ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

High-energy neutrino astronomy with IceCube

(neutrinos from dark matter annihilation?)

Gary C. Hill
University of Adelaide

CoEPP-CAASTRO Dark Matter Workshop, Sep 29 2014

THE UNIVERSITY of ADELAIDE

Photograph: Forest Banks

IceCube

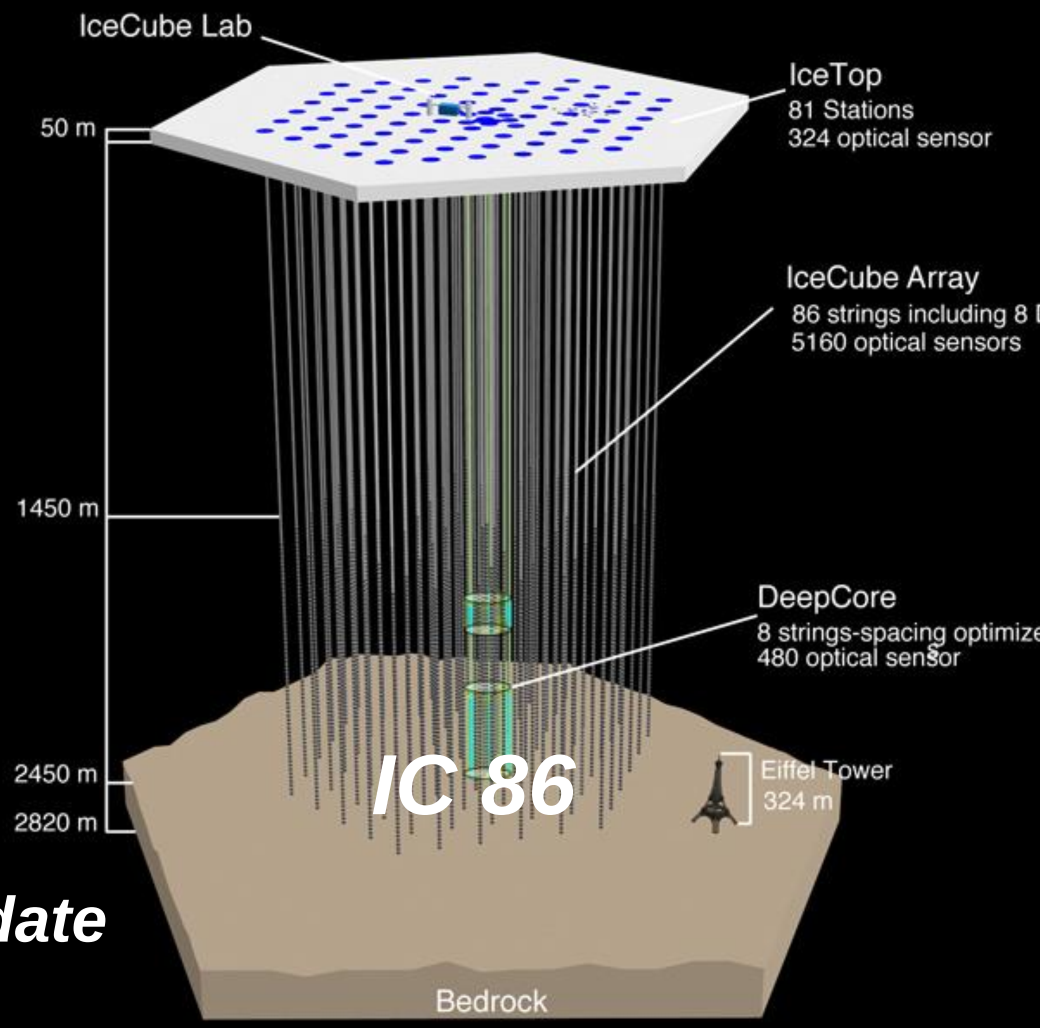
IceTop

Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

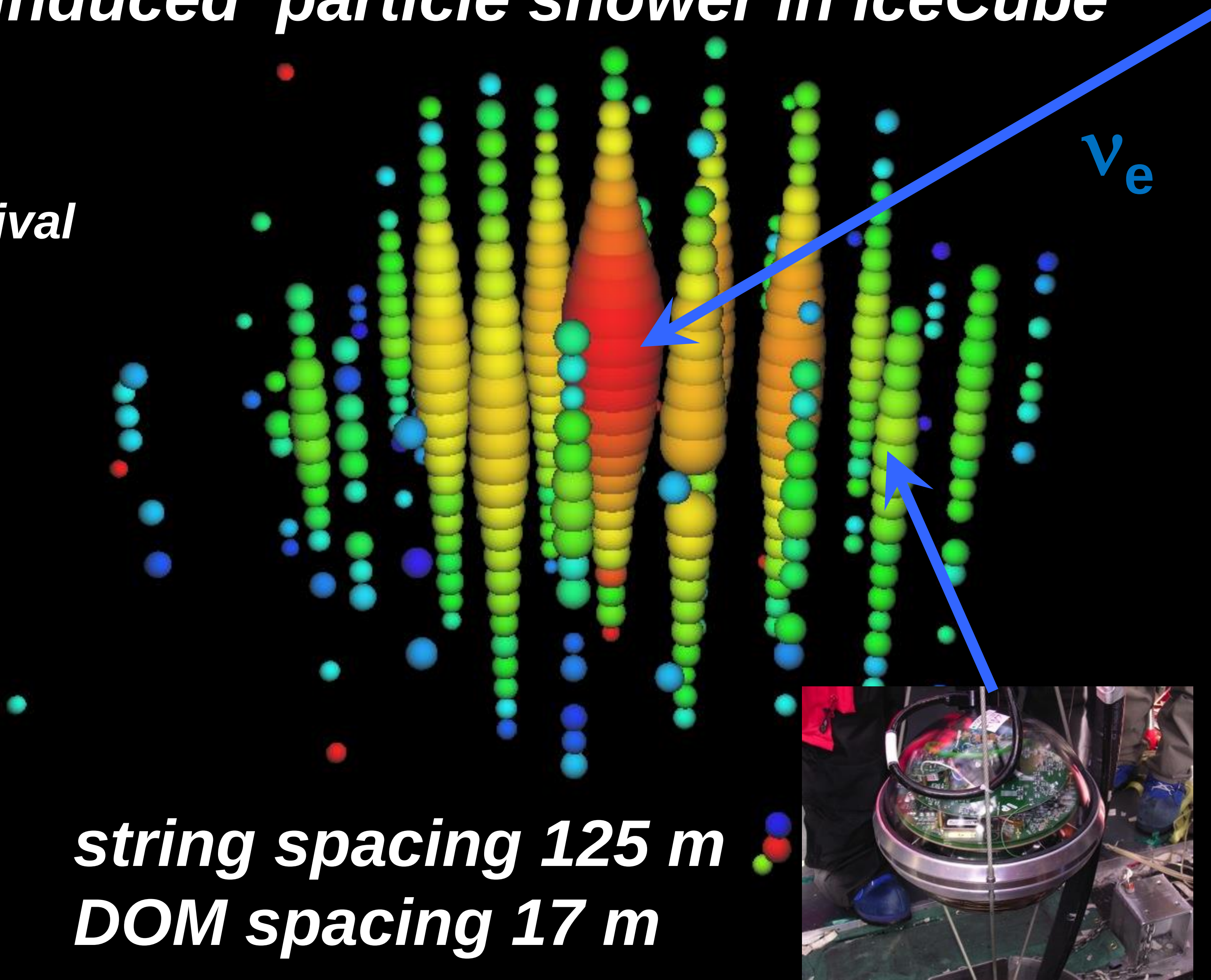
Partial detectors analysed:
IC40, IC59, IC79

Full detector:
IC86, 3 ½ years running to date
HESE: IC79/86-1
HESE-2: IC79/86-1/86-2

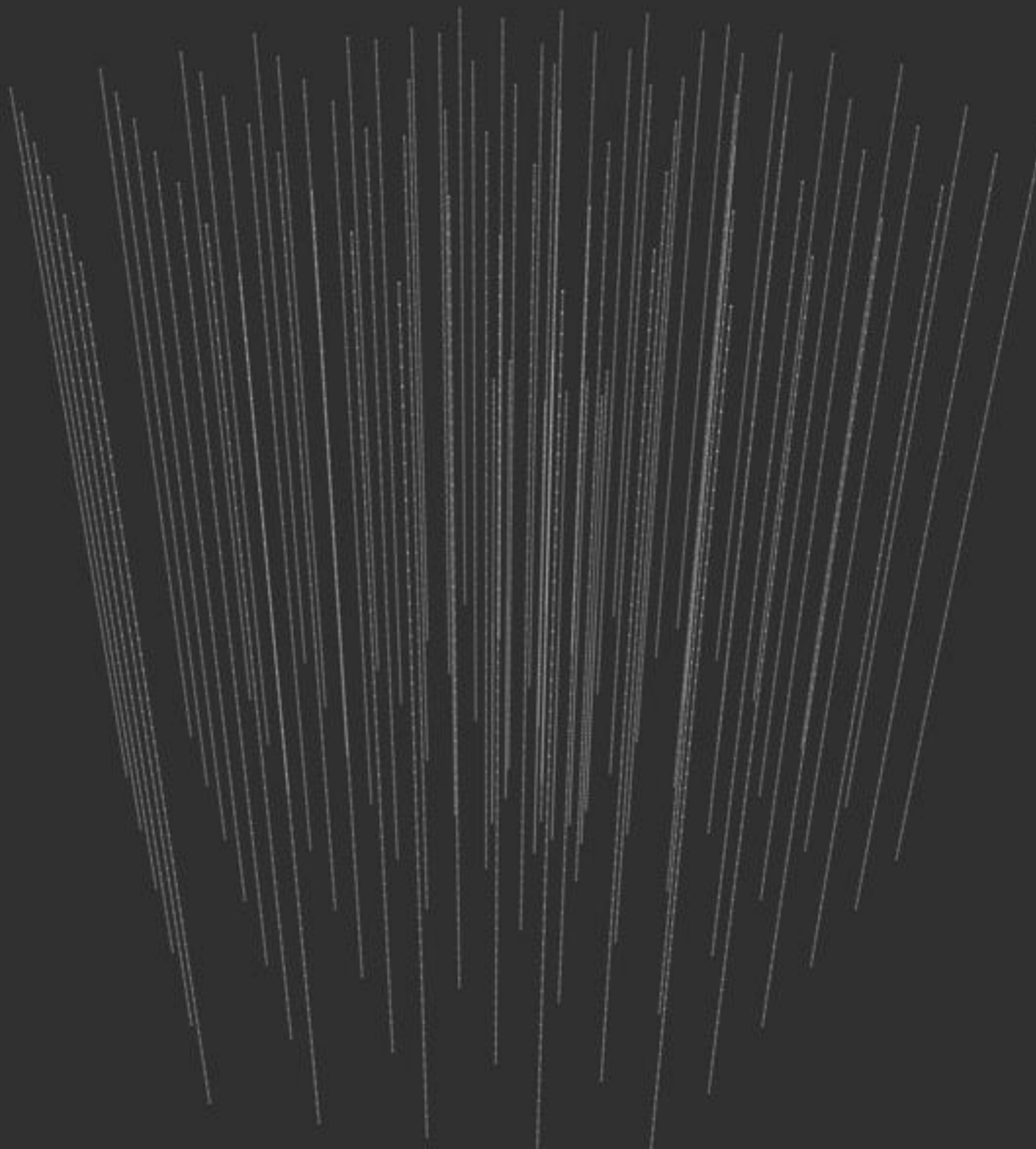


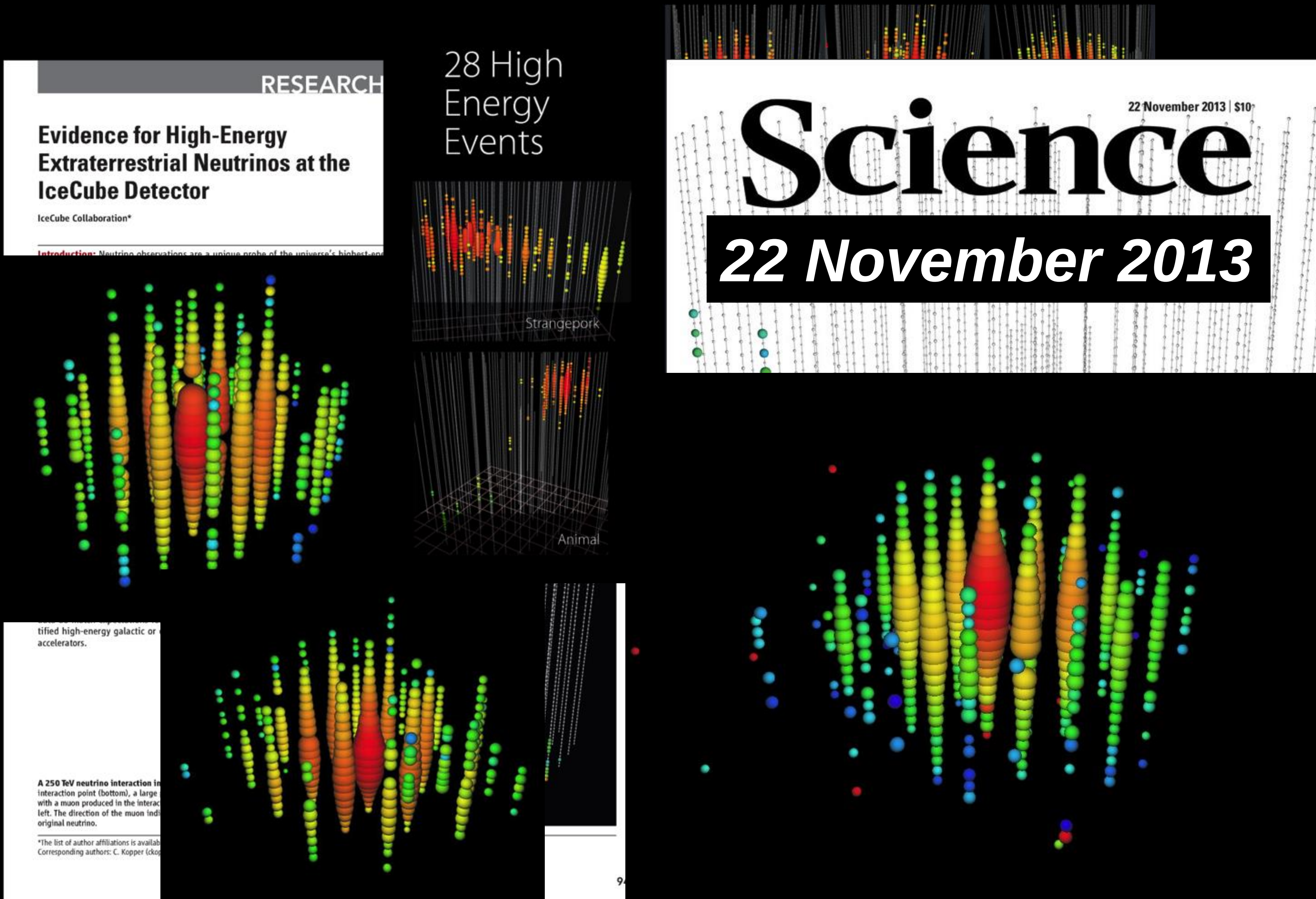
Cherenkov light from a 2 PeV neutrino induced particle shower in IceCube

photon arrival timings:
red - early
yellow
orange
green
blue - late



string spacing 125 m
DOM spacing 17 m



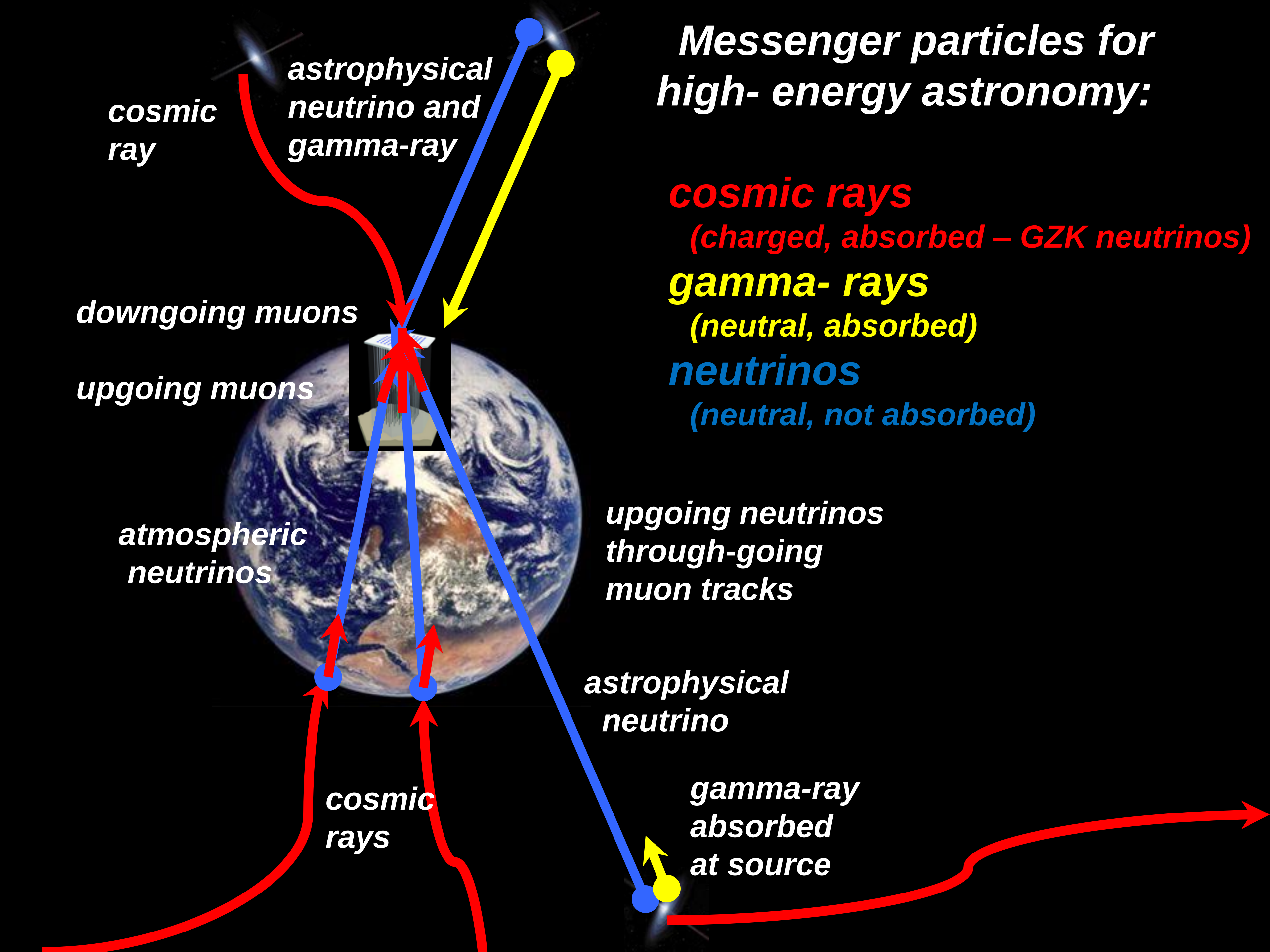

RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
22 November 2013
accelerators.

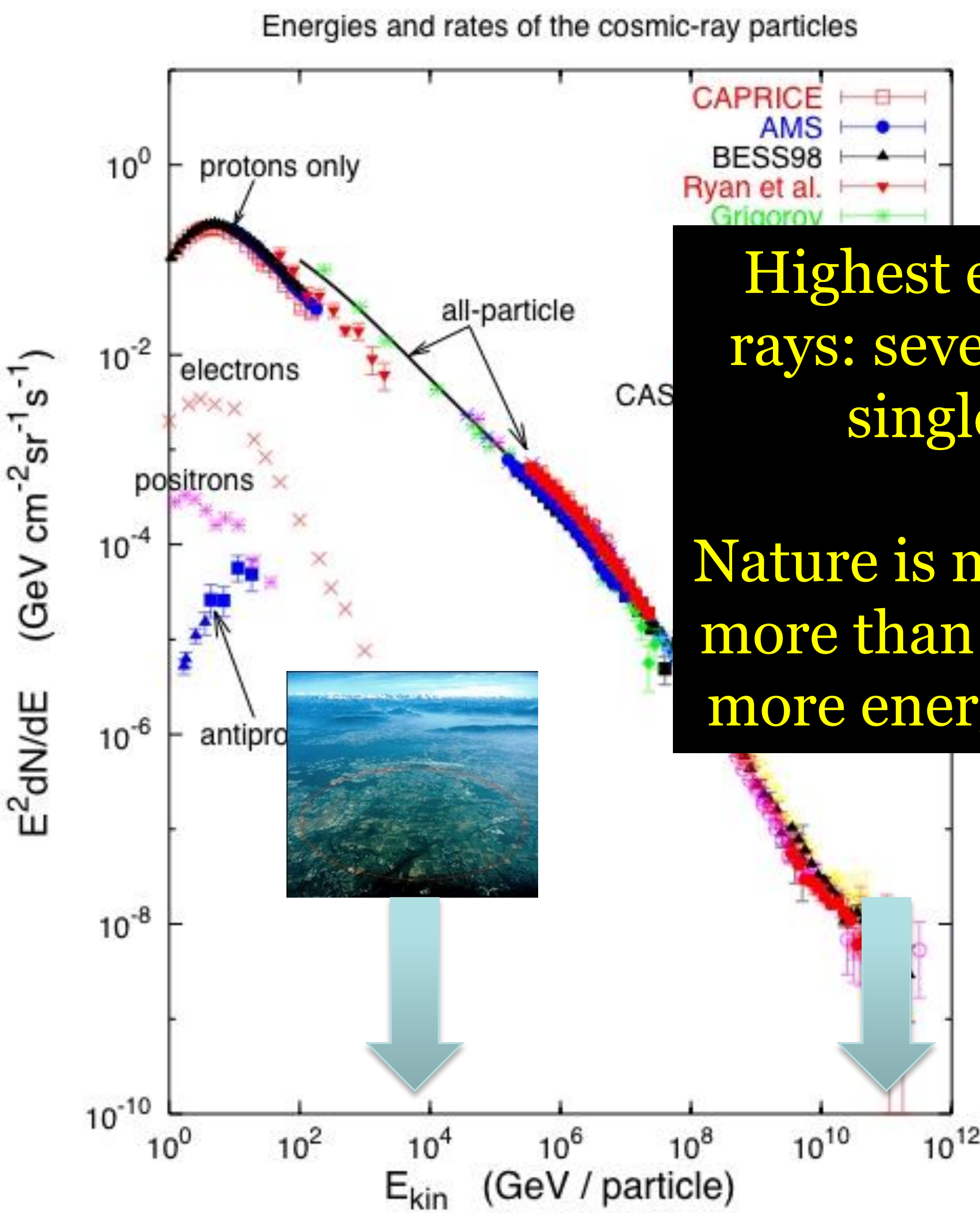
Messenger particles for high- energy astronomy:

cosmic rays
(charged, absorbed – GZK neutrinos)

gamma- rays
(neutral, absorbed)

neutrinos
(neutral, not absorbed)





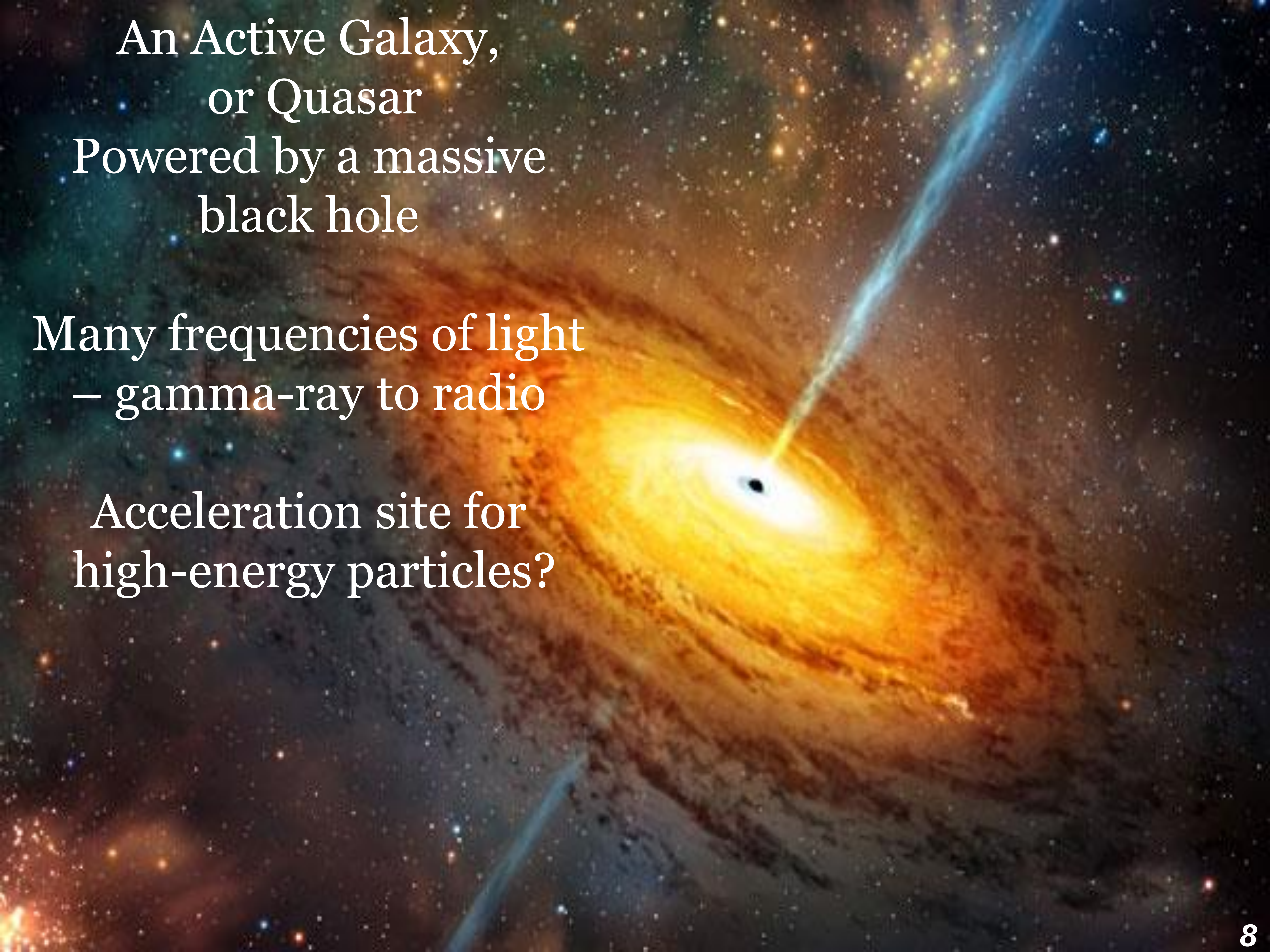
Highest energy cosmic rays: several Joules in a single particle!

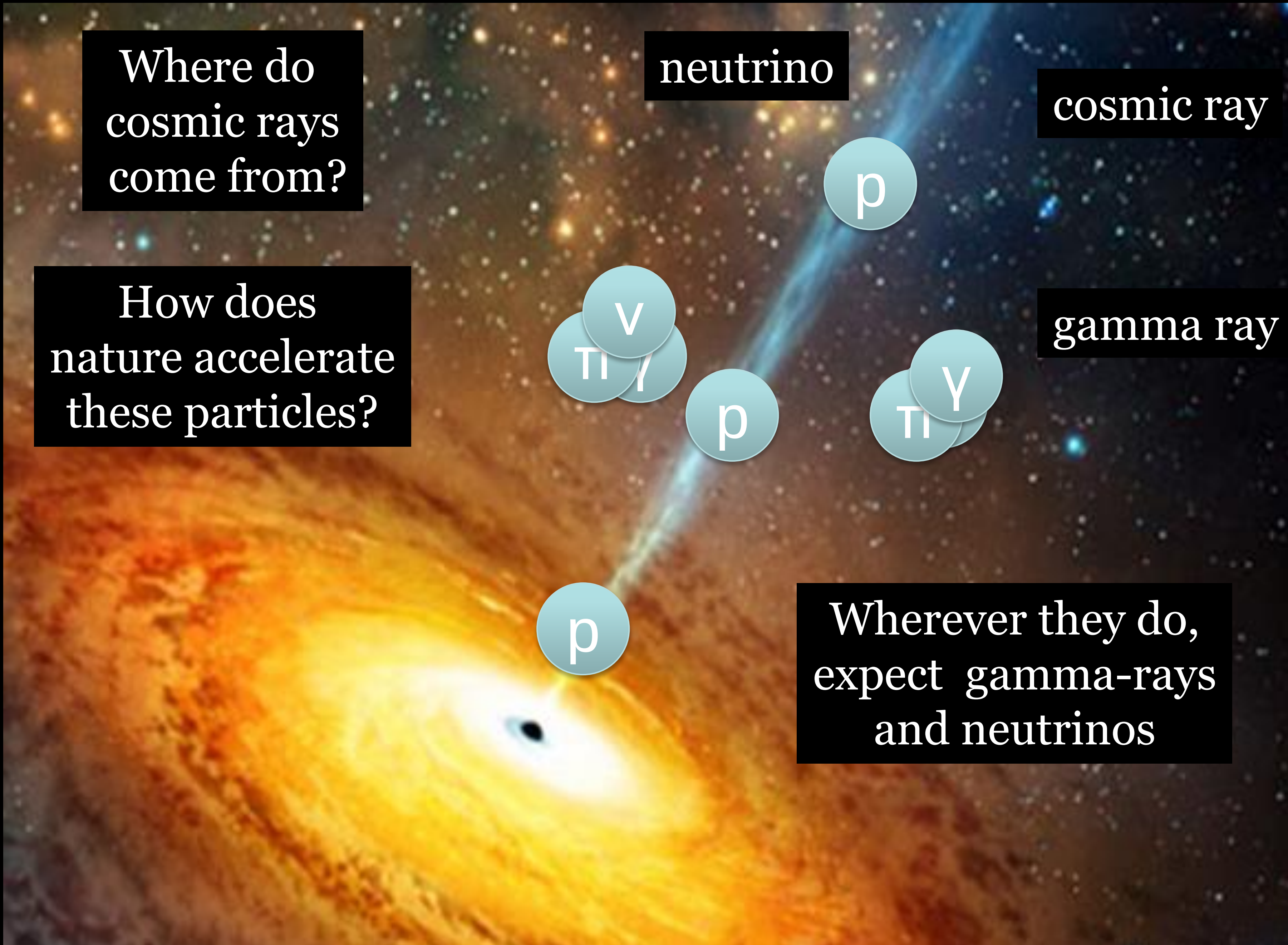
Nature is making particles more than a million times more energetic than LHC

An Active Galaxy,
or Quasar
Powered by a massive
black hole

Many frequencies of light
– gamma-ray to radio

Acceleration site for
high-energy particles?




Where do cosmic rays come from?
neutrino
cosmic ray
p
How does nature accelerate these particles?
ν
π
p
gamma ray
γ
π
p
Wherever they do, expect gamma-rays and neutrinos

Neutrino and gamma production in cosmic ray accelerators?

$$pp, p\gamma \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

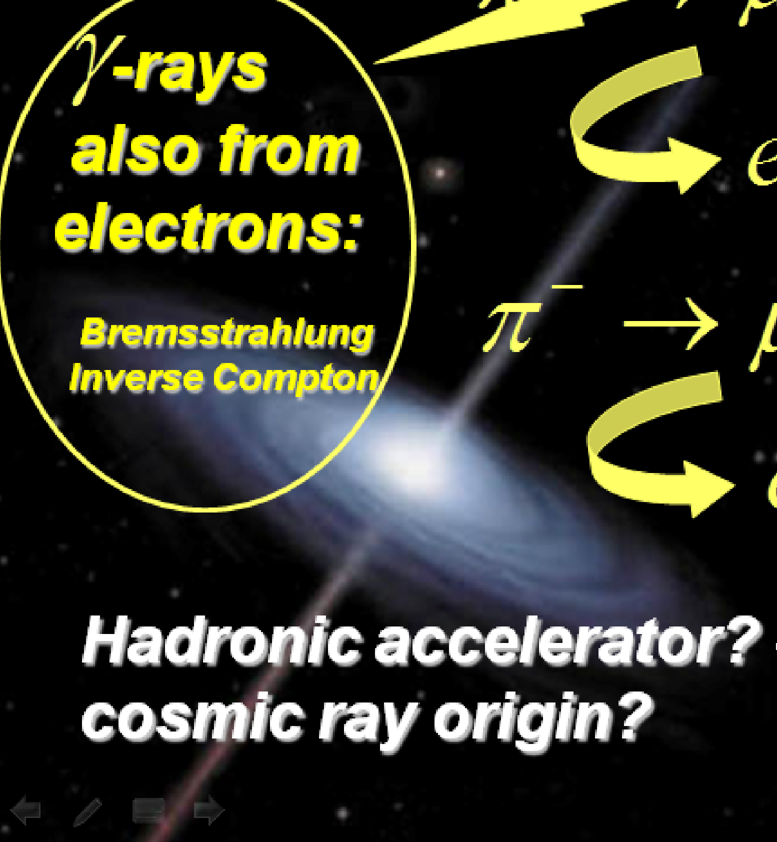
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

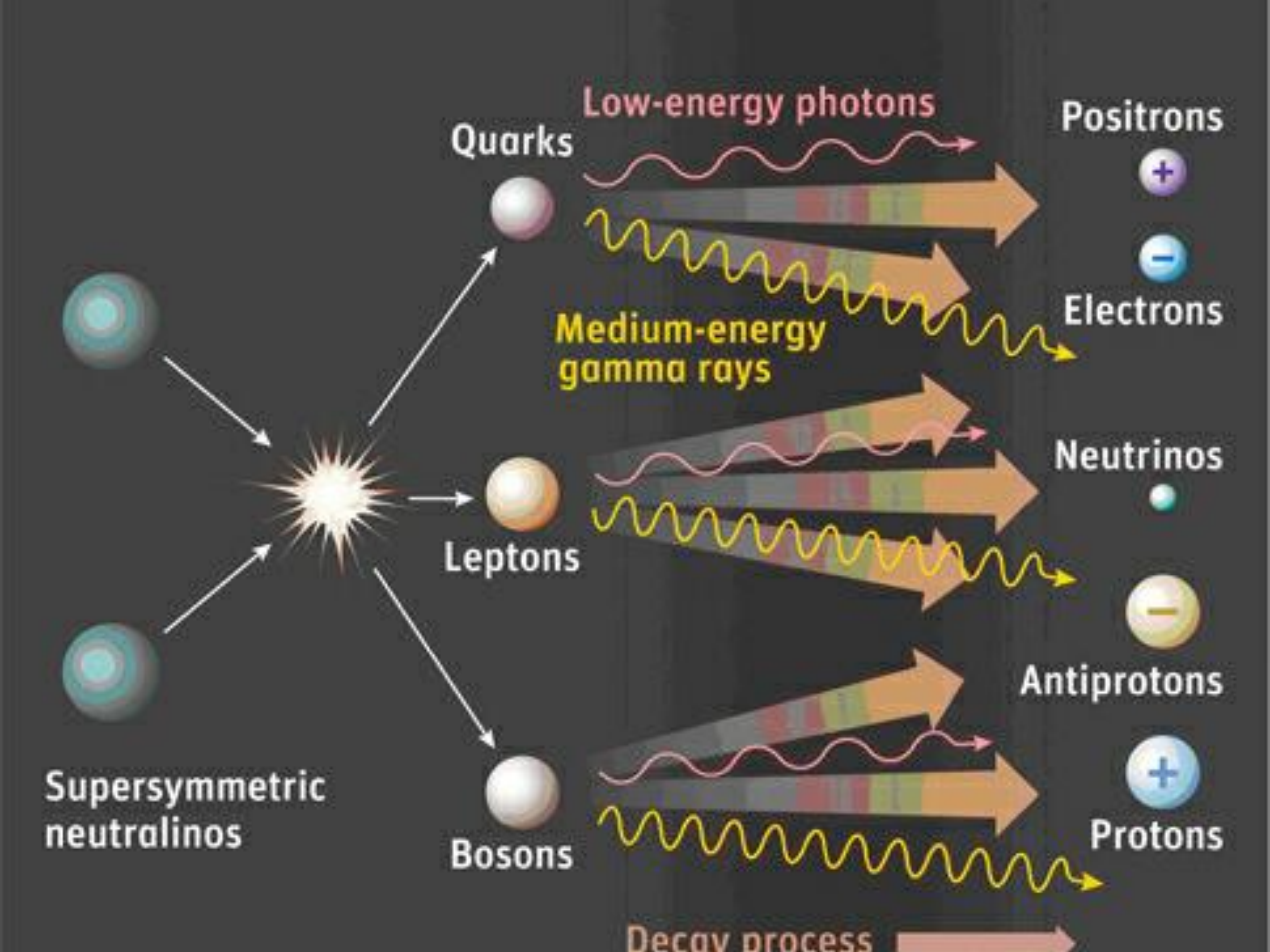
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

The TeV gammas?

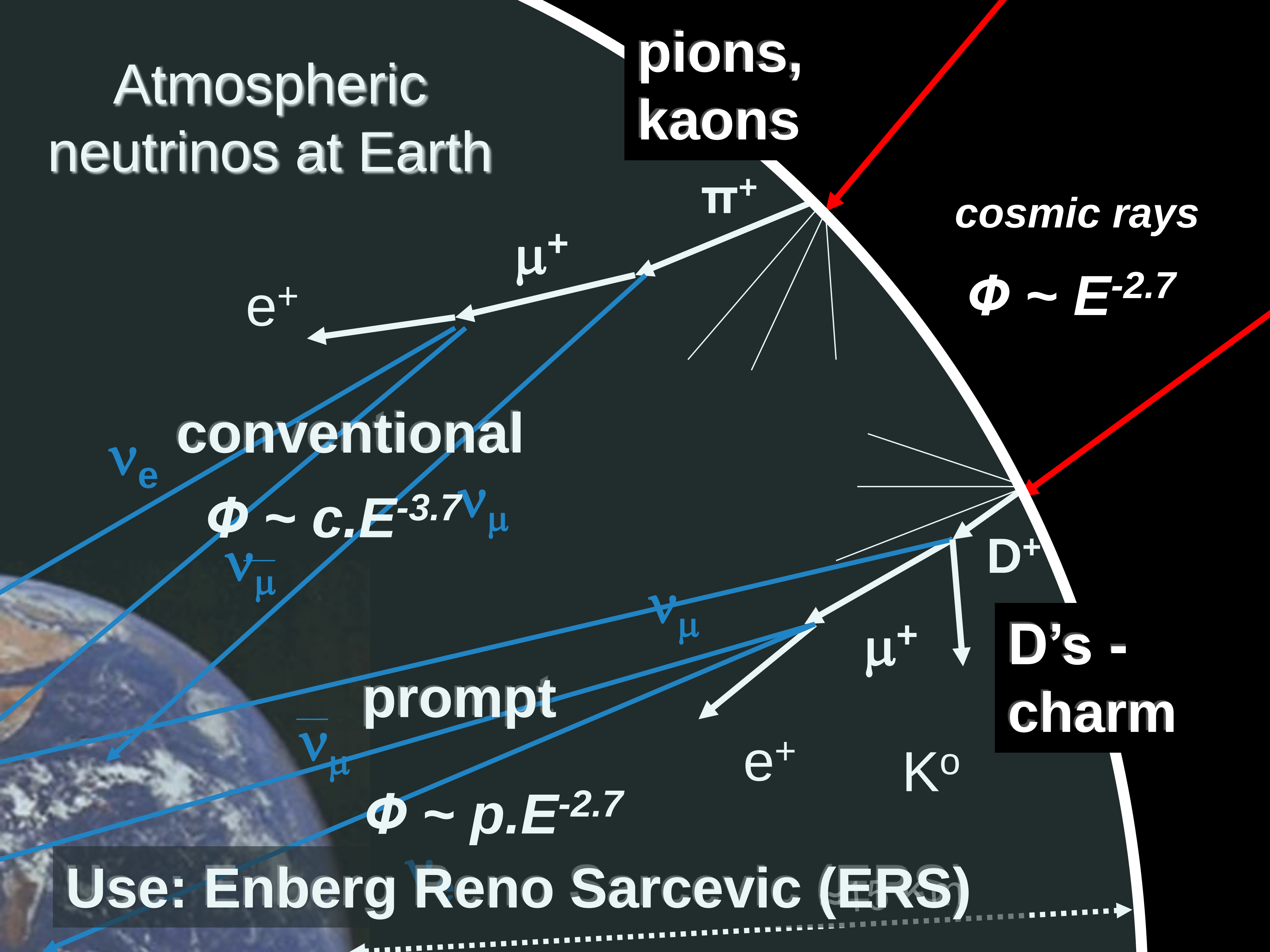
Let's look for these neutrinos!



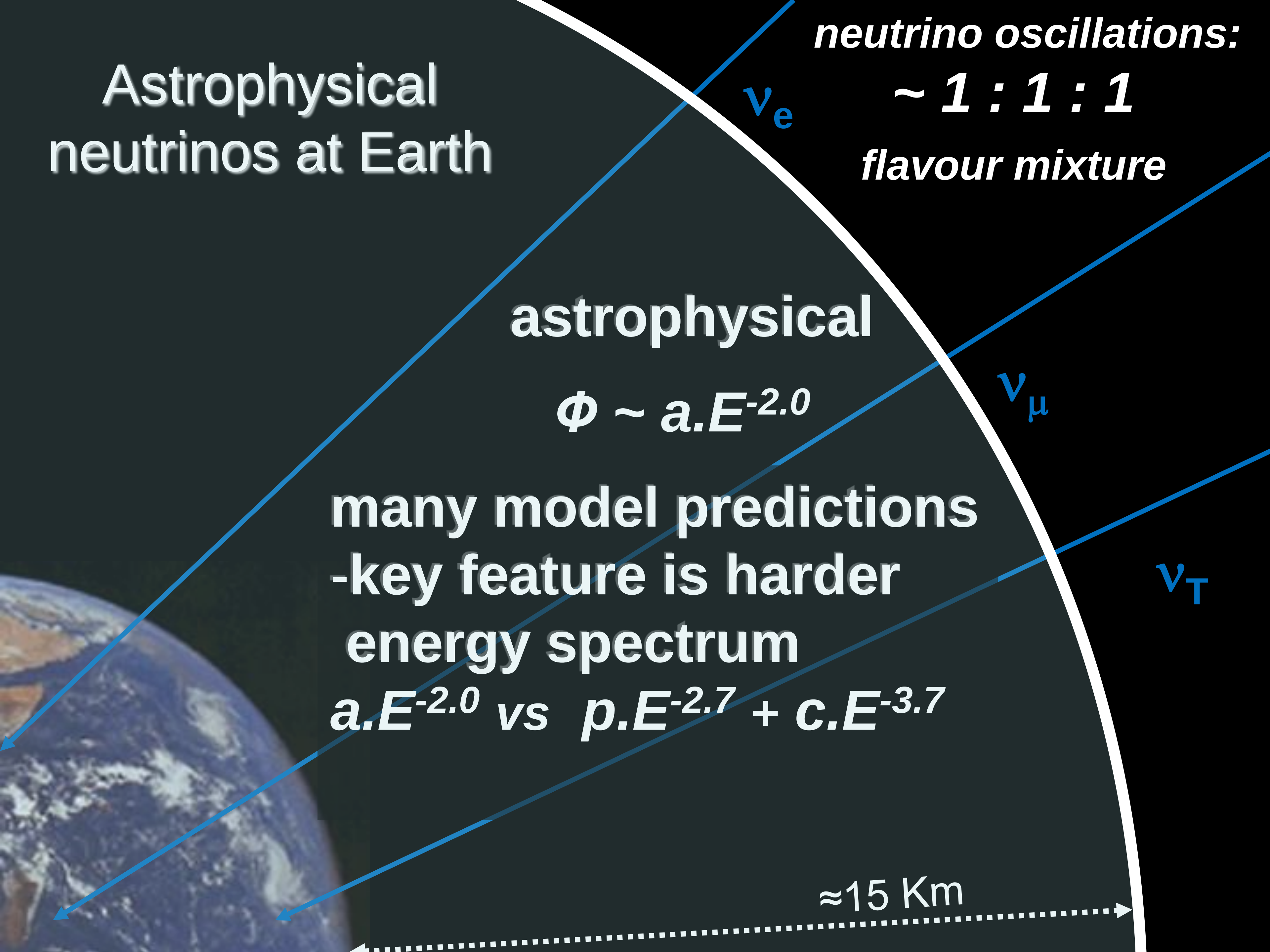
Hadronic accelerator? – cosmic ray origin?



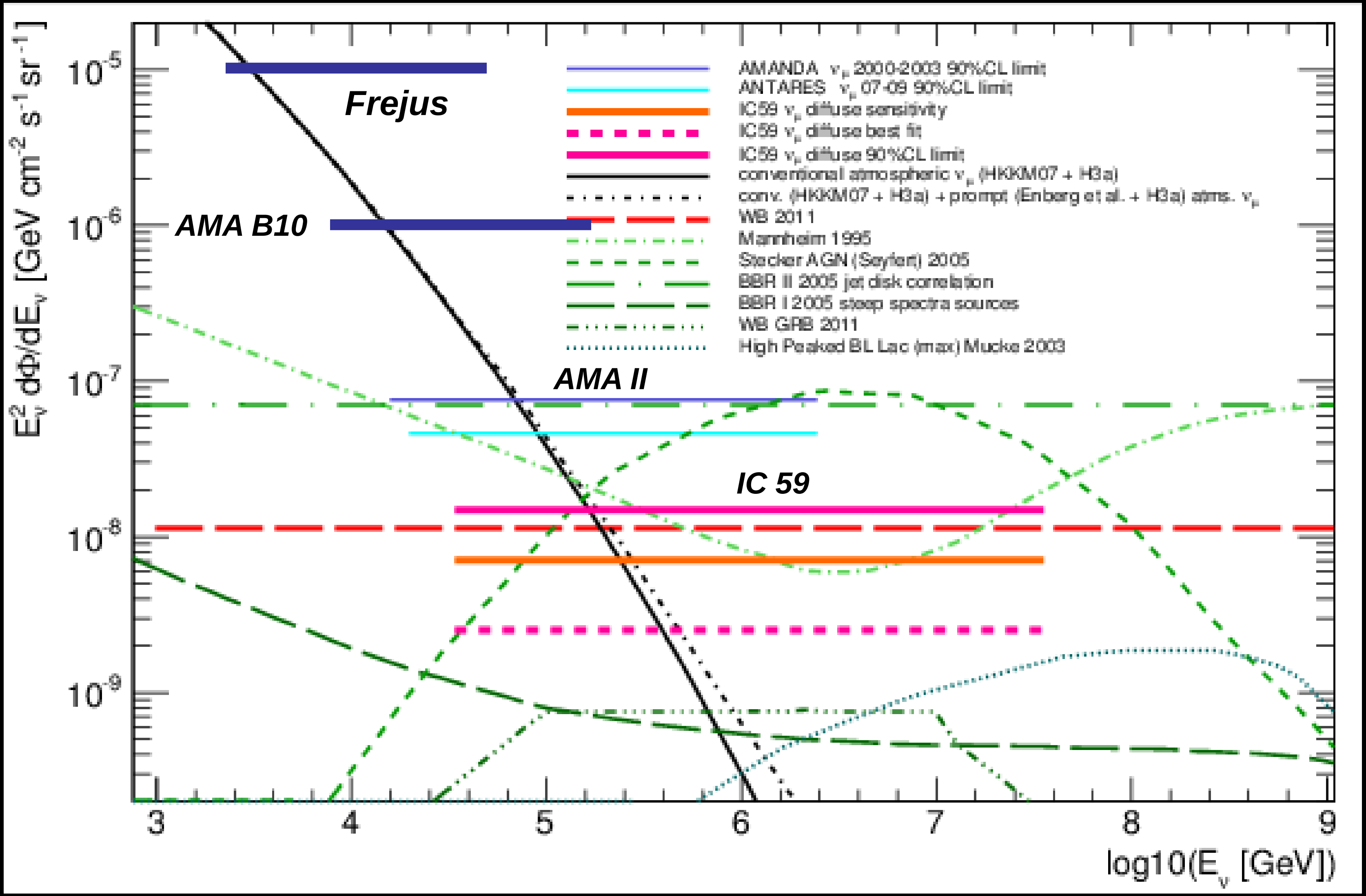
Low-energy photons
Quarks
Positrons
Electrons
Medium-energy gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric neutralinos
Bosons
Protons
Decay process

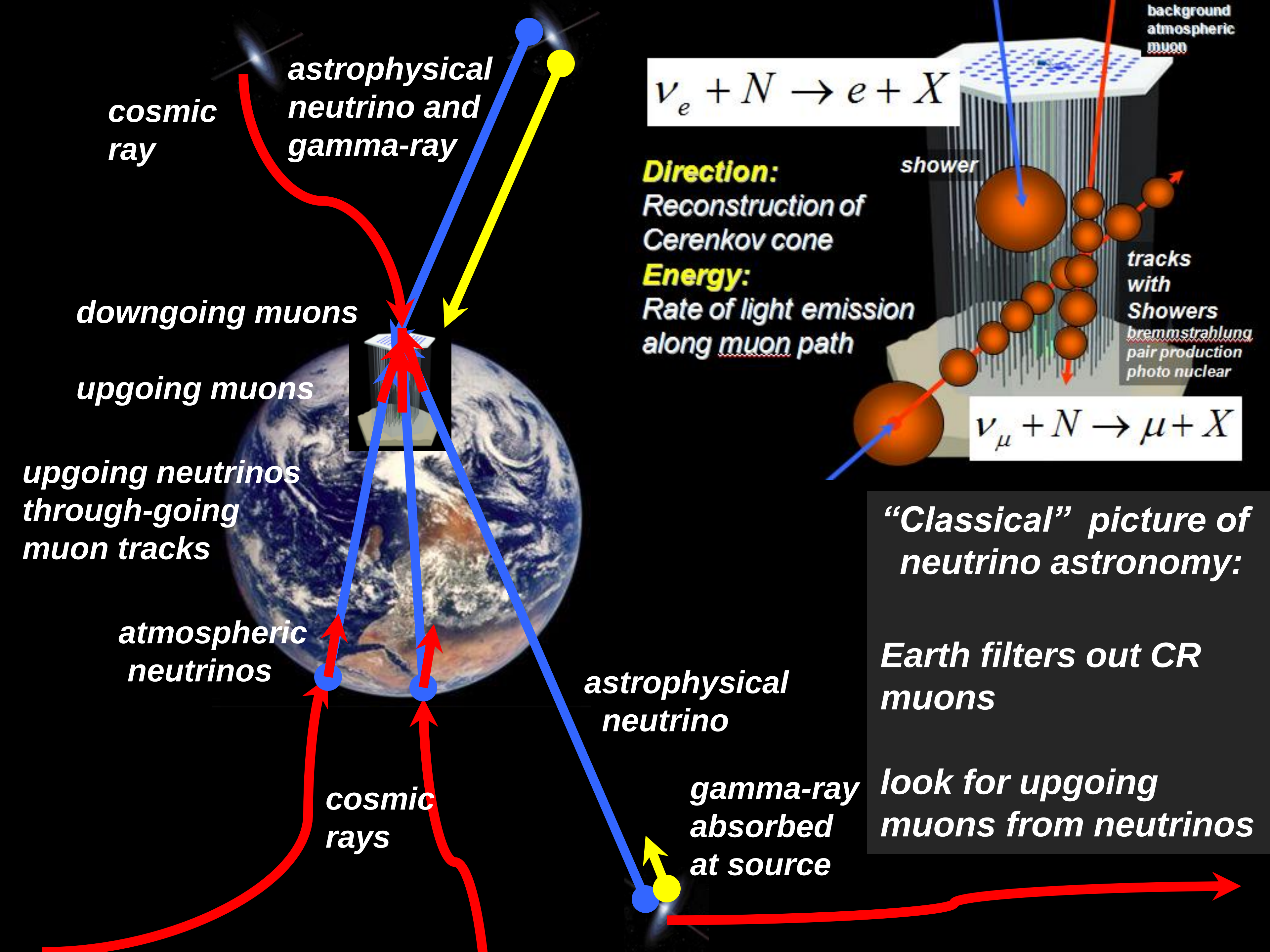


Atmospheric neutrinos at Earth
pions, kaons
cosmic rays
Φ ~ E^-2.7
π+
μ+
e+
conventional
νe
Φ ~ c.E^-3.7
νμ
ν̄μ
D+
νμ
μ+
D's - charm
prompt
ν̄μ
e+
Ko
Φ ~ p.E^-2.7
Use: Enberg Reno Sarcevic (ERS)


Astrophysical neutrinos at Earth
neutrino oscillations:
~ 1 : 1 : 1
flavour mixture
ν_e
ν_μ
ν_τ
astrophysical
$\Phi \sim a.E^{-2.0}$
many model predictions
-key feature is harder energy spectrum
$a.E^{-2.0}$ vs $p.E^{-2.7} + c.E^{-3.7}$
≈15 Km

The high-energy neutrino sky, a little history from Frejus to IceCube-59





“Classical” picture of neutrino astronomy:

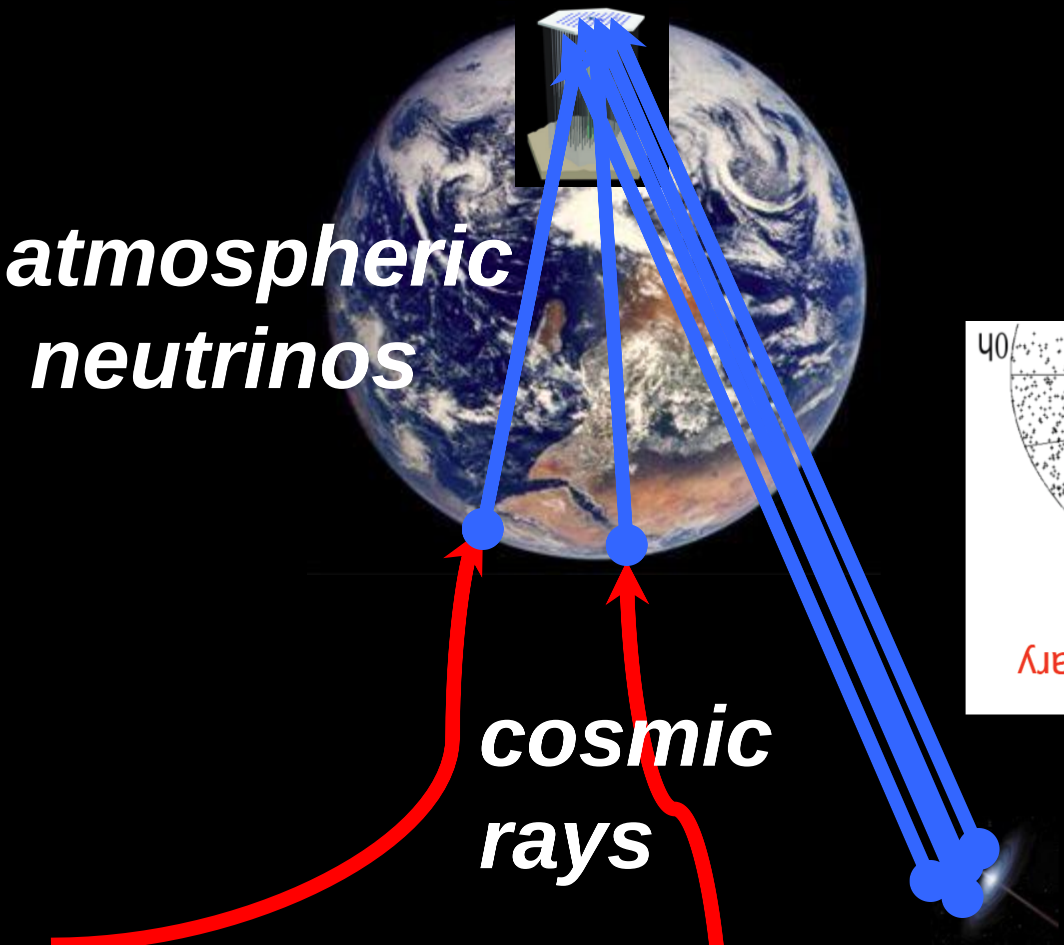
Earth filters out CR muons

look for upgoing muons from neutrinos

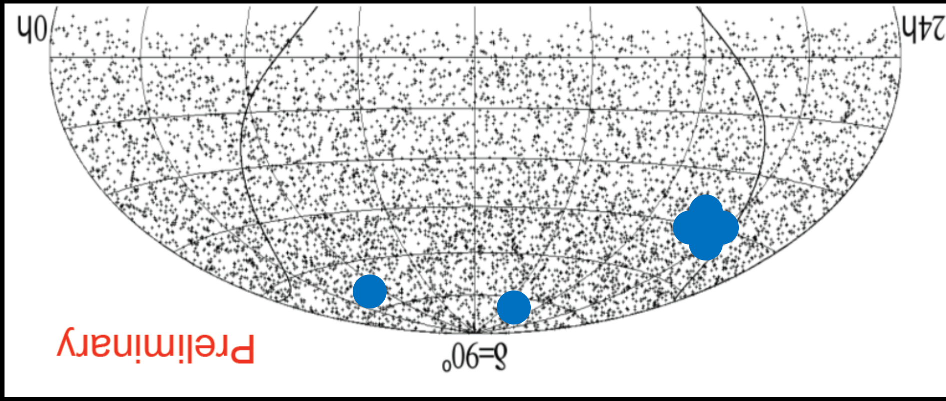
Looking down at the south pole into the northern sky

reject downgoing muons

upgoing neutrinos through-going muon tracks



astrophysical neutrino point source as excess on background?

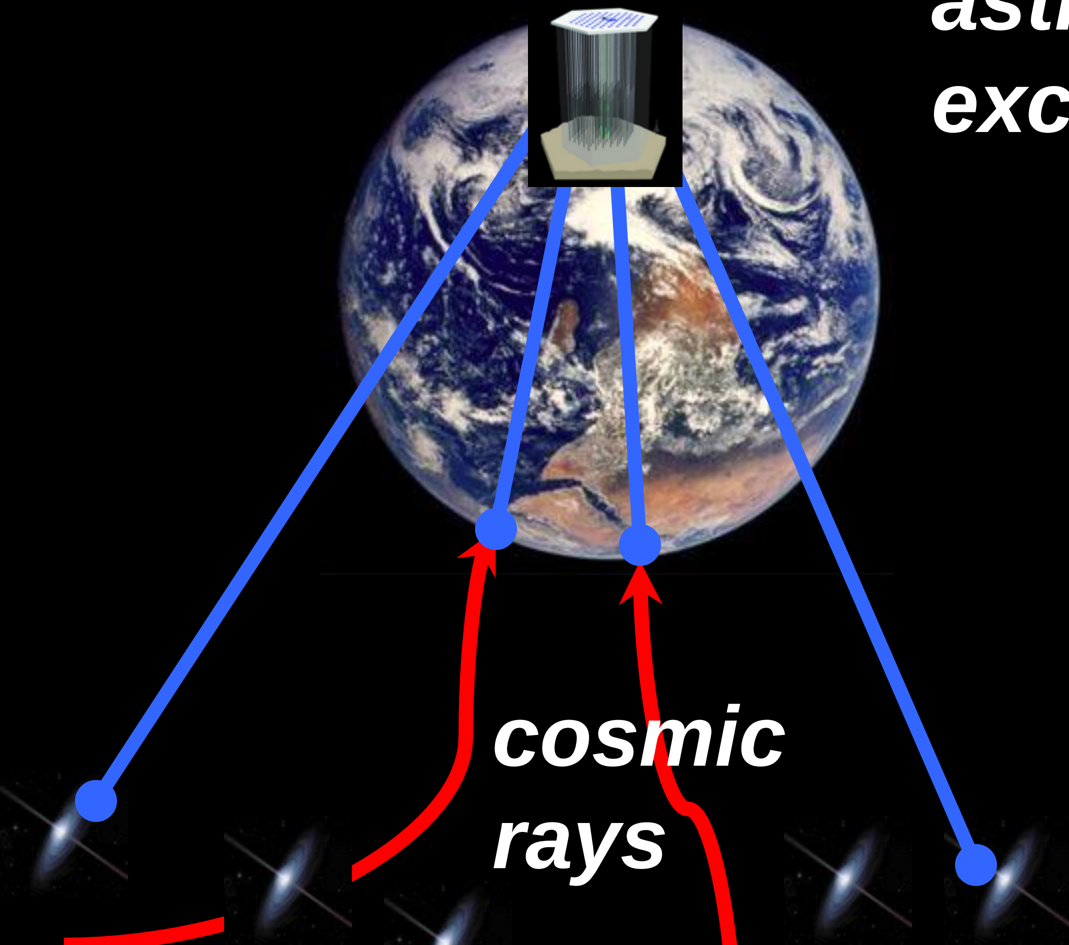


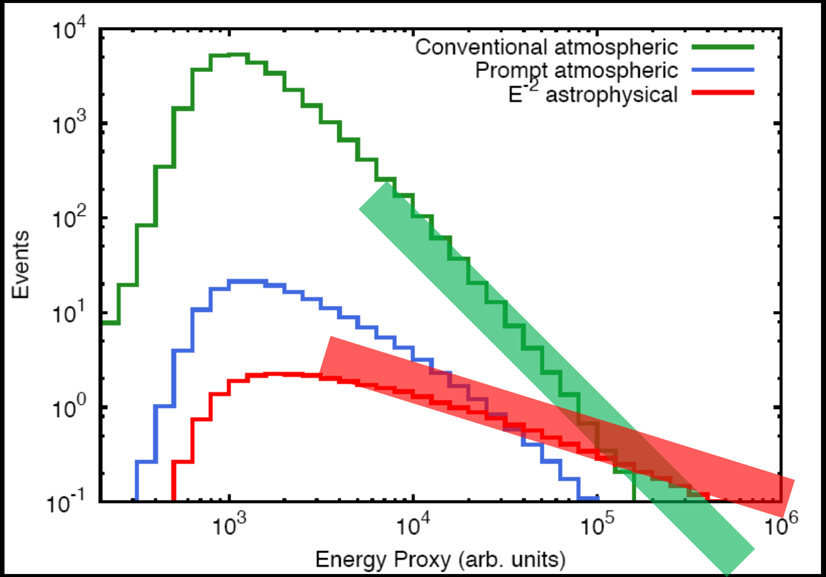
Looking down at the south pole into the northern sky

reject downgoing muons

upgoing neutrinos through-going muon tracks

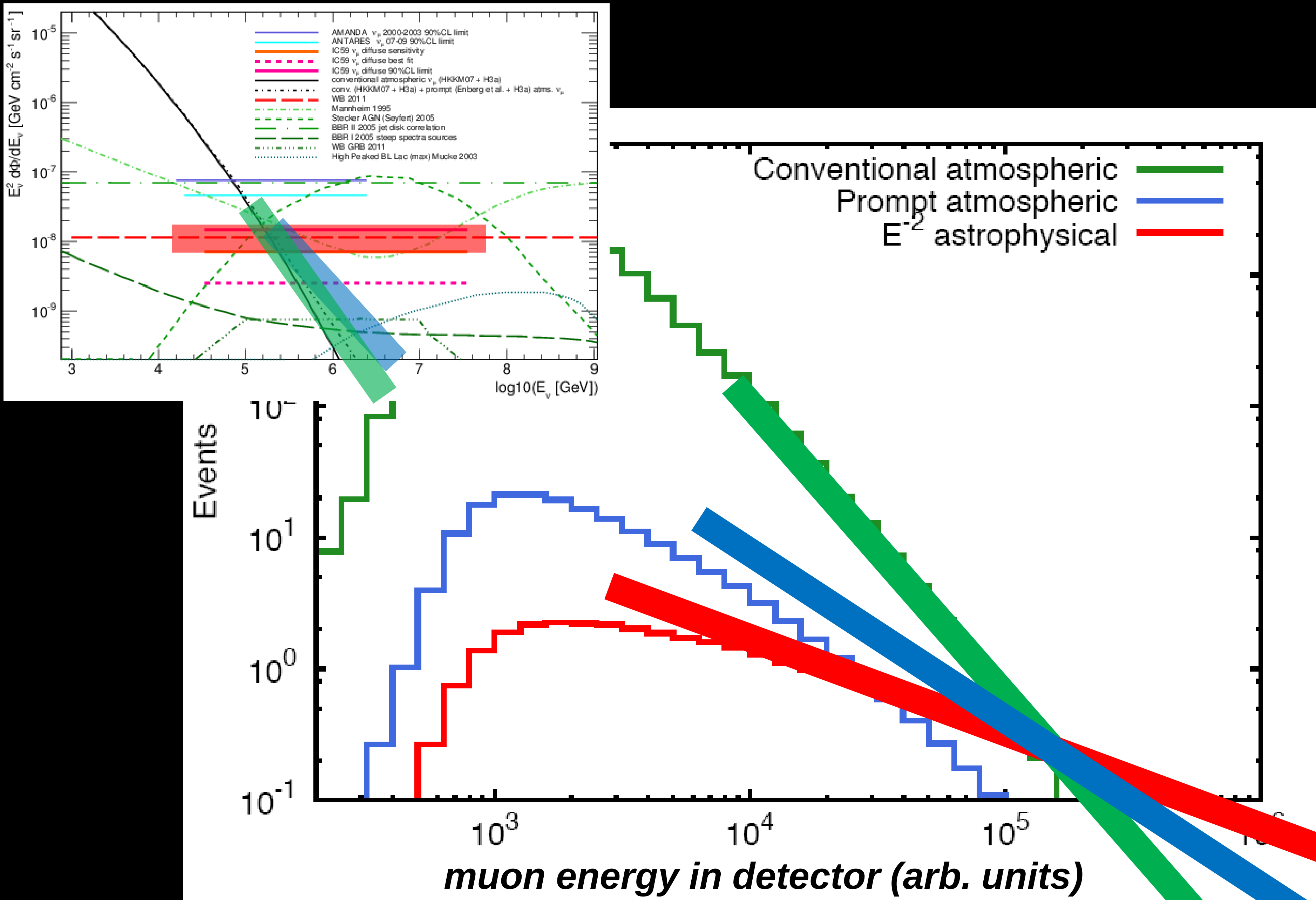
astrophysical neutrino excess at high energy?



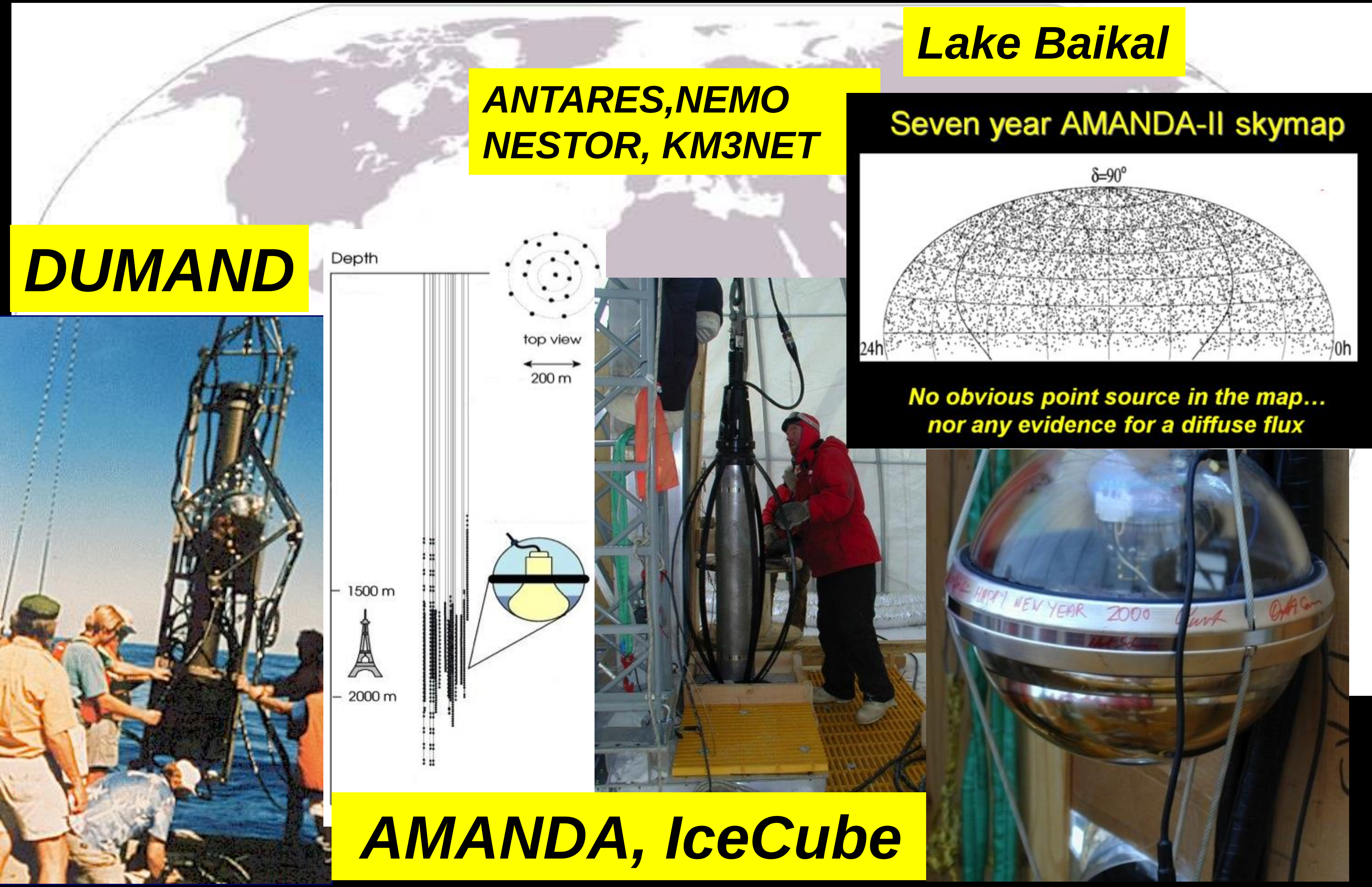


muon energy in detector

Atmospheric prompt is an important background



Optical Cherenkov neutrino detectors



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)

IceCube

IceTop

Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

Partial detectors analysed:
IC40, IC59, IC79

Full detector:
IC86, 3 ½ years running to date
HESE: IC79/86-1
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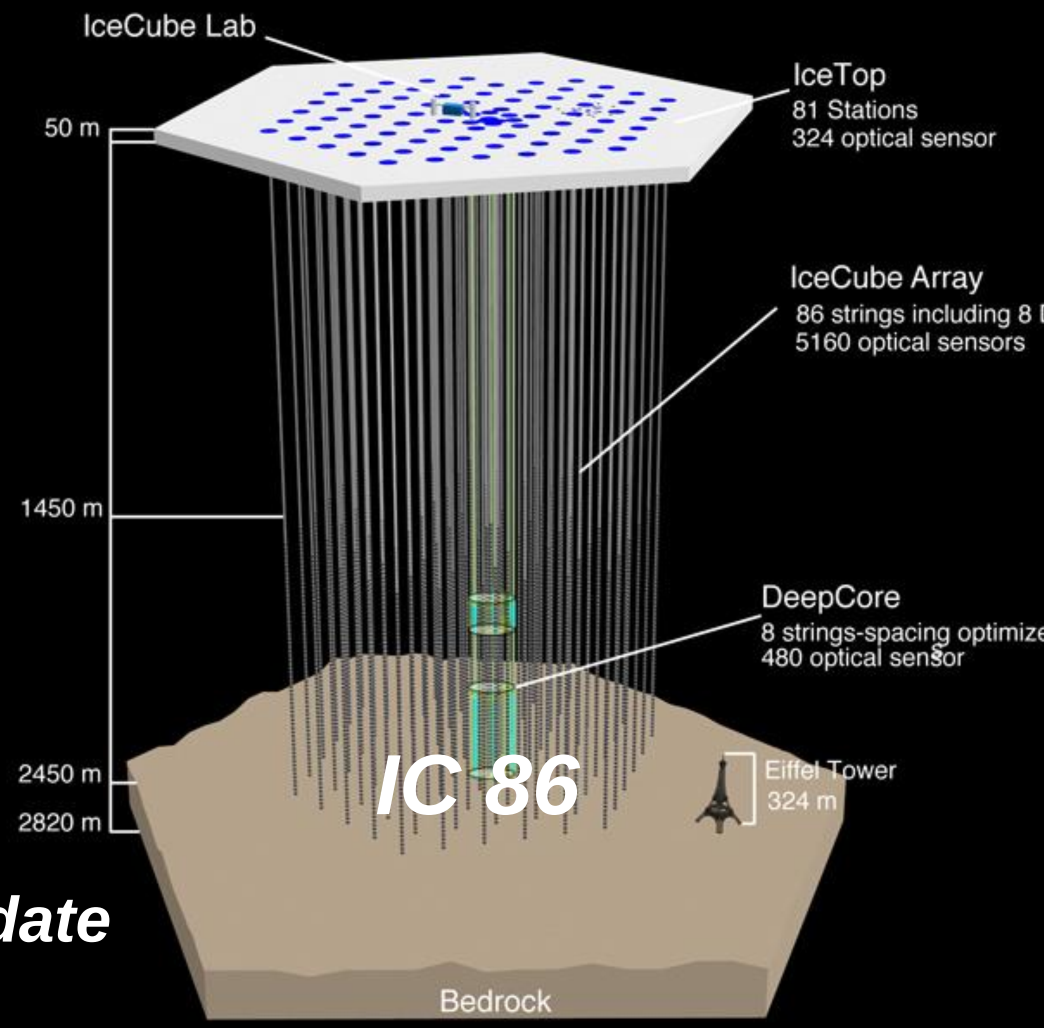
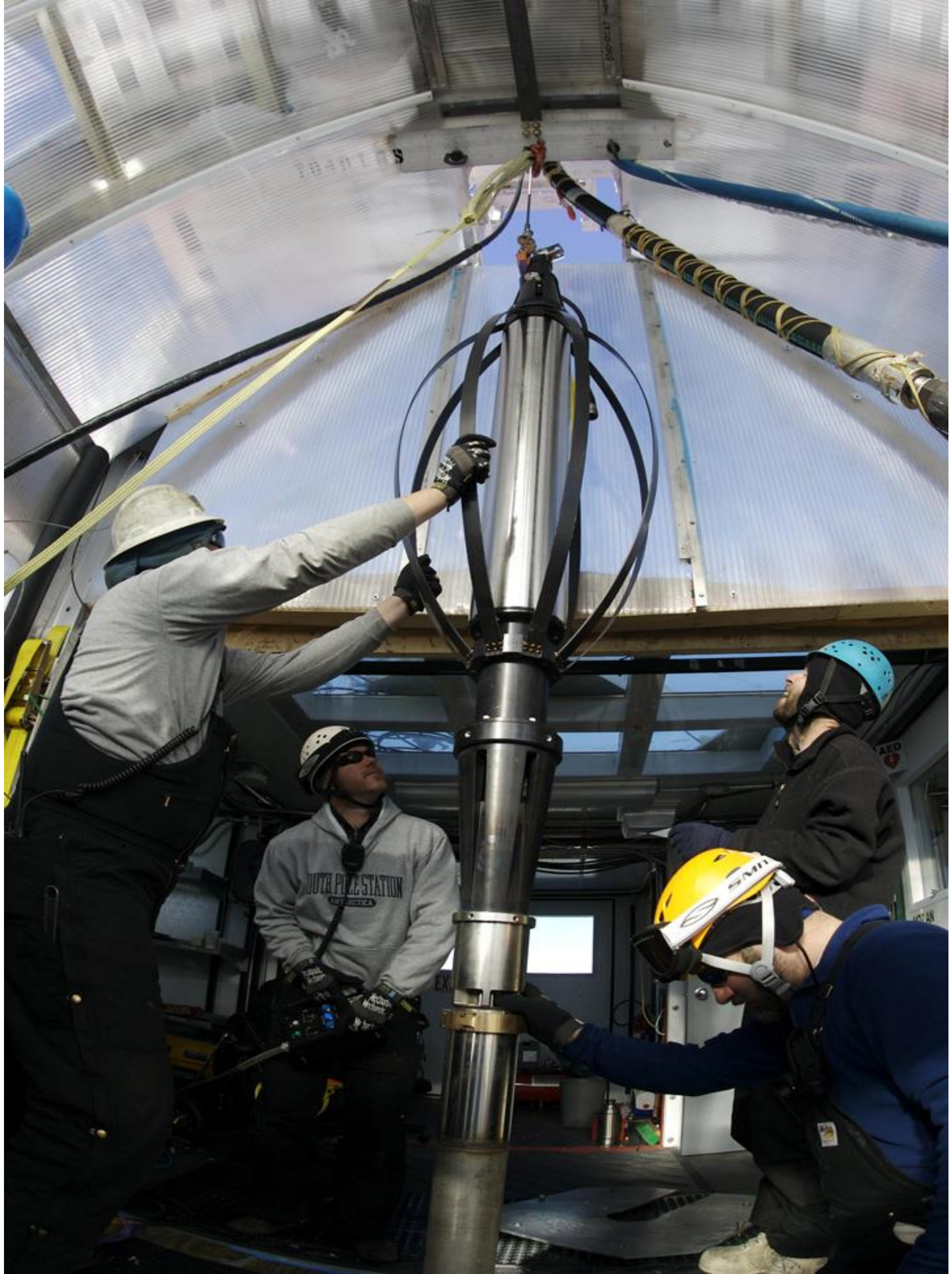


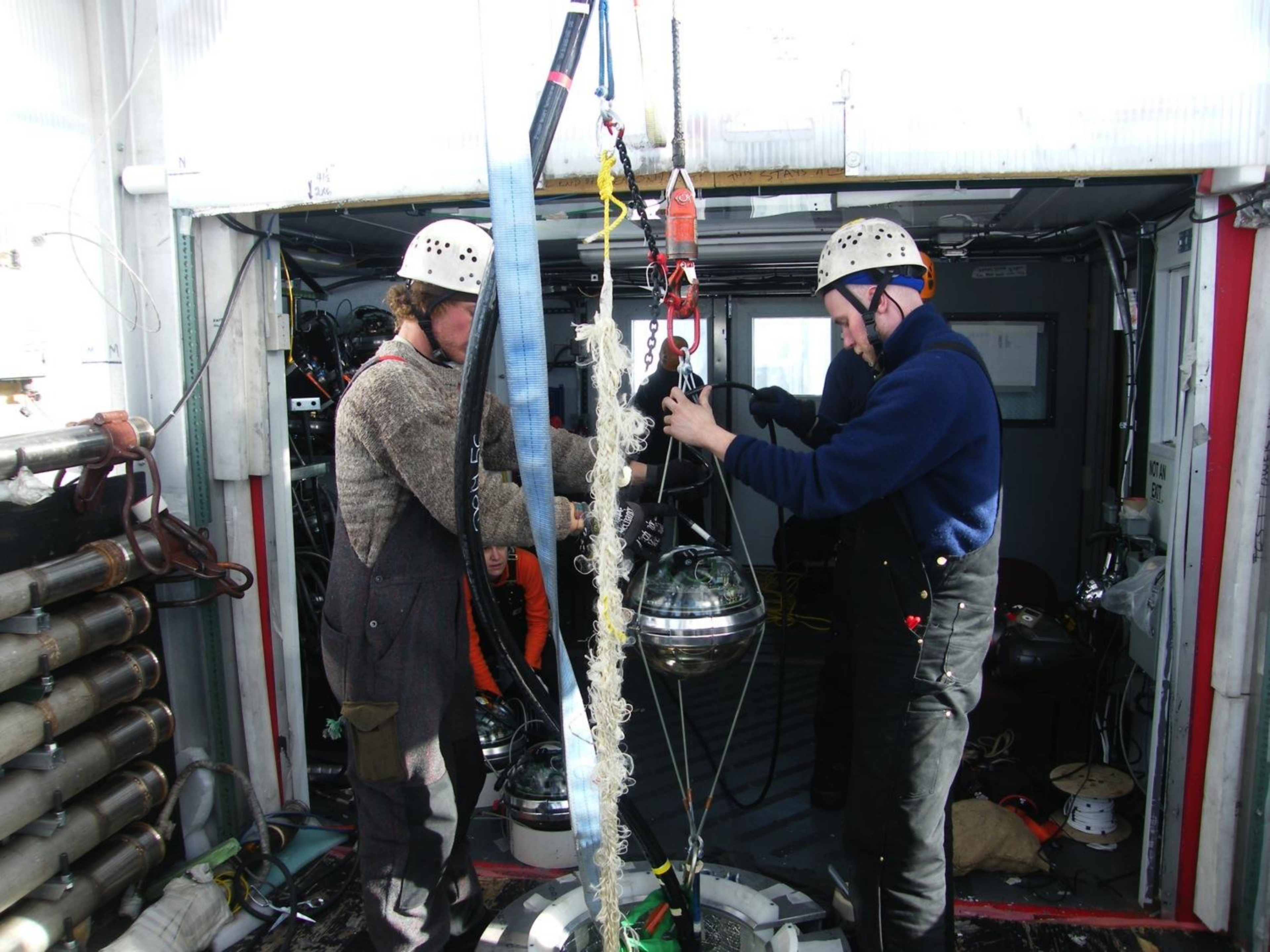

Logistics
9 million pounds of Cargo and fuel
300 Hercules LC 130 missions


Excellent infrastructure and support:
NSF / Raytheon Polar Services
NSF/ Lockheed Martin (ASC)

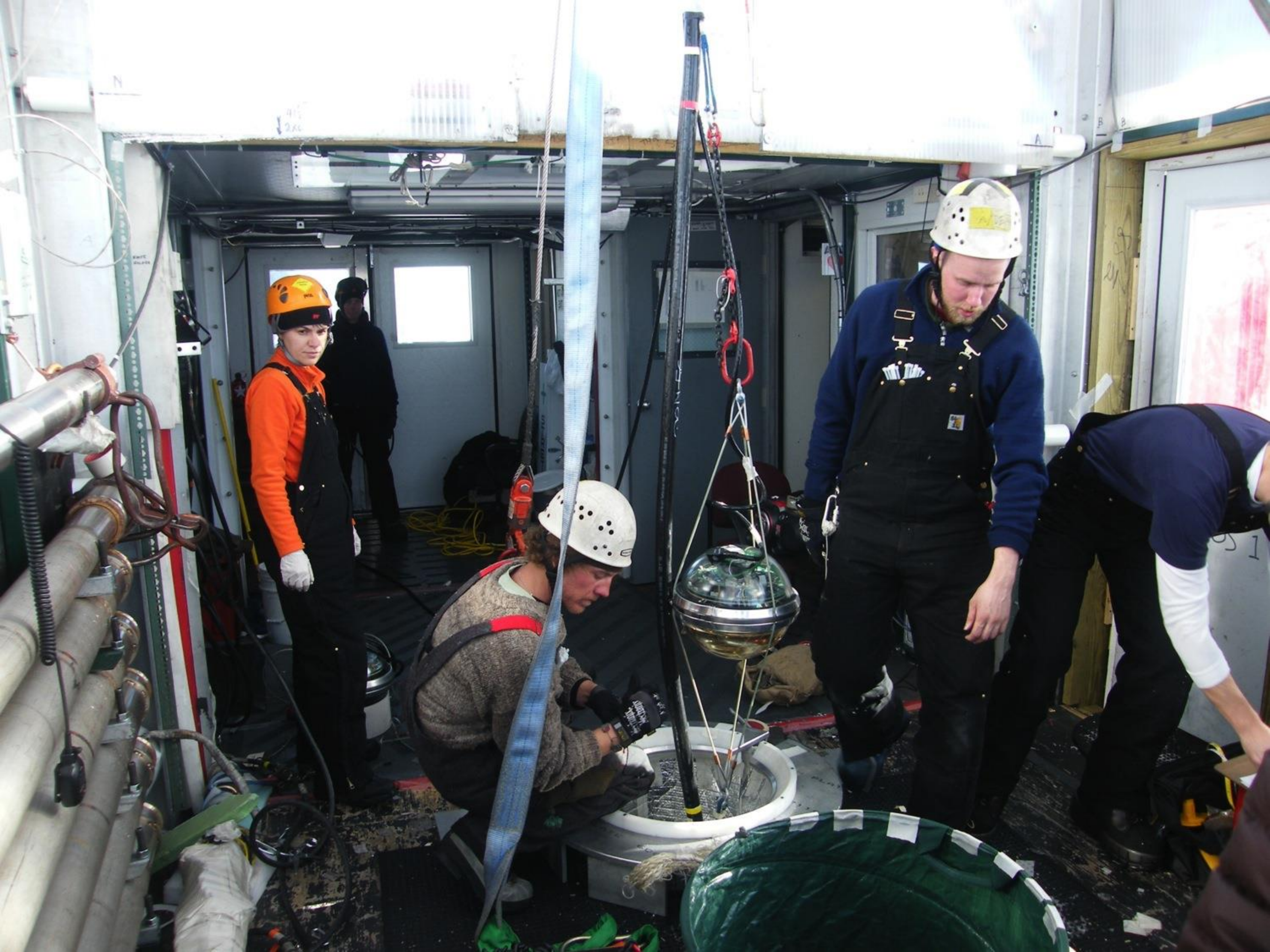

Drill hose reel
IceTop tanks
Heaters
Tower
Working time: Nov- mid-Feb

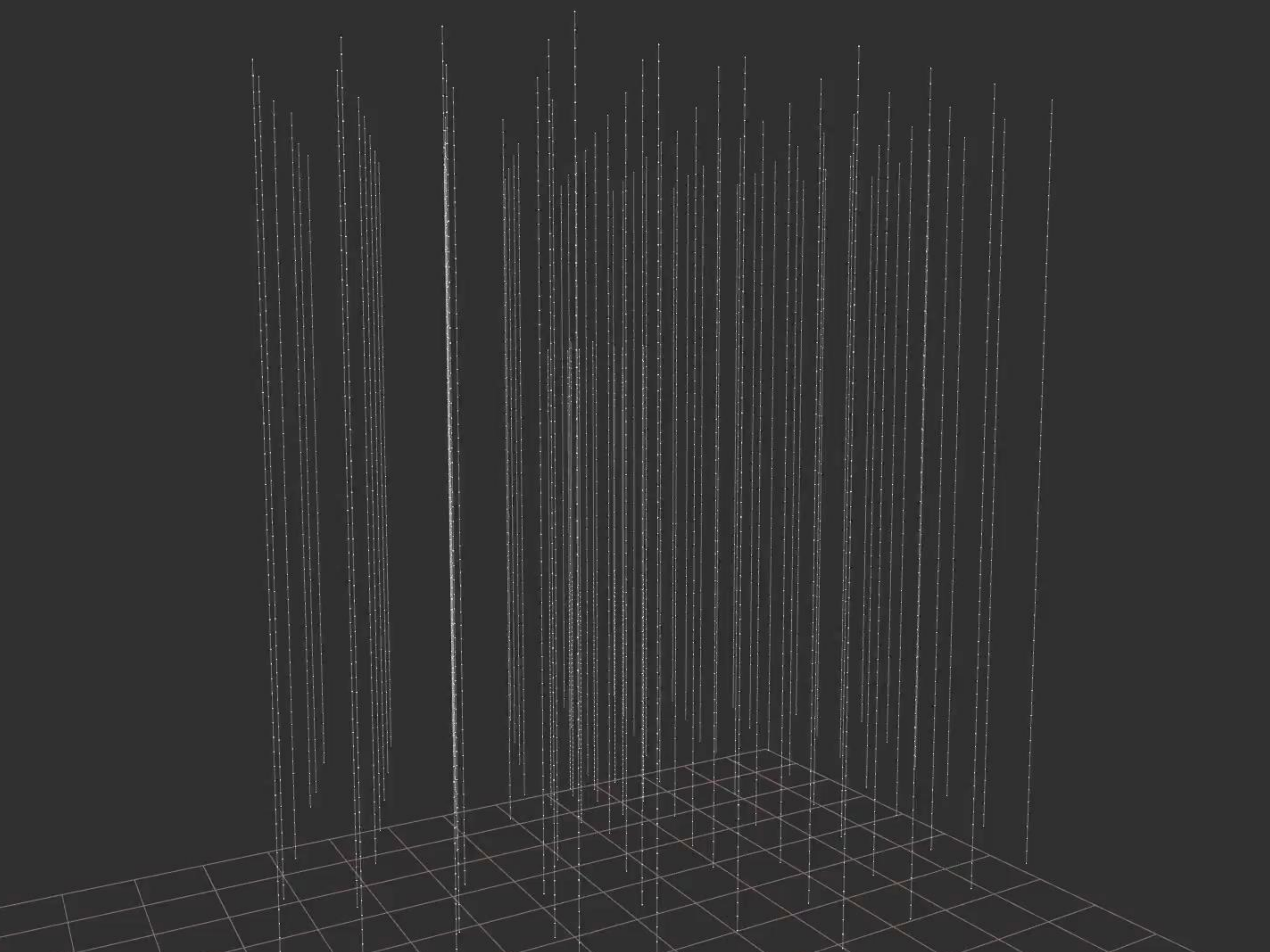

UTH POLE STATION
AED

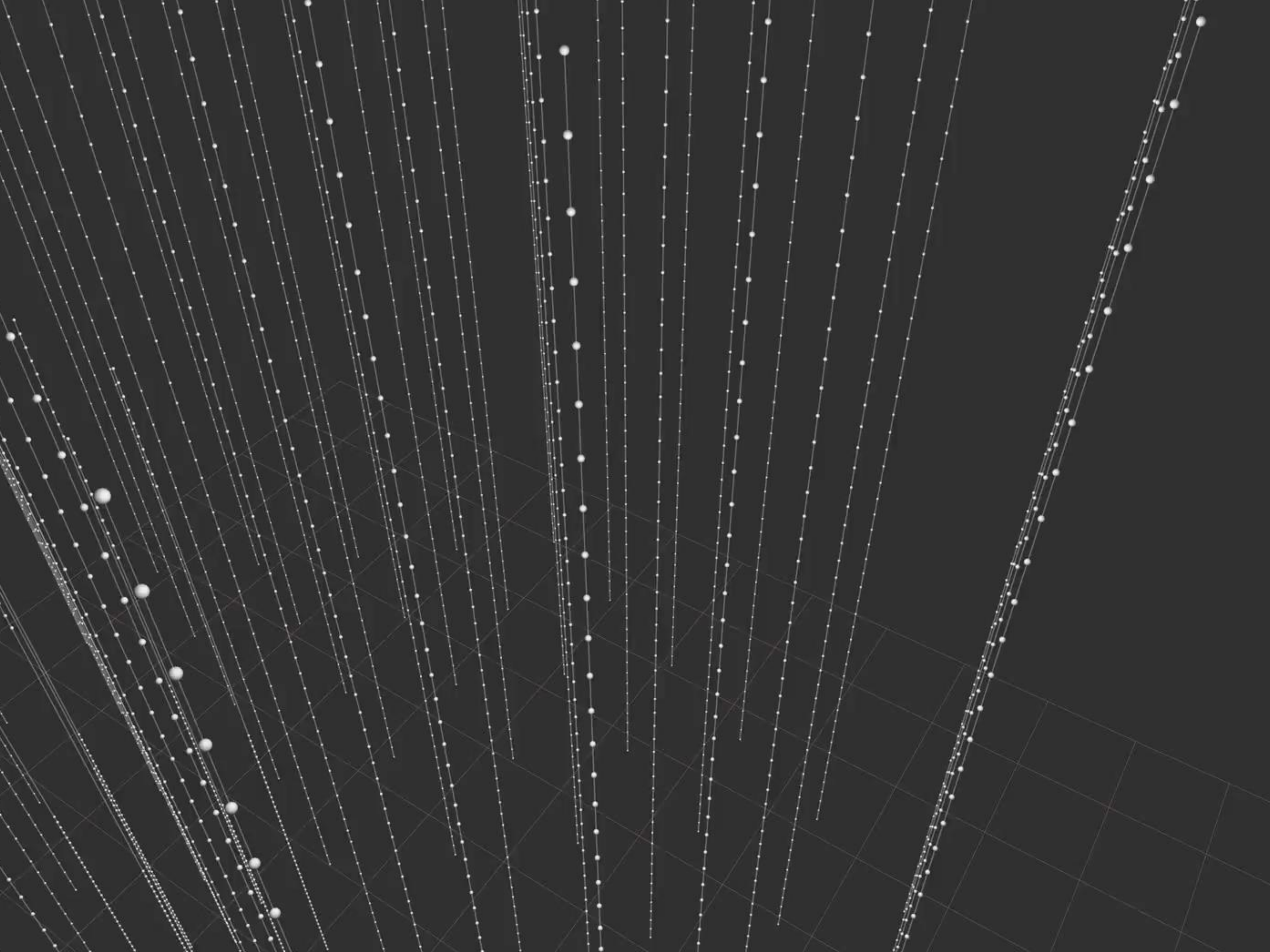

EXIT
TOS 1
2


NOT AN EXIT


DIGITAL







Neutrino event signatures

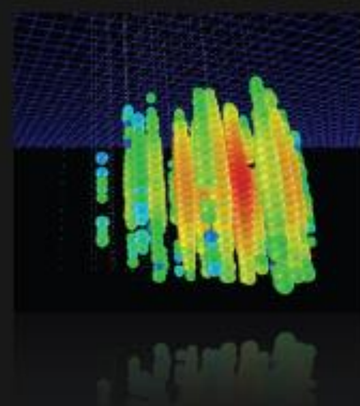
CC Muon Neutrino

$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

Neutral Current / Electron Neutrino



$$\nu_e + N \to e + X$$
$$\nu_x + N \to \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrsim 100$ TeV)

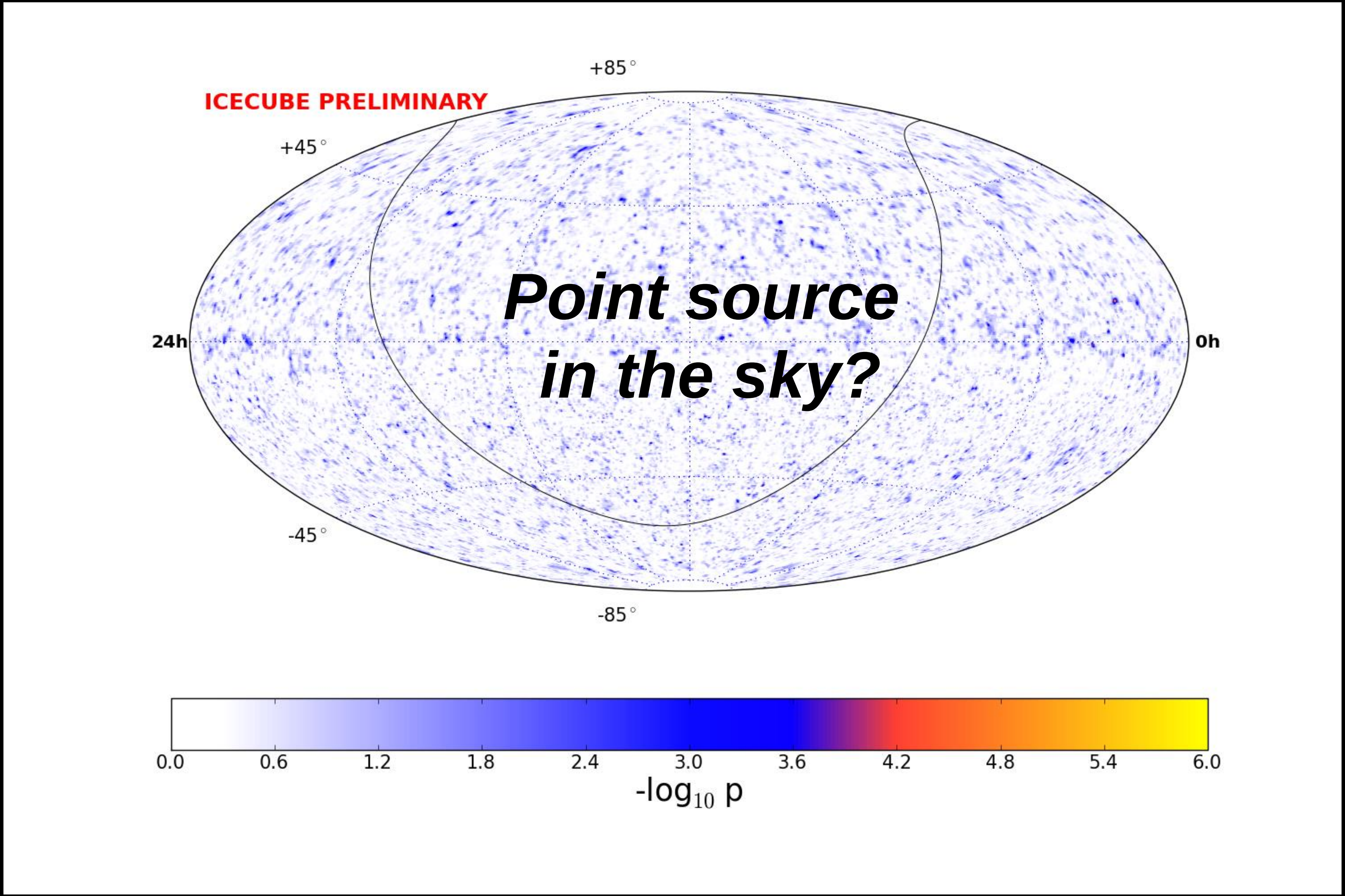
CC Tau Neutrino

$$\nu_\tau + N \to \tau + X$$

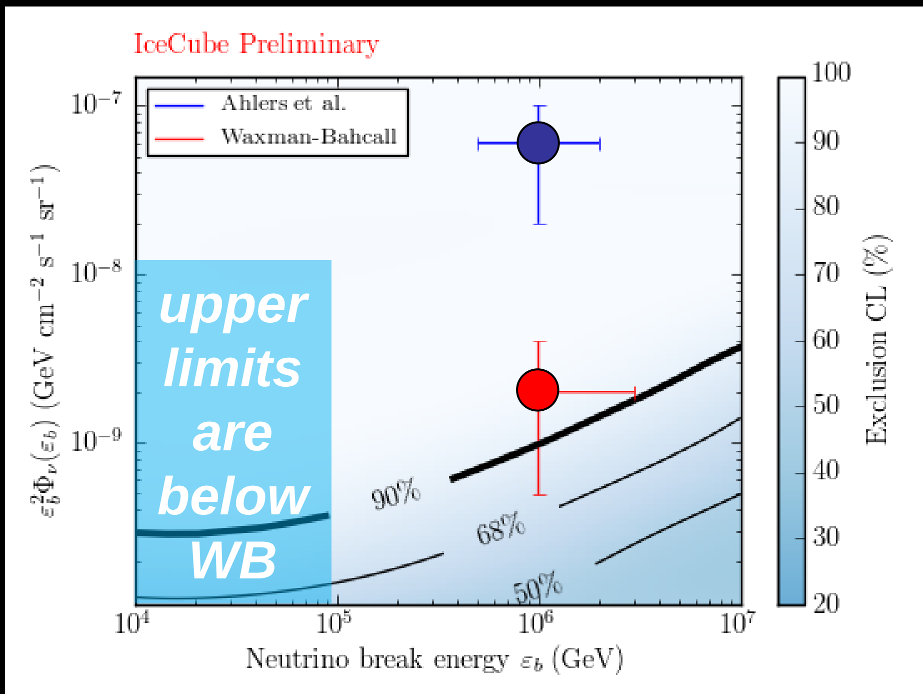
"double-bang" and other signatures (simulation)

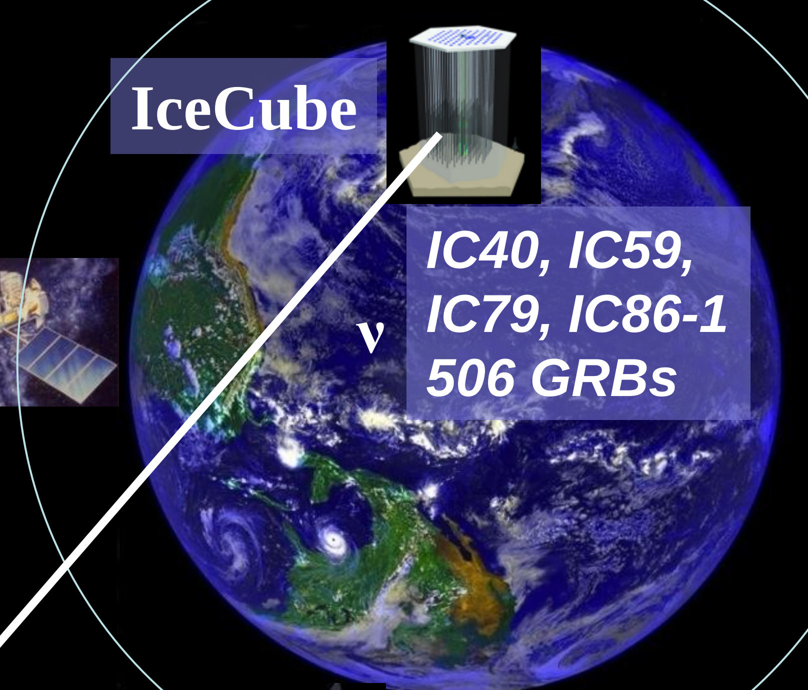
(not observed yet)

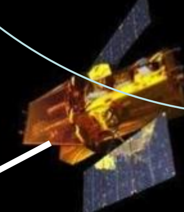
IC40+59+79+86 significance: all-sky through-going muons



Neutrinos in coincidence with gamma-ray bursts?







Gamma-ray satellites

Where are the neutrinos? Are GRBs really cosmic ray sources?

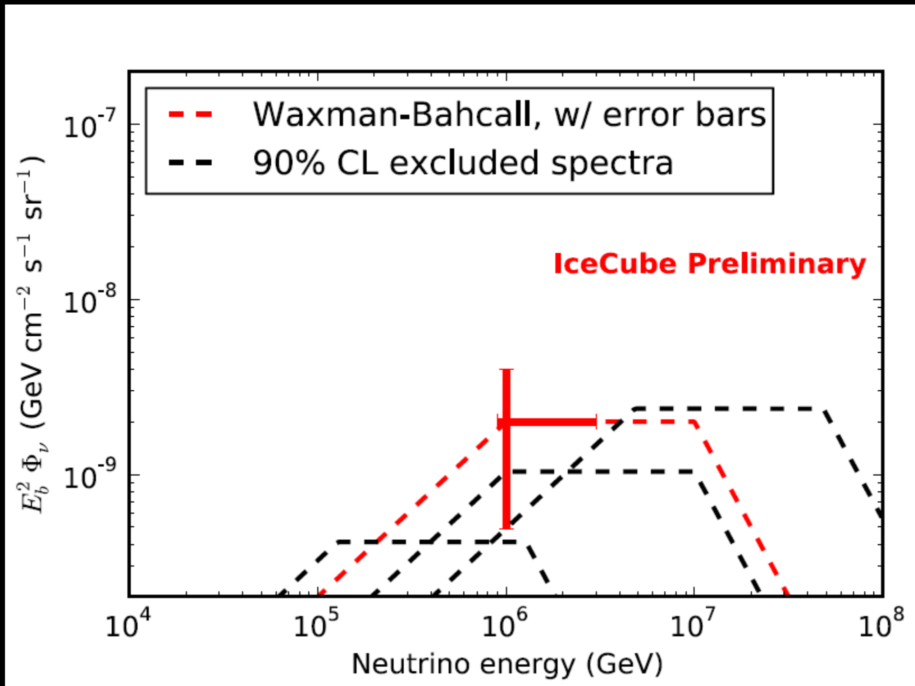
γ, ν

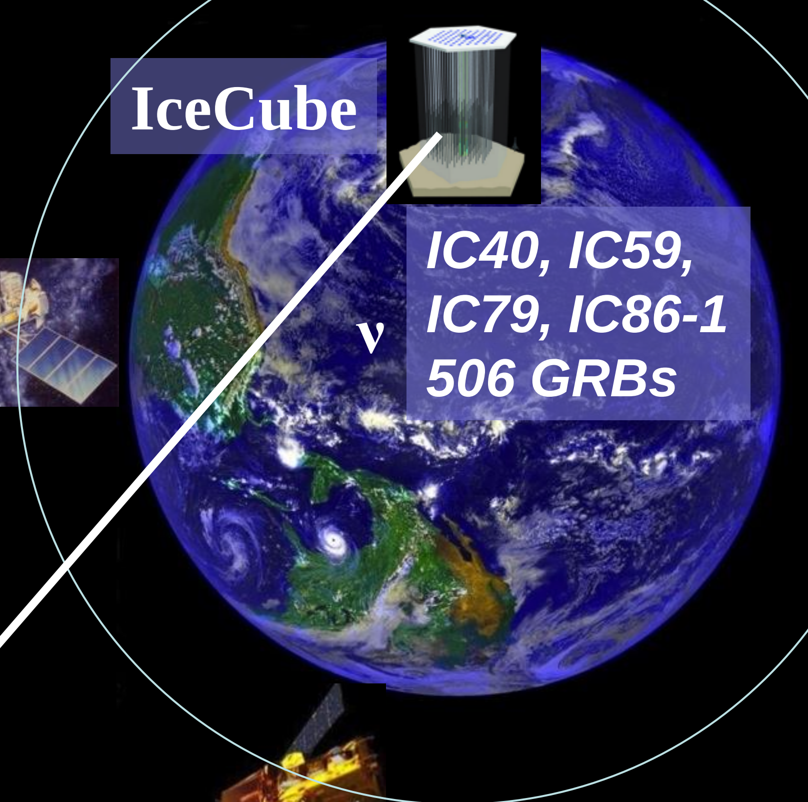
GRB timing/localization information from correlations among satellites

distant GRB

Direction plus time (10-100s) cuts – much reduced background

Neutrinos in coincidence with gamma-ray bursts?





IceCube

ν

IC40, IC59, IC79, IC86-1
506 GRBs

Gamma-ray satellites

γ, ν

Where are the neutrinos? Are GRBs really cosmic ray sources?

distant GRB

GRB timing/localization information from correlations among satellites

Direction plus time (10-100s) cuts – much reduced background

Detection of an extra-terrestrial diffuse flux of high-energy neutrinos!

Clues:

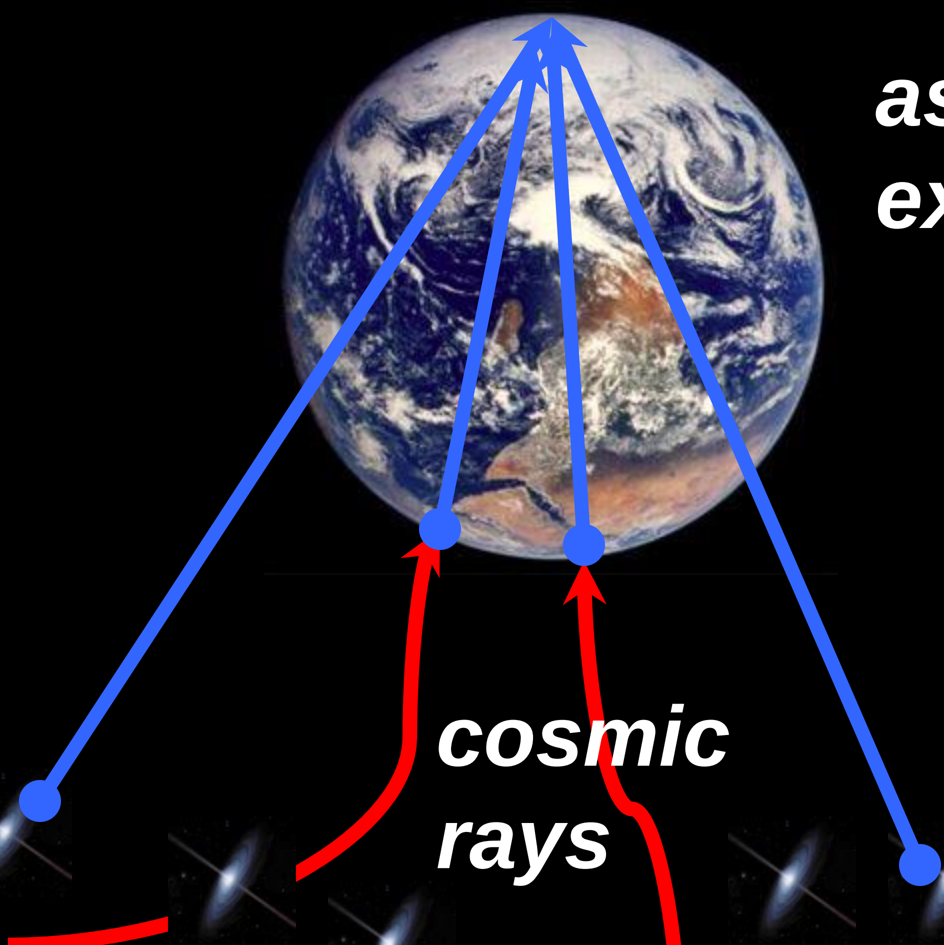
Diffuse muon analysis (IC59)
Diffuse shower analysis (IC40)
EHE GZK search – two 1 PeV cascades (IC79/86)

***Detection analyses:* (IC79/86)**
High Energy Starting Event (HESE)
Through-going upward muon

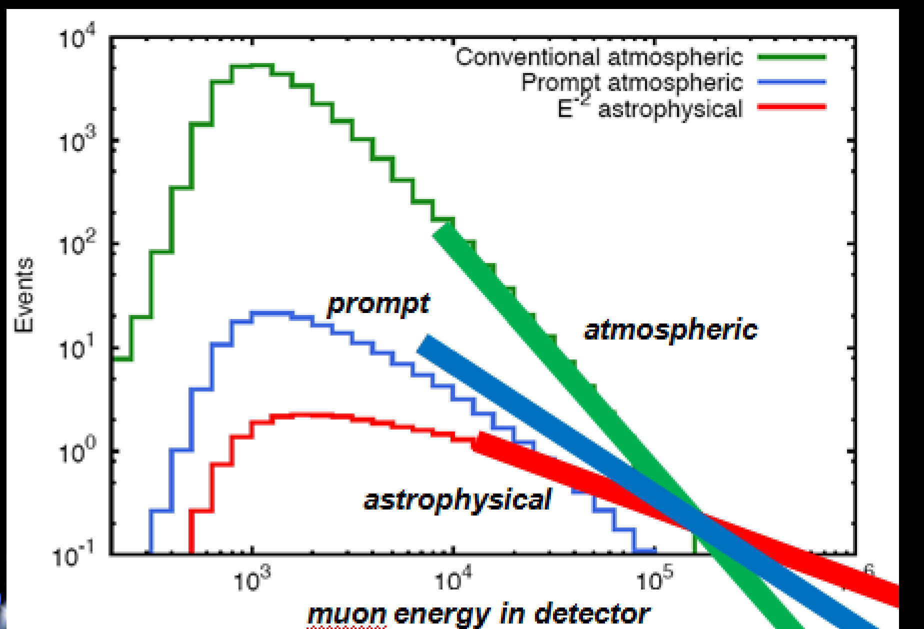
Looking down at the south pole into the northern sky

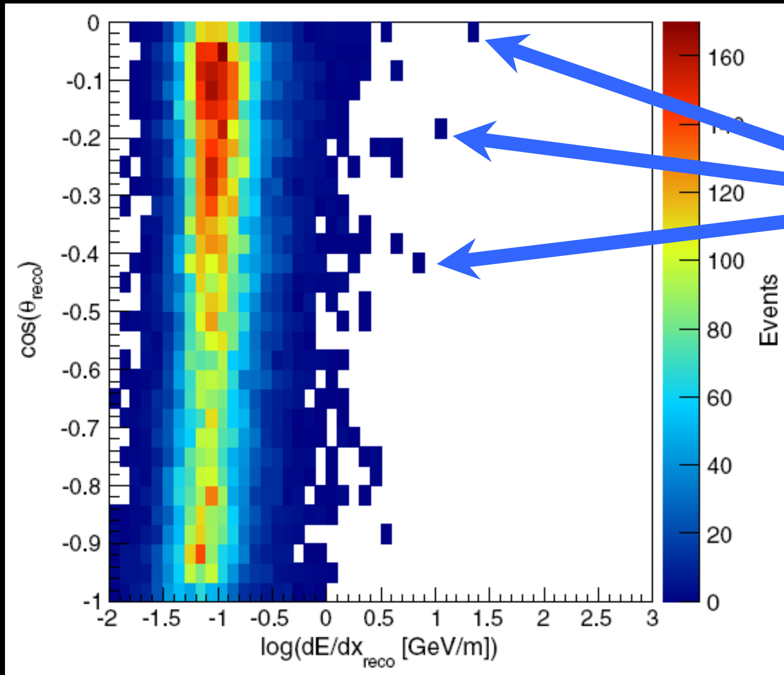
reject downgoing muons

upgoing neutrinos through-going muon tracks



astrophysical neutrino excess at high energy?





IC59 upgoing muon analysis

three high energy events lead to a non-zero astrophysical fit 1.8 sigma

+

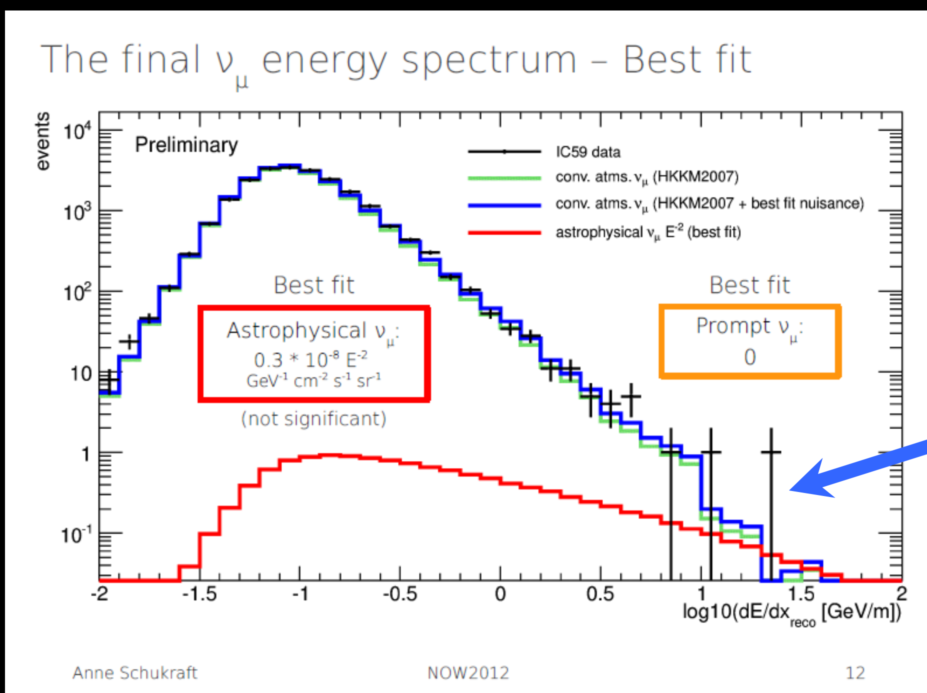
expected conventional atmospheric

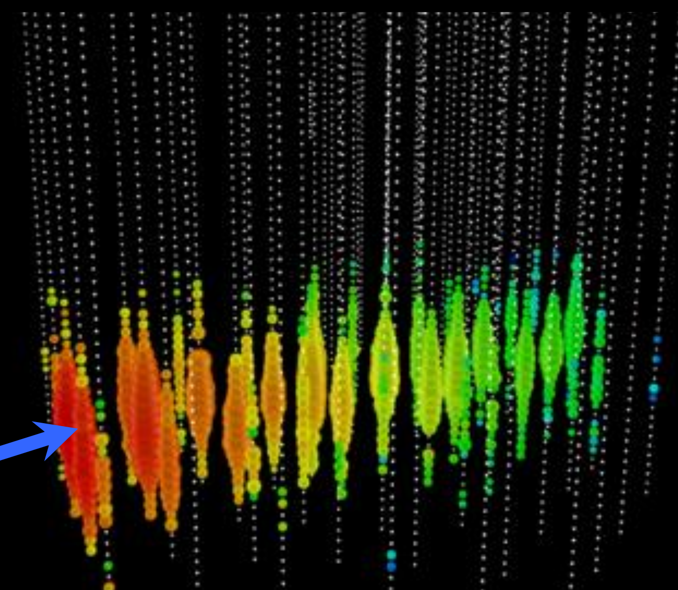
+

zero prompt

=

fit to data rejects bg-only at 1.8 sigma



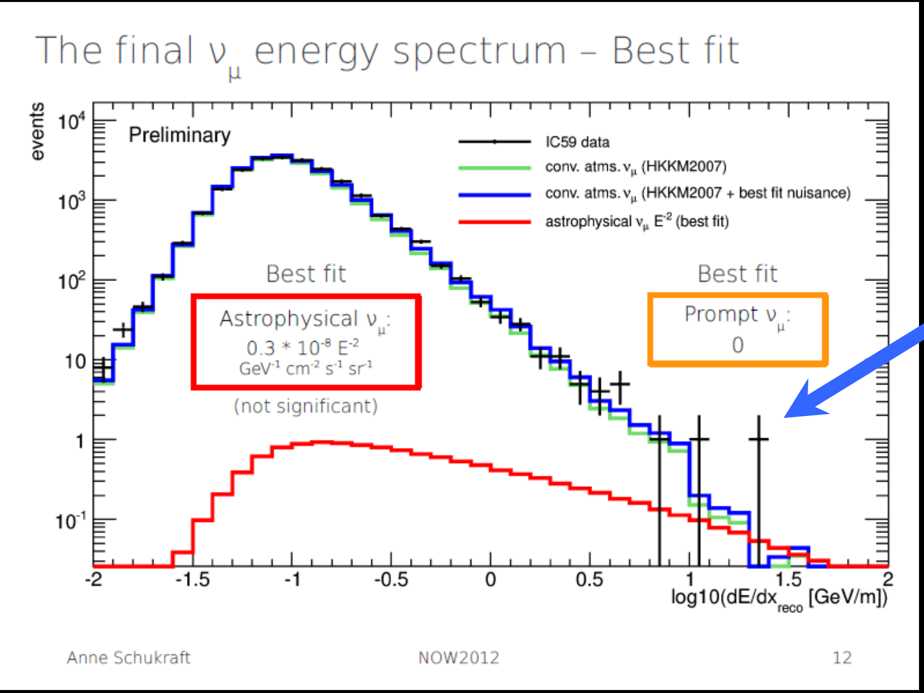


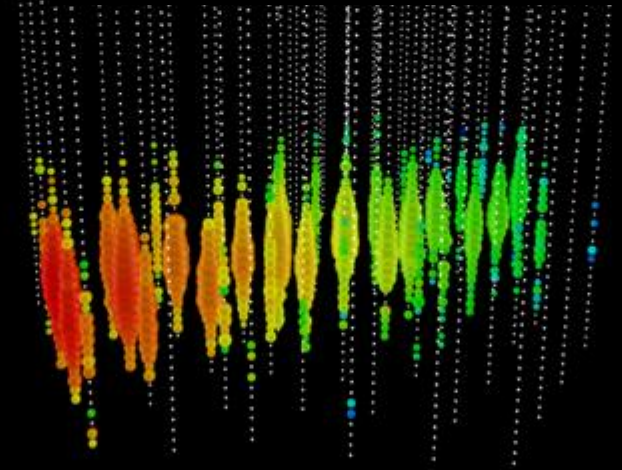
~1 PeV neutrino

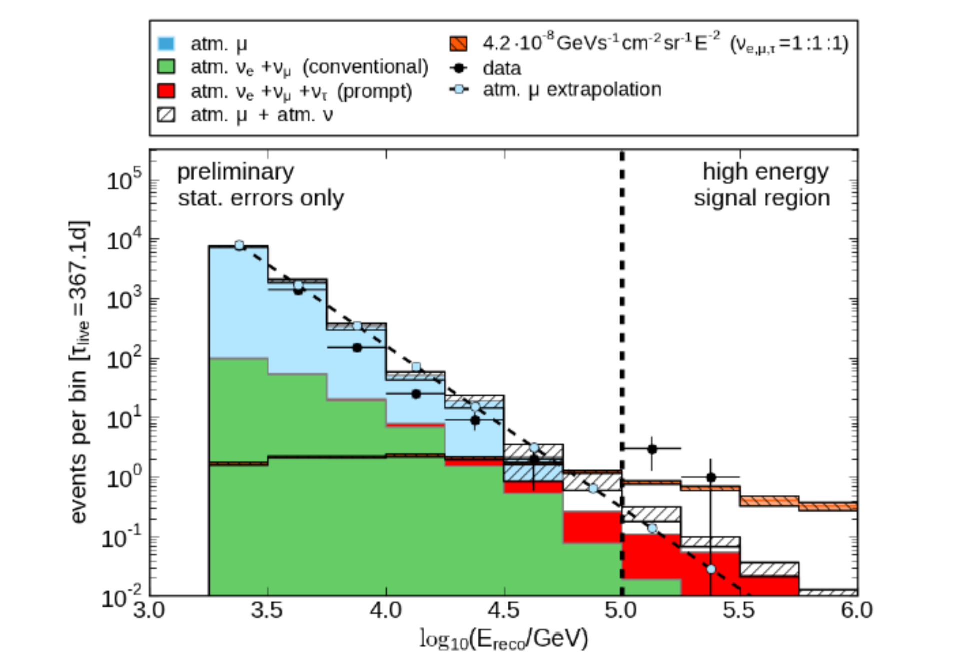
IC59 upgoing muon analysis

1.8 sigma excess

~1 PeV neutrino



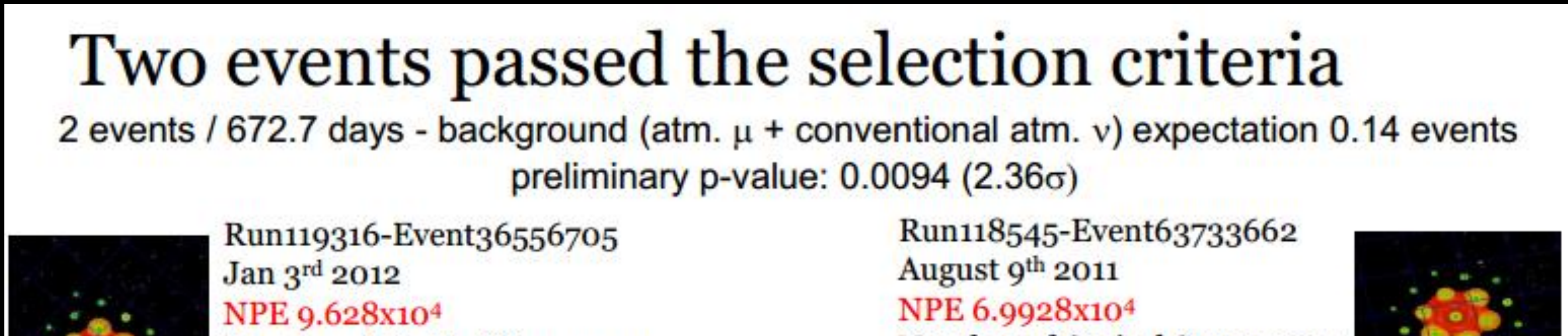




IC40 shower analysis

2.4 sigma excess

Flashback: Neutrino 2012, Kyoto



Two events passed the selection criteria

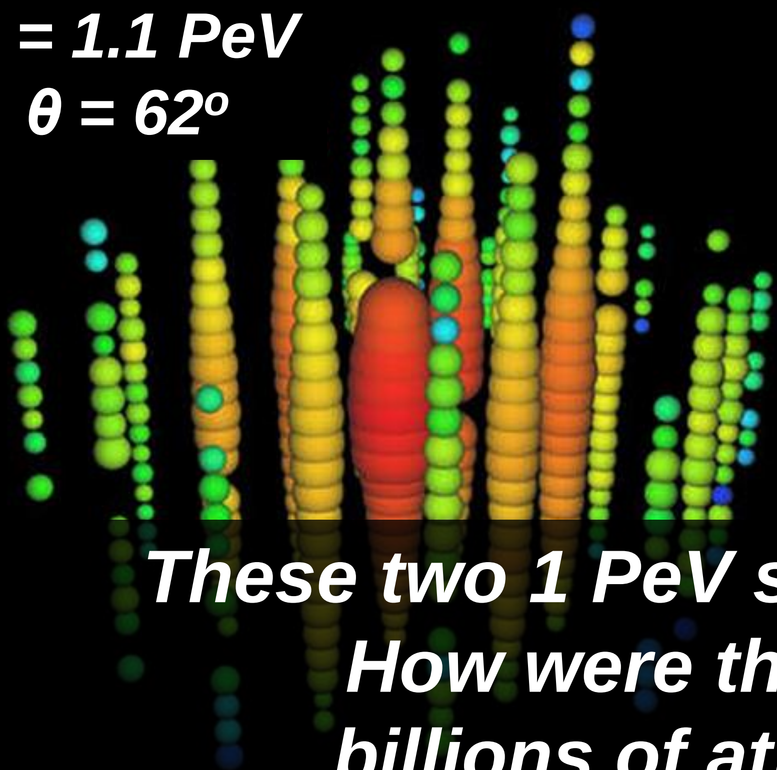
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

preliminary p-value: 0.0094 (2.36σ)

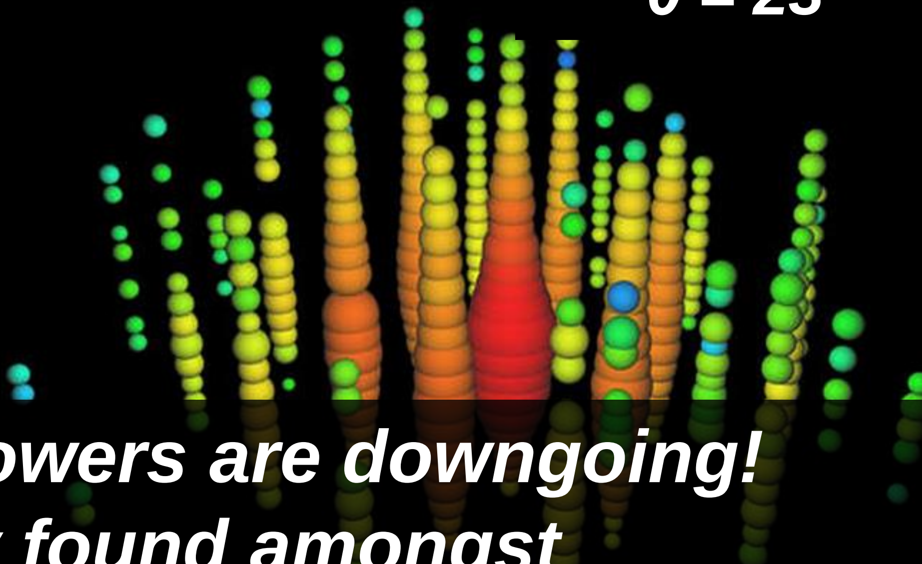
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4

Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4

E = 1.1 PeV
θ = 62º



E = 1.0 PeV
θ = 23º



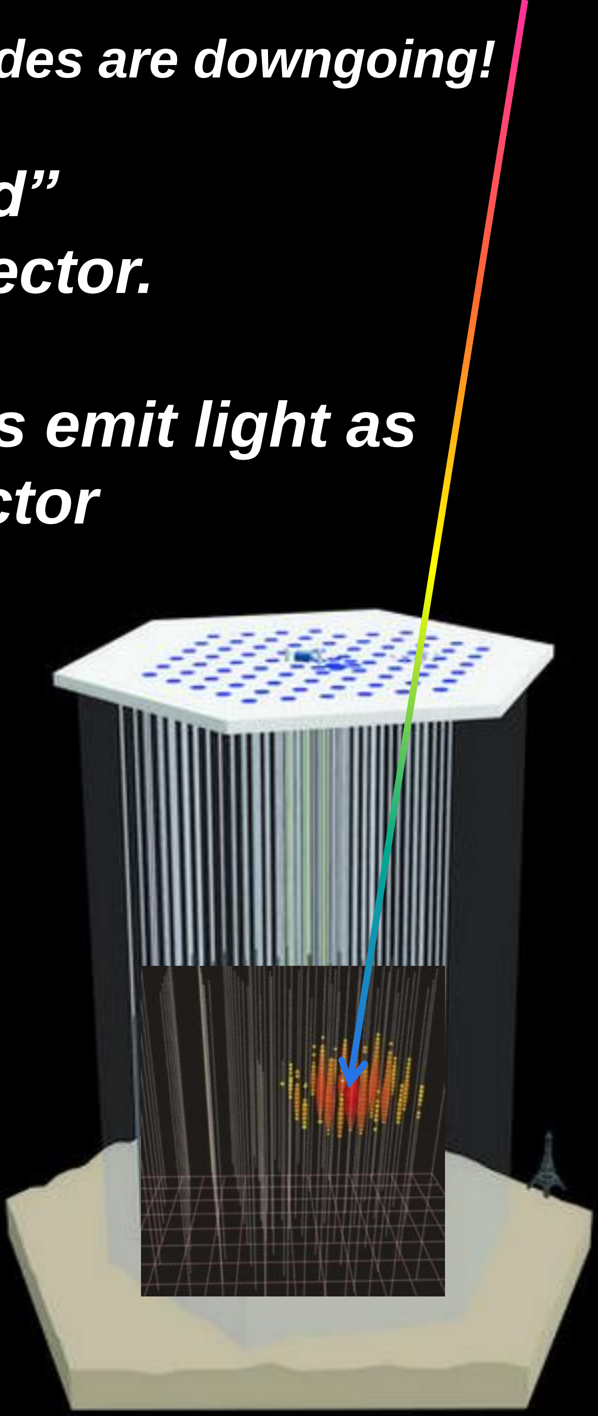
These two 1 PeV showers are downgoing!
How were they found amongst
billions of atmospheric muons?

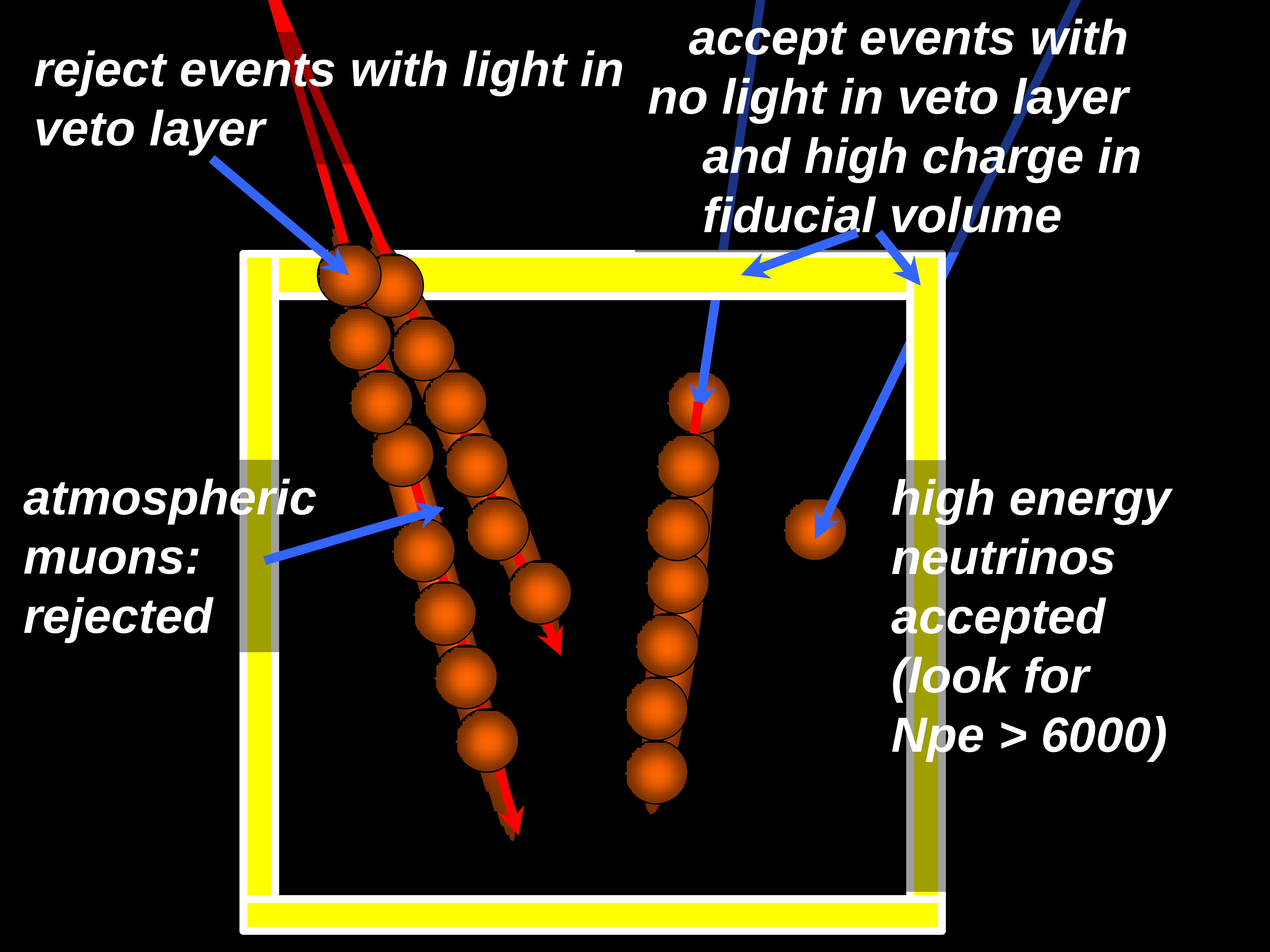
These two 1 PeV cascades are downgoing!

They are "contained"
-starting in the detector.

Atmospheric muons emit light as they enter the detector
-we can veto these!

"atmospheric muon self veto"




reject events with light in veto layer
accept events with no light in veto layer and high charge in fiducial volume
atmospheric muons: rejected
high energy neutrinos accepted (look for Npe > 6000)

These two 1 PeV cascades are downgoing!
Can they be atmospheric neutrinos?

PHYSICAL REVIEW D **79,** 043009 (2009)

Vetoing atmospheric neutrinos in a high energy neutrino telescope

Stefan Schönert,[1] Thomas K. Gaisser,[2] Elisa Resconi,[1] and Olaf Schulz[1]

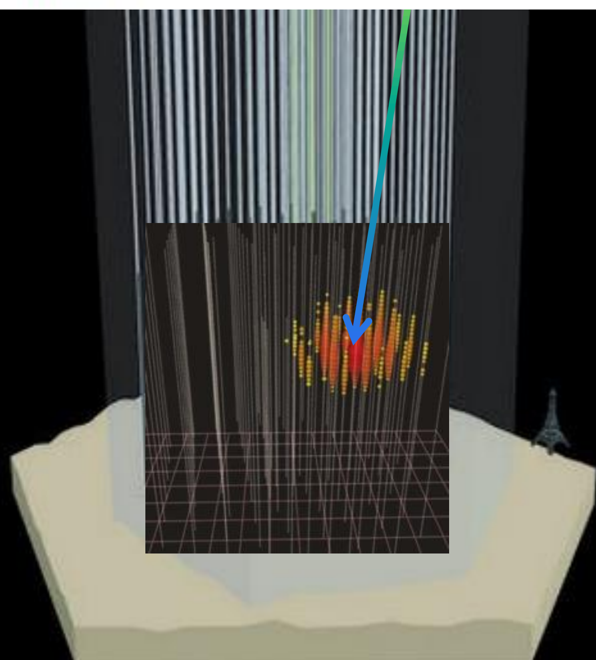
Schönert, Gaisser, Resconi, Schulz

We discuss the possibility to suppress downward atmospheric neutrinos in a high energy neutrino telescope. This can be achieved by vetoing the muon which is produced by the same parent meson decaying in the atmosphere. In principle, atmospheric neutrinos with energies $E_\nu > 10$ TeV and a zenith angle up to 60° can be vetoed with an efficiency of >99%. Practical realization will depend on the depth of the neutrino telescope, on the muon veto efficiency, and on the ability to identify downward-moving neutrinos with a good energy estimation.

“atmospheric neutrino self veto”

for muon-neutrinos:

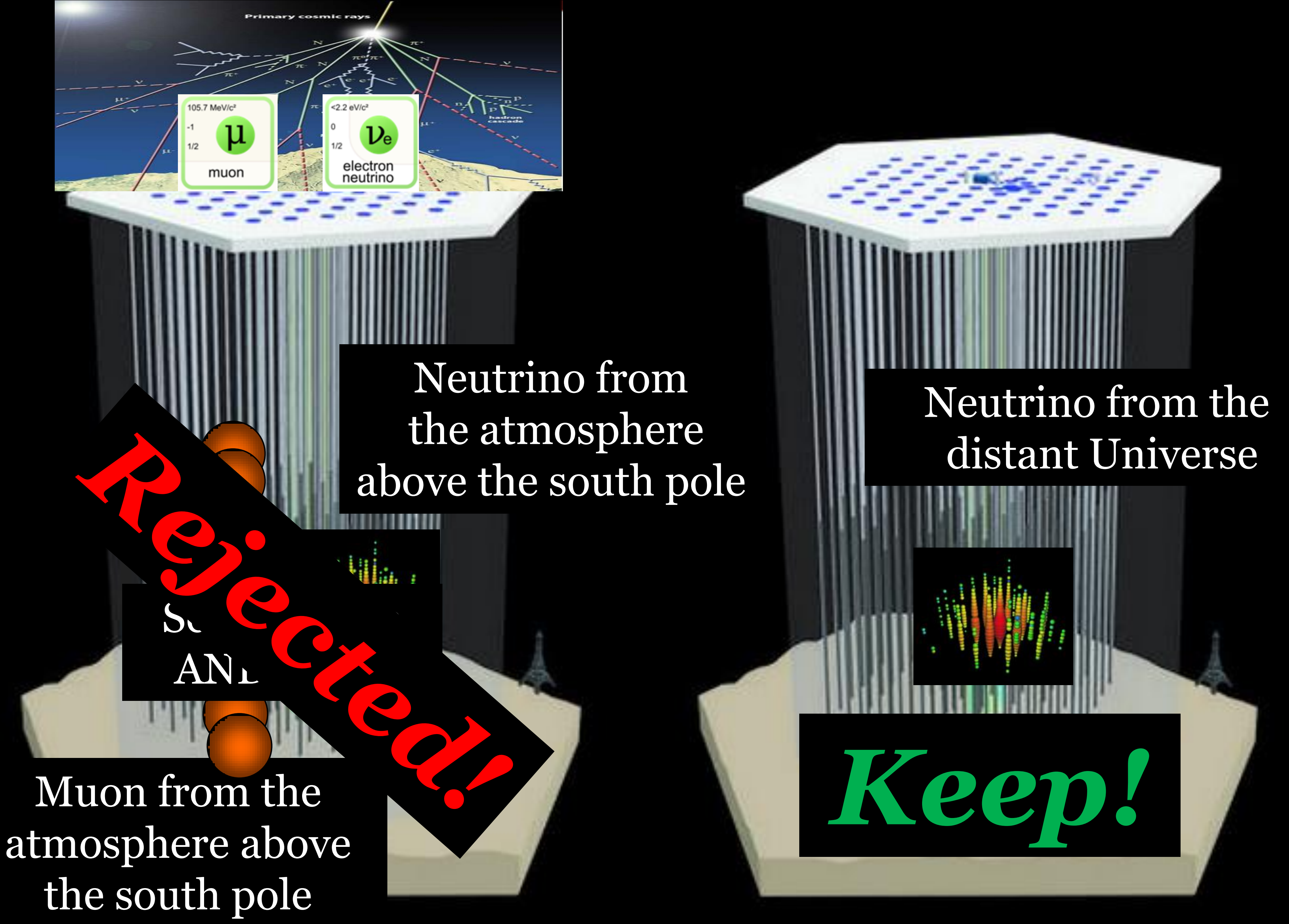
see muon from same parent meson decay

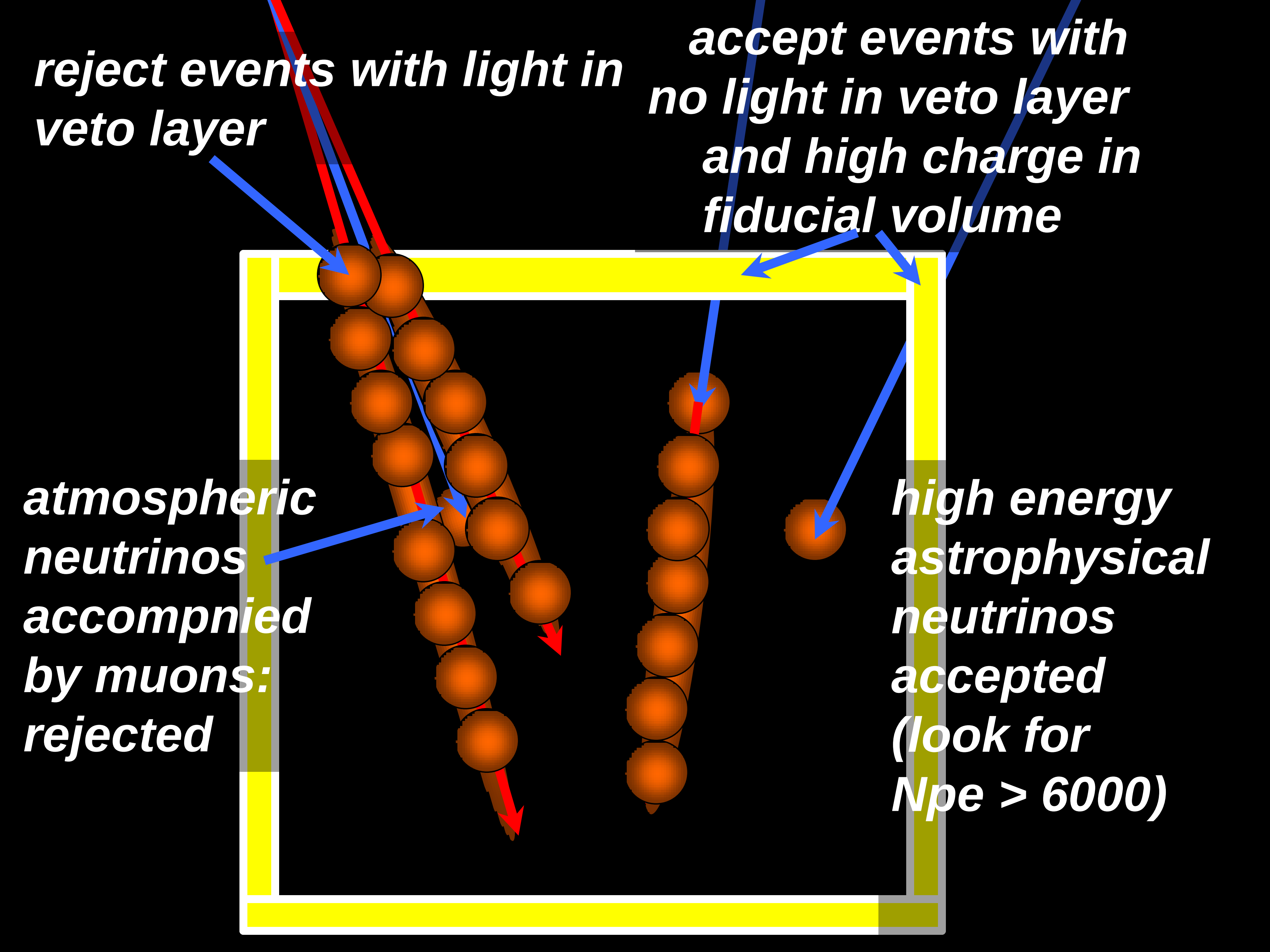


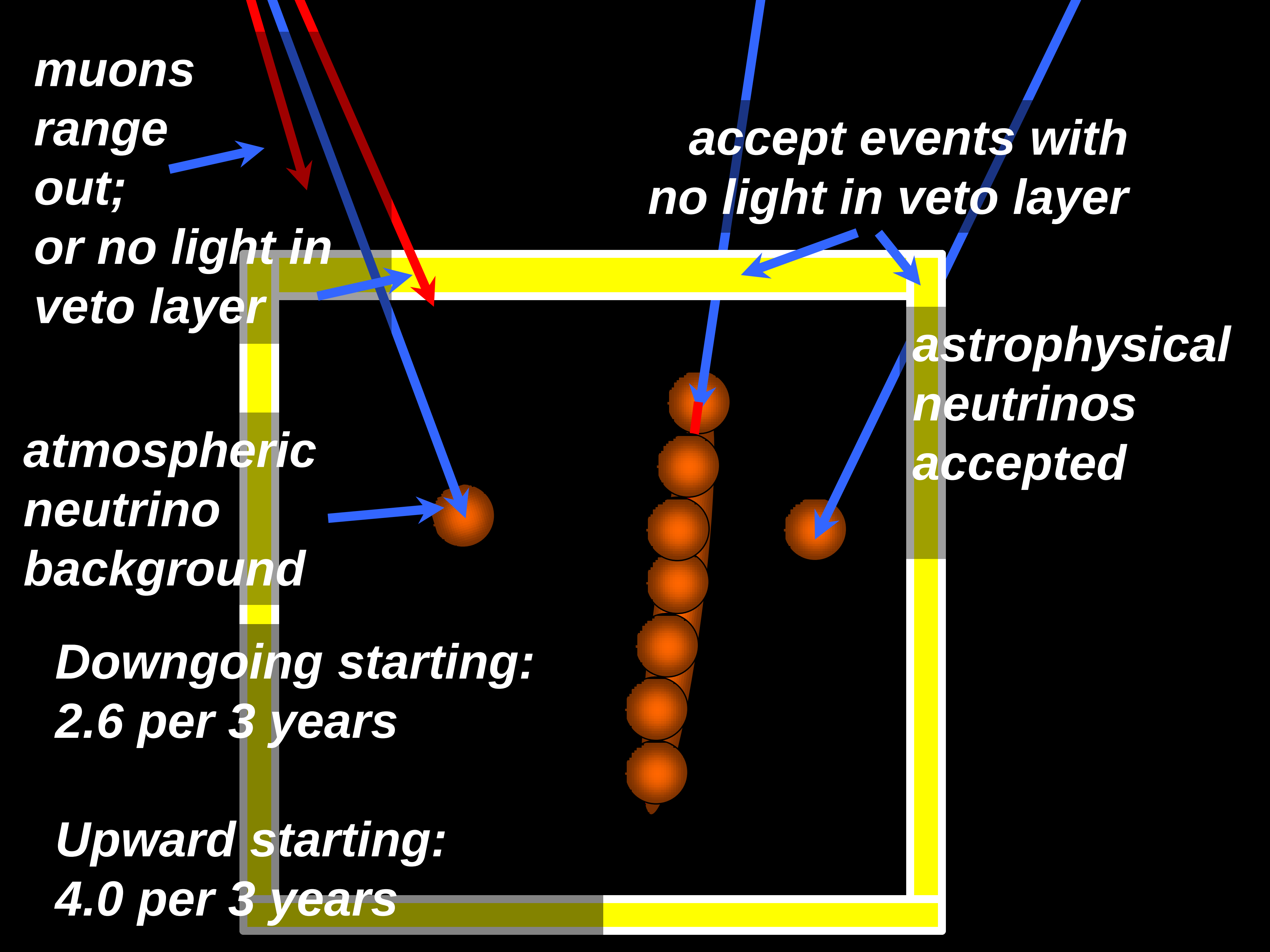
True also for electron and tau neutrinos:

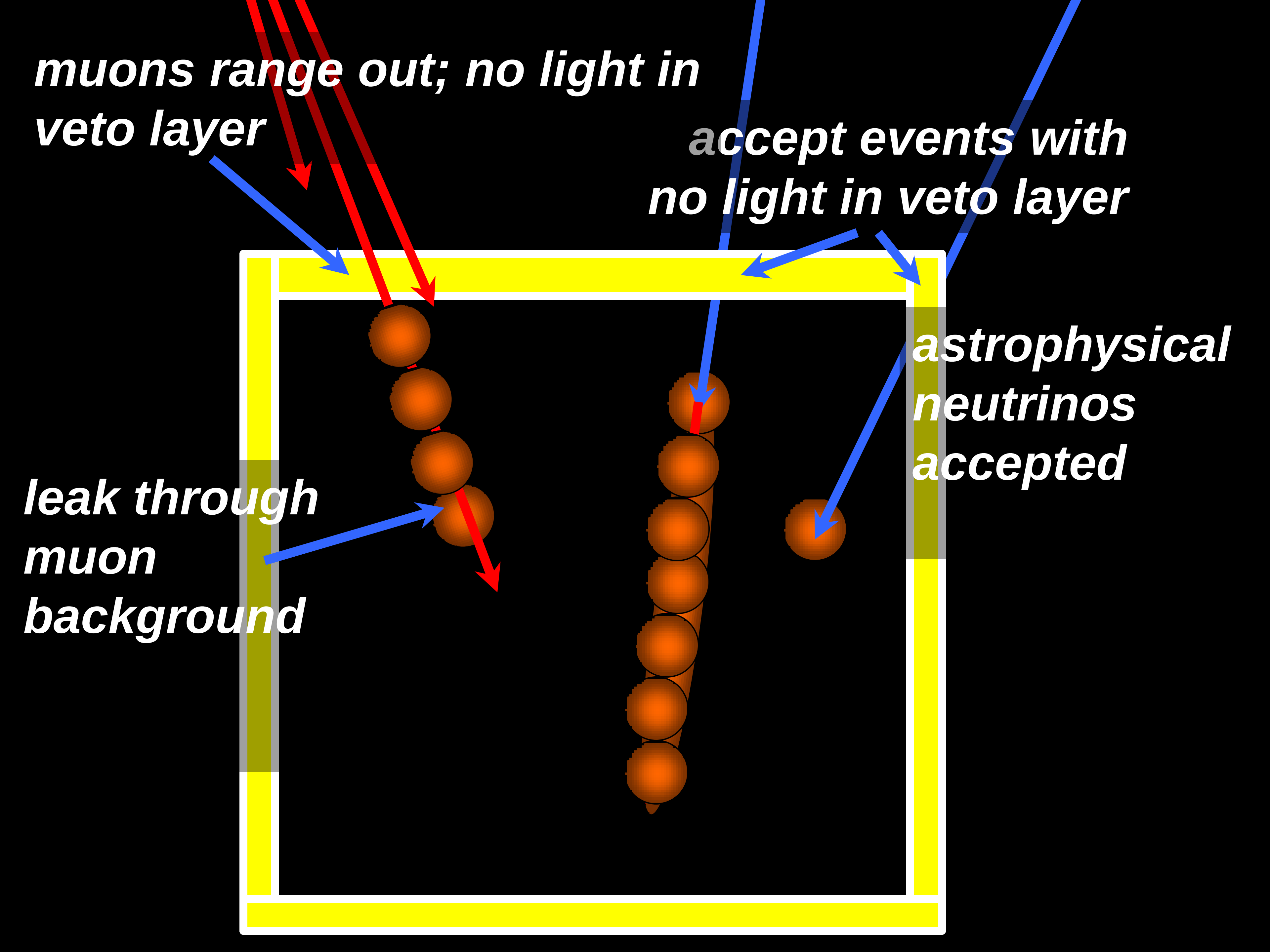
see muons from other decays in the entire air shower

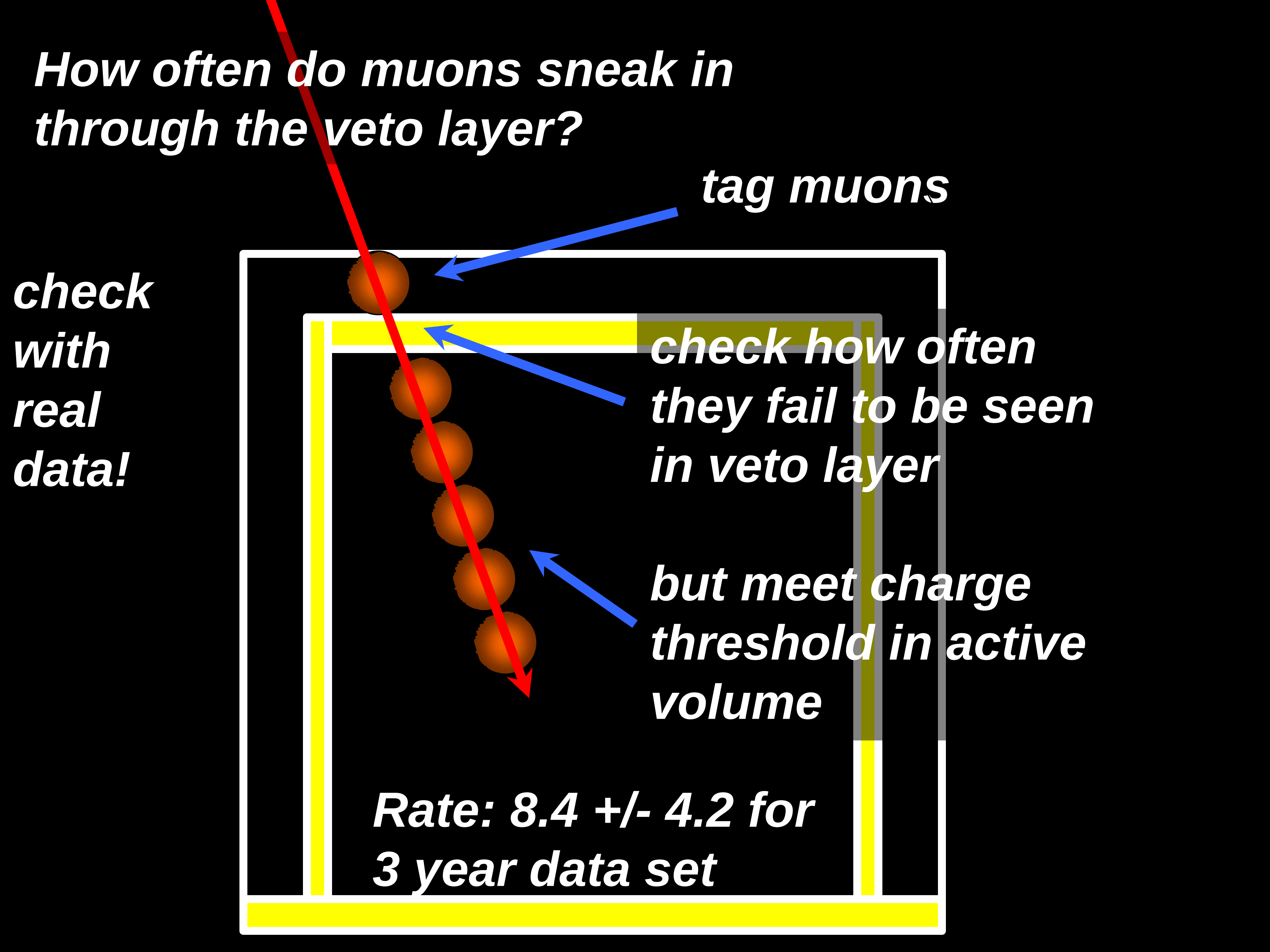
van Santen, Jero, Gaisser, Karle


Primary cosmic rays
105.7 MeV/c²
-1
1/2
μ
muon
<2.2 eV/c²
0
1/2
ν_e
electron neutrino
Neutrino from the atmosphere above the south pole
Rejected!
Muon from the atmosphere above the south pole
Neutrino from the distant Universe
Keep!


reject events with light in veto layer
accept events with no light in veto layer and high charge in fiducial volume
atmospheric neutrinos accompnied by muons: rejected
high energy astrophysical neutrinos accepted (look for Npe > 6000)


muons
range
out;
or no light in
veto layer
accept events with
no light in veto layer
astrophysical
neutrinos
accepted
atmospheric
neutrino
background
Downgoing starting:
2.6 per 3 years
Upward starting:
4.0 per 3 years


muons range out; no light in veto layer
accept events with no light in veto layer
astrophysical neutrinos accepted
leak through muon background


How often do muons sneak in through the veto layer?
tag muons
check with real data!
check how often they fail to be seen in veto layer
but meet charge threshold in active volume
Rate: 8.4 +/- 4.2 for 3 year data set

***backgrounds:* HESE-2 (IC79 + IC86-1 + IC86-2)**

6.6 +5.9 -1.6 ***atmospheric neutrinos***

8.4 +/- 4.2 ***downgoing muons***

15.0 ***total expected background***

backgrounds: *HESE-2 (IC79 + IC86-1 + IC86-2)*

6.6 +5.9 -1.6 *atmospheric neutrinos*

8.4 +/- 4.2 *downgoing muons*

15.0 *total expected background*

HESE (IC79 + IC86-1) :

26 new events (but no more at 1PeV)

28 events → *Science paper*

backgrounds: *HESE-2 (IC79 + IC86-1 + IC86-2)*

6.6 +5.9 -1.6 atmospheric neutrinos

8.4 +/- 4.2 downgoing muons

15.0 total expected background

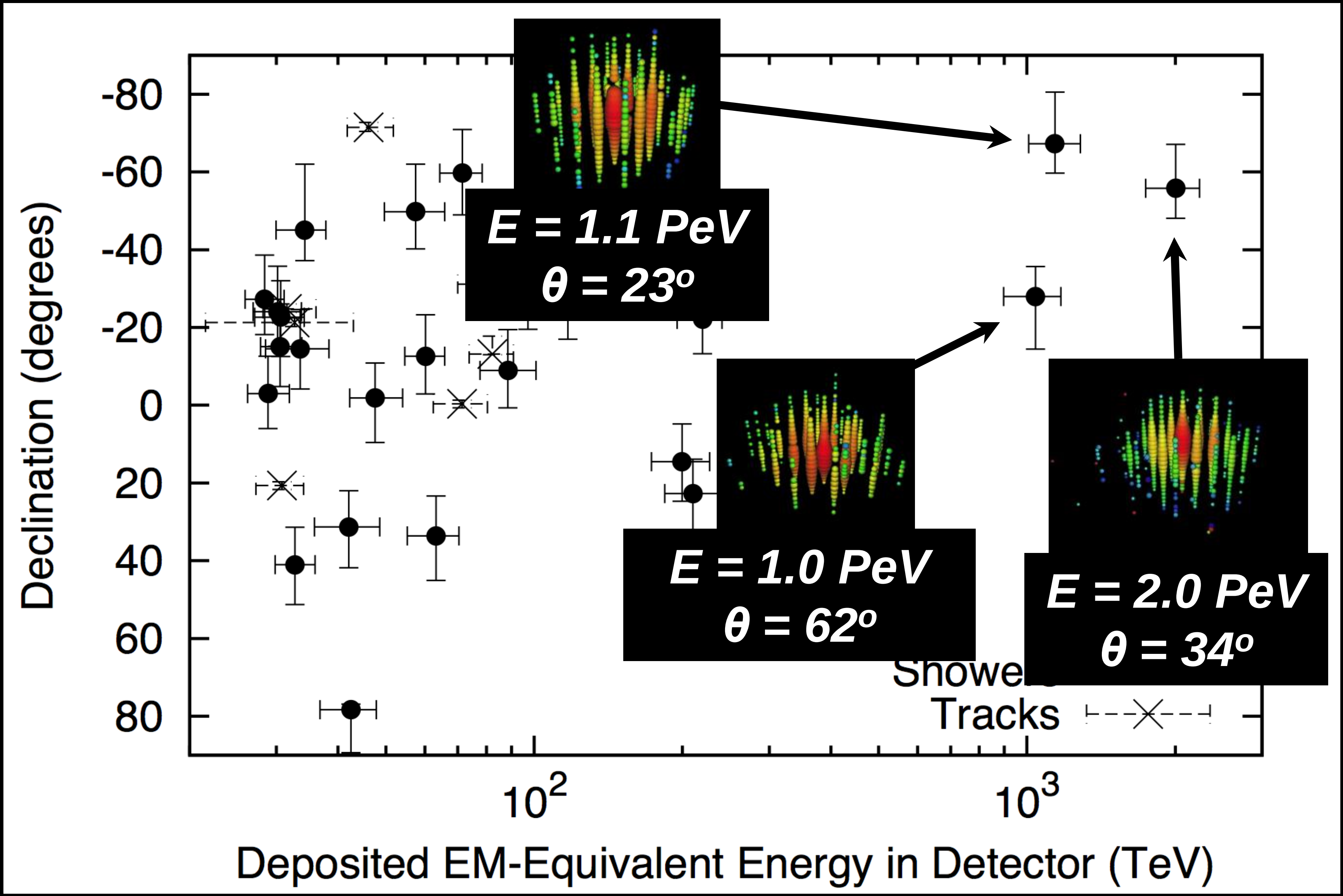
HESE (IC79 + IC86-1) :

26 new events (but no more at 1PeV)

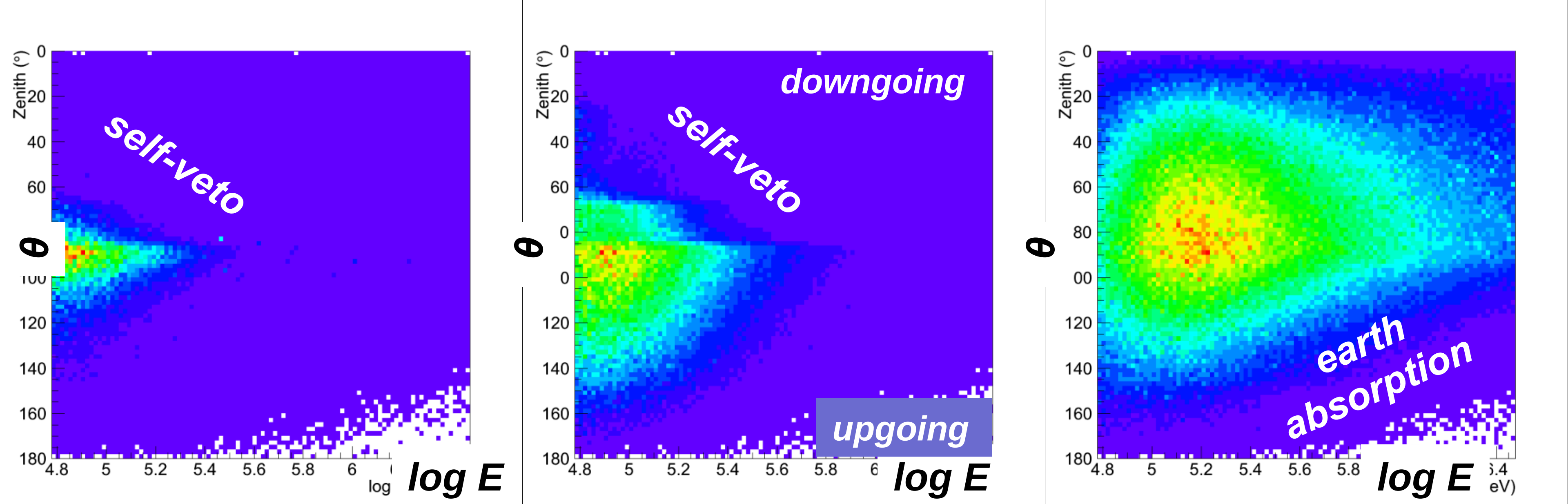
28 events → Science paper

HESE-2 (IC79 + IC86-1 + IC86-2):

28+9 = 37 events total → PRL submitted



E = 1.1 PeV
θ = 23º
E = 1.0 PeV
θ = 62º
E = 2.0 PeV
θ = 34º
Declination (degrees)
Deposited EM-Equivalent Energy in Detector (TeV)
Showers
Tracks
-80
-60
-40
-20
0
20
40
60
80
10^2
10^3



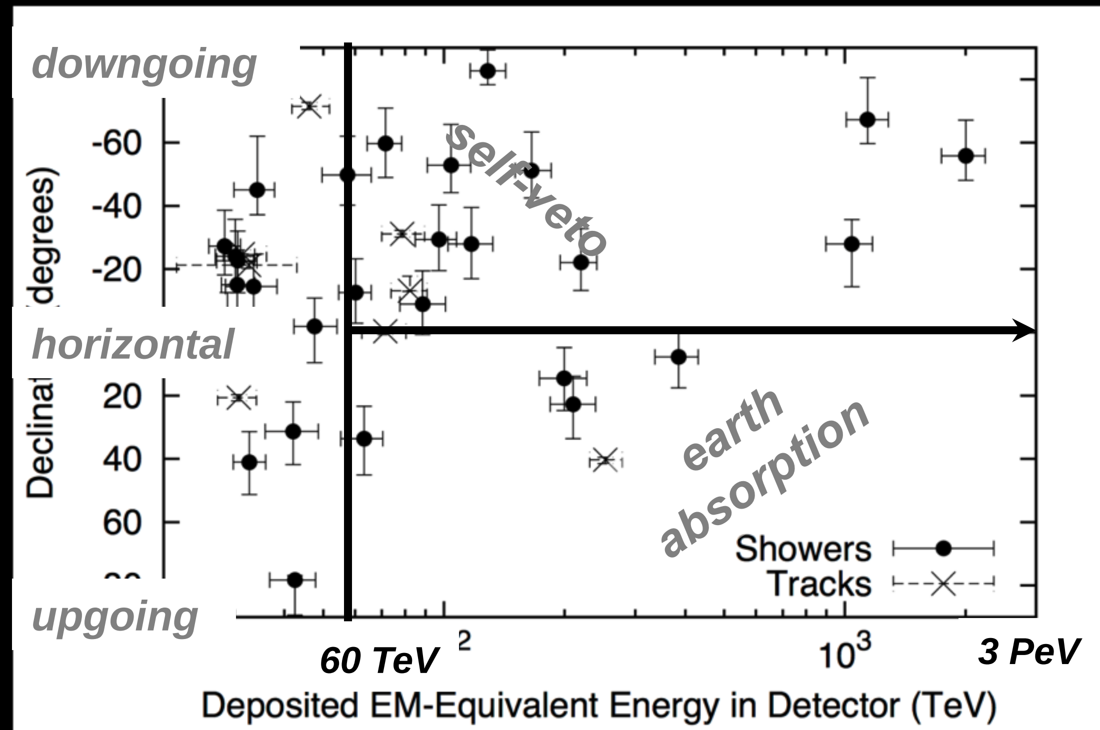
conventional + prompt + astrophysical

IC79/86-1/86-2 diffuse analysis forward folding

Fit (track/shower) data to mixture of

conventional
prompt
astrophysical

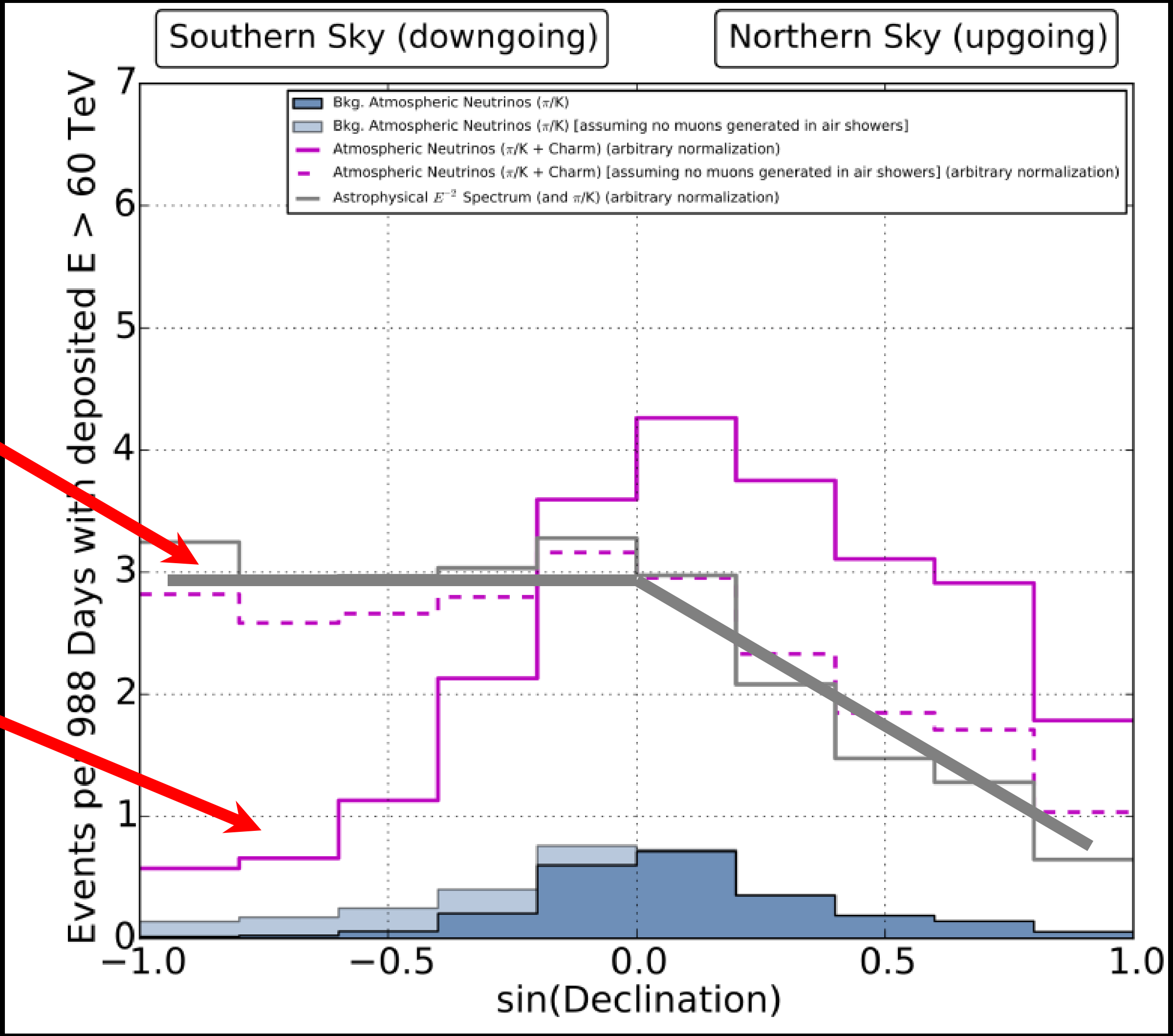
= data



The power of the self-veto

Without self-veto astro (grey) and prompt (dash-purple) have same zenith shape

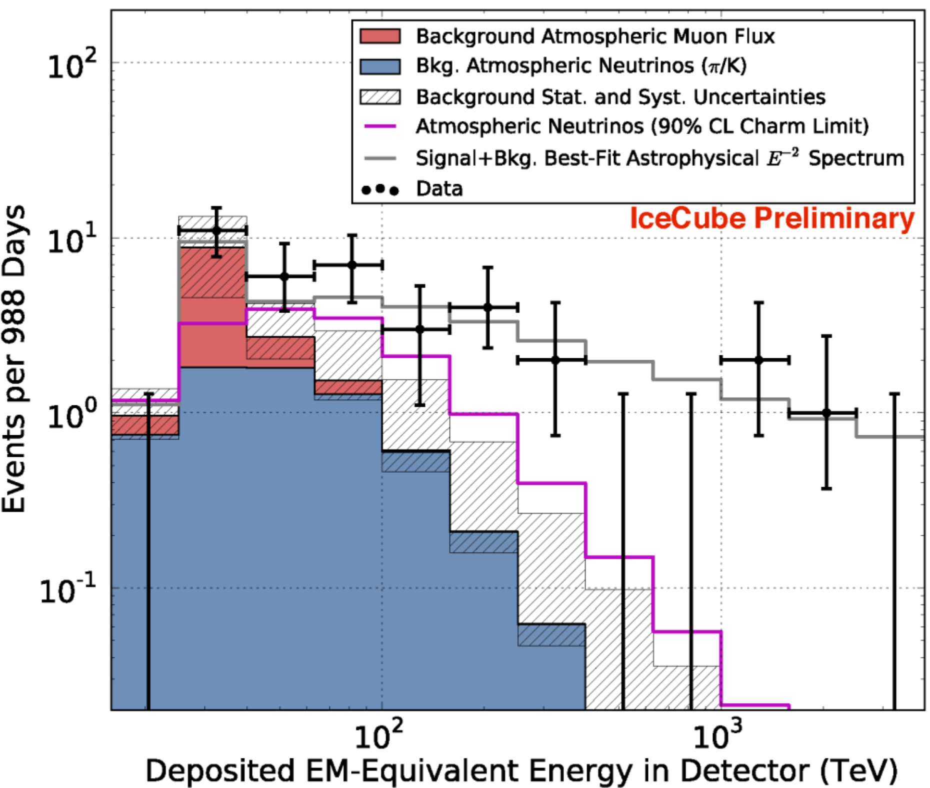
With self-veto prompt (solid-purple) is highly suppressed from above

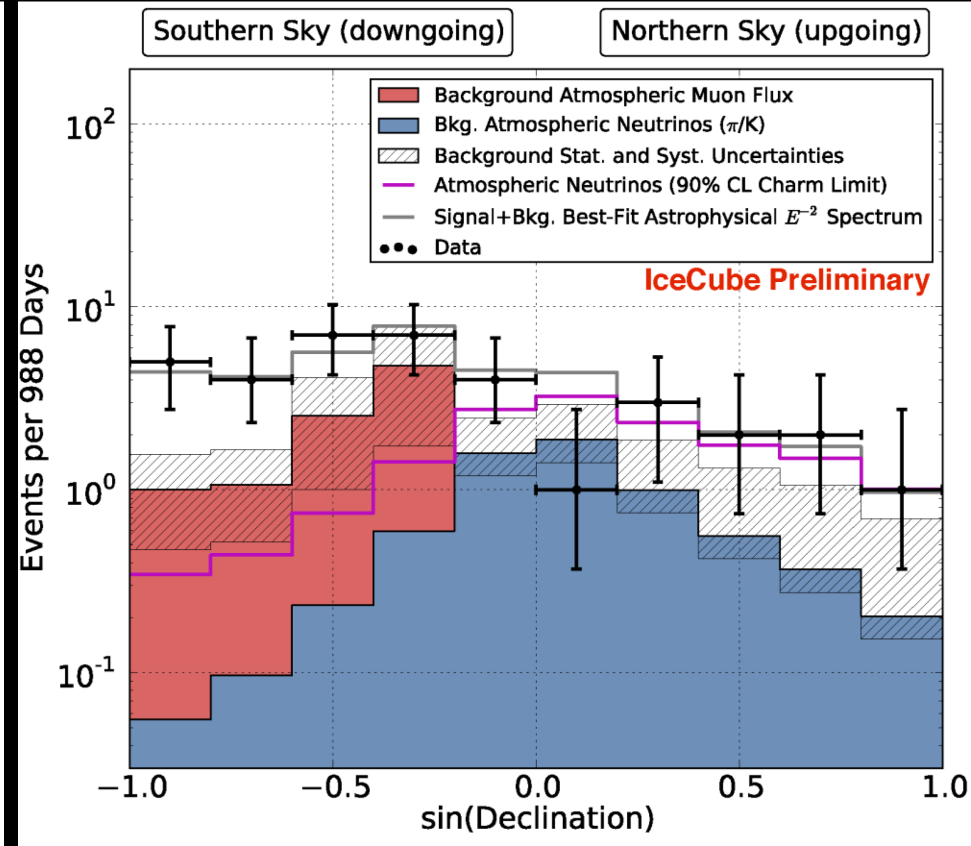


Global fit of energy vs angle to a mixture of atmospheric and astrophysical E^{-2} neutrinos

best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

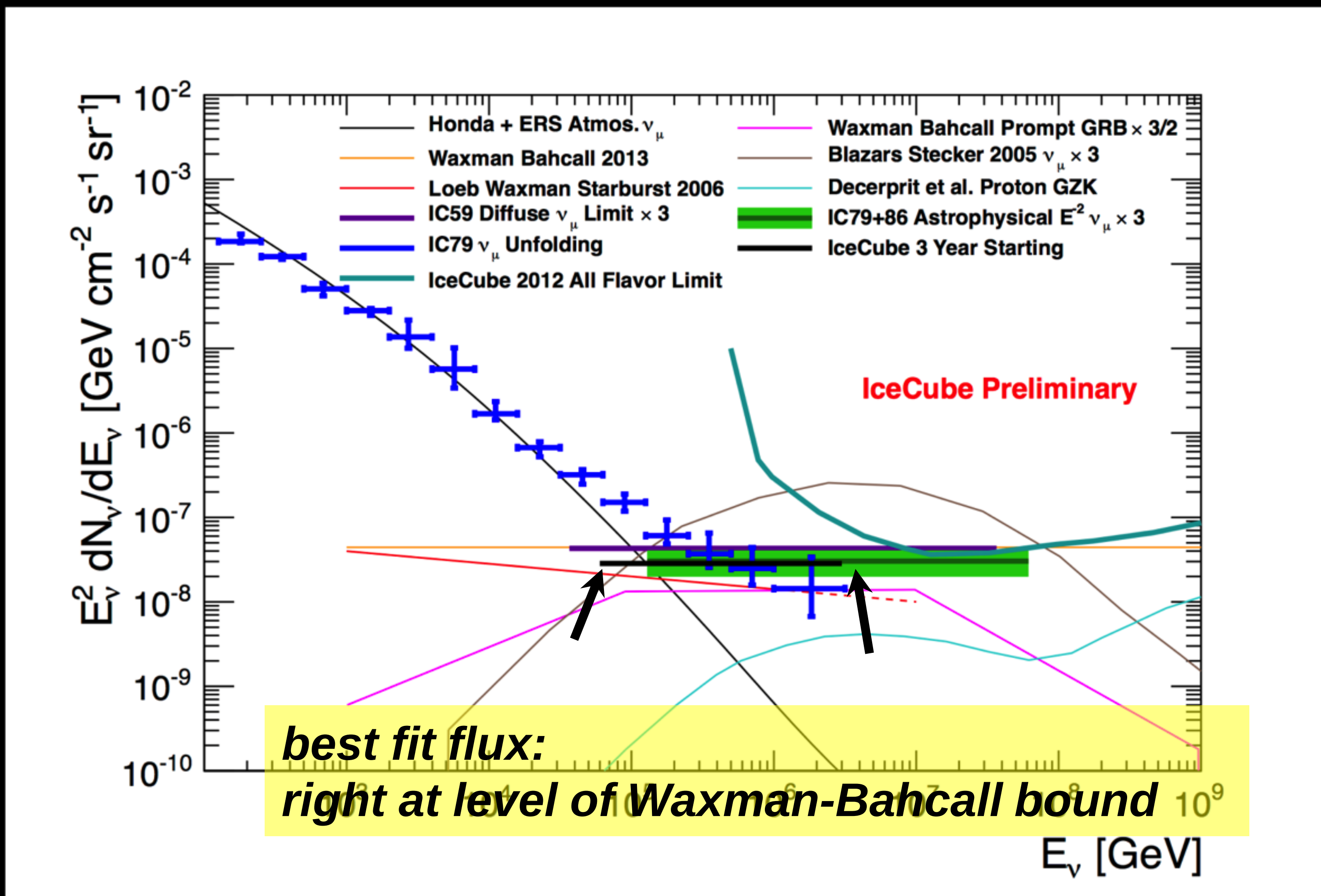
5.7 sigma rejection of atmospheric-only hypothesis





Global fit, energy (60 TeV – 3 PeV) vs angle,
best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (per flavour)

5.7 sigma rejection of atmospheric-only hypothesis

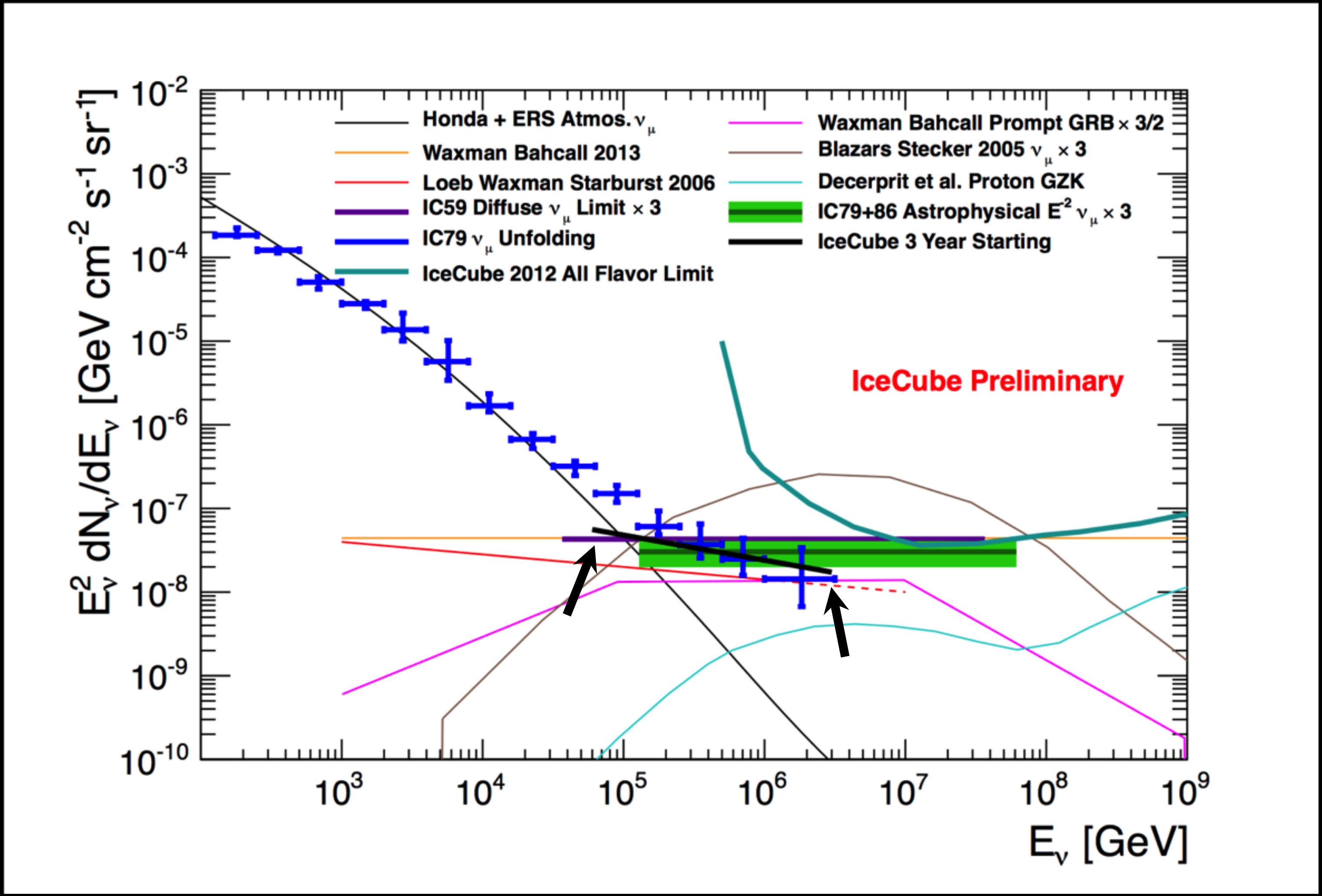


best fit flux:
right at level of Waxman-Bahcall bound

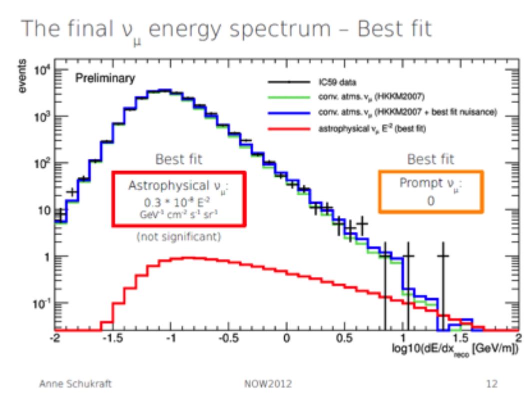
global fit, energy (60 TeV – 3 PeV) vs angle,

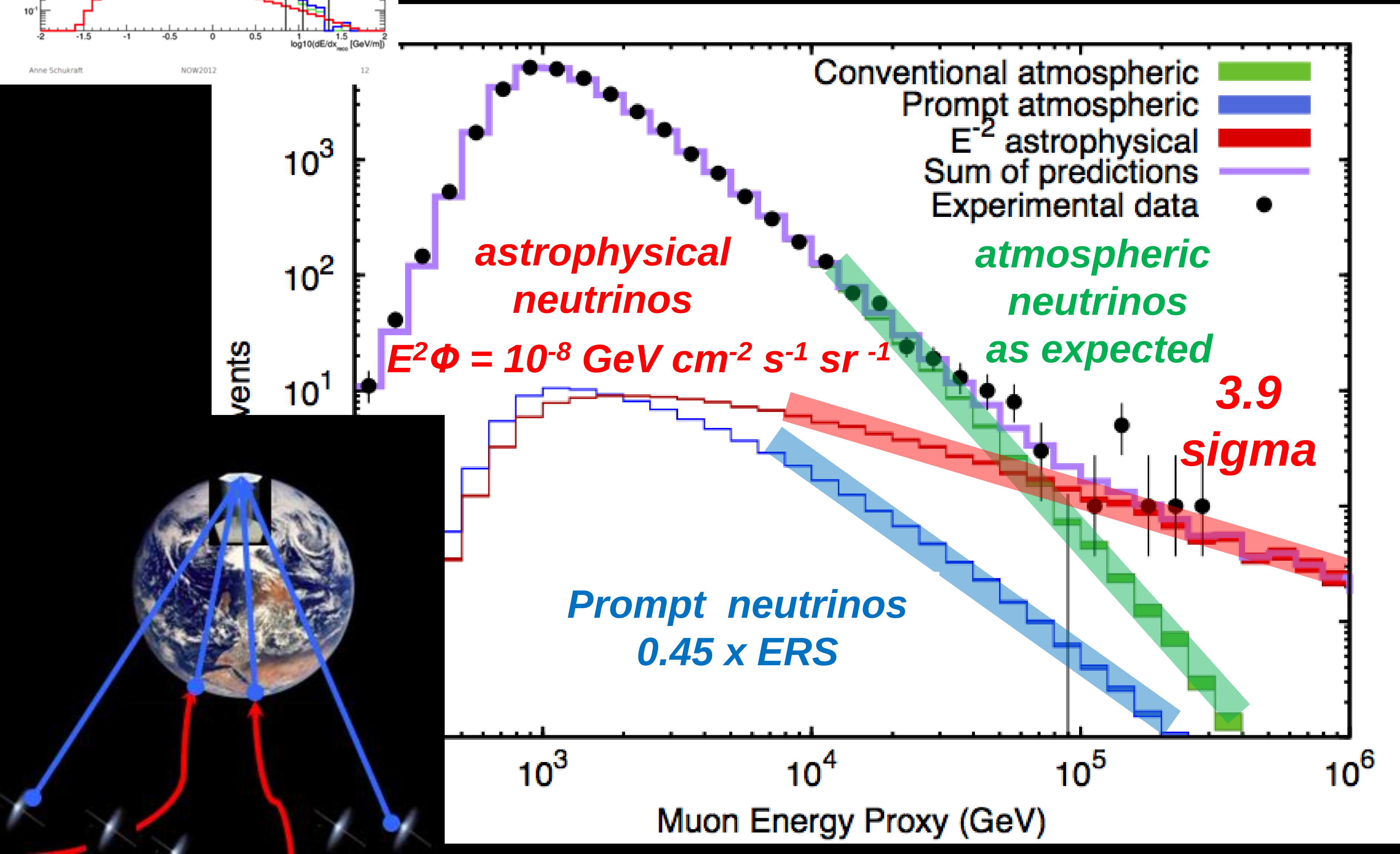
float astrophysical spectral index:

best fit spectral index = -2.3 +/- 0.3

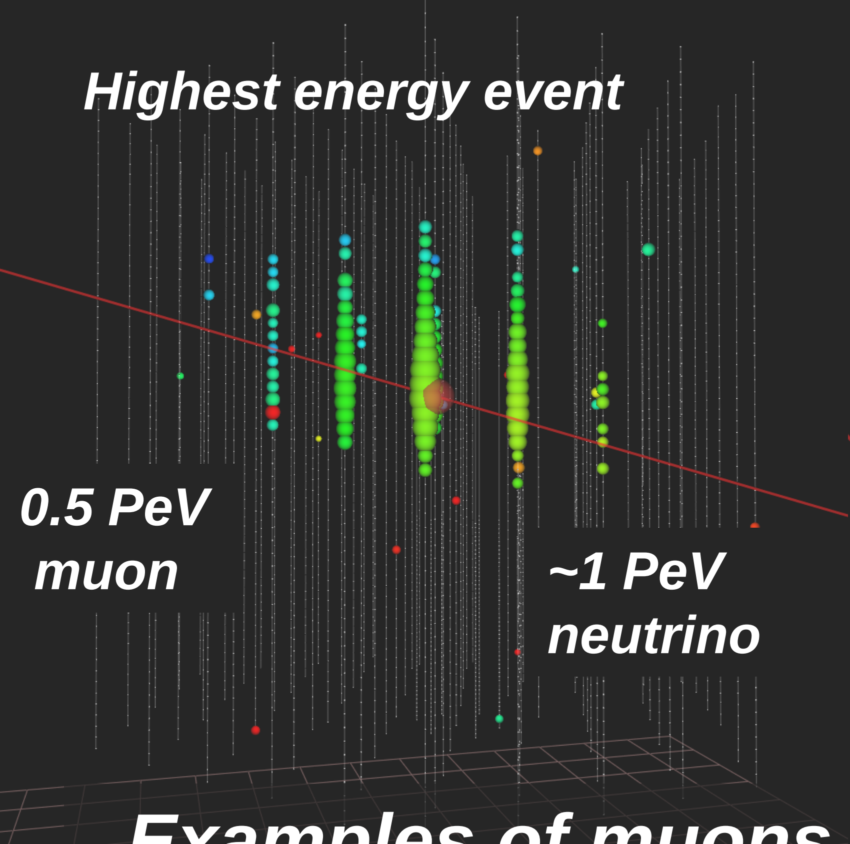


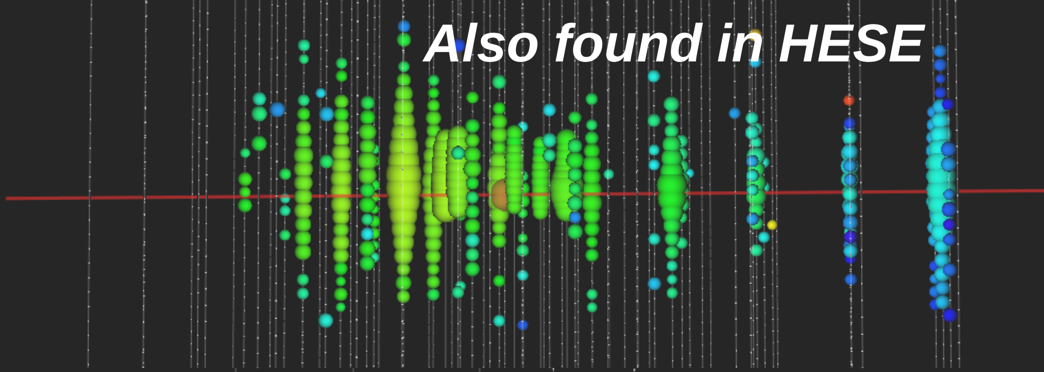
Hint from IC59 (1.8 sigma); now IC79/86-1 upgoing muon neutrinos give 3.9 sigma

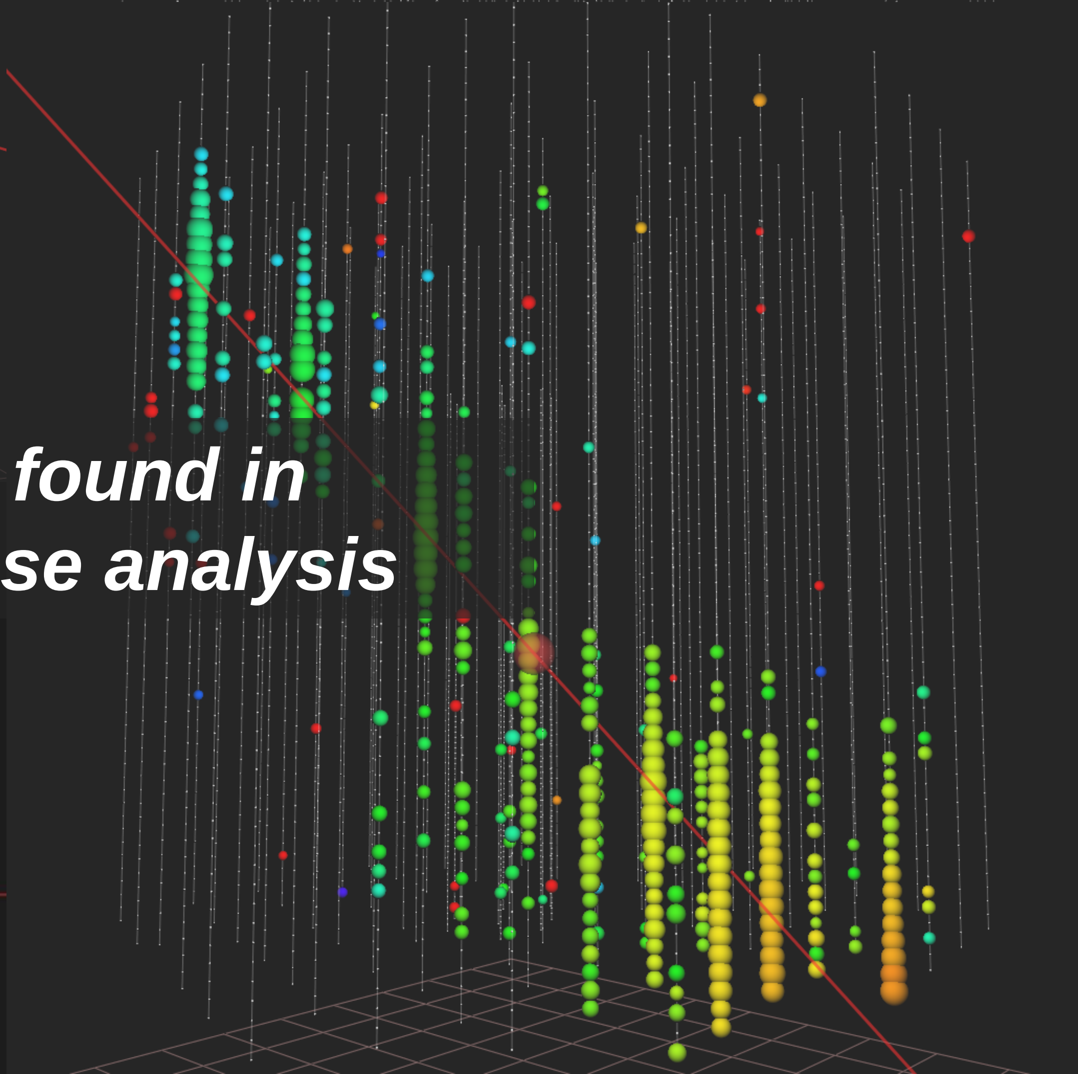


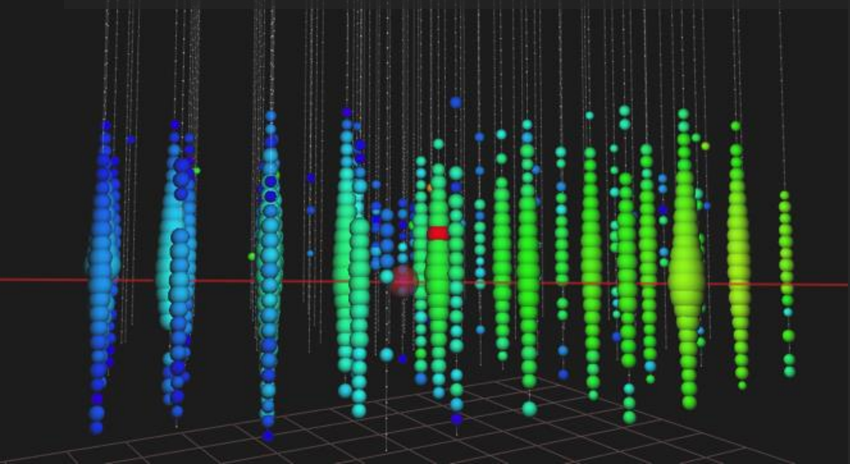


Examples of muons found in IC79/86 upgoing diffuse analysis





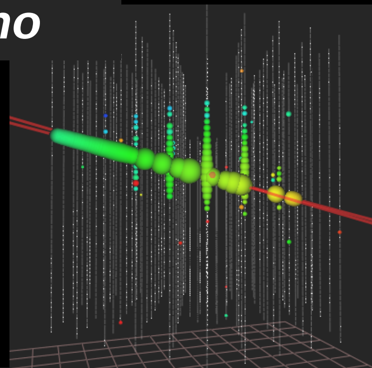




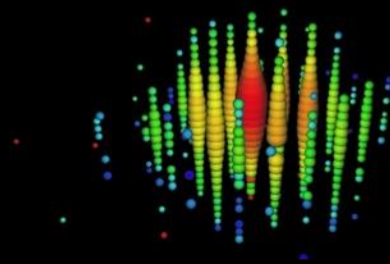
Through going muons

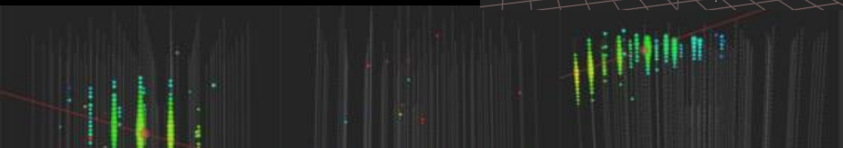
Contained vertex events

~1 PeV muon neutrino

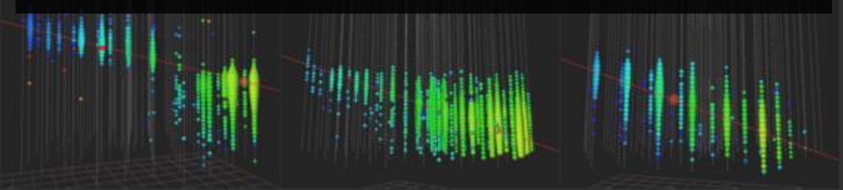


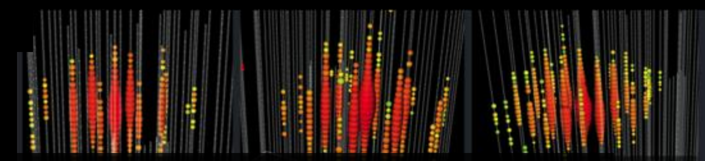
2 PeV electron neutrino



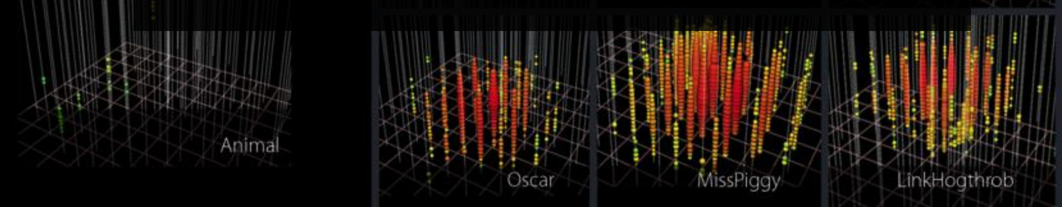


- northern hemisphere
- neutrino events (best fit) above 100 TeV muon energy:
  - astrophysical: 7 events/yr
  - atmospheric: 3 events/yr
- significance in first 2 years of data: 3.9 sigma (prel.)

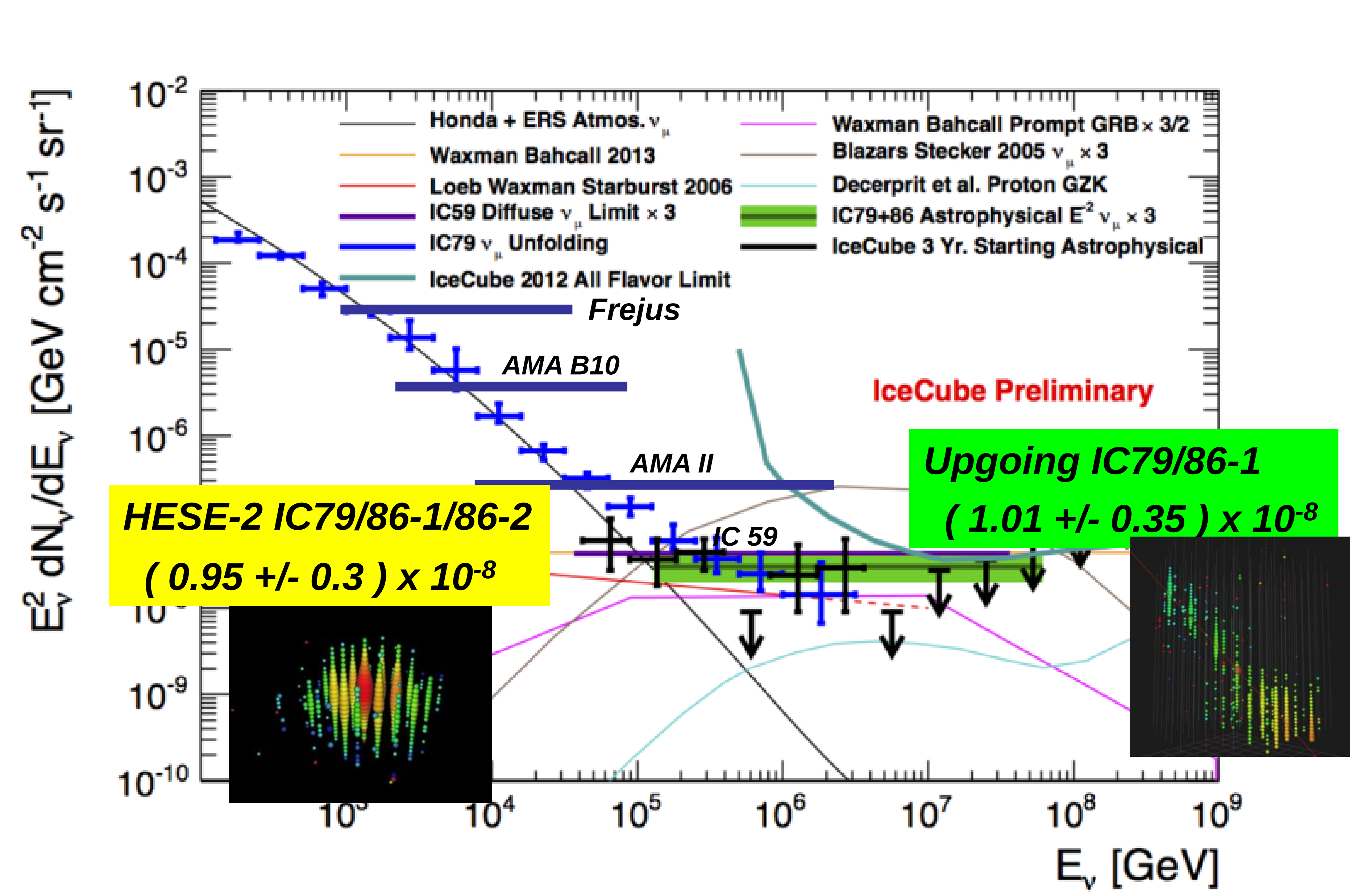




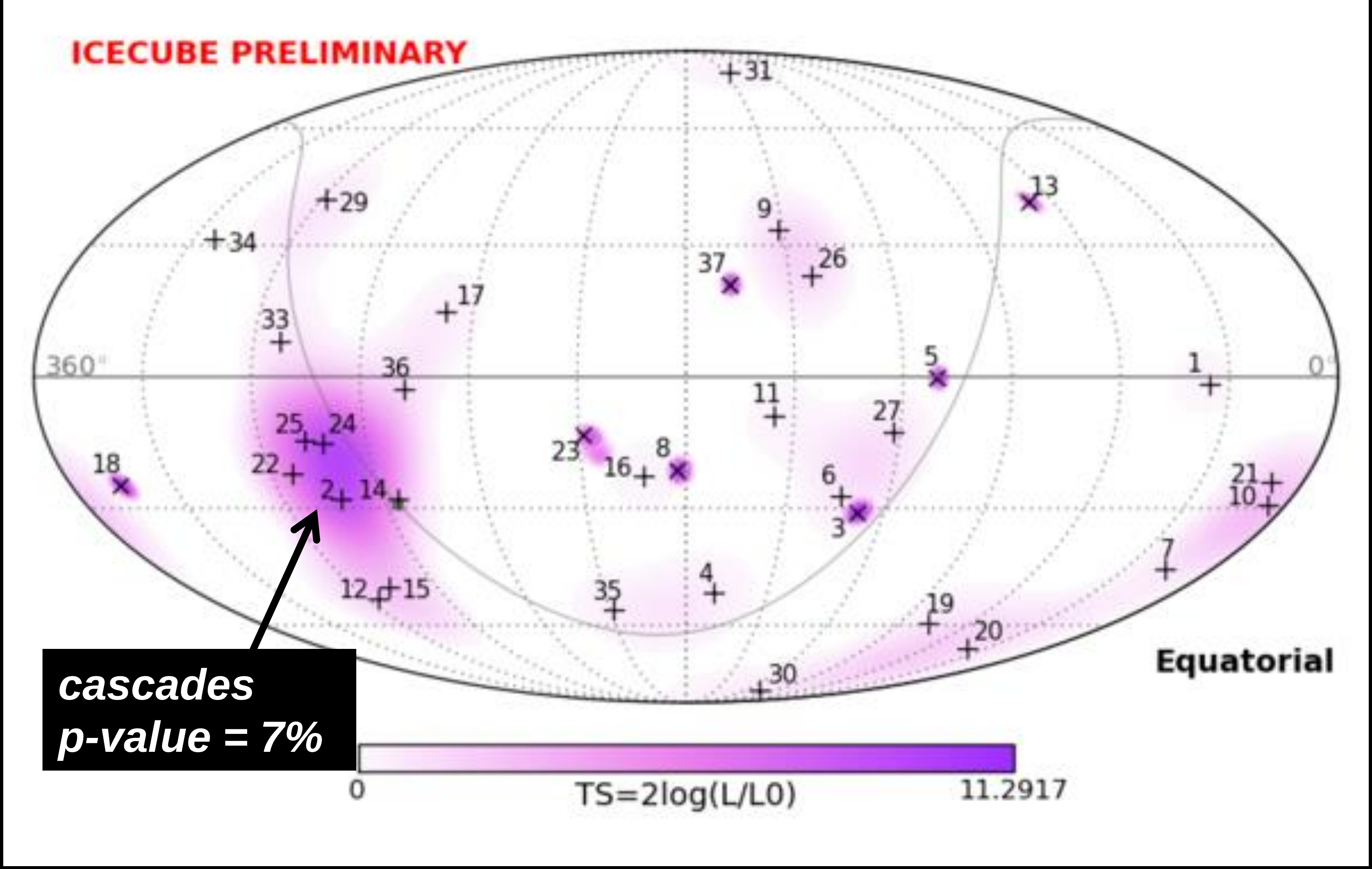
- mostly southern hemisphere
- neutrino events above 60 TeV:
  - astrophysical: 6 /yr
  - atmospheric: 1/yr
- significance in first 3 years of data: 5.7 sigma



Diffuse flux summary

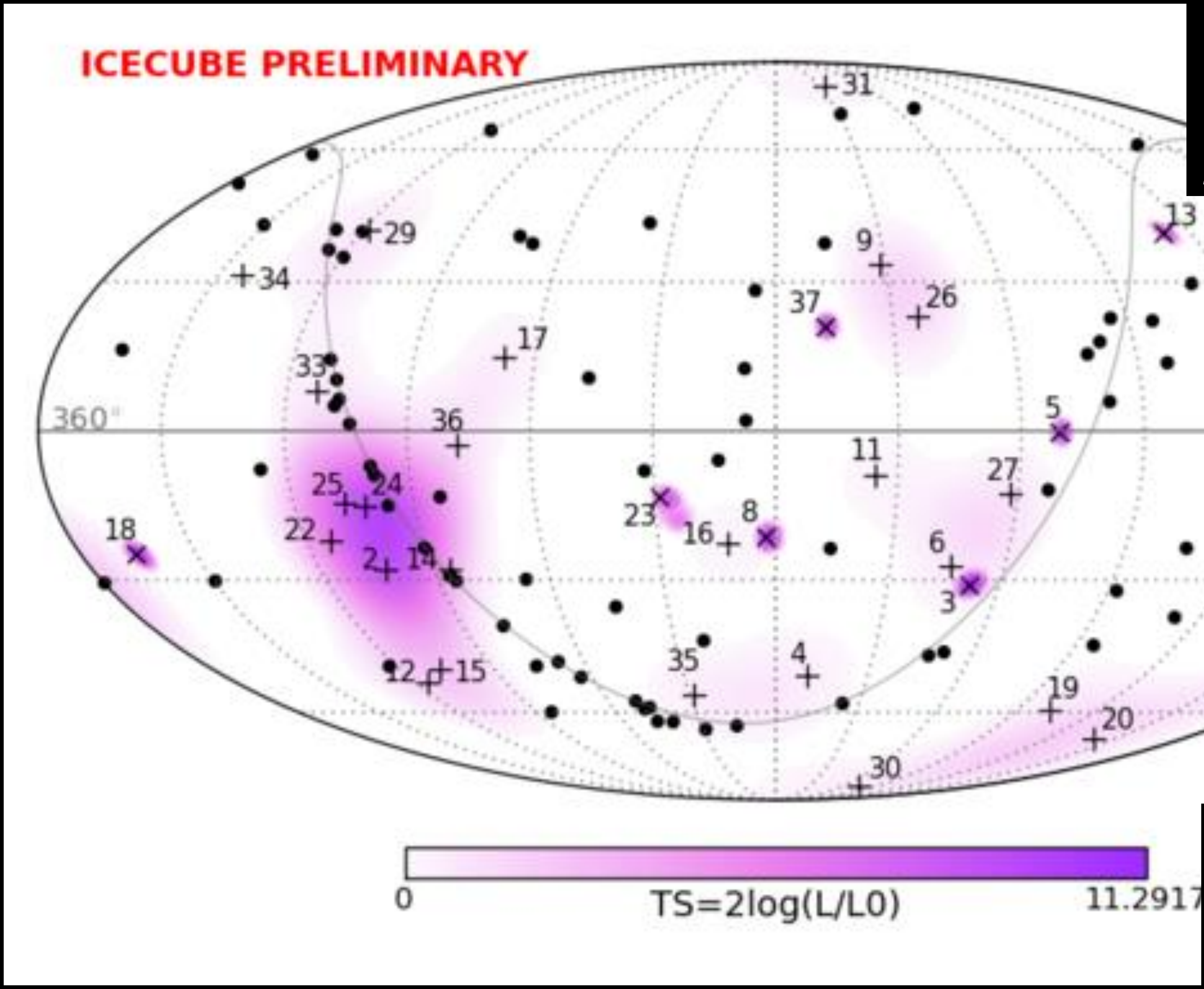


Do the HESE events cluster - is there a brighter than average source?



cascades
p-value = 7%

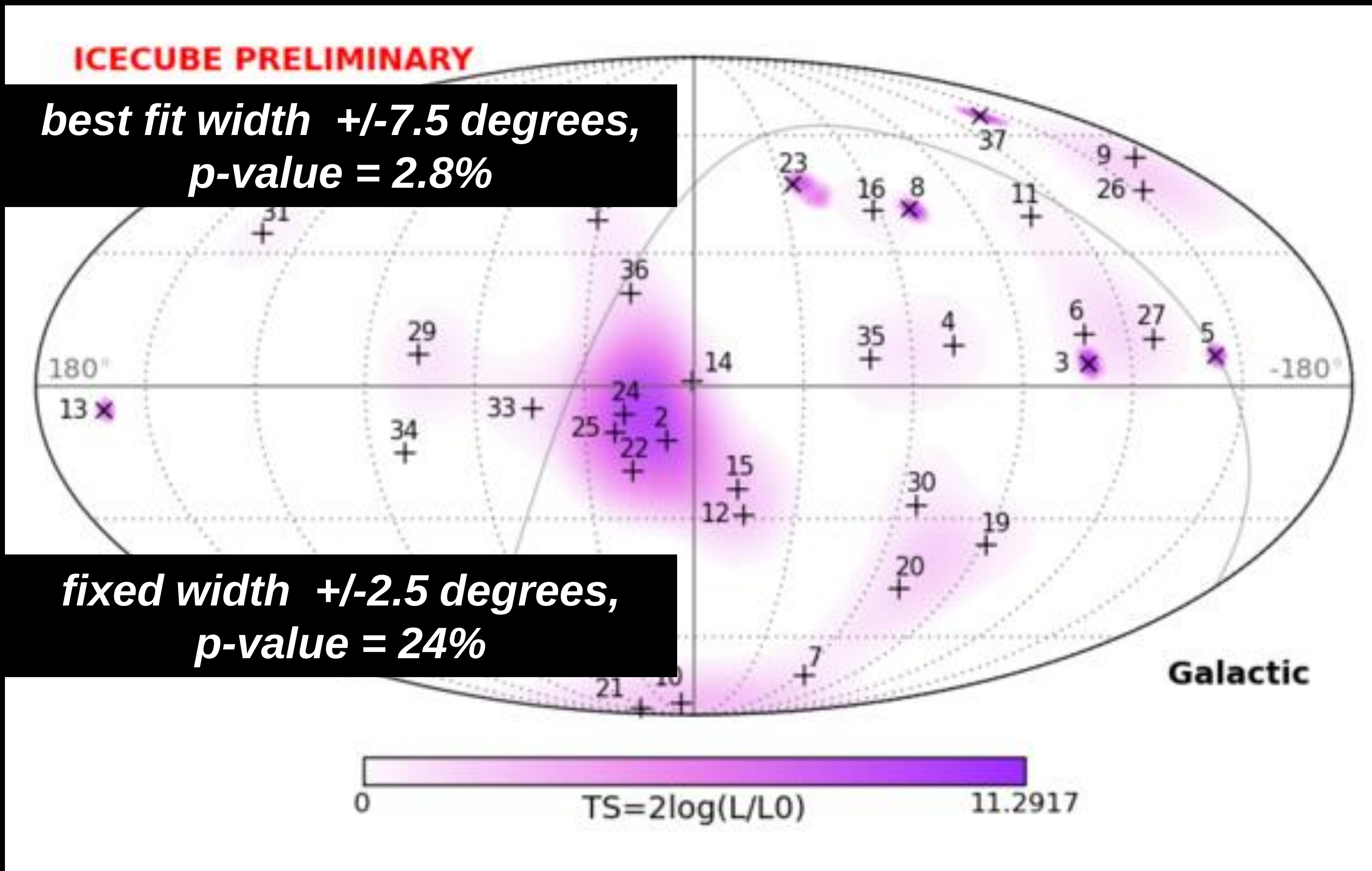
Do the events correlate with potential sources?



northern source list p-value = 28%

southern source list p-value = 8%

Do the events correlate with the galactic plane?



best fit width +/-7.5 degrees, p-value = 2.8%

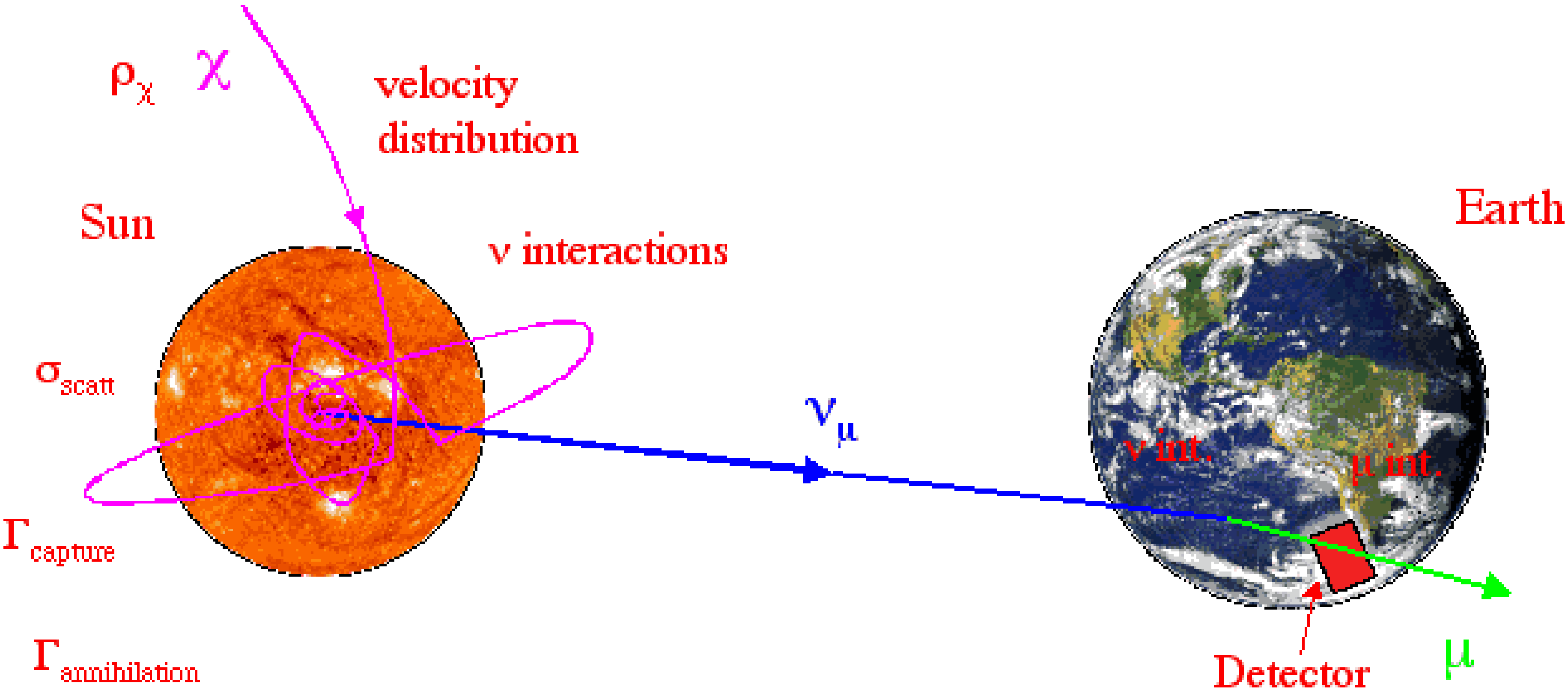
fixed width +/-2.5 degrees, p-value = 24%

Indirect dark matter detection?

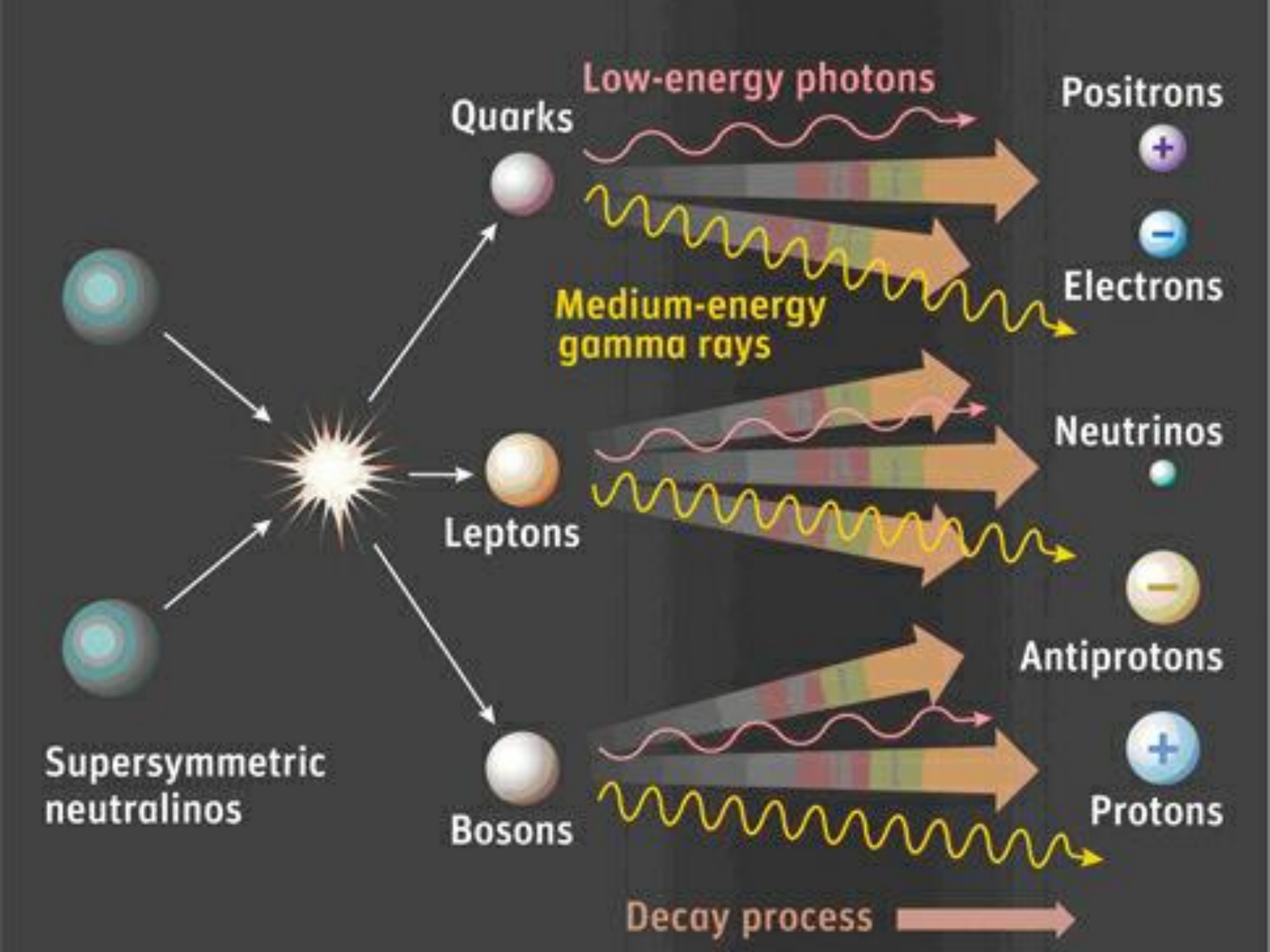
Dark matter accumulation in

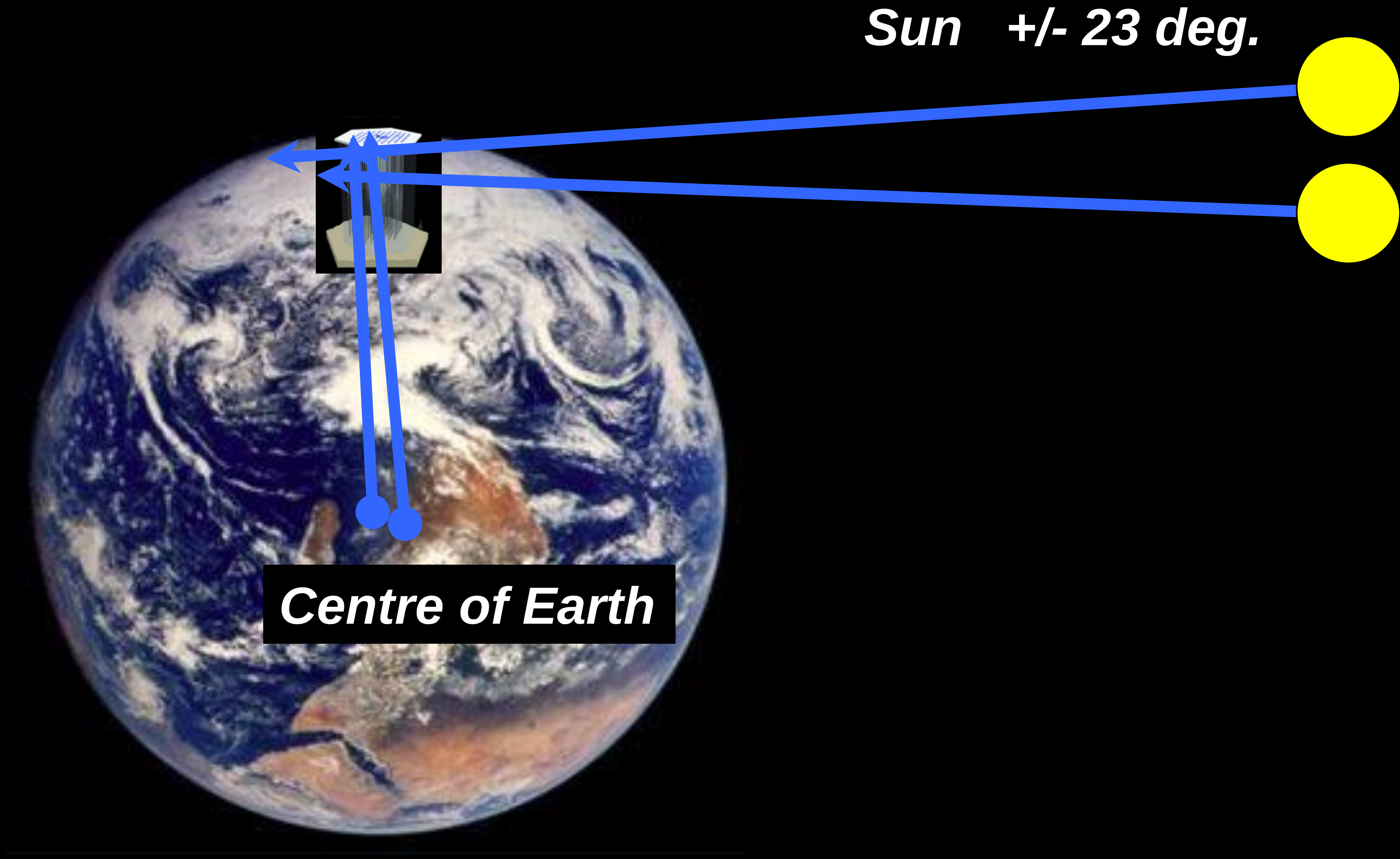
the sun
the earth
galactic halo
other galaxies

Annihilation to neutrinos…



ρχ
χ
velocity
distribution
Sun
ν interactions
Earth
σscatt
νμ
ν int.
μ int.
Γcapture
Γannihilation
Detector
μ


Low-energy photons
Quarks
Positrons
Electrons
Medium-energy
gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Protons
Bosons
Decay process


Sun +/- 23 deg.
Centre of Earth

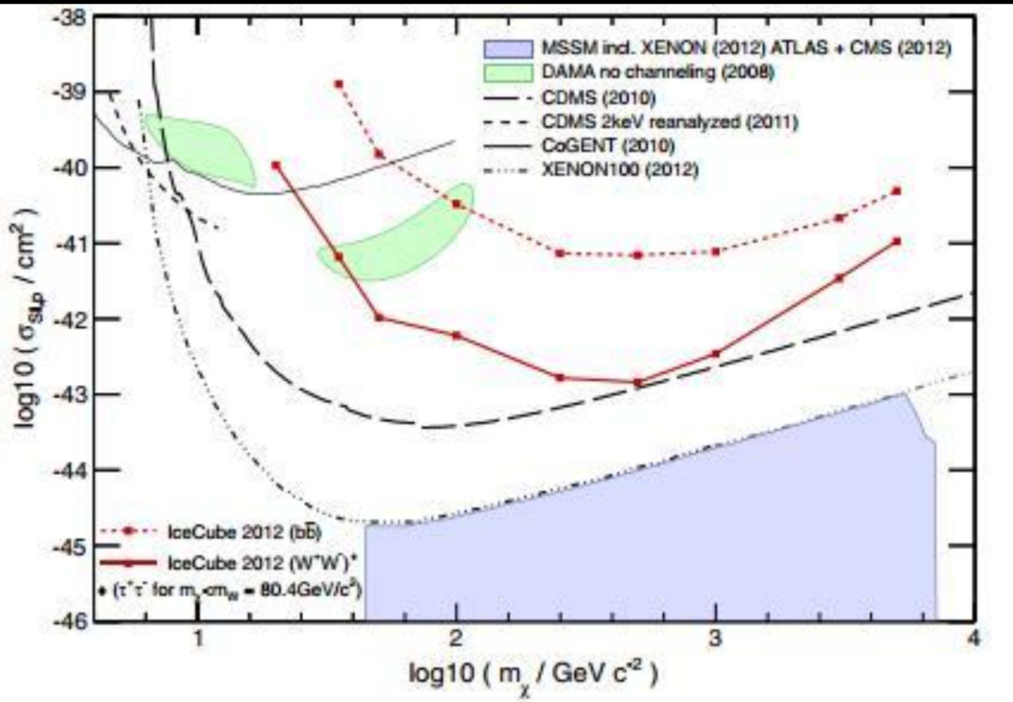
Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector

We have performed a search for muon neutrinos from dark matter annihilation in the center of the Sun with the 79-string configuration of the IceCube neutrino telescope. For the first time, the DeepCore subarray is included in the analysis, lowering the energy threshold and extending the search to the austral summer. The 317 days of data collected between June 2010 and May 2011 are consistent with the expected background from atmospheric muons and neutrinos. Upper limits are set on the dark matter annihilation rate, with conversions to limits on spin-dependent and spin-independent scattering cross sections of weakly interacting massive particles (WIMPs) on protons, for WIMP masses in the range 20–5000 GeV/c^2. These are the most stringent spin-dependent WIMP-proton cross section limits to date above 35 GeV/c^2 for most WIMP models.

TABLE I. Results from the combination of the three independent datasets. Upper 90% limits on the number of signal events μ_s^{90}, the WIMP annihilation rate in the Sun Γ_A, the muon flux Φ_μ and neutrino flux Φ_ν, and the WIMP-proton scattering cross-sections (spin-independent, $\sigma_{SI,p}$, and spin-dependent, $\sigma_{SD,p}$), at the 90% confidence level including systematic errors. The sensitivity $\overline{\Phi}_\mu$ (see text) is shown for comparison.

m_χ (GeV/c^2)	Channel	μ_s^{90}	Γ_A (s^{-1})	$\overline{\Phi}_\mu$ (km^{-2}y^{-1})	Φ_μ (km^{-2}y^{-1})	Φ_ν (km^{-2}y^{-1})	$\sigma_{SI,p}$ (cm^2)	$\sigma_{SD,p}$ (cm^2)
20	$\tau^+\tau^-$	162	2.46×10^{25}	5.26×10^{4}	9.27×10^{4}	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	70.2	1.03×10^{24}	1.03×10^{4}	1.21×10^{4}	1.02×10^{14}	6.59×10^{-42}	1.28×10^{-39}
35	$b\bar{b}$	128	1.99×10^{26}	5.63×10^{4}	1.04×10^{5}	6.29×10^{15}	1.28×10^{-39}	2.49×10^{-37}
50	$\tau^+\tau^-$	19.6	1.20×10^{23}	4.82×10^{3}	2.84×10^{3}	1.17×10^{13}	1.03×10^{-42}	2.70×10^{-40}
50	$b\bar{b}$	55.2	1.75×10^{25}	2.06×10^{4}	1.80×10^{4}	5.64×10^{14}	1.51×10^{-40}	3.96×10^{-38}
100	W^+W^-	16.8	3.35×10^{22}	1.49×10^{3}	1.19×10^{3}	1.23×10^{12}	6.01×10^{-43}	2.68×10^{-40}
100	$b\bar{b}$	28.9	1.82×10^{24}	7.57×10^{3}	5.91×10^{3}	6.34×10^{13}	3.30×10^{-41}	1.47×10^{-38}
250	W^+W^-	29.9	2.85×10^{21}	3.04×10^{2}	4.15×10^{2}	9.72×10^{10}	1.67×10^{-43}	1.34×10^{-40}
250	$b\bar{b}$	19.8	1.27×10^{23}	1.85×10^{3}	1.45×10^{3}	4.59×10^{12}	7.37×10^{-42}	5.90×10^{-39}
500	W^+W^-	25.2	8.57×10^{20}	1.46×10^{2}	2.23×10^{2}	2.61×10^{10}	1.45×10^{-43}	1.57×10^{-40}
500	$b\bar{b}$	30.6	4.12×10^{22}	8.53×10^{2}	1.02×10^{3}	1.52×10^{12}	6.98×10^{-42}	7.56×10^{-39}
1000	W^+W^-	23.4	6.13×10^{20}	1.19×10^{2}	1.85×10^{2}	1.62×10^{10}	3.46×10^{-43}	4.48×10^{-40}
1000	$b\bar{b}$	30.4	1.39×10^{22}	4.33×10^{2}	5.99×10^{2}	5.23×10^{11}	7.75×10^{-42}	1.00×10^{-38}
3000	W^+W^-	22.2	7.79×10^{20}	1.09×10^{2}	1.66×10^{2}	1.65×10^{10}	3.44×10^{-42}	5.02×10^{-39}
3000	$b\bar{b}$	26.1	4.88×10^{21}	2.52×10^{2}	3.47×10^{2}	1.89×10^{11}	2.17×10^{-41}	3.16×10^{-38}
5000	W^+W^-	22.8	8.79×10^{20}	1.01×10^{2}	1.58×10^{2}	1.77×10^{10}	1.06×10^{-41}	1.59×10^{-38}
5000	$b\bar{b}$	26.4	6.50×10^{20}	2.21×10^{2}	3.26×10^{2}	1.63×10^{11}	4.89×10^{-41}	7.29×10^{-38}

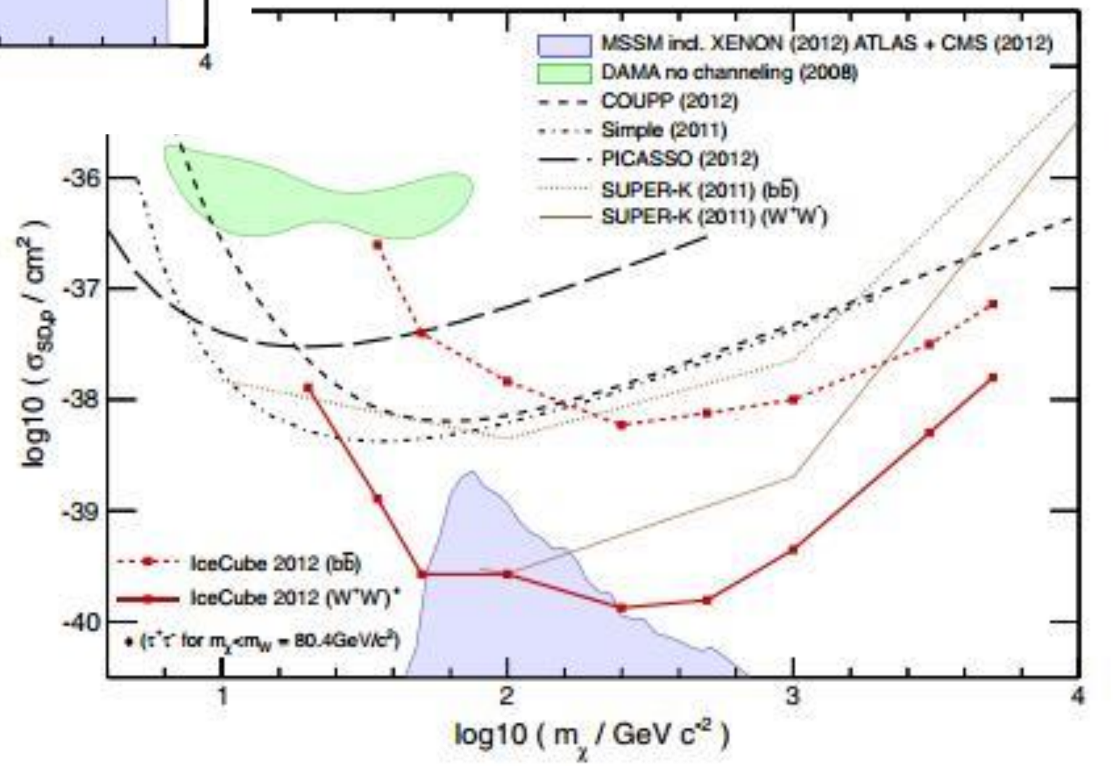
Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector



Limits on capture cross sections

Spin-independent

Spin-dependent



PRL **110**, 131302 (2013)

IceCube search for dark matter annihilation in nearby galaxies and galaxy clusters

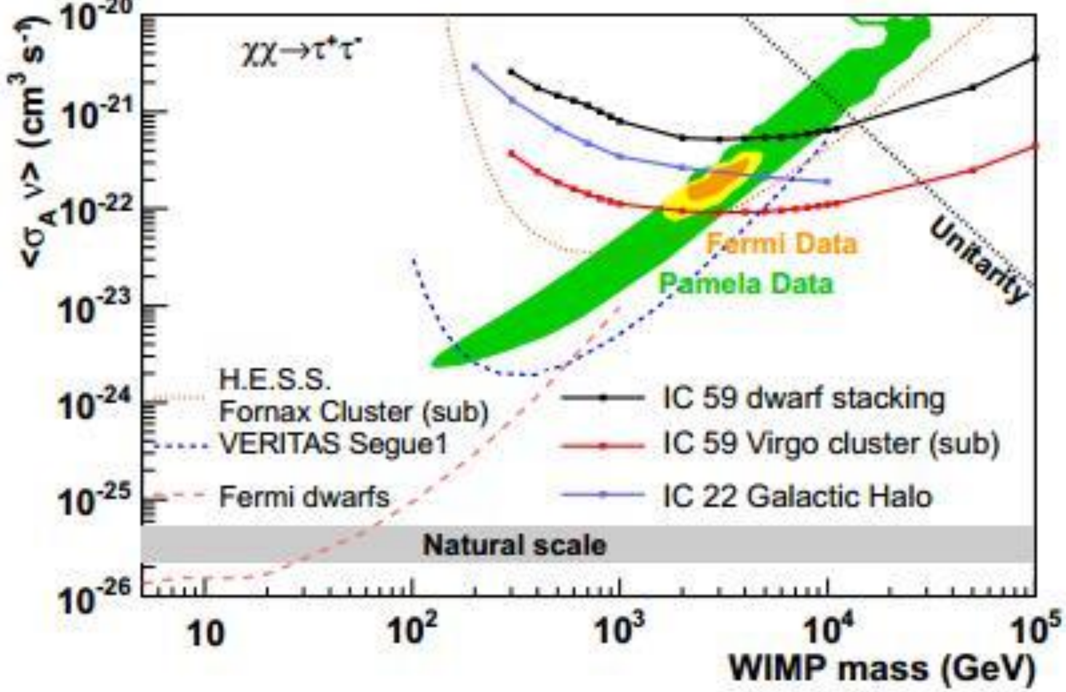
We present the results of a first search for self-annihilating dark matter in nearby galaxies and galaxy clusters using a sample of high-energy neutrinos acquired in 339.8 days of live time during 2009/10 with the IceCube neutrino observatory in its 59-string configuration. The targets of interest include the Virgo and Coma galaxy clusters, the Andromeda galaxy, and several dwarf galaxies. We obtain upper limits on the cross section as a function of the weakly interacting massive particle mass between 300 GeV and 100 TeV for the annihilation into $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\mu^+\mu^-$, and $\nu\bar{\nu}$. A limit derived for the Virgo cluster, when assuming a large effect from subhalos, challenges the weakly interacting massive particle interpretation of a recently observed GeV positron excess in cosmic rays.

Source	Right ascension	Declination	Distance [kpc]	Mass [$M_\odot$]	$\log_{10} J_{NFW}$ [$GeV^2 cm^{-5}$]	Boost factor
Segue 1	10h 07m 04s	+16°04'55"	23	1.58×10^7	19.6 ± 0.5 [40]	Not considered
Ursa Major II	08h 51m 30s	+63°07'48"	32	1.09×10^7	19.6 ± 0.4 [40]	Not considered
Coma Berenices	12h 26m 59s	+23°54'15"	44	0.72×10^7	19.0 ± 0.4 [40]	Not considered
Draco	17h 20m 12s	+57°54'55"	80	1.87×10^7	18.8 ± 0.1 [40]	Not considered
Andromeda	00h 42m 44s	+41°16'09"	778	6.9×10^{11}	19.2 [20]*	66
Virgo cluster	12h 30m 49s	+12°23'28"	22300	6.9×10^{14}	18.2 [41]*	980
Coma cluster	12h 59m 49s	+27°58'50"	95000	1.3×10^{15}	17.1 [41]*	1300

TABLE I. A list of potential astrophysical dark matter targets, their locations [37], distances, and masses [38], as well as J_{NFW} factors (see Sec. III) considered in this paper. Boost factors for Andromeda, Coma, and Virgo are applied, when subclusters are taken into account. According to Ref. [39], subclusters in dwarf galaxies do not usefully boost the signal. For the extended Virgo cluster, M87 was used as the central position. *For Andromeda and the galaxy clusters, no uncertainties are available.

Source	$\tau^+\tau^-$		$b\bar{b}$		W^+W^-		$\mu^+\mu^-$		$\nu\bar{\nu}$	
	estimated backgr.	observed events	estimated backgr.	observed events	estimated backgr.	observed events	estimated backgr.	observed events	estimated backgr.	observed events
Segue 1	8.7	10	13.3	18	8.2	12	8.7	10	4.3	6
Ursa Major II	7.4	8	5.2	1	7.4	8	4.6	1	3.5	1
Coma Berenices	4.7	1	11.6	4	4.7	1	8.3	3	4.7	1
Draco	5.6	8	13.4	15	5.6	8	5.6	8	4.5	8
Stacking (Seg1 + UMa II)	9.5	8	20.0	23	12.8	13	9.5	8	5.3	4
Virgo (subhalos)	92.1	89	322	325	103	102	92.1	89	94.7	92
Virgo (NFW)	9.6	9	23.9	19	9.6	9	9.6	9	5.9	5
Coma (subhalos)	17.5	17	35.8	40	14.0	15	14.0	15	13.5	15
Coma (NFW)	5.9	6	13.7	13	5.9	6	5.9	6	4.8	5
Andromeda (subhalos)	201	194	413	418	201	194	201	194	201	194
Andromeda (NFW)	6.4	2	6.7	1	6.4	2	6.4	2	4.3	0

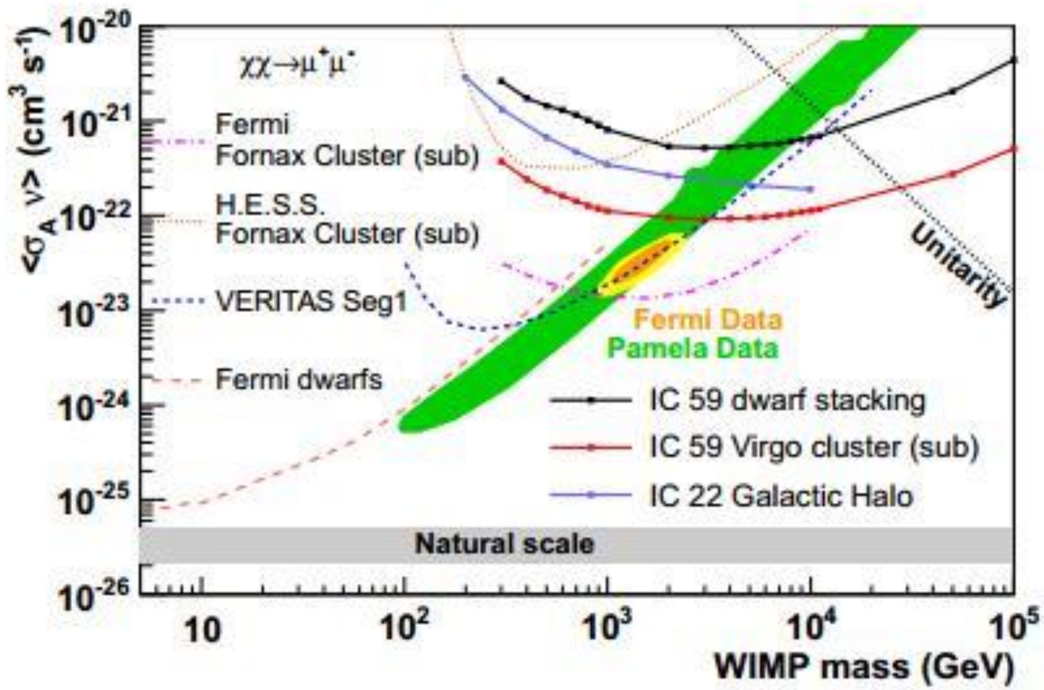
TABLE IV. Number of events as estimated from background and as observed in the data, for dwarf galaxies, galaxy clusters, and Andromeda. In some cases the same cut values and bin sizes were used for different annihilation channels, leading to the same number of events.

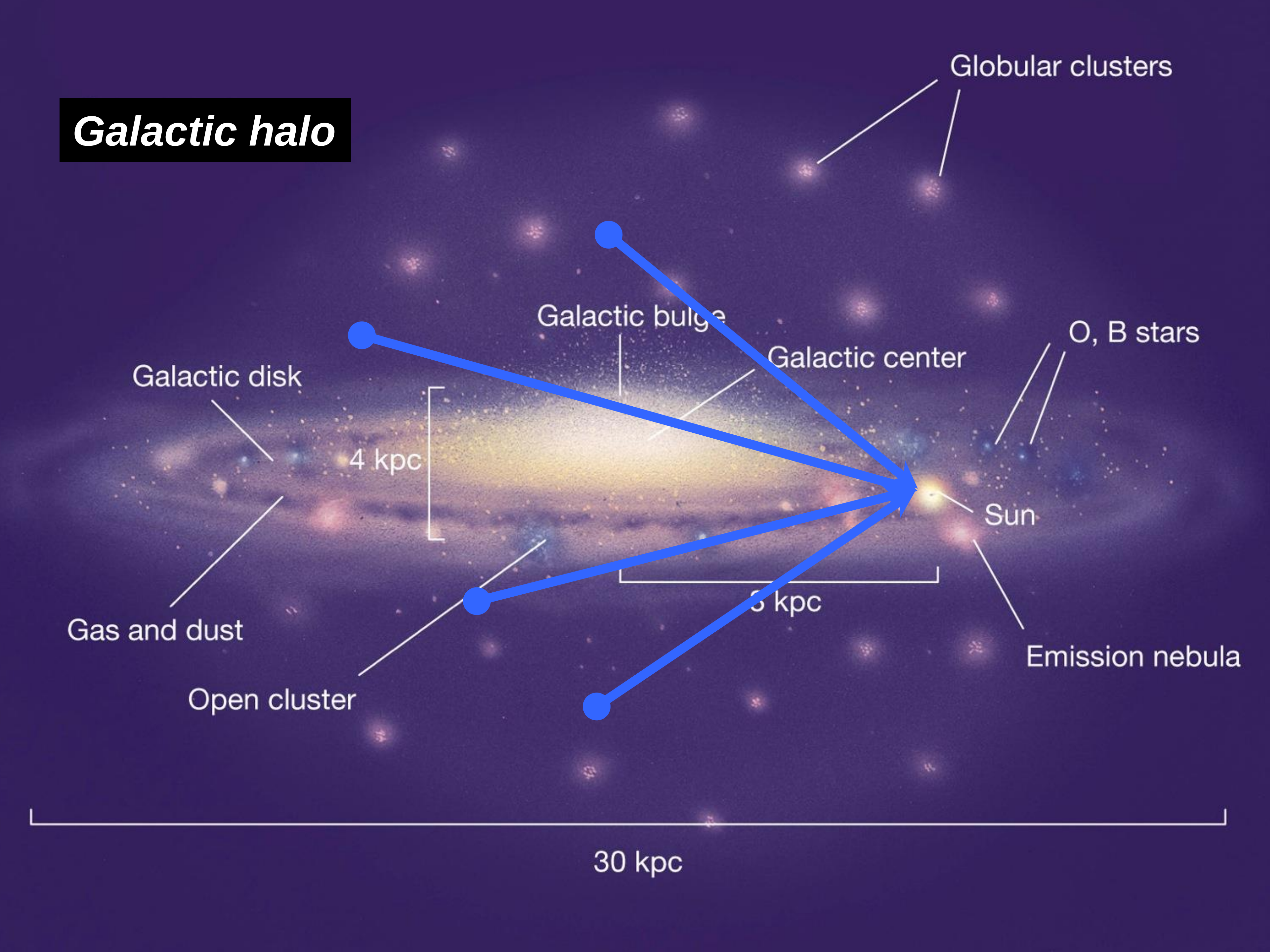


Velocity-averaged annihilation cross sections

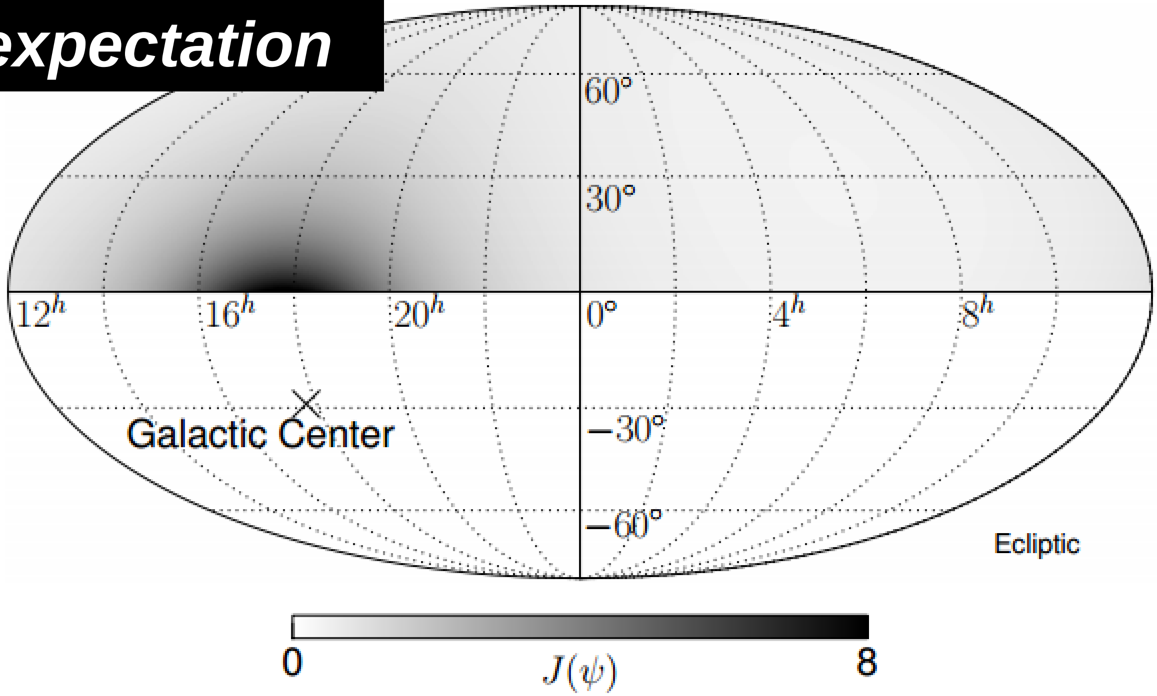
$\chi\chi \rightarrow \mu^+\mu^-$

$\chi\chi \rightarrow \tau^+\tau^-$

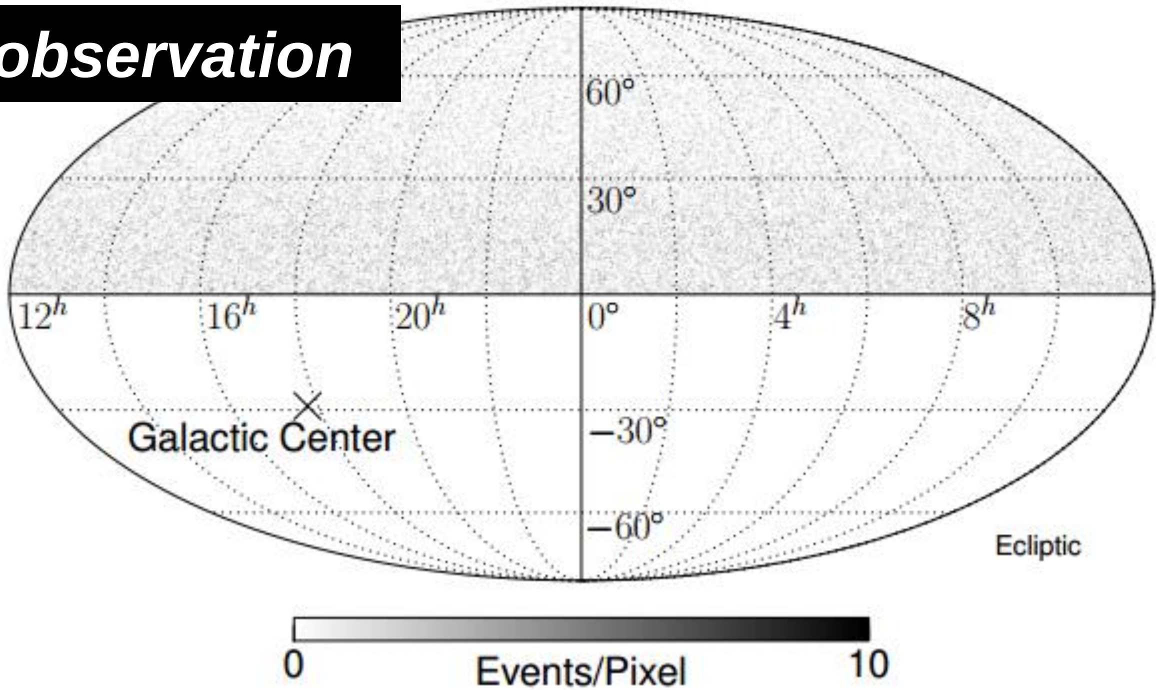



Galactic halo
Globular clusters
Galactic bulge
O, B stars
Galactic center
Galactic disk
4 kpc
Sun
kpc
Gas and dust
Emission nebula
Open cluster
30 kpc

expectation

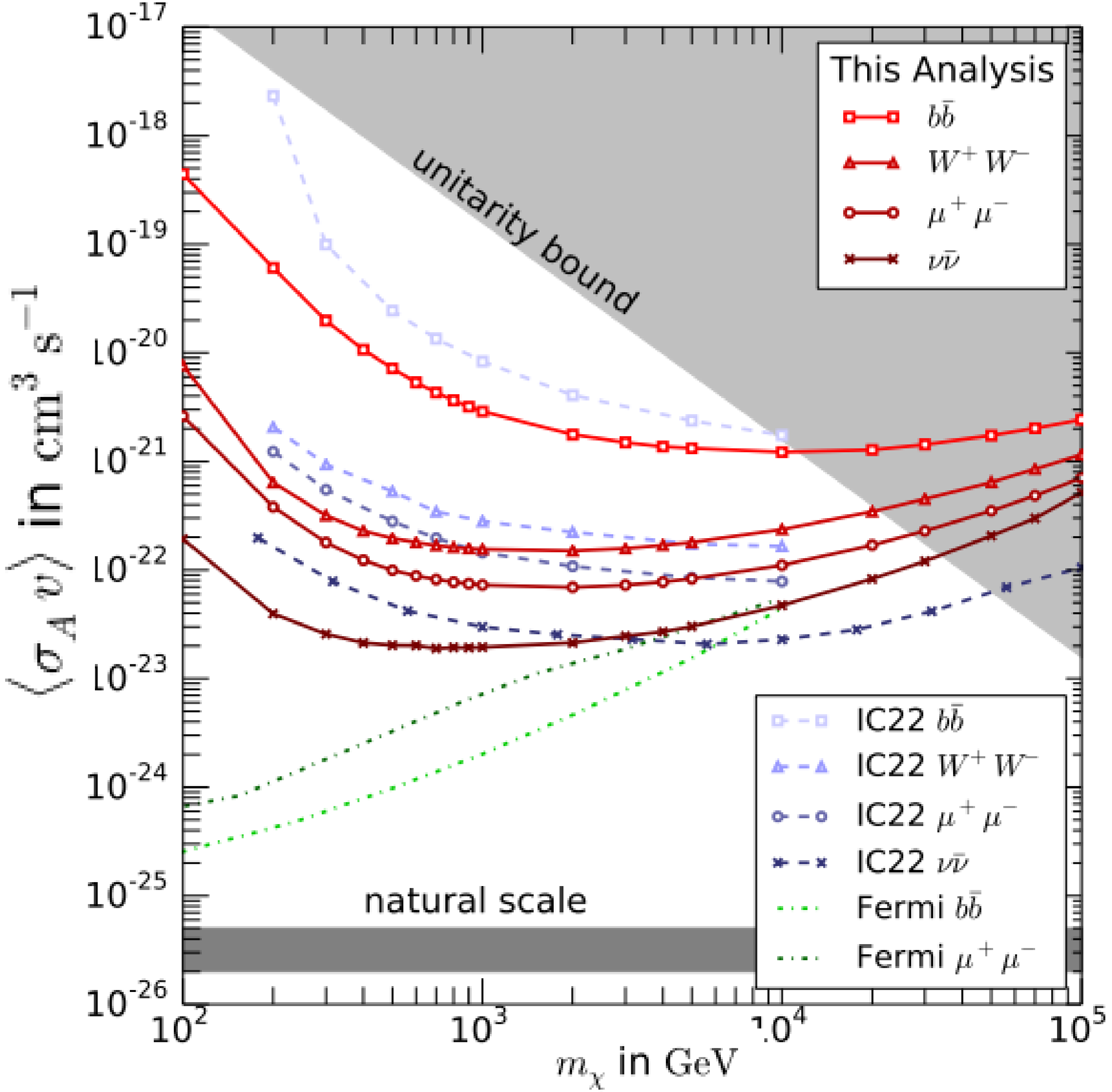


observation

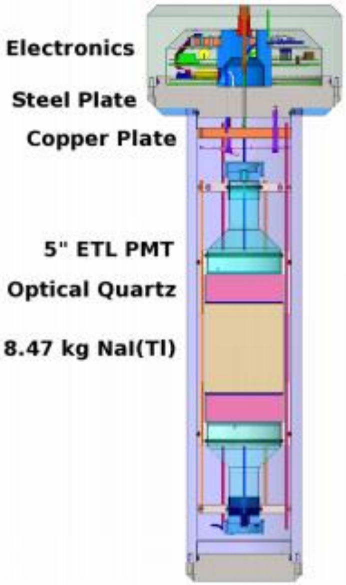


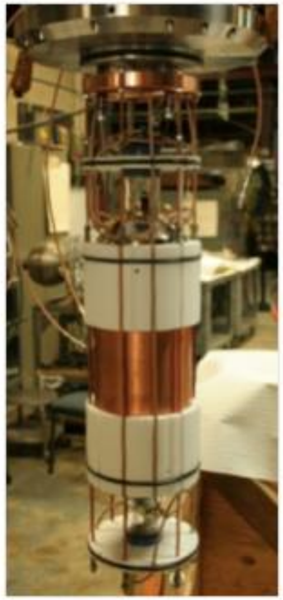
Power spectrum analysis:

coefficients mapped to single test statistic for clustering



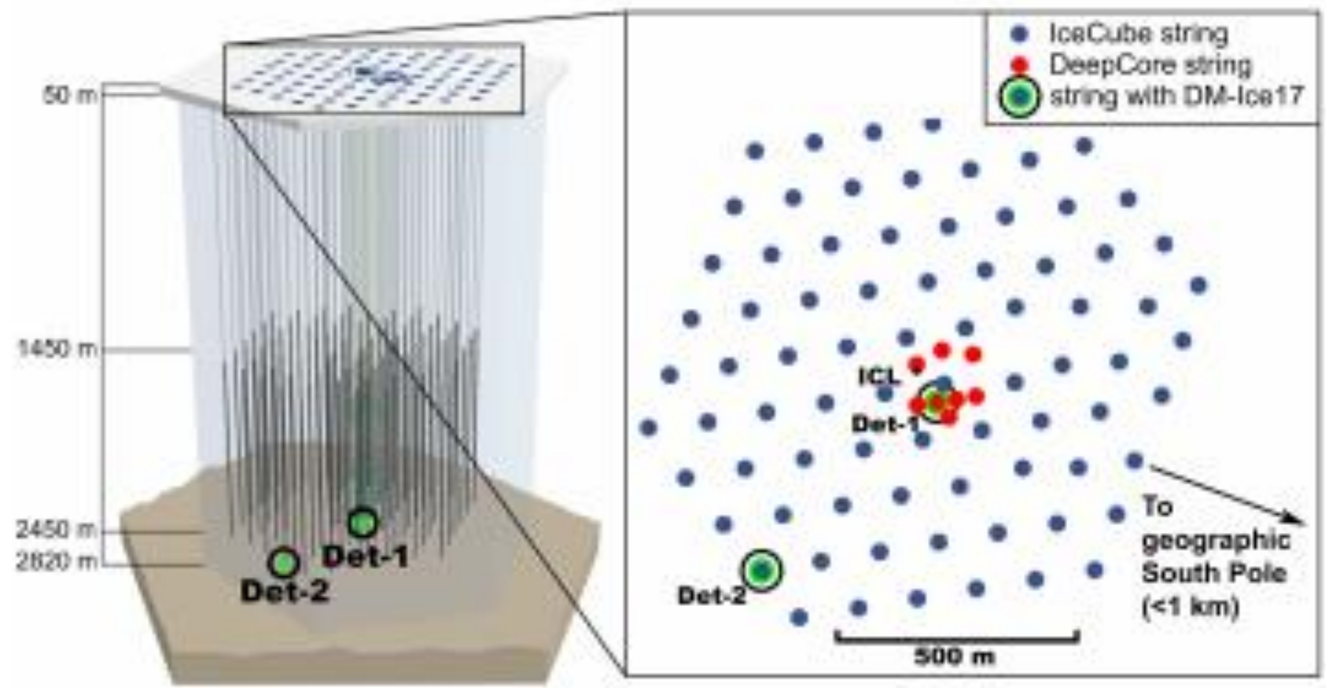
This Analysis
$b\bar{b}$
W^+W^-
$\mu^+\mu^-$
$\nu\bar{\nu}$
unitarity bound
IC22 $b\bar{b}$
IC22 W^+W^-
IC22 $\mu^+\mu^-$
IC22 $\nu\bar{\nu}$
Fermi $b\bar{b}$
Fermi $\mu^+\mu^-$
natural scale
$\langle\sigma_A v\rangle$ in $\mathrm{cm}^3\,\mathrm{s}^{-1}$
m_χ in GeV





DM-Ice:

direct detection



First data from DM-Ice17

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(The DM–Ice Collaboration)

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(Dated: August 14, 2014)

We report the first analysis of background data from DM-Ice17, a direct-detection dark matter experiment consisting of 17 kg of NaI(Tl) target material. It was co-deployed with IceCube 2457 m deep in the South Pole glacial ice in December 2010 and is the first such detector operating in the Southern Hemisphere. The background rate in the $6.5-8.0\,\mathrm{keV_{ee}}$ region is measured to be 7.9 ± 0.4 counts/day/keV/kg. This is consistent with the expected background from the detector assemblies with negligible contributions from the surrounding ice. The successful deployment and operation of DM-Ice17 establishes the South Pole ice as a viable location for future underground, low-background experiments in the Southern Hemisphere. The detector assembly and deployment are described here, as well as the analysis of the DM-Ice17 backgrounds based on data from the first two years of operation after commissioning, July 2011 – June 2013.

arxiv.org/pdf/1401.4804v2.pdf

IceCube has taken the first steps towards high-energy neutrino astronomy:

Where and how are these neutrinos produced?

New US NSF MREFC – submission later this year

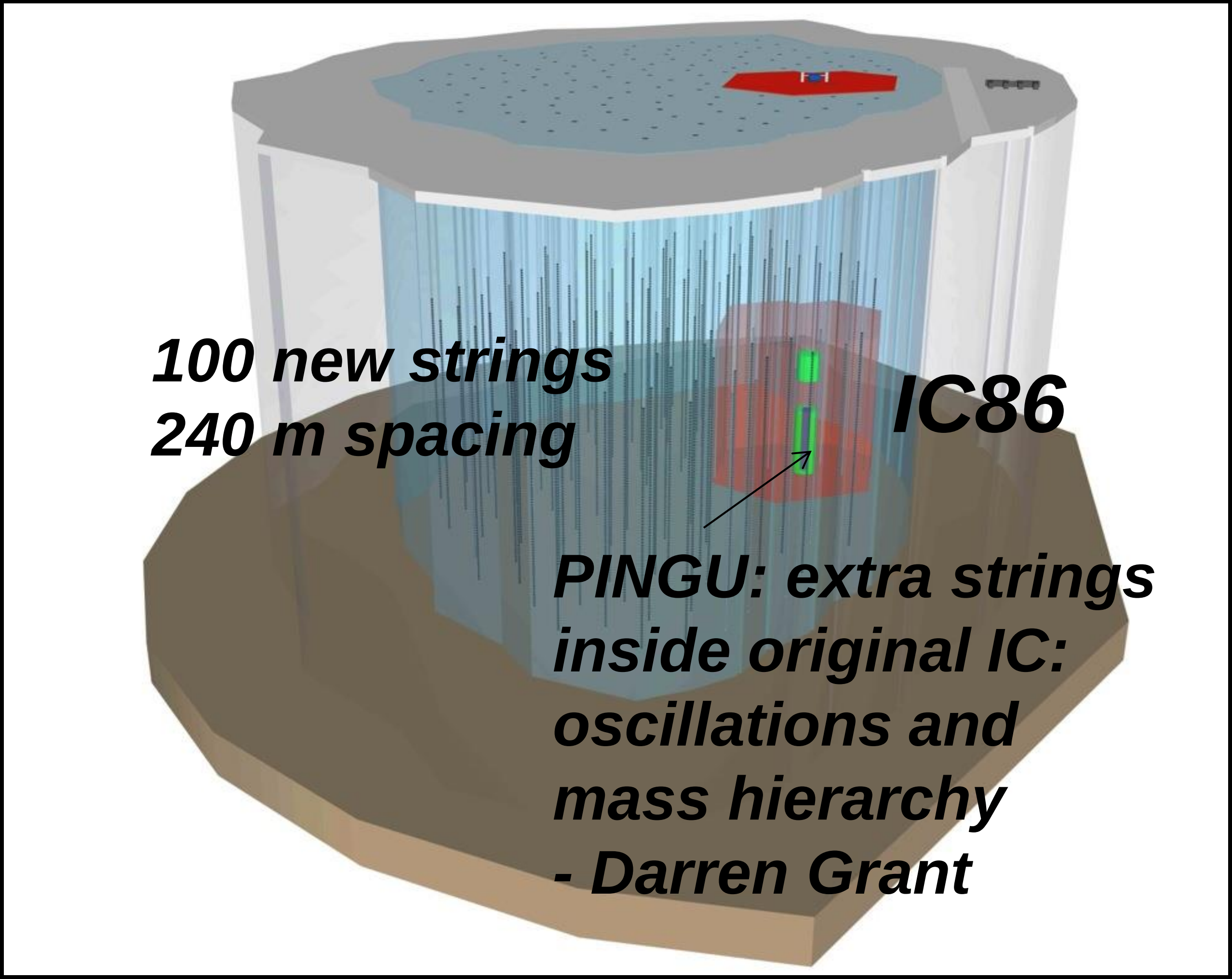
High energy extensions – increase volume for muons and cascades

Surface vetoes – improve ability to see downward (esp. throughgoing) astrophysical neutrinos

PINGU – oscillations and mass hierarchy

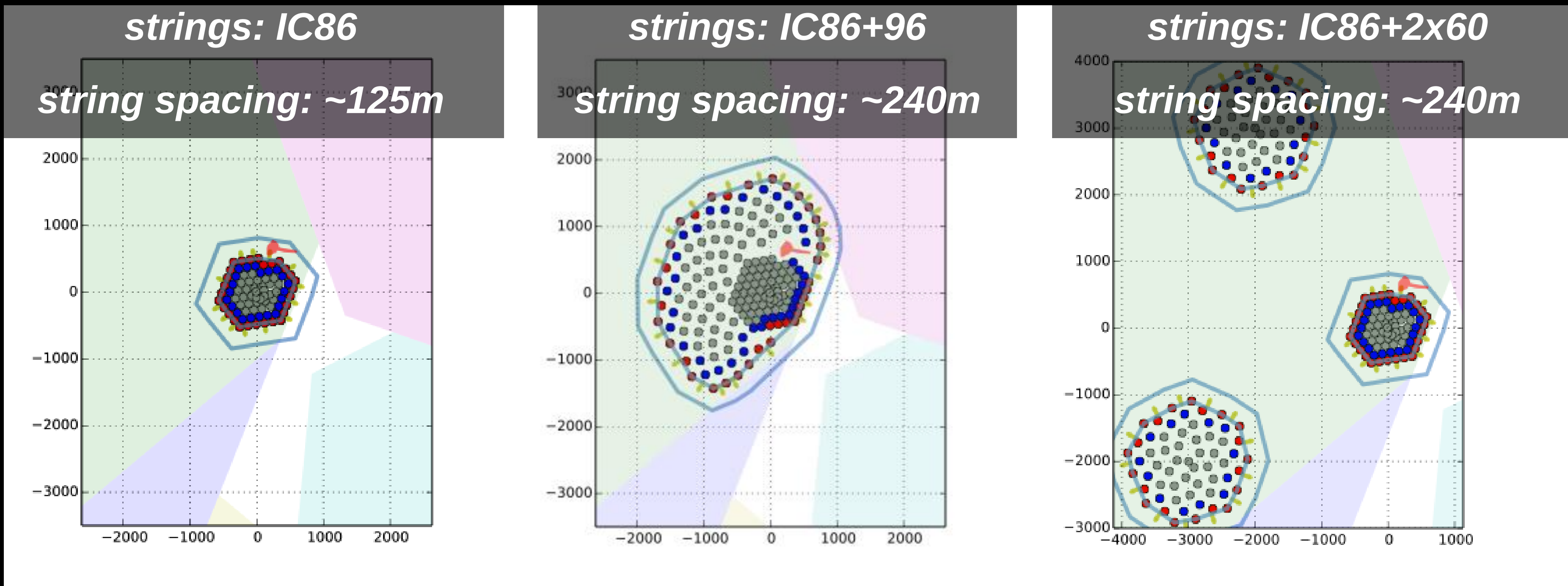
Photograph: Forest Banks

High energy extensions – increase volume for muons and cascades with more strings



Initial simulation studies of geometries

IceCube	***Sunflower 96***	***Supercluster***
strings: IC86	*strings: IC86+96*	*strings: IC86+2x60*
string spacing: ~125m	*string spacing: ~240m*	*string spacing: ~240m*



Angular resolution:

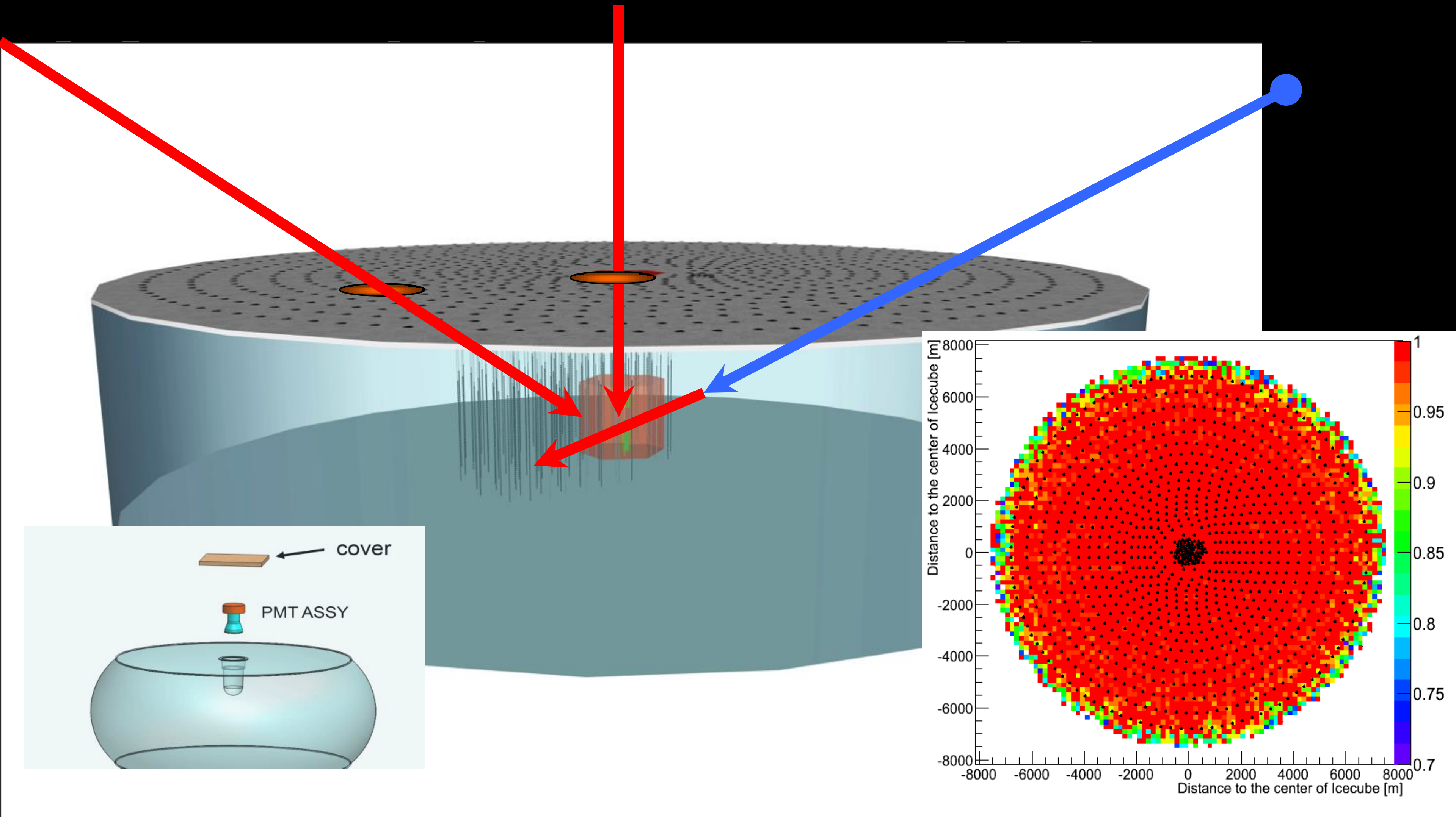
0.5°	***0.4°***	***0.4°***

Effective area:

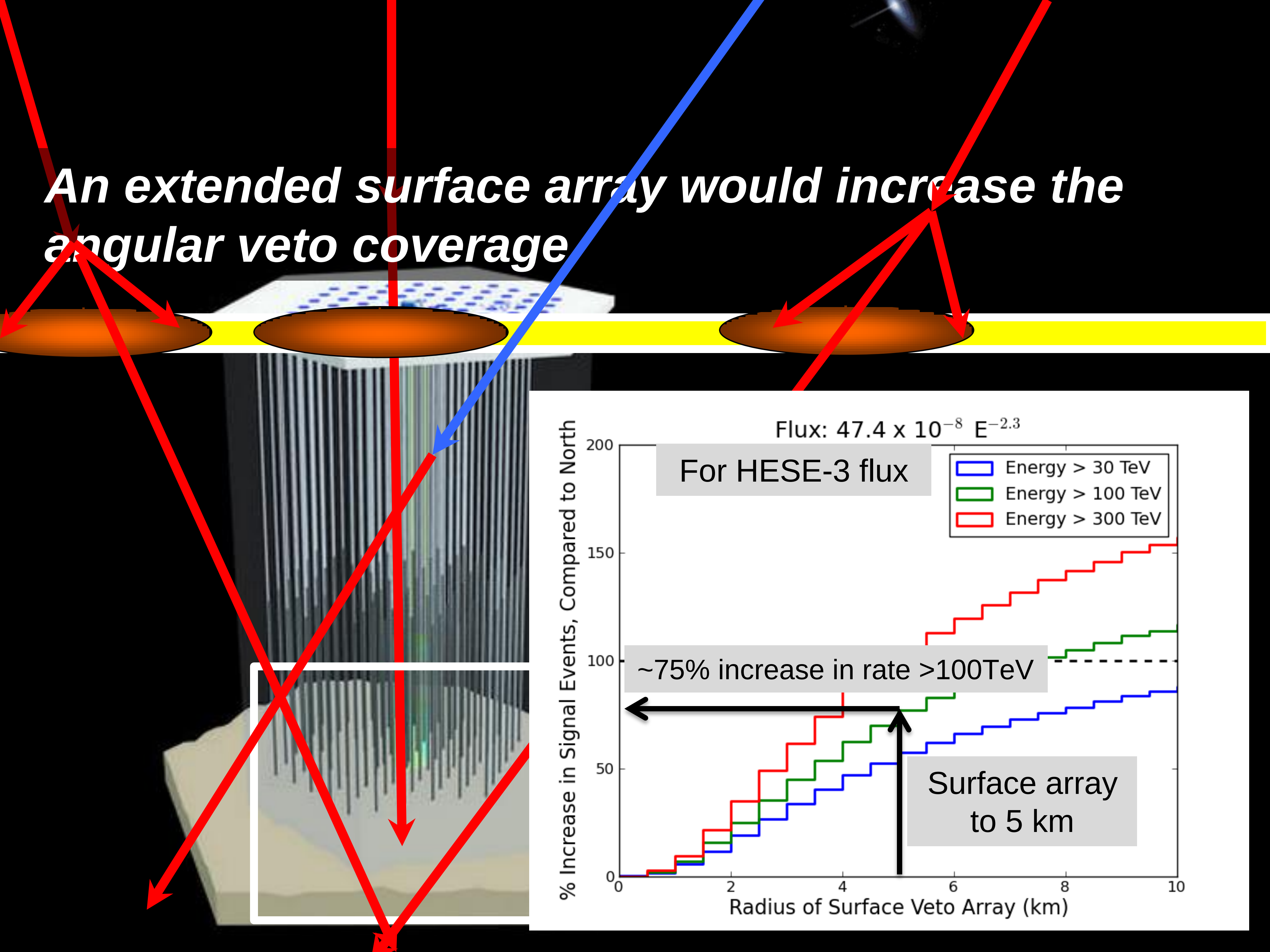
1.6 km²	***5.0 km²***	***6.5 km²***

1 PeV (cosmic primary) veto: reject most atmospheric muon AND neutrino background above 100 TeV.

An efficient surface veto, 100 km^2, for 3–5 sr background free cosmic muon neutrino and some shower detection

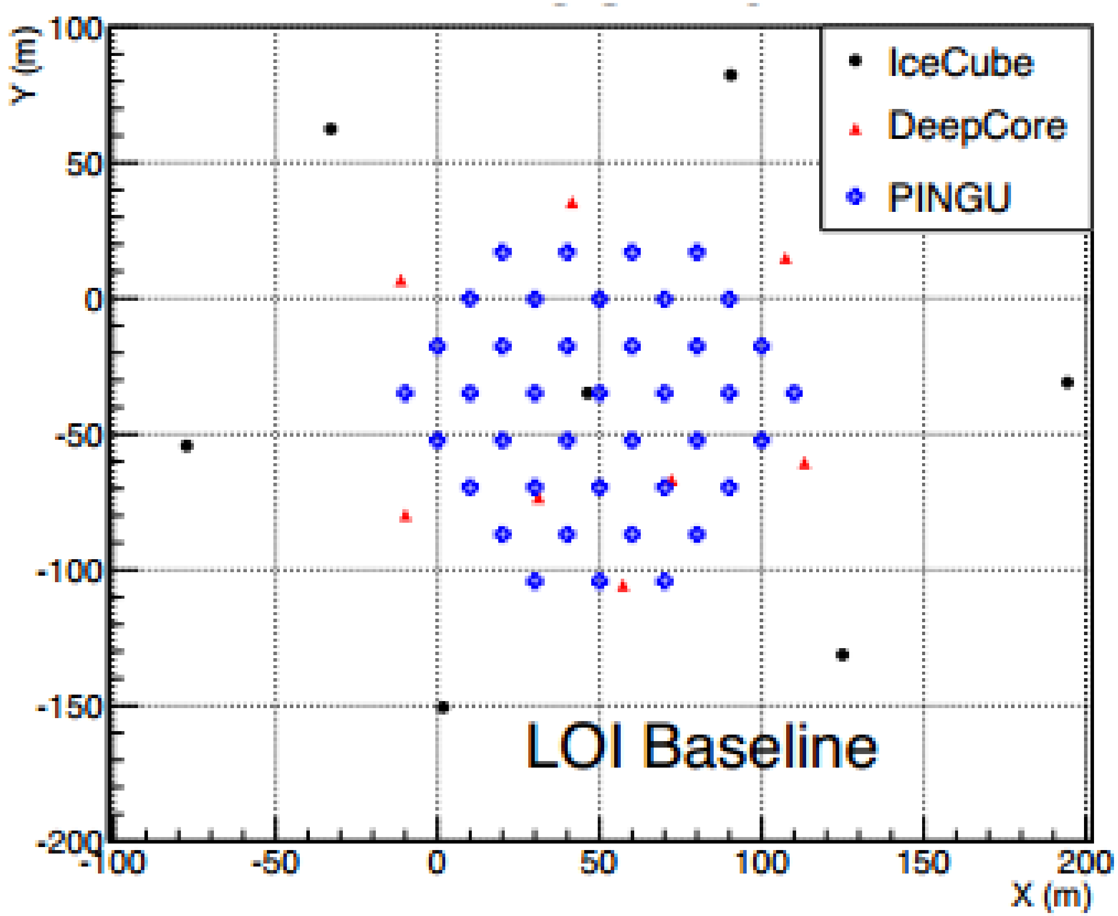


An extended surface array would increase the angular veto coverage



PRECISION ICECUBE NEXT GENERATION UPGRADE

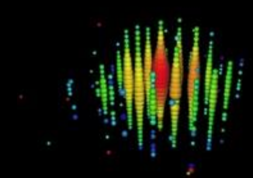
Measure the neutrino mass hierarchy:
subtle change to energy vs arrival direction of atmospheric neutrinos



40 strings
96 DOMs per string
3m spacing

IceCube has taken the first steps towards high-energy neutrino astronomy:

- diffuse flux: $\Phi = 10^{-8}\, E^{-2}\ \mathrm{GeV}^{-1}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}\, \mathrm{sr}^{-1}$ (1:1:1 flavour)
- contained vertex (5.7σ), upgoing muons (3.9σ)
- atmospheric prompt origin strongly rejected
- lack of correlation with galactic plane, and events at high galactic latitudes may suggest extra-galactic origin
- many theoretical speculations and attempts to correlate with sources have been proposed



proposal for a next generation detector
- increased in-ice volume
- enhanced surface veto
- PINGU