The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2246-37

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Science prospects of the completed IceCube neutrino detector

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IceCube, Wisconsin
USA

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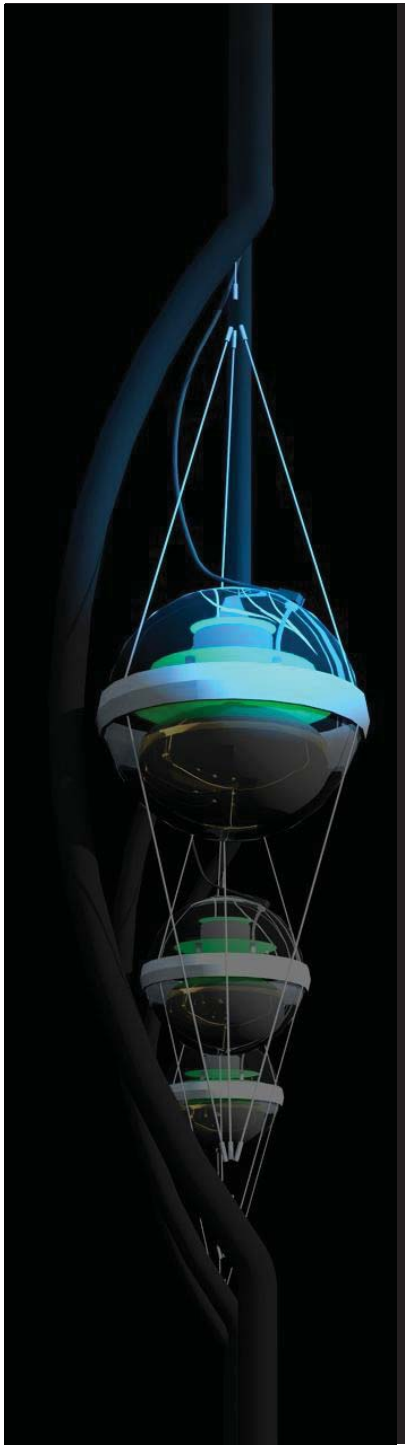
neutrino astronomy

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


50,000 year old sterile ice instead of water



- 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

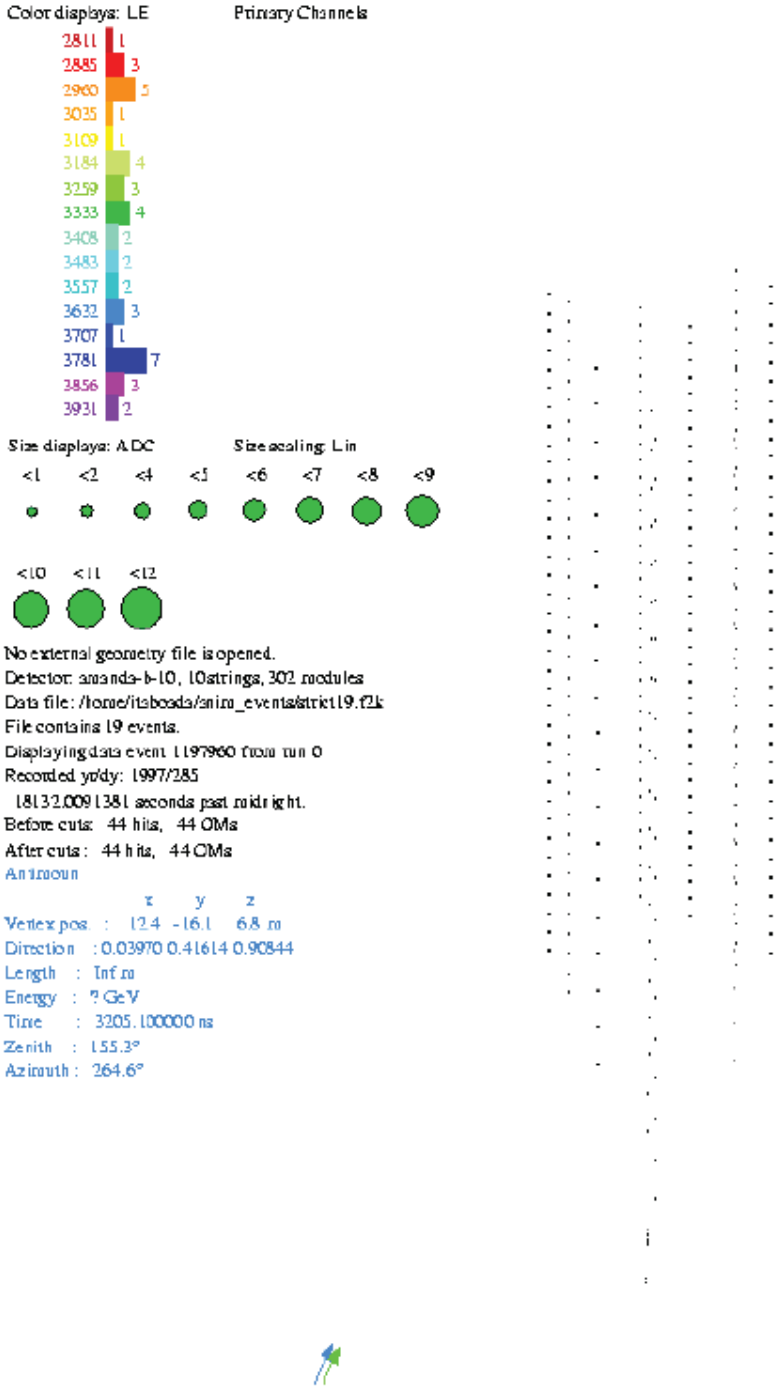
IceCube.wisc.edu

AMANDA Event Signatures: Muons

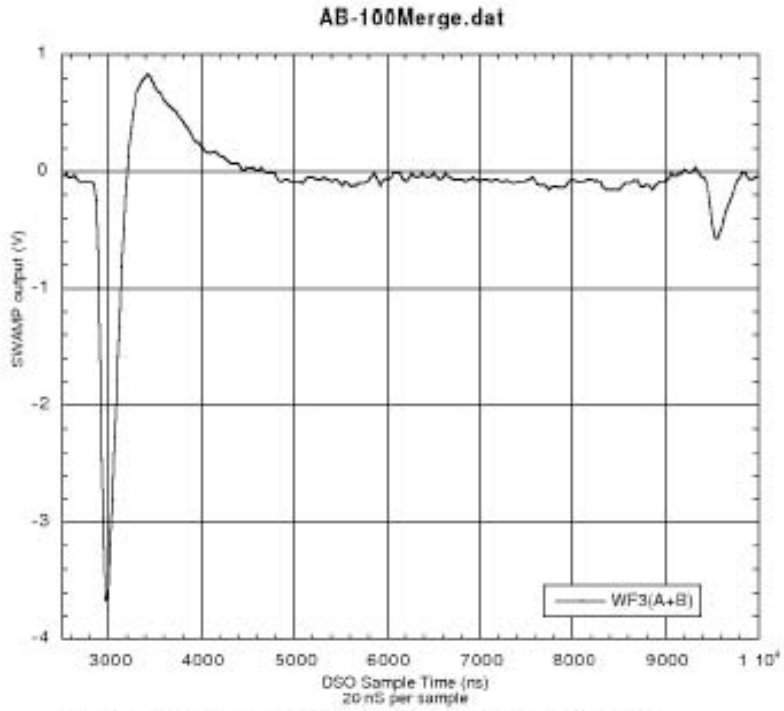
neutrino interaction

$\rightarrow$ muon track

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



AMANDA

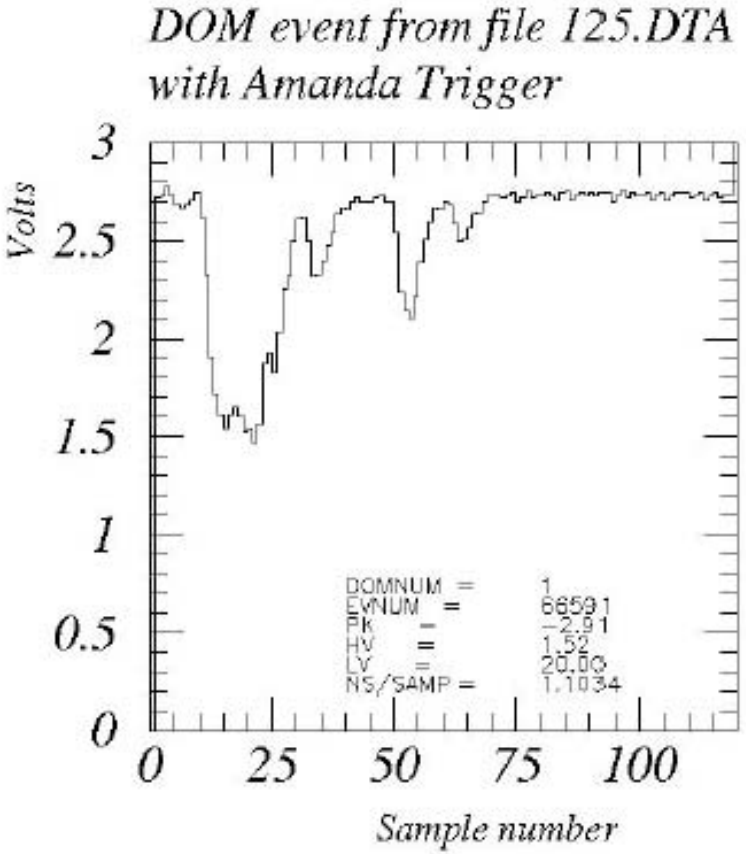


Signal recorded from SWedish AMPlifier outputs Jan '97 at the south pole of photomultiplier signals transmitted through approximately two kilometers of twisted quad transmission line.

Data: Tim Miller,
Prof. GTP@UIUL
July 3, 1997

7.5us

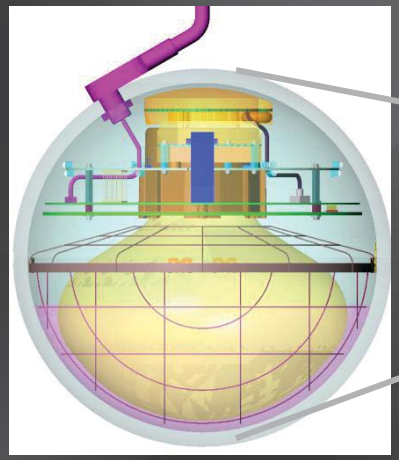
J-B-W DOM



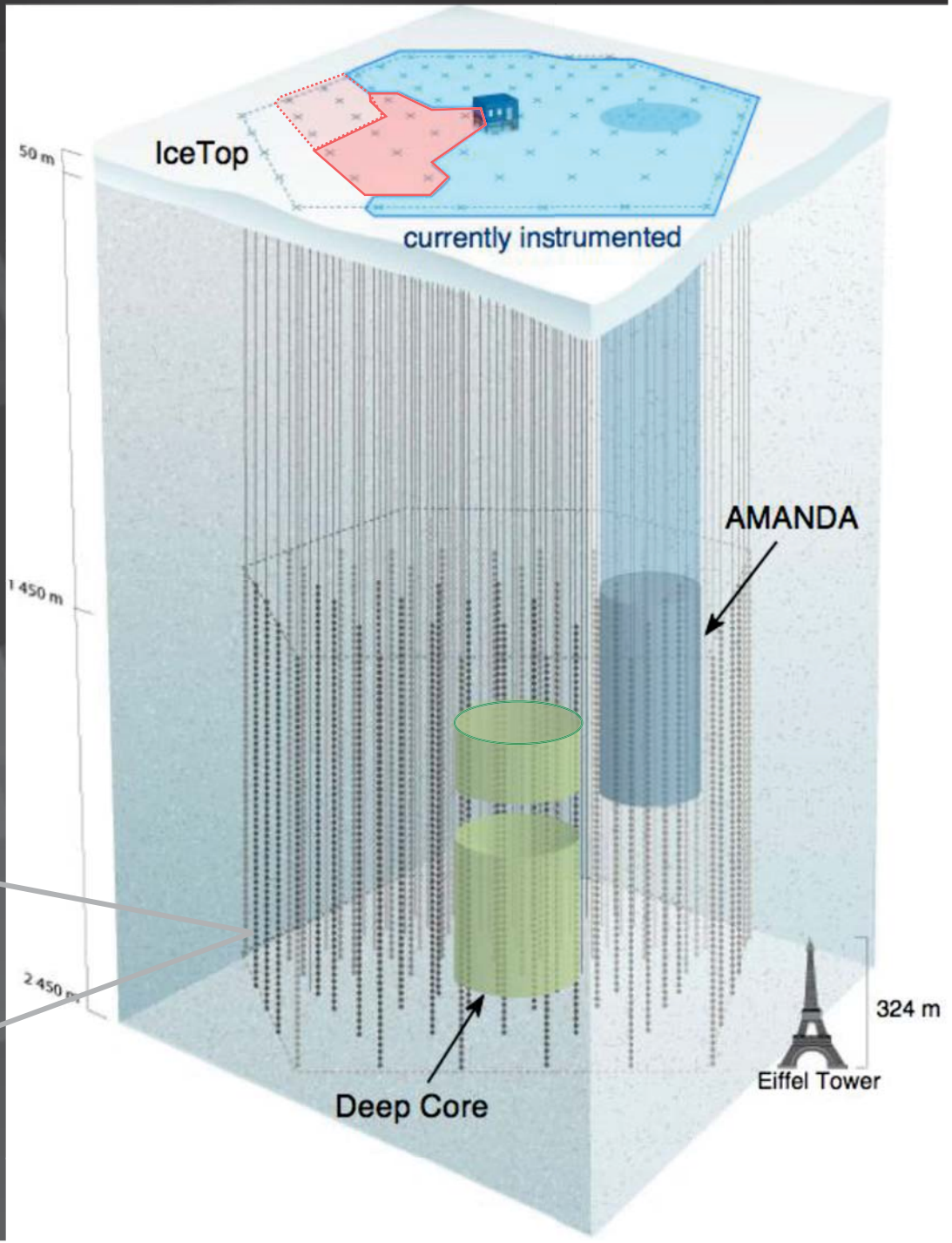
132ns

IceCube / Deep Core

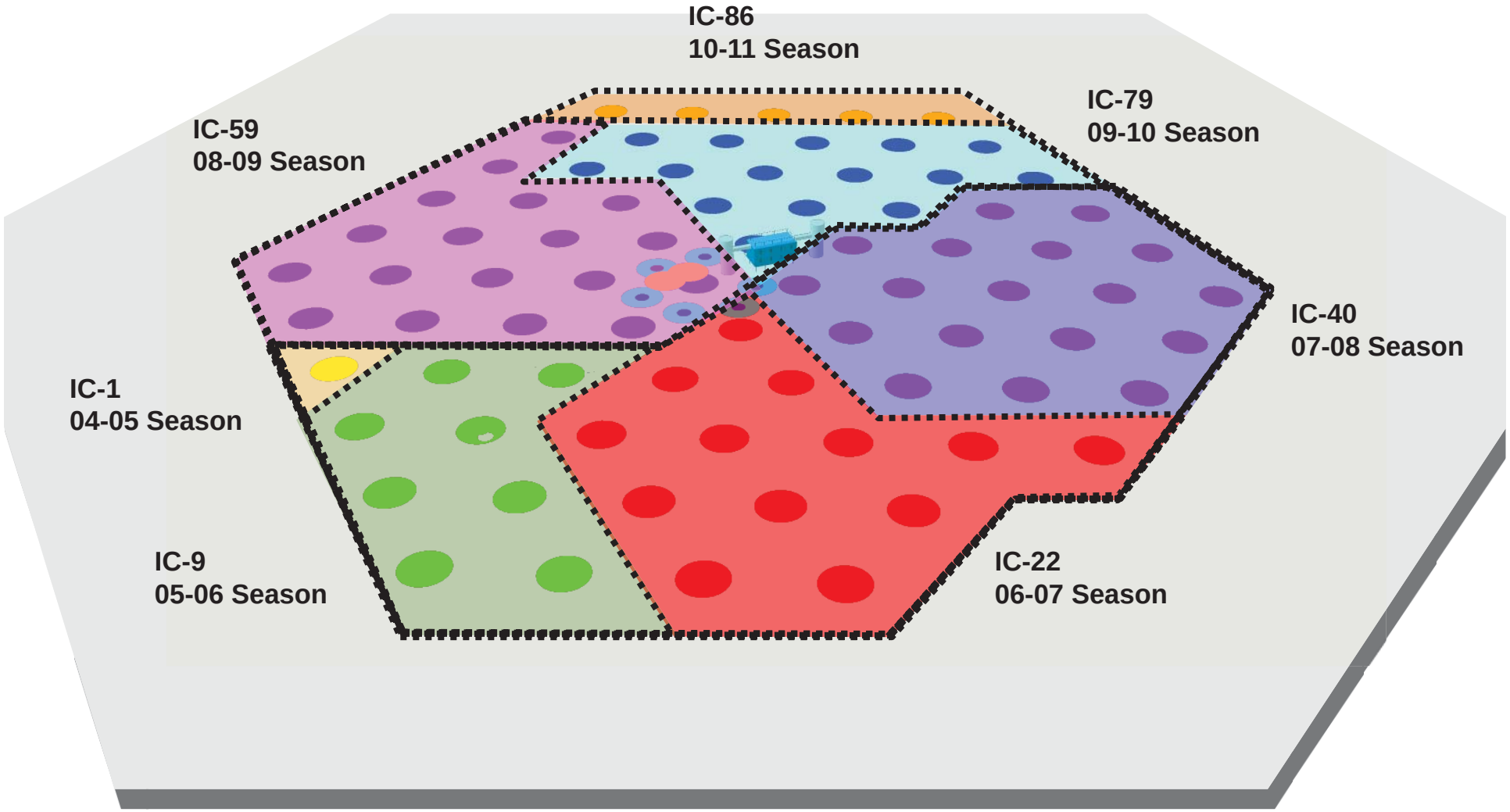
- detects Cherenkov light from showers and muon tracks initiated by neutrinos
- detects ~220 neutrinos and 1.7×10^8 muons per day
- threshold 10 GeV
- angular resolution 0.4~1 degree



5320 Digital Optical Modules (DOM)

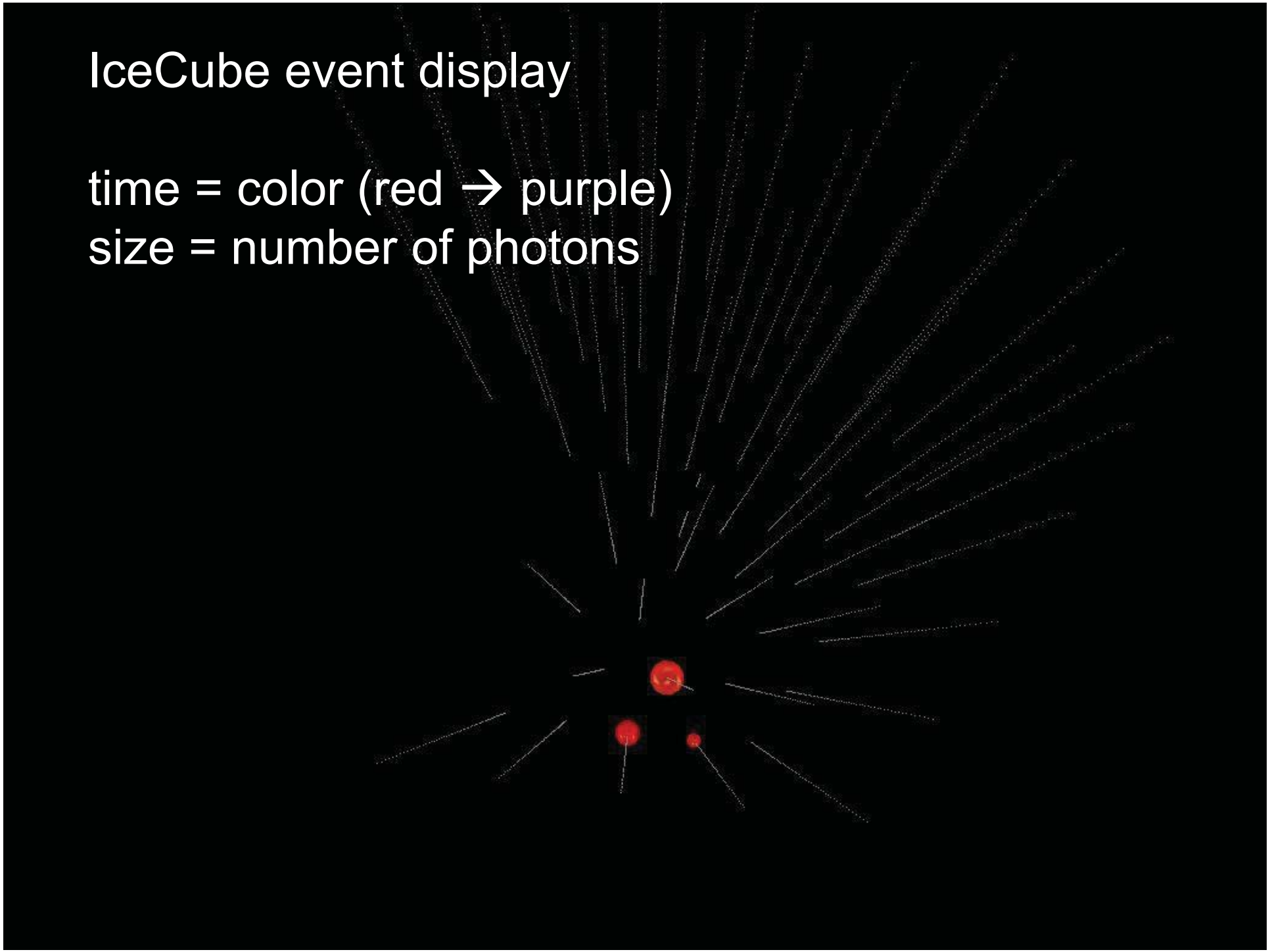


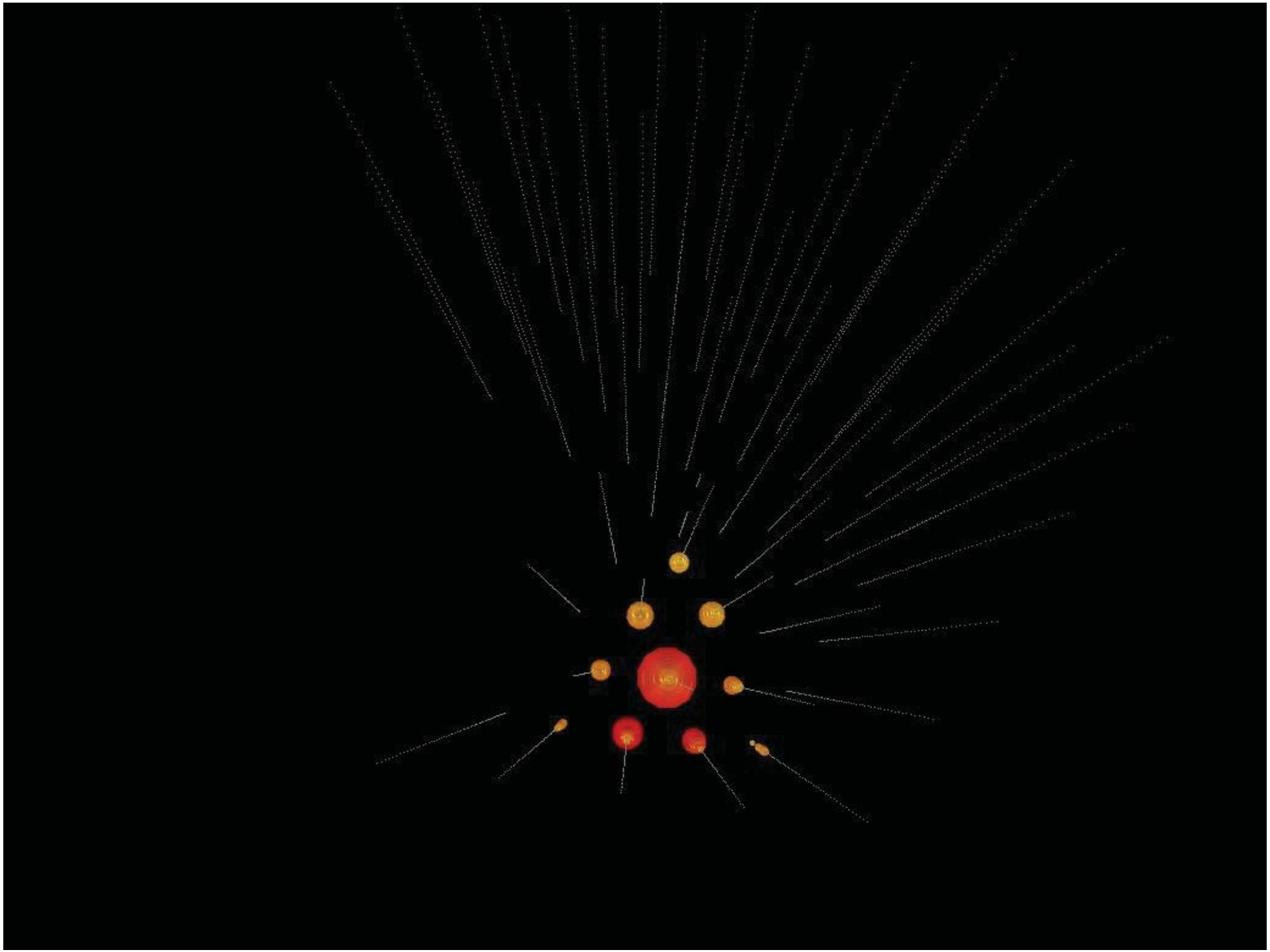
completed December 18, 2010

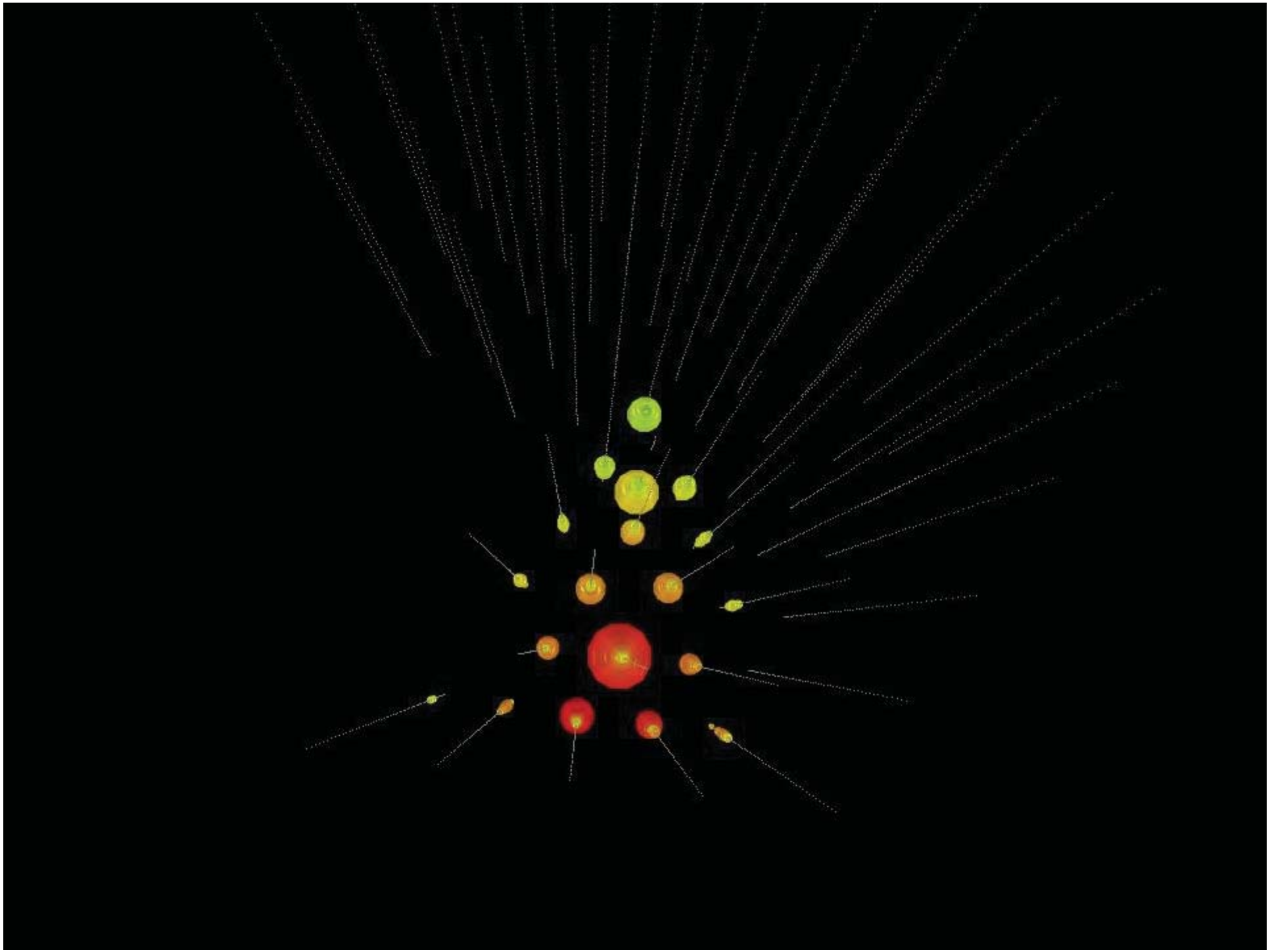


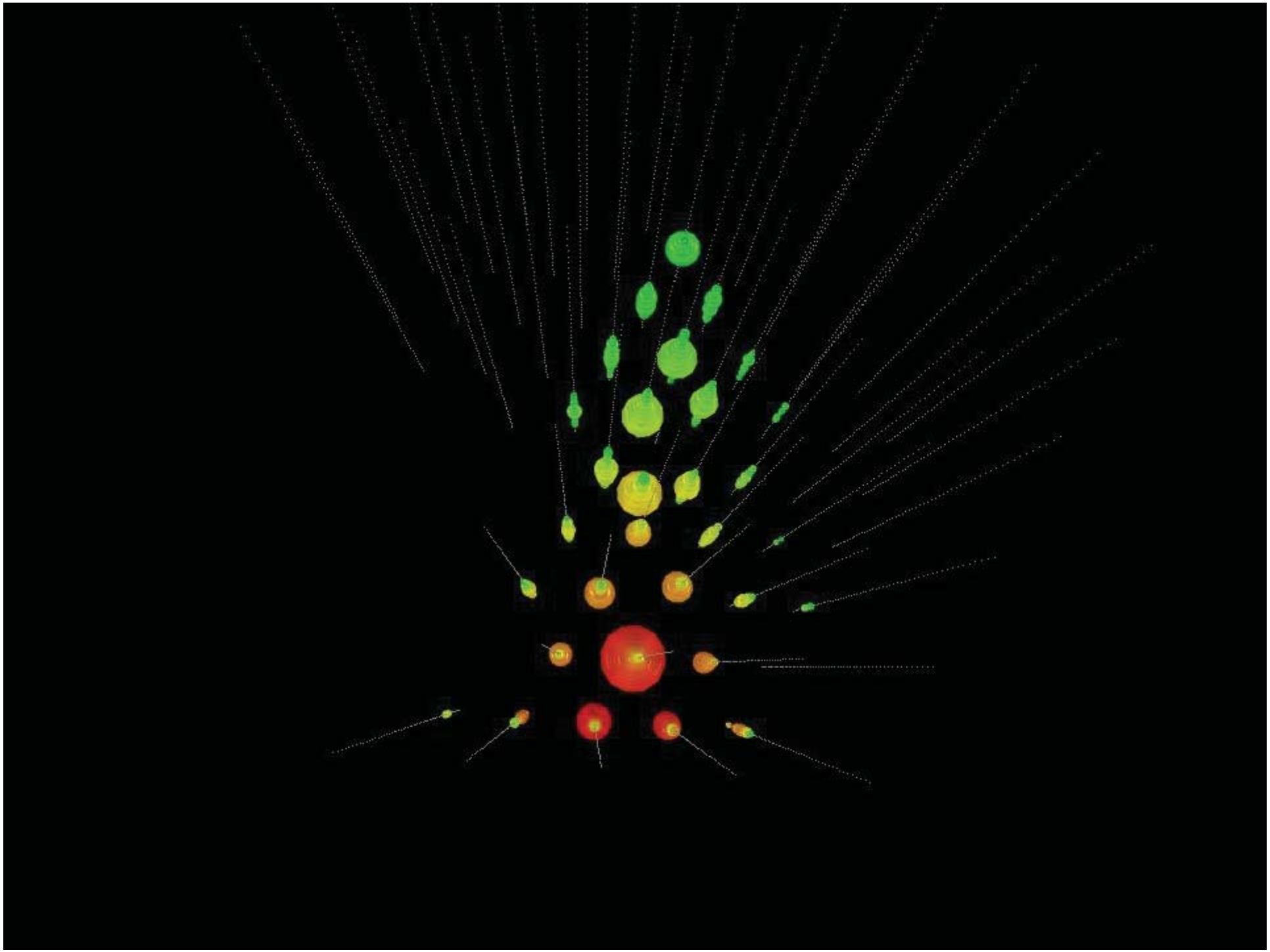
IceCube event display

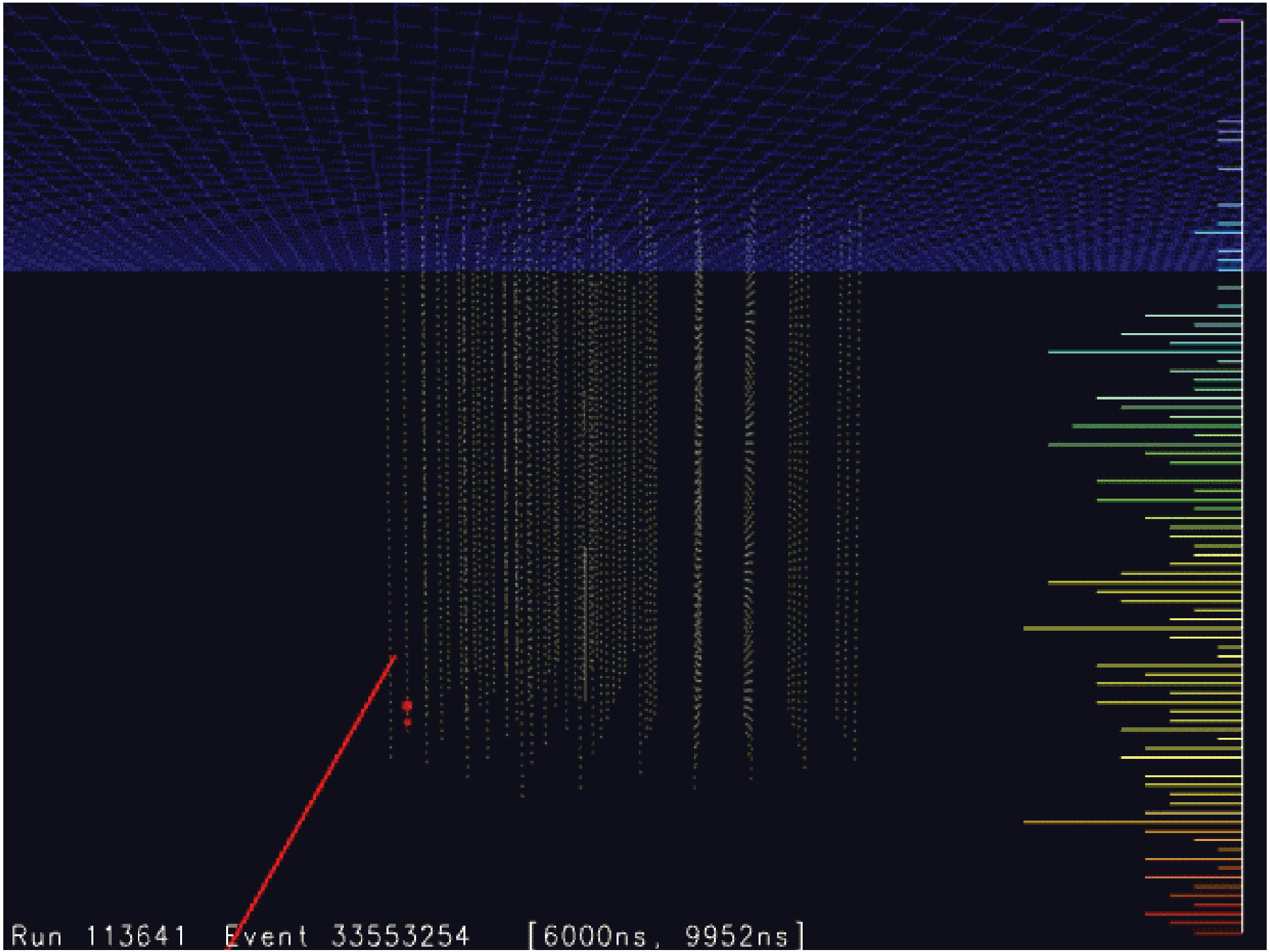
time = color (red → purple)
size = number of photons

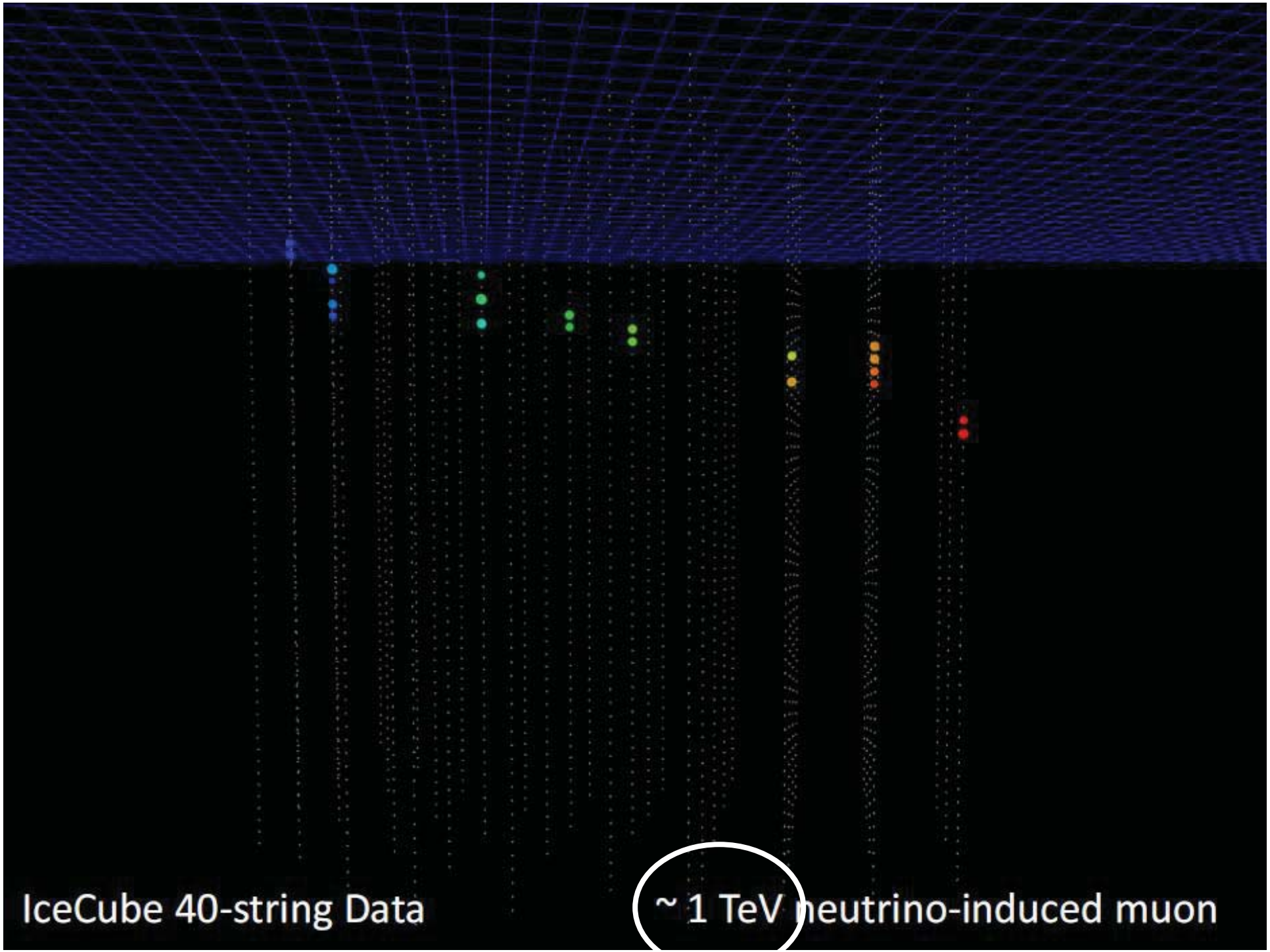




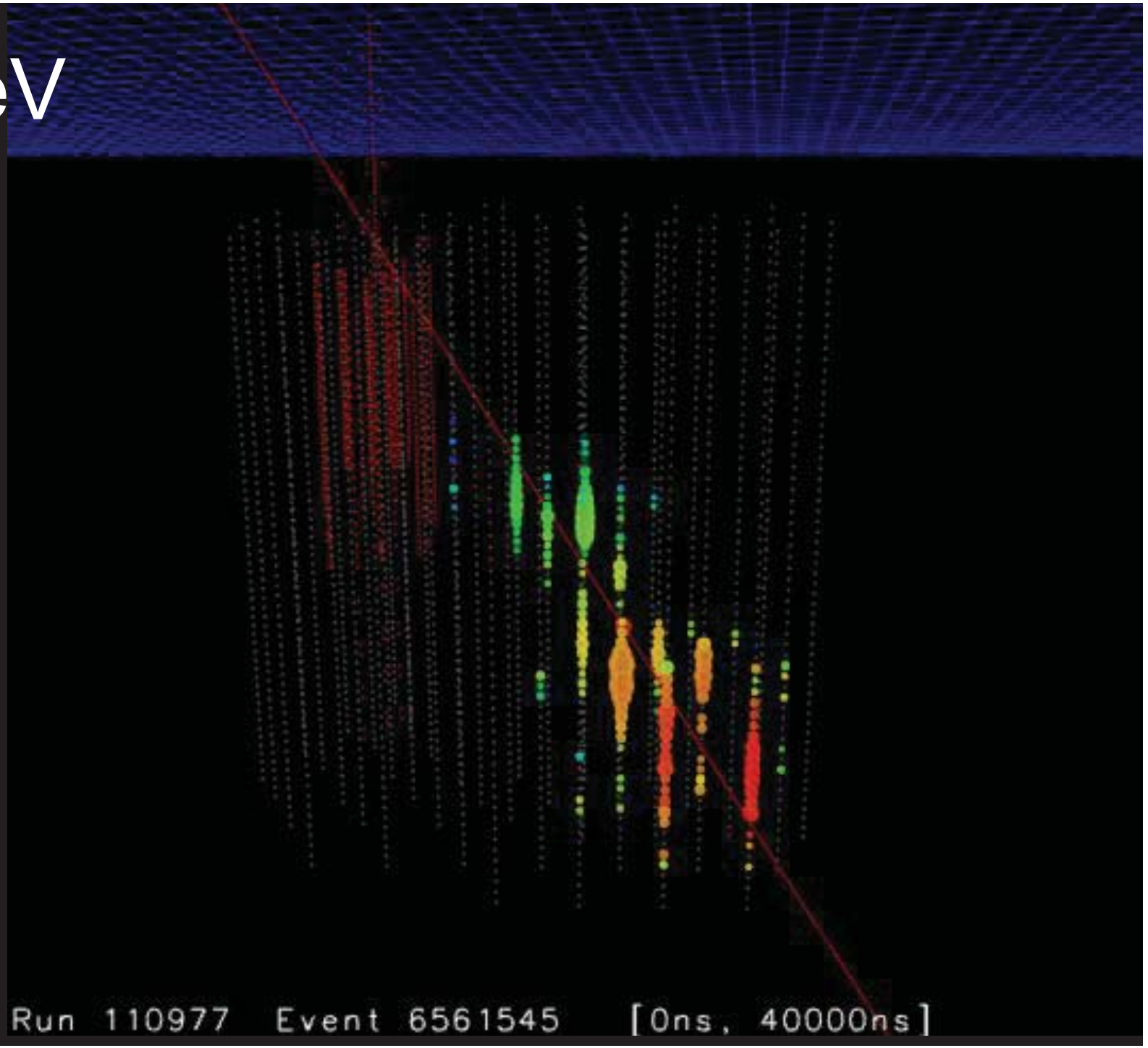




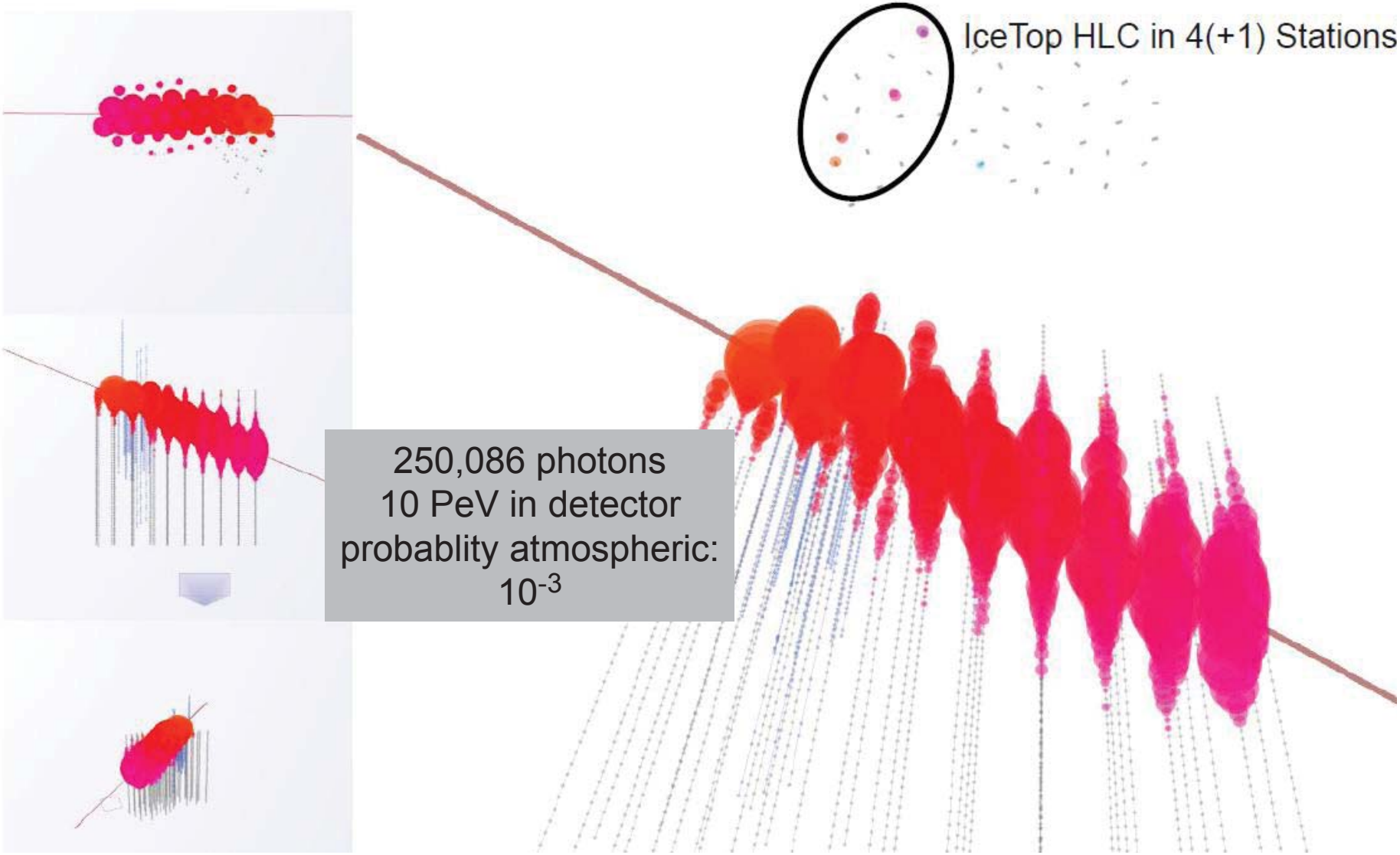

Run 113641 Event 33553254 [6000ns, 9952ns]


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

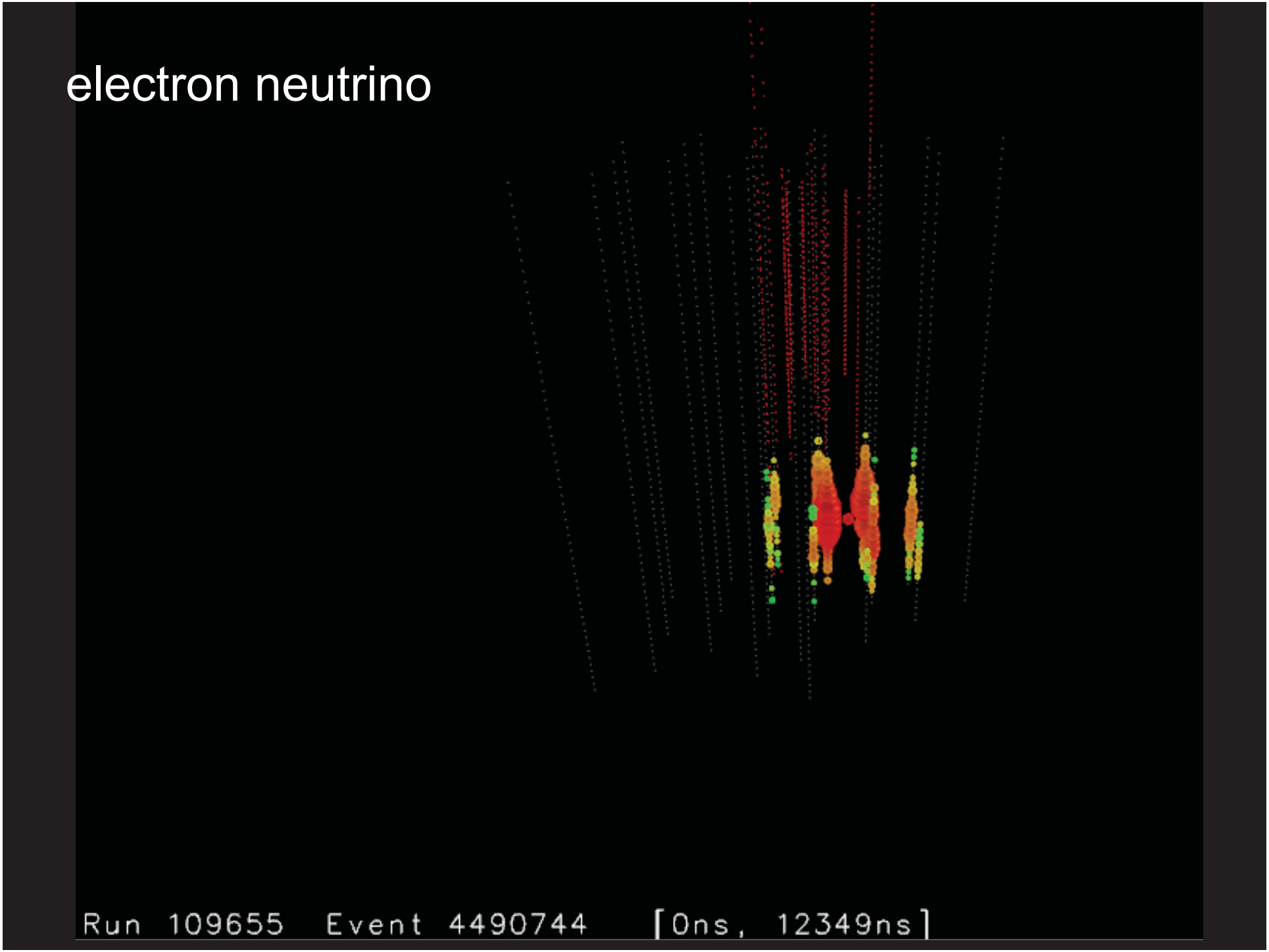
89 TeV



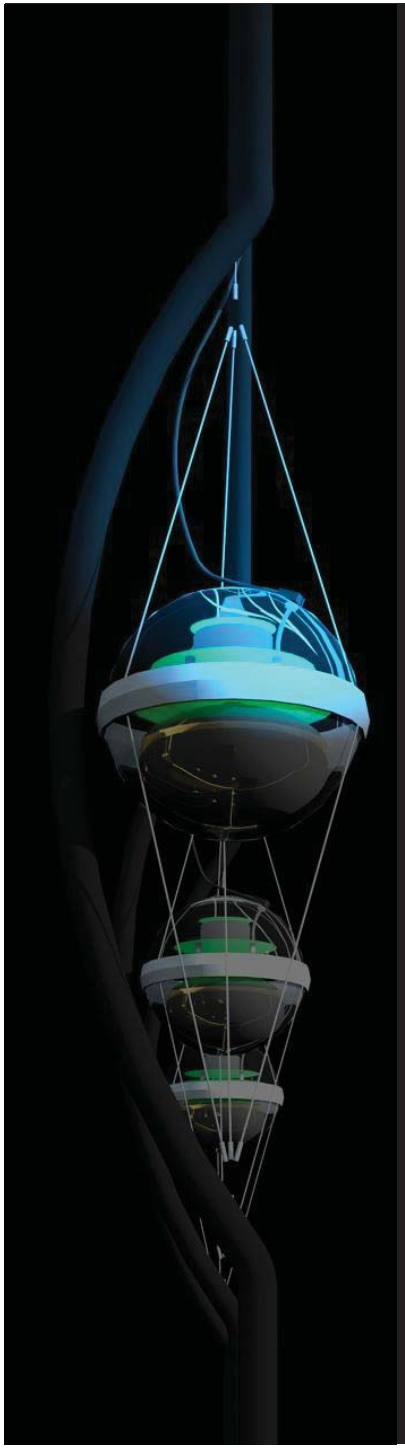
Biggest Shower in IC40 EHE Analysis



electron neutrino




seen: 14 events
predicted: 3 atmospheric and 4 background
Run 109655 Event 4490744 [0ns, 12349ns]



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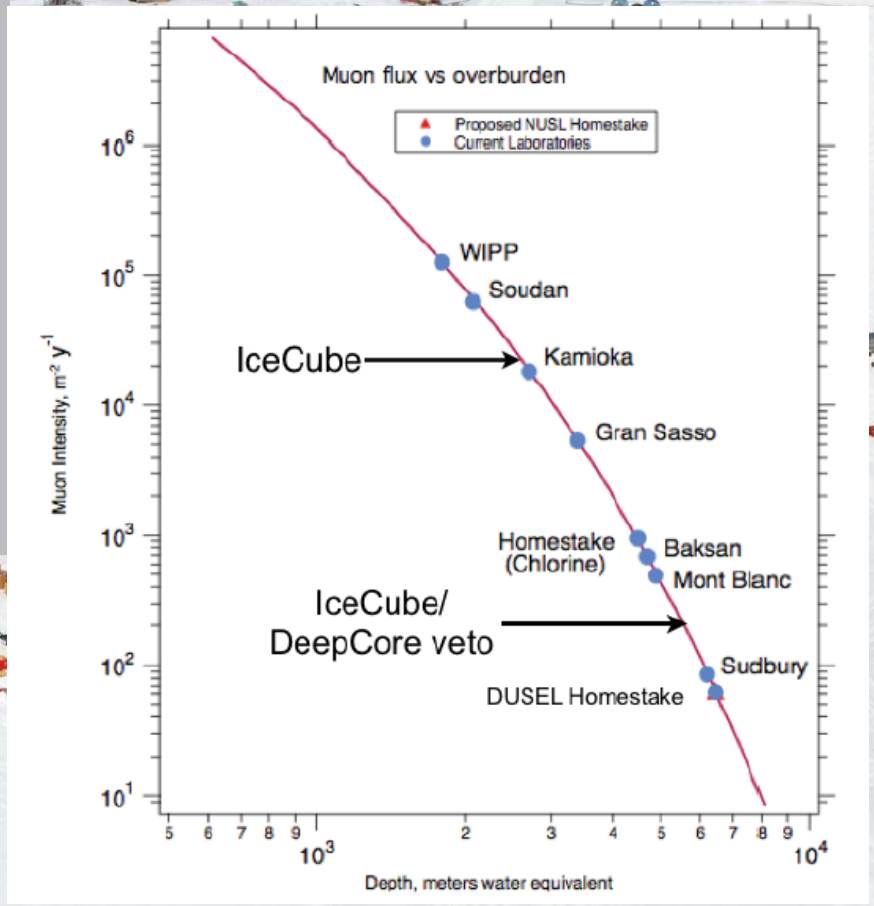
IceCube.wisc.edu


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

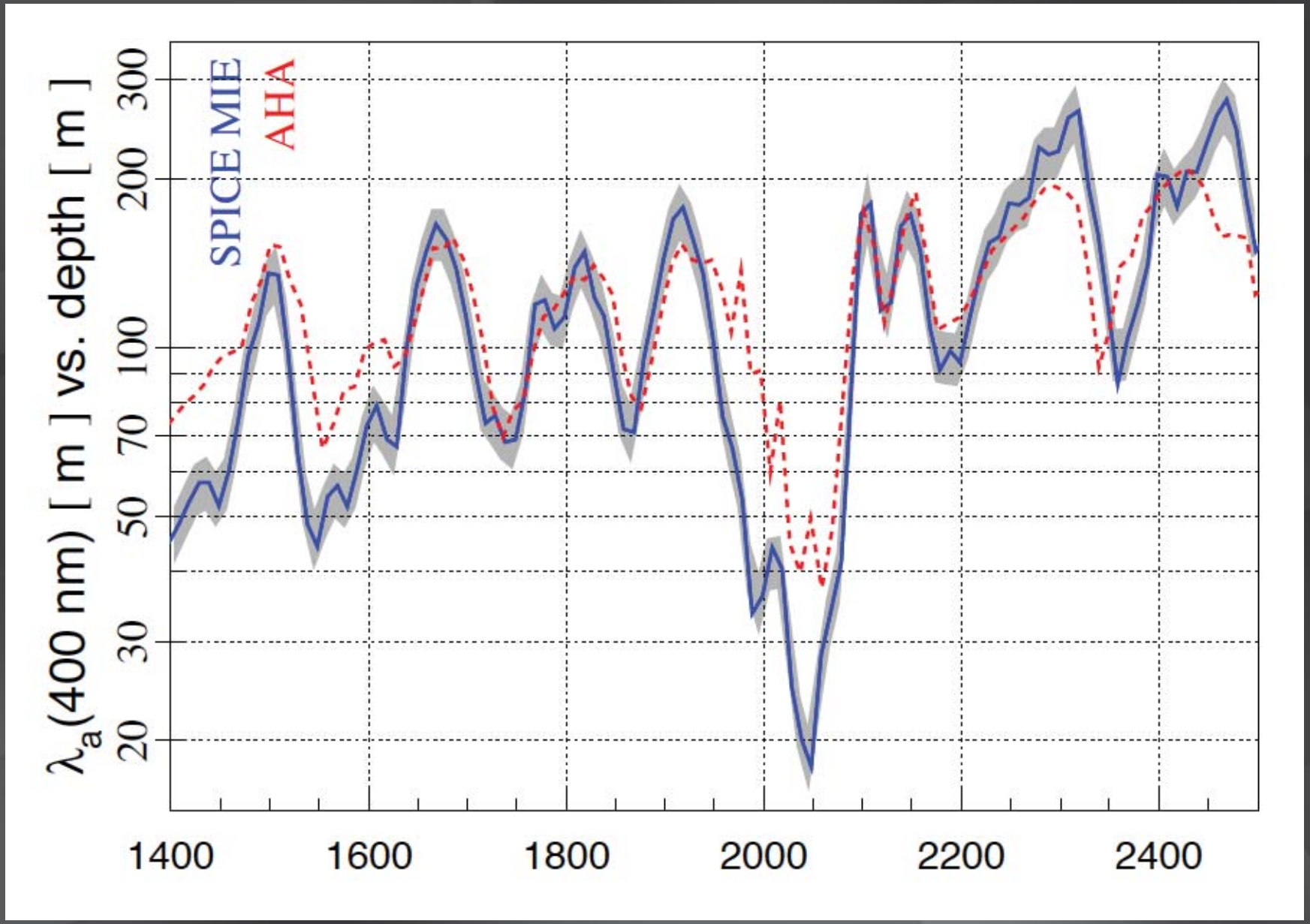
IceCube drilling to best low background site on Earth:

→ radio-pure ice
→ no seasonal variations (temperature, humidity,…)
→ shielded from cosmic rays by IceCube veto

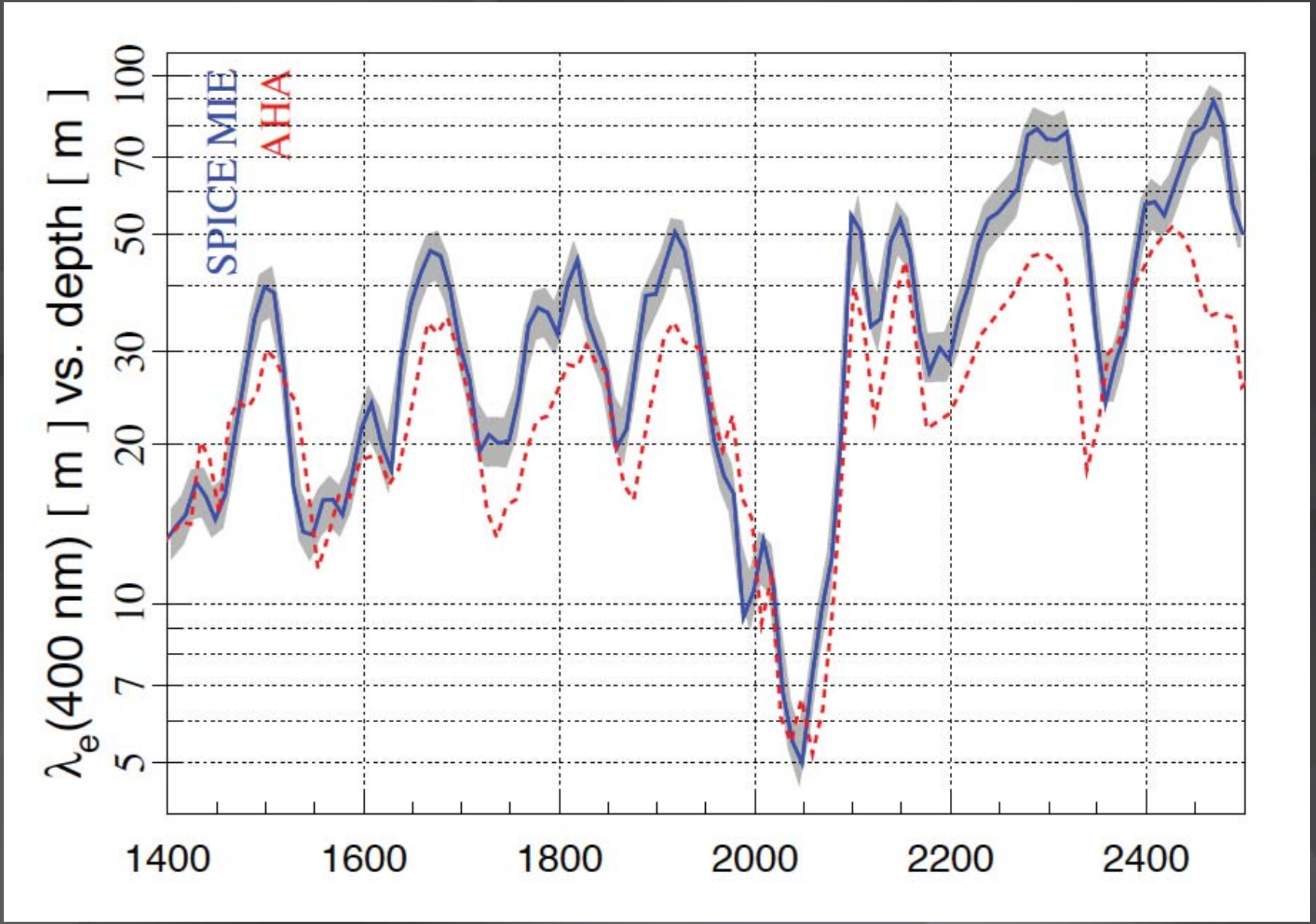
• DM-ice, DeepCore upgrades (towards proton decay?)
• < 700K$ per string of 60 ten inch PMTs (data to your pc)

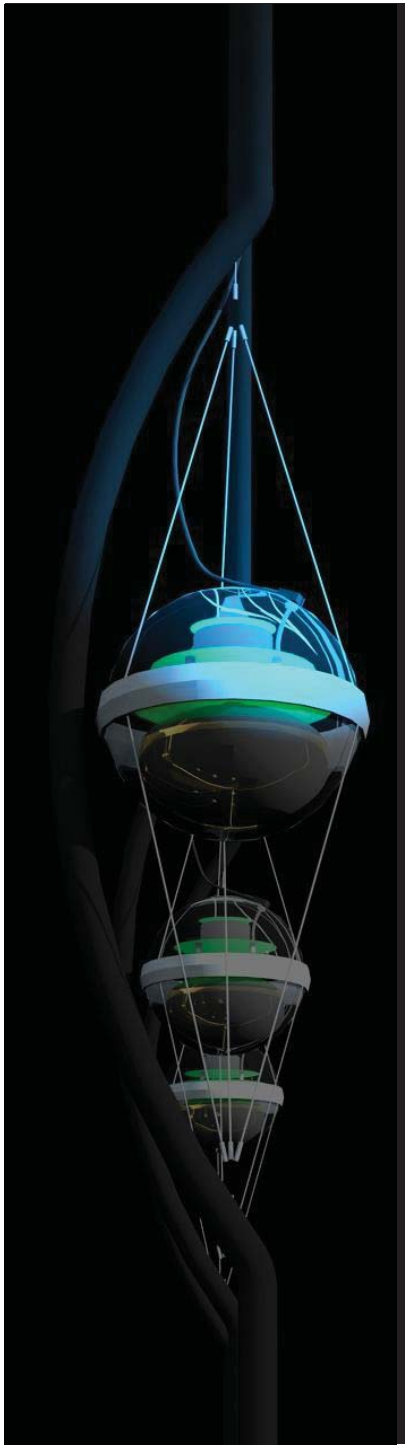


absorption length ← 220m →



scattering length ← 47m →





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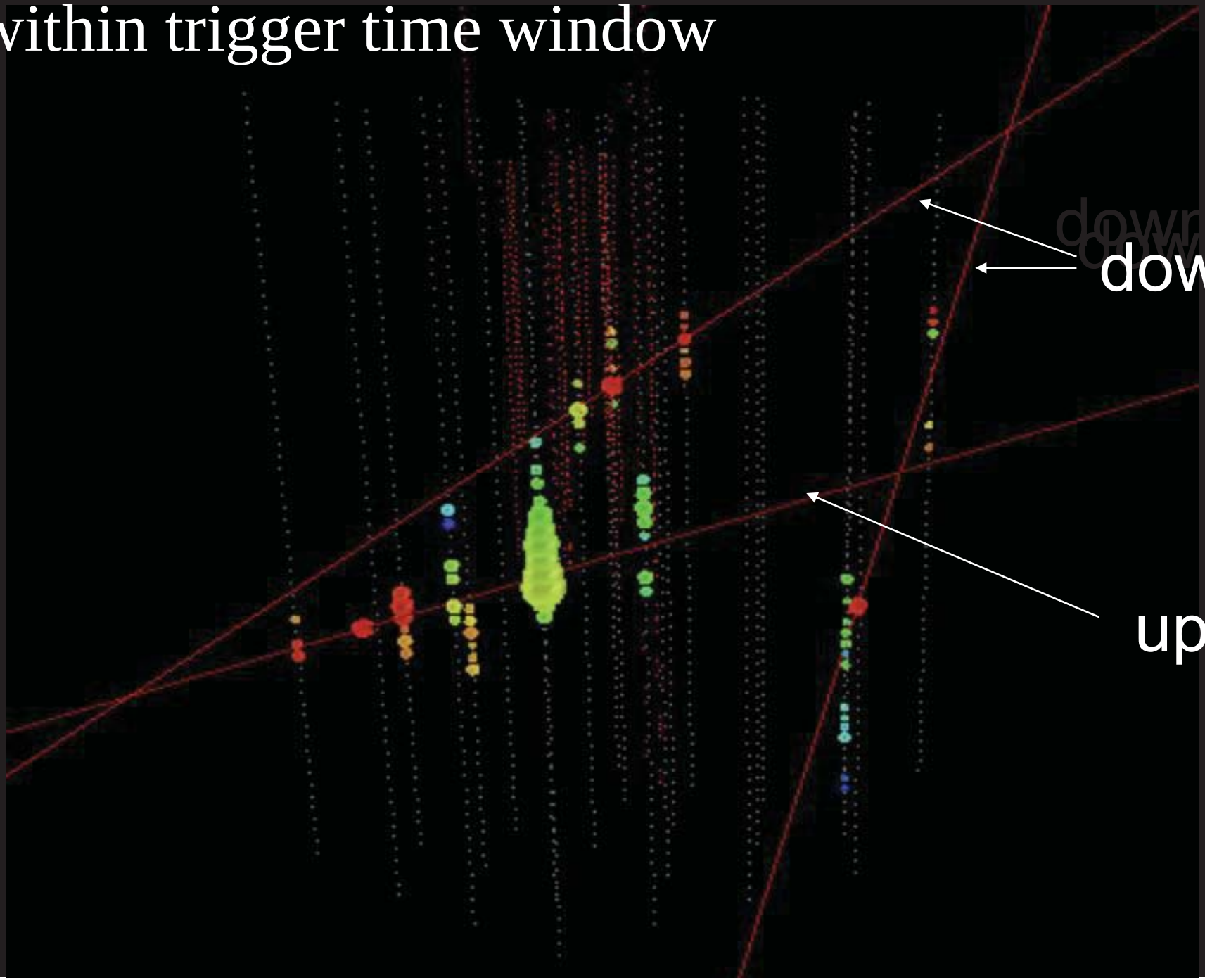
IceCube.wisc.edu

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 ** 1 every 6 minutes

within trigger time window



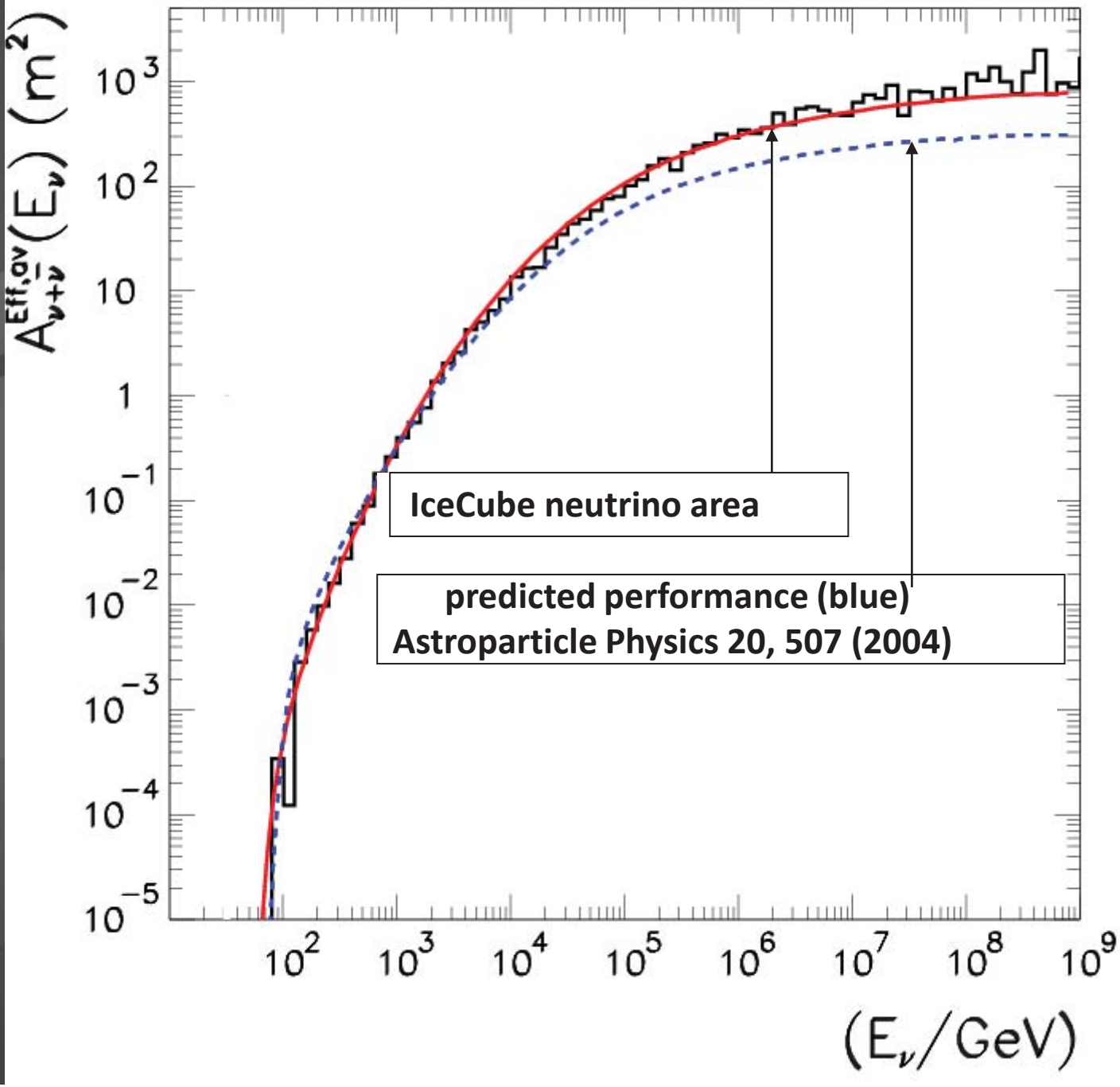
(not) final performance

IceCube performance

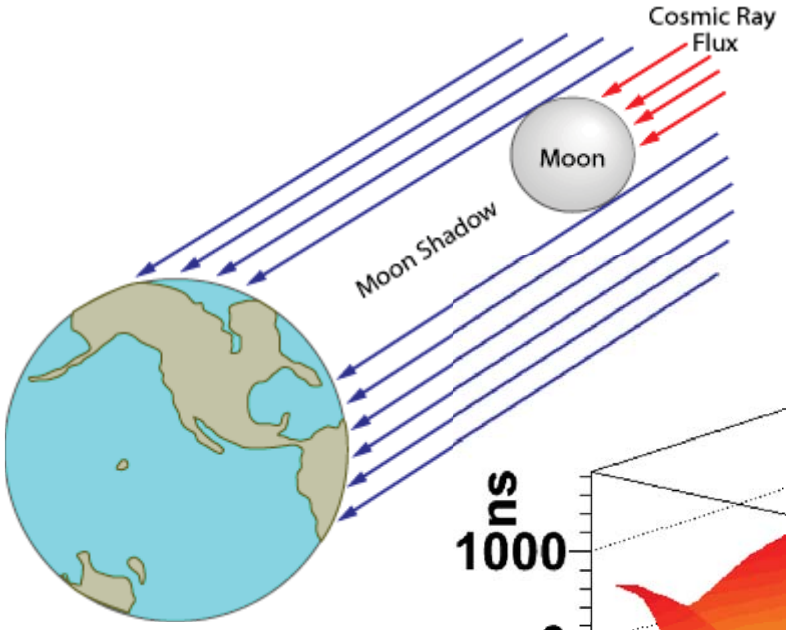
then
and
now

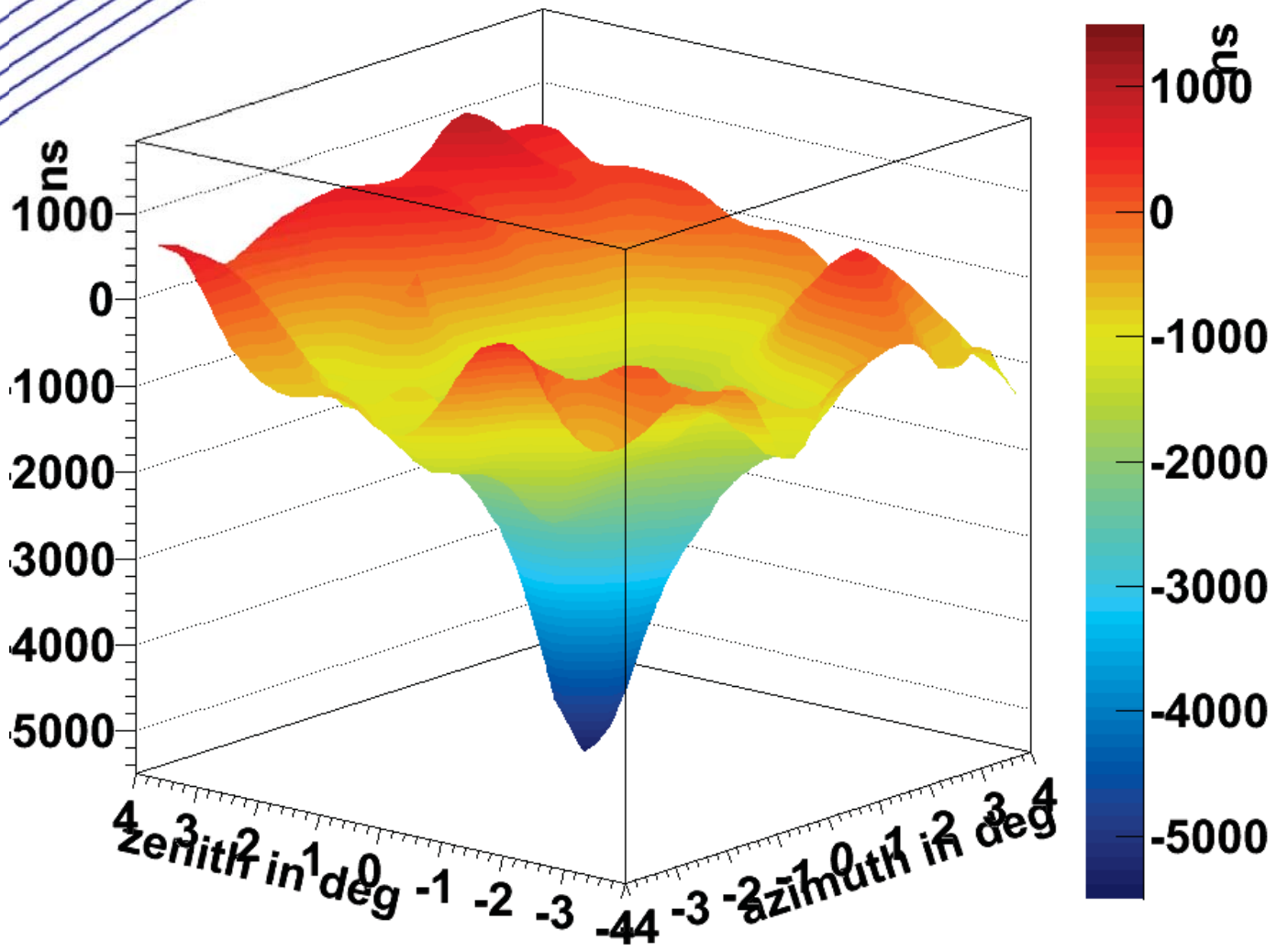
PeV: x2
EeV: x3

neutrino
“mirror”
area

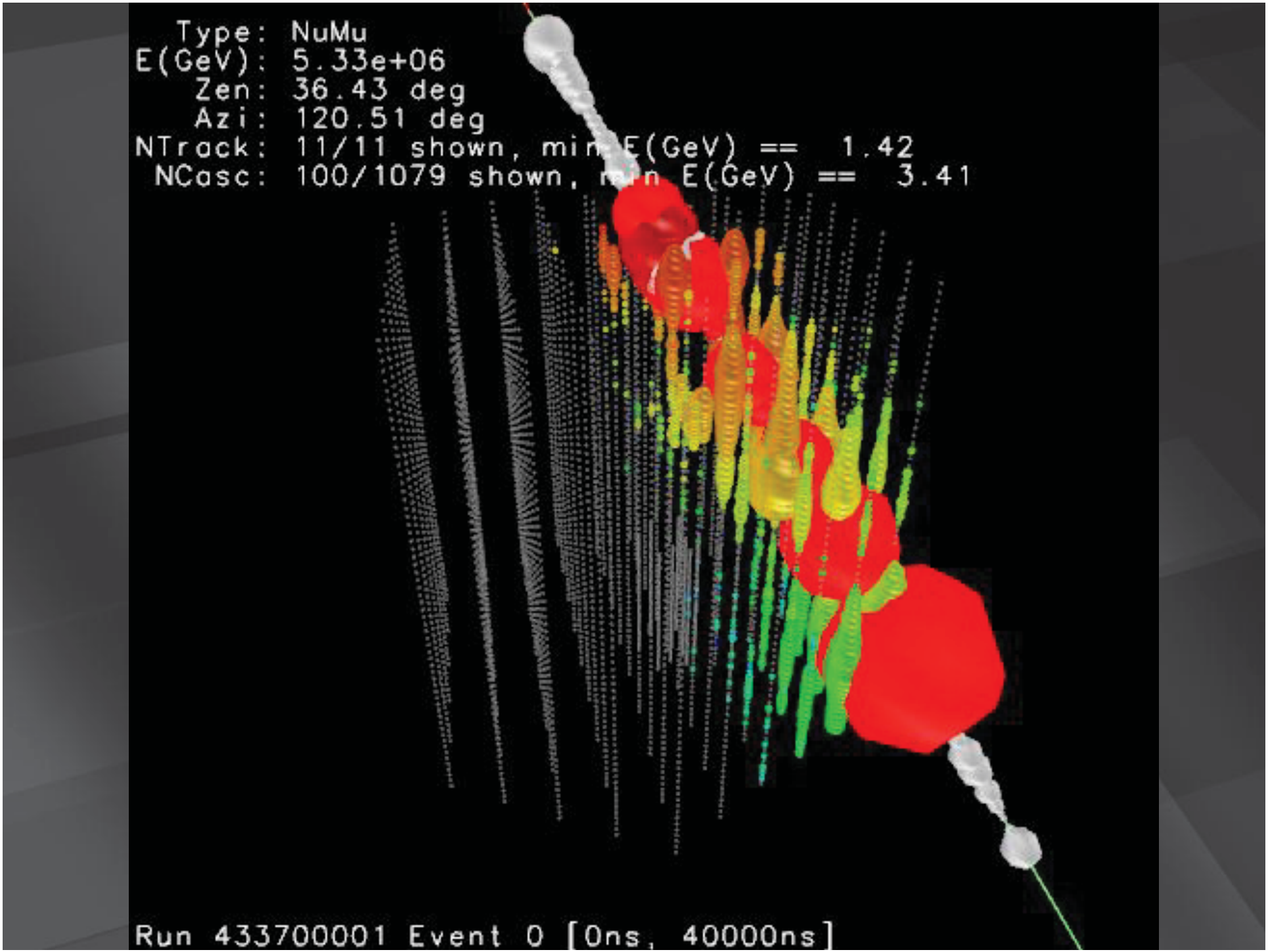


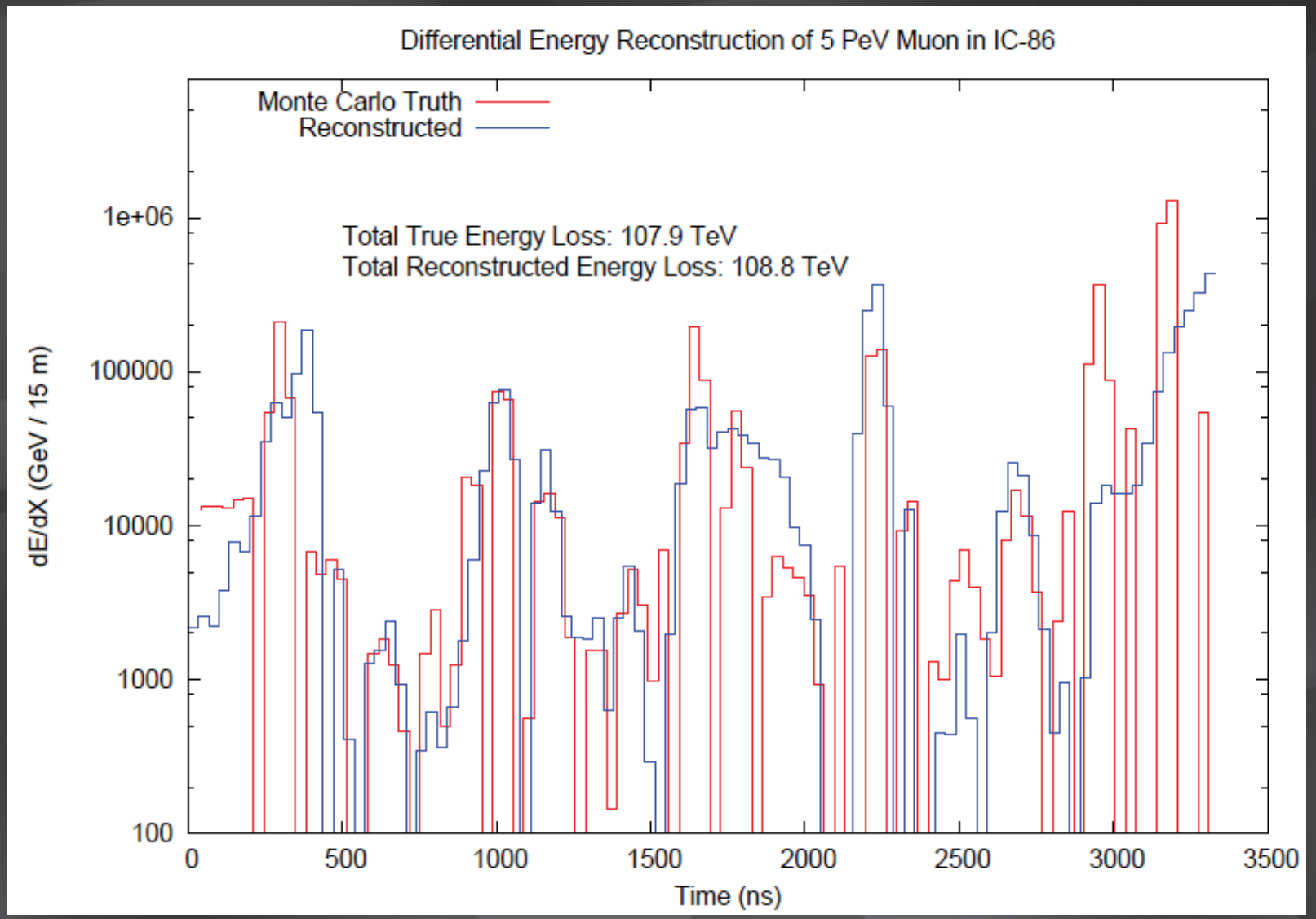
moon shadow





> 16 σ
< 1 deg


Type: NuMu
E(GeV): 5.33e+06
Zen: 36.43 deg
Azi: 120.51 deg
NTrack: 11/11 shown, min E(GeV) == 1.42
NCasc: 100/1079 shown, min E(GeV) == 3.41
Run 433700001 Event 0 [0ns, 40000ns]

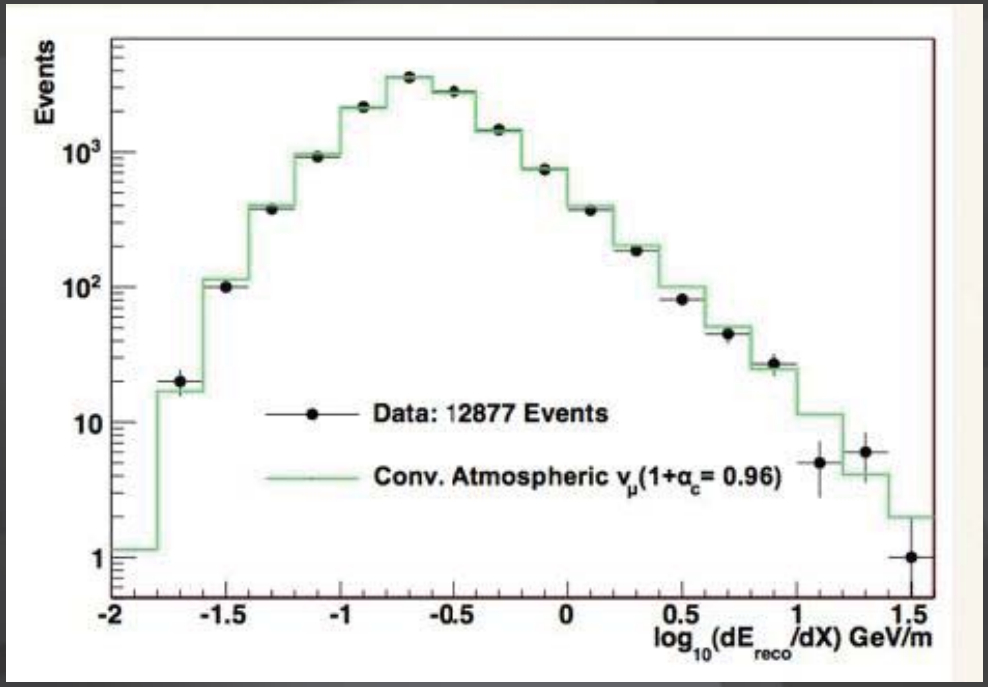


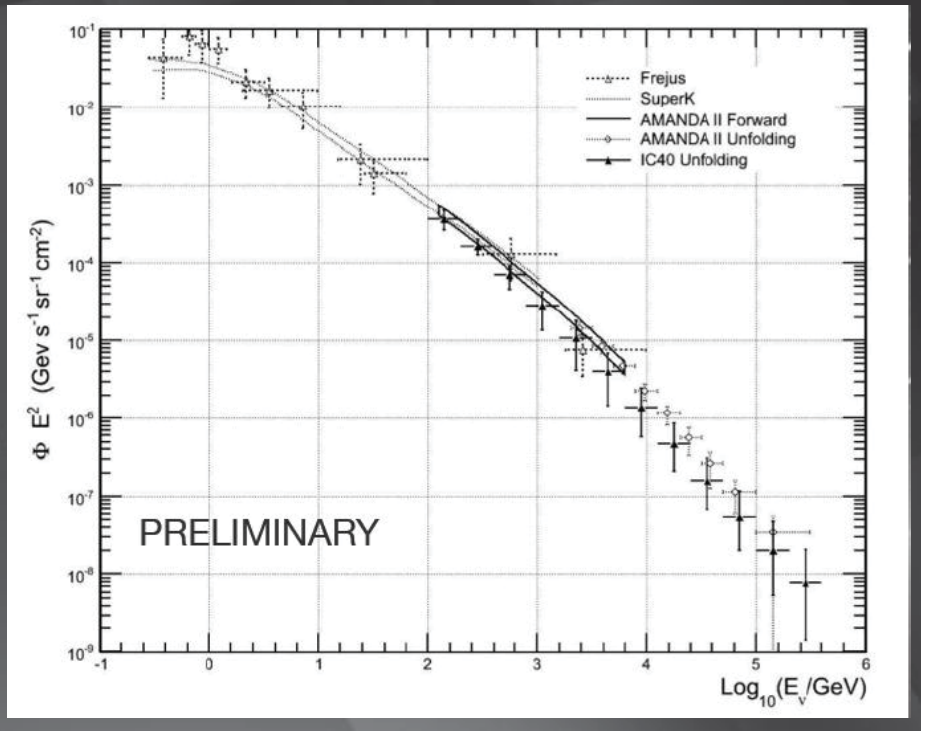
improved angular and energy resolution soon

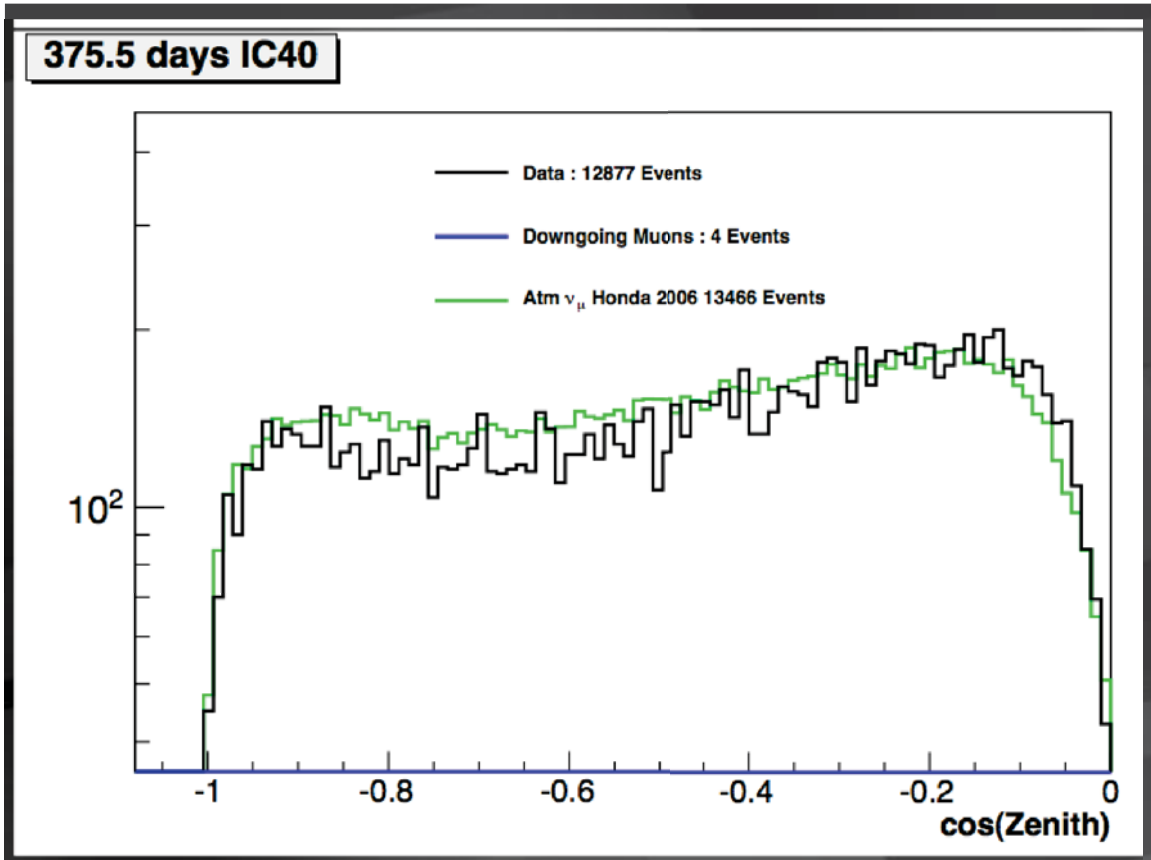
… on to IceCube science

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.

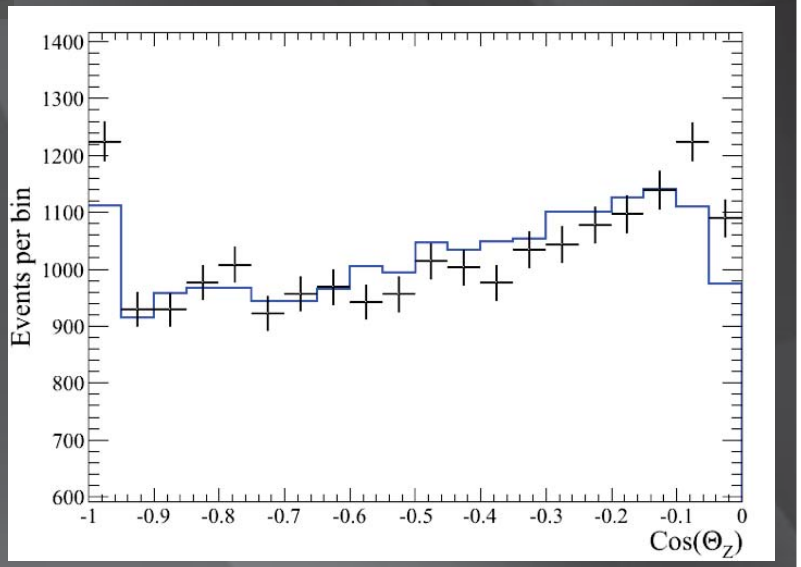
IceCube-40 atmospheric neutrino spectrum

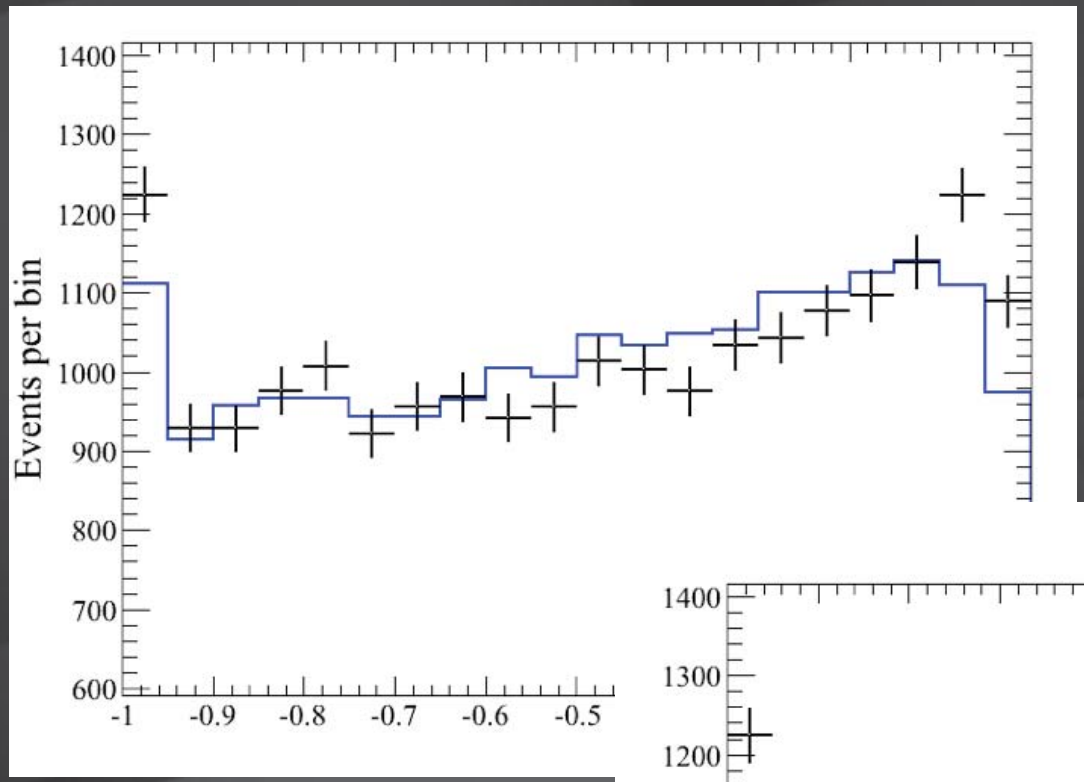






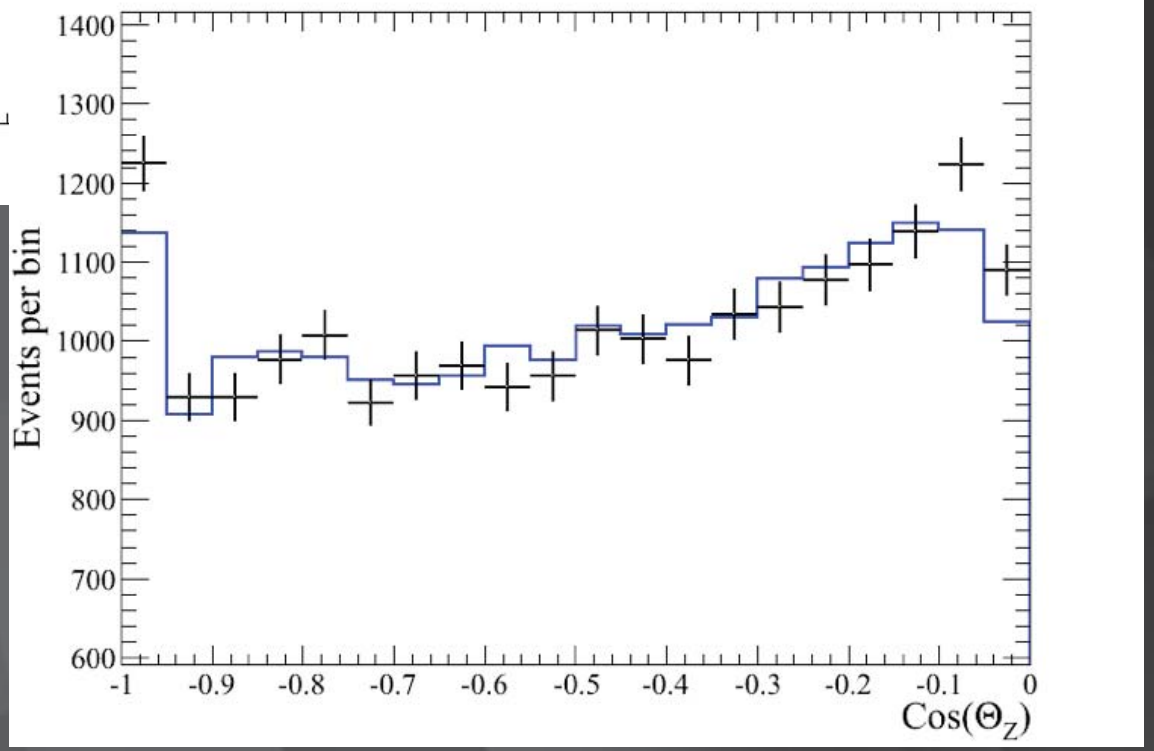
zenith angle
two analyses

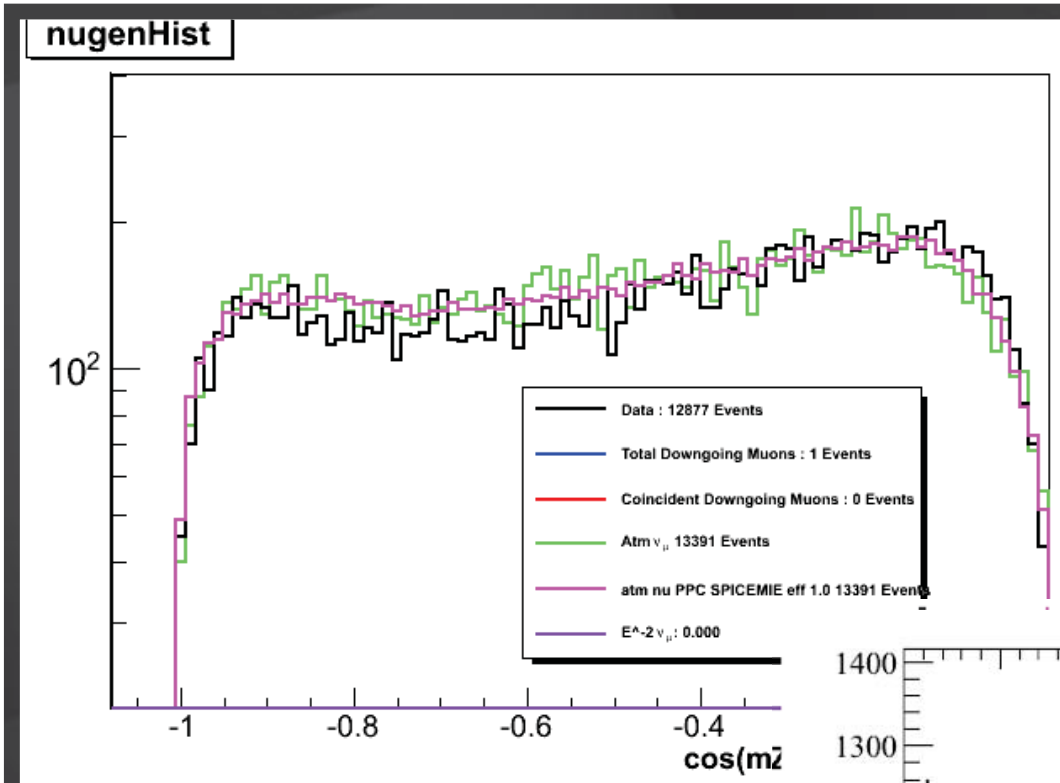



Events per bin
1400
1300
1200
1100
1000
900
800
700
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5

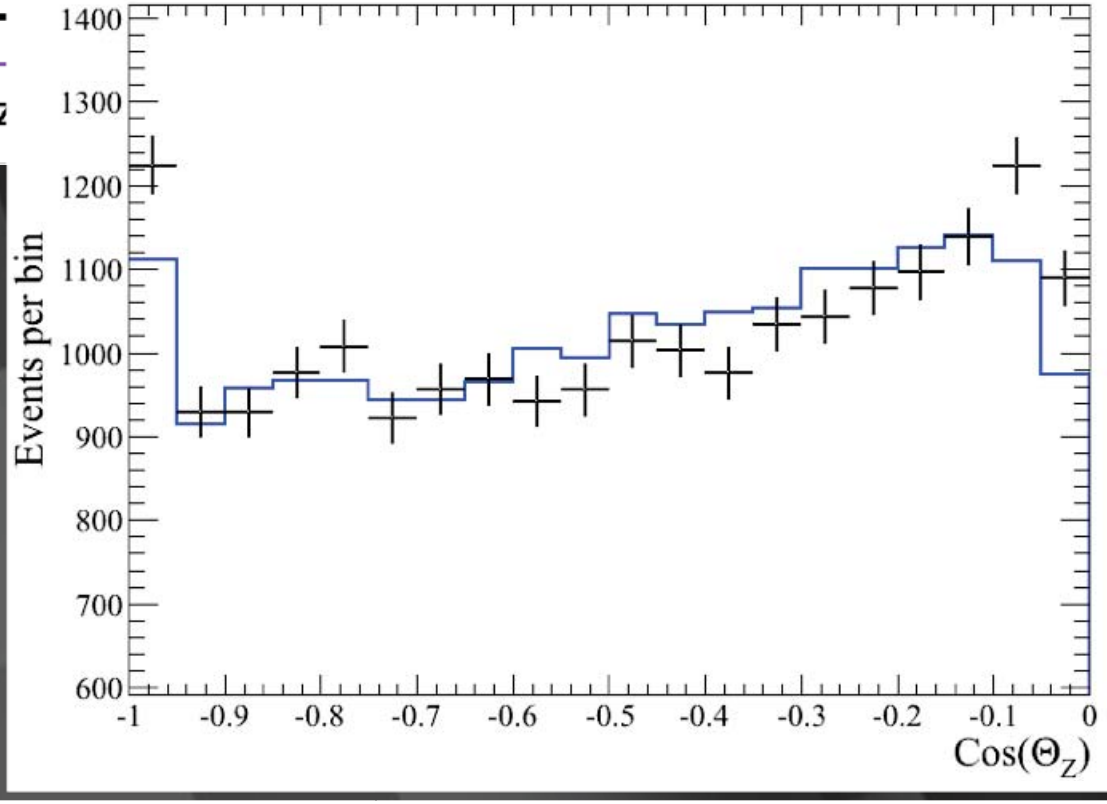
3

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



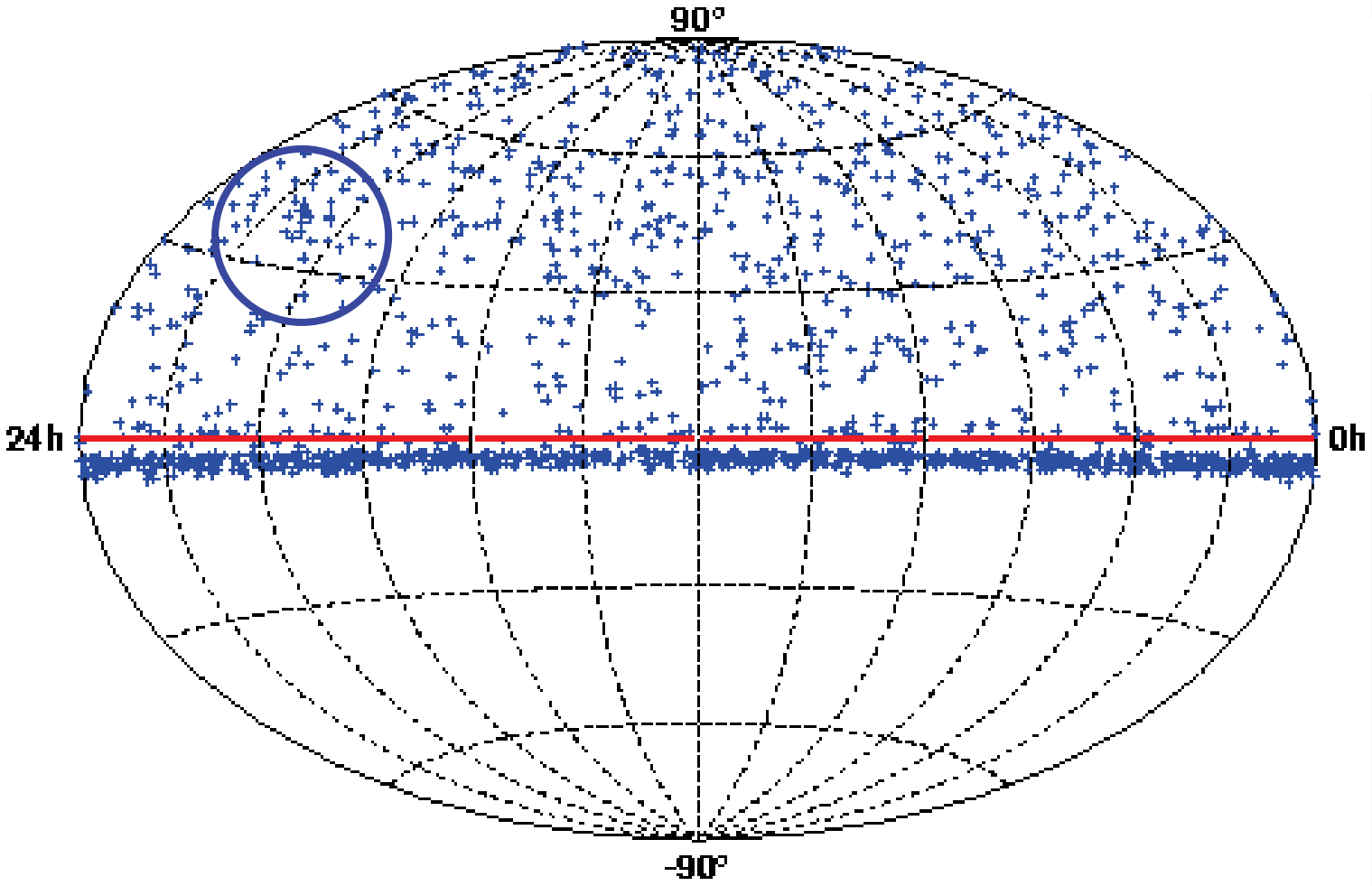
systematics !!!

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

early astronomy

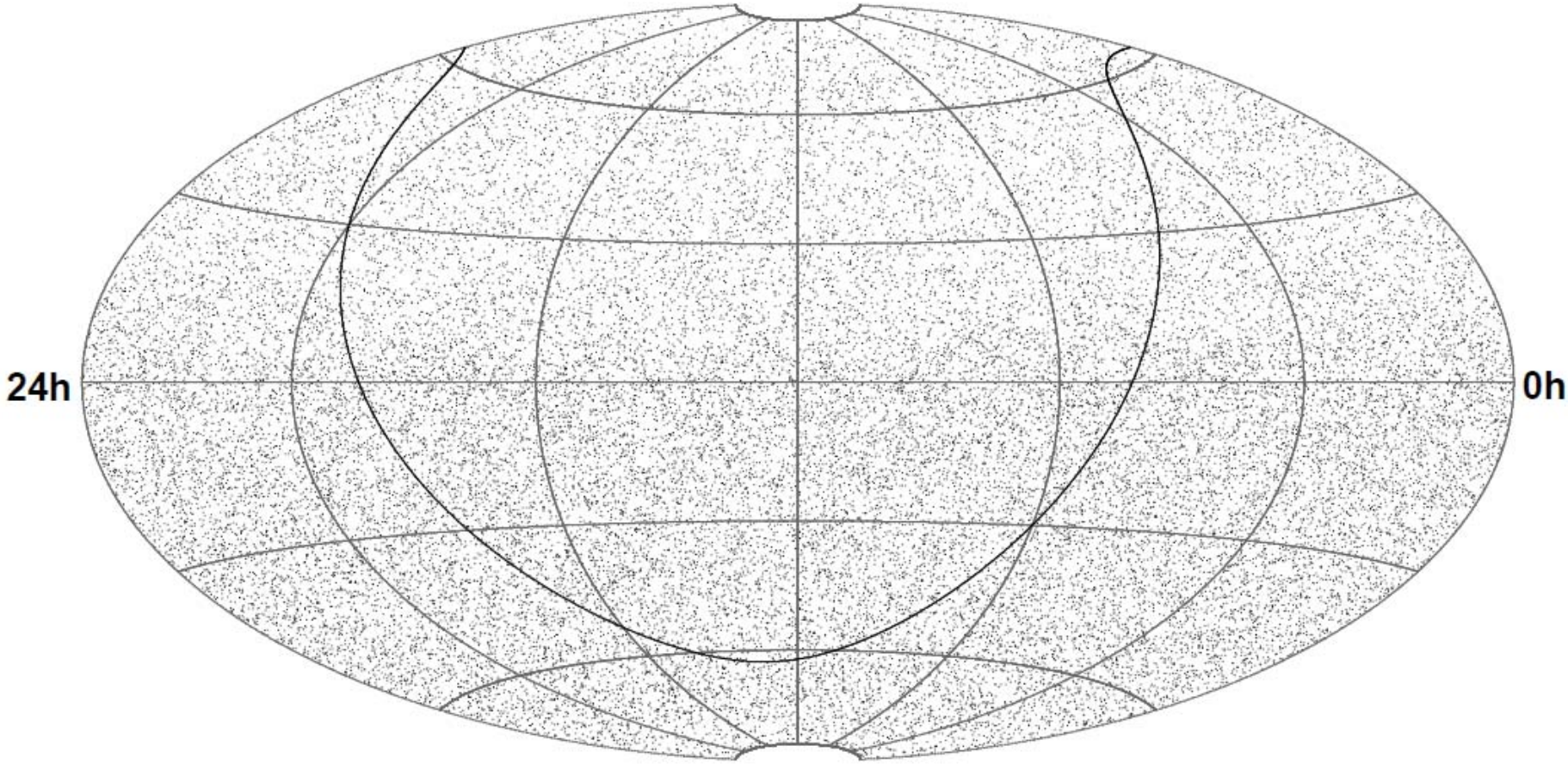
AMANDA 2000

directions of ~ 600 neutrinos



IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos

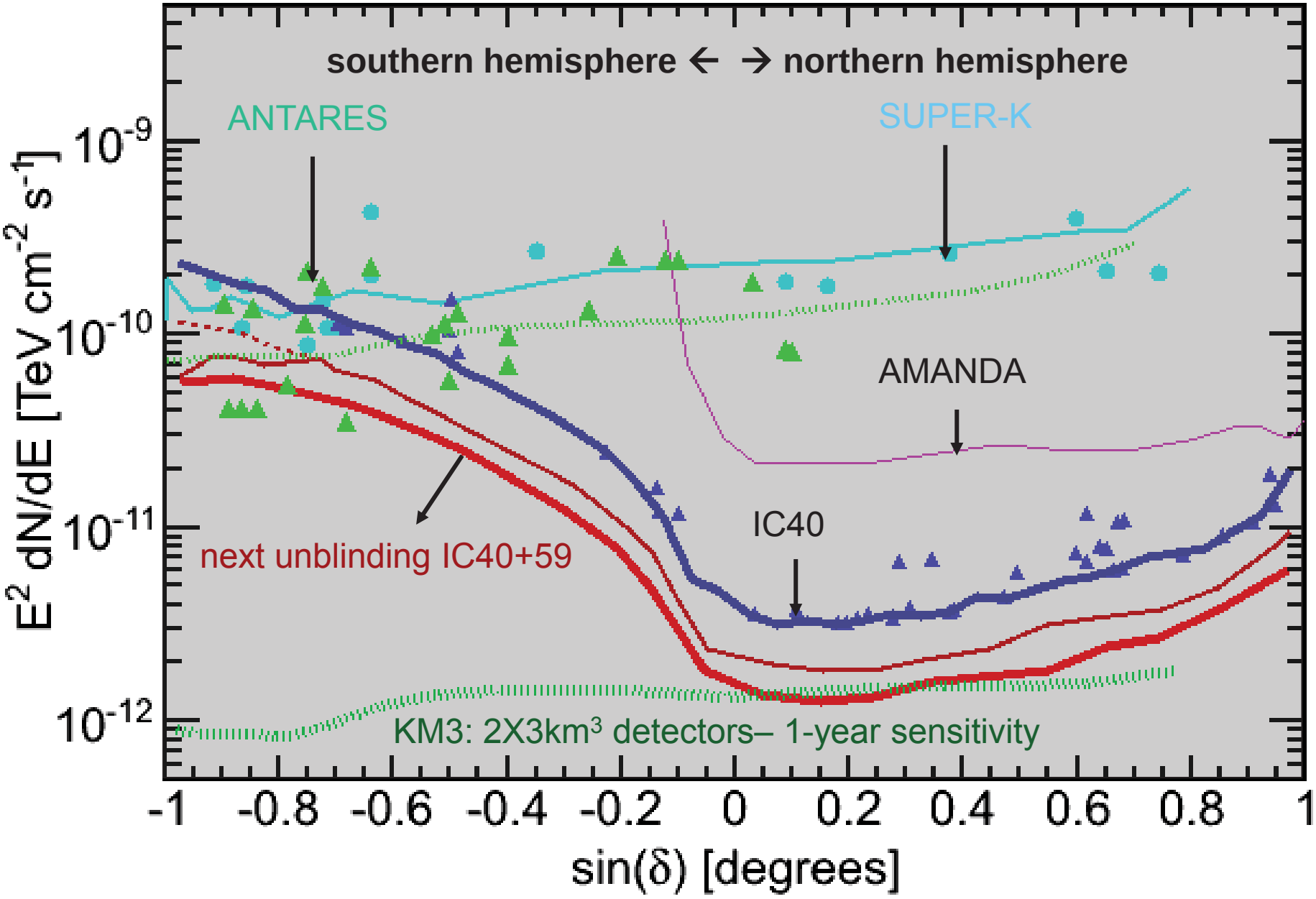


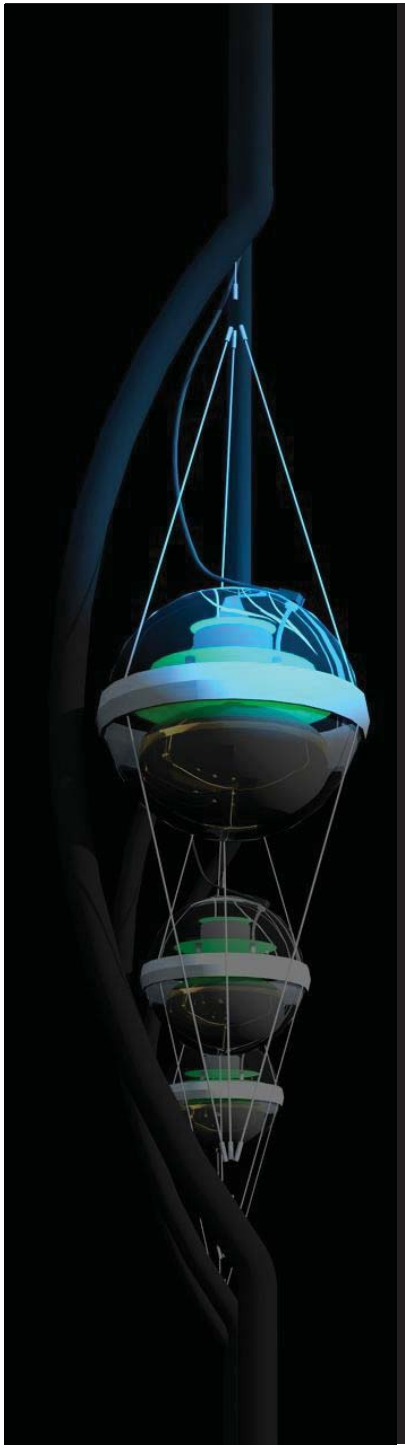
search for
- clustering
- high energy (>> 100 TeV)

southern sky: 23151 muons

- nothing seen in IC40
- … but not finished yet!
- nothing expected next?

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





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Galactic cosmic rays :

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

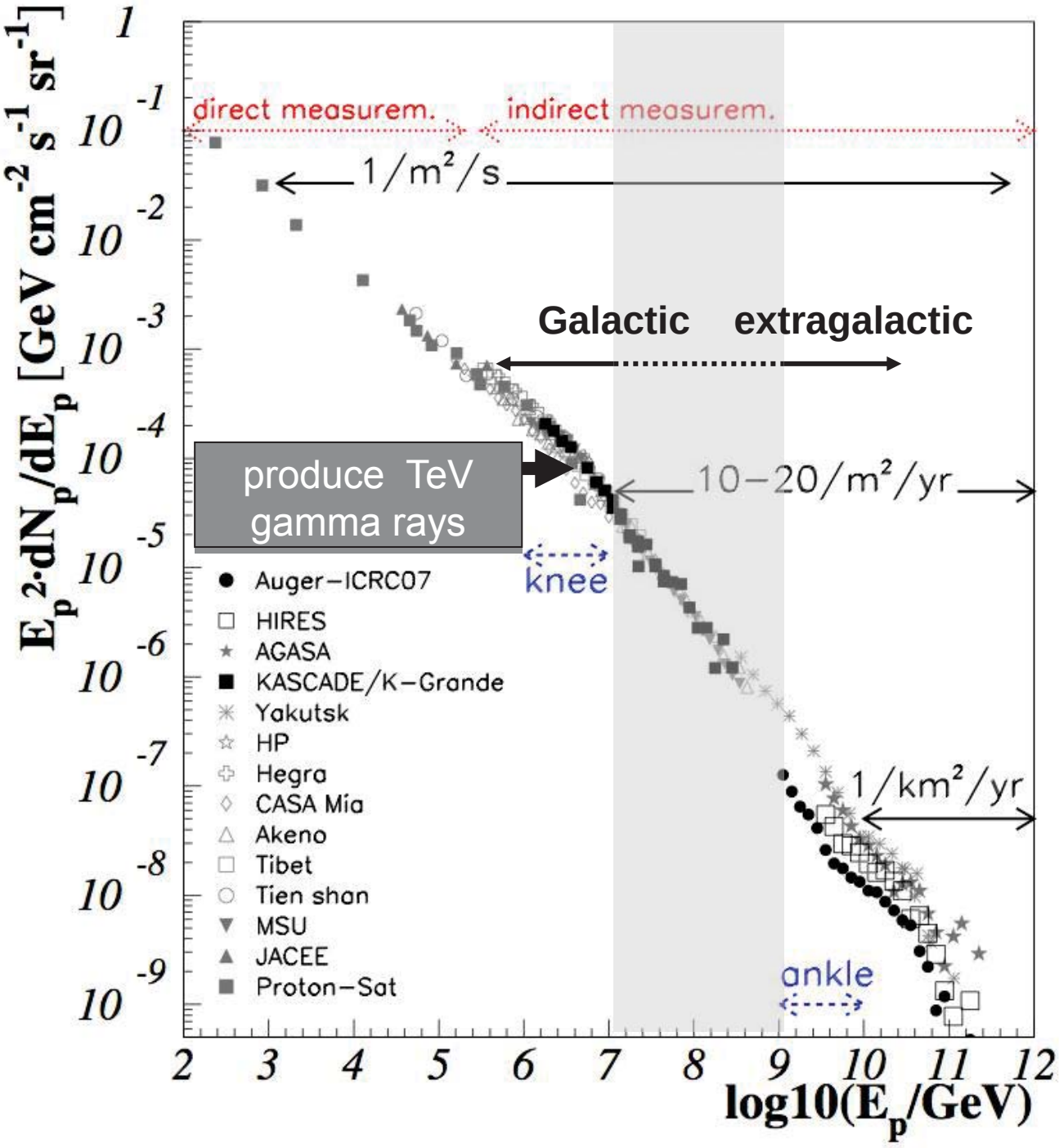
↓

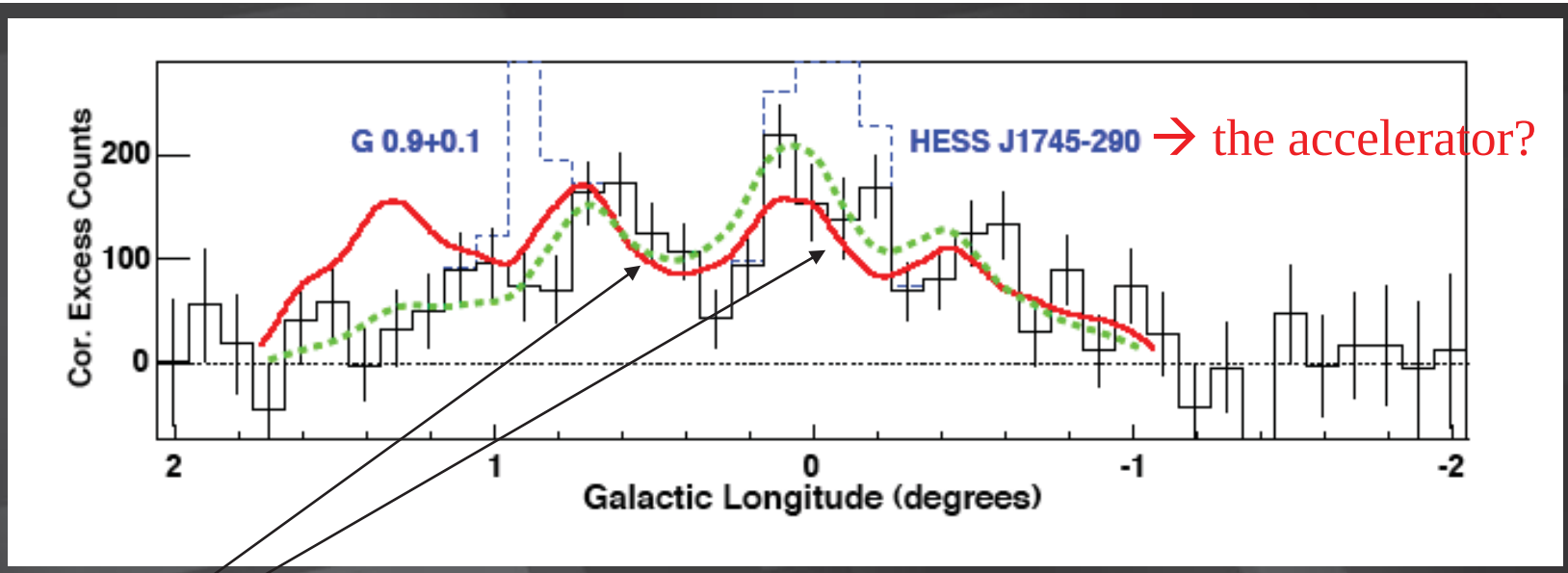
cr + p → pions

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

↓

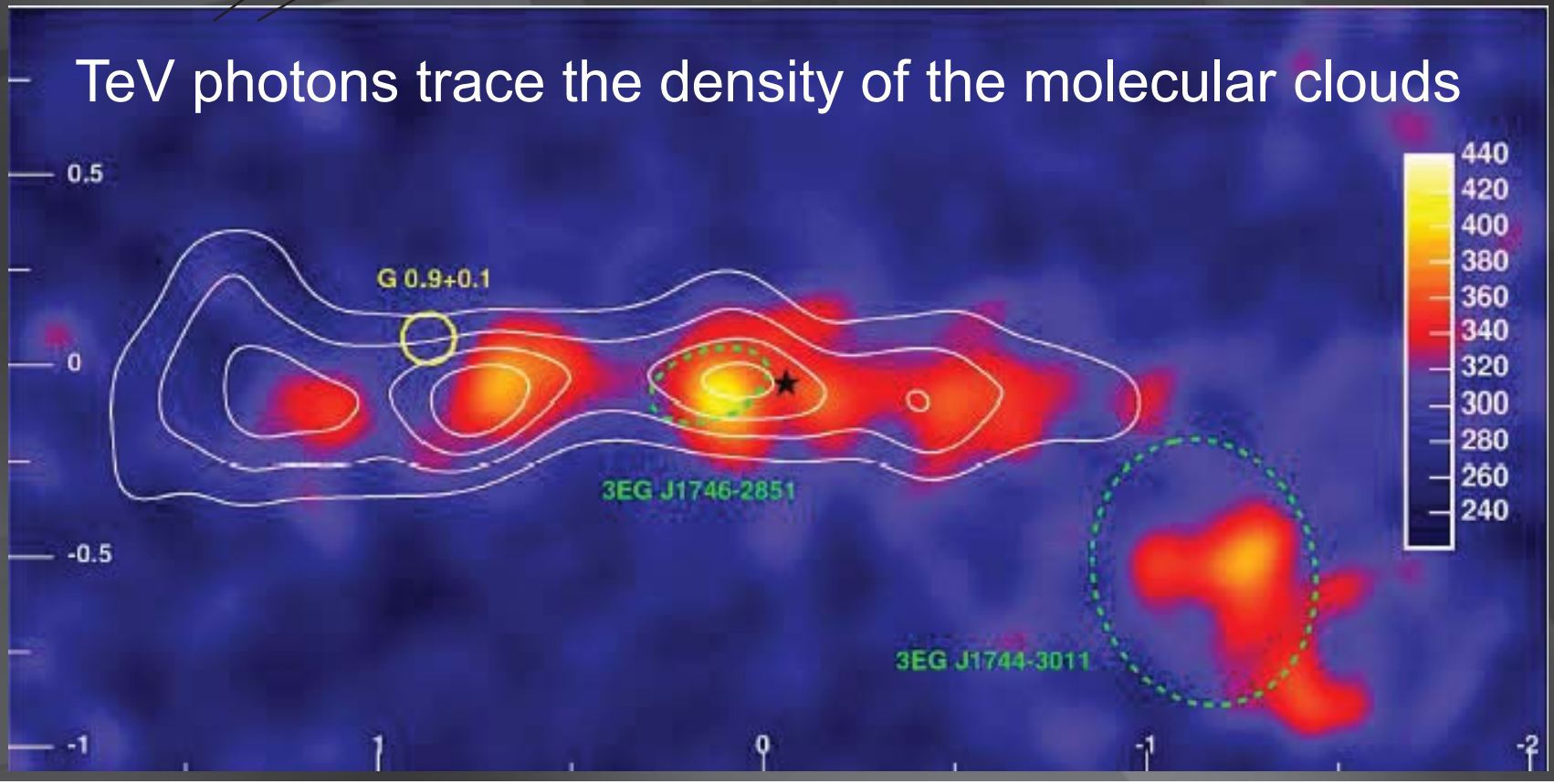
trace cosmic rays





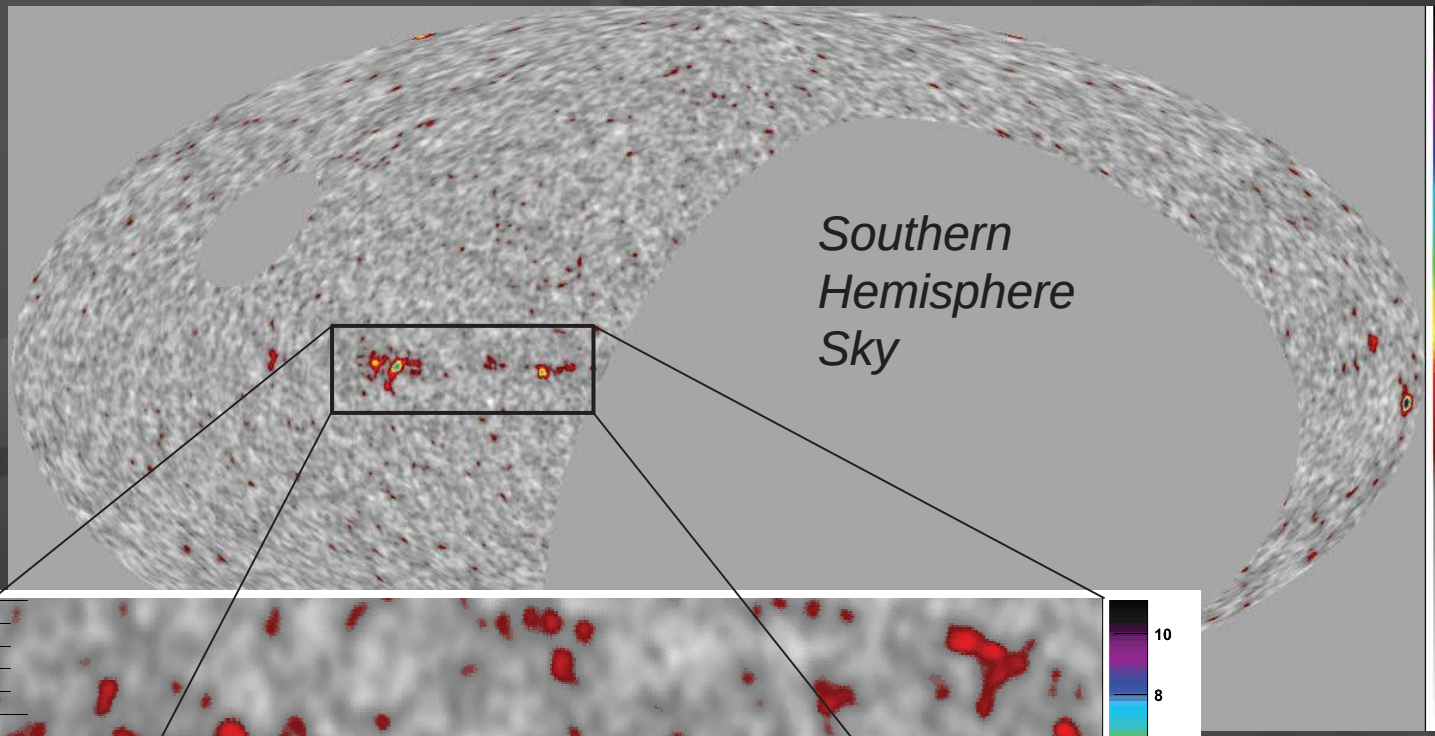
→ the accelerator?

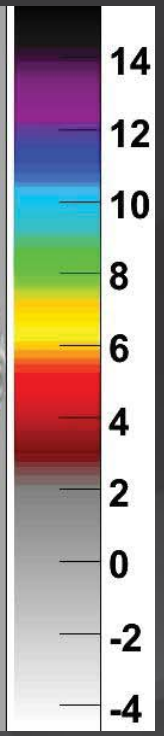
TeV photons trace the density of the molecular clouds



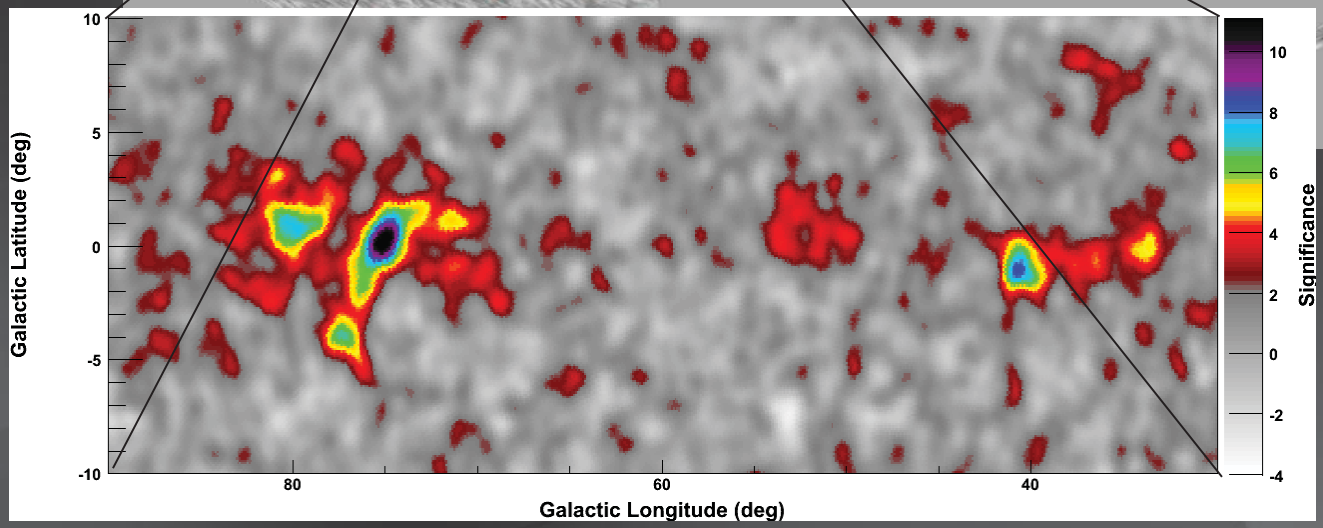
galactic plane in 10 TeV gamma rays :

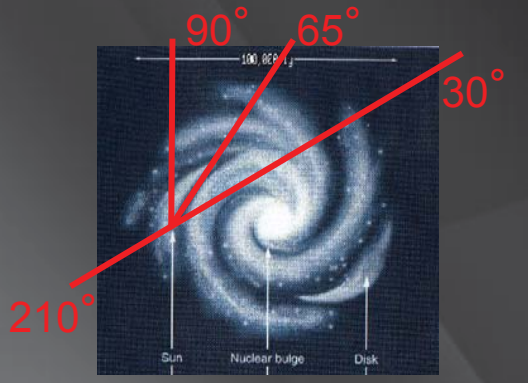
supernova remnants in star forming regions





Standard Deviations





milagro

neutral pions

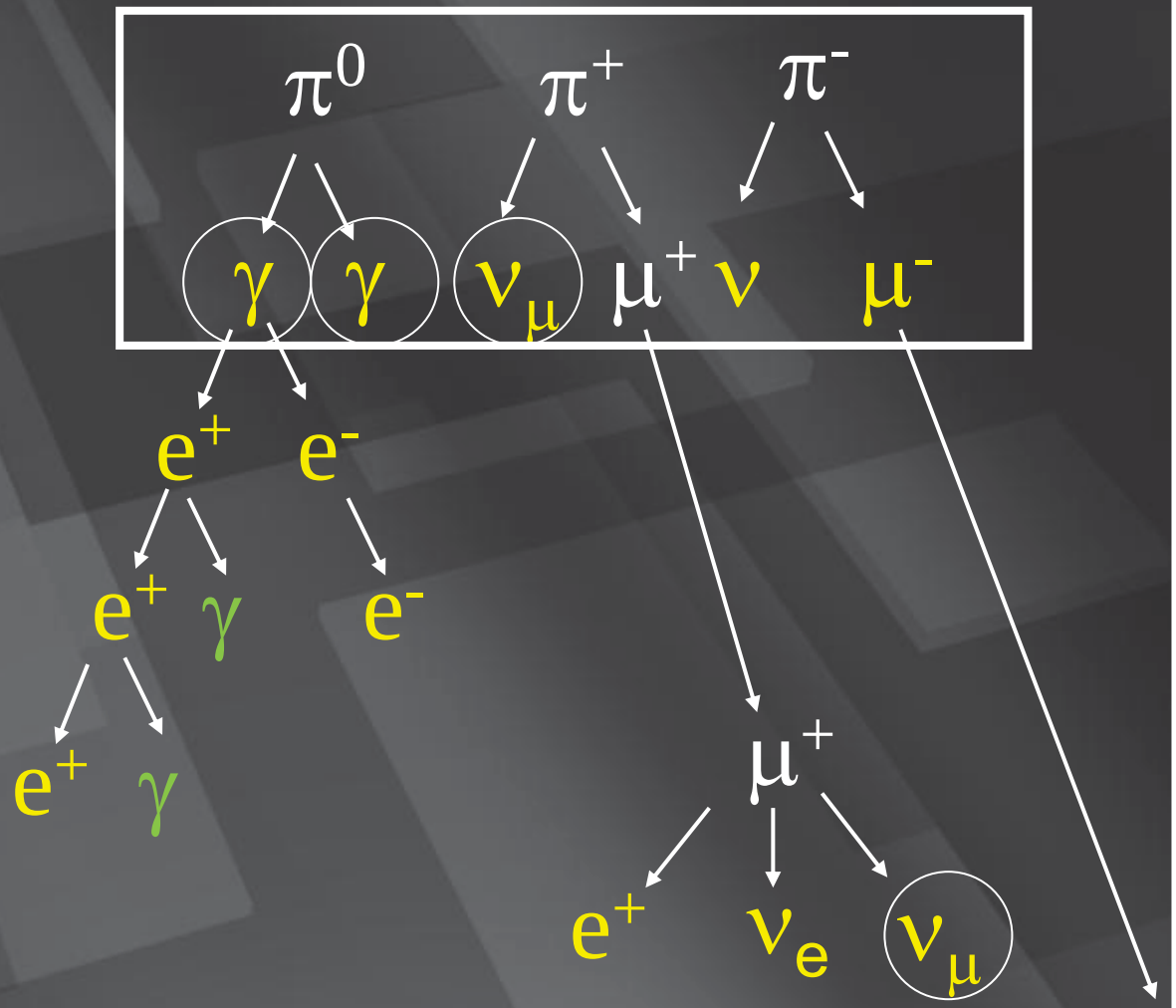
are observed as

gamma rays

charged pions

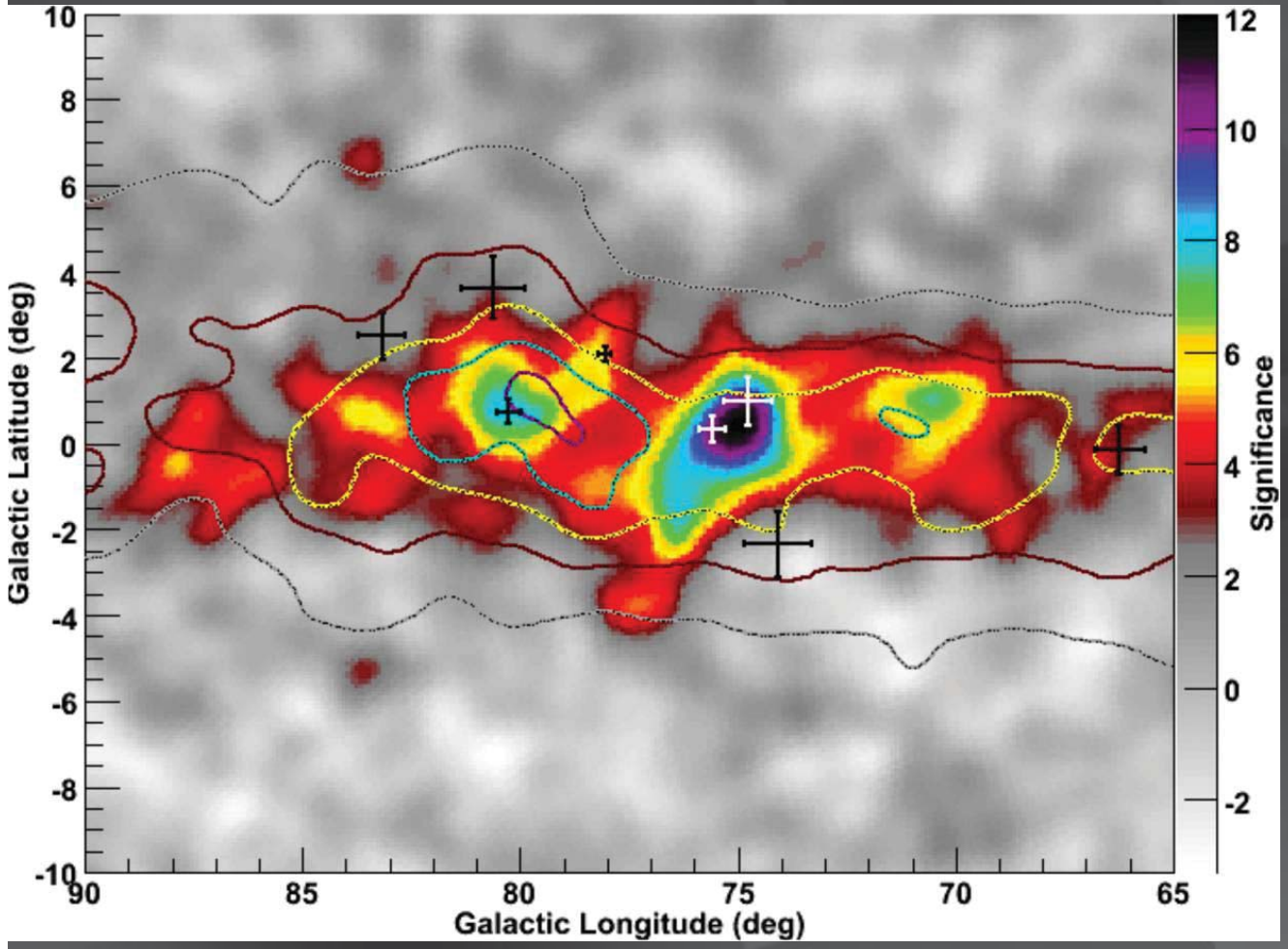
are observed as

neutrinos



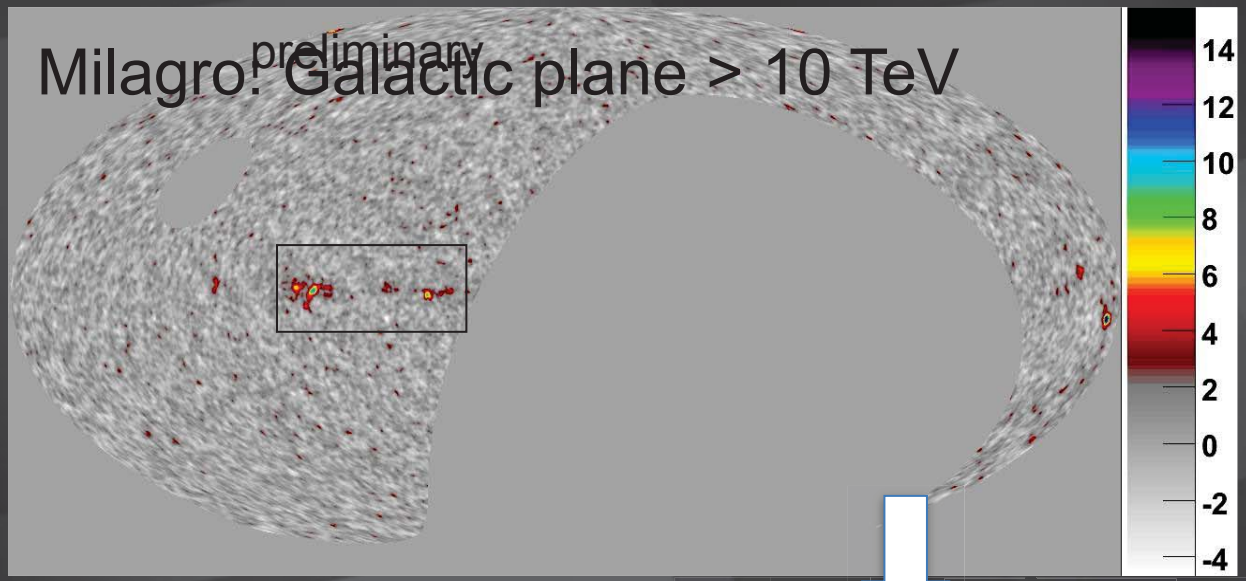
$$\nu_\mu + \nu_\mu = \gamma + \gamma$$

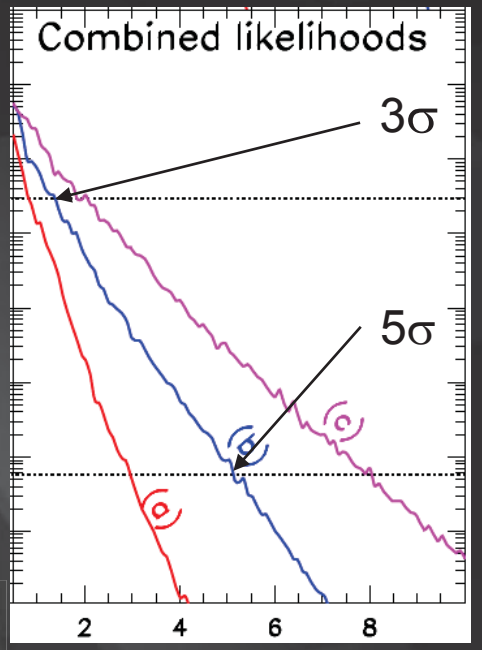
cygnus region : Milagro



translation of
TeV gamma rays
into
TeV neutrinos :

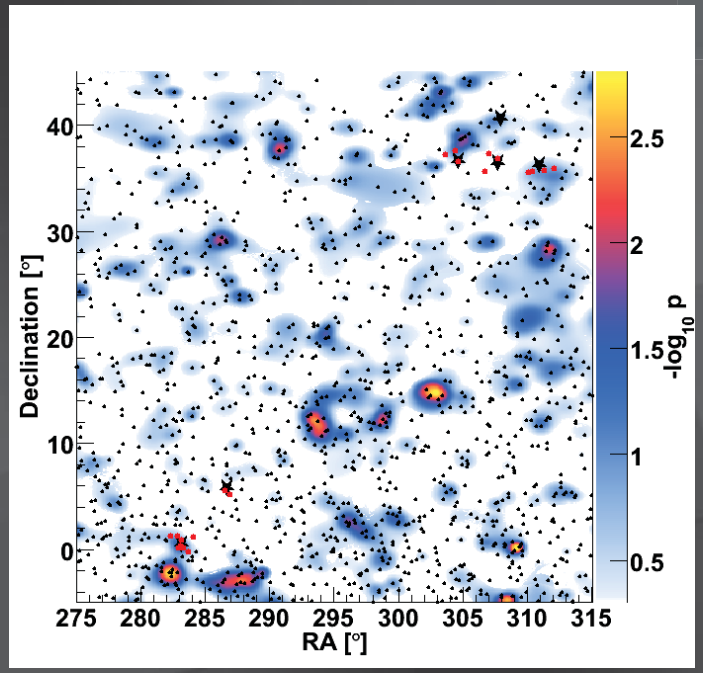
3 ± 1 ν per year in IceCube per source

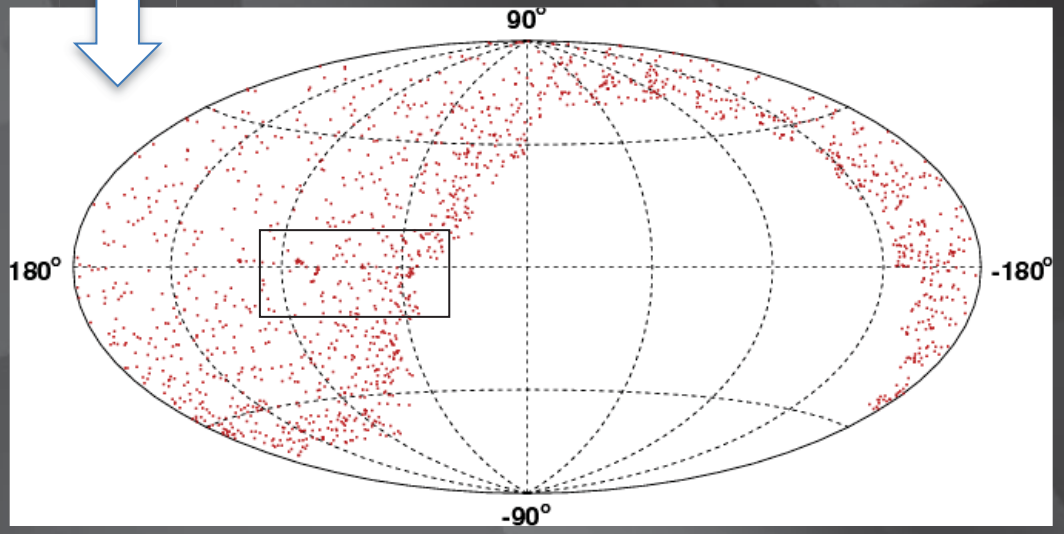




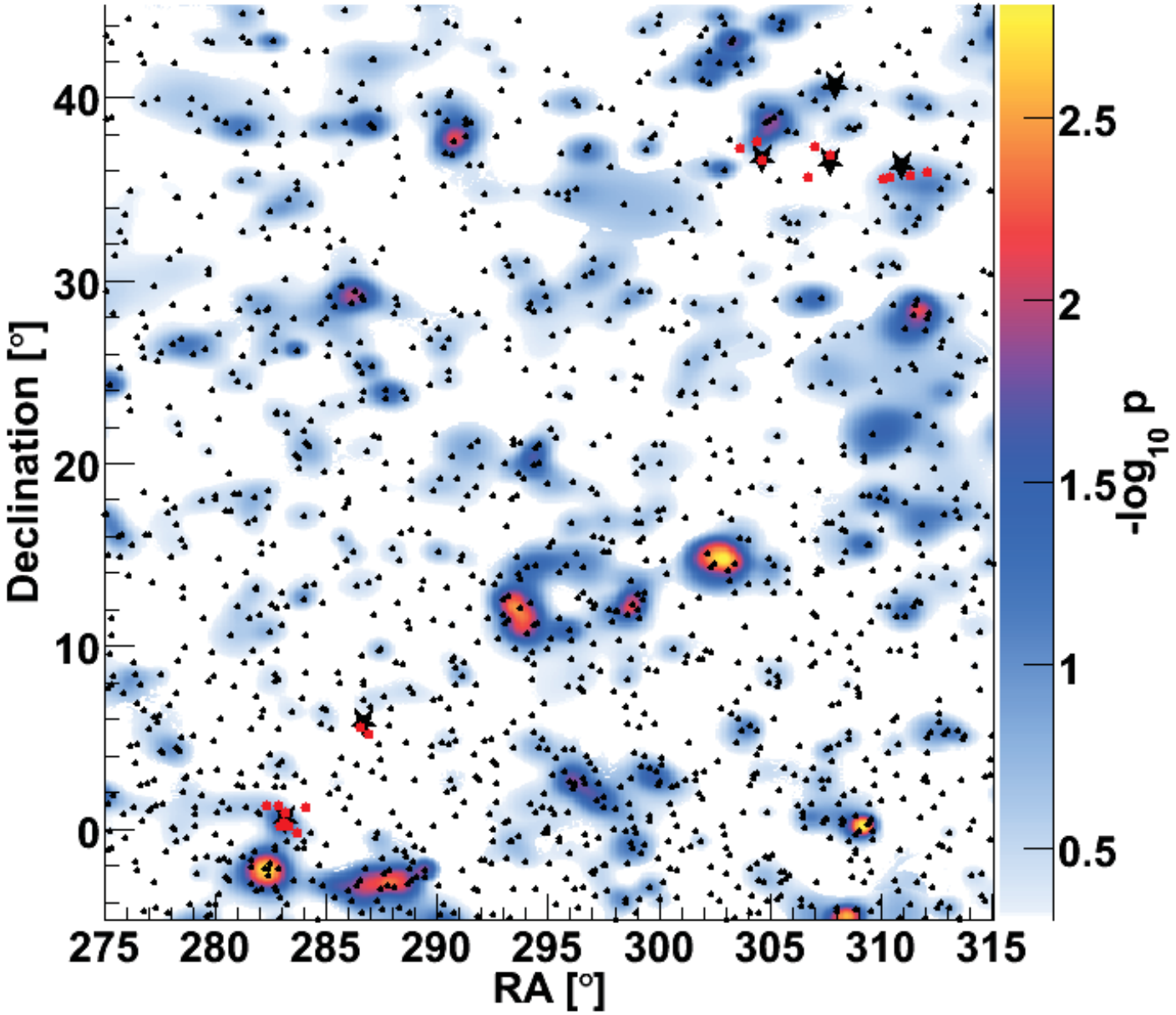
time in years

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





preliminary



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%

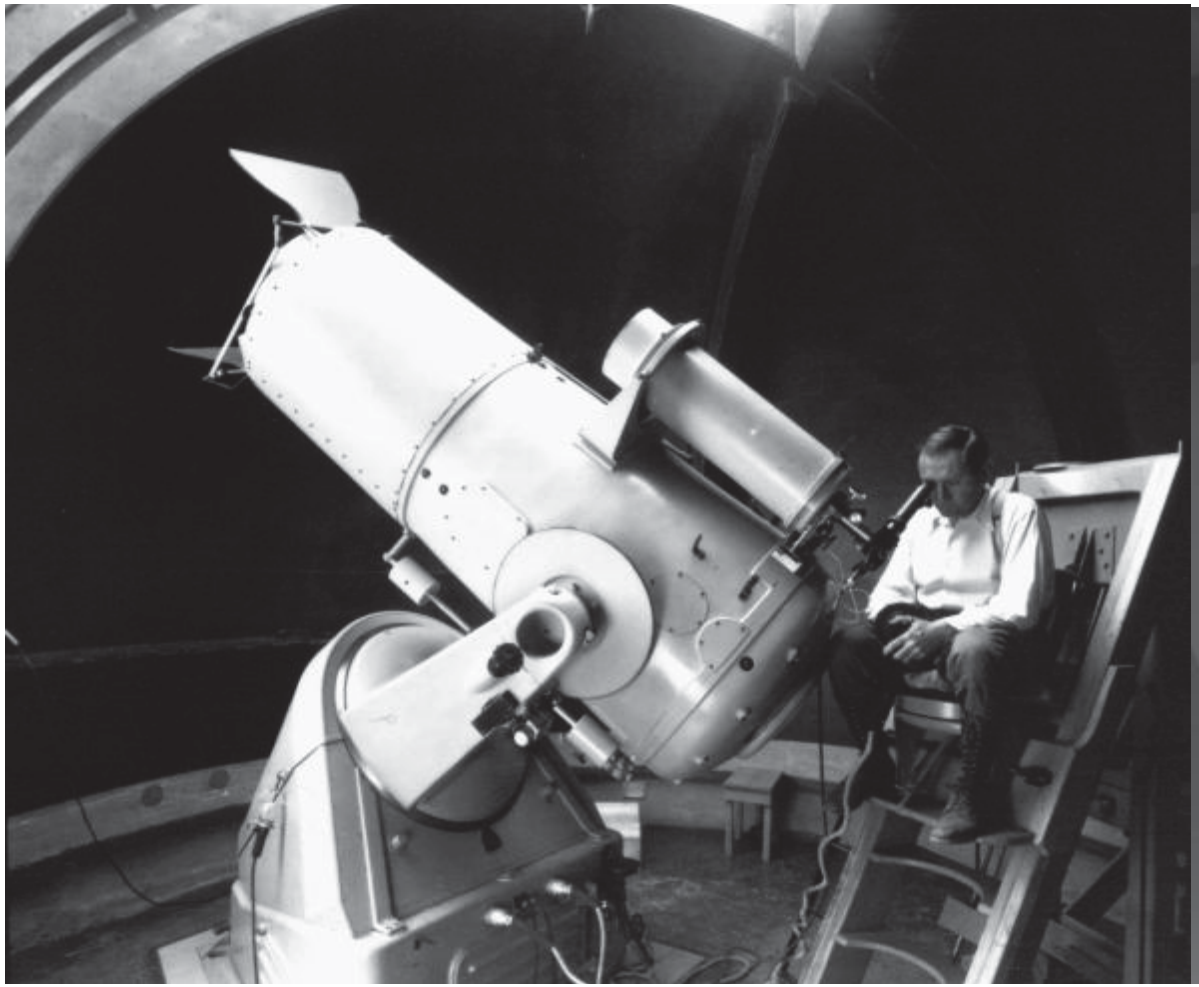
(a posteriori)

ON SUPER-NOVAE

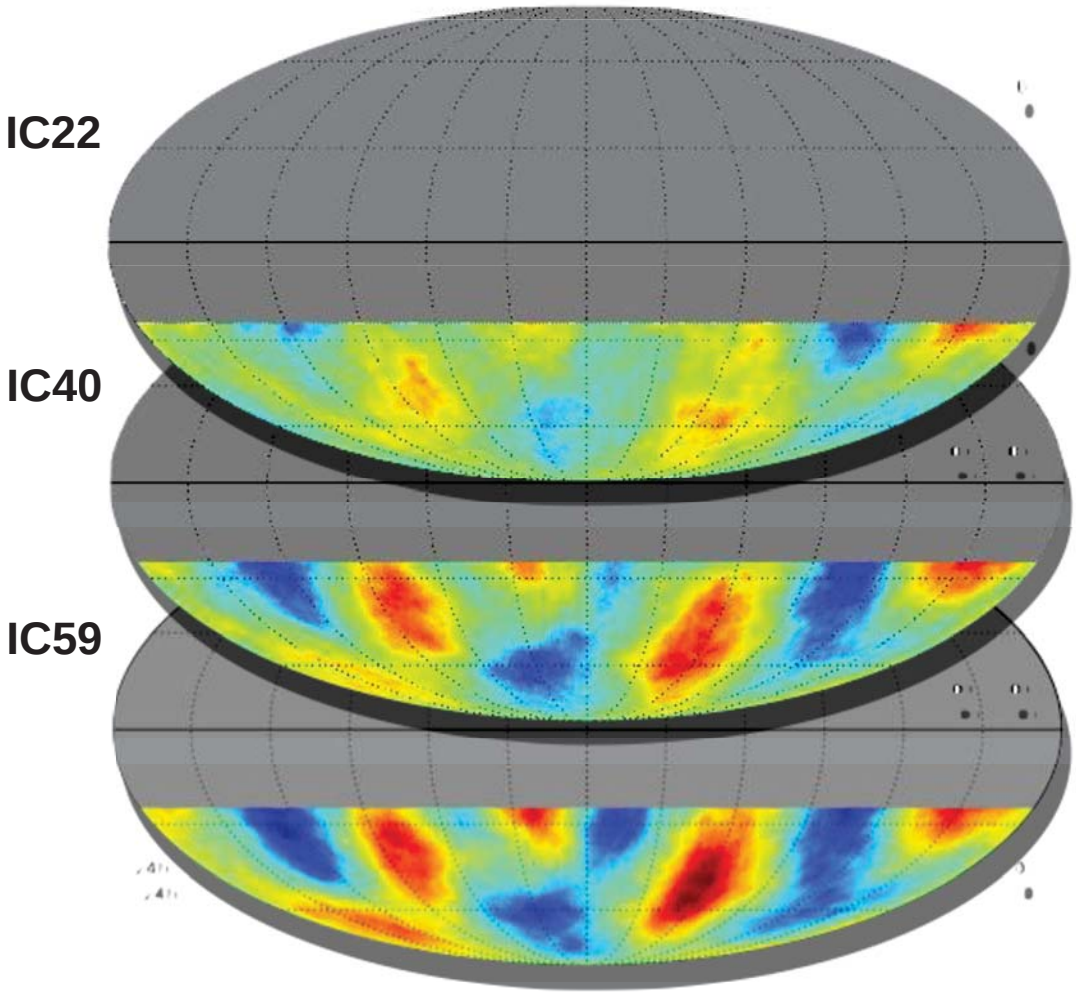
By W. Baade and F. Zwicky

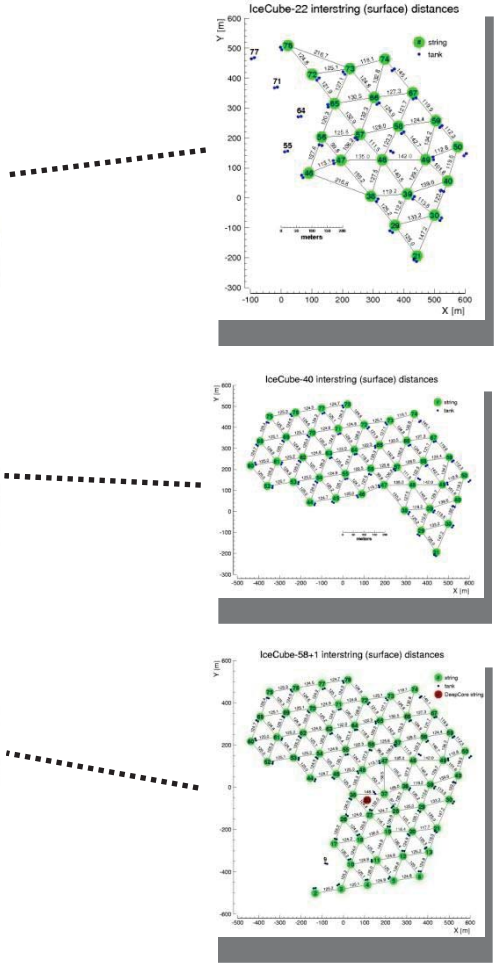
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

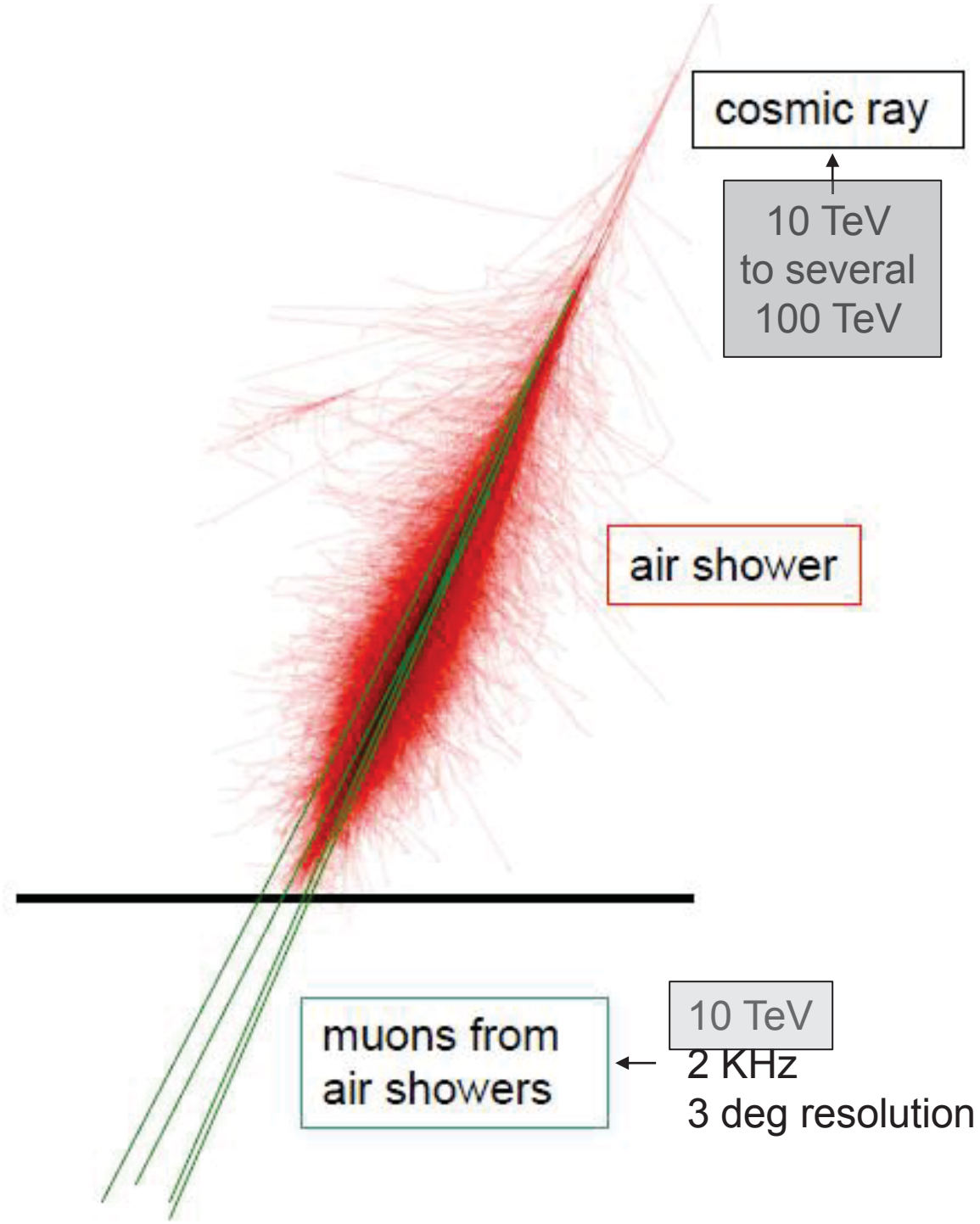


IC22 and IC40 : muon astronomy (!)





Different geometries, same structure

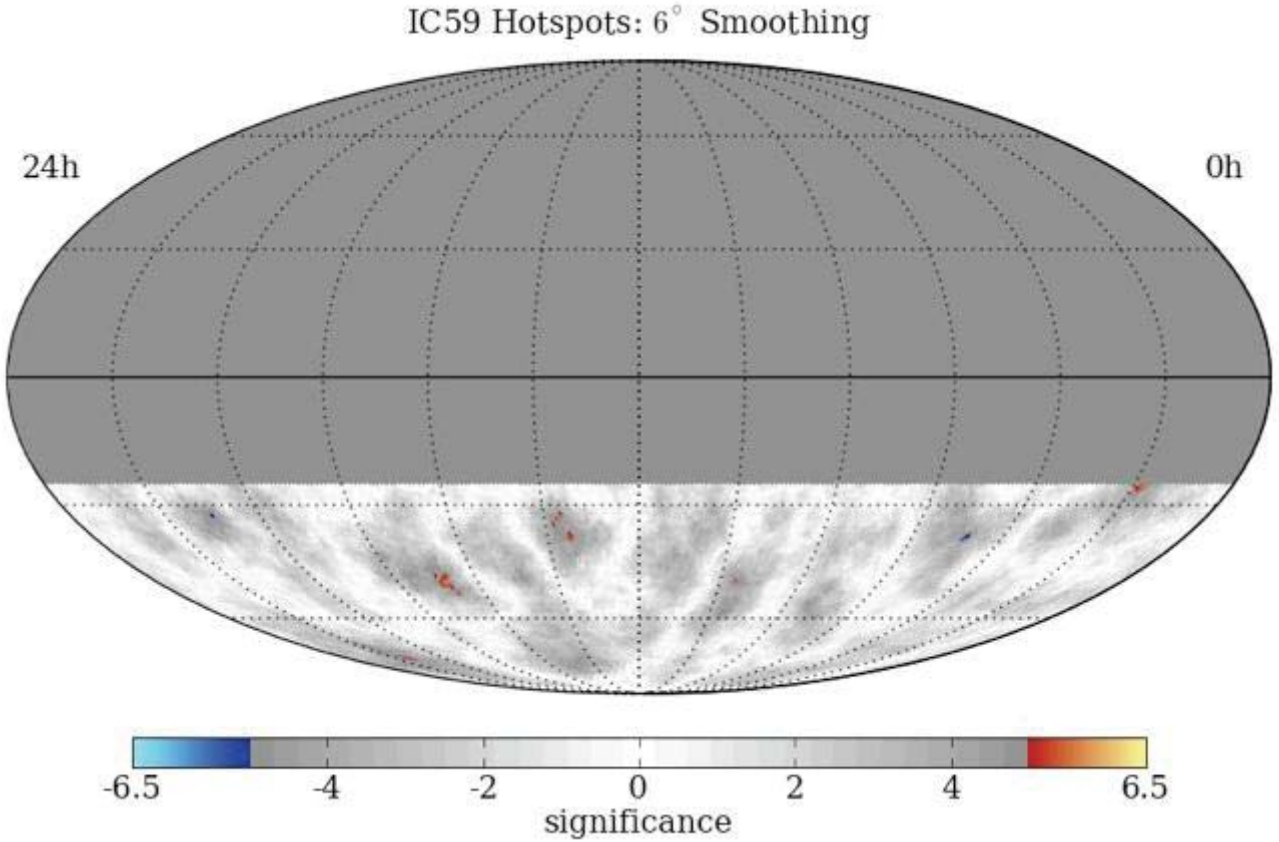


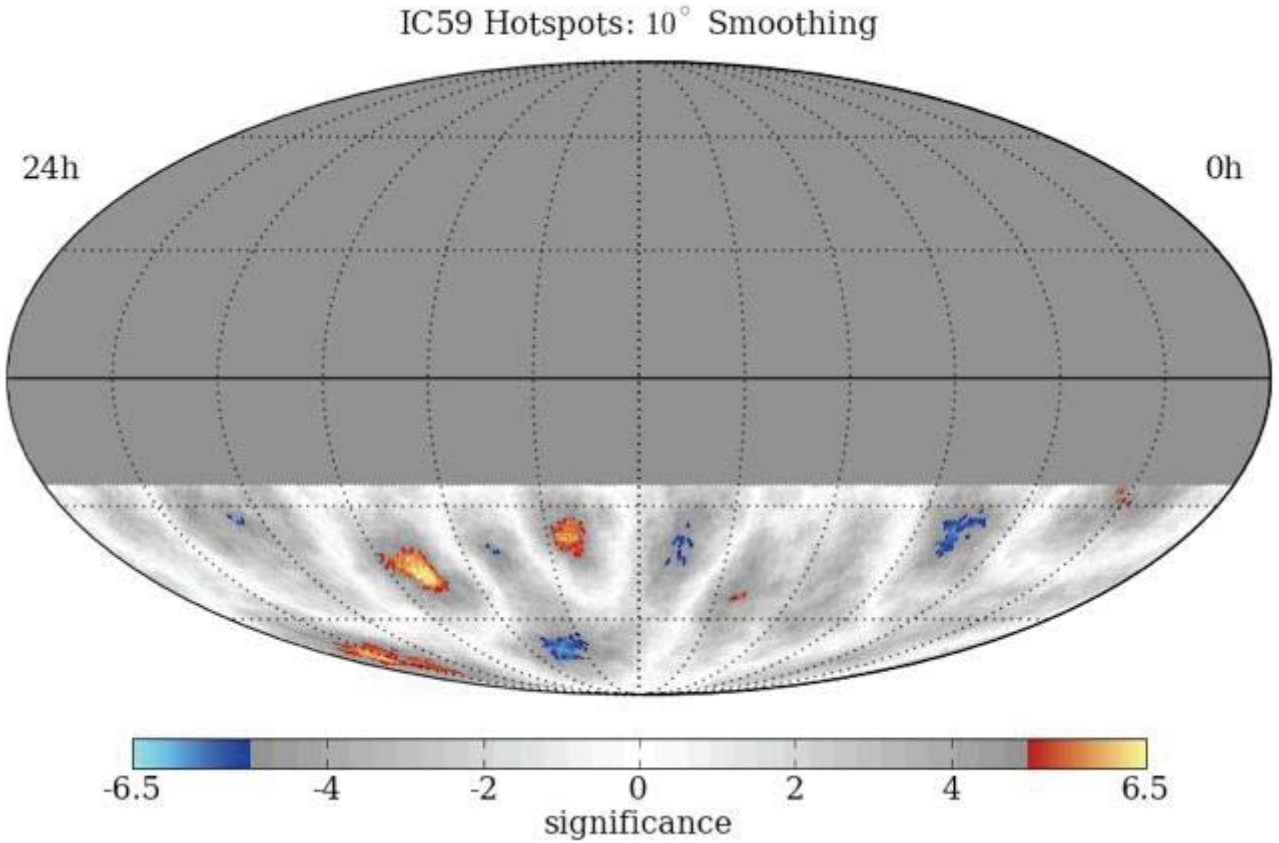
cosmic rays in IceCube

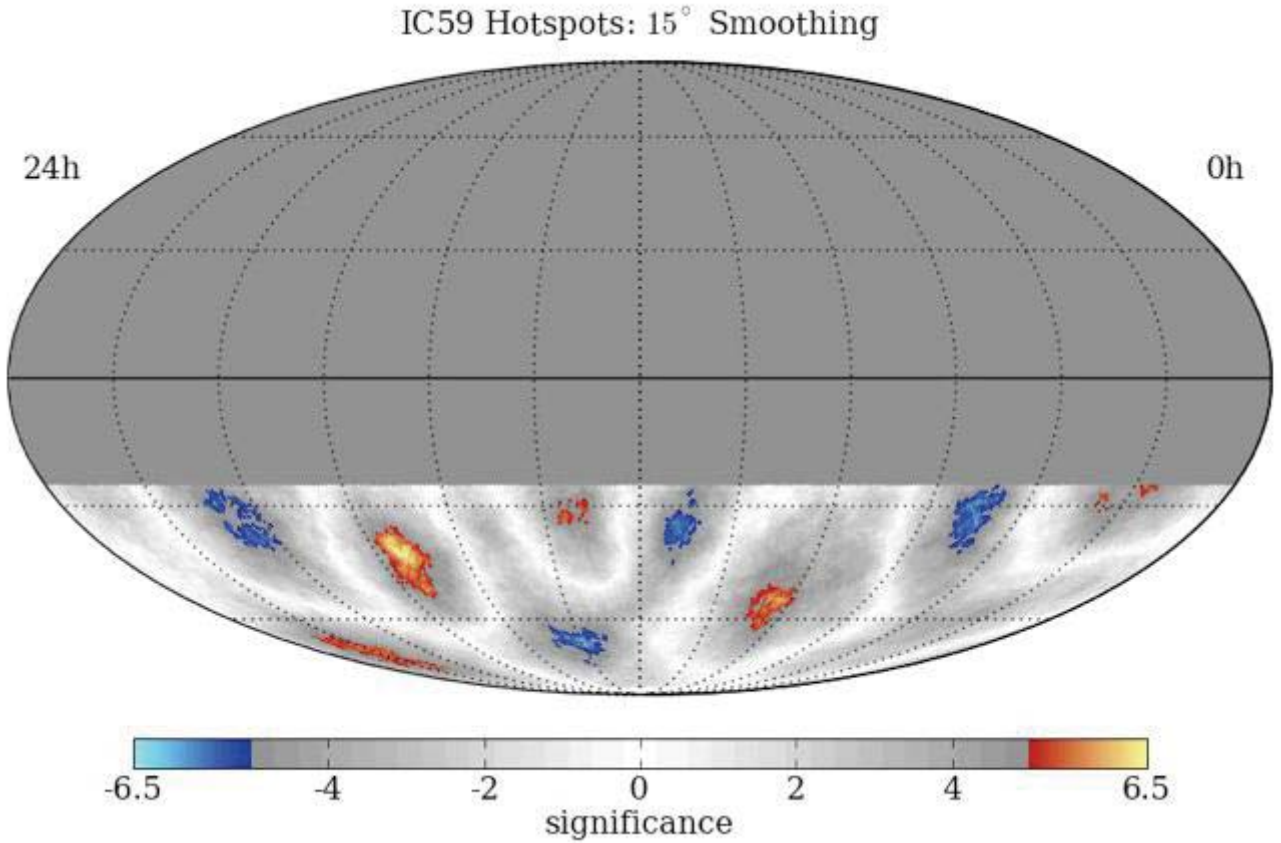
- we map the highest energy Galactic cosmic rays, but…
- their gyroradius is < 1 pc in microgauss magnetic field
- closest sources > 100 pc

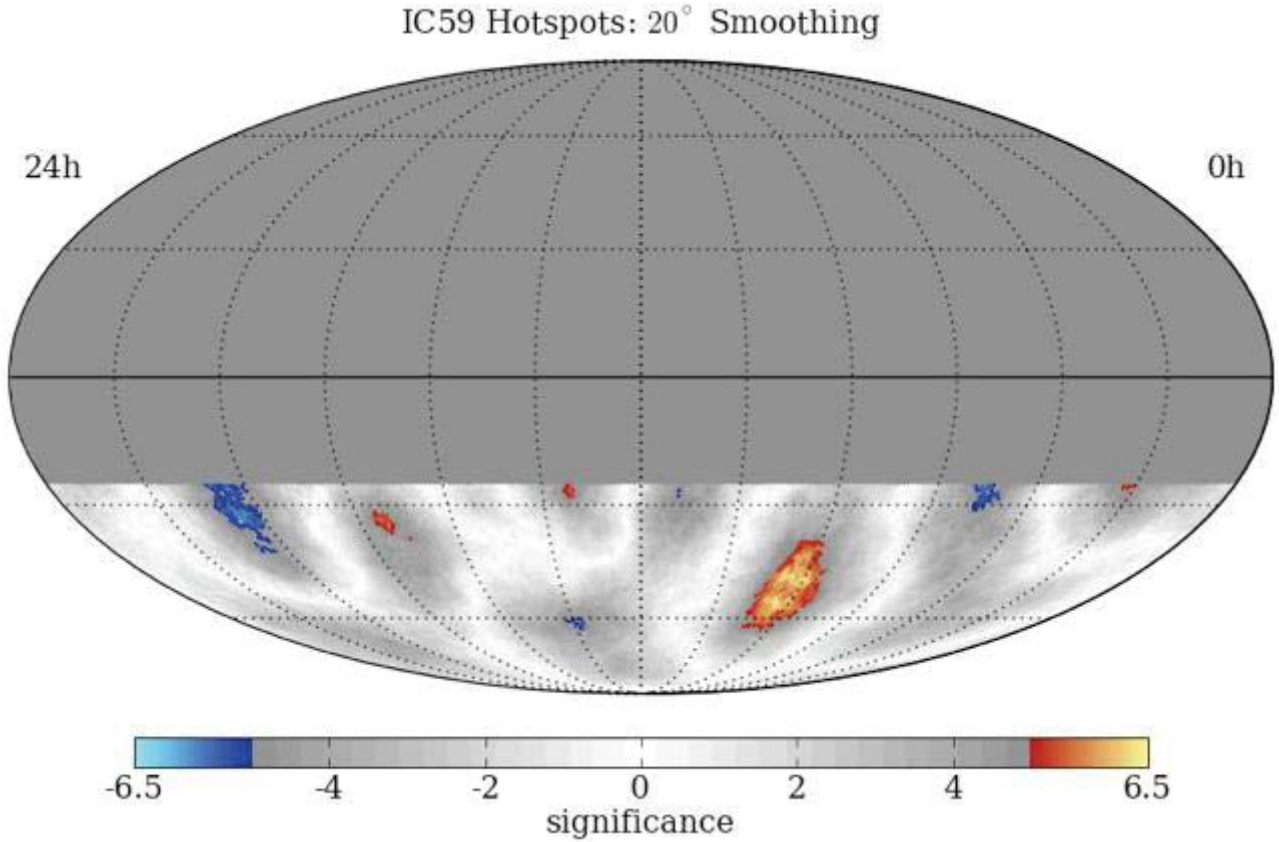
should not point!

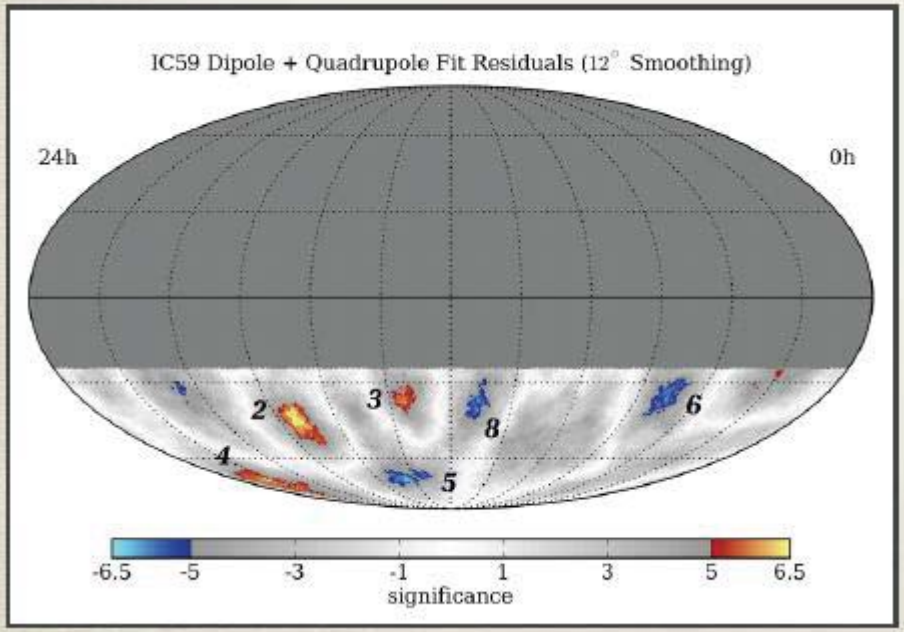
→ that's why we detect neutrinos!

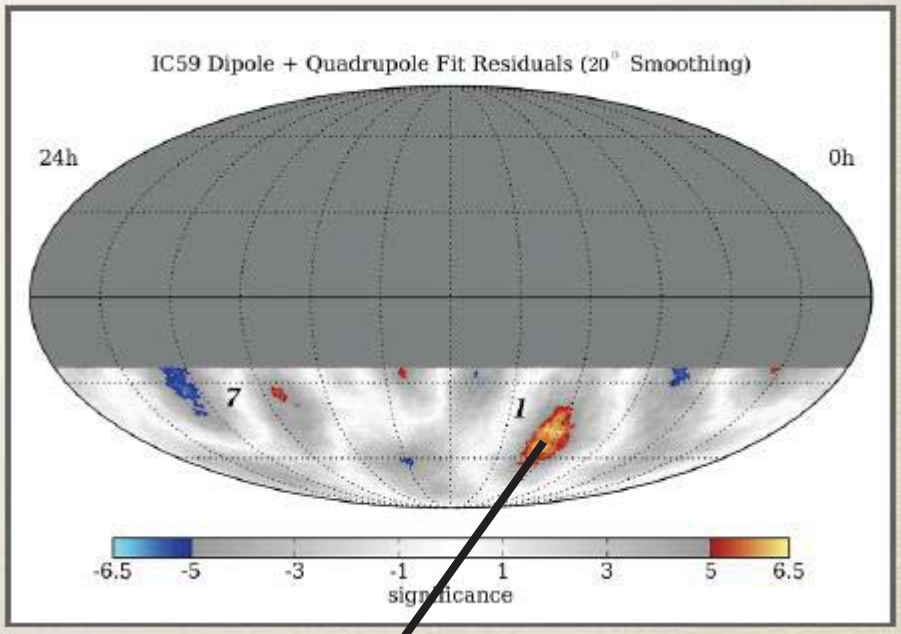

IC59 Hotspots: 6° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance


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

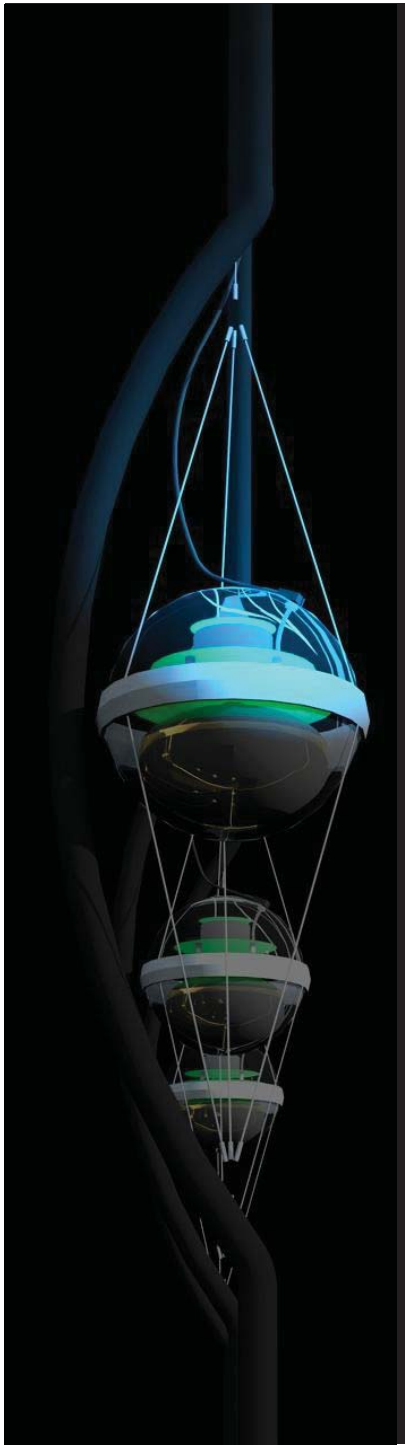

IC59 Hotspots: 20° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance





Vela

- closest supernova remnant
- strongest gamma ray source



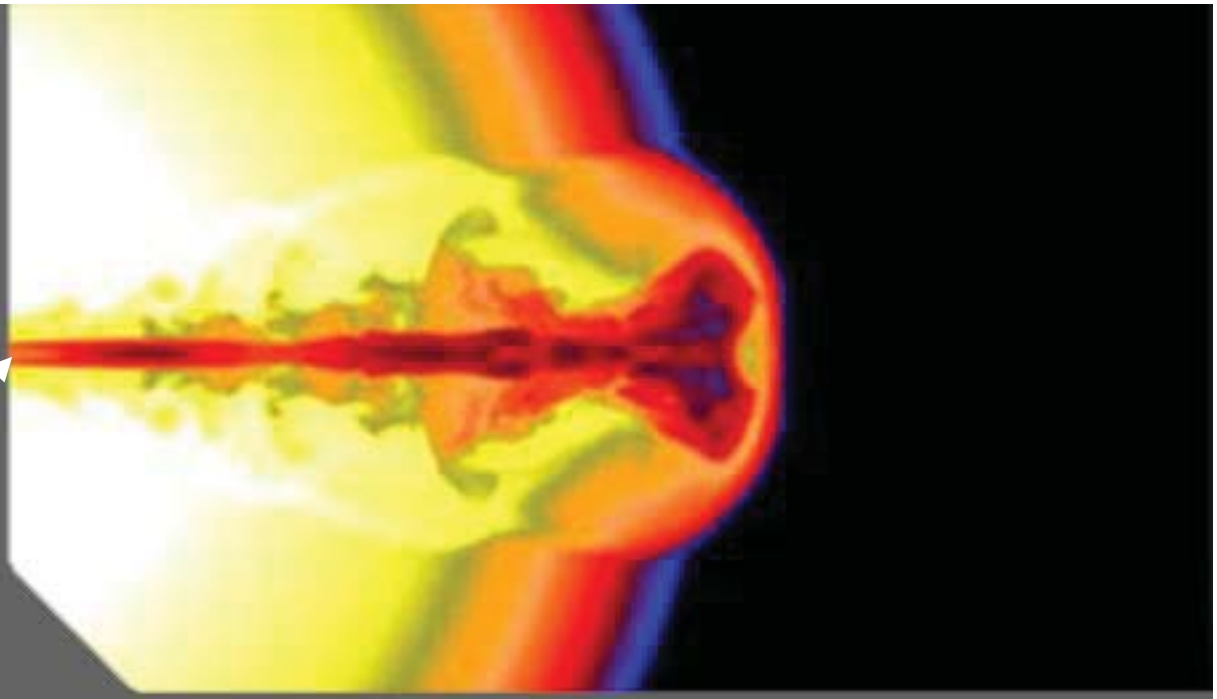
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

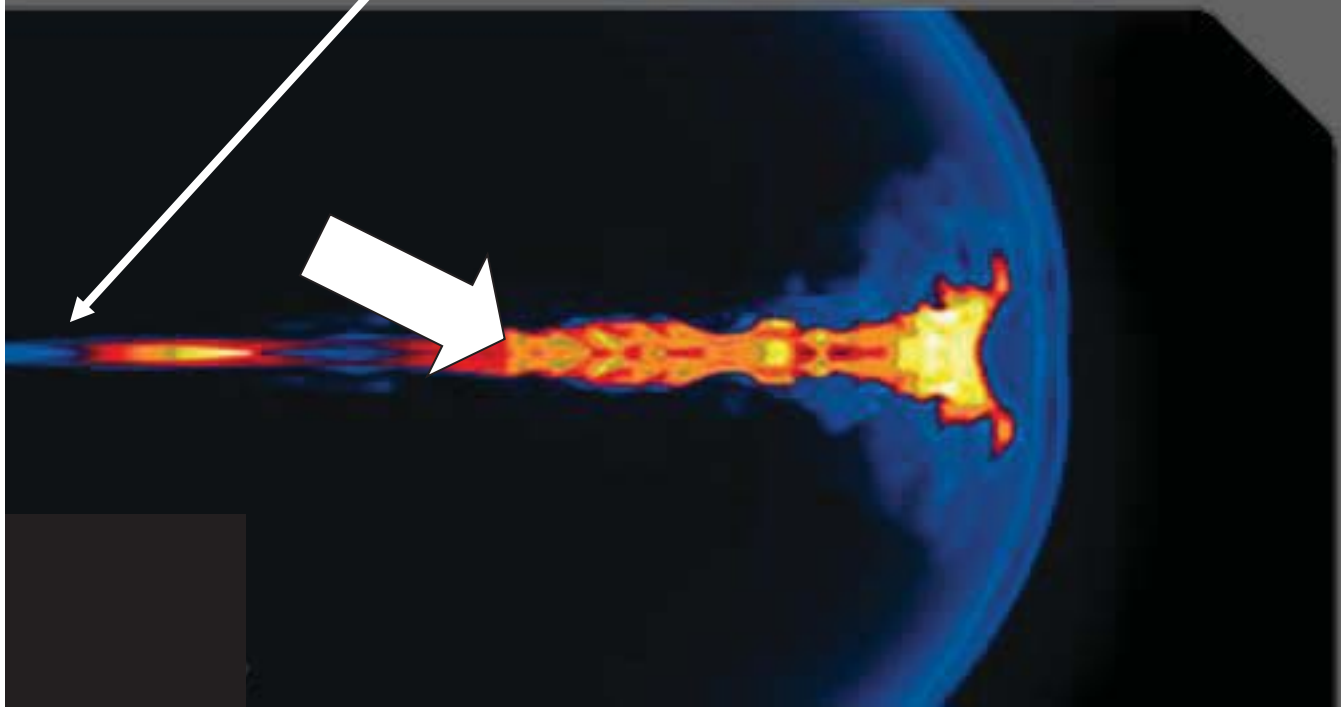
IceCube.wisc.edu

collapse of massive star produces a

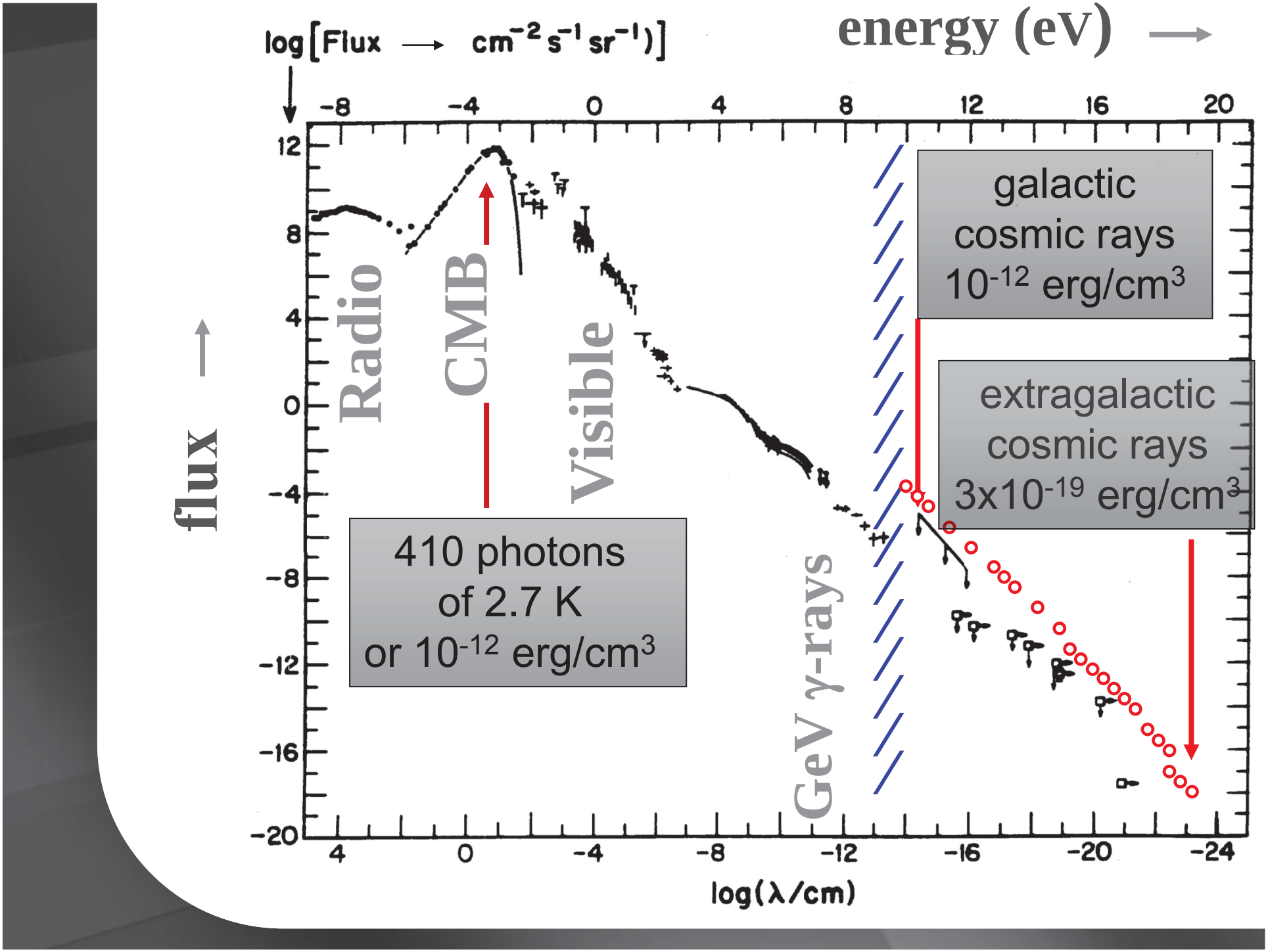
gamma ray burst

spinning black hole

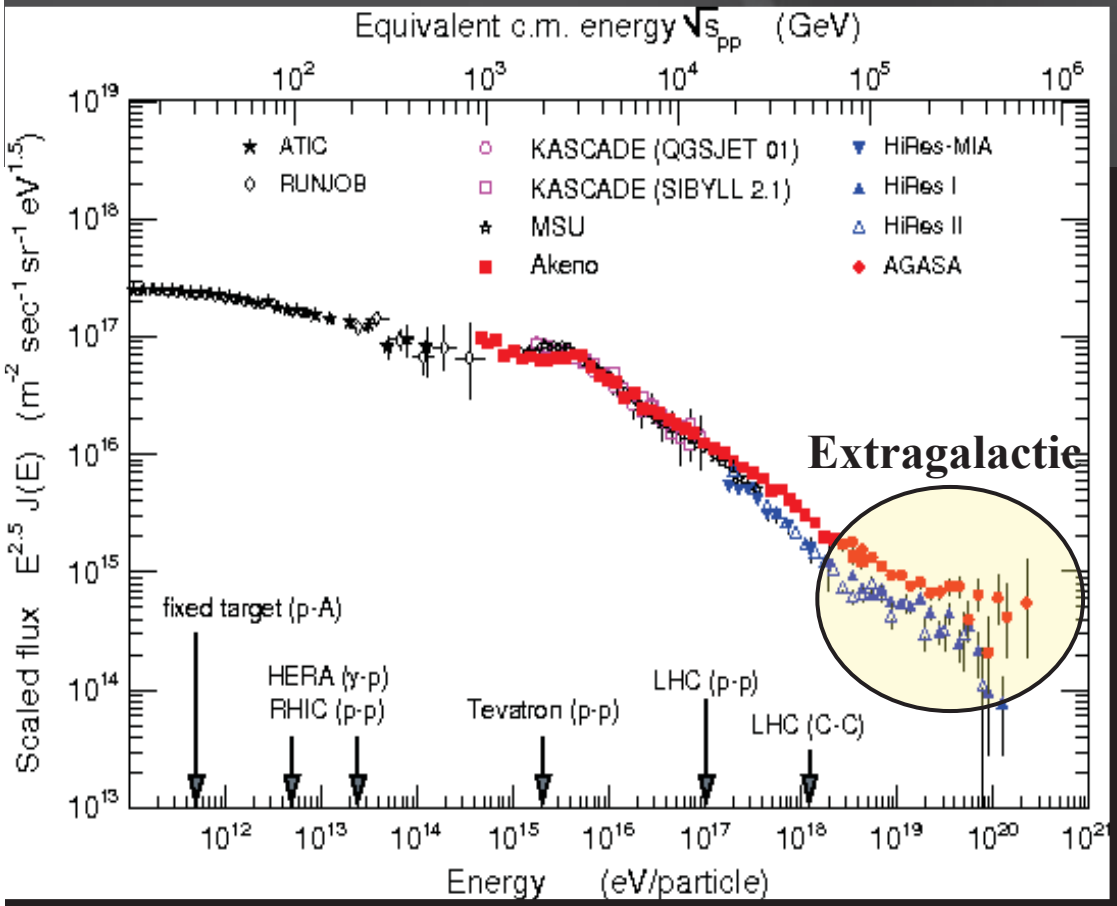




photons and protons coexist in the fireball if…
GRB are the sources of the cosmic rays
→
neutrino production


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux →
Radio
CMB
Visible
GeV γ-rays
410 photons
of 2.7 K
or 10⁻¹² erg/cm³
galactic
cosmic rays
10⁻¹² erg/cm³
extragalactic
cosmic rays
3x10⁻¹⁹ erg/cm³
log(λ/cm)

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

3×10^{-19} erg / cm^3

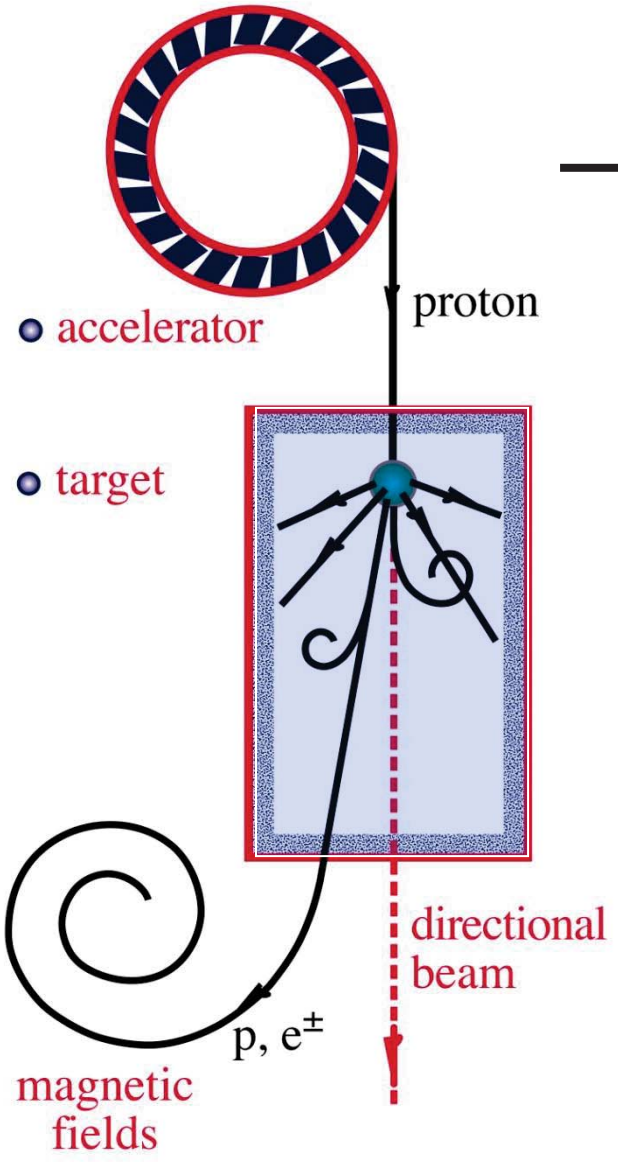
Gamma-Ray Bursts:

2×10^{52} ergs x 300/Gpc^3 x 10^{10} yr

3×10^{-19} erg / cm^3

GRBs provide environment and energy to explain the extragalactic cosmic rays!

ν and γ beams : heaven and earth



black hole

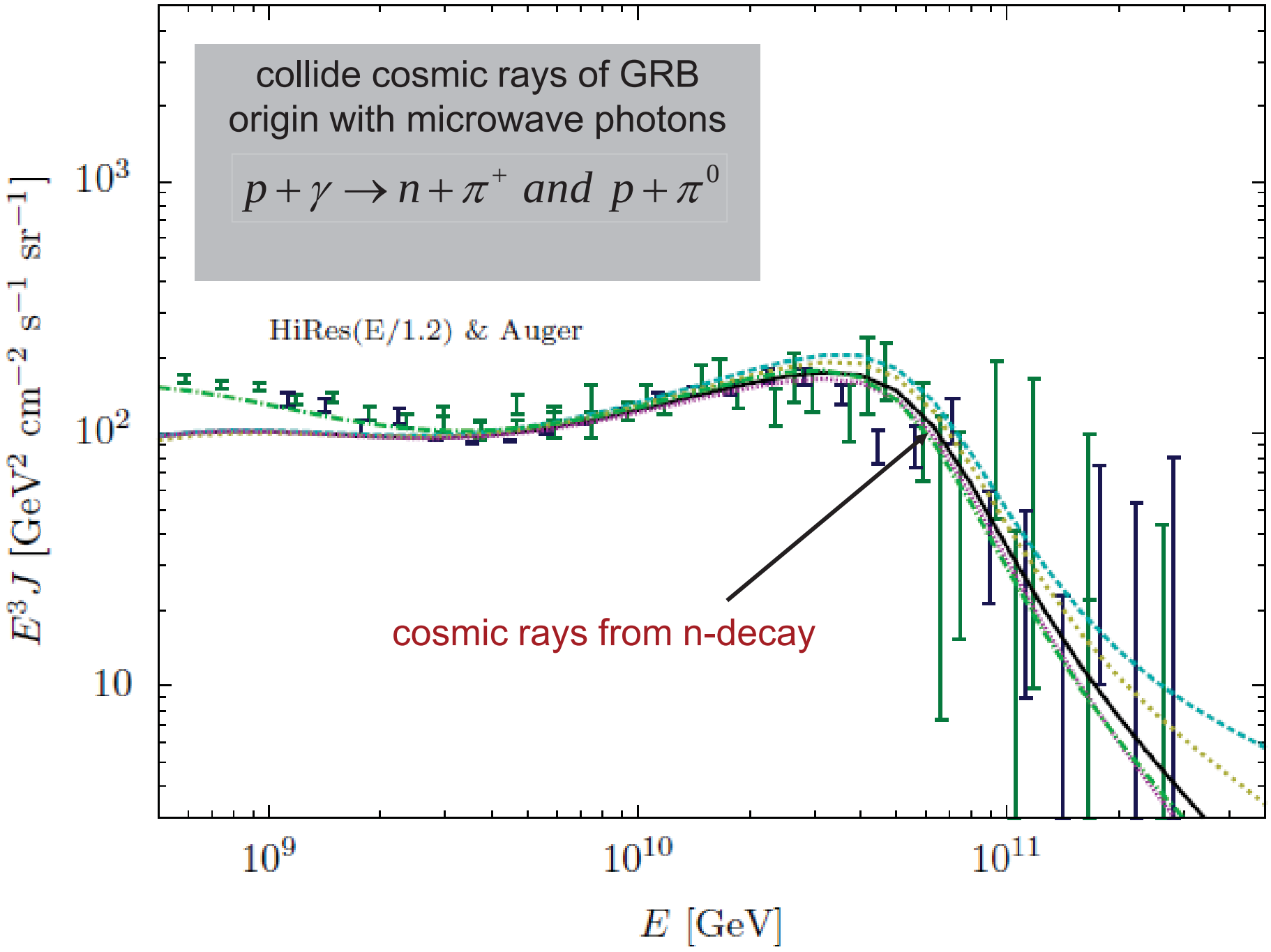
radiation

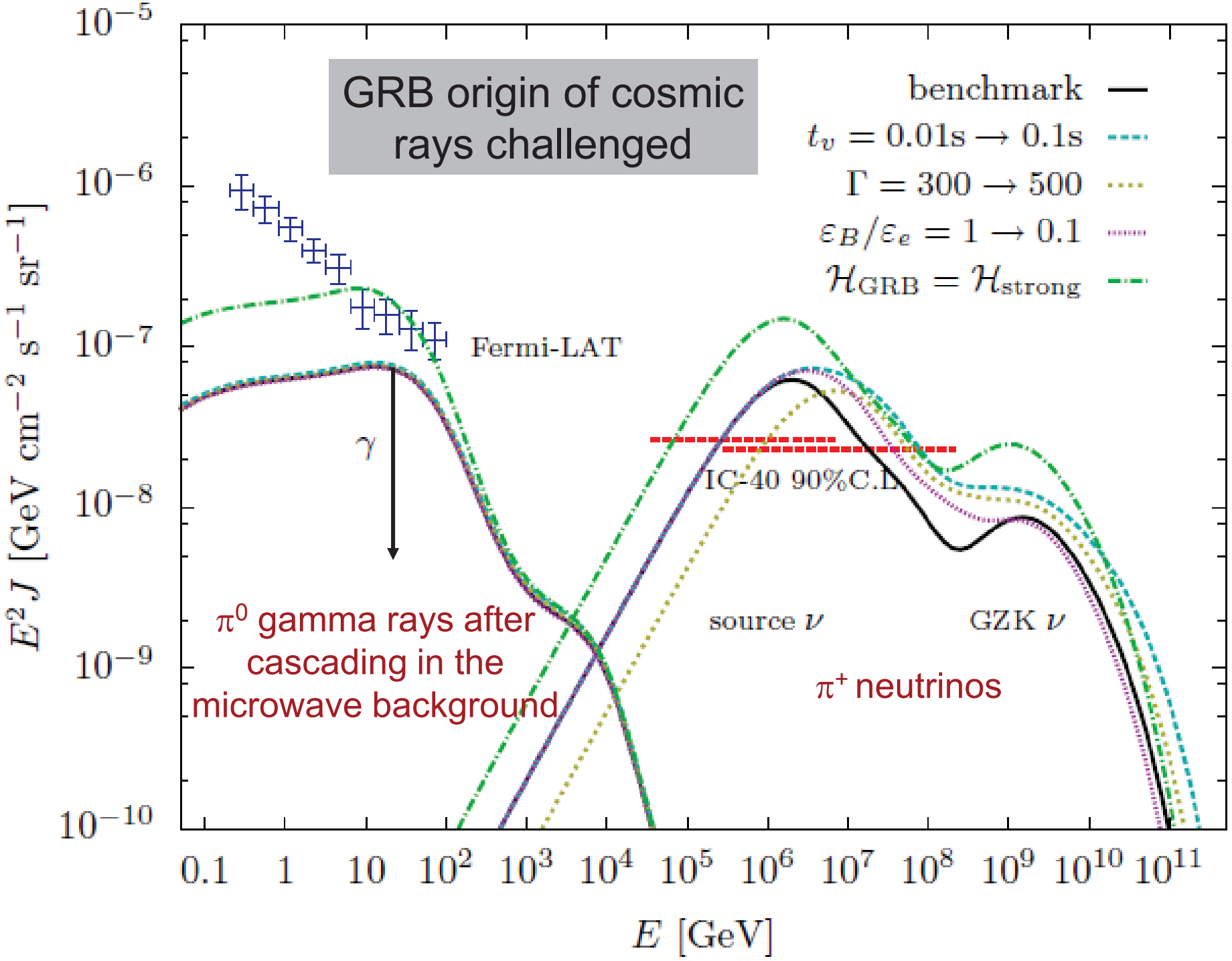
$p + \gamma \rightarrow n + \pi^+$

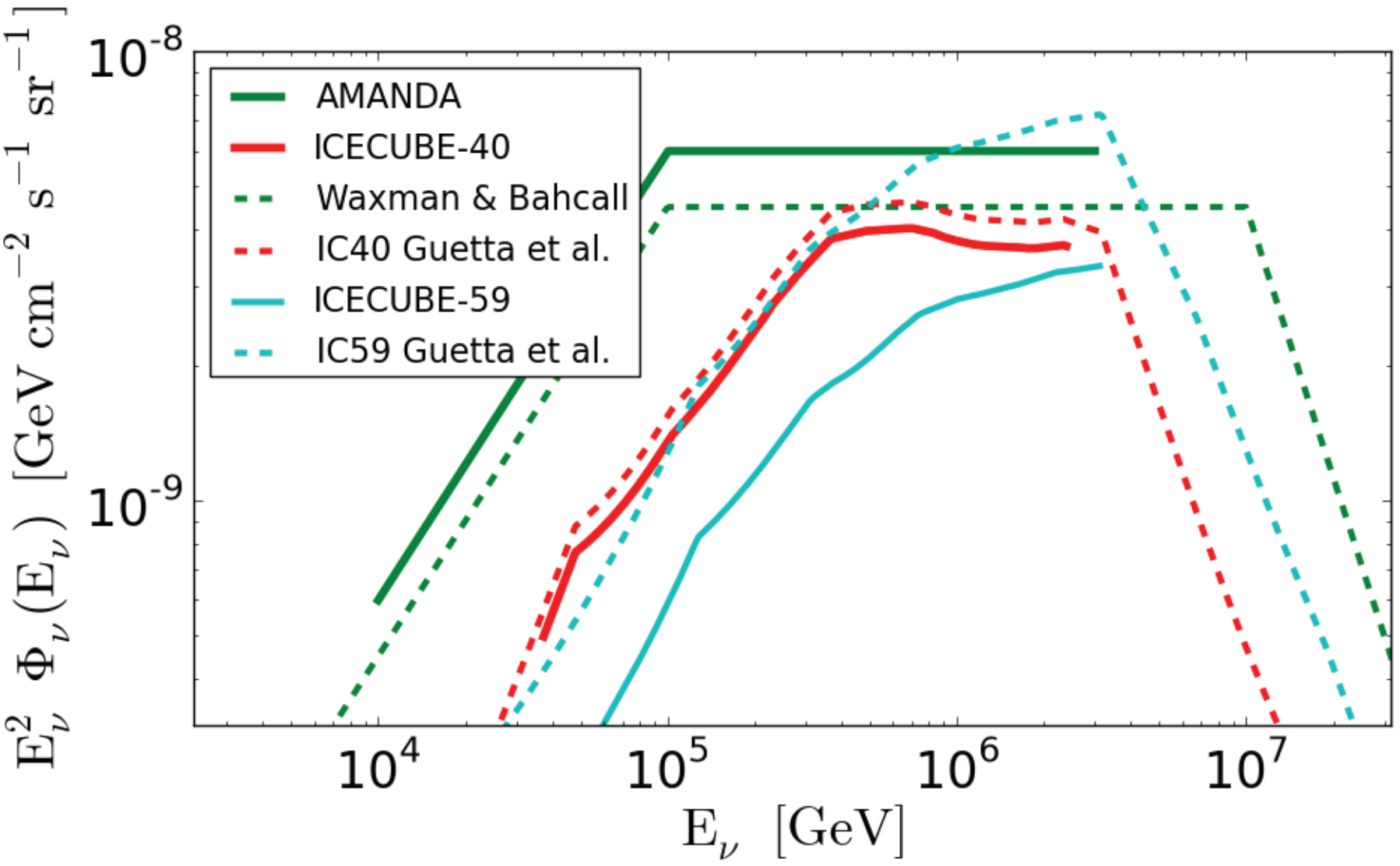
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma


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
$t_v = 0.01\text{s} \to 0.1\text{s}$
$\Gamma = 300 \to 500$
$\varepsilon_B/\varepsilon_e = 1 \to 0.1$
$\mathcal{H}_{\rm GRB} = \mathcal{H}_{\rm strong}$
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}


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}]

GRB on probation

- 3×10^{-19} erg/cm^3 over 10^{10} years
  $= 5 \times 10^{44}$ TeV Mpc^{-3} yr

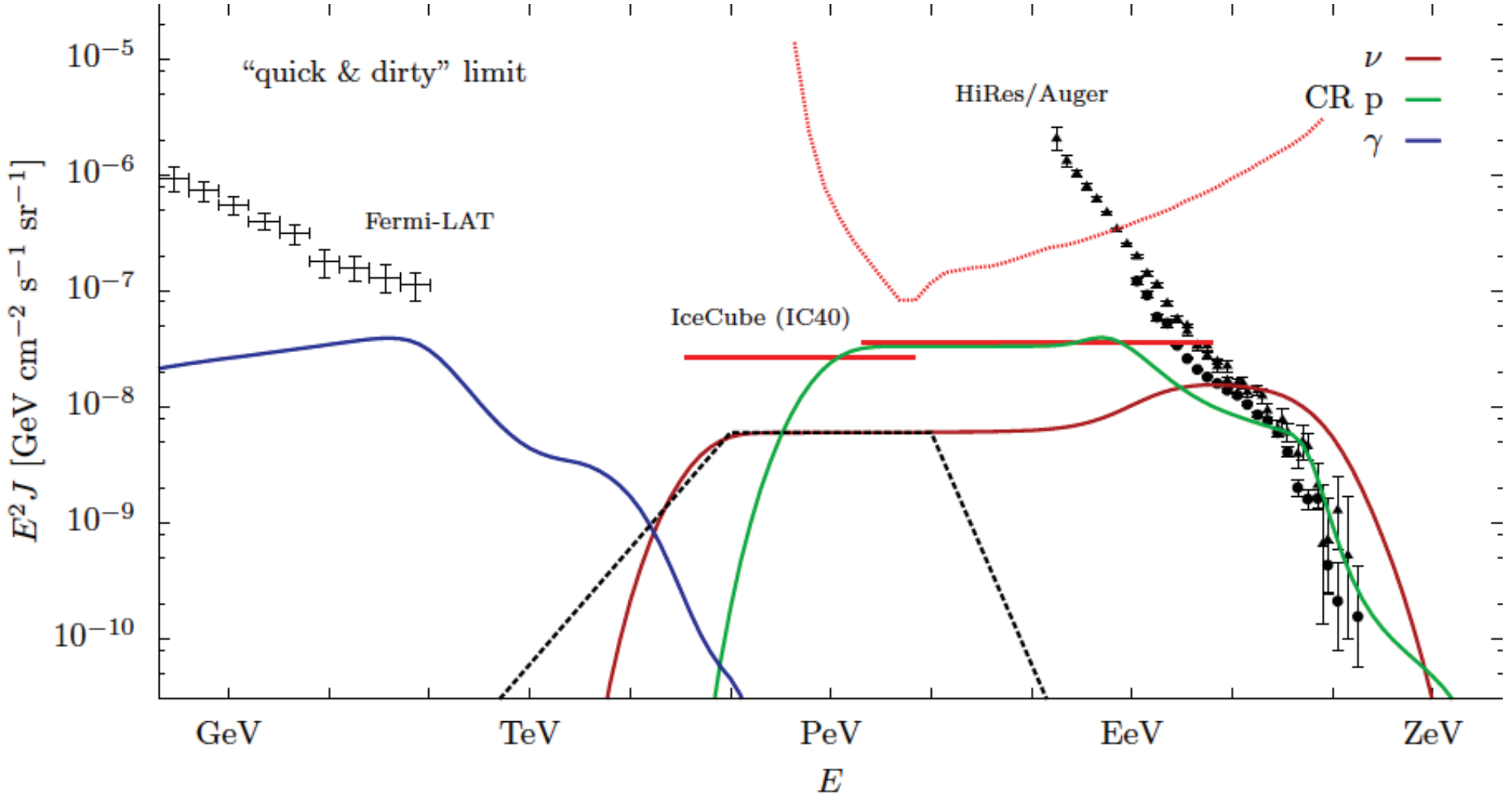
- reduce by ten
- more reasonable 2×10^{51} erg per GRB
- cannot explain the cosmic rays above the knee
- escape IceCube 40 string diffuse bound

→ new prediction for 40+59 2-year data

Waxman: 12.4 events

Guetta: 14.5 events

none seen



GRB only yield the highest energy particles, not the cosmic rays above the knee

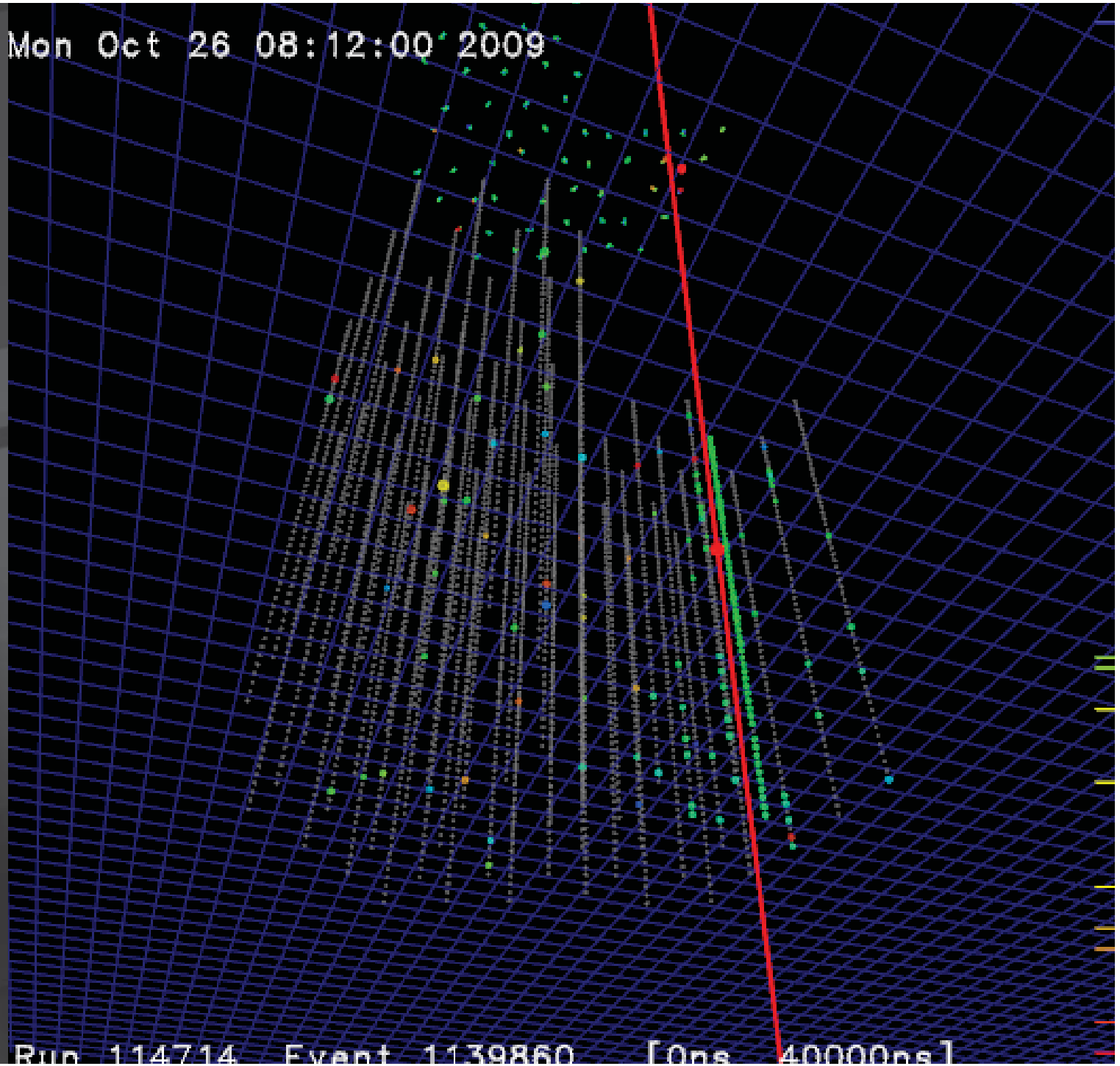
NOT a GRB

neutrino(?) within 40 s duration of the burst

azimuth of burst 87.11 deg

observed 87.97+/- 0.3

we keep looking !!!



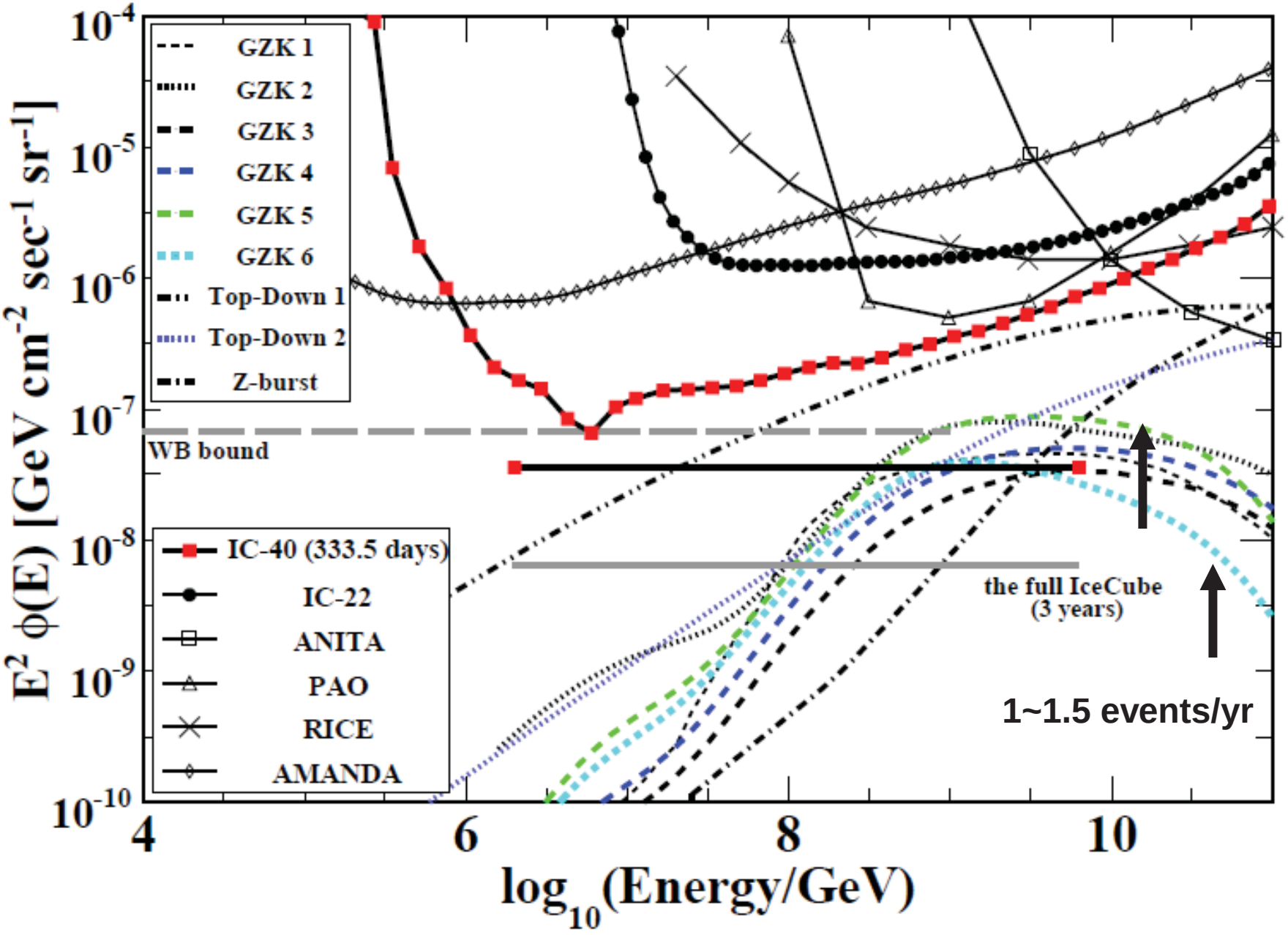
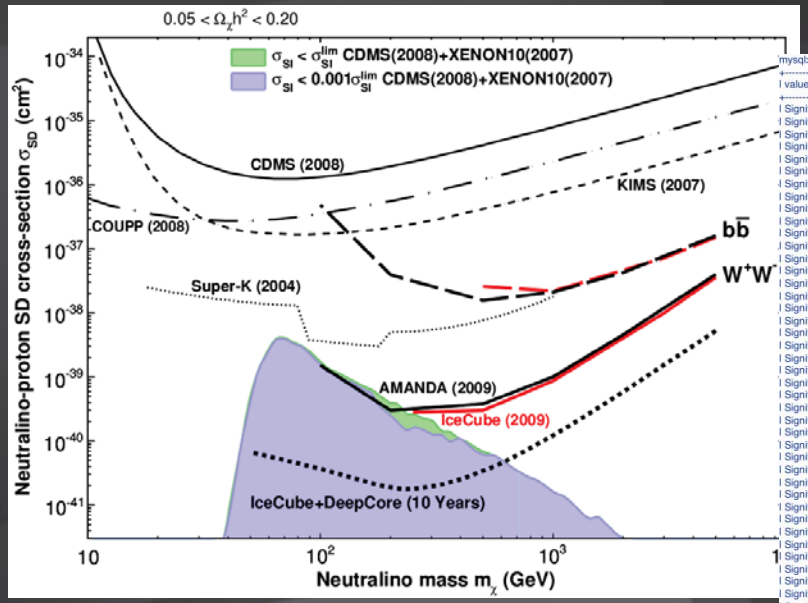
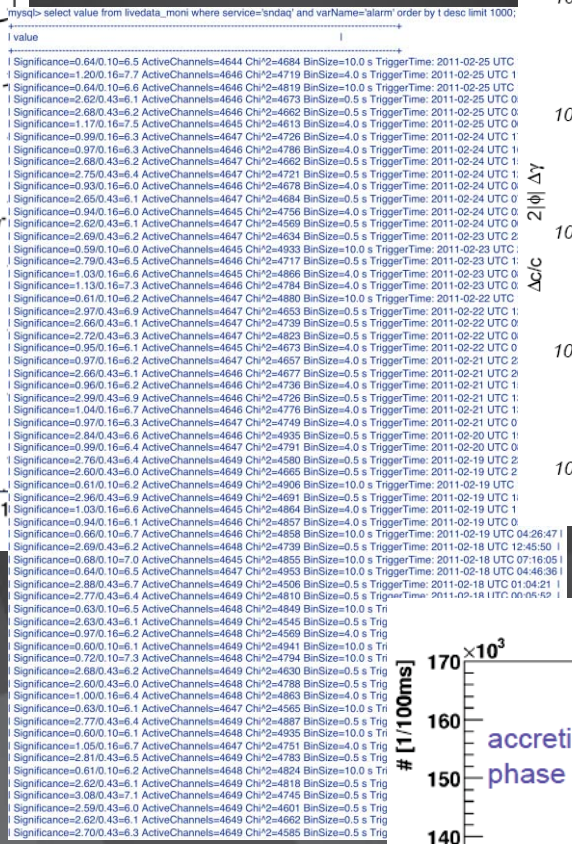
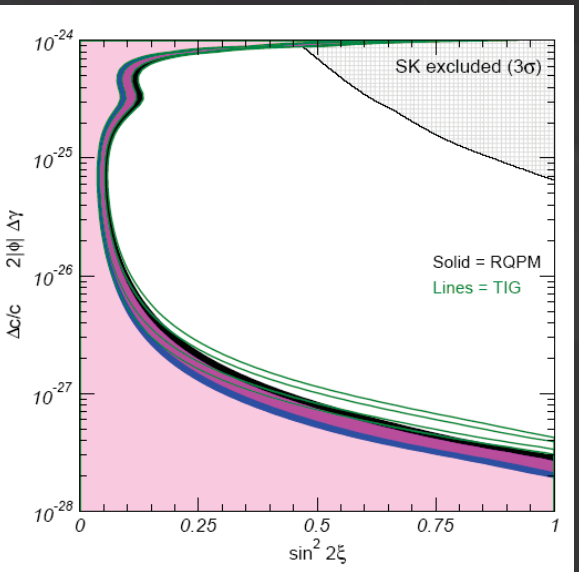

GZK 1
GZK 2
GZK 3
GZK 4
GZK 5
GZK 6
Top-Down 1
Top-Down 2
Z-burst
WB bound
IC-40 (333.5 days)
IC-22
ANITA
PAO
RICE
AMANDA
the full IceCube
(3 years)
1~1.5 events/yr
$E^2 \phi(E)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
$\log_{10}$(Energy/GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
4
6
8
10

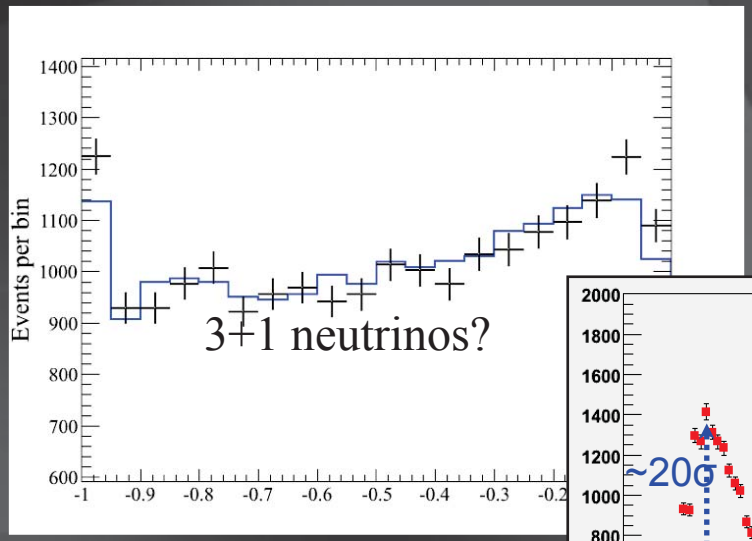
Table 3: *Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight and IceCube-40[54] (IC40, 2008-09) results with predicted events for a three-year exposure for ARA-37.*

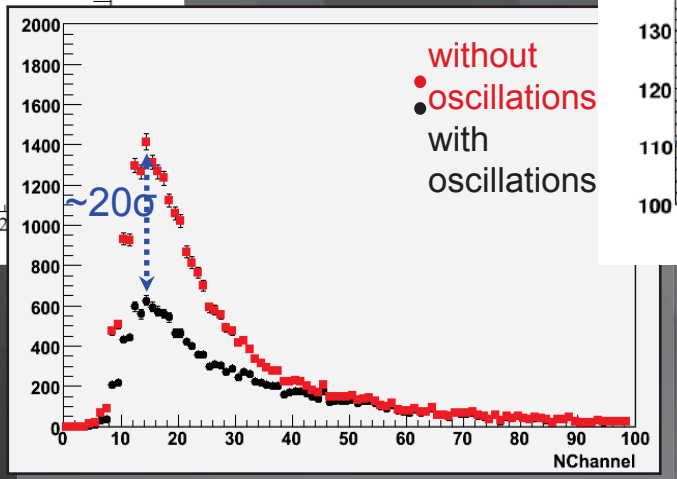
Model & references N_ν:	ANITA (2008)	IC40 0.9 yr	ARA 3 yrs
Baseline cosmogenic models:			
Protheroe & Johnson 1996[45]	0.6	0.5	59
Engel, Seckel, Stanev 2001[46]	0.33	0.4	47
Kotera *et al.* 2010[47]	0.5	0.33	59
Strong source evolution models:			
Engel, Seckel, Stanev 2001[46]	1.0	1.12	148
Kalashev *et al.* 2002[48]	5.8	0.98	146
Barger *et al.* 2006[50]	3.5	6.2	154
Yuksel & Kistler 2007[51]	1.7	1.7	221
Mixed-Iron-Composition:			
Ave *et al.* 2005[52]	0.01	0.05	6.6
Stanev 2008[53]	0.0002	0.013	1.5
Kotera *et al* 2010[47] upper	0.08	0.64	11.3
Kotera *et al.* 2010[47] lower	0.005	0.04	4.1
Fermi cascade-bounded models:			
Ahlers *et al.* 2010[55]	0.09	0.43	20.7

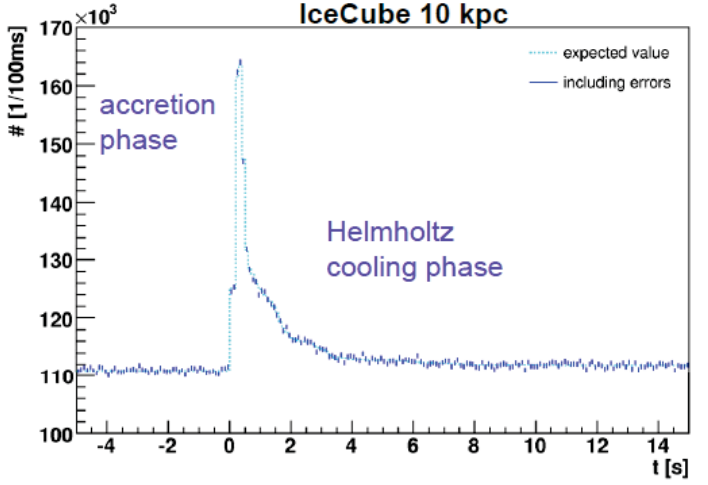




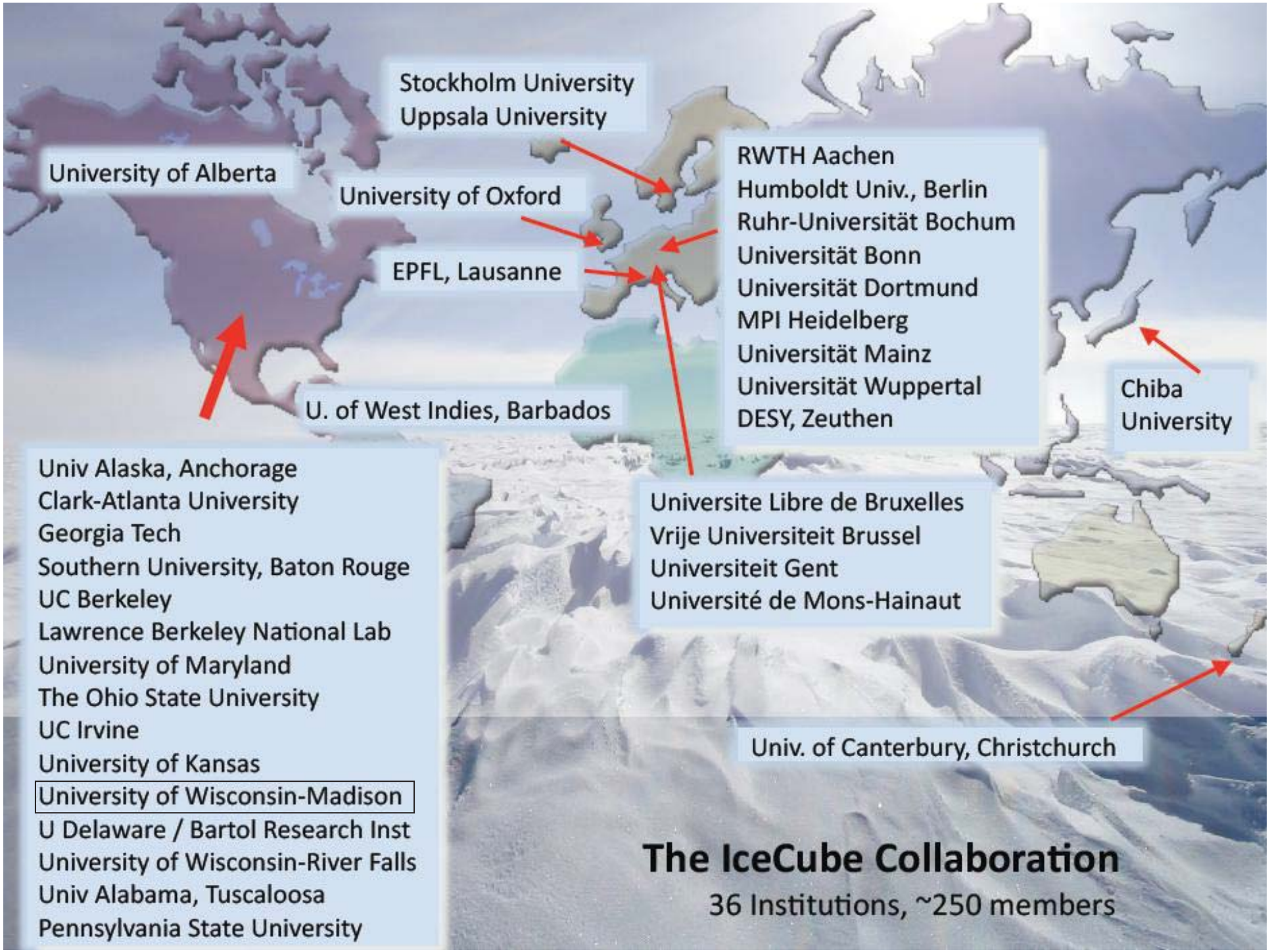




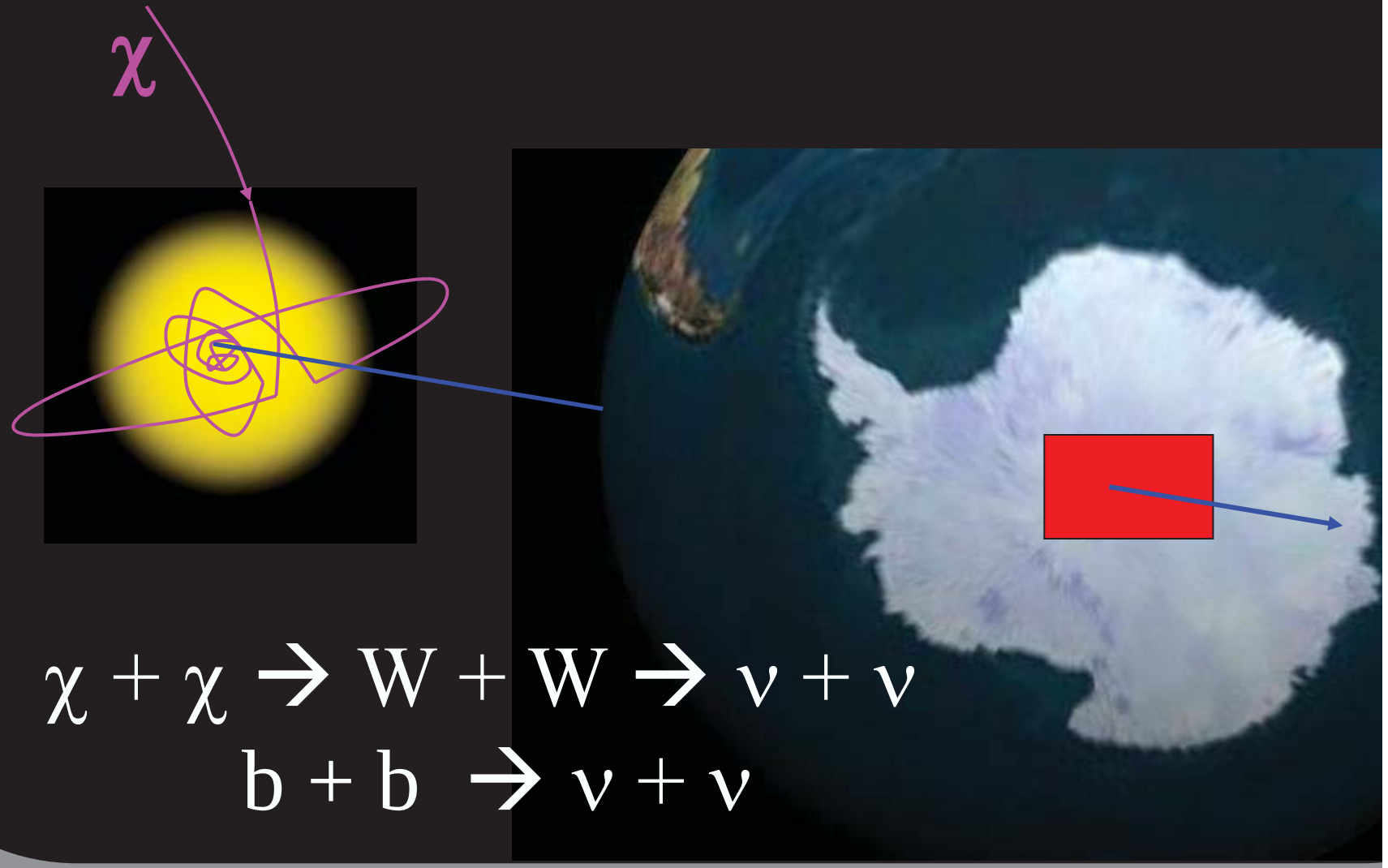




IceCube science

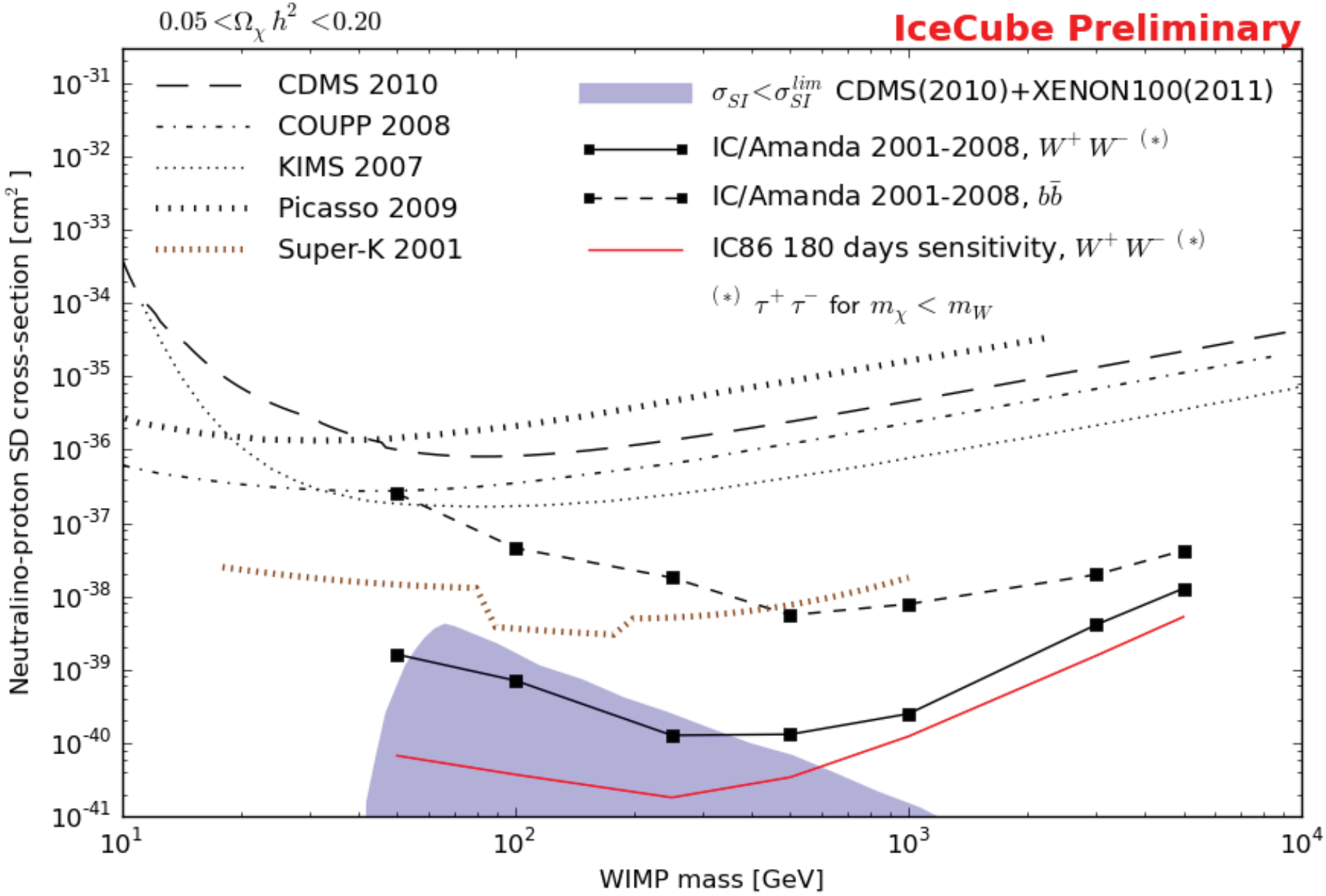

Stockholm University
Uppsala University
University of Alberta
University of Oxford
EPFL, Lausanne
RWTH Aachen
Humboldt Univ., Berlin
Ruhr-Universität Bochum
Universität Bonn
Universität Dortmund
MPI Heidelberg
Universität Mainz
Universität Wuppertal
DESY, Zeuthen
Chiba University
U. of West Indies, Barbados
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

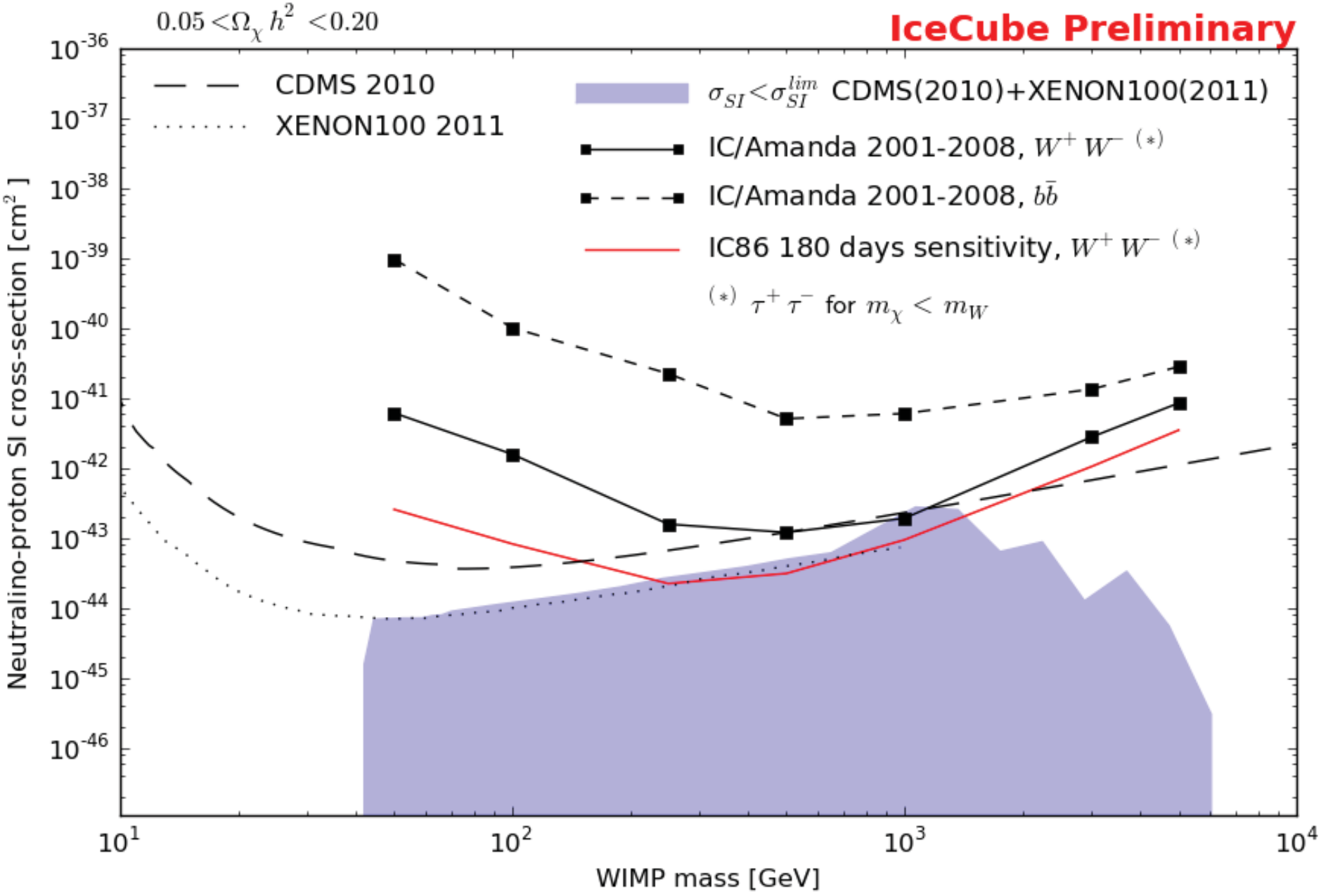
WIMP Capture and Annihilation



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

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

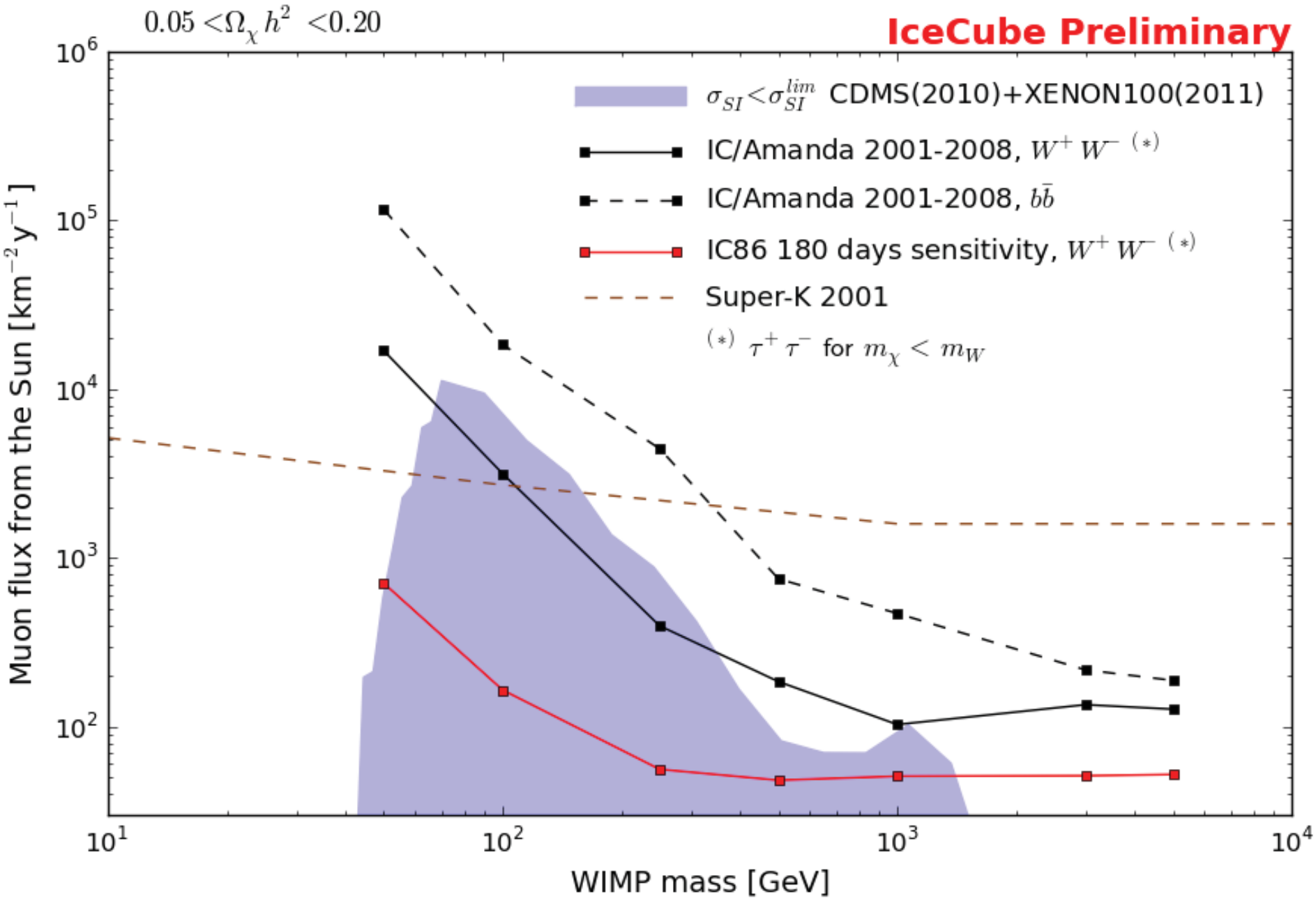

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
COUPP 2008
KIMS 2007
Picasso 2009
Super-K 2001
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, W^+W^- $(*)$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, W^+W^- $(*)$
$(*)$ $\tau^+\tau^-$ for $m_\chi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

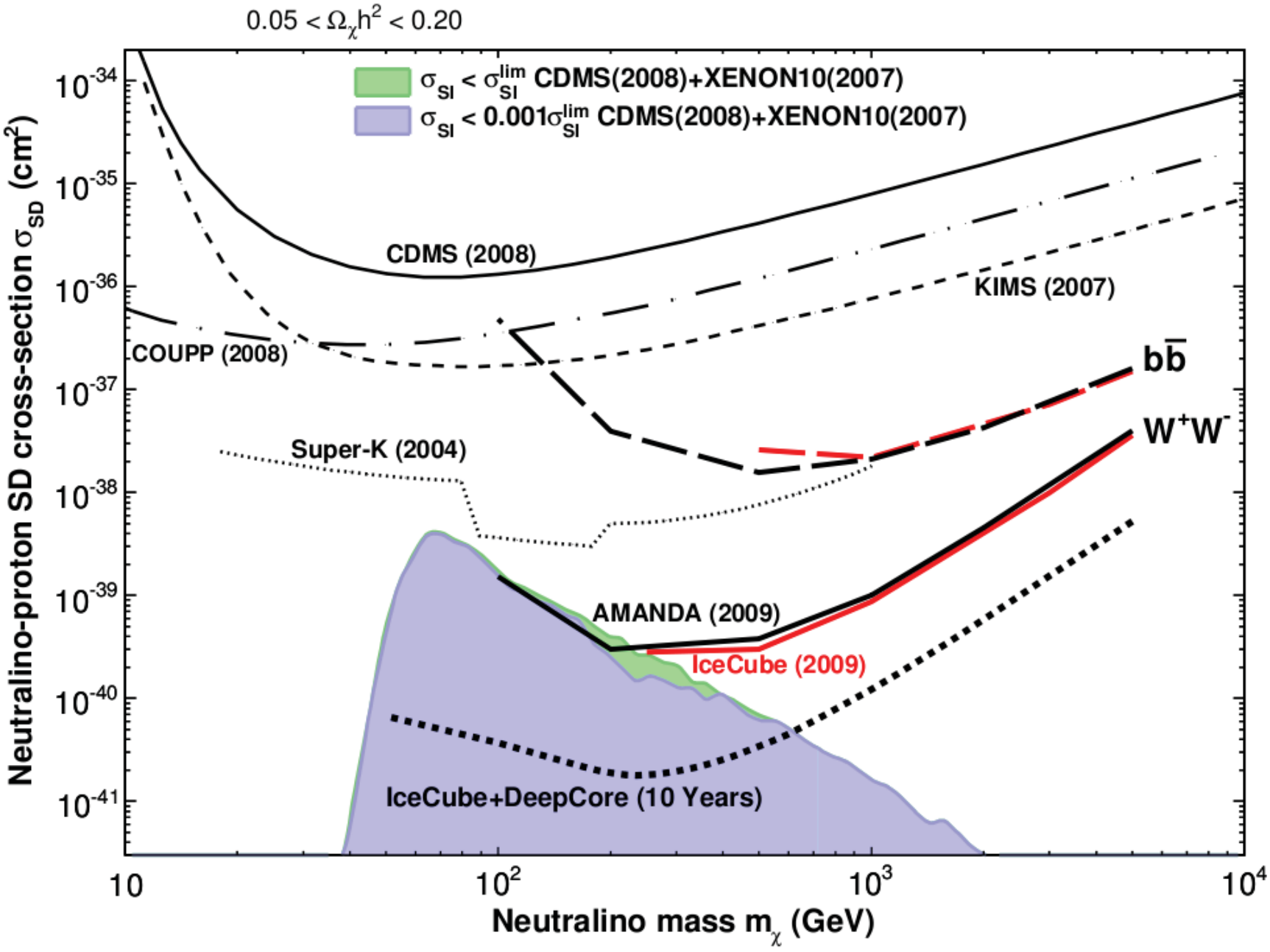

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
XENON100 2011
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, $W^+ W^-$ $^{(*)}$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, $W^+ W^-$ $^{(*)}$
$^{(*)}$ $\tau^+ \tau^-$ for $m_\chi < m_W$
Neutralino-proton 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

conclusions

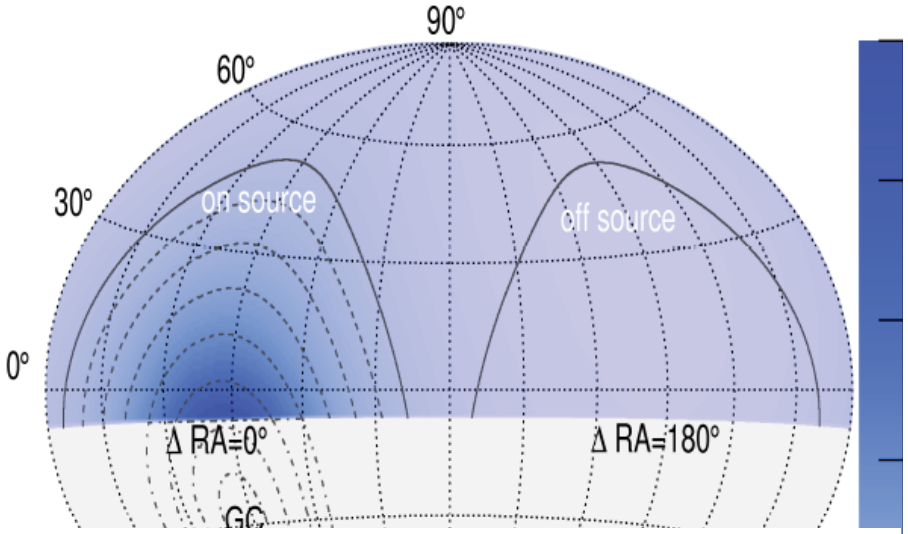
- Hess 1912…. and still no conclusion
- the instrumentation is in place …
- … supernova remnants and GRB are in close range !

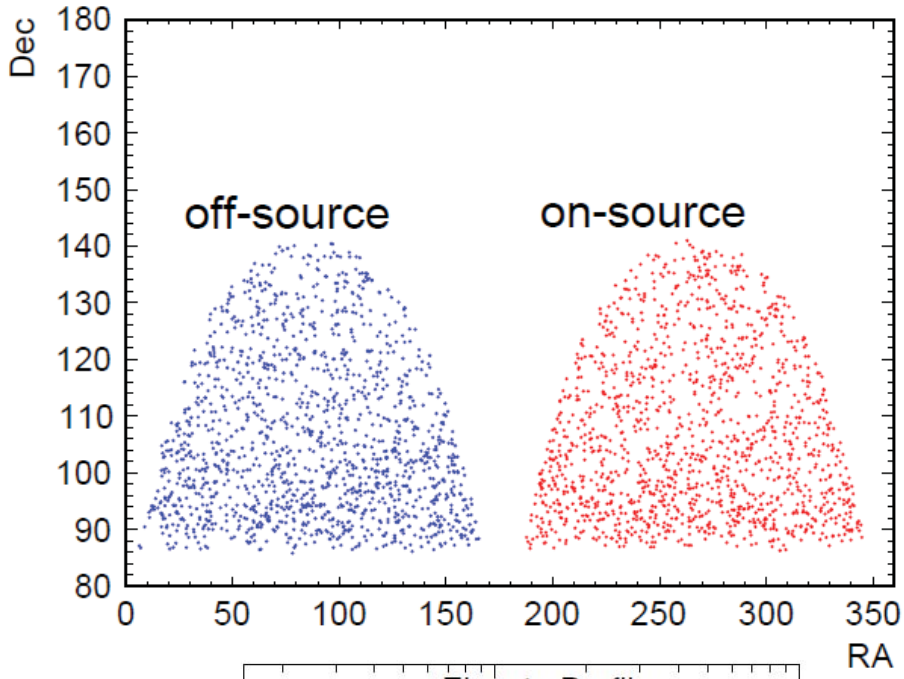
back up slides

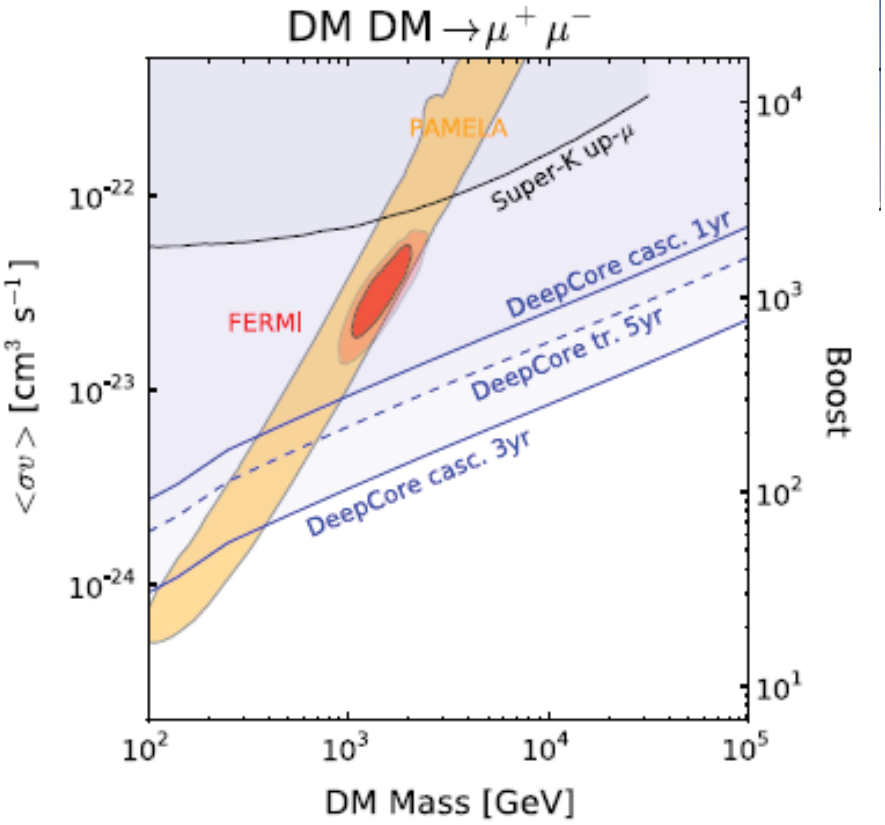

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, W^+W^- $(*)$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, W^+W^- $(*)$
Super-K 2001
$(*)$ $\tau^+\tau^-$ for $m_\chi < m_W$
Muon flux from the Sun [km^{-2}y^{-1}]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

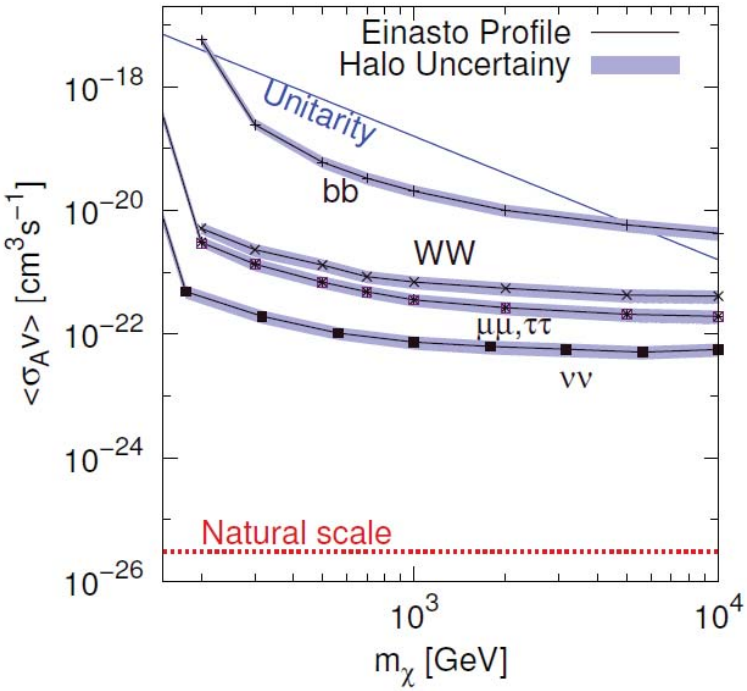


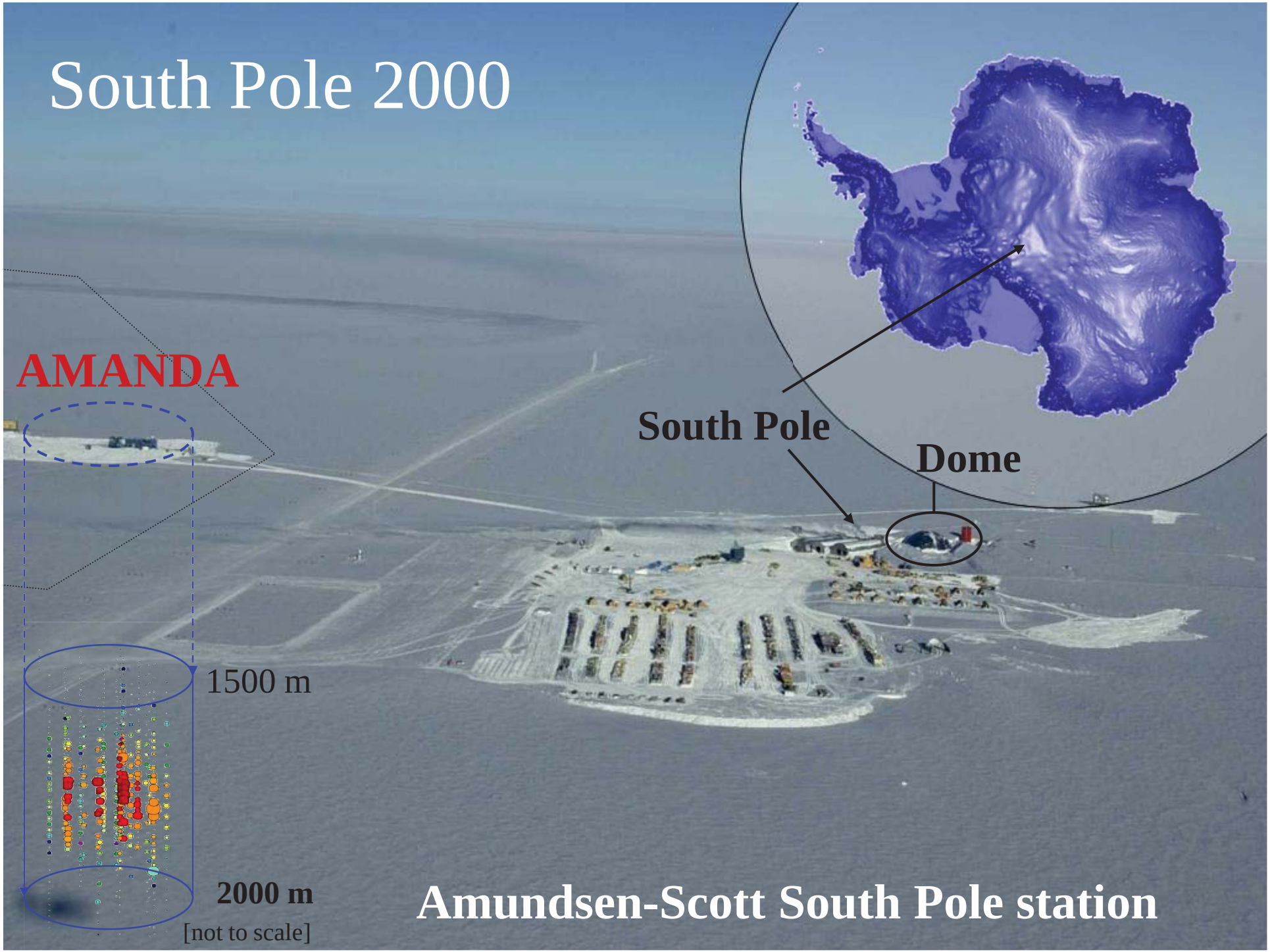
arXiv:0906.1615


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 Uncertainty
Unitarity
bb
WW
μμ,ττ
νν
Natural scale
<σ_A v> [cm³s⁻¹]
m_χ [GeV]


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

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

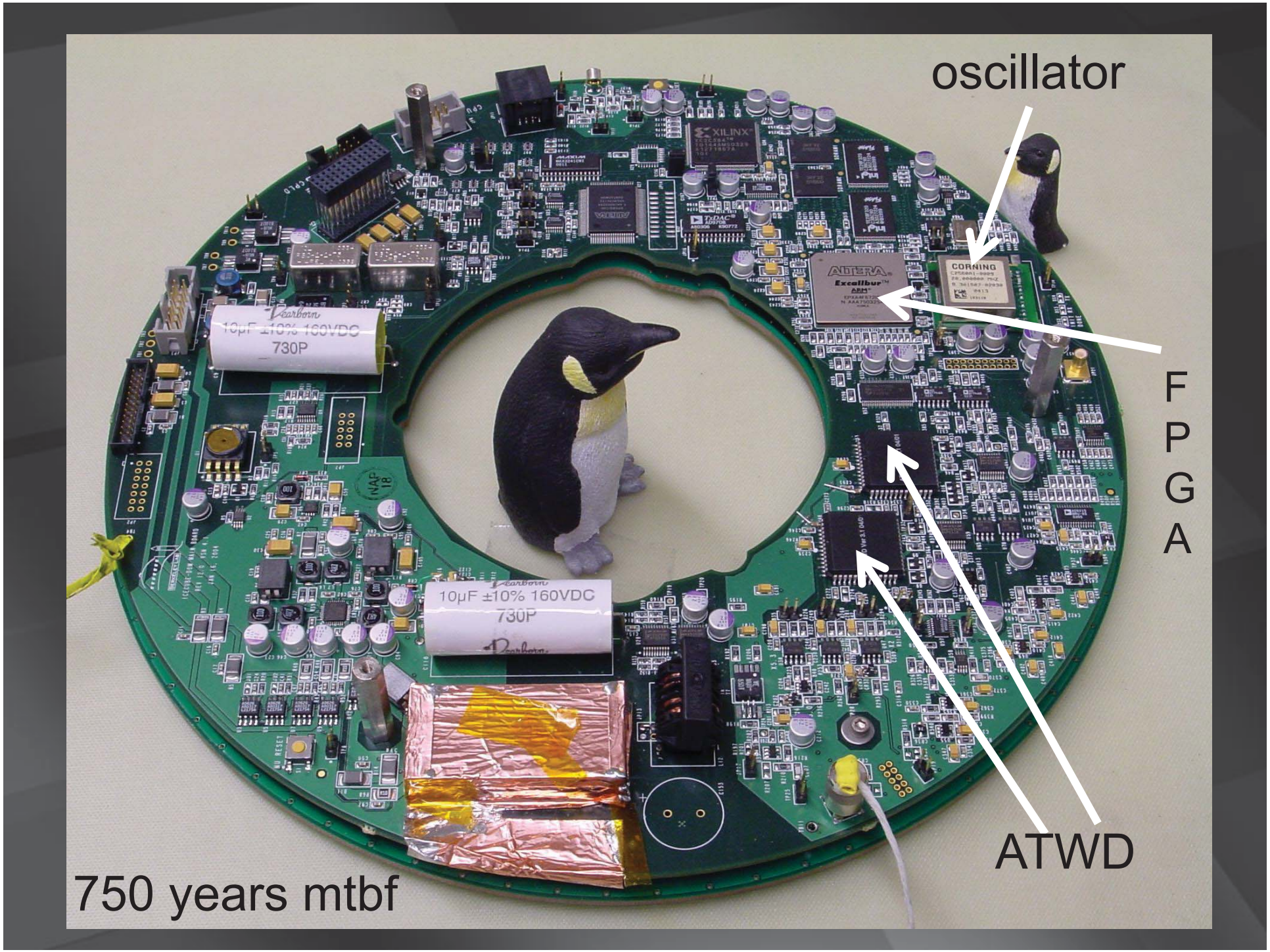
WHAT DO WE REALLY NEED?

- 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

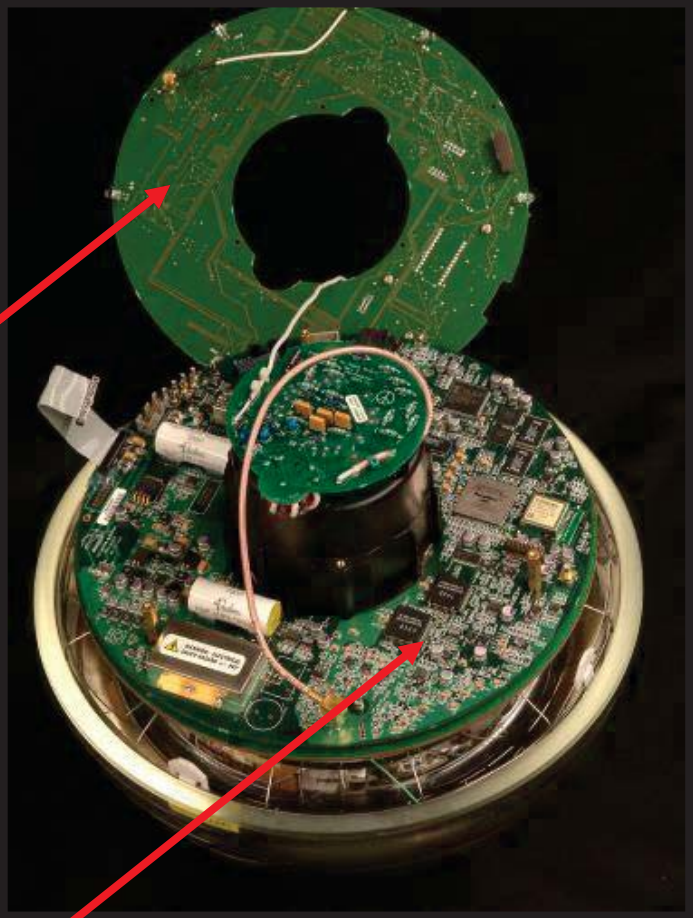
Each optical module must become a complete semi-autonomous data acquisition platform, linked in an all digital decentralized network

- “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?”


oscillator
FPGA
ATWD
750 years mtbf
XILINX
ALTERA
Excalibur
CORNING
Dearborn
10µF ±10% 160VDC
730P

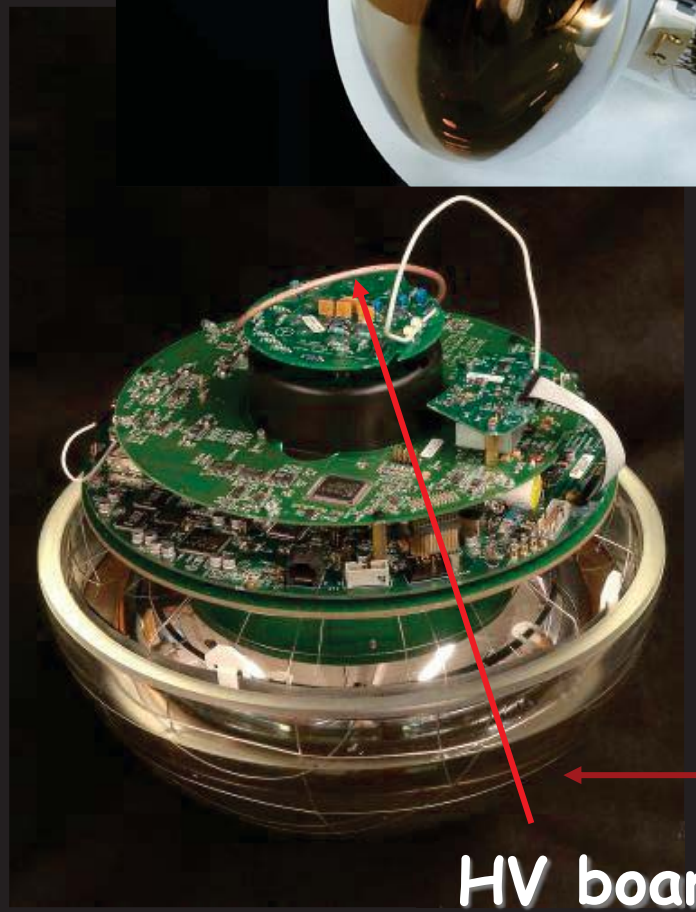
architecture of independent DOMs

10 inch pmt

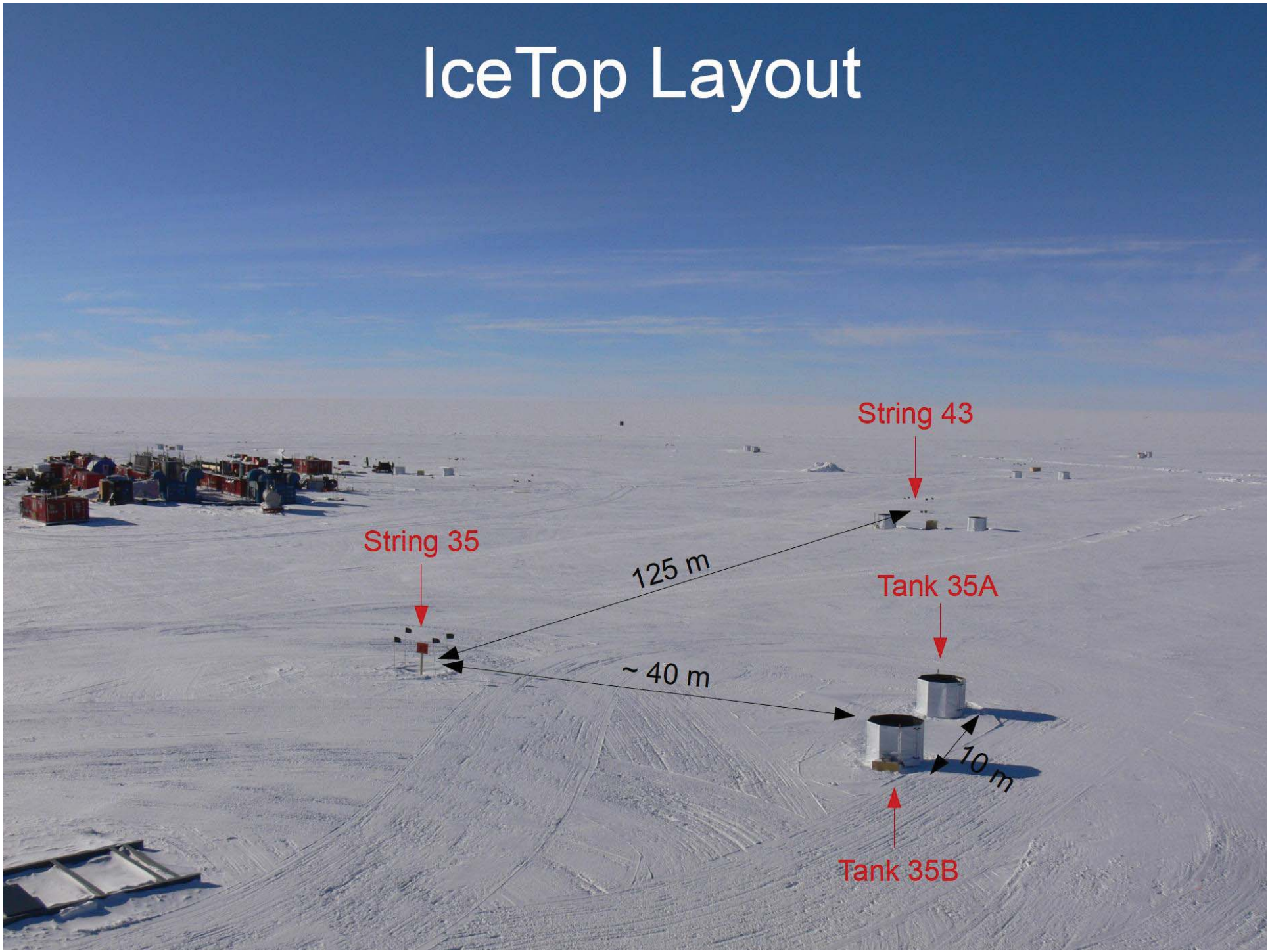


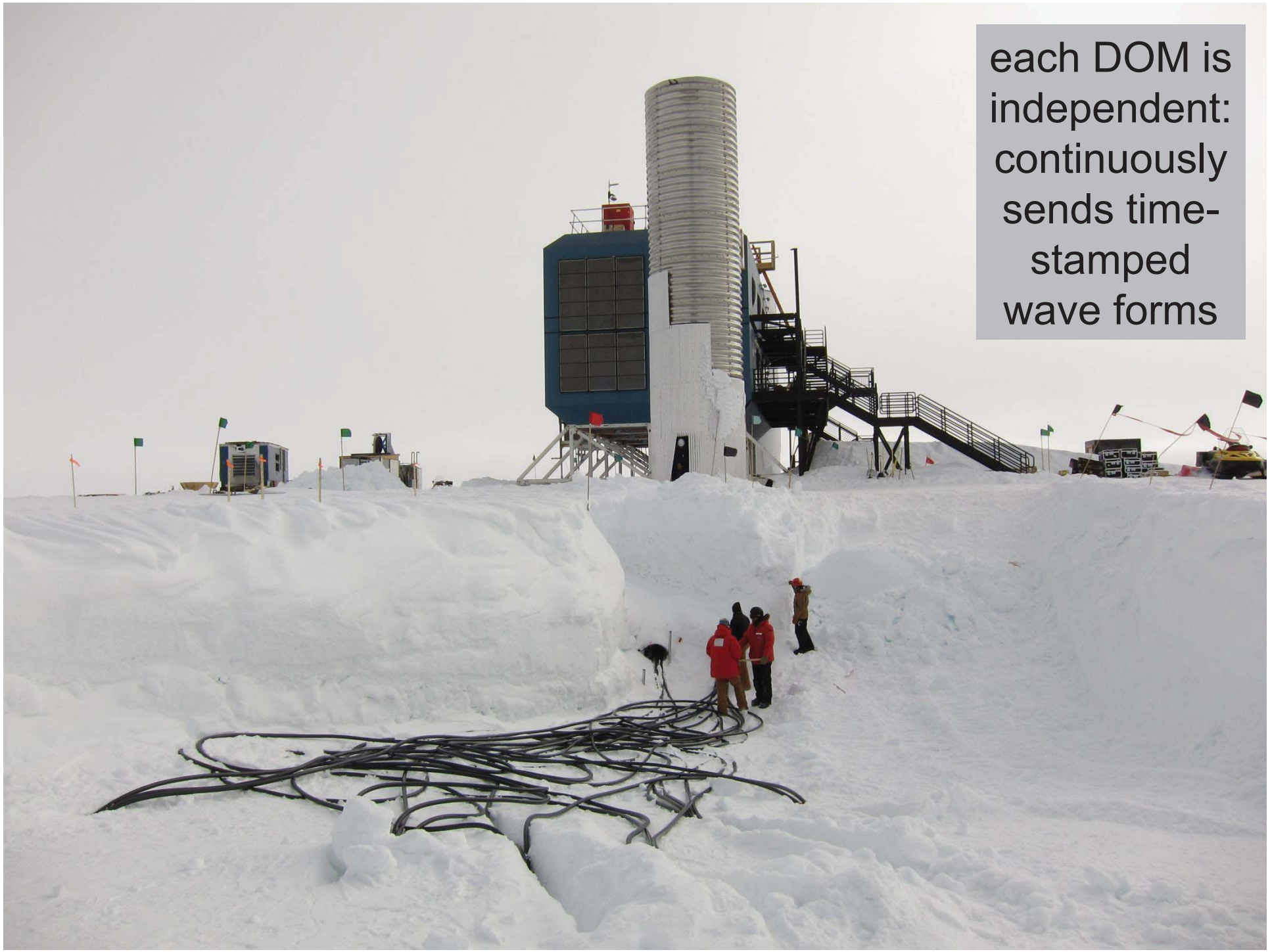
LED flasher board

main board

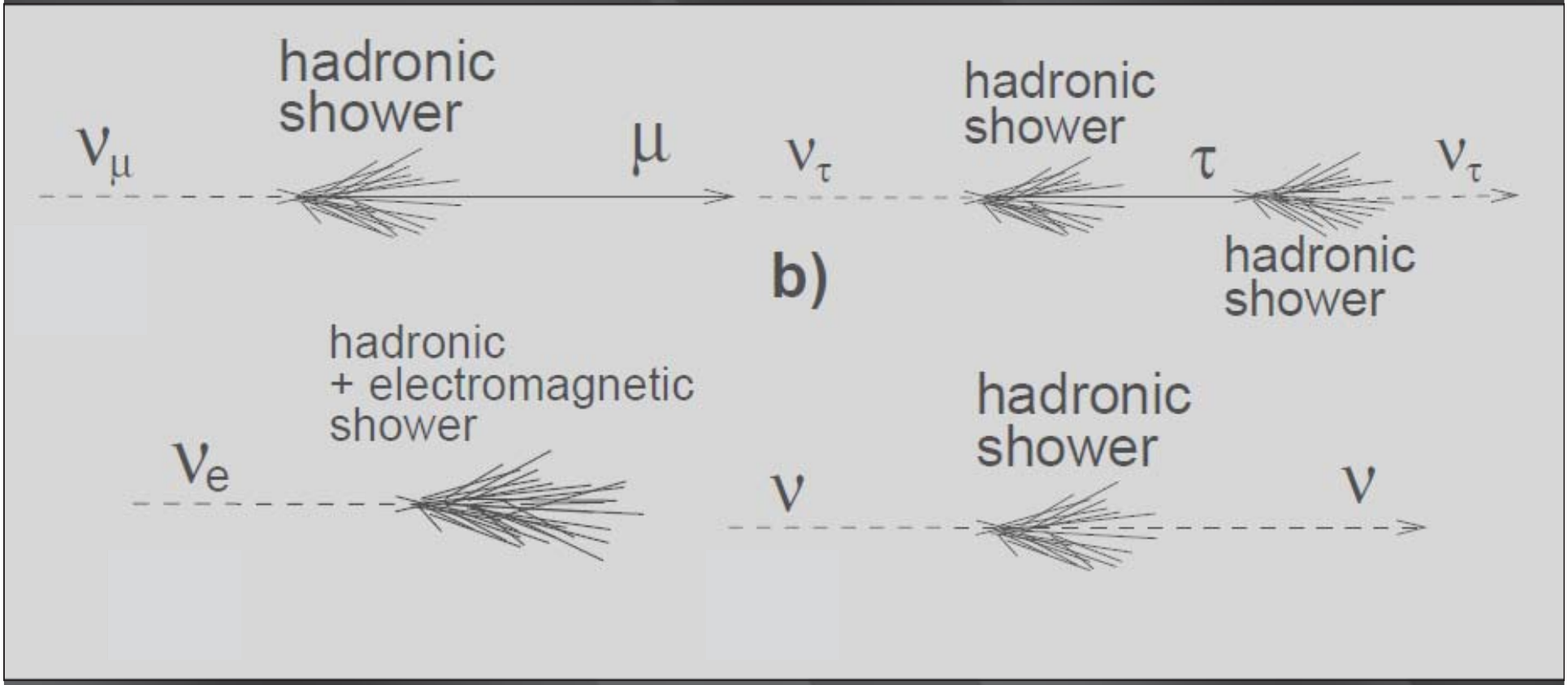


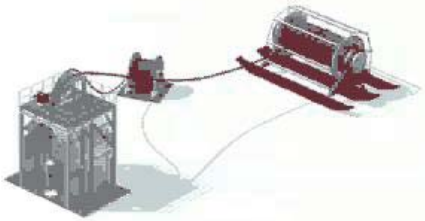
HV board


IceTop Layout
String 43
String 35
125 m
Tank 35A
~ 40 m
10 m
Tank 35B


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

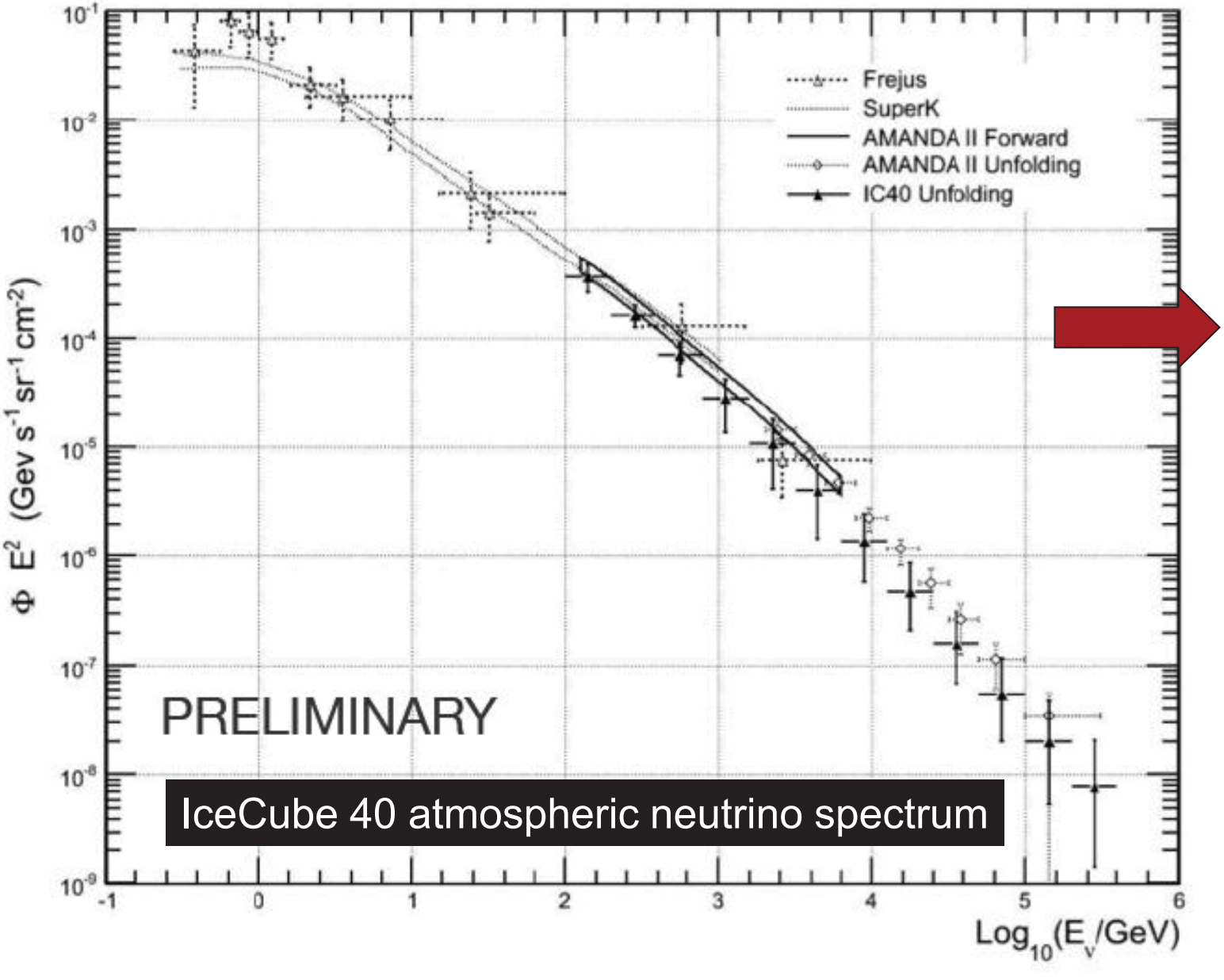
neutrino flavors

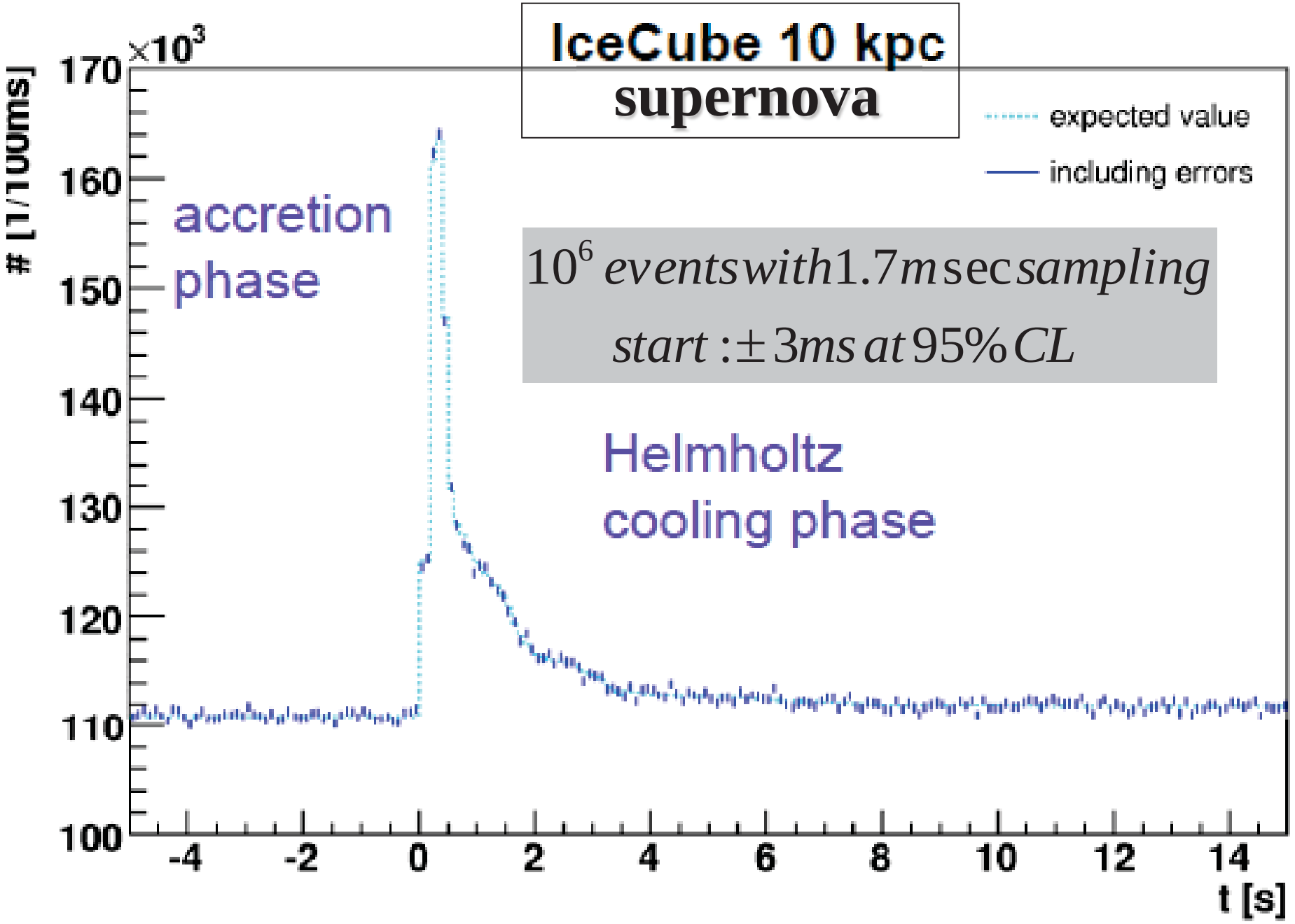




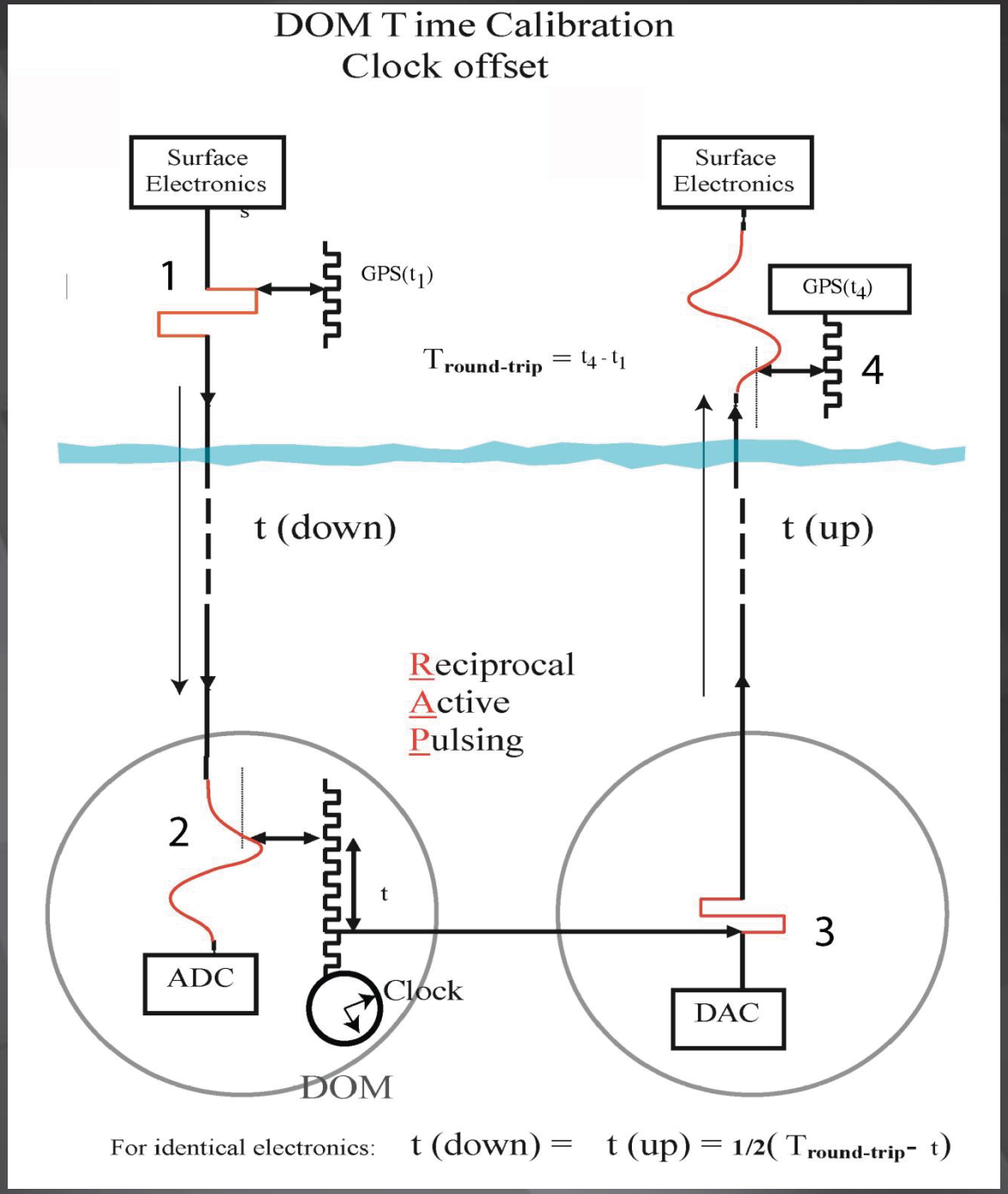
cosmic neutrinos:

energy: >> 100 TeV

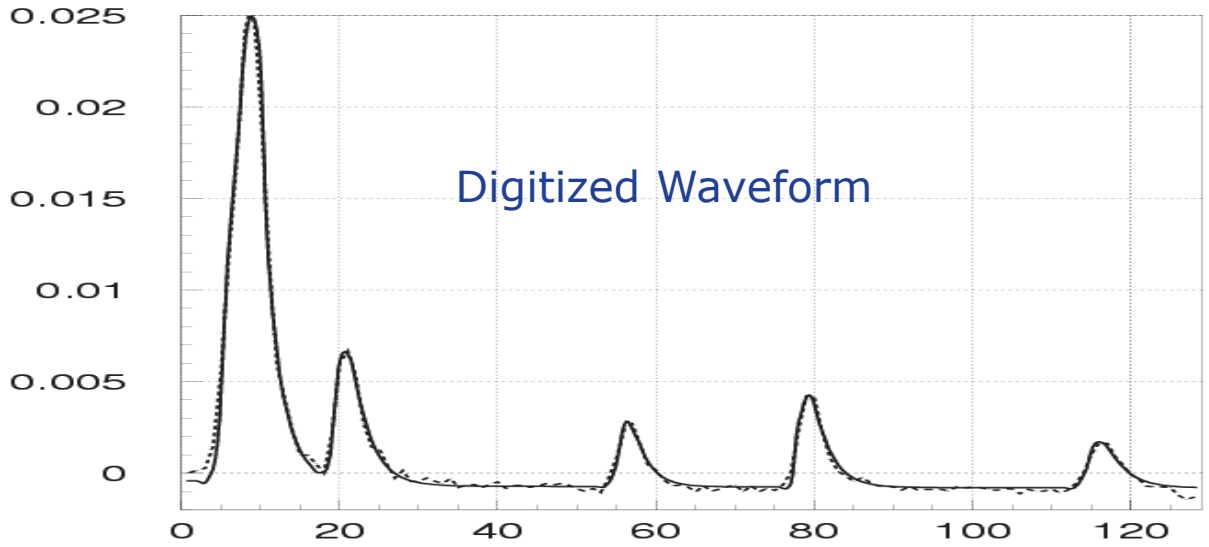



IceCube 10 kpc
supernova
expected value
including errors
accretion
phase
10^6 events with 1.7 msec sampling
start : ± 3ms at 95% CL
Helmholtz
cooling phase
[1/1ums]
×10^3
170
160
150
140
130
120
110
100
-4
-2
0
2
4
6
8
10
12
14
t [s]

2 nanosecond timing across 1 km^3

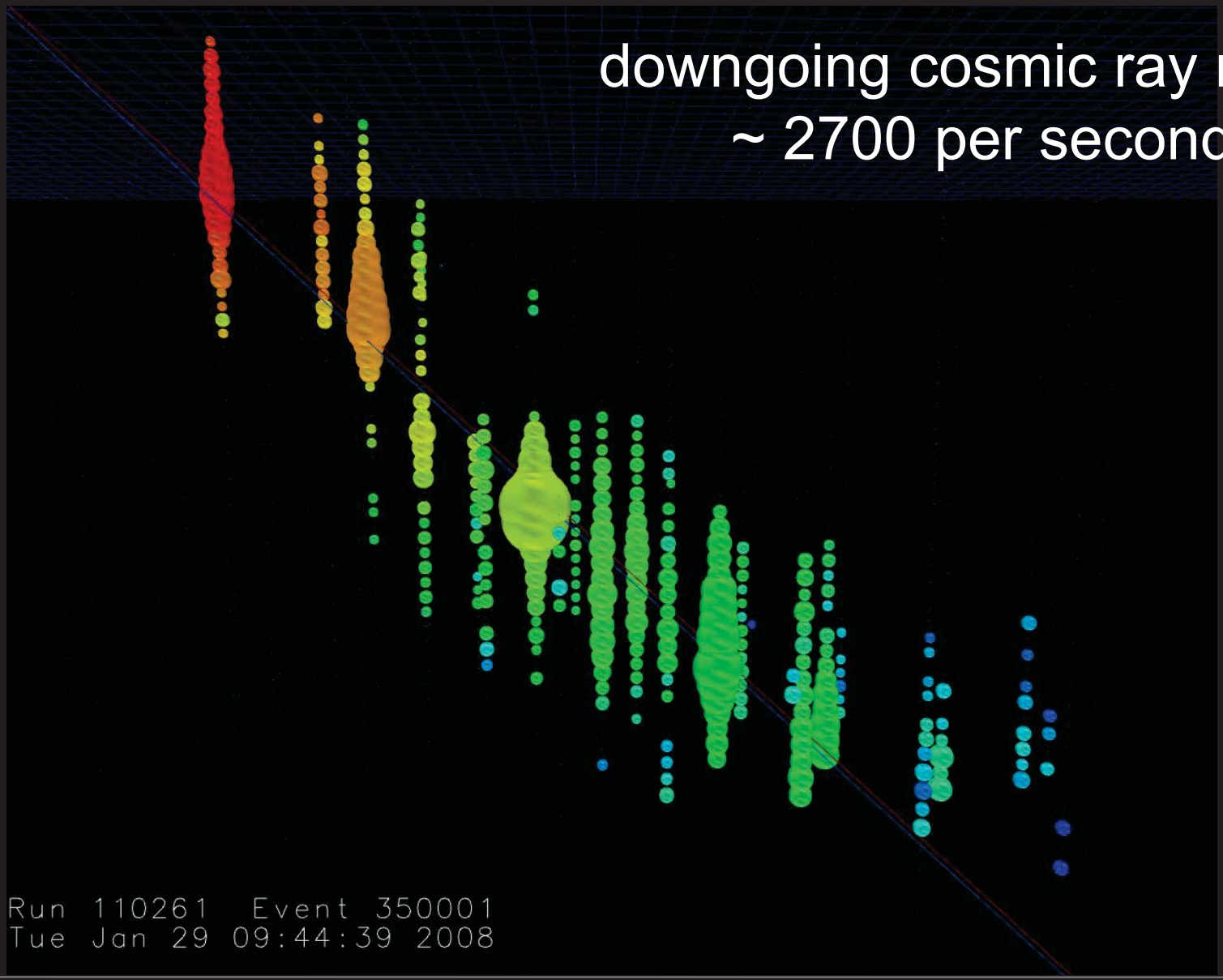


The Digital Optical Module (DOM)



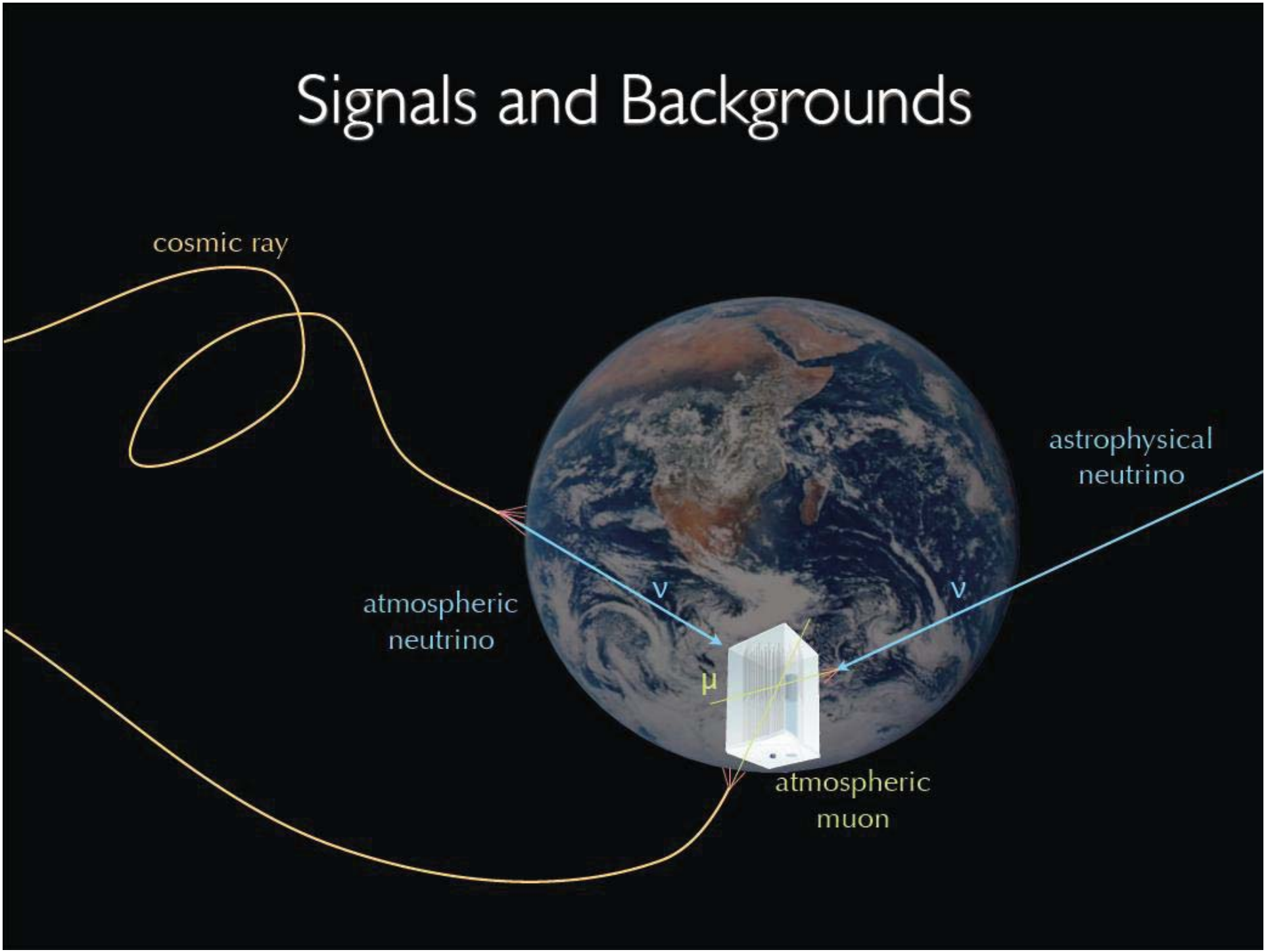
- Onboard capture of PMT waveforms
  - 300 MHz for ~400 ns with custom chip
  - 40 MHz for 6.4 μsec with comm. fast ADC
- Absolute timing resolution < 2 ns (RMS)
- Dynamic range ~1000 p.e./10 ns
- Deadtime < 1%
- Noise rate ~700 Hz (260 Hz w/ artif. deadtime)
- Failure rate < 1%

Muon event in IceCube

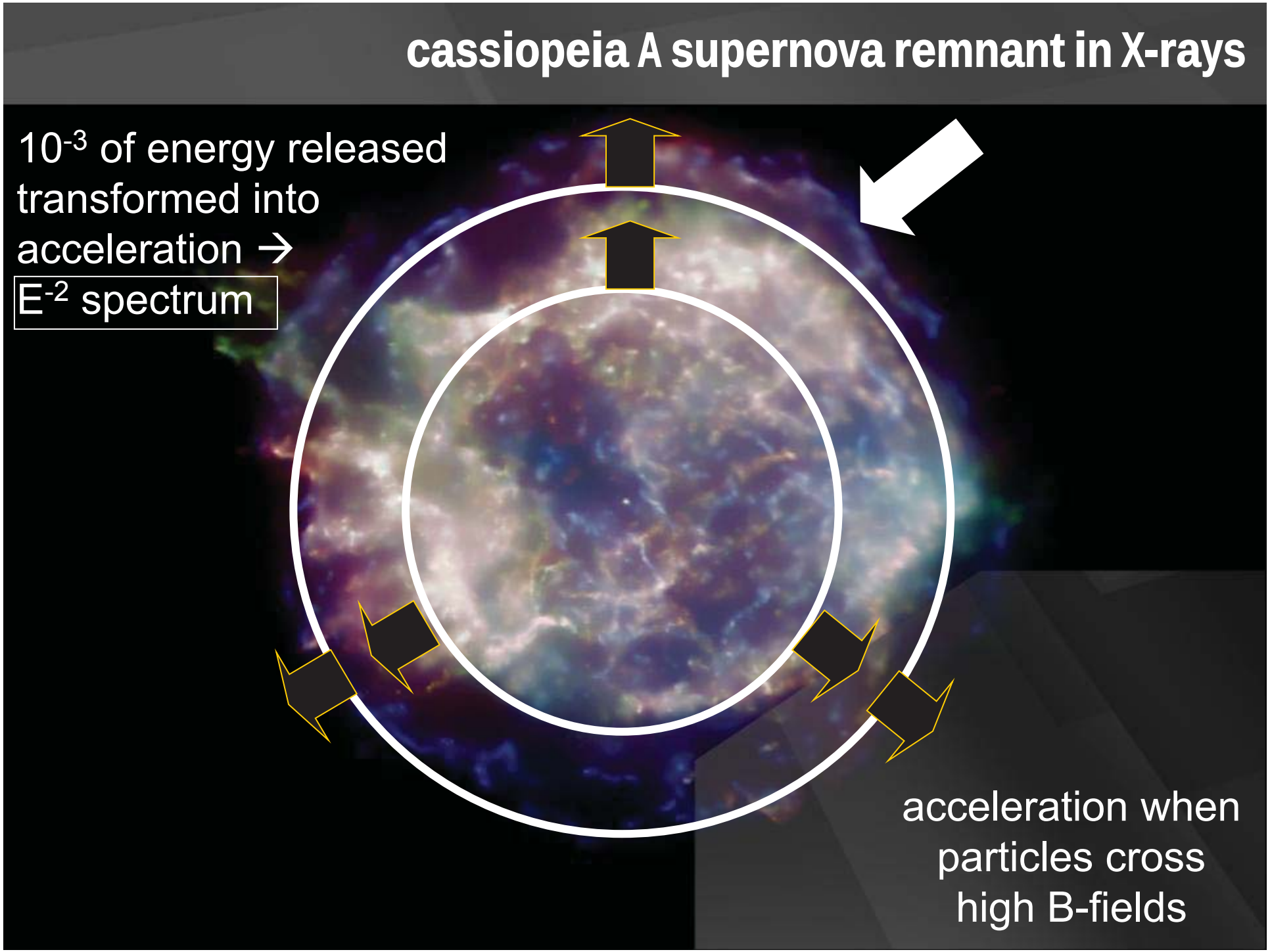


downgoing cosmic ray muon
~ 2700 per second

Signals and Backgrounds



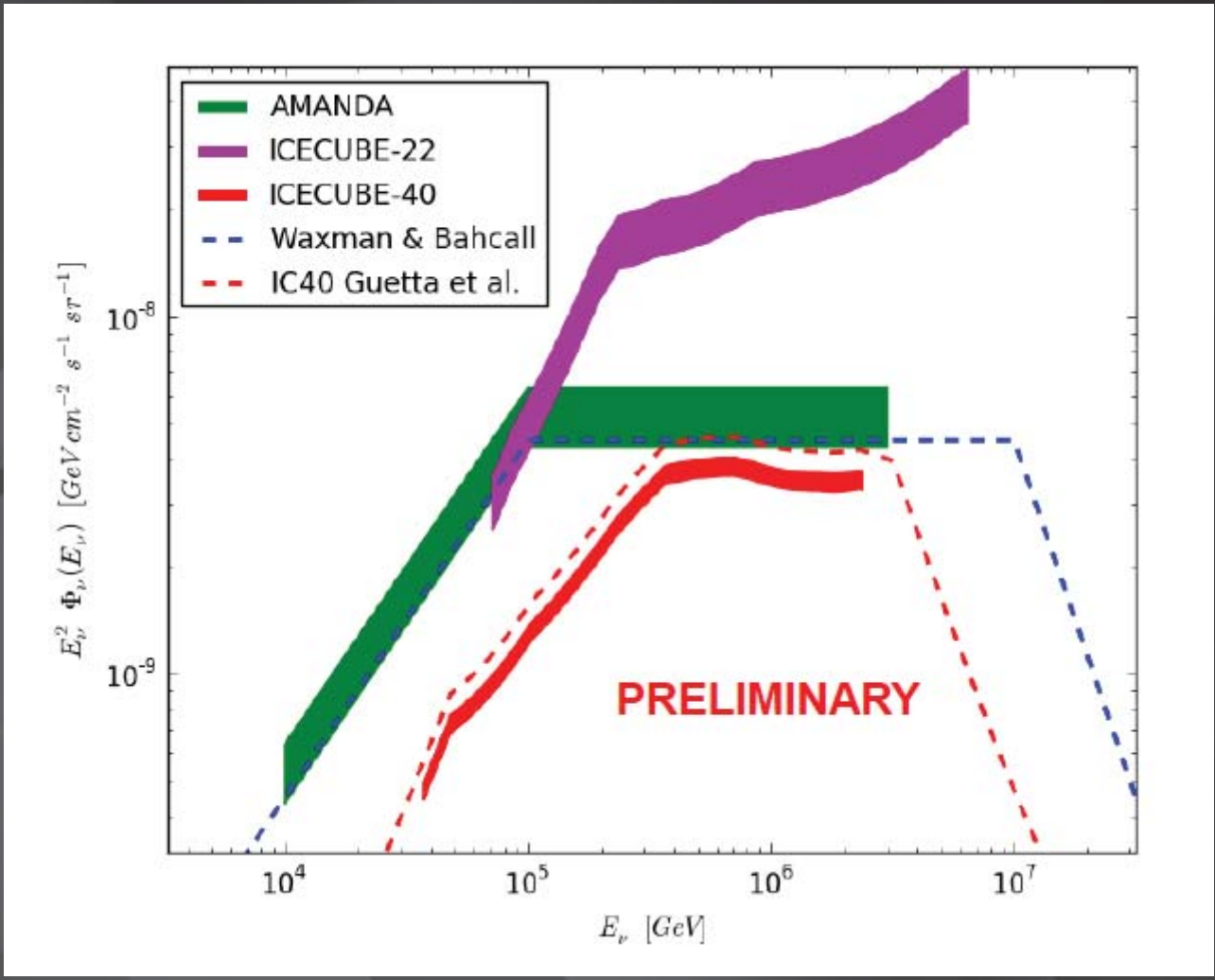
cassiopeia A supernova remnant in X-rays



GRB

protons and photons co-exist in the fireball →

ν production



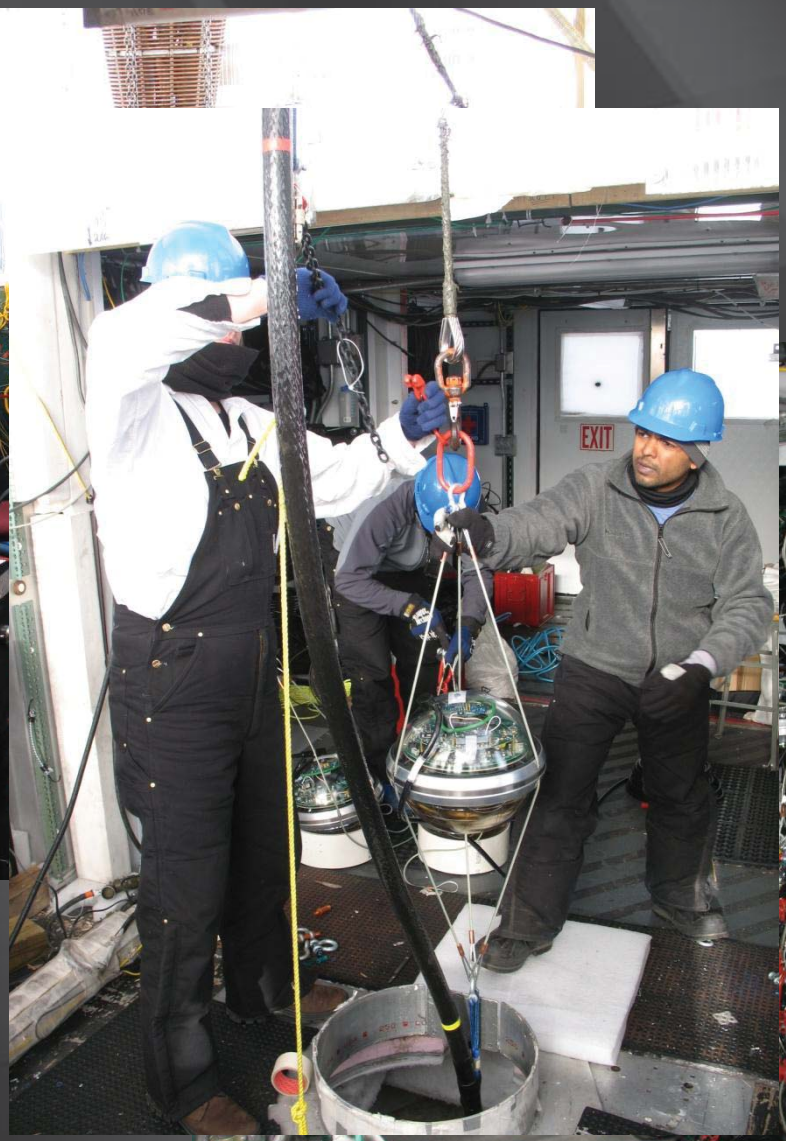
- proton flux = observed cosmic ray flux (WB)
- observation of 117 burst with IceCube-40 strings
- 4 events expected, none seen

→ energy in extra-galactic cosmic rays is ~ 3×10^{-19} erg/cm^3

2×10^{52} erg per gamma ray burst

energy in cosmic rays ~ photons

drilling and deployment



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