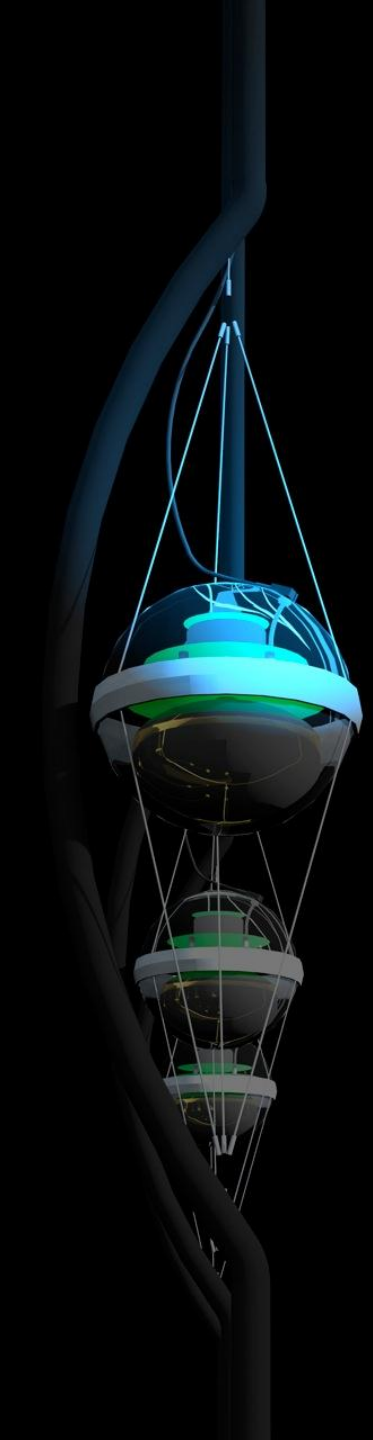
neutrino "astronomy"

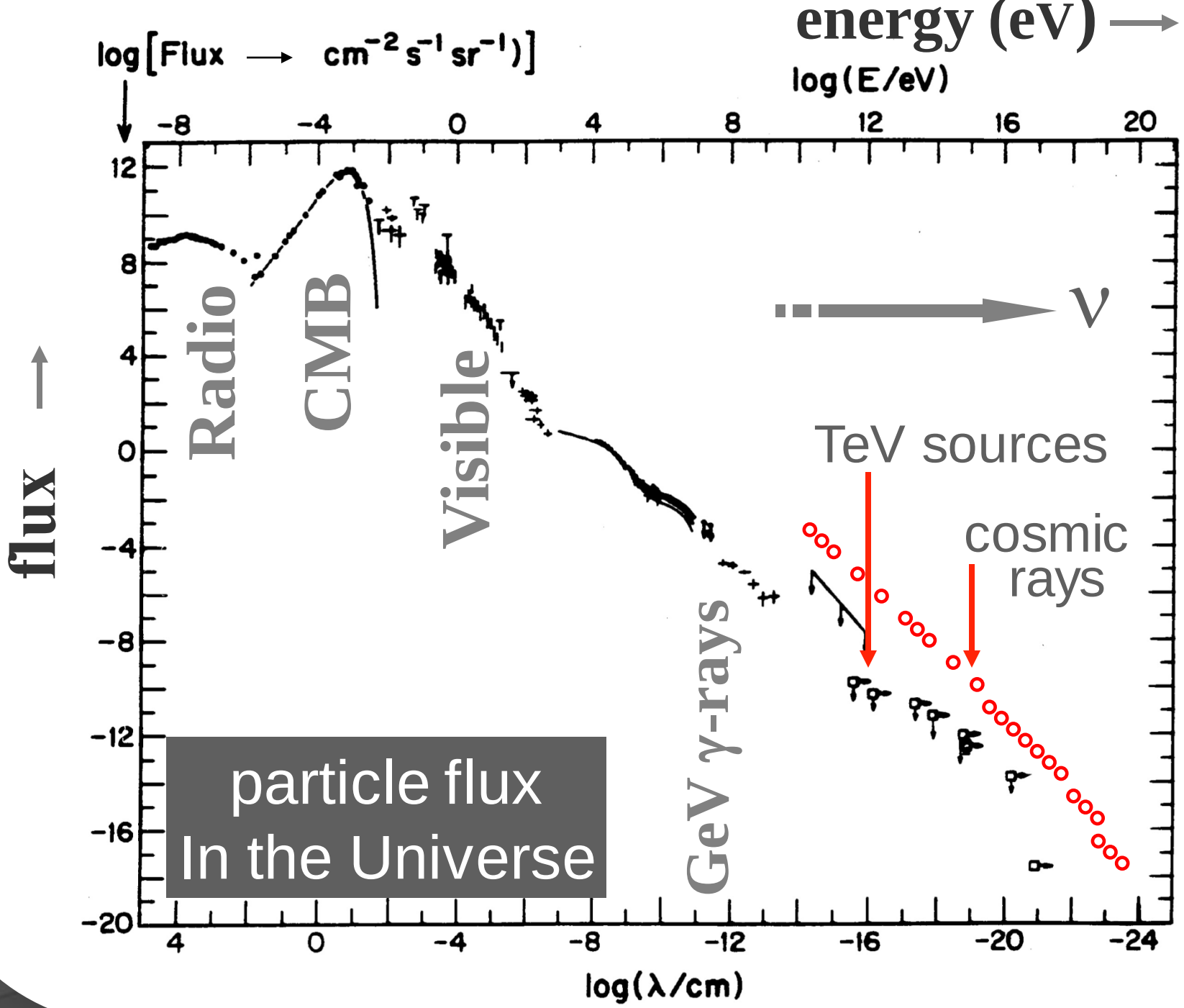
francis halzen
university of wisconsin
http://icecube.wisc.edu



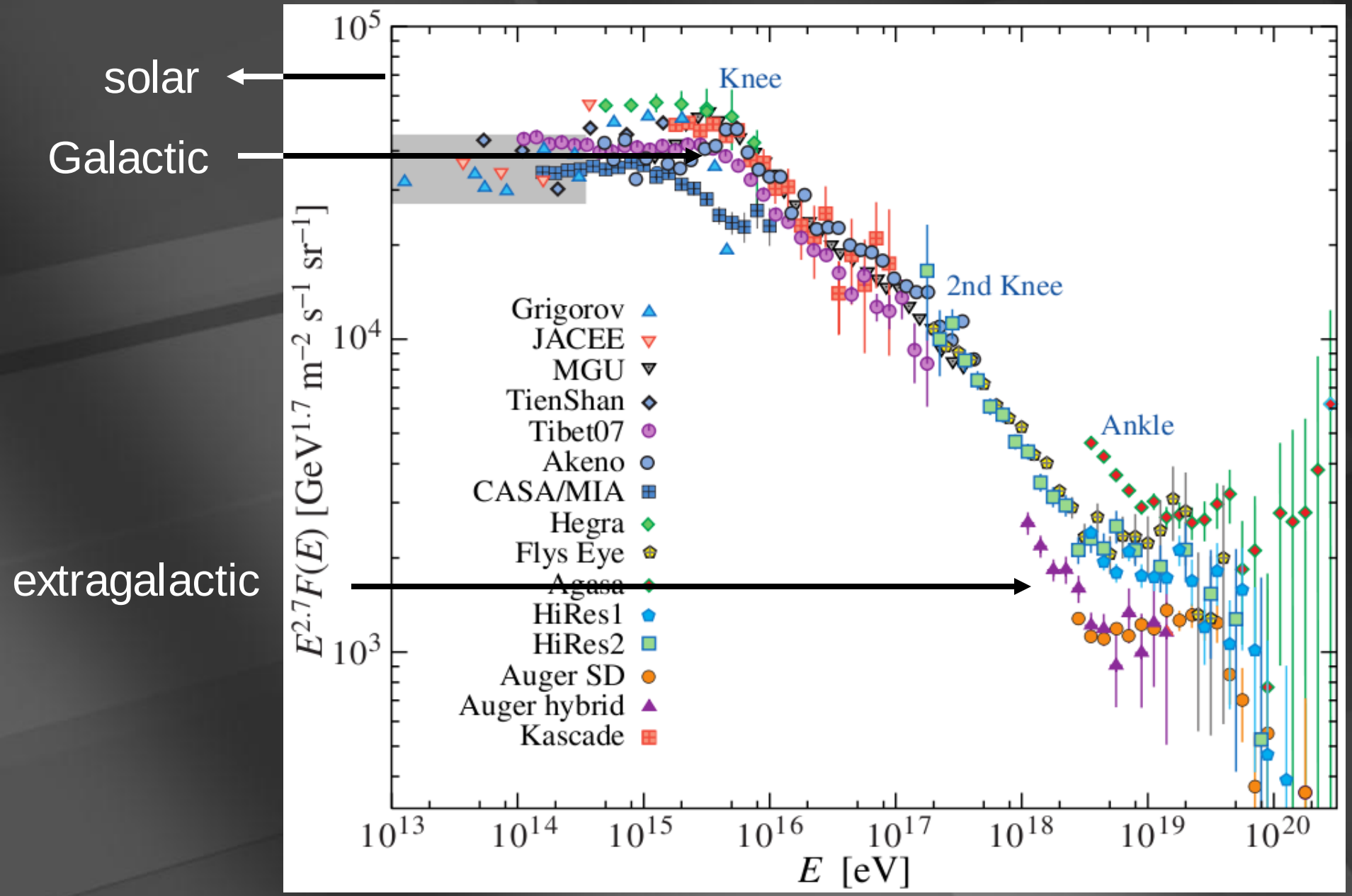
- introduction
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

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 ray spectrum



cosmic rays interact with the microwave background

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

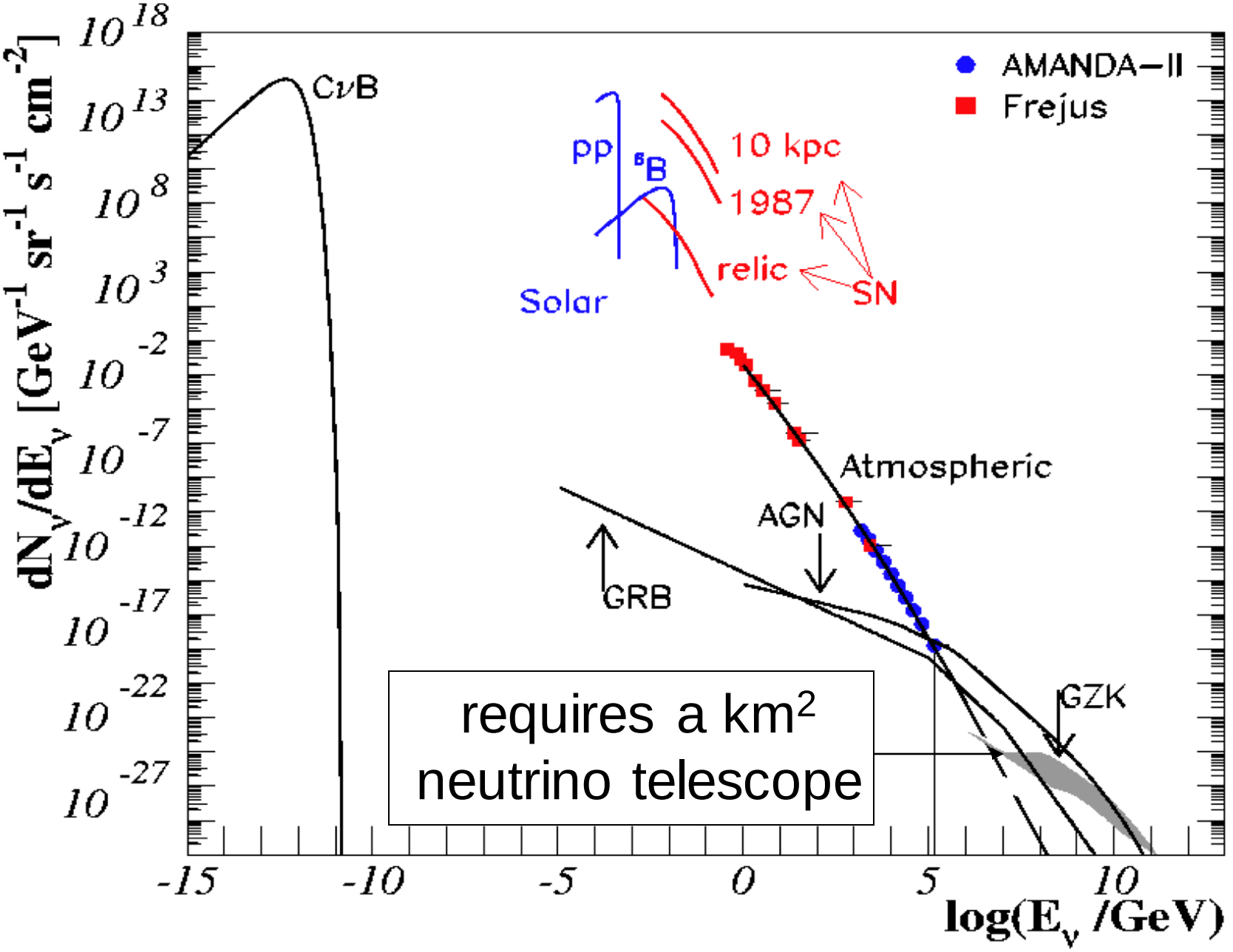
cosmic rays disappear, neutrinos appear

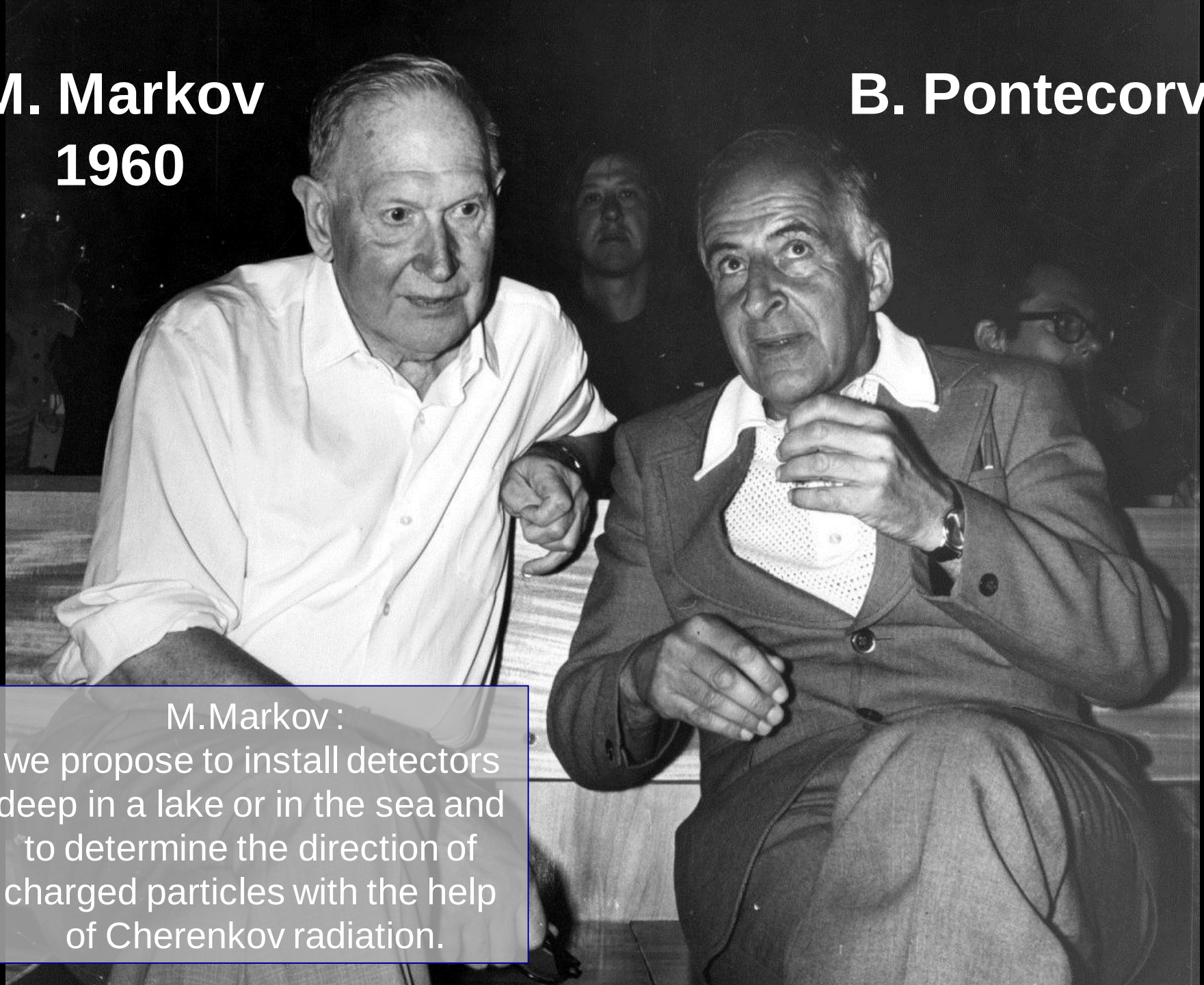
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

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

~ 1 GZK event per kilometer cube per year

neutrino sky



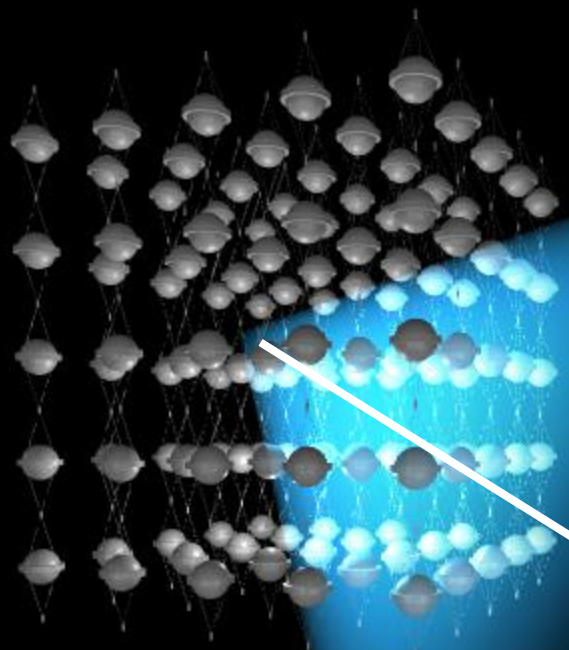


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

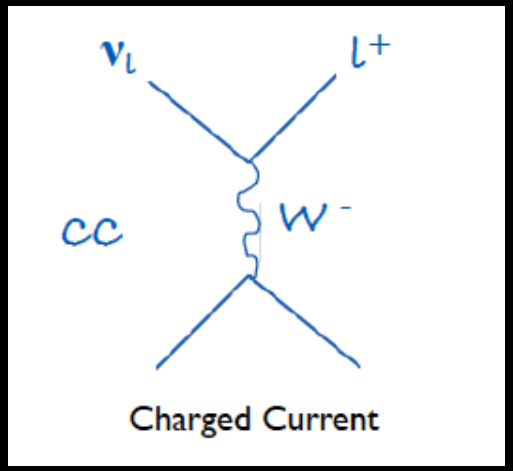
photomultiplier tube

- shielded and optically transparent medium

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



μ

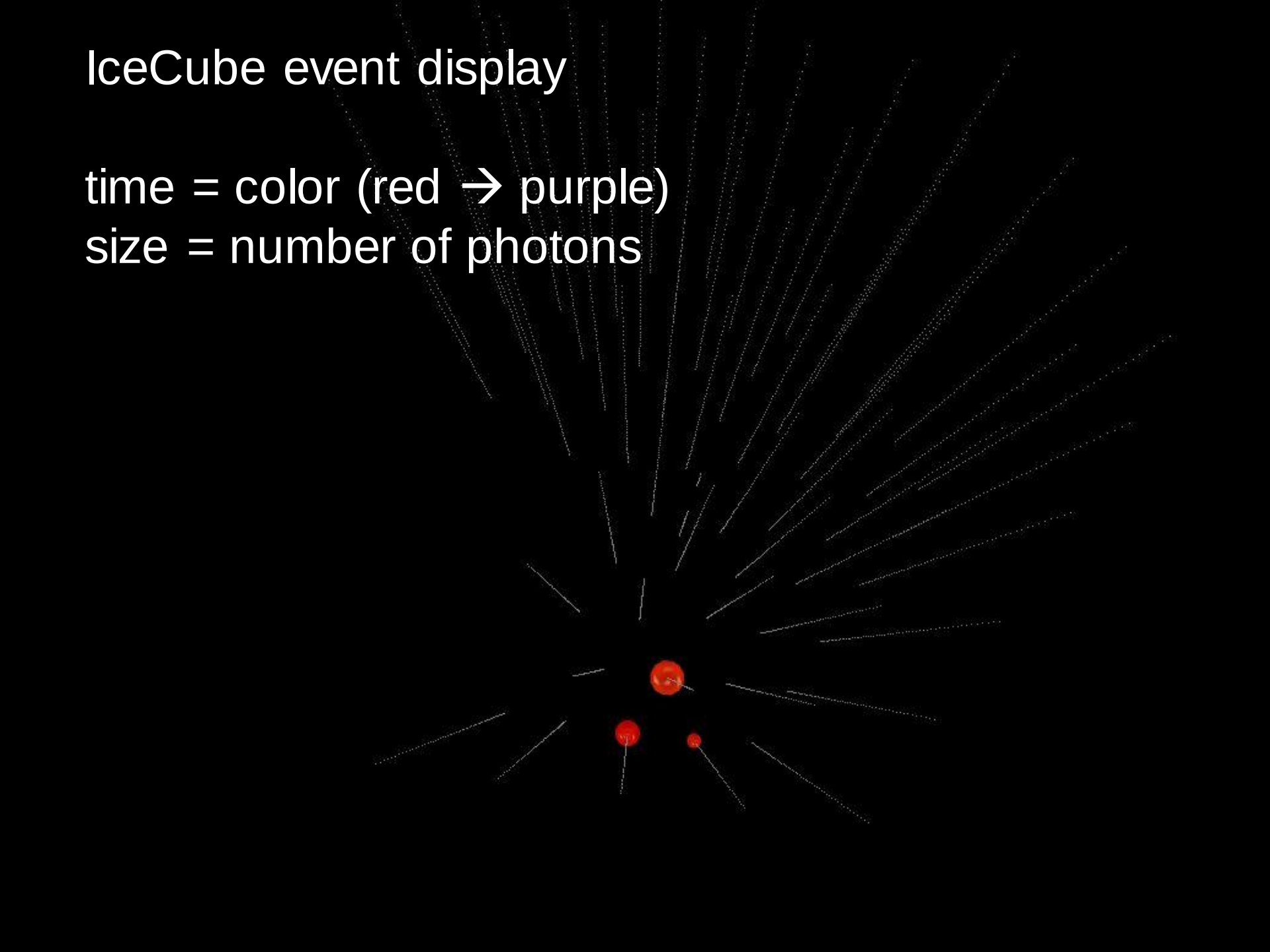


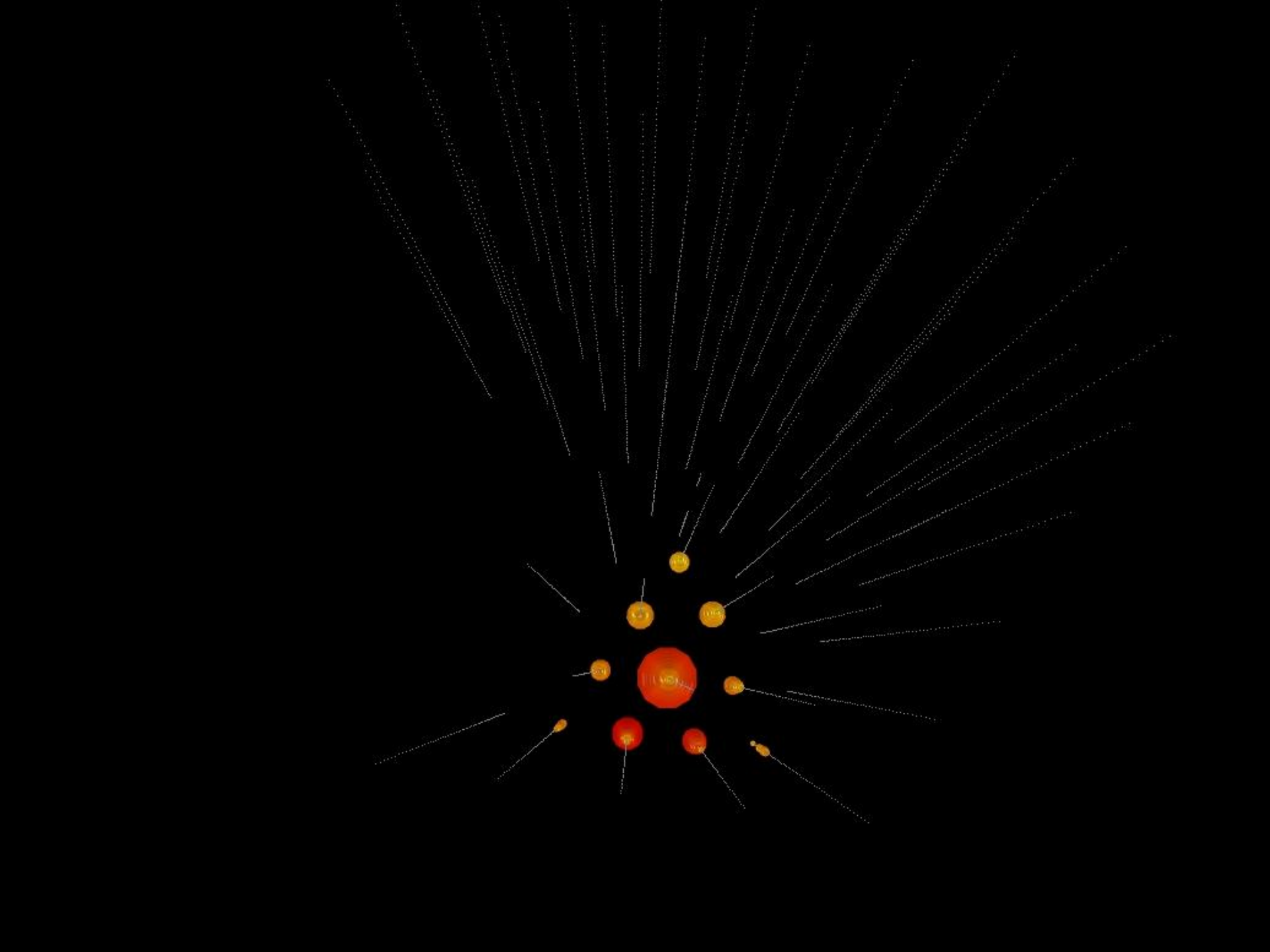
ν

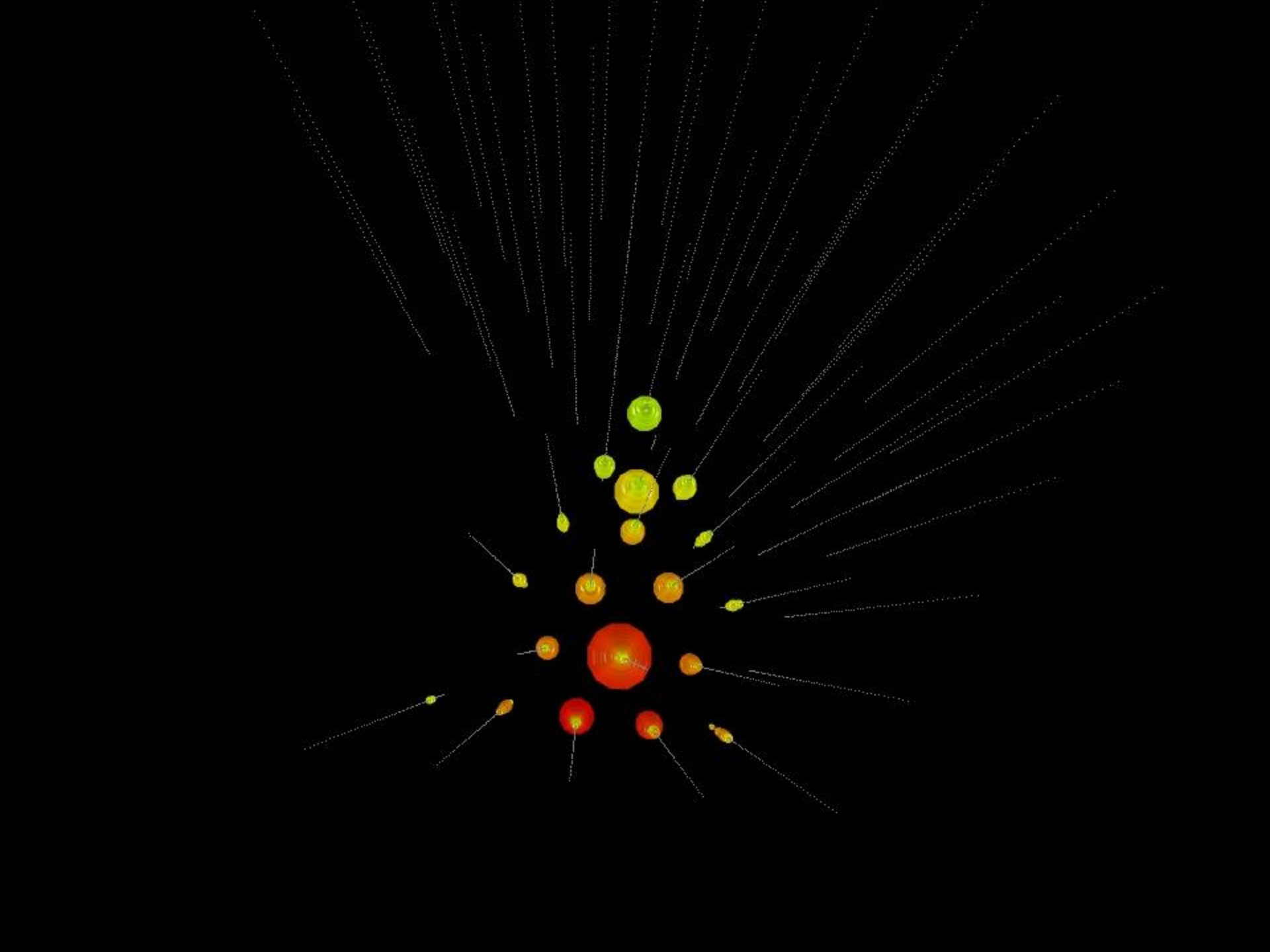
- lattice of photomultipliers

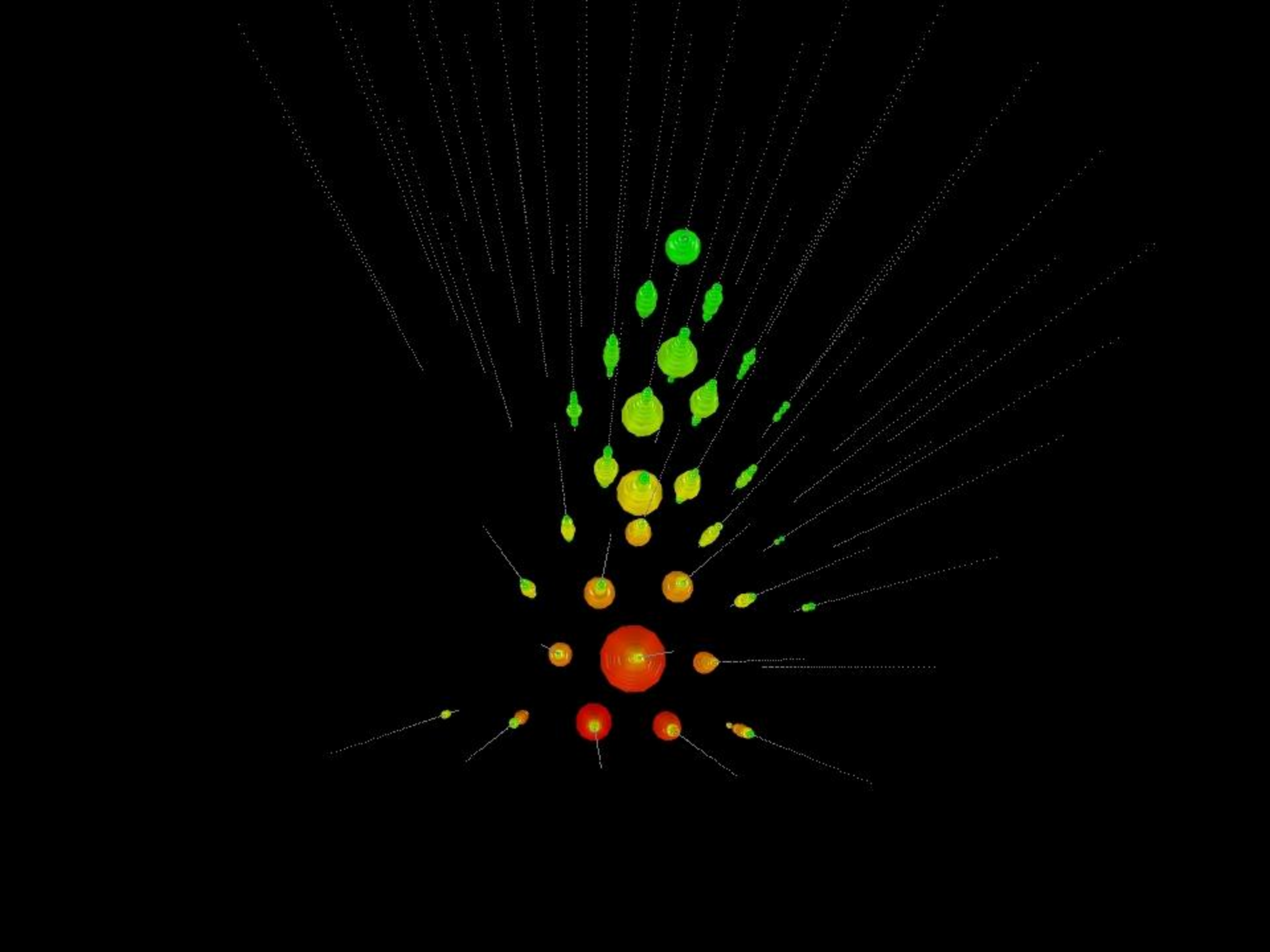
IceCube event display

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

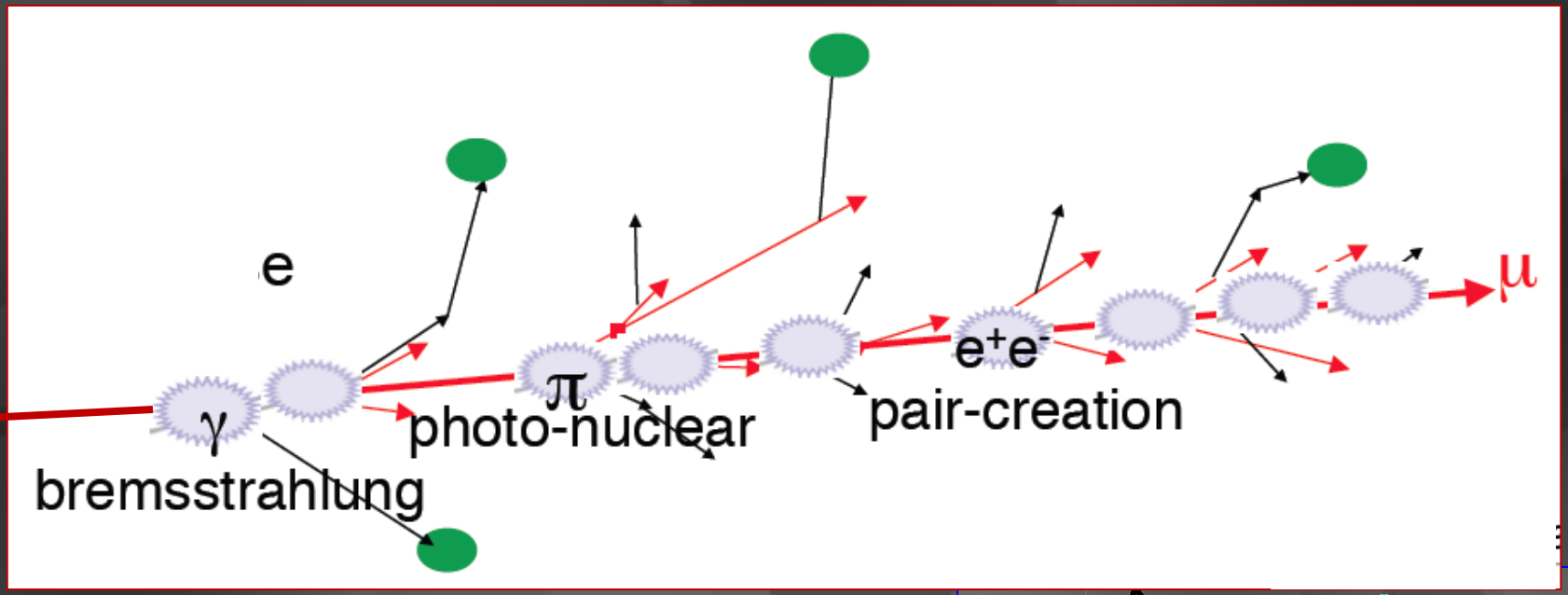




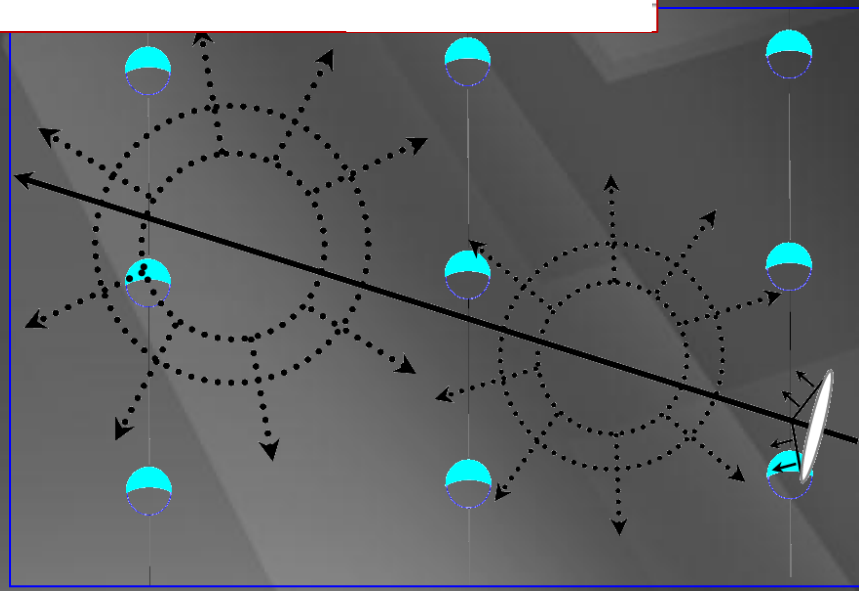




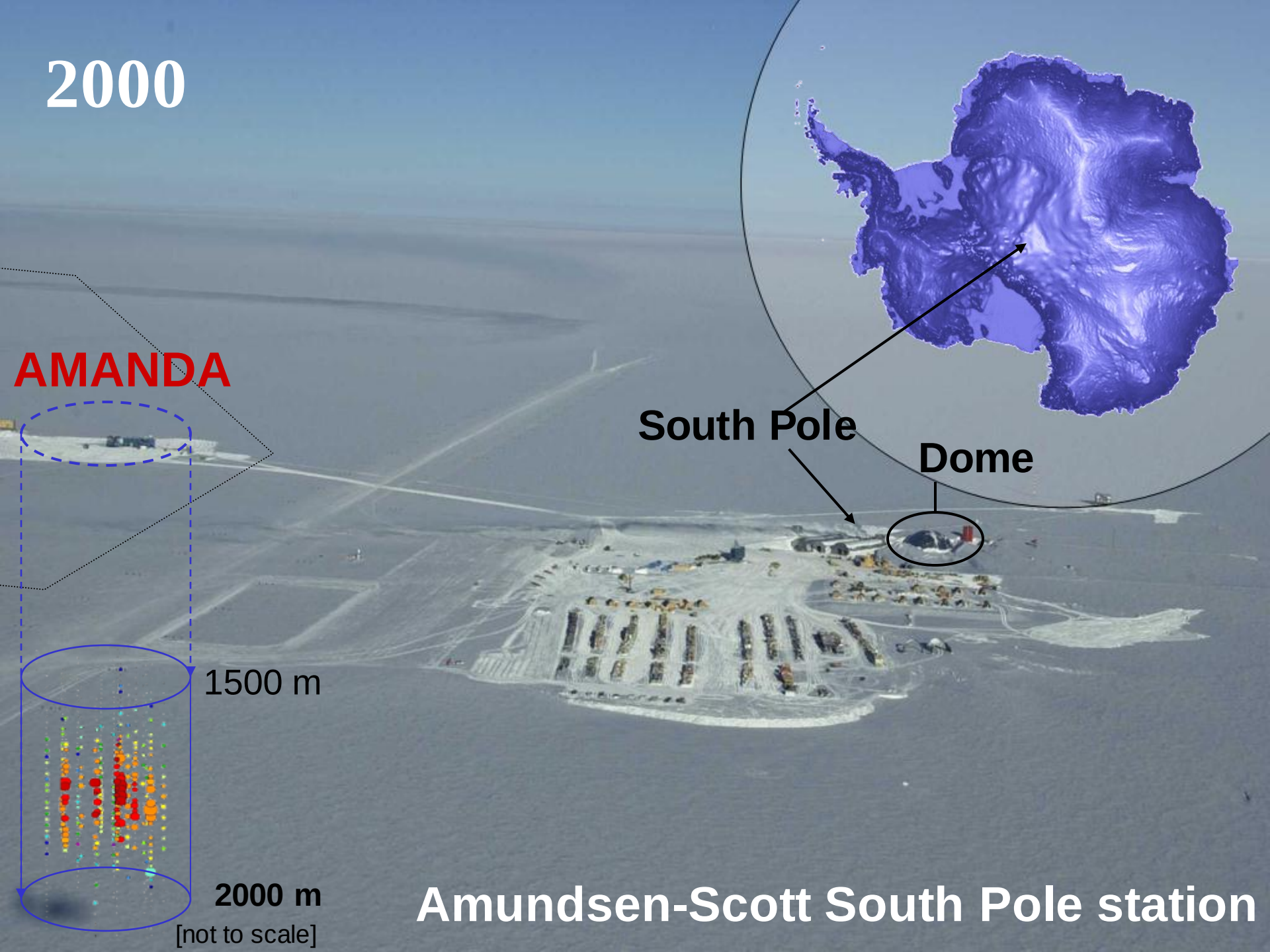
energy measurement (> 1 TeV)



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



why did it take so long ?

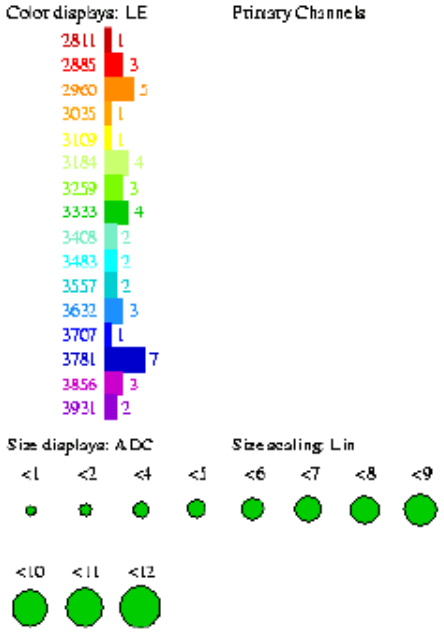

2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

AMANDA event: muon neutrino

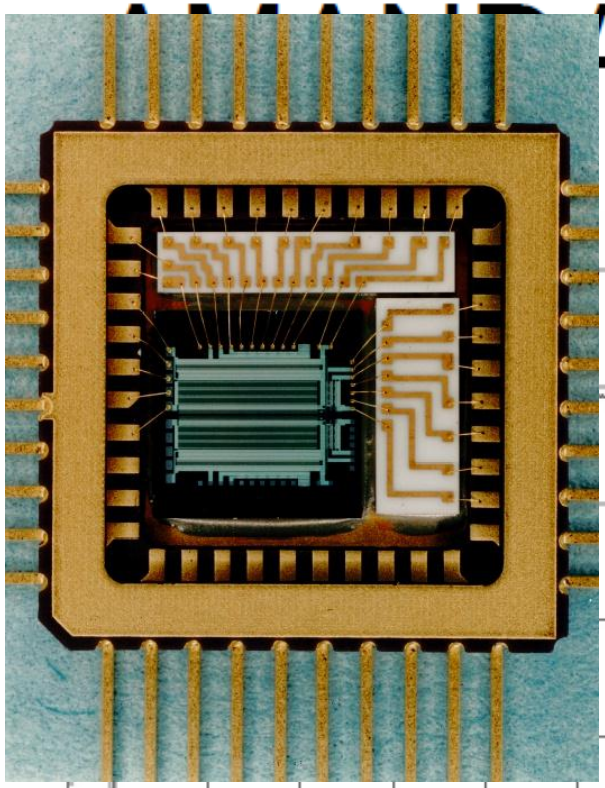
neutrino interaction creates muon track

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

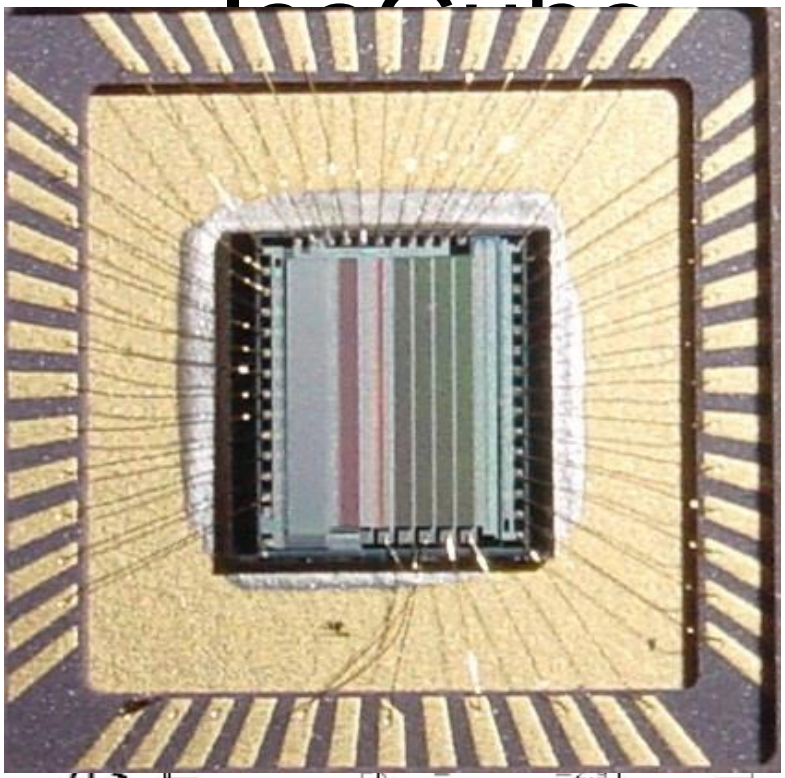
but analog photo-multipler after 2 km… not pretty

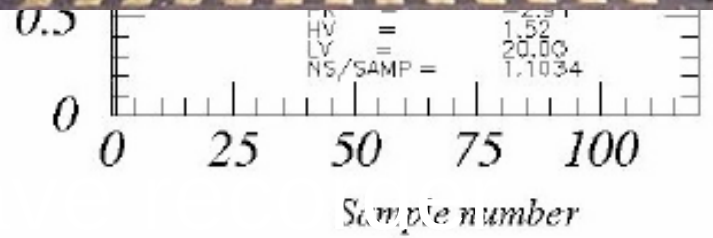


AMANDA



Signal recorded from SWedish AMPlifier outputs Jan '97 at the south pole of photomultiplier signals transmitted t rough approximate'y two kilometers of twisted quad transmiss.on \n

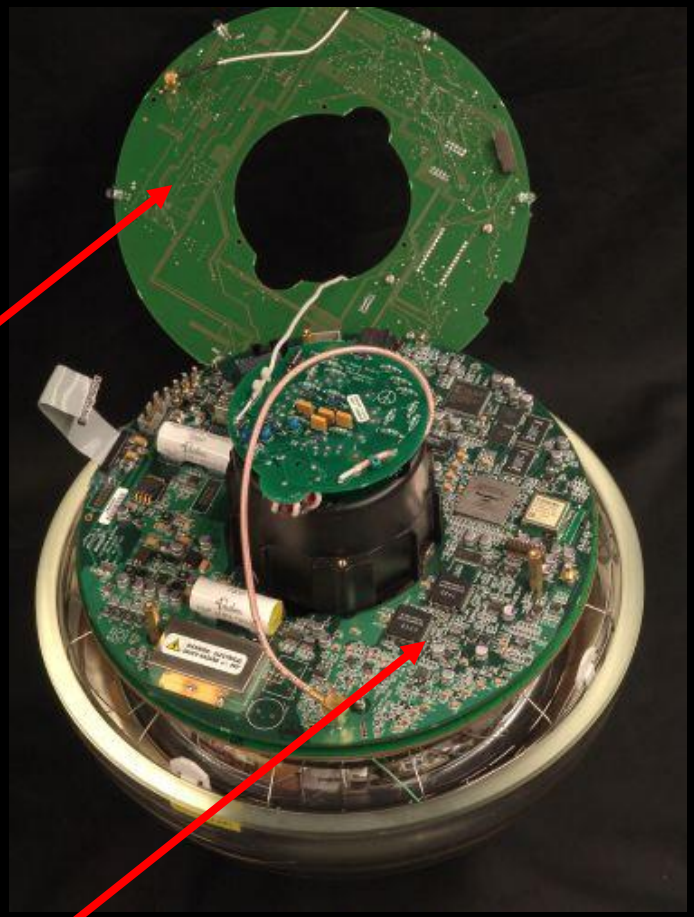


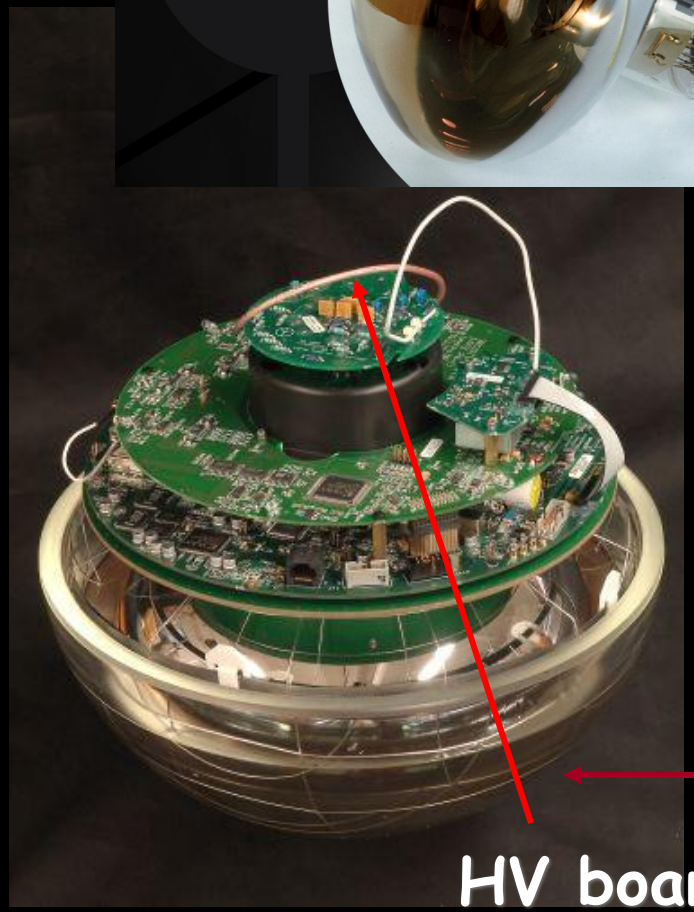


7.5us

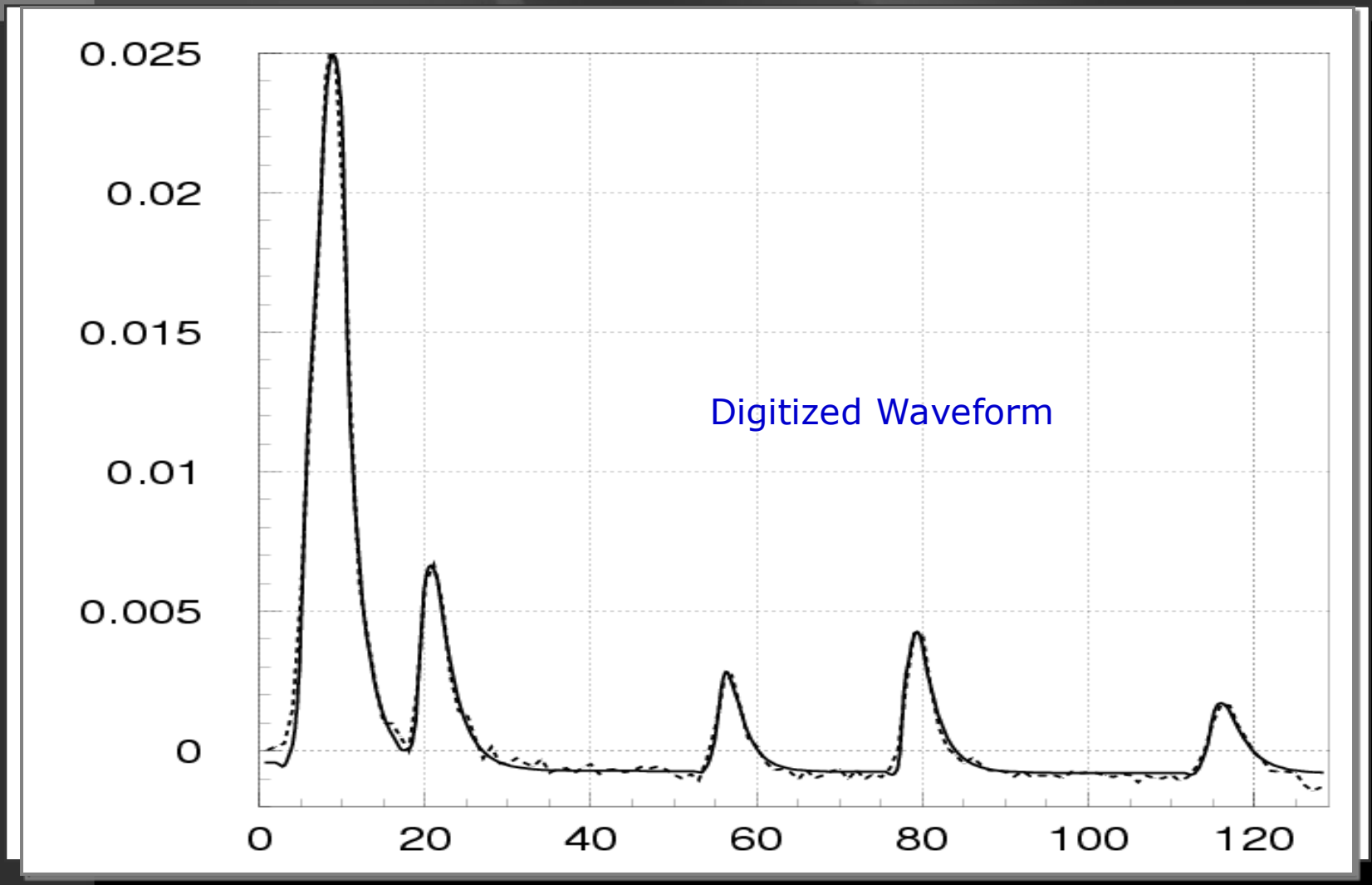
132ns

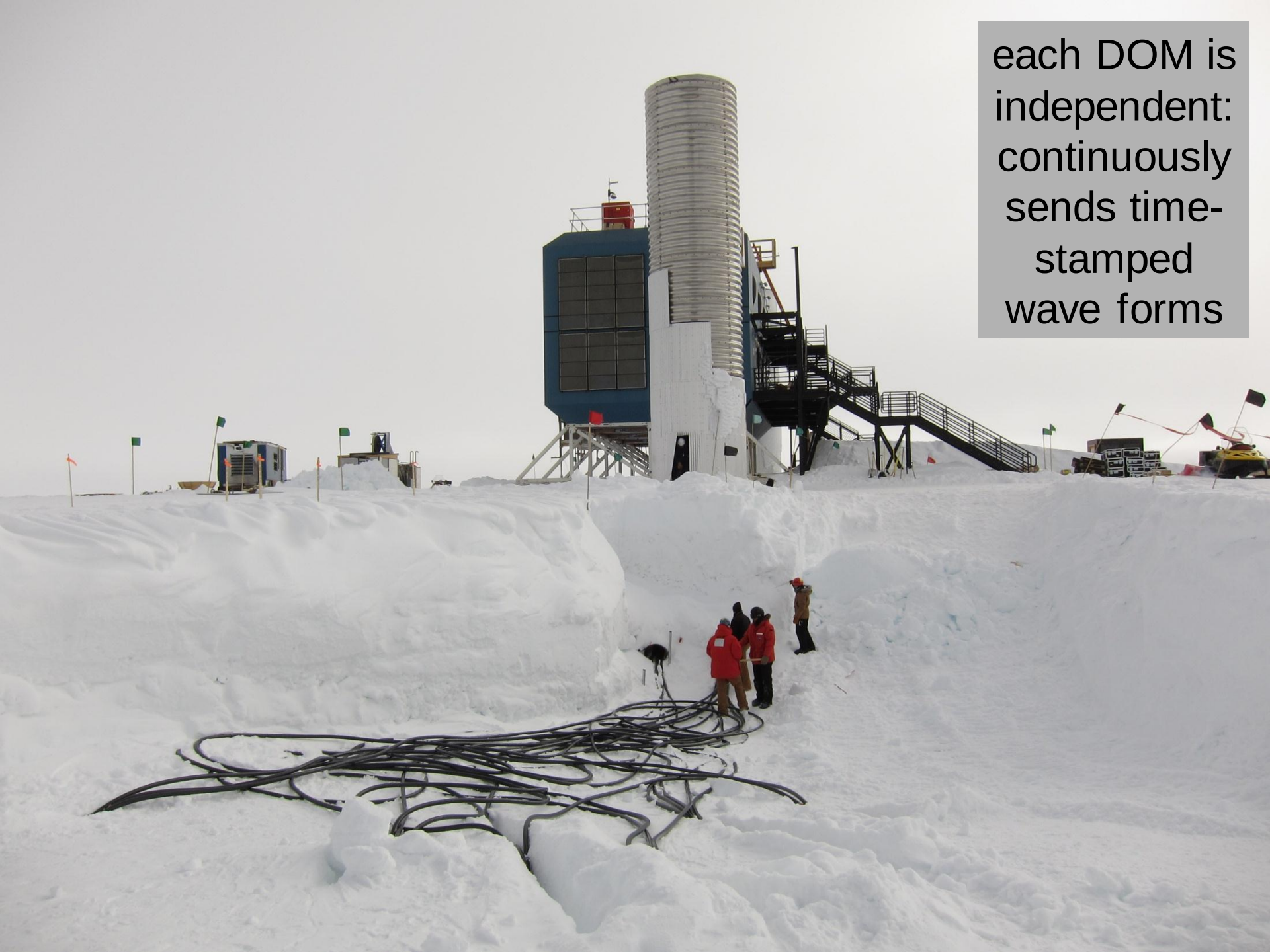
architecture of independent DOMs





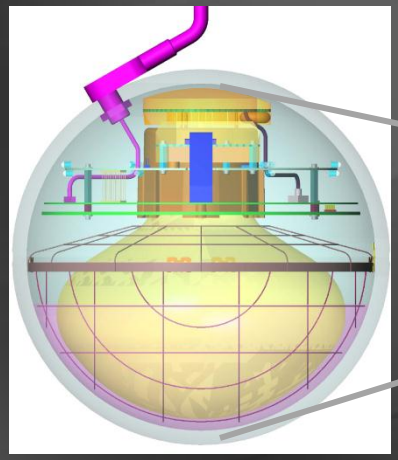
each DOM is an autonomous unit



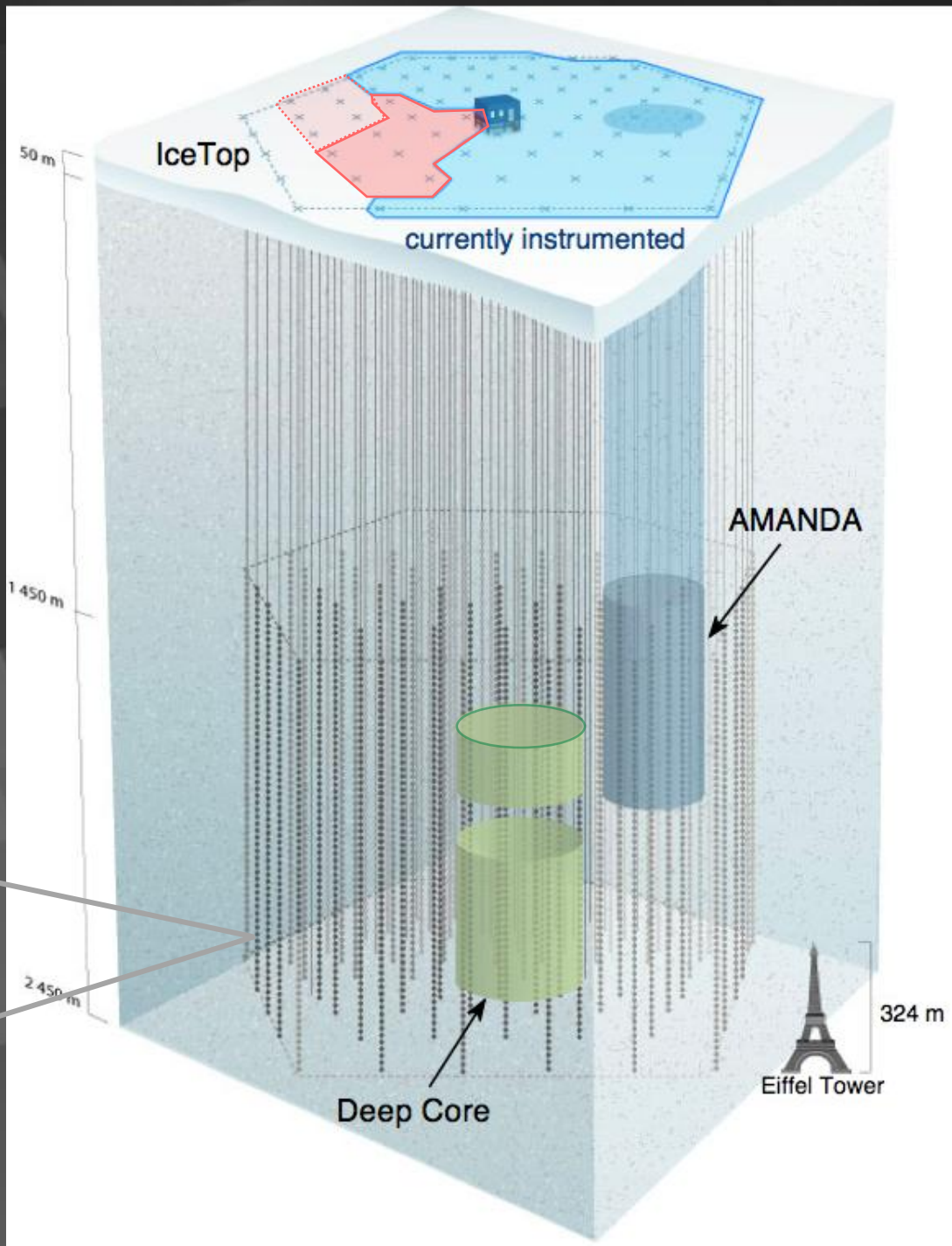

each DOM is independent: continuously sends time-stamped wave forms

IceCube / Deep Core

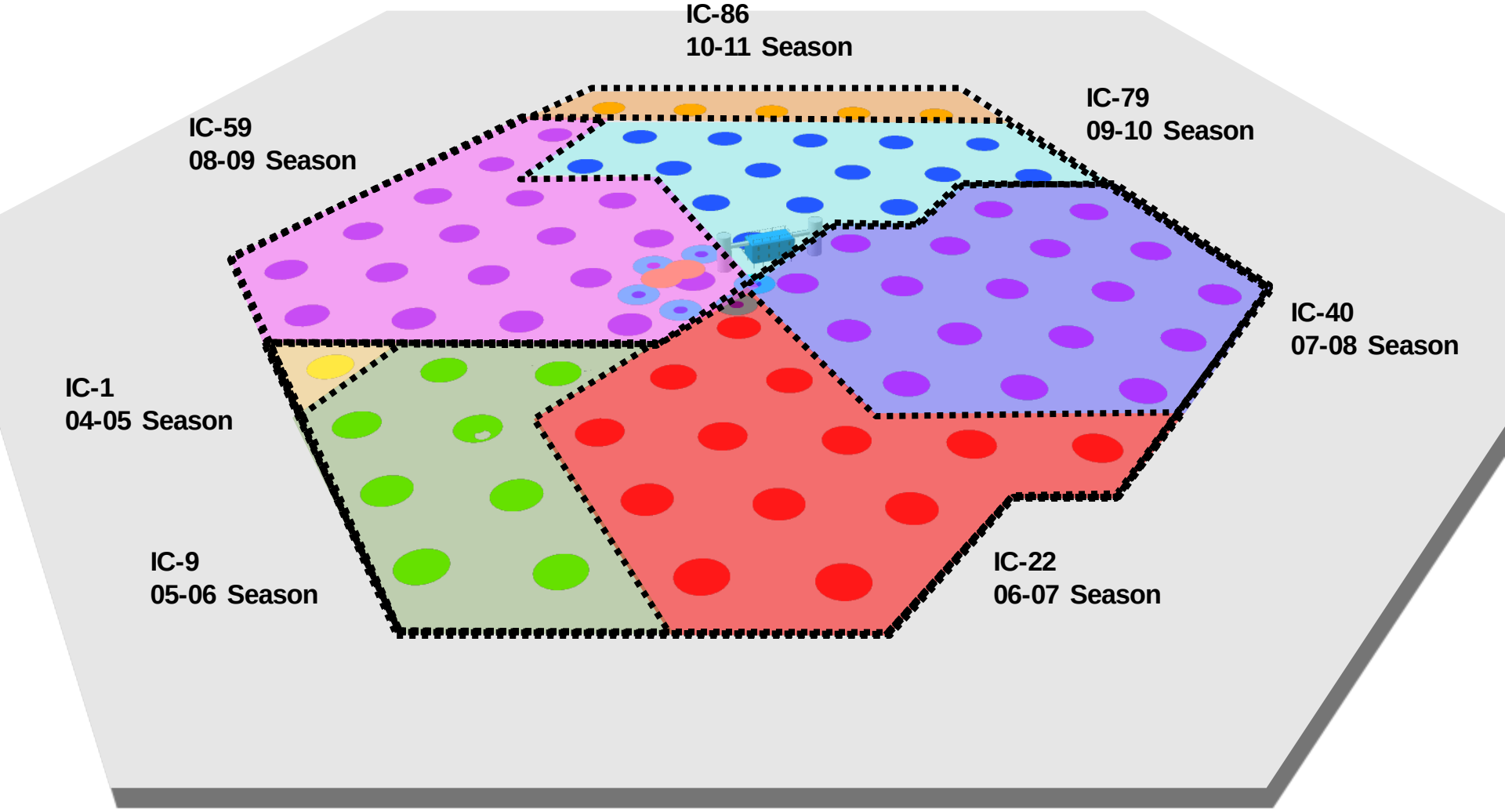
- 5320 optical modules on 86 strings (+ IceTop)
- detects ~220 neutrinos and 1.7×10^8 muons per day
- threshold 10 GeV
- angular resolution
  < 1 degree

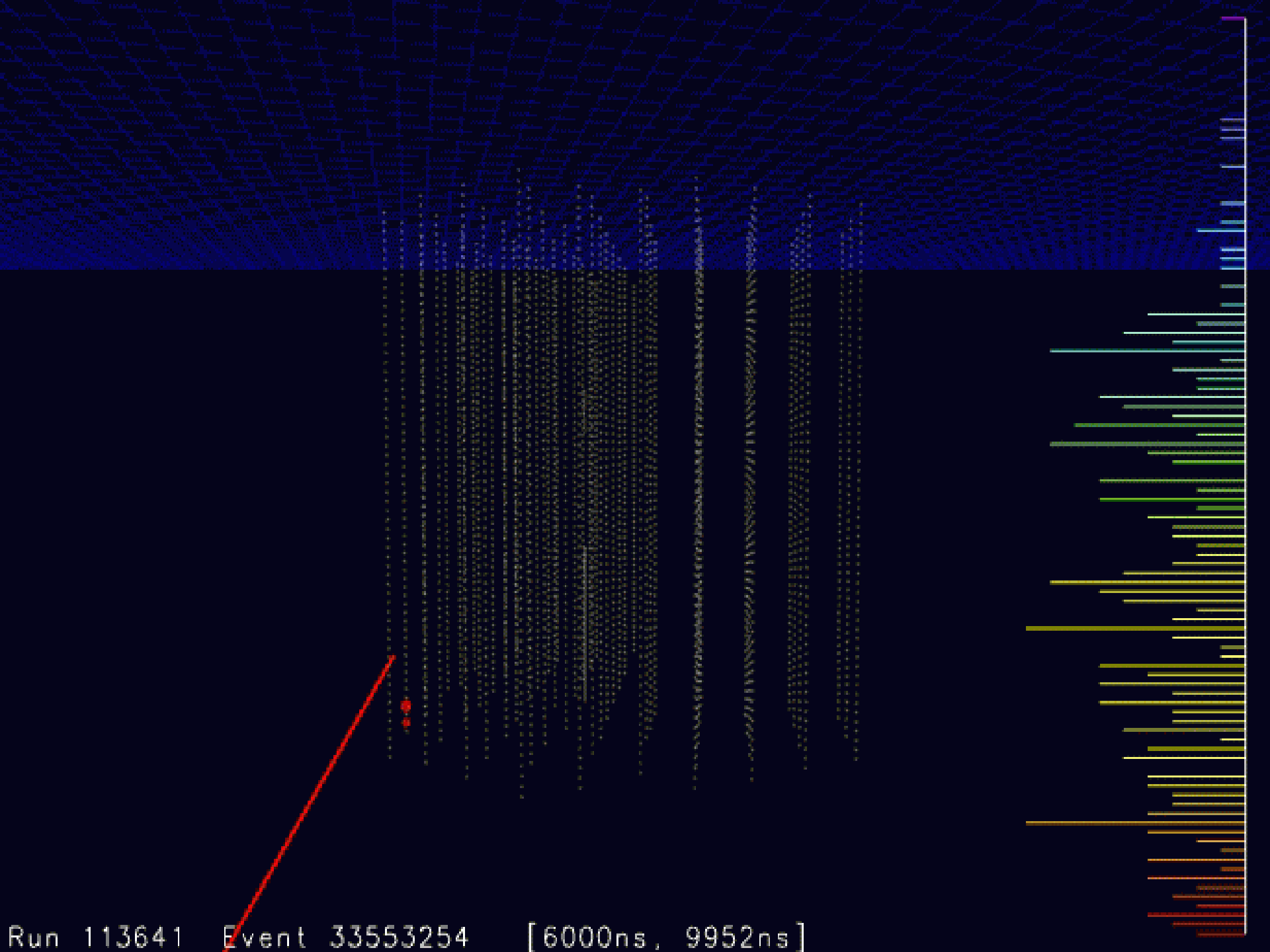


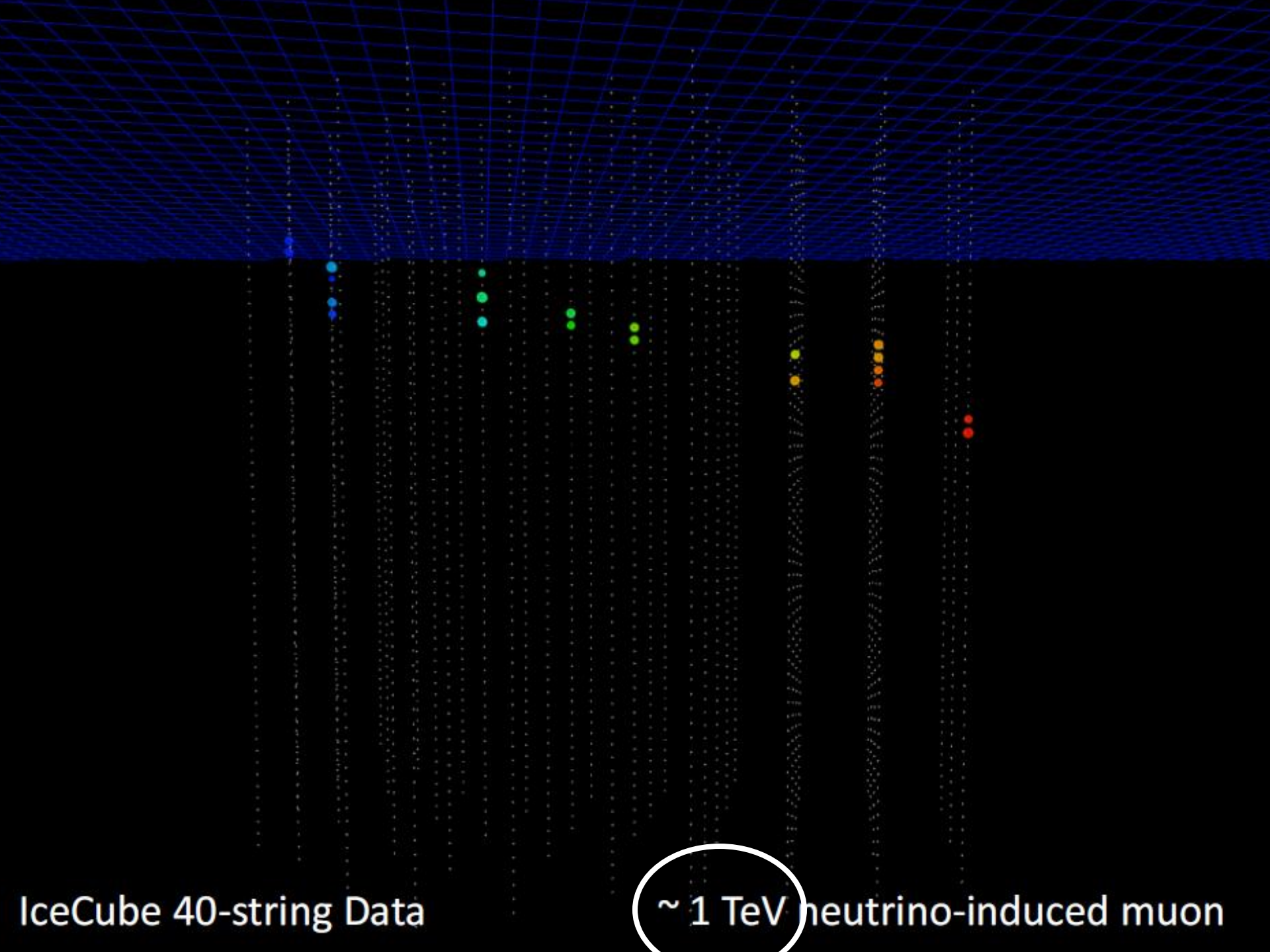
Digital Optical Module (DOM)



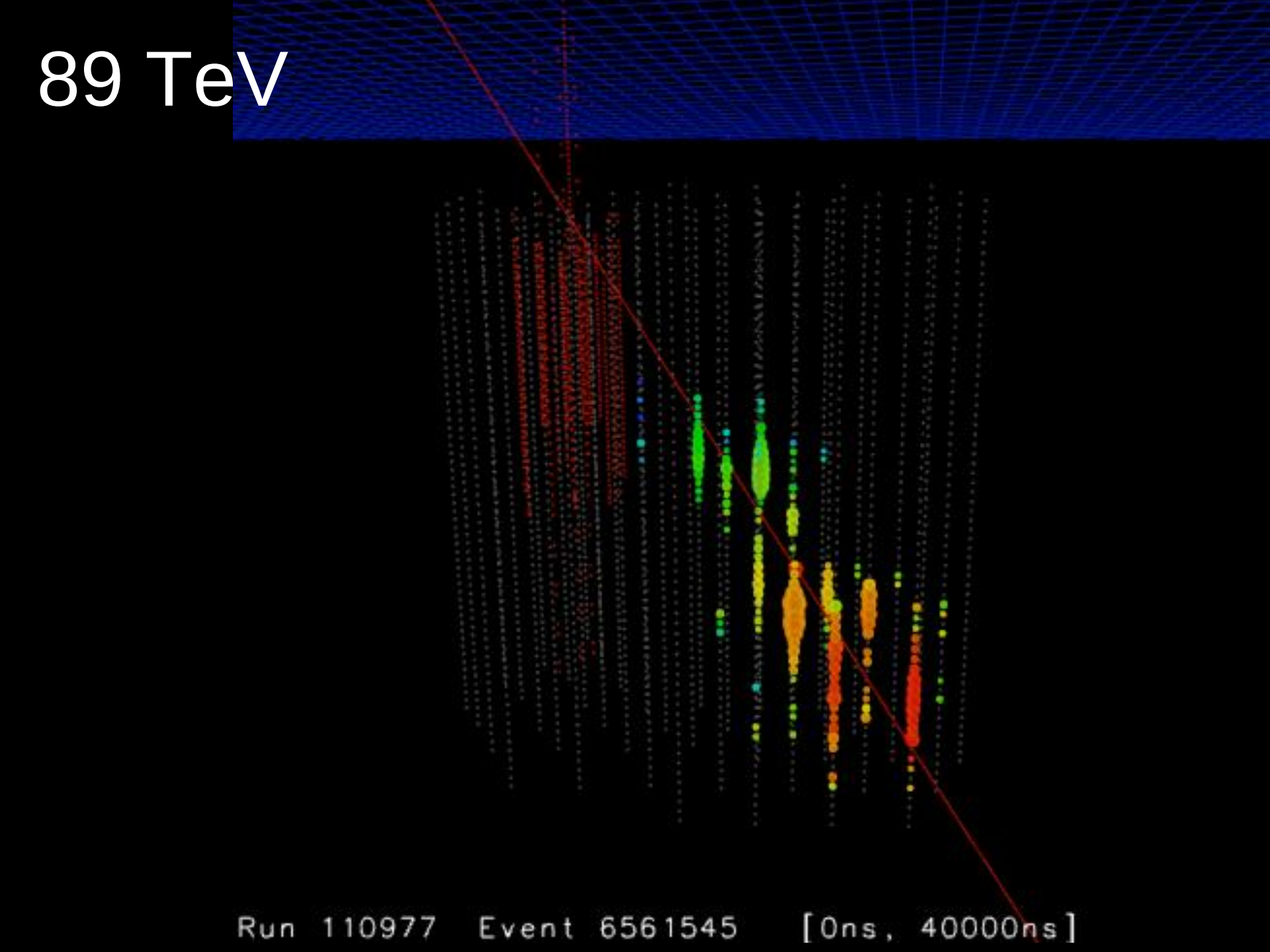
completed December 18, 2010

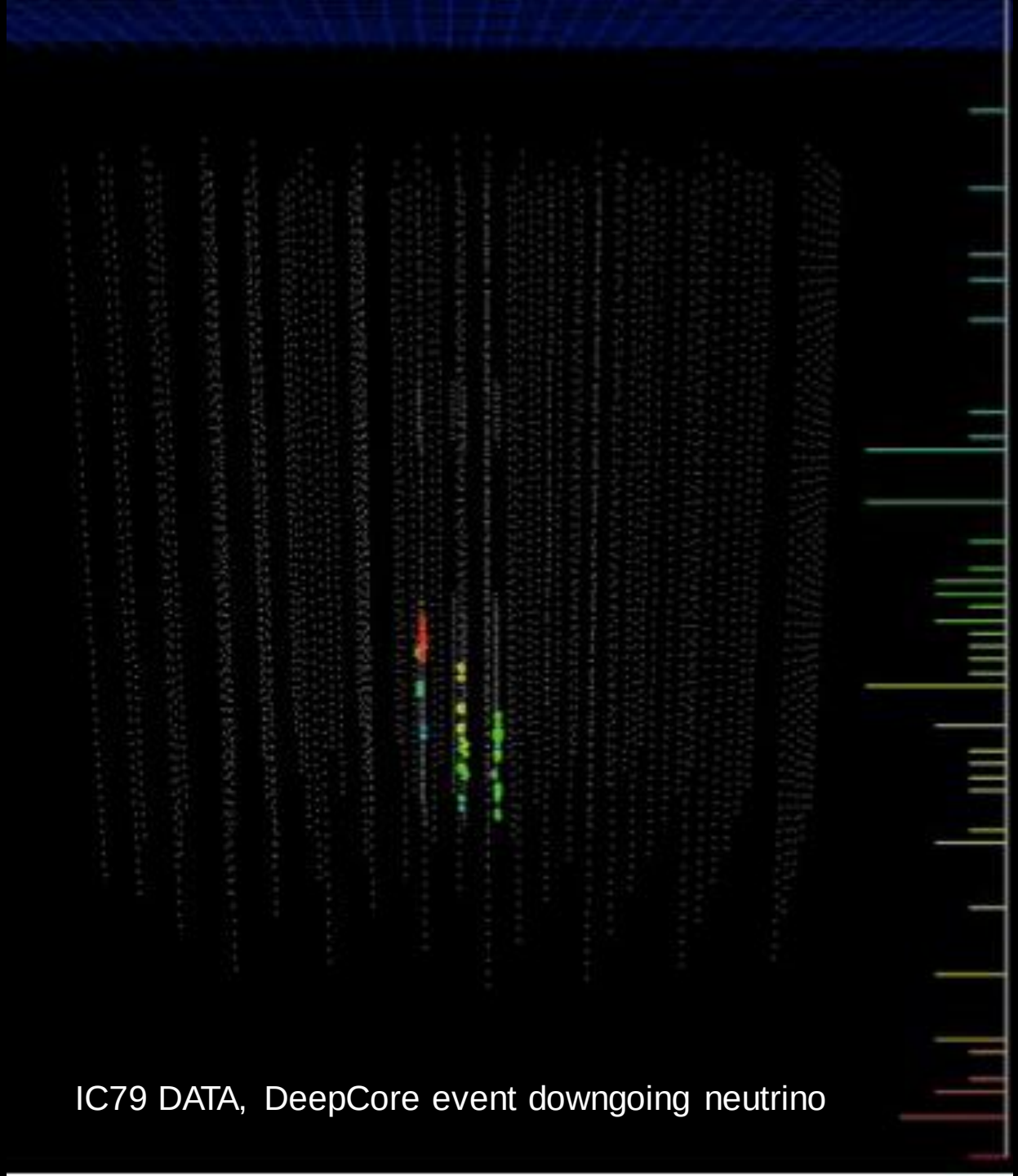



Run 113641 Event 33553254 [6000ns, 9952ns]


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

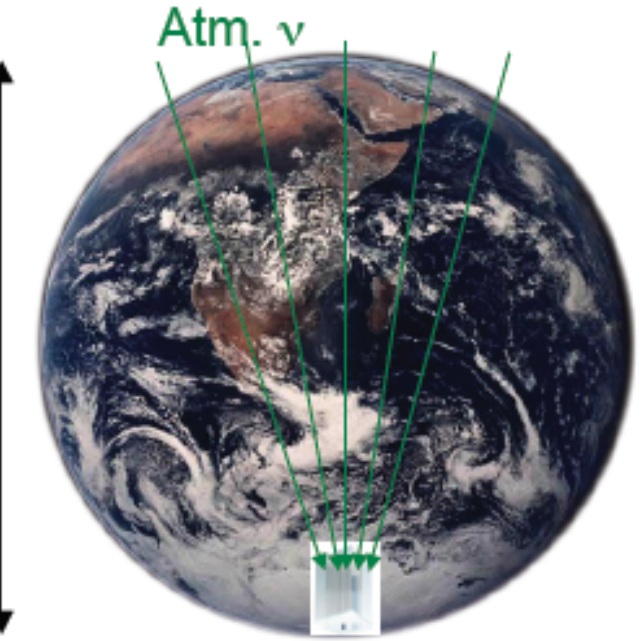
89 TeV

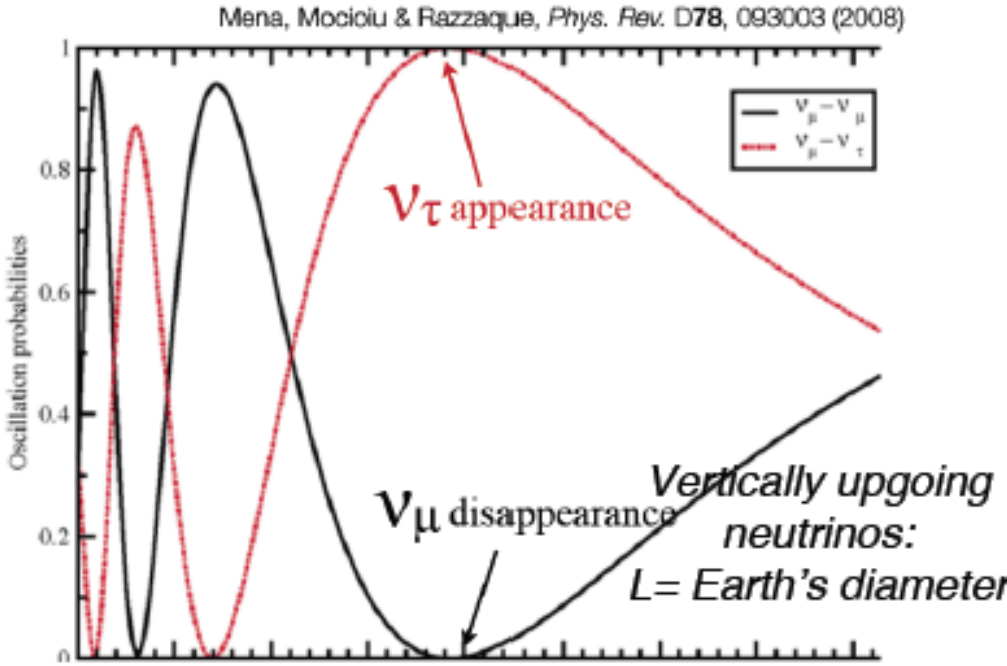


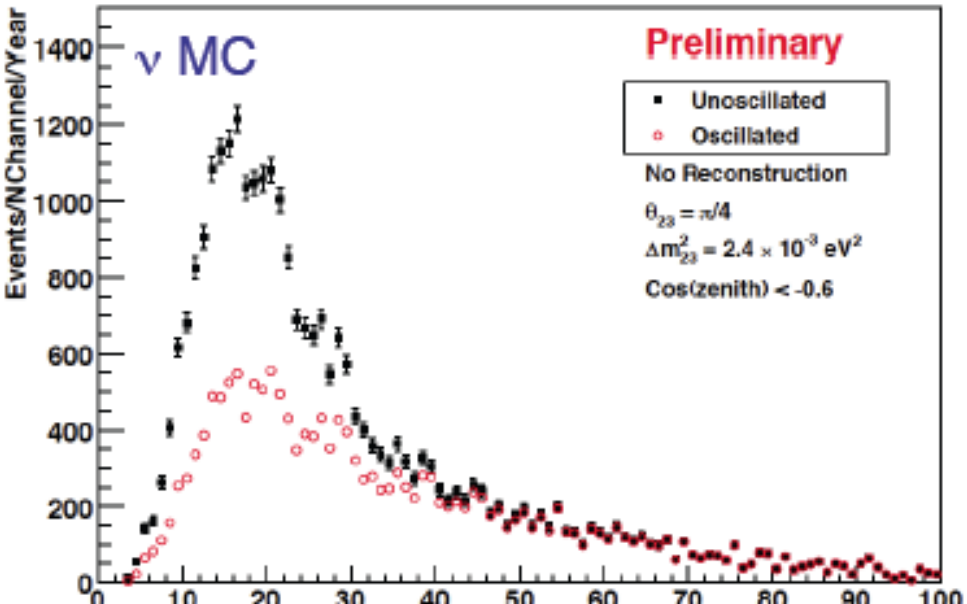


IC79 DATA, DeepCore event downgoing neutrino

Neutrino Oscillations with DeepCore

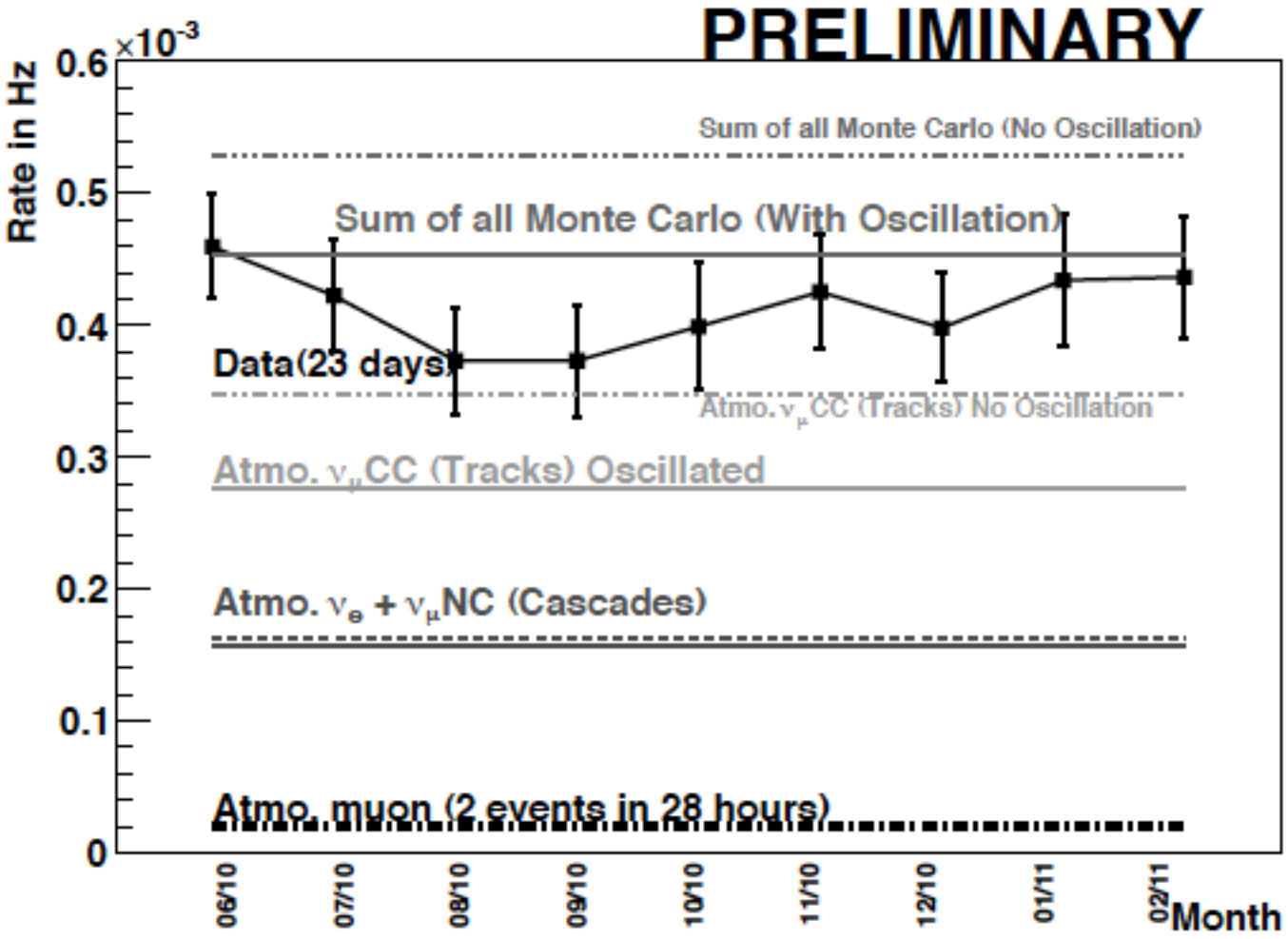


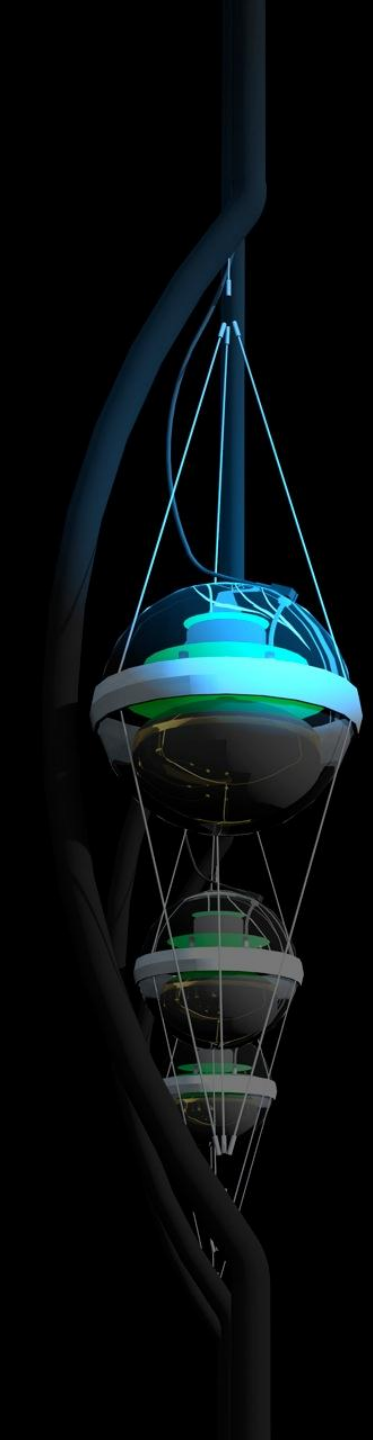




ν_μ disappearance MC

- 3-flavor oscillations
- signal simulation only
- lifetime= 1 year IC79


PRELIMINARY
Rate in Hz
×10⁻³
0.6
0.5
0.4
0.3
0.2
0.1
0
Sum of all Monte Carlo (No Oscillation)
Sum of all Monte Carlo (With Oscillation)
Data(23 days)
Atmo. ν_μ CC (Tracks) No Oscillation
Atmo. ν_μ CC (Tracks) Oscillated
Atmo. ν_e + ν_μ NC (Cascades)
Atmo. muon (2 events in 28 hours)
06/10
07/10
08/10
09/10
10/10
11/10
12/10
01/11
02/11
Month



- introduction

- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons

- search for the sources of the Galactic cosmic rays

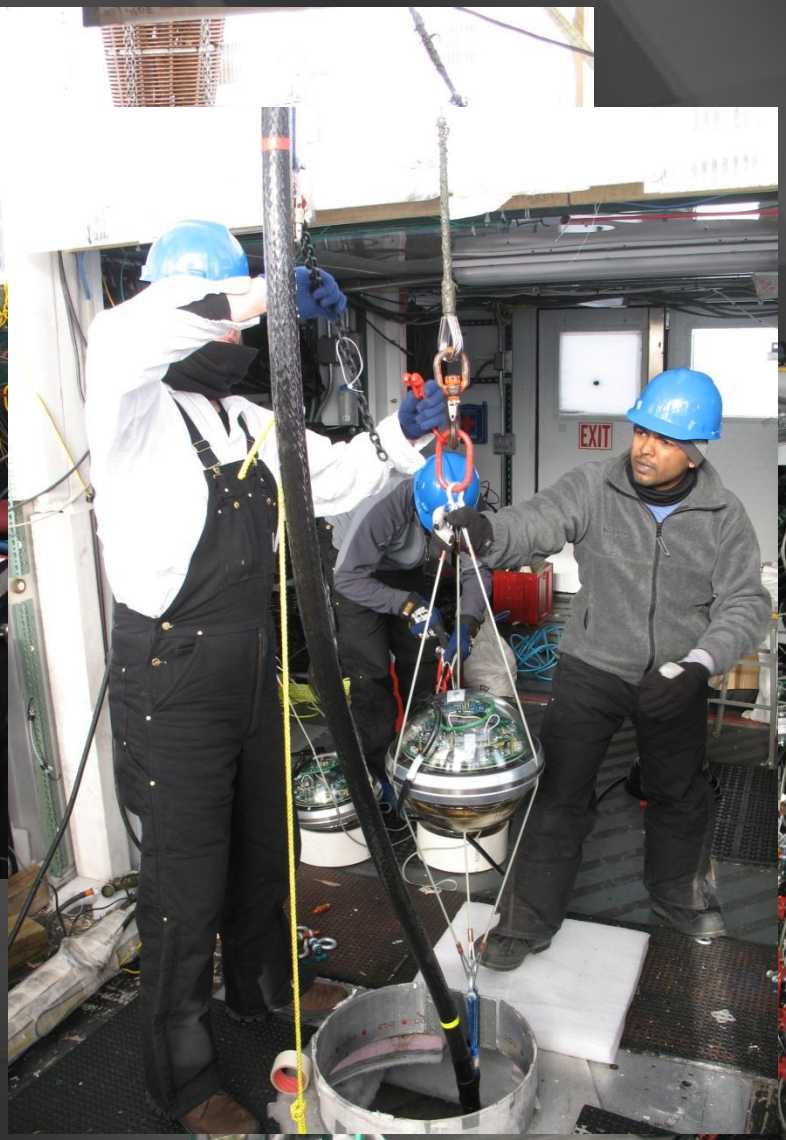
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

dark matter

IceCube.wisc.edu

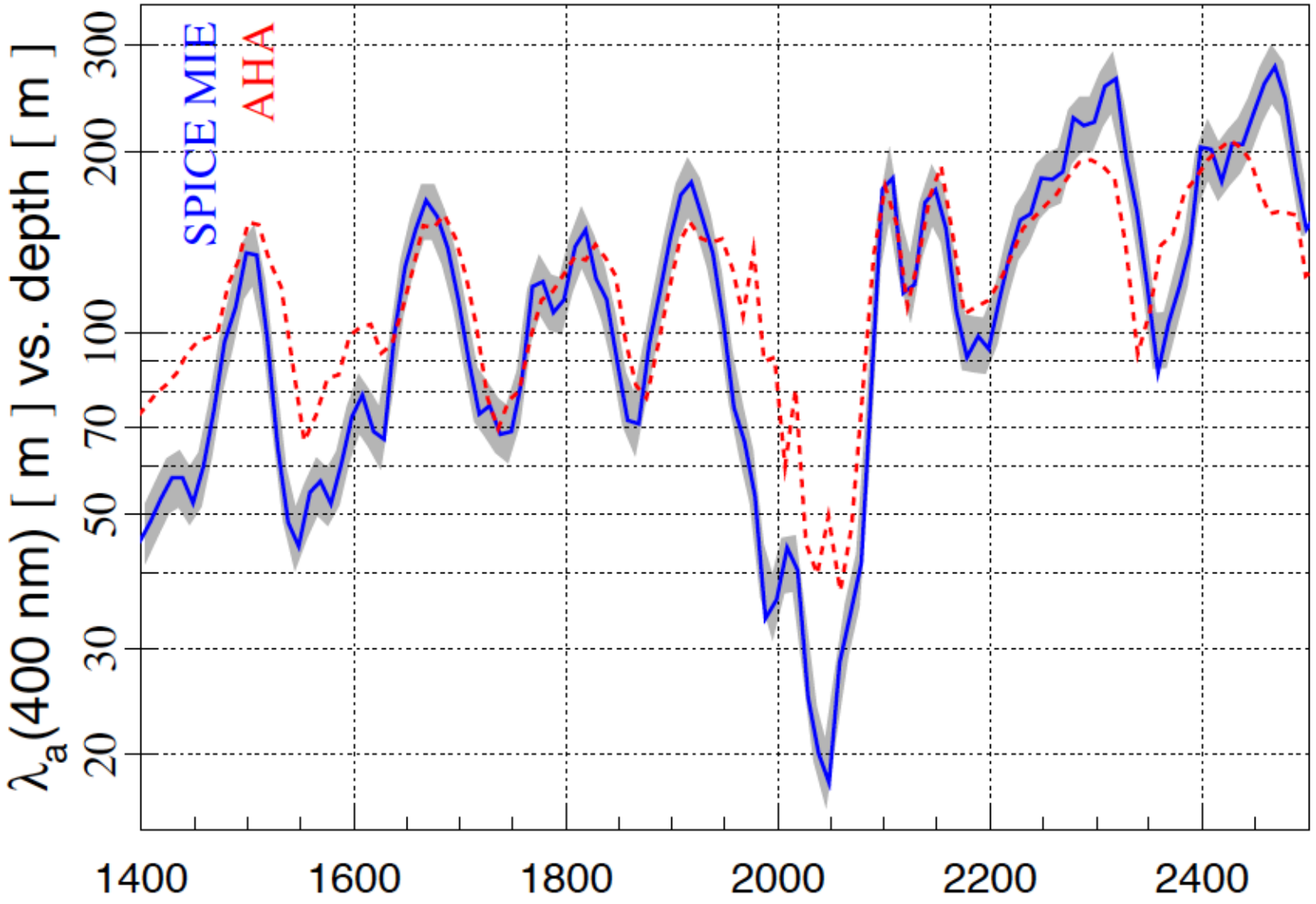

5 megawatt power plant

drilling and deployment

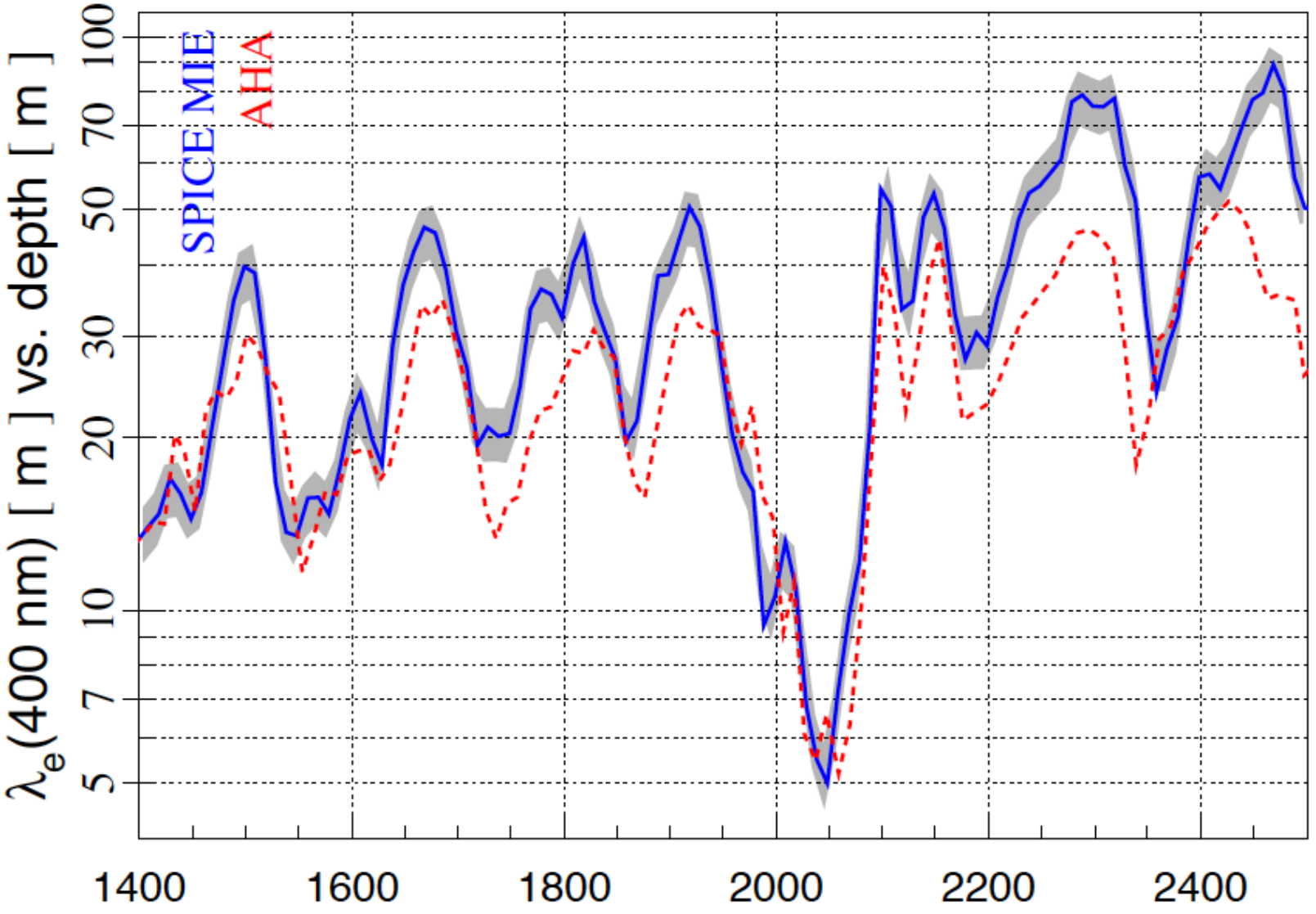


drill and install 60 DOMs in less than 2 days

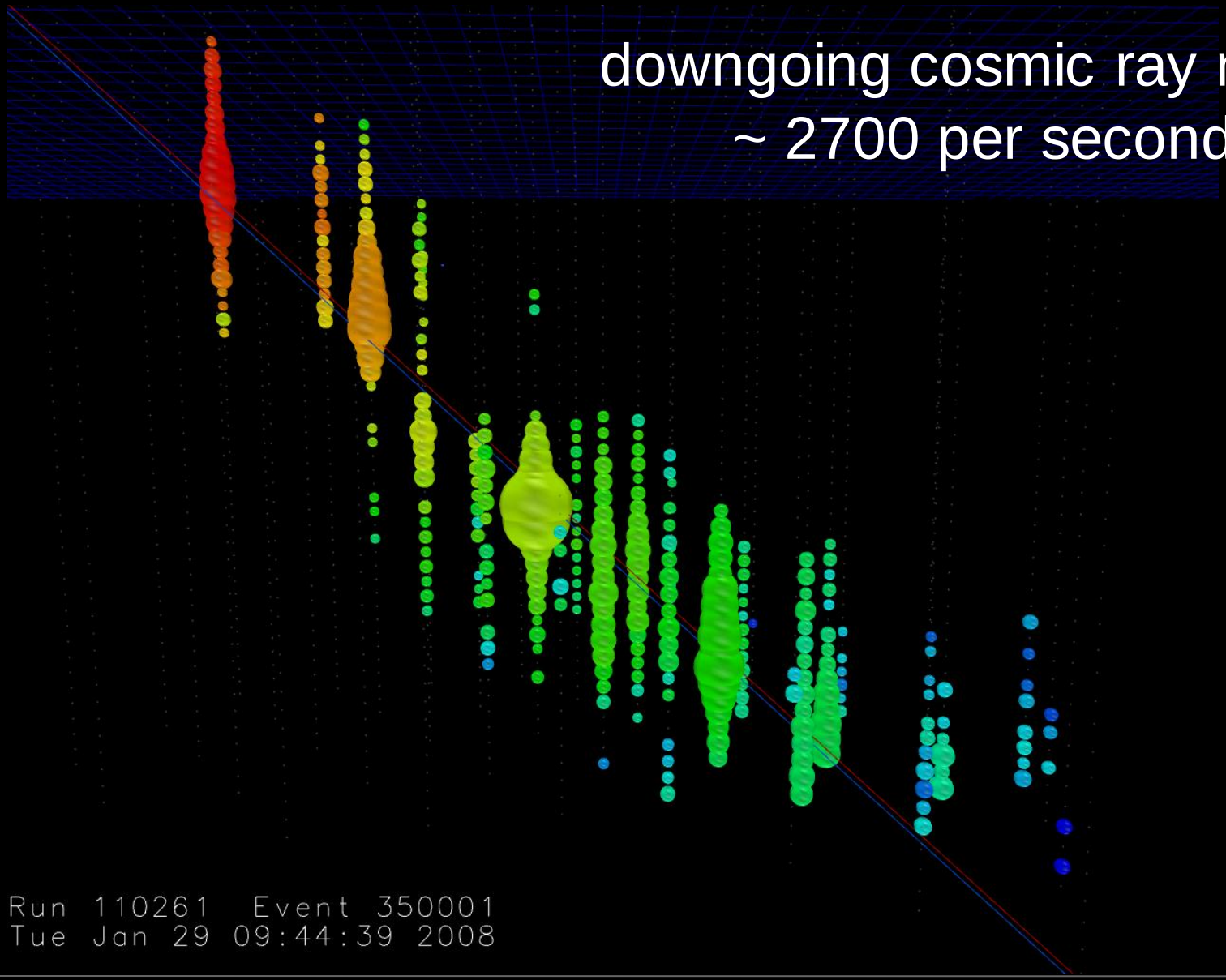
absorption length ← 220m →



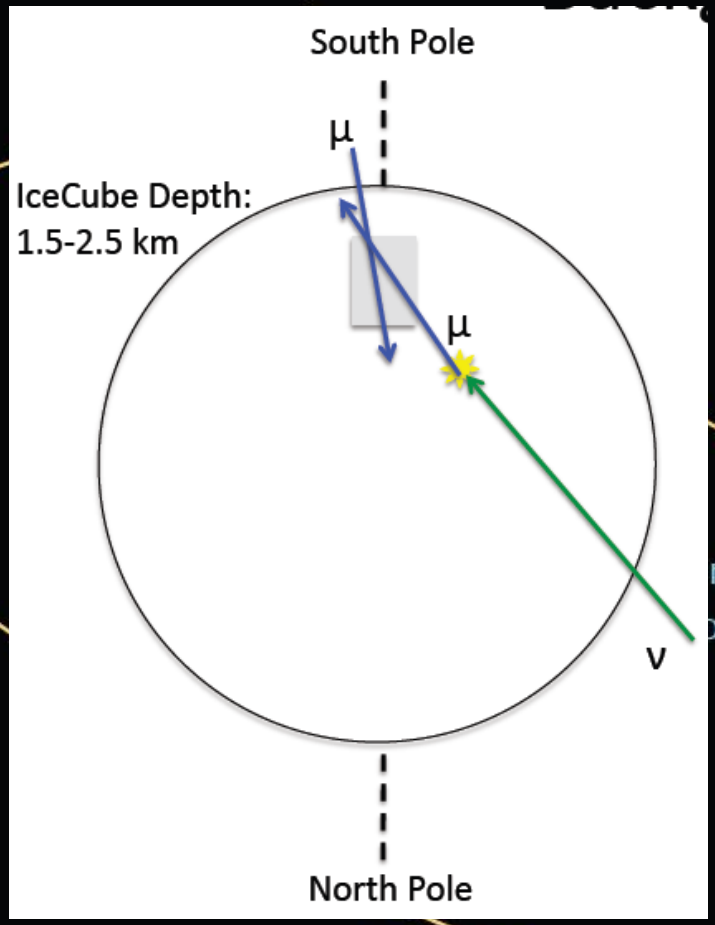
scattering length ← 47m →

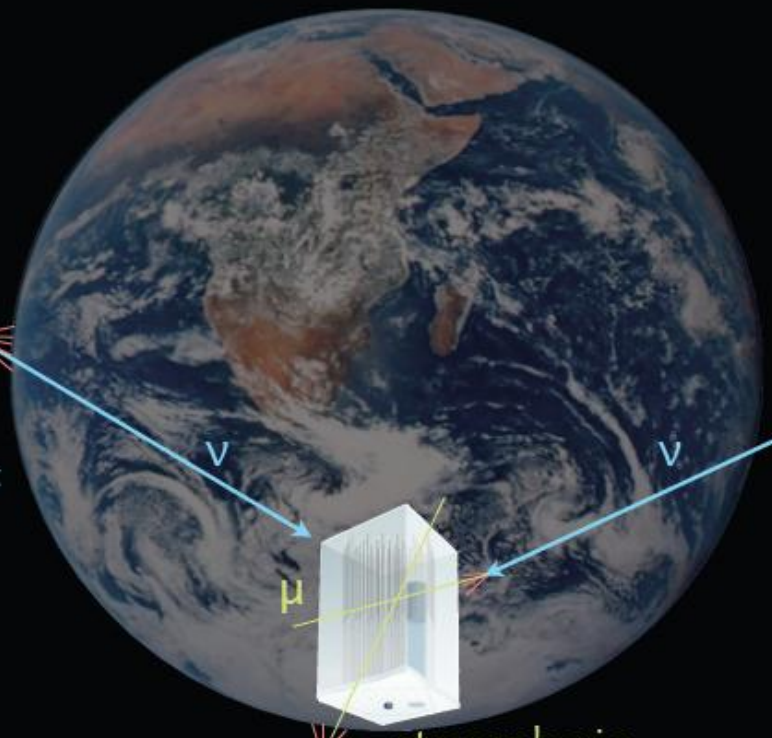


Muon event in IceCube



Signals and Backgrounds





astrophysical
neutrino

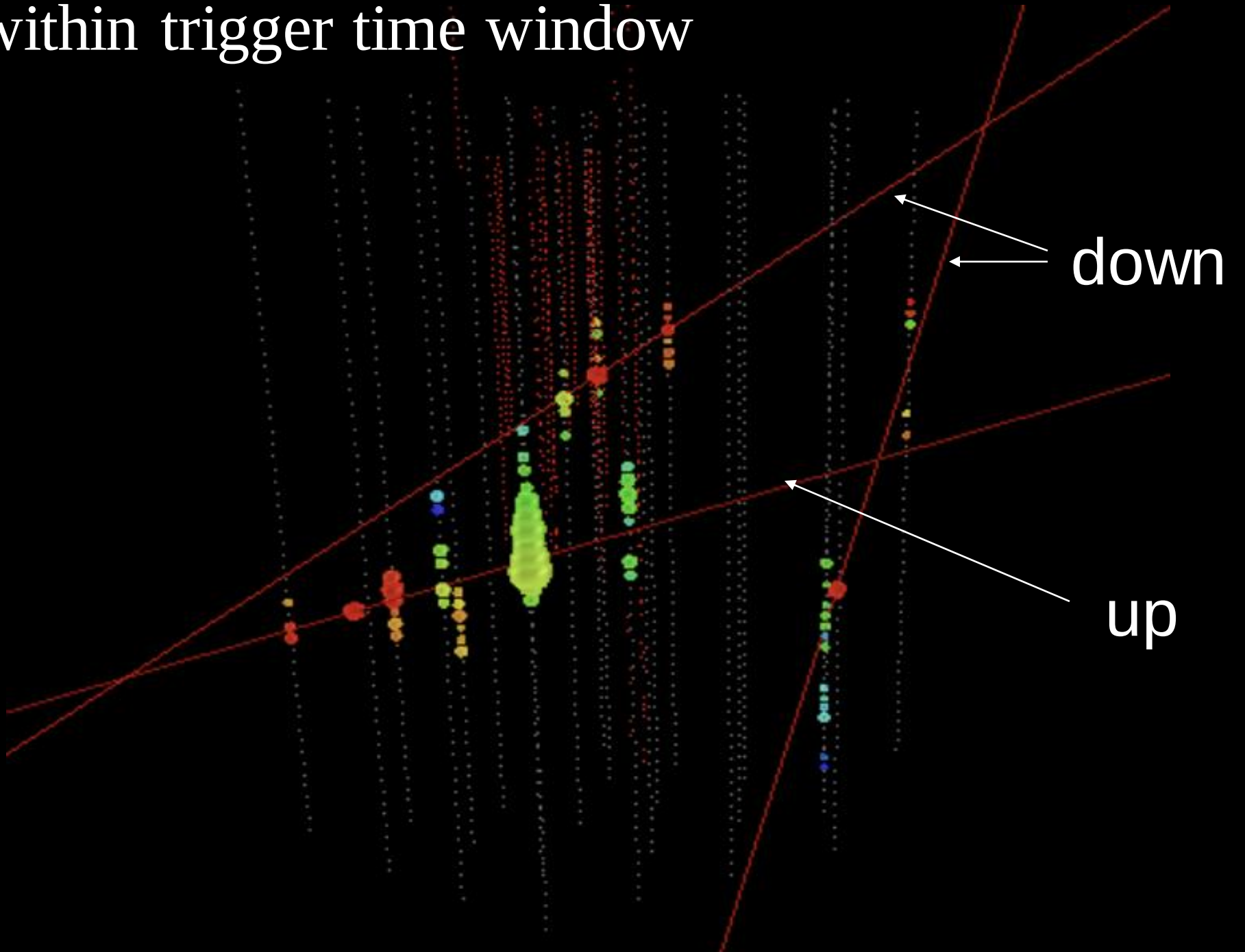
atmospheric
muon

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 ** 1 every 6 minutes

within trigger time window



(not) final performance

present (!)

IceCube

performance

then

and

now

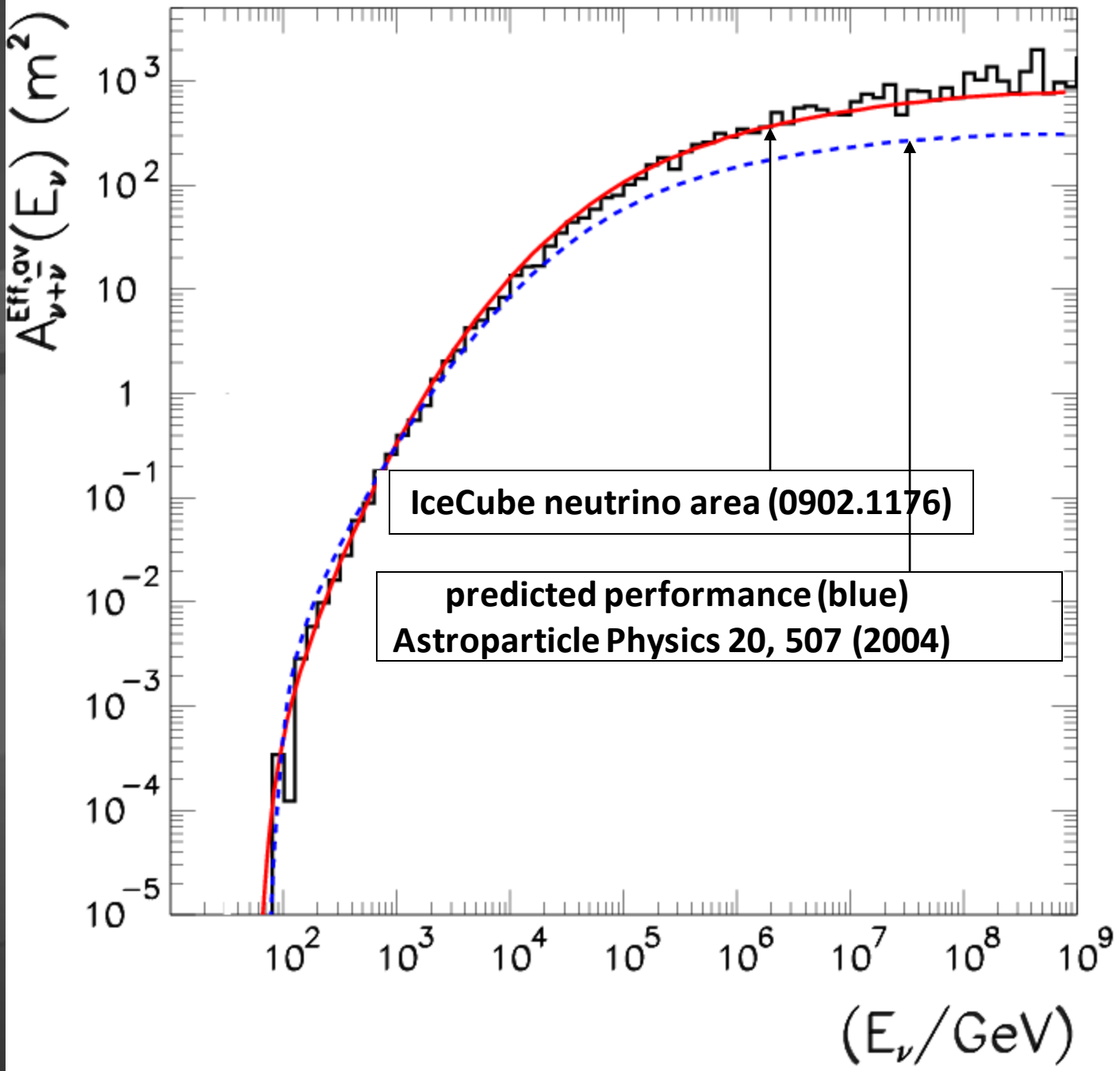
PeV: x2

EeV: x3

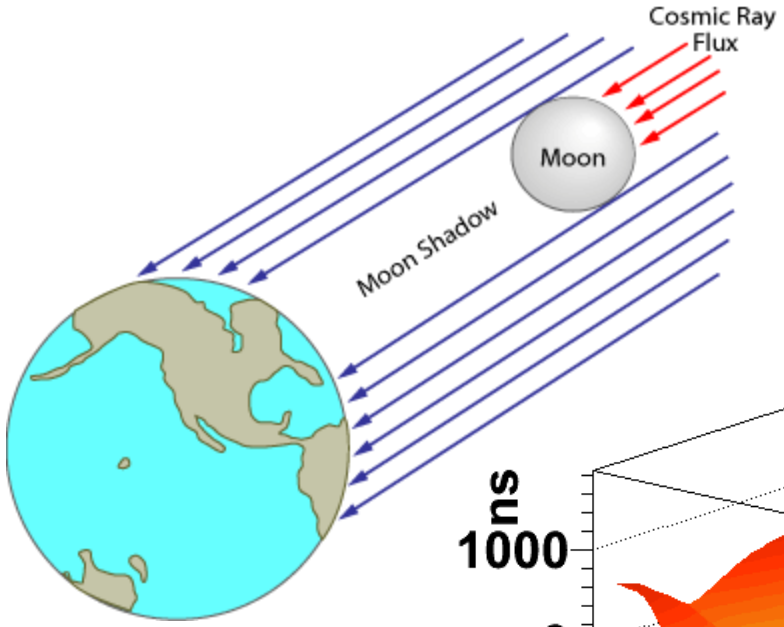
neutrino

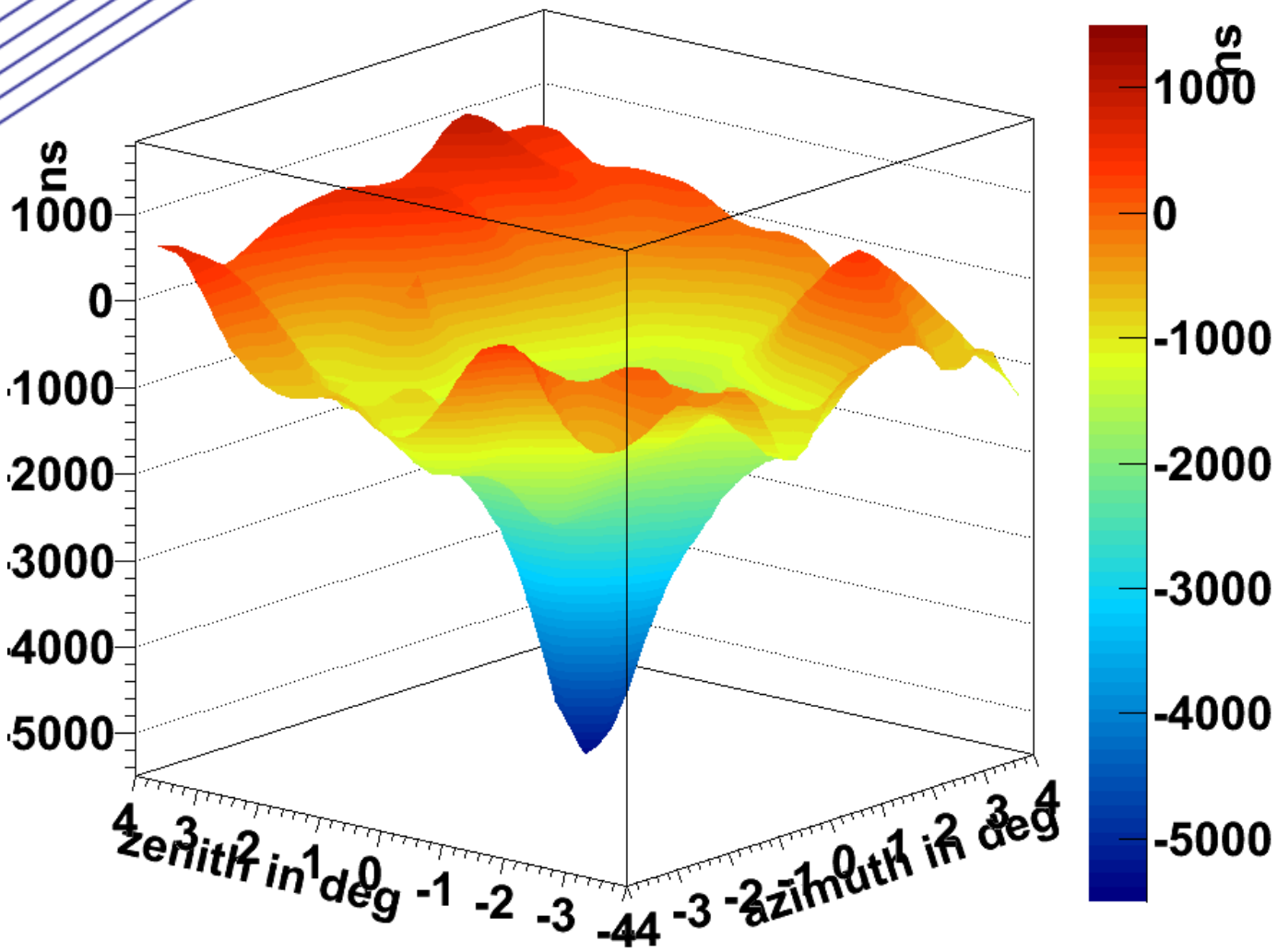
“mirror”

area

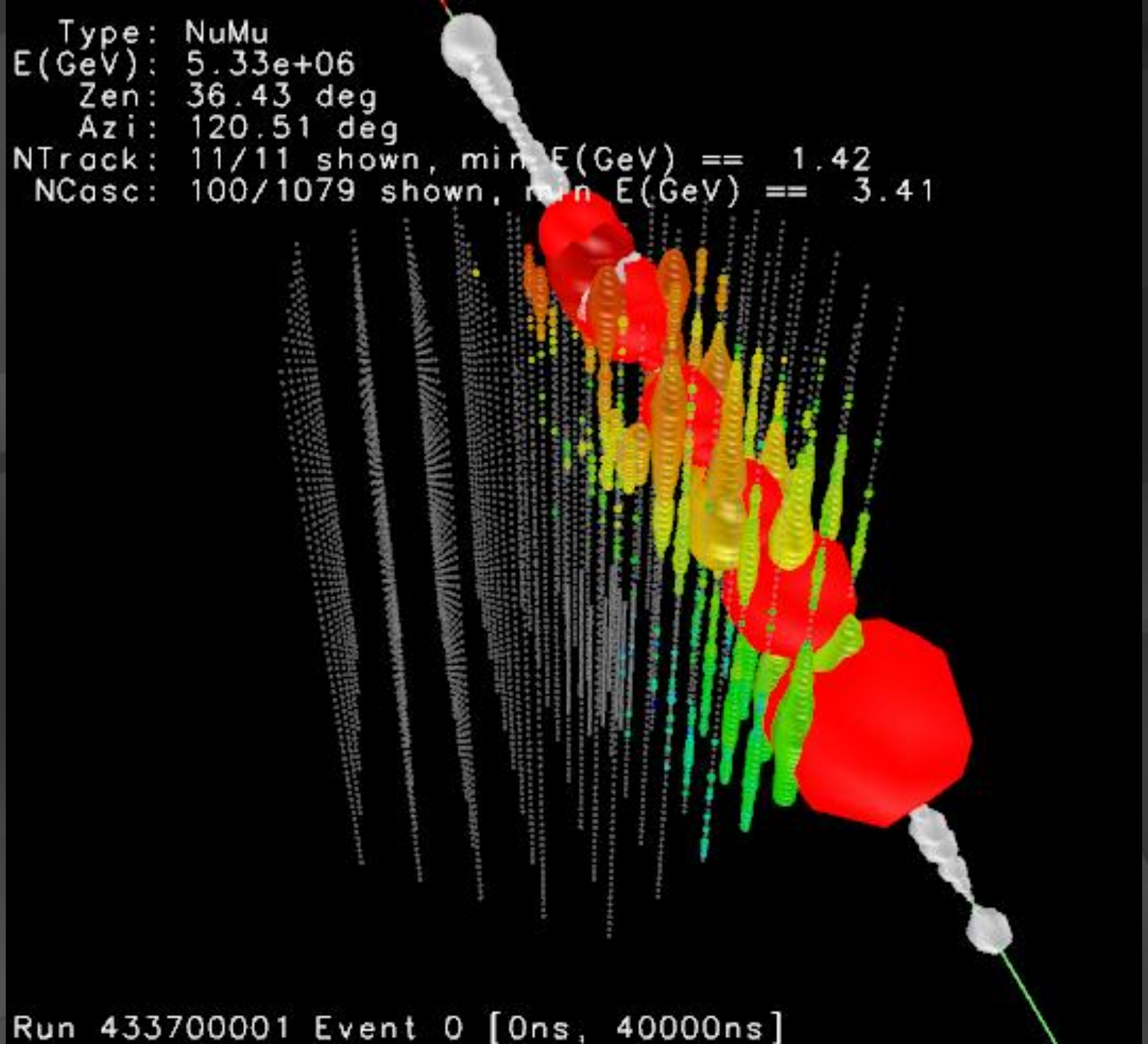


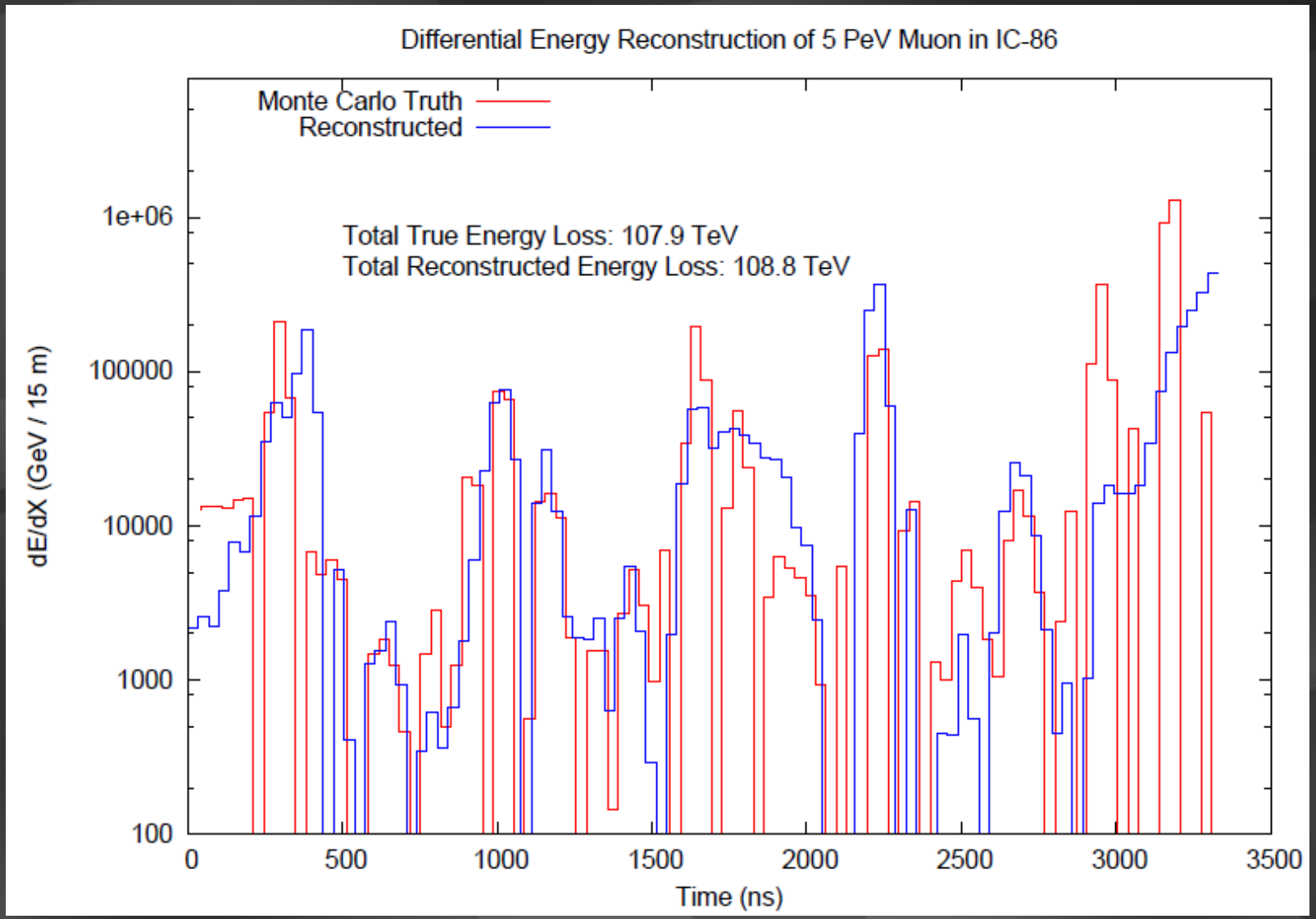
moon shadow





> 16 σ
~ 0.1 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]

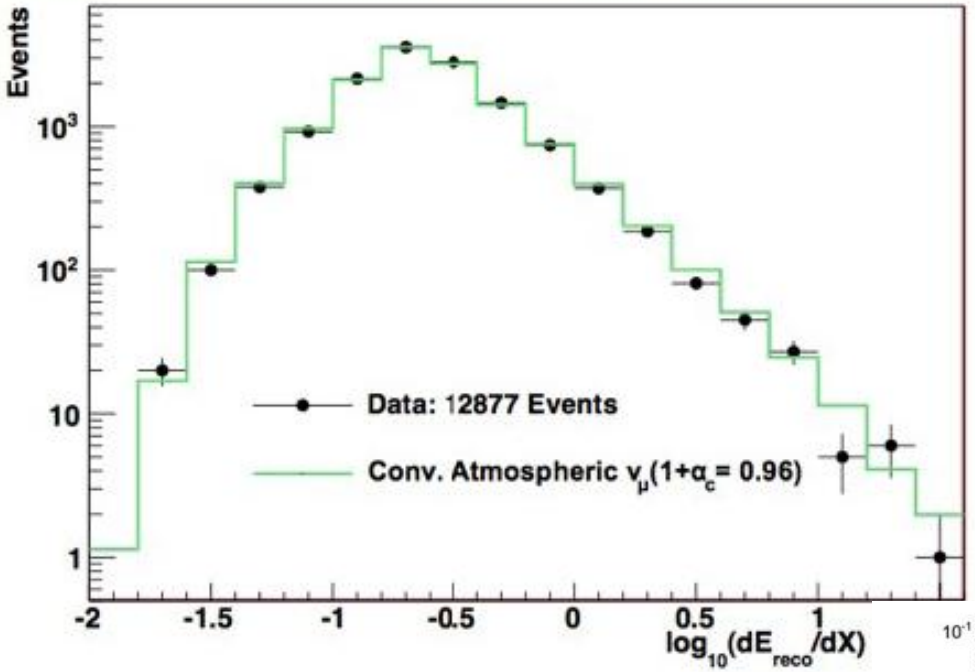


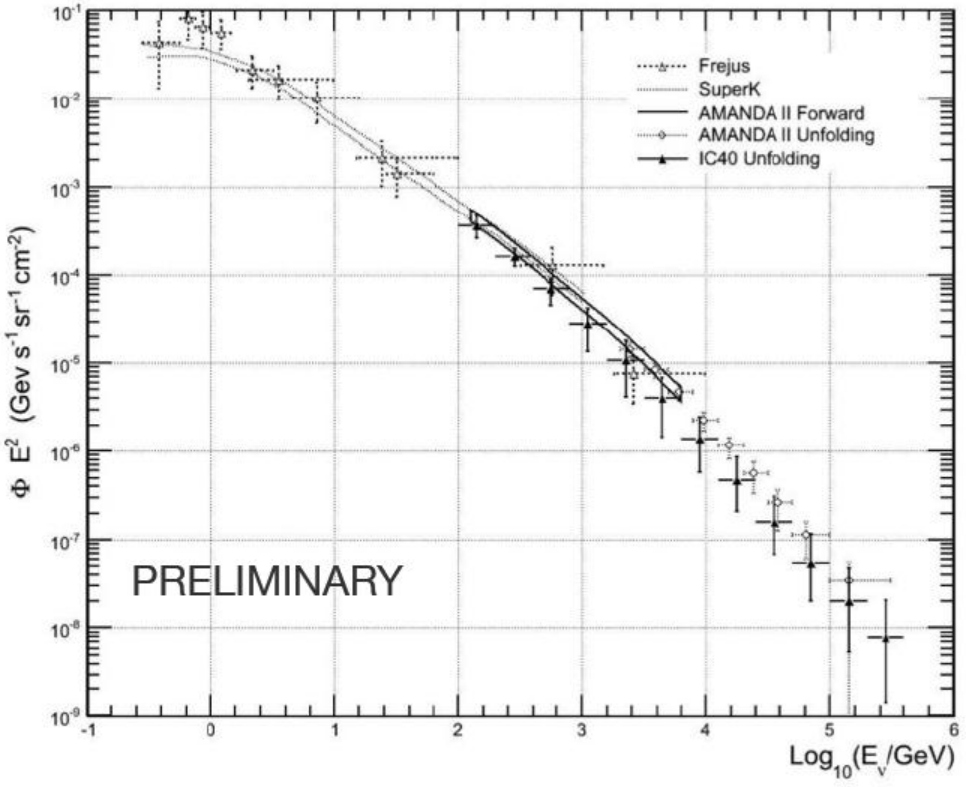
improved angular and energy resolution soon

… 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.

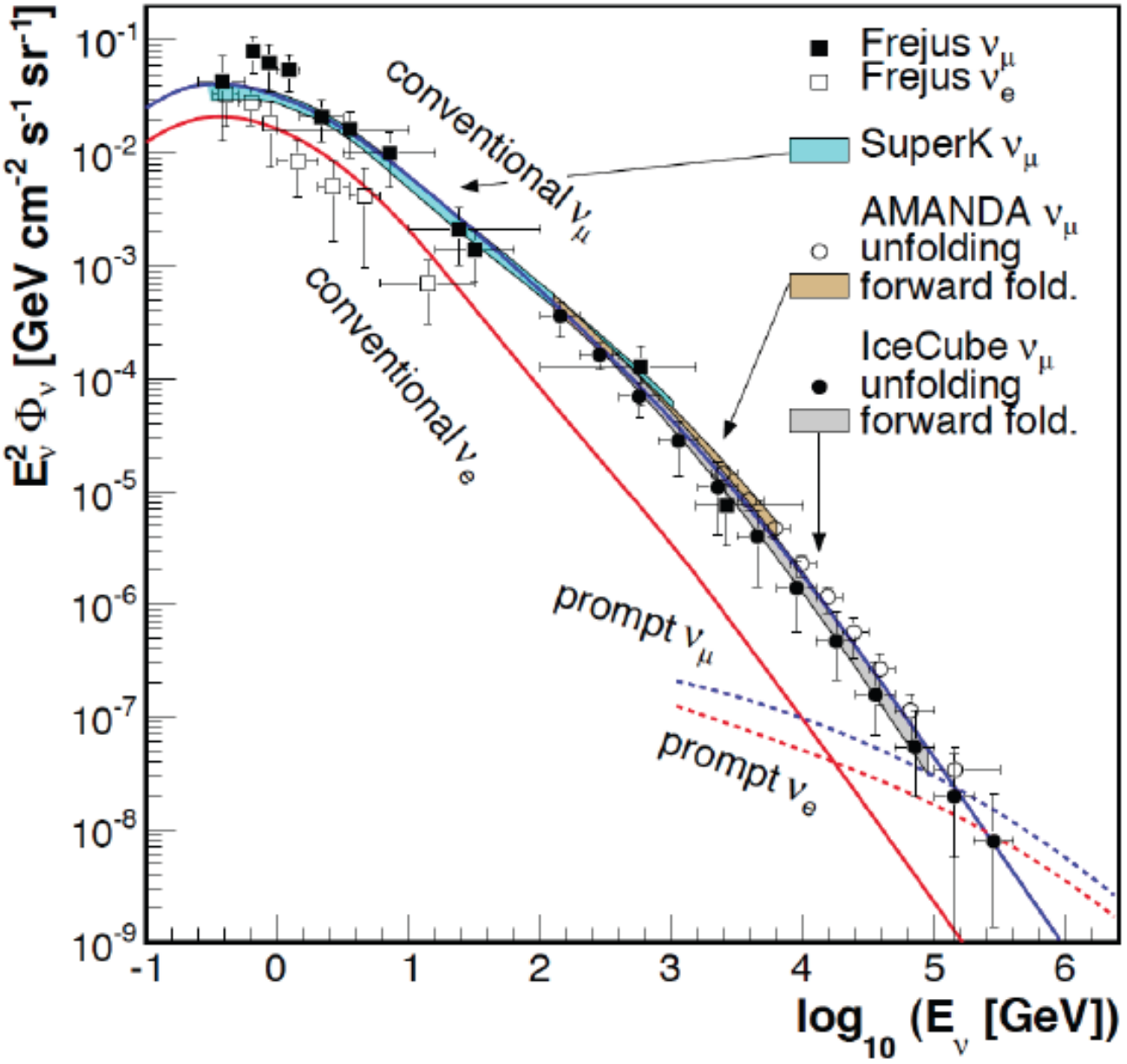
IceCube-40 atmospheric neutrino spectrum



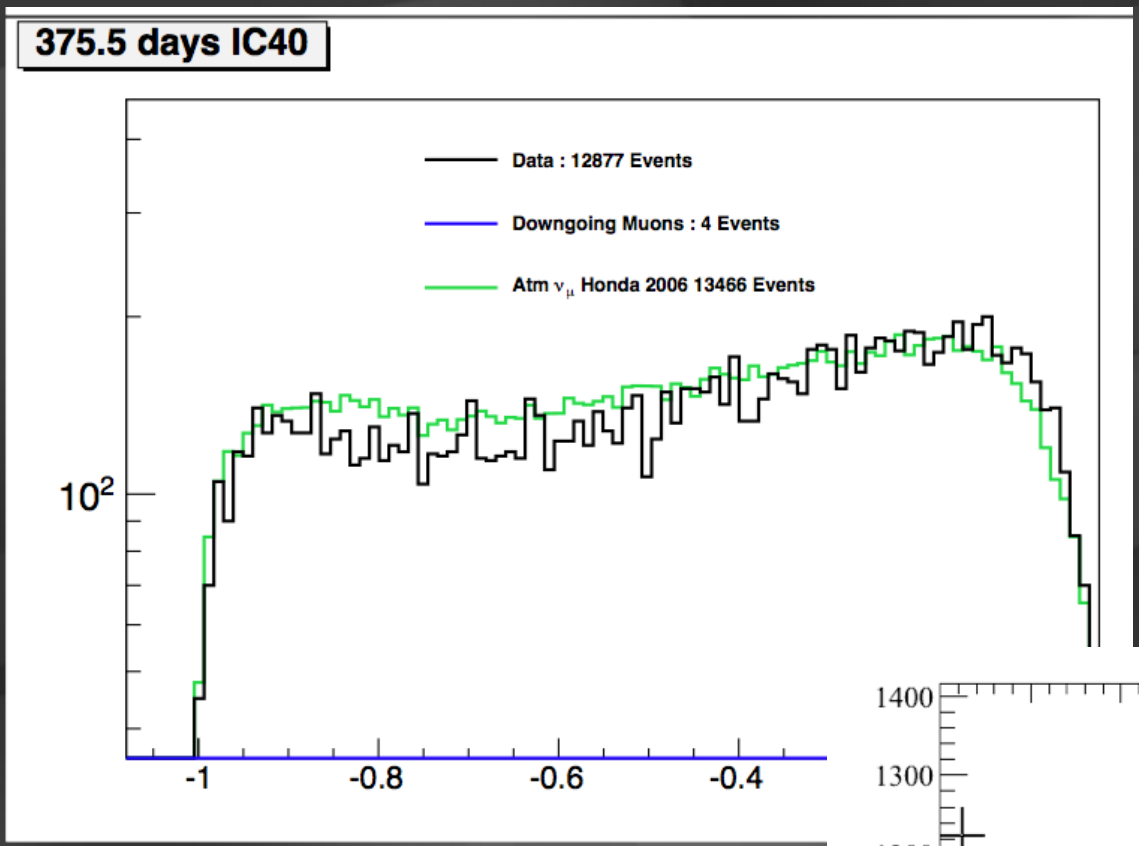


cosmic neutrinos:

energy:
>> 100 TeV

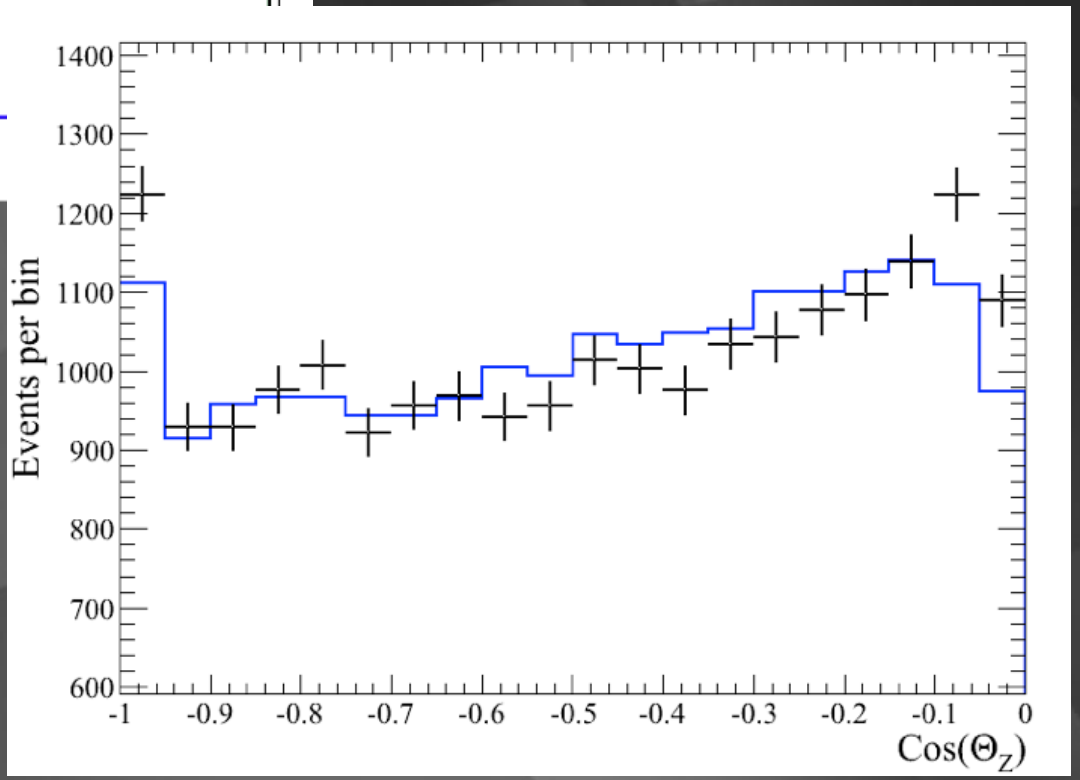


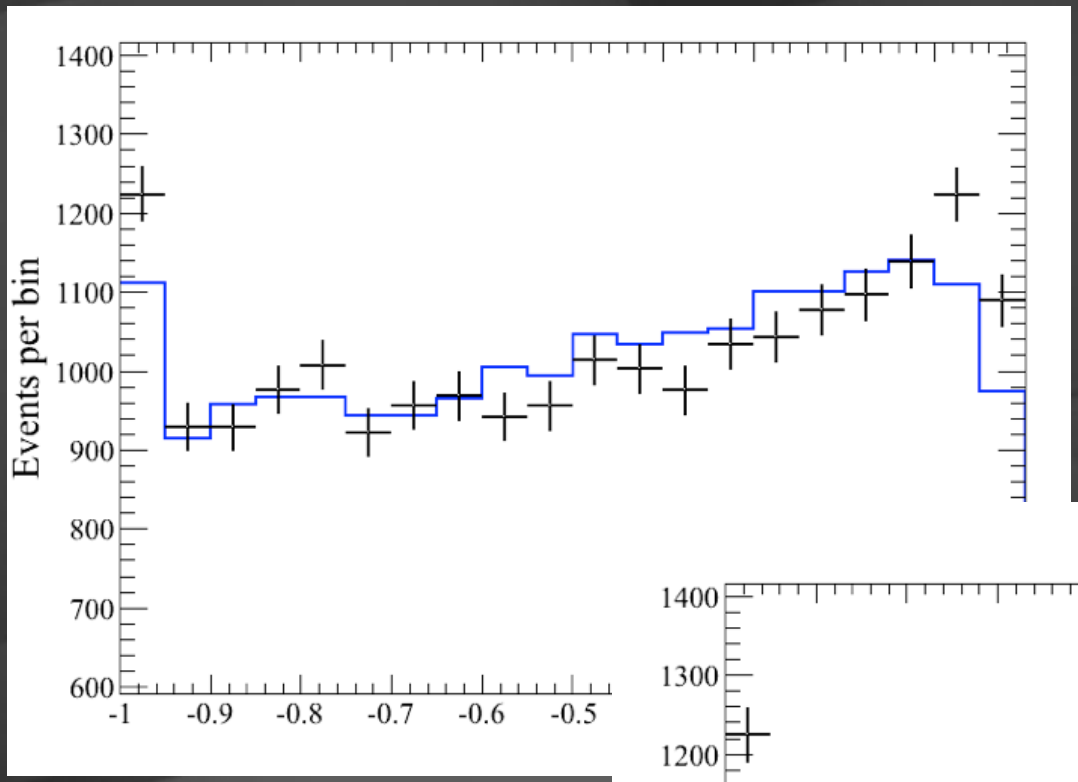
atmospheric neutrino spectrum to >100 TeV



zenith angle
two analyses

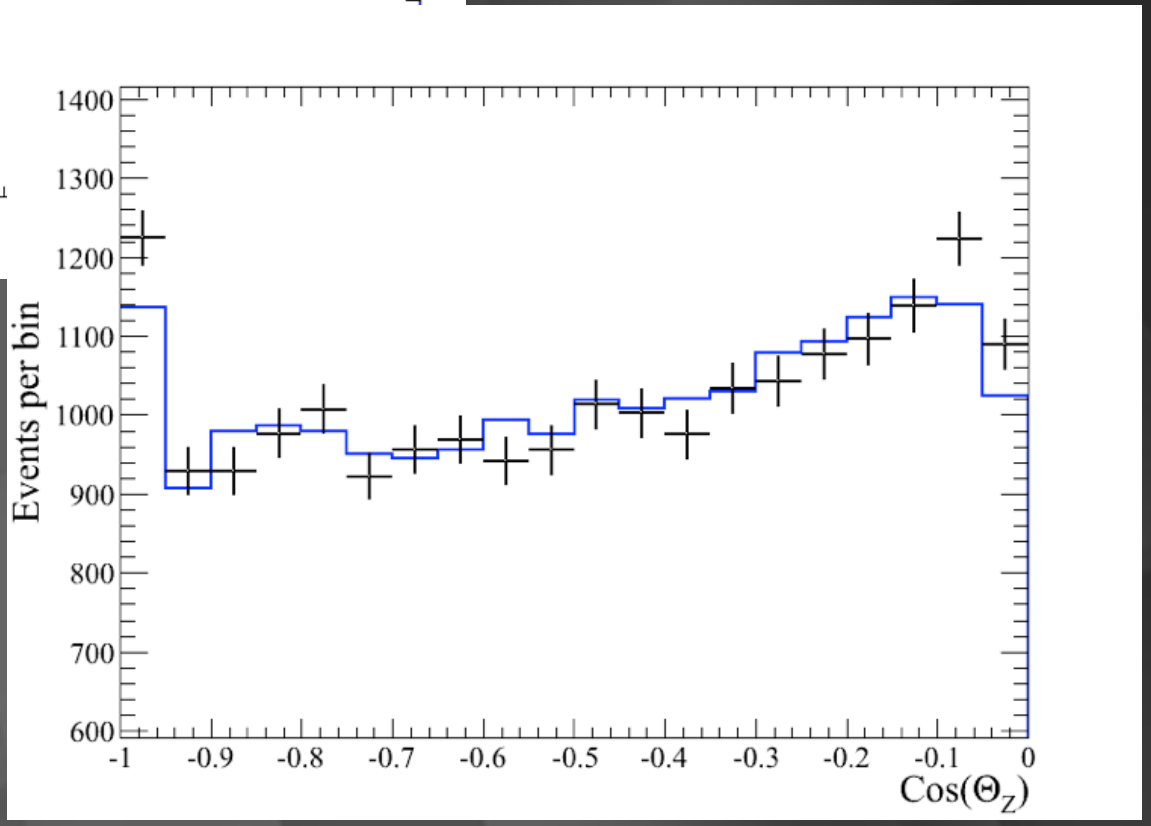
matter effect
of eV sterile ν's ?

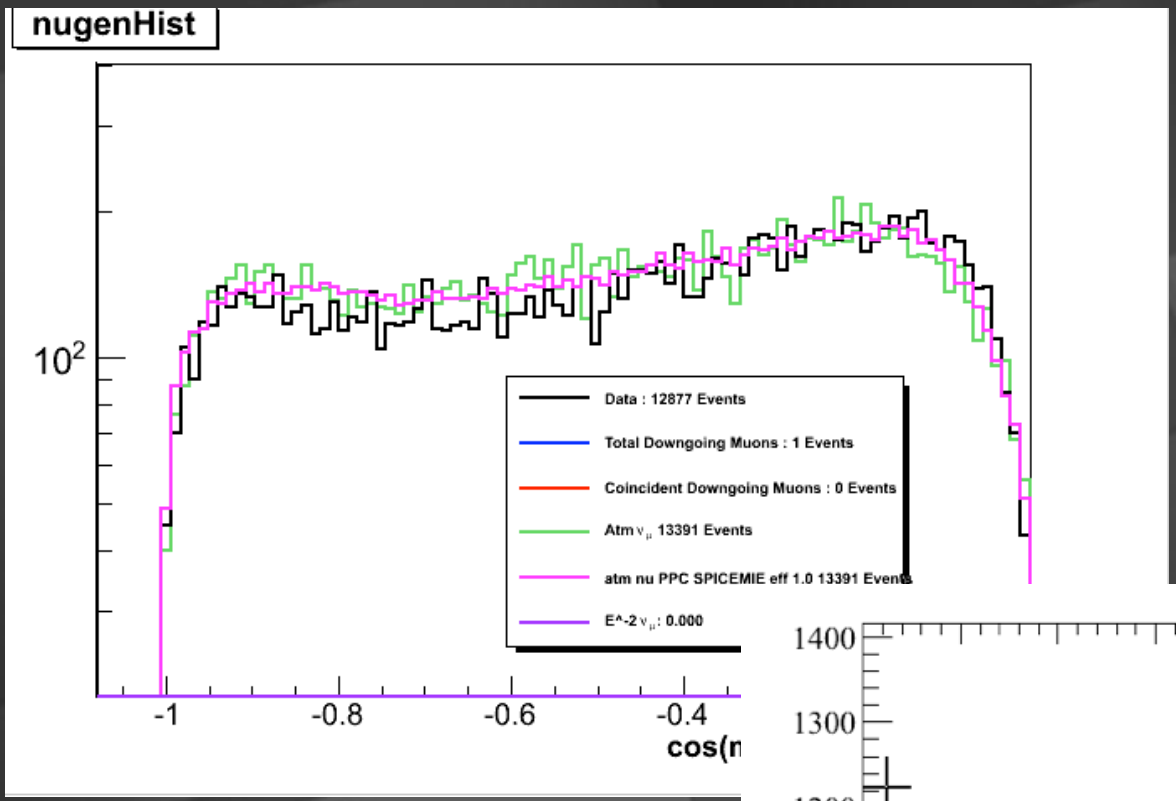



Events per bin
1400
1300
1200
1100
1000
900
800
700
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5

3

3+1

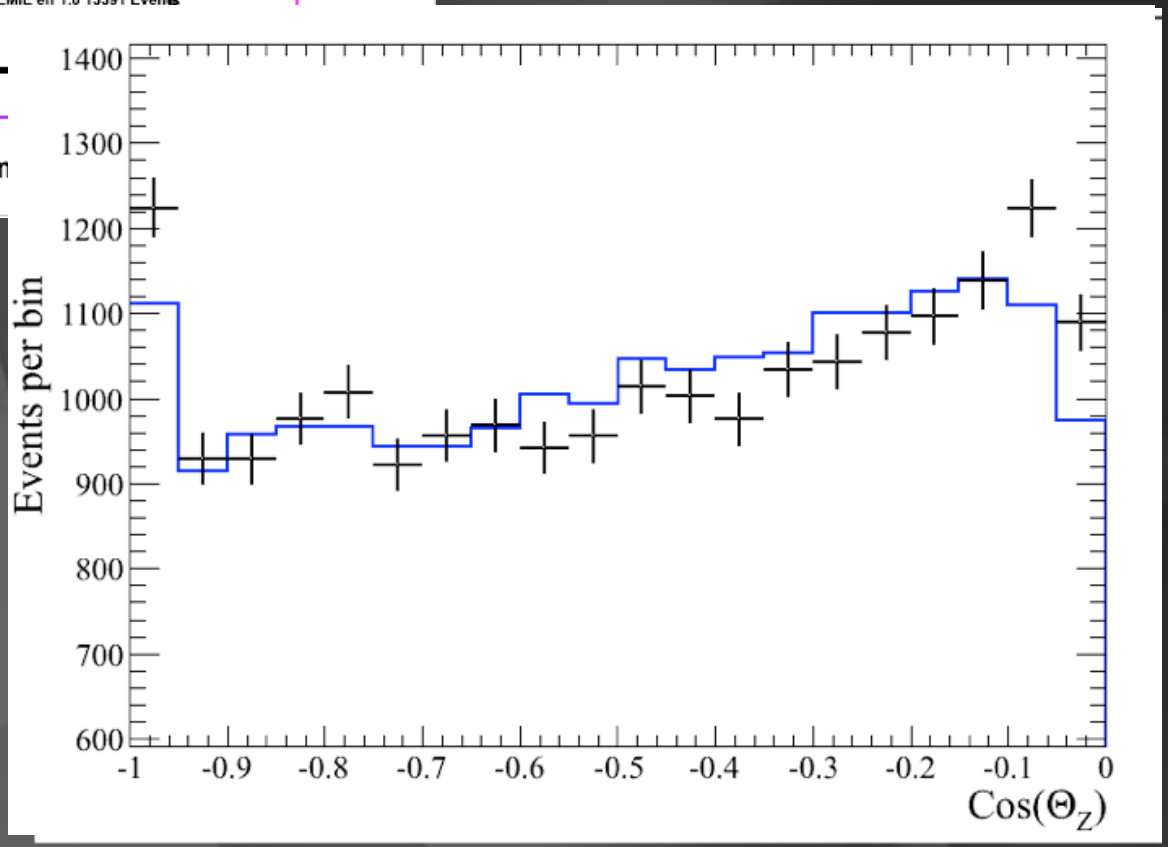

Events per bin
1400
1300
1200
1100
1000
900
800
700
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cos(Θz)



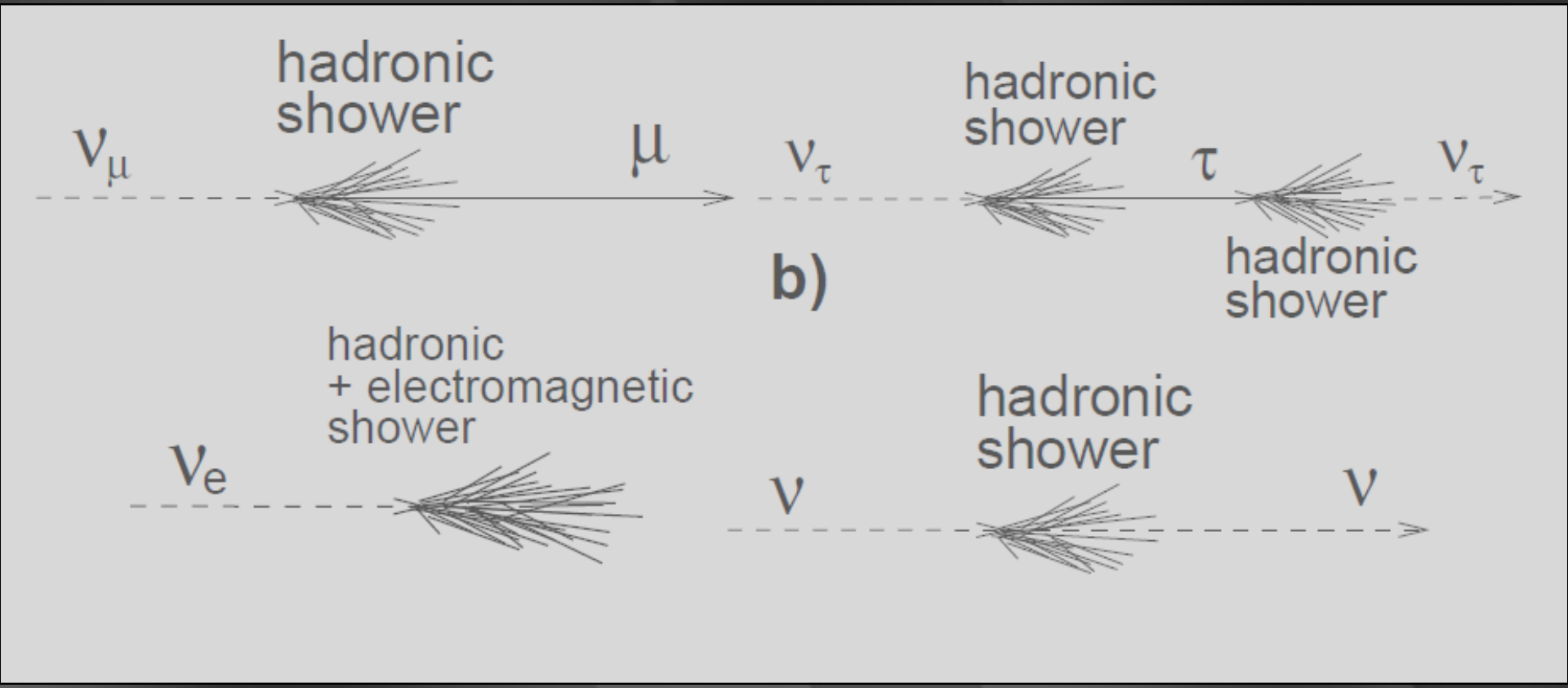
zenith angle
two analyses

systematics !!!

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

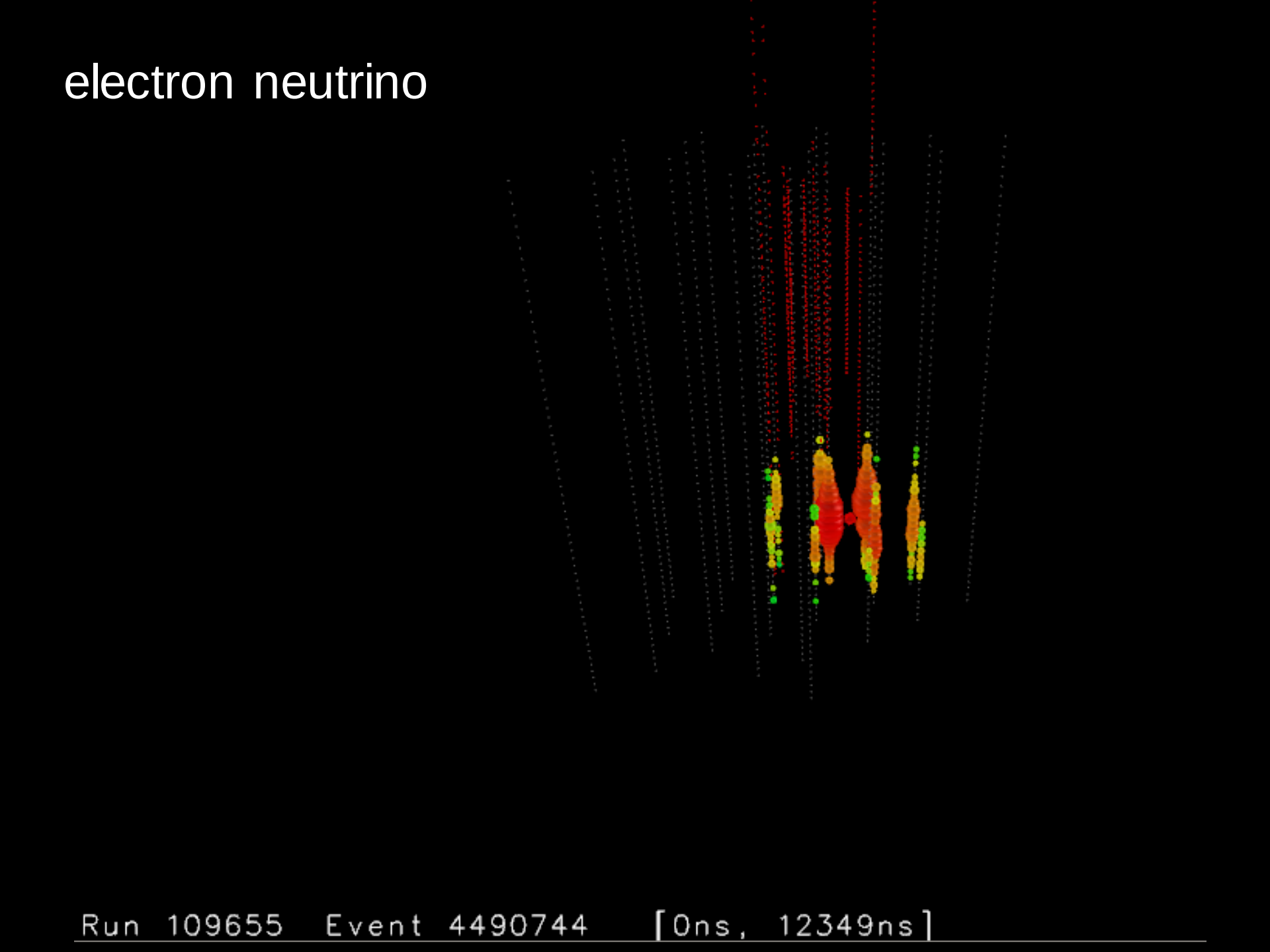


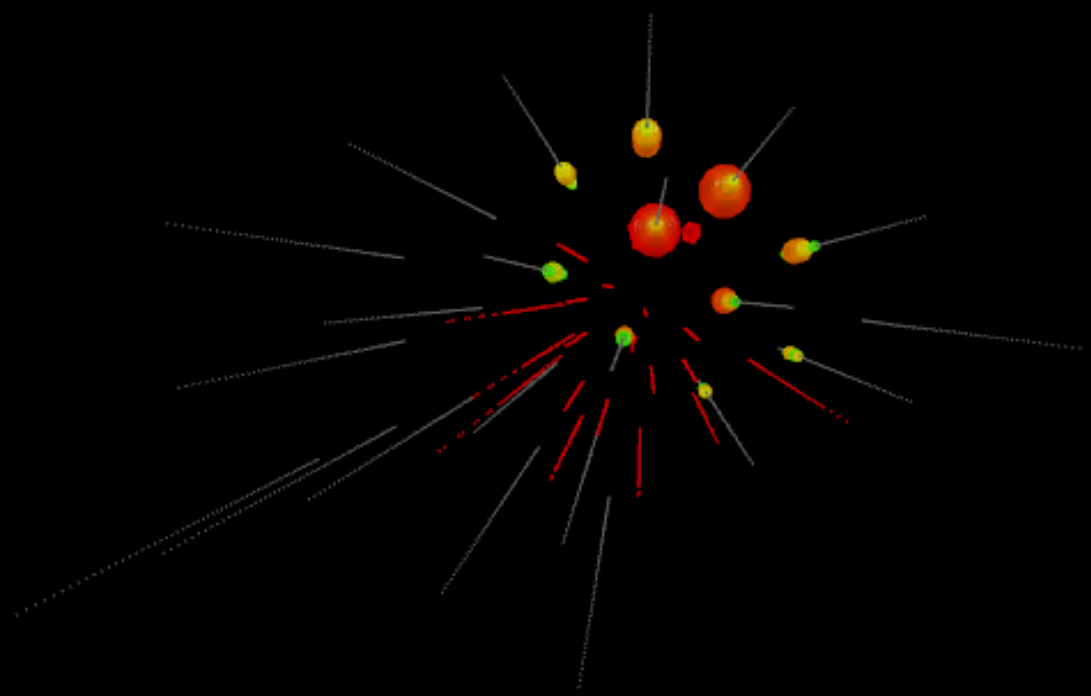
neutrino flavors



(also ν_e appearance)

electron neutrino

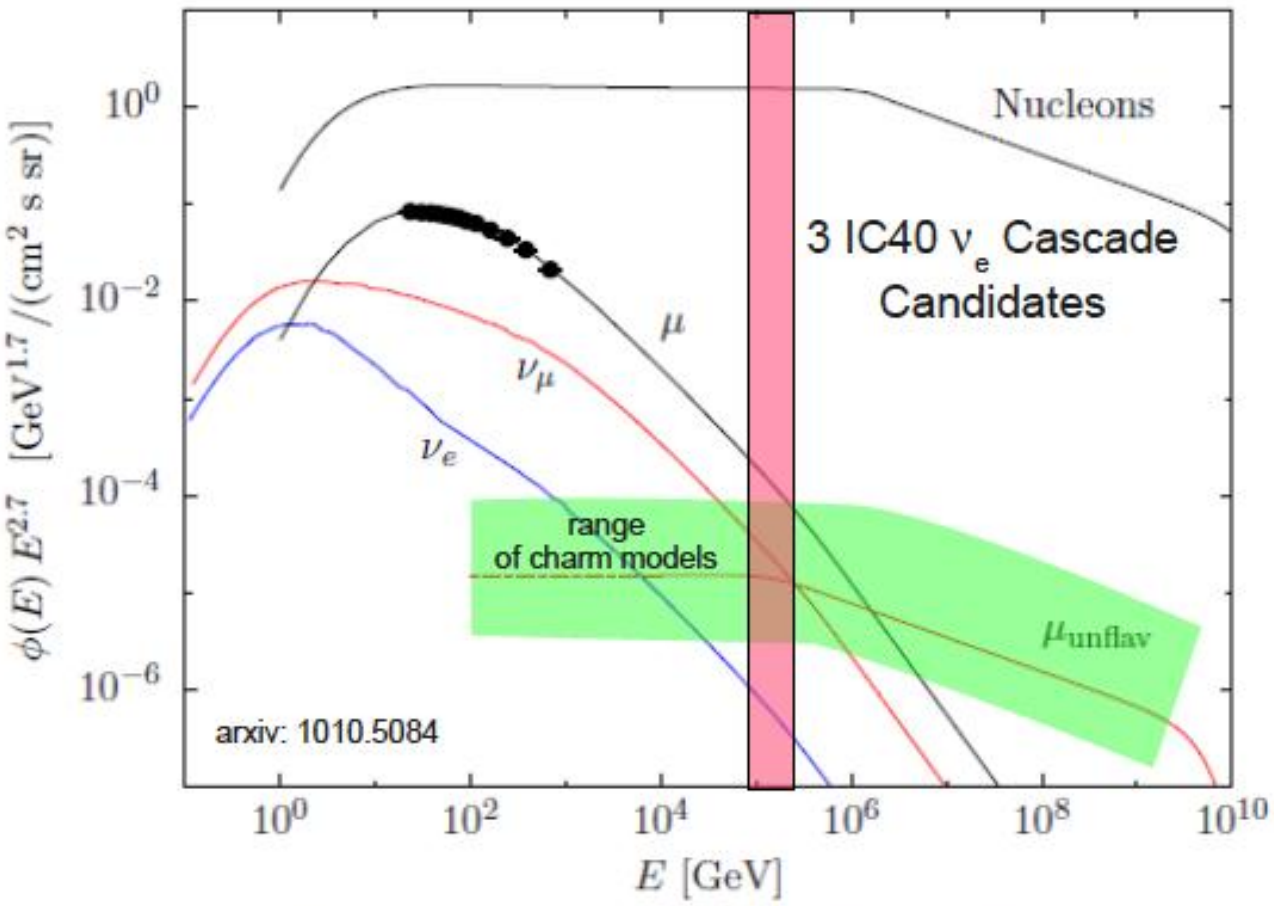


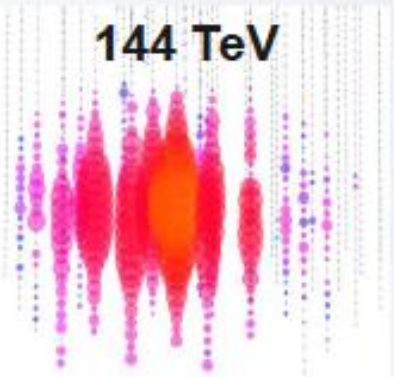


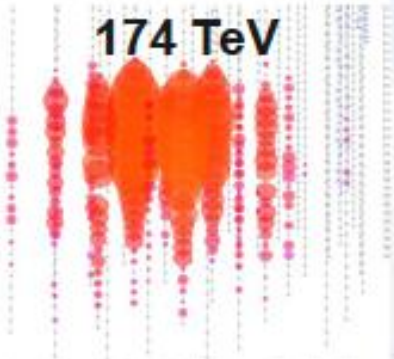
seen: 14 events

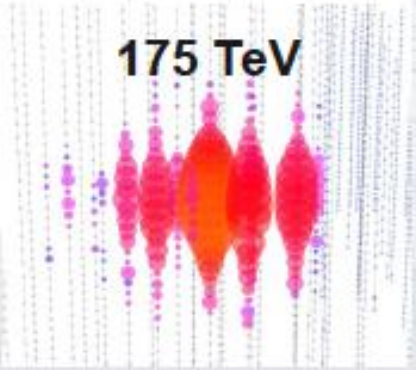
predicted: 3 atmospheric and 4 background

Run 109655 Event 4490744 [0ns, 12349ns]









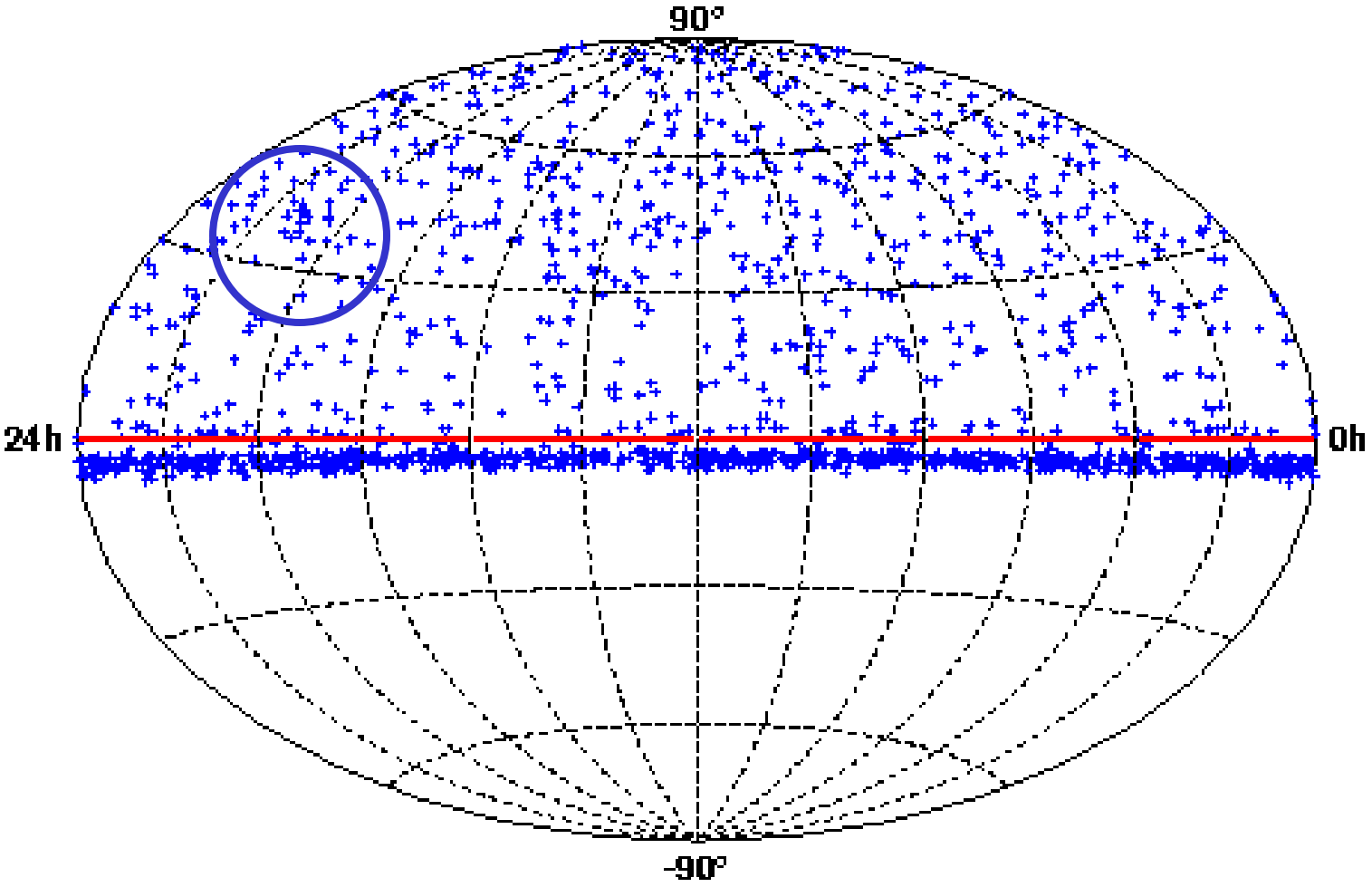
Three strong ν_e candidate events above 100 TeV in IC40

(+1 in IC22)

early astronomy

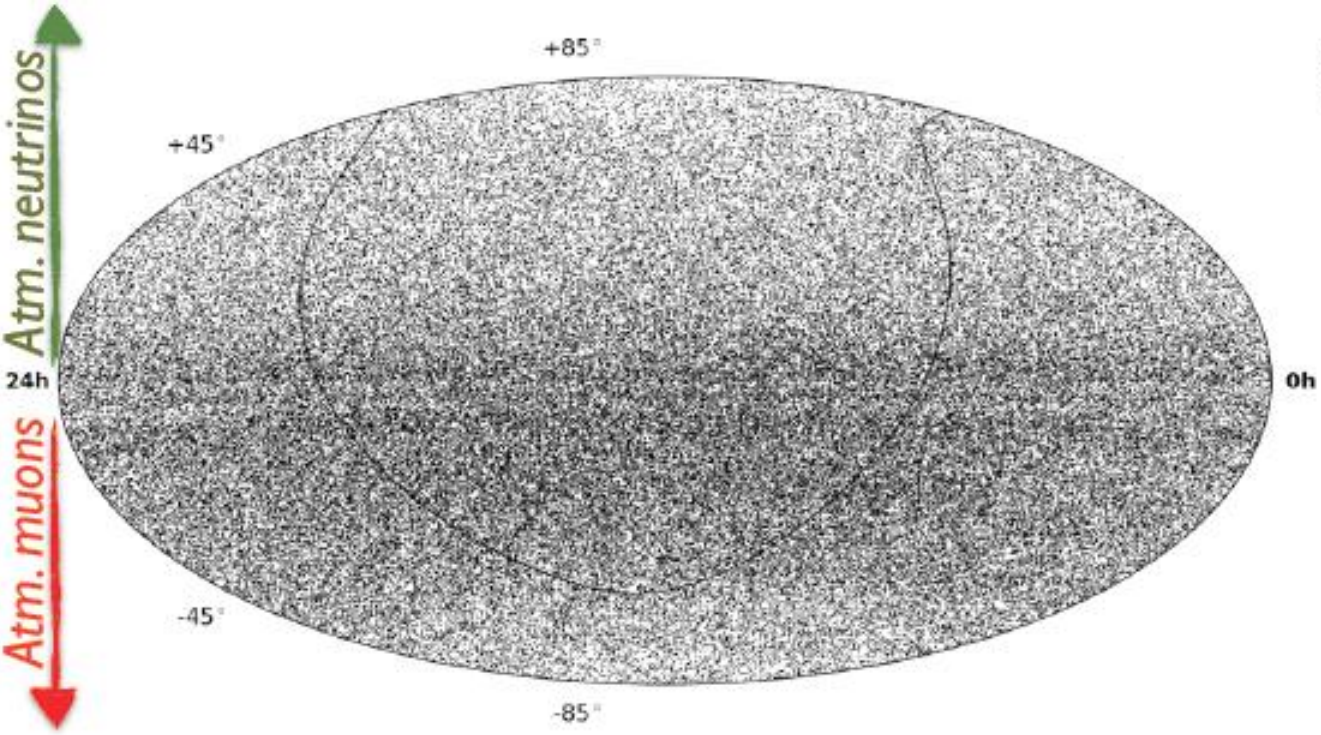
AMANDA 2000

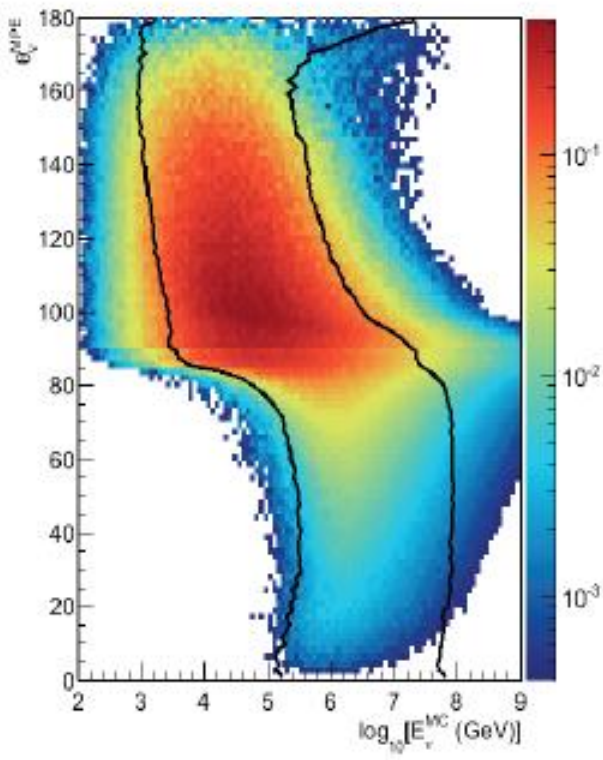
directions of ~ 600 neutrinos



IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos





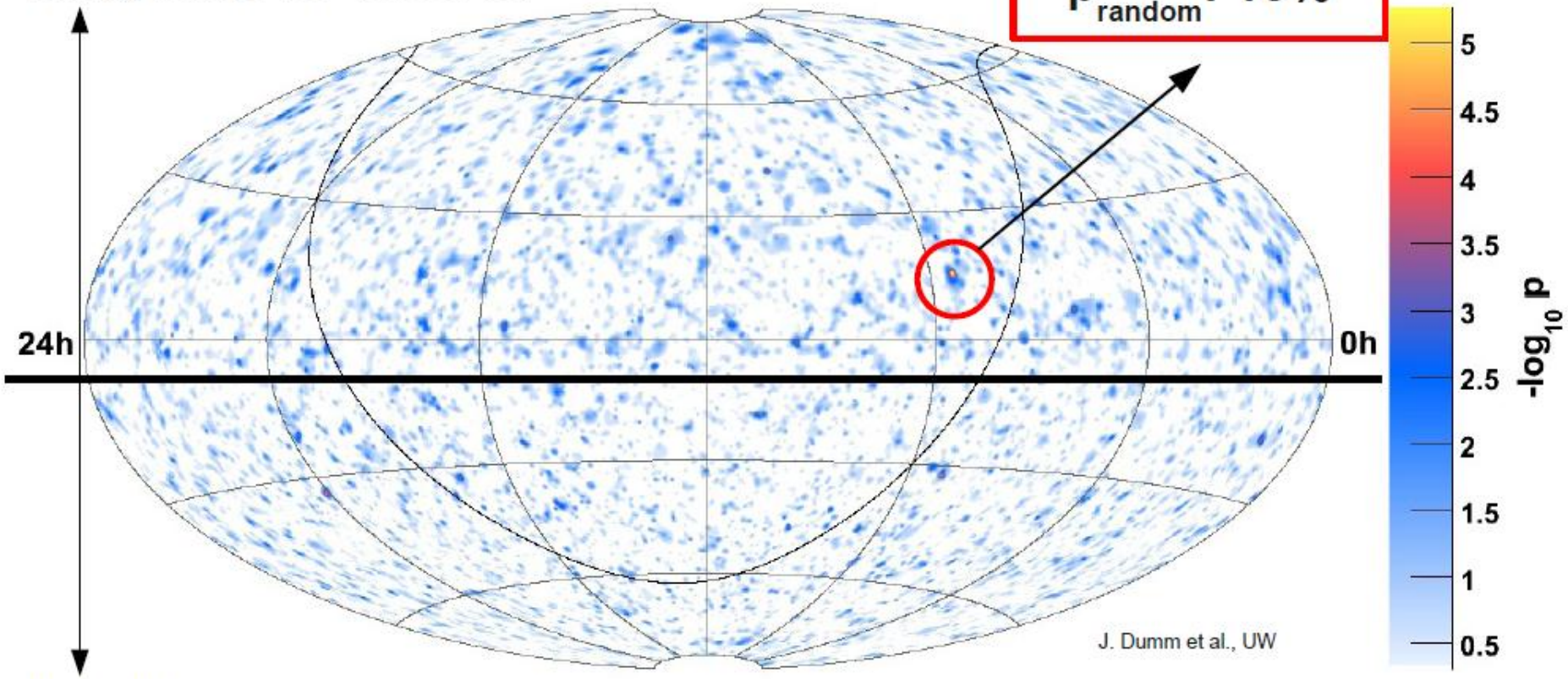
- *Total events: 43339 (upgoing) + 64230 (downgoing)*
- *Livetime: 348 days (IC59) + 375 days (IC40)*

- clustering
- high energy (>> 100 TeV)

southern sky: 23151 muons

IC40 Point Source Search

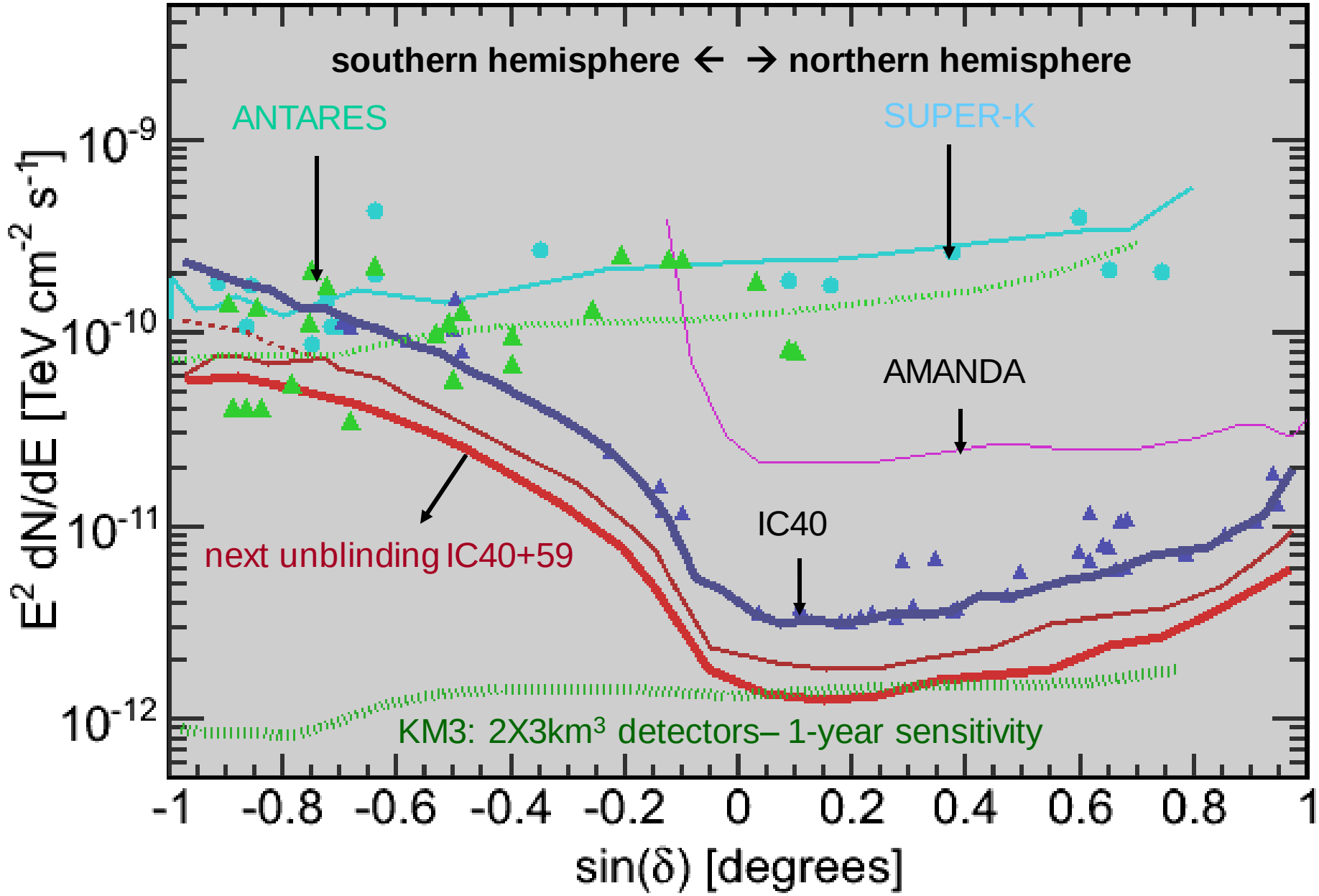
Below Horizon:
Data dominated by atmospheric **Neutrinos**
Energy Range 10s-100s of TeV

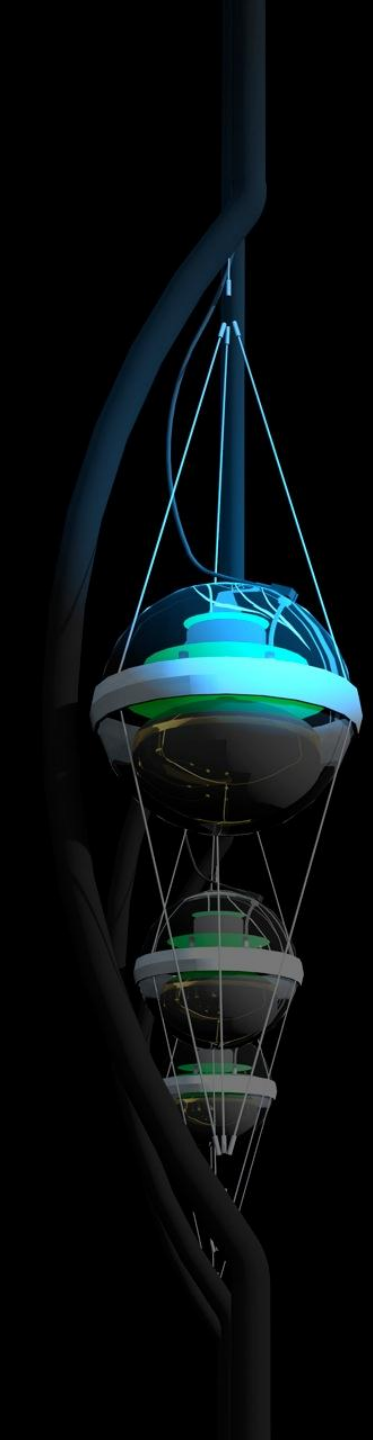


Above Horizon:
Data dominated by atmospheric **Muons**
Energy Range >PeV, increasing with angle

- nothing seen yet (ongoing)
- nothing expected (next)

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





- introduction
- 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

dark matter

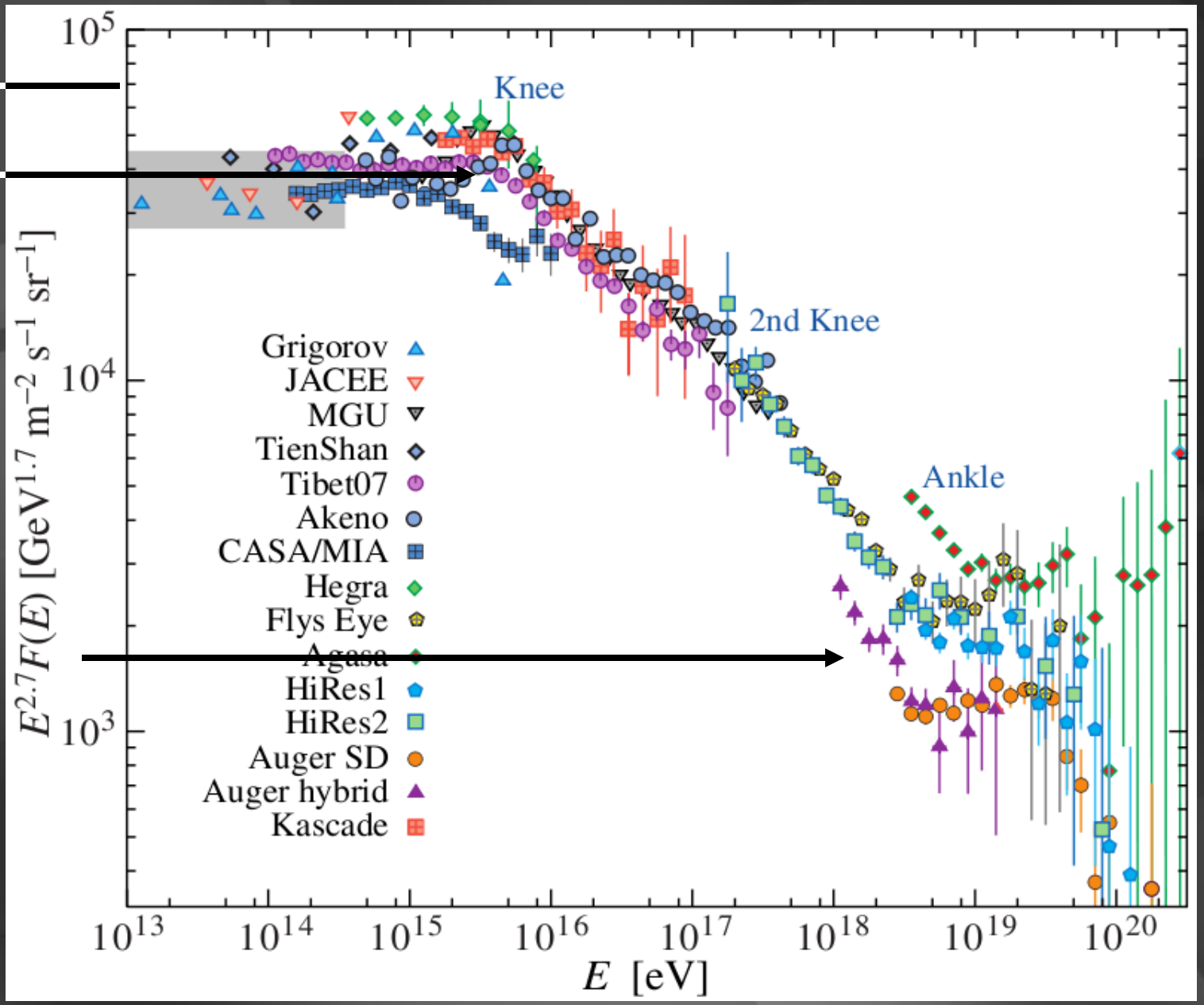
IceCube.wisc.edu

solar cosmic rays

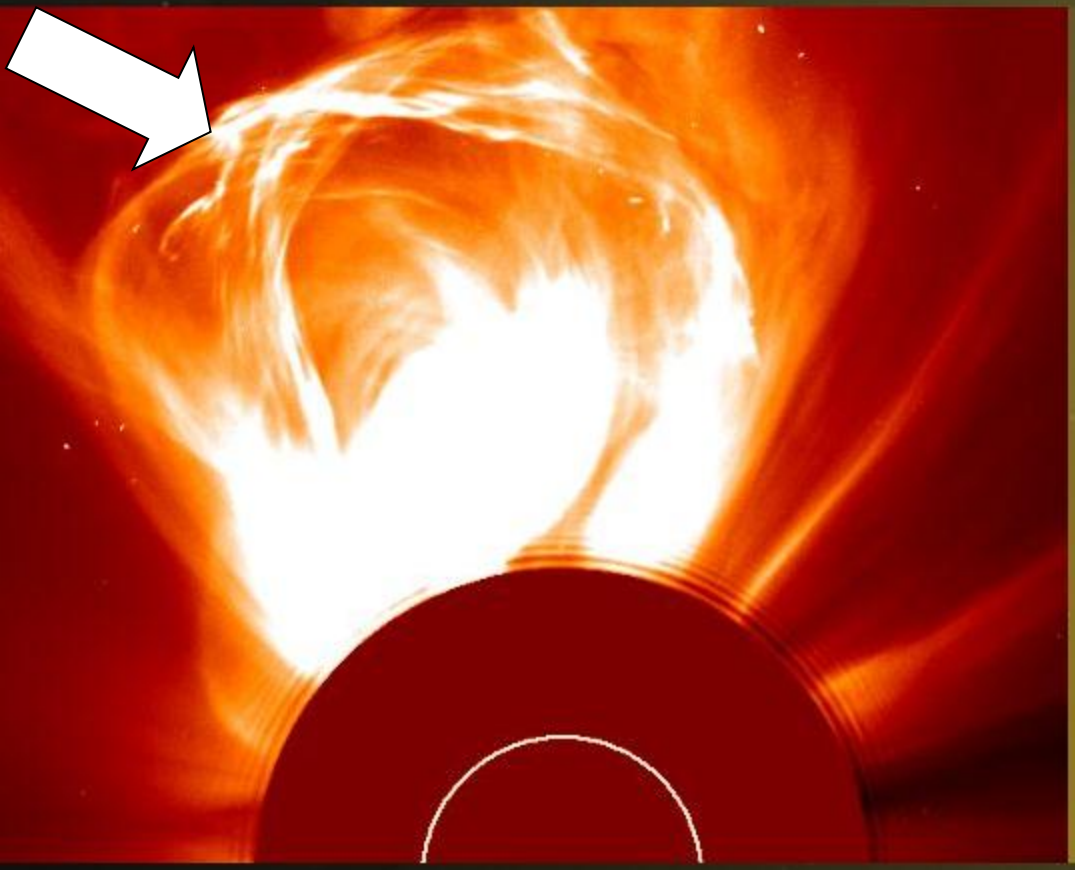
… often wrong, but never in doubt …

Galactic: supernova remnants?

extragalactic: gamma ray bursts? active galaxies?



particle acceleration in solar flare

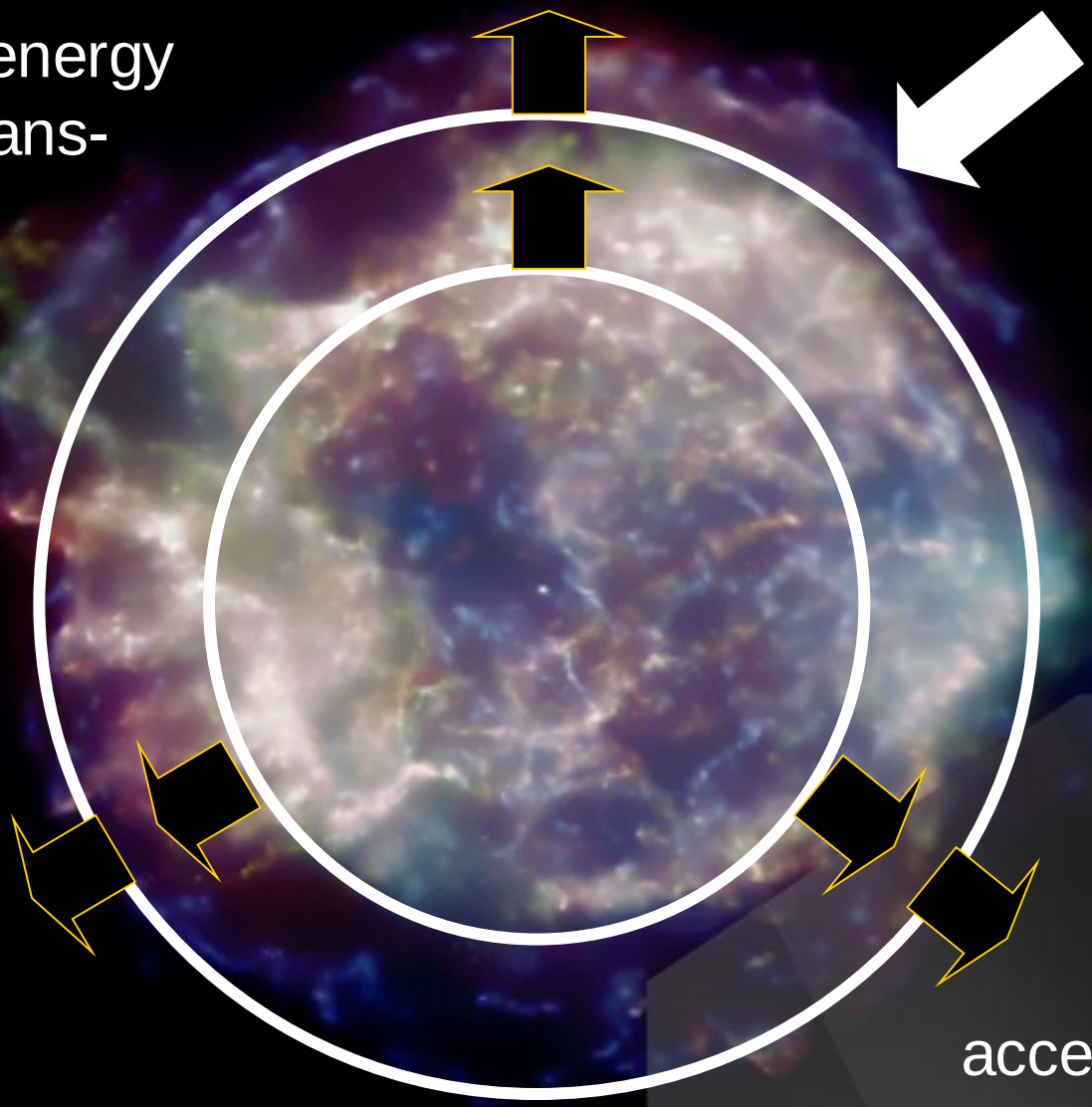


coronal
mass
ejection
→
10 GeV
particles

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})

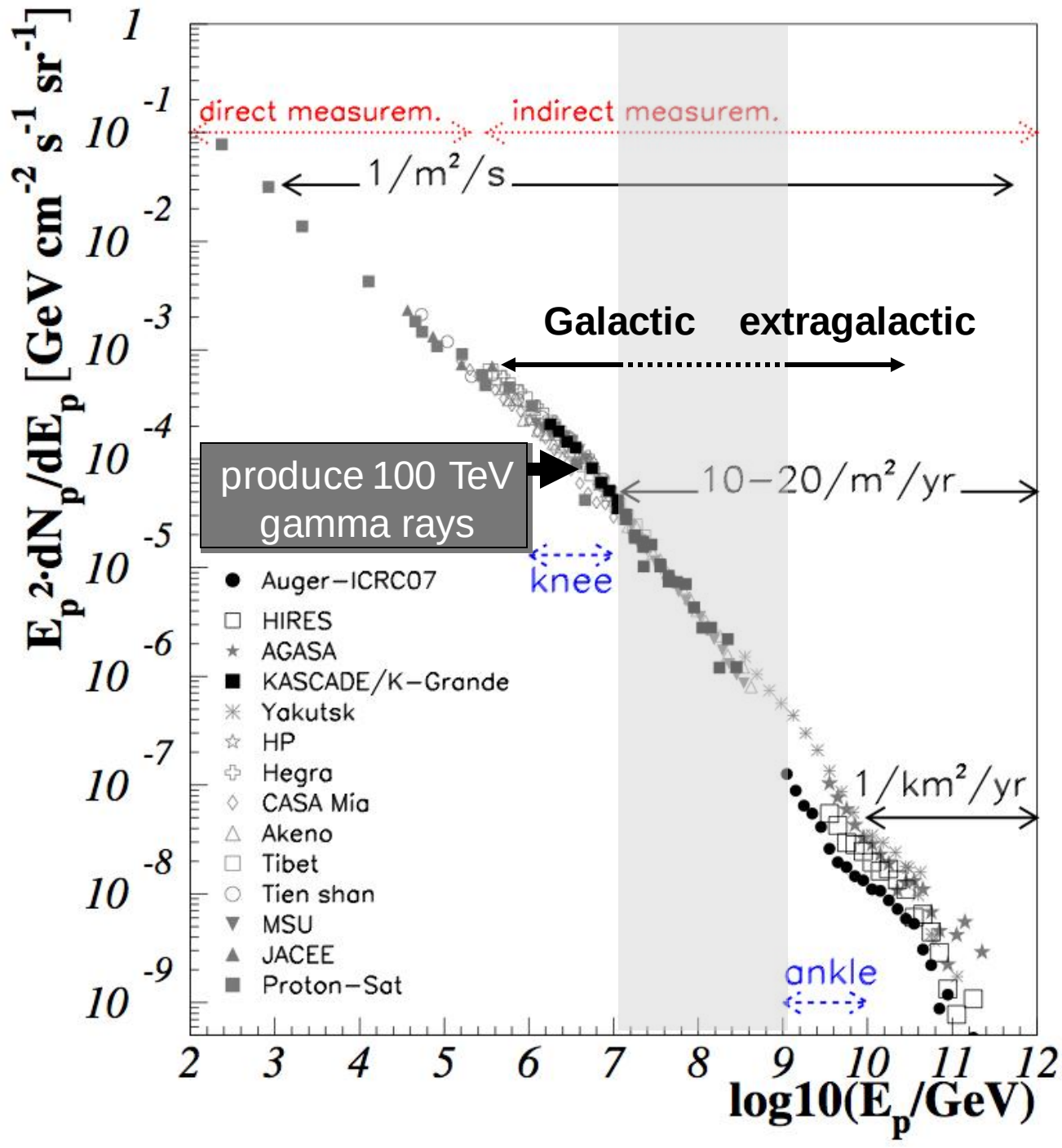
↓

cr + p → pions

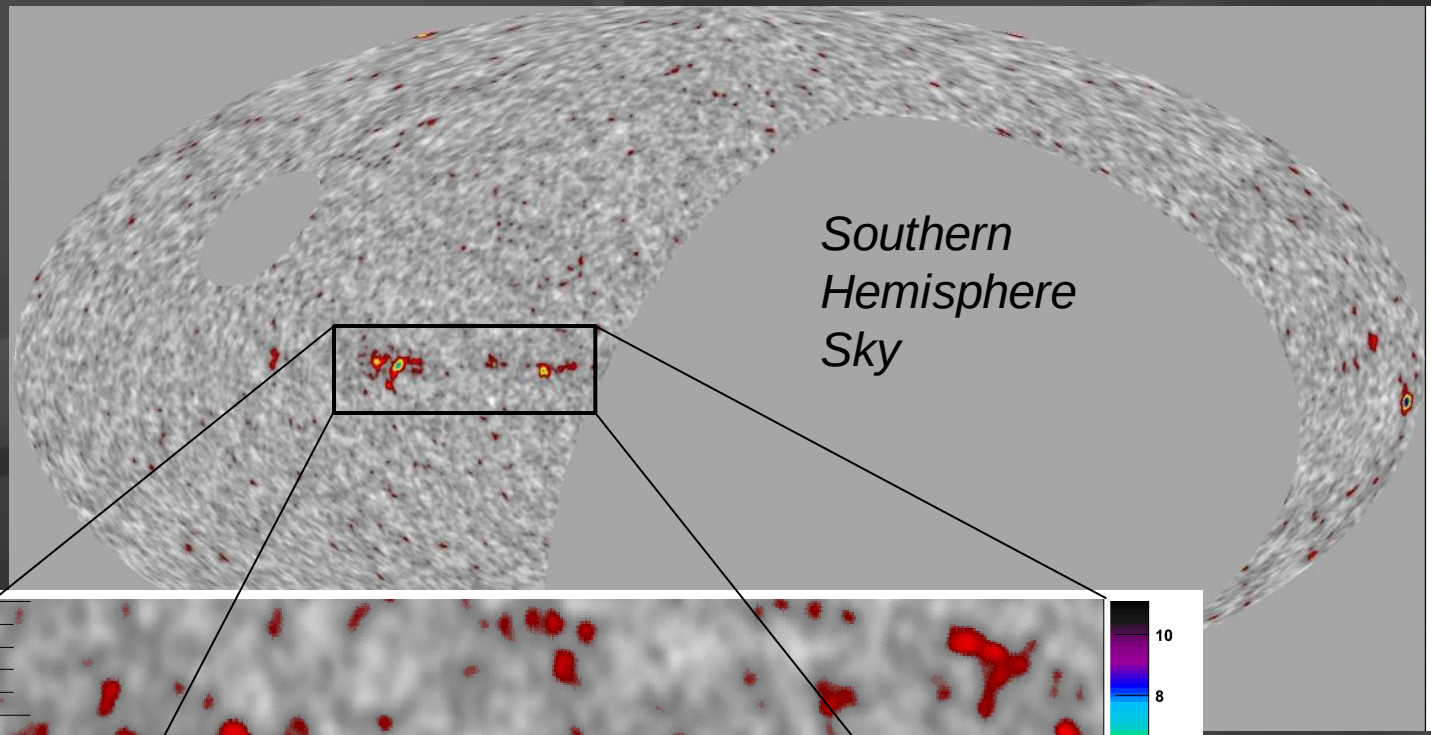
$\pi^0 \rightarrow \gamma\gamma$

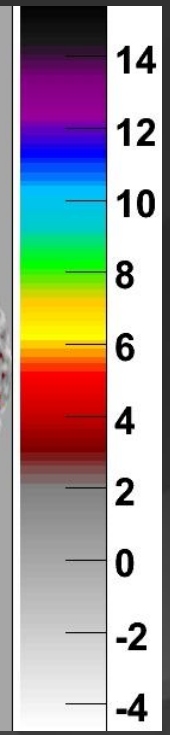
↓

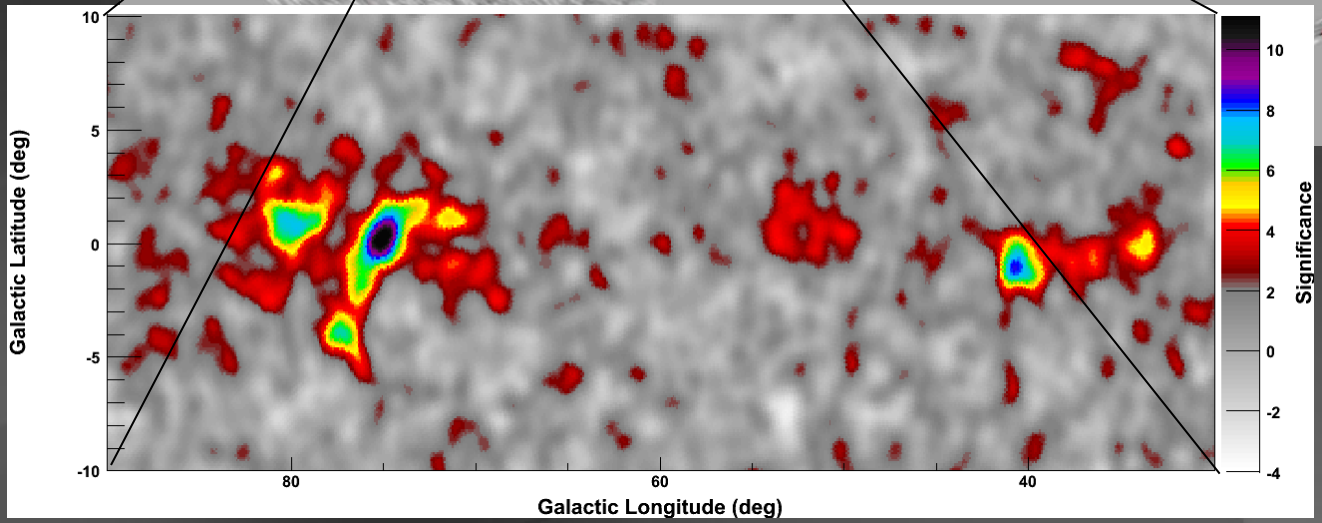
trace cosmic rays

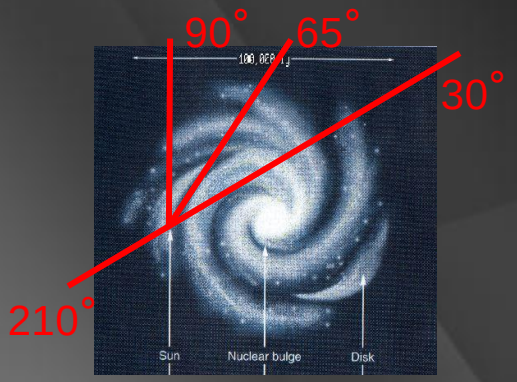


galactic plane in 10 TeV gamma rays :
supernova remnants in star forming regions





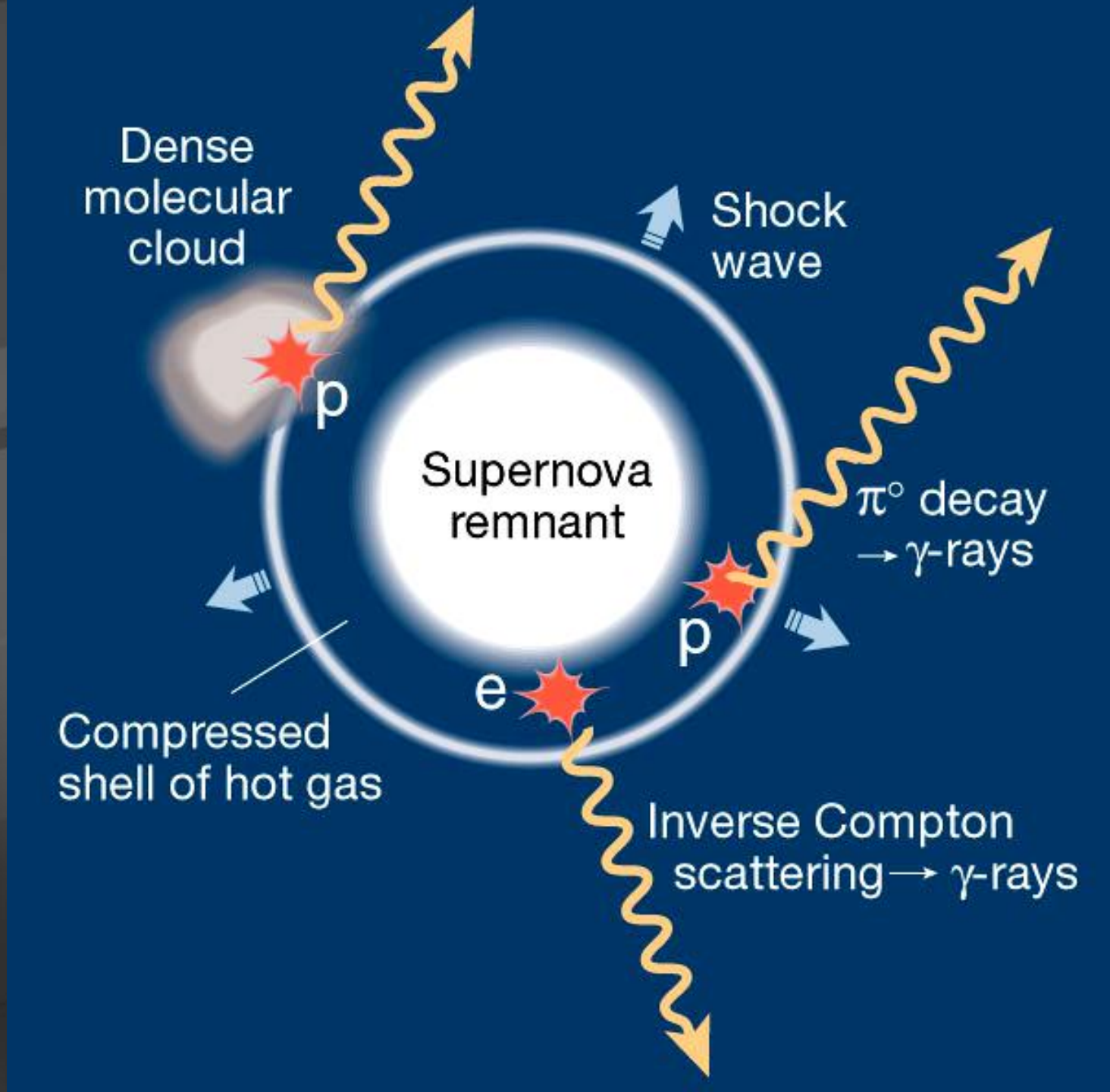




milagro

neutrinos from supernova remnants:

molecular clouds as beam dumps



neutral pions

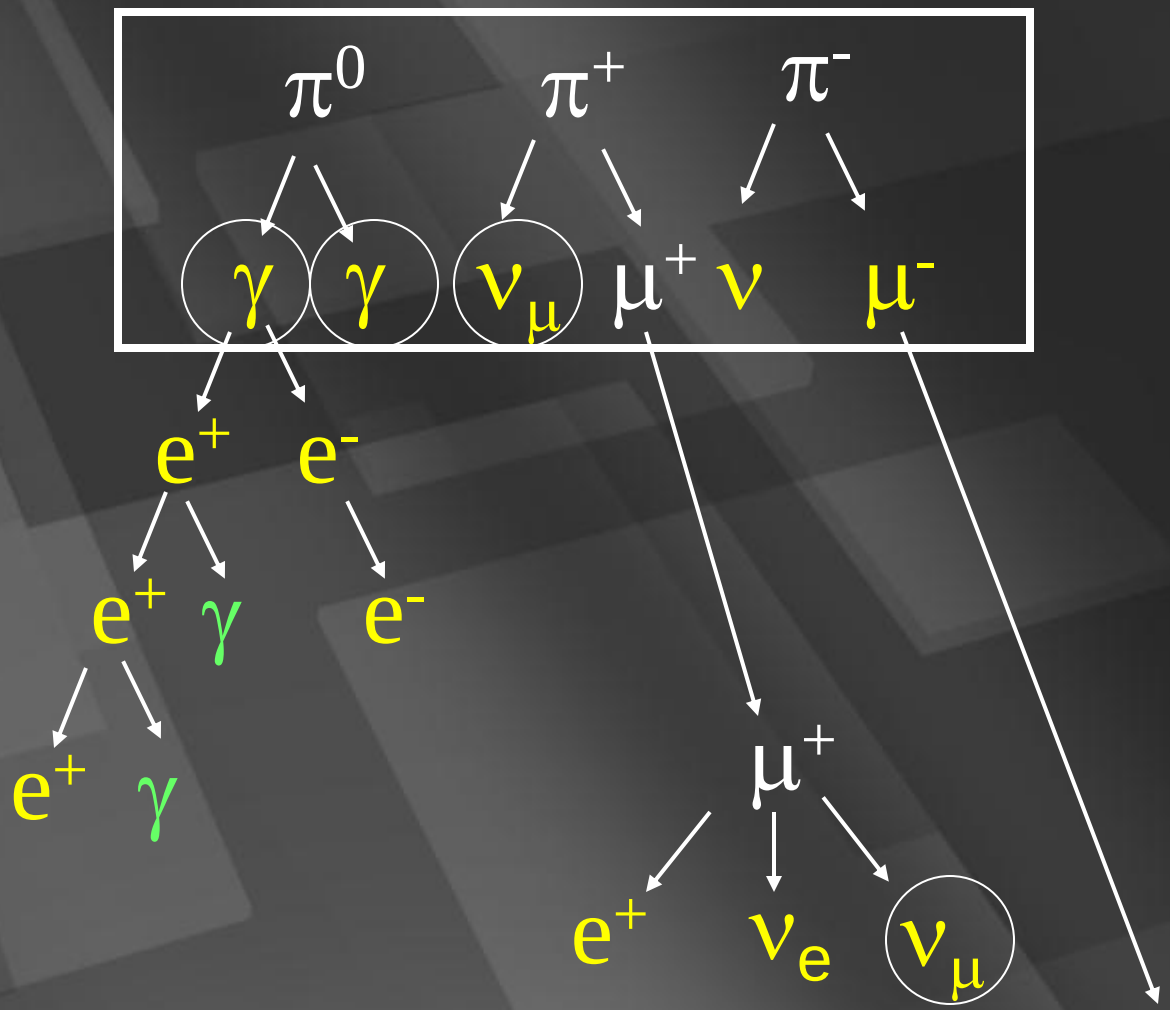
are observed as

gamma rays

charged pions

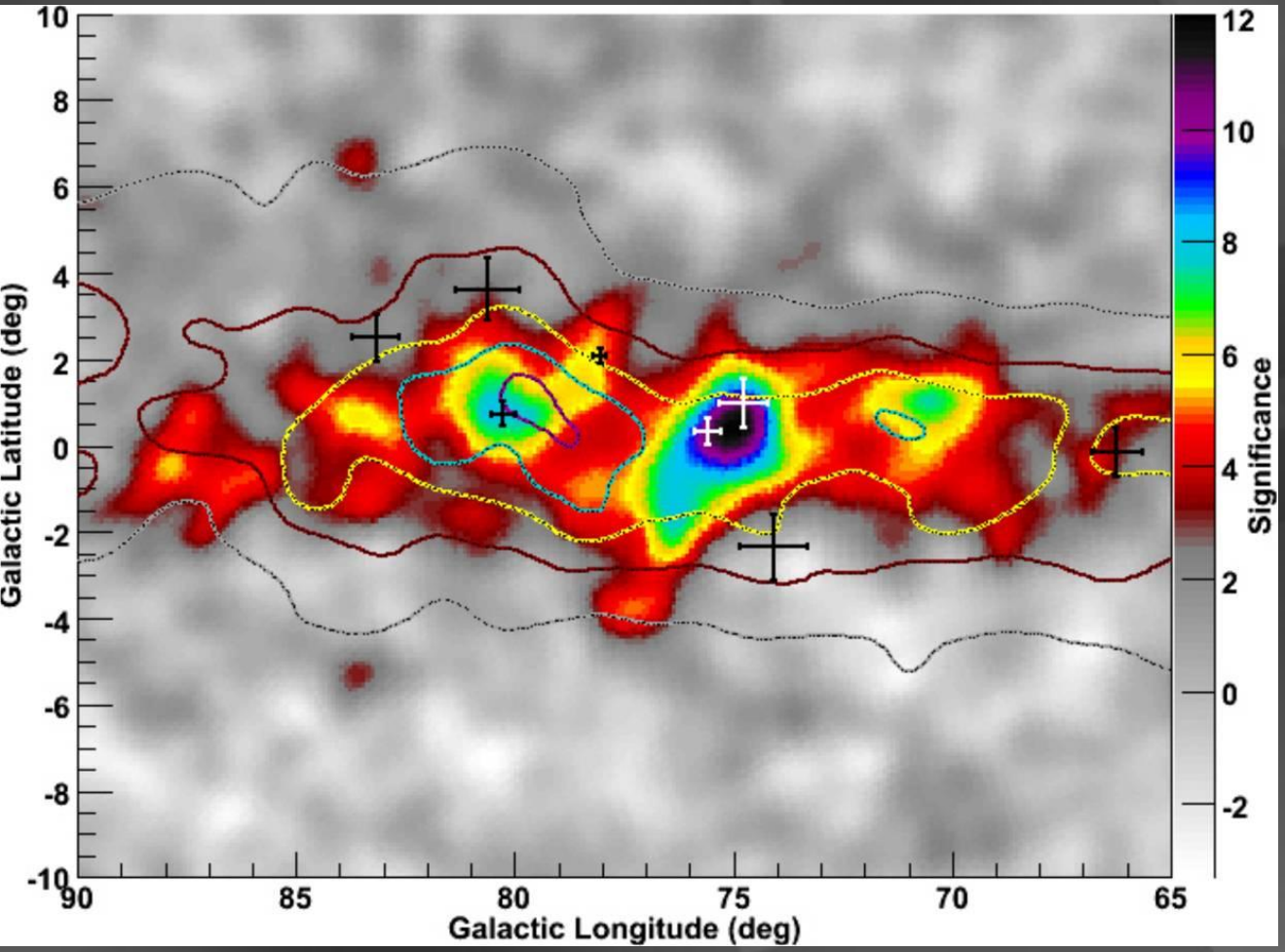
are observed as

neutrinos



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

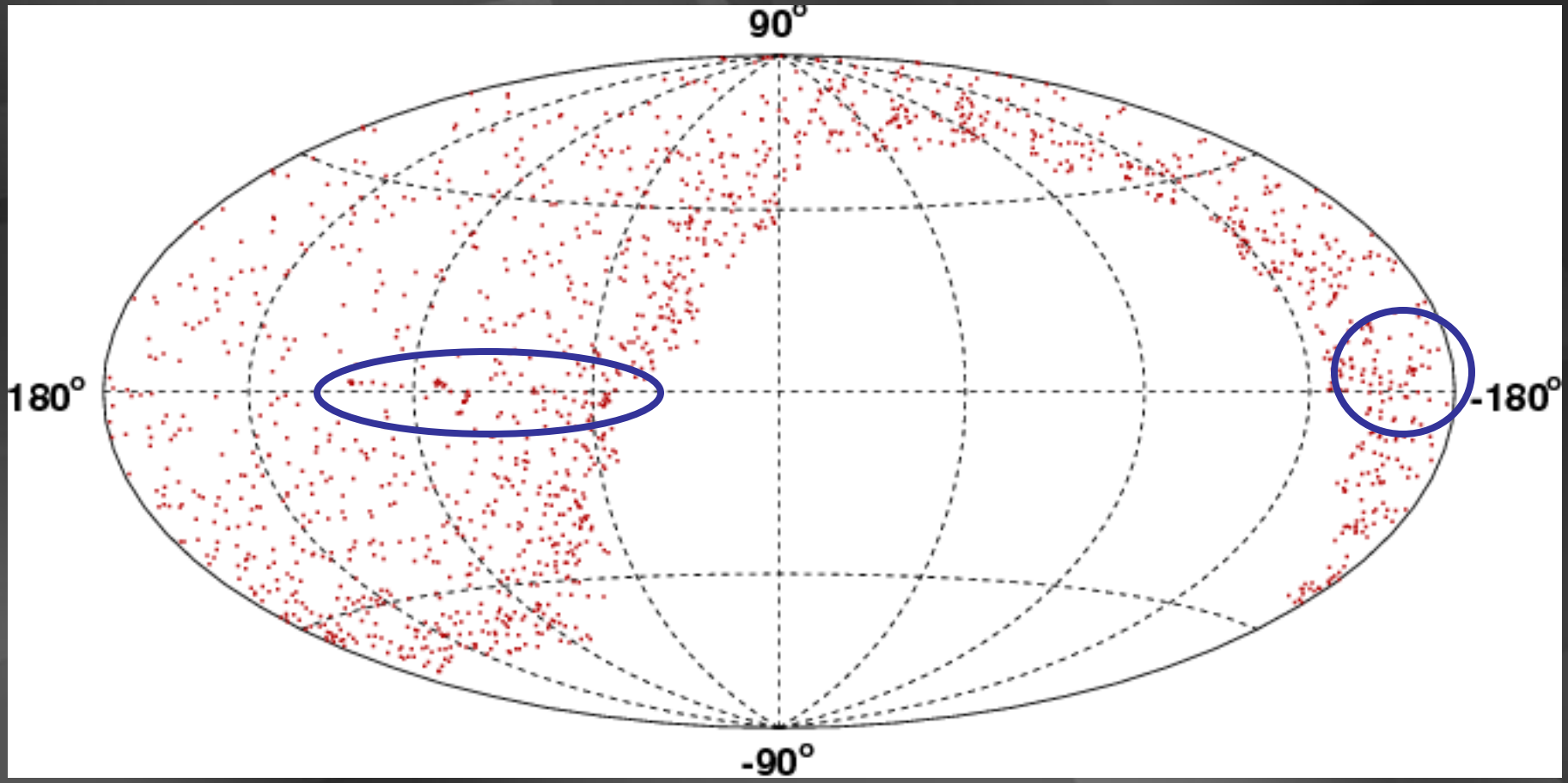
cygnus region : Milagro



translation of TeV gamma rays into TeV neutrinos :

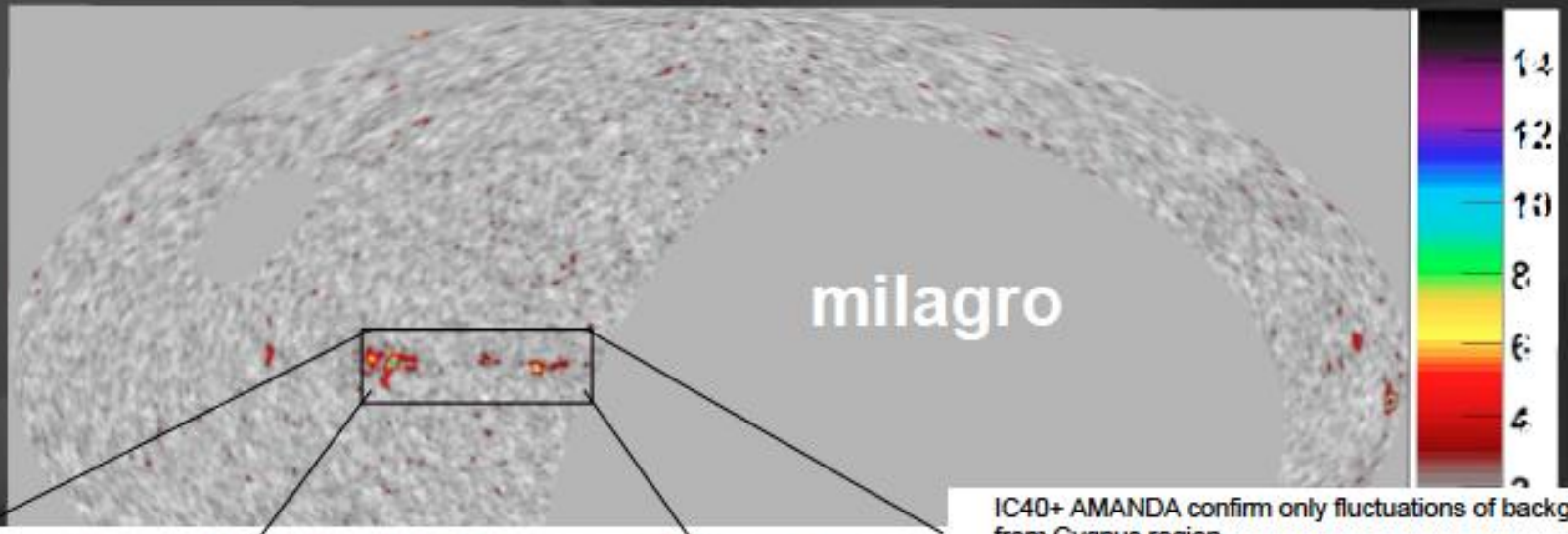
3 ± 1 ν per year in IceCube per source

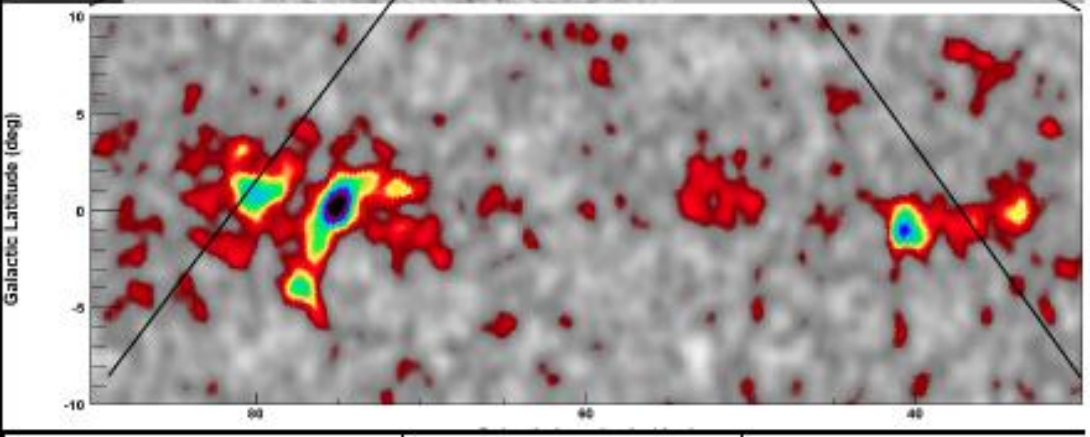
5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV



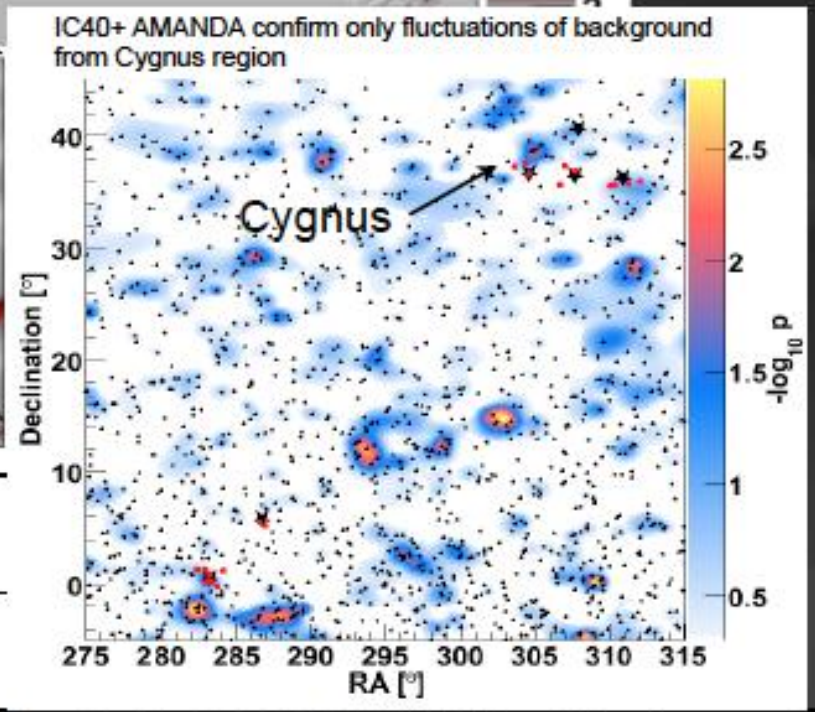
	IC59	IC40
J2019+37	-	0.28
J1908+06	0.33	-
J2031+41 (cyg ob2)	-	0.18
J2043+36 (C1)	0.44	0.28
J2032+37 (C2)	-	
J1852+01	-	0.035

Stacking the Milagro Pevatrons (SNR in molecular clouds)





Catalogue	Med Sens	upper limit (90%cl)
6 Milagro SNR	2.9x prediction	7.2 x prediction



Model (Gonzalez-Garcia et al., arXiv:0902.1176): if E^{-2} cut-off at 300 TeV (10% of the knee of their CR primaries) => 5σ in 3 yr of IceCube

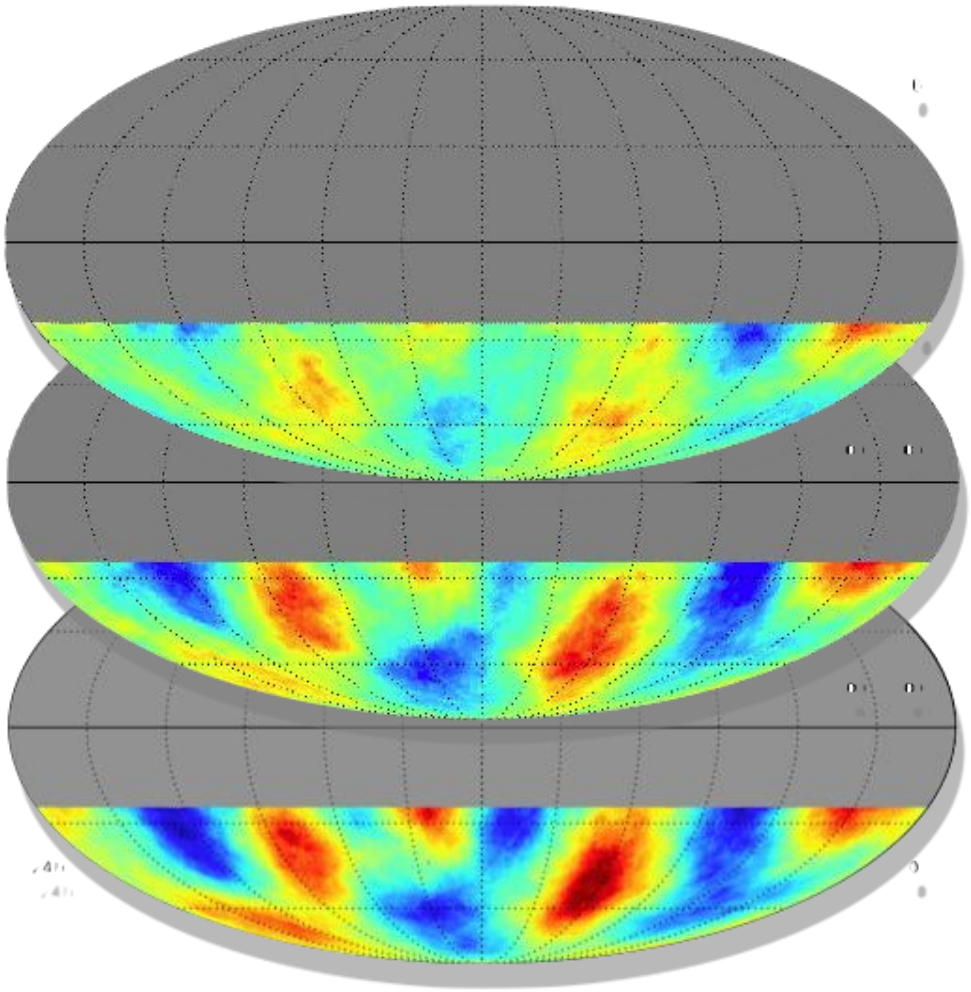
first surprise

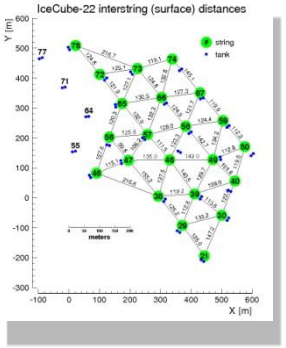
IC22 and IC40 : muon astronomy (!)

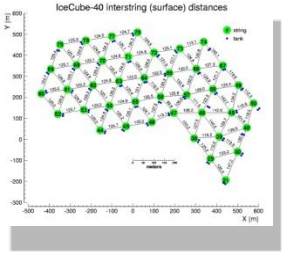
IC22

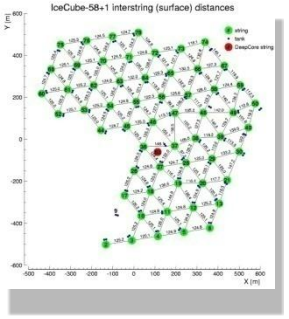
IC40

IC59

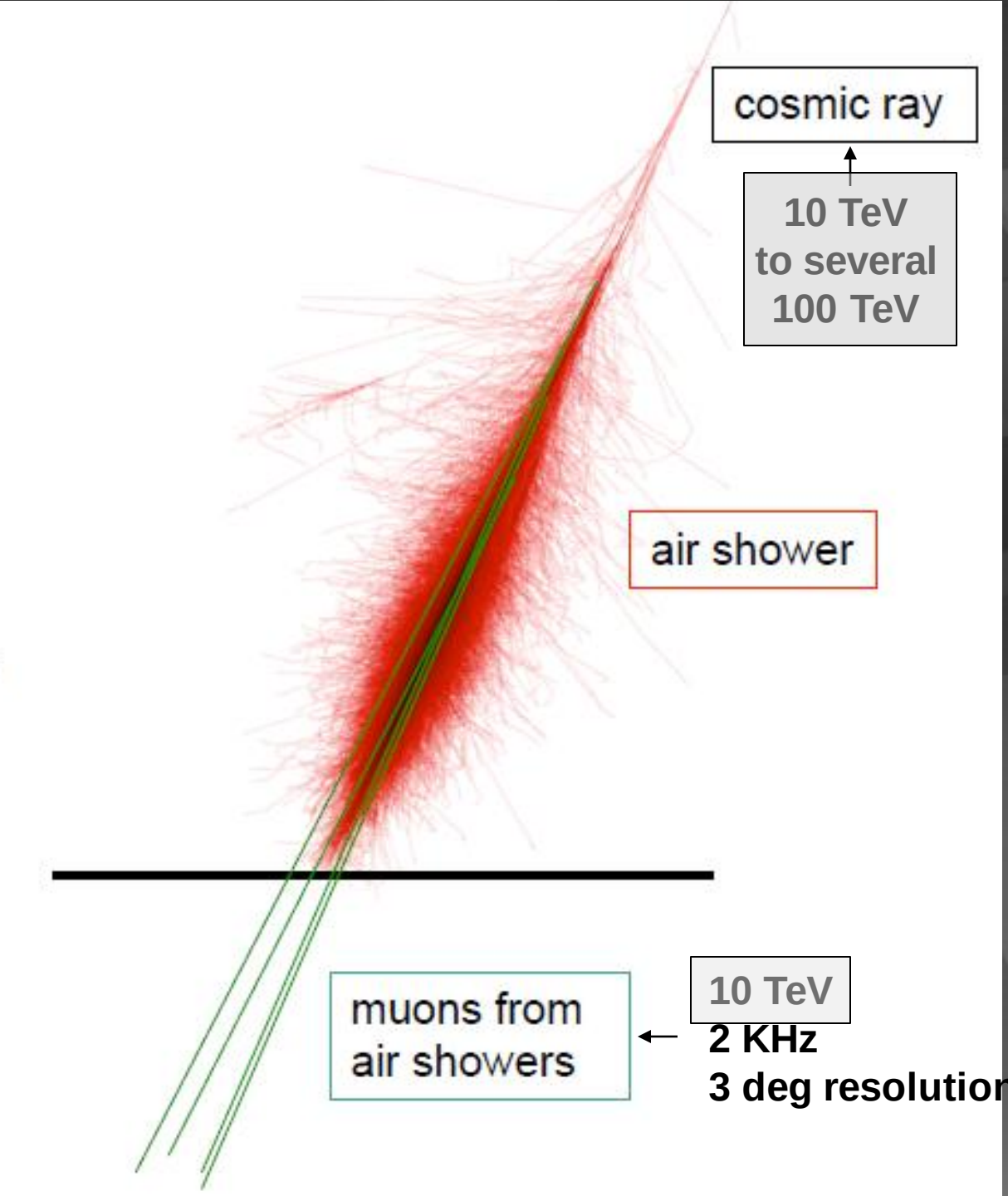








Different geometries, same structure

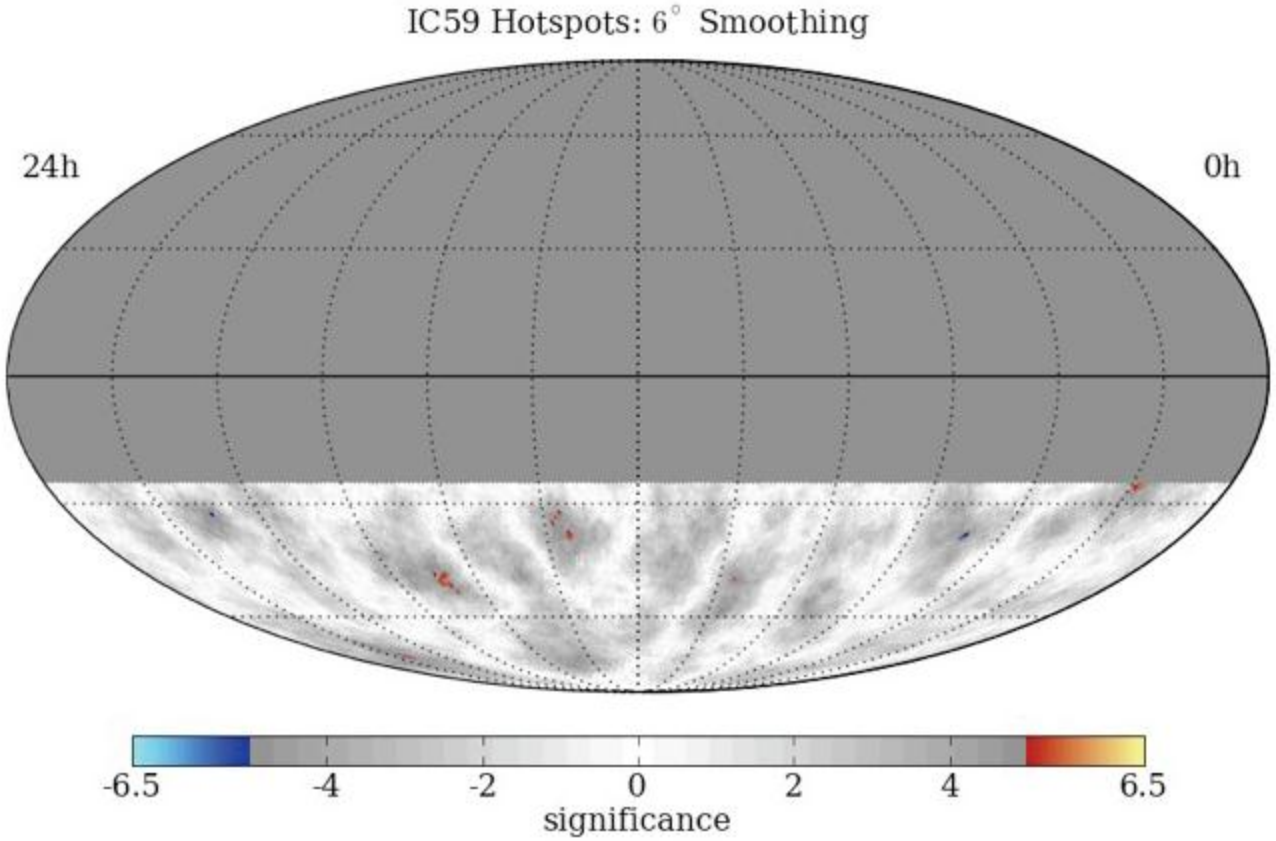


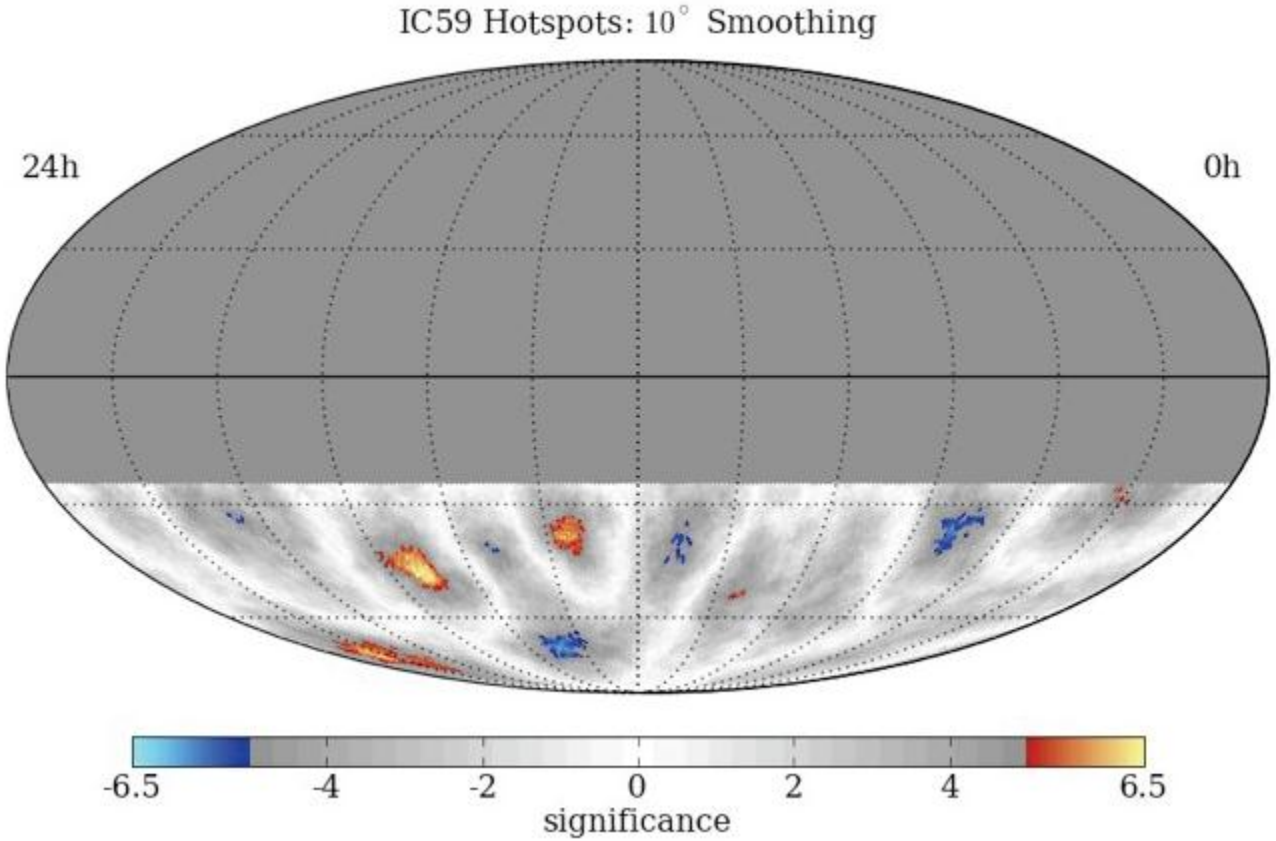
cosmic rays in IceCube

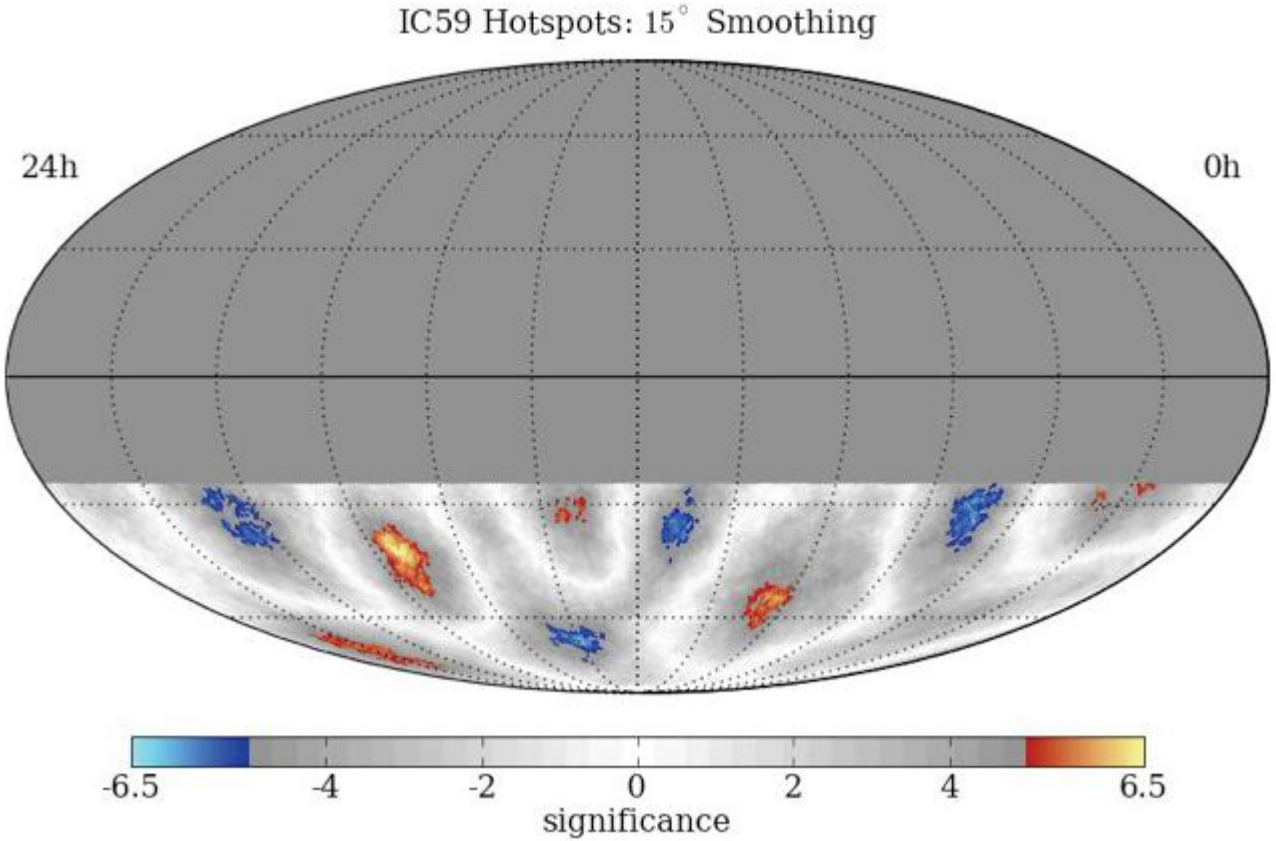
- we map the highest energy Galactic cosmic rays, but…
- their gyroradius is < 1 pc in microgauss magnetic field
- closest sources > 100 pc

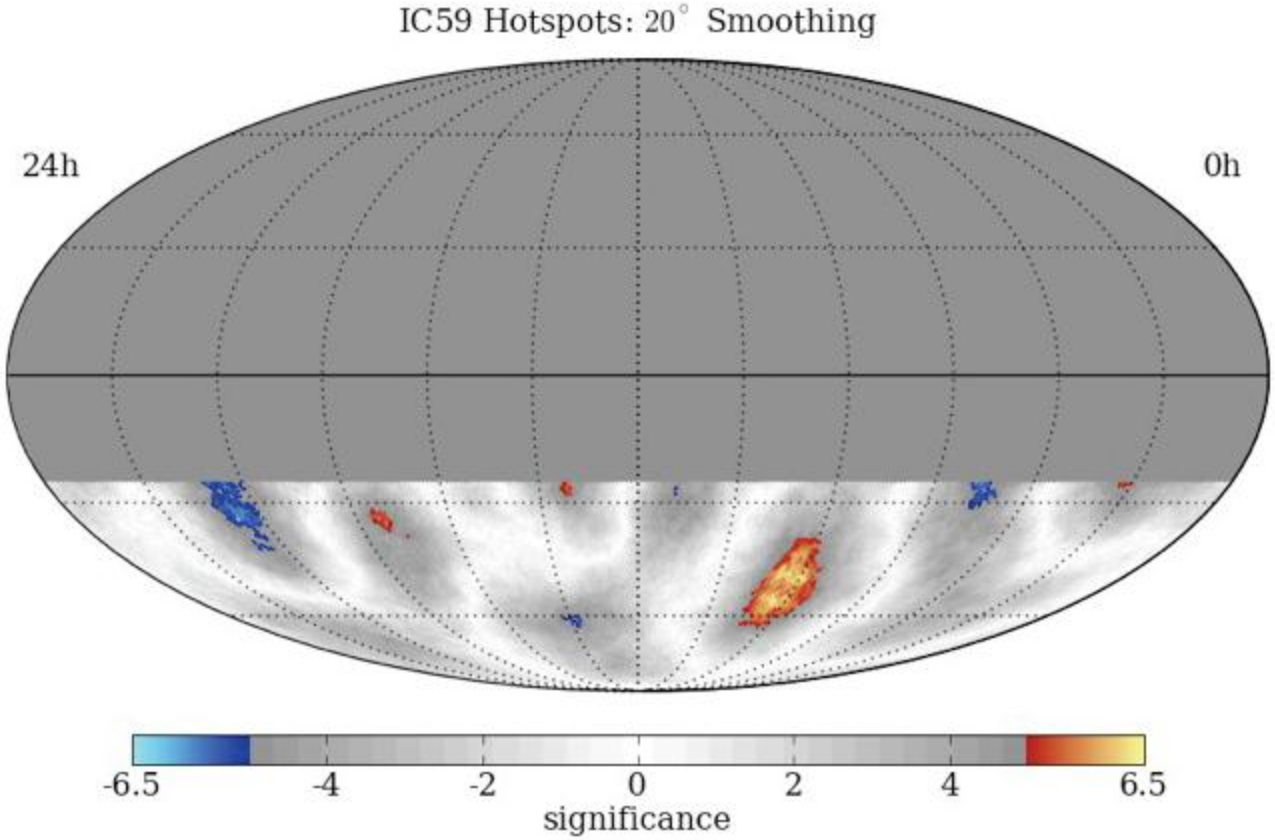
should not point!
→ that's why we detect neutrinos!

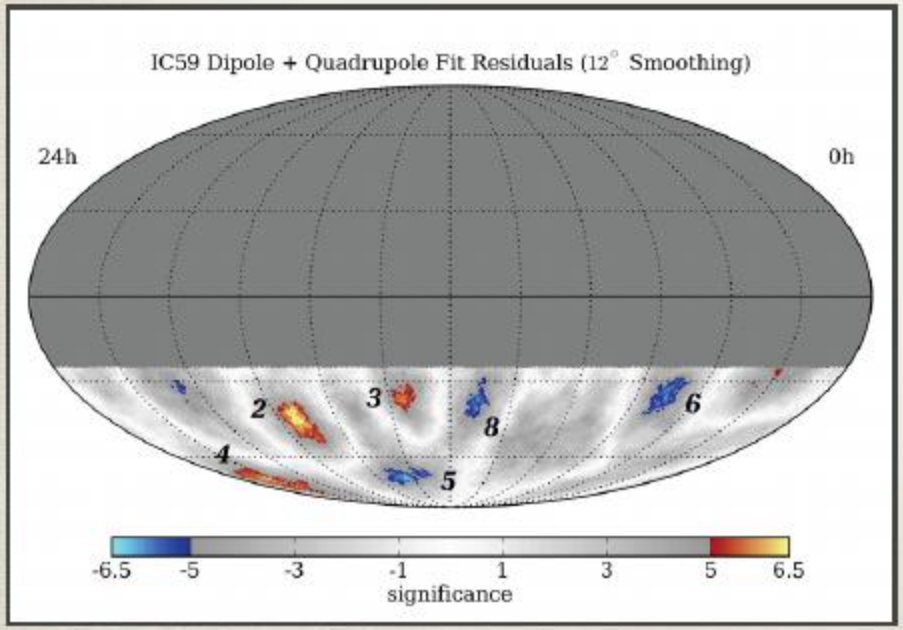
32 billion muons/ 59 strings

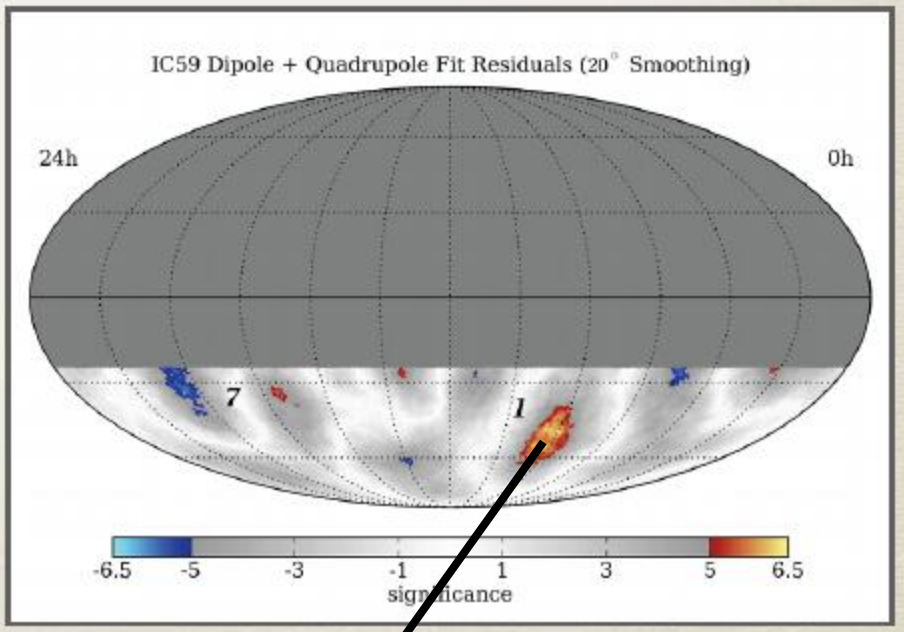



IC59 Hotspots: 10° Smoothing
24h
0h
-6.5
-4
-2
0
2
4
6.5
significance


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

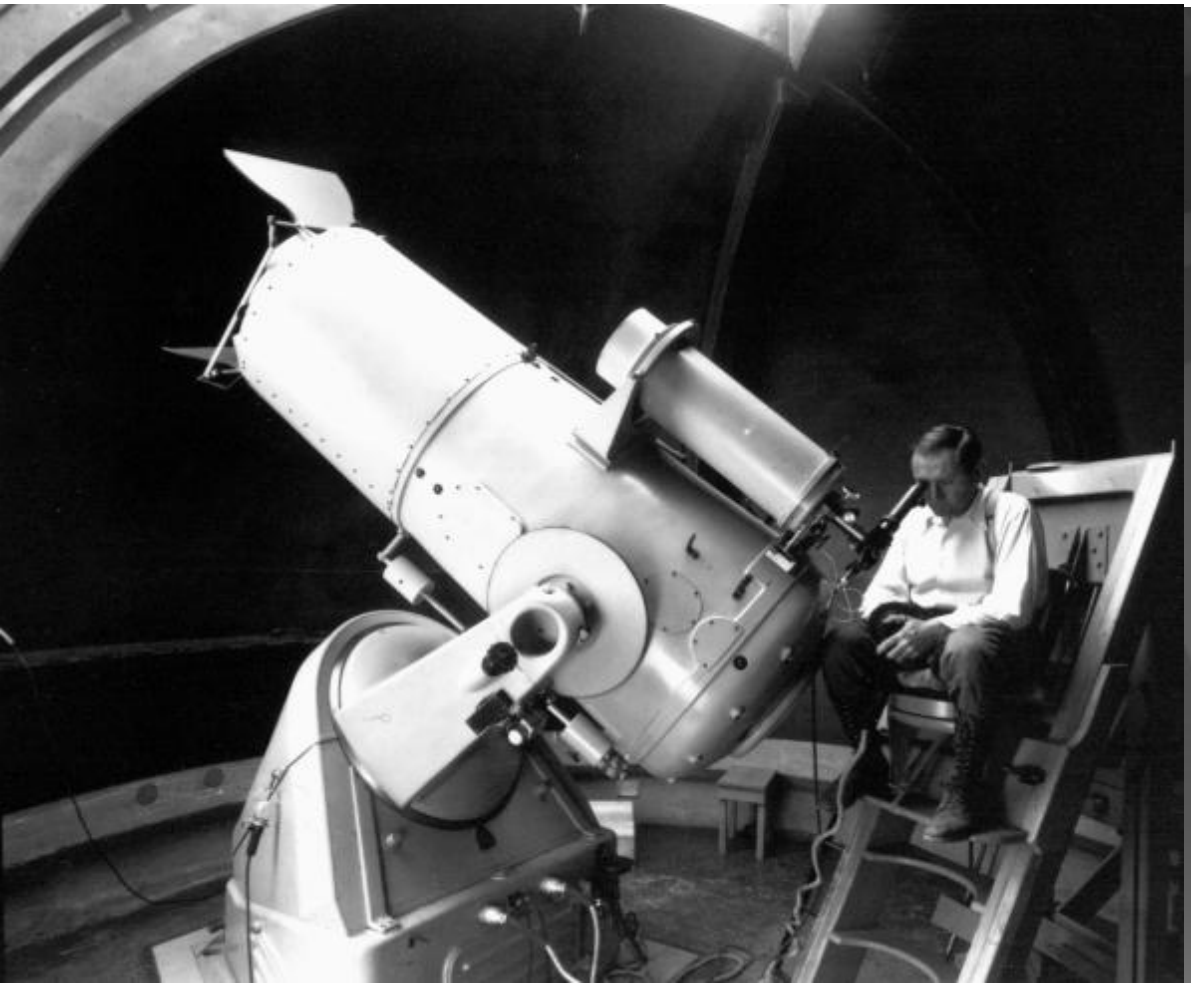
- closest supernova remnant
- strongest gamma ray source

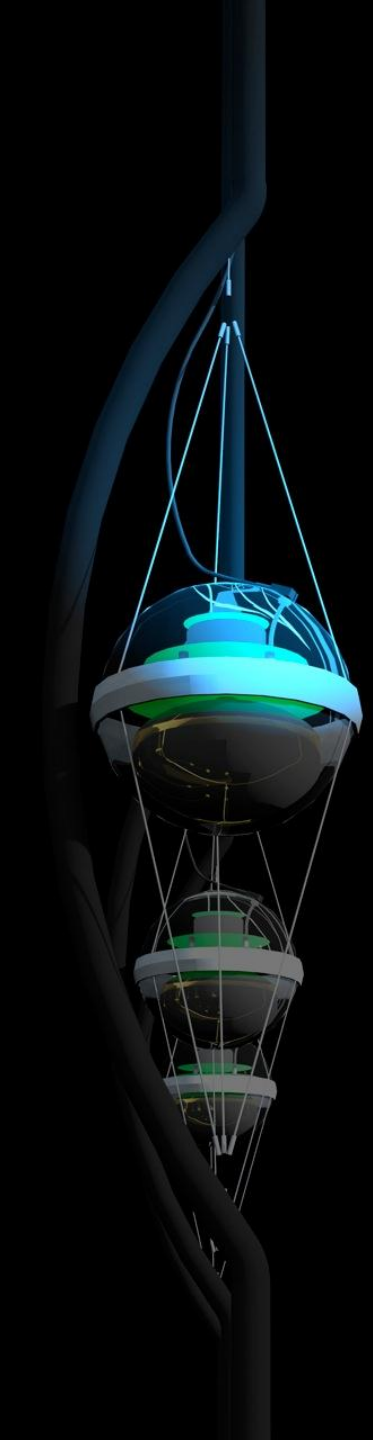
ON SUPER-NOVAE

By W. Baade and F. Zwicky

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

Communicated March 19, 1934



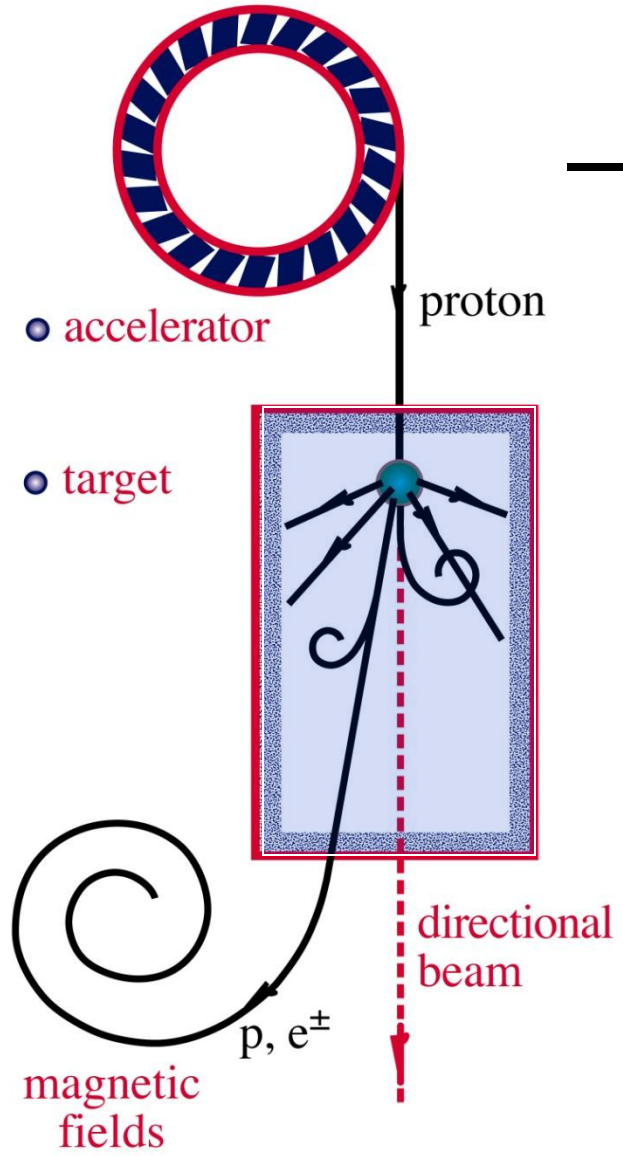


- introduction
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

dark matter

IceCube.wisc.edu

ν and γ beams : heaven and earth



black hole

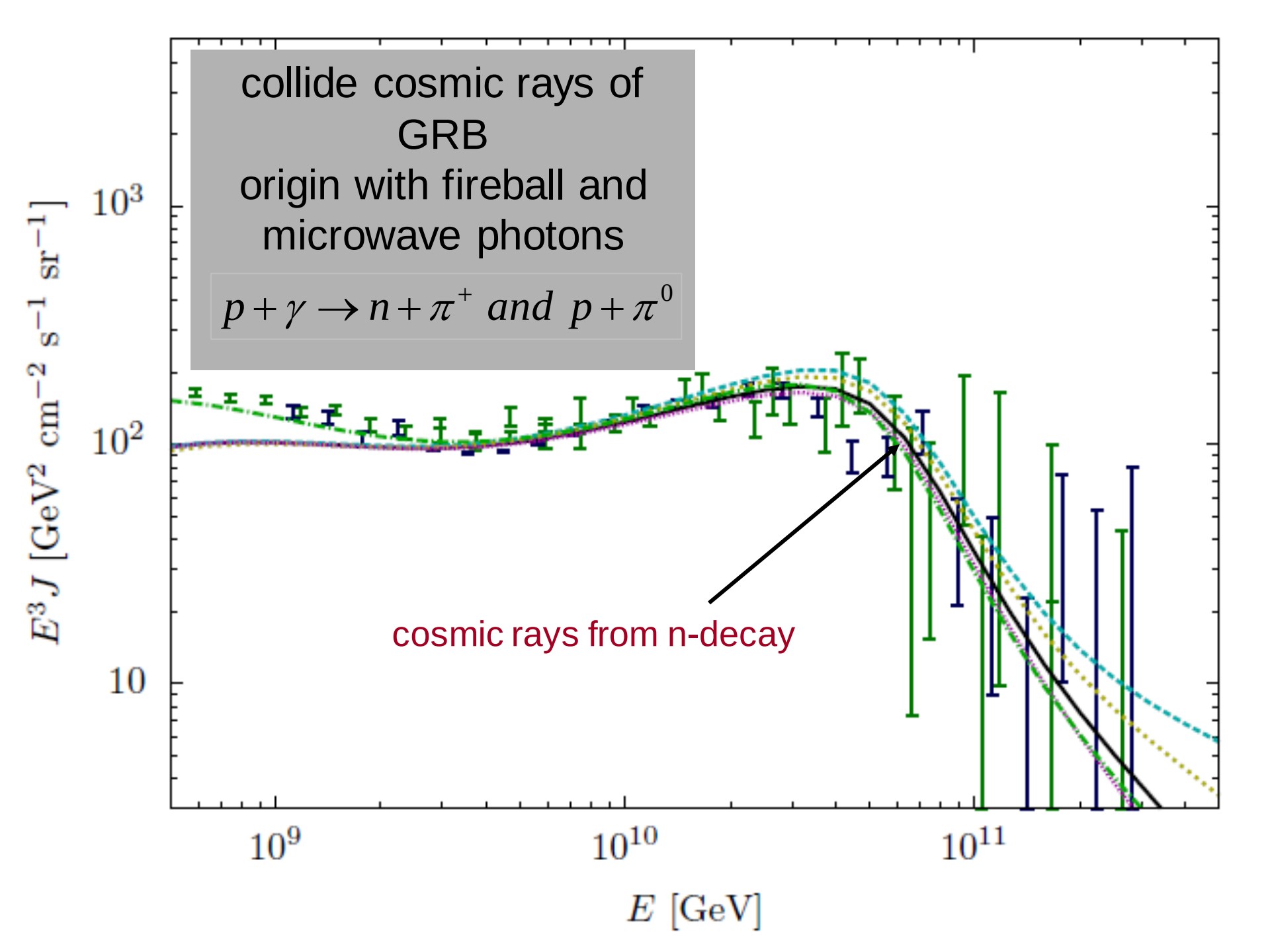
radiation and dust

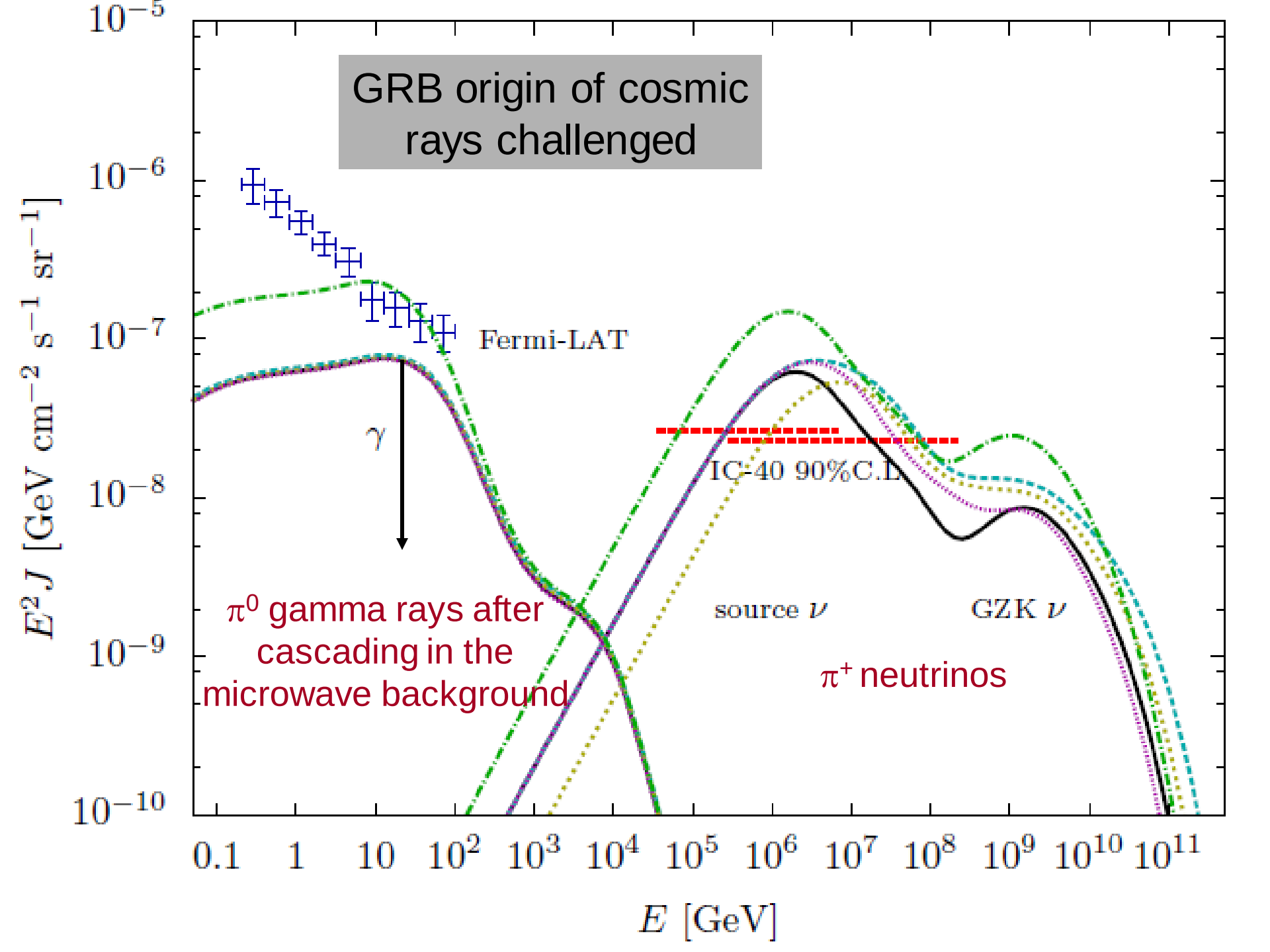
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma


collide cosmic rays of GRB origin with fireball and microwave photons
$p + \gamma \rightarrow n + \pi^+$ and $p + \pi^0$
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
Fermi-LAT
γ
IC-40 90%C.L.
source ν
GZK ν
π+ neutrinos
π0 gamma rays after cascading in the microwave background
E² 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
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

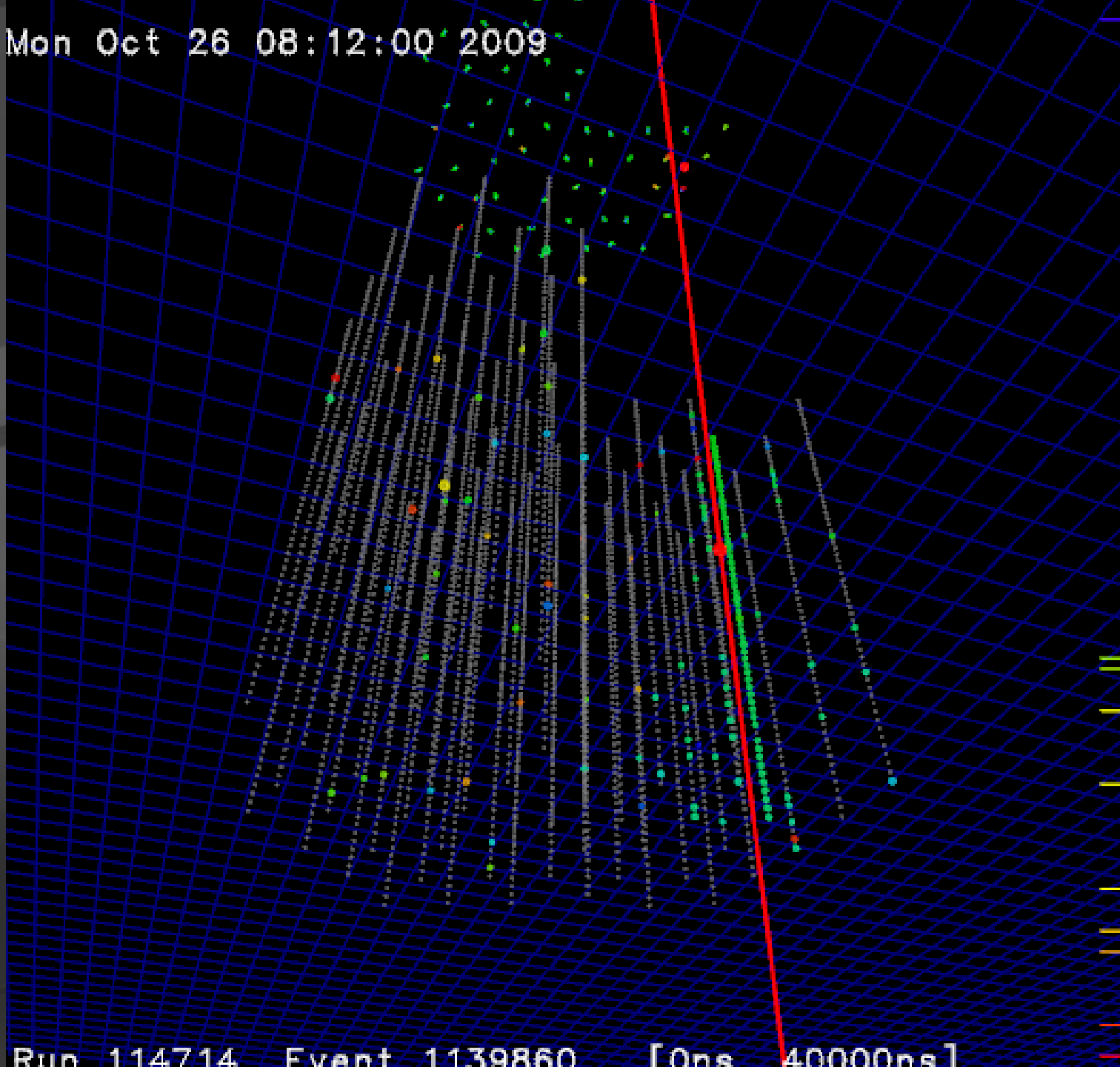
NOT a GRB

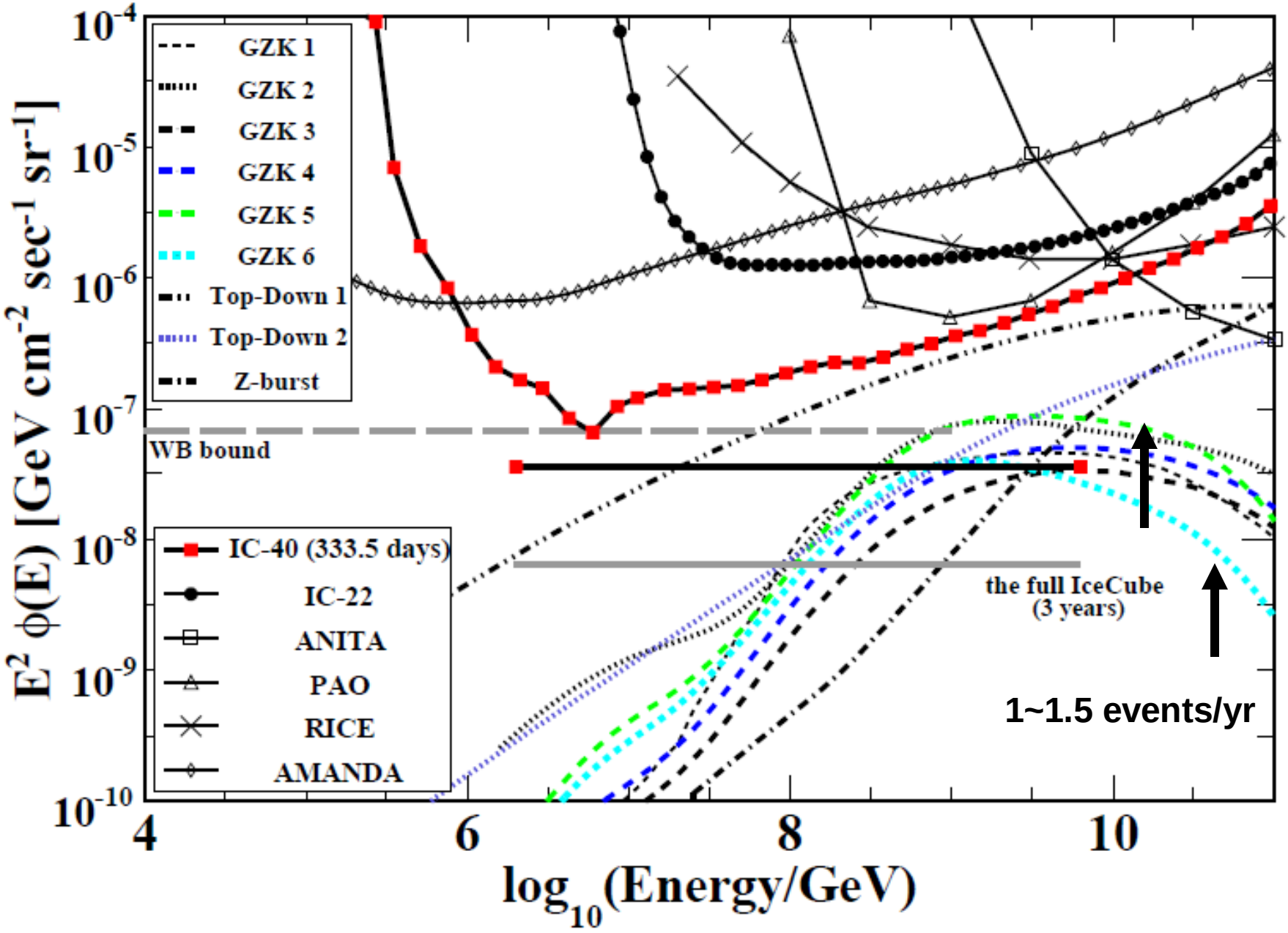
neutrino(?) within 40 s duration of the burst

azimuth of burst
87.11 deg

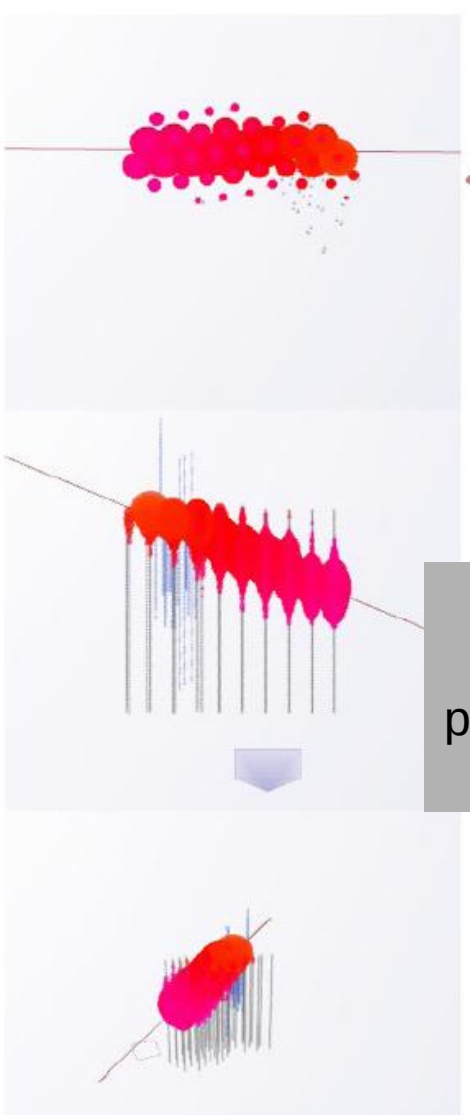
observed
87.97+/- 0.3

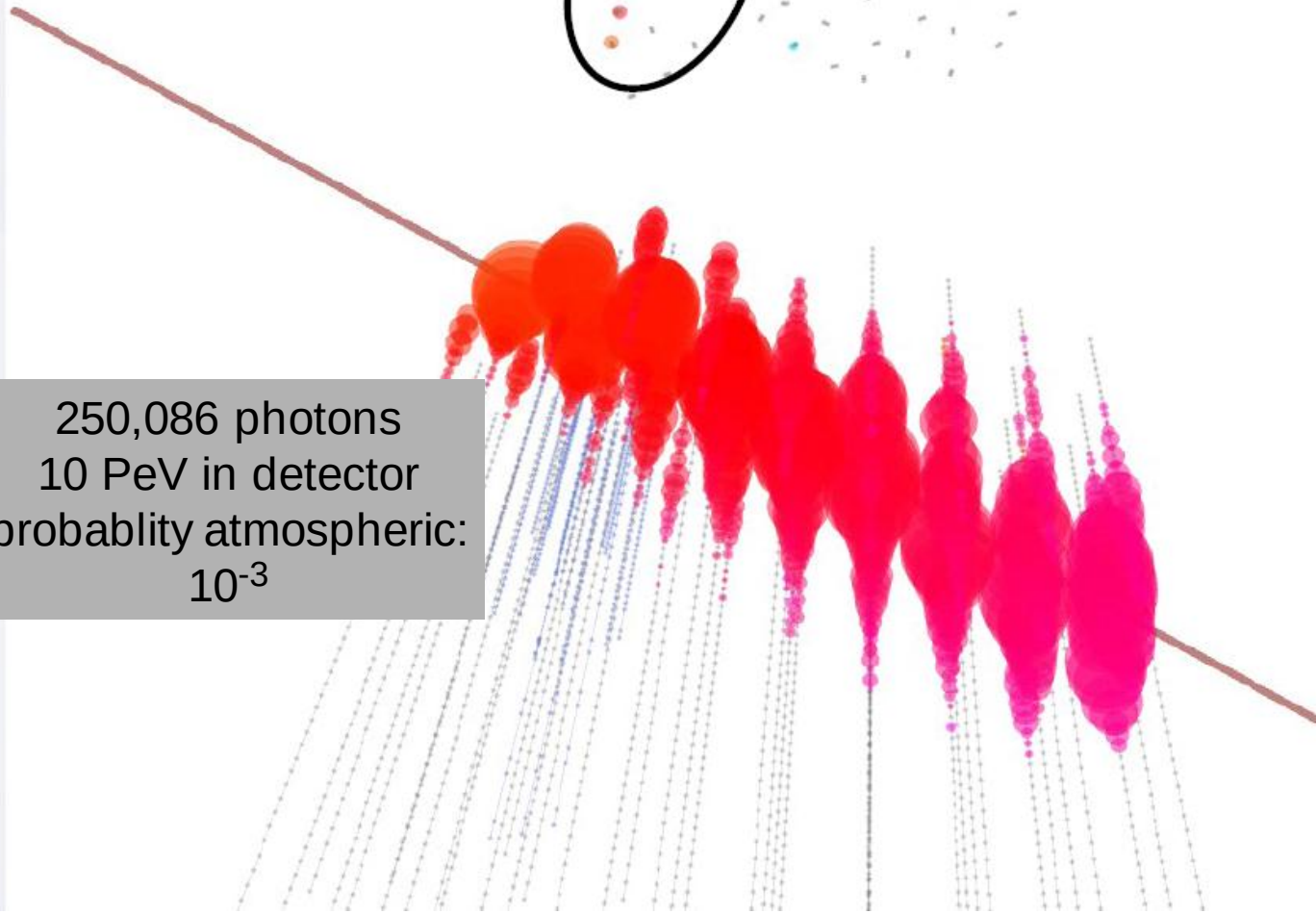
we keep looking !!!



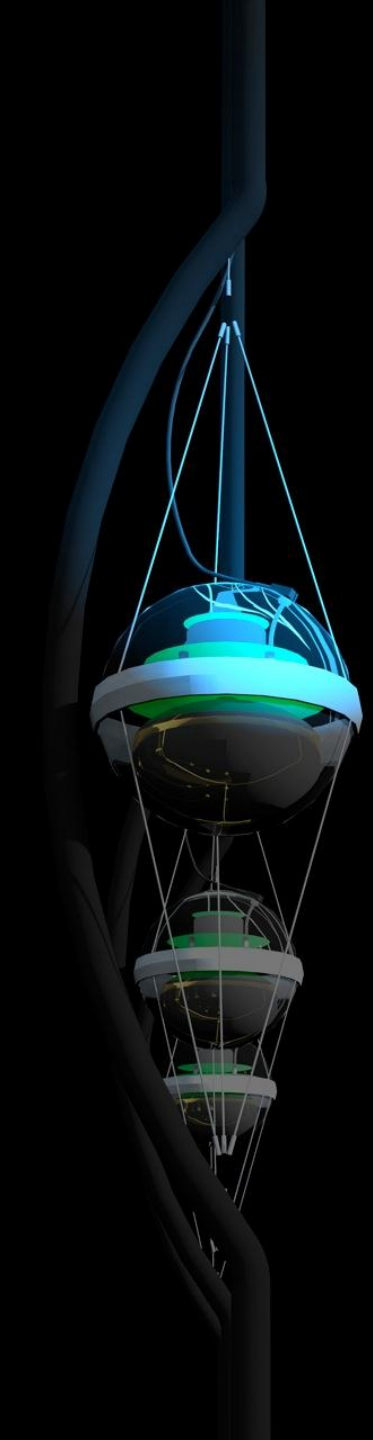

GZK 1
GZK 2
GZK 3
GZK 4
GZK 5
GZK 6
Top-Down 1
Top-Down 2
Z-burst
WB bound
IC-40 (333.5 days)
IC-22
ANITA
PAO
RICE
AMANDA
the full IceCube
(3 years)
1~1.5 events/yr
$E^2 \phi(E)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
$\log_{10}$(Energy/GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
4
6
8
10

Biggest Shower in IC40 EHE Analysis





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



- introduction
- 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

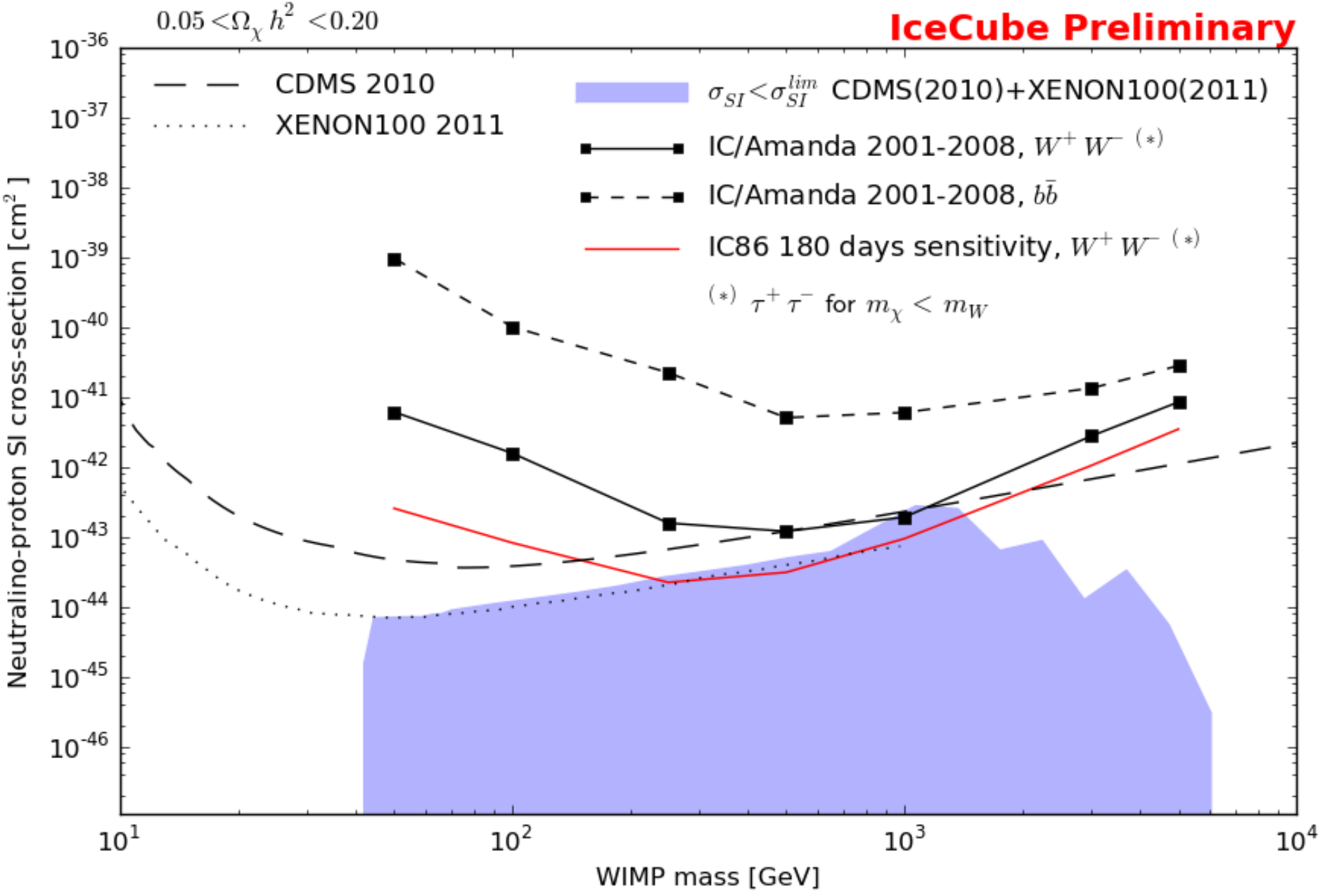
dark matter

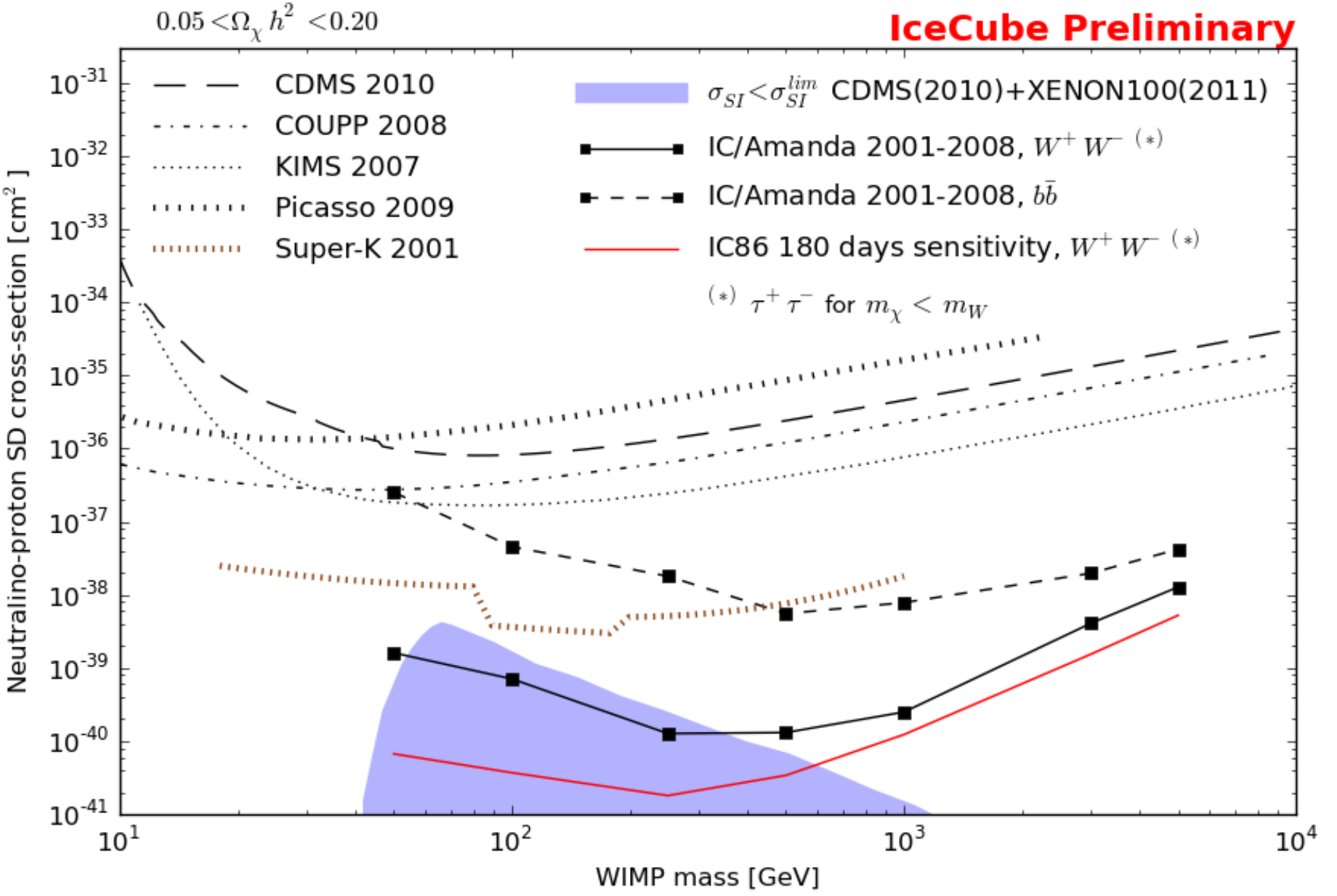
IceCube.wisc.edu

WIMP Capture and Annihilation

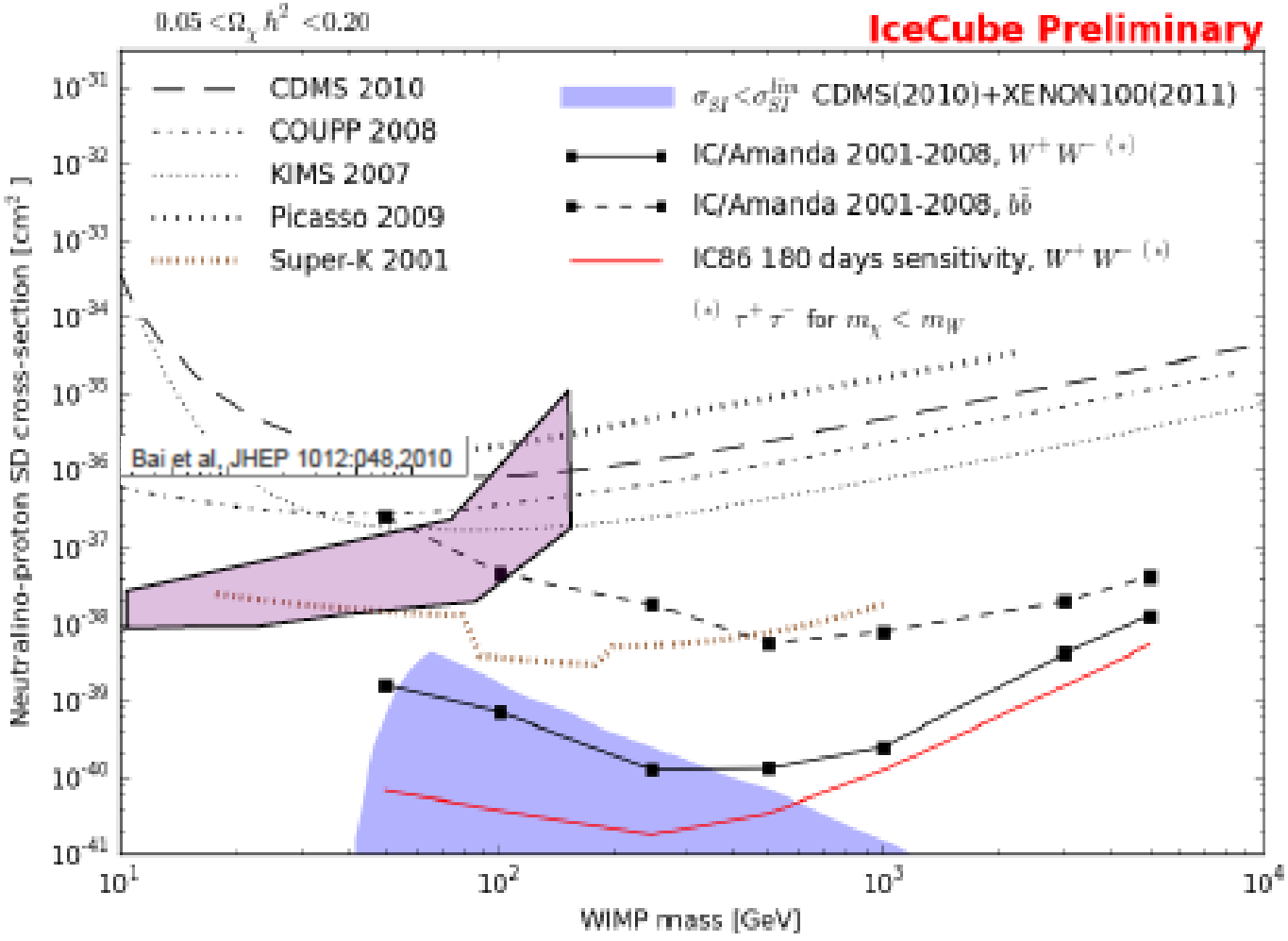
1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the south pole, convert into muons in the ice

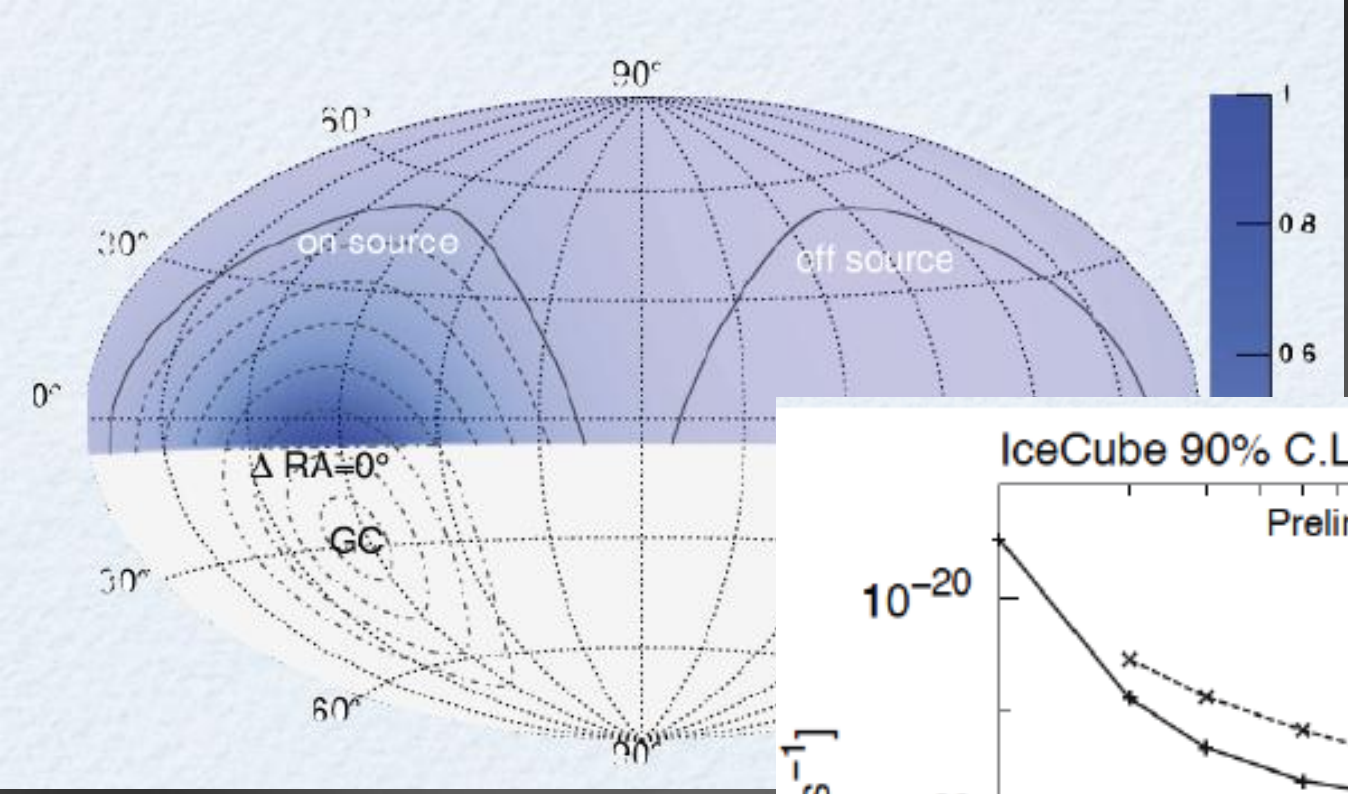
$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$
$$b + b \rightarrow \nu + \nu$$


$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
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

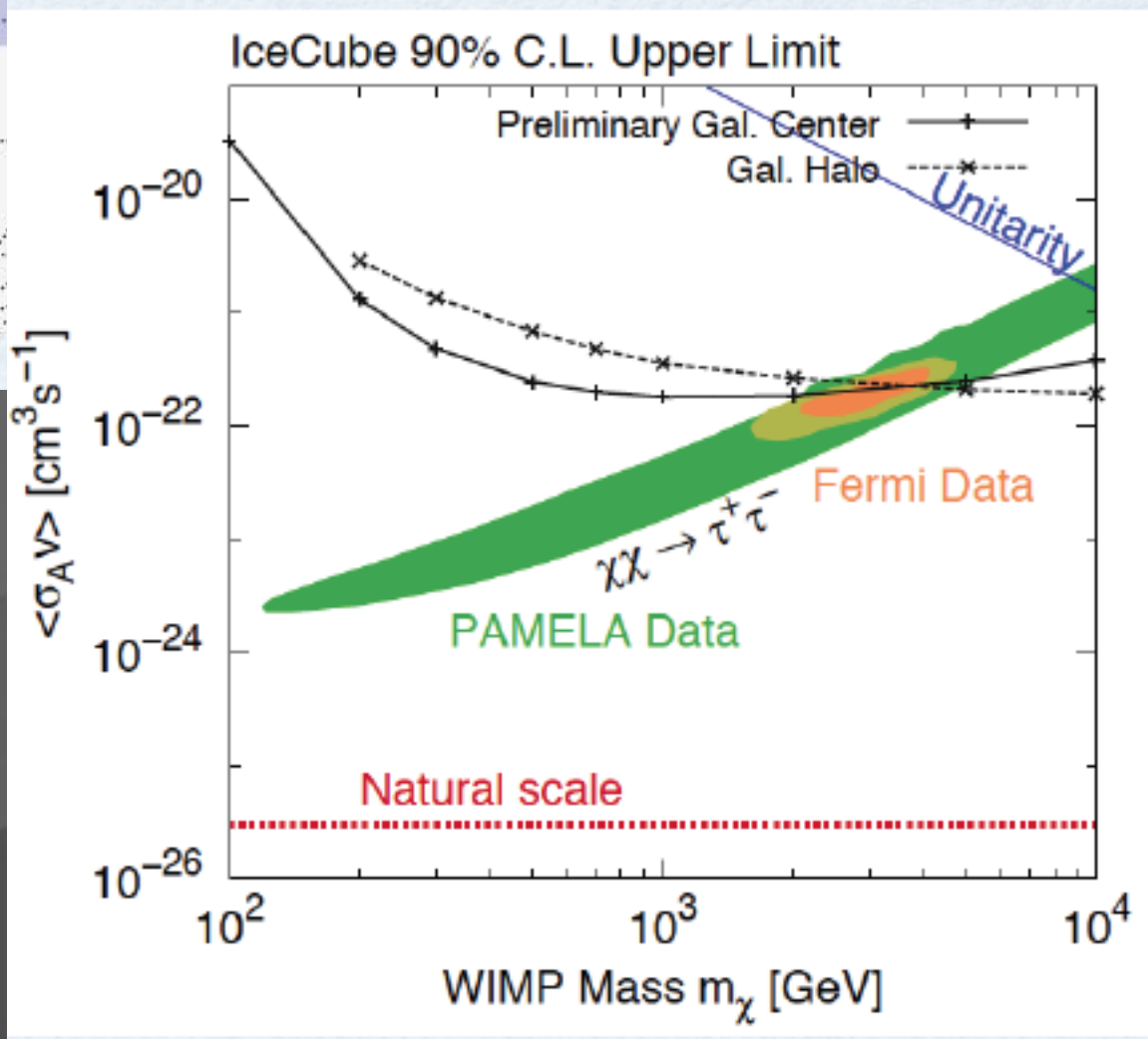

$0.05 < \Omega_\chi h^2 < 0.20$
IceCube Preliminary
CDMS 2010
COUPP 2008
KIMS 2007
Picasso 2009
Super-K 2001
$\sigma_{SI} < \sigma_{SI}^{lim}$ CDMS(2010)+XENON100(2011)
IC/Amanda 2001-2008, $W^+ W^-$ $^{(*)}$
IC/Amanda 2001-2008, $b\bar{b}$
IC86 180 days sensitivity, $W^+ W^-$ $^{(*)}$
$^{(*)}$ $\tau^+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

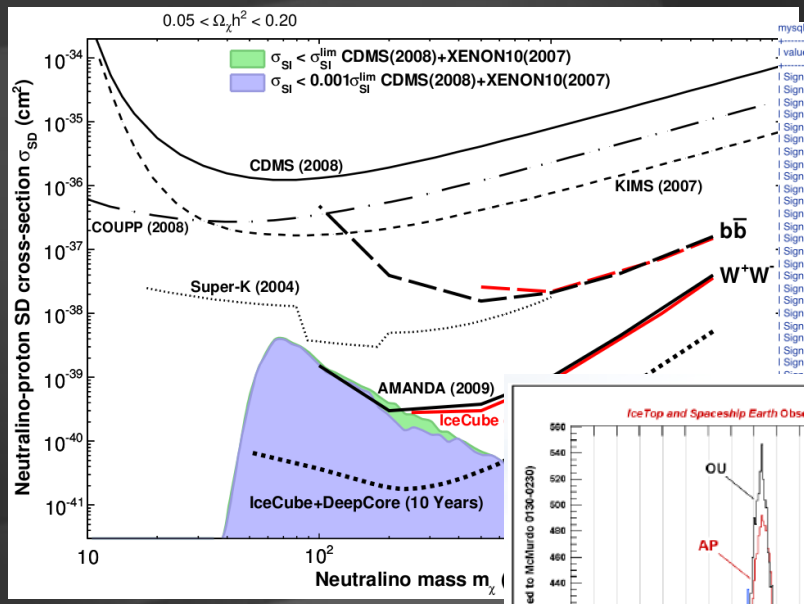
90% CL **neutralino-p Xsection** limit

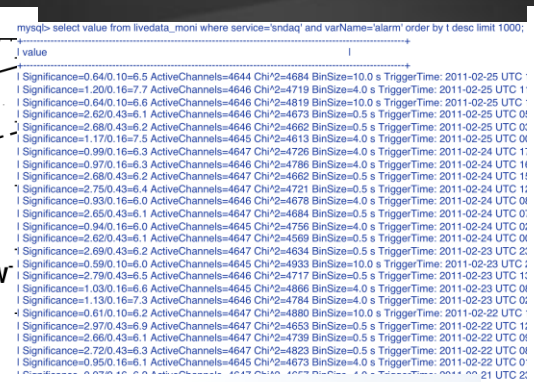


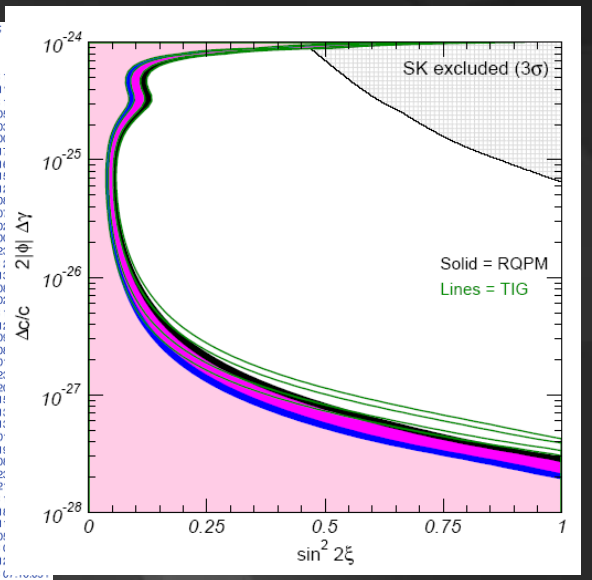


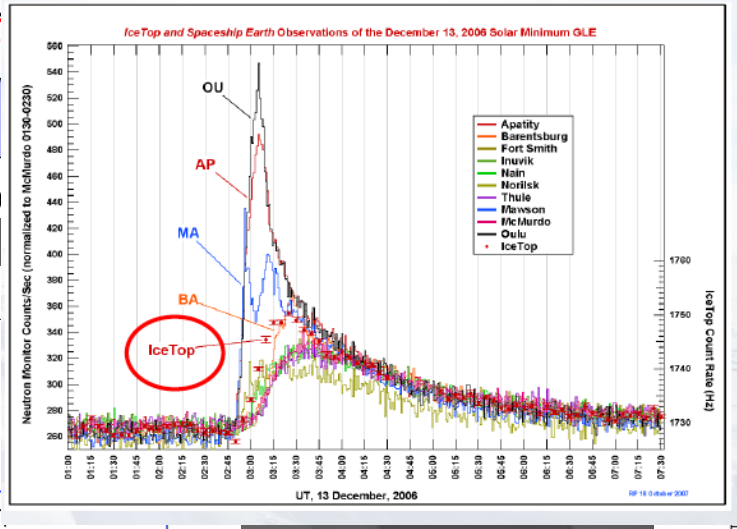
Galactic Center in neutrinos and muons

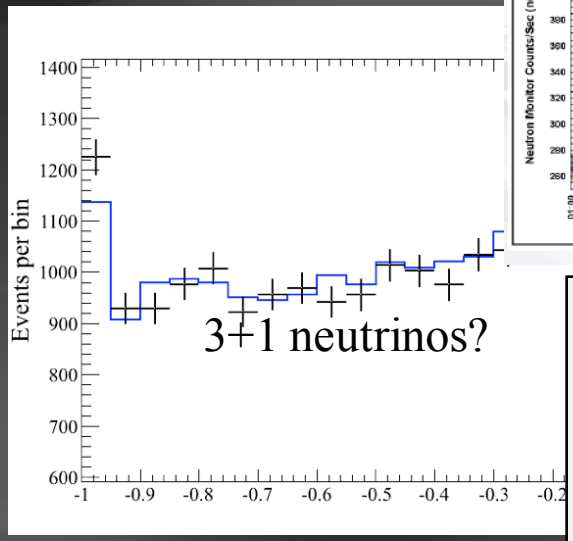


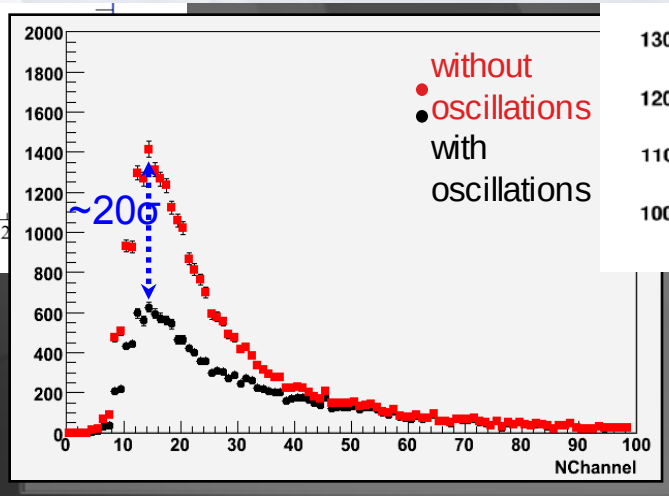


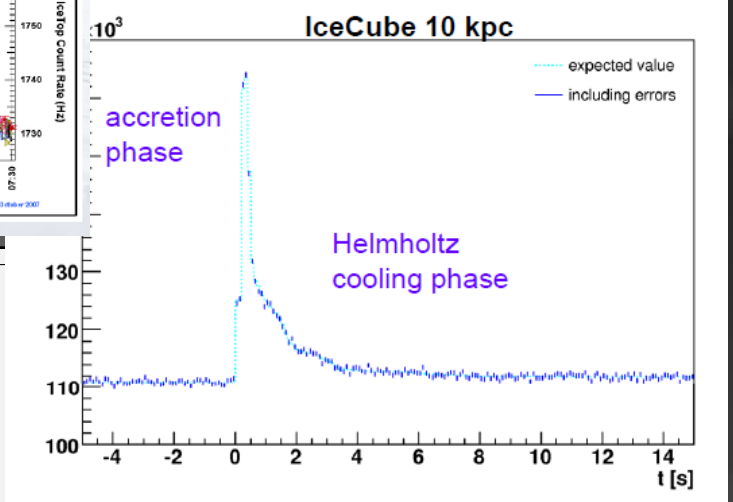








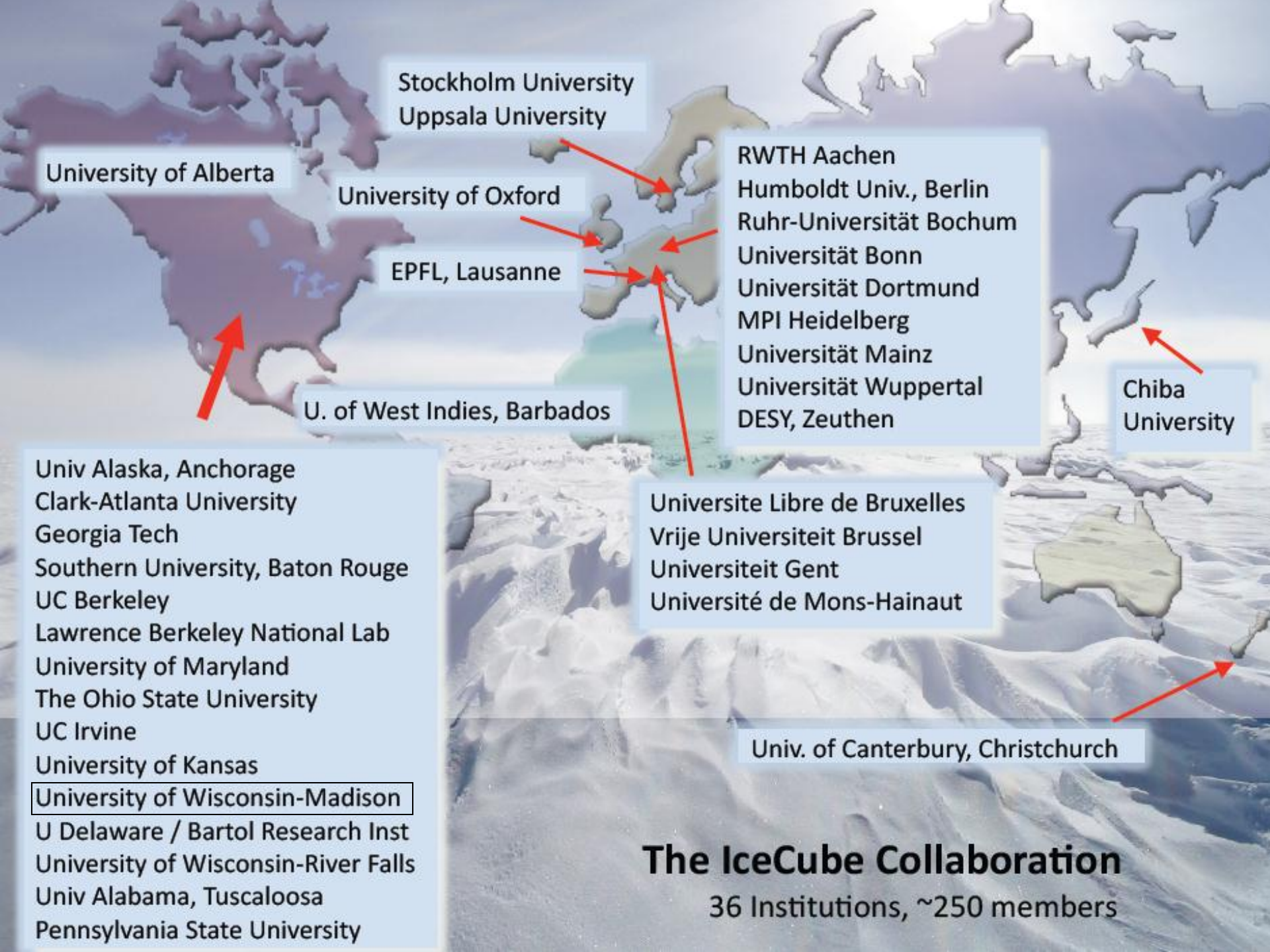




IceCube science

Conclusions

- 5 years to depression, 10 to despair
- Hess 1912…. and still no conclusion
- the instrumentation is in place …
- … supernova remnants and GRB are in close range !
- dark matter ?


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