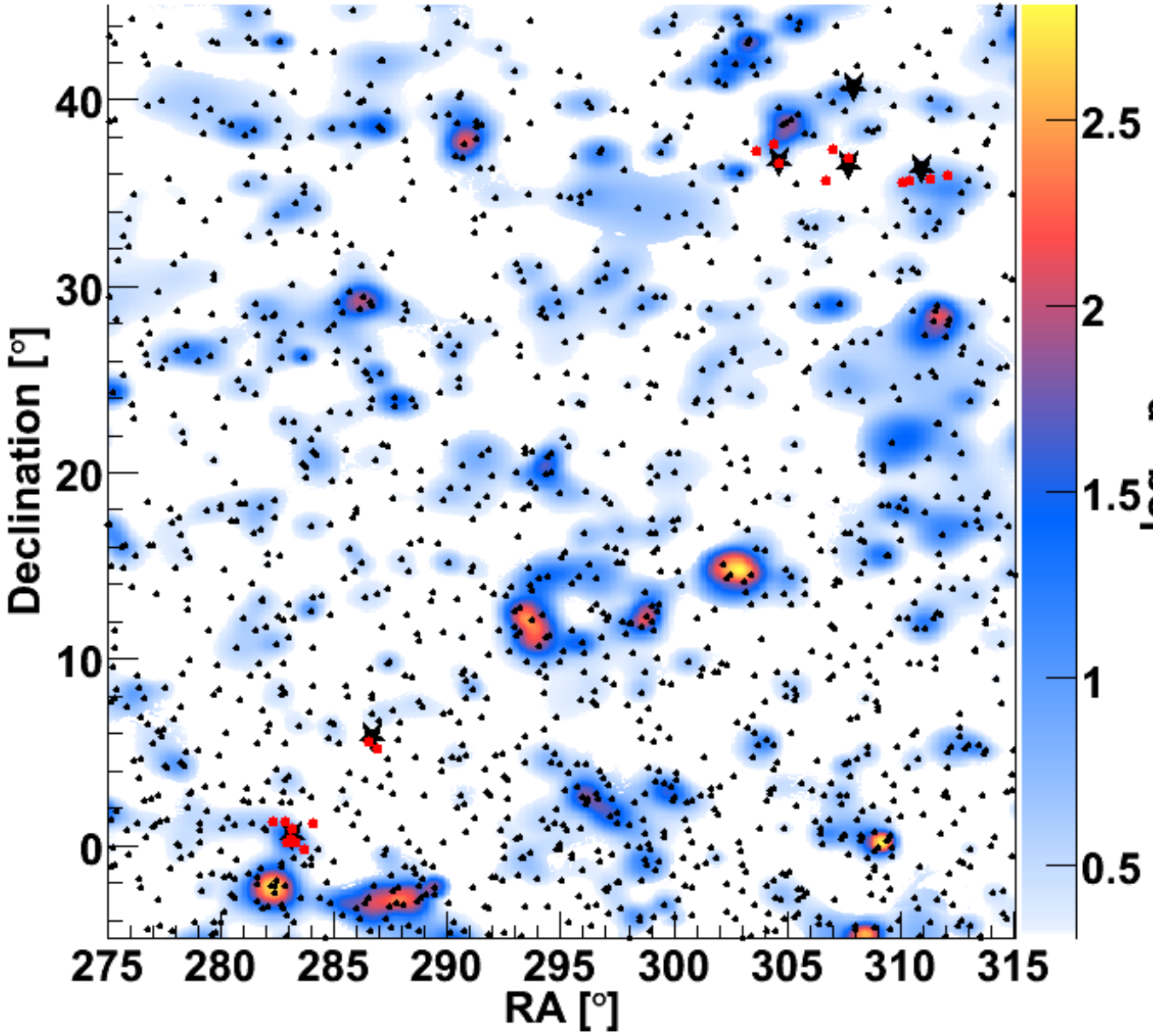
5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV

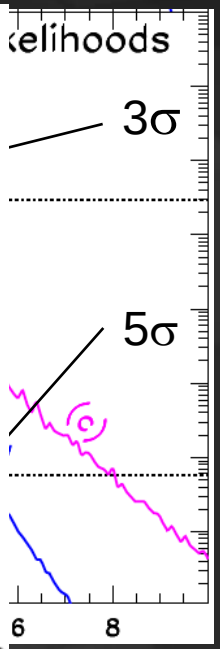


Milagr

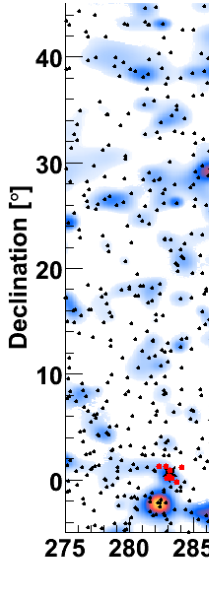


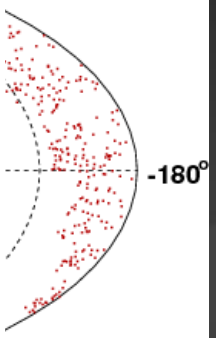
preliminary





years





20,000 atmospheric neutrinos later …

Preliminary

STACKING 6 MILAGRO SNR

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

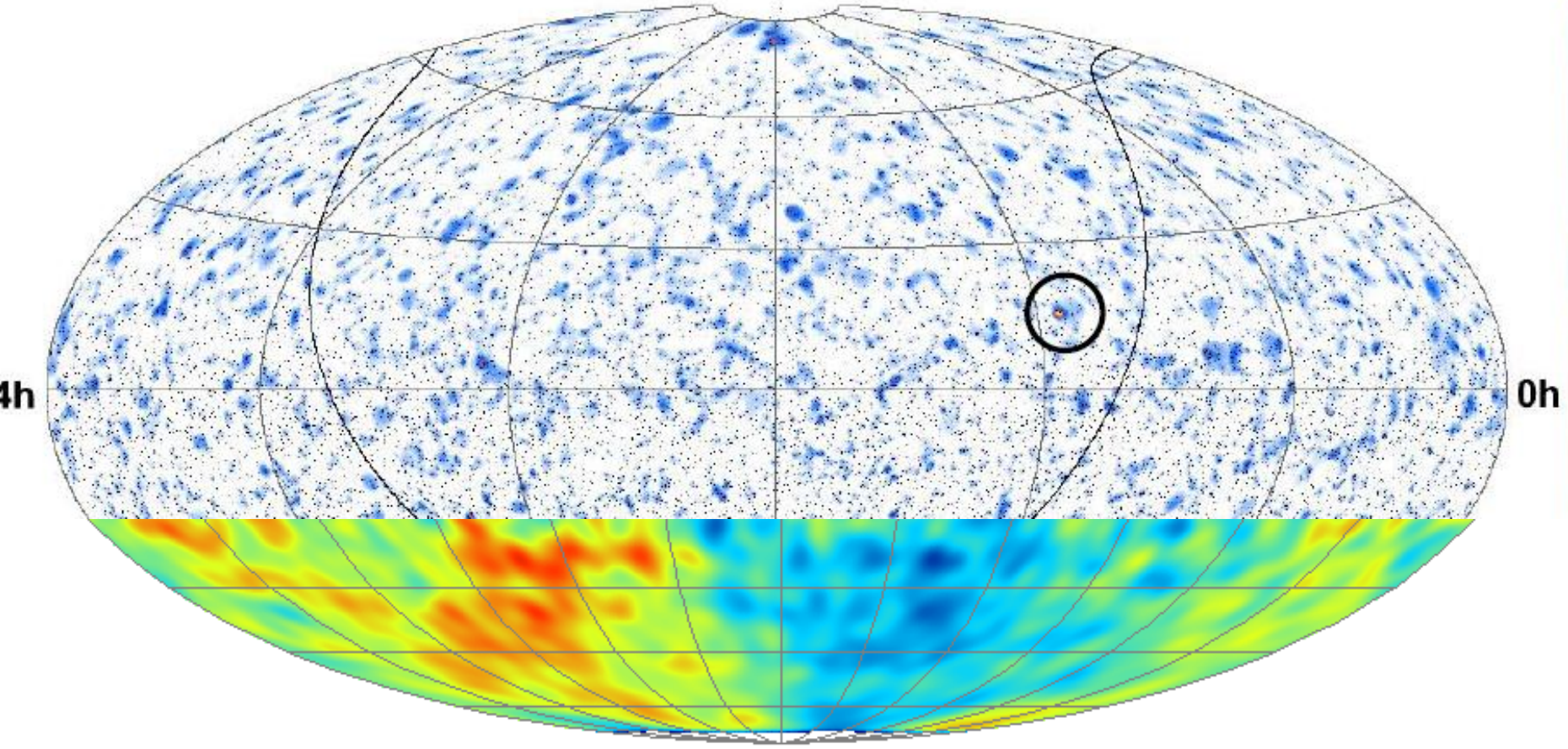
3.0 events in IC40 predicted by flux from Halzen, Kappes, O'Murchadha (2008)

p-values of 6 Milagro SNR stacked searches:

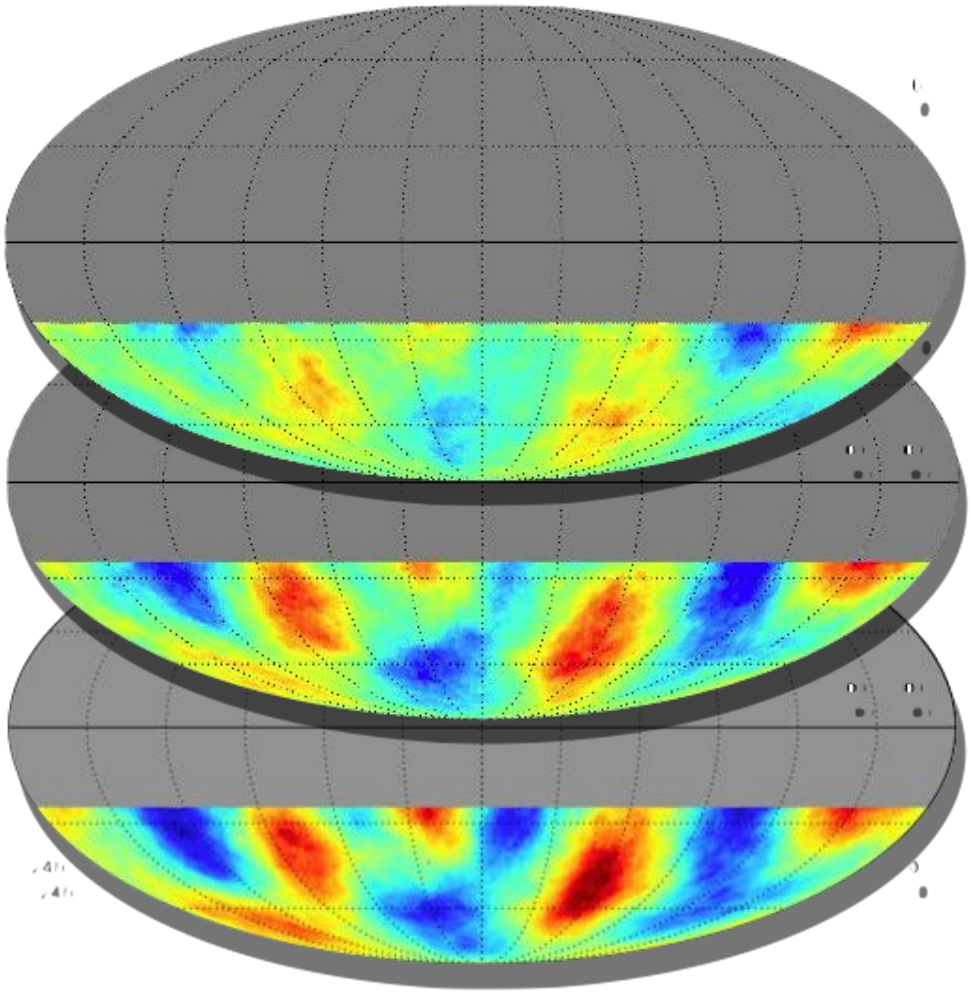
AMANDA 7-yr	22-strings	40-strings
20%	27%	2.3%

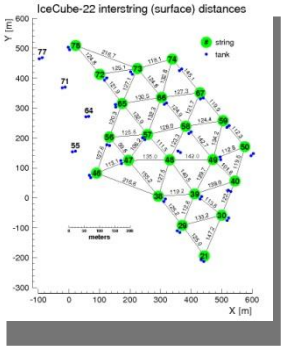
(a posteriori)

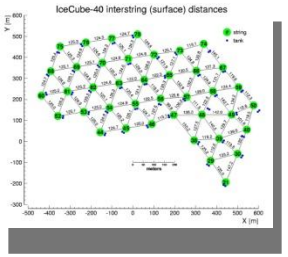
first surprise

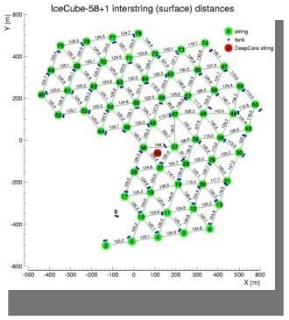

4h
0h

IC22 and IC40 : muon astronomy (!)

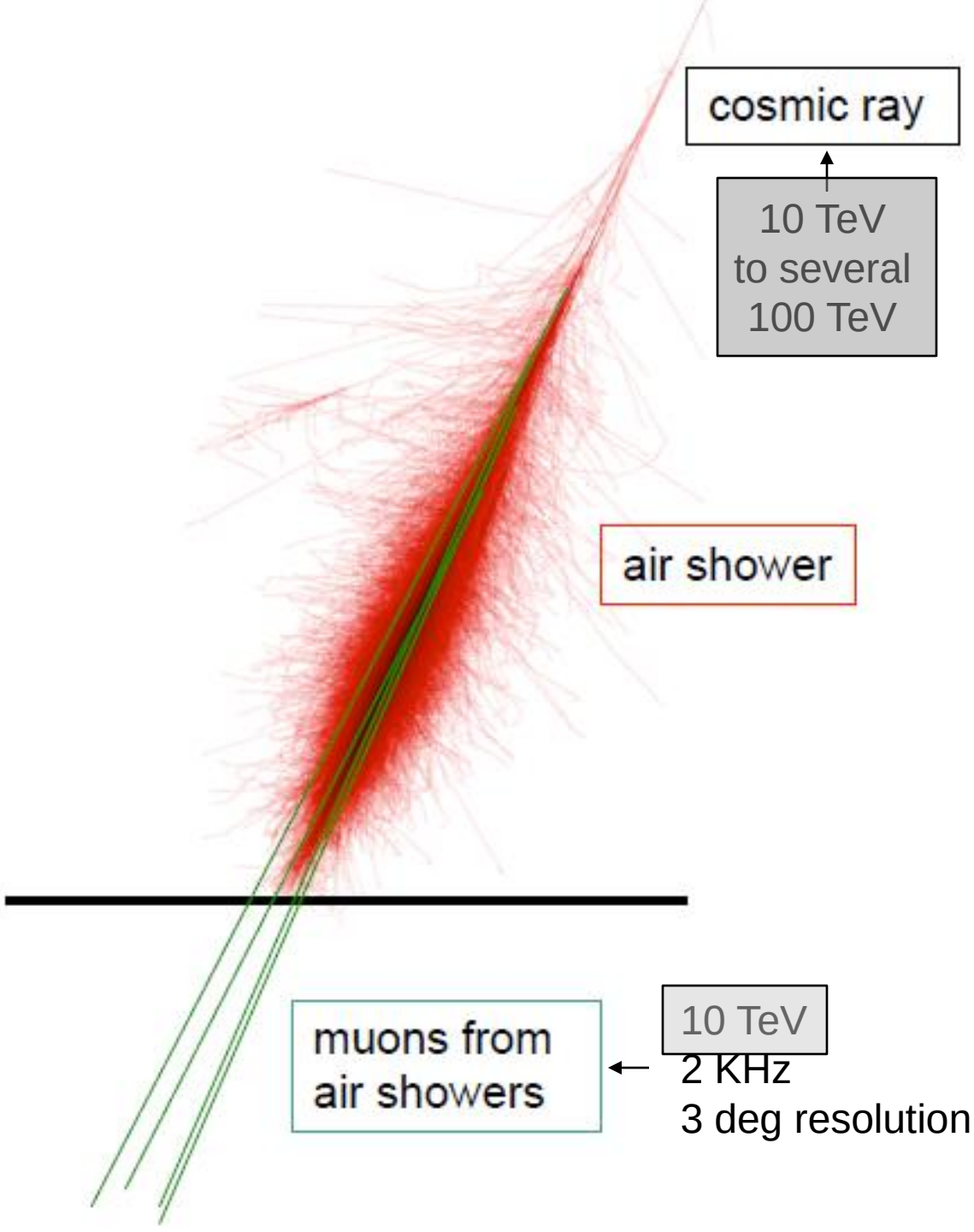








Different geometries, same structure

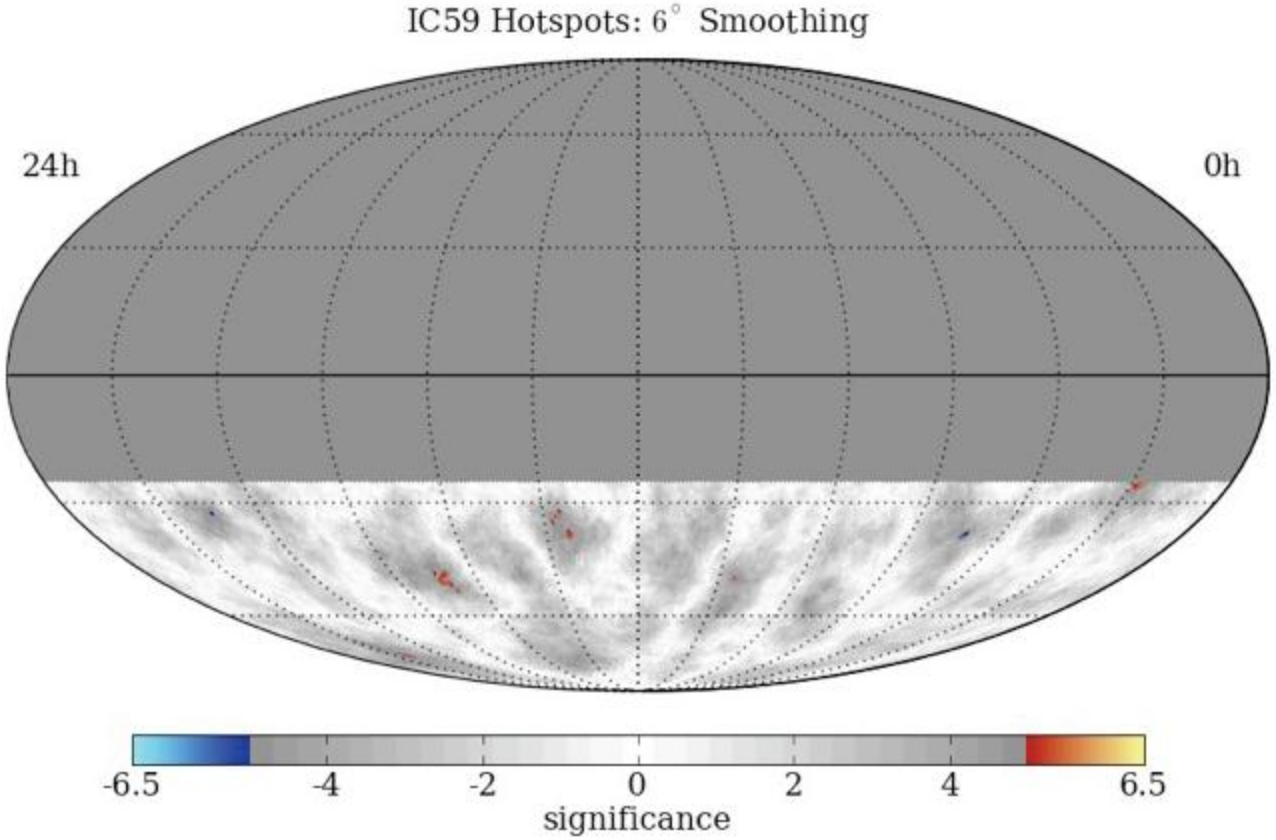


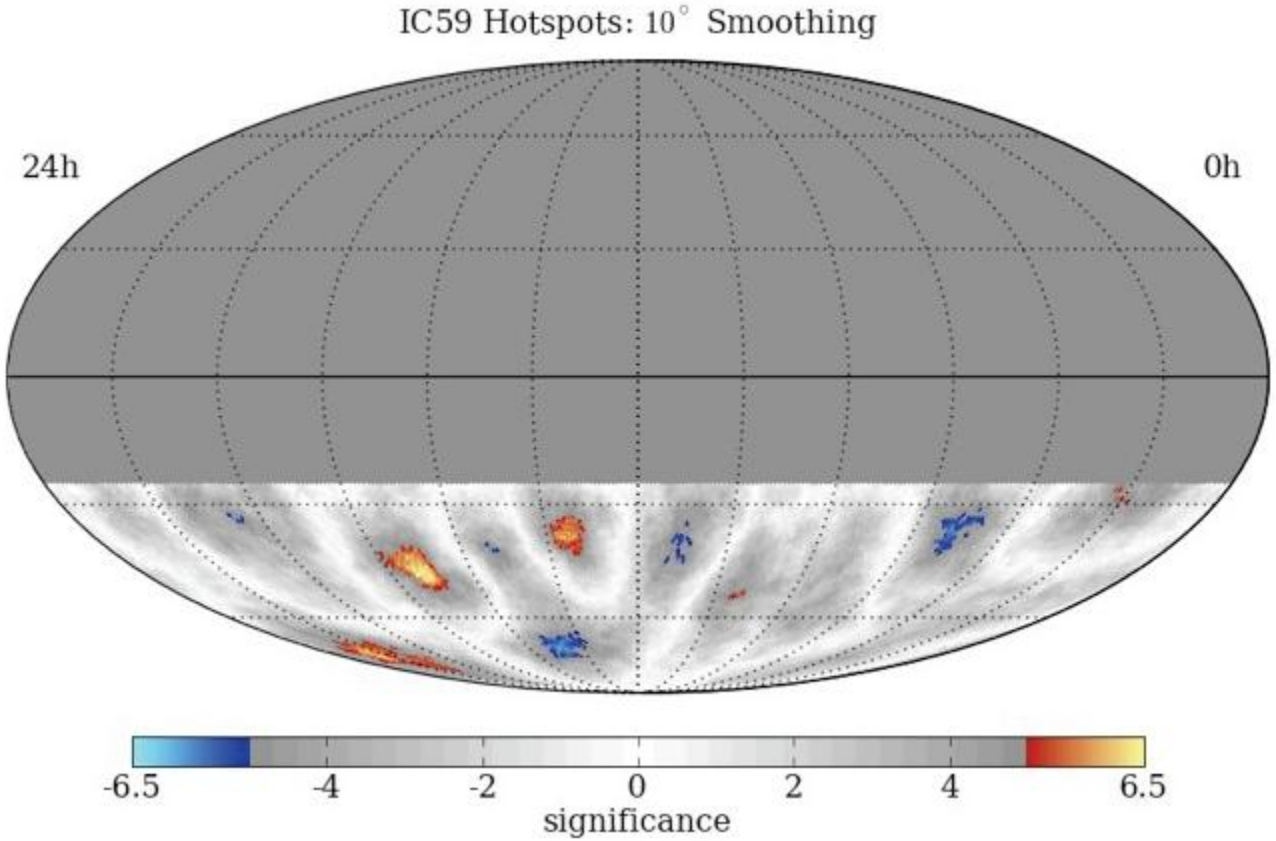
cosmic rays in IceCube

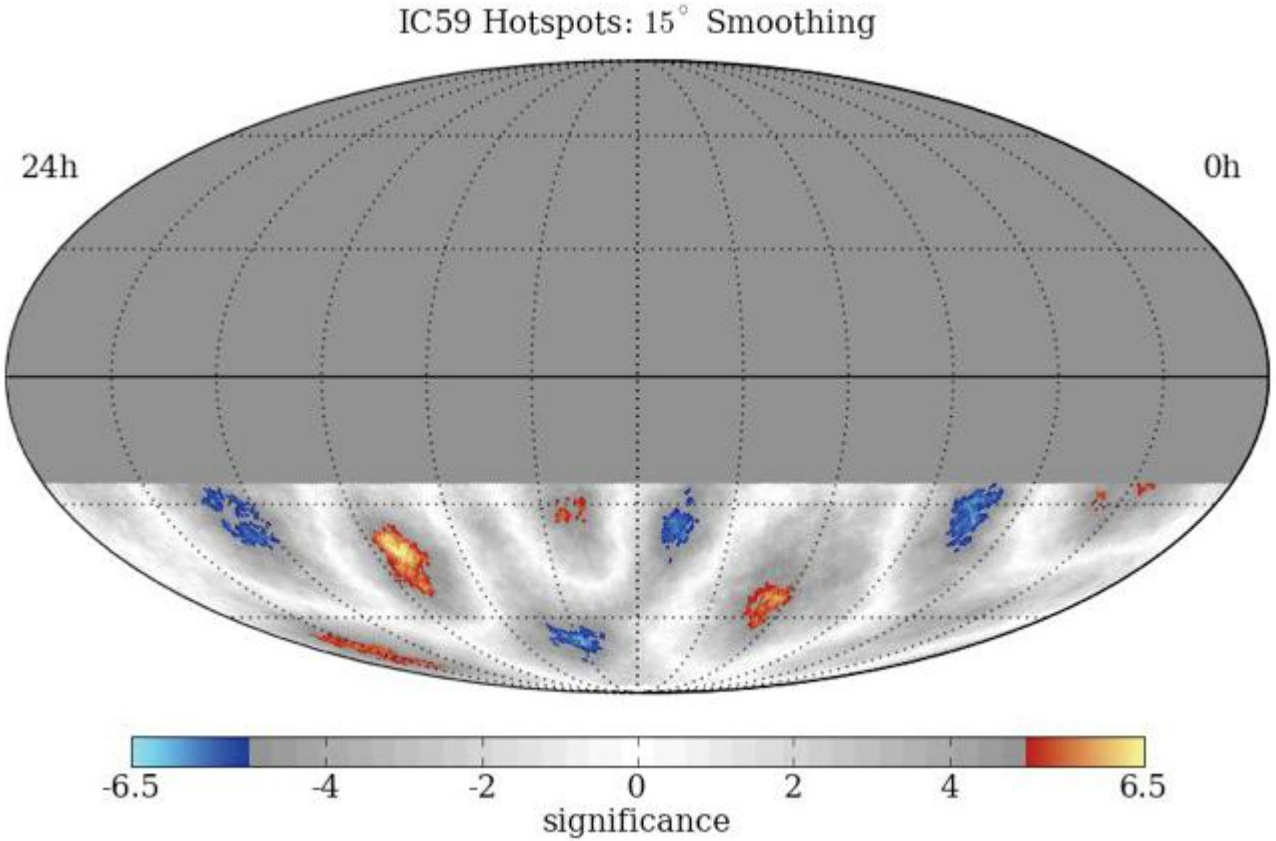
- we map the highest energy Galactic cosmic rays, but…
- their gyroradius is < 1 pc in microgauss magnetic field
- closest sources > 100 pc

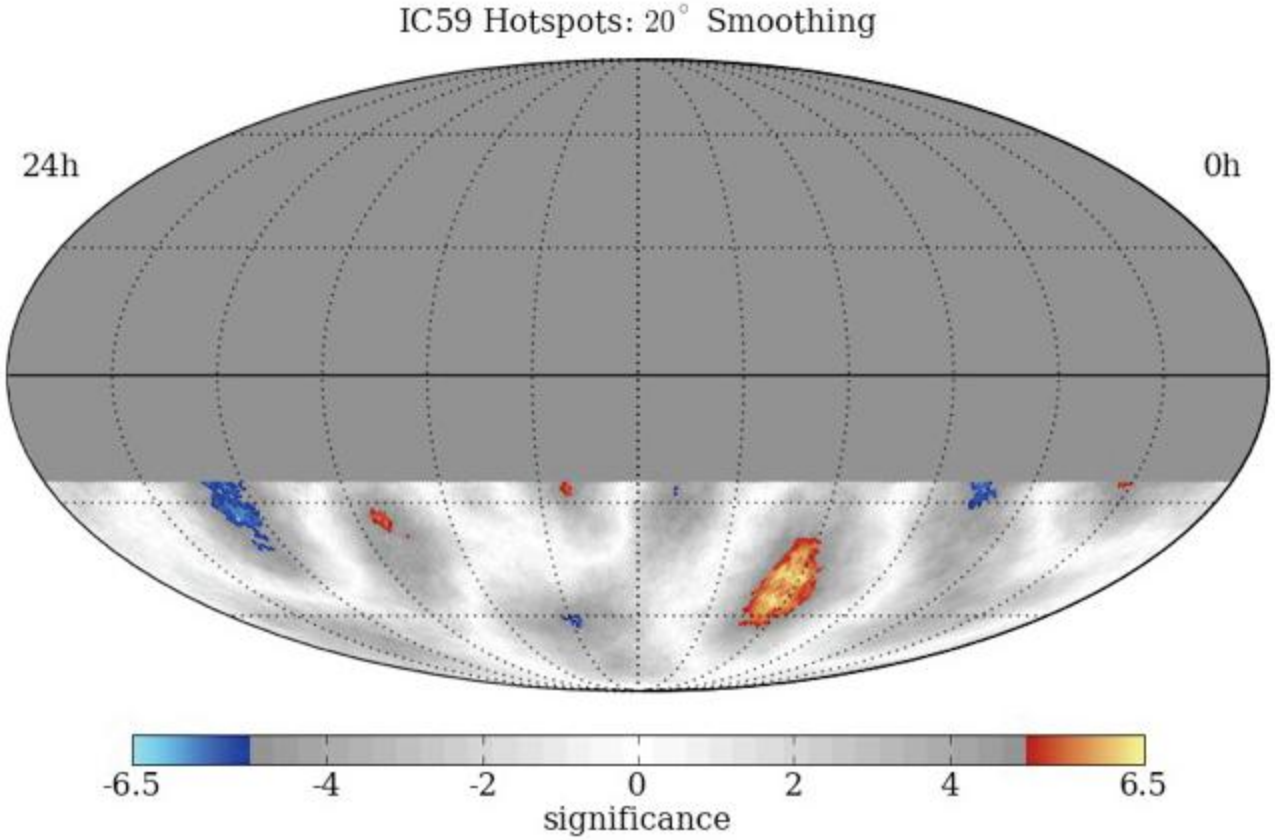
should not point!

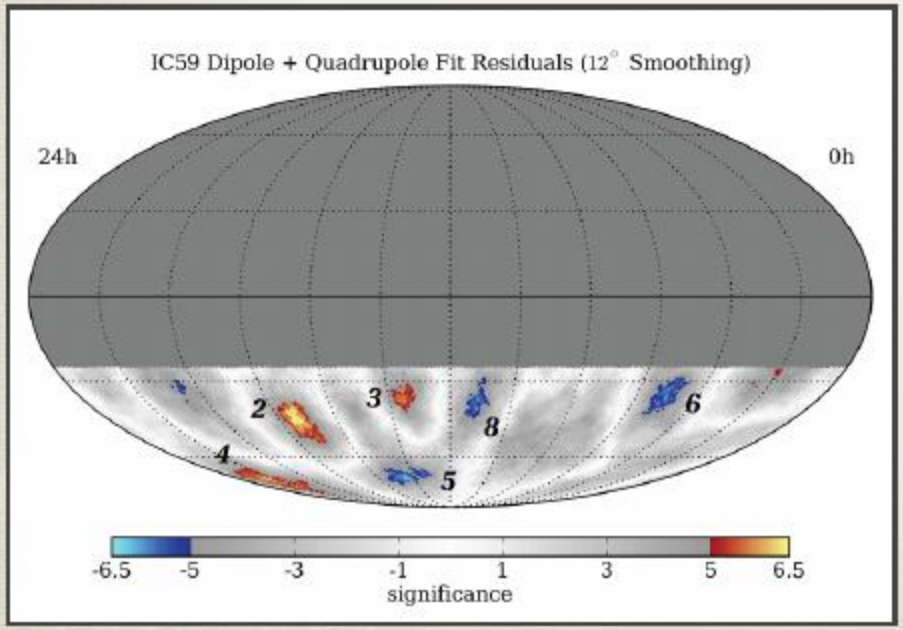
→ that's why we detect neutrinos!

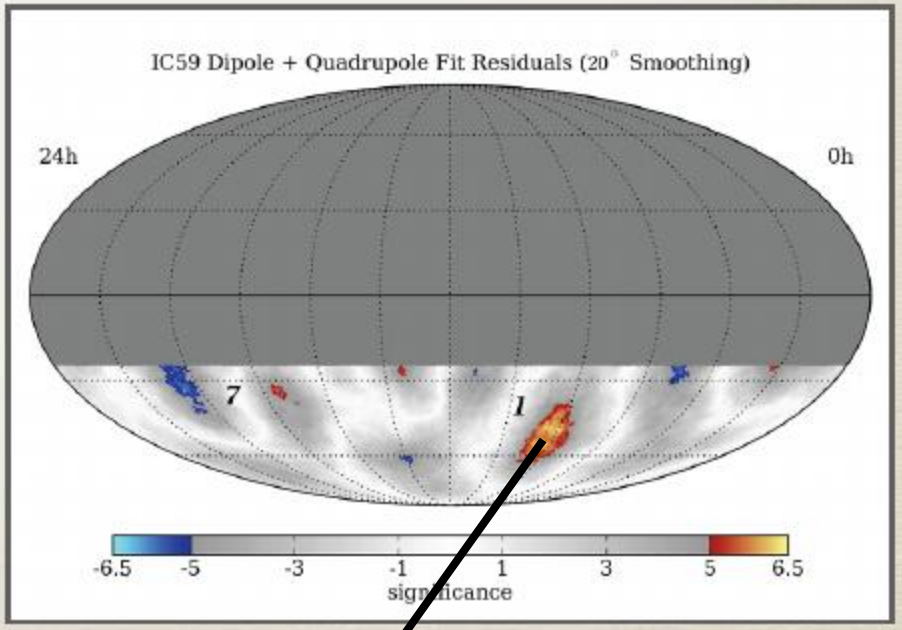

IC59 Hotspots: 6° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance


IC59 Hotspots: 10° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance


IC59 Hotspots: 15° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance

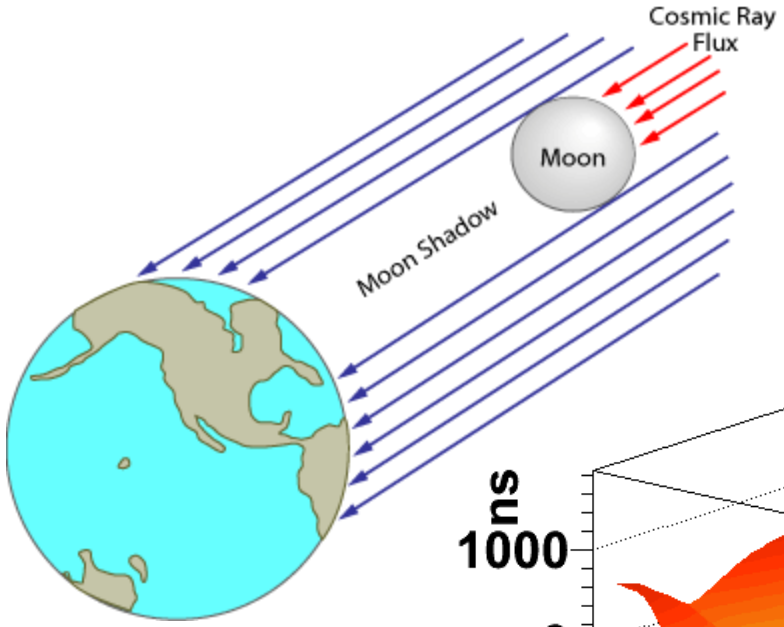

IC59 Hotspots: 20° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance



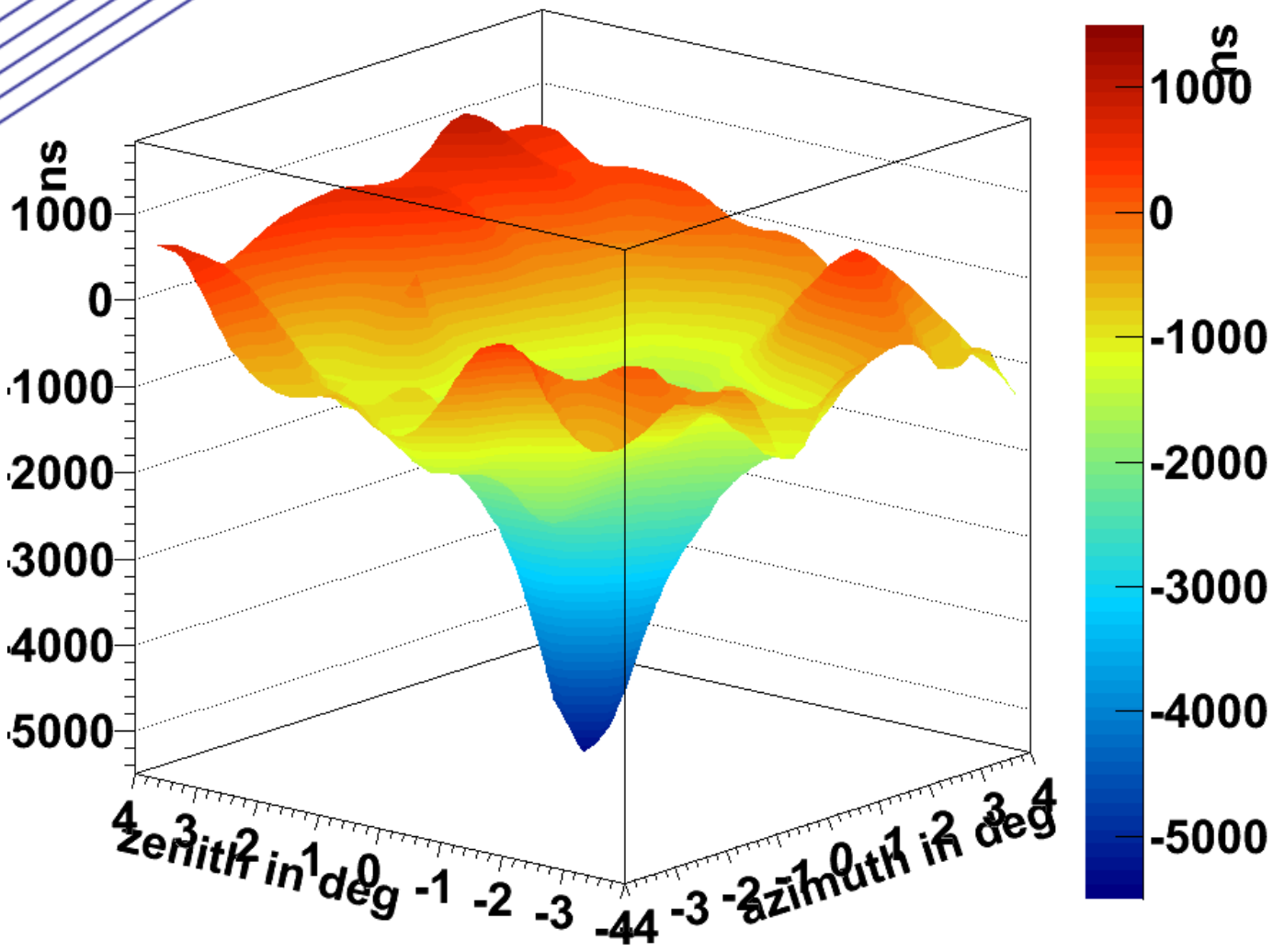


Vela

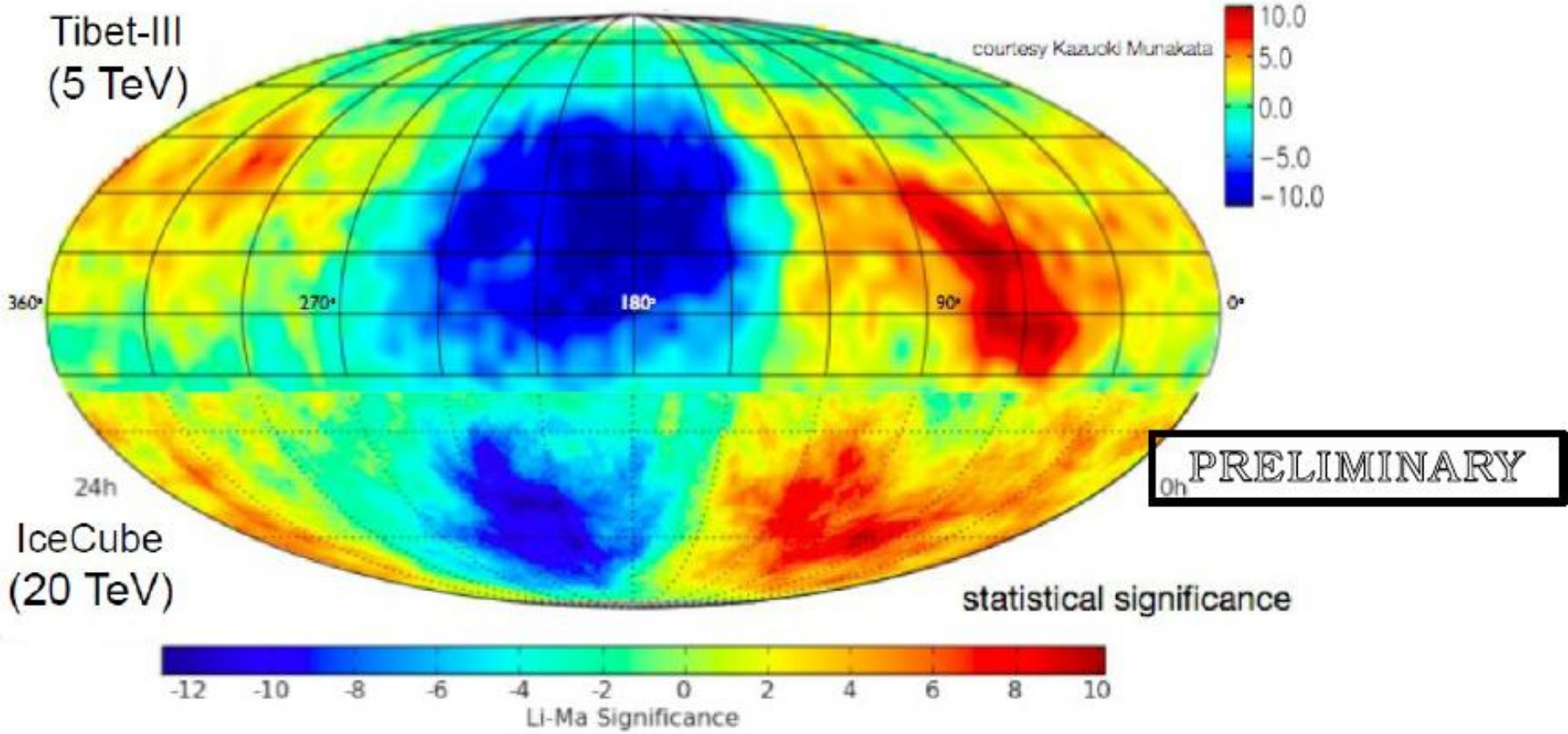
- closest supernova remnant
- strongest gamma ray source



moon shadow



> 16 σ
< 1 deg

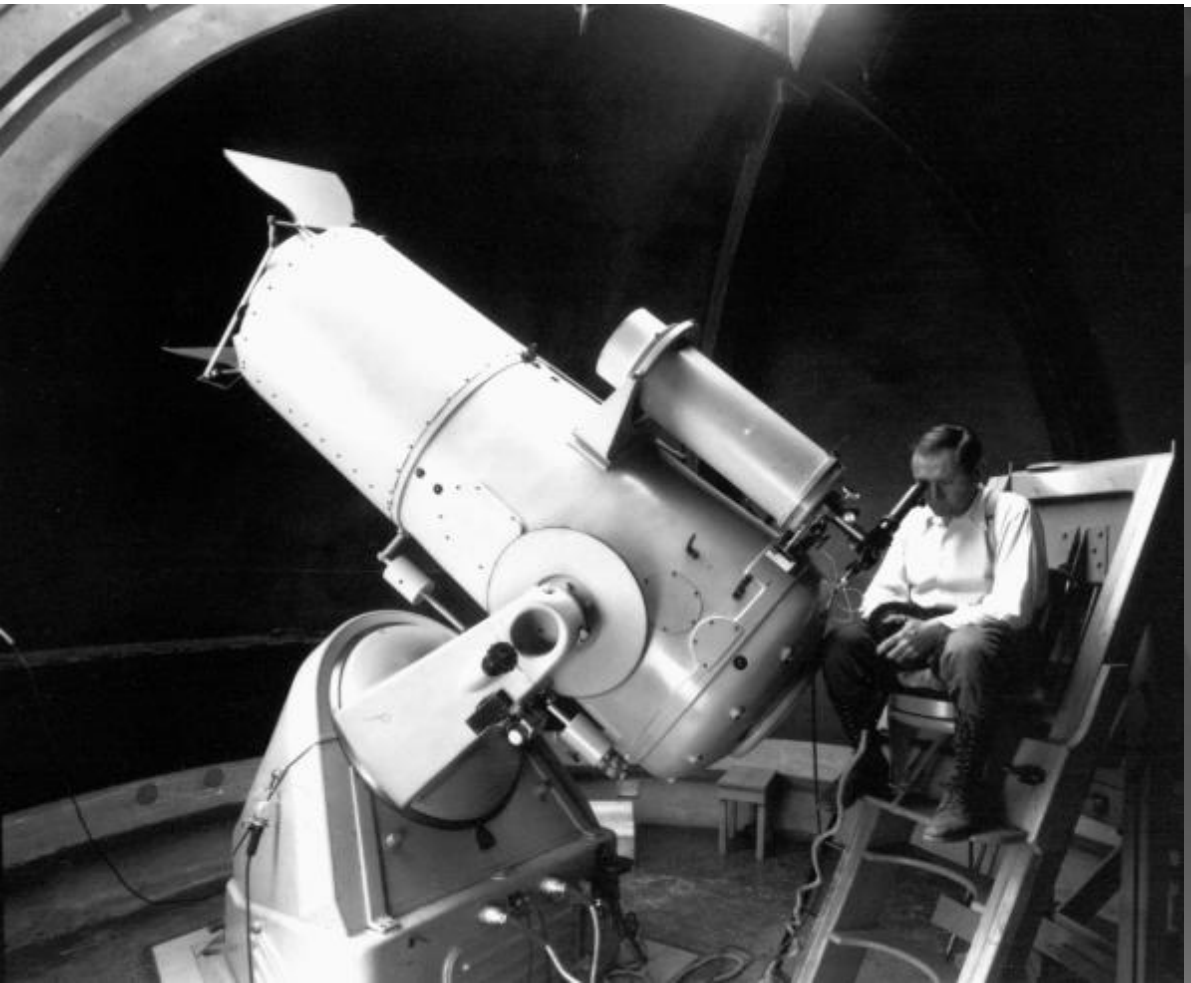

Tibet-III
(5 TeV)
courtesy Kazuoki Munakata
10.0
5.0
0.0
−5.0
−10.0
360°
270°
180°
90°
0°
24h
0h
PRELIMINARY
IceCube
(20 TeV)
statistical significance
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
Li-Ma Significance

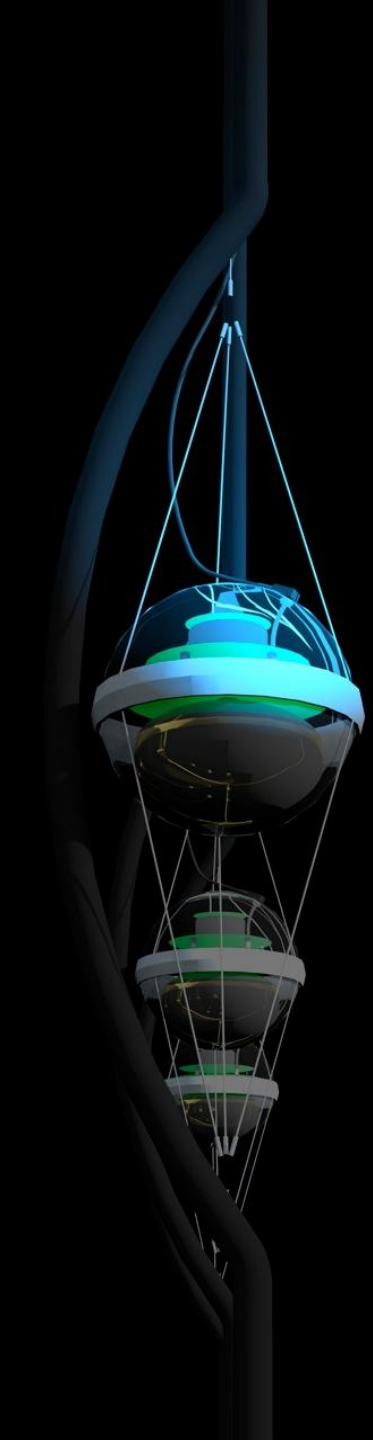
ON SUPER-NOVAE

By W. Baade and F. Zwicky

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

Communicated March 19, 1934





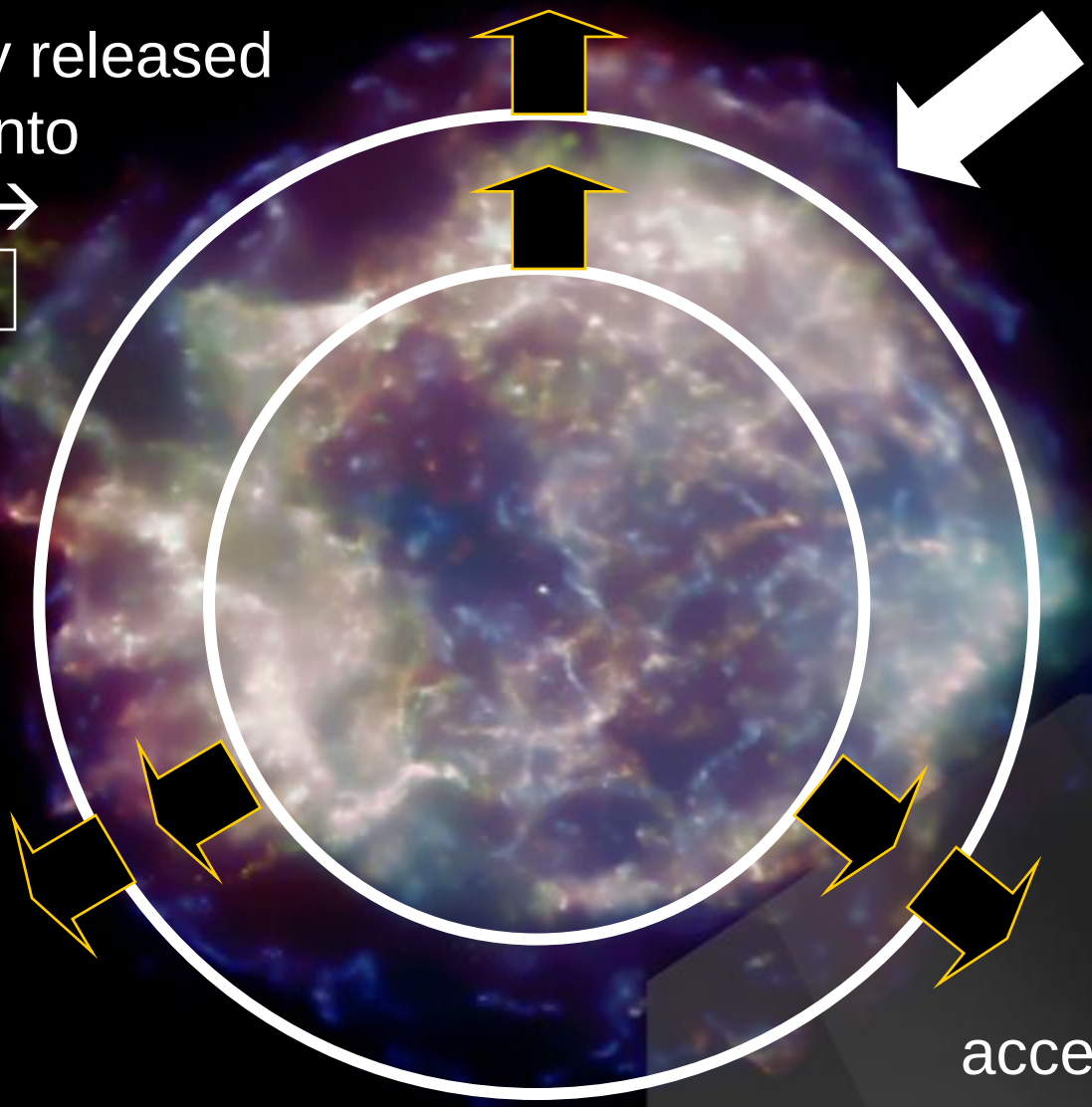
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

IceCube.wisc.edu

cassiopeia A supernova remnant in X-rays

10^{-3} of energy released transformed into acceleration →

E^{-2} spectrum

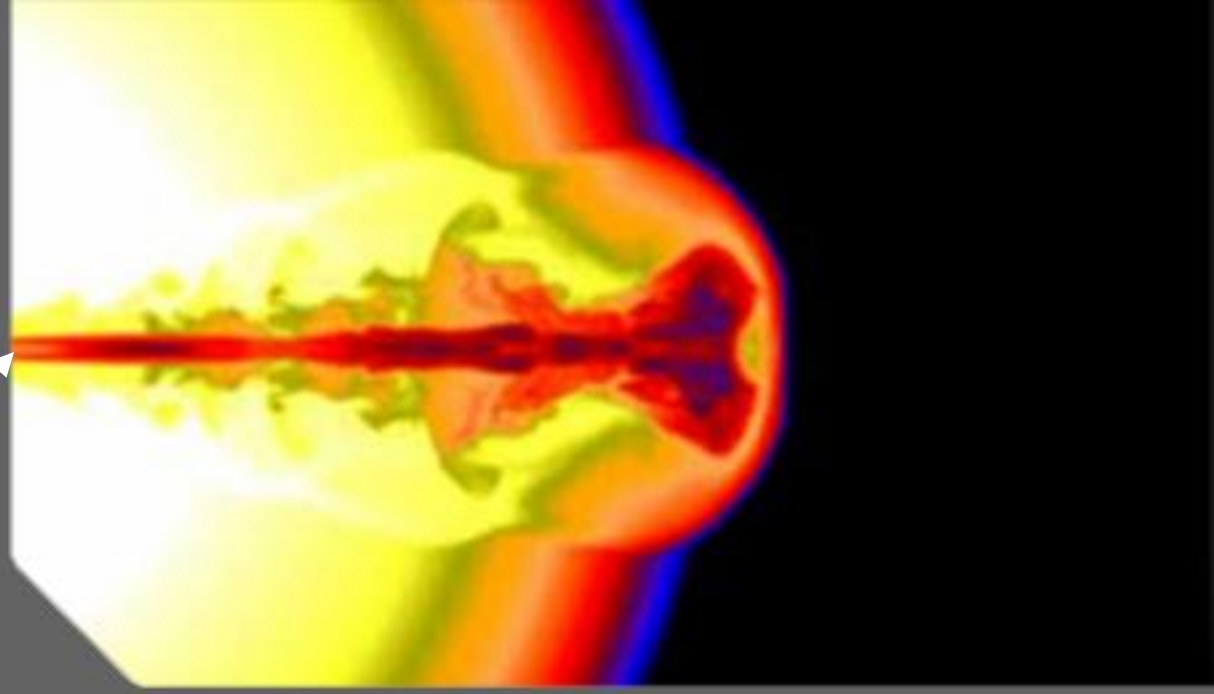


acceleration when particles cross high B-fields

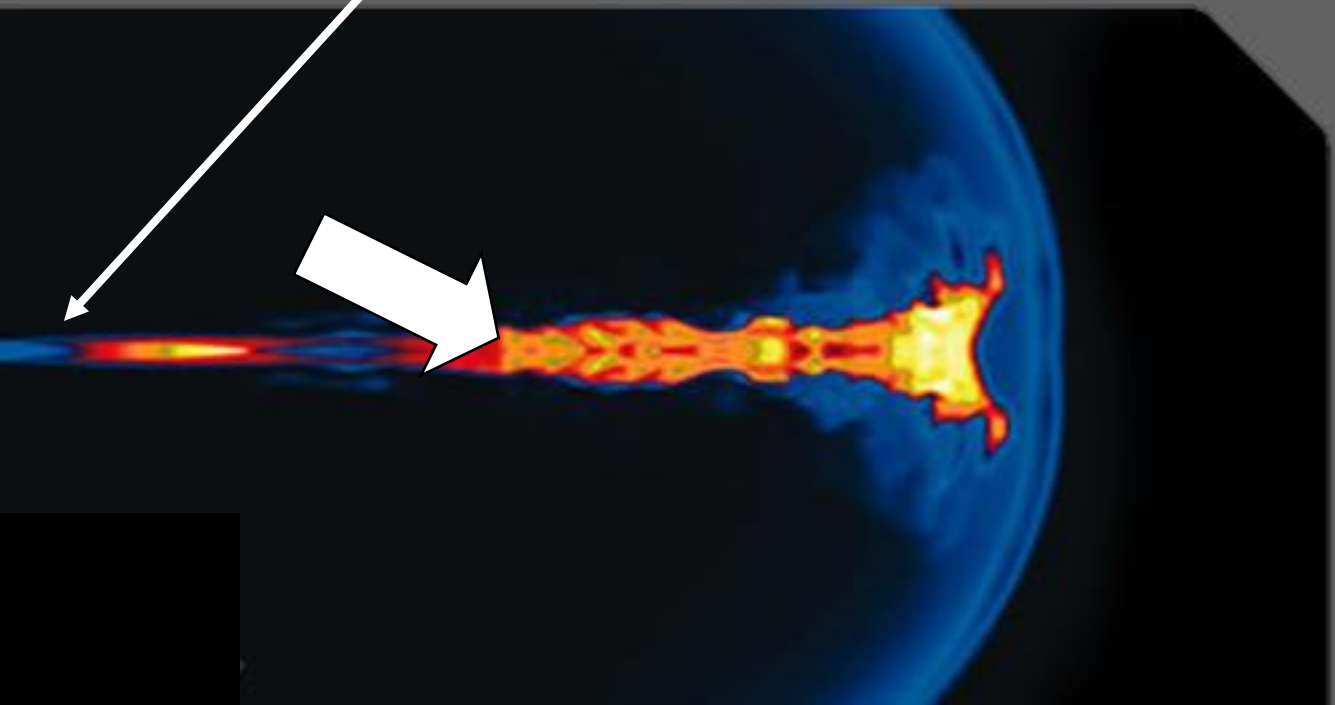
and if the star collapses to a black hole …

collapse of massive star produces a

gamma ray burst



spinning black hole

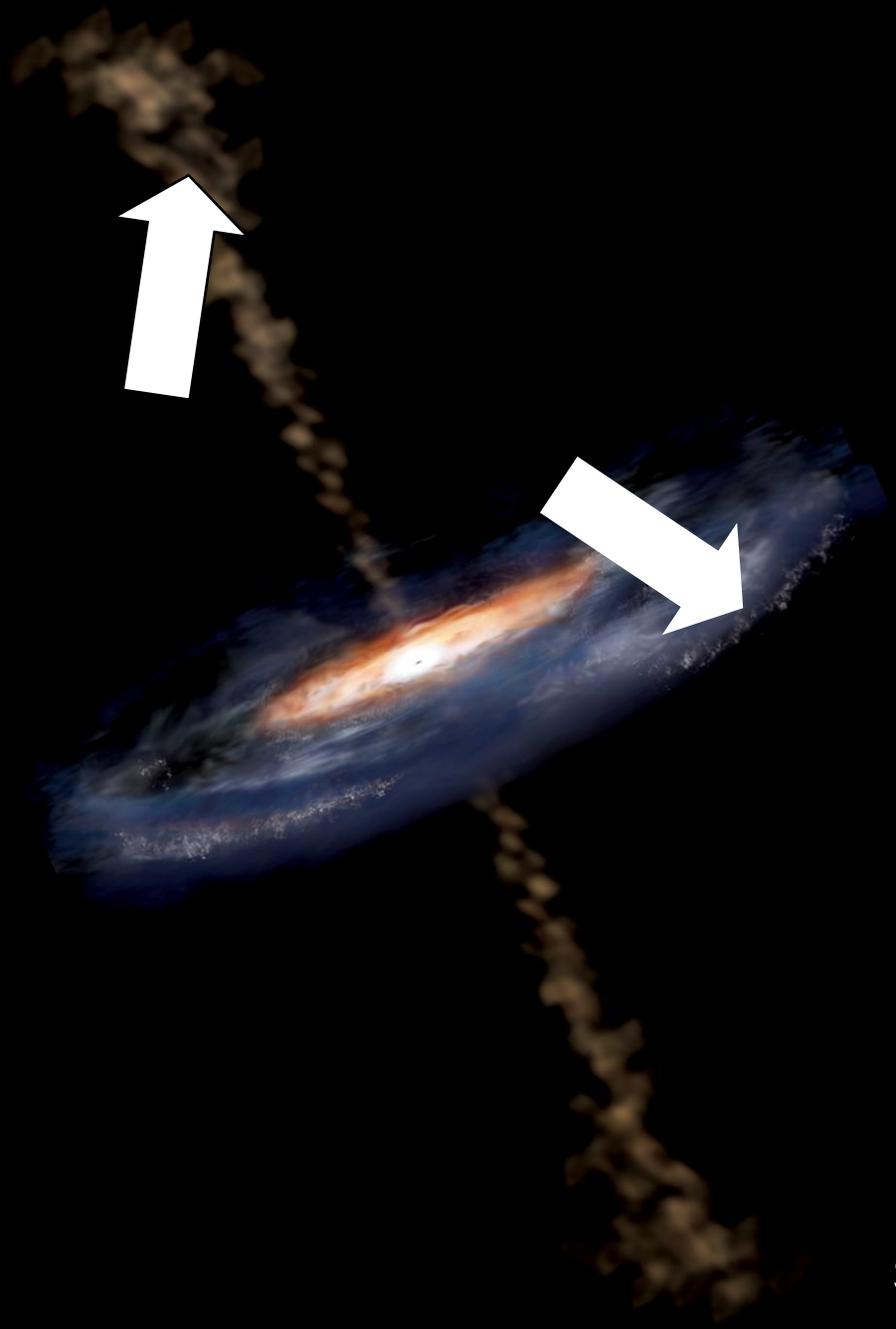


shocks produced in the outflow of the spinning black hole:

electrons

and

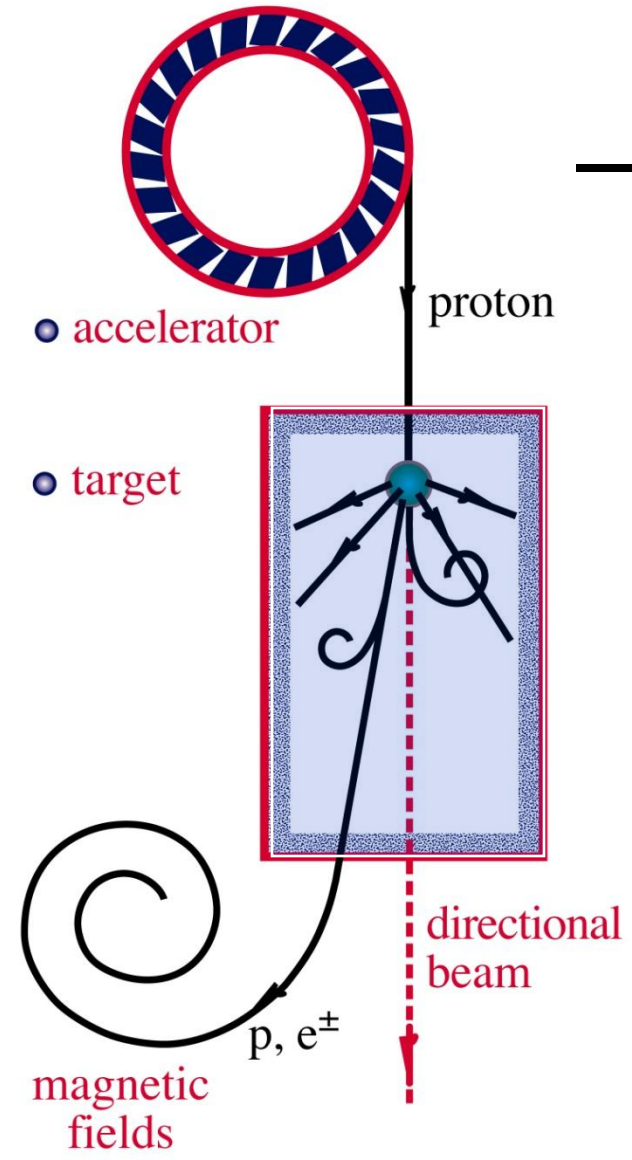
protons ?



active galaxy

particle flows near supermassive black hole

ν and γ beams : heaven and earth



black hole

radiation and dust

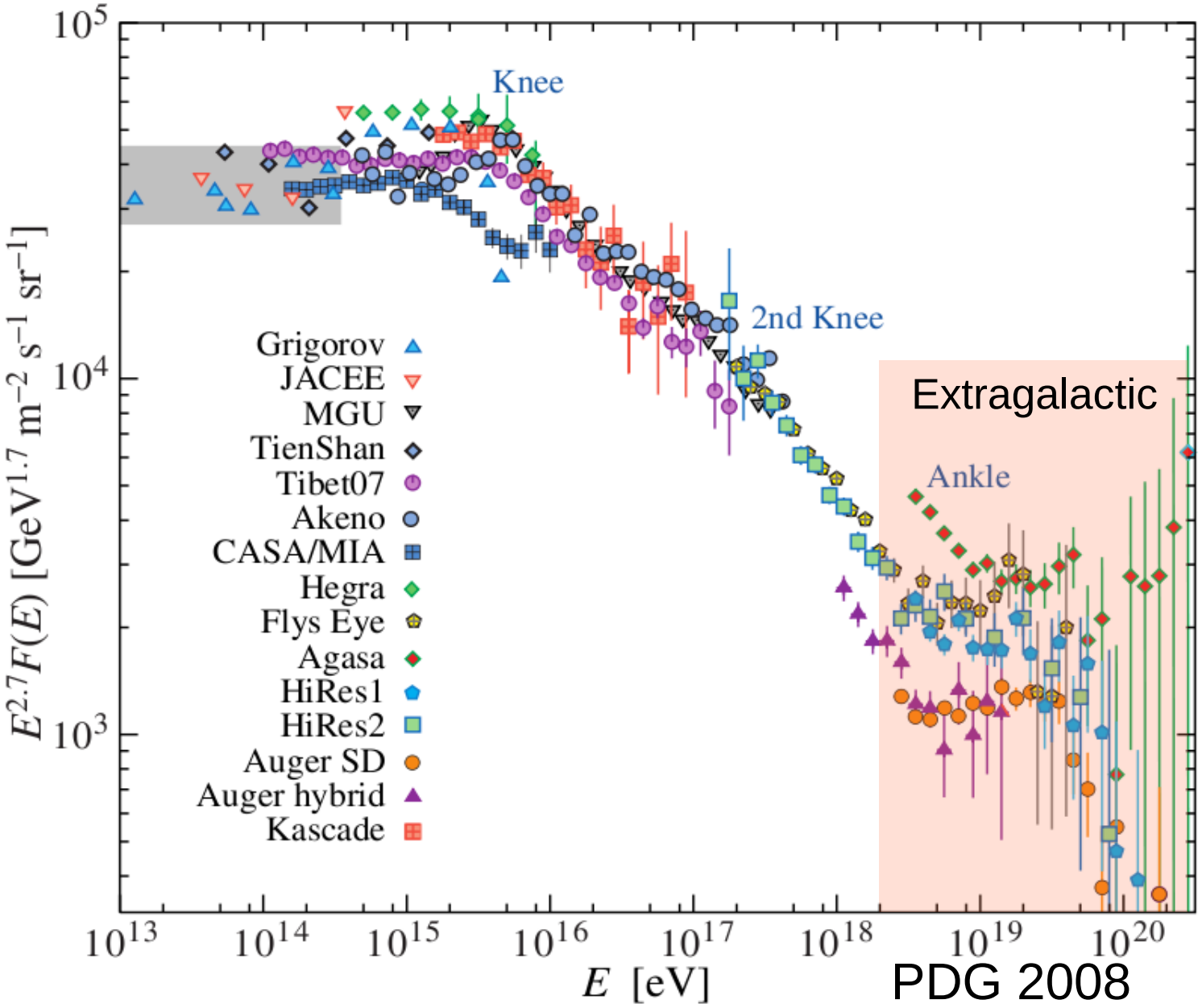
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

cosmic rays



PDG 2008

cosmic rays interact with the microwave background

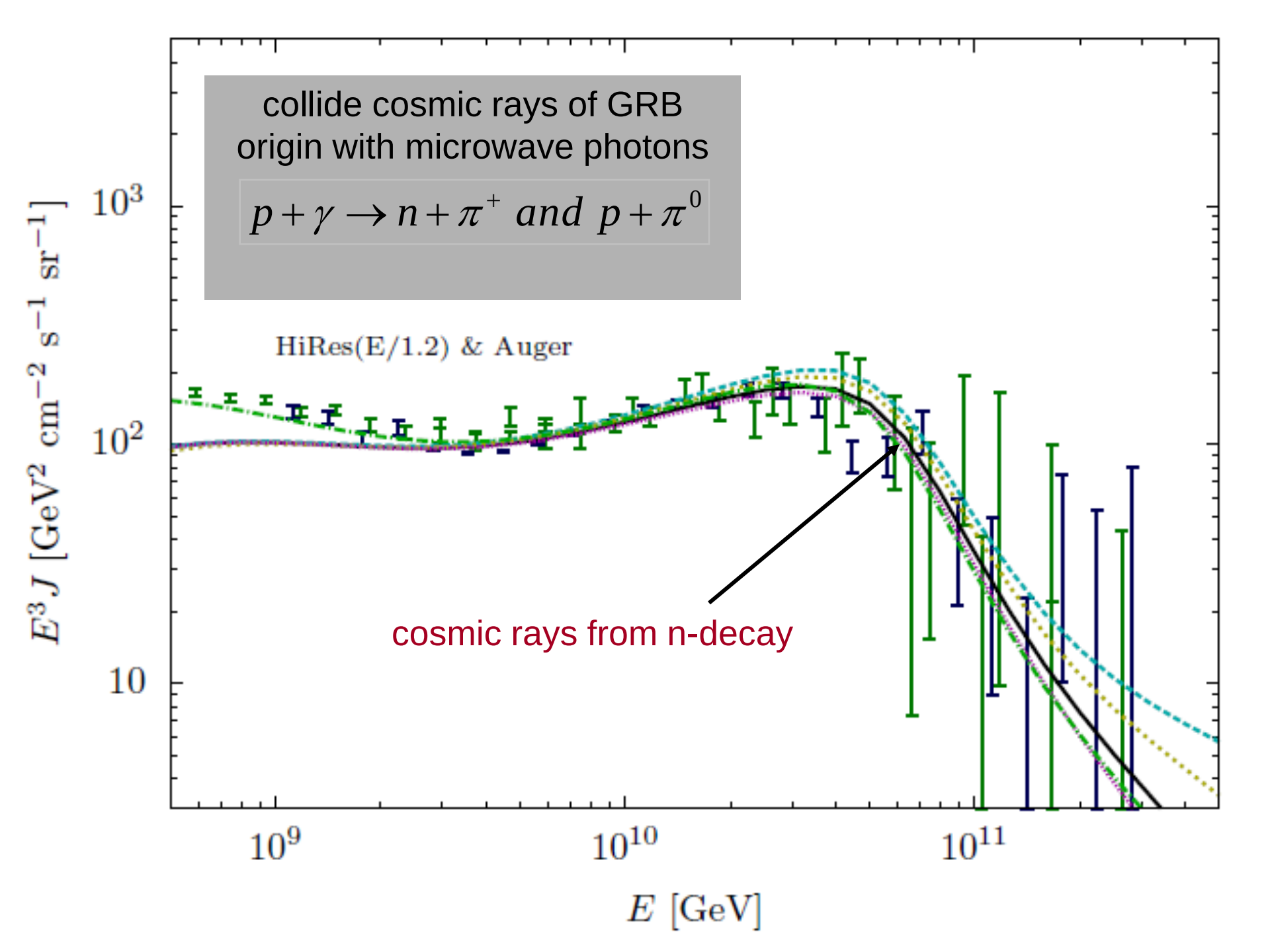
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

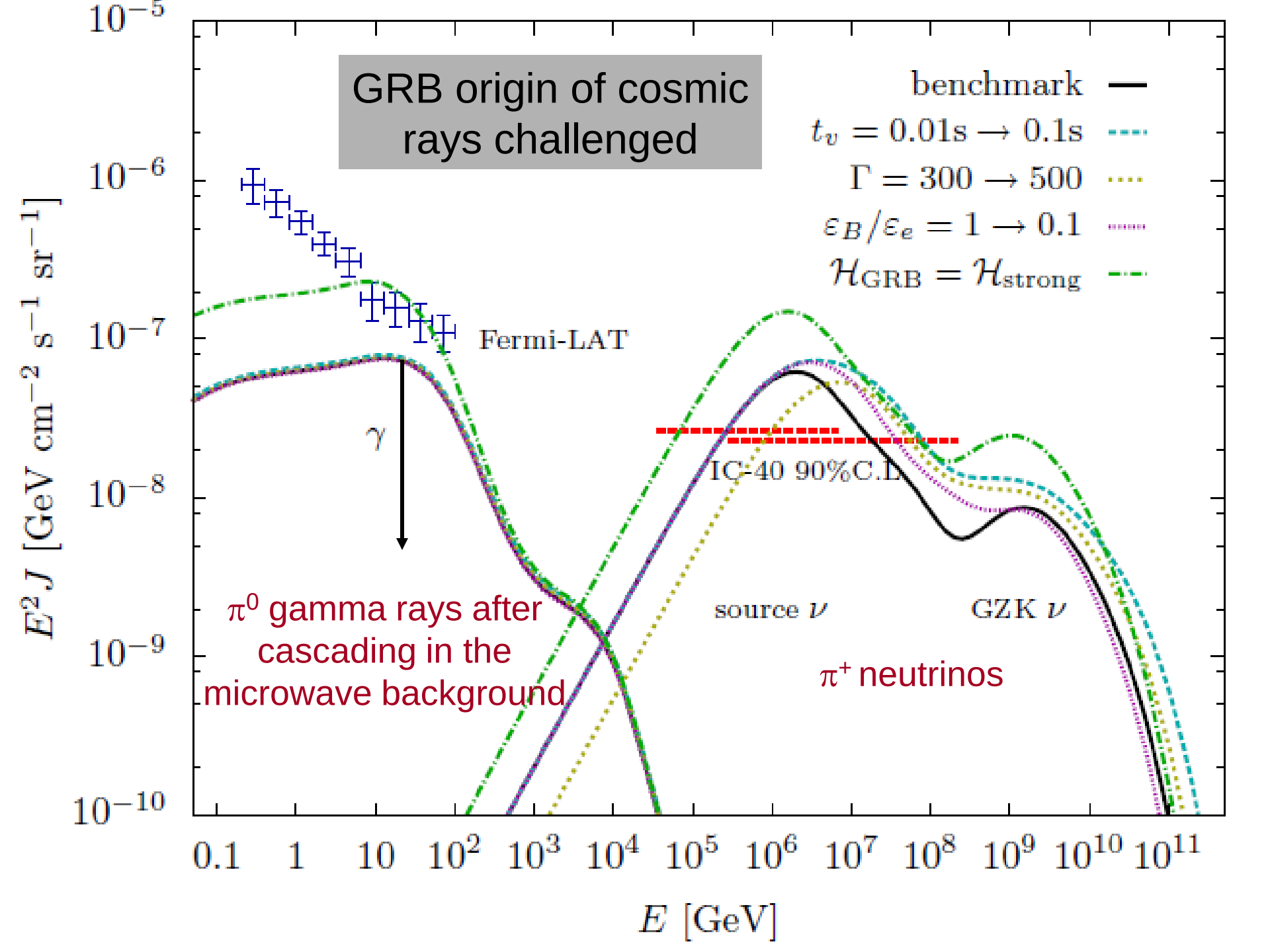
cosmic rays disappear, neutrinos appear

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

$$E_{\upsilon} \geq 2 \times 10^{6} \, TeV$$

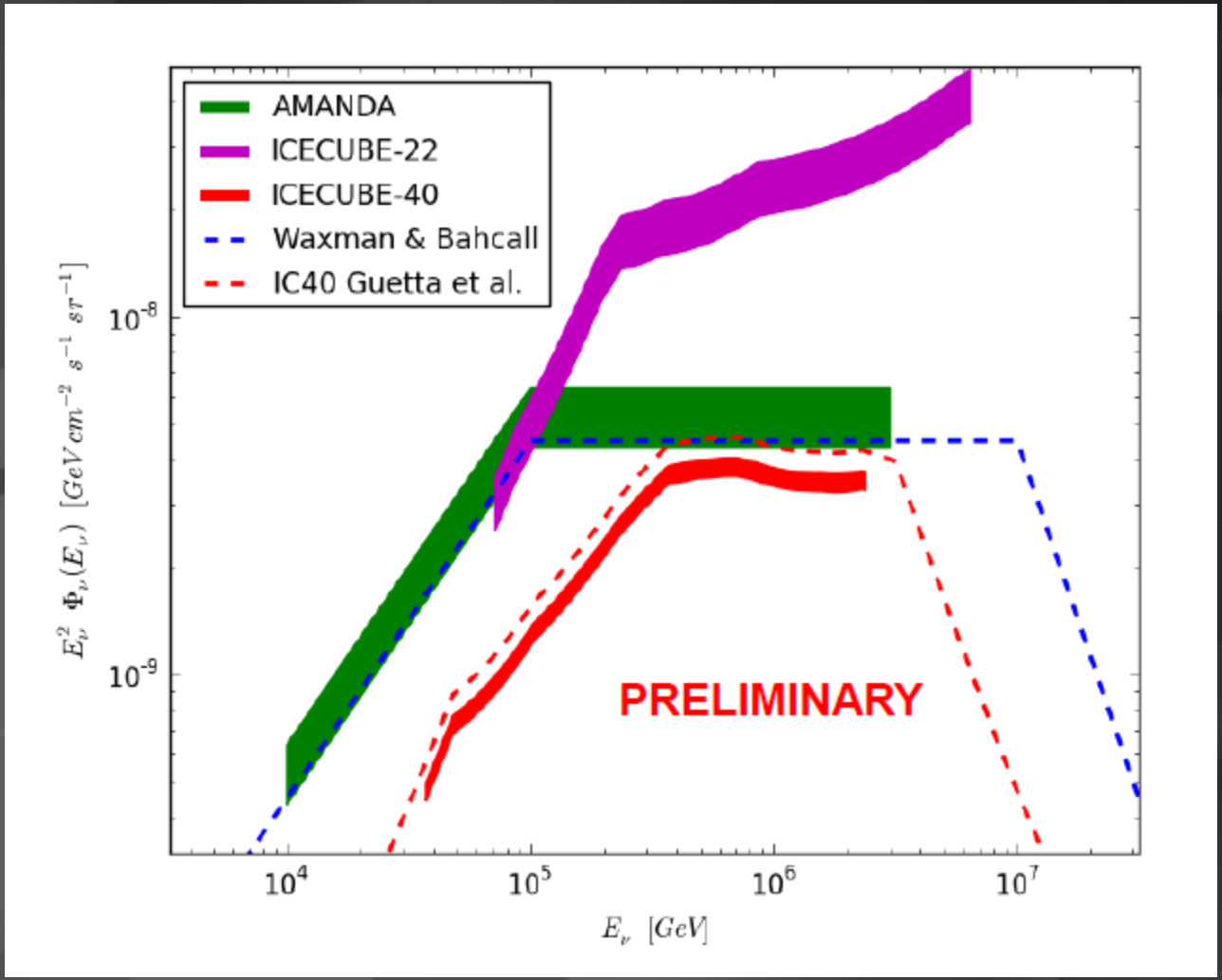
~ 1 GZK event per kilometer cube per year


collide cosmic rays of GRB origin with microwave photons
$p+\gamma \rightarrow n+\pi^{+}\ and\ p+\pi^{0}$
HiRes(E/1.2) & Auger
cosmic rays from n-decay
$E^3 J$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
10^3
10^2
10
10^9
10^{10}
10^{11}
E [GeV]

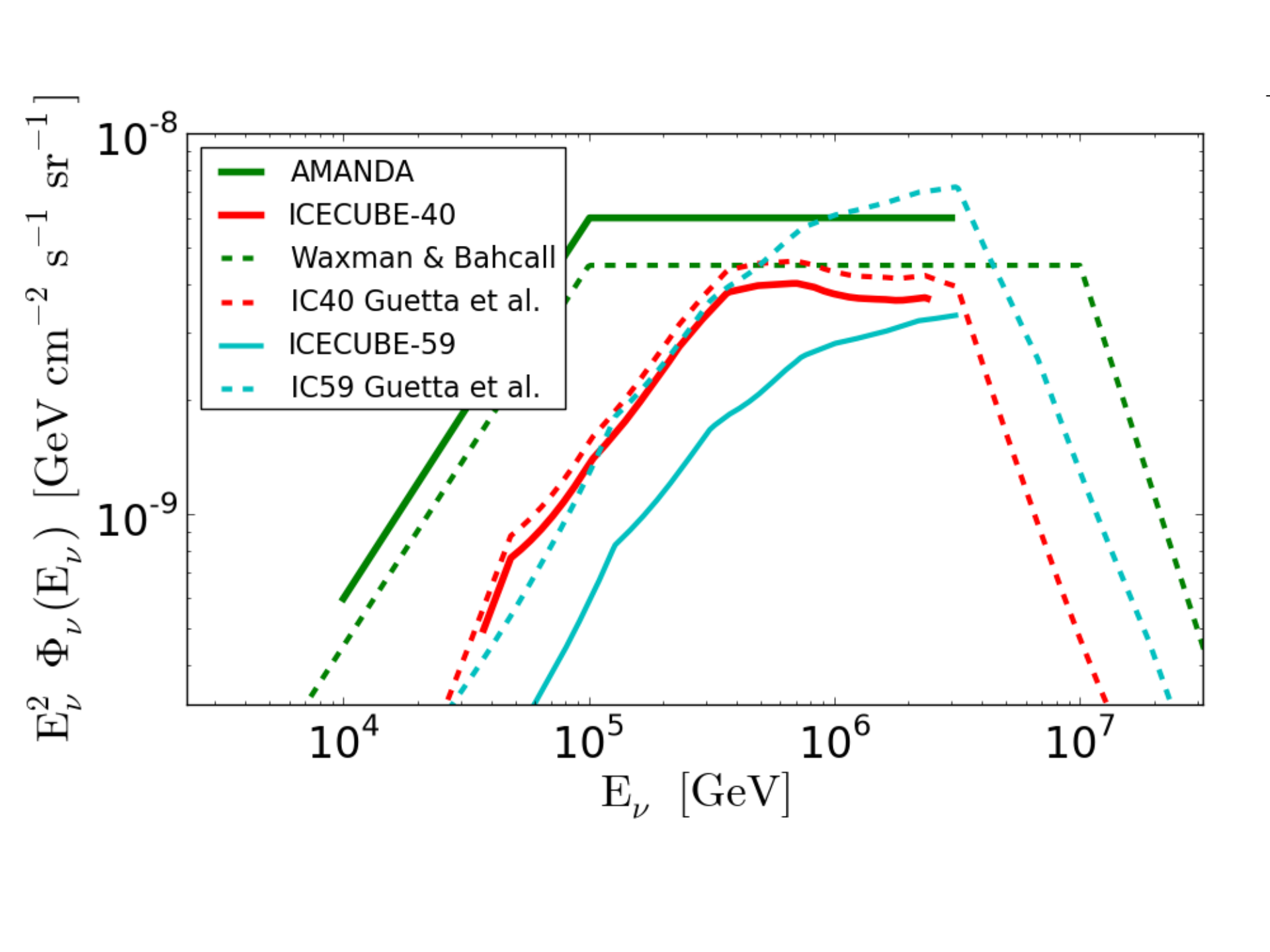

GRB origin of cosmic rays challenged
benchmark
$t_v = 0.01\text{s} \rightarrow 0.1\text{s}$
$\Gamma = 300 \rightarrow 500$
$\varepsilon_B/\varepsilon_e = 1 \rightarrow 0.1$
$\mathcal{H}_{\text{GRB}} = \mathcal{H}_{\text{strong}}$
Fermi-LAT
γ
IC-40 90%C.L.
source ν
GZK ν
π^0 gamma rays after cascading in the microwave background
π^+ neutrinos
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

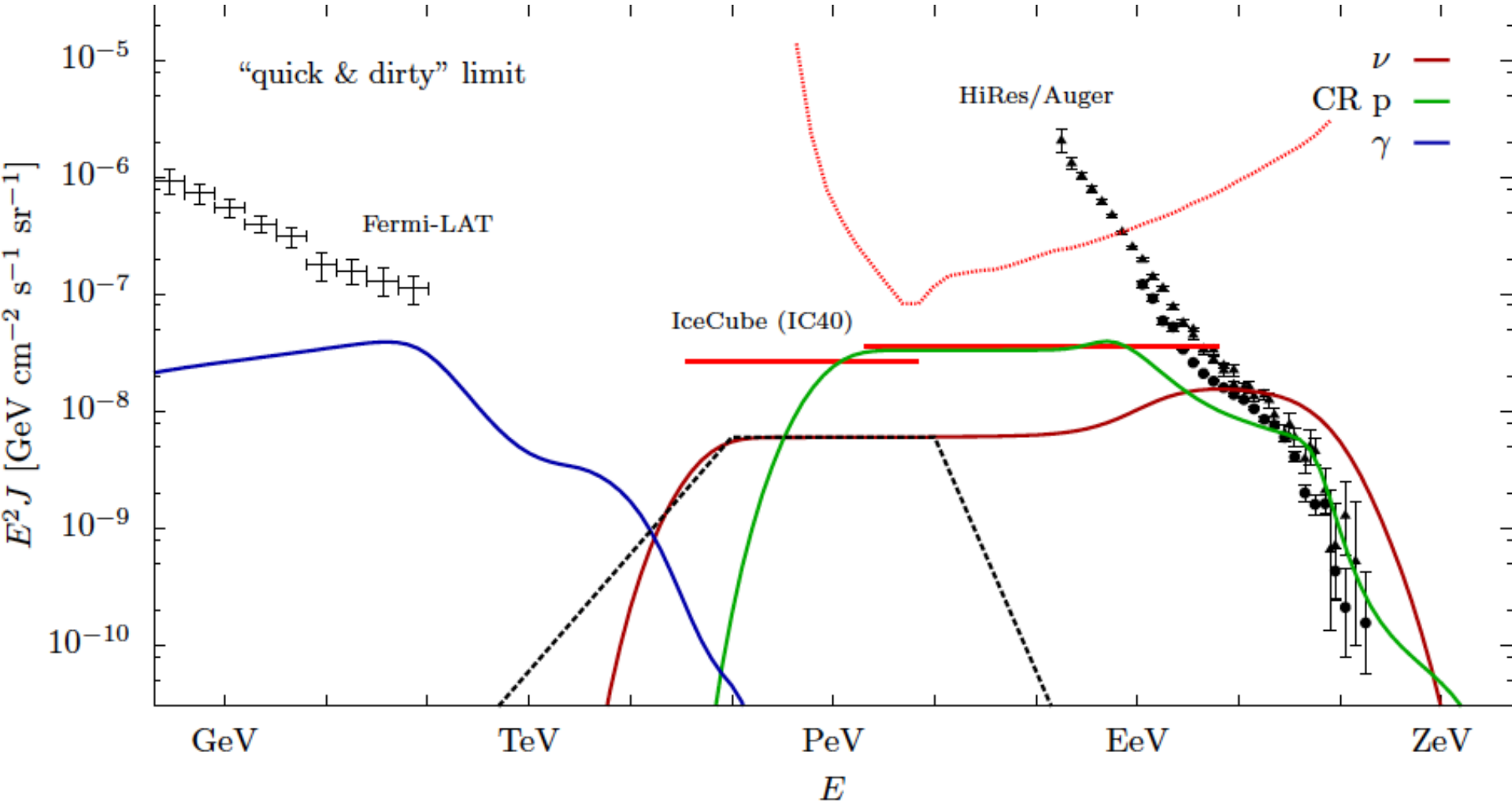
GRB
protons and photons co-exist in the fireball →

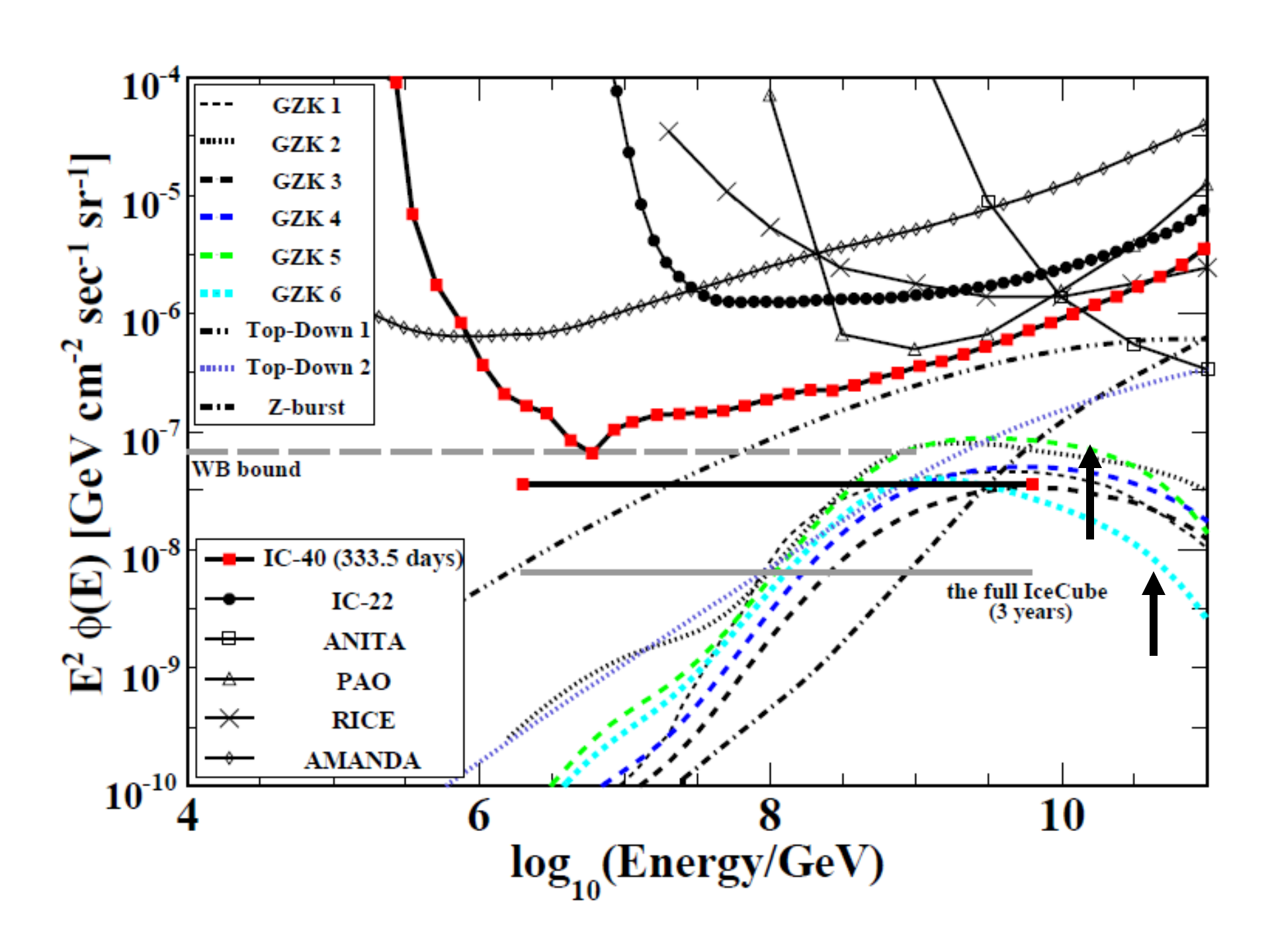
ν production



- 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}]


"quick & dirty" limit
HiRes/Auger
CR p
ν
γ
Fermi-LAT
IceCube (IC40)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
GeV
TeV
PeV
EeV
ZeV
E


GZK 1
GZK 2
GZK 3
GZK 4
GZK 5
GZK 6
Top-Down 1
Top-Down 2
Z-burst
WB bound
IC-40 (333.5 days)
IC-22
ANITA
PAO
RICE
AMANDA
the full IceCube
(3 years)
$E^2 \phi(E)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
$\log_{10}$(Energy/GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
4
6
8
10

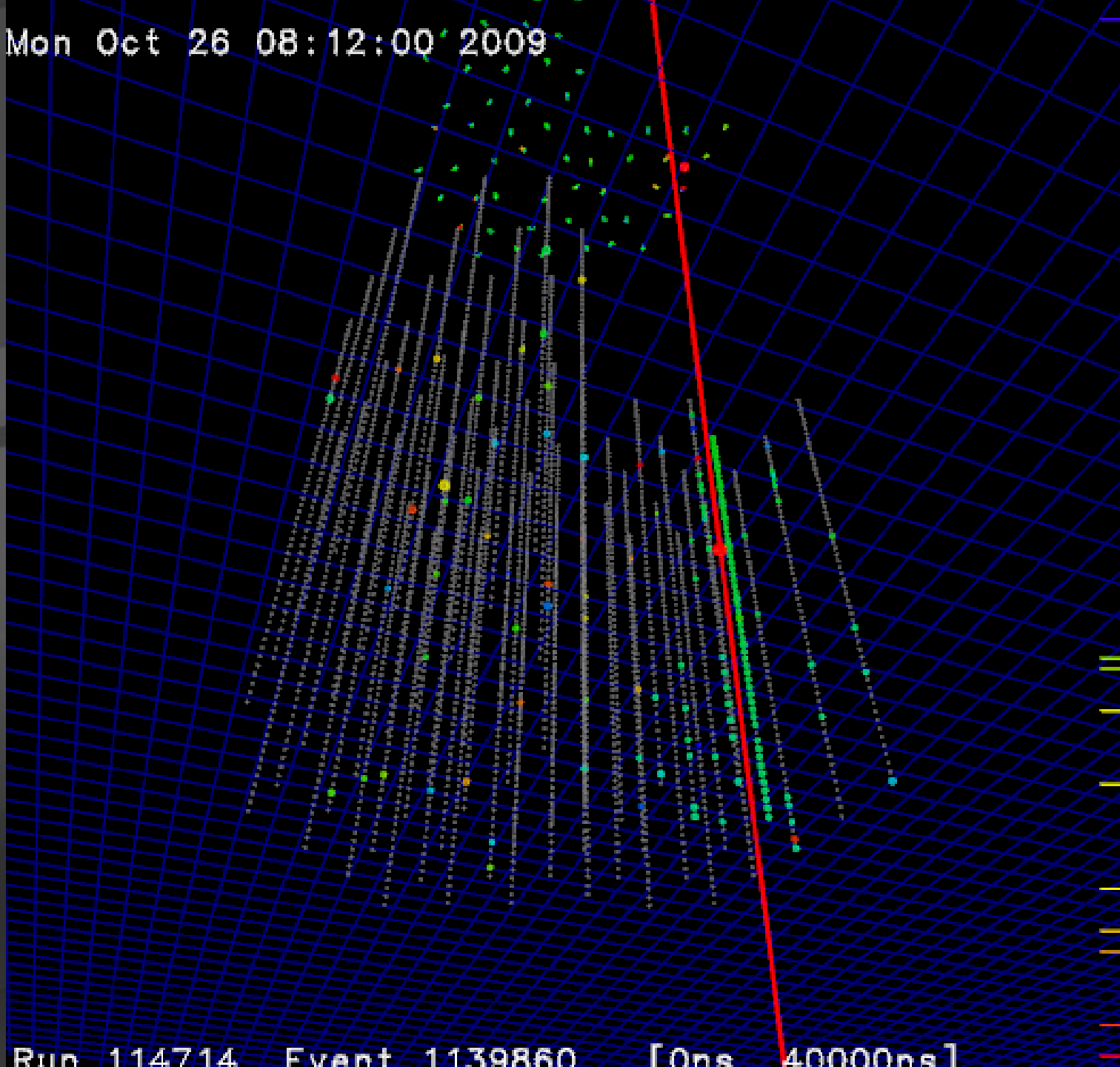
NOT a GRB

neutrino(?) within 40 s duration of the burst

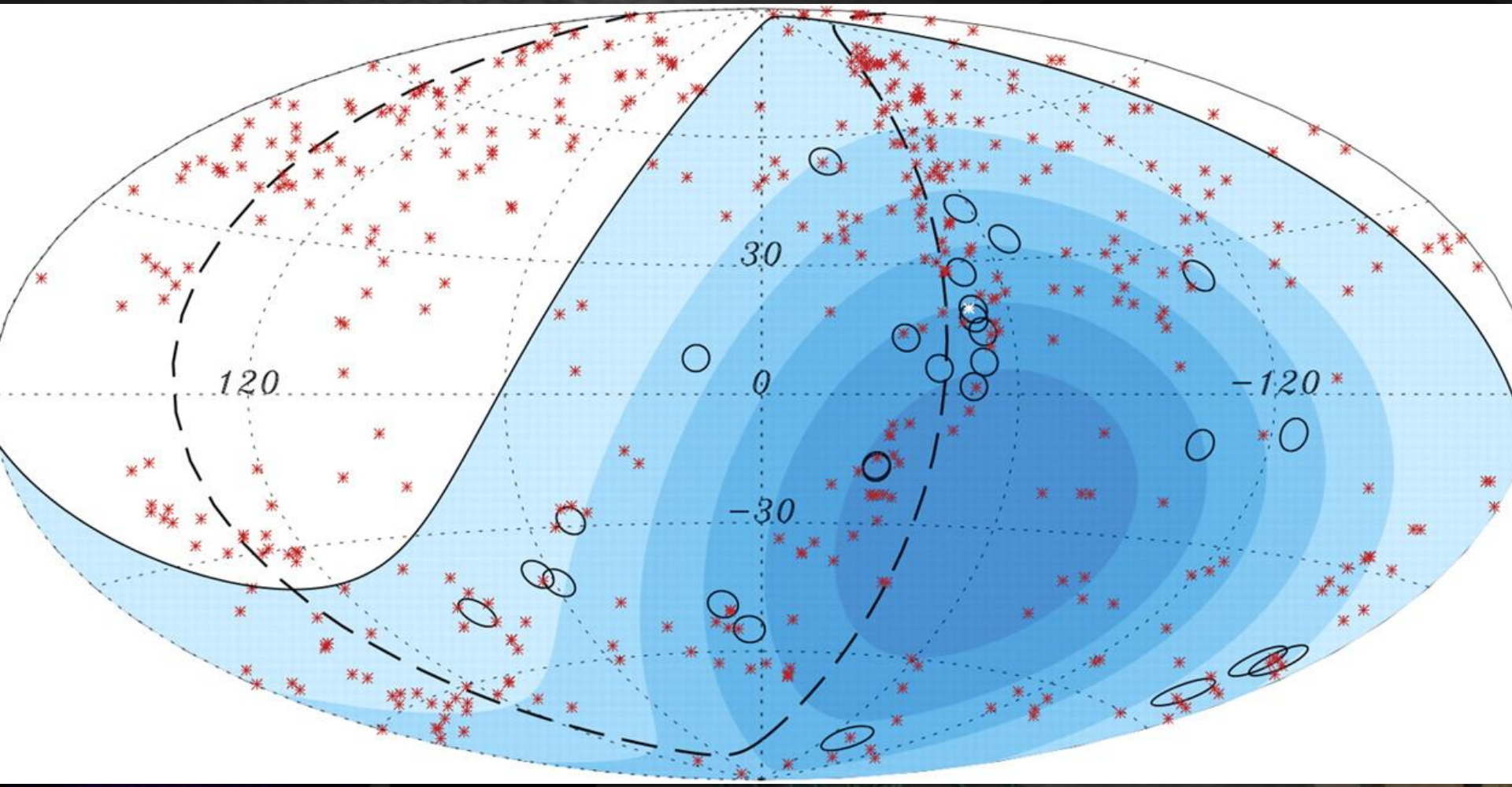
azimuth of burst
87.11 deg

observed
87.97+/- 0.3

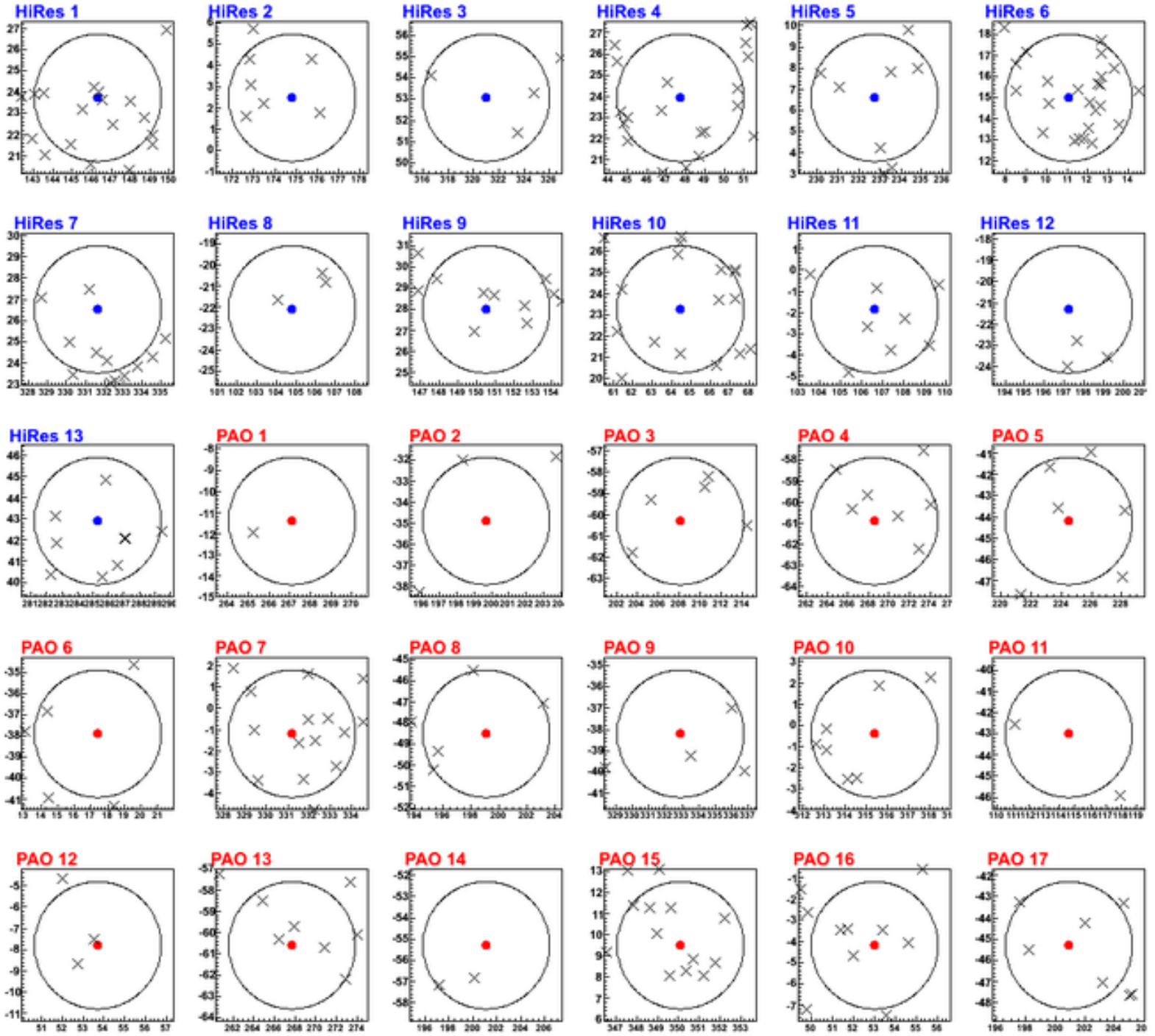
we keep looking !!!



Auger : the sources revealed ?



correlation of arrival directions with active galaxies


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	IC-22
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

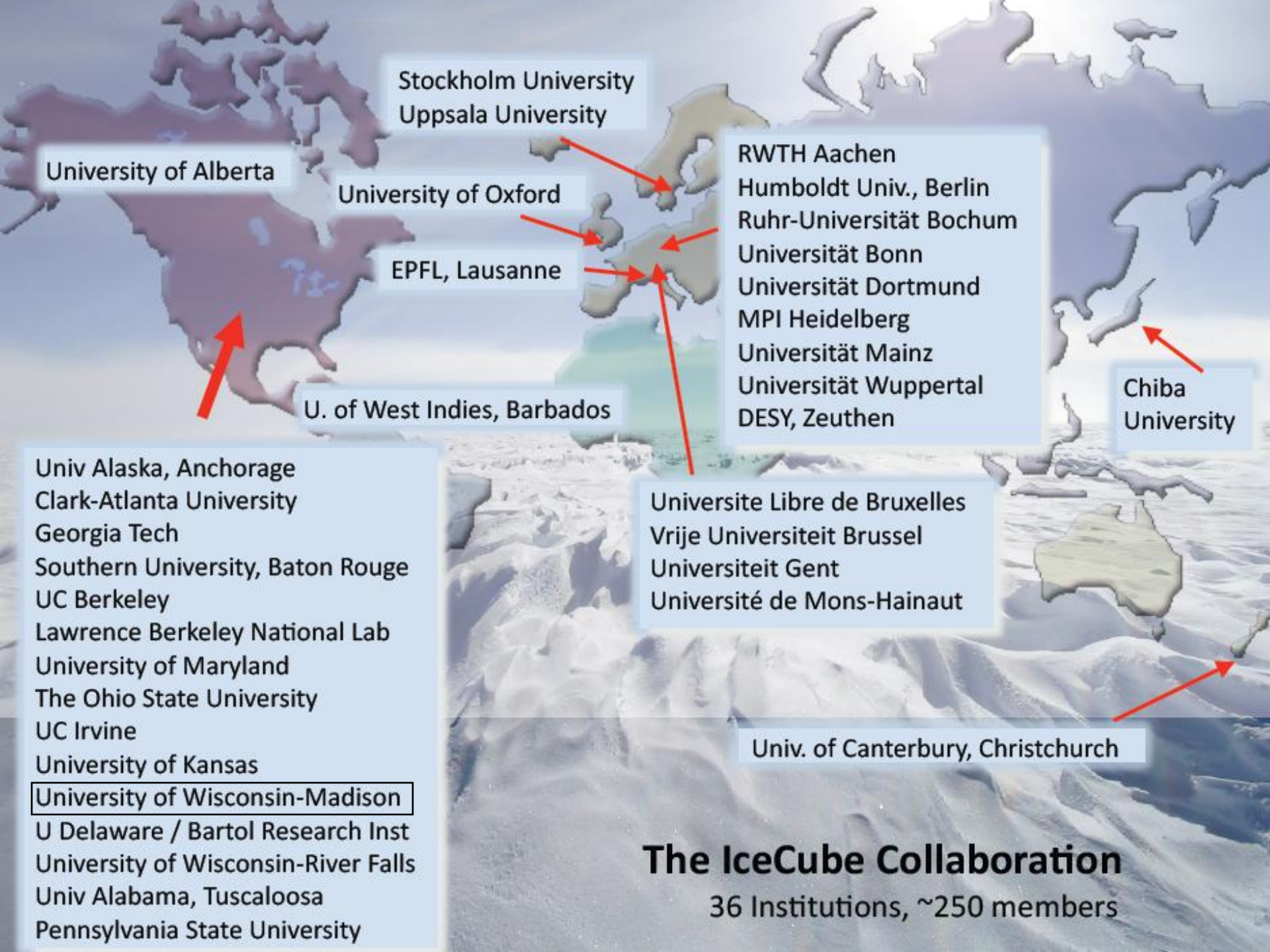
RA 11.07° Dec. 14.99°

…

IceCube : particle physics with one million atmospheric neutrinos

Particle Physics

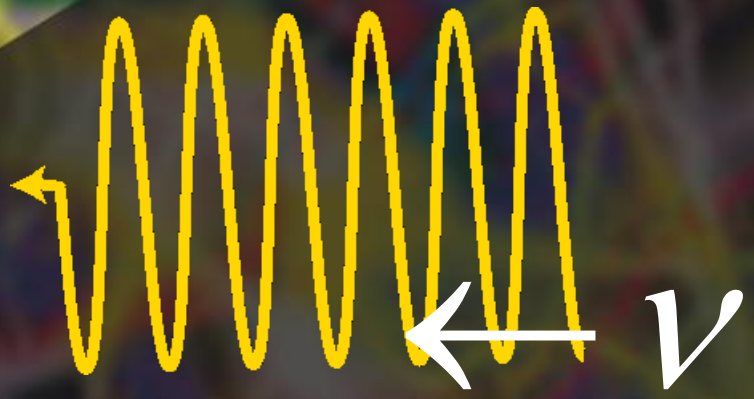
- DeepCore: oscillations, tau neutrino appearance, hierarchy
- measurement of the high-energy neutrino cross section
- TeV-scale gravity, *quantum decoherence*
- physics beyond 3-flavor oscillations
- test special and general relativity with new precision
- search for magnetic monopoles
- *search for neutralino (or other) dark matter*
- search for topological defects / cosmological remnants
- search for non-standard model neutrino interactions
- search for leptoquarks
- …


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

quantized space: matter where the geometry is activated

quantized space: matter where the geometry is activated

$$\lambda \sim \frac{1}{E} \rightarrow 10^{-33}\,cm$$



Lorentz violation from Planck scale

violation of Lorentz invariance may be a tool to study Planck scale physics

→ interaction with Planck mass particles distort spacetime

→ Planck scale vacuum fluctuations probed by high energy neutrinos

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{\varsigma M_{Planck}}\right)^n \pm \ldots$$

modification to dispersion relation leads to an energy dependent speed of light.

sensitivity to Planck scale !

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

$$\Delta t \approx \frac{1+n}{2}\left(\frac{d}{c}\right)\left(\frac{E_\nu}{\varsigma M_{Planck}}\right)^n$$

from a source at a distance d; for instance a GRB.

Lorentz violation: ΔE vs Δt

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

$$\Delta t \approx \frac{1+n}{2}\left(\frac{d}{c}\right)\left(\frac{E_\nu}{\varsigma M_{Planck}}\right)^n$$

from a source at a distance d; for instance a GRB.

Lorentz violation: ΔE vs Δt

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

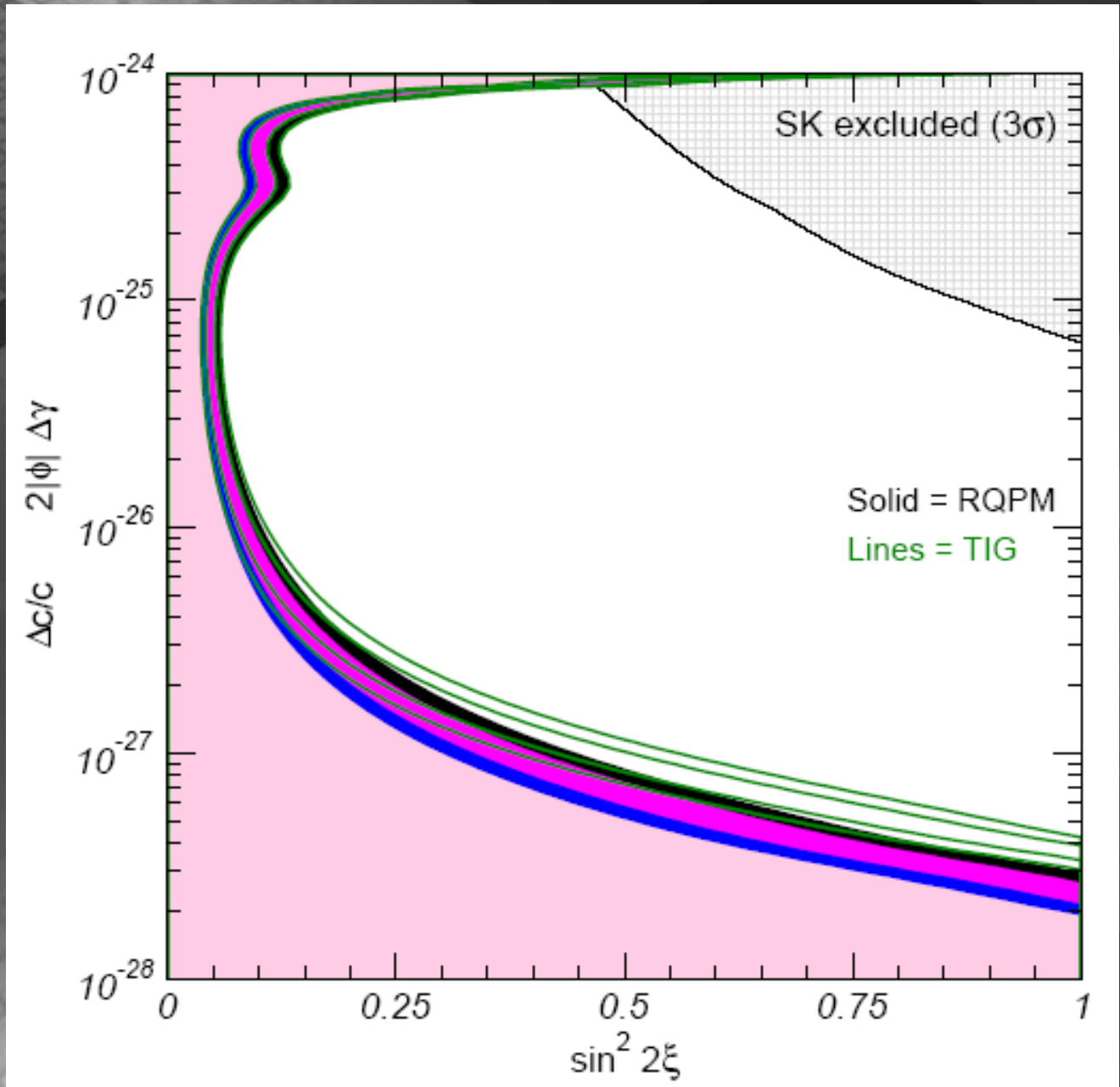
$$energy\,scale \cong \frac{d}{c}\frac{\Delta E}{\Delta t} \cong M_{Planck}$$

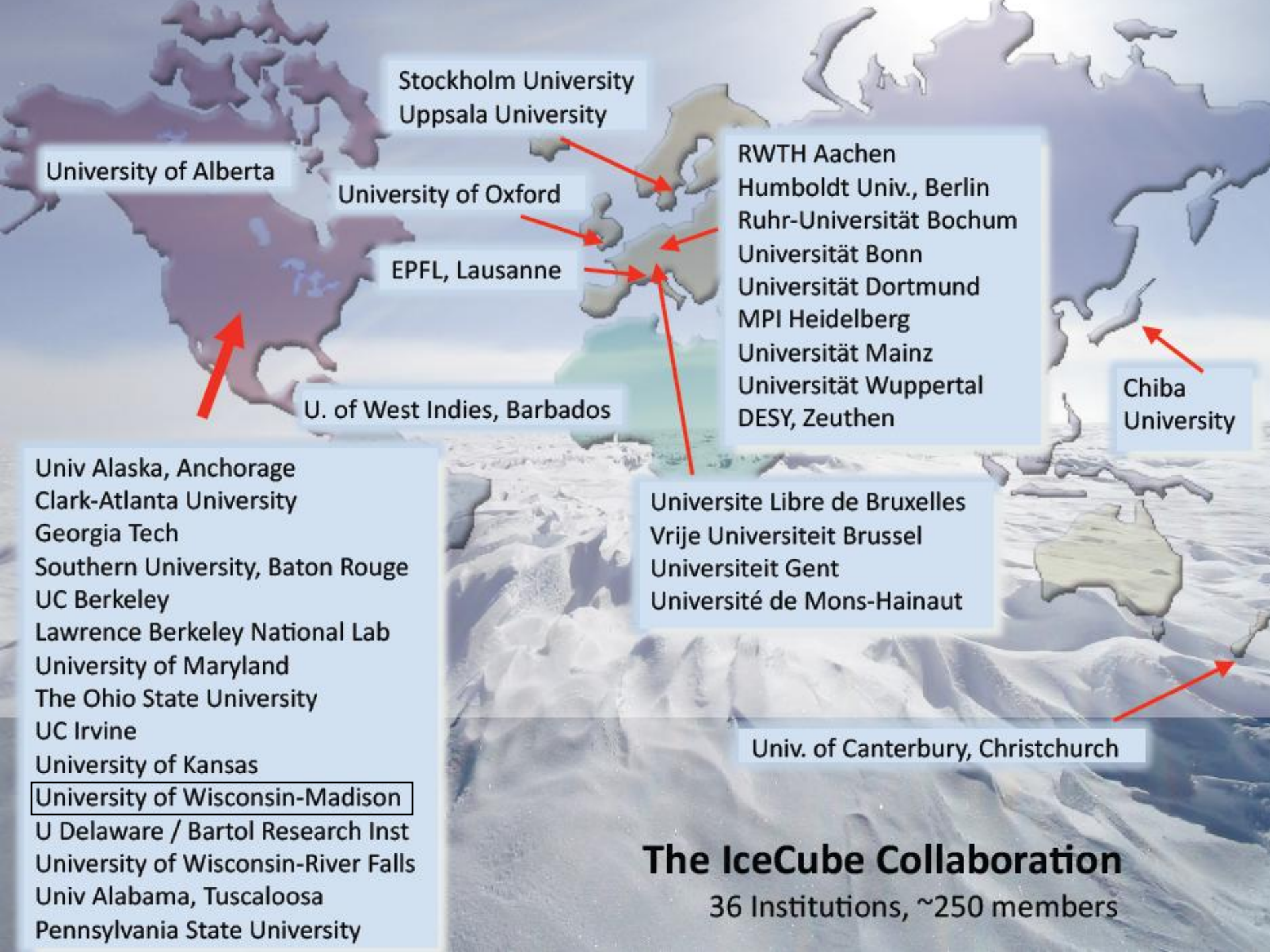
from a source at a distance d; for instance a GRB.

IceCube

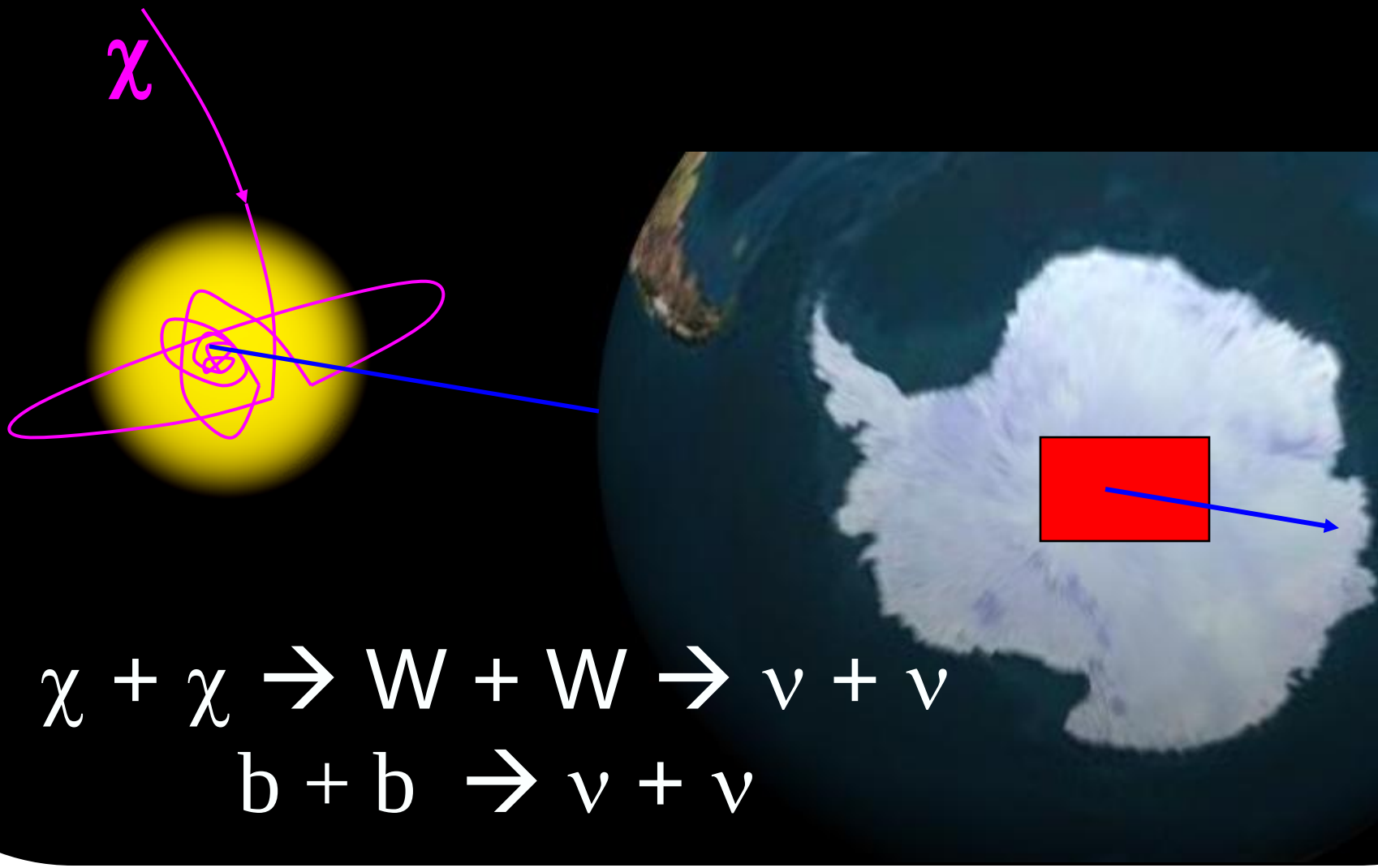
tests
- equivalence principle
and
- Lorentz invariance

…general relativity will not last 200 years…
M. Turner




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

WIMP Capture and Annihilation



$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

$$b + b \rightarrow \nu + \nu$$

- capture

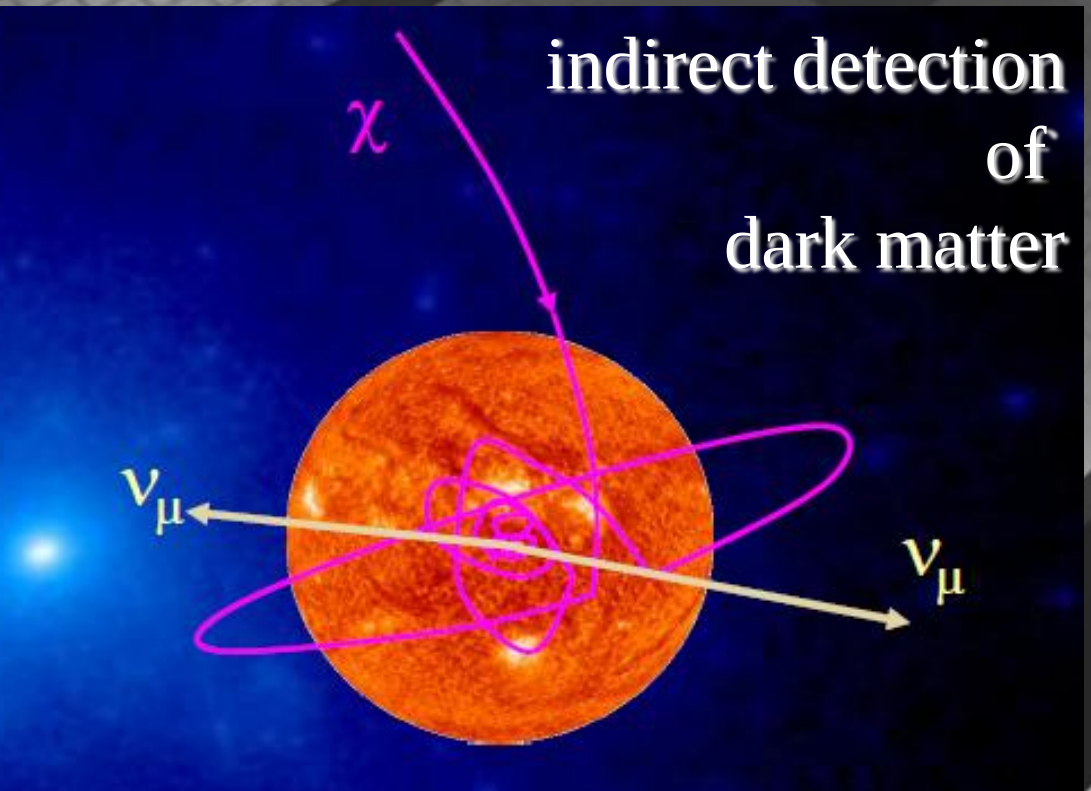
$$\frac{dN}{dt} = C_{cap} - C_{ann} N^2$$

- equilibrium

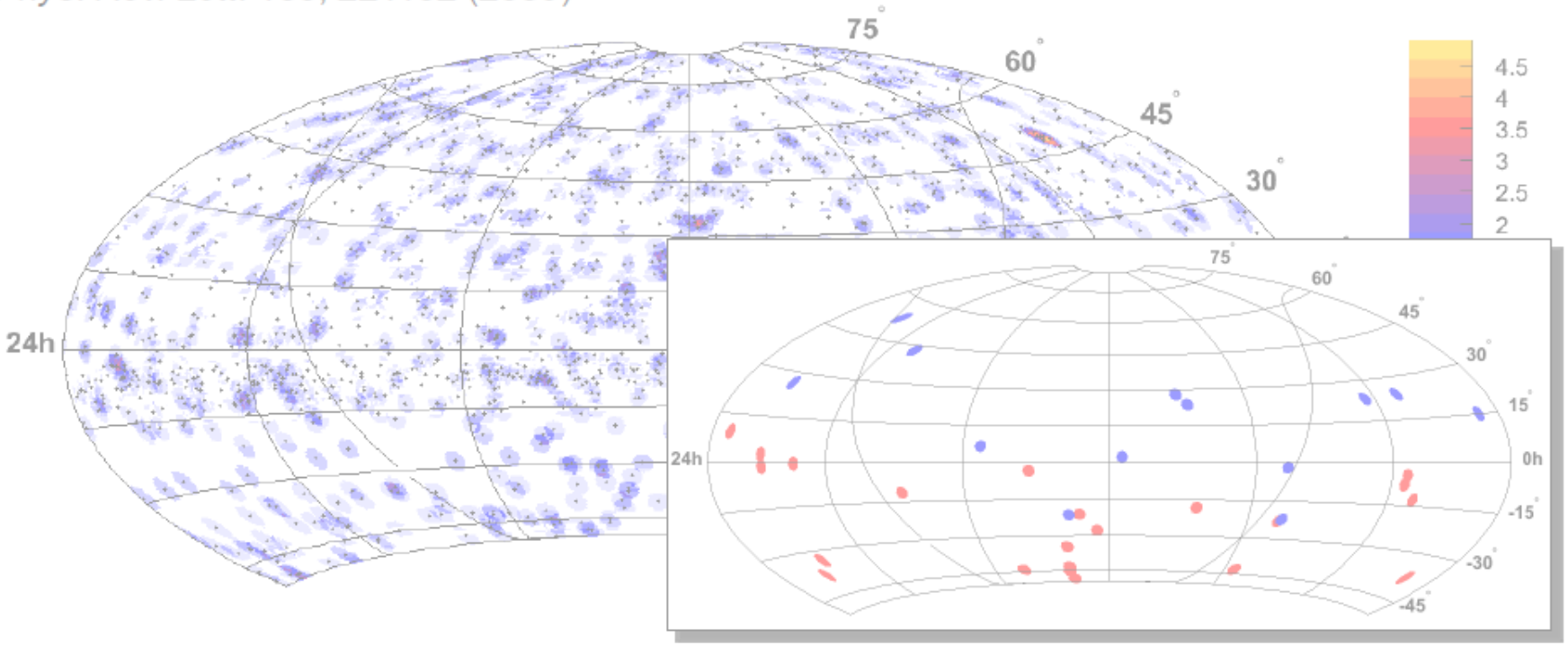
$$\Gamma_{ann} = \frac{1}{2} C_{ann} N^2 = \frac{1}{2} C_{cap}$$

neutrino flux

wimp-nucleon cross section



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



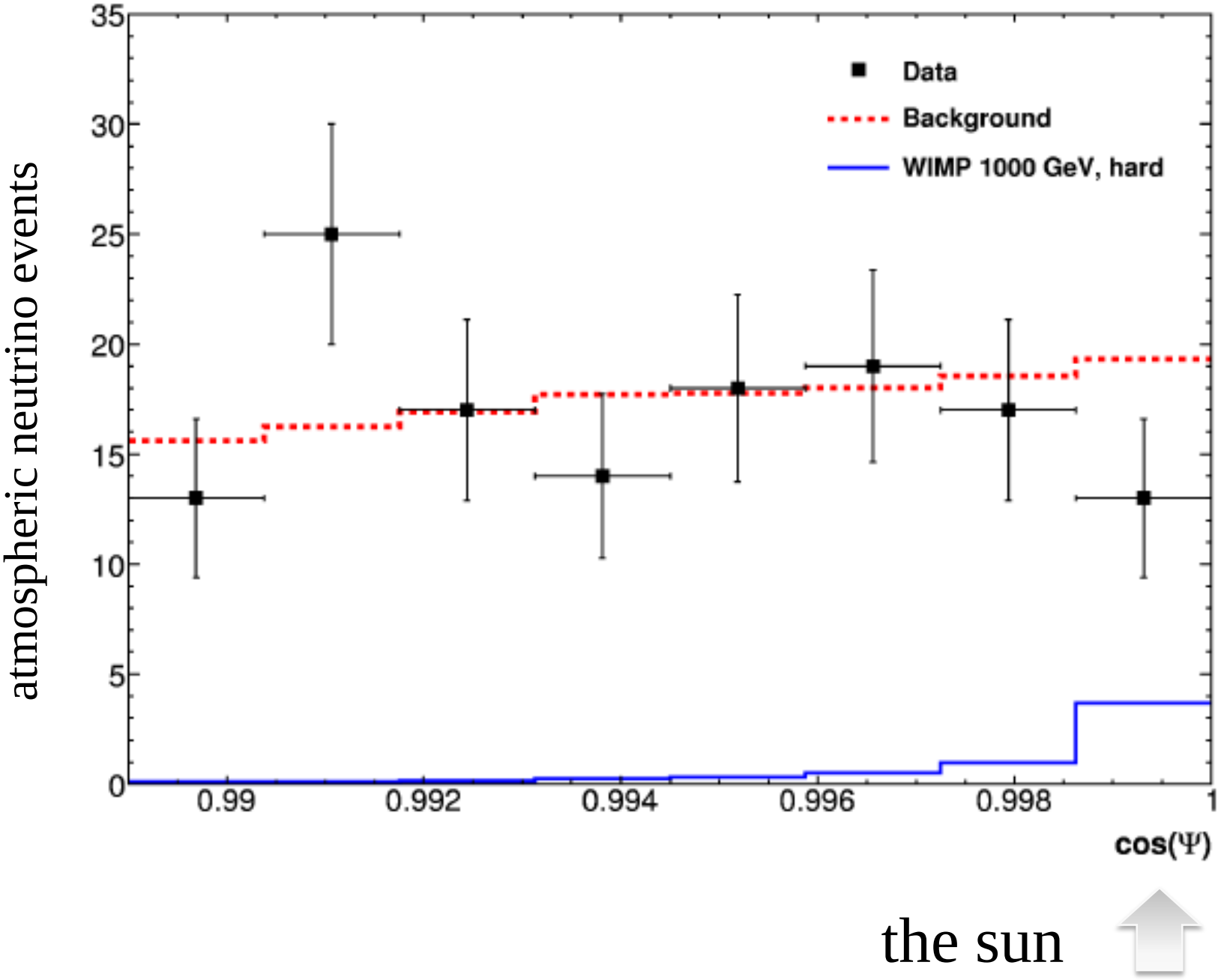
Look for neutrinos from entire sky by demanding high energies (~PeV)

- 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)

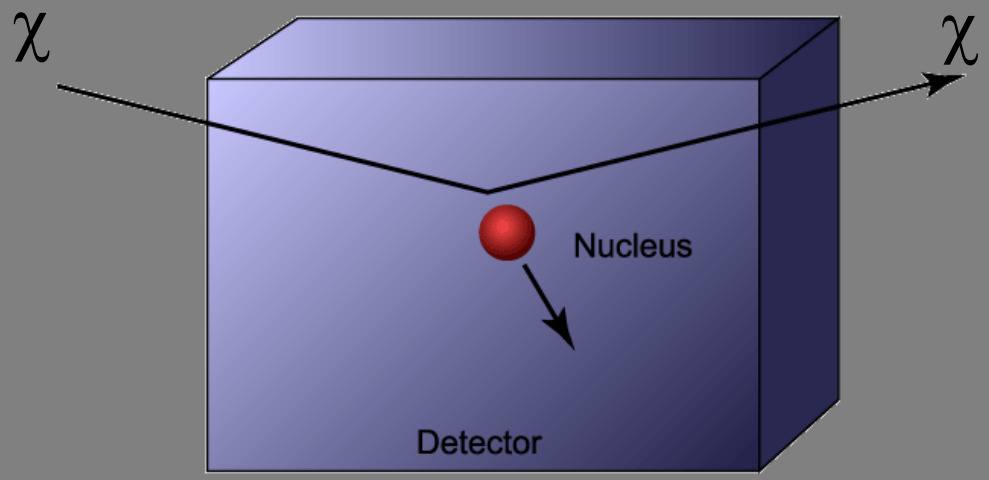
wait one year → effect disappears


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

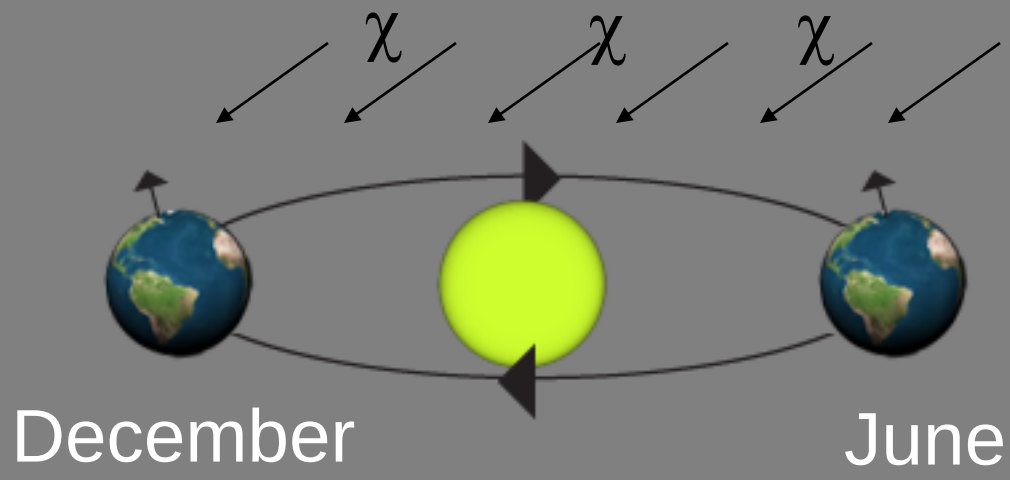
dark matter

- supersymmetry comes in 2 flavors: spin-independent (favors direct detection because of A^2) and spin-dependent
- IceCube is competitive for spin-dependent
- can probe most of the interesting parameter space of the MSSM
- [astrophysics is known (no toothfairies)]

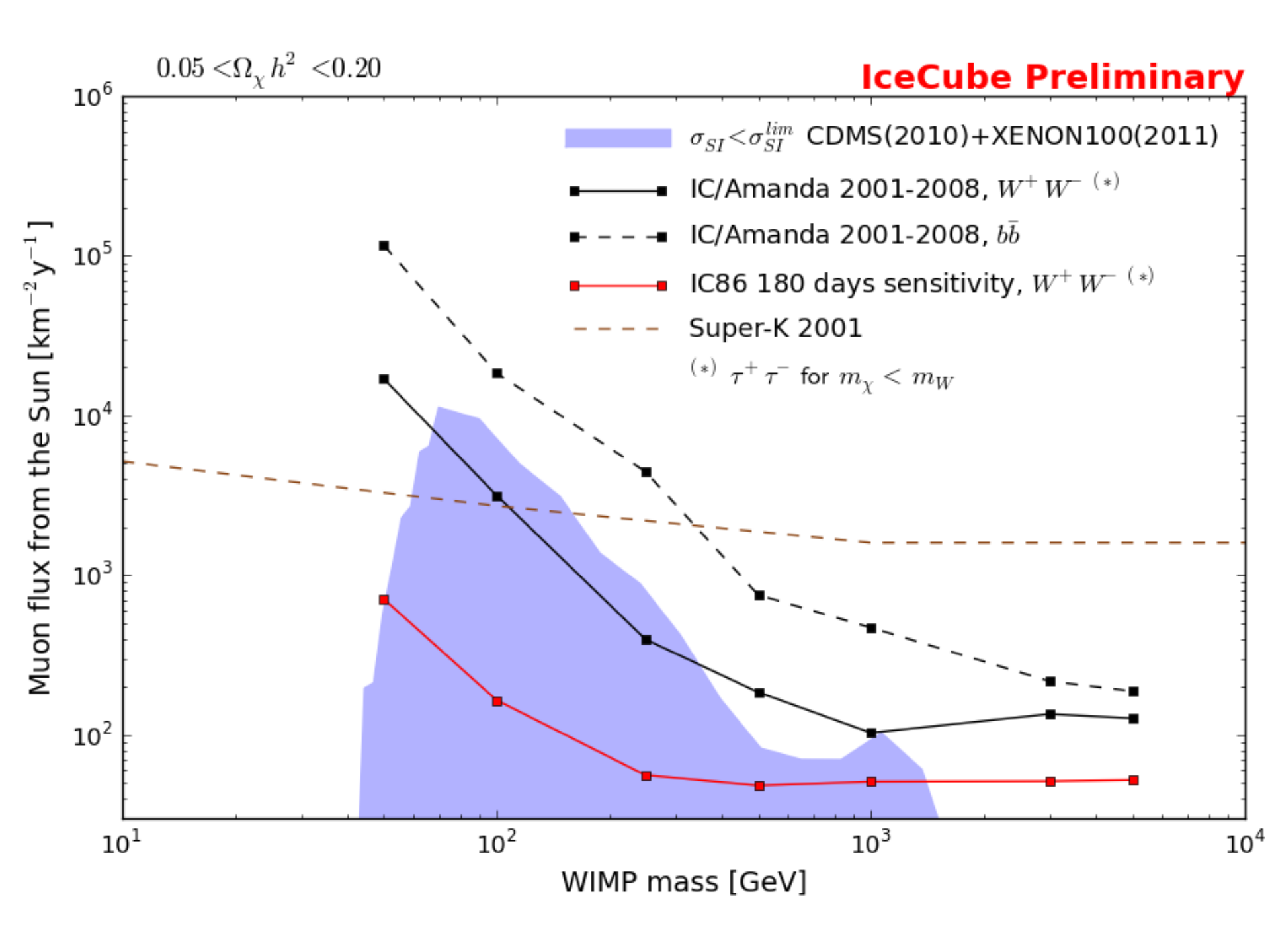
direct detection - general principles

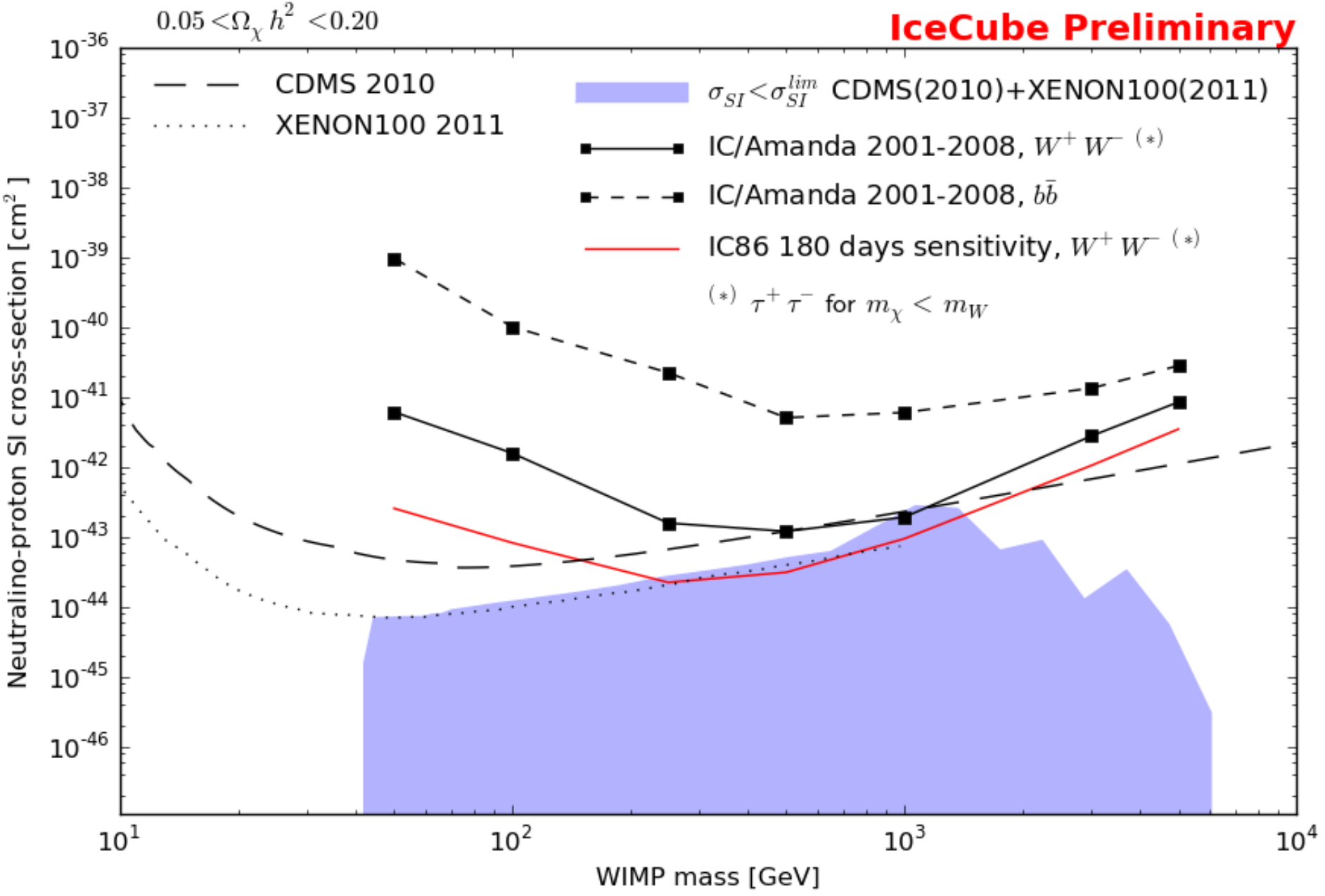


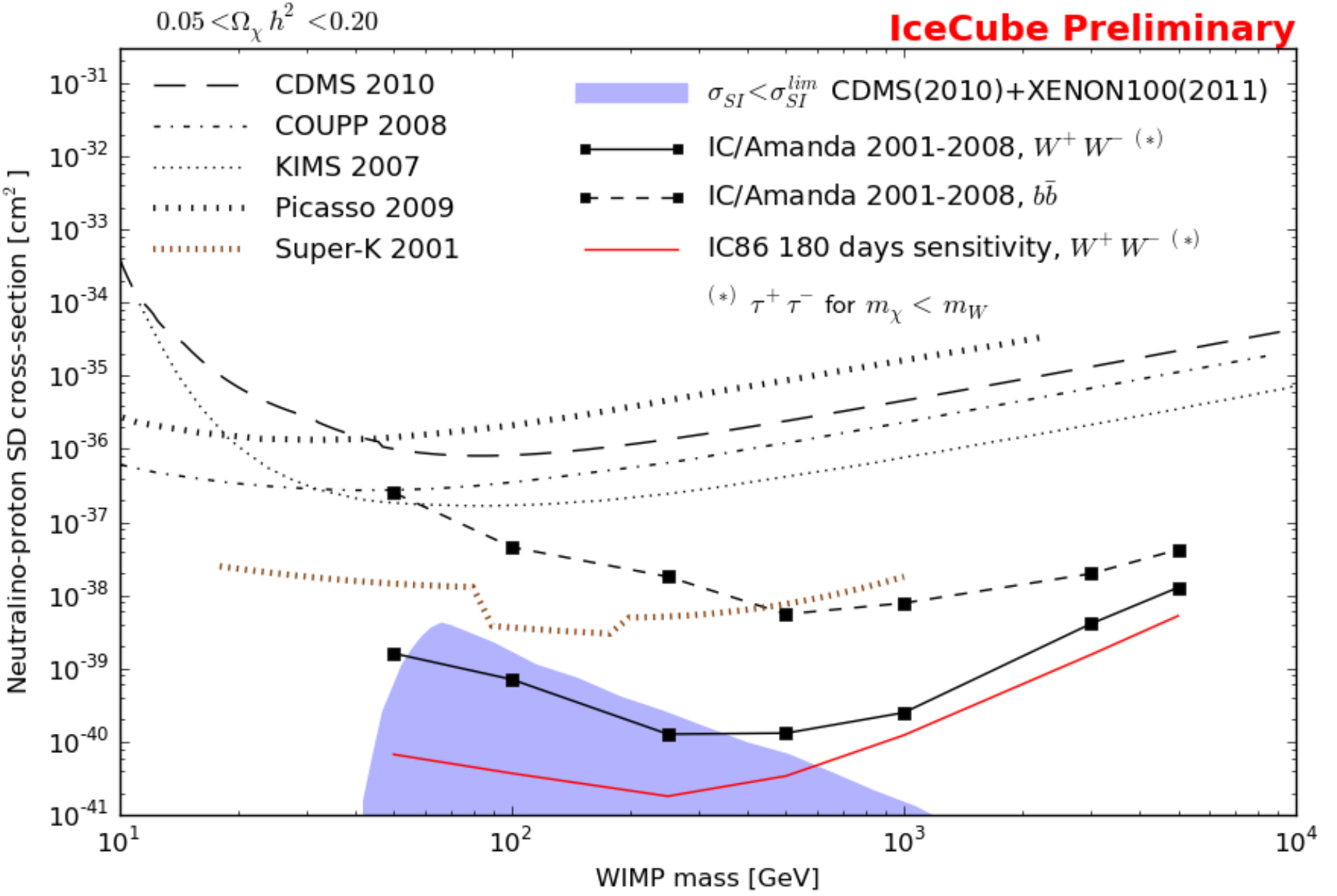
- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds

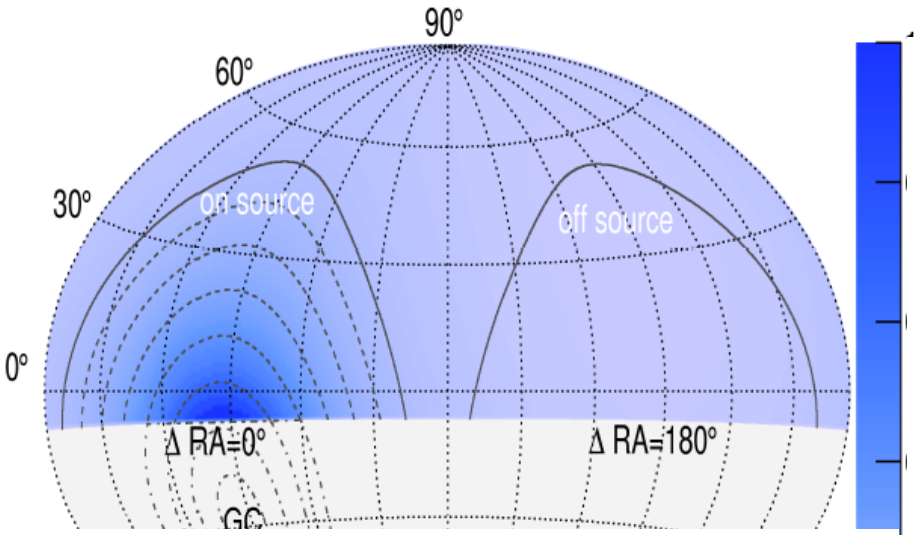


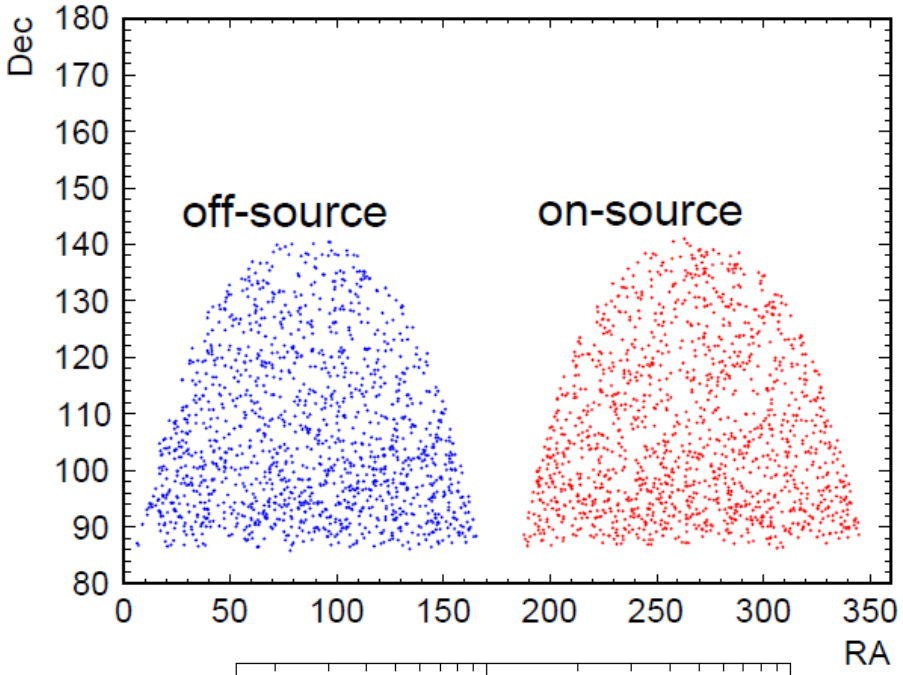
- Search for an annual modulation due to the Earth's motion around the Sun

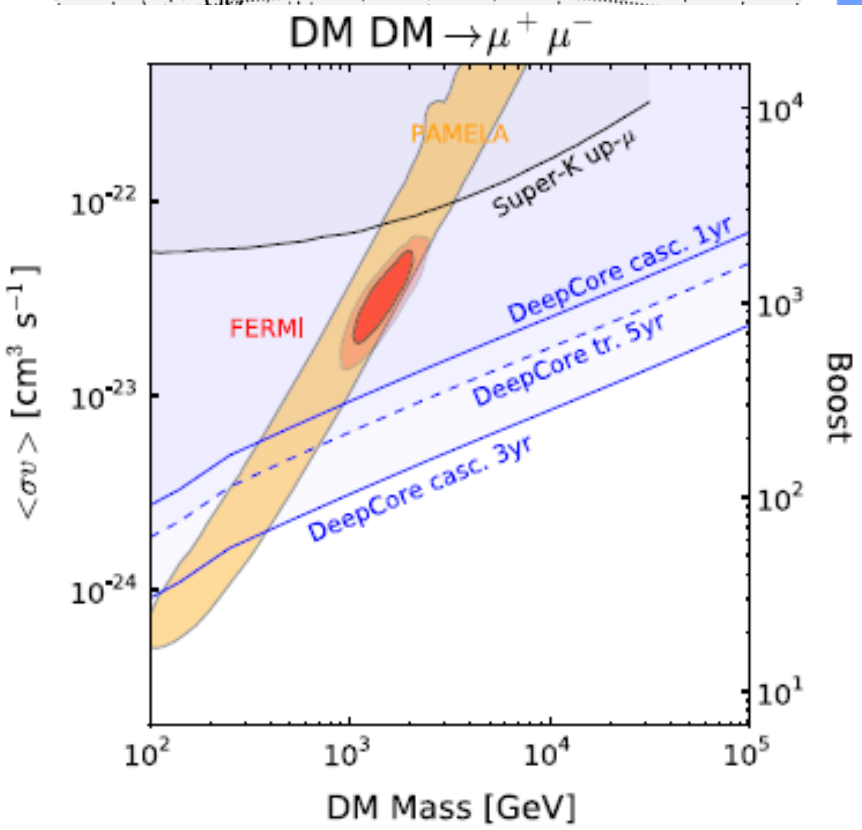

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, W^+W^- $(*)$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, W^+W^- $(*)$
Super-K 2001
$(*)$ $\tau^+\tau^-$ for $m_\chi < m_W$
Muon flux from the Sun [km^{-2} y^{-1}]
WIMP mass [GeV]
10^6
10^5
10^4
10^3
10^2
10^1
10^2
10^3
10^4

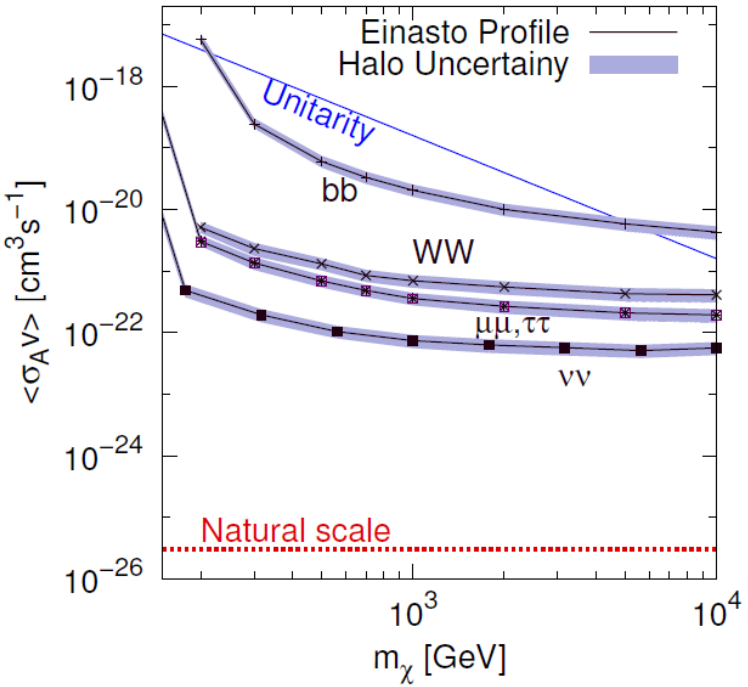

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
XENON100 2011
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, W^+W^- $^{(*)}$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, W^+W^- $^{(*)}$
$^{(*)}$ $\tau^+\tau^-$ for $m_\chi < m_W$
Neutralino-proton SI cross-section [cm^2]
WIMP mass [GeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^1
10^2
10^3
10^4


$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
COUPP 2008
KIMS 2007
Picasso 2009
Super-K 2001
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, W^+W^- $^{(*)}$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, W^+W^- $^{(*)}$
$^{(*)}$ $\tau^+\tau^-$ for $m_\chi < m_W$
Neutralino-proton SD cross-section [cm^2]
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^1
10^2
10^3
10^4
WIMP mass [GeV]


90°
60°
30°
0°
on source
off source
Δ RA=0°
Δ RA=180°
GC


Dec
180
170
160
150
140
130
120
110
100
90
80
off-source
on-source
0
50
100
150
200
250
300
350
RA

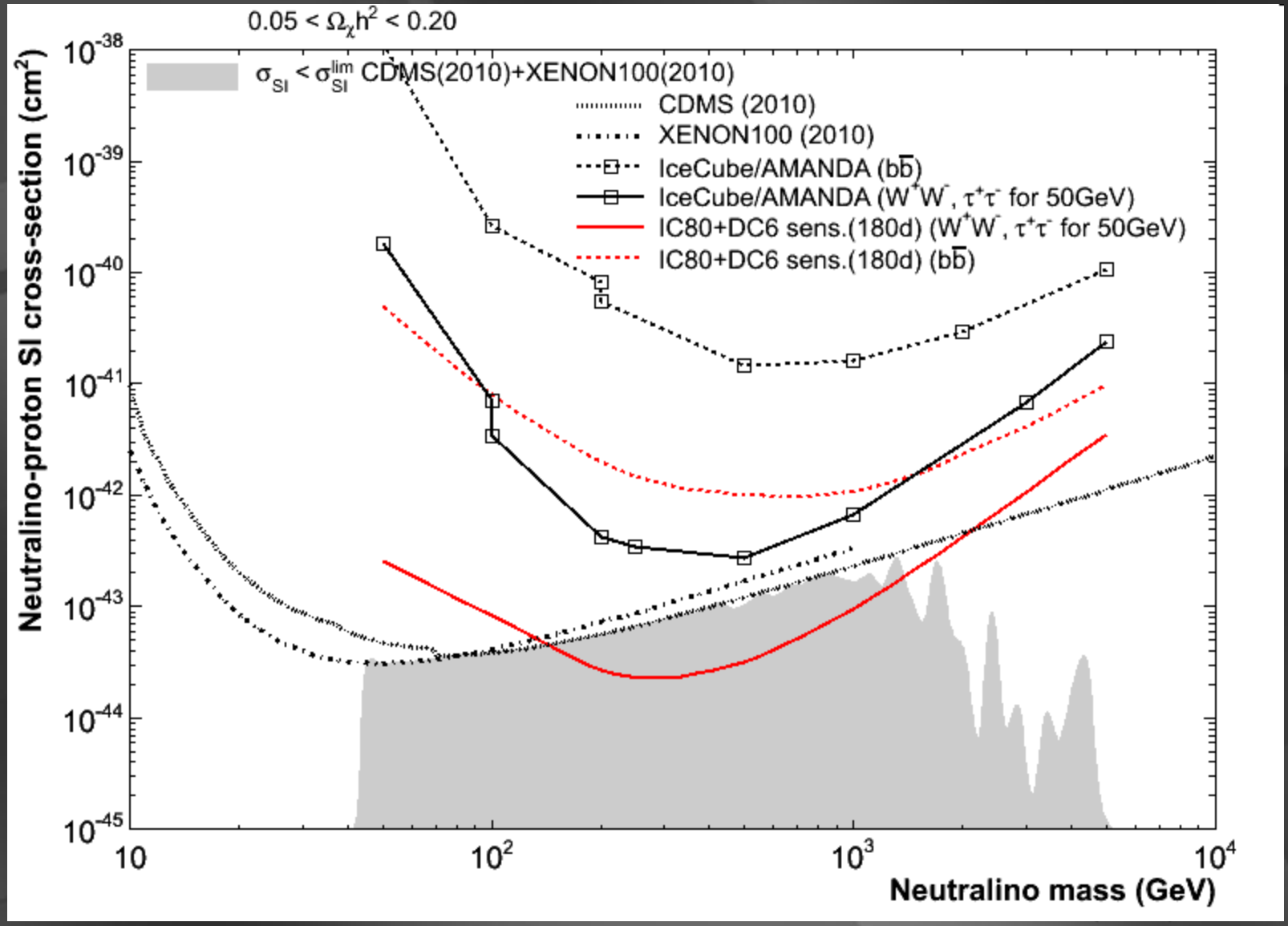

DM DM → μ⁺ μ⁻
PAMELA
Super-K up-μ
FERMI
DeepCore casc. 1yr
DeepCore tr. 5yr
DeepCore casc. 3yr
<σv> [cm³ s⁻¹]
Boost
DM Mass [GeV]

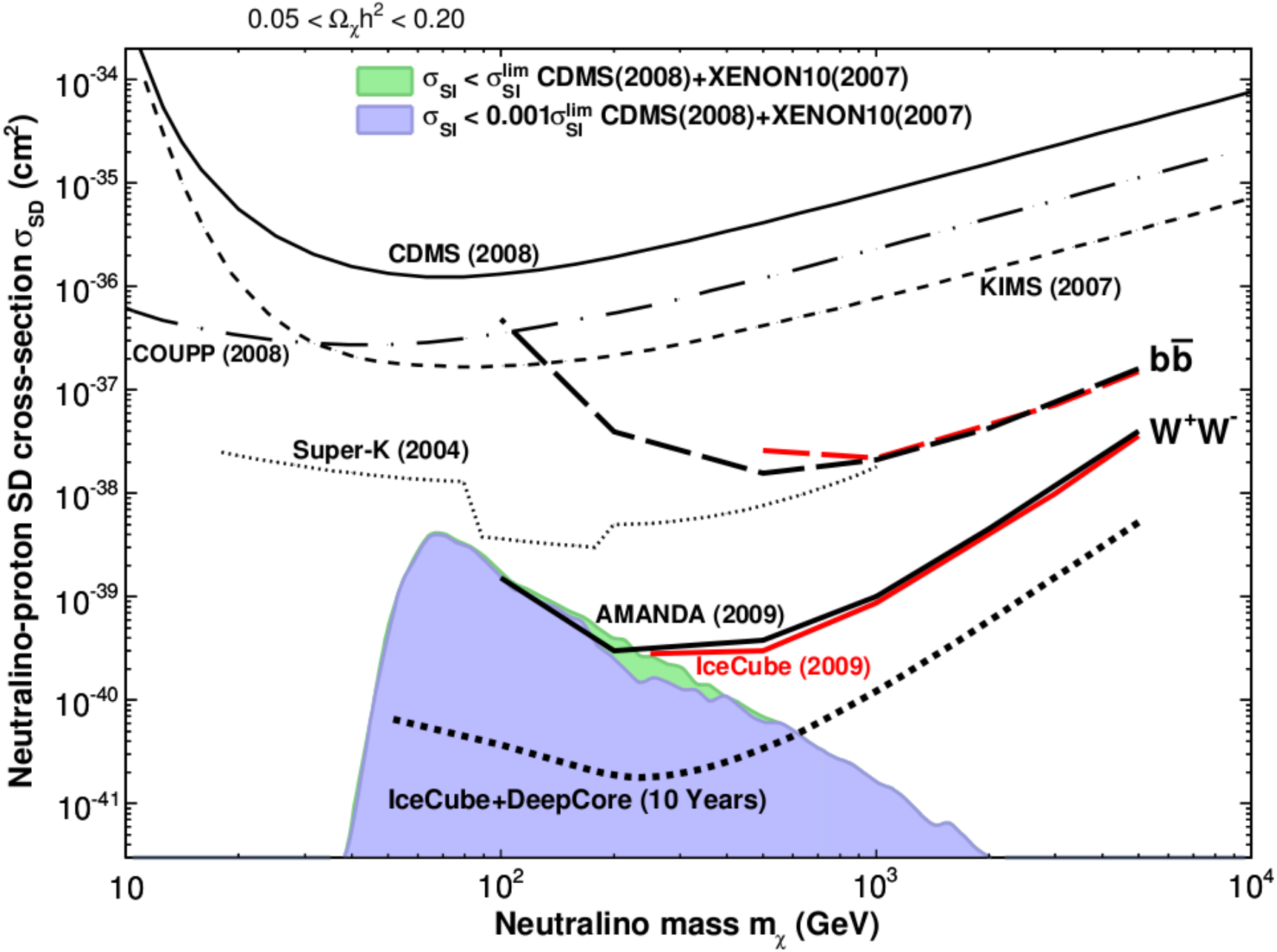

Einasto Profile
Halo Uncertainy
Unitarity
bb
WW
μμ,ττ
νν
Natural scale
<σA v> [cm³s⁻¹]
mχ [GeV]

conclusions

- Hess 1912…. and still no conclusion
- the instrumentation is in place …
- … supernova remnants and GRB are in close range !

sensitivity to wimps with spin-*independent* interactions





arXiv:0906.1615