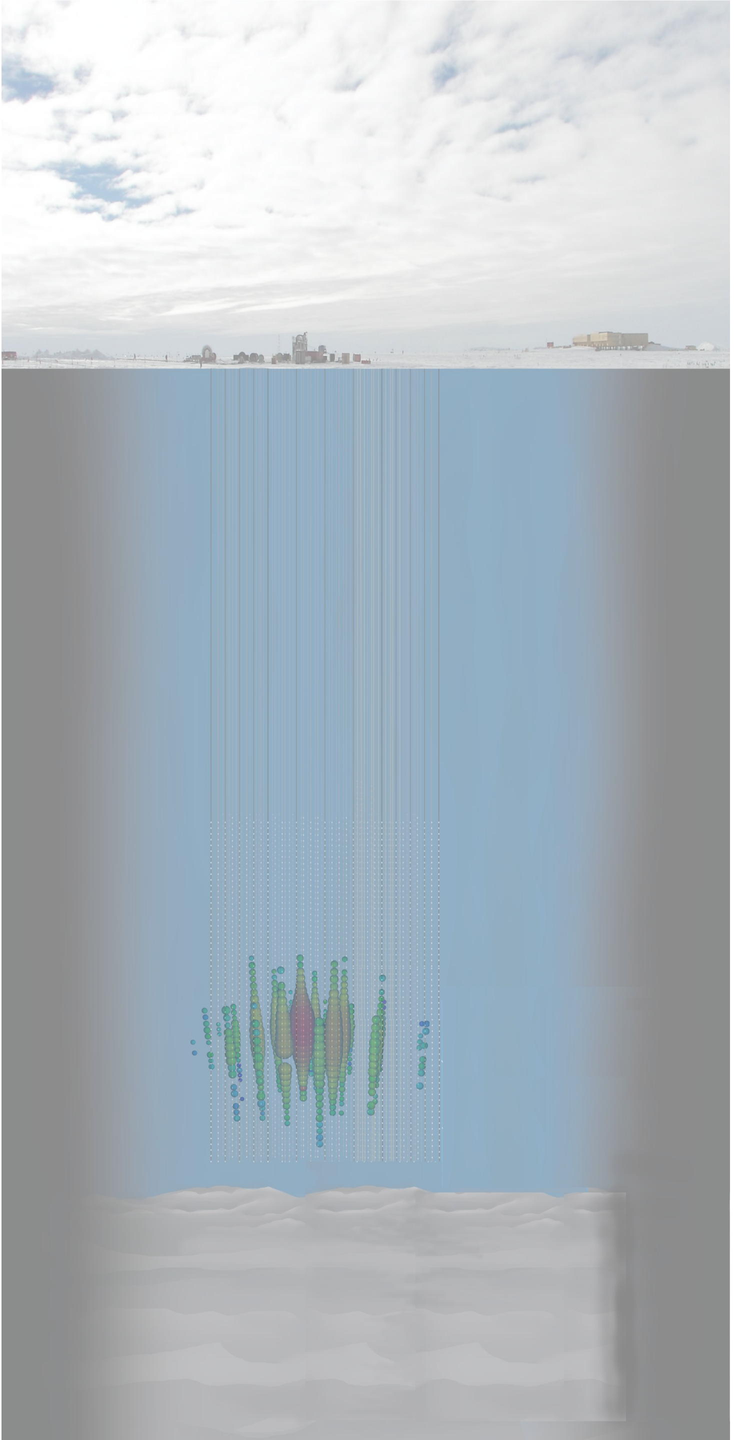
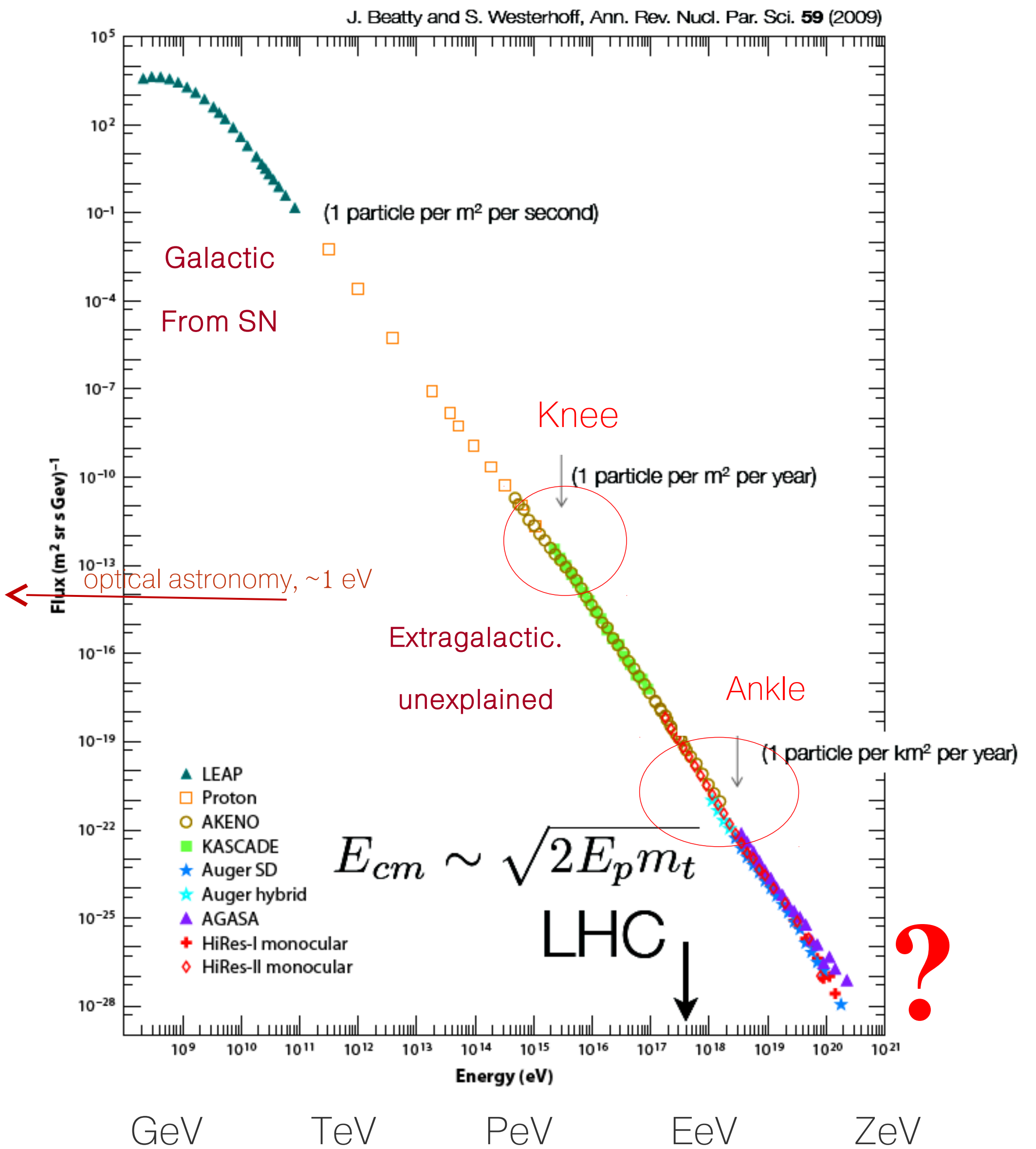


IceCube

Carlos de los Heros
Uppsala University

TAE 2014
Benasque 25 September, 2014



Today we know CR's are p's, γ's and heavier nuclei

CR's detected at extremely high energies

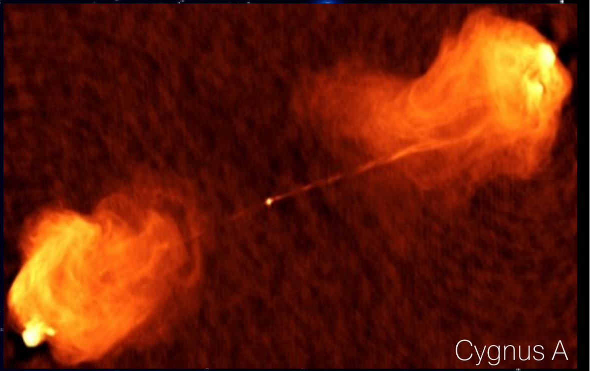
Sources: where do we expect them from?

Sources should also produce neutrinos (undetected so far ?)

How?:

→ **neutrino telescopes**

aim of neutrino telescopes: neutrino astronomy

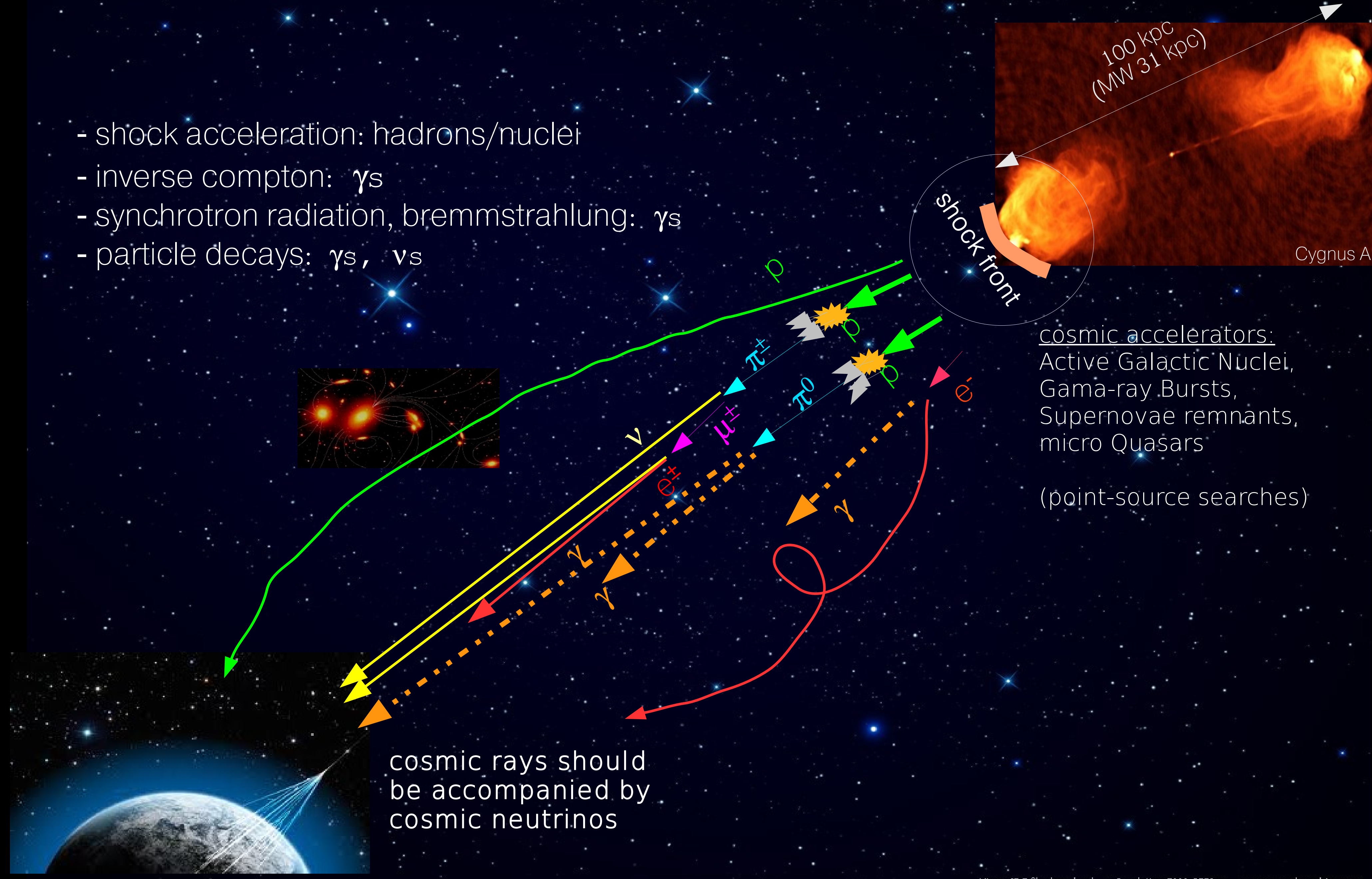

Cygnus A

<u>cosmic accelerators:</u>
Active Galactic Nuclei,
Gama-ray Bursts,
Supernovae remnants,
micro Quasars

(point-source searches)

particle production in cosmic accelerators

- shock acceleration: hadrons/nuclei
- inverse compton: γs
- synchrotron radiation, bremmstrahlung: γs
- particle decays: γs , νs



<u>cosmic accelerators:</u>
Active Galactic Nuclei,
Gama-ray Bursts,
Supernovae remnants,
micro Quasars

(point-source searches)

cosmic rays should
be accompanied by
cosmic neutrinos

- Astroparticle physics studies the cosmos through these ‘signatures’:

hadrons (p/nuclei), **leptons** (e^+,e^-), **photons and neutrinos**:

- protons are charged → deflected by intergalactic magnetic fields

(only very high energy CR’s, E>10^{18} eV, useful for astronomy: they can point)

- γ’s easily absorbed by intervening matter
- ν’s extremely difficult to detect (only weak interaction)

Detectors:

p/nuclei, e's: Air shower arrays (surface), satellites (space)

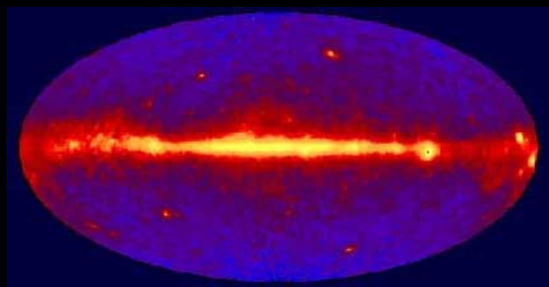
γ’s, e's: Cherenkov telescopes (surface), satellites (space)

ν’s: neutrino ‘telescopes’ (underground/underwater)

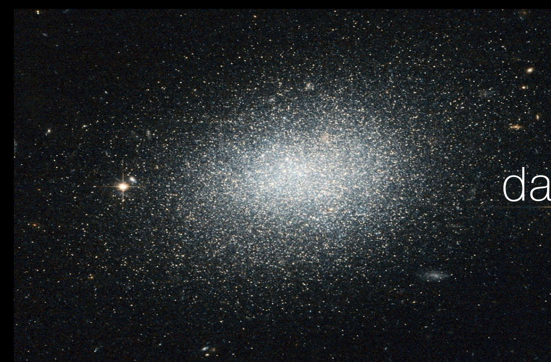
physics with neutrino telescopes

cosmic accelerators
AGN, GRBs, μQSrs, SN remnants
(point-source searches)

Supernovae

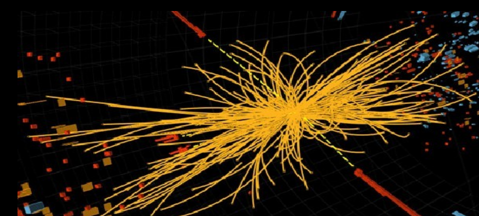


diffuse neutrino flux
(all-sky searches)



dark matter

cosmic rays

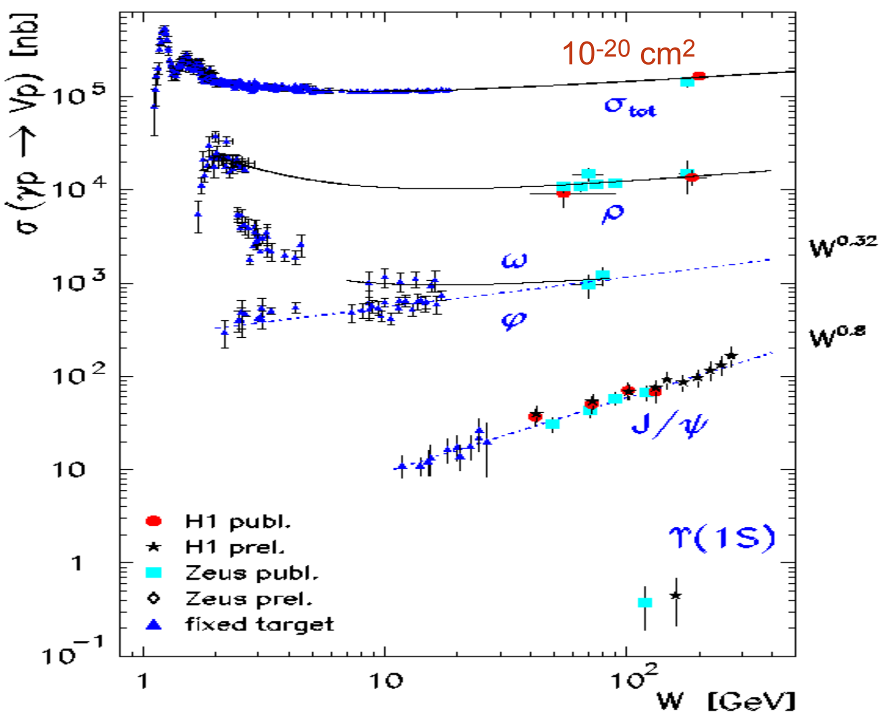


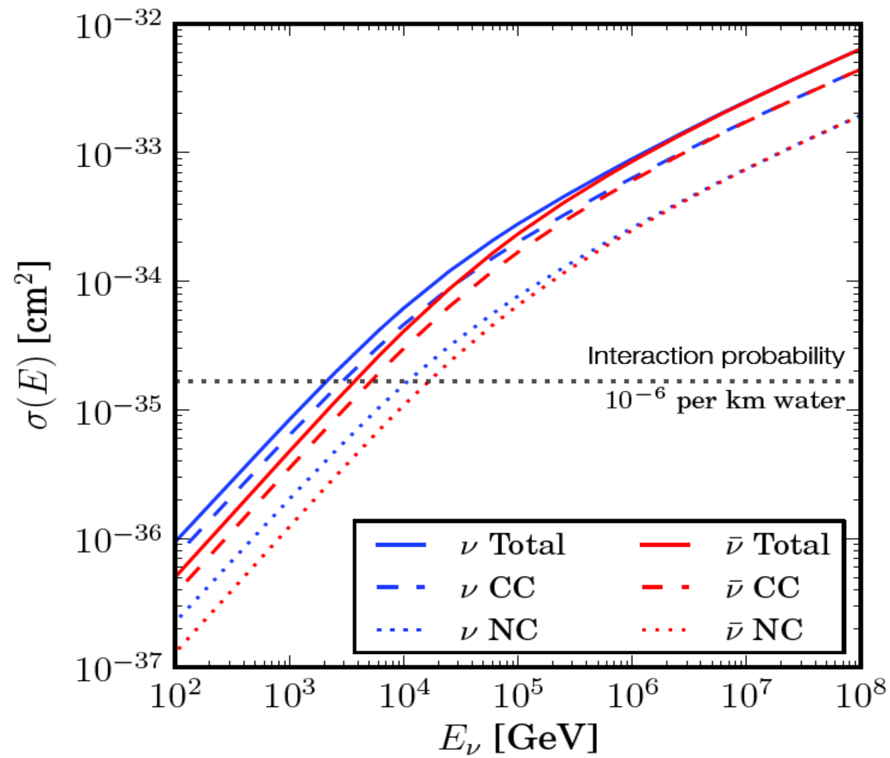
particle physics:
neutrino properties
fundamental laws...

reminder: neutrino Xsection with matter

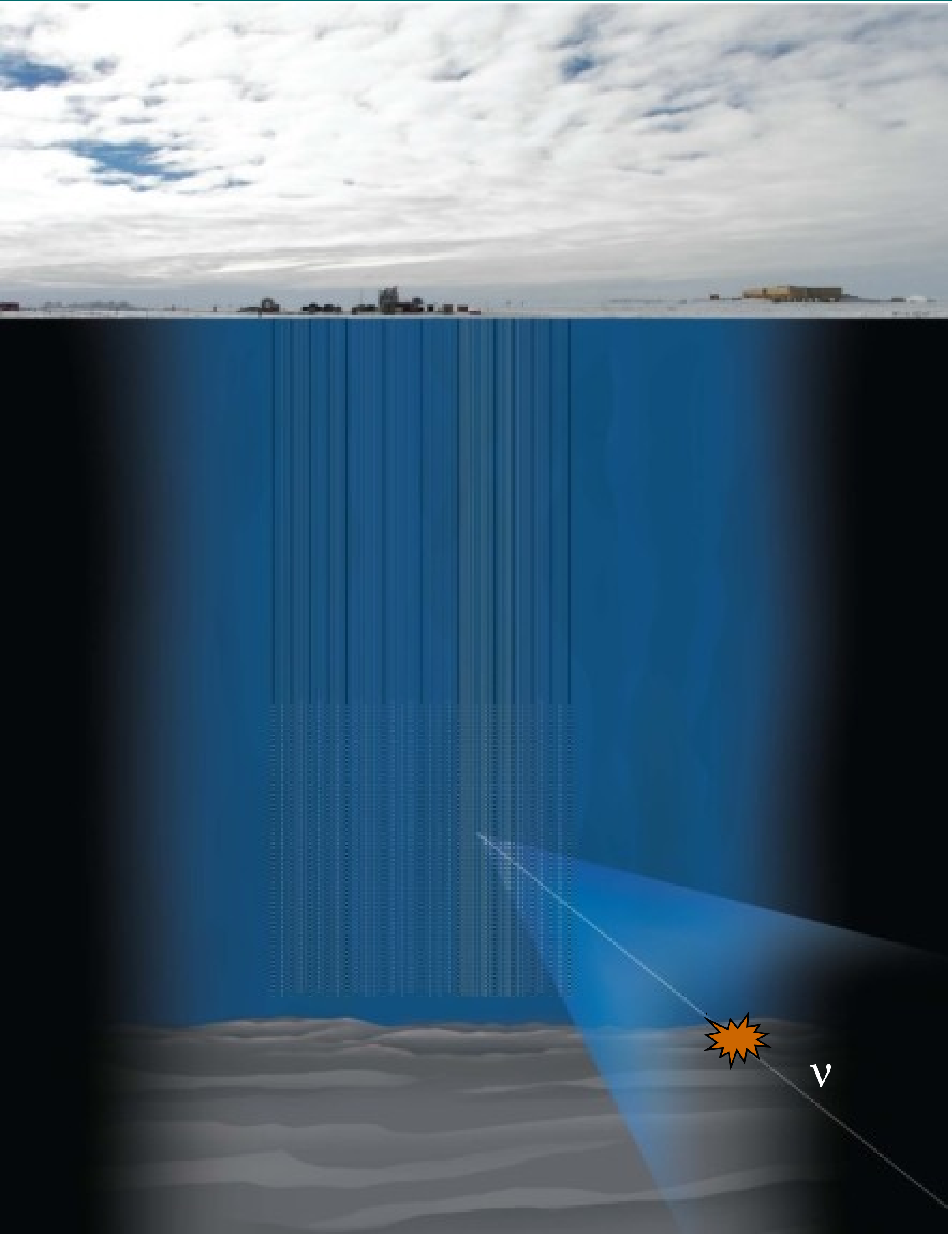
R. Ghandi *et al*, Astropart. Phys. 5, 81 (1996); J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84, 1307, 2012

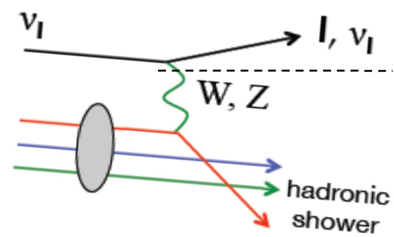
compare: γ+p Xsection





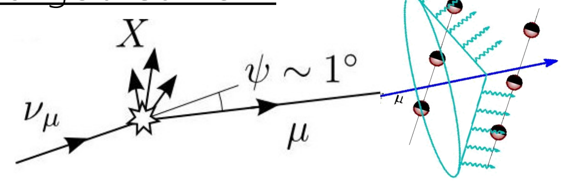
(1 barn $=10^{-24}$ cm^2 1 nanobarn $=10^{-33}$ cm^2)



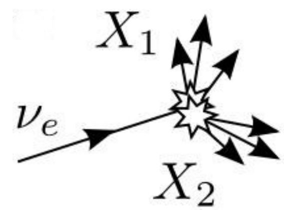


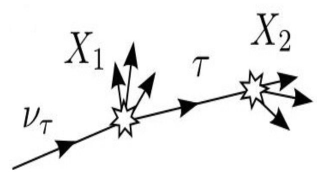
Detect Cherenkov light of interaction products

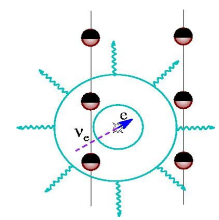
charged current



μ tracks > 100m @ E> 100 GeV



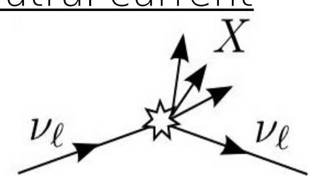


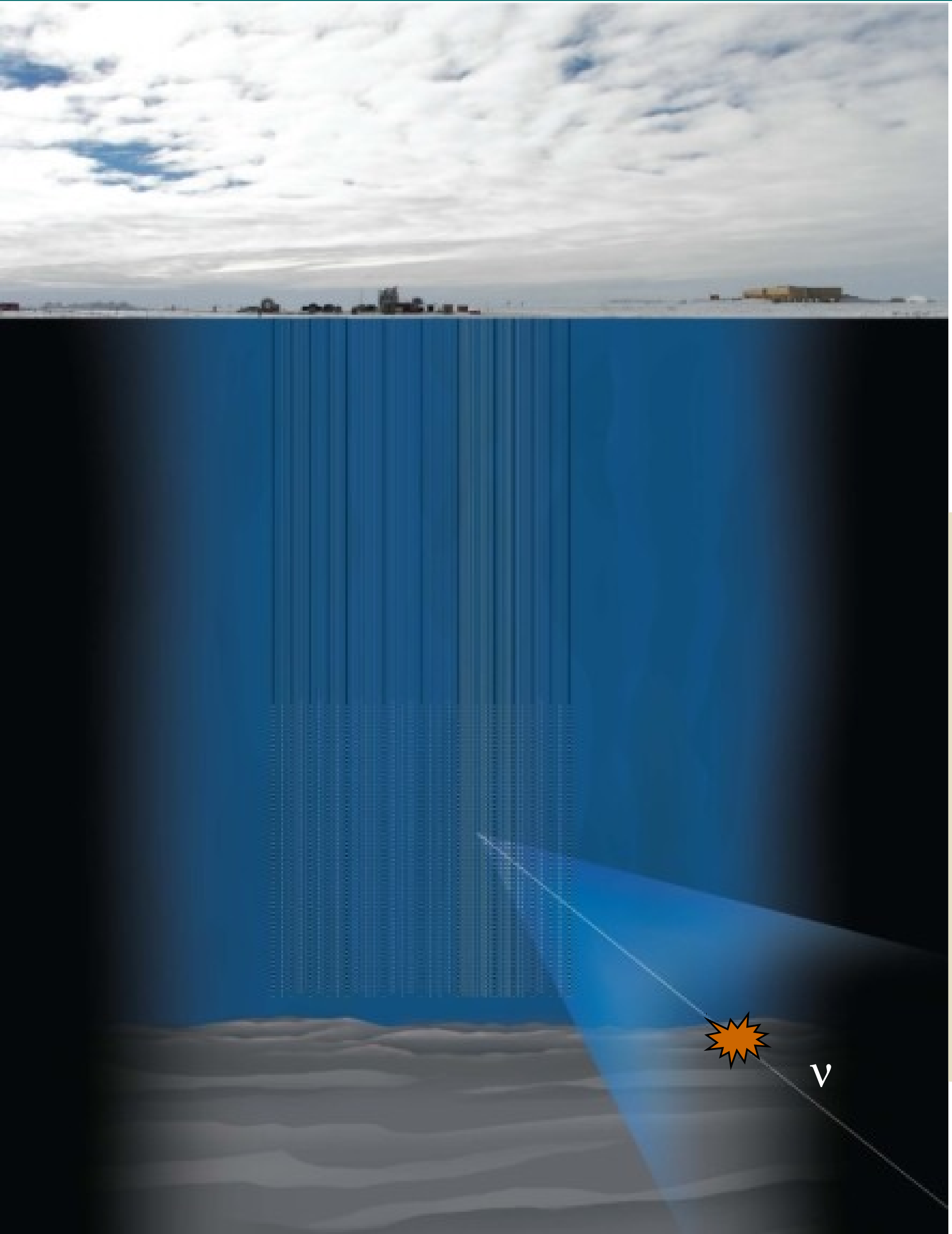


e^{+-} :electromagnetic shower

τ^{+-} : hadronic shower

neutral current



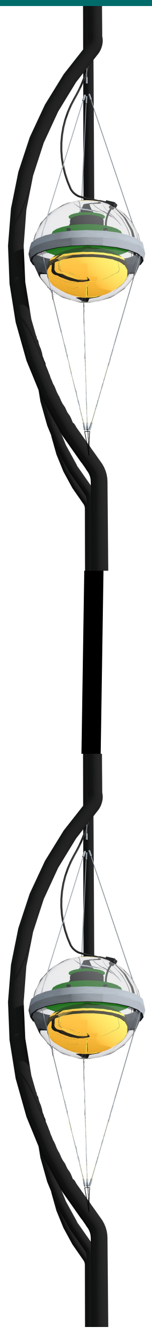


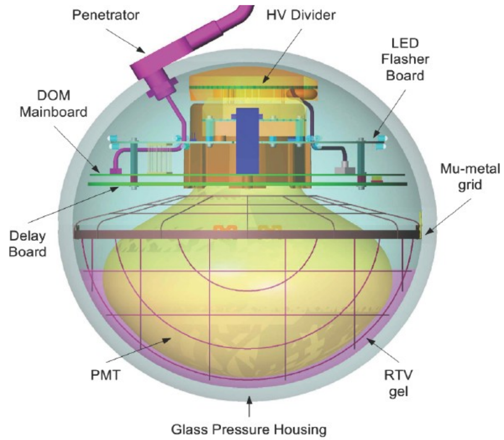
Array of optical modules in a transparent medium to detect the light emitted by relativistic secondaries produced in charged-current ν-nucleon interactions

Need ns timing resolution

Need HUGE volumes (tiny Xsects & fluxes)

the IceCube neutrino telescope



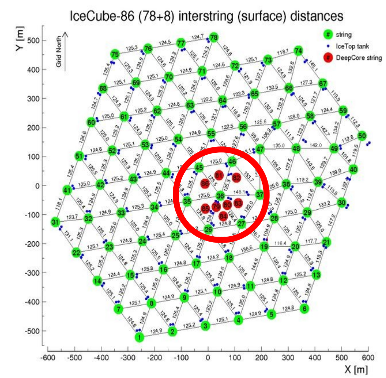


- PMT: Hamamatsu, 10''
- Digitizers:
  - ATWD: 3 channels. Sampling 300MHz, capture 400 ns
  - FADC: sampling 40 MHz, capture 6.4 µs
  - Dynamic range 500pe/15 nsec, 25000 pe/6.4 µs
- Flasher board:
  - 12 controllable LEDs at 0° or 45°

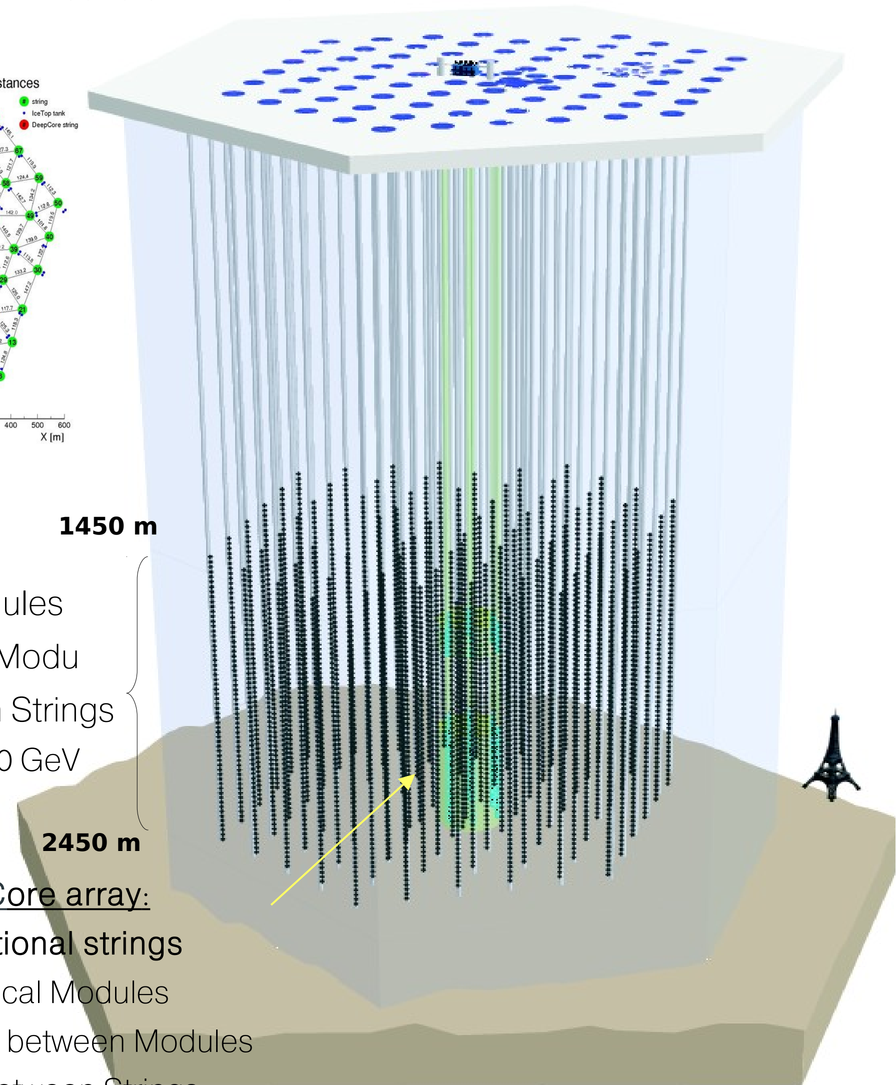
· Dark Noise rate ~ 500 Hz
· Local Coincidence rate ~ 15 Hz
· Deadtime < 1%
· Timing resolution ≤ 2-3 ns
· Power consumption: 3W

Clock stability: 10^{-10} ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec
at 2 ns precision

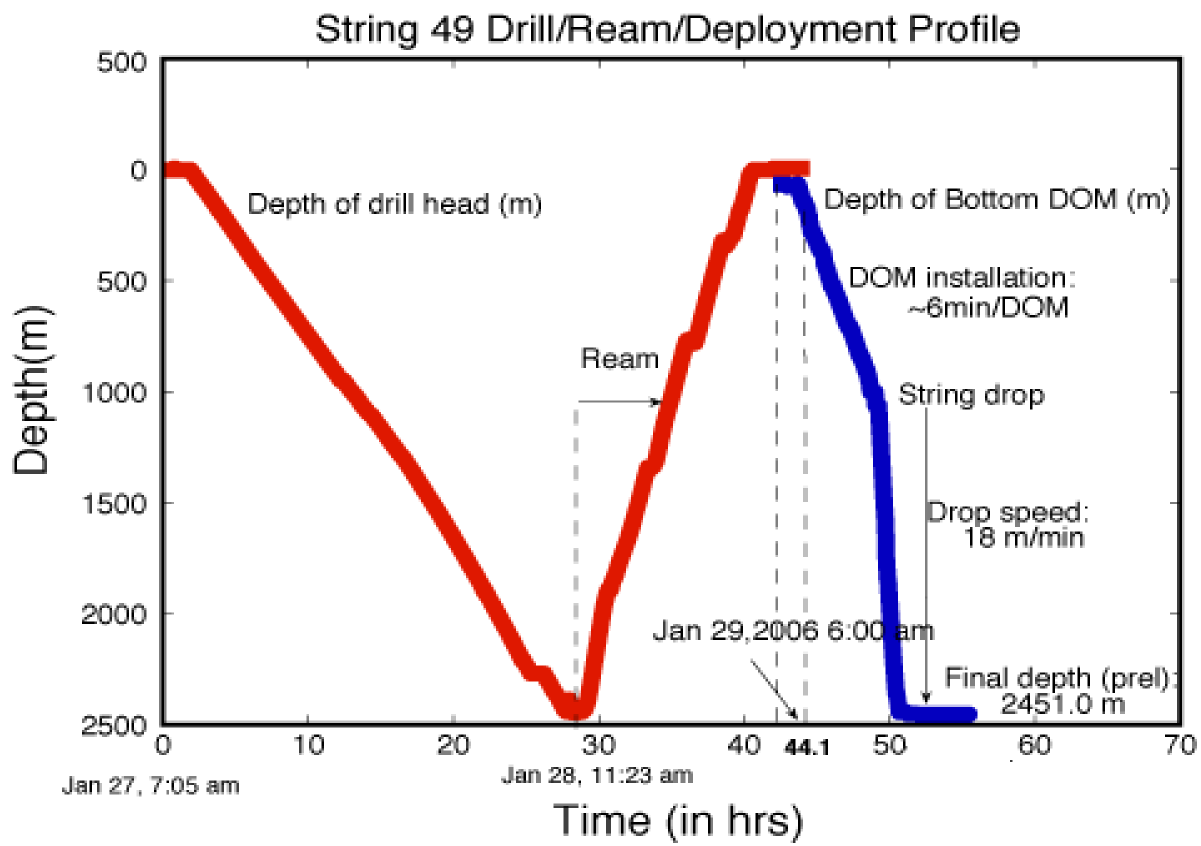
IceTop: Air shower detector
80 stations/2 tanks each
threshold ~ 300 TeV



InIce array:
80 Strings
60 Optical Modules
17 m between Modu
125 m between Strings
ν threshold ≲100 GeV

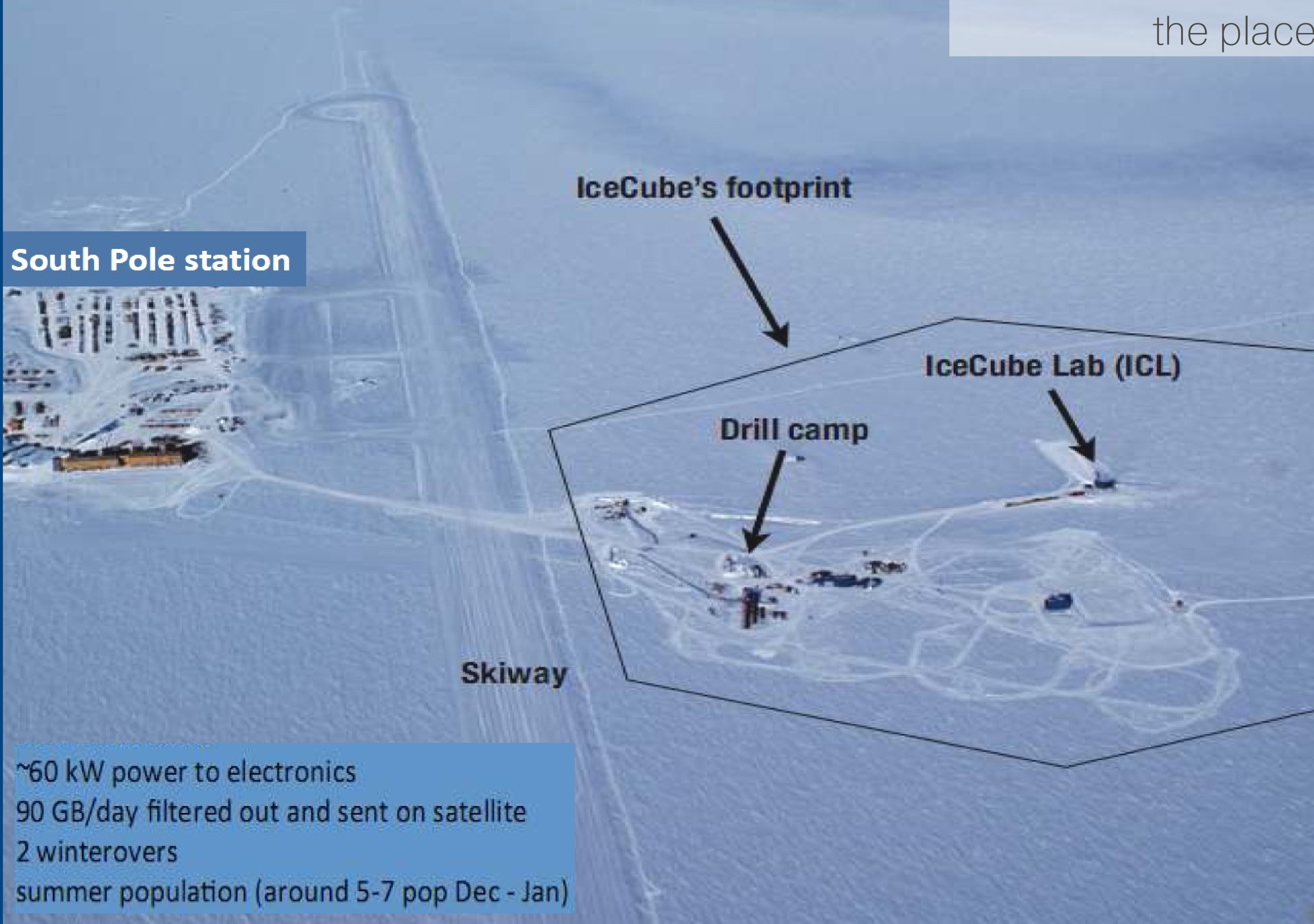


DeepCore array:
6 additional strings
60 Optical Modules
7/10 m between Modules
72 m between Strings
ν threshold ~10 GeV



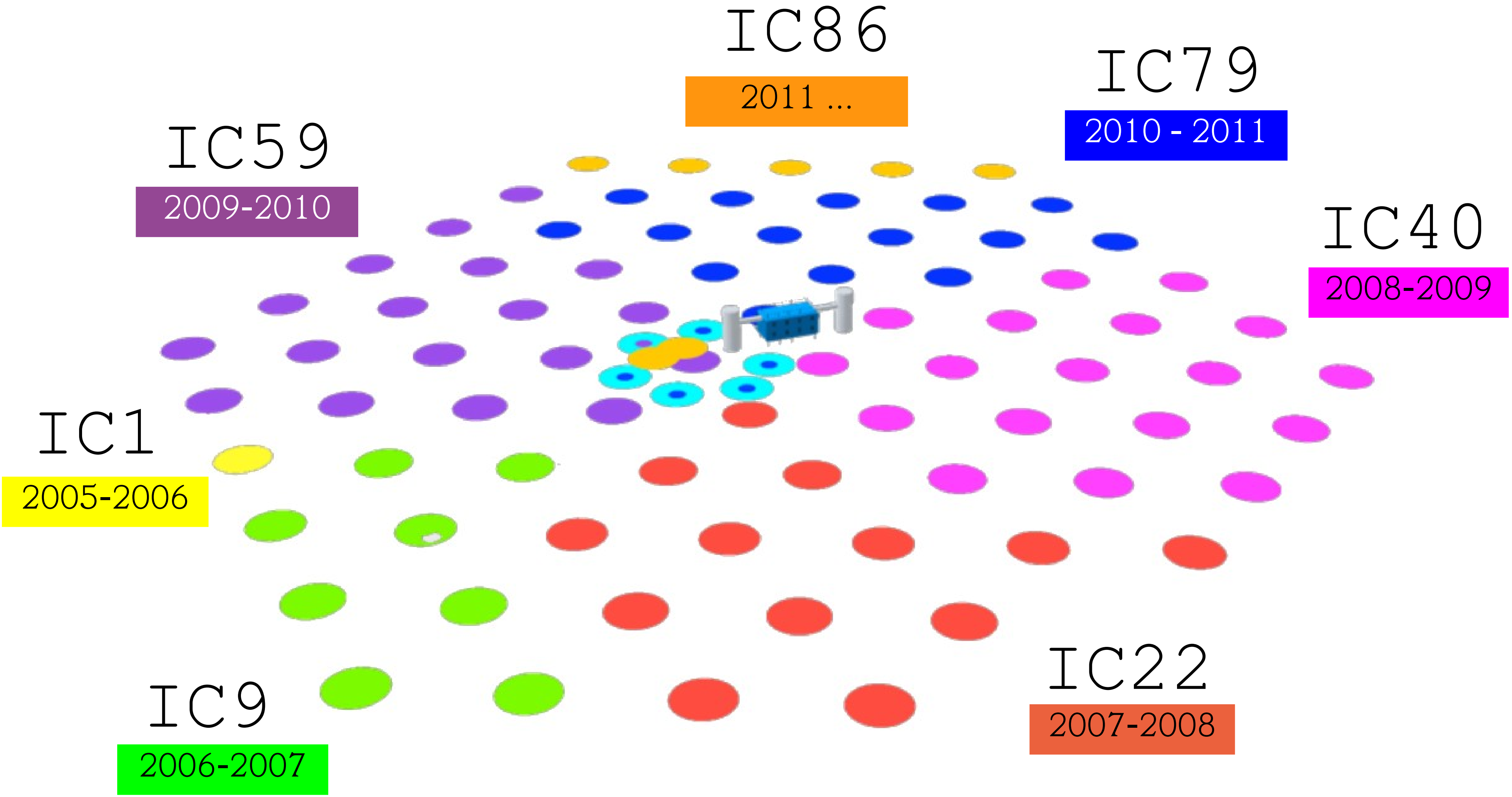
5MW x 30 hrs = 0.56 TJ!

AMANDA drilling (1950m) 90 hrs deployment: 18 hrs
IceCube drilling (2450m) 40 hrs, deployment: 10 hours


South Pole station
IceCube's footprint
IceCube Lab (ICL)
Drill camp
Skiway
~60 kW power to electronics
90 GB/day filtered out and sent on satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)


Ctra. los Baños
Camino P
Camino Rodiella
Camino N
Camino Rigau
Río Ésera
Calle Mayor
Barranco San Martín
Calle Horno
Calle de los Molinasos
Camino Somedes
Av. de la Estación
Calle Mirador de Cerler
Barranco de la Rodiella
0
1 km
Av. los Tilos
Camino B
Camino Campalent
Calle San Pedro
Camino M
Calle F
Camino Arguilla
Camino San Antón
Paseo de Eriste
Camino L
Barranco Fondo
Partida el Regoso
Río Ésera
Camino B
Paseo de Eriste
Calle Peguera
Calle Remáscaro
Río Ésera
Camino del Vivero
Paseo Anciles
Google


Ctra. los Baños
Camino P
Camino Rodiella
Camino N
Camino Rinau
Río Ésera
Calle Mayor
Barranco San Martín
Calle de los Molinasos
Camino Somedes
Calle Horno
Av. de la Estación
Calle Mirador de Cerler
Barranco de la Rodiella
Av. los Tilos
Camino B
Camino Campalen
Calle San Pedro
Camino M
Calle F
Camino Arguilla
Camino San Antón
Paseo de Eriste
Camino L
Barranco Fondo
Partida el Regoso
Camino B
Río Ésera
Paseo de Eriste
Calle Peguera
Calle Remáscaro
Río Ésera
Camino del Vivero
Paseo Anciles
0
1 km
Google

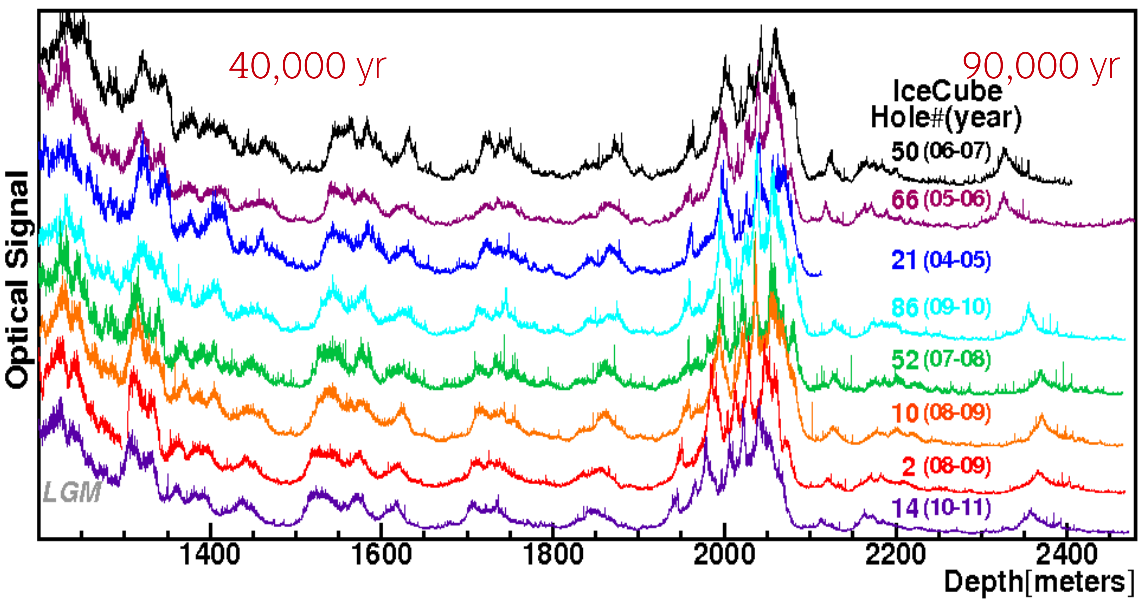


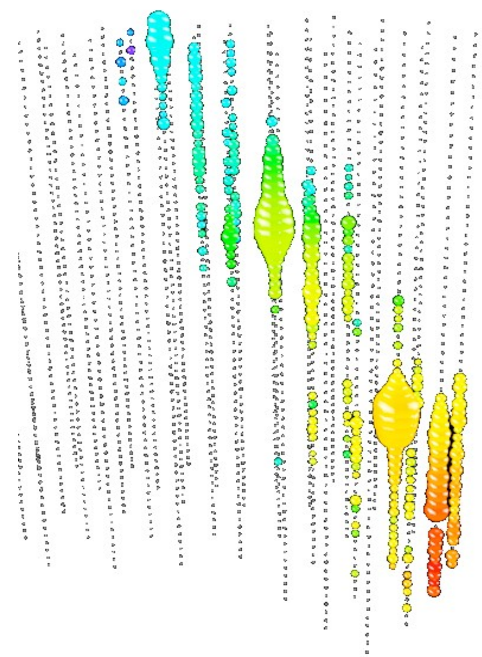
Data taking since 2005 – completed in 2010!

We do not fill our detector with a well known and calibrated Cherenkov radiator (as accelerator experiments do)

We fill the ice with our detector → Need characterization of an unknown medium

Deep ice at South Pole is extremely clear, $\lambda_{absorption}$~100 m, but presents dust layers of decreased transparency





This presents a challenge for photon collection at some depths

example of track reconstruction in IceCube

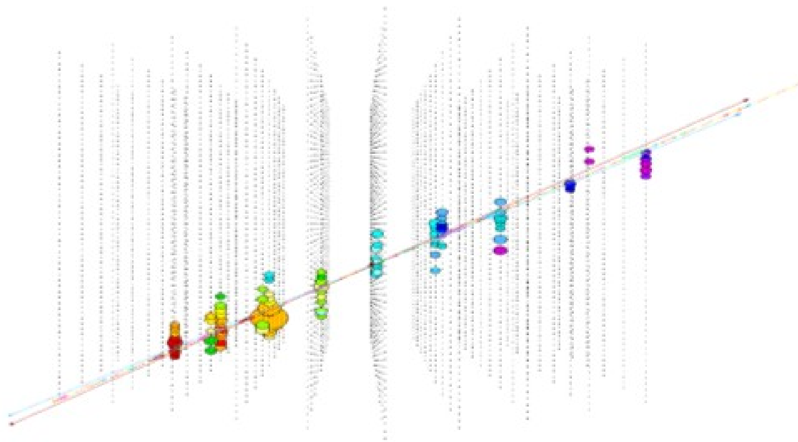


Figure 13: A 10-TeV muon track in IceCube.

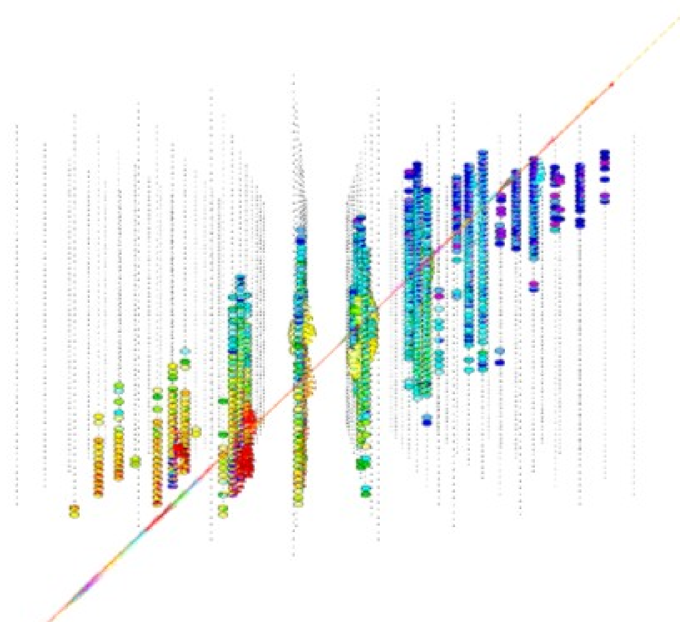
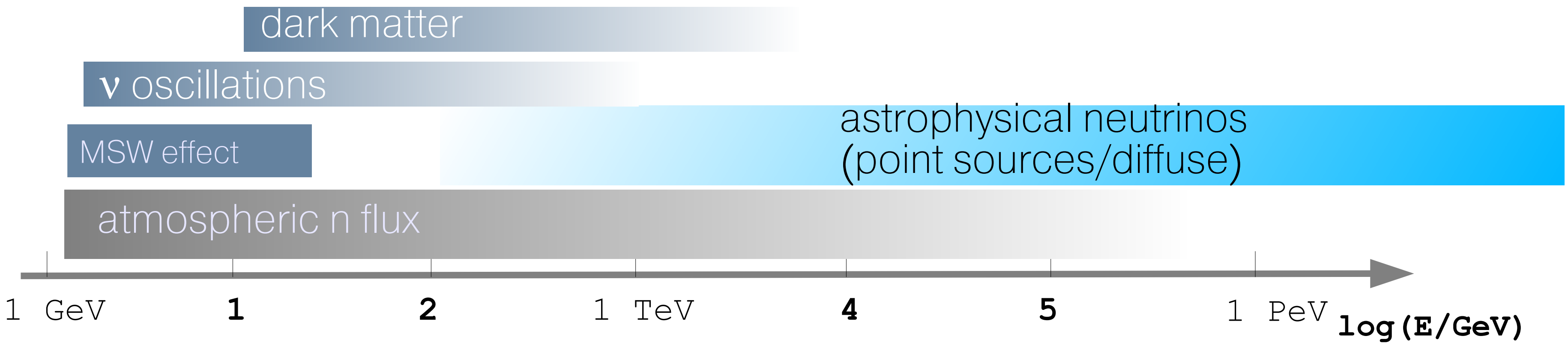
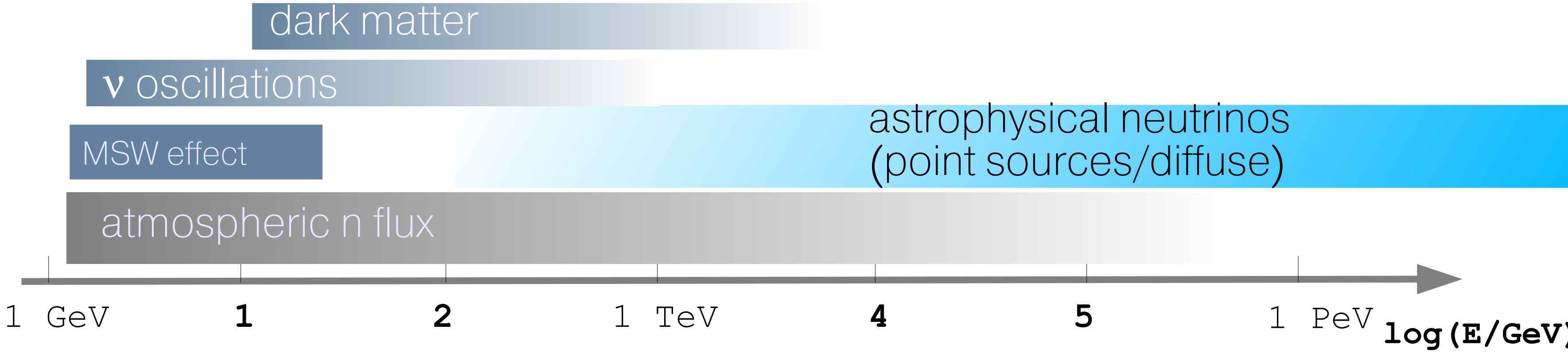


Figure 14: A 6-PeV muon track in IceCube.

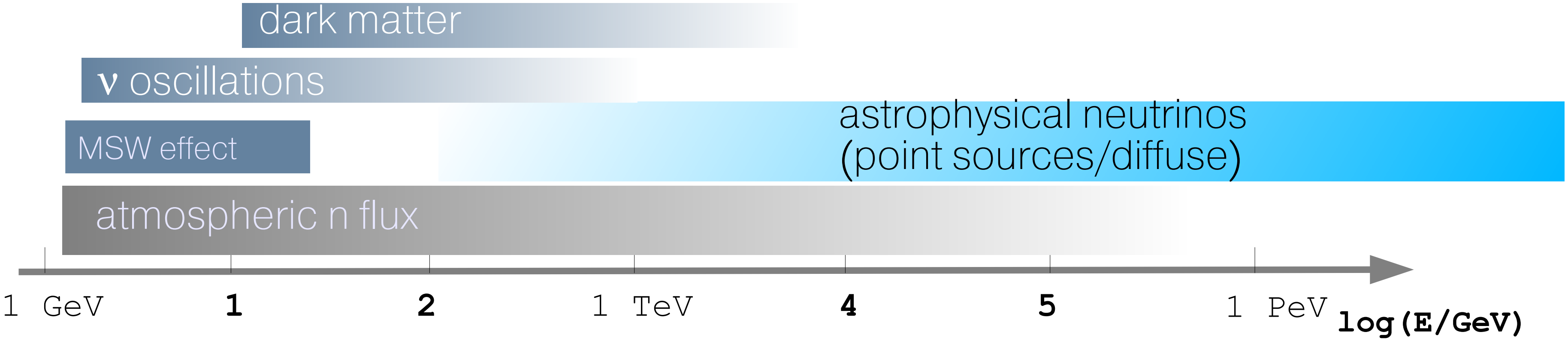

dark matter
ν oscillations
MSW effect
astrophysical neutrinos
(point sources/diffuse)
atmospheric n flux
1 GeV
1
2
1 TeV
4
5
1 PeV
log(E/GeV)

neutrino telescopes are multipurpose...



... multi-flavour detectors

neutrino telescopes are multipurpose...



... multi-flavour detectors

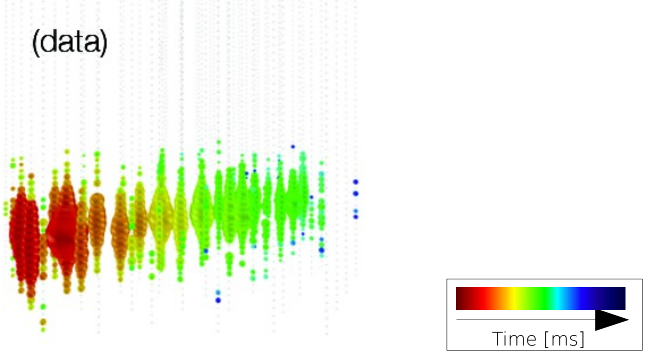
neutrino event signatures in IceCube:

<u>tracks</u>:

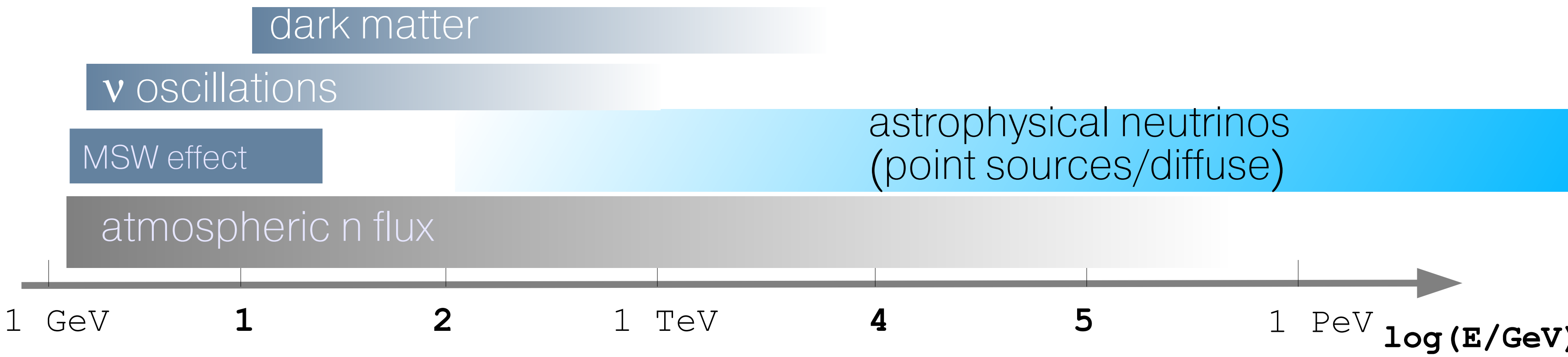
ν_μ + N -> μ + X

angular resolution ~ 1°

can measure dE/dX only



neutrino telescopes are multipurpose...



... multi-flavour detectors

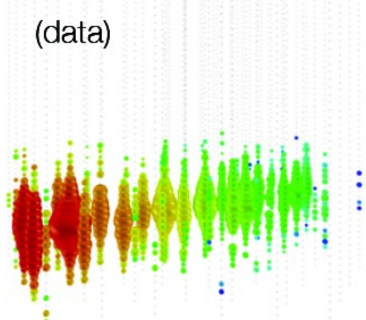
neutrino event signatures in IceCube:

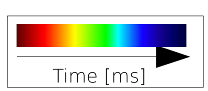
tracks:

$\nu_\mu + N \rightarrow \mu + X$

angular resolution ~ 1^o

can measure dE/dX only





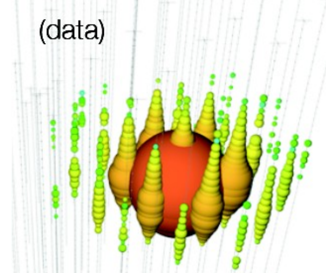
cascades:

$\nu_e + N \rightarrow e + X$

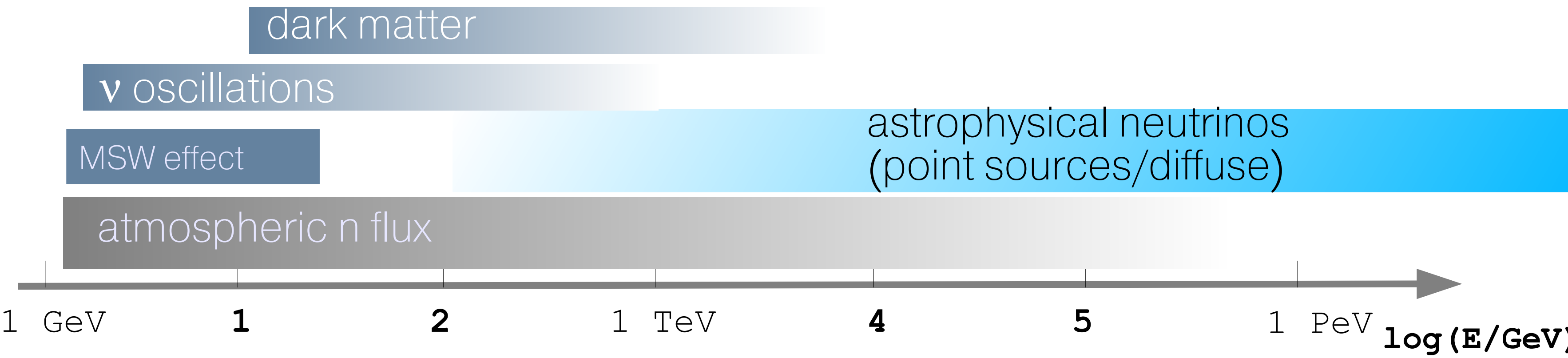
$\nu_i + N \rightarrow \nu_i + X$

angular resolution ≥ 10^o

energy resolution ~ 15%



neutrino telescopes are multipurpose...



... multi-flavour detectors

neutrino event signatures in IceCube:

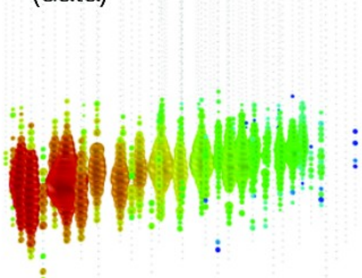
tracks:

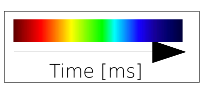
$\nu_\mu + N \rightarrow \mu + X$

angular resolution ~ 1^o

can measure dE/dX only

(data)





cascades:

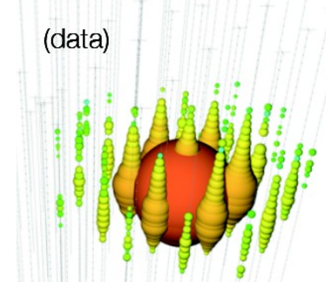
$\nu_e + N \rightarrow e + X$

$\nu_i + N \rightarrow \nu_i + X$

angular resolution ≥ 10^o

energy resolution ~ 15%

(data)



Tau neutrino, CC

$\nu_\tau + N \rightarrow \tau + X$

(simulation)

Measure fluxes of

atmospheric muons

atmospheric neutrinos

at higher energies and better statistics

than previous experiments

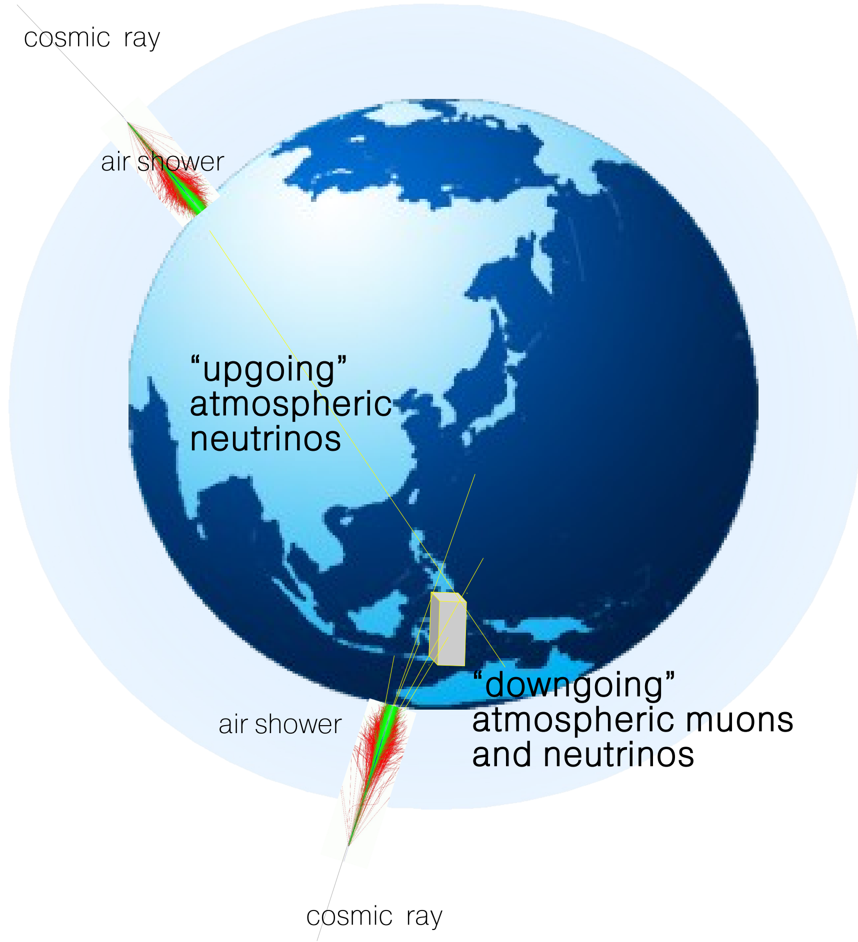
Any deviations from known physics is

new neutrino physics

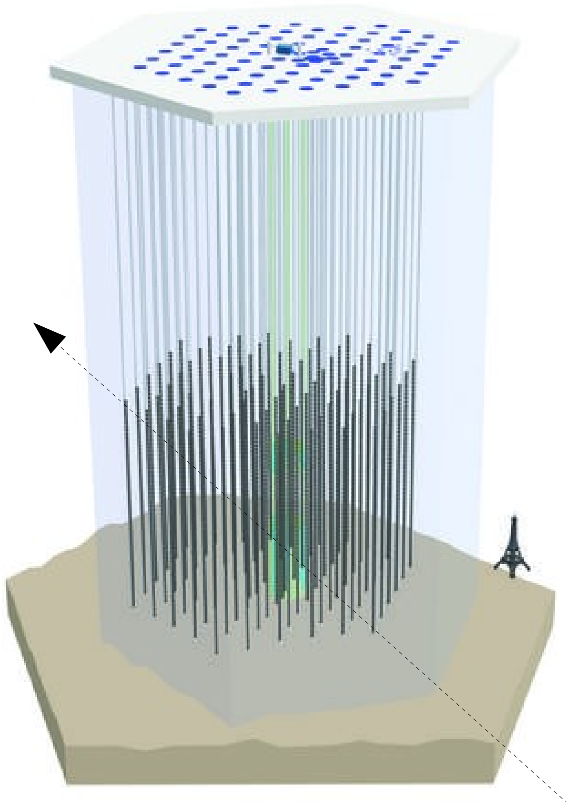
new particle physics

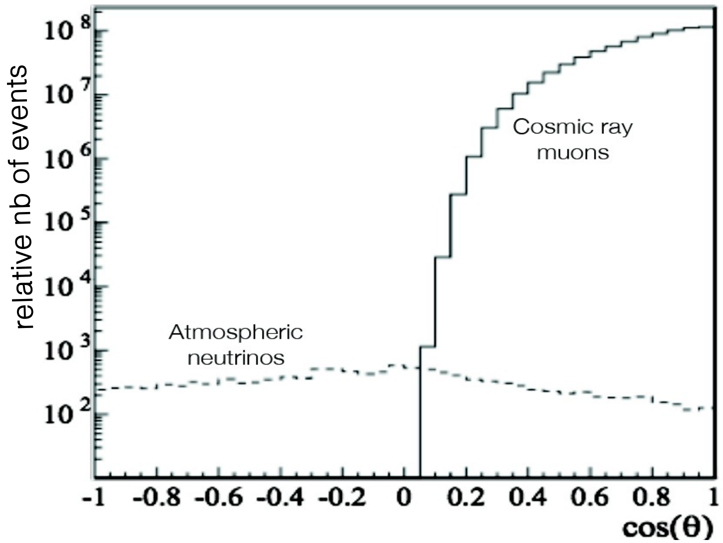
new astrophysics

backgrounds



@ IceCube: downgoing → Southern Hemisphere
upgoing → Northern Hemisphere



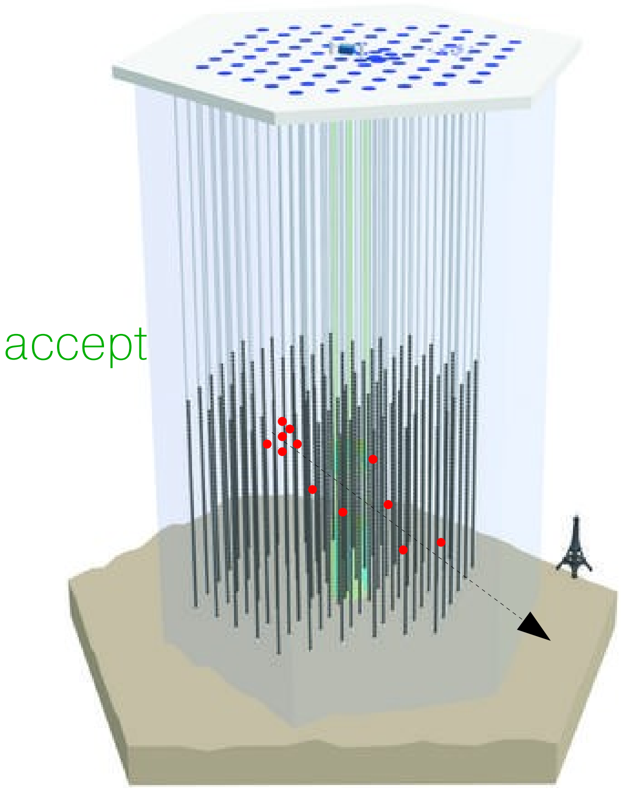


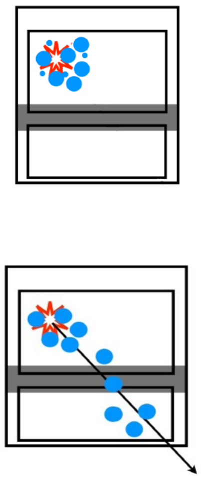
below the horizon
(upgoing tracks)

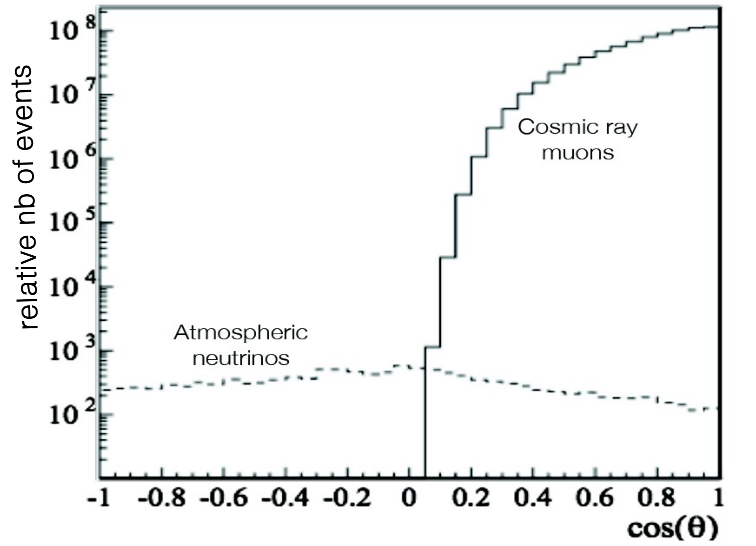
Earth has filtered
all cosmic ray products
except neutrinos

To identify **ν**'s:

a) use Earth as a filter, ie, look for upgoing tracks, cos(**θ**)<0







below the horizon (upgoing tracks)

Earth has filtered all cosmic ray products except neutrinos

above the horizon (downgoing tracks)

High energetic muons can penetrate km in water or ice

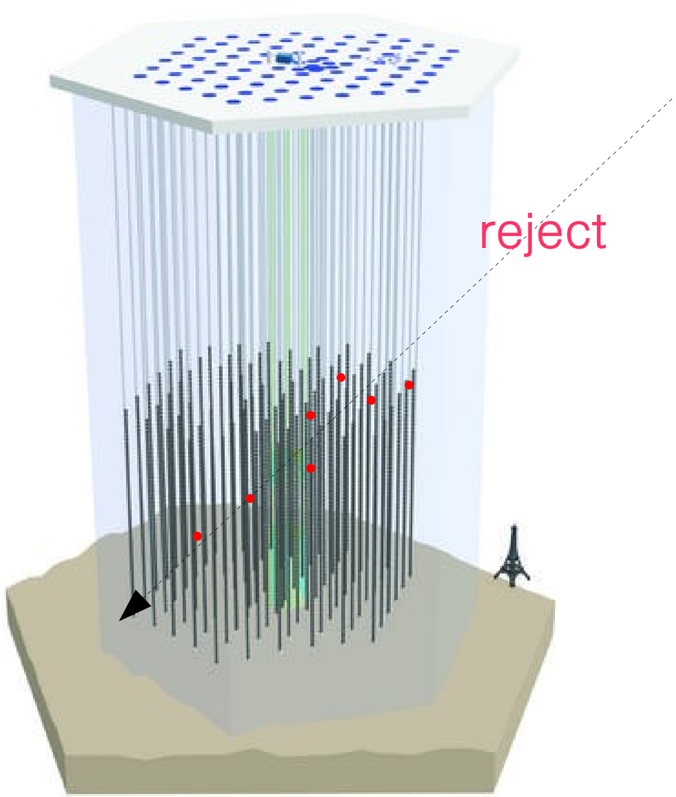
To identify **ν**'s:

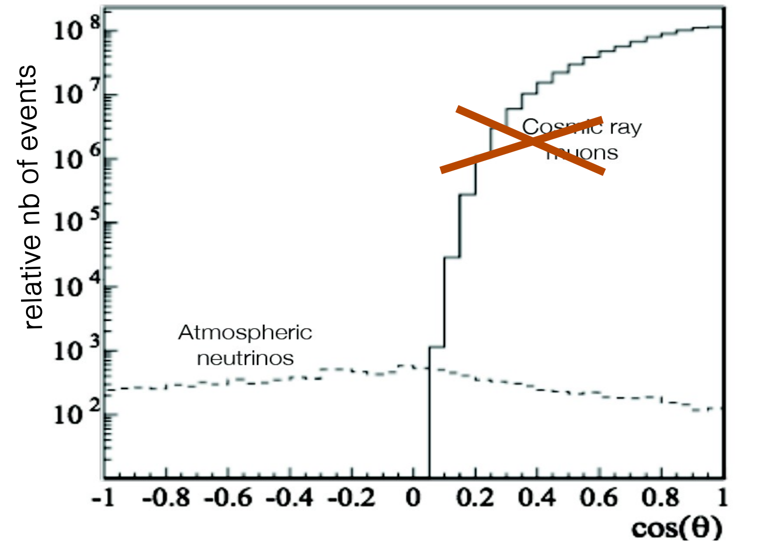
a) use Earth as a filter, ie, look for upgoing tracks, cos(θ)<0

b) define "starting tracks" in the detector. Use any angle full sky sensitivity

using IceCube outer strings as a veto:
Require no causally connected hits in outer string(s) layer(s)

--> access to southern hemisphere sources, galactic center and all-year Sun visibility





below the horizon (upgoing tracks)

Earth has filtered all cosmic ray products except neutrinos

above the horizon (downgoing tracks)

High energetic muons can penetrate km in water or ice

To identify **ν**'s:

a) use Earth as a filter, ie, look for upgoing tracks, cos(**θ**)<0

b) define “starting tracks” in the detector. Use any angle

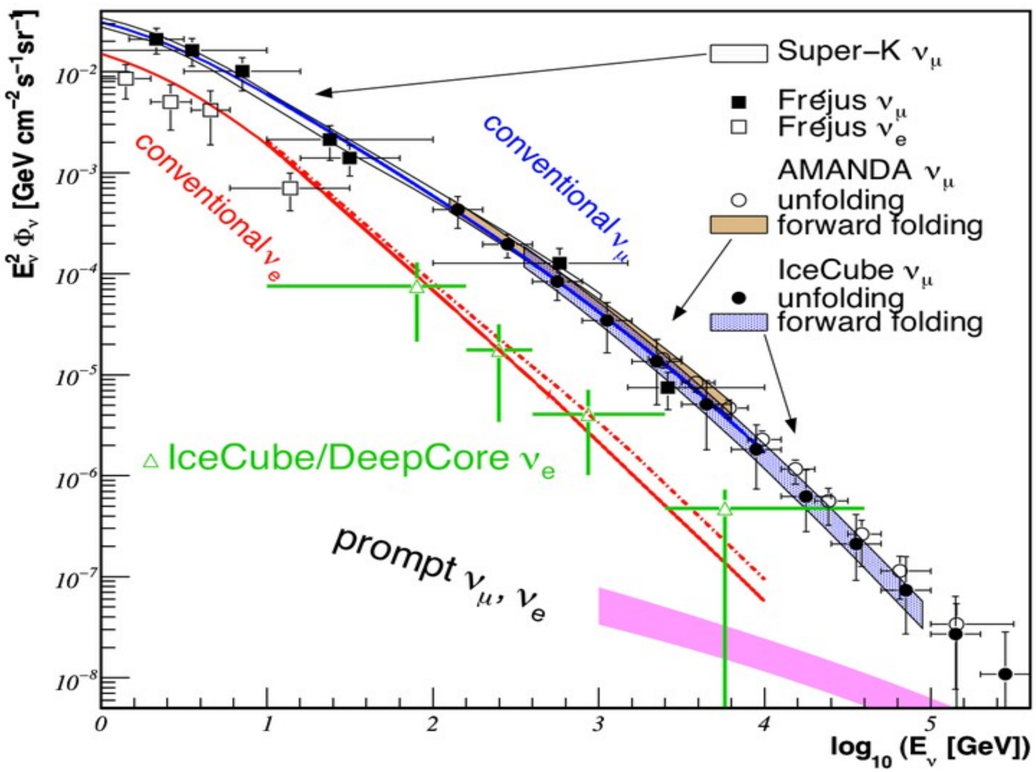
$$CR + N \to \pi's + X$$

$\pi \to \mu + \nu_\mu$

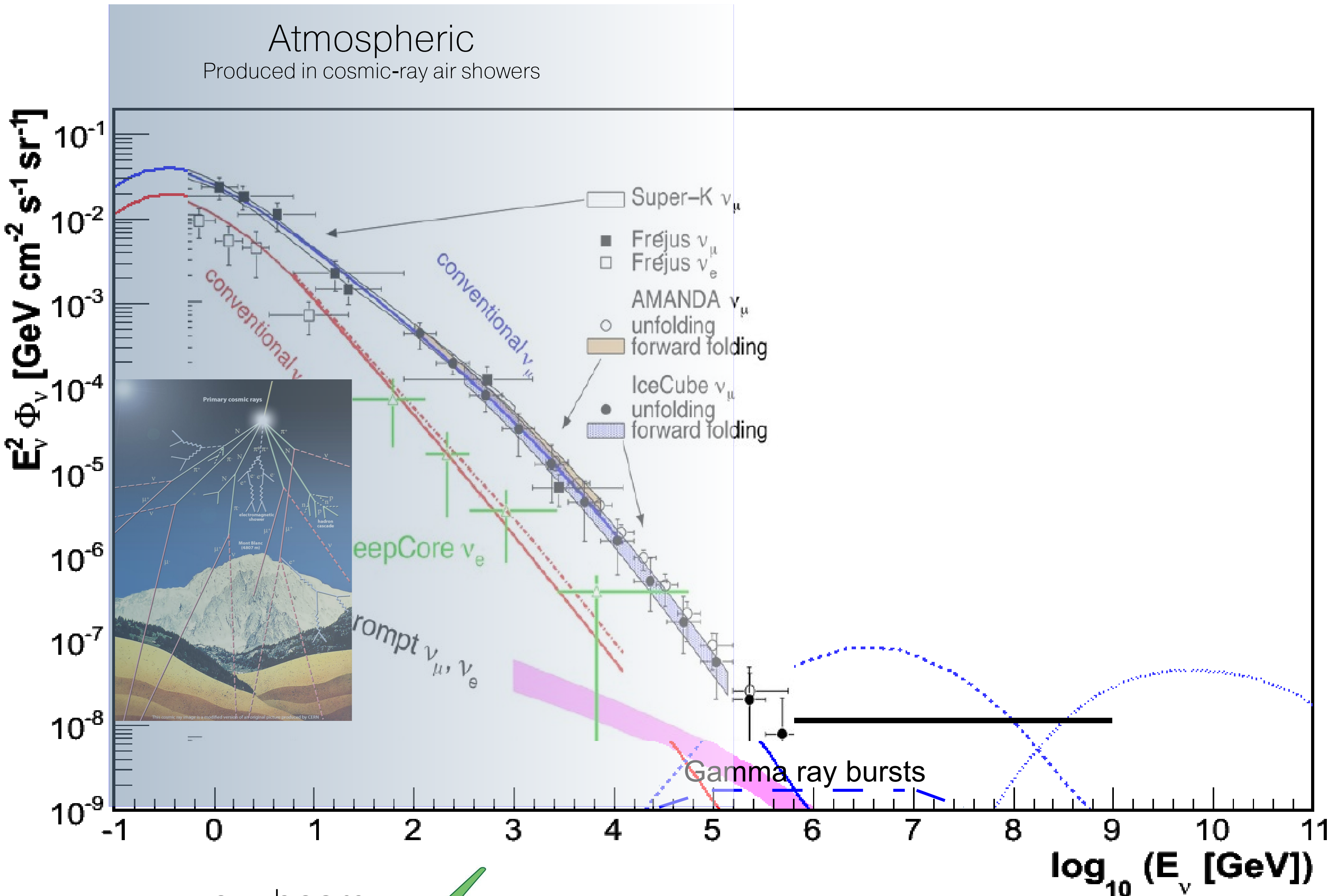
$\mu \to e + \nu_e + \nu_\mu$

expected flavour ratio:

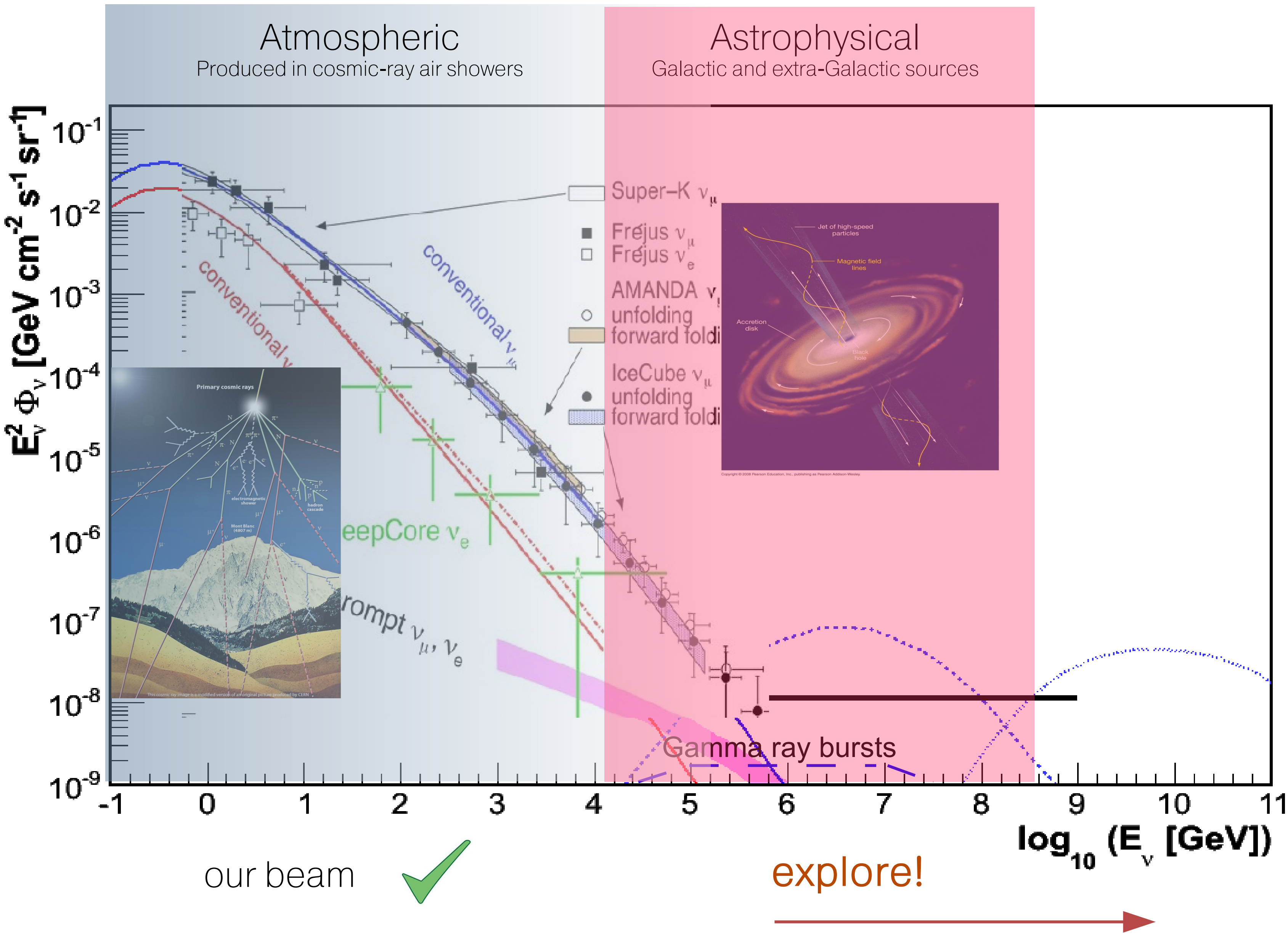
$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$

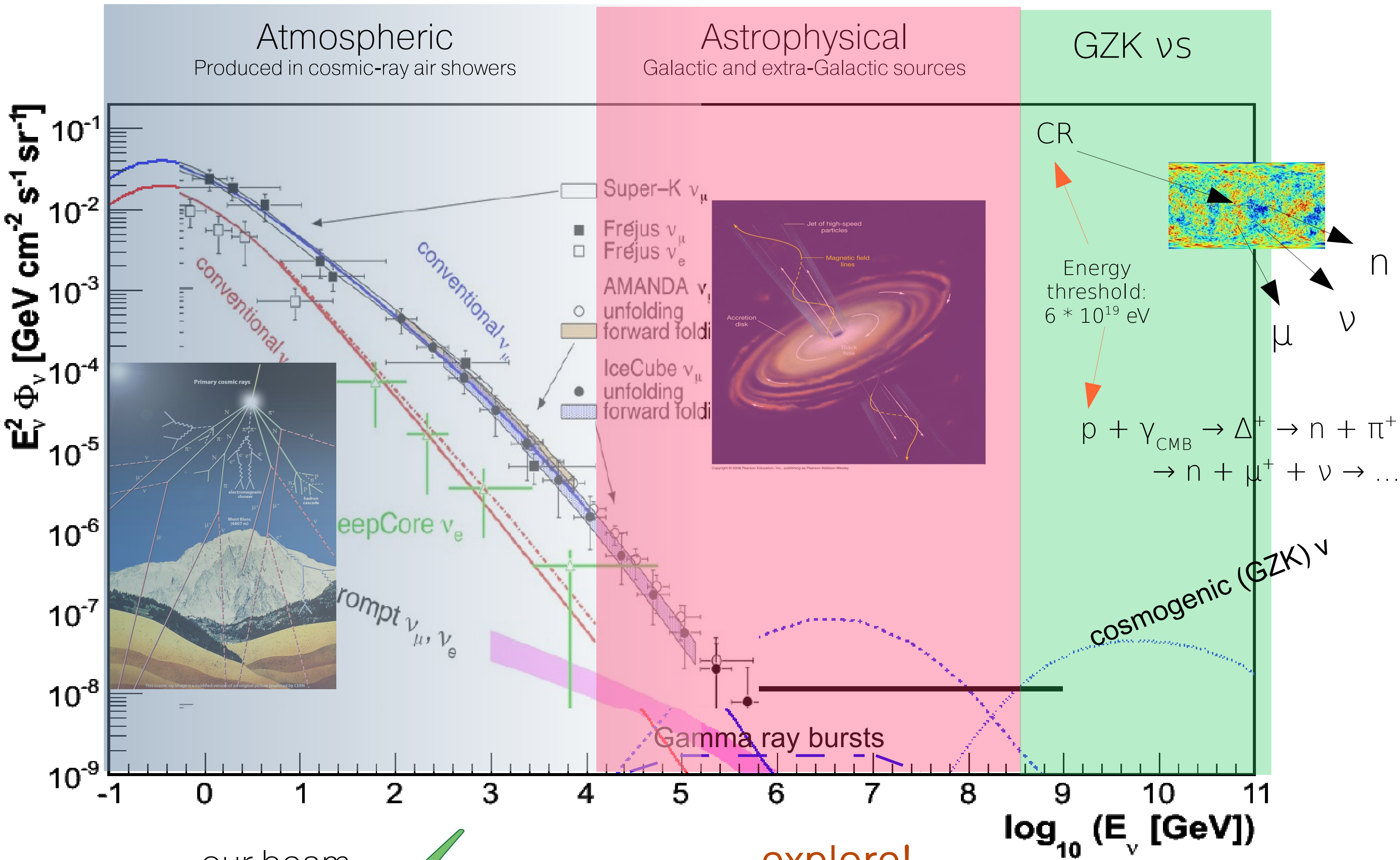


measurements agree with predictions based on the cosmic ray flux and neutrino production physics


Atmospheric
Produced in cosmic-ray air showers
$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Super–K ν_μ
Fréjus ν_μ
Fréjus ν_e
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
eepCore ν_e
rompt ν_μ, ν_e
Primary cosmic rays
Gamma ray bursts
-1
0
1
2
3
4
5
6
7
8
9
10
11
$\log_{10}$ (E_ν [GeV])

our beam ✓


Atmospheric
Produced in cosmic-ray air showers
Astrophysical
Galactic and extra-Galactic sources
Super–K ν_μ
Fréjus ν_μ
Fréjus ν_e
AMANDA
unfolding
forward foldi
IceCube ν_μ
unfolding
forward foldi
conventional ν_μ
conventional
eepCore ν_e
rompt ν_μ, ν_e
Gamma ray bursts
$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
$\log_{10}(E_\nu$ [GeV])
our beam
explore!



our beam ✓

explore!

Even if individual sources not strong enough, contribution from all sources within the Hubble radius can be detectable

→ diffuse flux

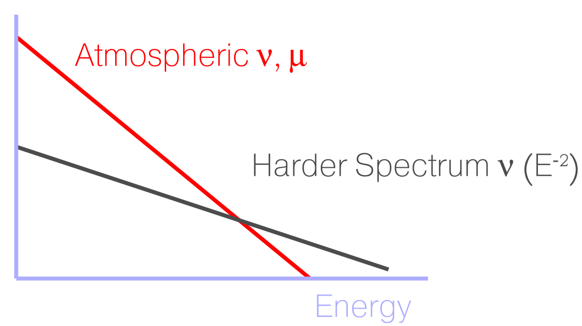
Expect hard spectrum 2.0 – 2.4 (production as shock acceleration)

advantage over point-source search: **can detect weaker fluxes**

but: **higher background**

<u>Signature</u>:

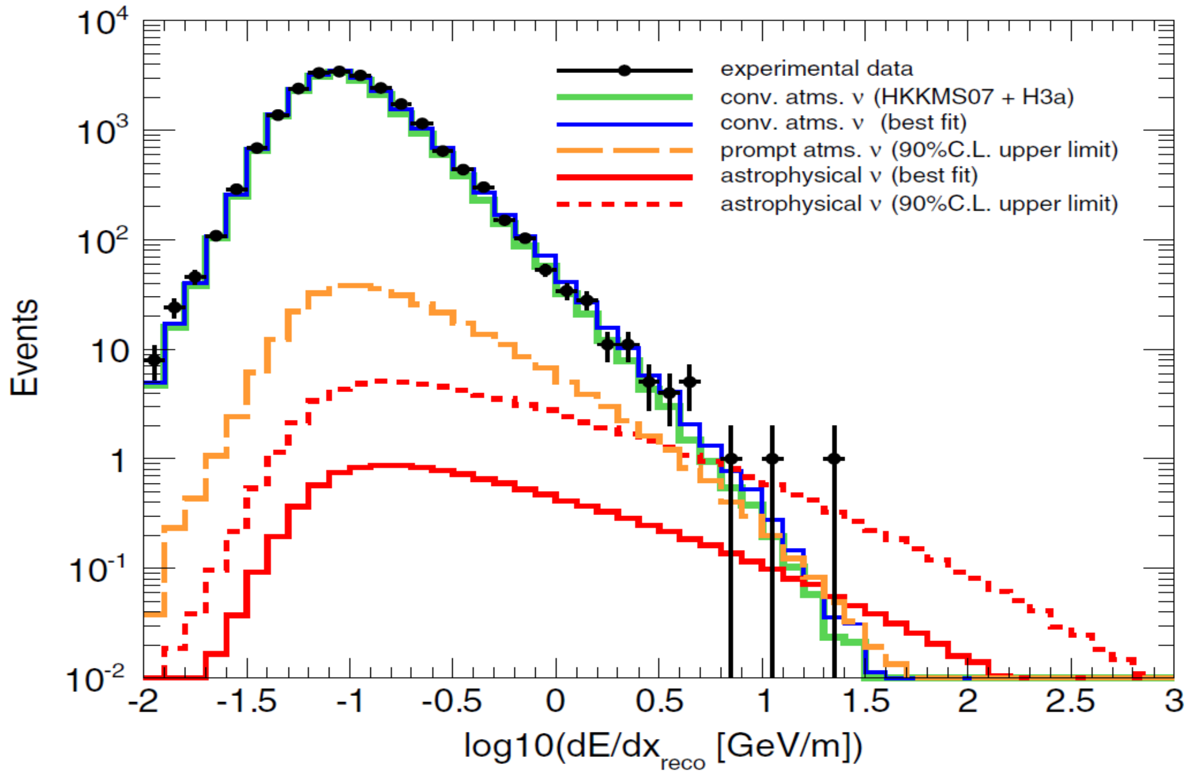
excess of high energy neutrinos over irreducible background of atmospheric neutrinos

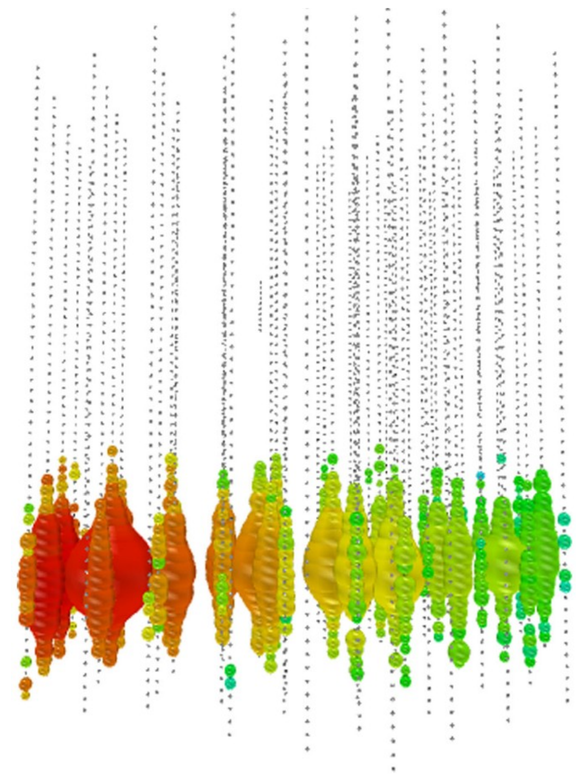


Search for a diffuse flux of astrophysical muon neutrinos with the IceCube 59-string configuration.

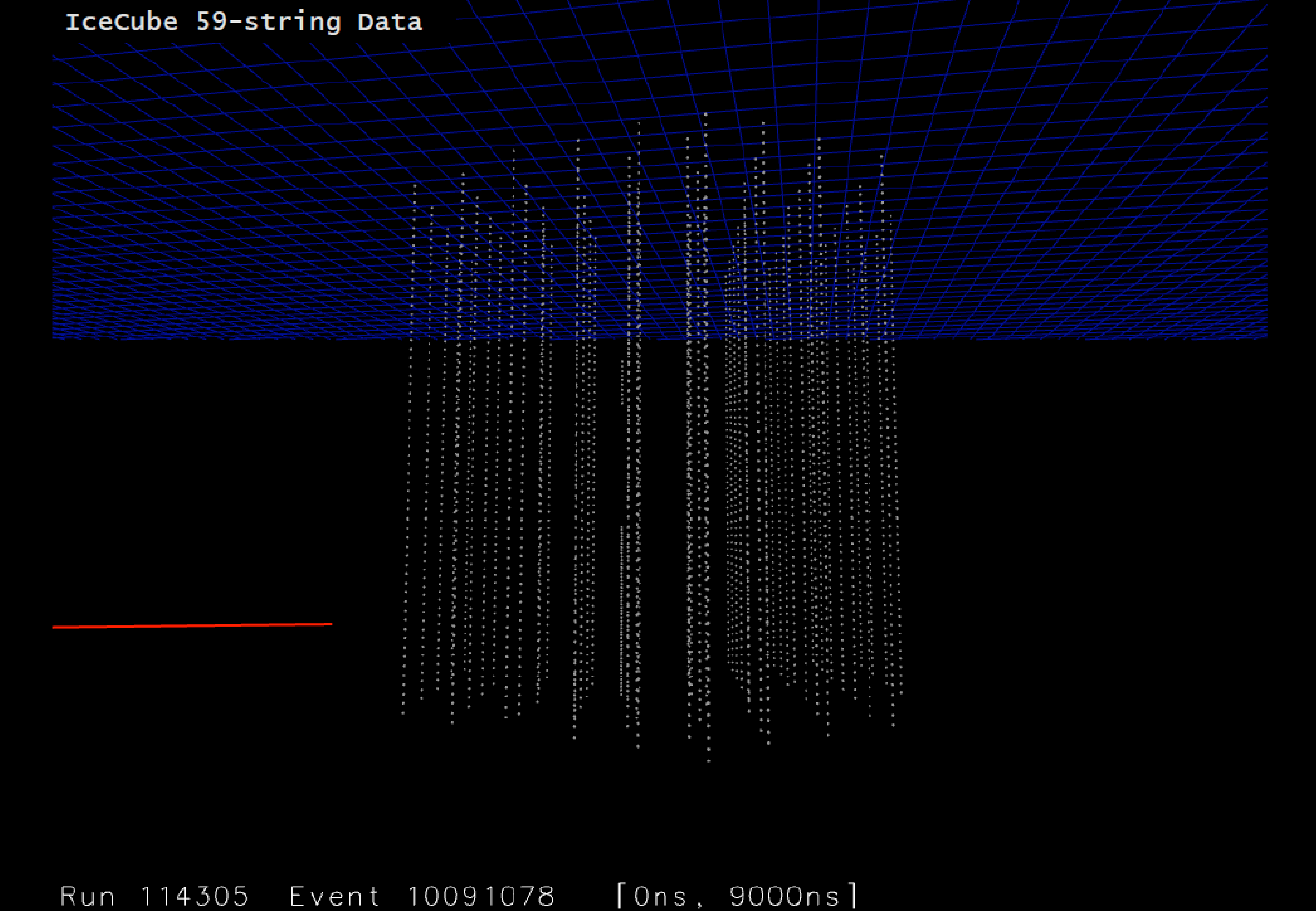
(Phys. Rev. D 89, 062007 (2014))

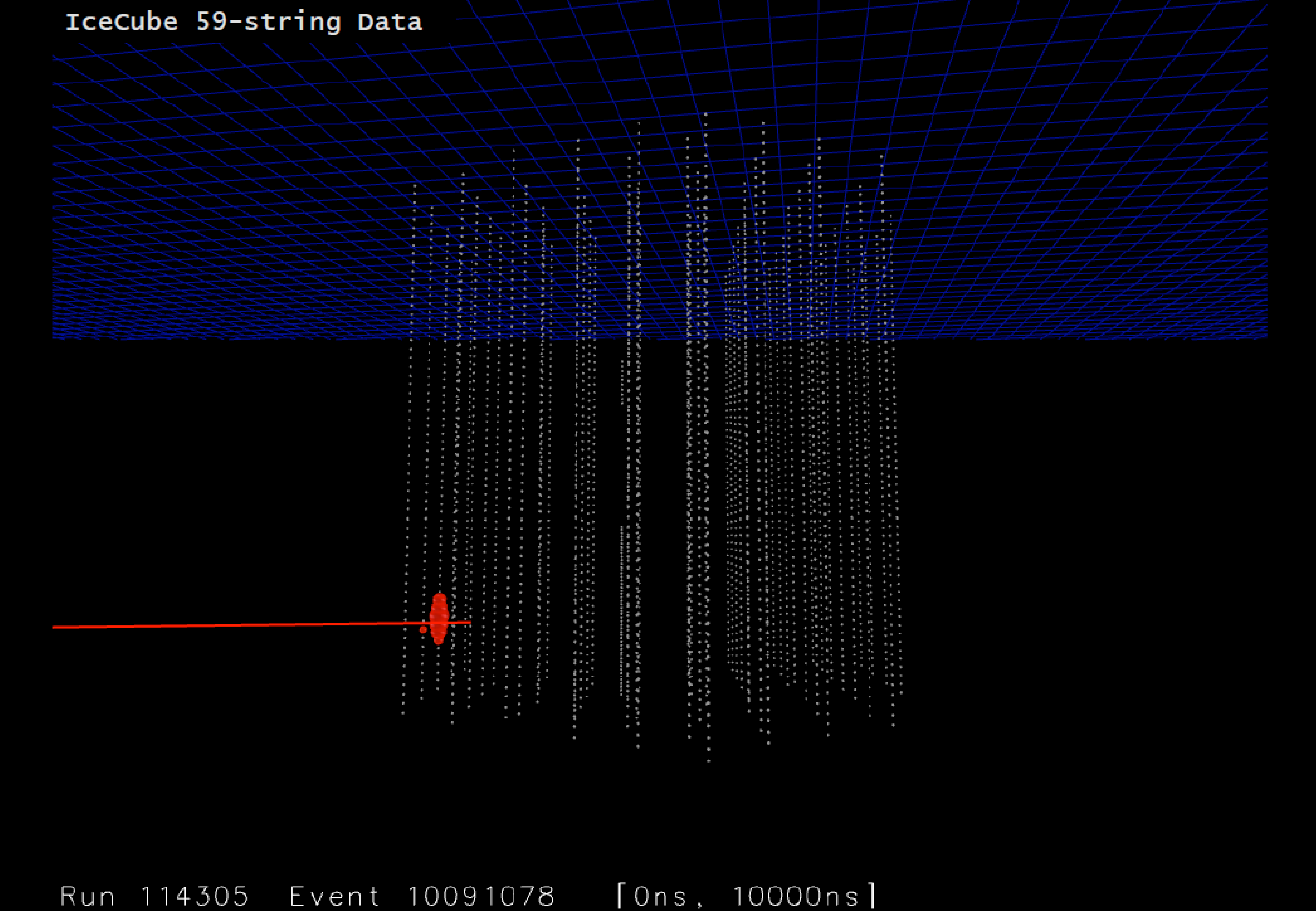
high-energy excess of 1.8σ compared to the background scenario of a pure conventional atmospheric model.

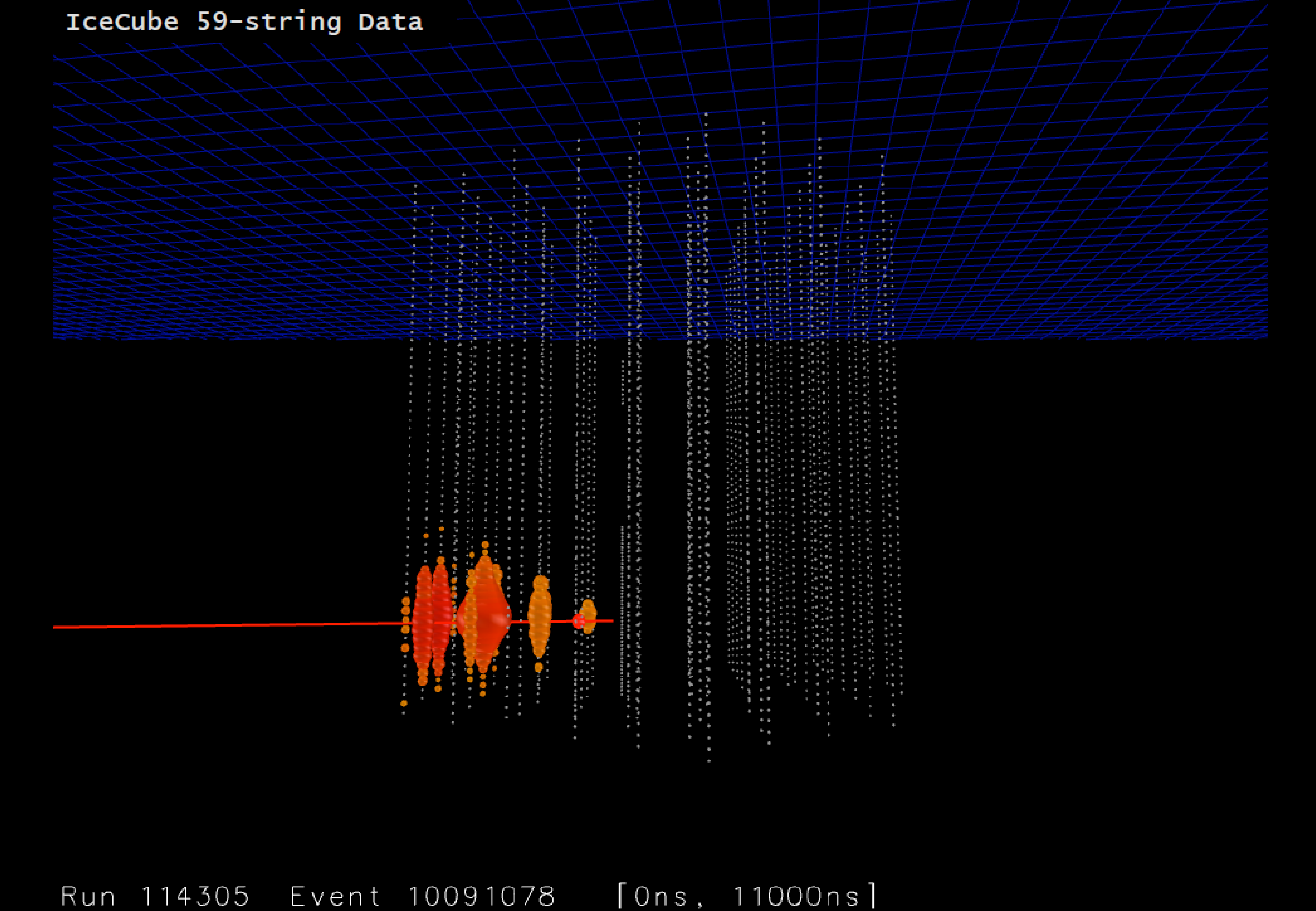


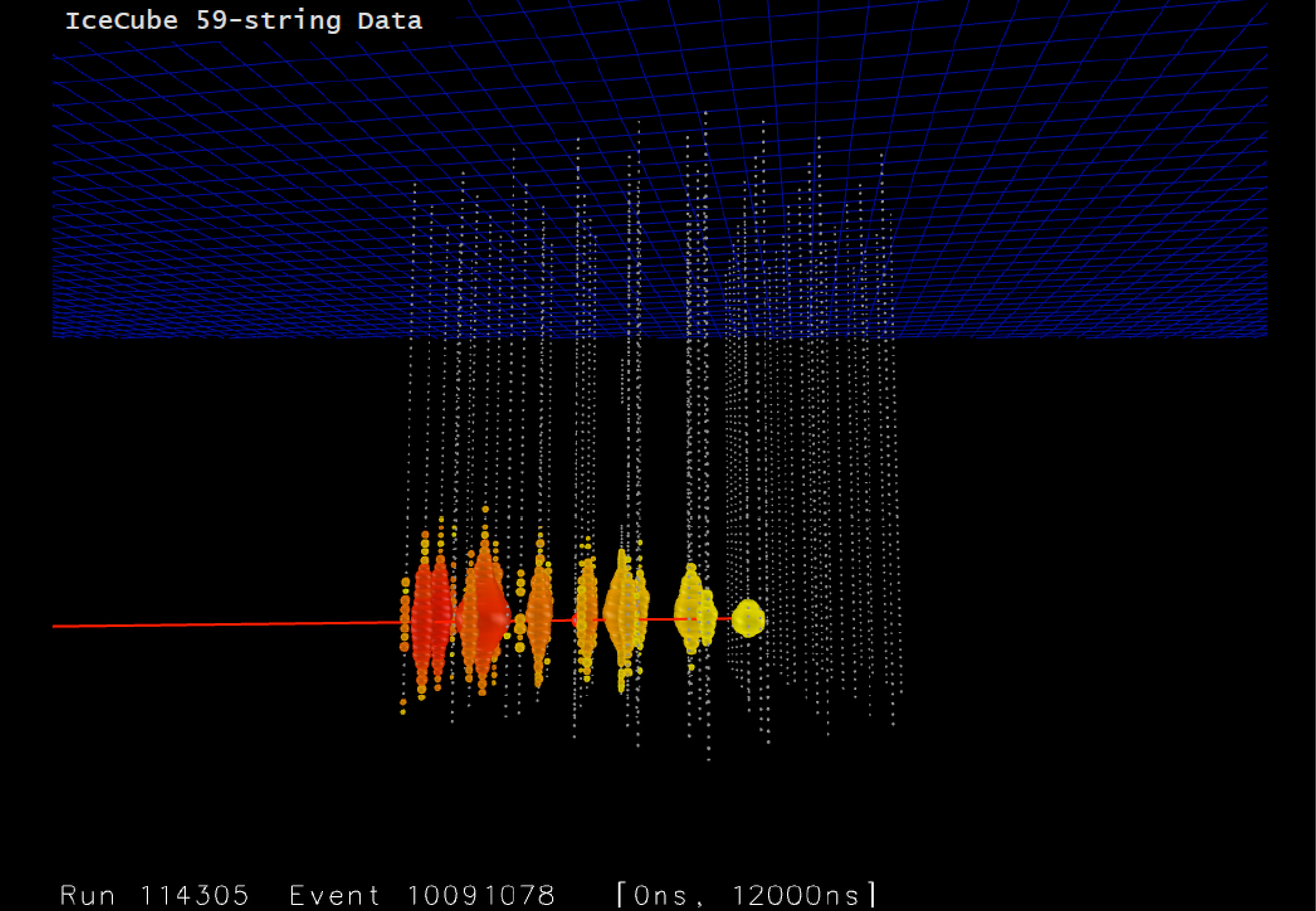


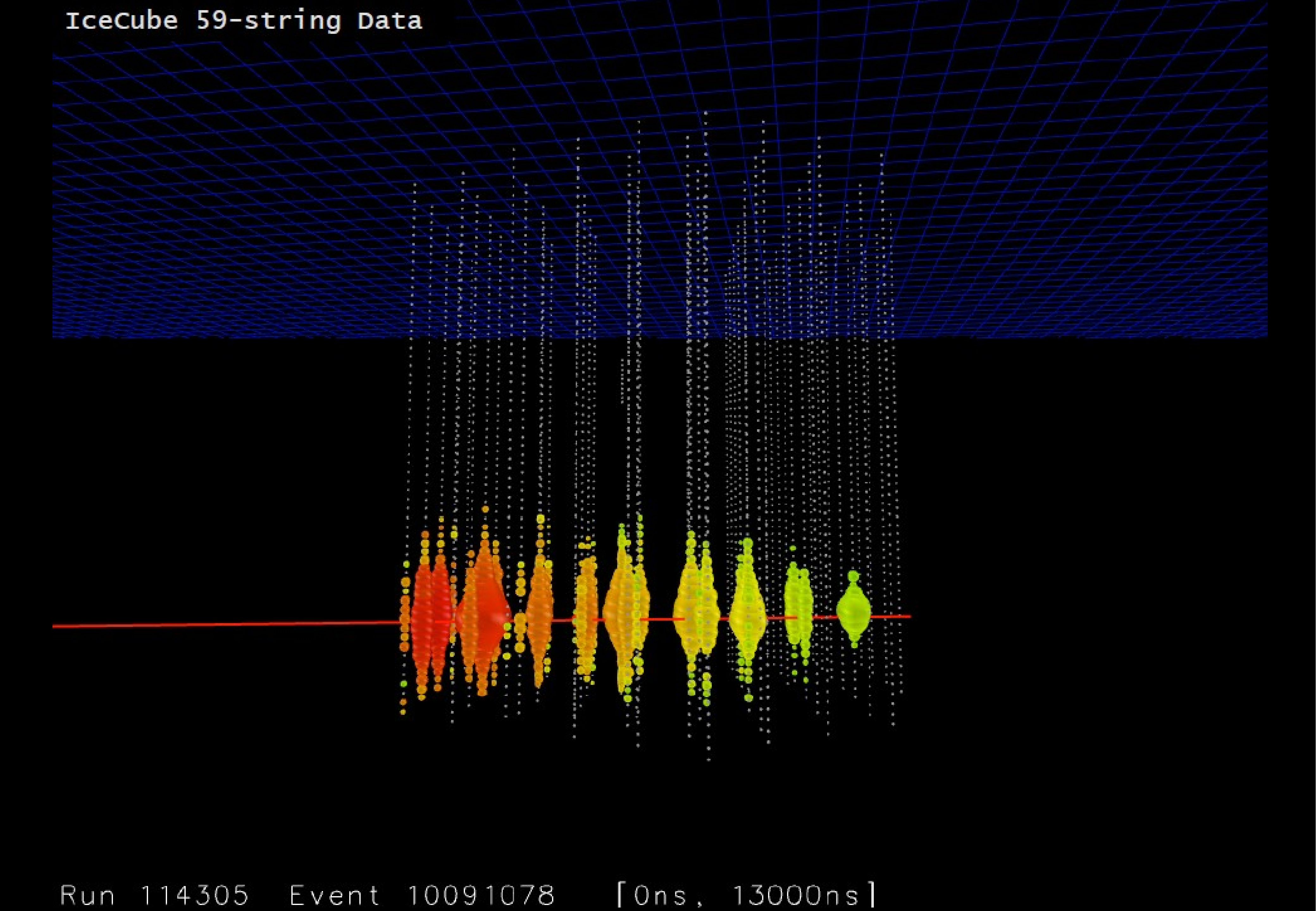
limit to a E^{-2} $\nu_\mu + \bar{\nu}_\mu$ flux: $0.25 \times 10^{-8}\ E^{-2}\ GeV\ cm^{-2}\ s^{-1}\ sr^{-1}$

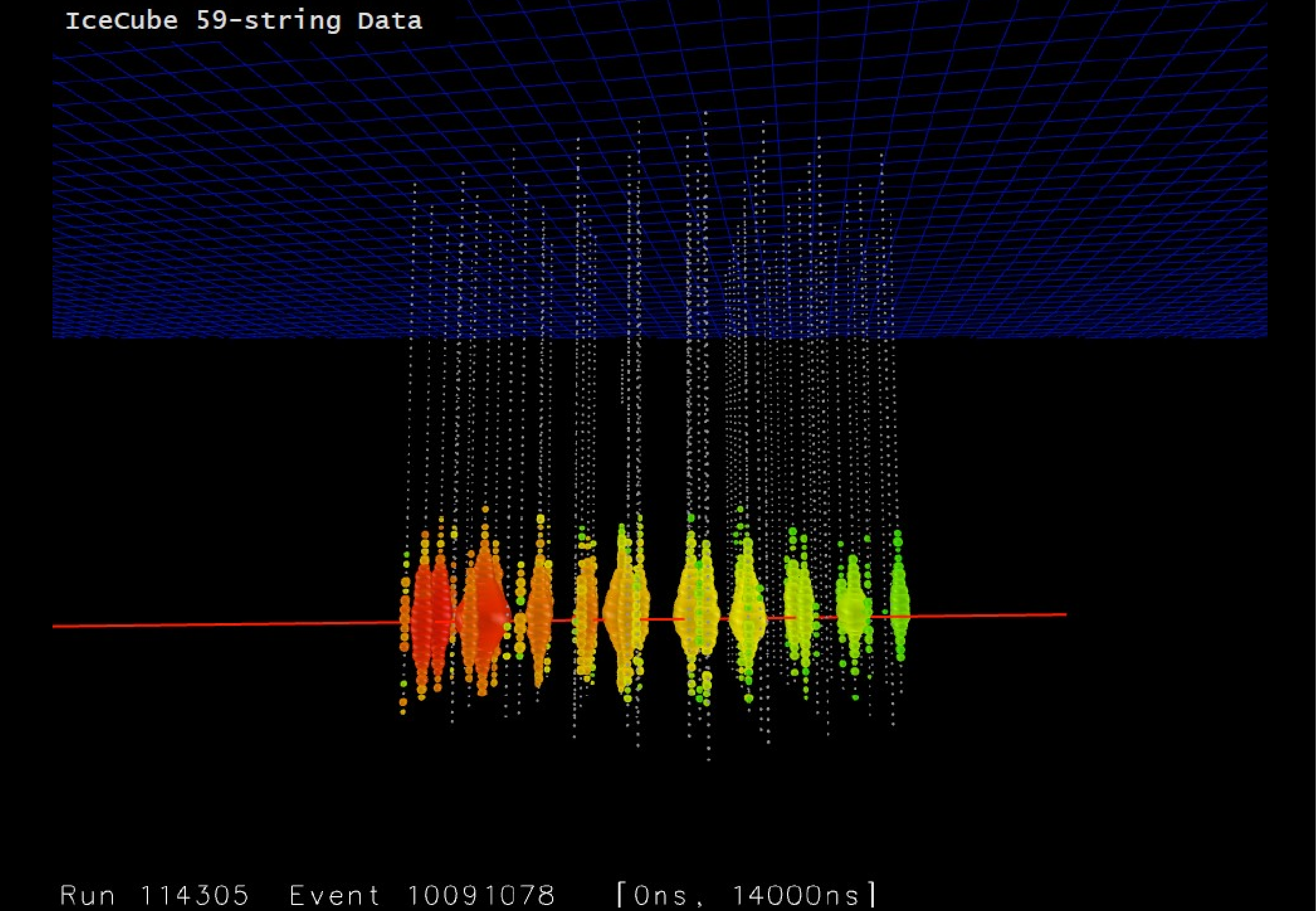

IceCube 59-string Data
Run 114305   Event 10091078   [0ns, 9000ns]

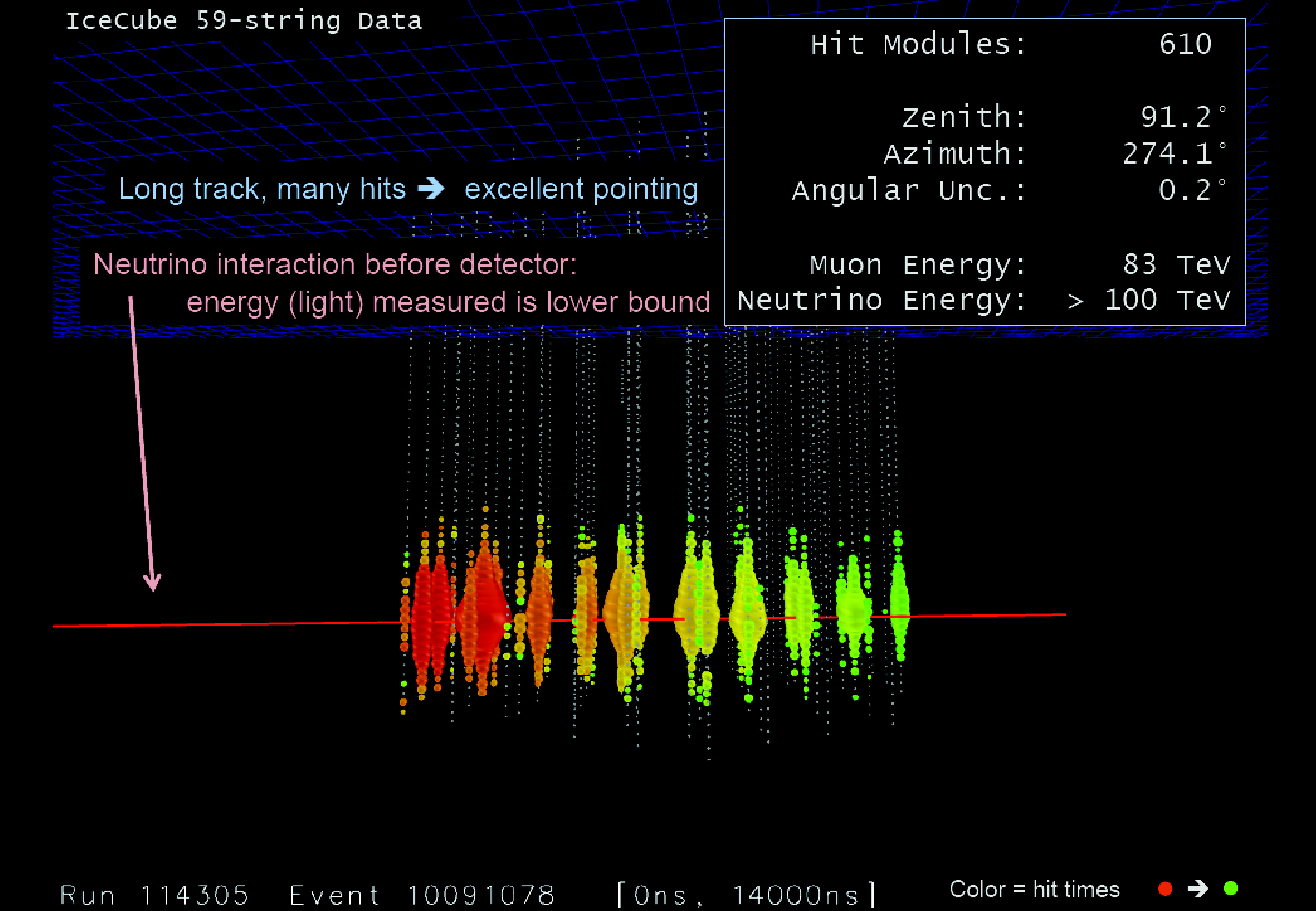

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 10000ns]


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 11000ns]


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 12000ns]


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 13000ns]


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 14000ns]

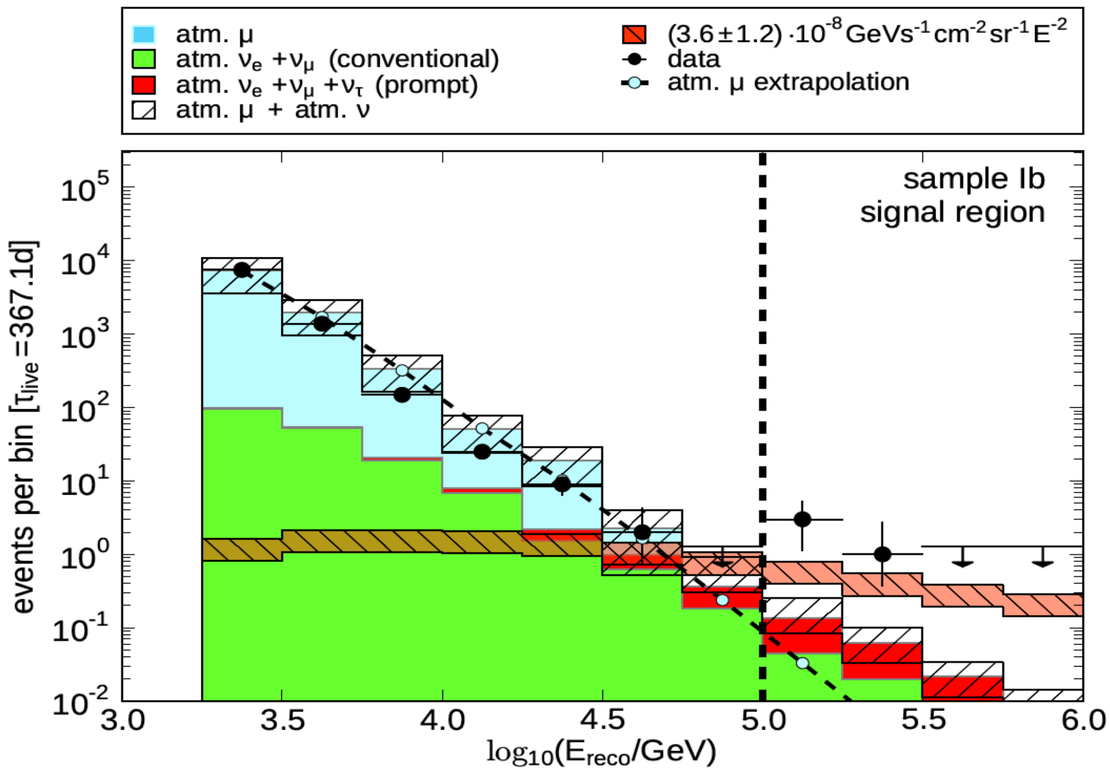


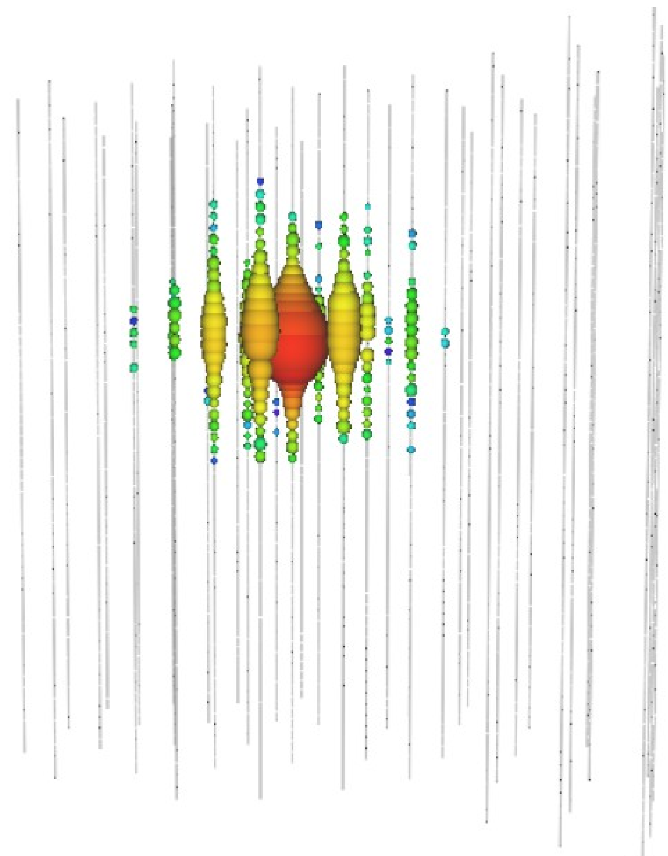
IceCube 59-string Data
Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV
Long track, many hits → excellent pointing
Neutrino interaction before detector:
energy (light) measured is lower bound
Run 114305 Event 10091078 [0ns, 14000ns]
Color = hit times

Search for neutrino-induced particle showers with IceCube-40

(Phys. Rev. D 89, 102001 (2014))

high-energy excess of 2.7σ compared to the background scenario of a pure conventional atmospheric model.





limit to a E^{-2} all-flavor flux: 7.46×10^{-8} E^{-2} *GeV cm^{-2} s^{-1} sr^{-1}* (between 25 TeV and 5 PeV)

search for UHE neutrinos: first observation of PeV neutrino events

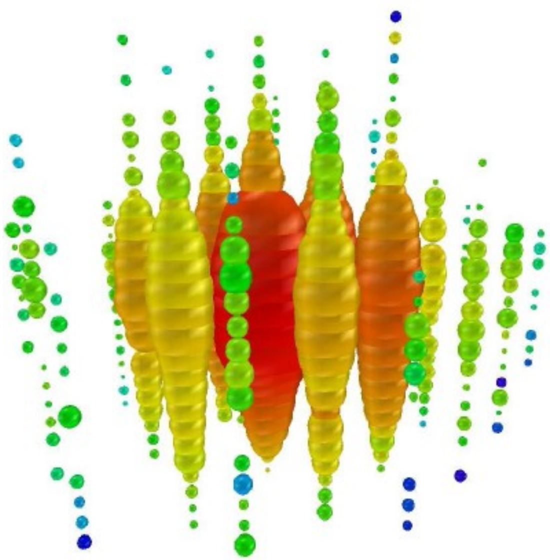
search for high energy (>1PeV neutrinos): little expected background → simplifies the analysis

Analysis based on a few cuts on deposited charge and event reconstruction quality

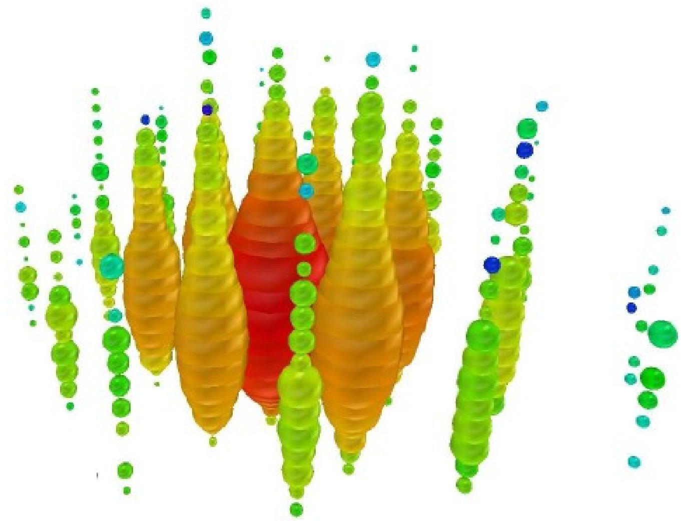
2 events in 672.7 days between May 2010- May 2012,

0.08 events expected from atm μ + atm ν (including charm)

significance (over background-only hypothesis): 2.8σ

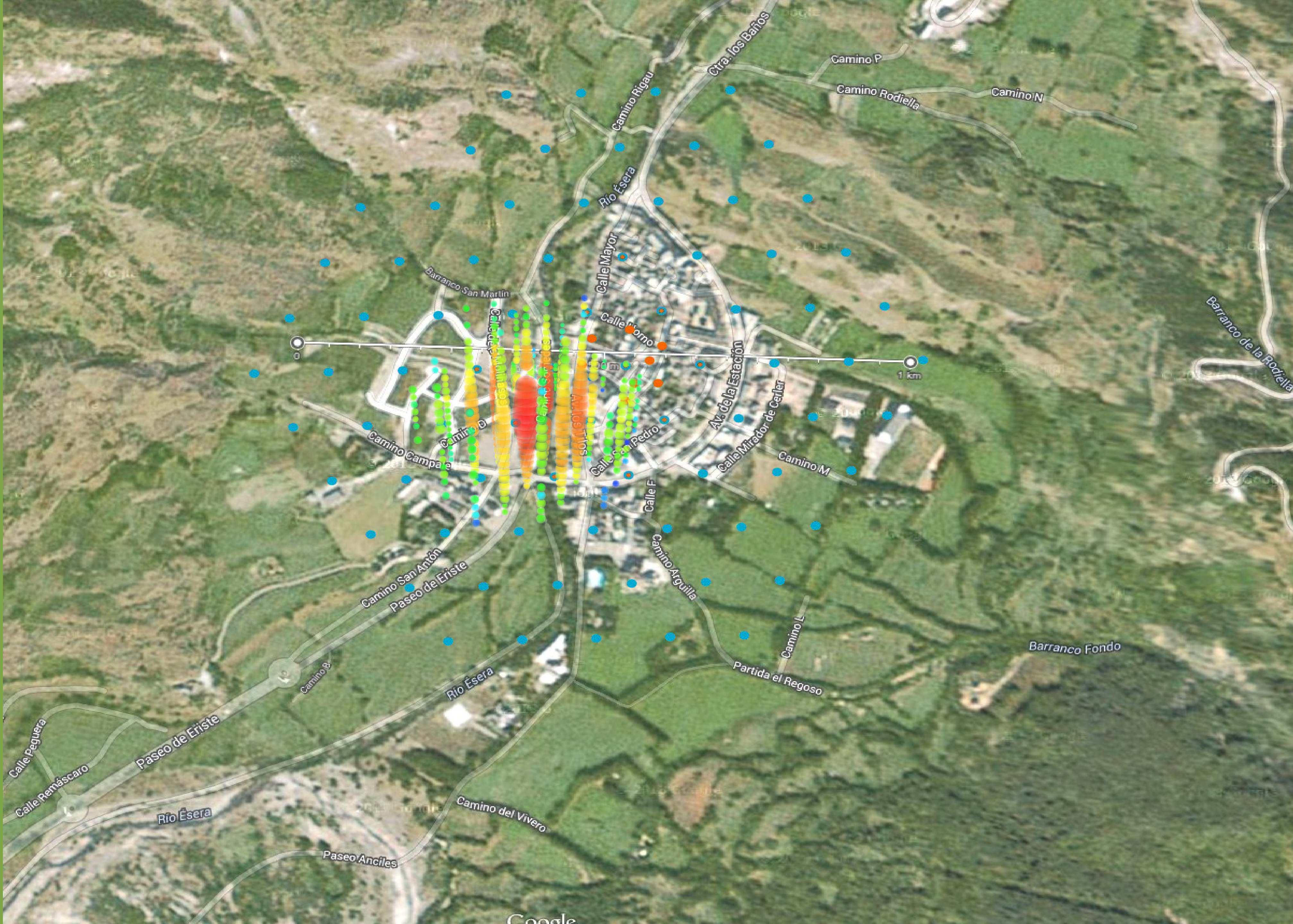


Aug. 8, 2011
Npe 6.992×10^4
N_{DOM} 354



Jan 3, 2012
Npe 9.628×10^4
N_{DOM} 312

deposited energy: 1.04 PeV 1.14 PeV (~15% uncert)

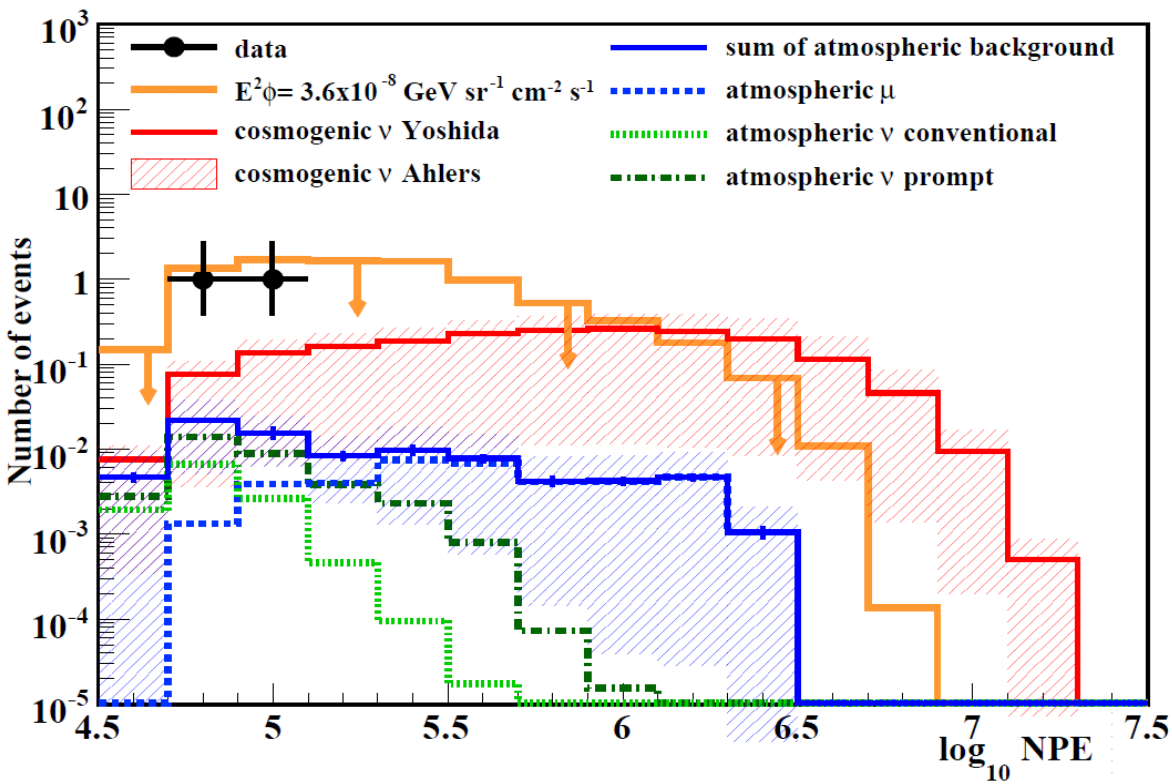

Ctra. los Baños
Camino P
Camino Rodiella
Camino N
Camino Rigau
Río Ésera
Calle Mayor
Barranco San Martín
Barranco de la Rodiella
0
1 km
Av. de la Estación
Calle Mirador de Cerler
Camino M
Calle F
Camino Arguilla
Camino San Antón
Paseo de Eriste
Camino L
Barranco Fondo
Partida el Regoso
Camino B
Río Ésera
Calle Peguera
Calle Remáscaro
Paseo de Eriste
Río Ésera
Camino del Vivero
Paseo Anciles
Google

search for high energy (>1PeV neutrinos): little expected background → simplifies the analysis

Analysis based on a few cuts on deposited charge and event reconstruction quality

2 events in 672.7 days between May 2010- May 2012,
0.08 events expected from atm μ + atm ν (including charm)

significance (over background-only hypothesis): 2.8σ



there should be more if we lower the energy threshold!

What do we expect?

showers: only charge current ν_μ gives a track

all other flavours and interactions produce a shower at the vertex

mostly on the Southern sky

Earth absorbs high energy neutrinos

Backgrounds

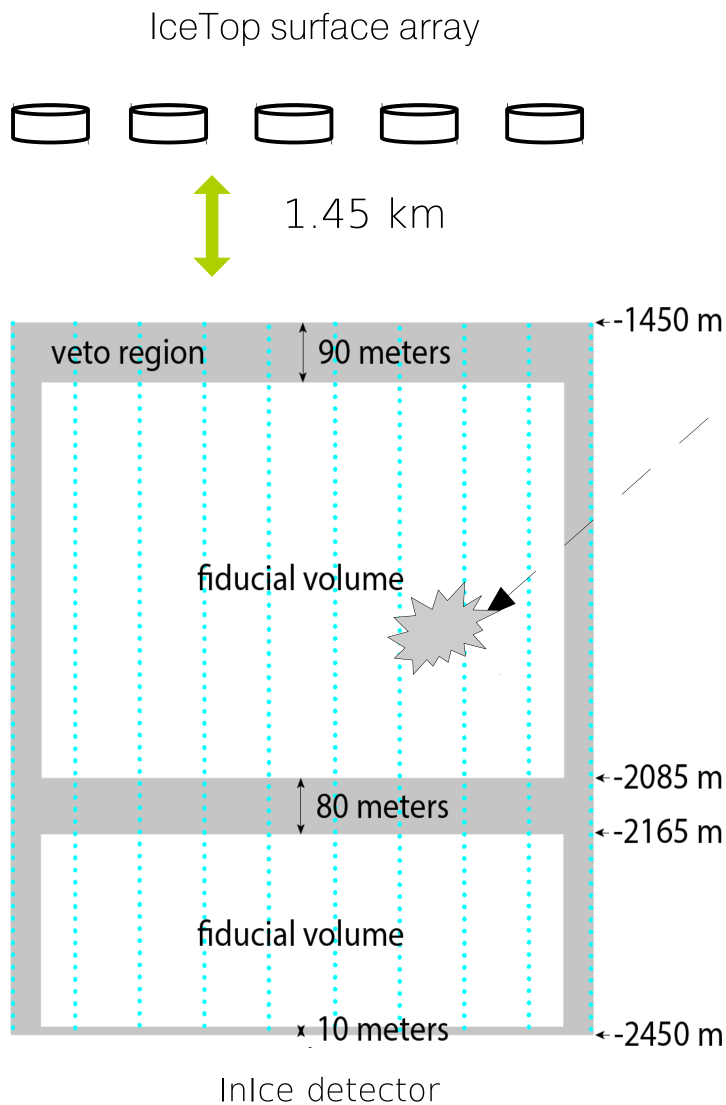
penetrating cosmic-ray muons which sneak through the veto and atmospheric neutrinos (reduced since we are looking at very high energies)

High-energy contained vertex search

Take advantage of completed, i.e. big, detector to define a veto:

- top 5 layers of modules (=90 m)
- bottom layer of modules (=10 m)
- outer layer of strings

- reject tracks entering the detector from outside (atmospheric μ's)



Requirements: All-sky

Challenge:
Atmospheric ν and μ background

Strategy:

Look for starting events in the detector

→ these must be neutrinos!!!

High-energy contained vertex search: strategy

- Explicitly aim at high energies: cut on Npe> 6000

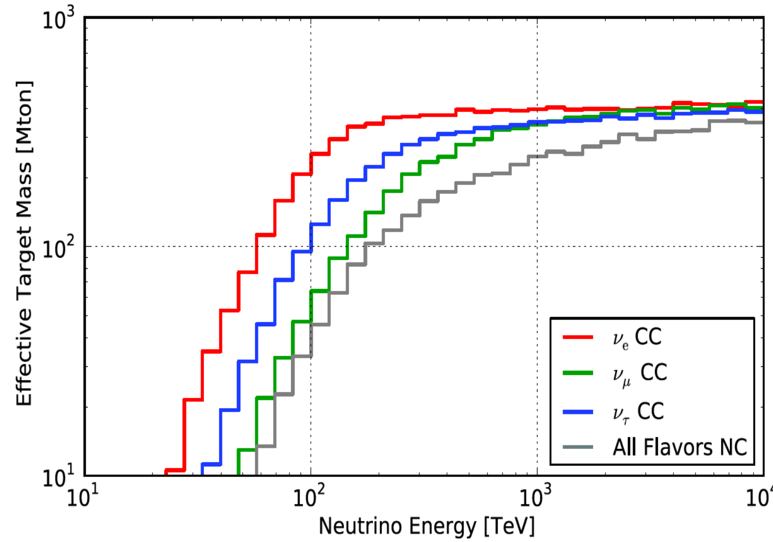
- 400 Mton effective fiducial volume

- Sensitive to all flavors above 60 TeV

- Estimate atmospheric muon background from data

  .reject incomming muons when there is early charge deposited in the veto region

  .estimate remaining background by "inverted" early-charge cut:
    i) require signal in outer veto layer,
    ii) see efficiency of next layer to detect muon



- Atmospheric neutrino background low at PeV energies, ~0.1 events/year

- Use IceTop information to reject events, even if starting (atmospheric ν's from an air shower)

High-energy contained vertex search: results

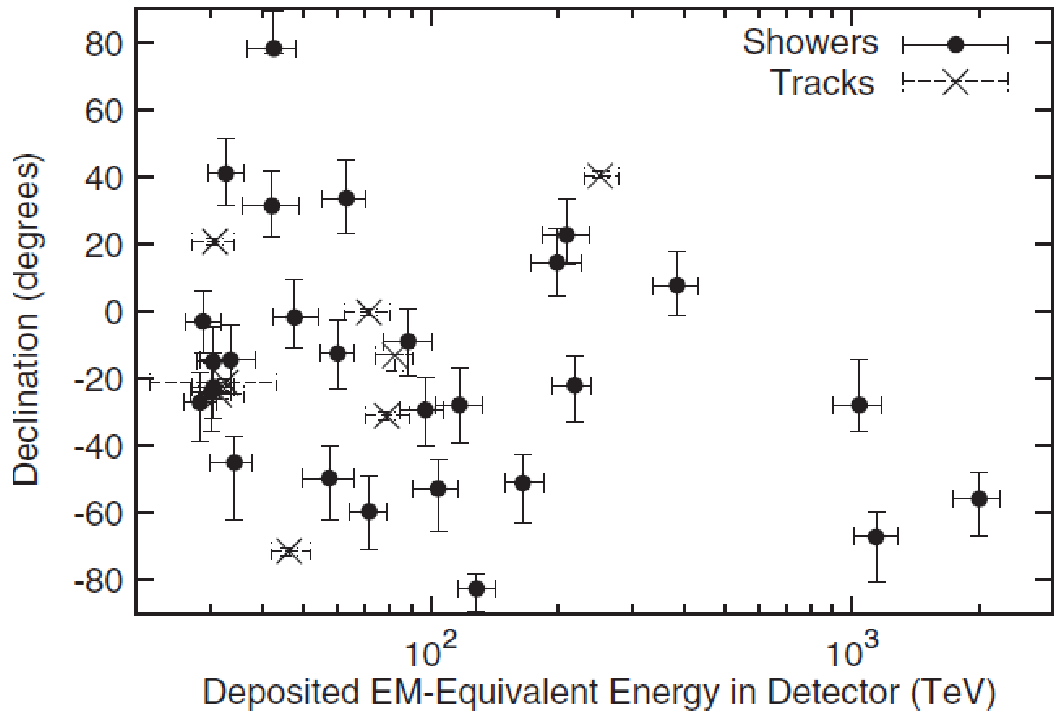
36 events in three years of data,
998 days between 2010 and 2013
(they contain the first two PeV events)

8 tracks
28 cascades

estimated background:

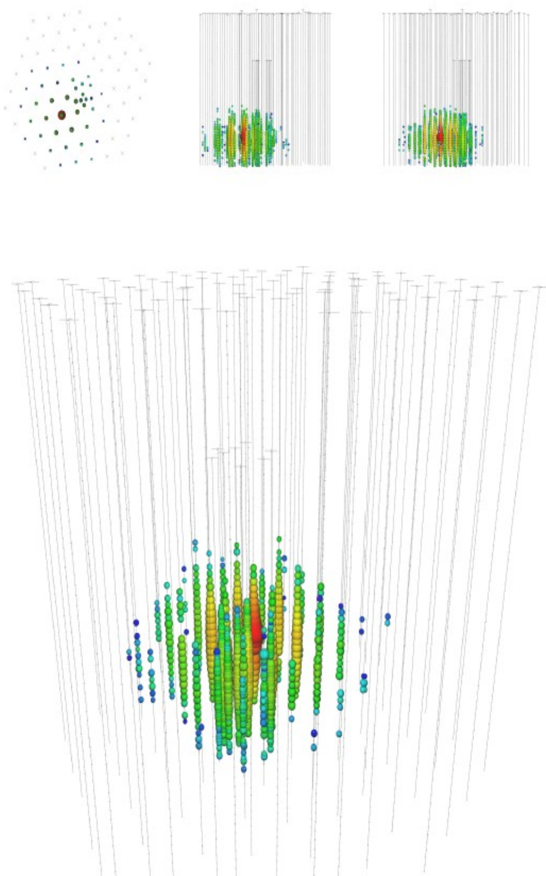
6.6 $^{+5.9}_{-1.6}$ atmospheric neutrinos

8.4 ± 4.2 atmospheric muons

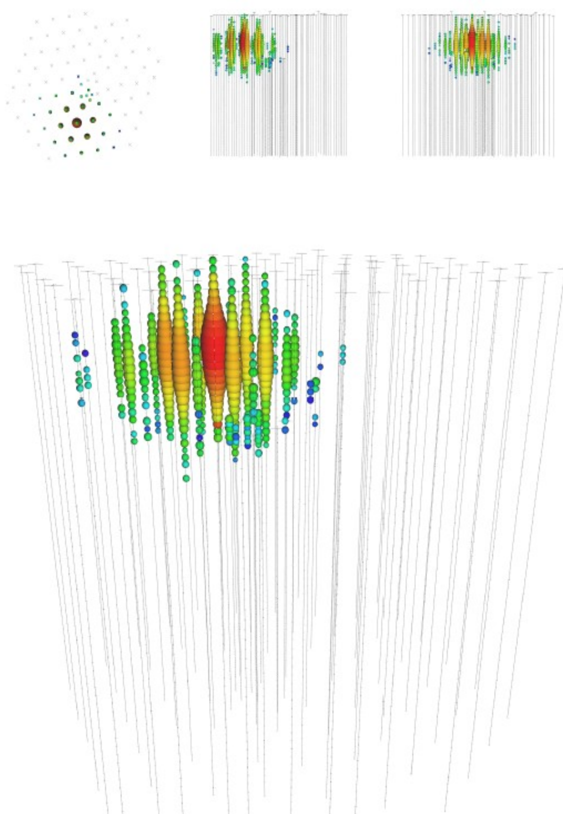


significance (over background-only hypothesis): 5.7σ

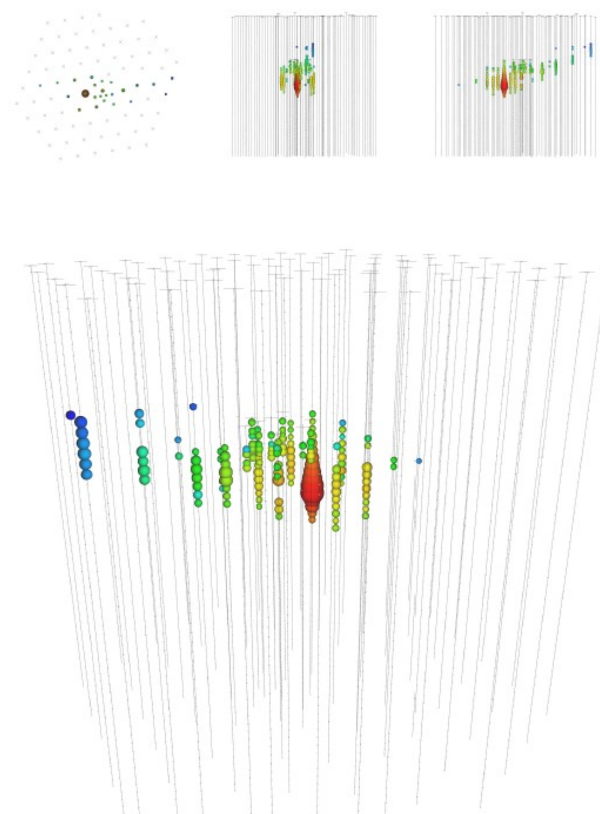
High-energy contained vertex search: some examples



deposited energy 129 TeV
Dec, RA: -92,7°, 103.2°

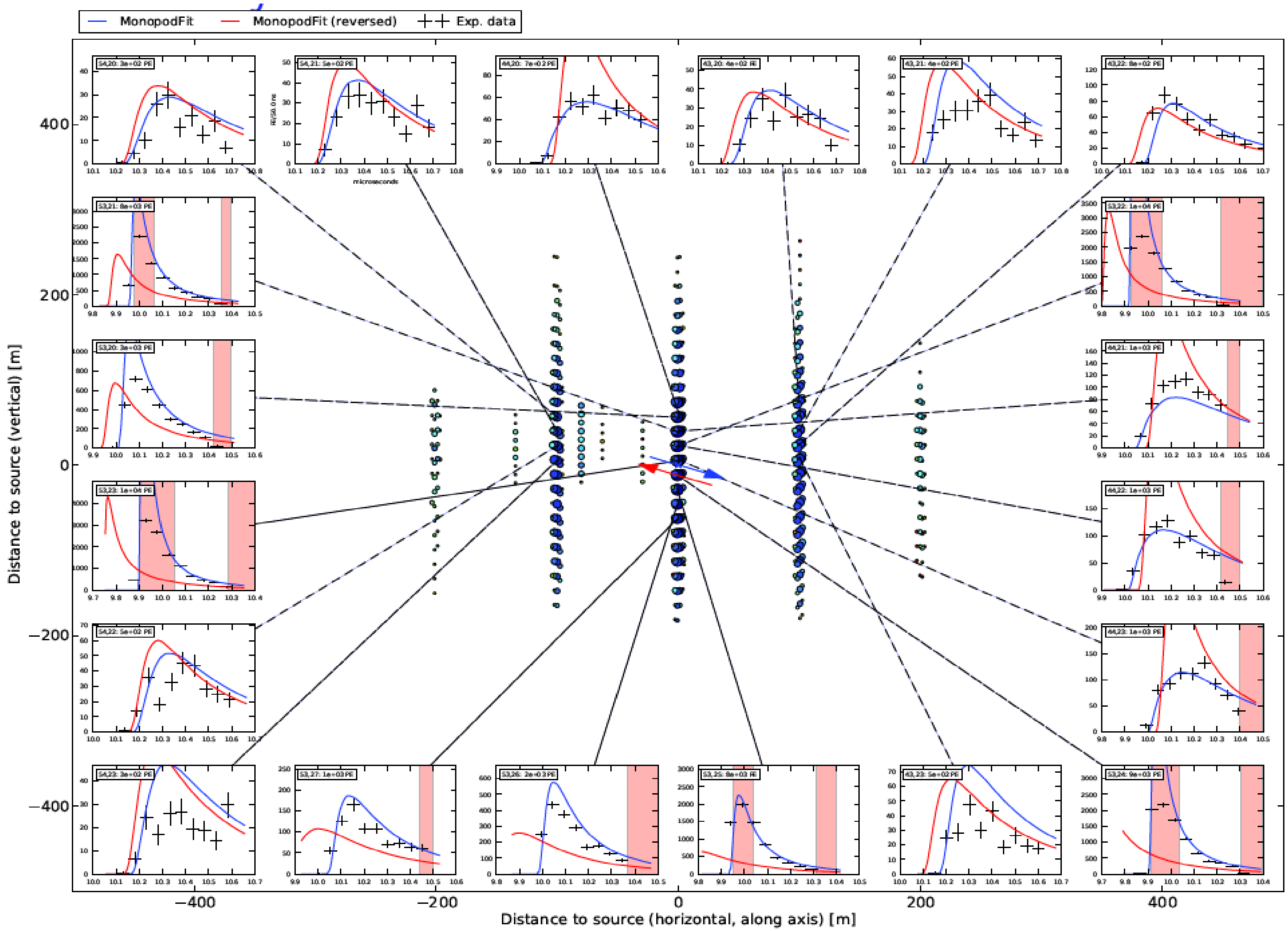


deposited energy 2004 TeV
Dec, RA: -55.8°, 208.4°



deposited energy 31 TeV
Dec, RA: 20.7°, 167.3°

observation of PeV events: sanity checks



Time residual distributions

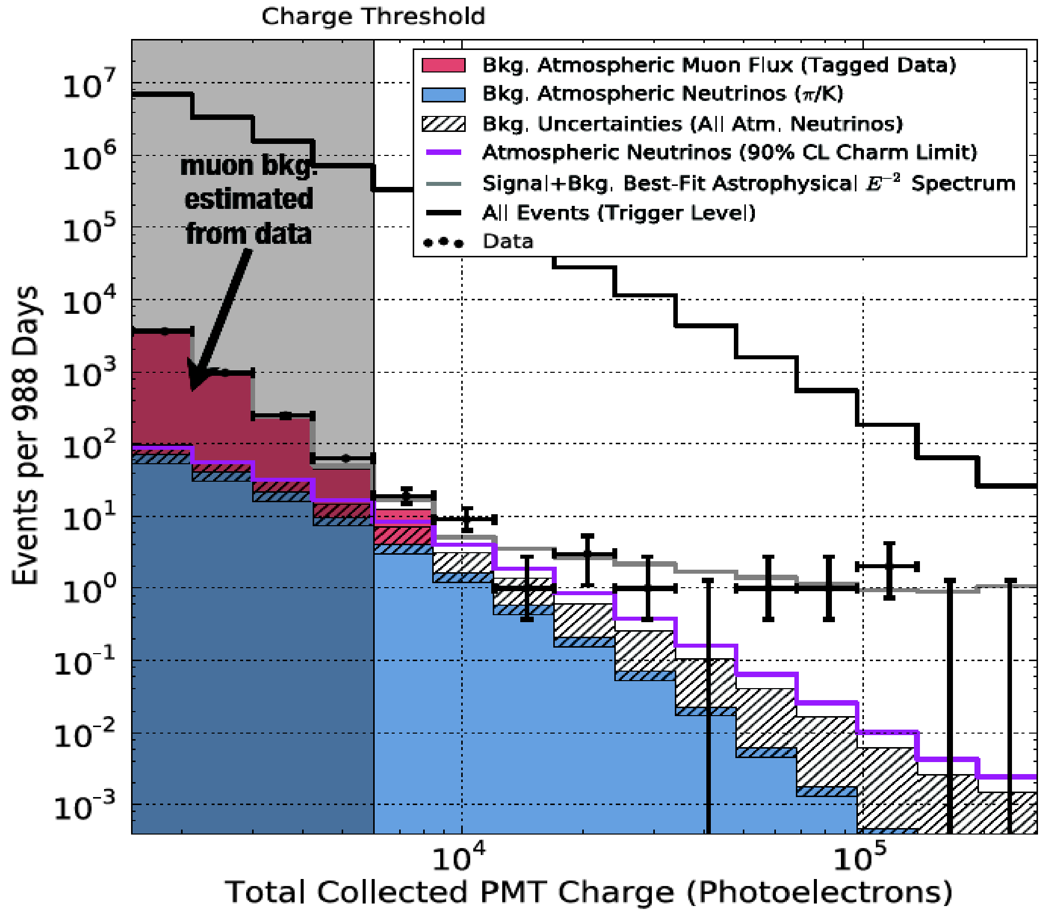
best cascade fit
reversed orientation for illustrative purpose

High-energy contained vertex search: charge distribution

Fits well to the atmospheric muon background predicted at low energies (total charge below 6000 pe)

Hatched region represents expected background fom conventional and prompt atmospheric neutrino flux

Harder than expected spectrum at high energies

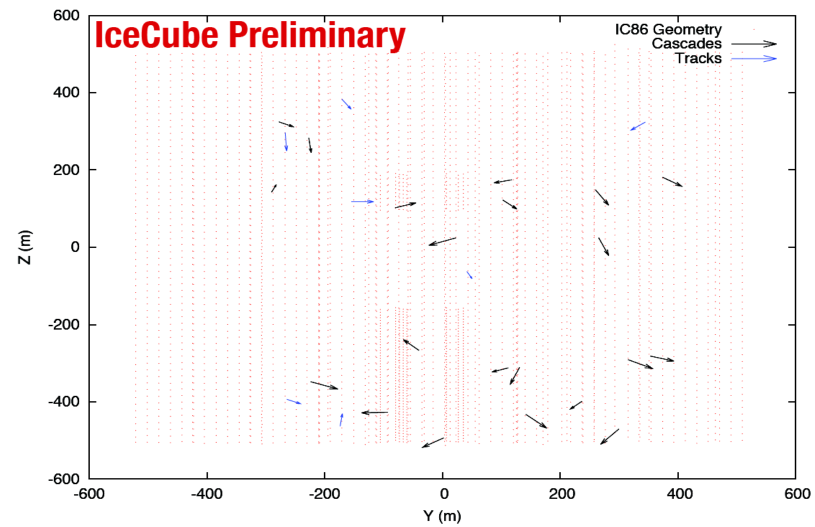


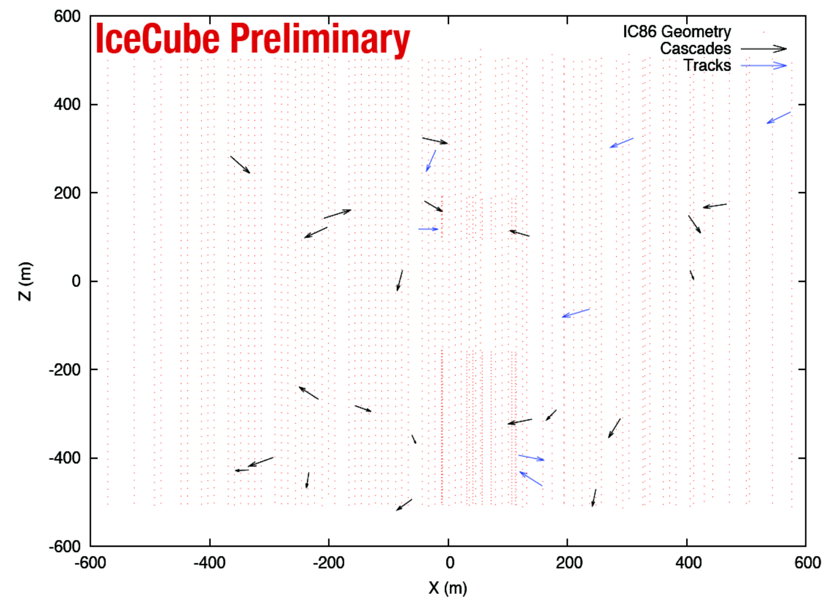
best fit to a E^{-2} flux: $0.95 \pm 0.3\ 10^{-8}\ E^{-2}$ *GeV cm^{-2} s^{-1} sr^{-1}*

High-energy contained vertex search: distribution in detector

Events uniformly distributed in location and direction over the detector volume

Background from sneaking atmospheric muons will cluster on detector boundaries. No such effect observed

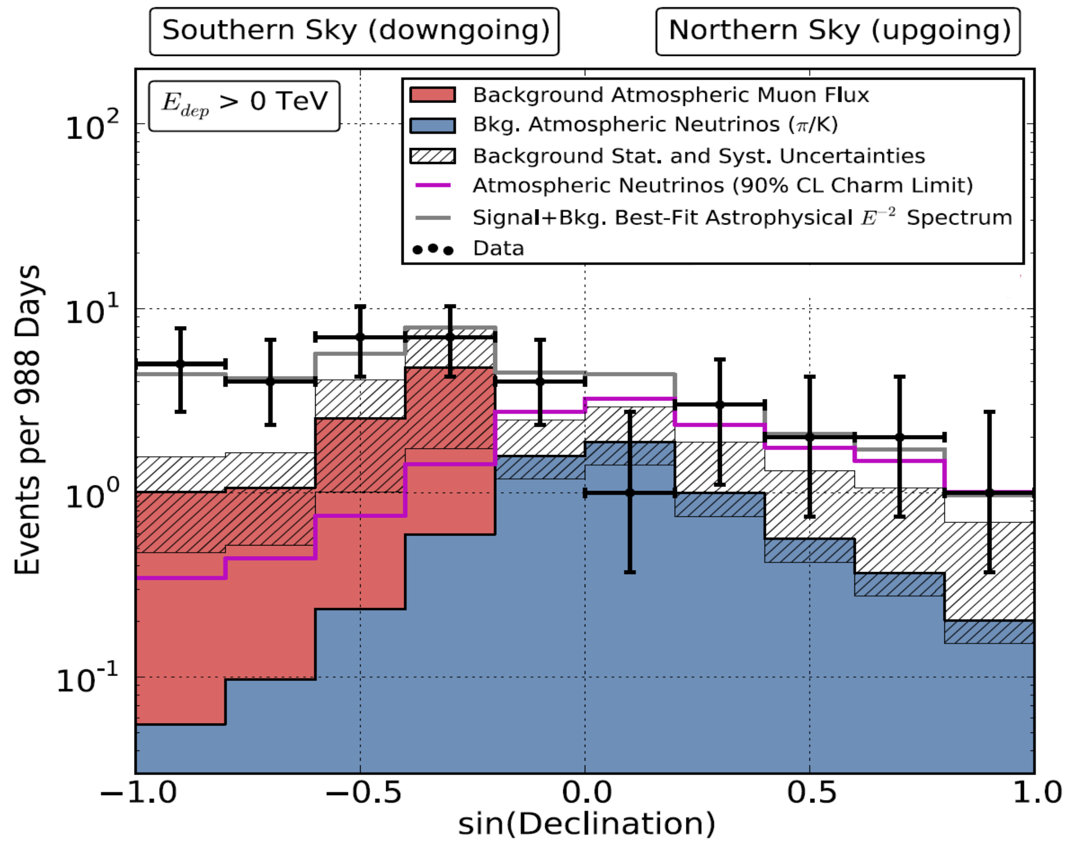




High-energy contained vertex search: angular distribution

compatible with isotropic flux

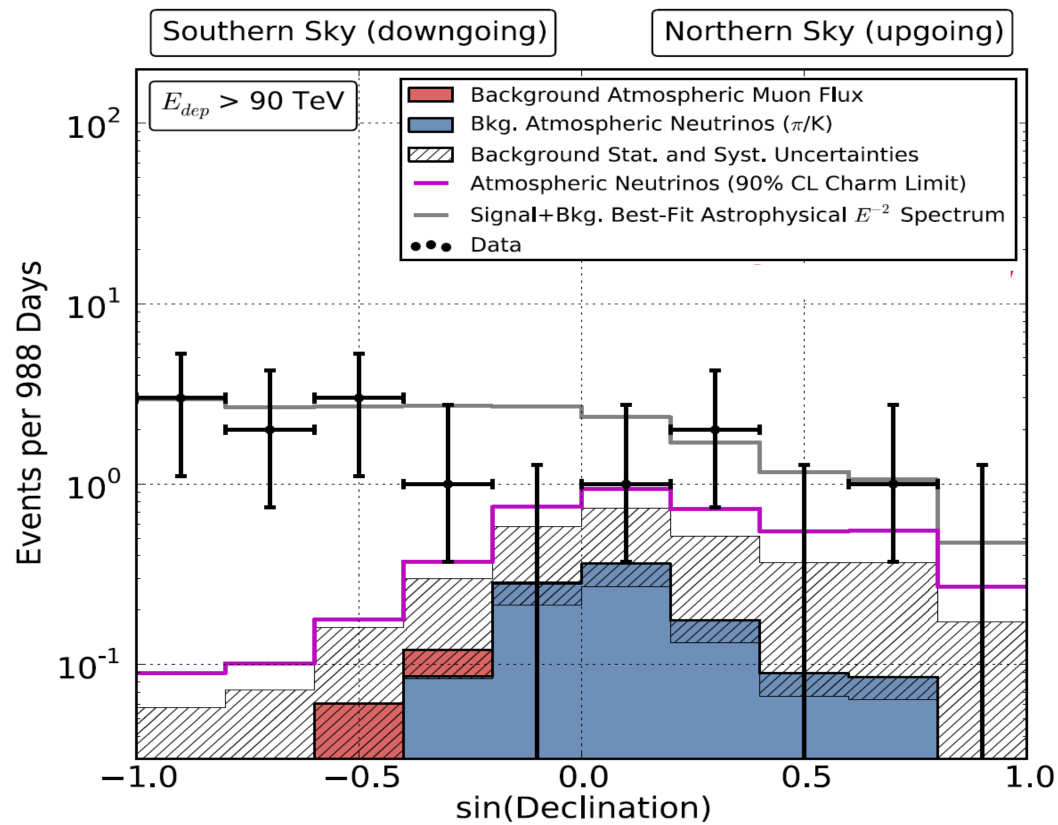
Earth absorption noticeable for events coming from the northern hemisphere



High-energy contained vertex search: angular distribution

compatible with isotropic flux

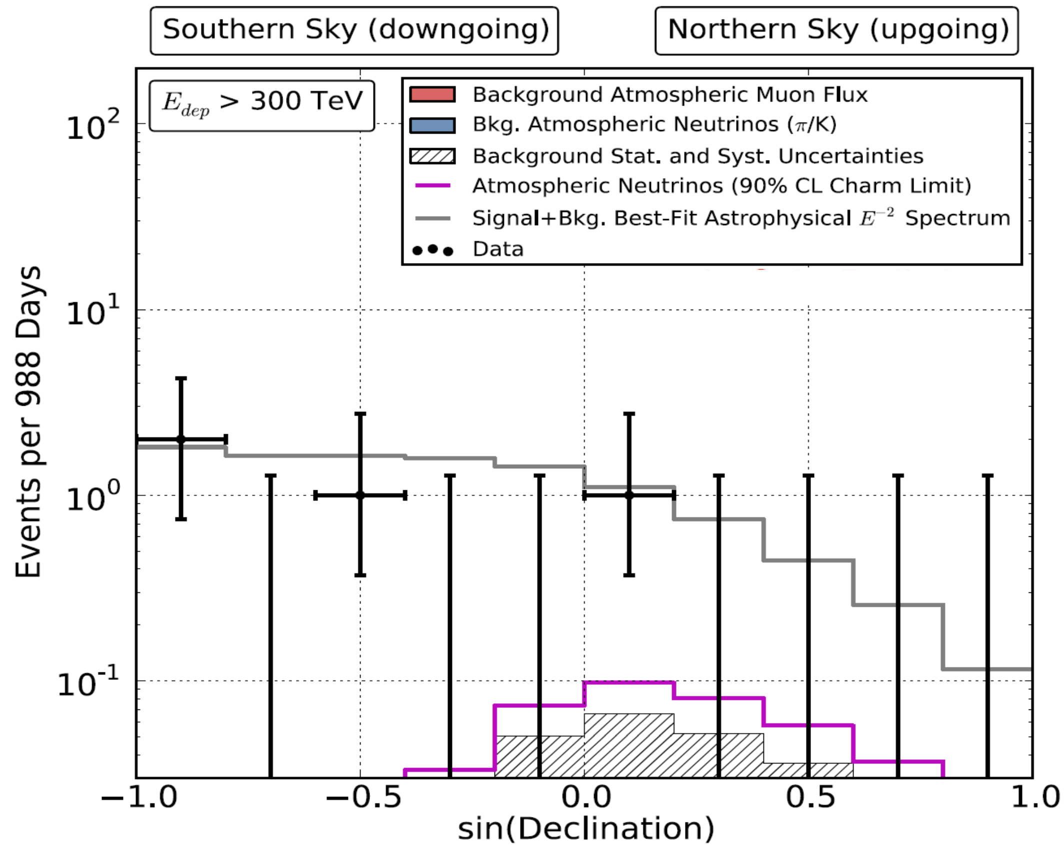
Earth absorption noticeable for events coming from the northern hemisphere



High-energy contained vertex search: angular distribution

compatible with isotropic flux

Earth absorption noticeable for events coming from the northern hemisphere



High-energy contained vertex search: skymap

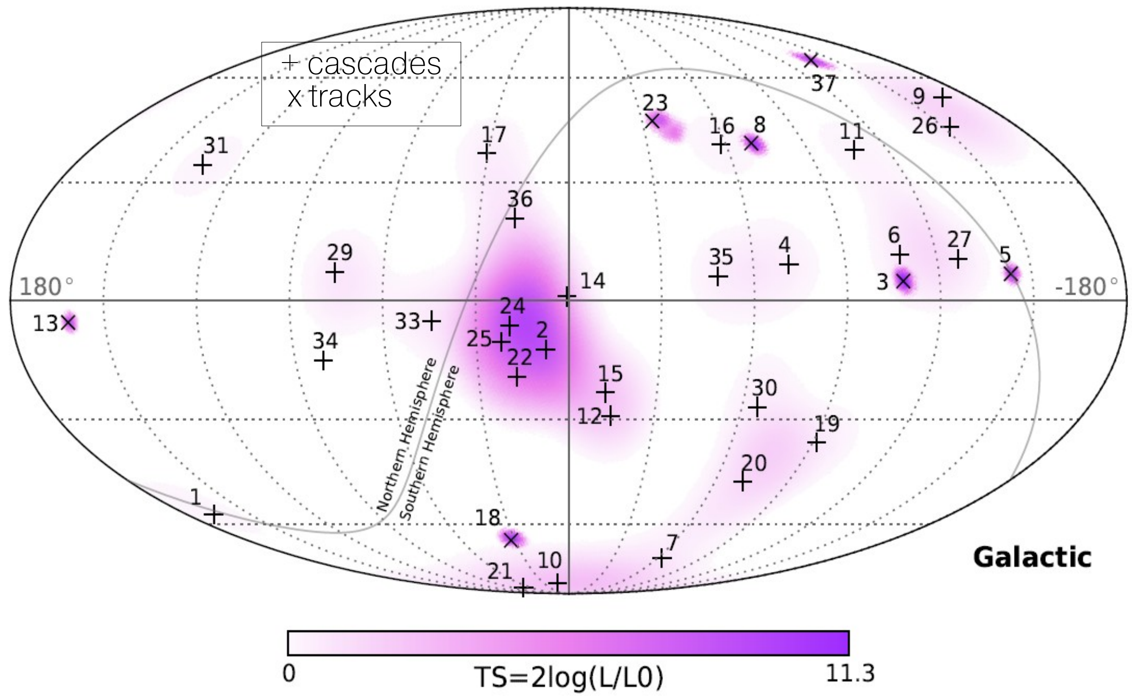
Compatible with isotropic flux

Most significant excess close
(not at) the Galactic Center

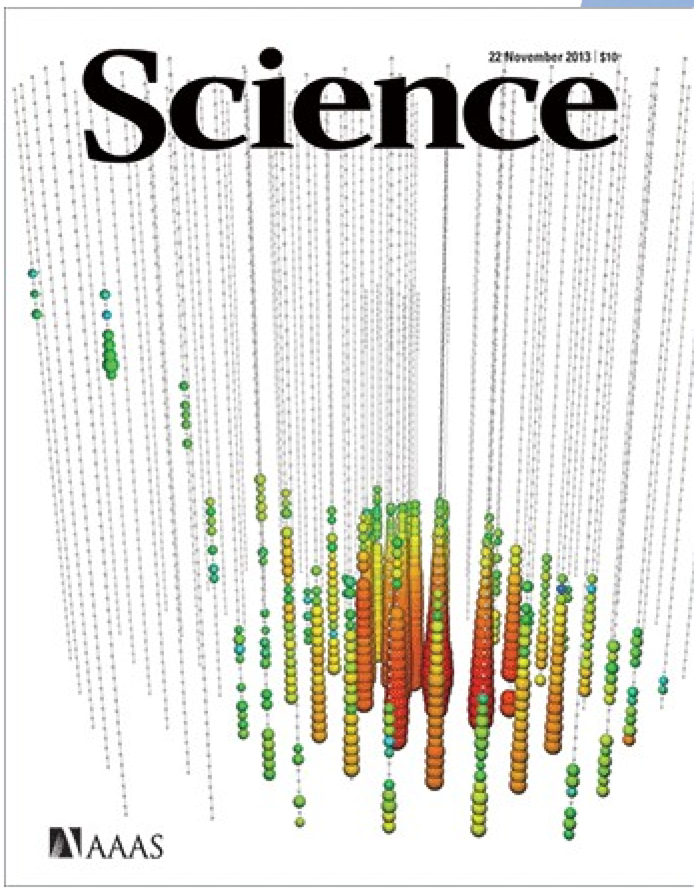
Only 7% significance
(bad pointing of cascades)

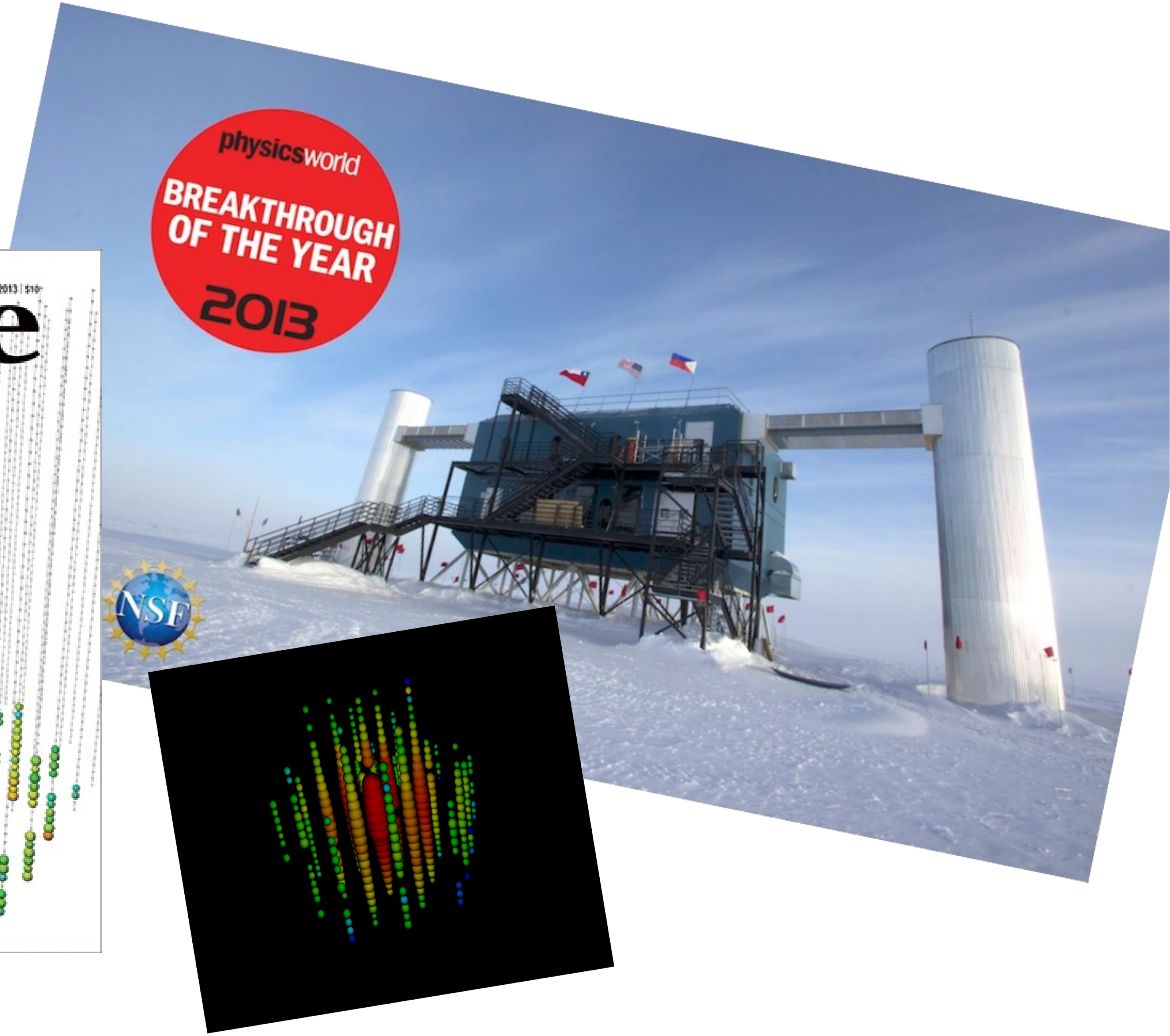
Searches for correlation with GRBs, the galactic plane or time clustering do not find any significance either

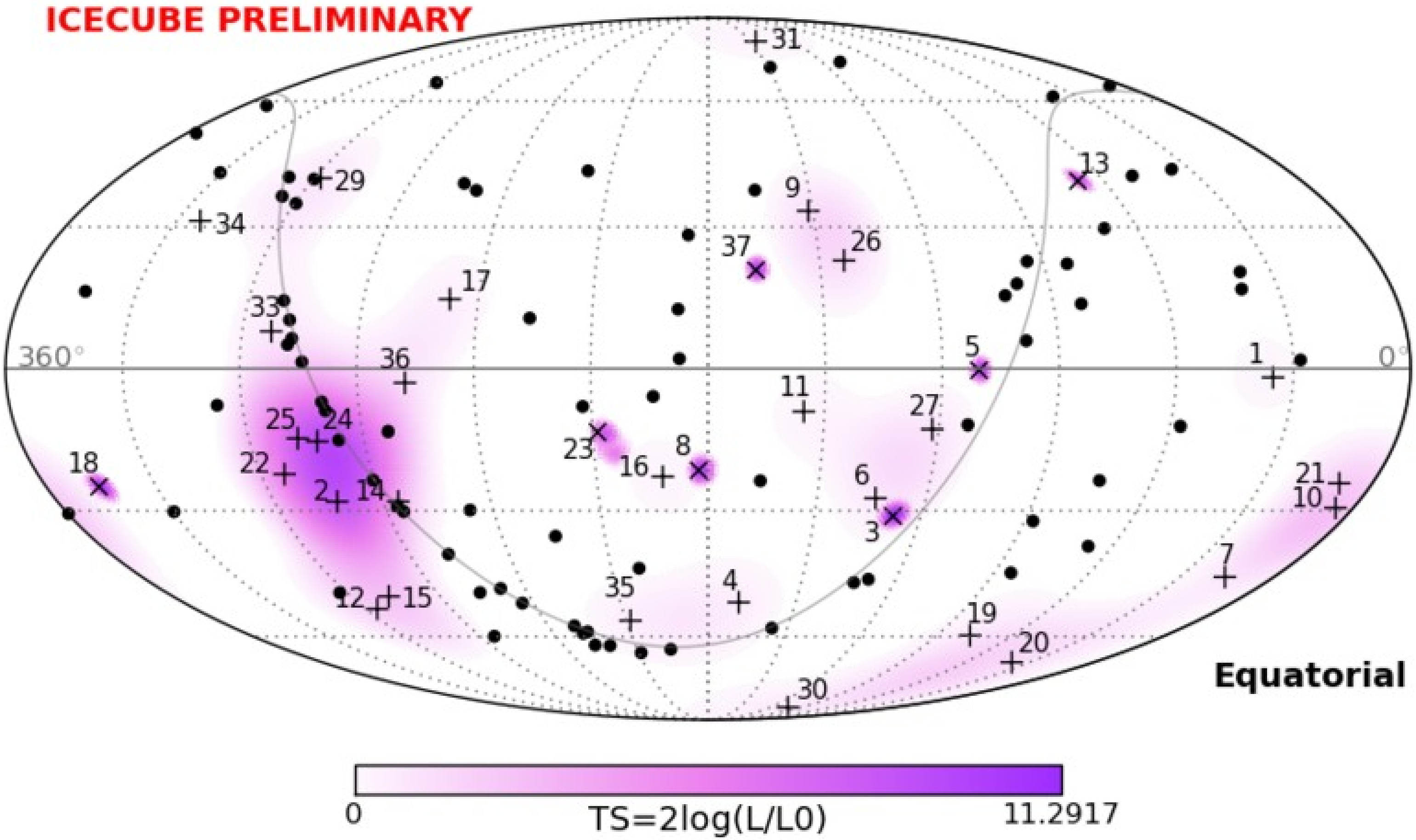
Remember: "only" 37 events



diffuse high energy neutrino search: the IceCube discovery






ICECUBE PRELIMINARY
360°
0°
Equatorial
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
33
34
35
36
37
0
TS=2log(L/L0)
11.2917

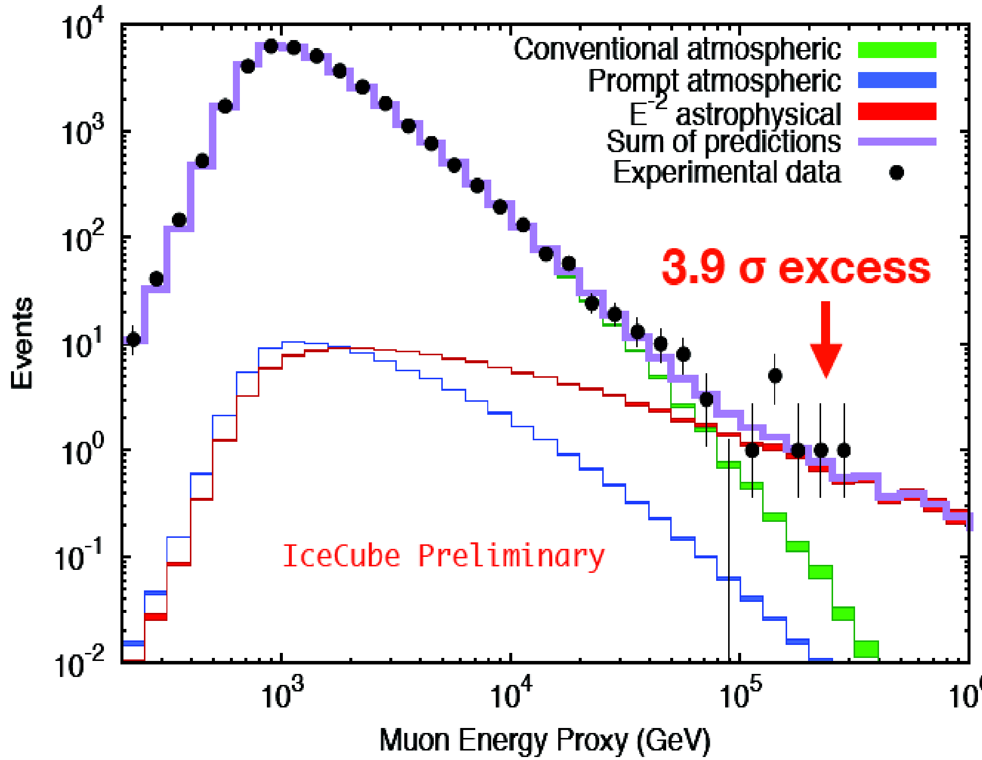
Search for an excess high-energy muon flux from the northen sky

The high-energy starting sample is dominated by cascades from the southern sky

→ Look for an excess in muons from the northern sky

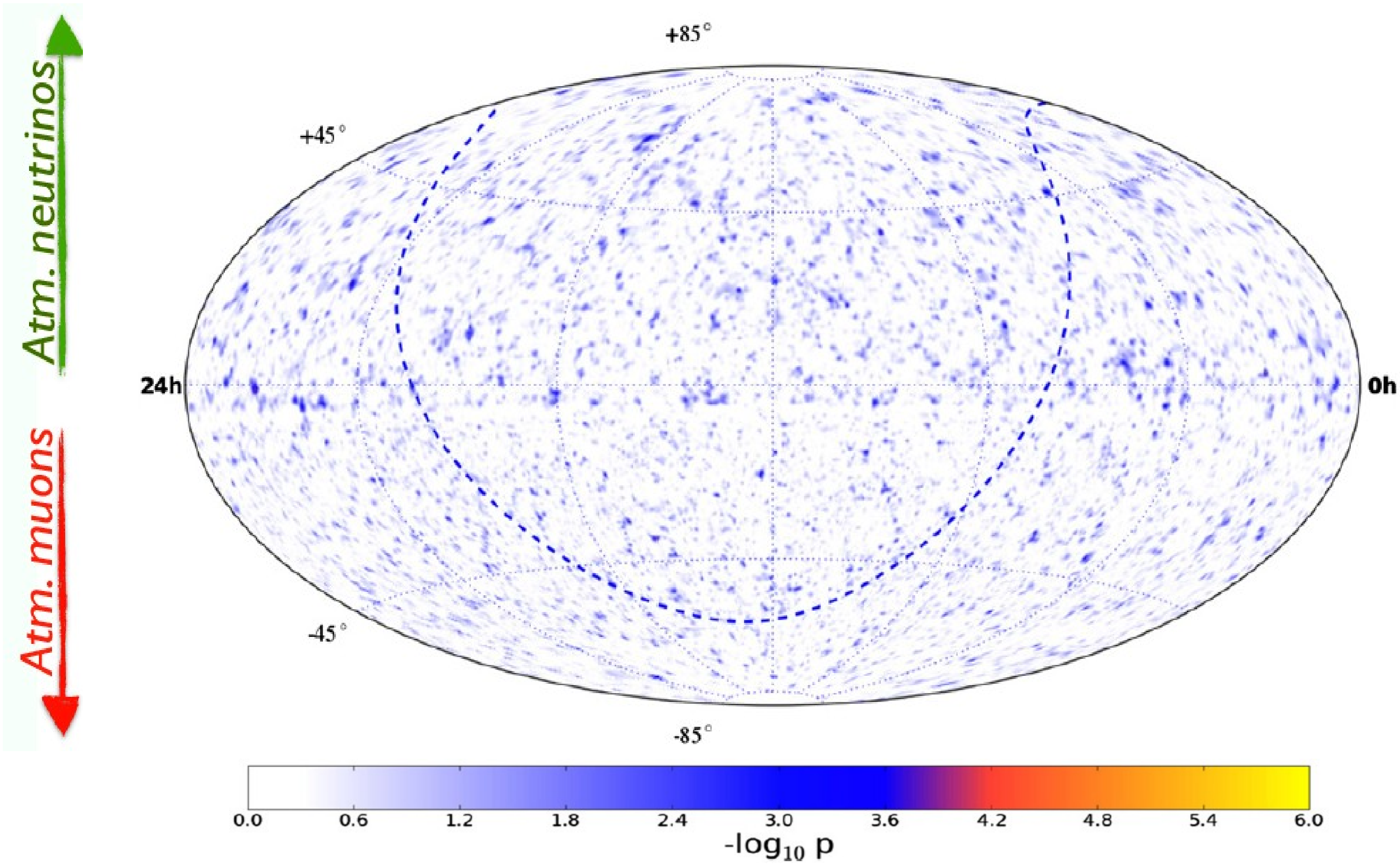
Only sensitive to ν_μ CC at energies where the Earth is not opaque to neutrinos

Ongoing analysis



IC40+IC59+IC79 neutrino sky.

total livetime 1039 d
total number of events: 108317 upgoing,
146018 downgoing (atm muons)

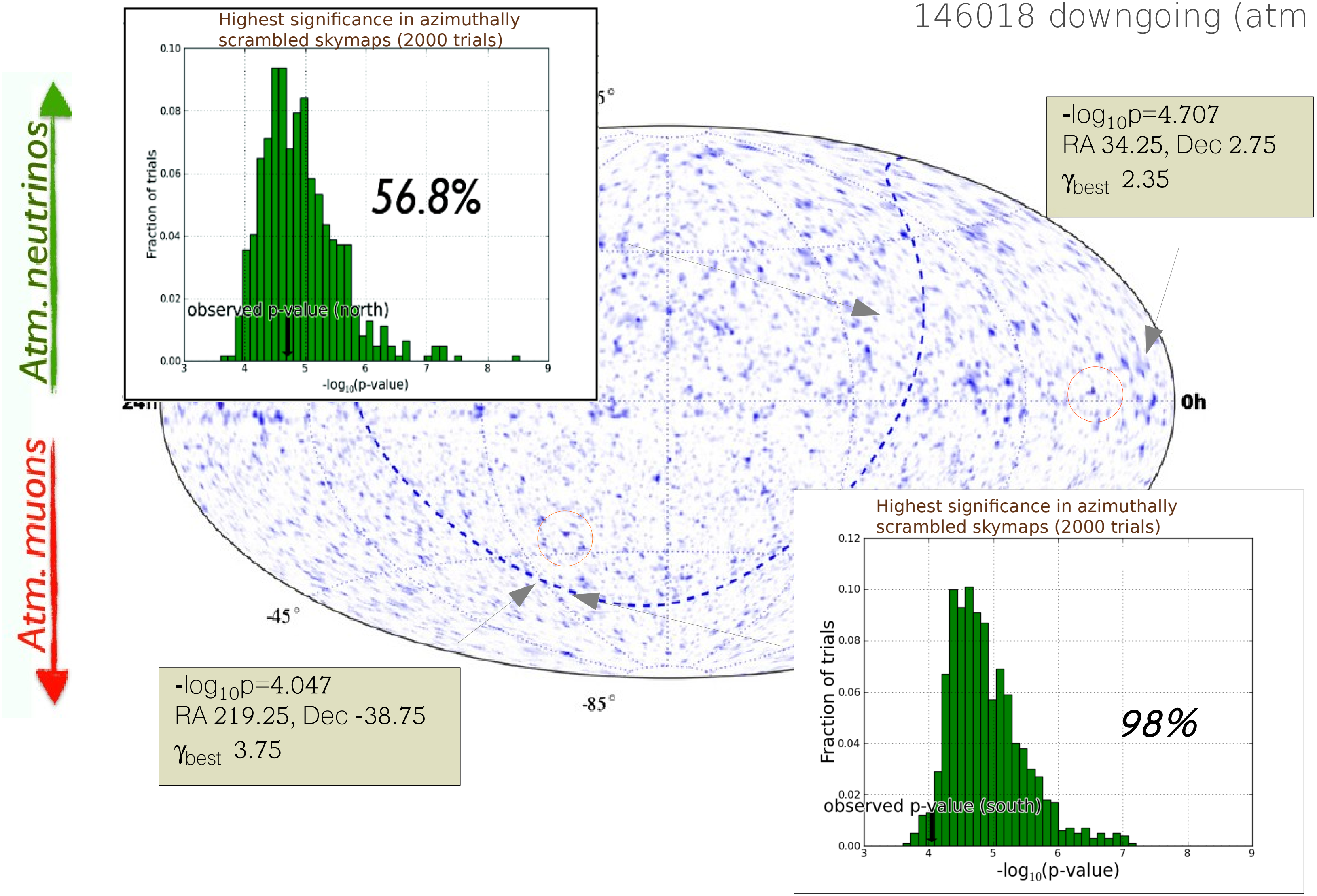


The Astrophysical Journal, 779, 132 (2013)

IC40+IC59+IC79 neutrino sky.

total livetime 1039 d

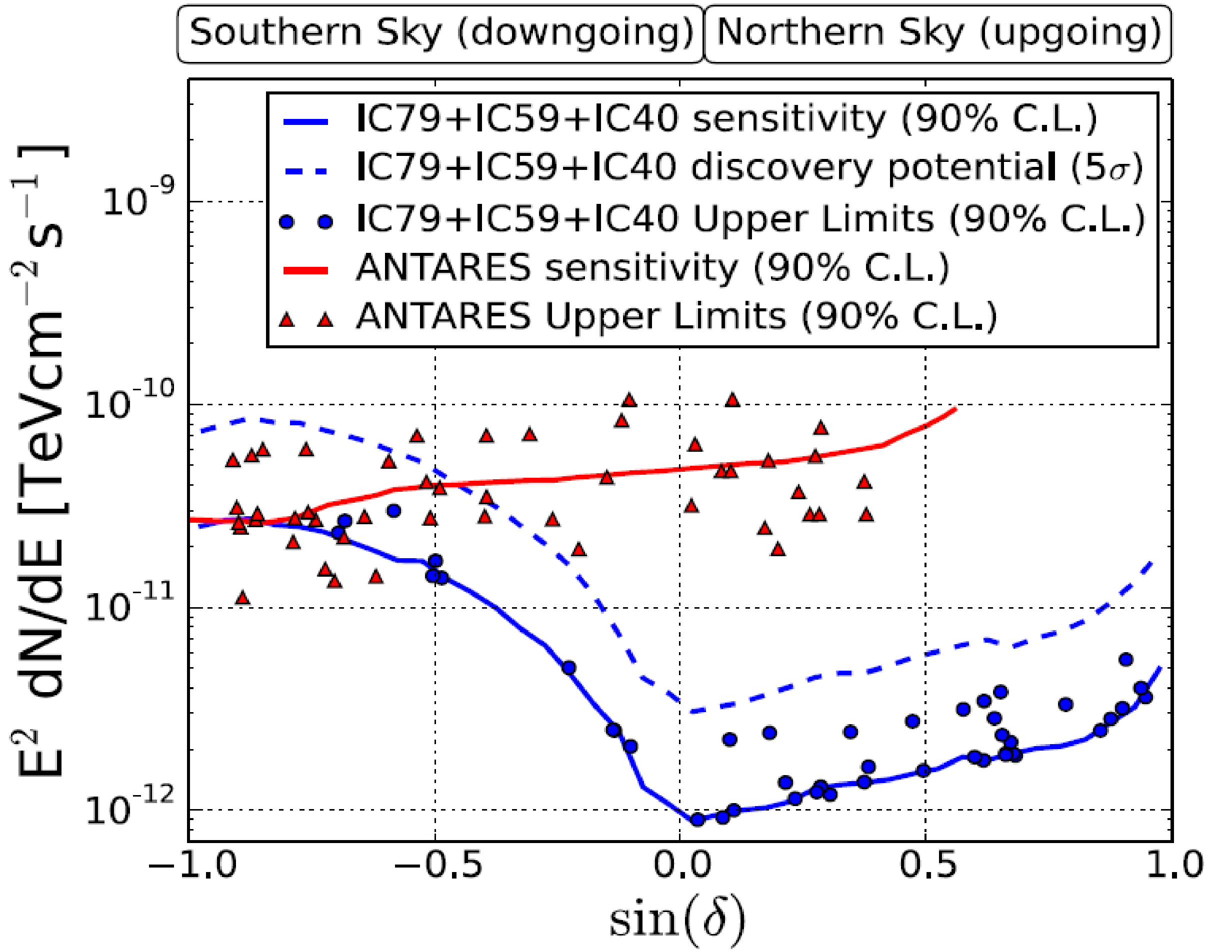
total number of events: 108317 upgoing,
146018 downgoing (atm muons)



IC40+IC59+IC79 point source limits.

Upper limits on a E^{-2} spectrum from a list of astrophysical objects (Blazars, SN remnants...)

The Astrophysical Journal, 778:1 (17pp), 2013



Two Complementary searches:

"Model-Dependent" search:

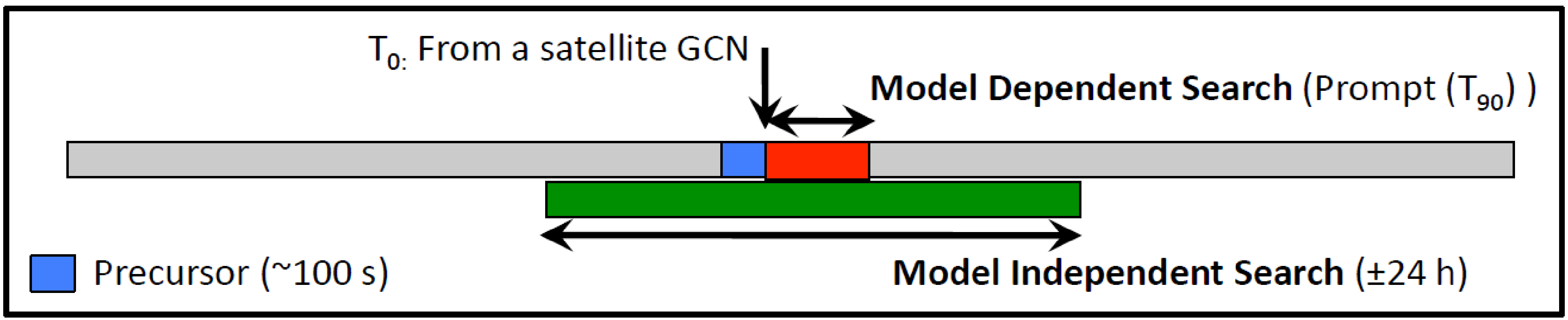
- **Time-window** defined by start and end of observed gamma emission (**T_{90} typically ~ 30 s**)
- Use model predictions of neutrino flux and energy spectrum to weight the search

⇒**Most sensitive if models are right**

"Model-Independent" search:

- **Time window** expands from **± 10 s to ± 1 day** (NB: neutrinos closer to GRB T_0 given more significance)
- No specific weighting to model predictions, search at all neutrino energies

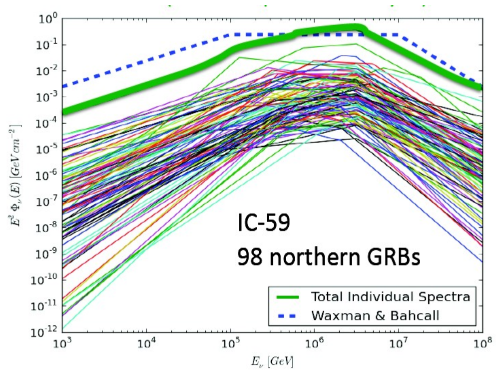
⇒**"Catch-all" analysis**

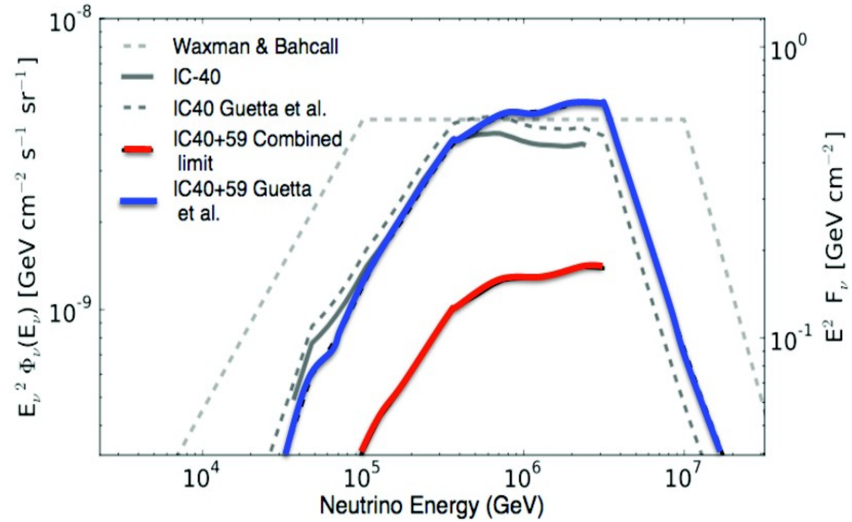


IceCube-40 + IceCube-59 results:

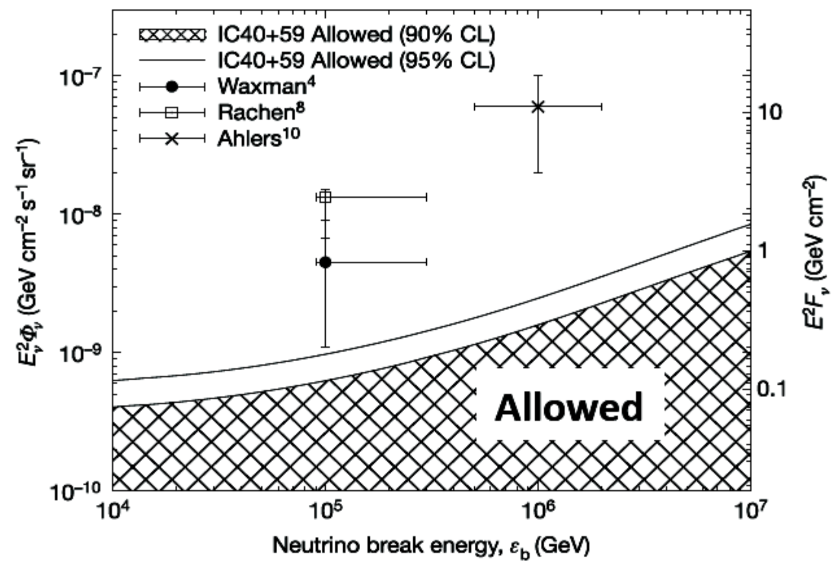
2008-9 (40-string) data:
117 GRBs in northern sky

2009-10 (59-string) data:
98 GRBs in northern sky
another 85 GRBs in southern sky also analyzed





Because of short duration, searches are very low-background.



Constraints

Observed 0 events

Model prediction:
8.4 events (Guetta et al.)
excluded at > 3 σ
(upper limit ≈ 2.3 events)

Non-observation of neutrinos with first IceCube data
➔Revisit theory, revise predictions
➔Some models now strongly excluded,

Nature, Vol. 484, 351 (2012)

WIMPS

- Arise in extensions of the Standard Model
- Assumed to be stable: relics from the Big Bang
- weak-type Xsection gives needed relic density

$$\Omega_\delta h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann} v \rangle_{fr}} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- mass from few GeV to few TeV
- **MSSM** candidate: lightest neutralino,

$$\tilde{\chi}^0_1 = N_1 \mathbf{B} + N_2 \mathbf{W}^3 + N_3 \mathrm{H}^0_1 + N_4 \mathbf{H}^0_2$$

- **UED**: lightest 'rung' in the Kaluza-Klein ladder

SIMPZILLAS

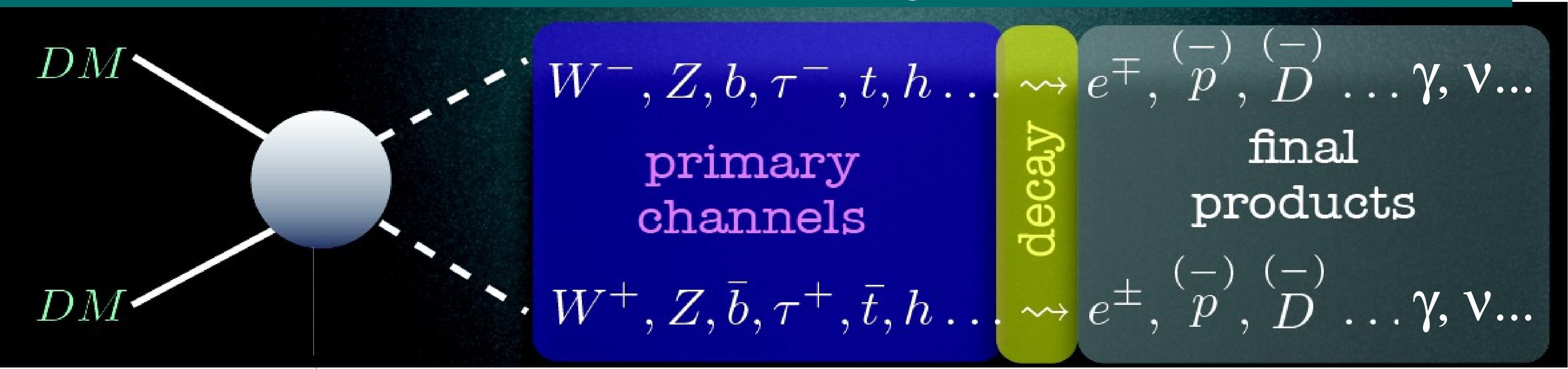
- Non-thermal, non-weakly interacting stable relics

A wealth of candidates from different theoretical models:

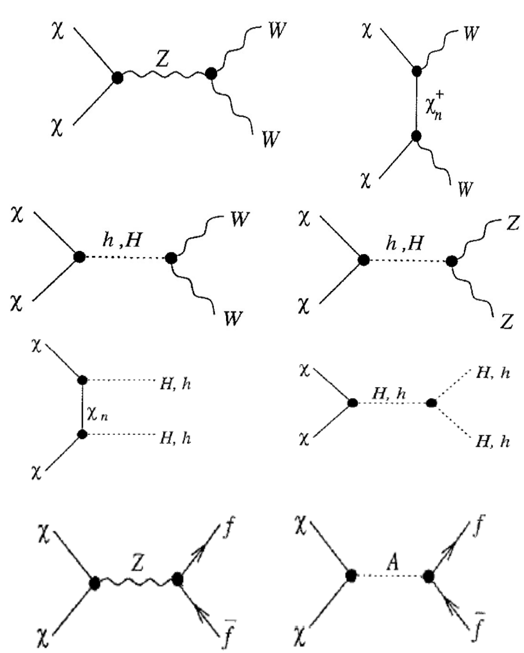
- dark baryons
- MACHOs – BHs, neutron stars, white/brown dwarfs…
- neutrinos
- primordial Black Holes
- **W**eakly **I**nteracting **M**assive **P**articles
  (LSPs from "x"MSSM, Kaluza-Klein modes…)
  Non-weakly Interacting Supermassive particles
  (Simpzillas)
- axions
- many others

… + (alternative gravity theories)

indirect signatures of dark matter annihilation



your theory here
(not necessarily SUSY...)



…. etc

astrophysics inputs
(and uncertainties...):
products have to be
transported to the Earth

Here is where **ν's** are
advantageous

The prediction of a neutrino signal from dark matter annihilation is complex and involves many subjects of physics

- relic density calculations (cosmology)
- dark matter distribution in the halo (astrophysics)
- velocity distribution of the dark matter in the halo (astrophysics)
- physical properties of the dark matter candidate (particle physics)
- interaction of the dark matter candidate with normal matter (for capture)
  (nuclear physics/particle physics)
- self interactions of the dark matter particles (annihilation) (particle physics)
- transport of the annihilation products to the detector (astrophysics/particle physics)

dark matter searches with neutrino telescopes

Sun

Earth

$\text{probes } \sigma^{SD}_{\chi-N}, \ \sigma^{SI}_{\chi-N}$

- complementary to direct detection
- different systematic uncertainties
  - hadronic (not nuclear)
  - local density
  - can benefit from co-rotating disk

dwarves & distant halos

Milky Way Halo

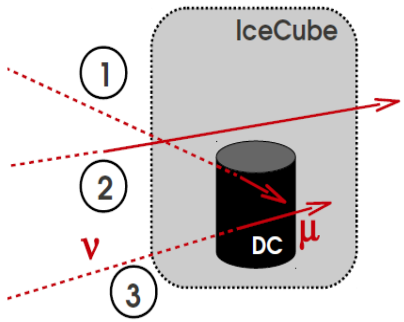
Milky Way Center

$\text{probes } \langle \sigma_A \ v \rangle$

- complementary to searches with other messangers (γ, CRs…)
- shared astrophysical systematic uncertainties (halo profiles…)
- more background-free

IceCube results from 317 days of livetime between 2010-2011:

All-year round search:

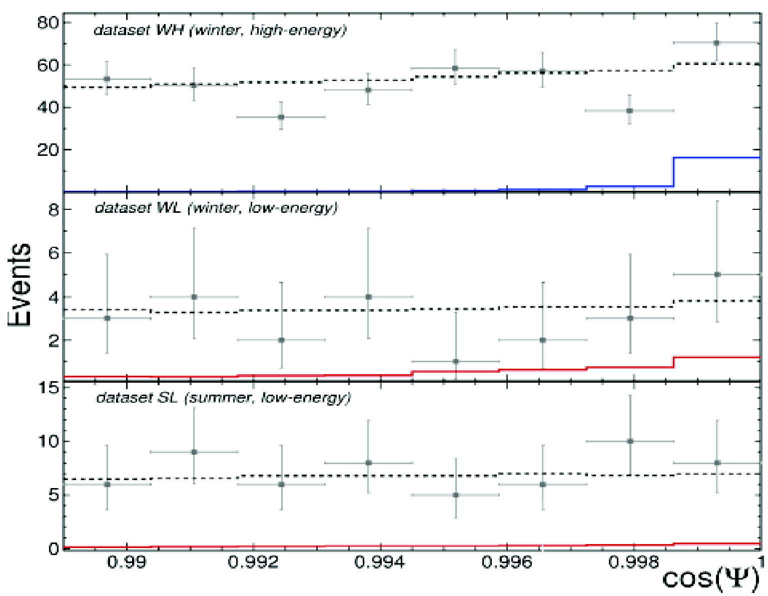


Extend the search to the southern hemisphere by selecting starting events
→ Veto background through location of interaction vertex
- muon background: downgoing, no starting track
- WIMP signal: require interaction vertex within detector volume

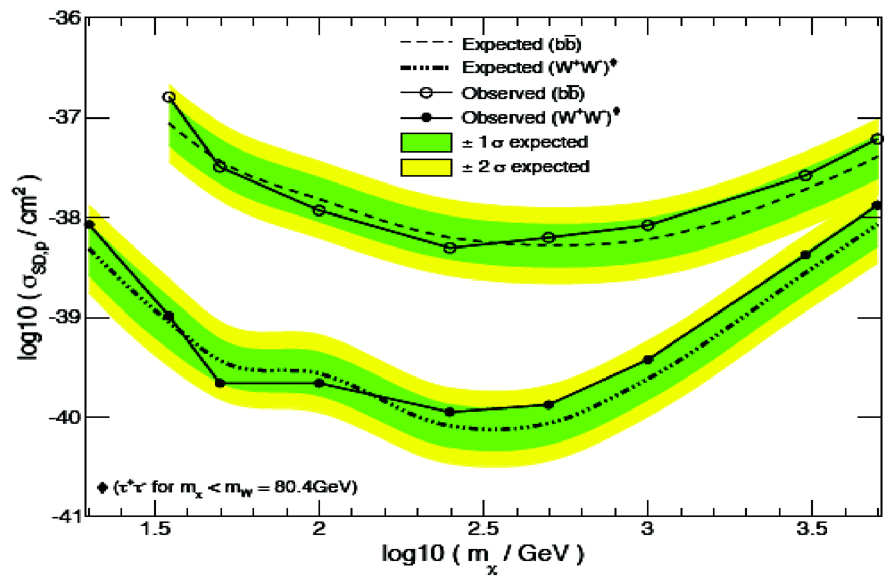
Background estimated from time-scrambled data
Analysis reaches neutrino energies of ~20 GeV
Assumes equilibrium between capture and annihilation

$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$$

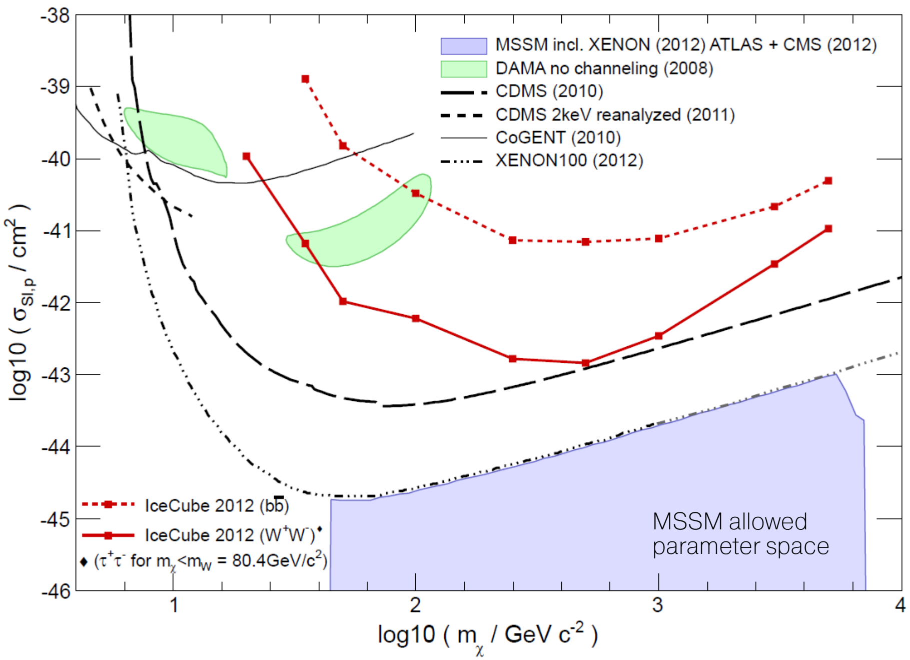
Unblinded events in different samples



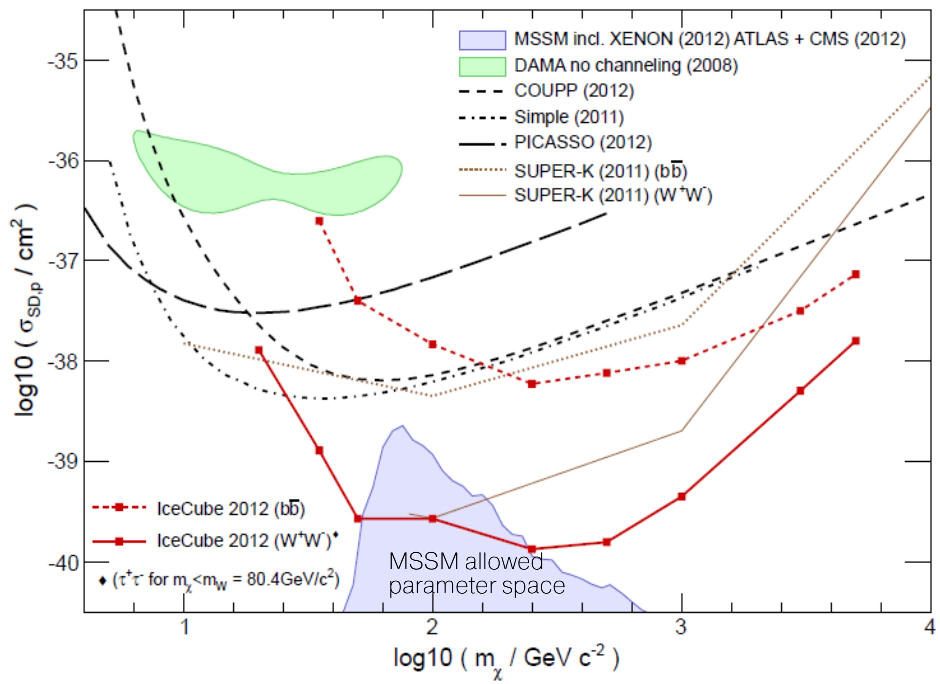
Expected sens. vs. observed result



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



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

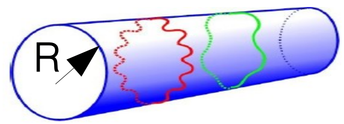


- most stringent SD cross-section limit for most models
- complementary to direct detection search efforts
- different astrophysical & nuclear form-factor uncertainties

Universal Extra Dimensions:

models originally devised to unify gravity and electromagnetism.

No experimental evidence against a space 3+δ+1 as long as the extra dimensions are 'compactified'



$$n\frac{\lambda}{2} = 2\pi R, \qquad n\frac{h}{2p} = 2\pi R \;\Rightarrow\; p = n\frac{h}{4\pi R}$$

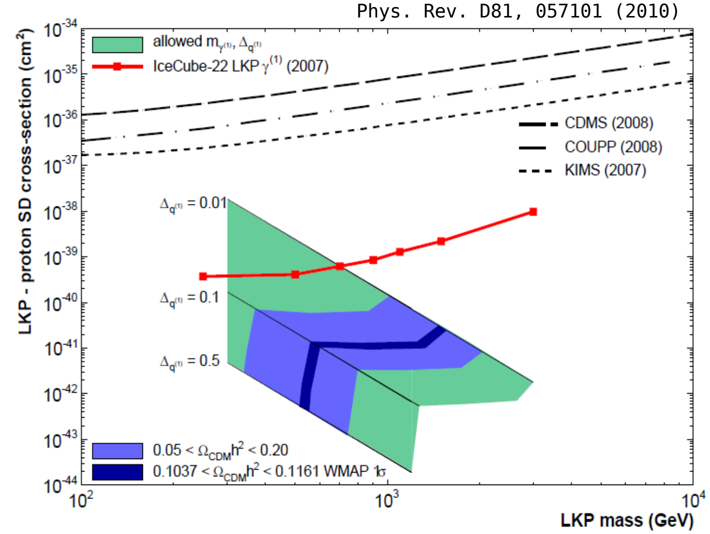
$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

$$m_n^2 = \frac{n^2}{c^2R^2} + m_o^2$$

n=1 → Lightest Kaluza-Klein mode, B^1
good DM candidate

90% CL LKP-p Xsection limit vs LKP mass

Phys. Rev. D81, 057101 (2010)



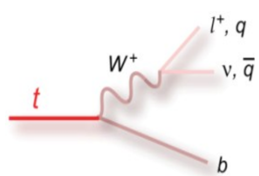
Superheavy dark matter:

- Produced **non-thermally** at the end of inflation through vacuum quantum fluctuations or decay of the inflaton field

- strong Xsection (simply means non-weak in this context)

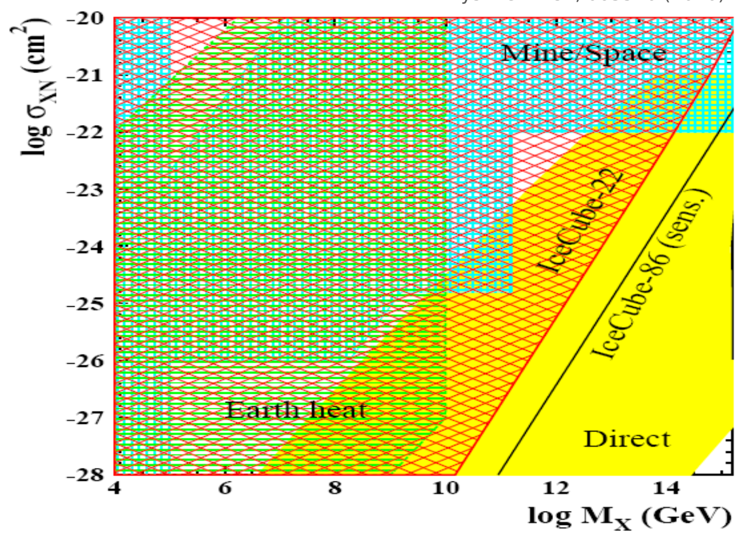
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

$S+S \rightarrow t\,\bar{t}$ dominant



90% CL S-p Xsection limit *vs* S mass

Phys. Rev. D81, 063510 (2010)



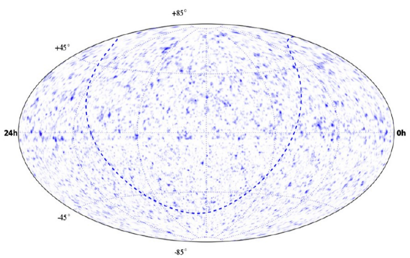
search for dark matter accumulated in the Galactic Center/Halo

probe DM annihilation cross section

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\rm los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

measurement



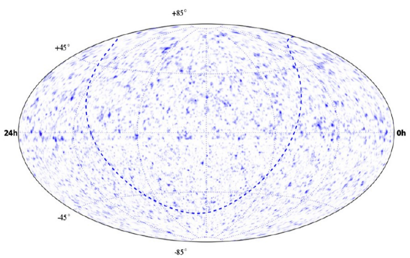
probe DM annihilation cross section

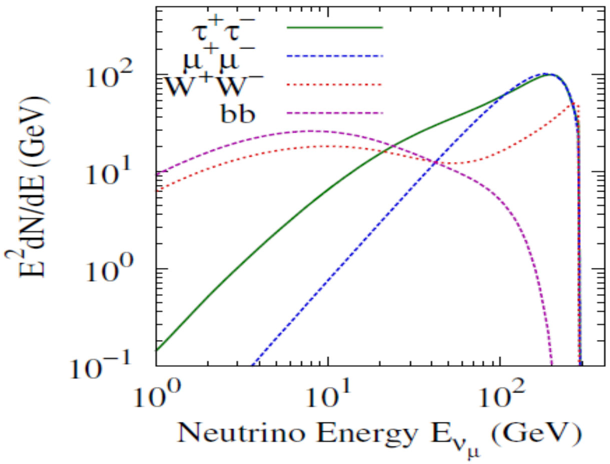
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f \quad \text{X} \quad \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

measurement

particle physics model





search for dark matter accumulated in the Galactic Center/Halo

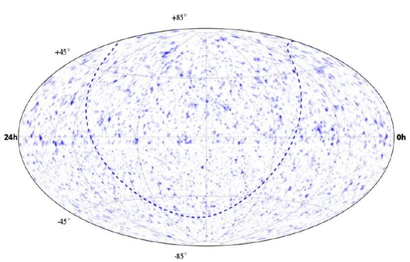
probe DM annihilation cross section

line of sight contribution

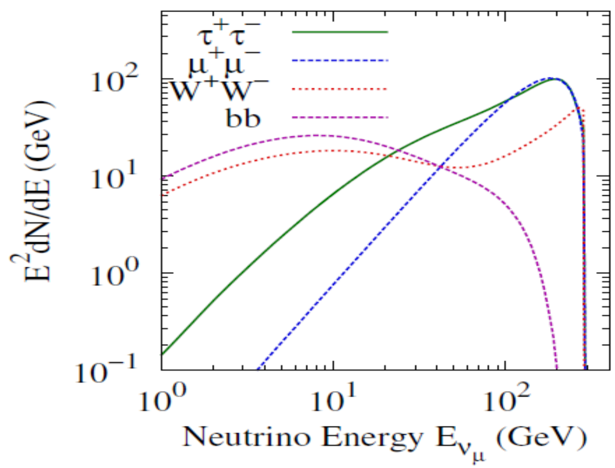
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\rm los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

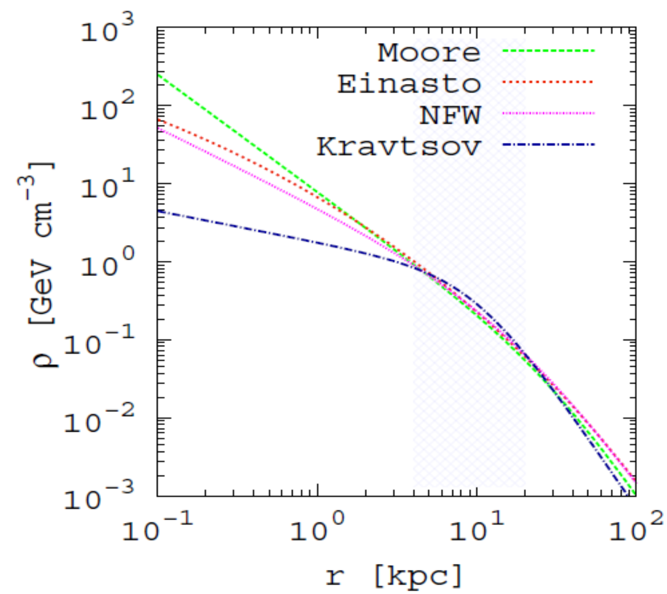
measurement



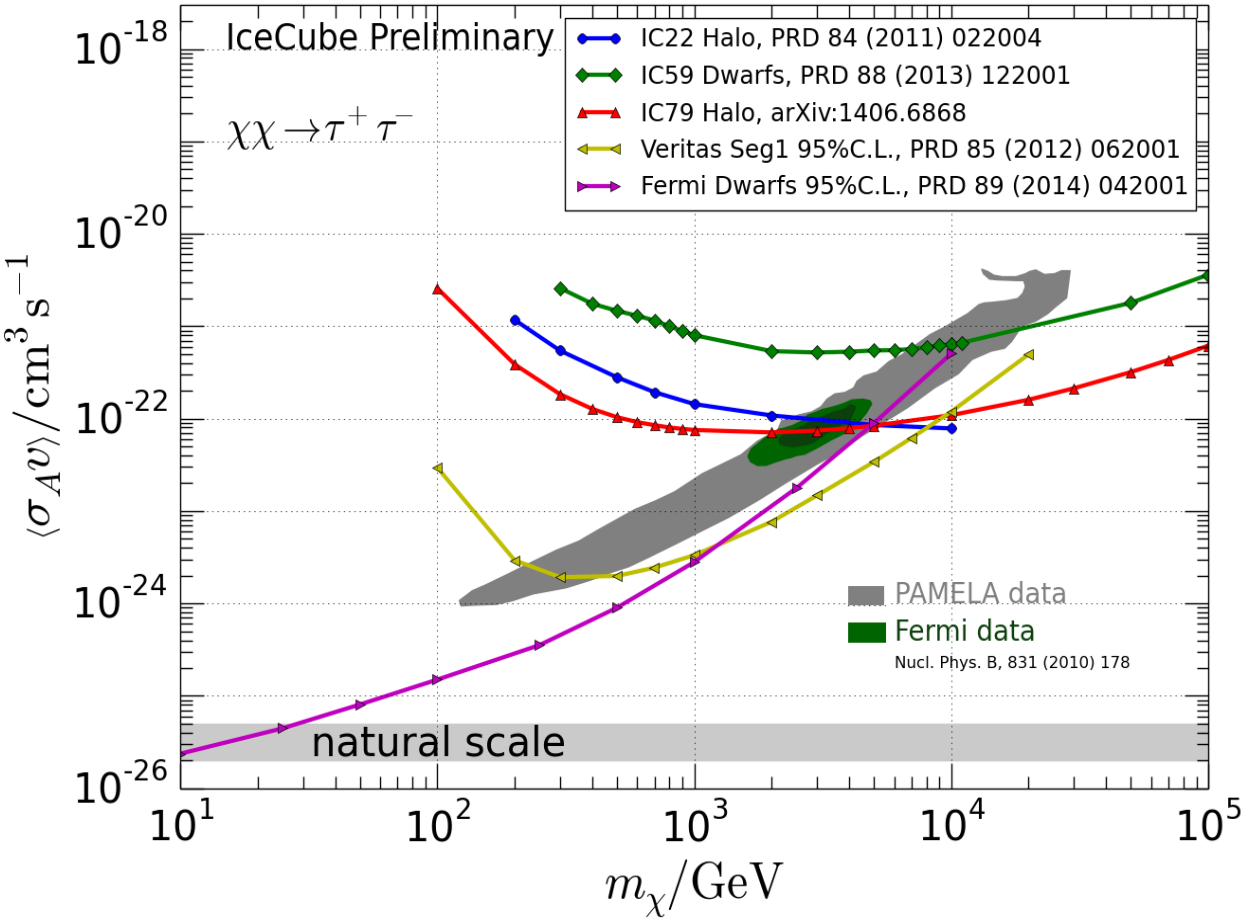
particle physics model



halo model



search for dark matter accumulated in the Galactic Center/Halo: results

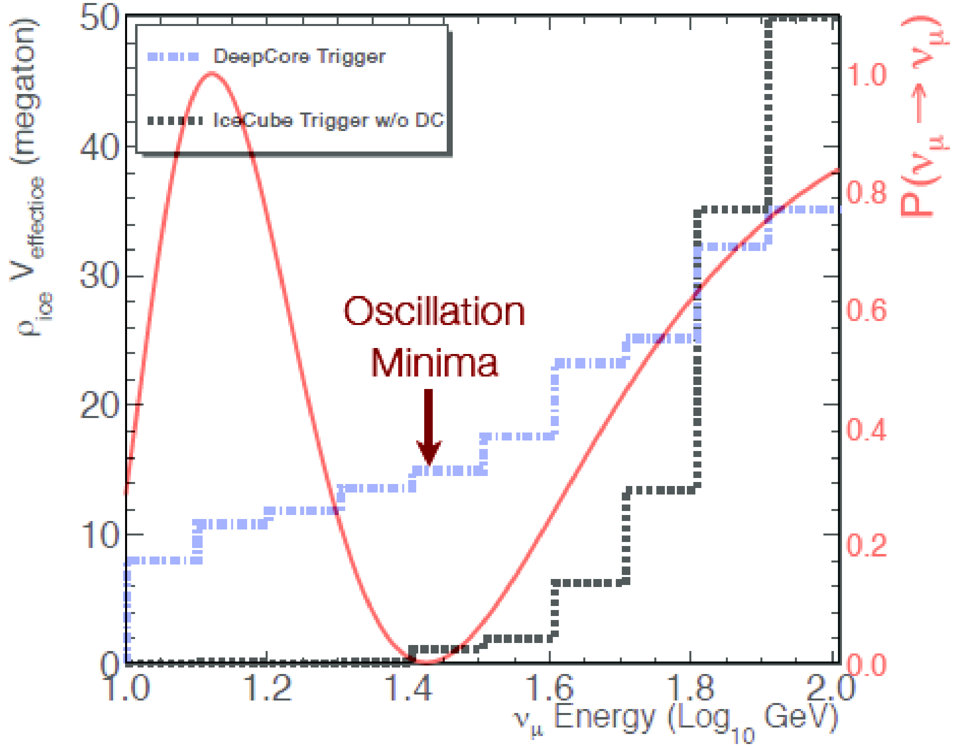


IceCube DeepCore

- Original IceCube design focused on neutrinos with energies above a few hundred GeV

- DeepCore provides ~25 MTon volume with lower energy threshold
    - Higher efficiency far outweighs reduced geometrical volume
    - Note: comparison at trigger level – analysis efficiencies not included (typically ~10%)

- $\mathcal{O}(10^5)$ atmospheric neutrino triggers per year

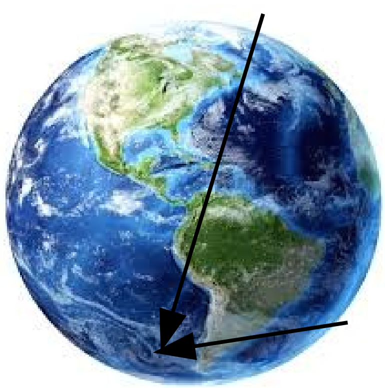


- Energy threshold at trigger level ~10 GeV
- Covers first oscillation maximum @25 GeV
- High statistics available

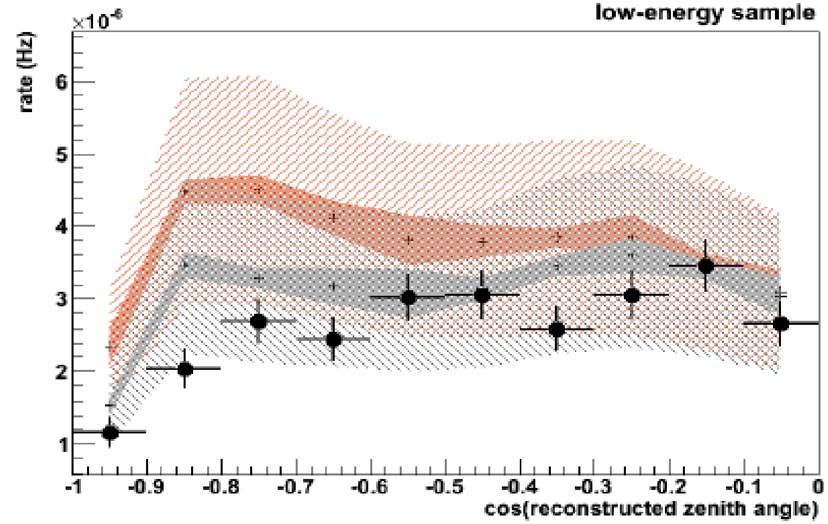
→ measure atmospheric muon rate as a function of energy and angle

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

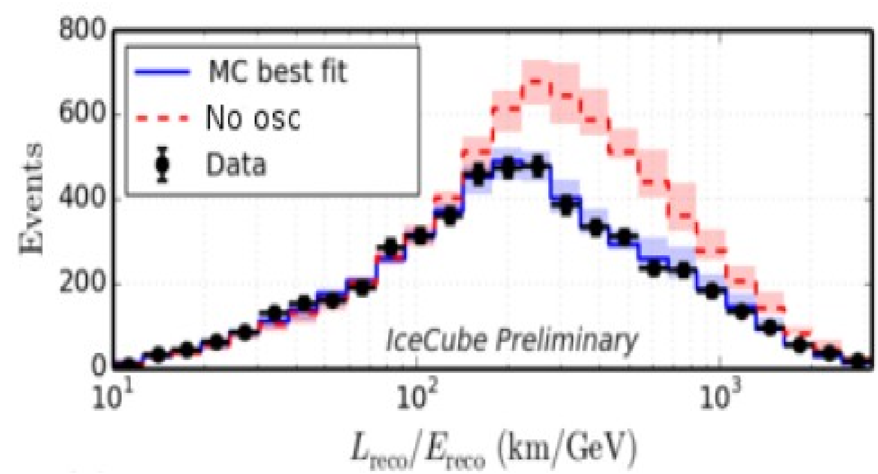
$L/E \rightarrow \Theta_{zenith}/E$



just rate measurement



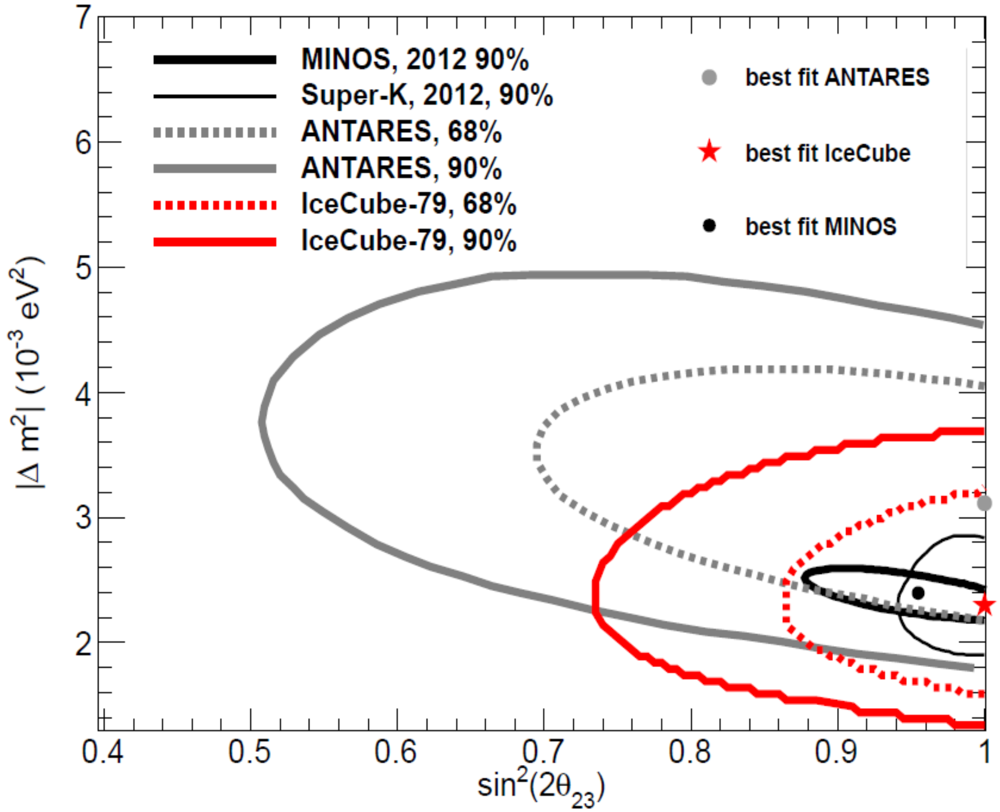
adding energy reconstruction



- Energy threshold at trigger level ~10 GeV
- Covers first oscillation maximum @25 GeV
- High statistics available

→ measure atmospheric muon rate as a function of energy and angle

Phys. Rev. Lett. 111, 081801 (2013)



Results:

IceCube sees neutrino oscillations @5.6σ consistent with world-average best fit

Two directions

Higher energy

Point sources

Neutrino flavor ratios

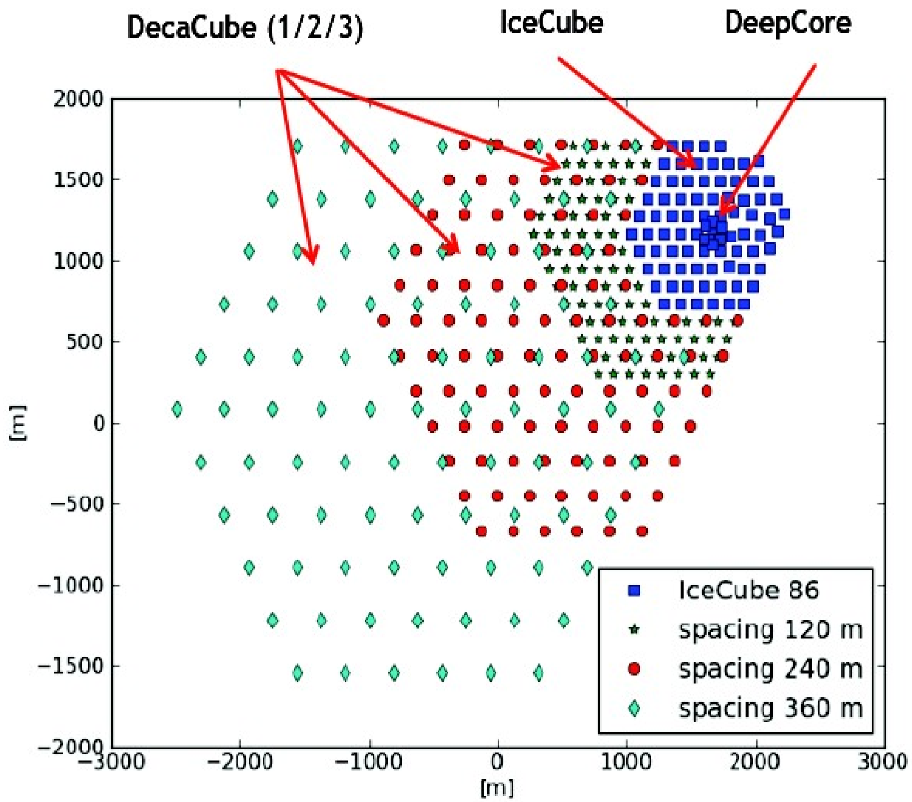
Lower Energy (reach the $O(1)$ GeV threshold)

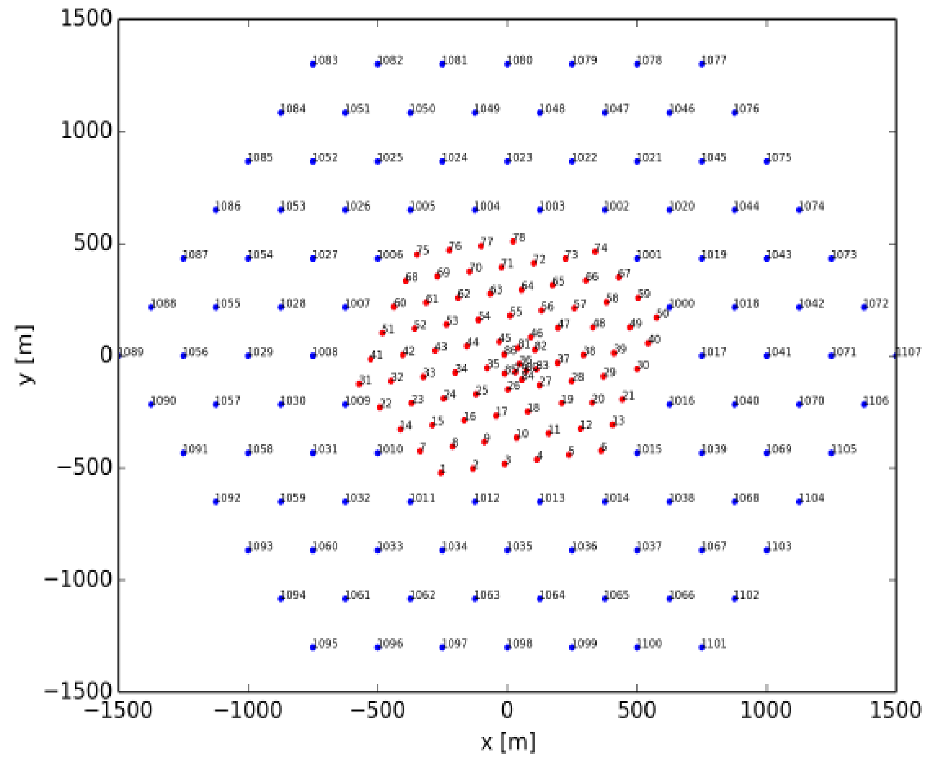
Resolve neutrino mass hierarchy

Improve on on-going neutrino oscillation studies

GeV dark matter


GVD
KM3NET
IceCube Gen2



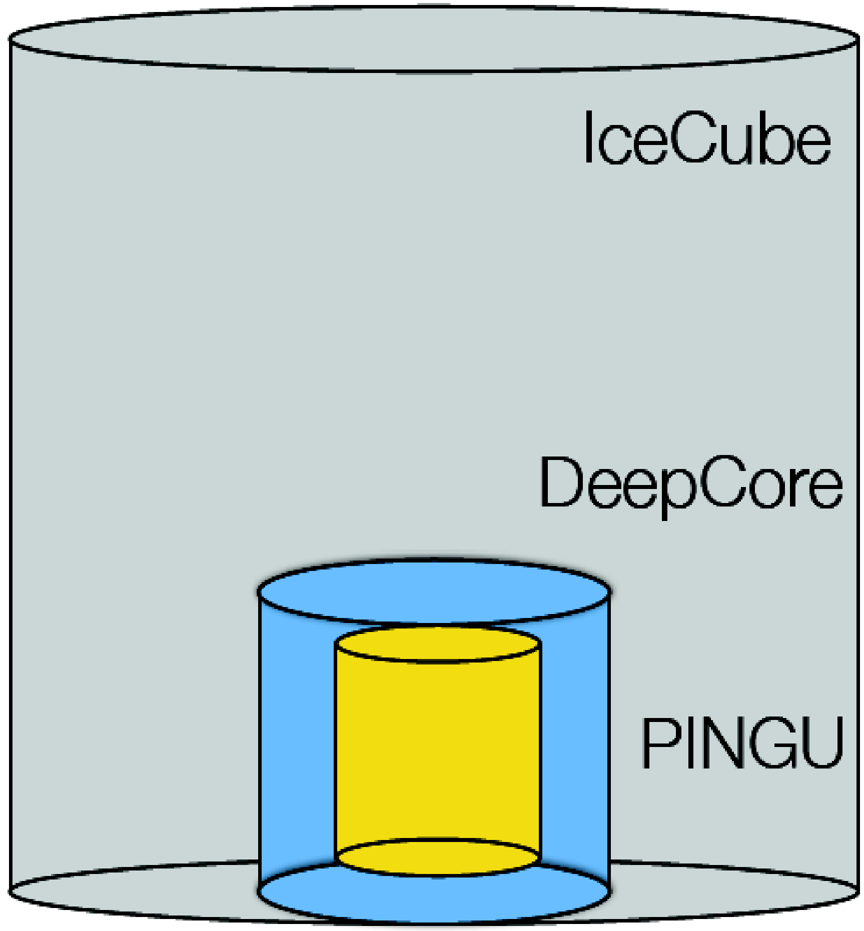


Multipole configurations under study

R&D and design optimization ongoing, including a surface veto

PINGU: Precision IceCube Next Generation Upgrade

- DeepCore showed the potential of going down in energy.
- How low could we go?
- Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV),
- Use **existing** and well tested technology



Aims:

Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay highs statistics SuperNova detection

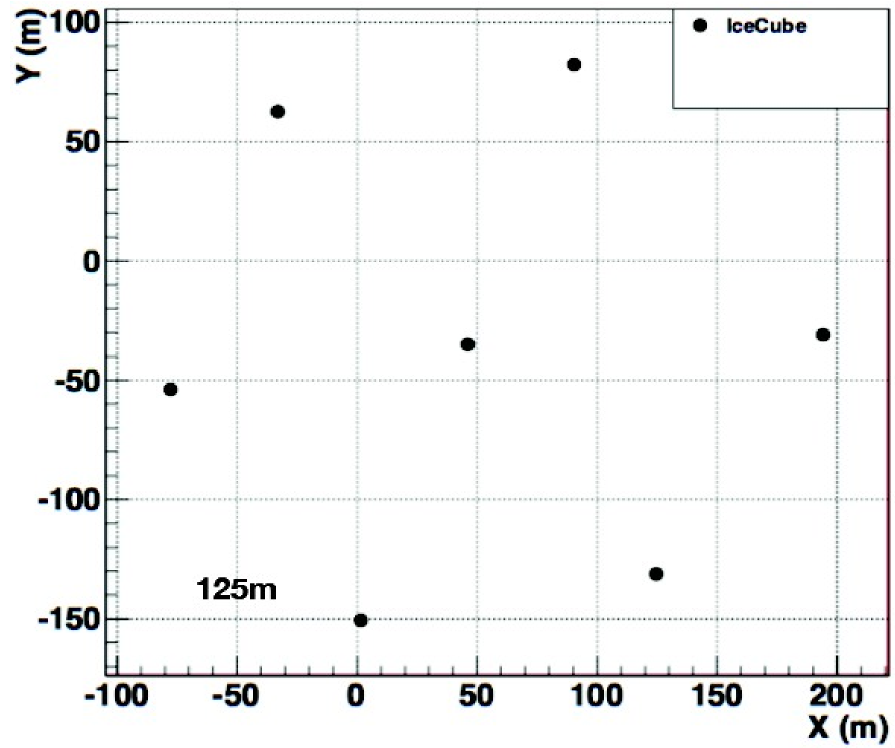
PINGU: Precision IceCube Next Generation Upgrade

• DeepCore showed the potential of going down in energy.

• How low could we go?

• Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV),

•Use **existing** and well tested technology



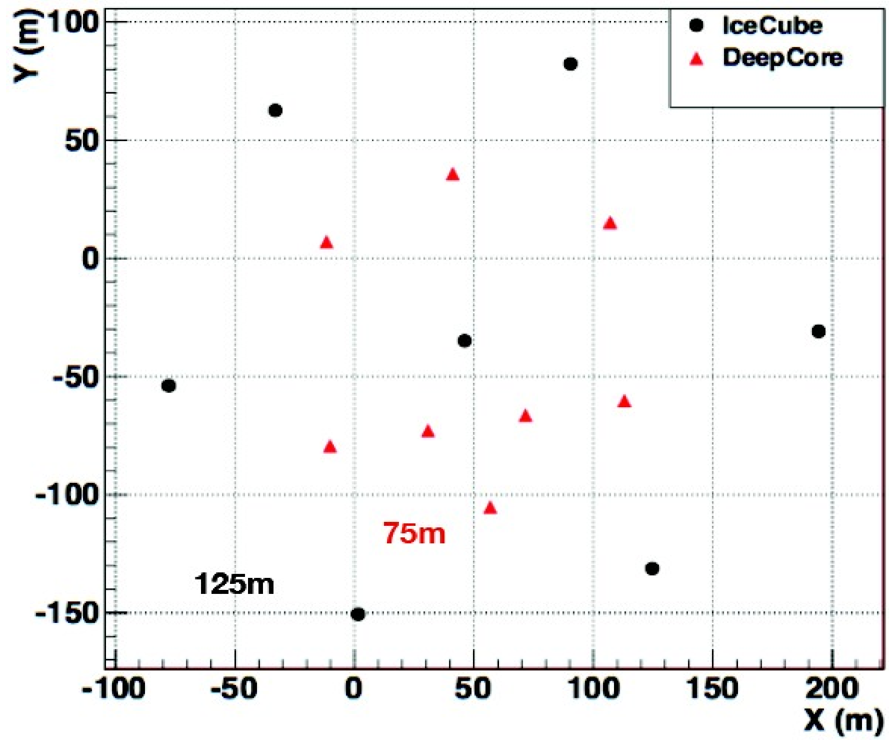
Aims:

Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay highs statistics SuperNova detection

PINGU: Precision IceCube Next Generation Upgrade

- DeepCore showed the potential of going down in energy.
- How low could we go?
- Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV),
- Use **existing** and well tested technology



Aims:

Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay highs statistics SuperNova detection

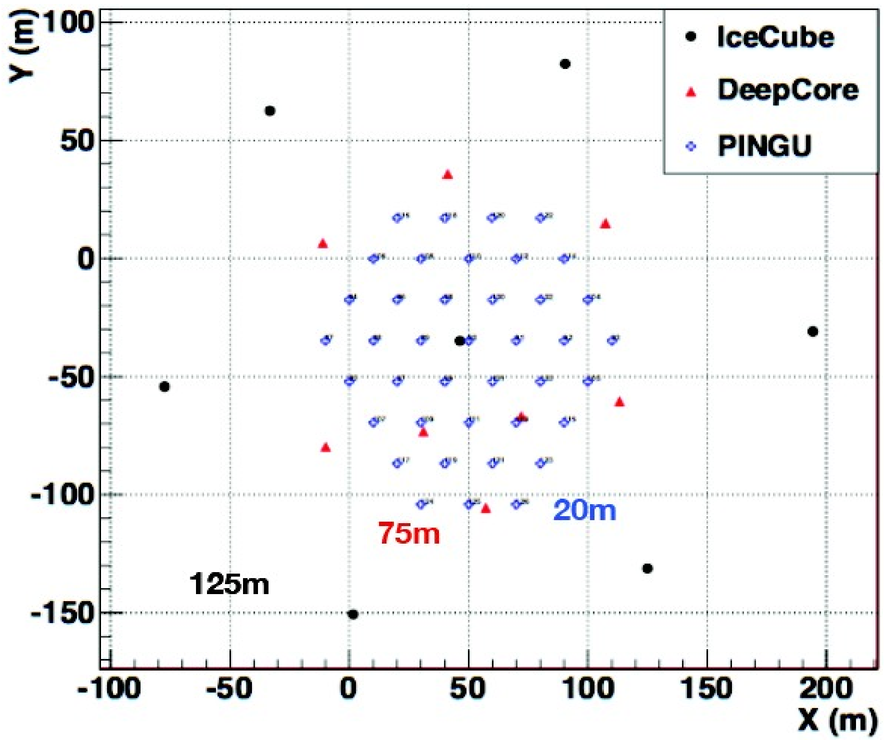
PINGU: Precision IceCube Next Generation Upgrade

- DeepCore showed the potential of going down in energy.
- How low could we go?
- Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV),
- Use **existing** and well tested technology

Aims:

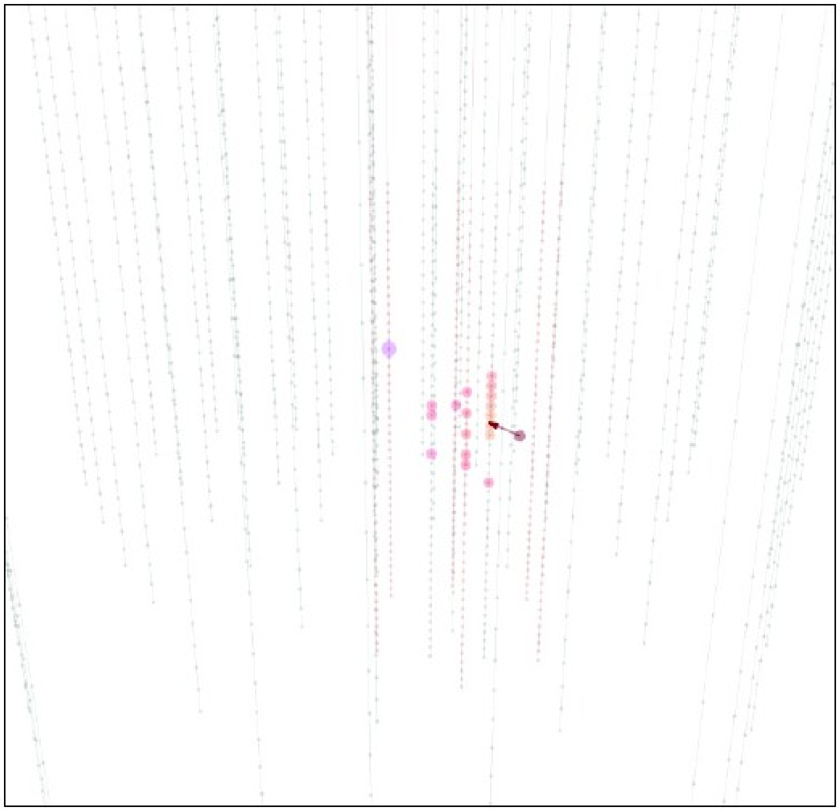
Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay highs statistics SuperNova detection



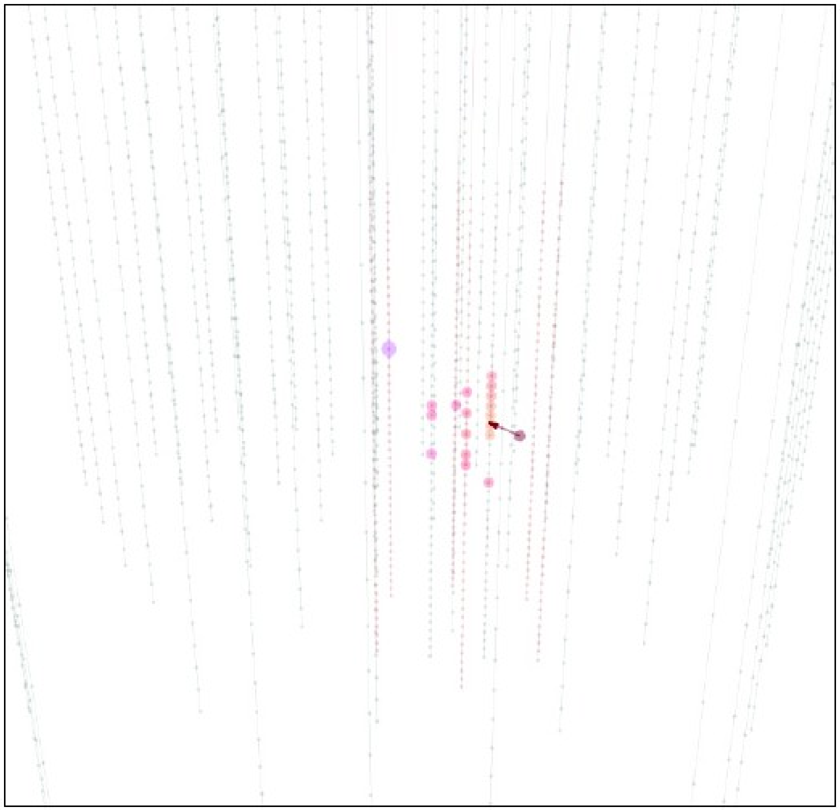
40 strings
22m horizontal spacing
3m vertical spacing (96 DOMs/string)

9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade

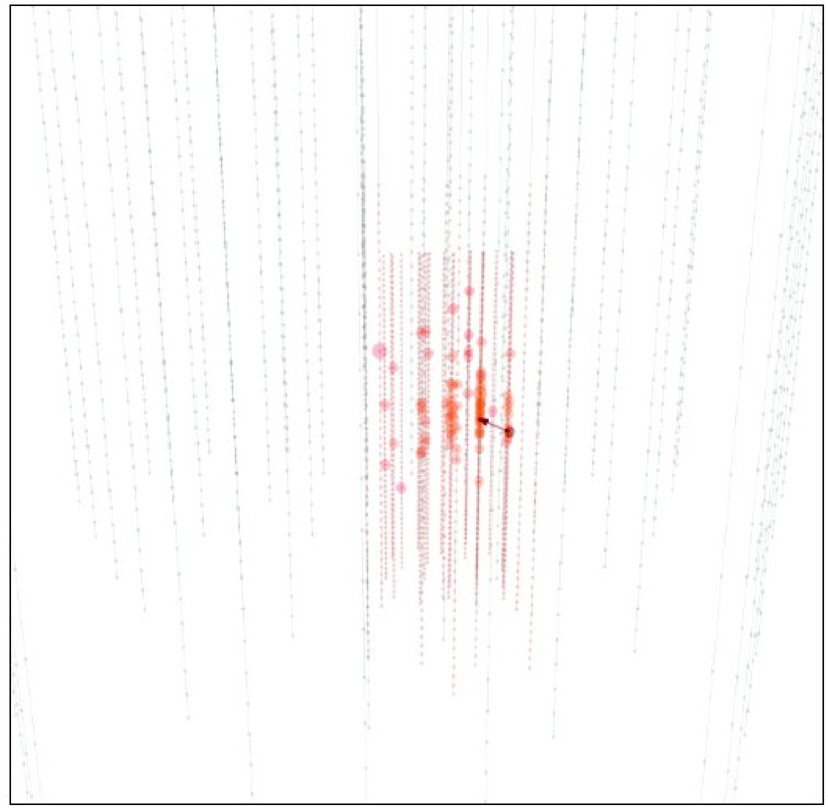


DeepCore only: 20 hit modules

9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade



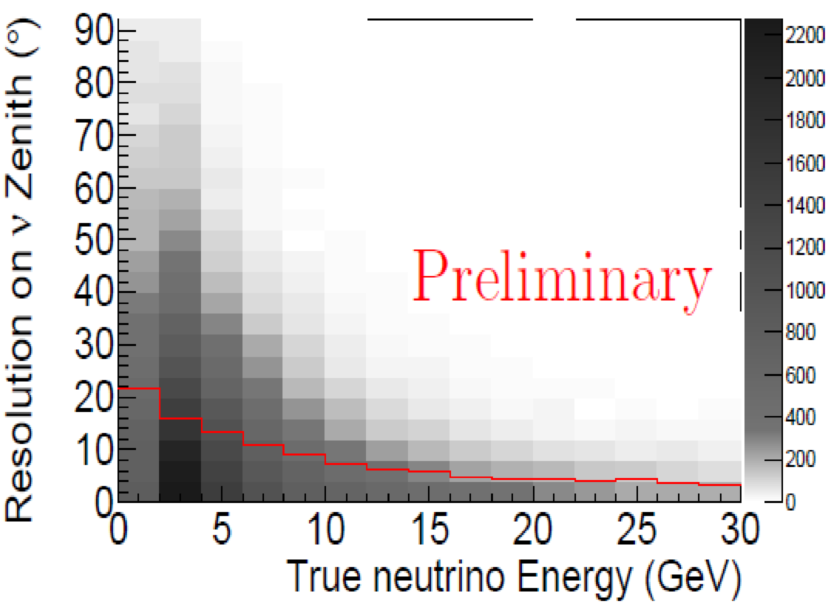
DeepCore only: 20 hit modules

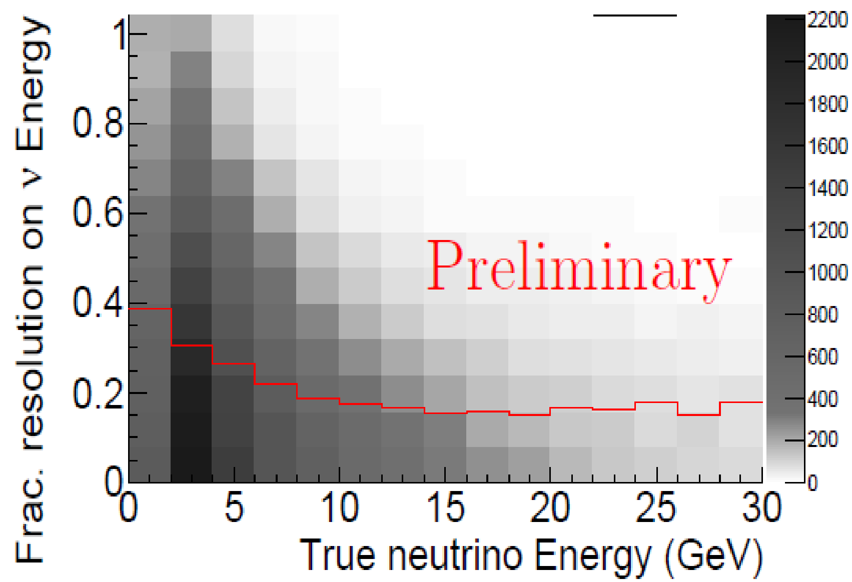


PINGU: 50 hit modules

- IF energy and angular resolution can be brought to the O(1 GeV) and O(10°) level

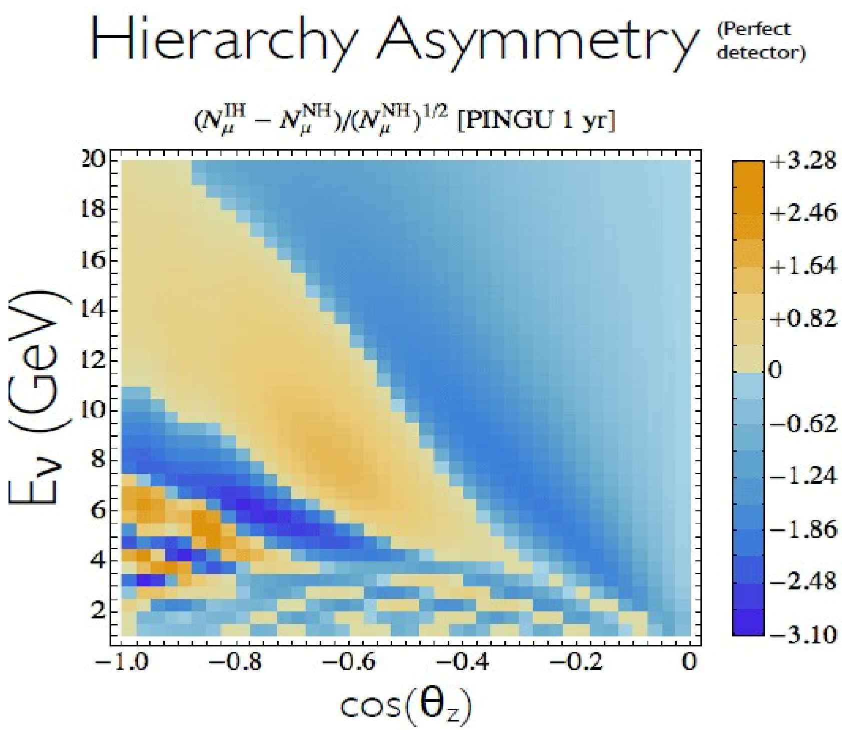
→ hierarchy measurement possible

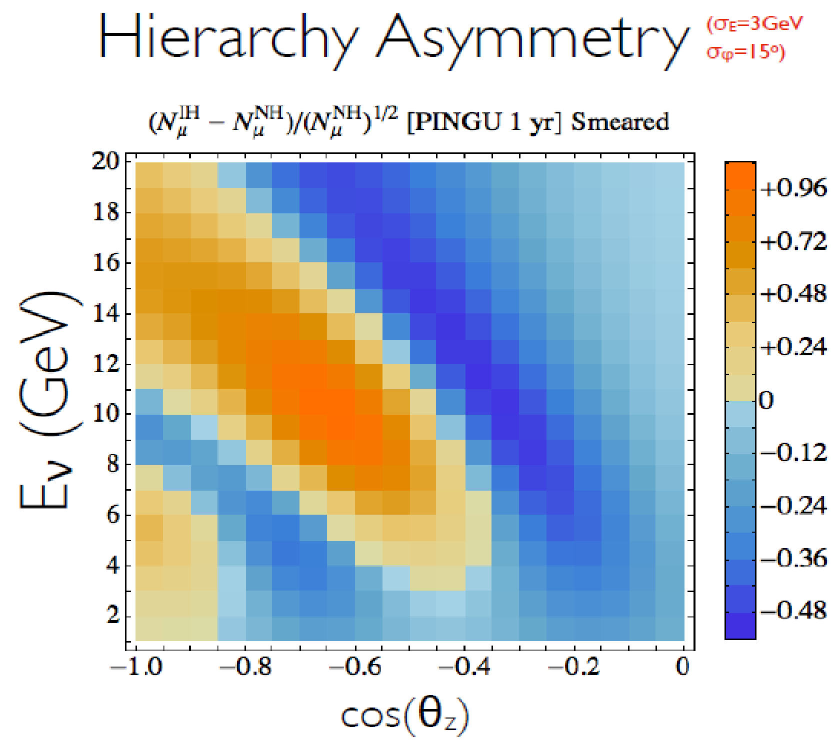




- IF energy and angular resolution can be brought to the O(1 GeV) and O(10°) level

→ hierarchy measurement possible



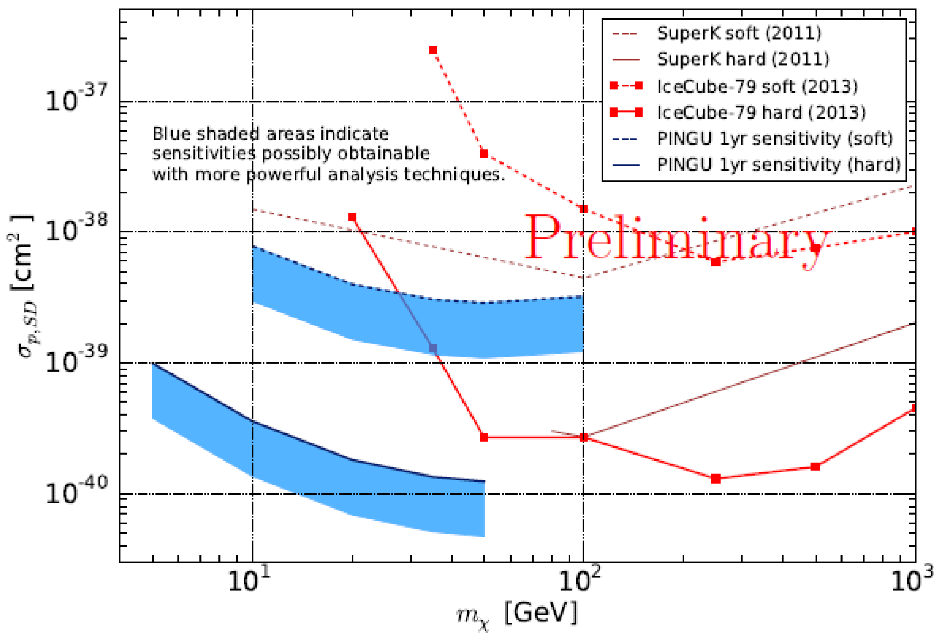


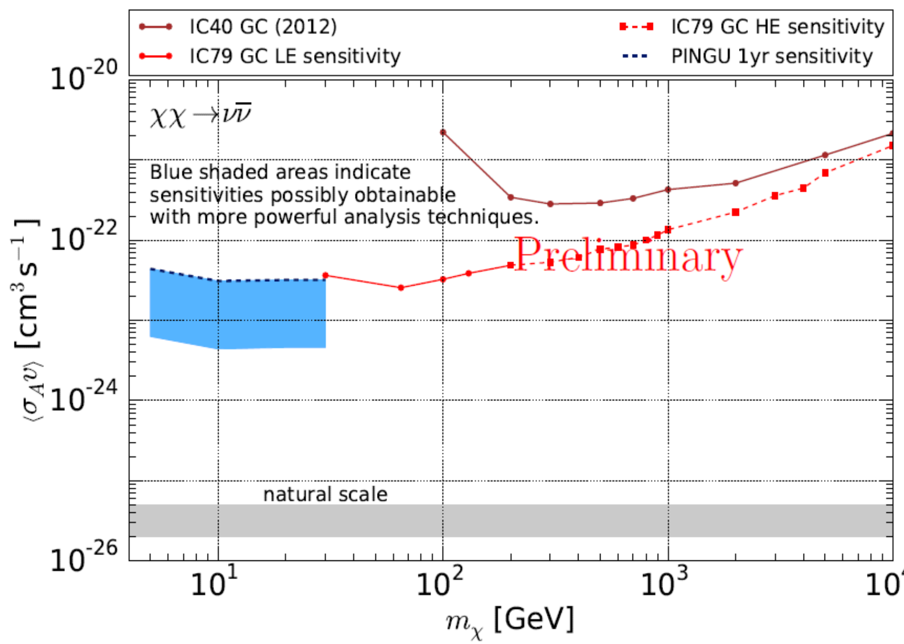
Akhmedov, Razzaque, Smirnov. arXiv:1205.7071v2

Lowering the energy threshold allows to reach lower WIMP masses, *O* (few GeV)

- Sensitivity study based on current IceCube analysis techniques

- Assume complete background rejection of downgoing atmospheric muons through veto techniques





blue shaded areas ==> range of possibly obtainable sensitivity with improved analysis techniques

└> use of signal and background spectral information

conclusions

IceCube has been (is) extremely successful in its physics programme

5.7 sigma evidence for non-atmospheric neutrinos at TeV energies

Impact on models of neutrino emission in GRBs and AGNs

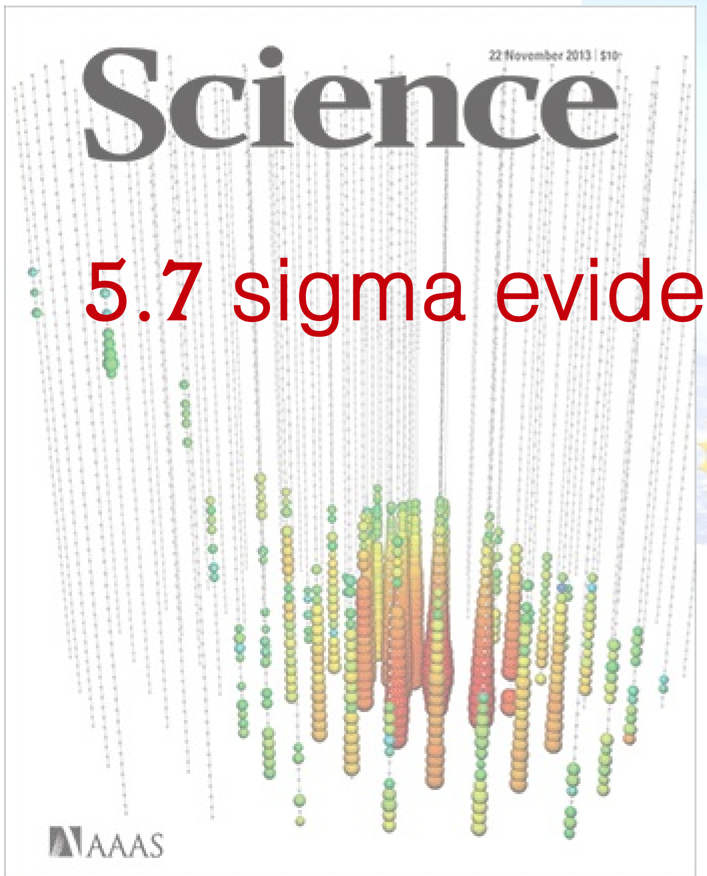
Competitive limits on dark matter

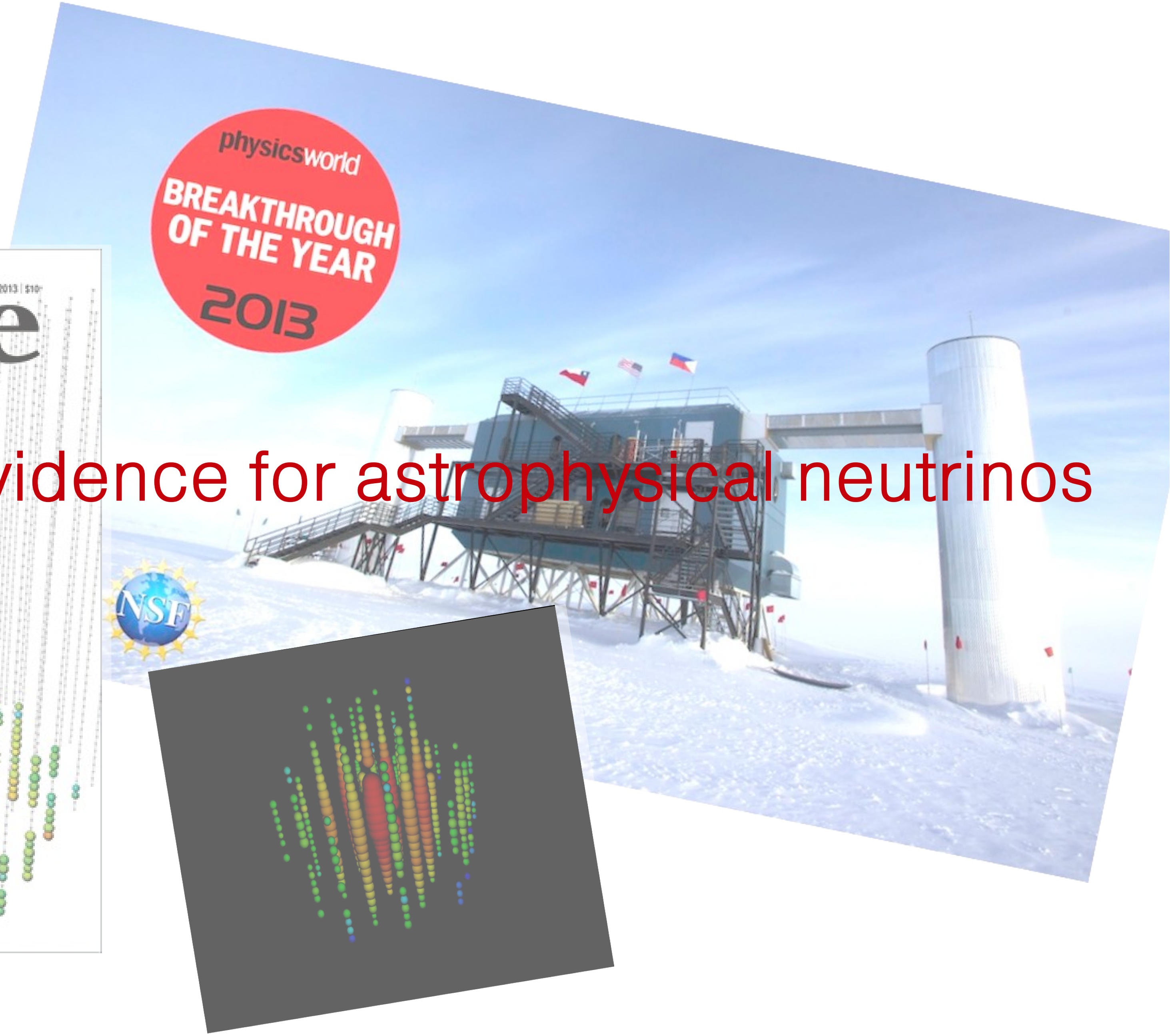
Ongoing efforts for a high-energy and a low-energy extensions

R&D efforts on new optical module designs

And what I have not talked about:

- monopole searches
- cosmic ray composition
- cosmic ray anisotropies
- extended-source searches
- exotic neutrino oscillation scenarios
- sterile neutrino searches
- SuperNovae searches
- TeV gravity searches
- Combined searches with CTAs, air-shower arrays and gravitational wave detectors
- ….

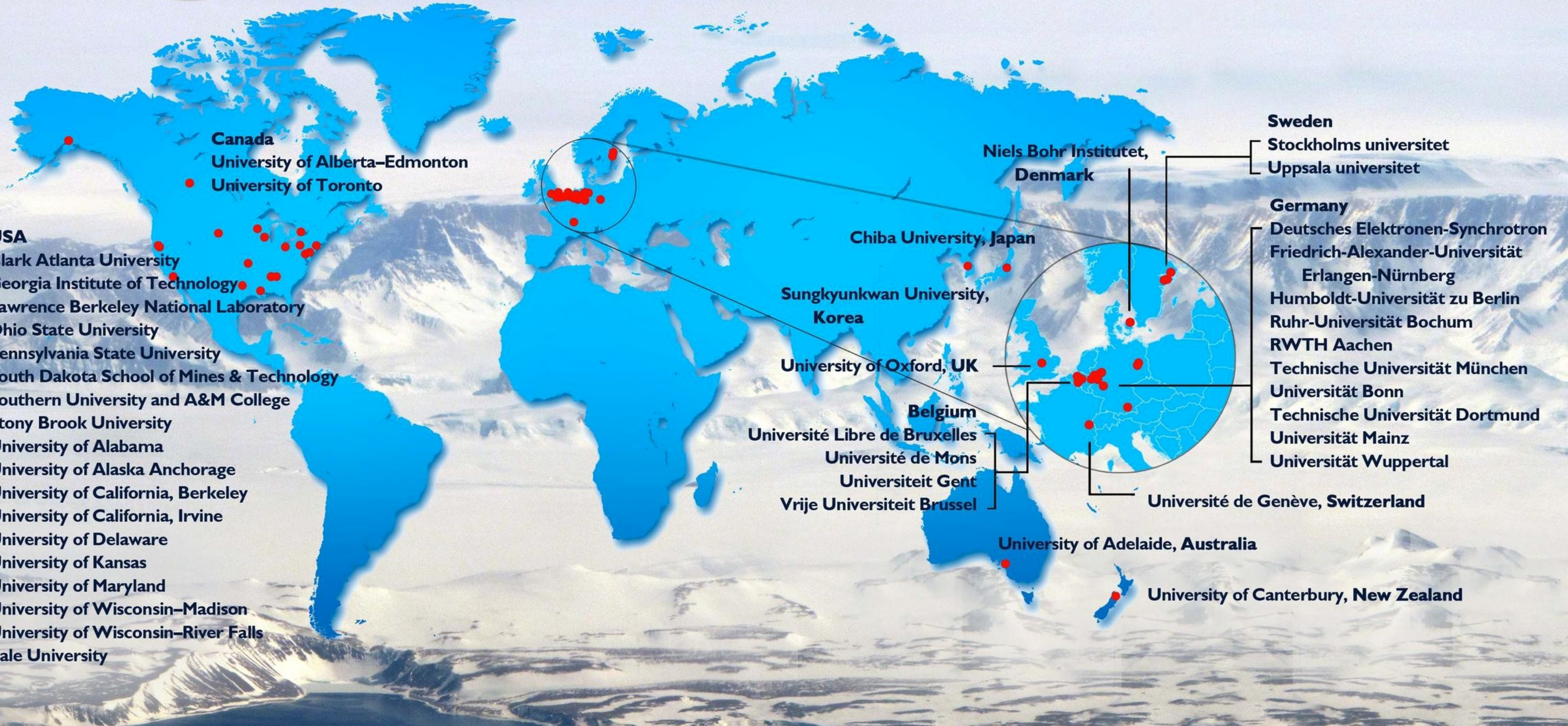




5.7 sigma evidence for astrophysical neutrinos

FIN

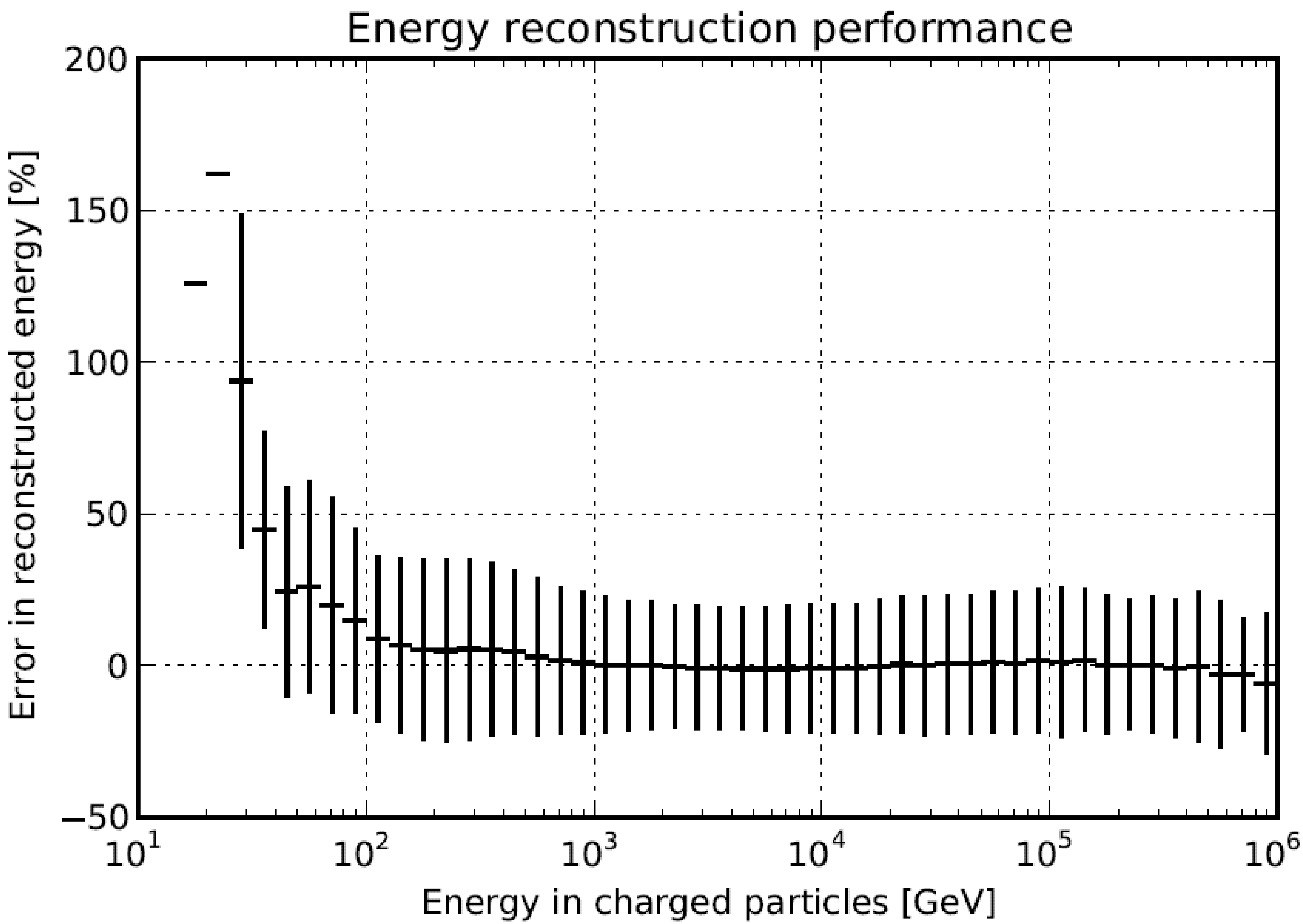
The IceCube Collaboration



Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Energy Reconstruction of EM Showers



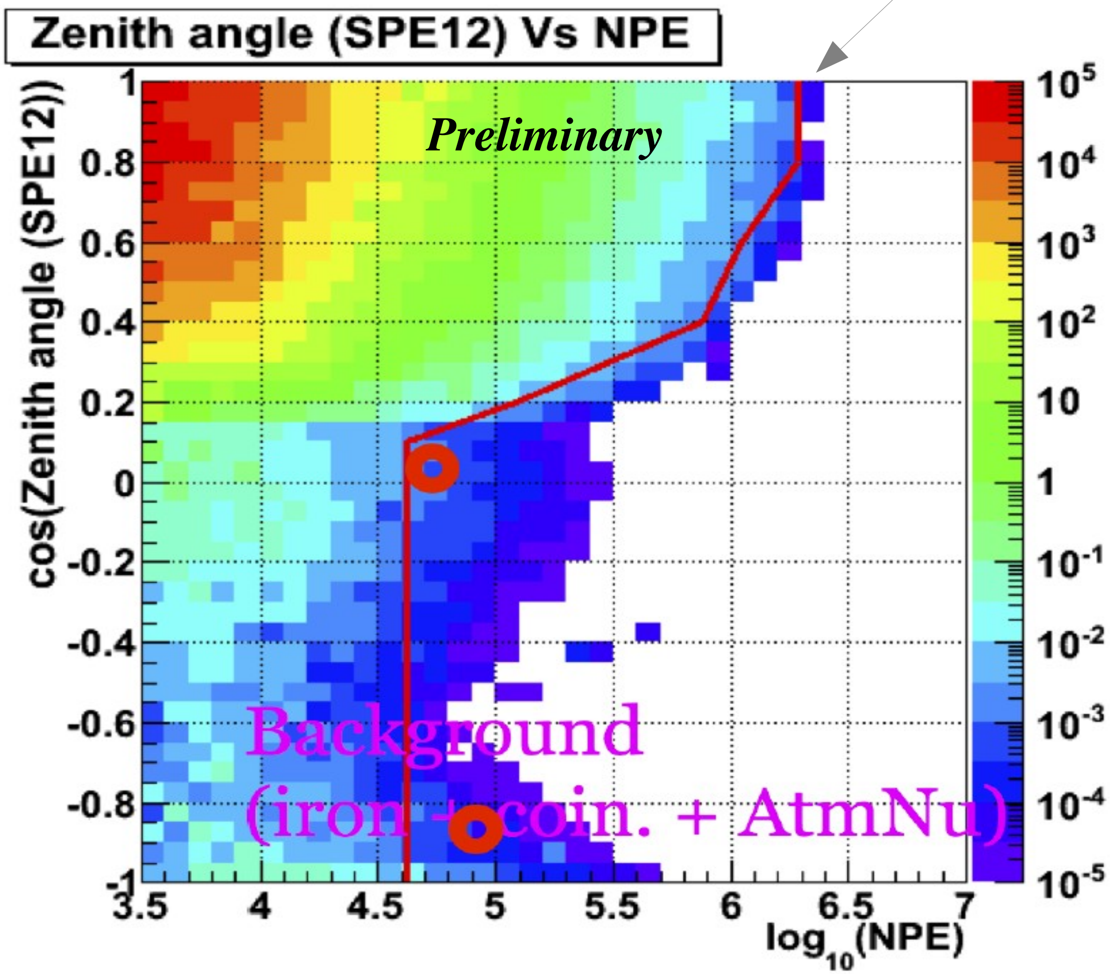
PRELIMINARY

cut used in the GZK analysis

downgoing

horizontal

upgoing



LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi{\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Background pdf:

$$\mathcal{B}_i = B(\theta_i) \cdot P_{atm}(E_i)$$

Likelihood:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Maximize wrt:

- γ, the neutrino spectral index
- $\mathbf{n_s}$, number of signal events

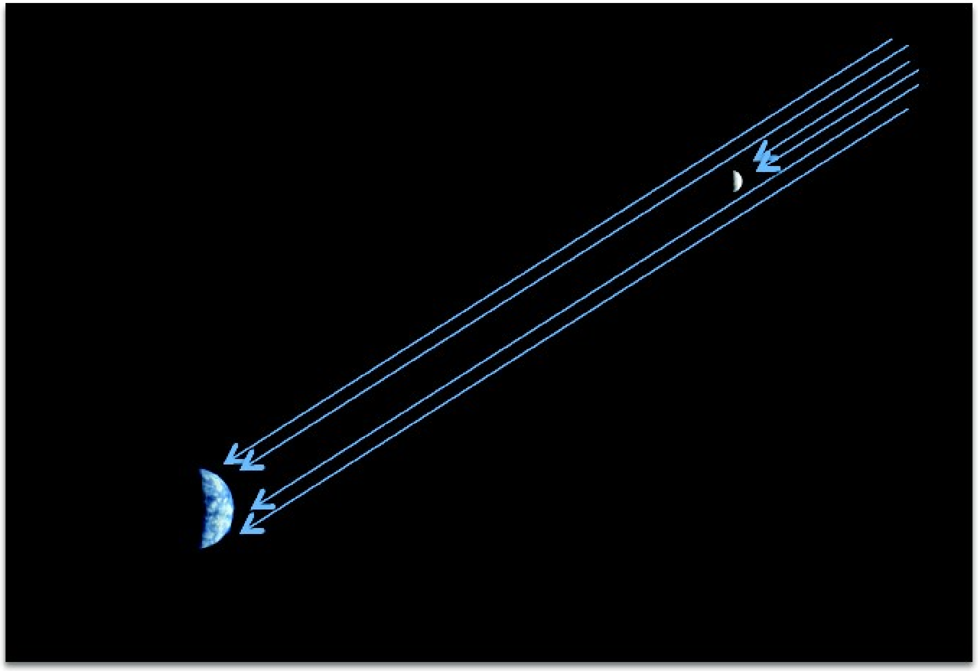
Maximization of the likelihood ratio:

$$\log \lambda = \log \left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Estimates that maximize the Likelihood

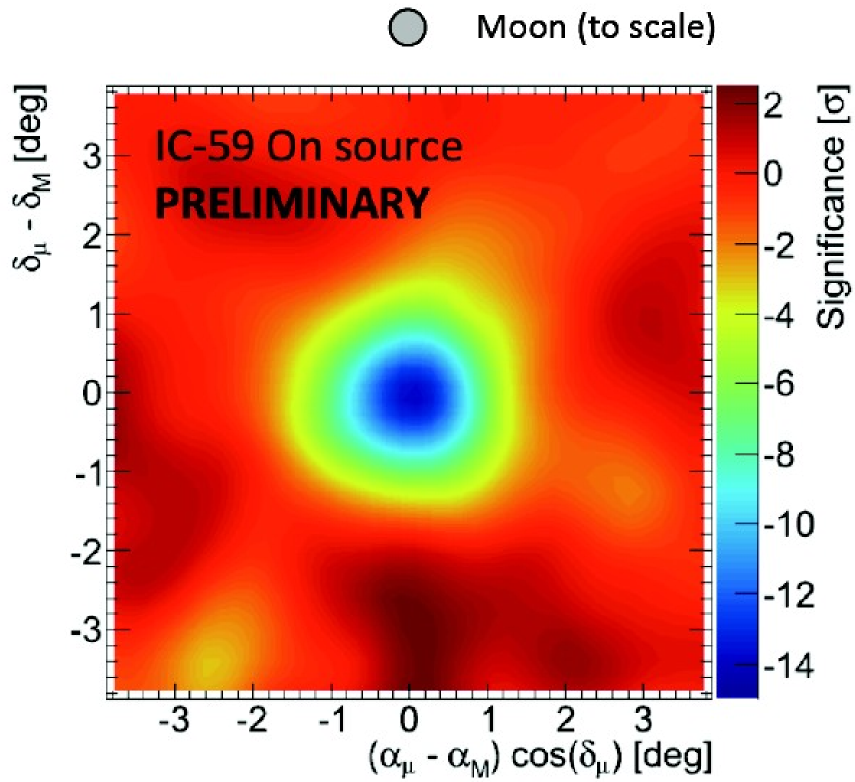
The final significance is determined by scrambling the data in r.a. and repeating the analysis.

Cosmic Ray Moon Shadow



Cosmic rays are blocked by the moon (radius 0.25°)

Causes small point-like deficit of cosmic ray showers detected by IceCube



Spoiler alert: there are no neutrino sources bright enough to calibrate pointing with!

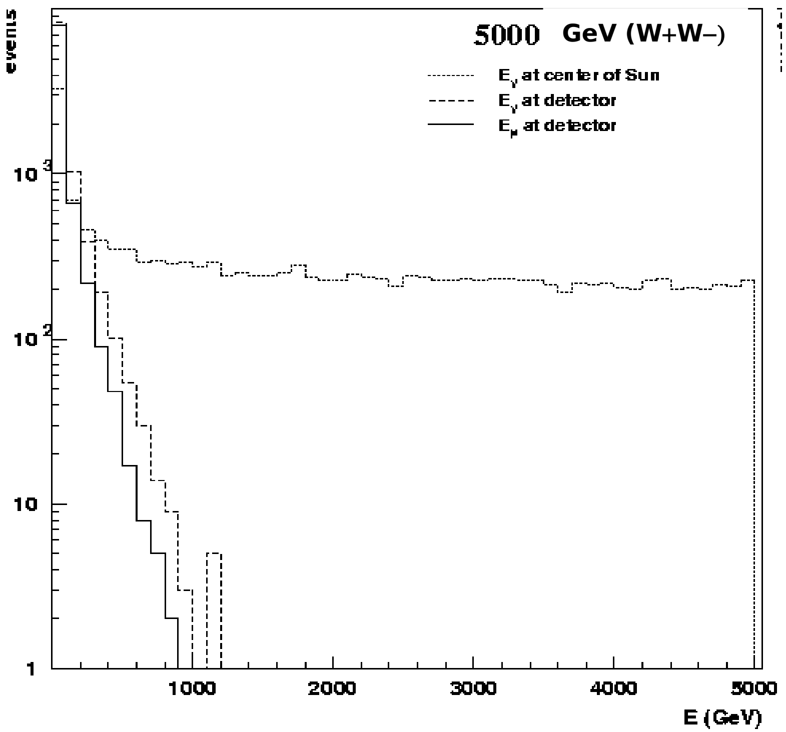
But, cosmic ray moon shadow "negative" source is used to verify:

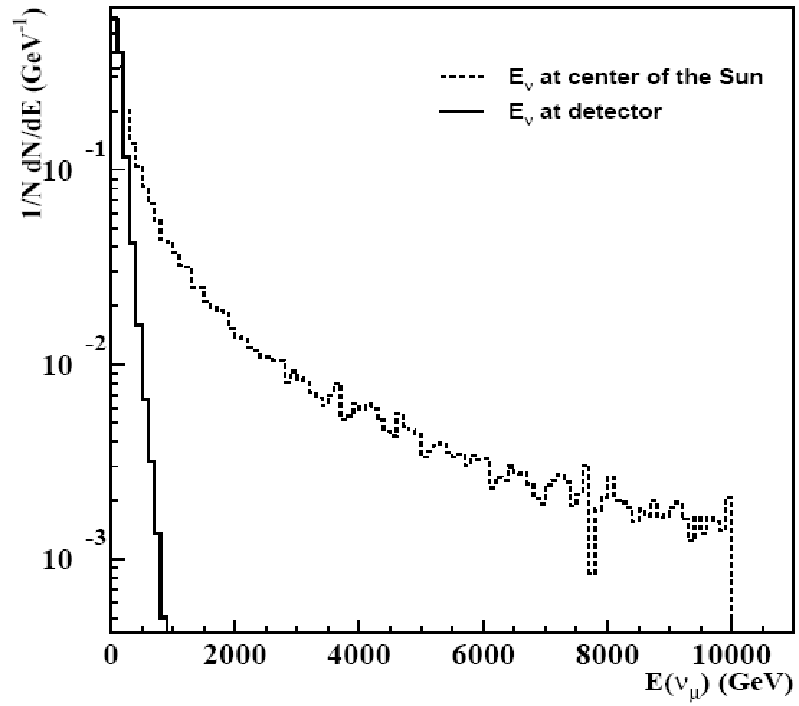
- absolute pointing is correct
- ~1° typical point spread function (size of deficit and shape agree with sim.)

searches from the Sun: neutrino energies at the detector

5000 GeV Neutralino → WW @ Sun

Simpzilla → $t\bar{t}$ @ Sun





: Indirect dark matter searches from the **Sun** are a low-energy analysis in neutrino telescopes: even for the highest DM masses, we do not get muons above few 100 GeV

Not such effect for the Earth and Halo (no ν energy losses in dense medium)

N_{data}, N_{bck}

Ψ_{data}, Ψ_{bck}

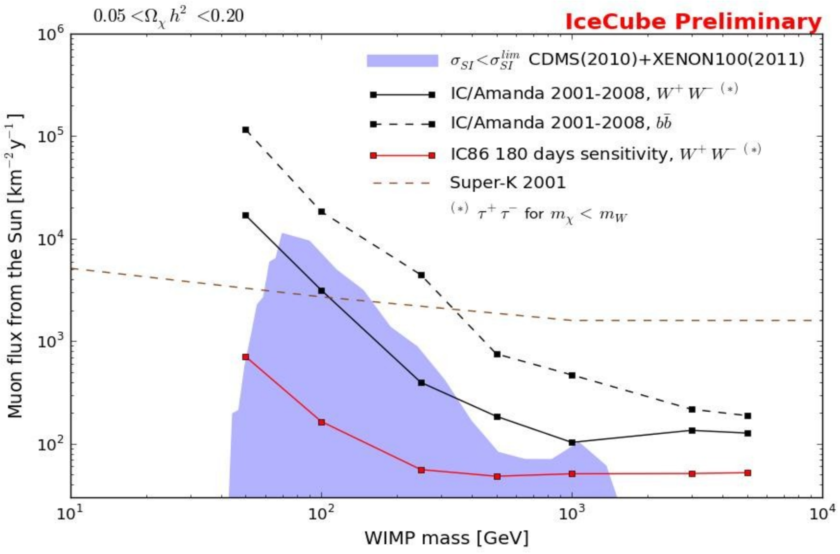
$\rightarrow N_{90}$ $\longrightarrow$ $\Gamma_{\nu\mu} \leqslant \frac{N_{90}}{V_{eff} \cdot t}$

Experimentally obtained quantity: allowed number of signal events still compatible with background, at 90% confidence level

Use model to convert to a muon flux

$$\Gamma_{\nu\mu}(m_\chi) = \Gamma_A \cdot \frac{1}{4\pi R_\oplus^2} \int_0^{m_\chi} \sum B_{\chi\bar{\chi}\to X} \left(\frac{dN_\nu}{dE_\nu}\right) \times \sigma_{\nu+N\to\mu+\ldots}(E_\nu | E_\mu \geqslant E_{thr})\, \rho_N\, dE_\nu$$

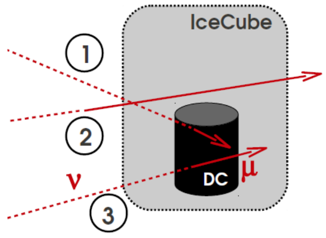
$$\longrightarrow \quad \phi_\mu(E_\mu \geqslant E_{thr}) = \frac{\Gamma_A}{4\pi D_\odot^2} \int_{E_{thr}}^{\infty} dE_\mu \frac{dN_\mu}{dE_\mu}$$



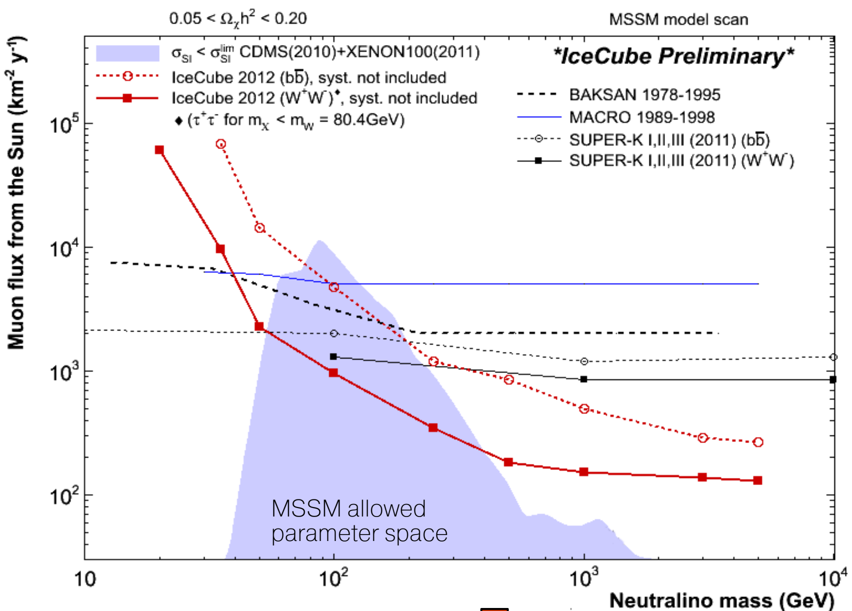
IceCube results from 317 days of livetime between 2010-2011:

All-year round search:

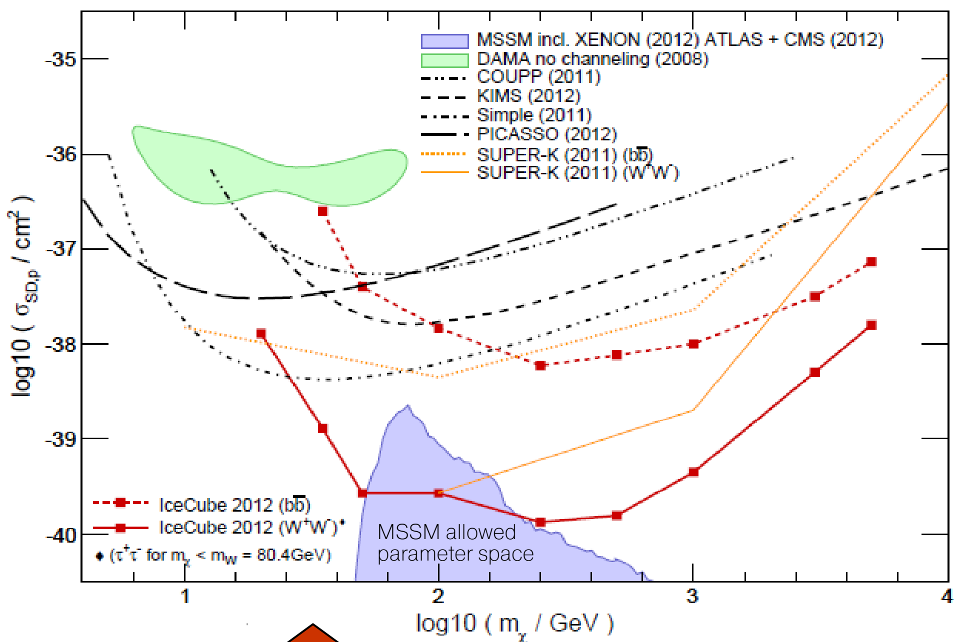
Extend the search to the southern hemisphere by selecting starting events
→ Veto background through location of interaction vertex
- muon background: downgoing, no starting track
- WIMP signal: require interaction vertex within detector volume



90% CL **muon flux limit** from the Sun



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



$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$$

(particle physics and solar model)

Assume (ie. model dependent) effective quark-DM interaction,

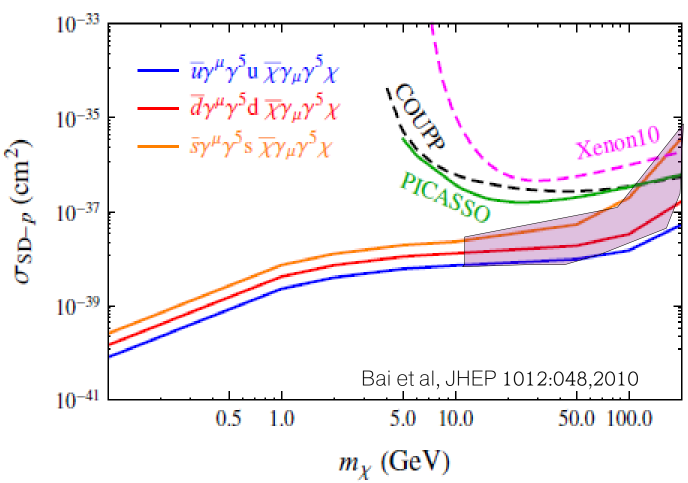
$$\lambda^2/\Lambda^2\,(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$$

and look for monojets in $p\bar{p}$ collisions,

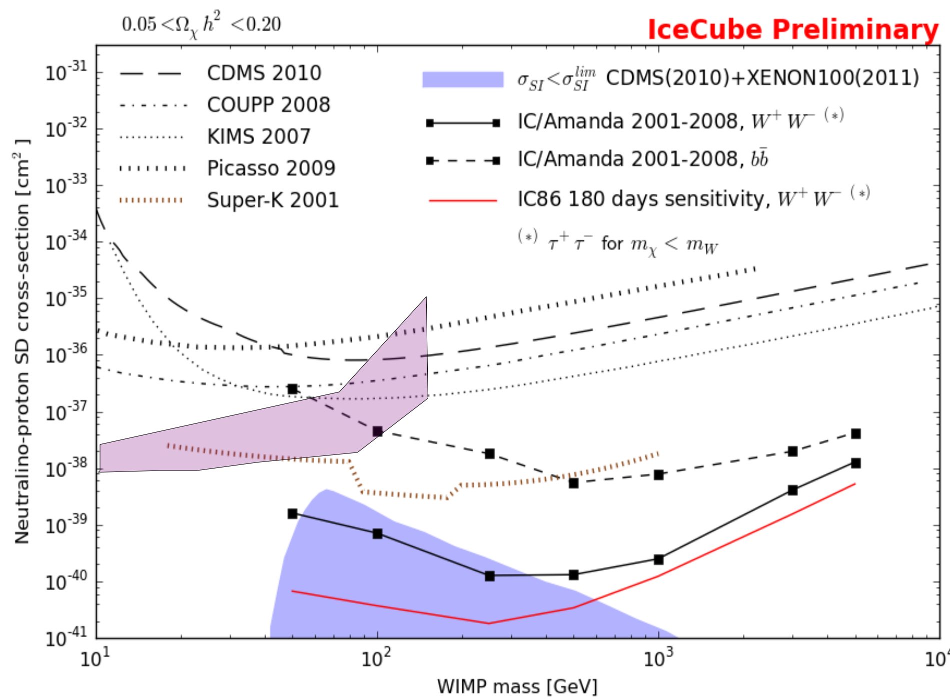
$$p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$$

(as opposed to the SM process $p\bar{p} \rightarrow Z$+jet and $p\bar{p} \rightarrow W$+jet)

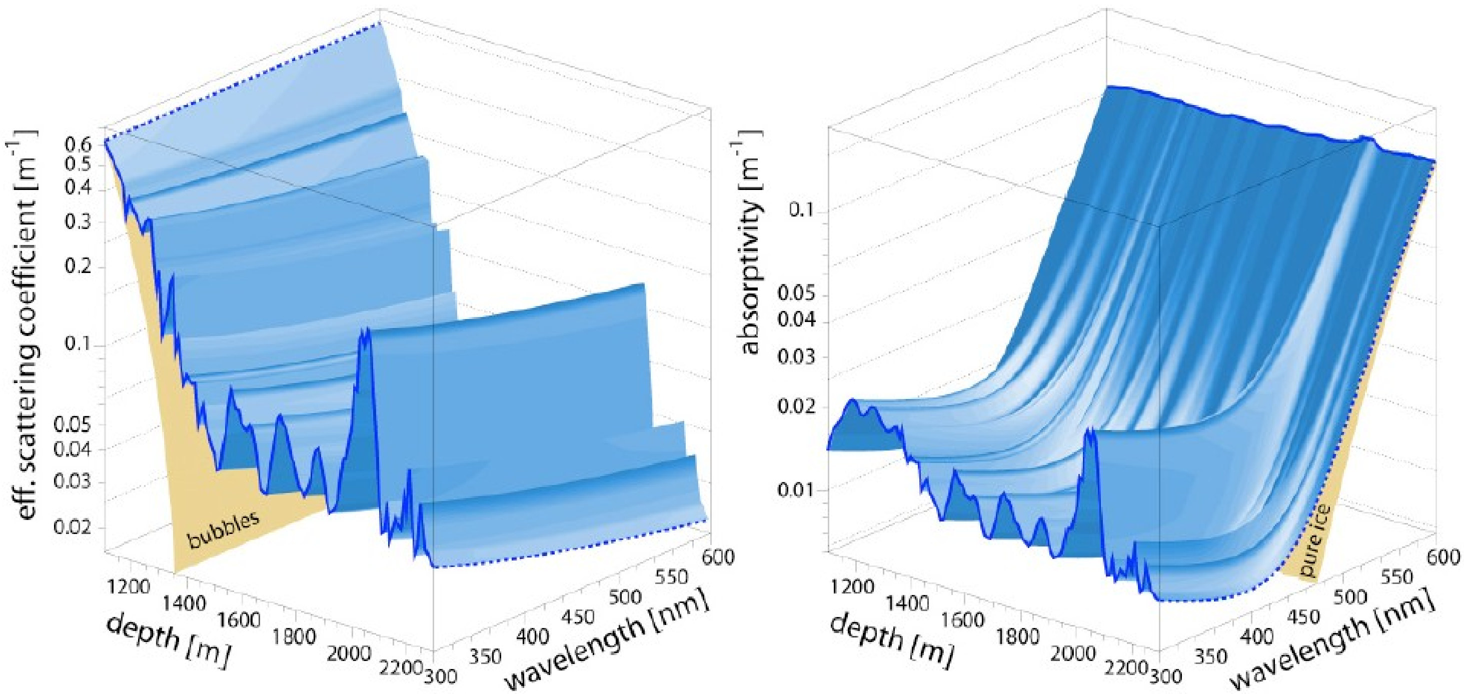
Constrains from monojet searches at the TeVatron:



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



- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $<\lambda_{eff}>$ ~ 47 m, $<\lambda_{abs}>$ ~ 155 m



- Constant temperature ~ -35C