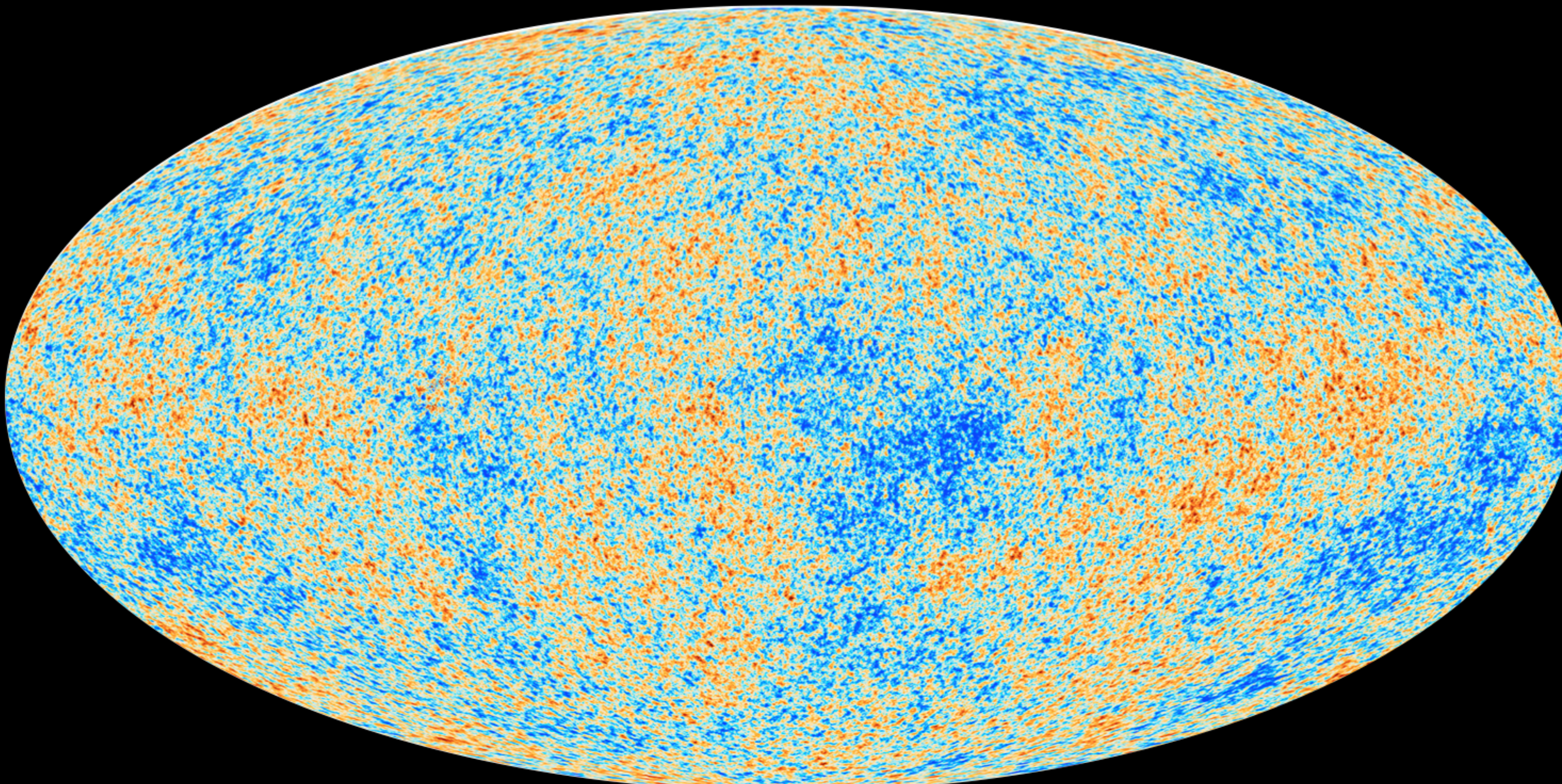
IceCube: the discovery of cosmic neutrinos
francis halzen

- some history, cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

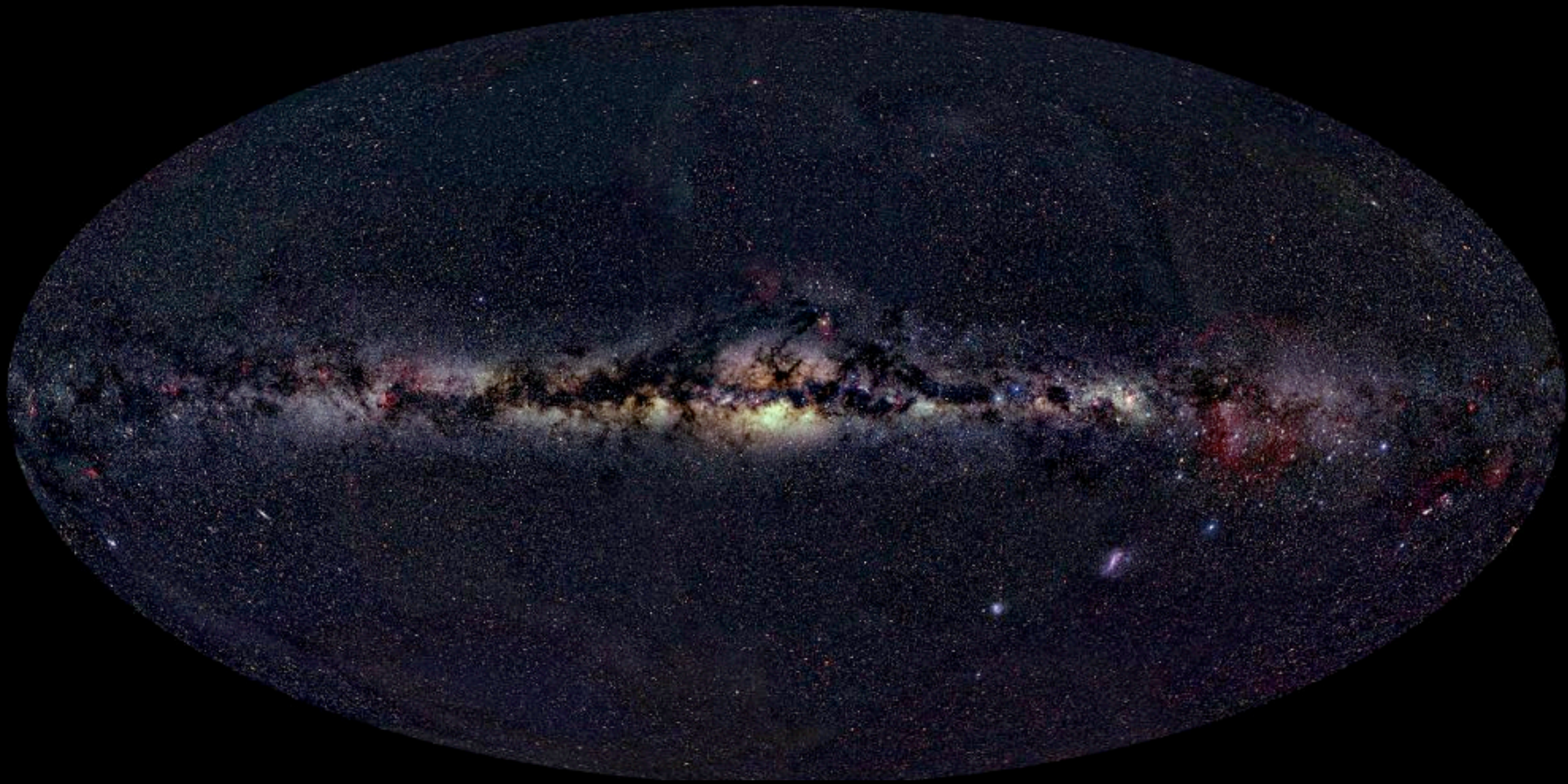
IceCube.wisc.edu

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



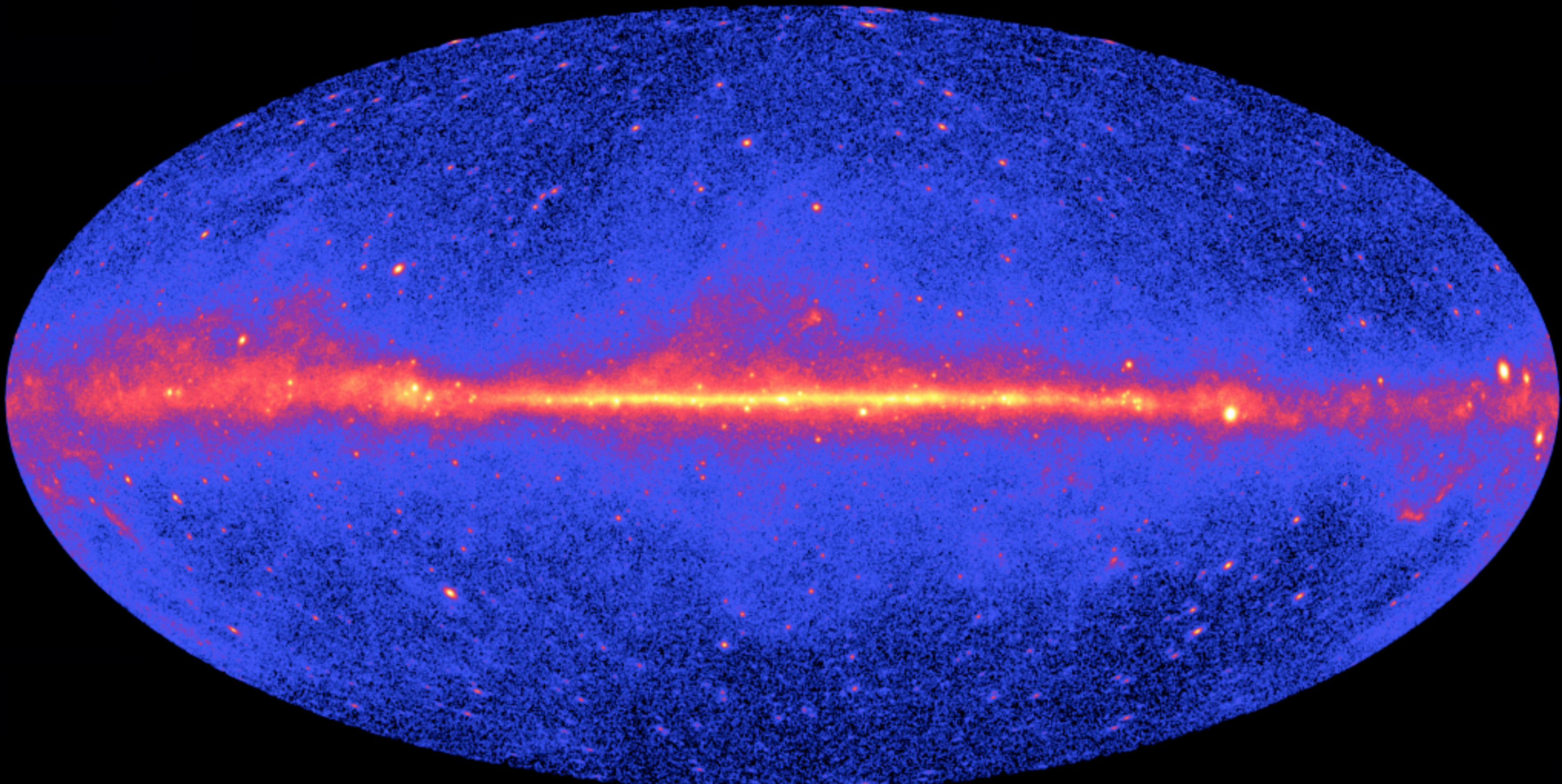
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m $\Leftrightarrow$ energy = 1 eV

Cosmic Horizons – Gamma Radiation

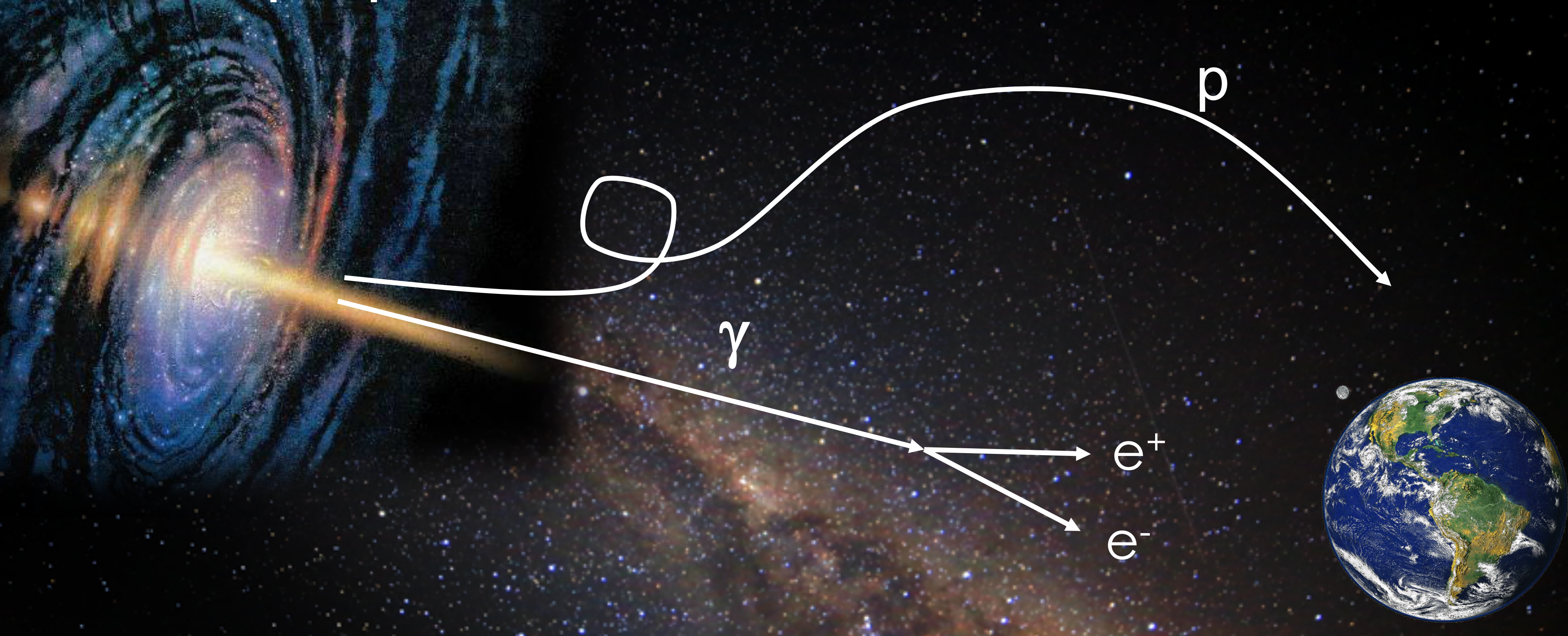


wavelength = 10^{-15} m ⇔ energy = 10^{9} eV

Cosmic Horizons – Highest Energies

wavelength = 10^{-21} m $\Leftrightarrow$ energy = 10^{3} TeV

The opaque Universe

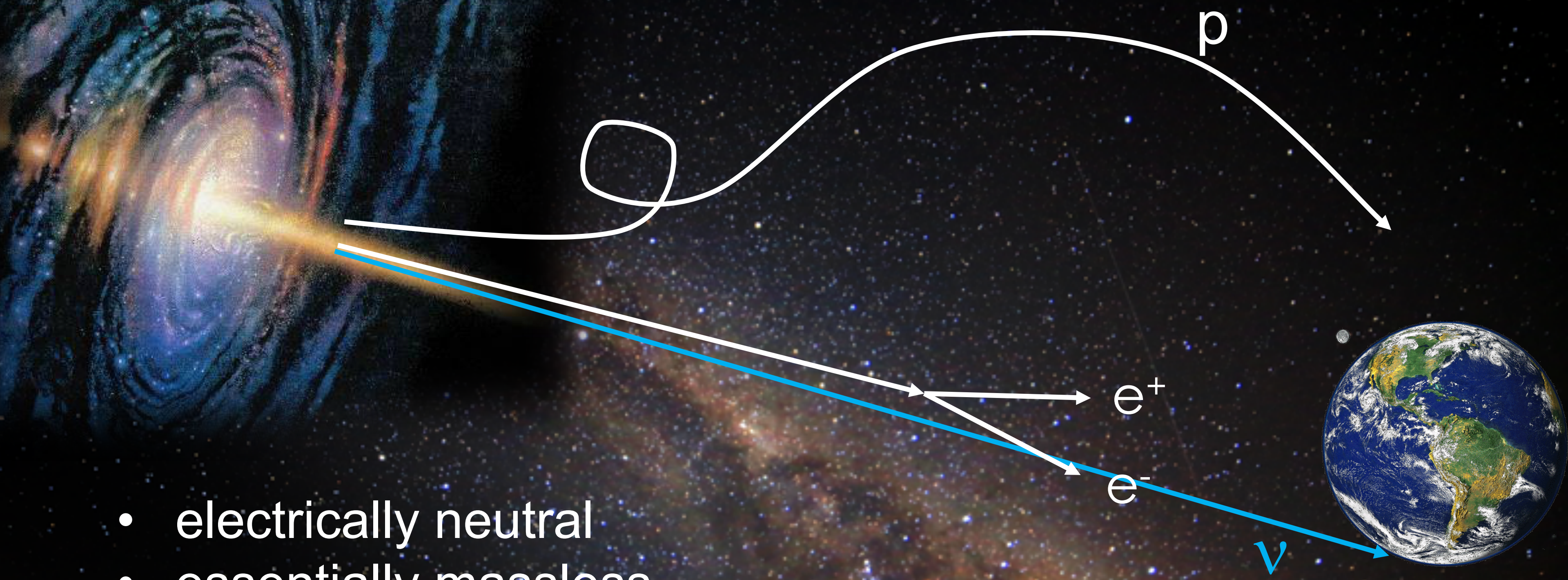


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

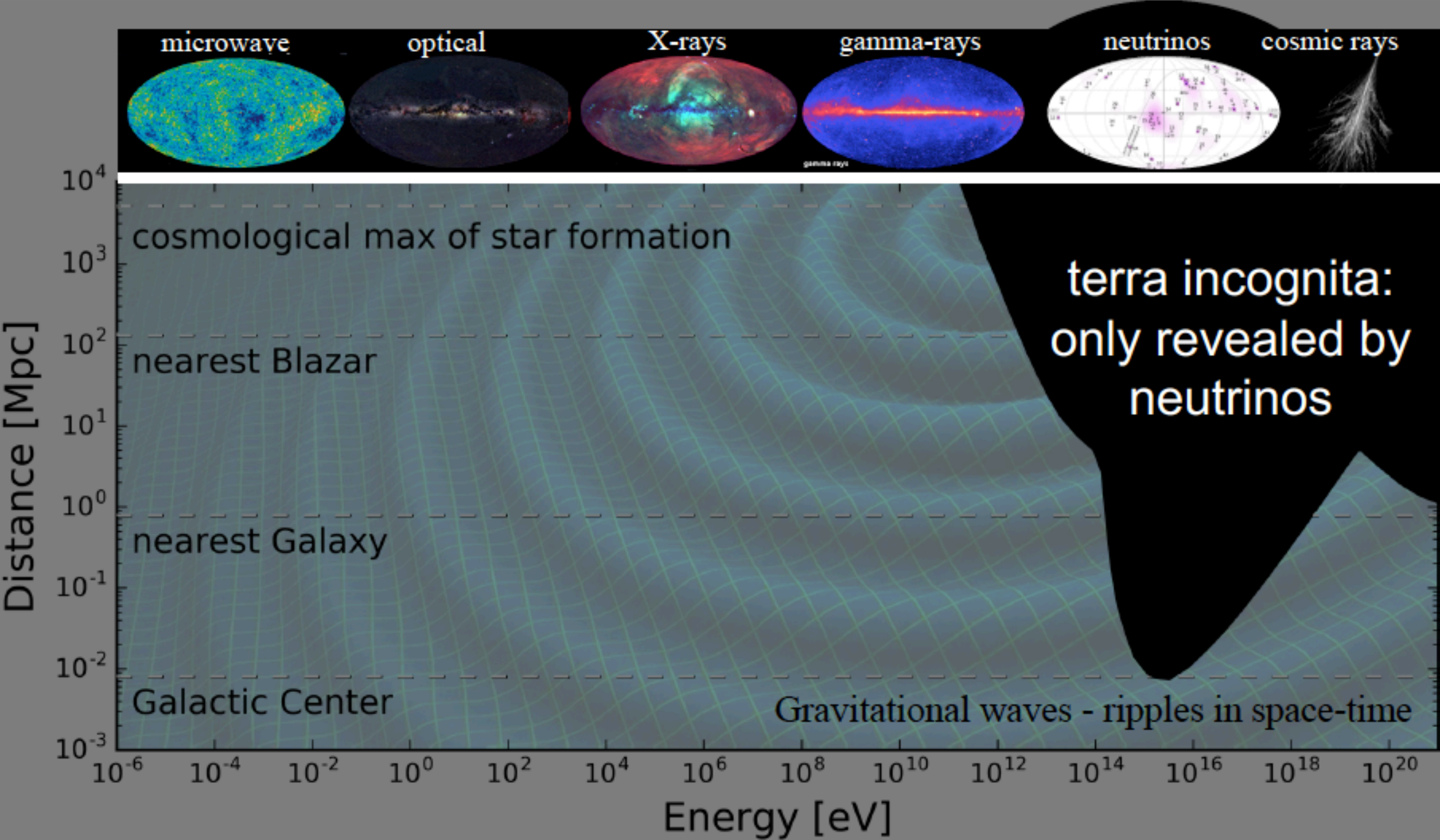
enter: neutrinos

Neutrinos? Perfect Messenger

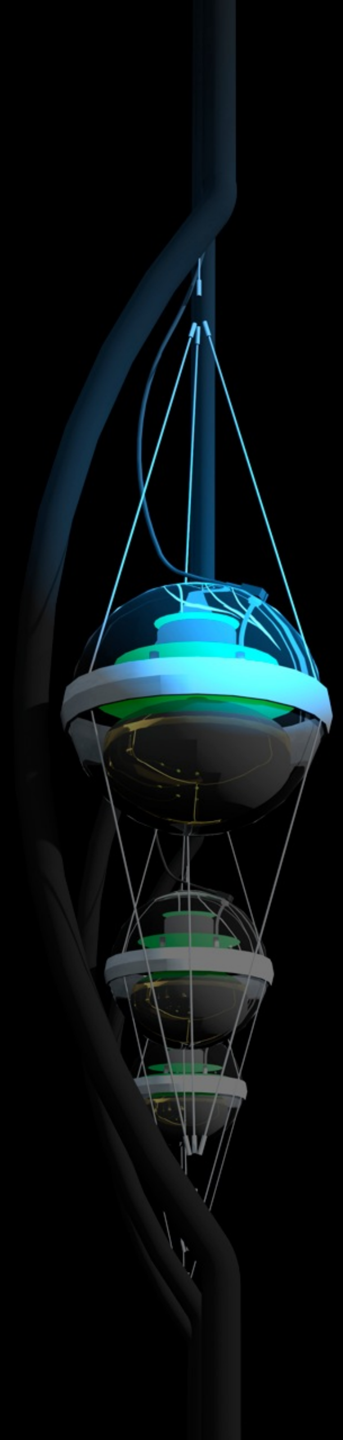


- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?



- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays



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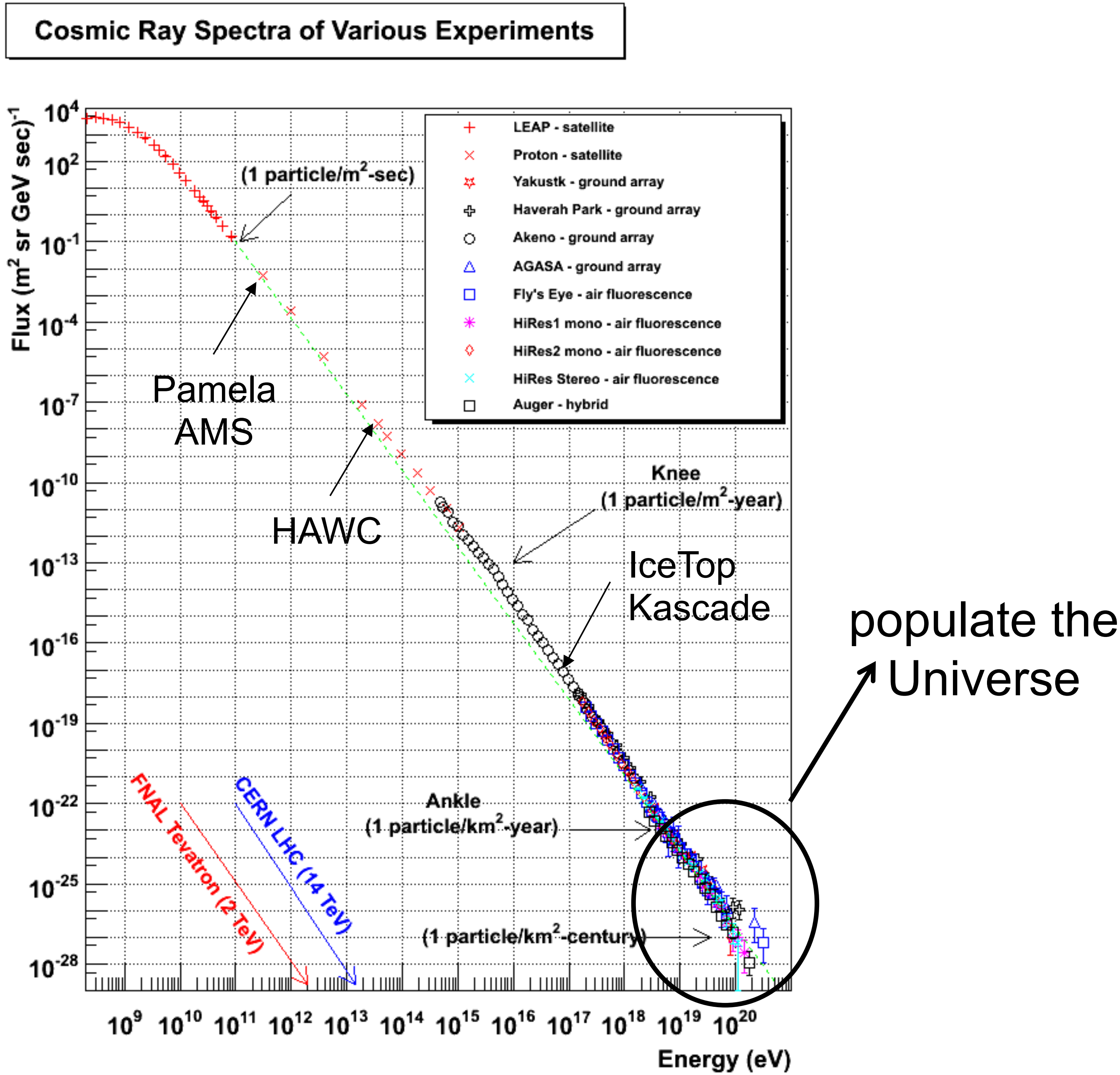
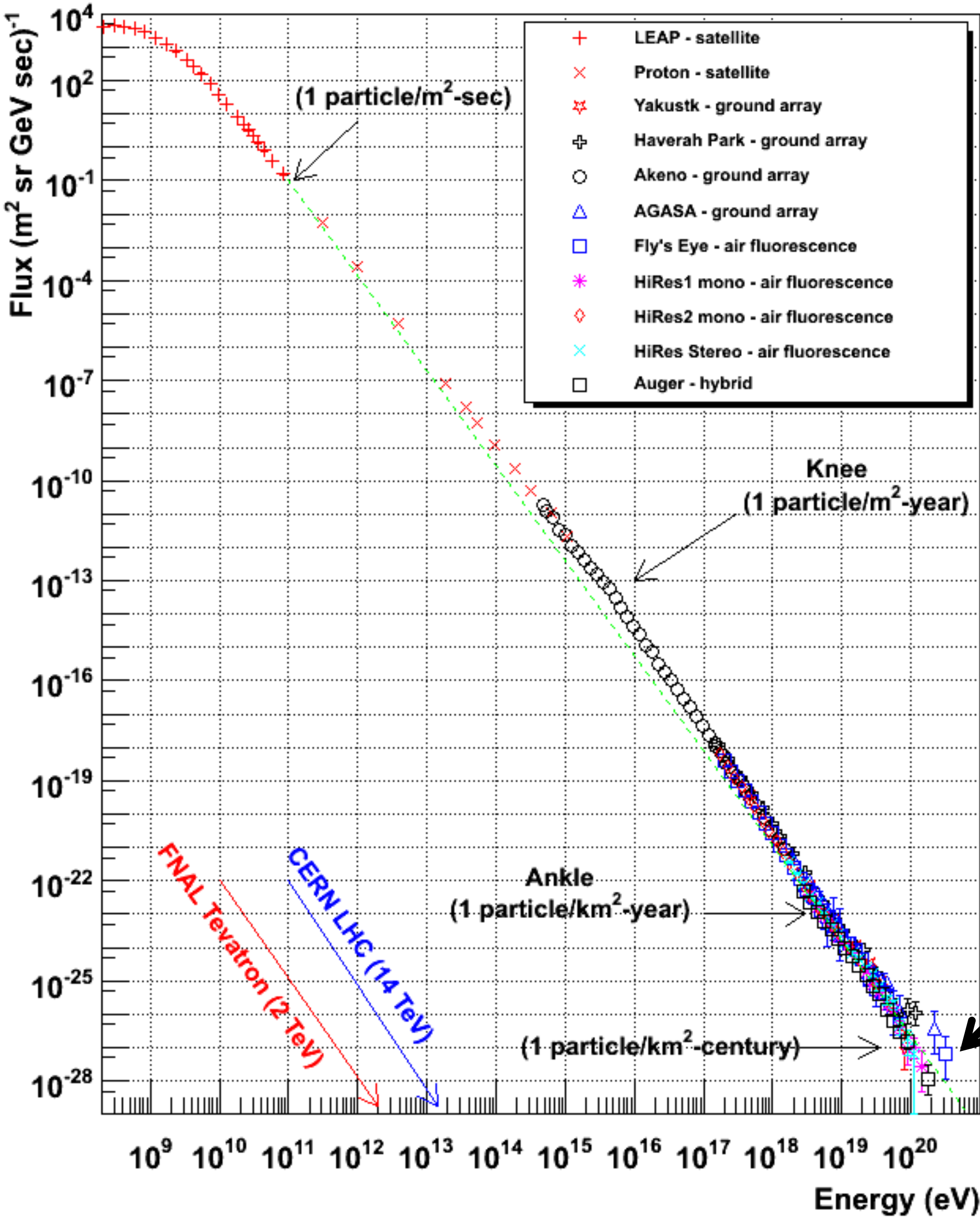

Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)^-1
10^4
10^2
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m^2-sec)
Pamela
AMS
HAWC
Knee
(1 particle/m^2-year)
IceTop
Kascade
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
populate the
Universe

origin of cosmic rays: oldest problem in astronomy

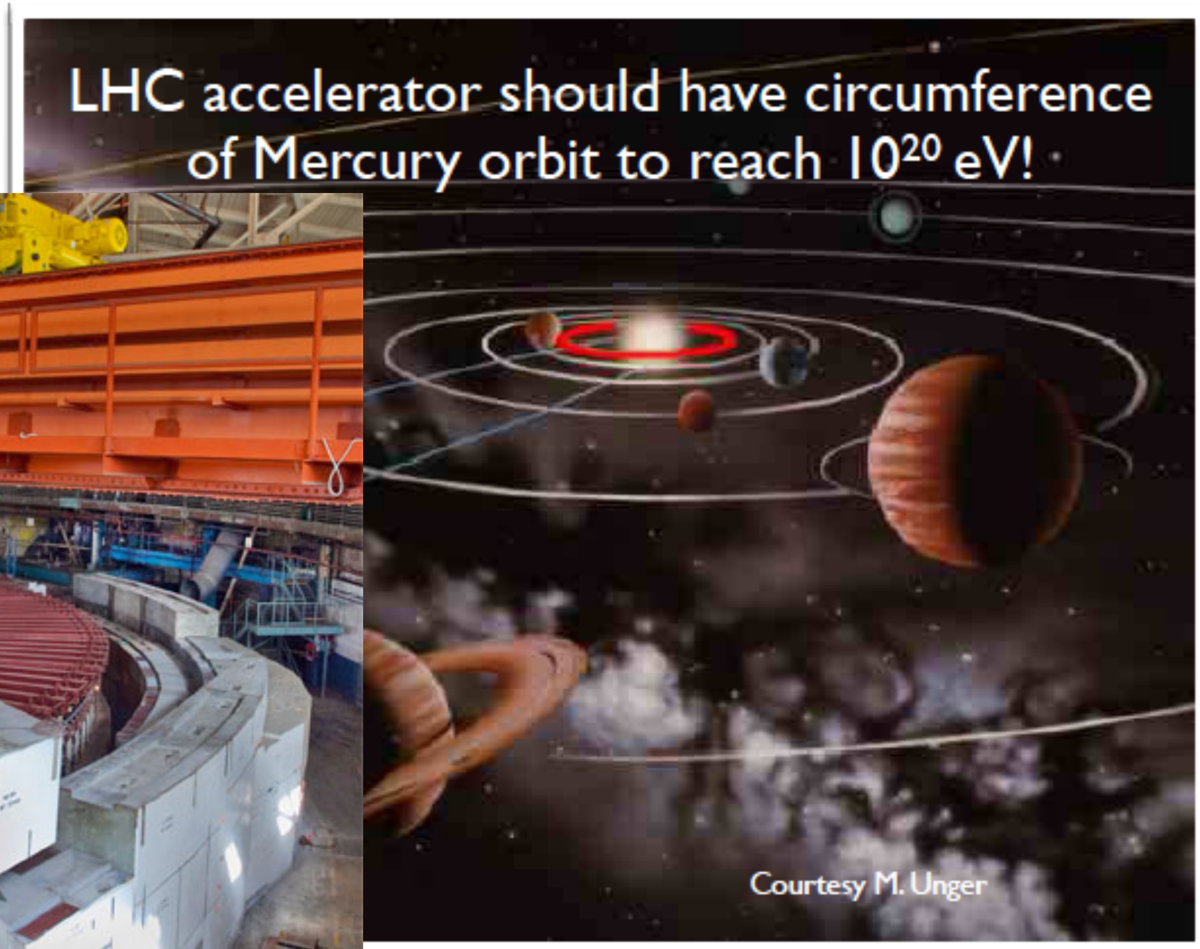


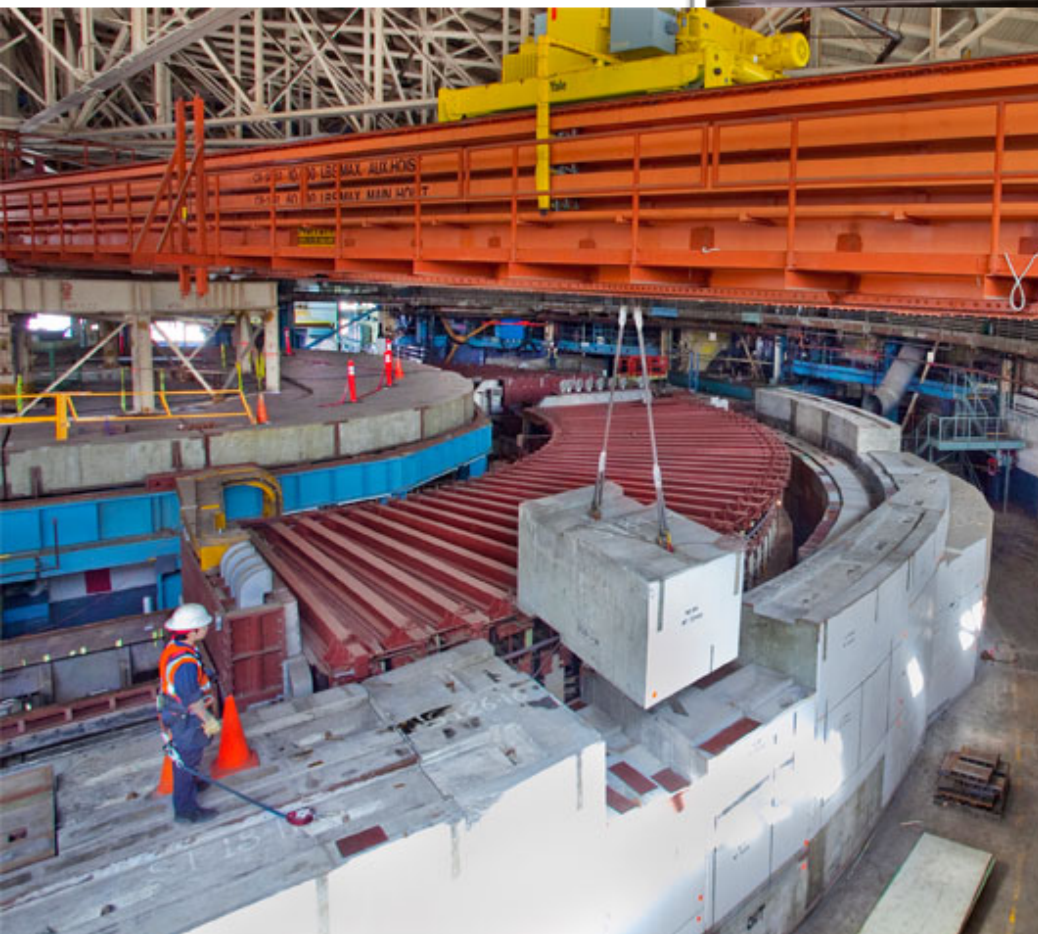
cosmic ray challenge

both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

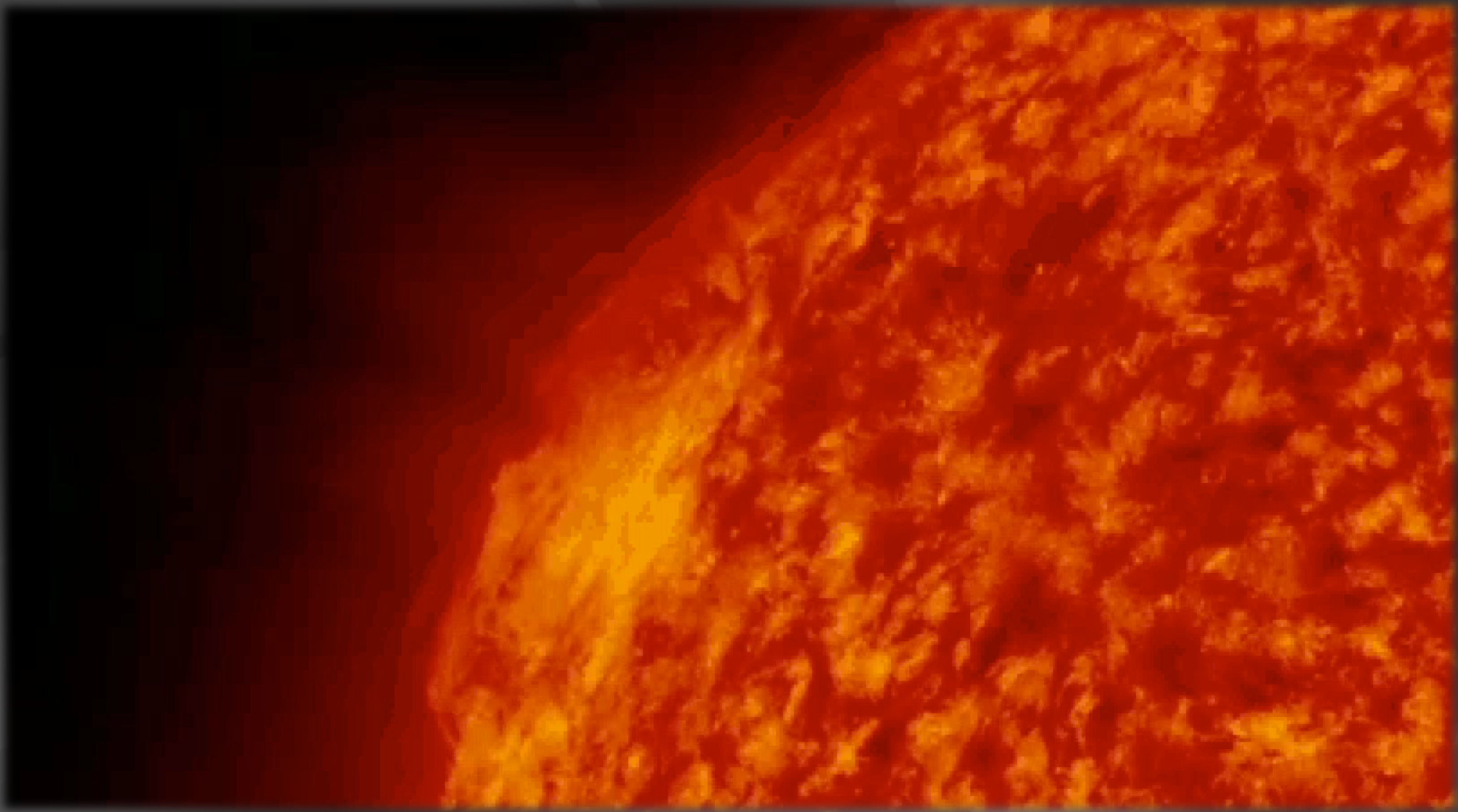
cosmic ray accelerators



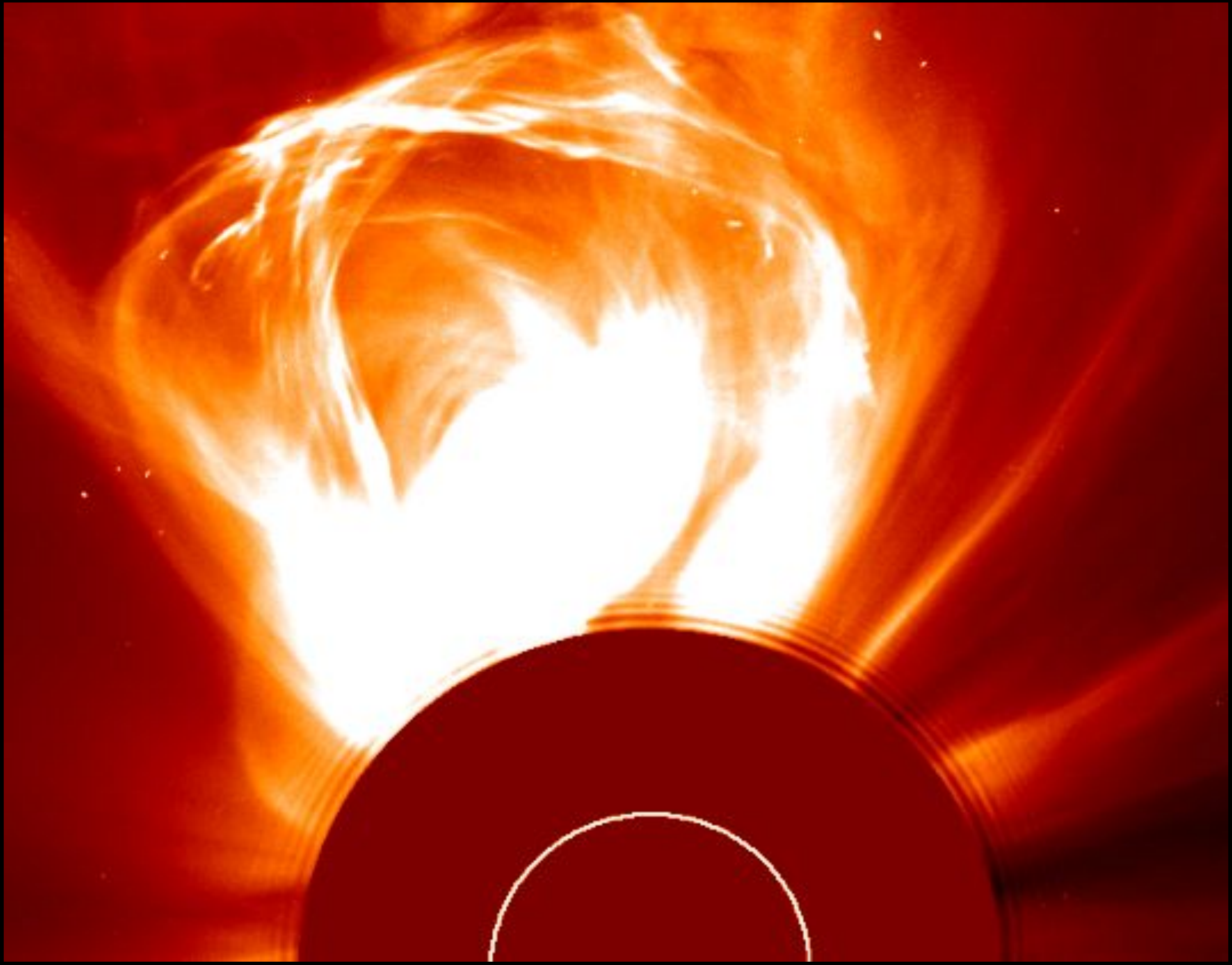


accomodating energy and luminosity are challenging

the sun constructs an accelerator



the sun constructs an accelerator



- accelerator must contain the particles

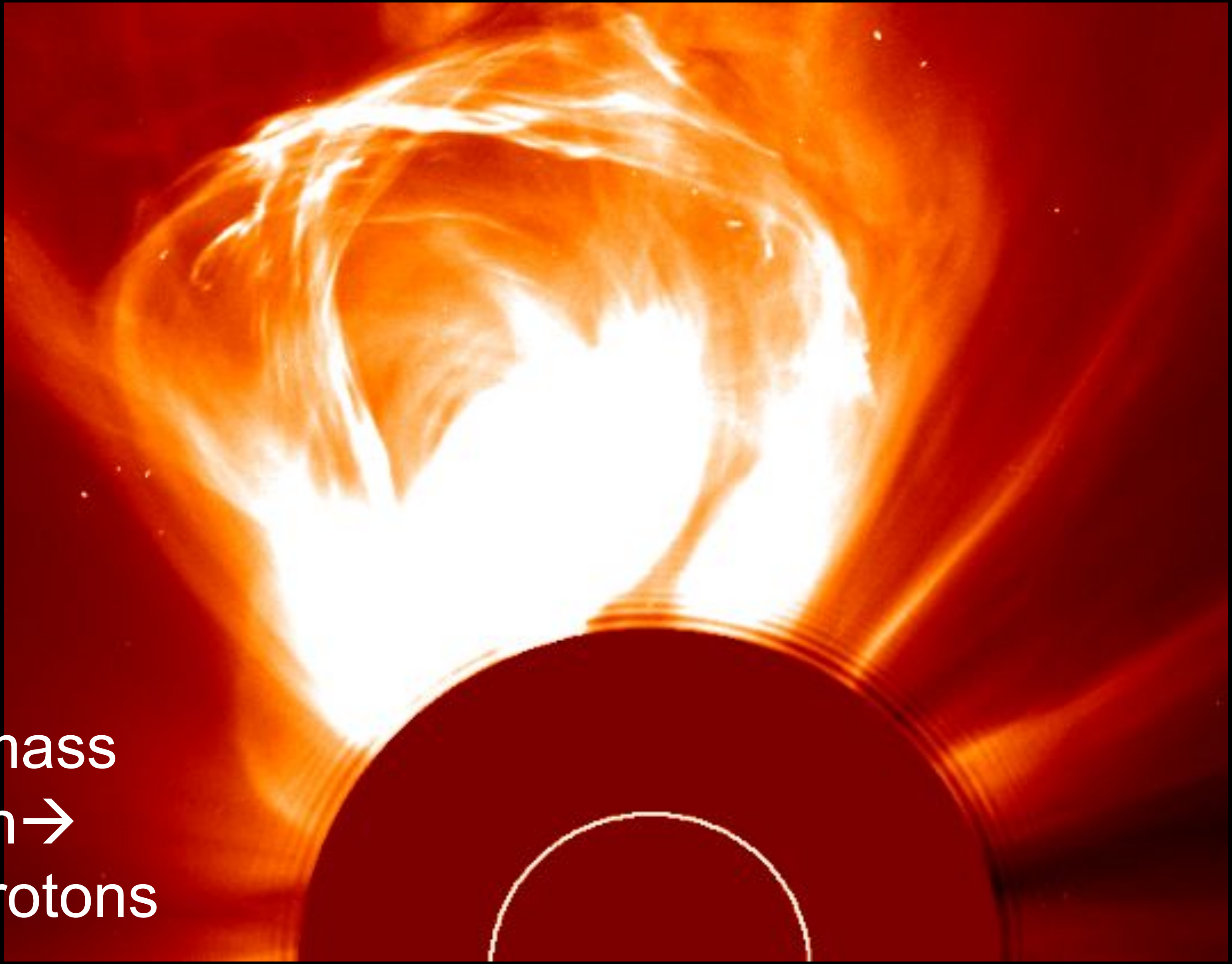
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \leq R$$

$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

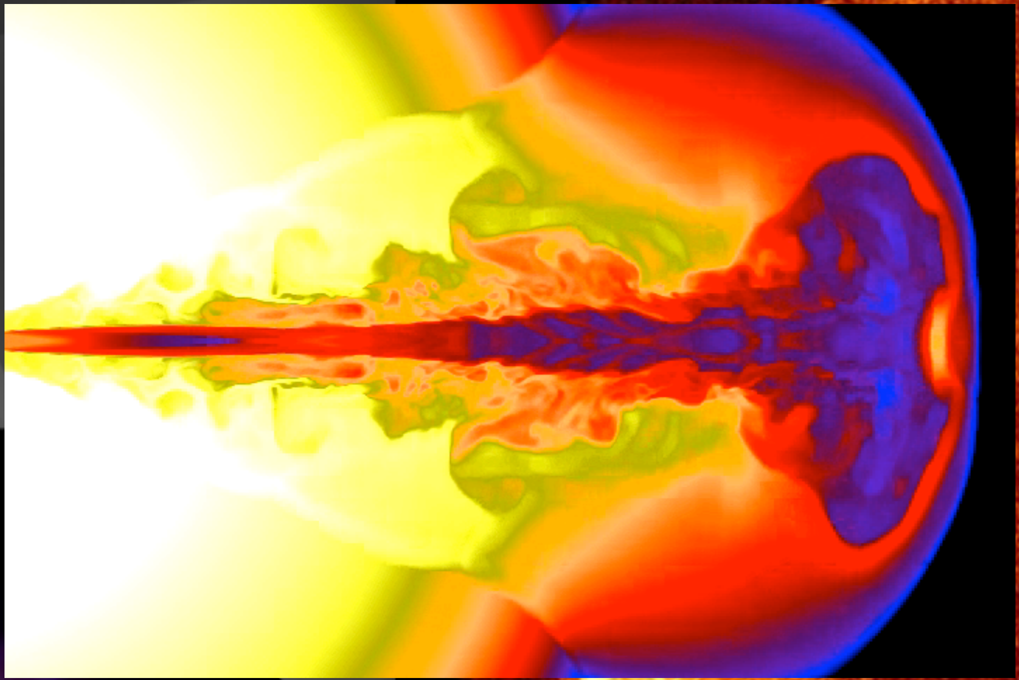
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

the sun constructs an accelerator

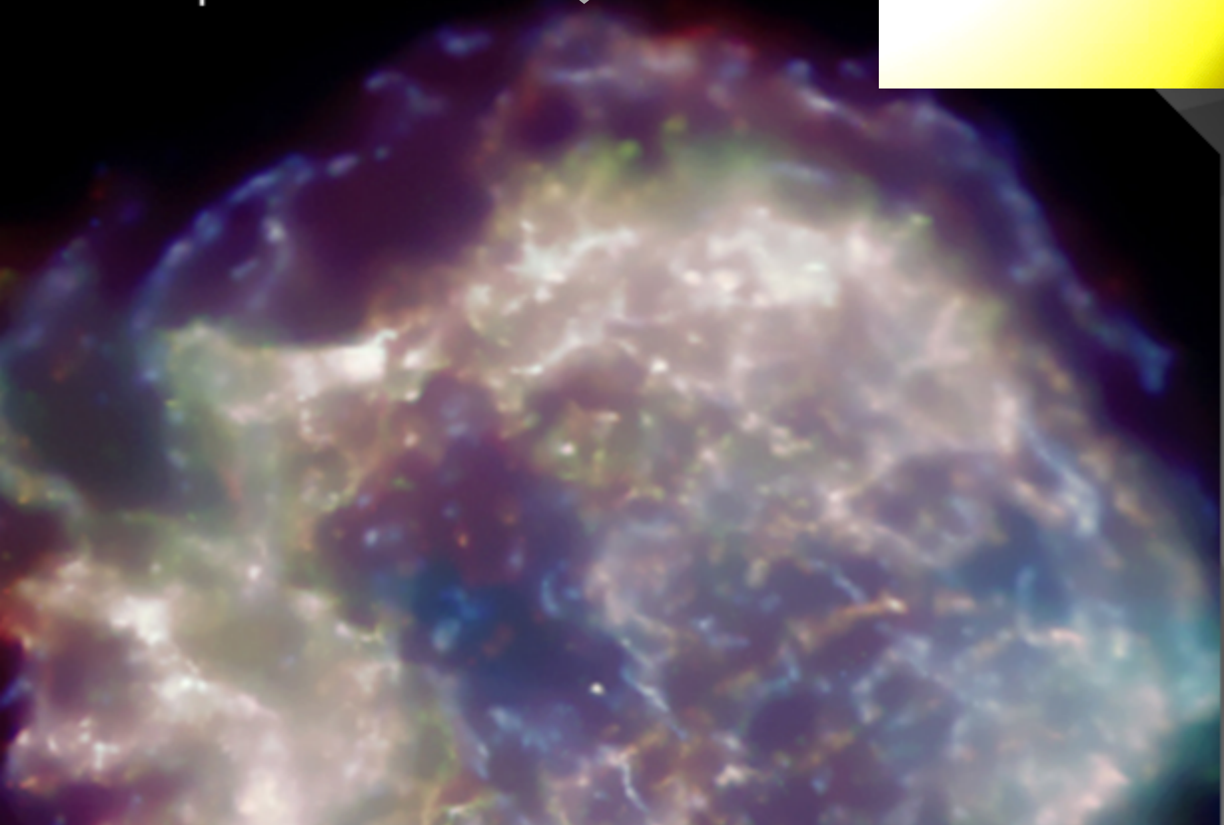


coronal mass ejection→ 10 GeV protons

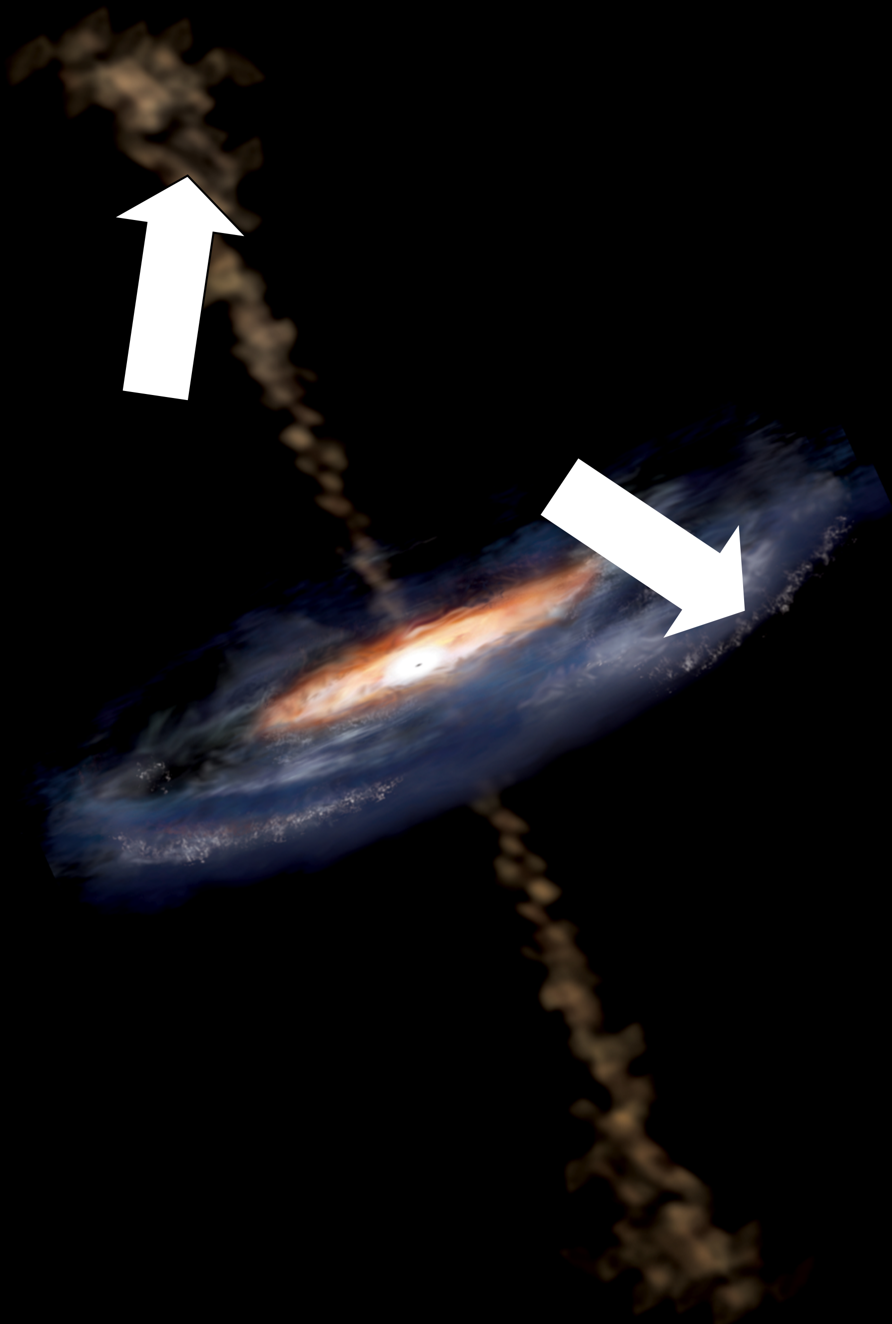
supernova remnants



Chandra
Cassiopeia A

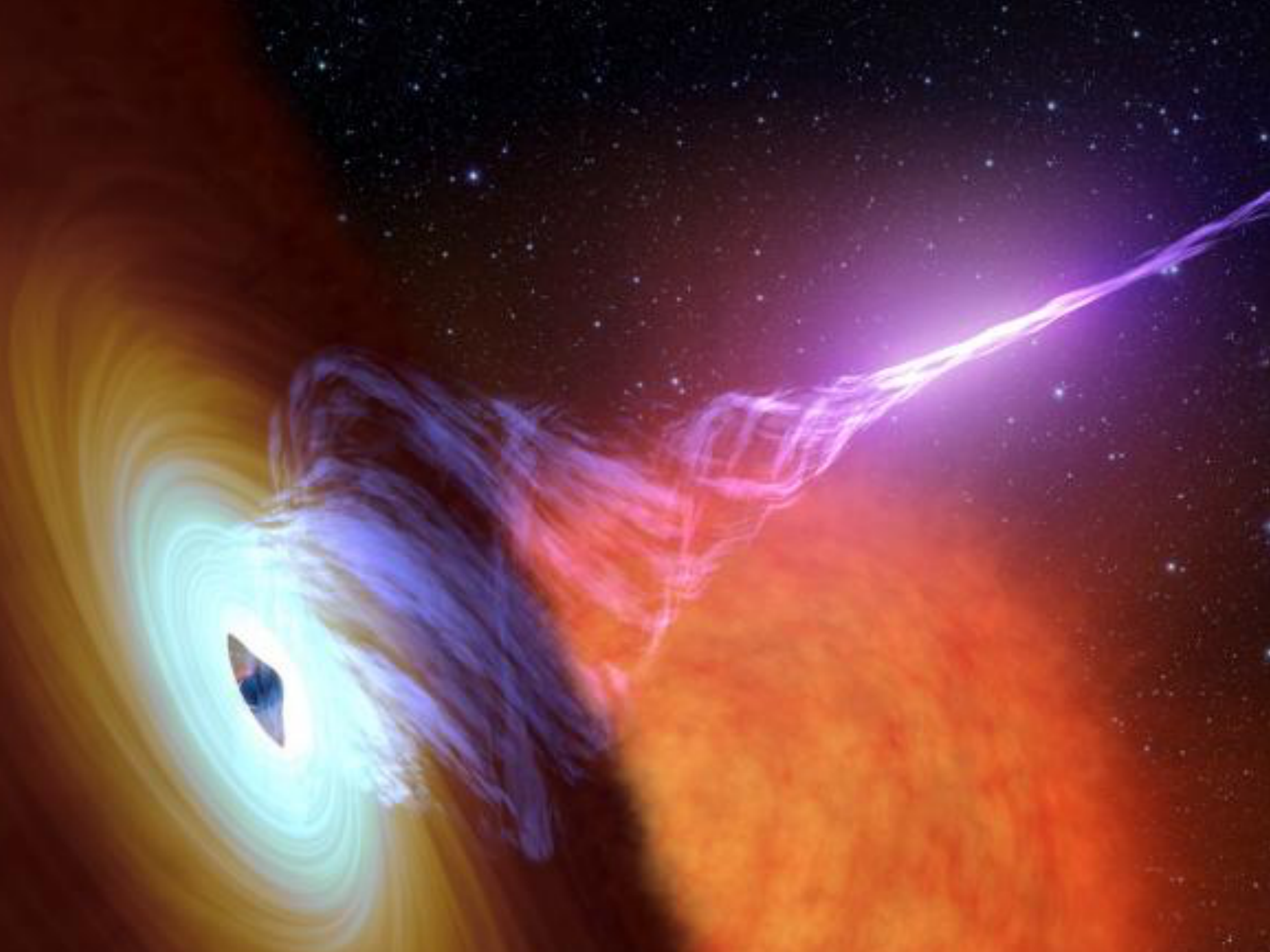


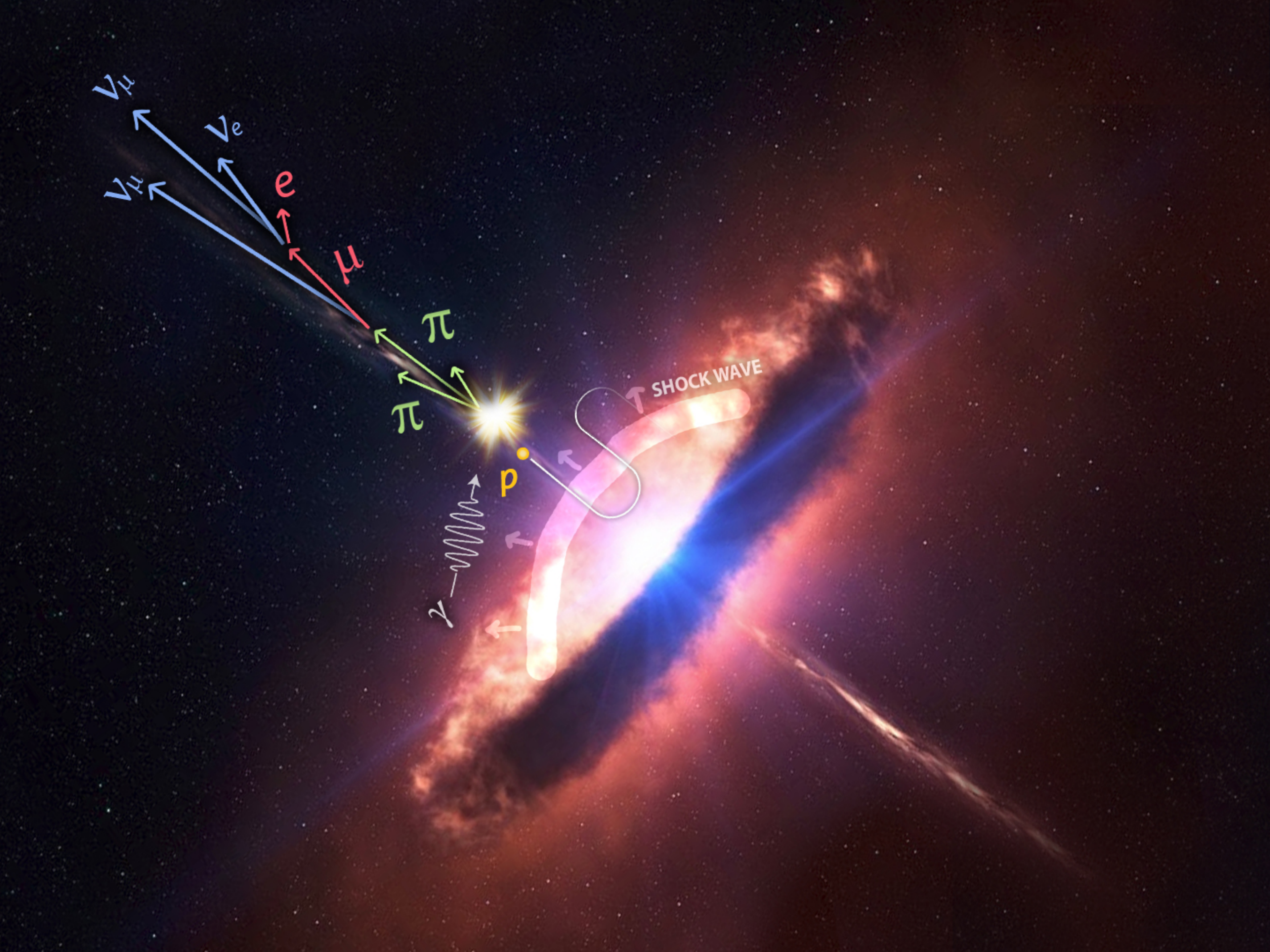
gamma ray bursts



active galaxy

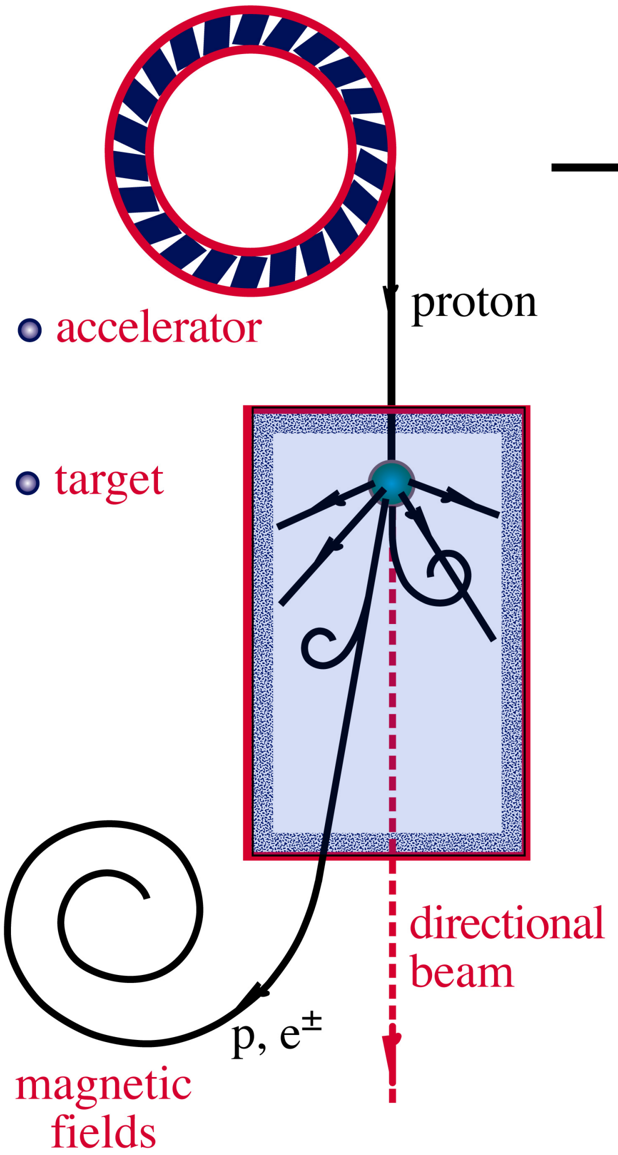
particle flows near
supermassive
black hole





νμ
νe
e
νμ
μ
π
π
p
γ
SHOCK WAVE

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

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

~ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

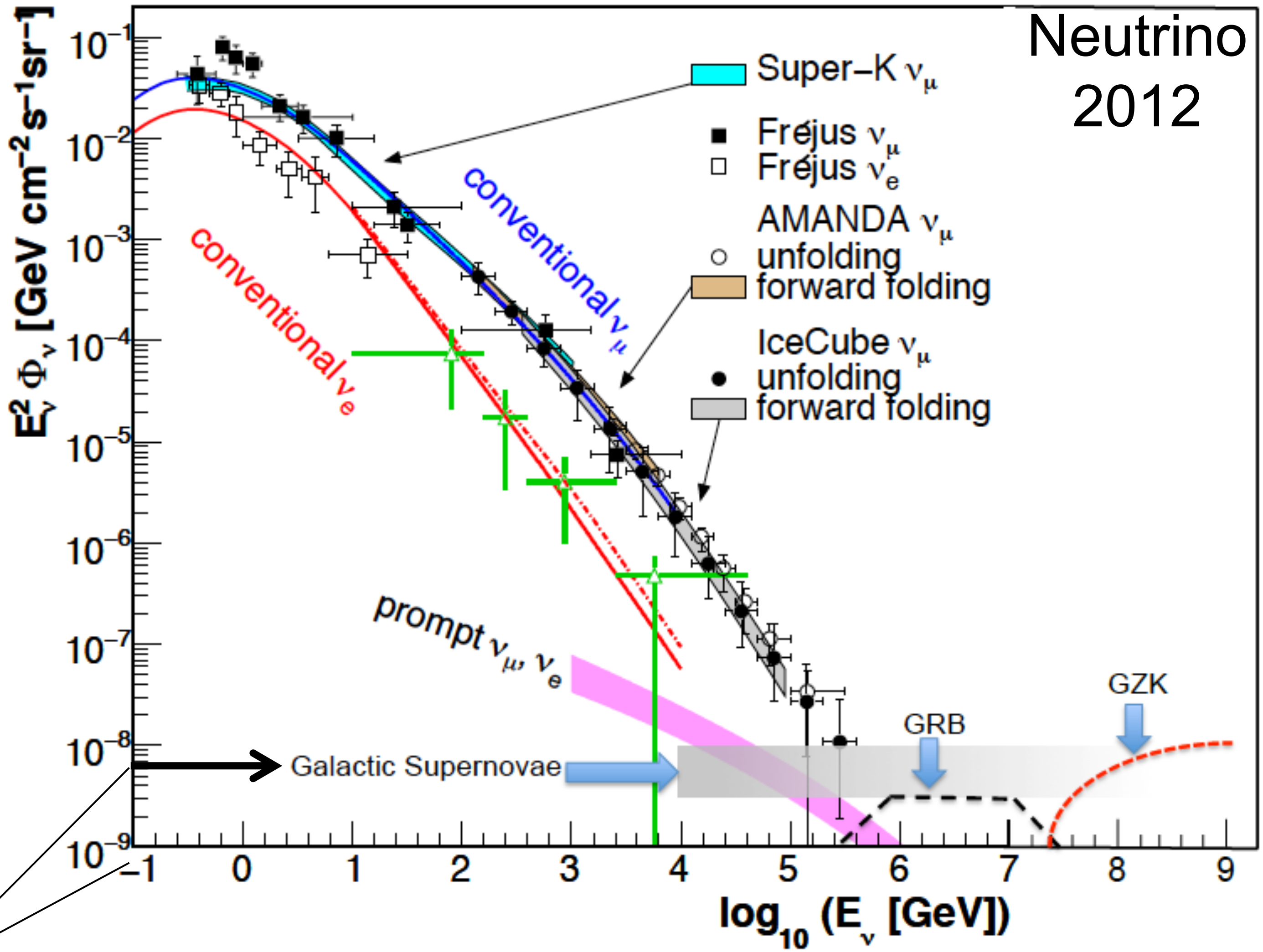
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

$dN/dE \sim E^{-2}$

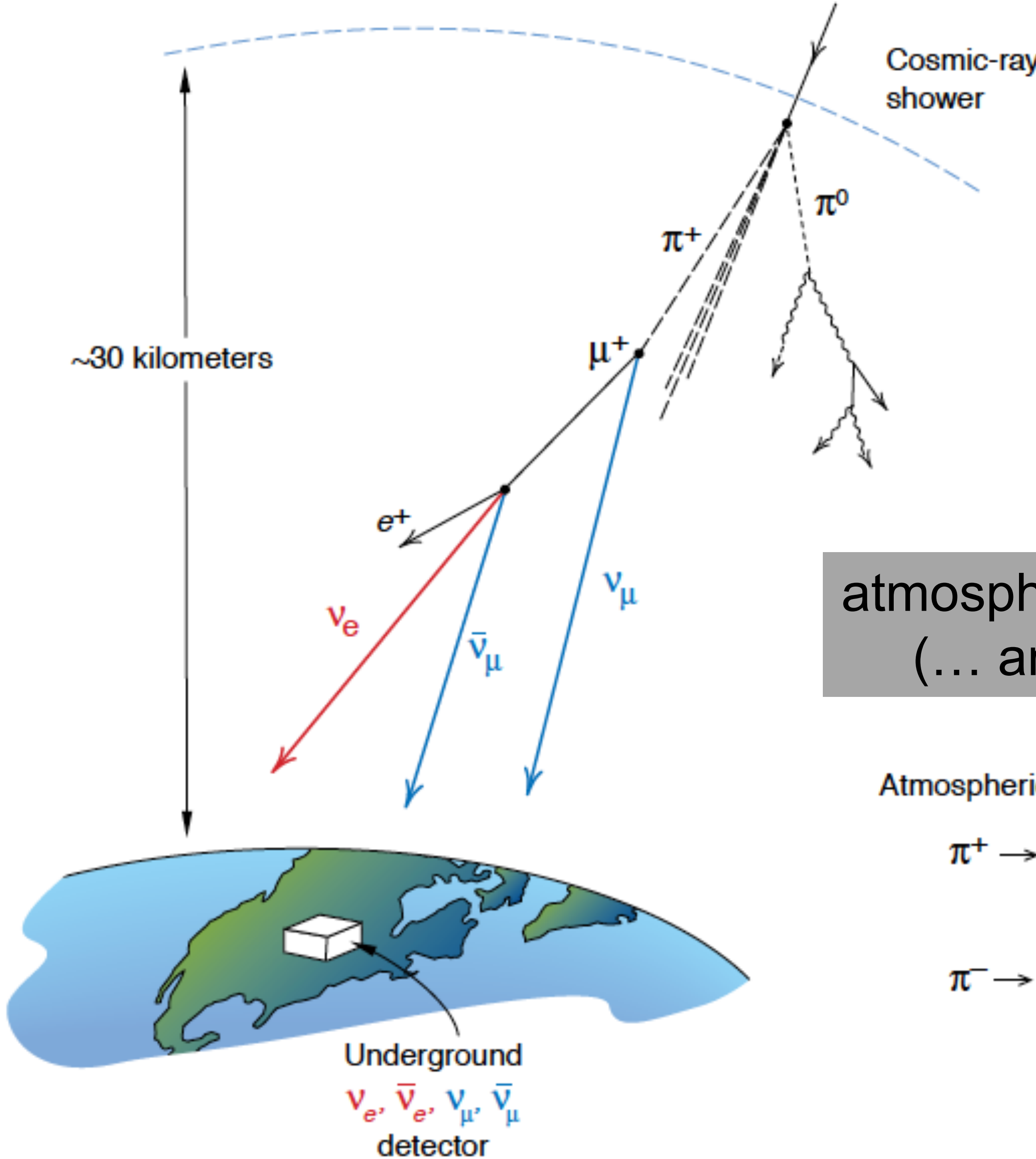
10-10^2 events per year for a fully efficient km^3 detector



atmospheric | cosmic

100 TeV

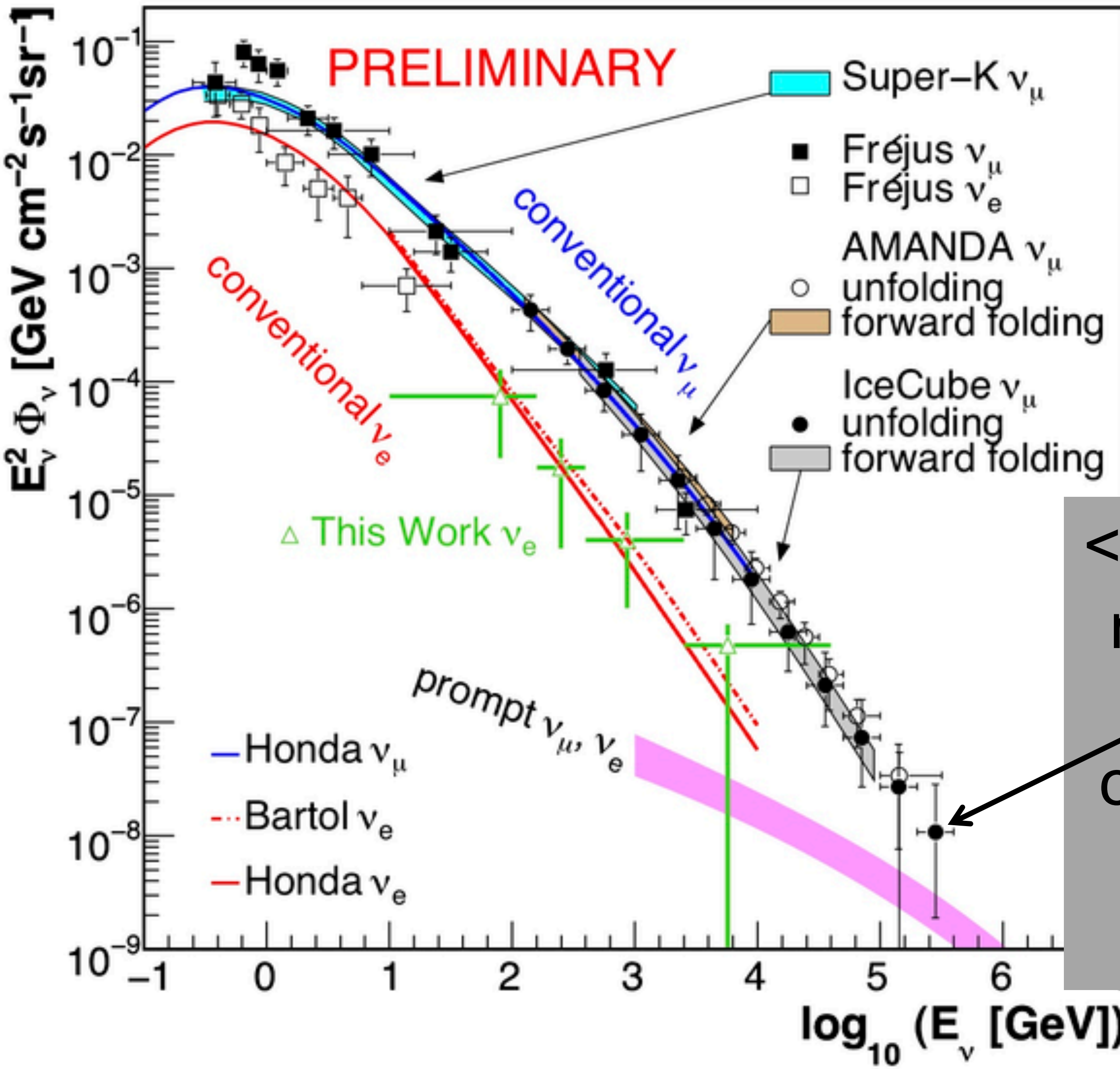
atmospheric neutrinos (… and muons!)



Atmospheric neutrino source

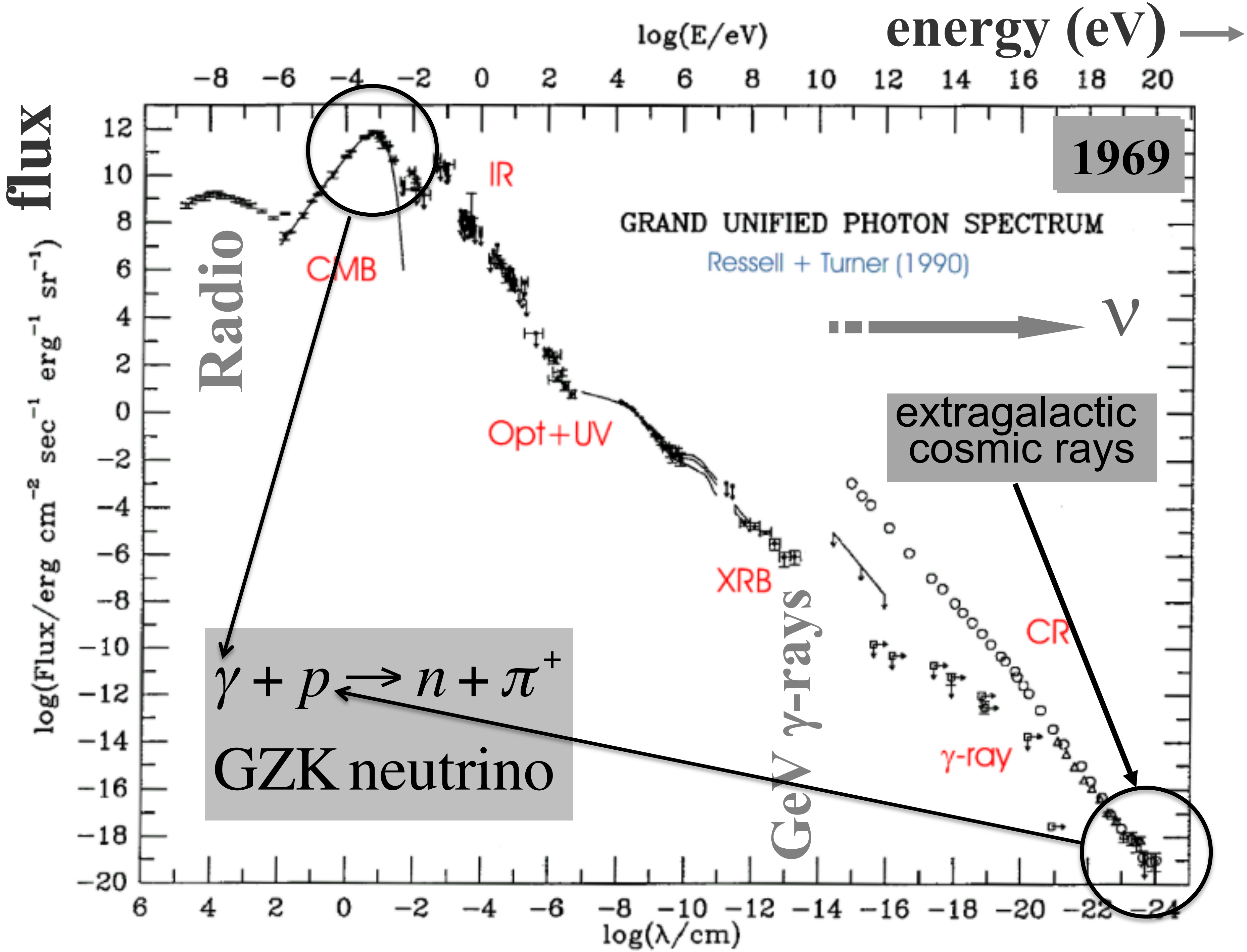
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



< 1 atmospheric neutrino event per cubic kilometer per year (charm?)

atmospheric neutrino spectrum



energy (eV)
log(E/eV)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
γ-ray
CR
ν
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^{+}$
GZK neutrino

cosmic rays interact with the microwave background

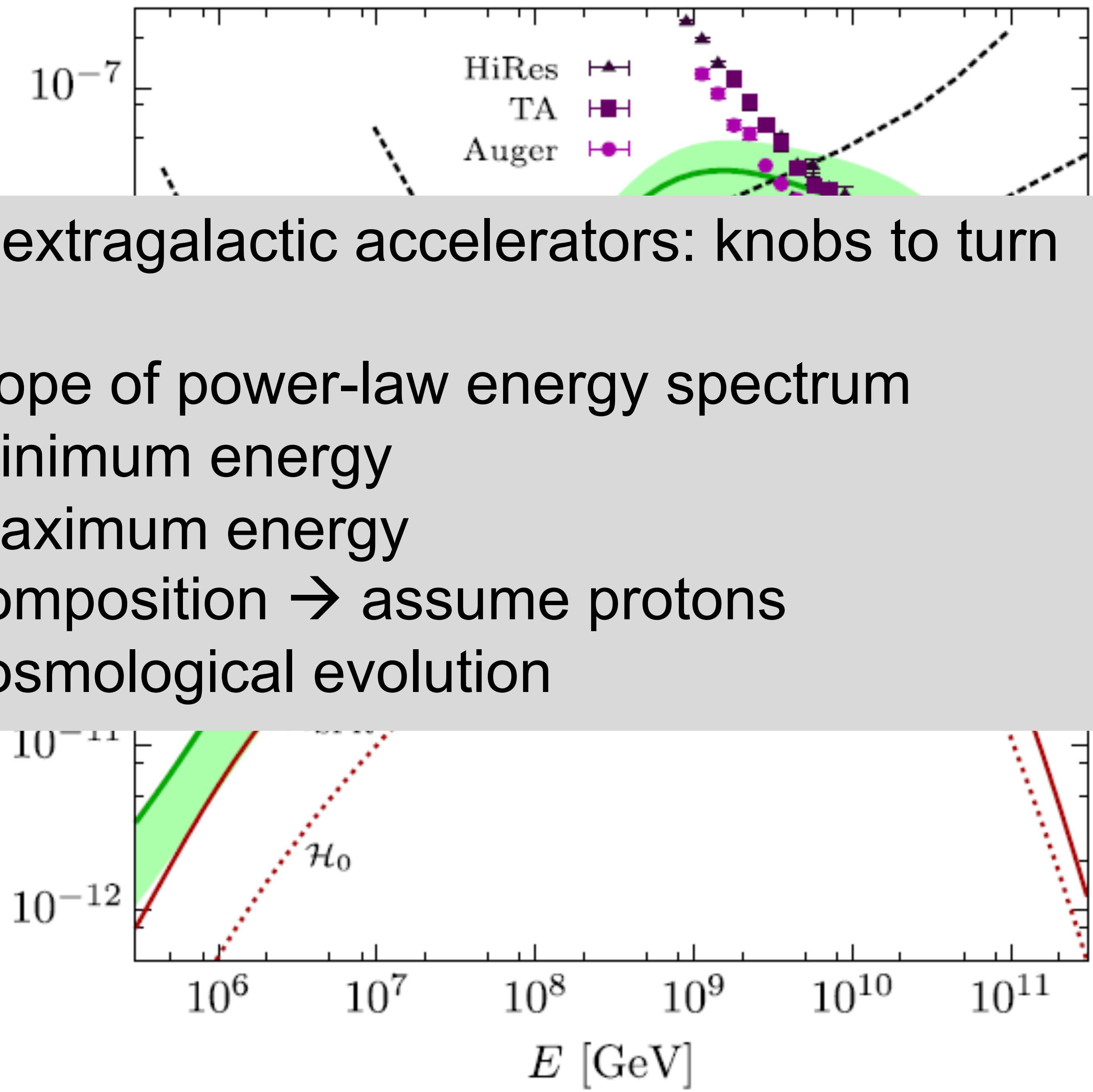
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

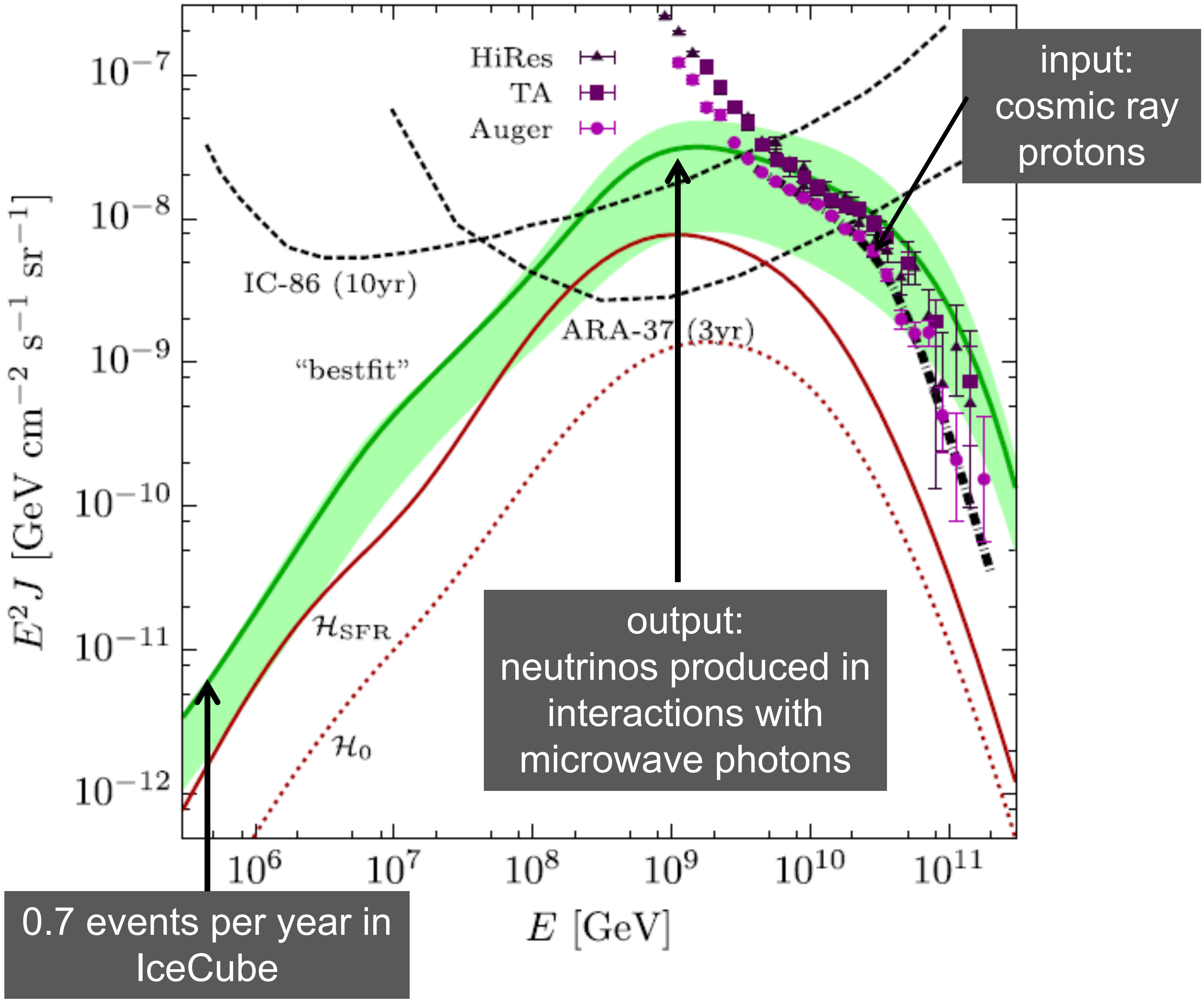
1 event per cubic kilometer per year

...but it points at its source!

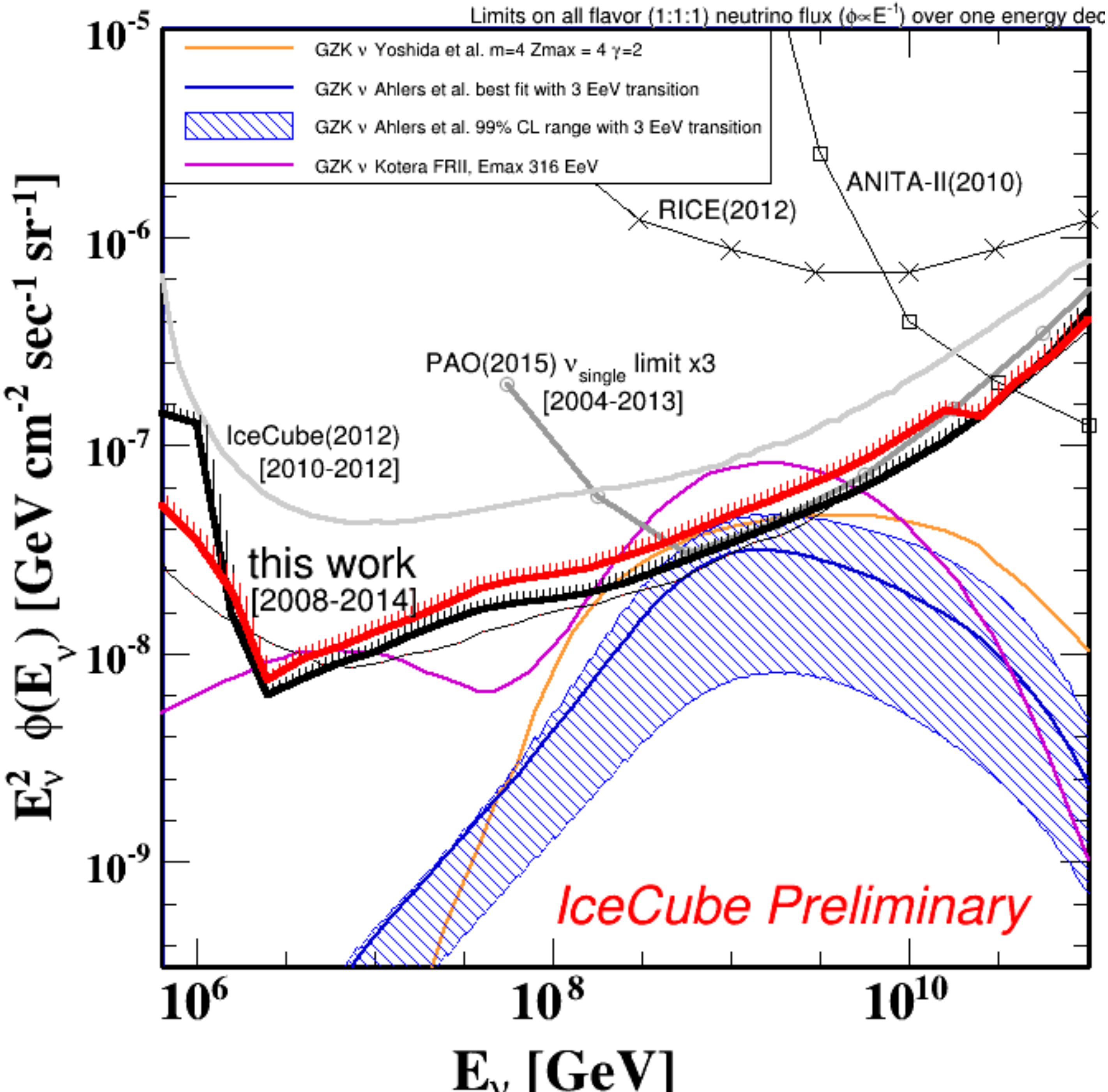


the extragalactic accelerators: knobs to turn

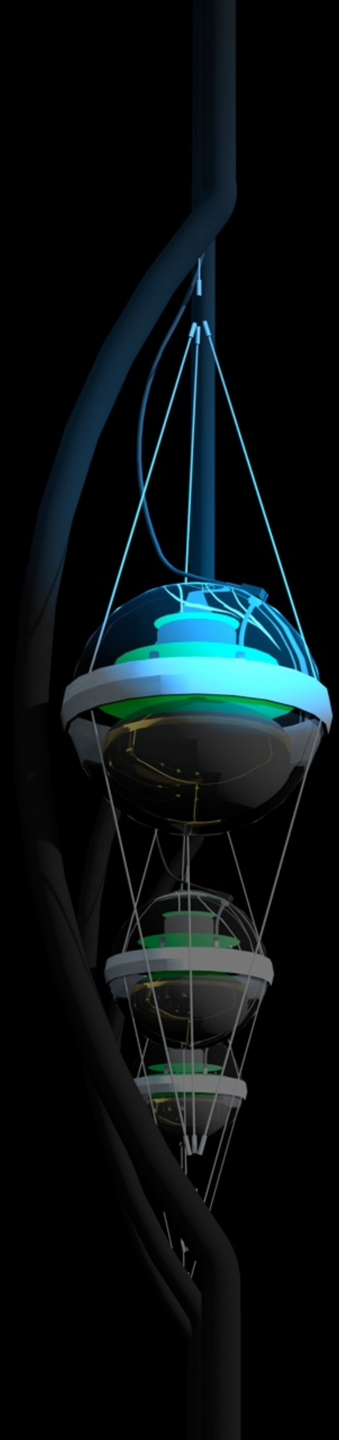
- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
input: cosmic ray protons
output: neutrinos produced in interactions with microwave photons
0.7 events per year in IceCube



Limits on all flavor (1:1:1) neutrino flux (φ∝E^-1) over one energy dec
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
$E_\nu^2\ \phi(E_\nu)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
E_ν [GeV]



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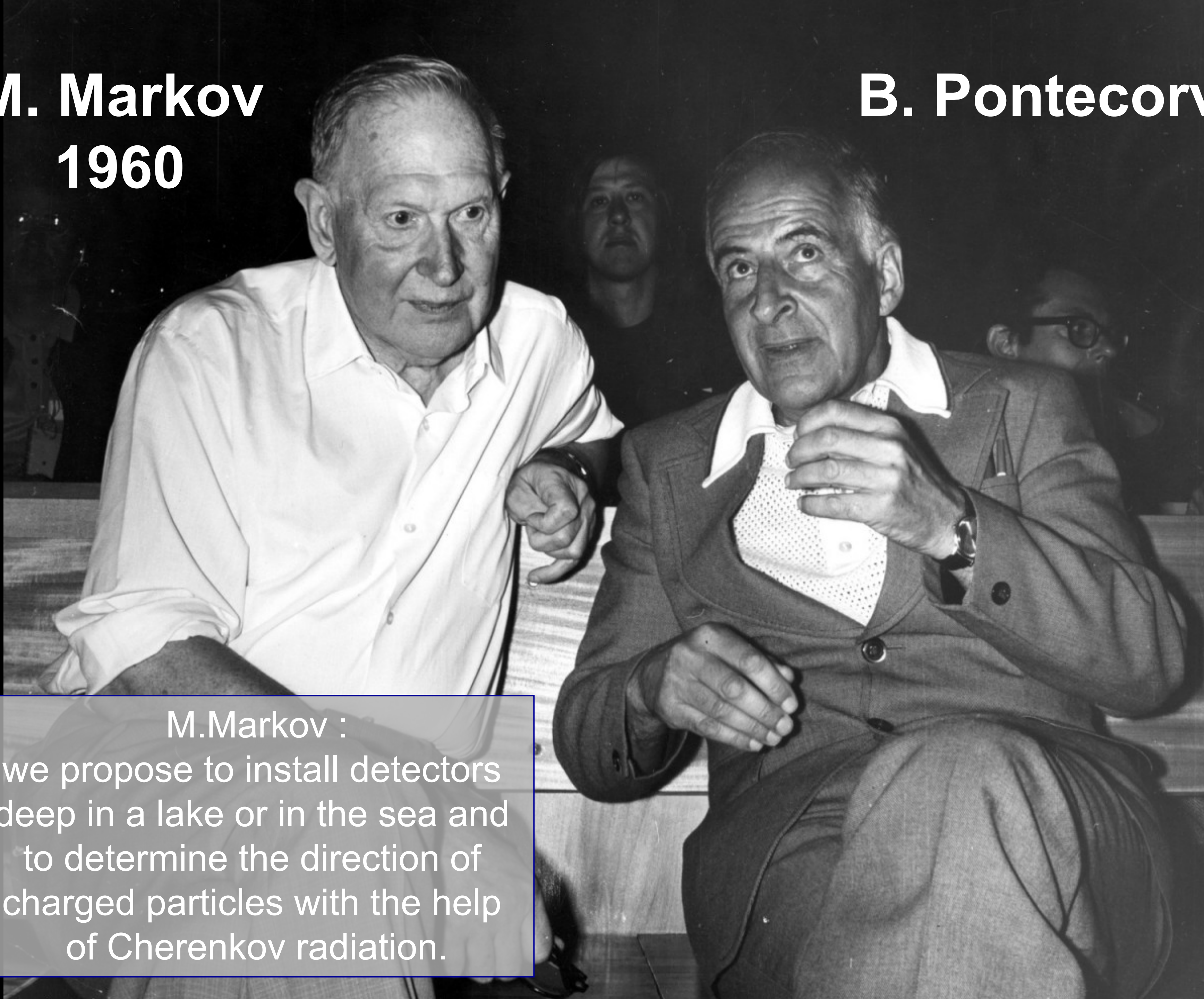
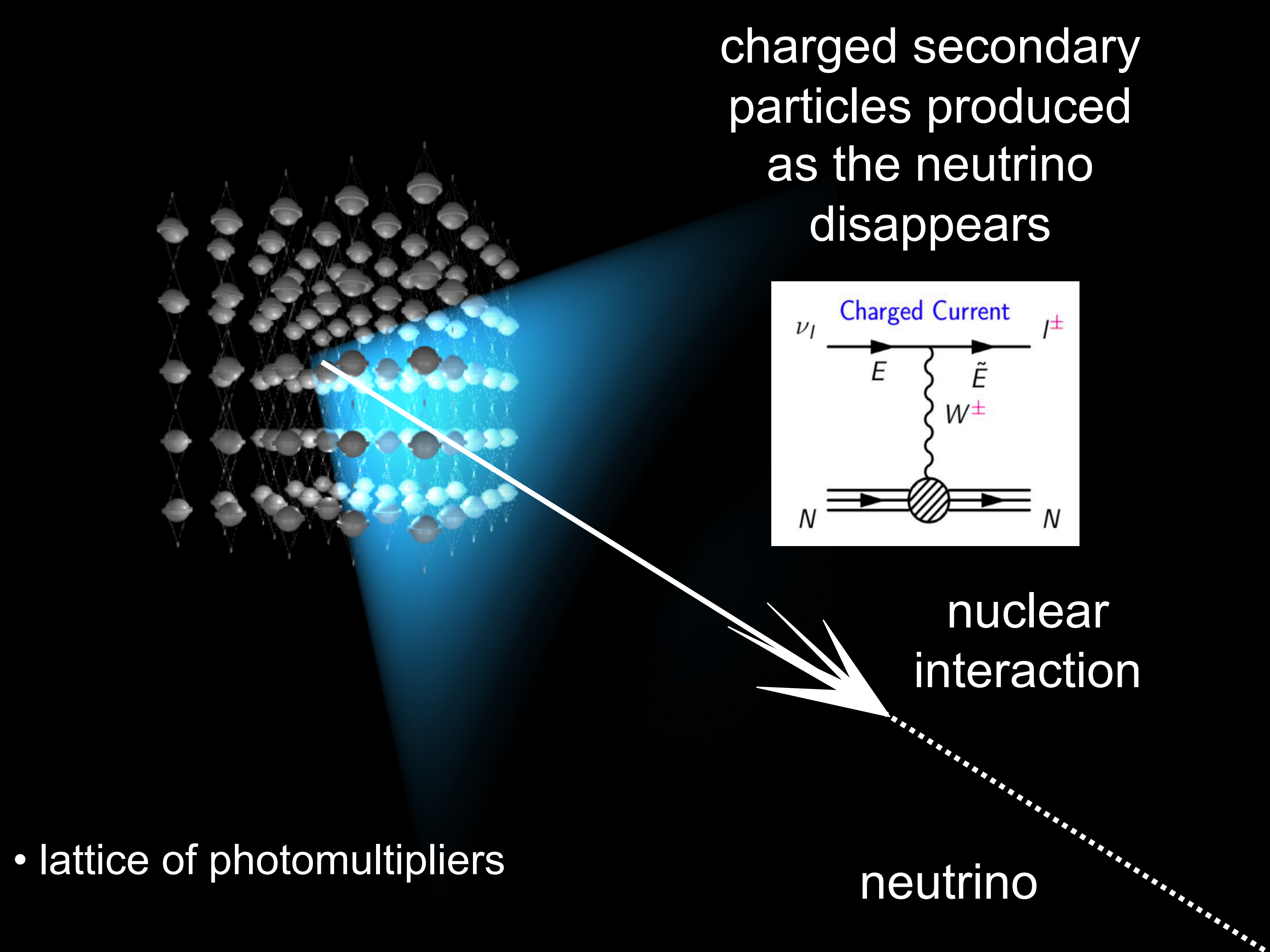
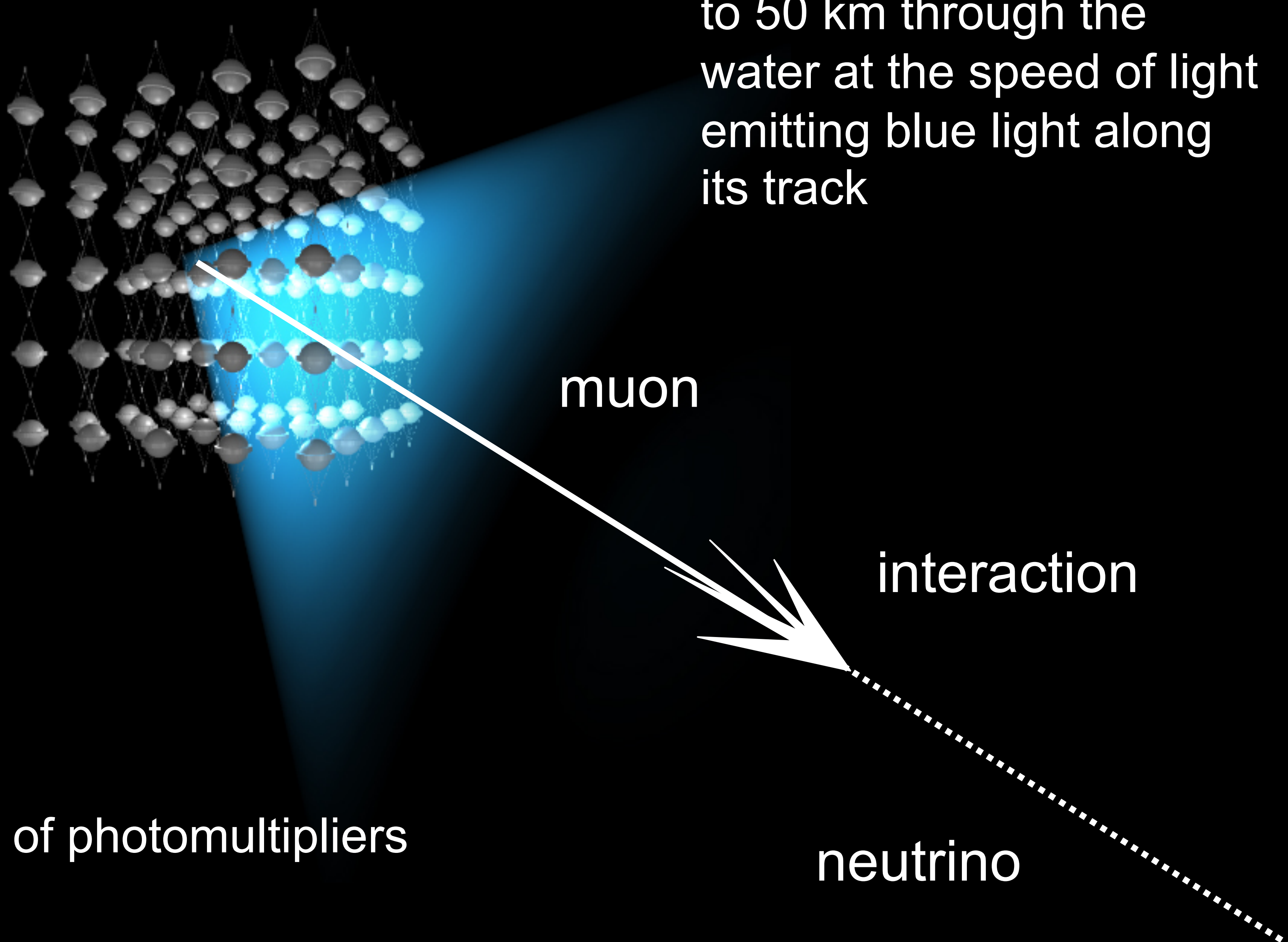

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

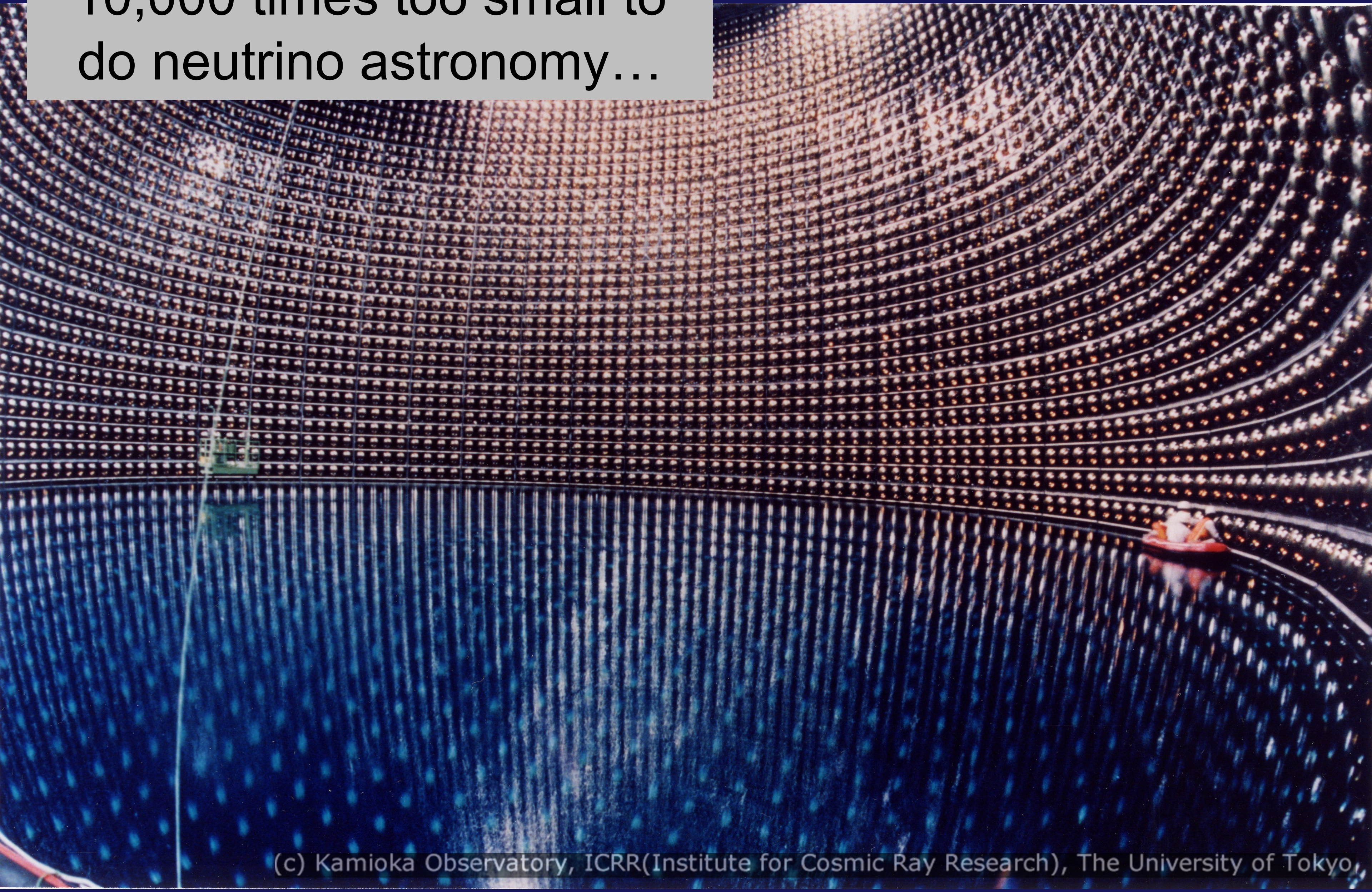

charged secondary particles produced as the neutrino disappears
Charged Current
ν_l
$l^\pm$
E
$\tilde{E}$
$W^\pm$
N
N
nuclear interaction
• lattice of photomultipliers
neutrino

- speed of light in water < c
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



- lattice of photomultipliers

10,000 times too small to do neutrino astronomy…



standing on the shoulder of giants

1987: DUMAND test string

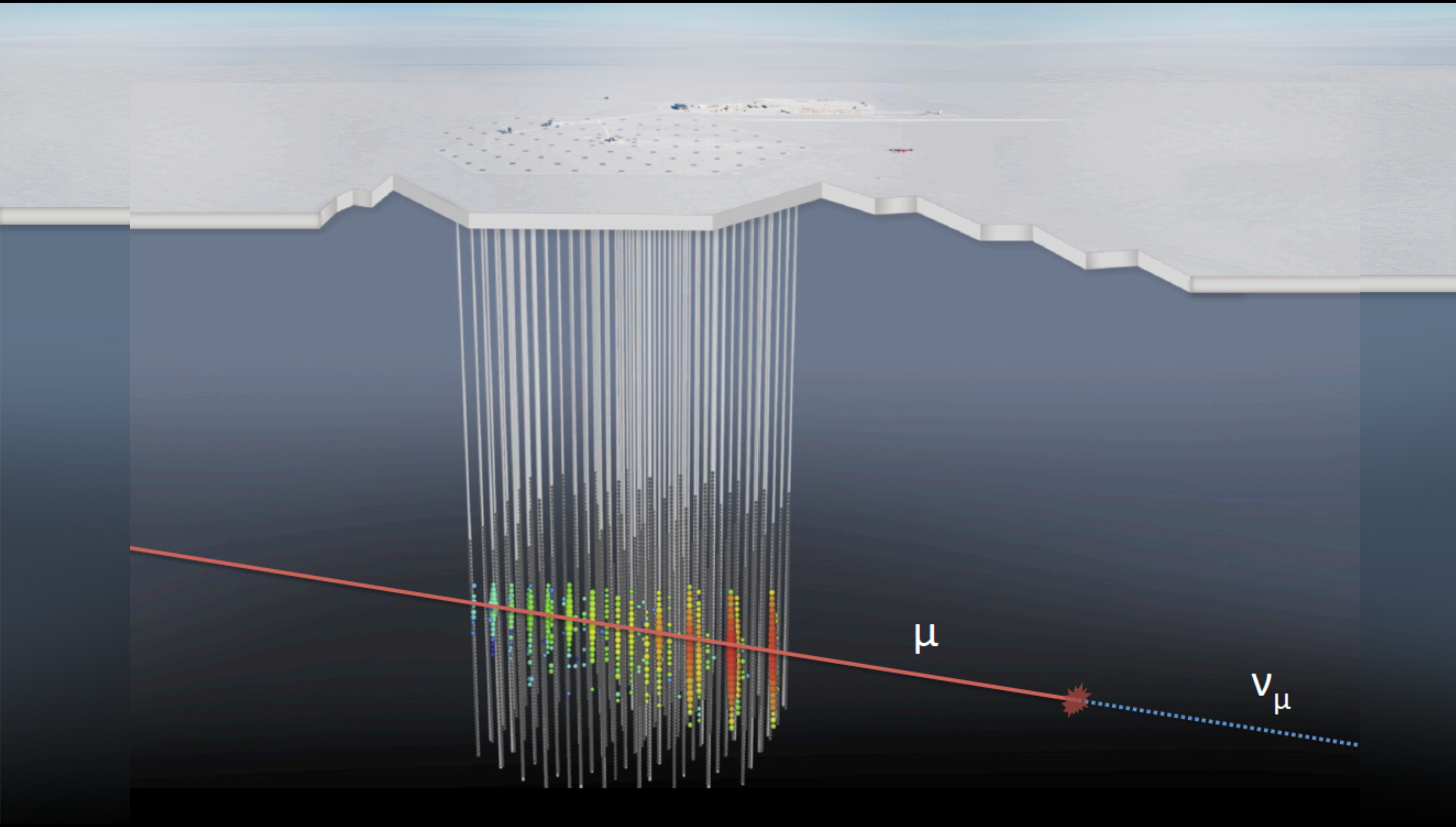
Lake Baikal experiment observes atmospheric neutrinos


ANTARES
Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
ANTARES
450 m
40 km to shore
Junction Box
70 m
Interlink cables
© François Montanet

ice 1.4 kilometers below geographic South Pole


ultra-transparent ice below 1.5 km

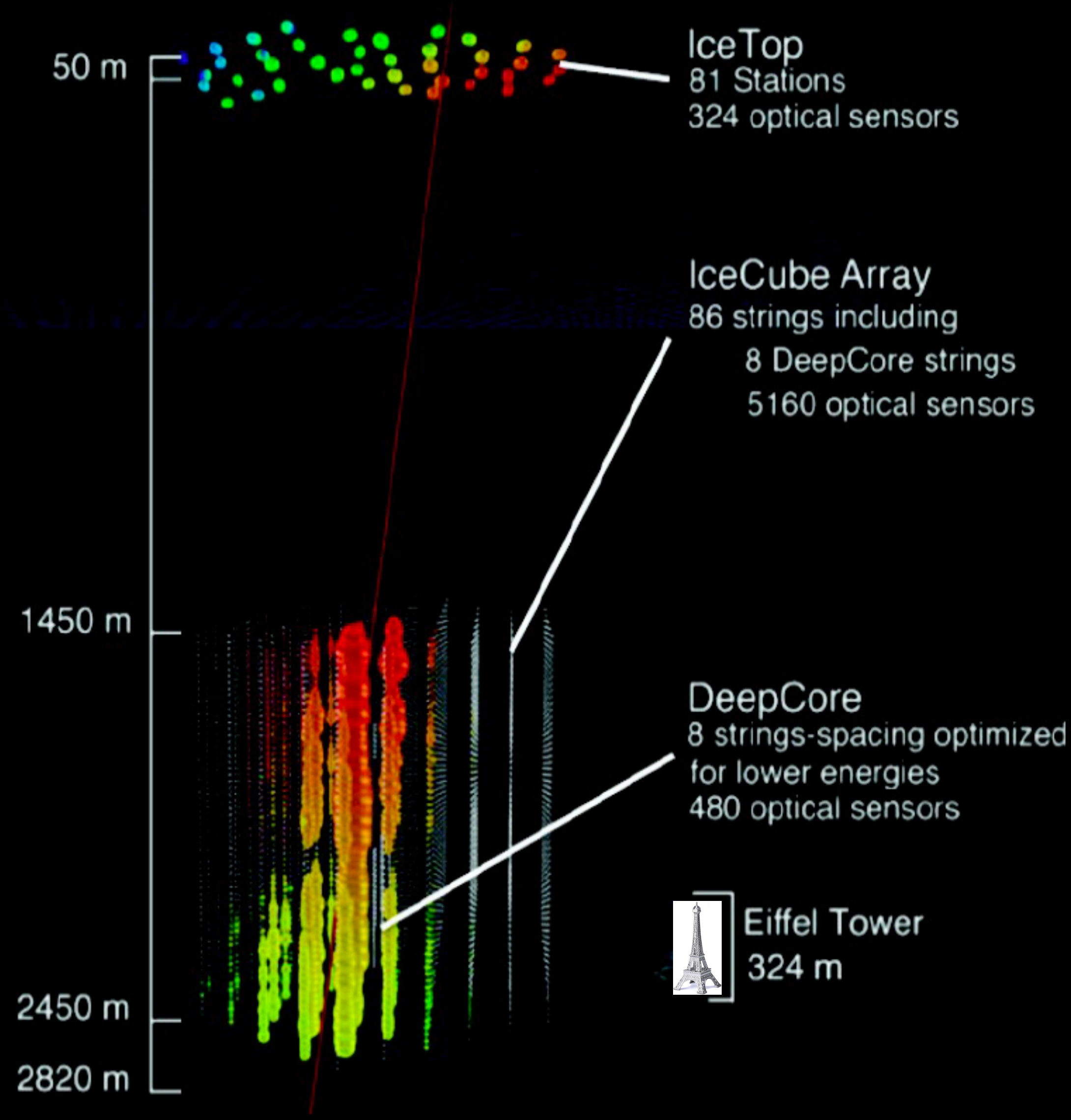
instrument 1 cubic kilometer of natural ice below 1.45 km

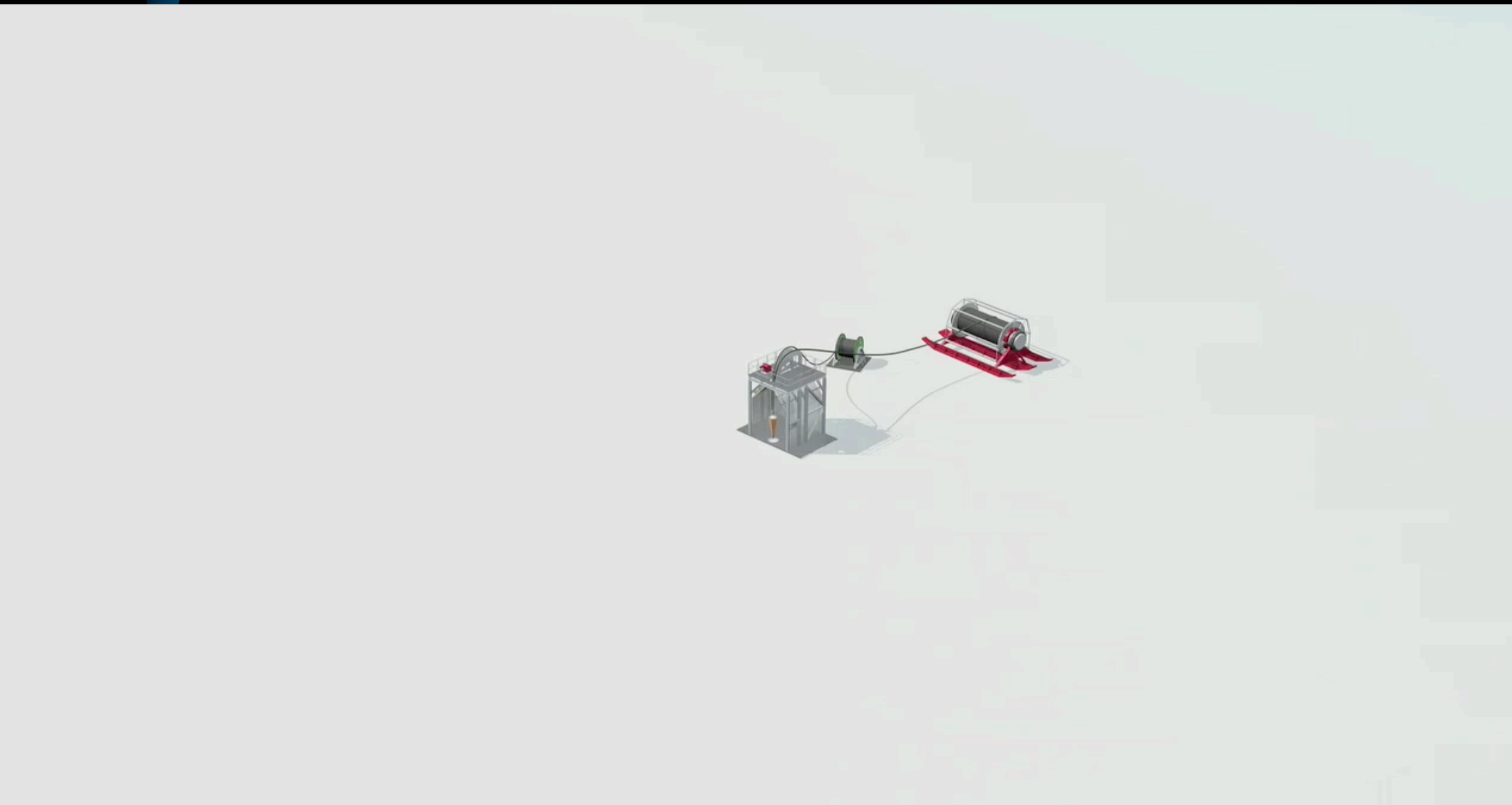


the IceCube Neutrino Observatory

5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

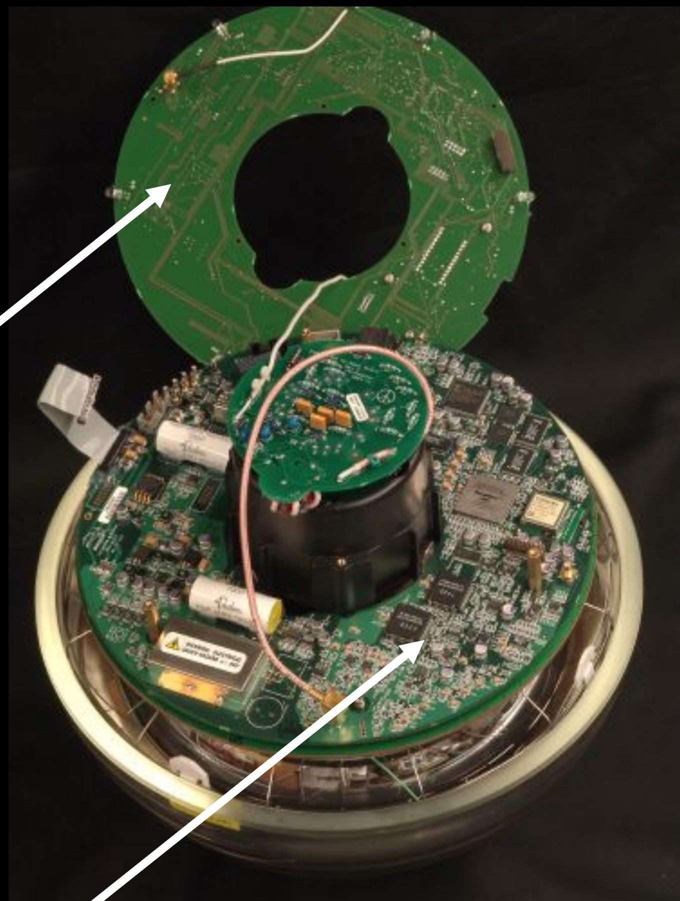
2 ns time resolution

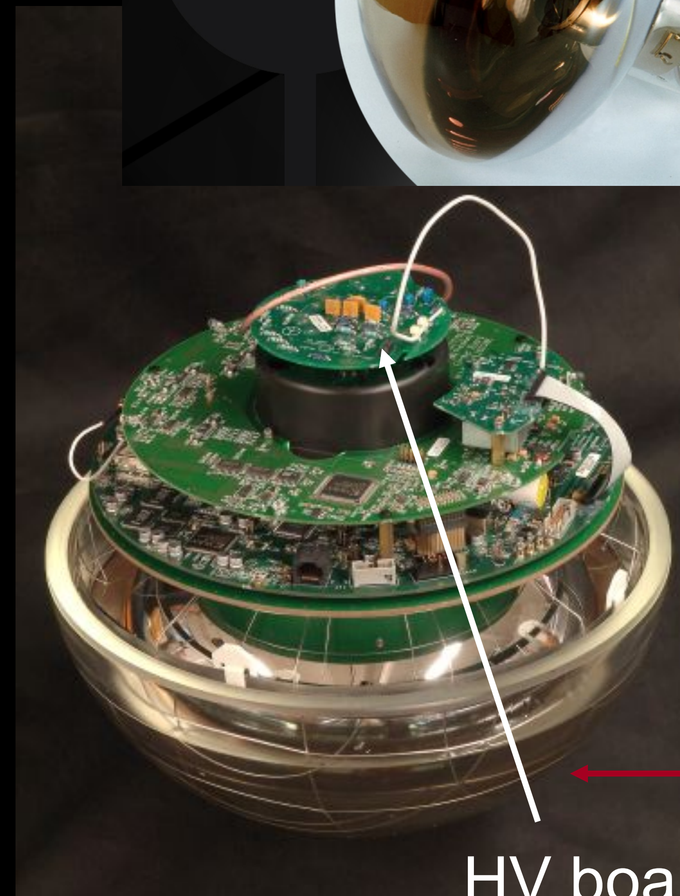




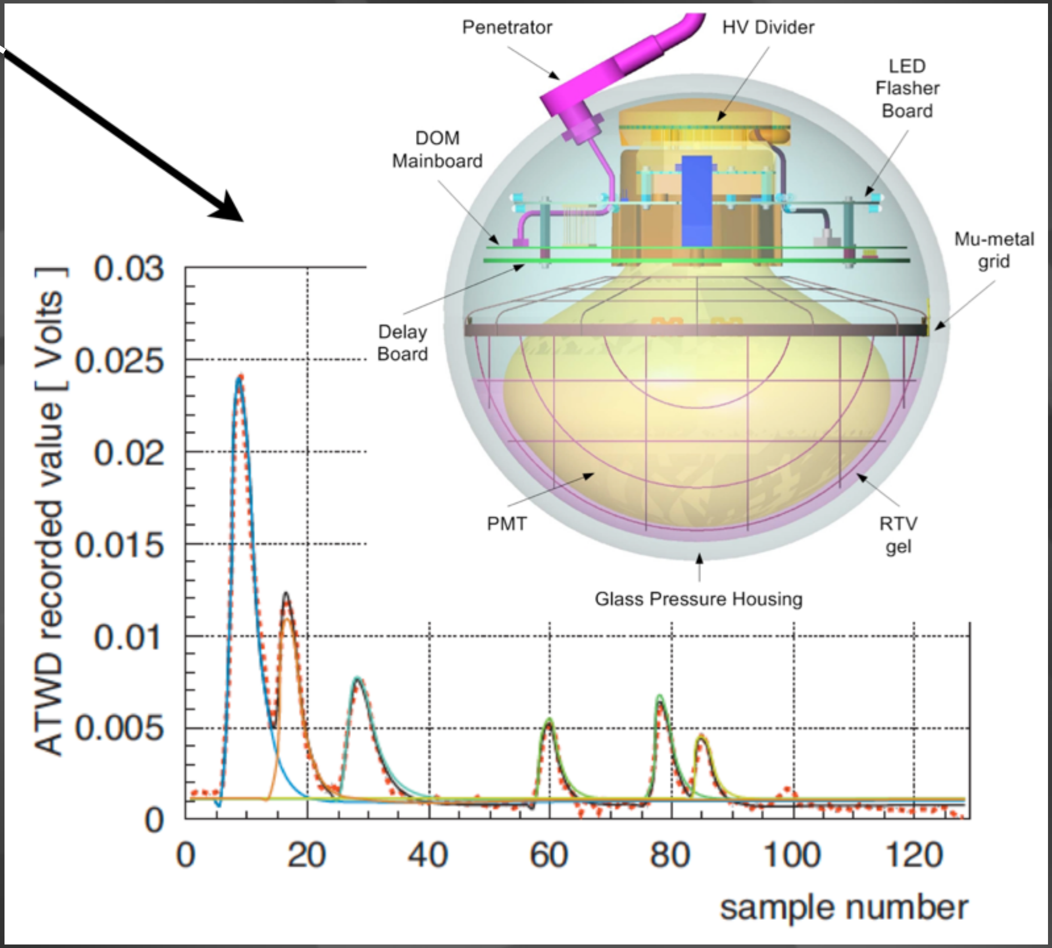
photomultiplier tube -10 inch

architecture of independent DOMs

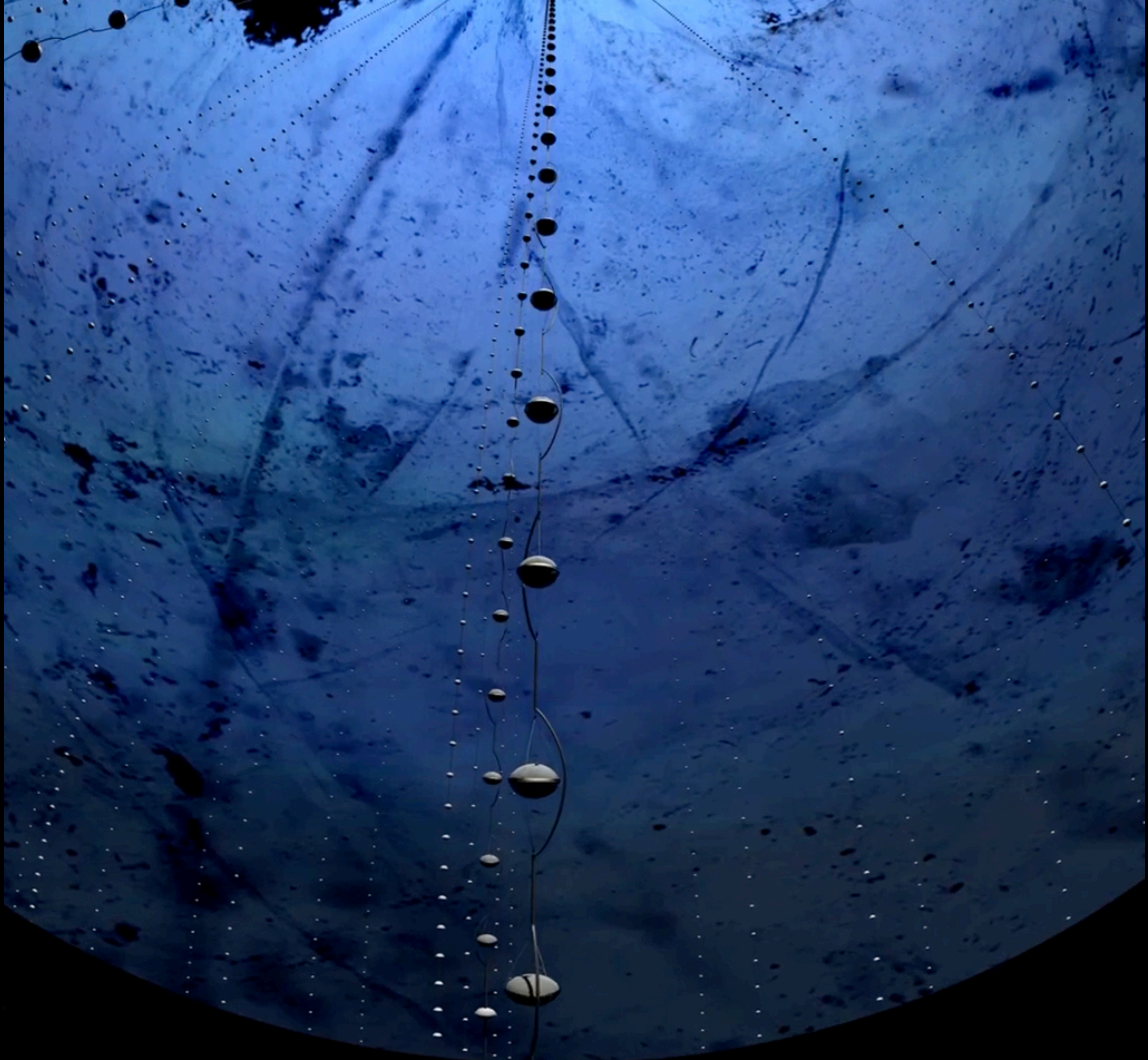


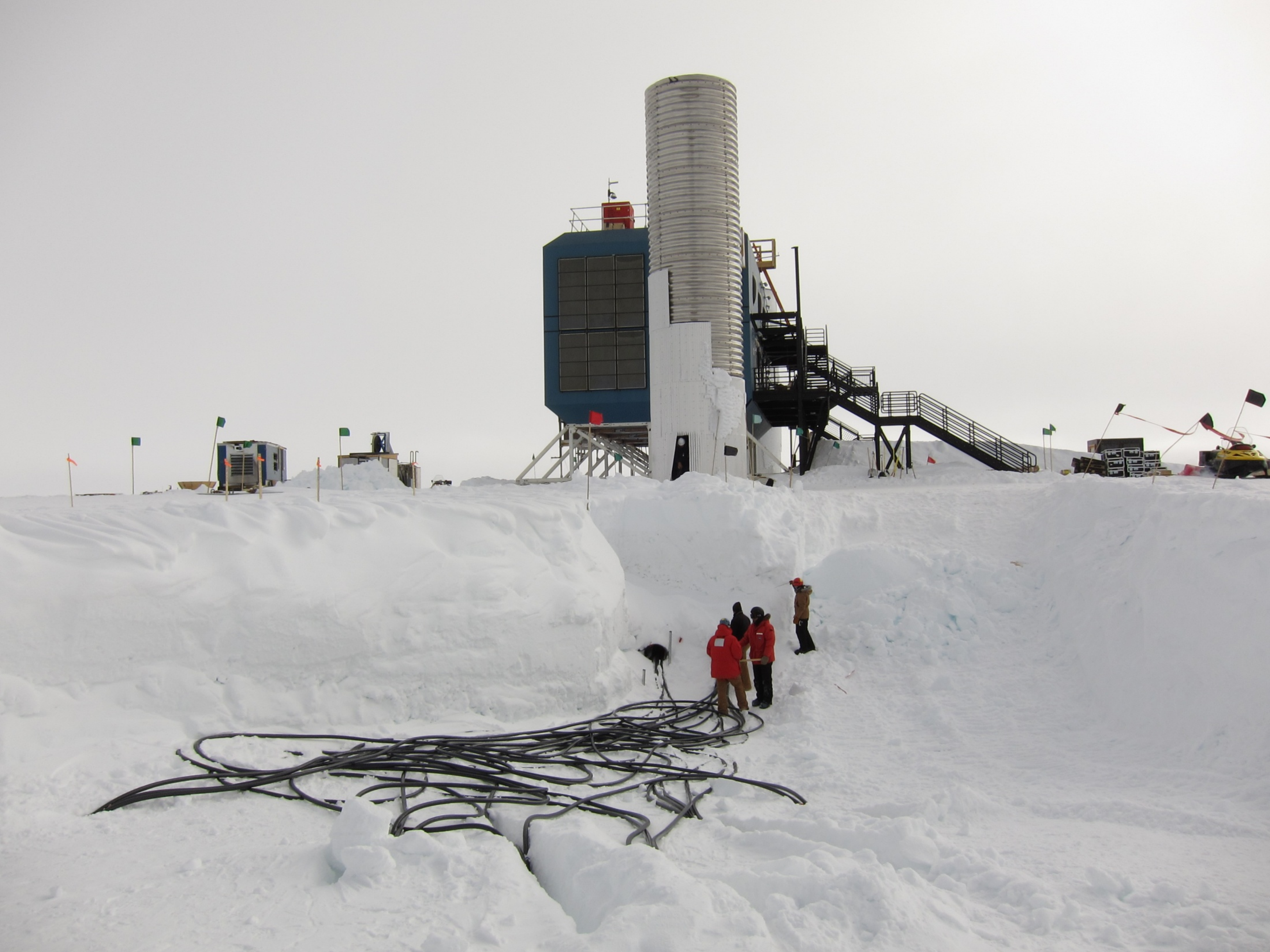


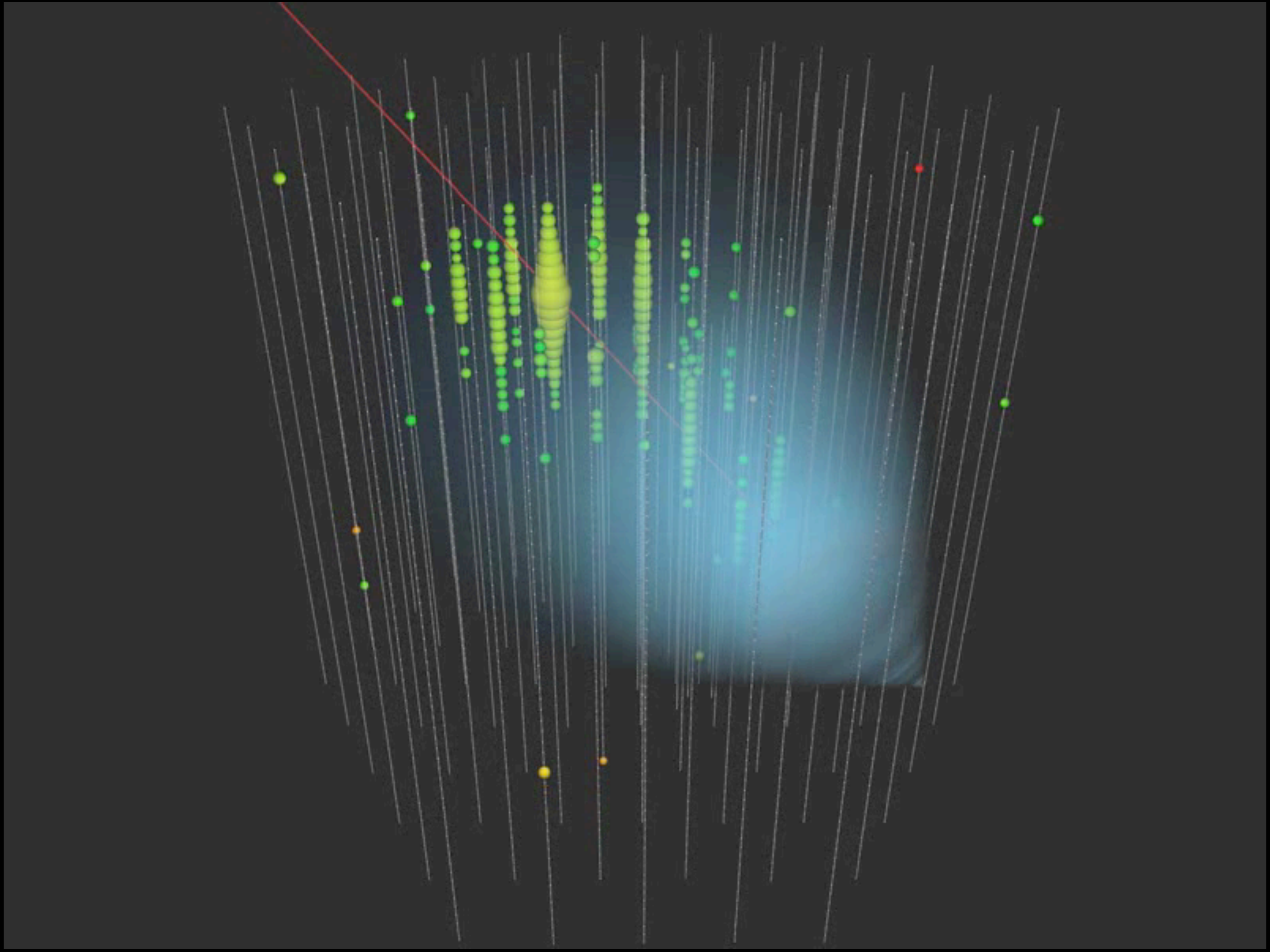
… each Digital Optical Module independently collects light signals like this, digitizes them,



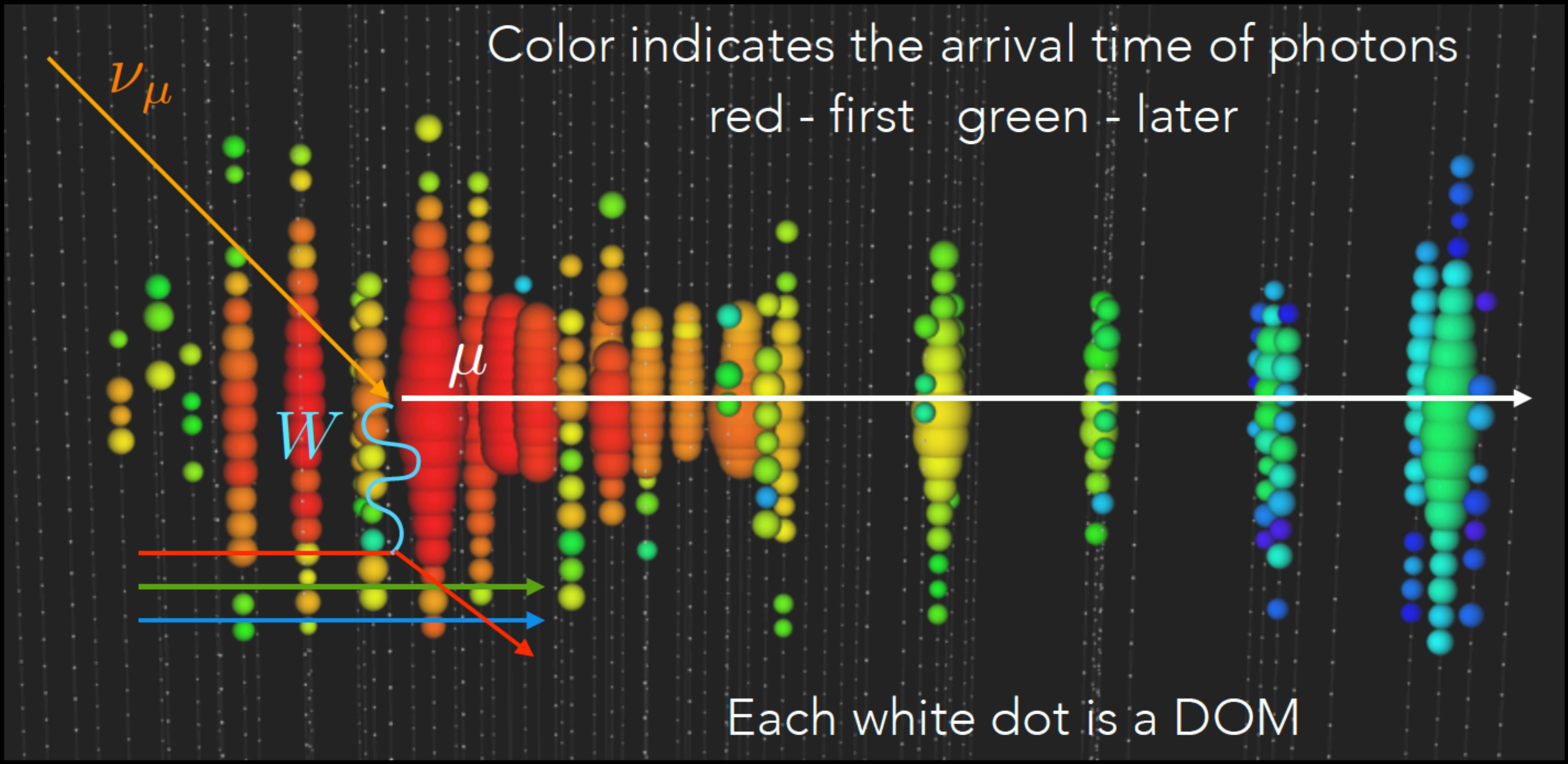
…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…



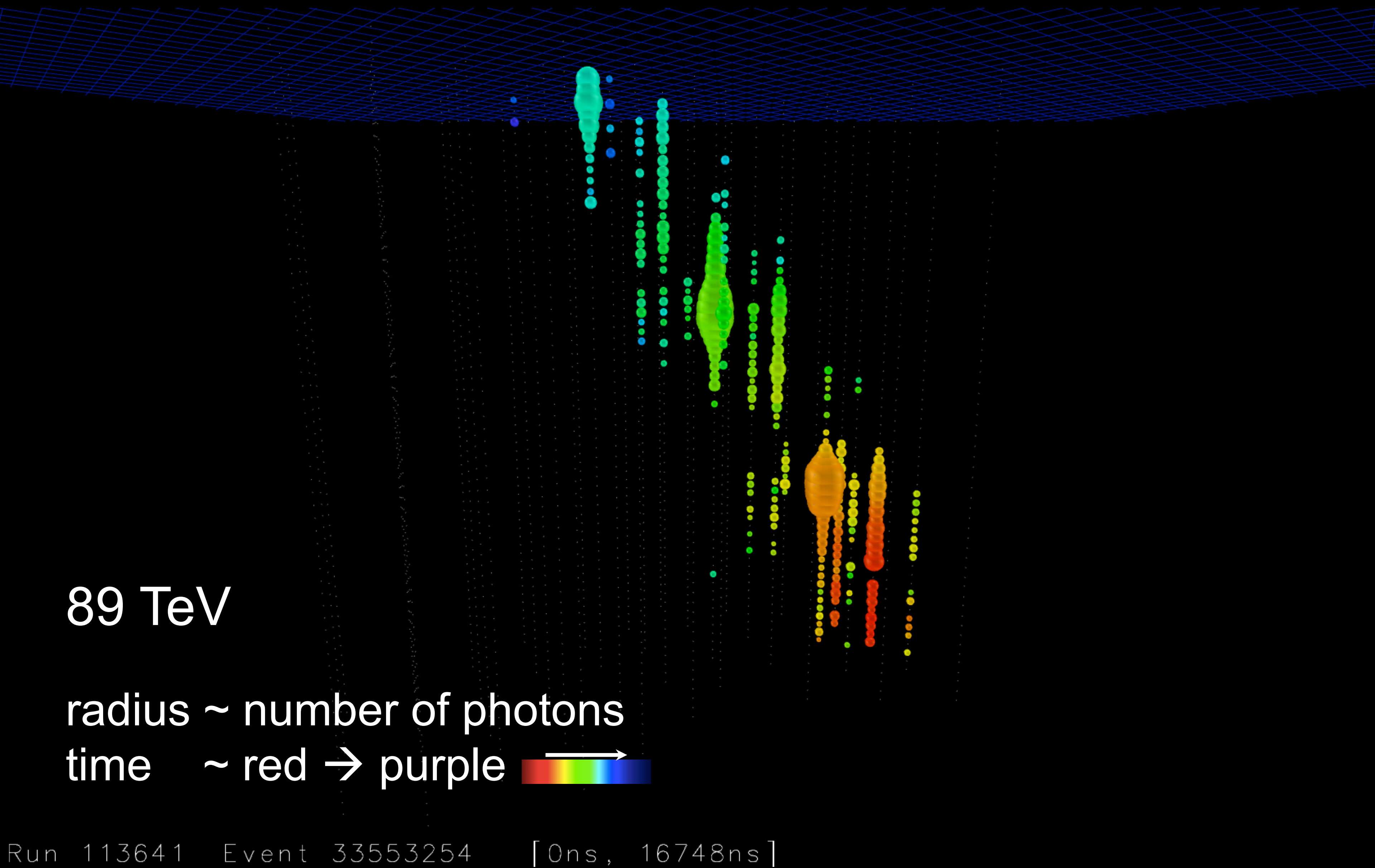




muon track: color is time; number of photons is energy



Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

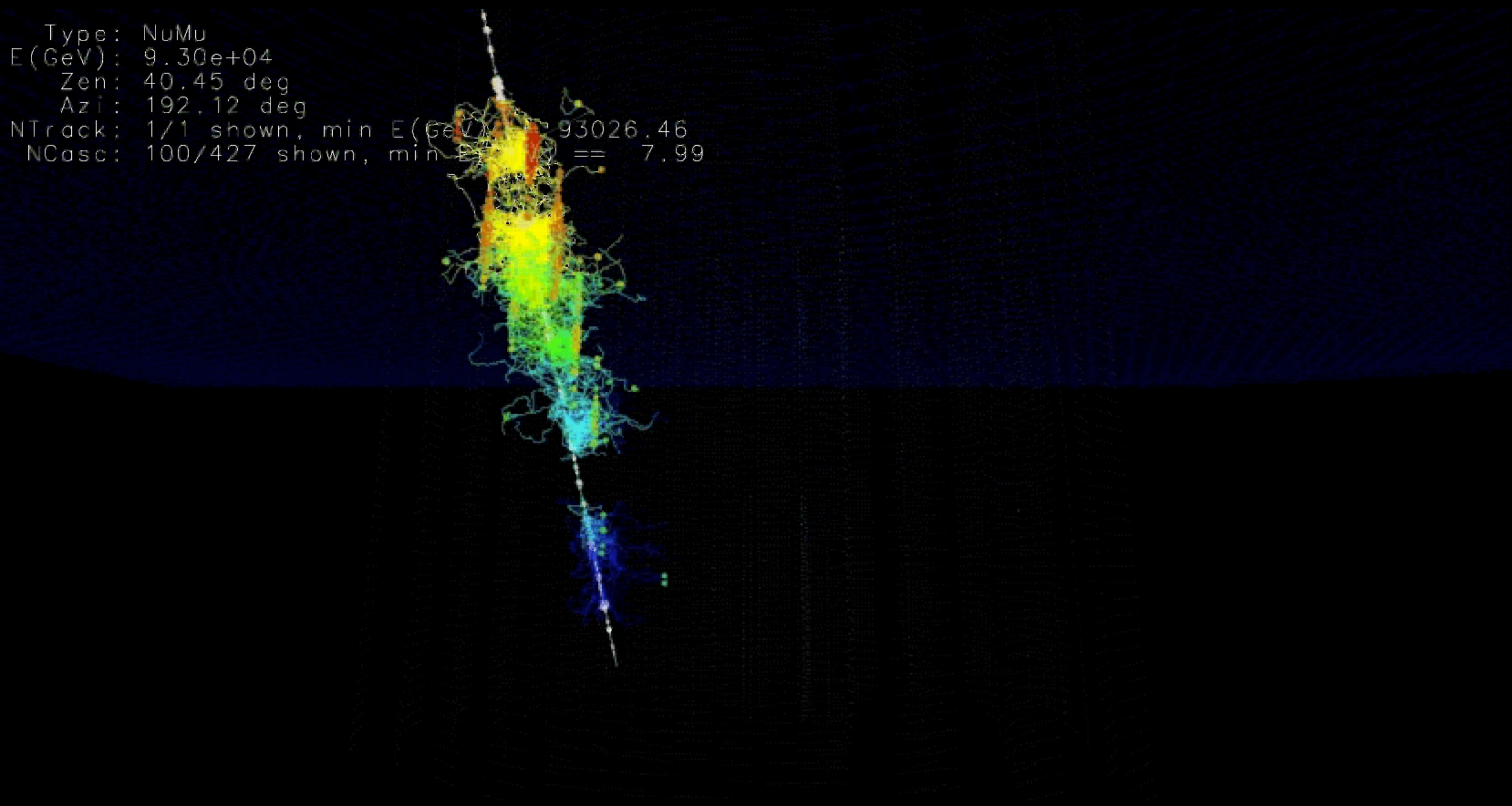


89 TeV

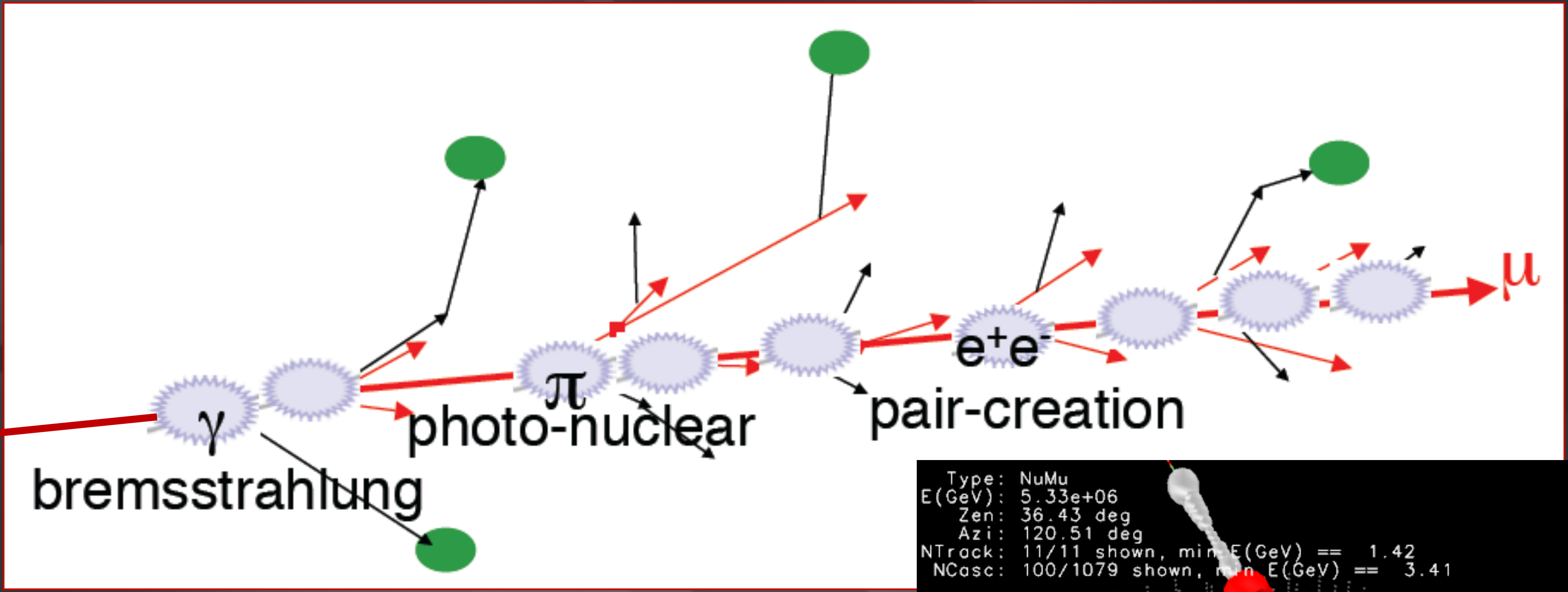
radius ~ number of photons

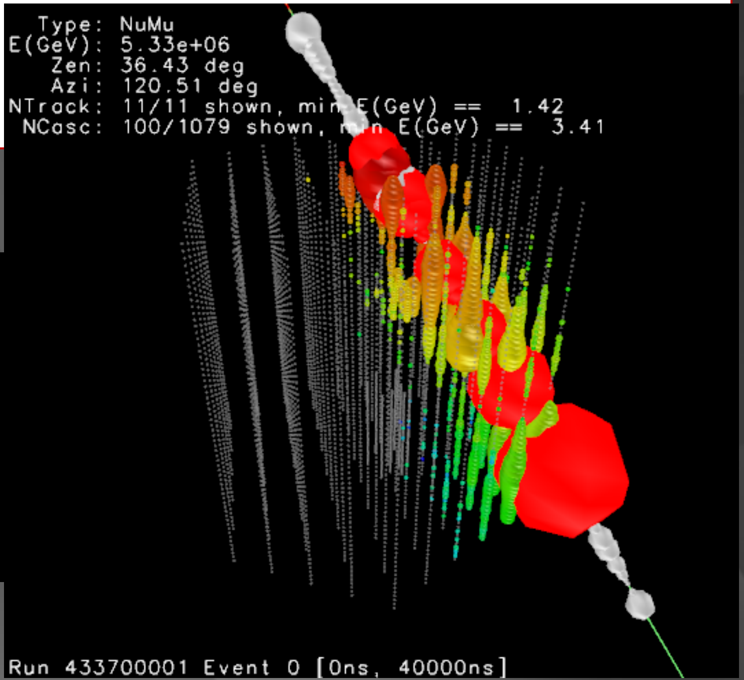
time ~ red → purple

93 TeV muon: light ~ energy

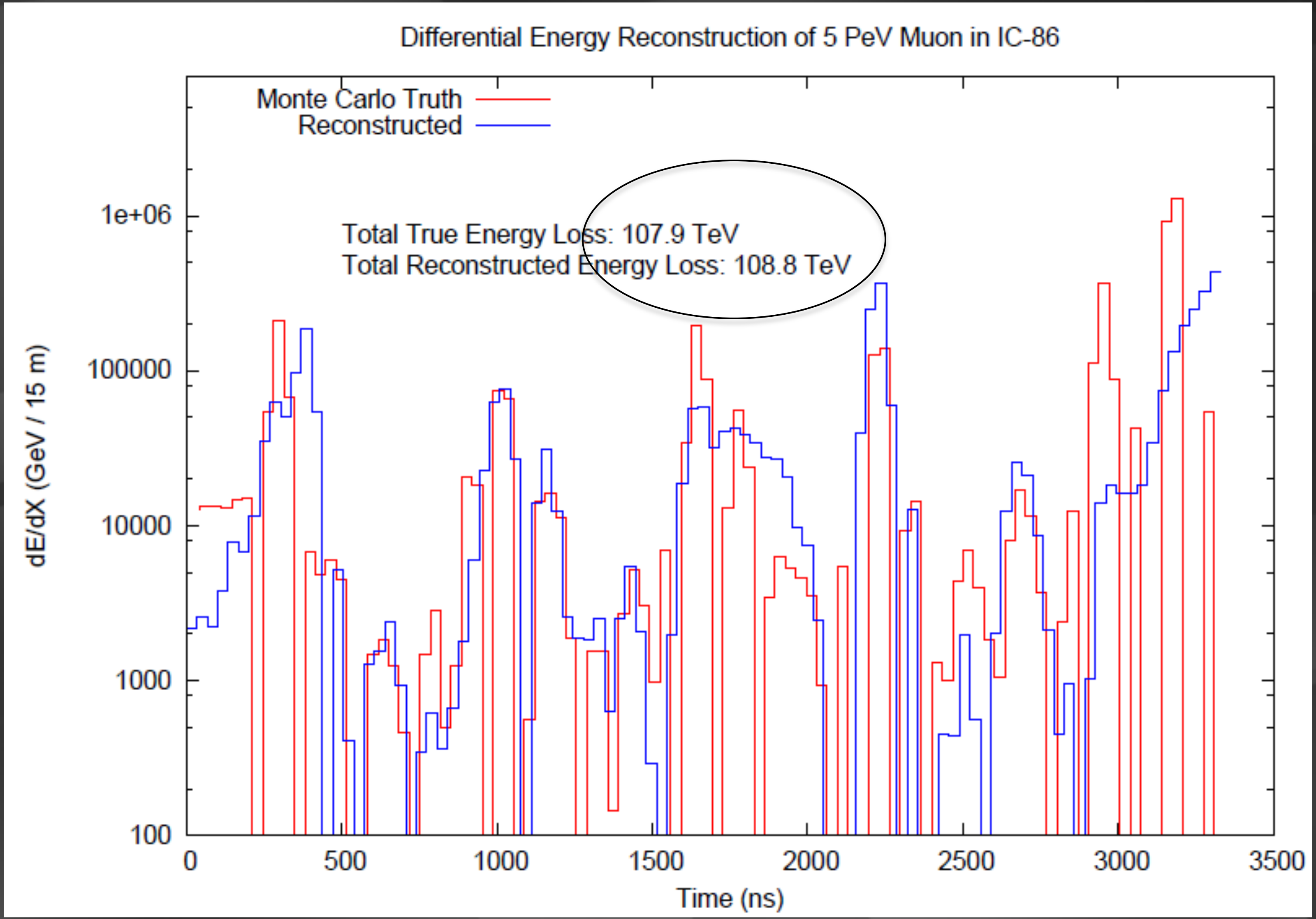


energy measurement (> 100 TeV)





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

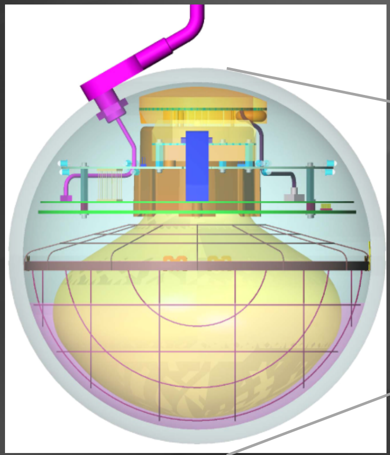


1.1 km

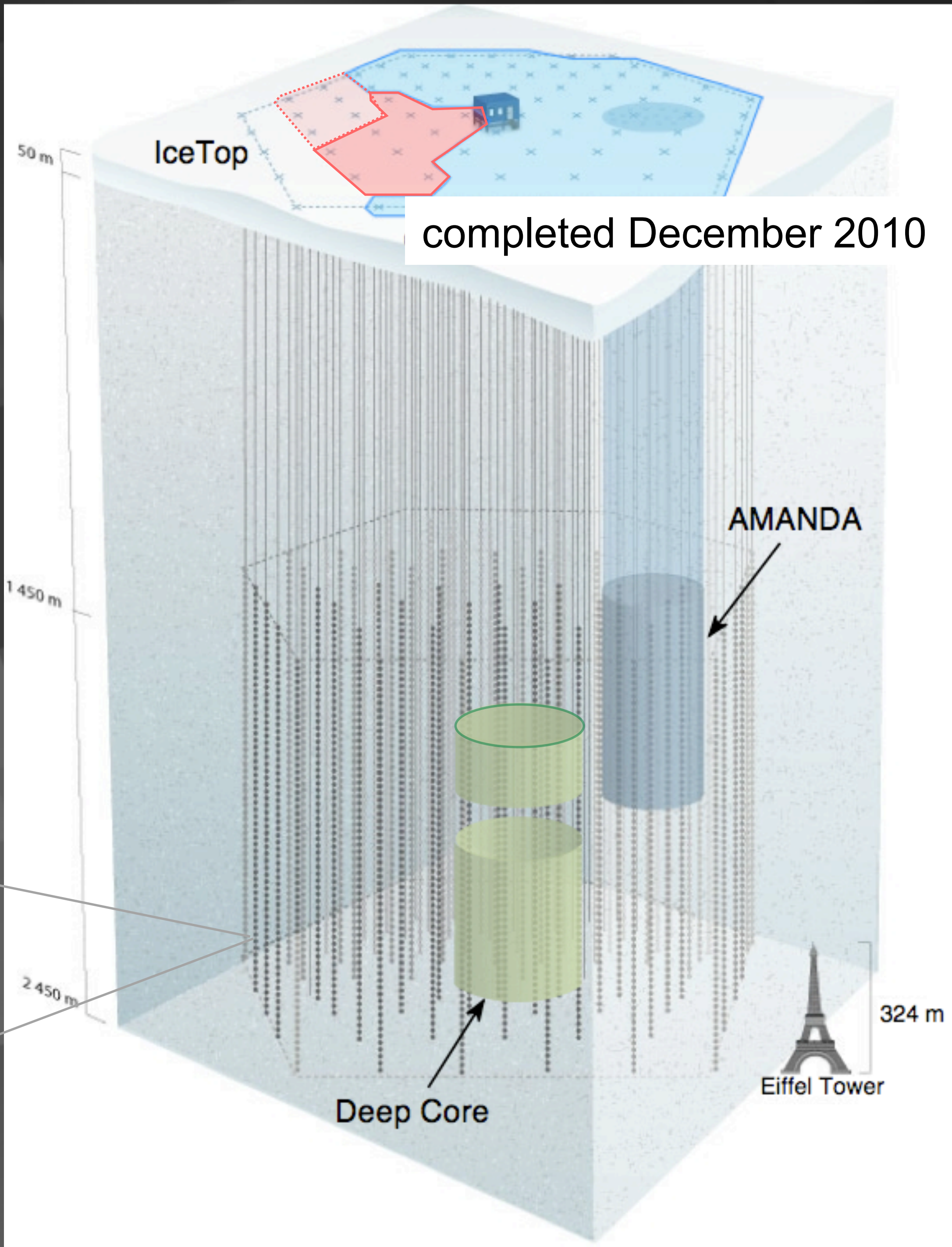
improving angular and energy resolution

IceCube / Deep Core

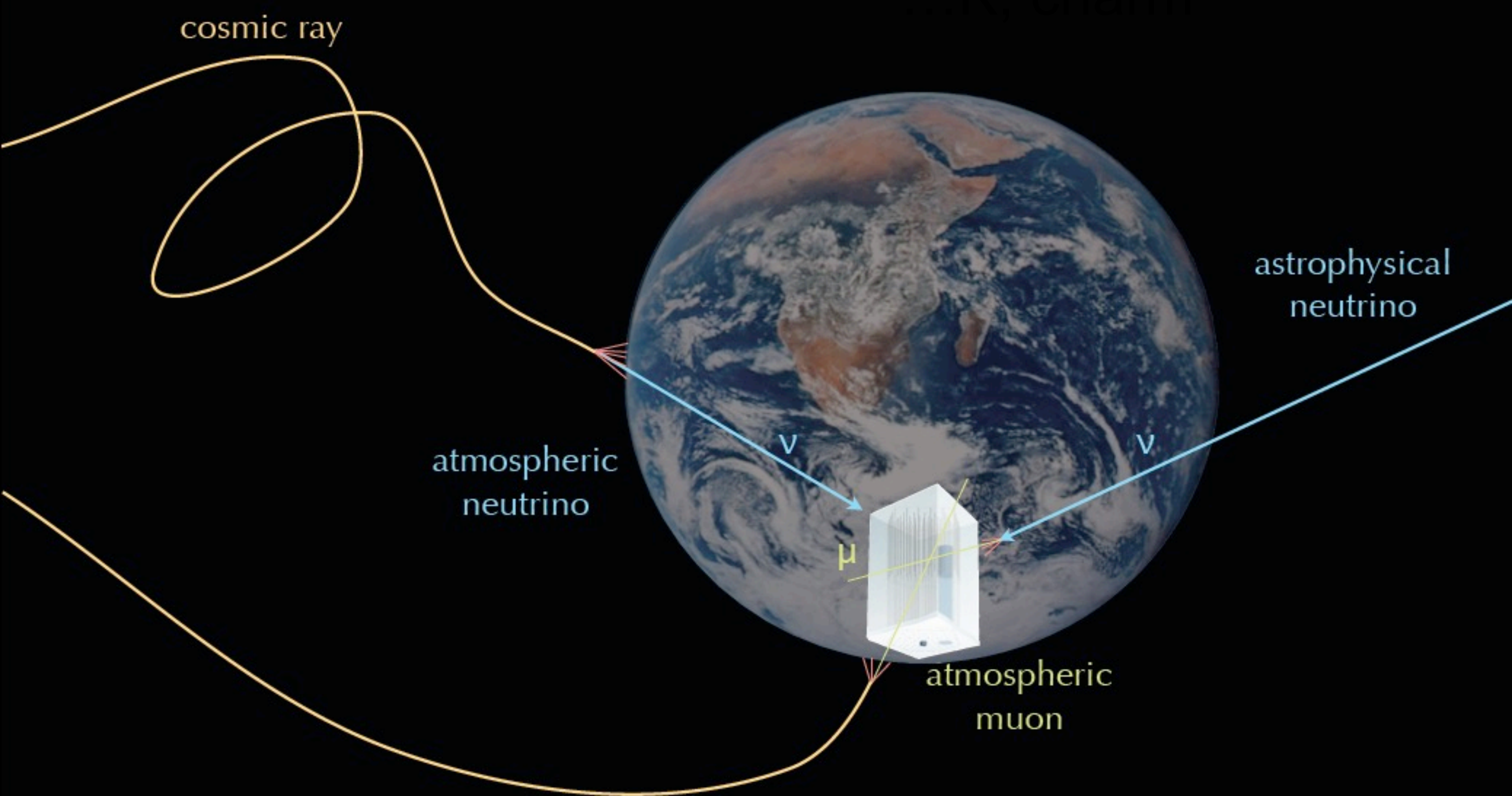
- 5160 optical sensors between 1.5 ~ 2.5 km
- 5 GeV to infinity
- < 0.4 degree muon track ~ 5 degree shower
- < 15% energy resolution

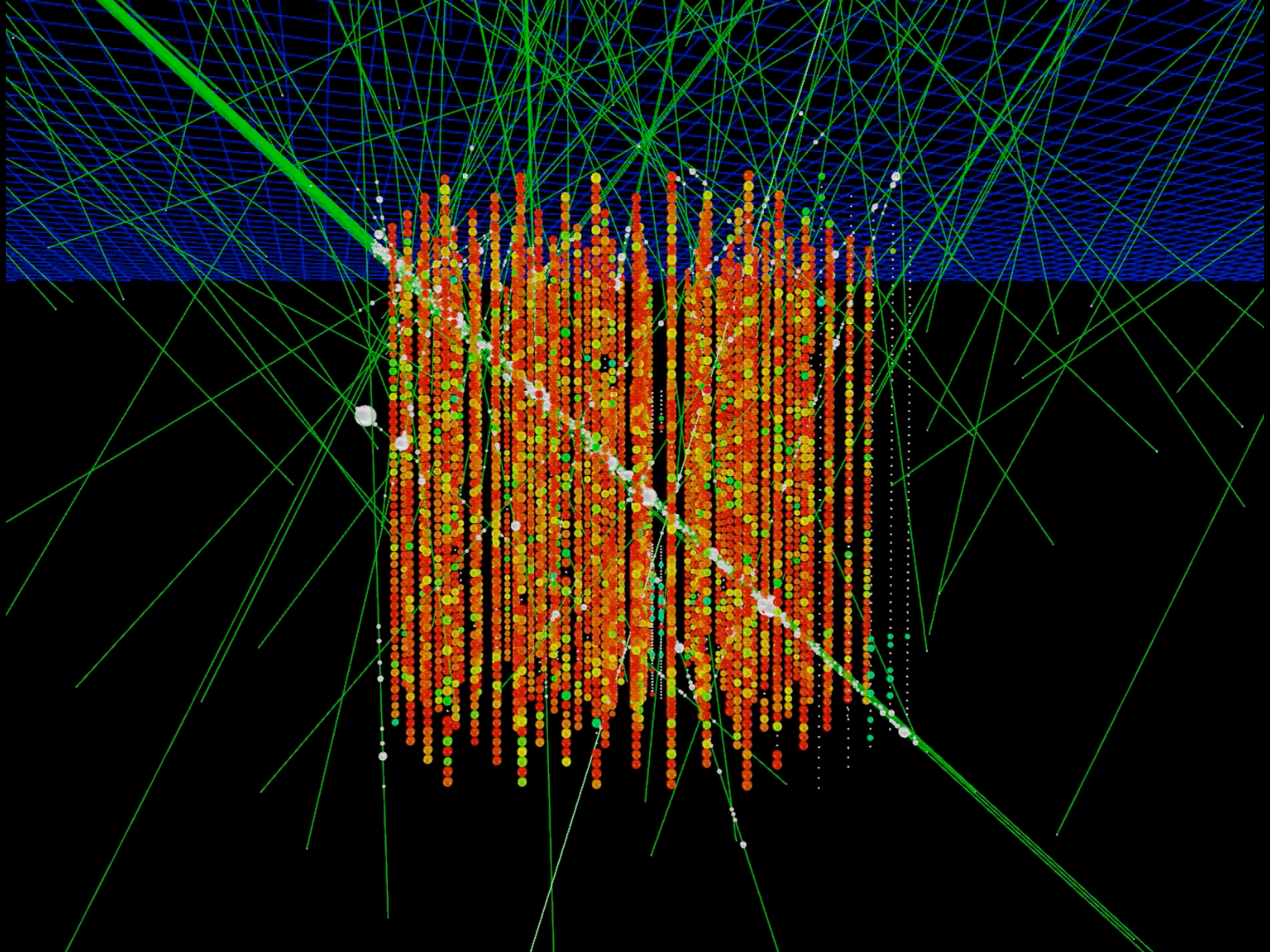


Digital Optical Module (DOM)



Signals and Backgrounds





… you looked at 10msec of data !

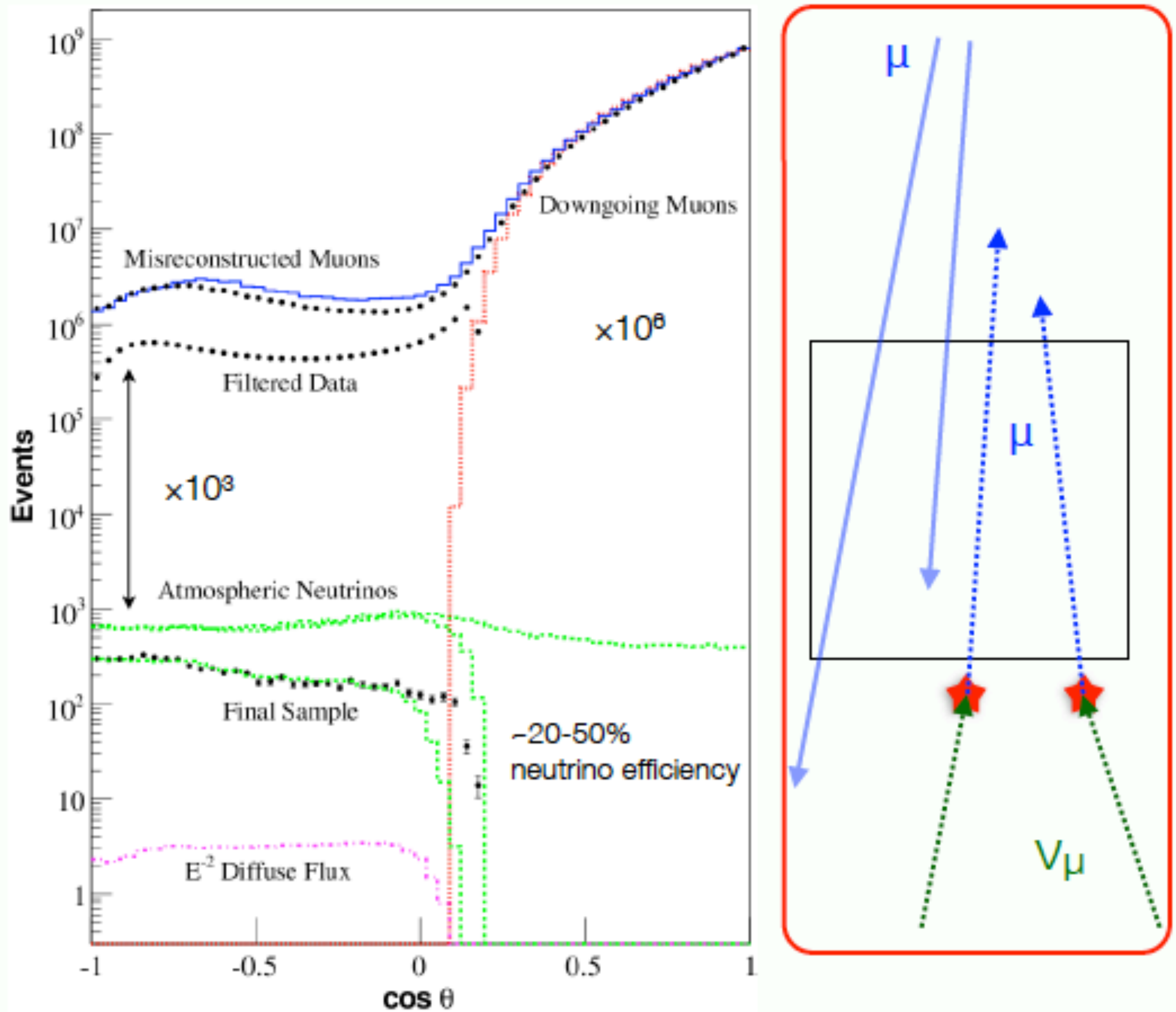
muons detected per year:

• atmospheric*	μ	~ 10^{11}
• atmospheric**	$\nu \rightarrow \mu$	~ 10^{5}
• cosmic	$\nu \rightarrow \mu$	~ 120

* 3000 per second

** 1 every 6 minutes

through-going
(tracks)



selection cuts for on-line numu extraction

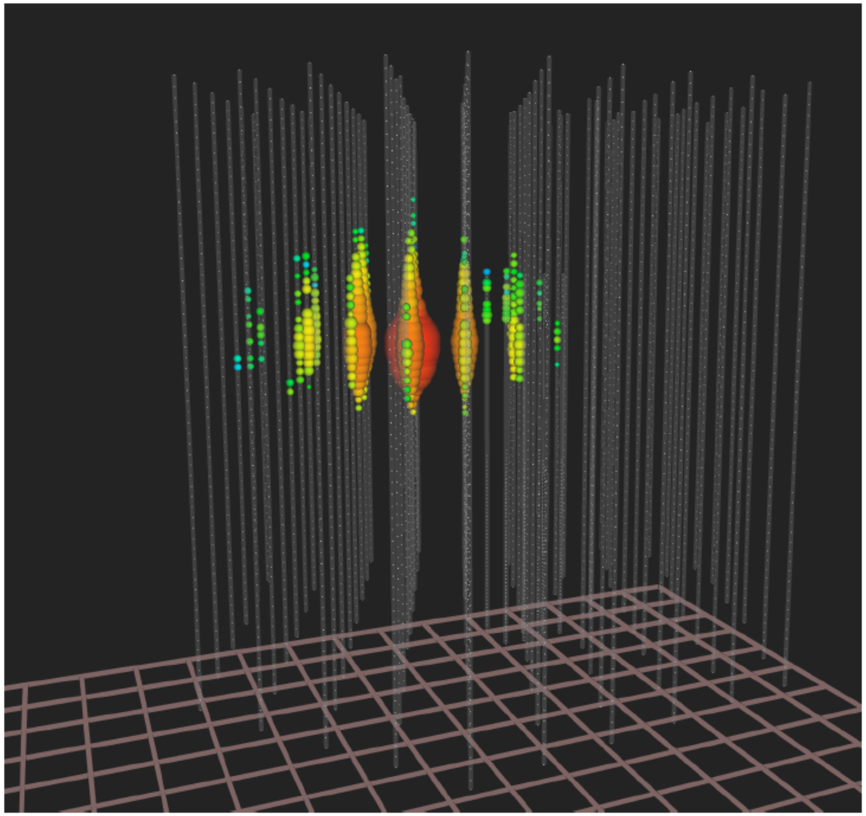
Cut Level	Selection criterion	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	$\cos\theta_{\mathrm{MPE}} \leq 0$	1010.5	1523.81	7.166	6.23
1	$\mathrm{SLogL}(3.5) \leq 8$	282.49	504.44	5.826	5.62
2	$N_{\mathrm{Dir}} \geq 9$	8.839	22.01	3.076	4.06
3	$((\cos\theta_{\mathrm{MPE}} > -0.2)$ AND $(L_{\mathrm{Dir}} \geq 300$ m$)$ OR $(\cos\theta_{\mathrm{MPE}} \leq -0.2)$ AND $(L_{\mathrm{Dir}} \geq 200$ m$))$	1.124	4.30	2.313	3.69
4	$\Delta_{\mathrm{Split/MPE}} < 0.5$	0.100	2.15	1.899	3.26
5	$((\cos\theta_{\mathrm{MPE}} \leq -0.07)$ OR $((\cos\theta_{\mathrm{MPE}} > -0.07)$ AND $(\Delta_{\mathrm{SPE/Bayesian}} \geq 35)))$	0.080	2.08	1.880	3.25
6	$((\cos\theta_{\mathrm{MPE}} \leq -0.04)$ OR $((\cos\theta_{\mathrm{MPE}} > -0.04)$ AND $(\Delta_{\mathrm{SPE/Bayesian}} \geq 40)))$	0.075	2.06	1.875	3.24

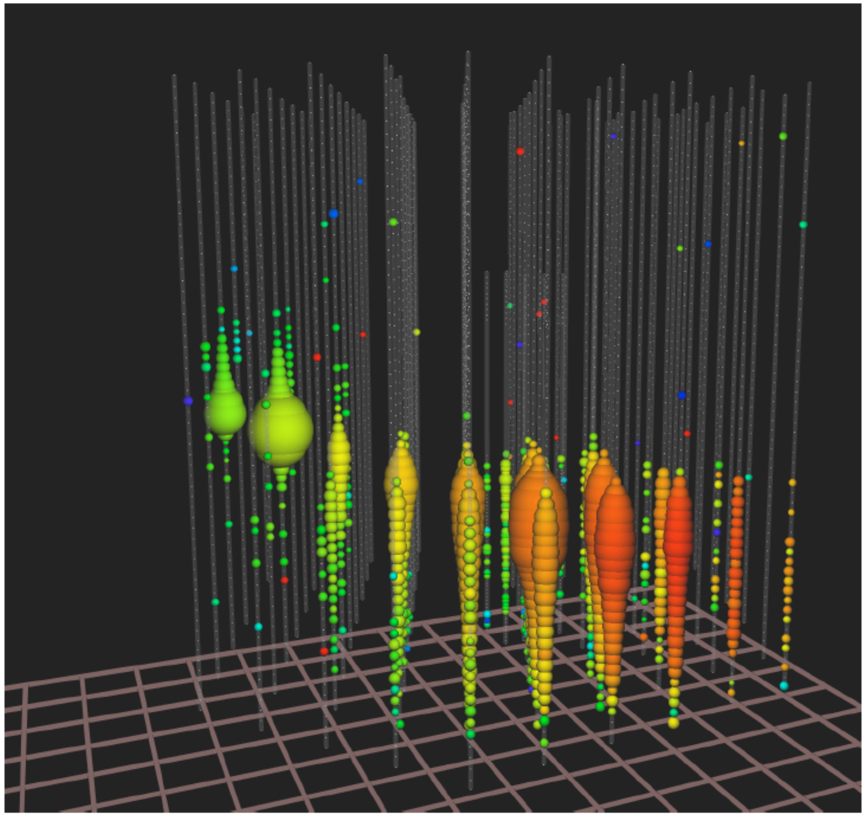
Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction by Honda [71], but atmospheric-muon rate is calculated from CORSIKA simulations. The event rate for IceCube data stream corresponds to the total livetime of 332.36 days. The astrophysical neutrino flux is estimated assuming $dN/dE = 1 \cdot 10^{-8}$ GeVcm^{-2}s$^{-1}(\frac{E}{\mathrm{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)

…as opposed to 35 in original AMANDA publication

neutrinos interacting
inside the detector

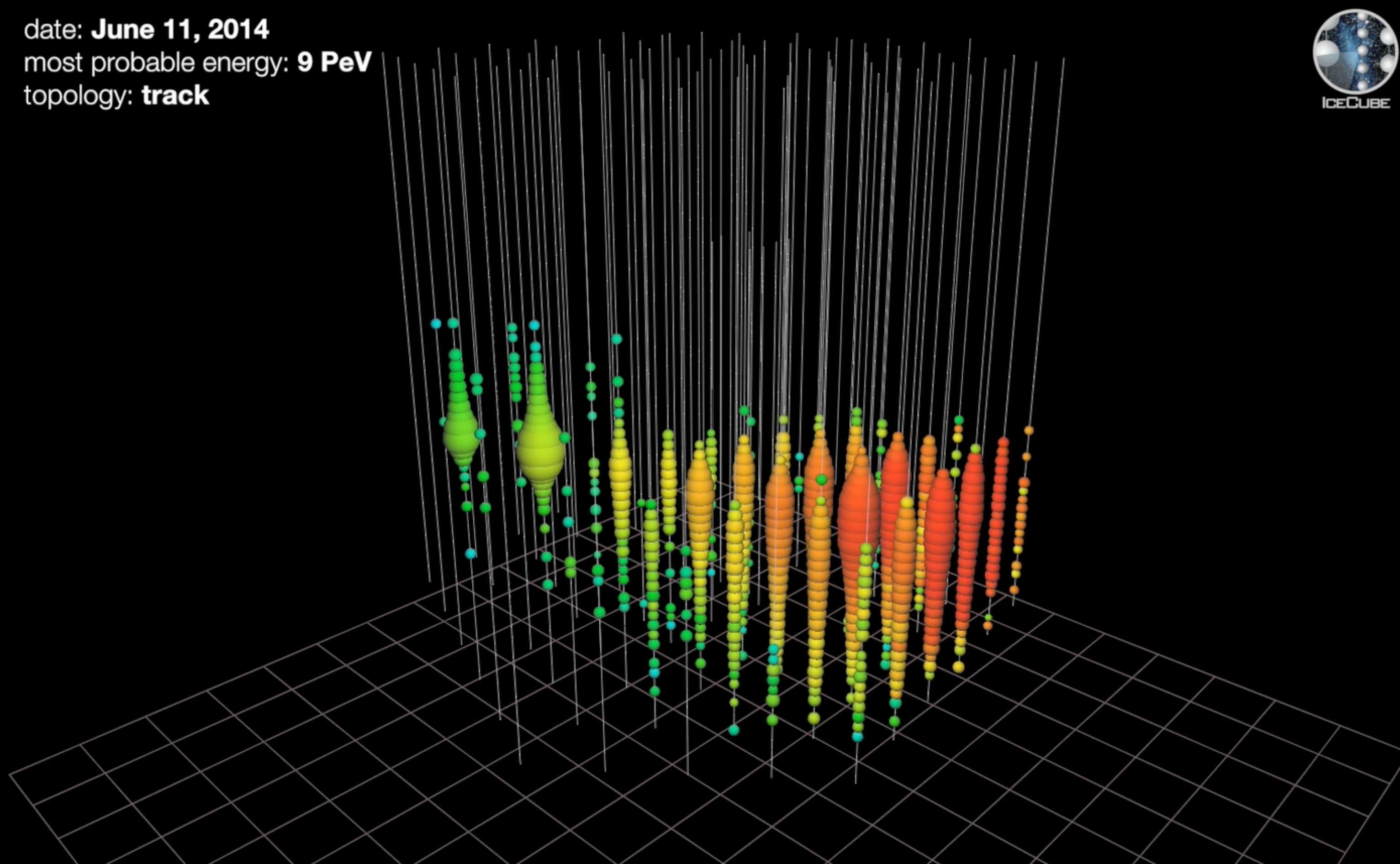
muon neutrinos
filtered by the Earth



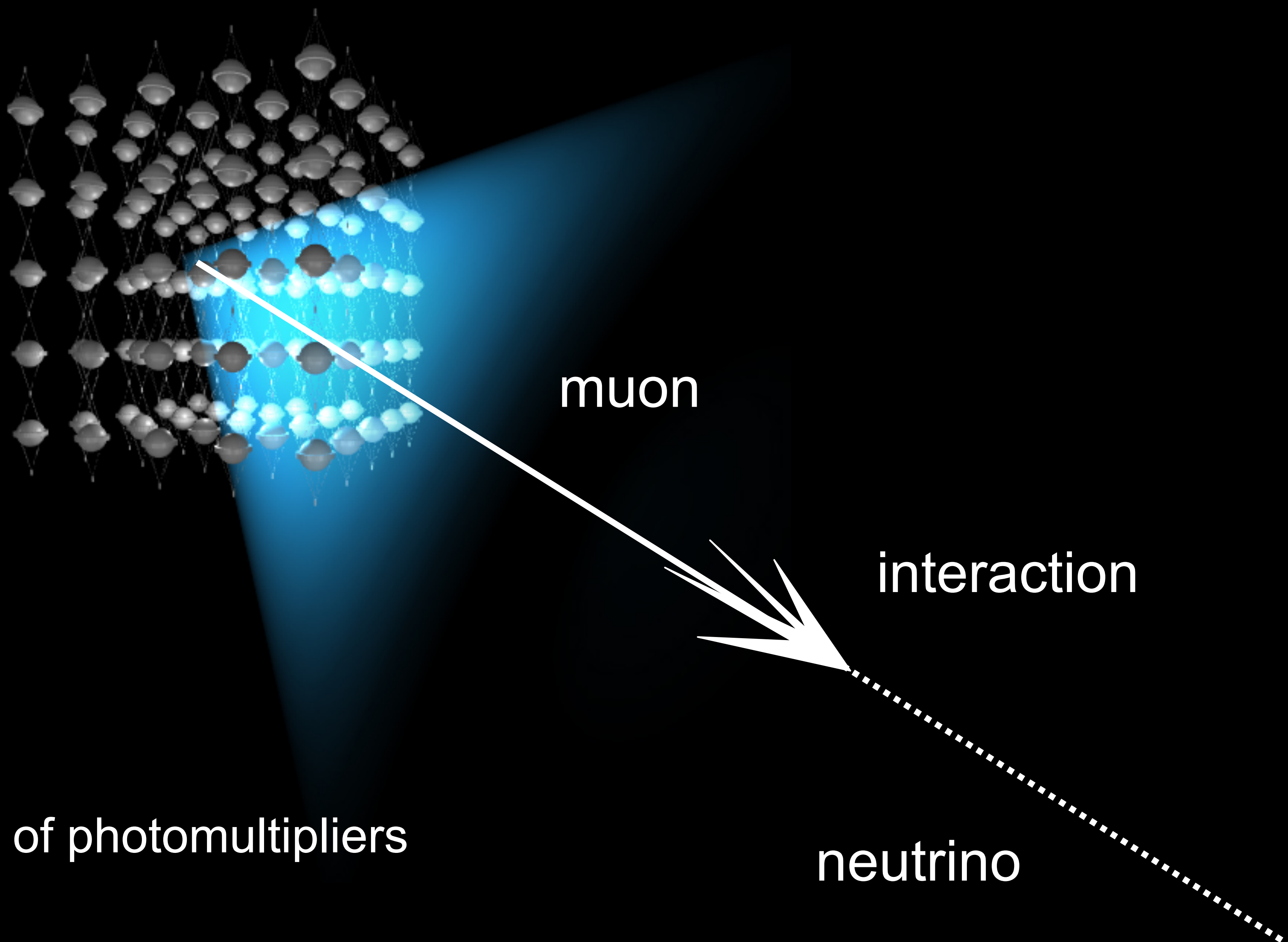


total energy measurement
all flavors, all sky

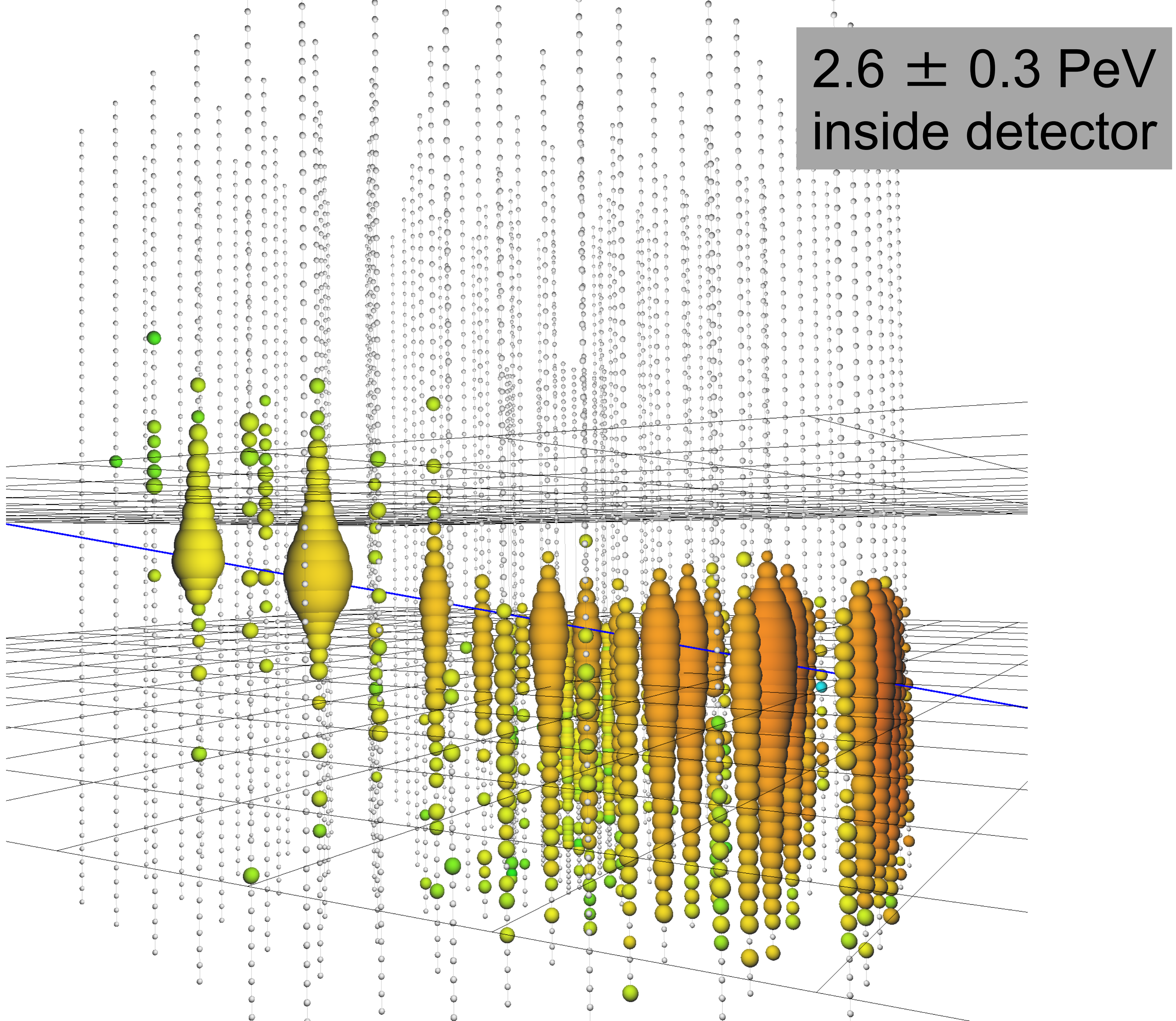
astronomy: angular resolution
superior (<0.4°)



date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube

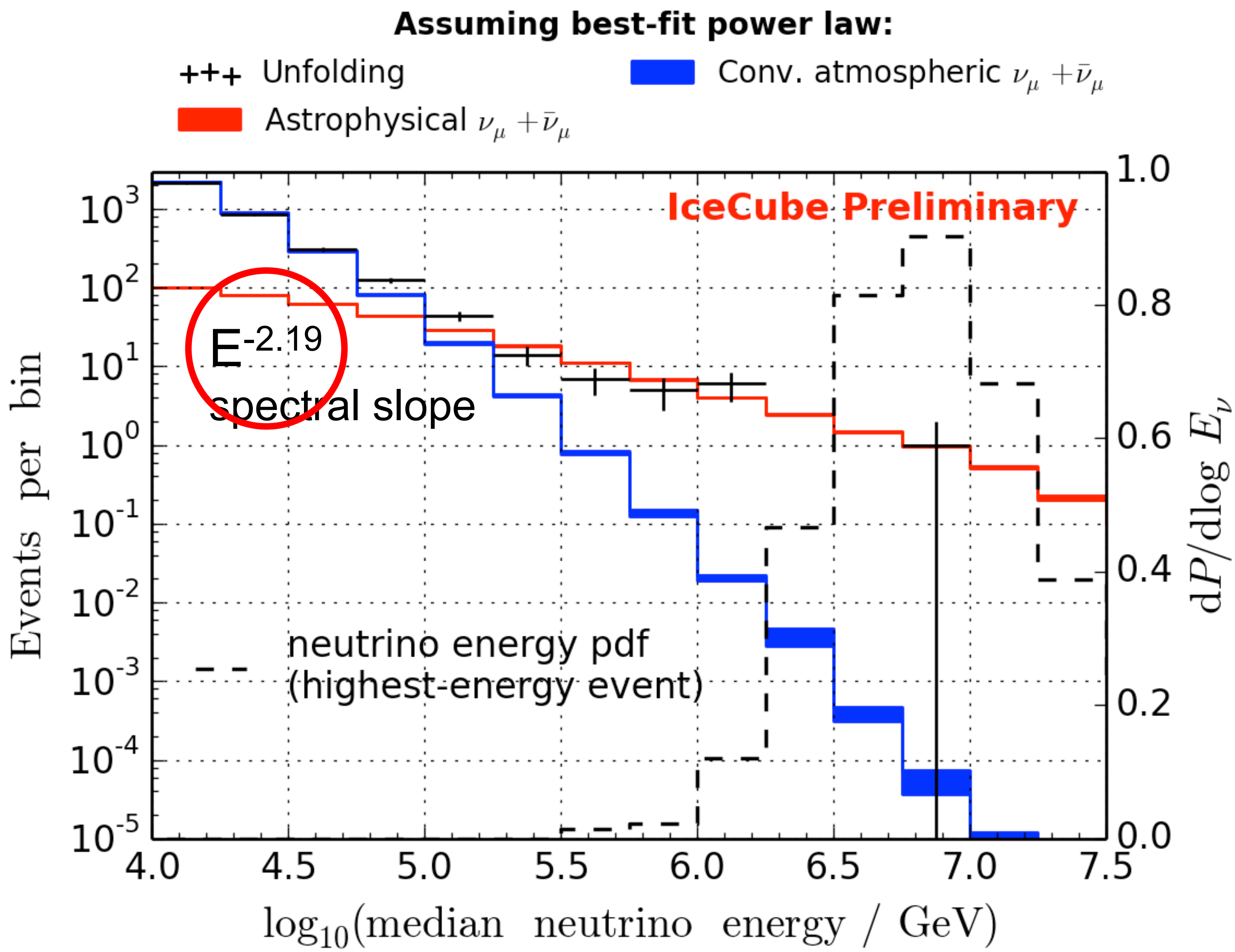


• lattice of photomultipliers


2.6 ± 0.3 PeV
inside detector

~ 550 cosmic neutrinos in a background of ~340,000 atmospheric

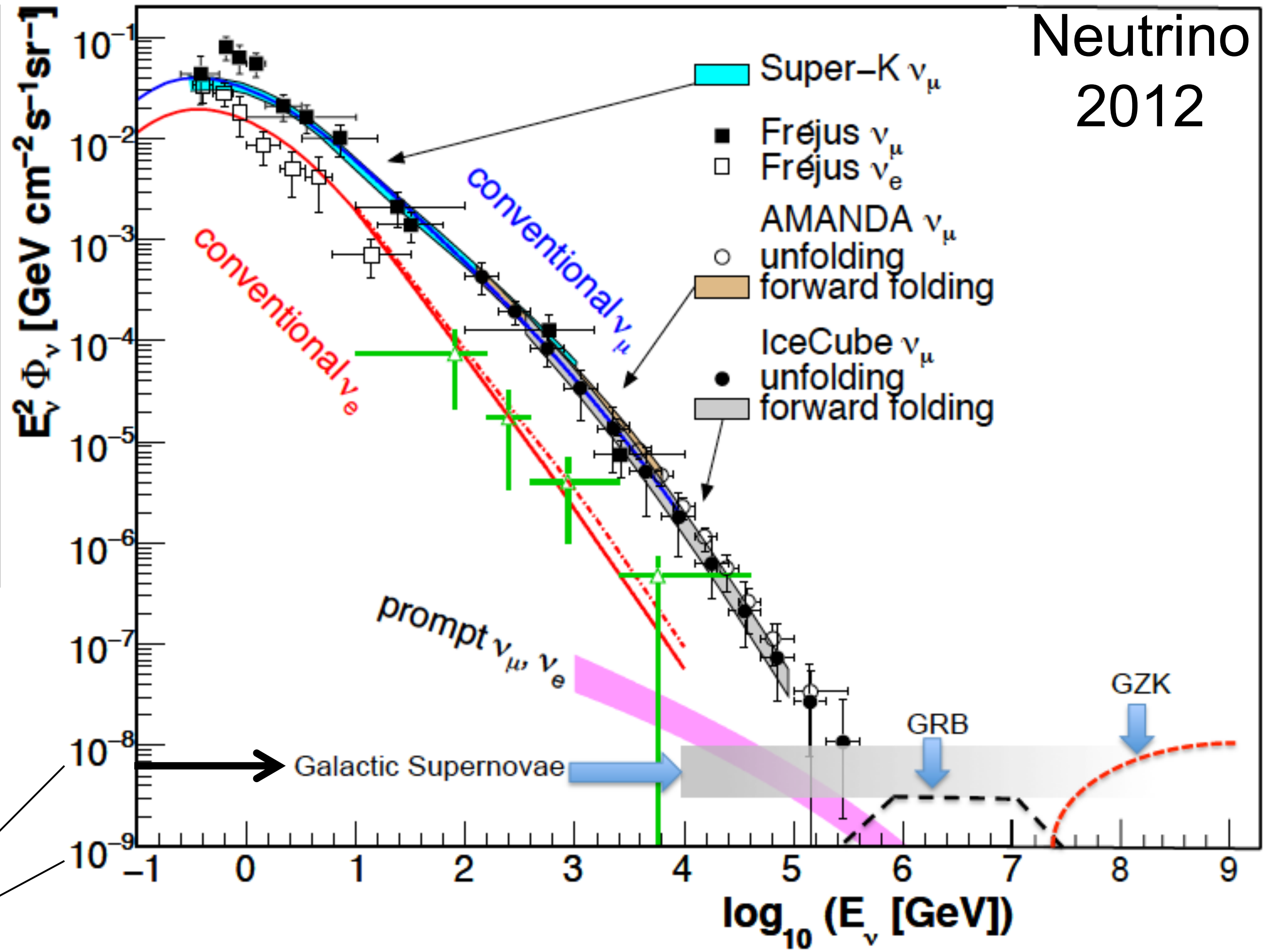
atmospheric background: less than one event/deg^2/year



above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

$dN/dE \sim E^{-2}$



10—100 events per year for fully efficient detector

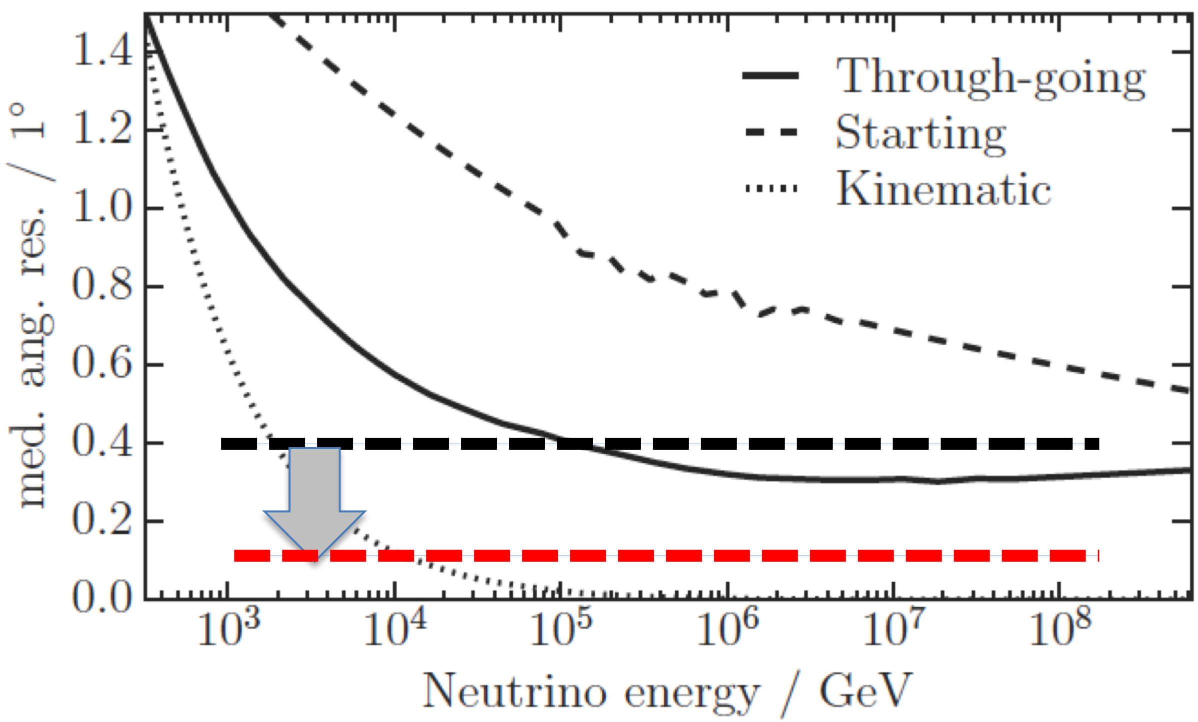
atmospheric

cosmic

100 TeV

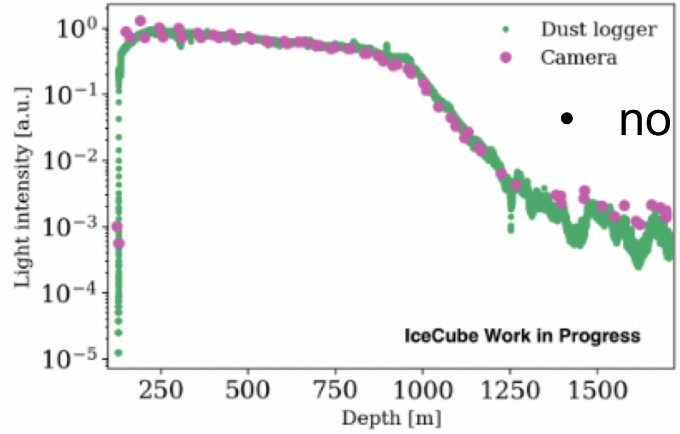
astronomy happens here:

- through-going muons with resolution 0.2~0.4^0
- goal 0.1^0

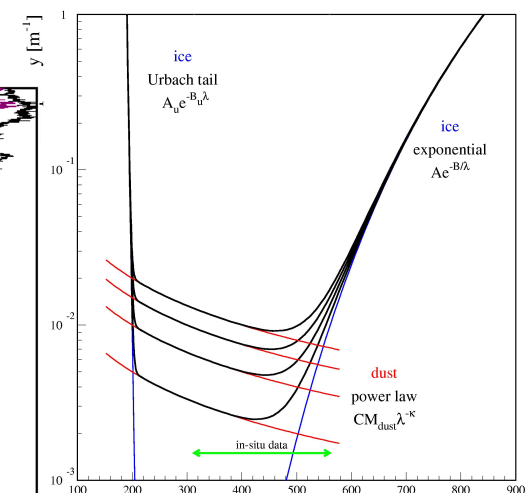


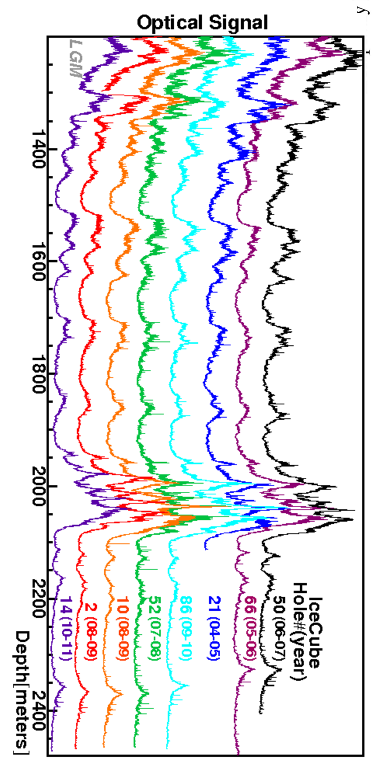
ice: step by step

- hole ice ?

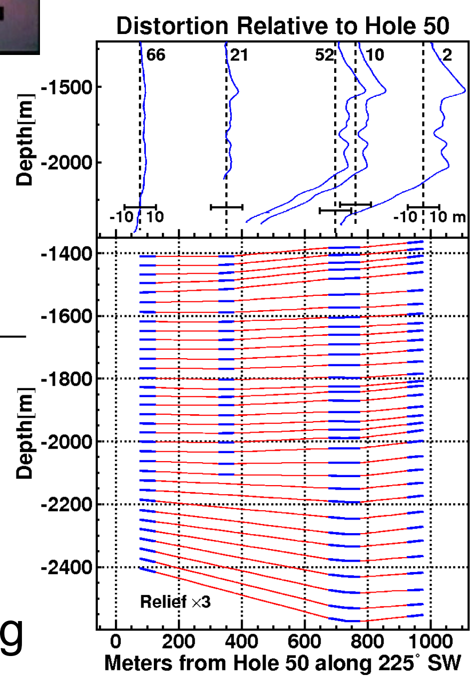


- no air bubbles/hydrates below 1350 m
- > 100 m absorption length limited by dust
- ice layers

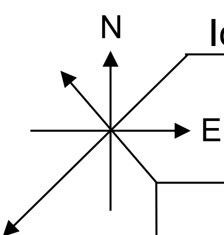




- tilted ice layers



- some birefringence ?

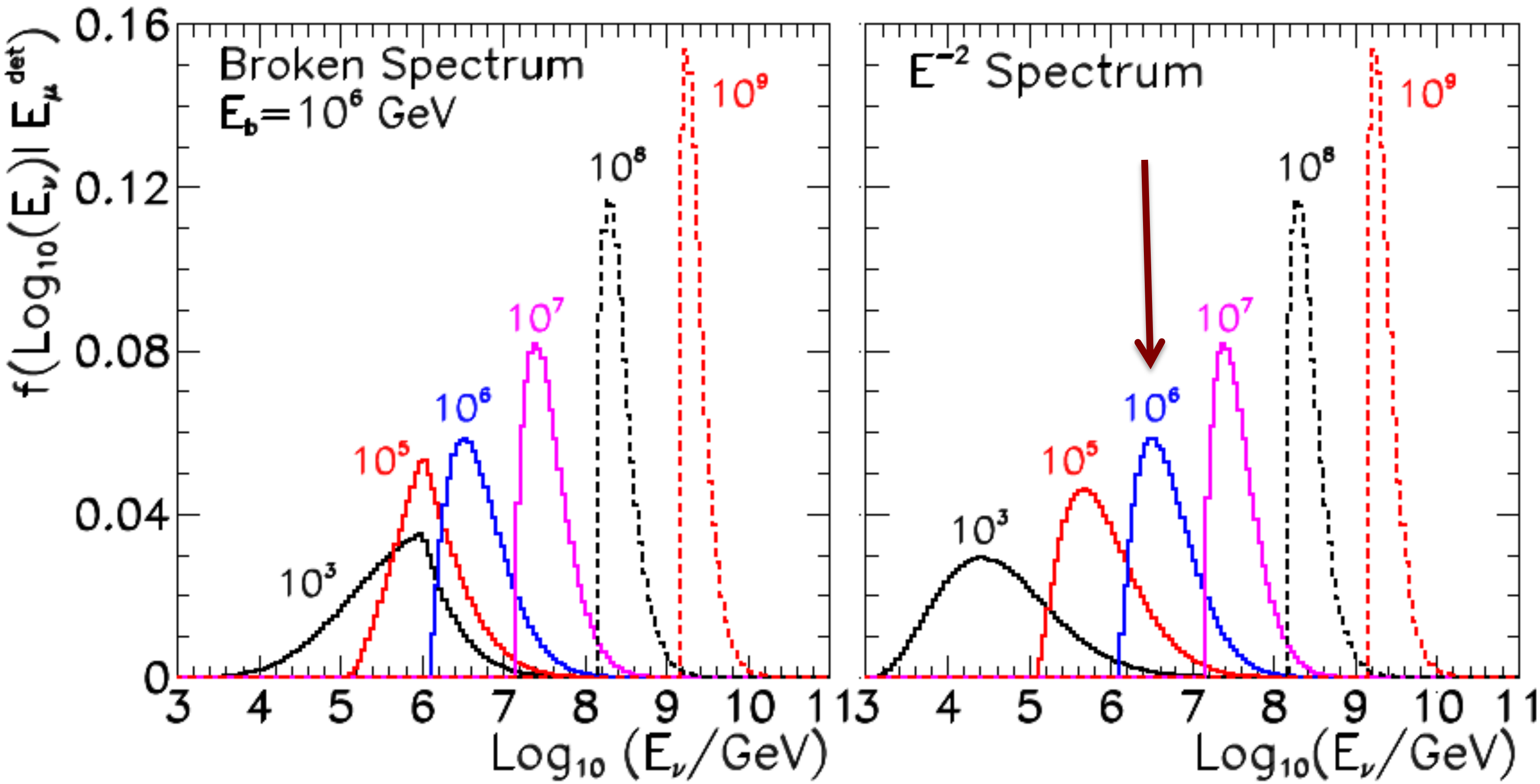


Ice Layer tilt direction
225° SW

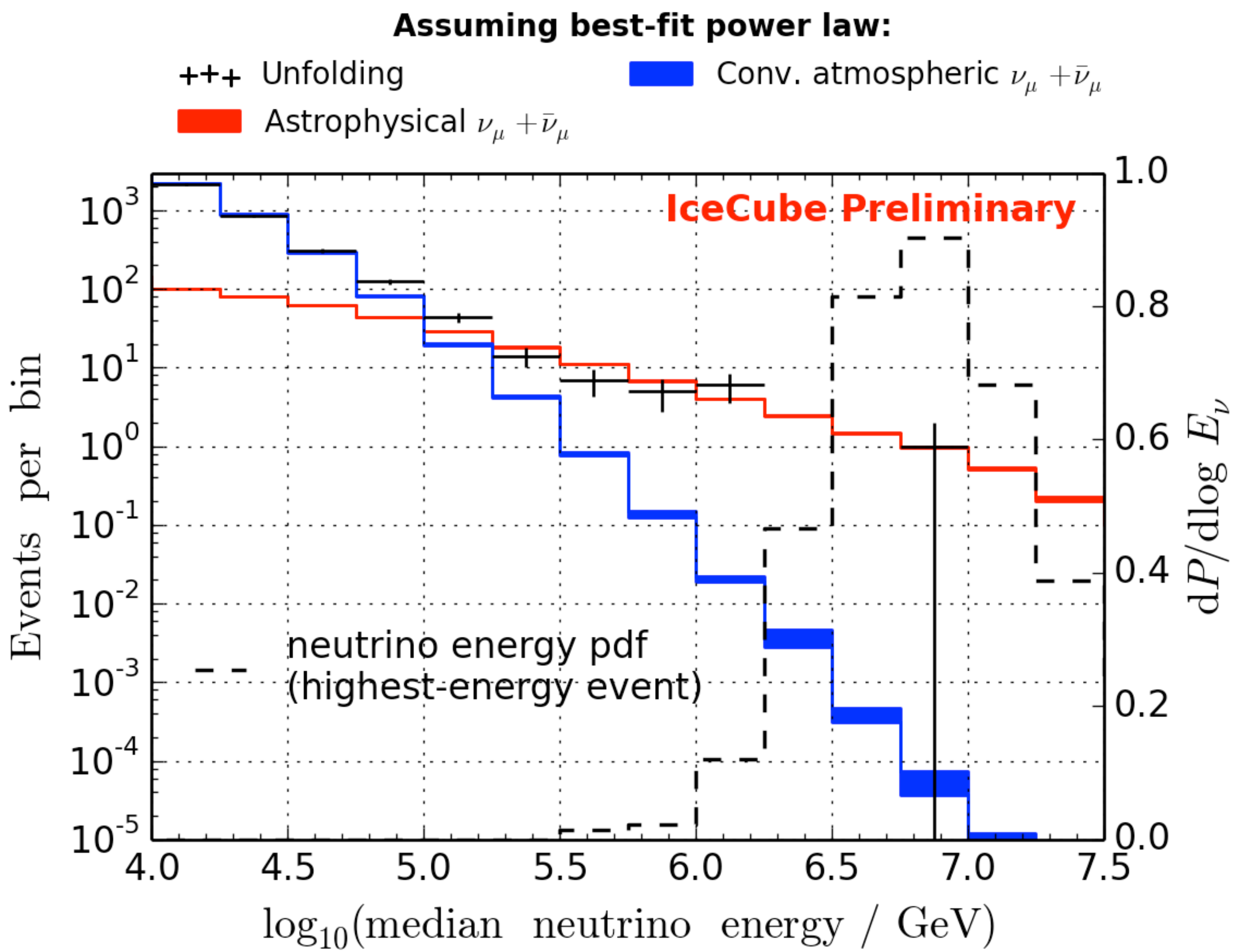
Ice flow direction
41° NW

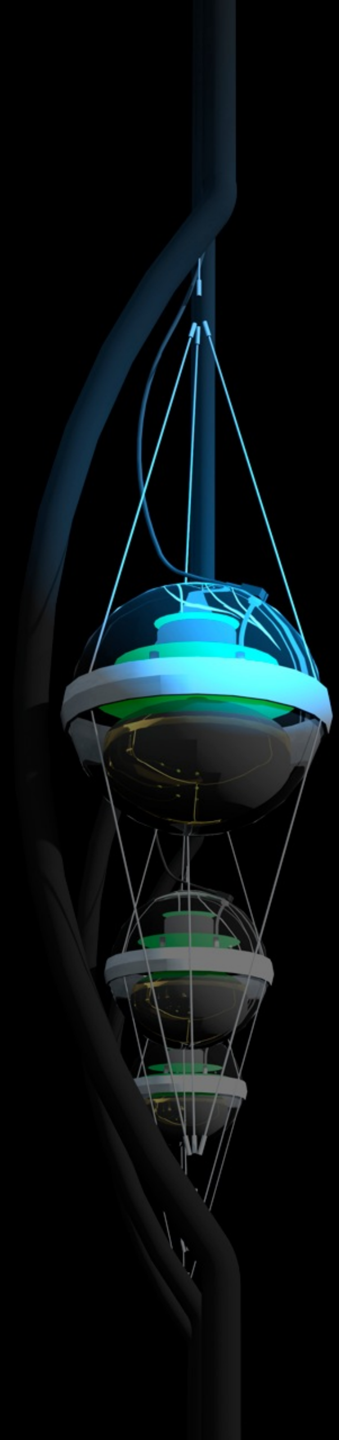
- anisotropy
~8% less scattering
41° NW

distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube



muon neutrinos through the Earth → 5.6 sigma





IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

cosmic rays interact with the microwave background

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

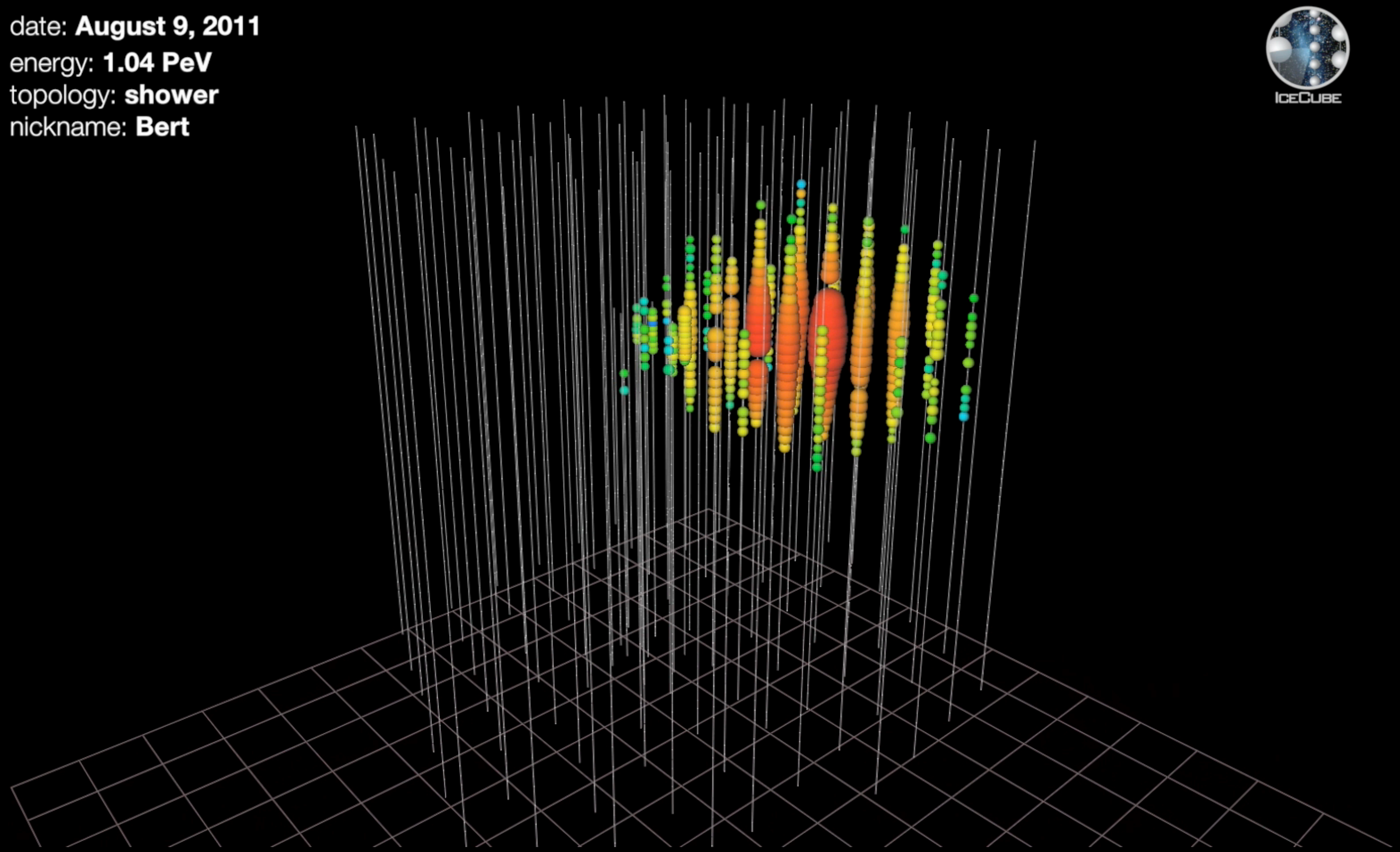
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

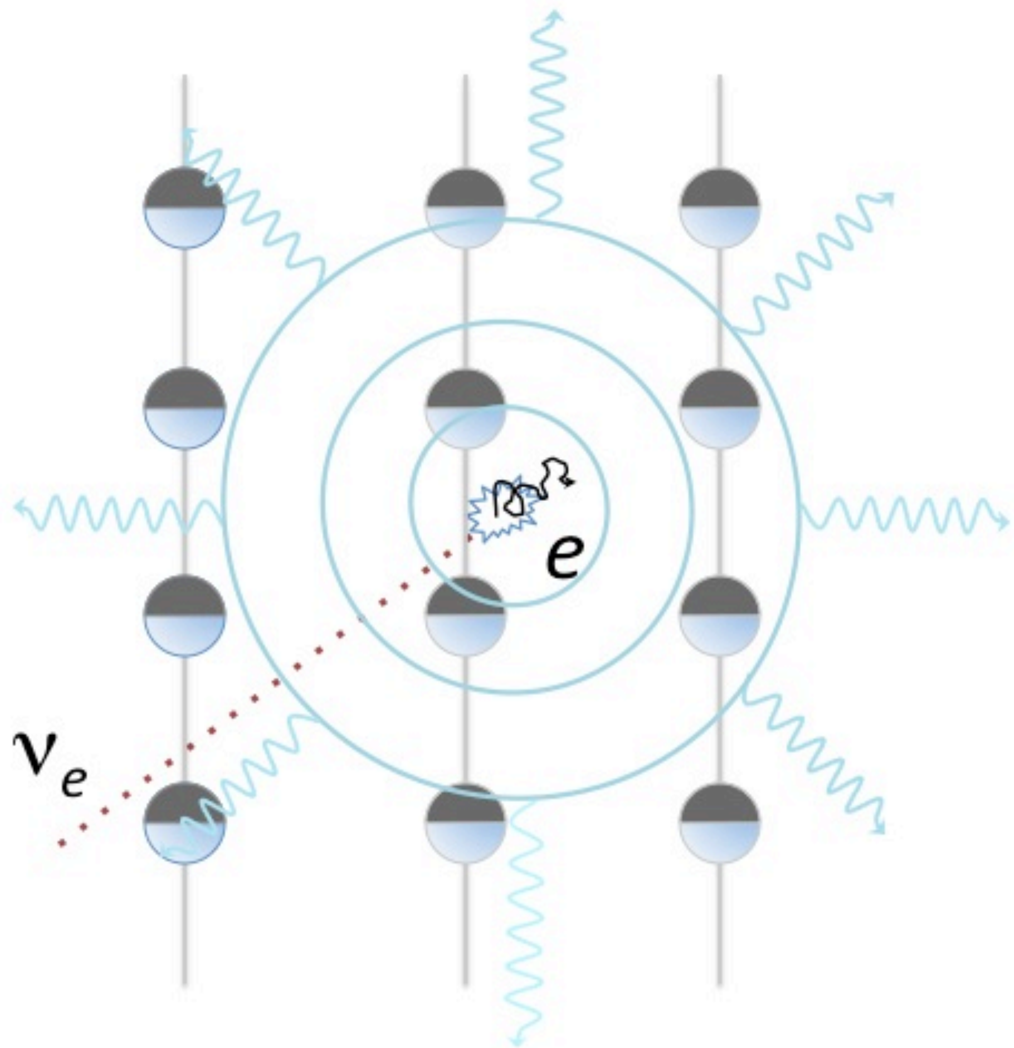
GZK neutrino search: two neutrinos with > 1,000 TeV

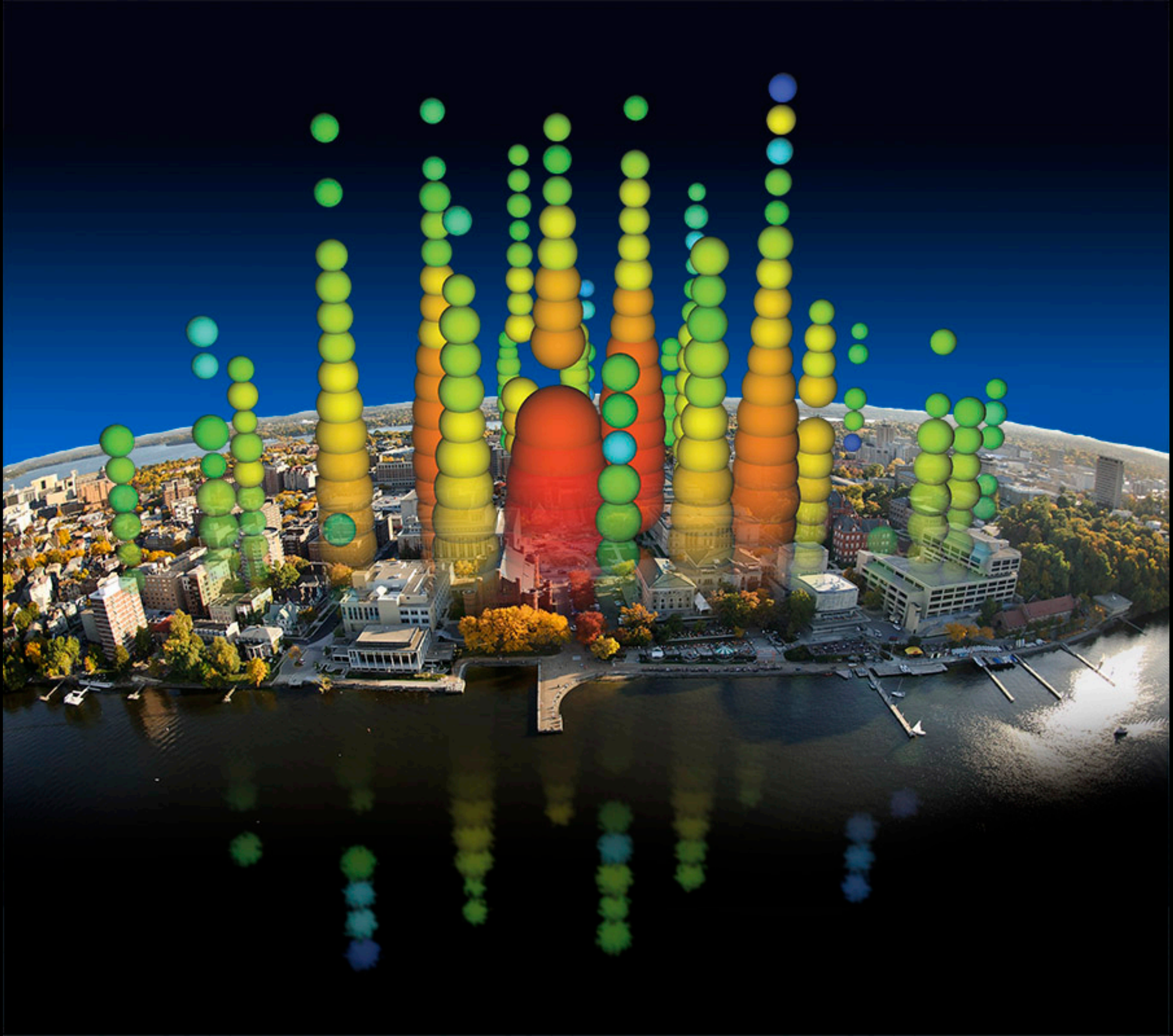


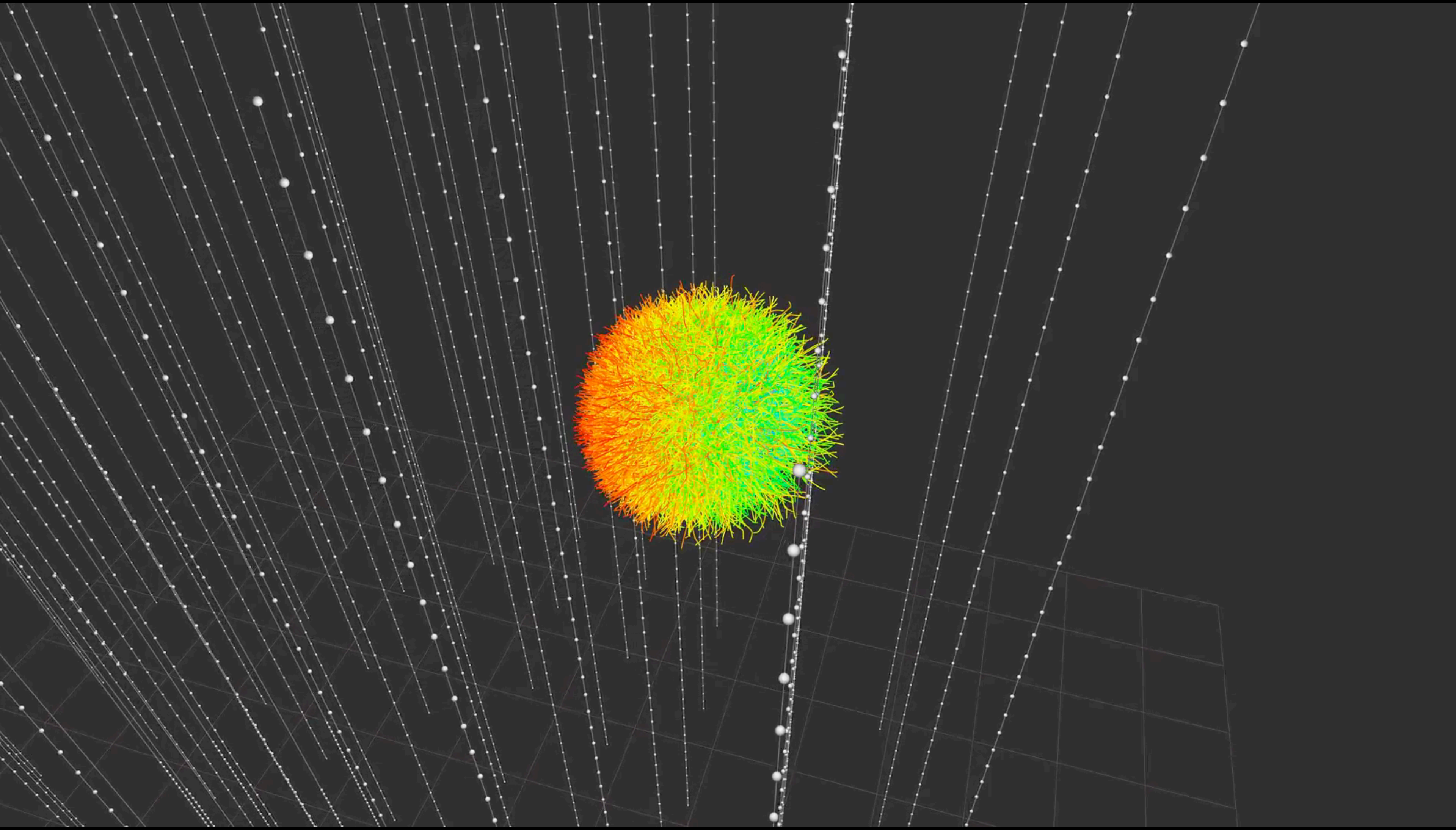
electron showers versus muon tracks

PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

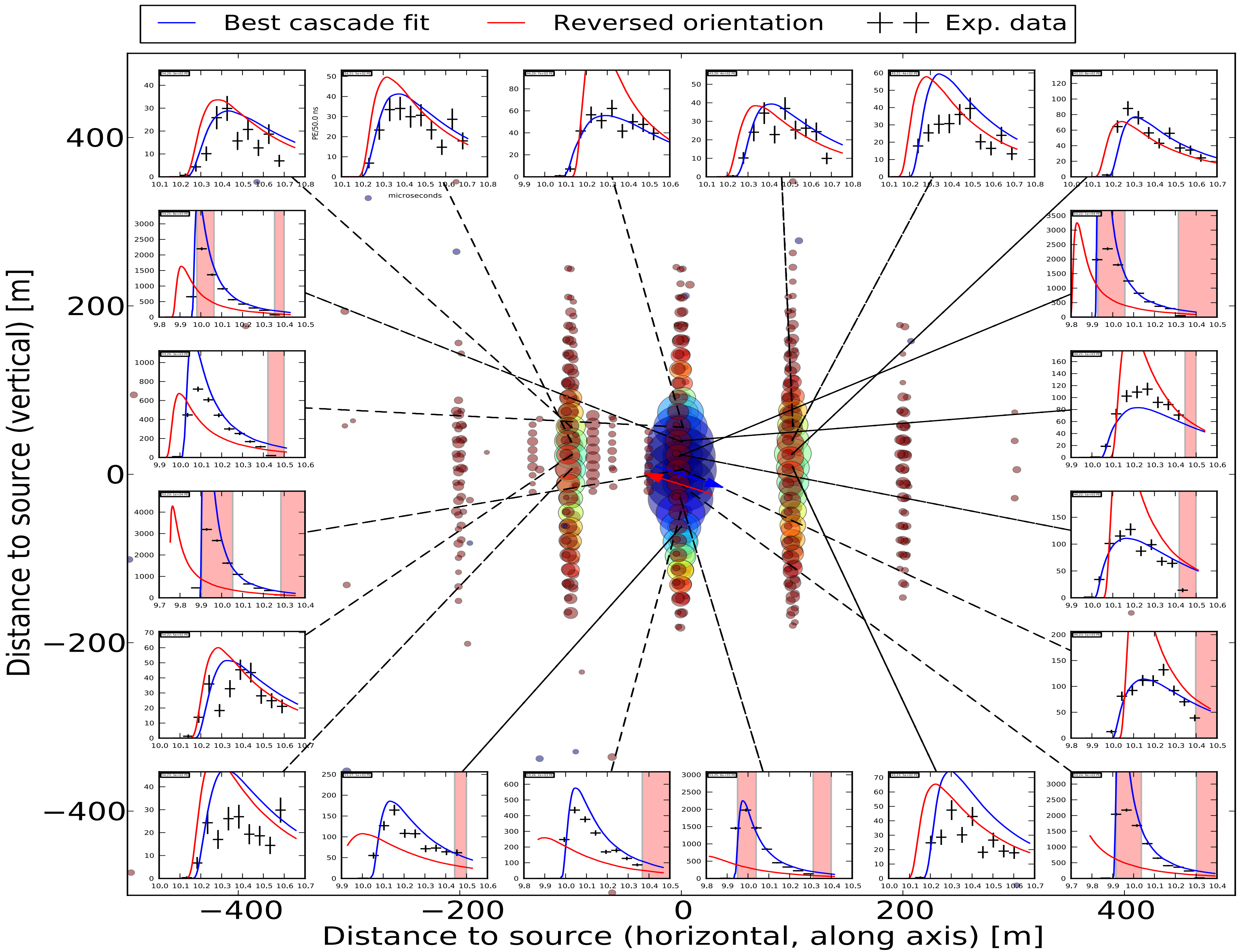






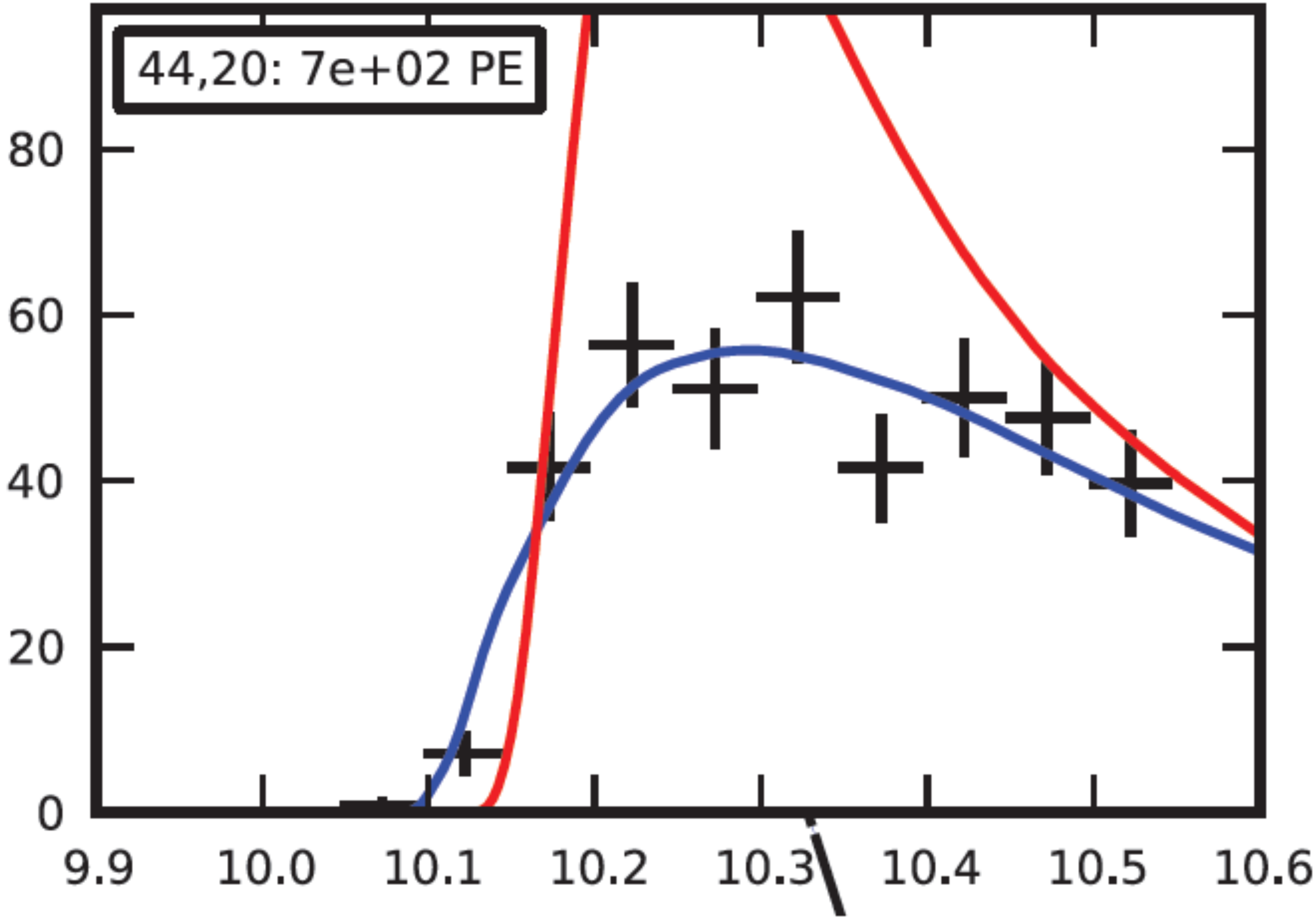
size = energy

color = time = direction

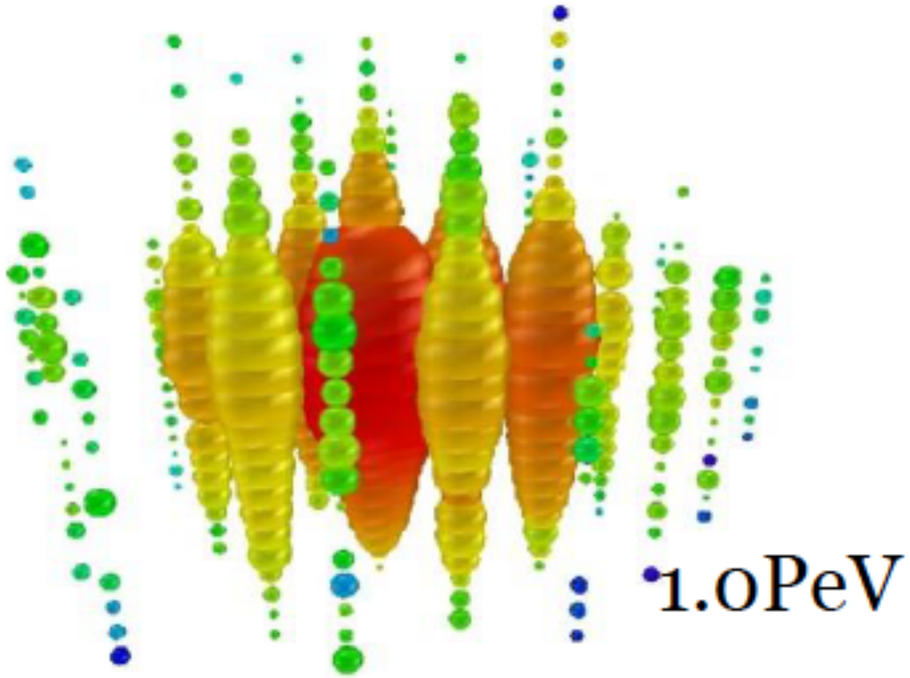


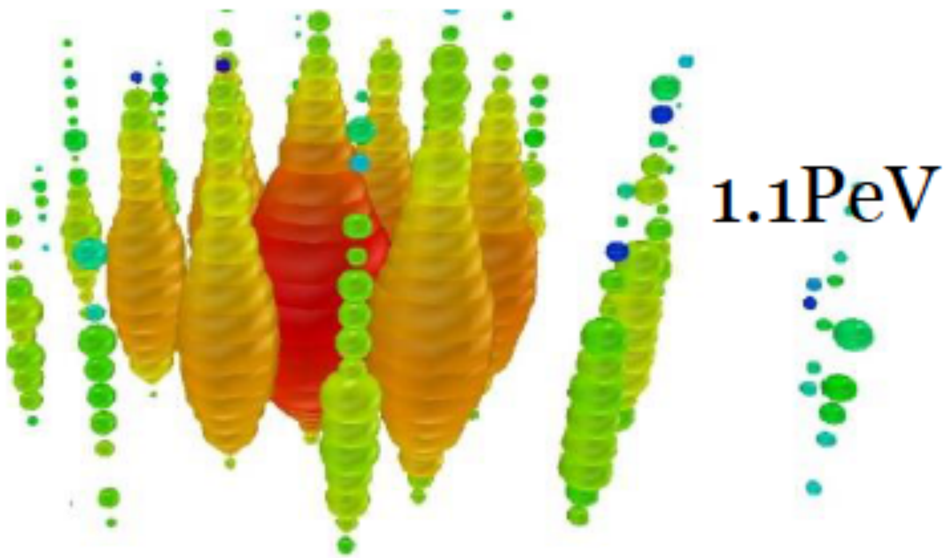
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction



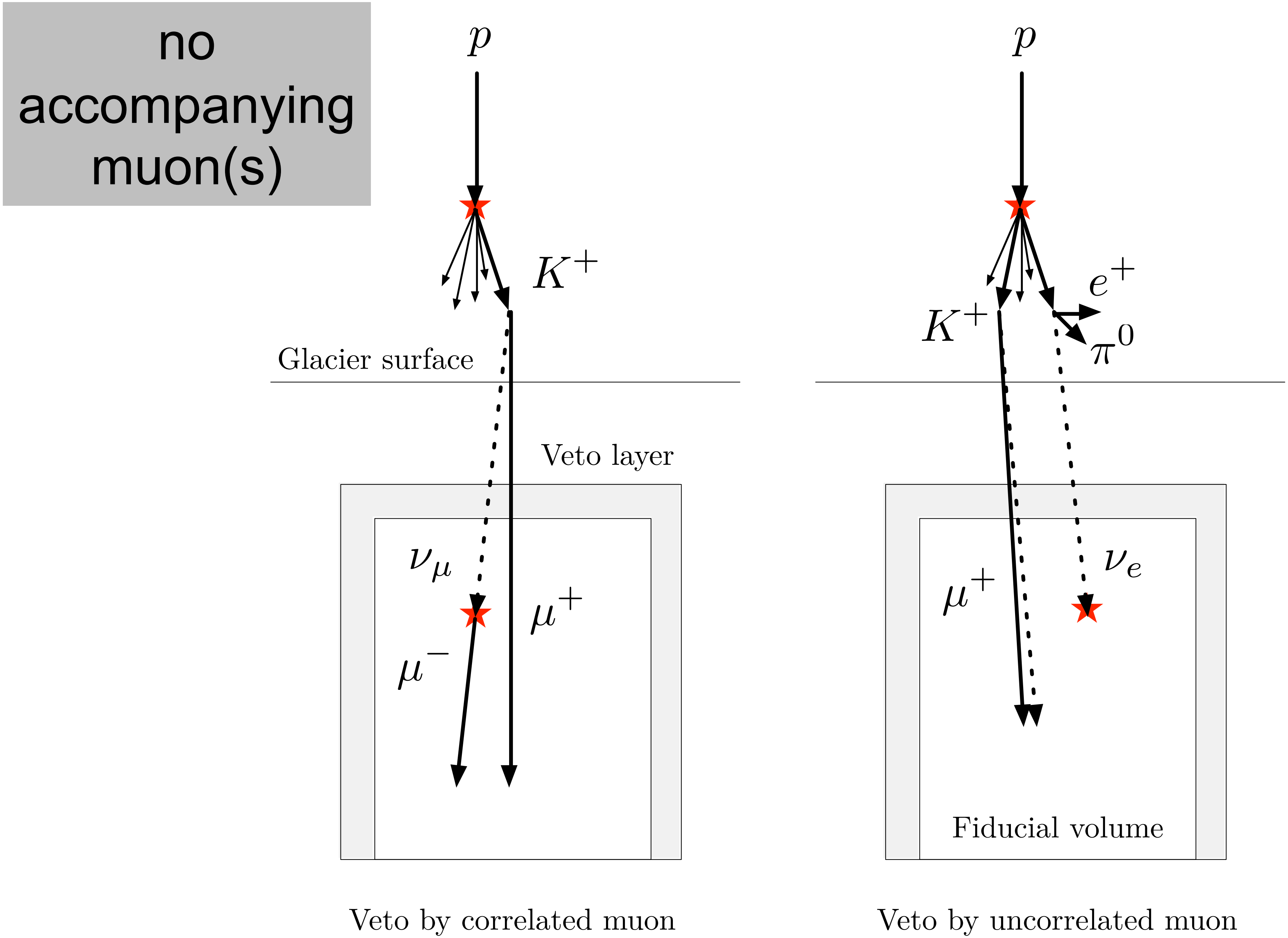


• energy

1,041 TeV
1,141 TeV
(15% resolution)

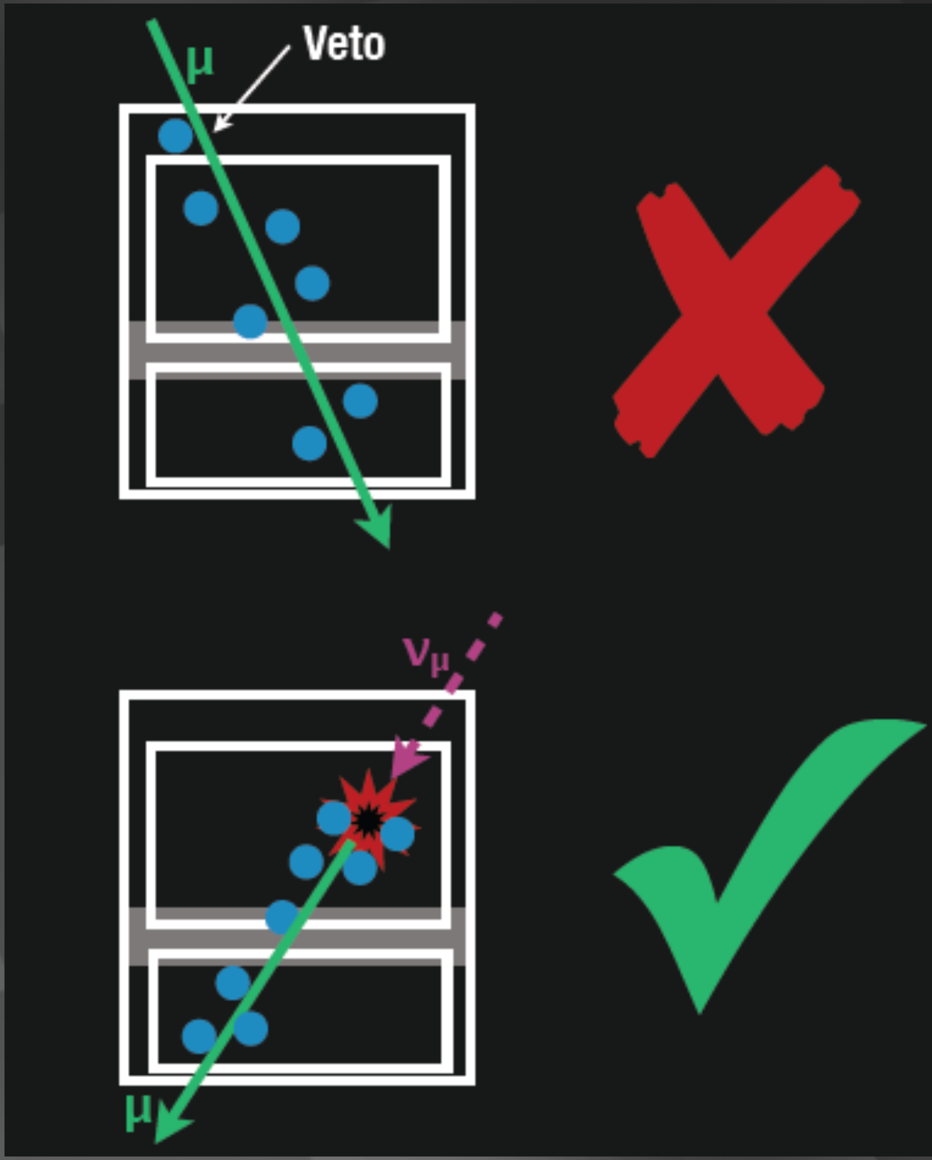
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ flux at present level of diffuse limit

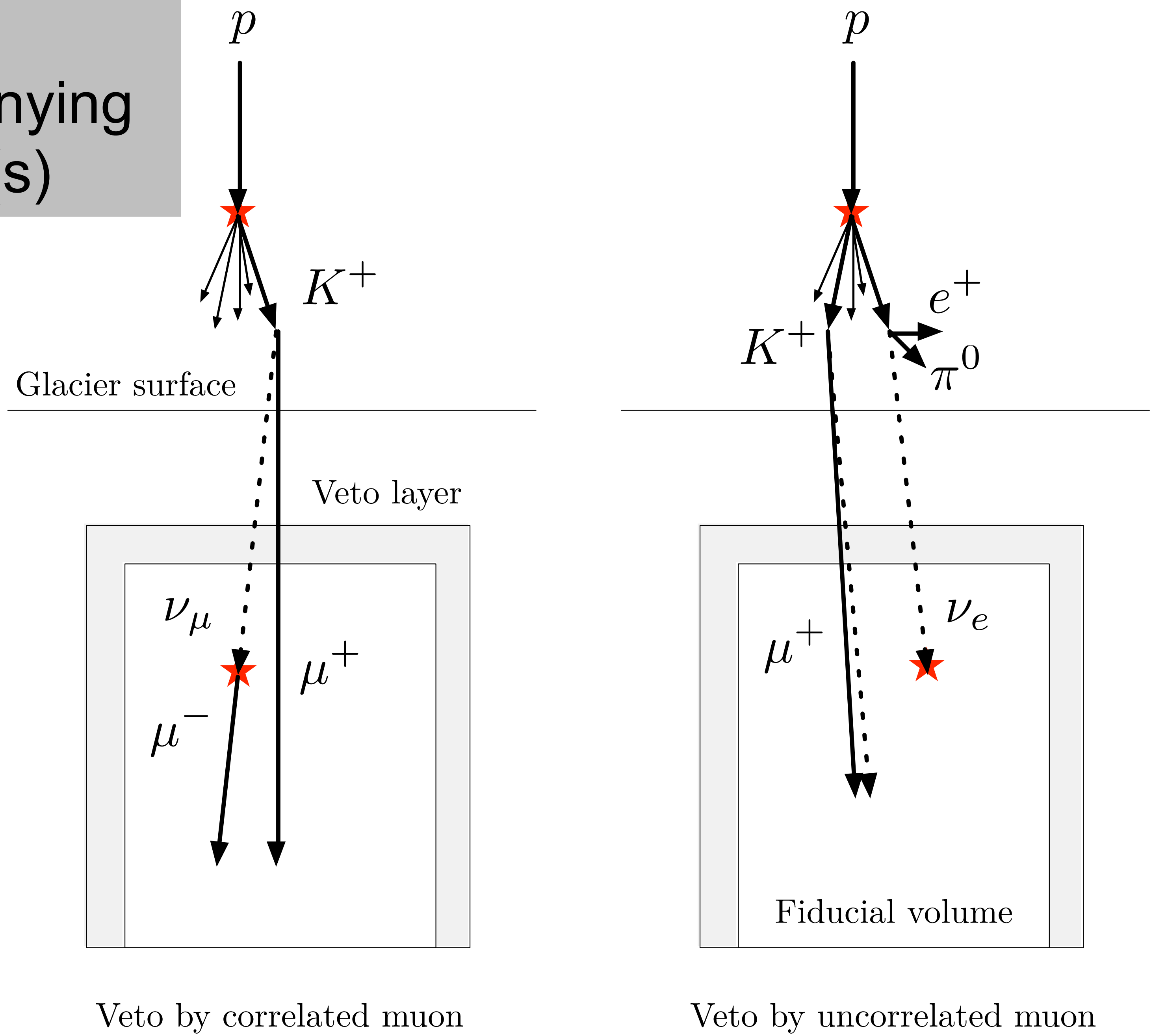

no accompanying muon(s)
p
K+
Glacier surface
Veto layer
νμ
μ+
μ−
Veto by correlated muon
p
e+
K+
π0
νe
μ+
Fiducial volume
Veto by uncorrelated muon

events starting inside the detector

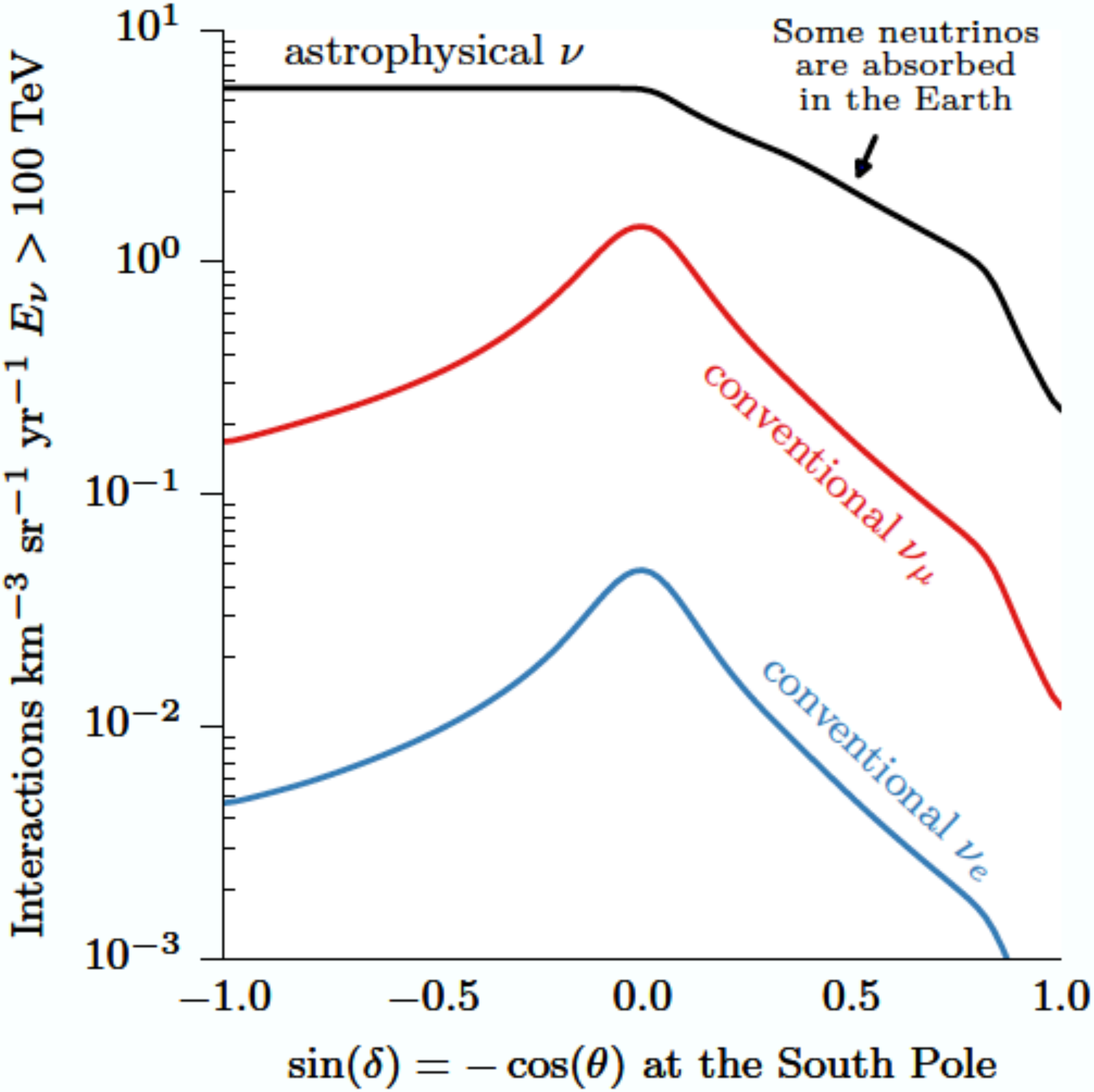
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for *atmospheric* neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



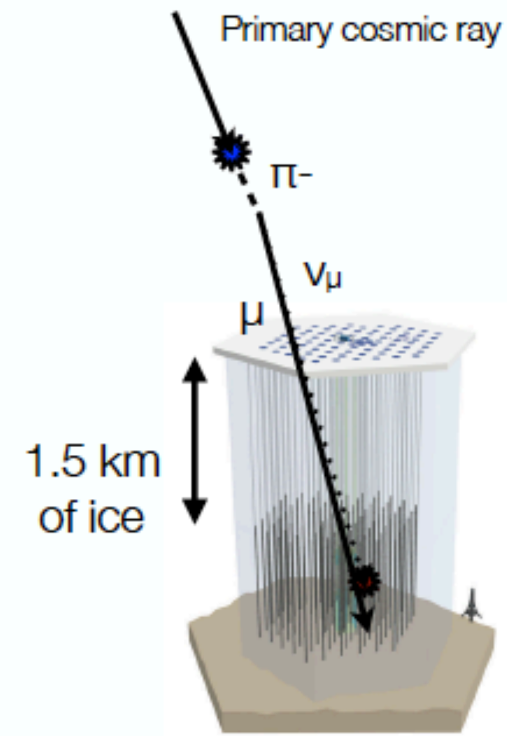
no accompanying muon(s)



Atmospheric neutrino self-veto



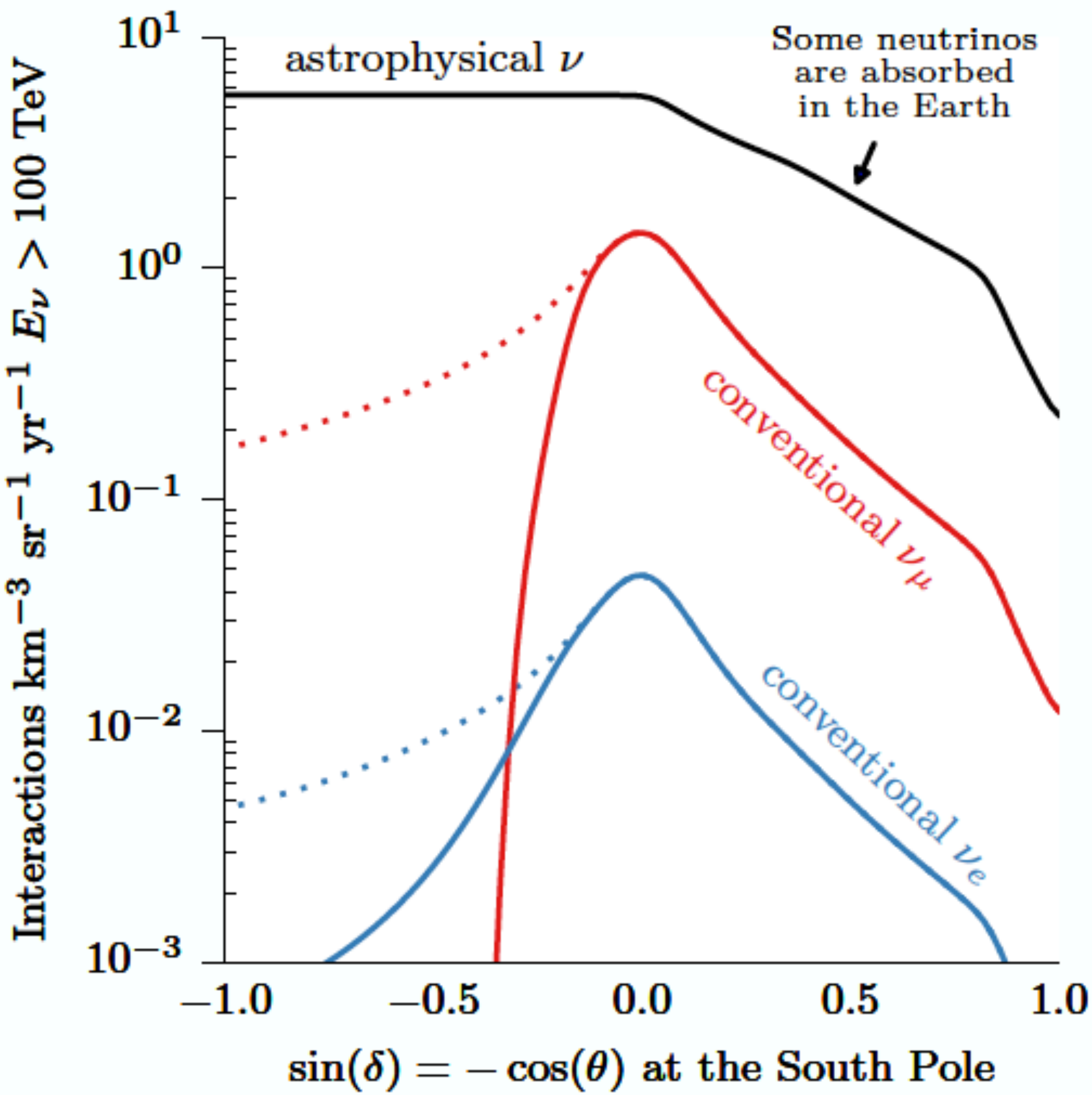
An active muon veto removes down-going atmospheric neutrinos.



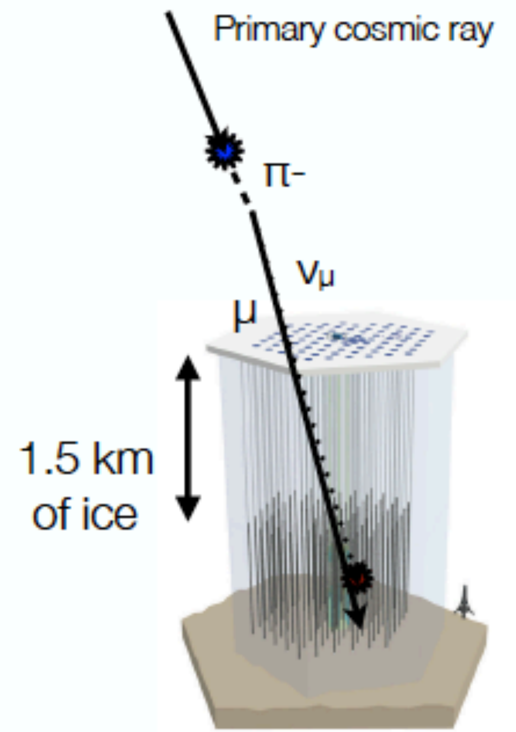
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



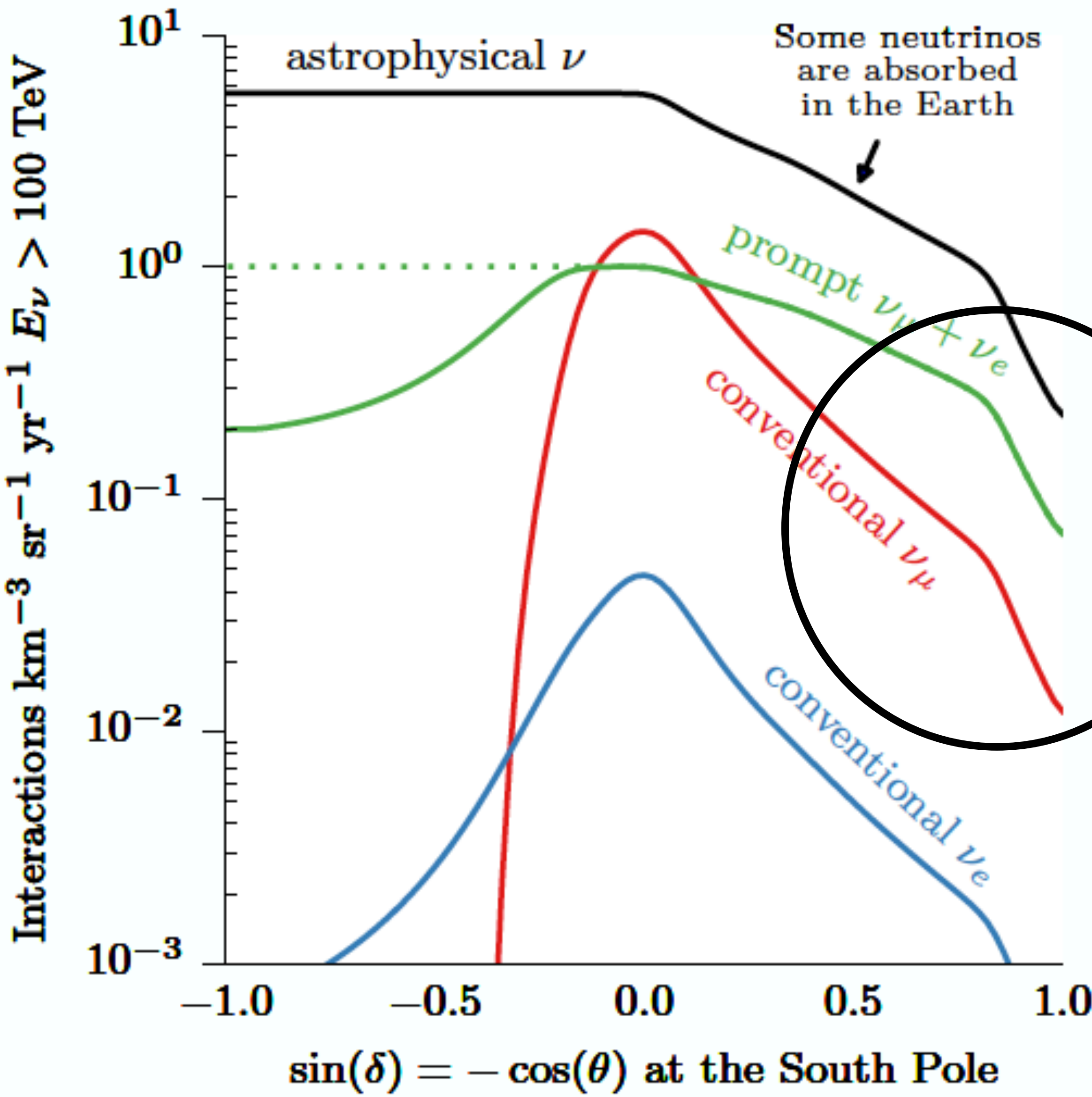
An active muon veto removes down-going atmospheric neutrinos.



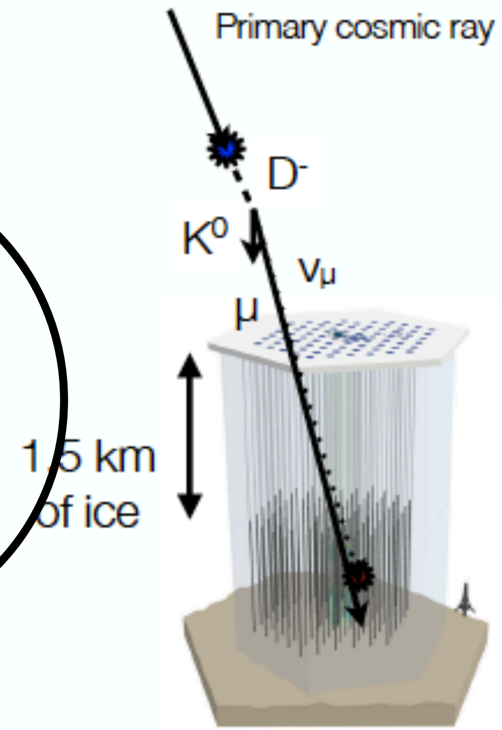
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



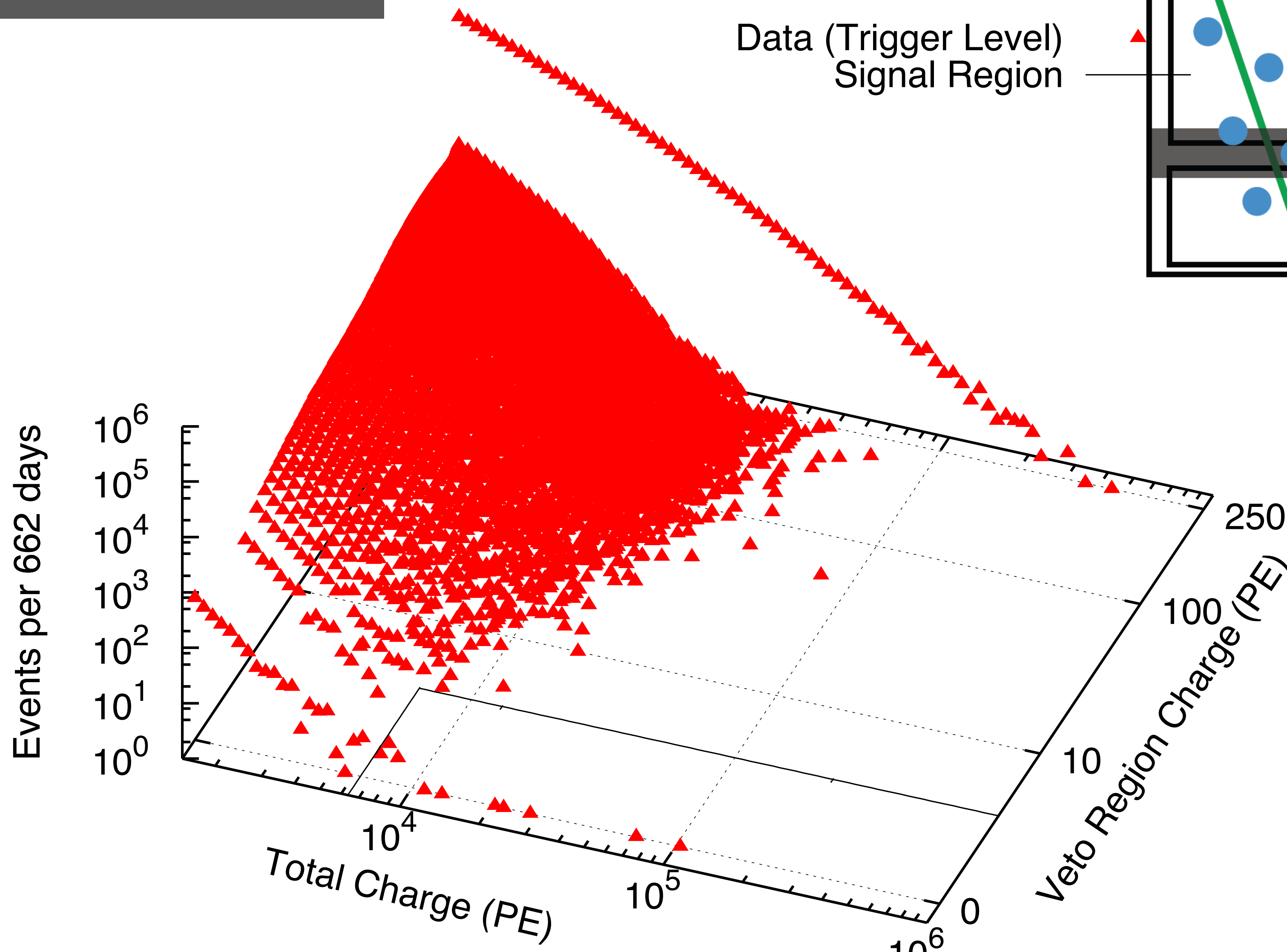
Prompt atmospheric neutrinos are vetoed, too.

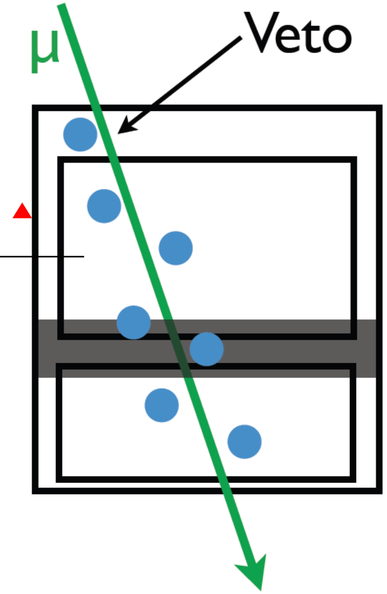


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

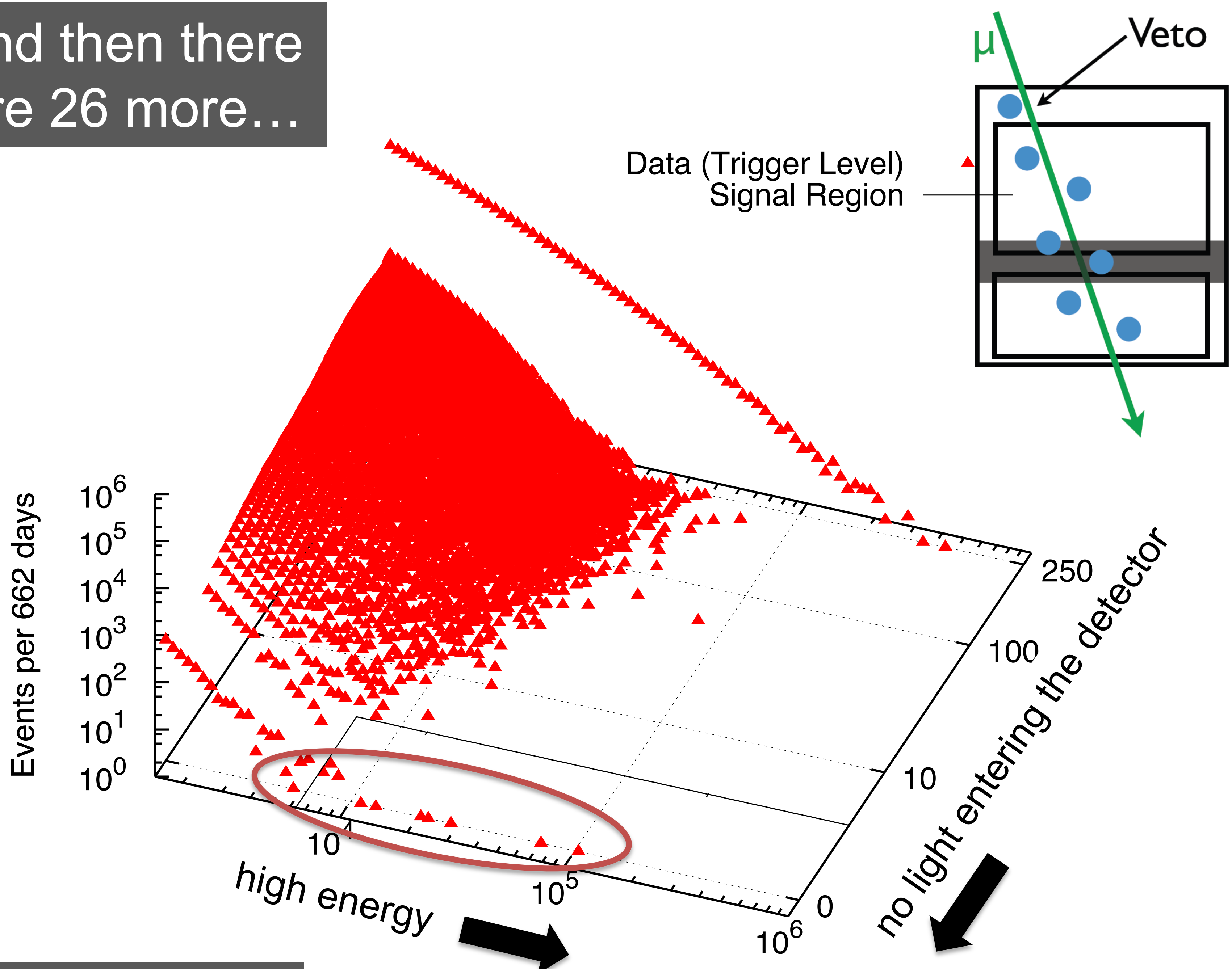
…and then there were 26 more…



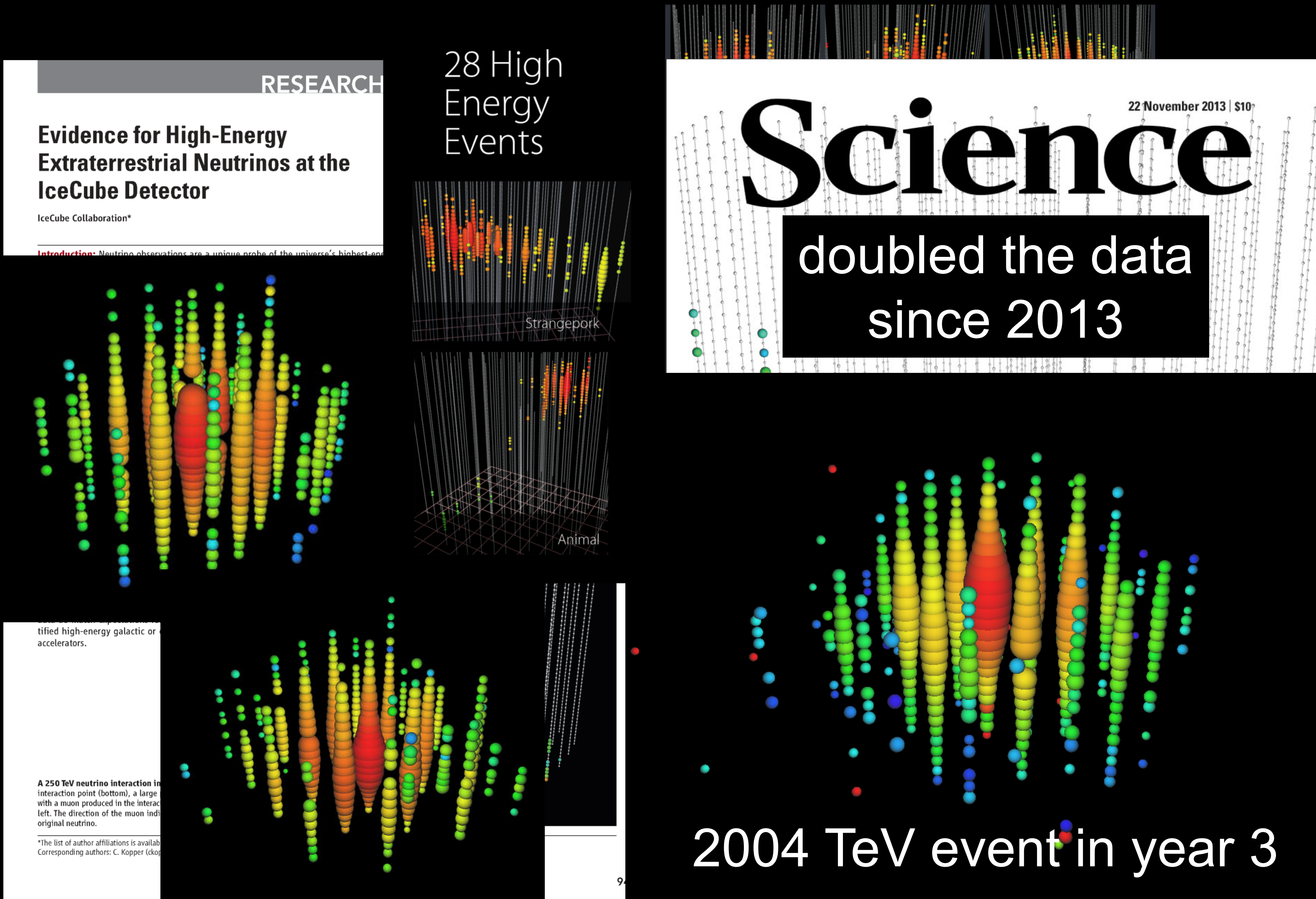


data: 86 strings one year

…and then there were 26 more…



data: 86 strings one year

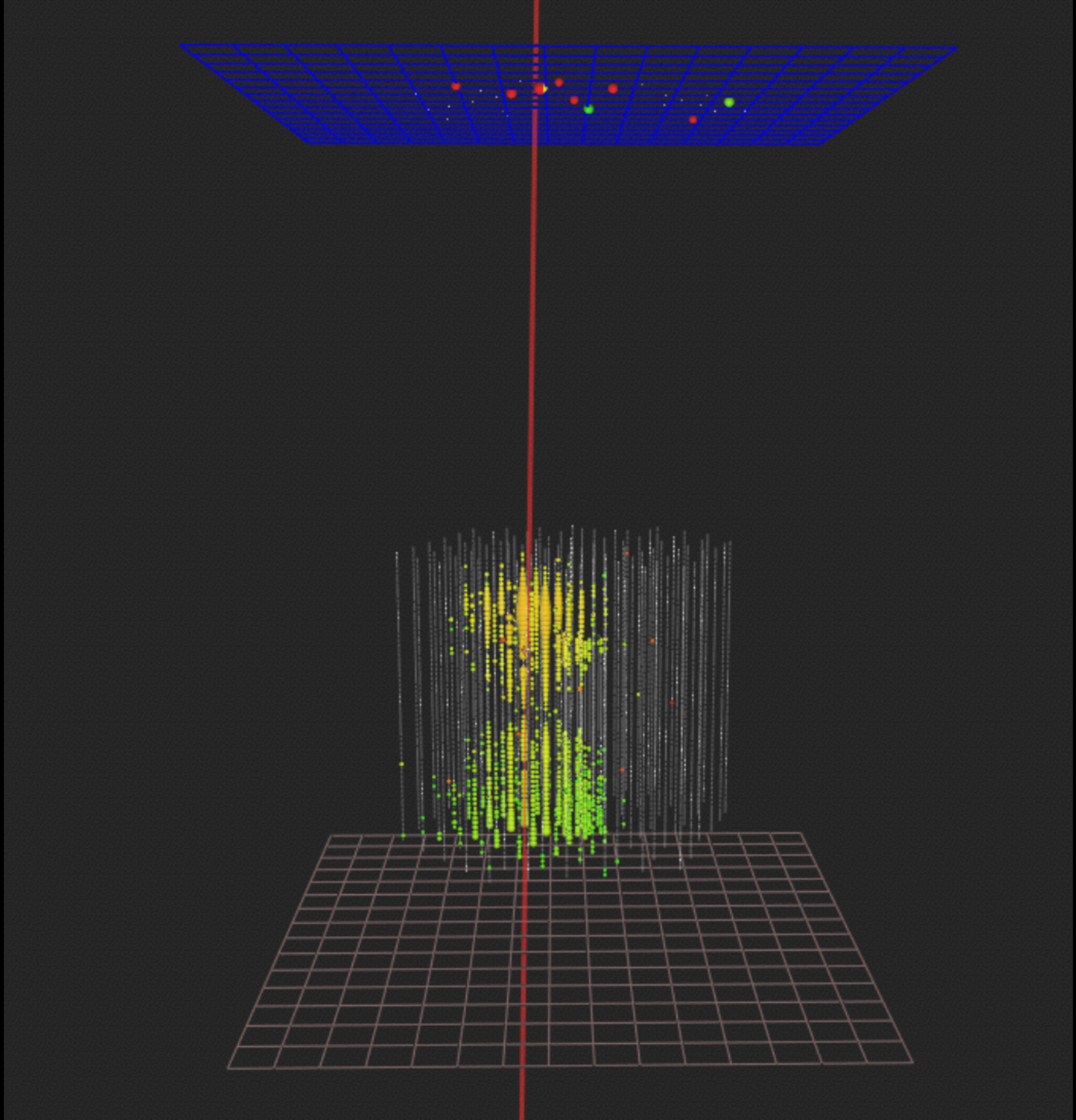

RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
accelerators.
Science
22 November 2013 | $10
doubled the data since 2013
2004 TeV event in year 3

430 TeV inside detector

PeV ν_μ

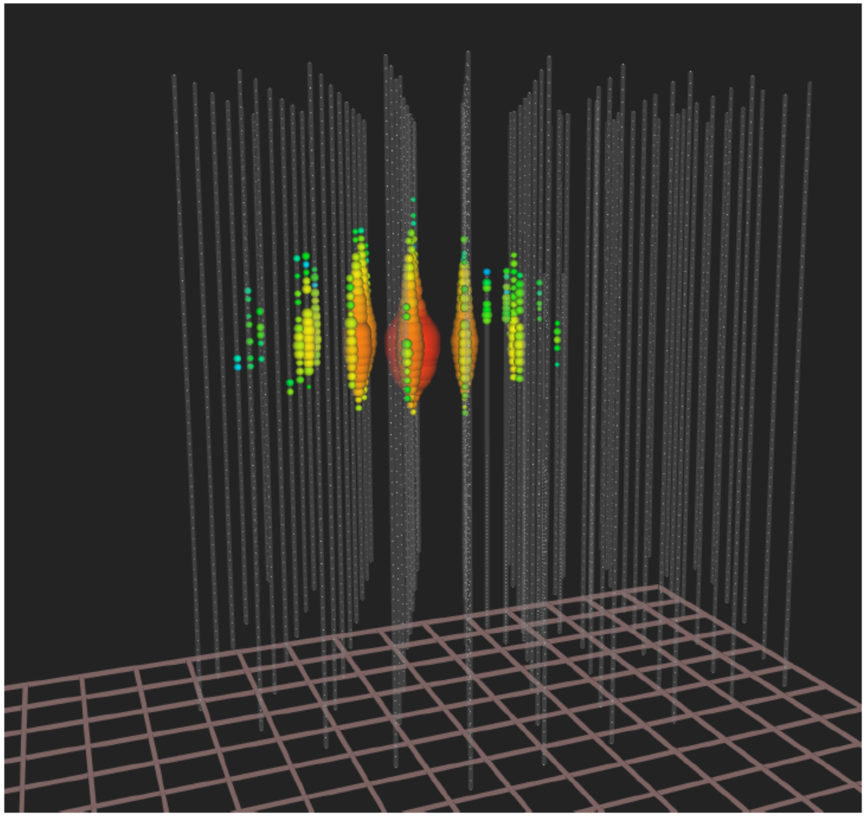
no air shower

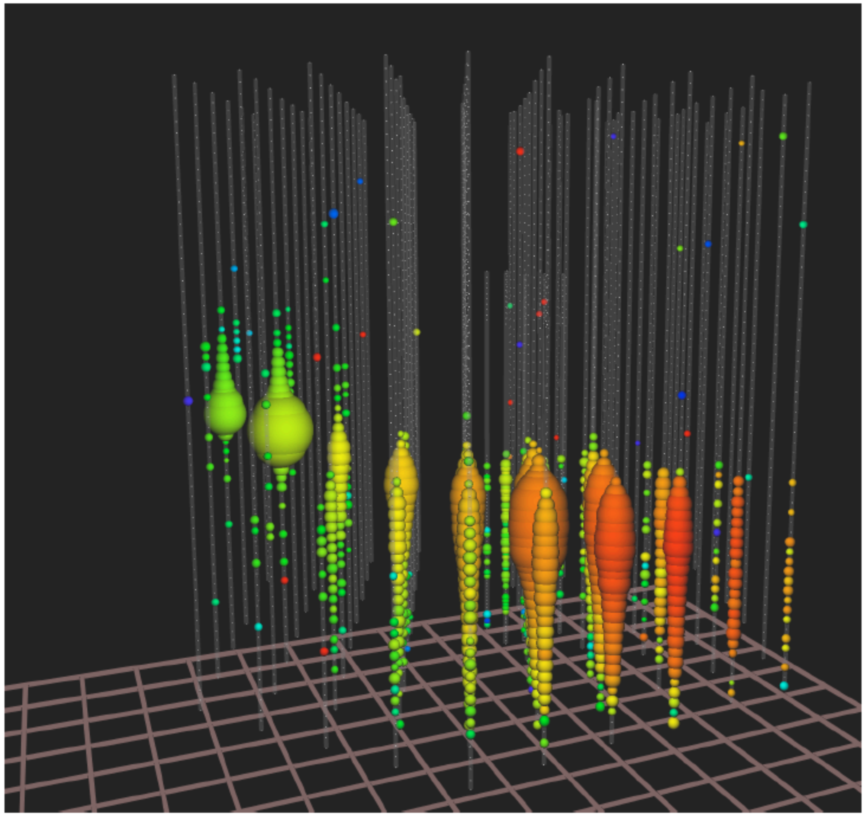
all cosmic neutrinos are isolated by self-veto



neutrinos interacting inside the detector

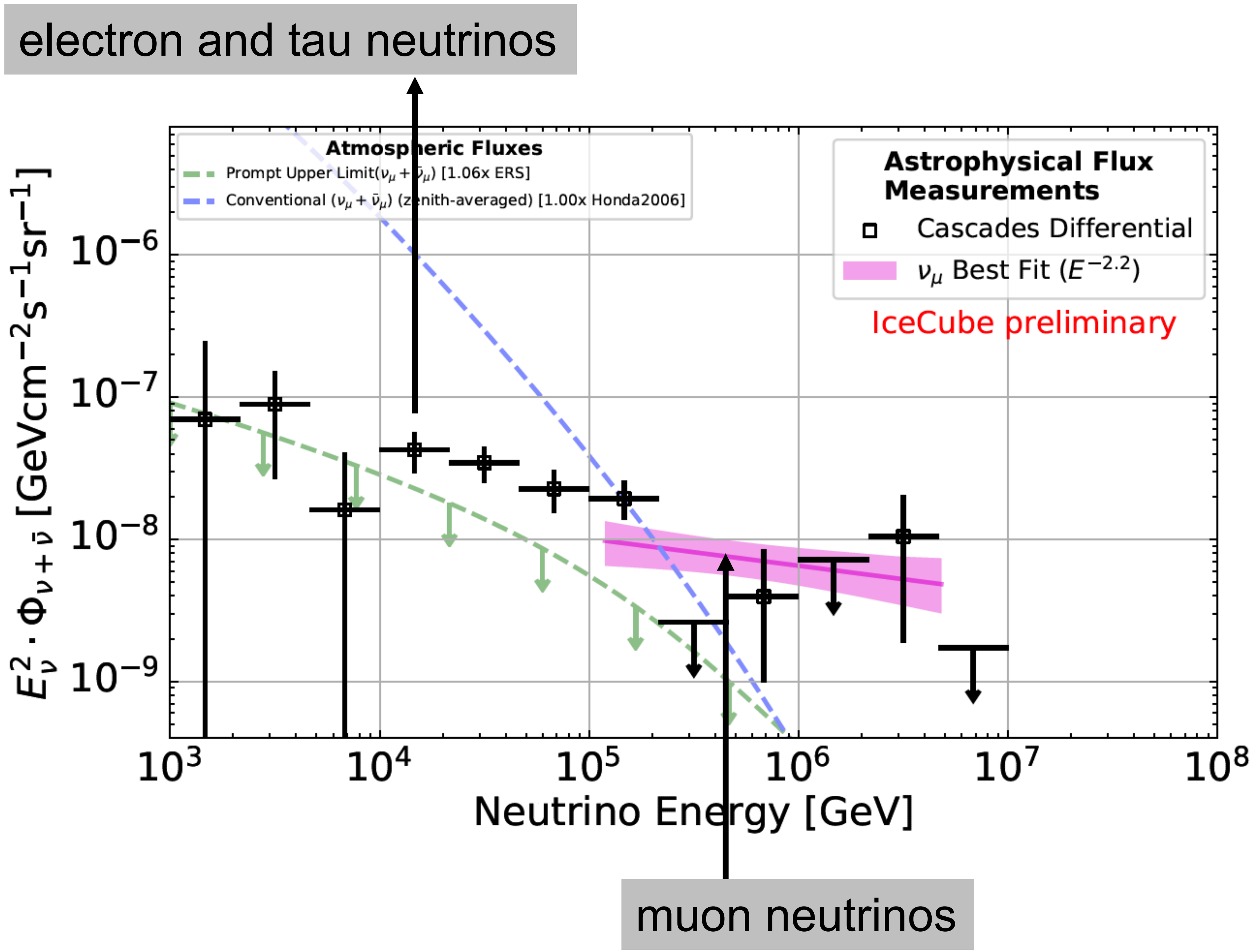
muon neutrinos filtered by the Earth





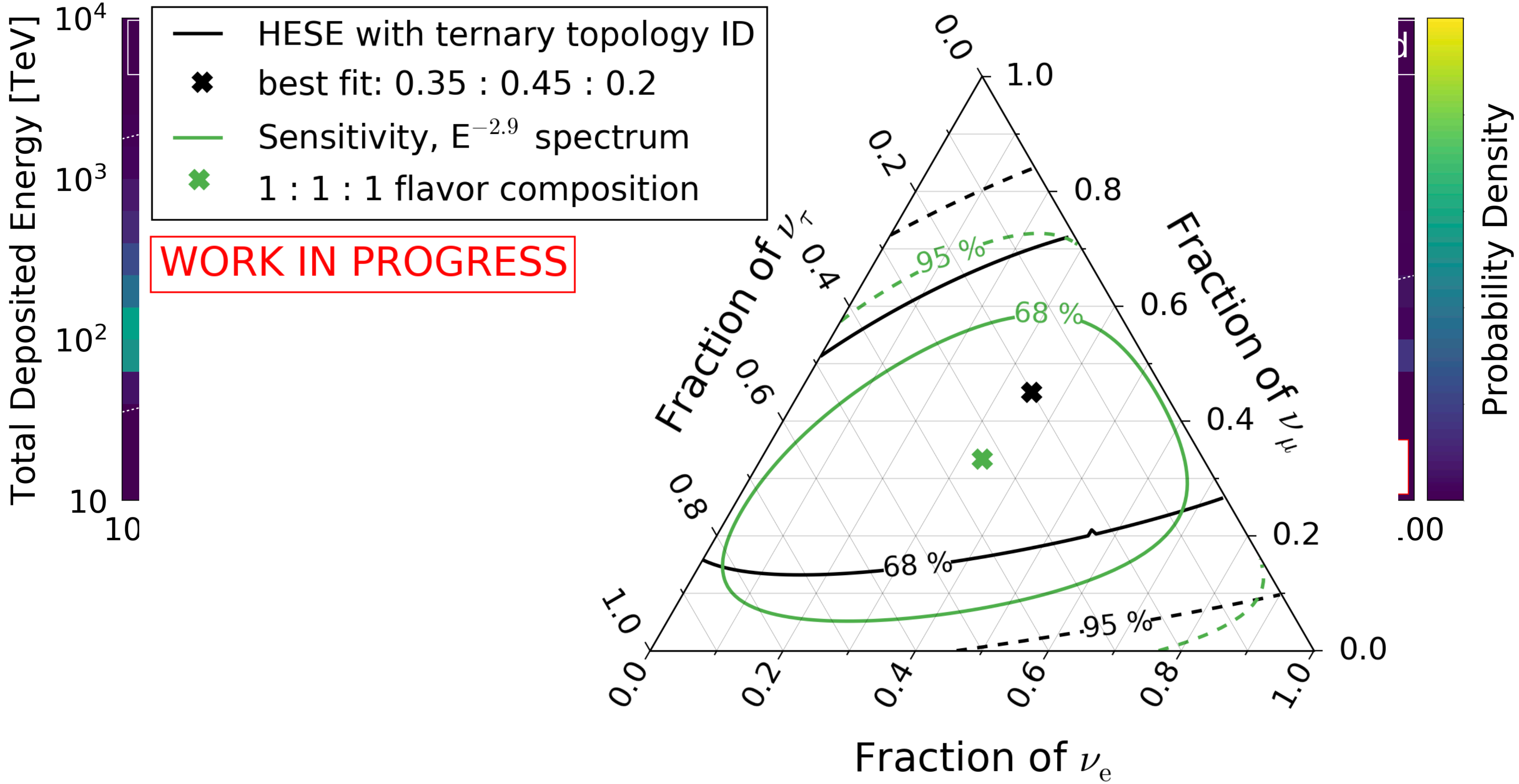
total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.4°)



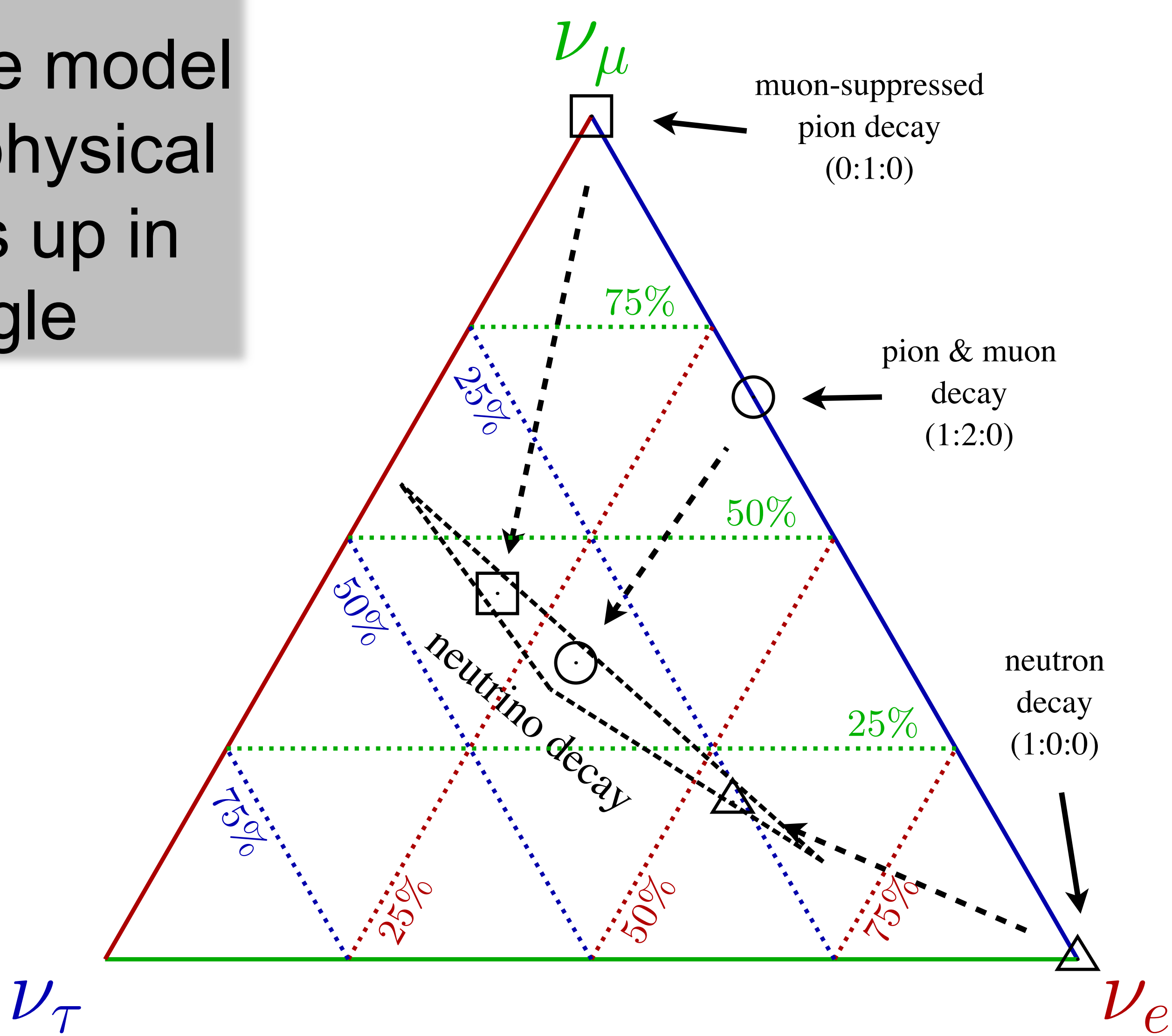
electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
muon neutrinos

high-energy starting events – 7.5 yr



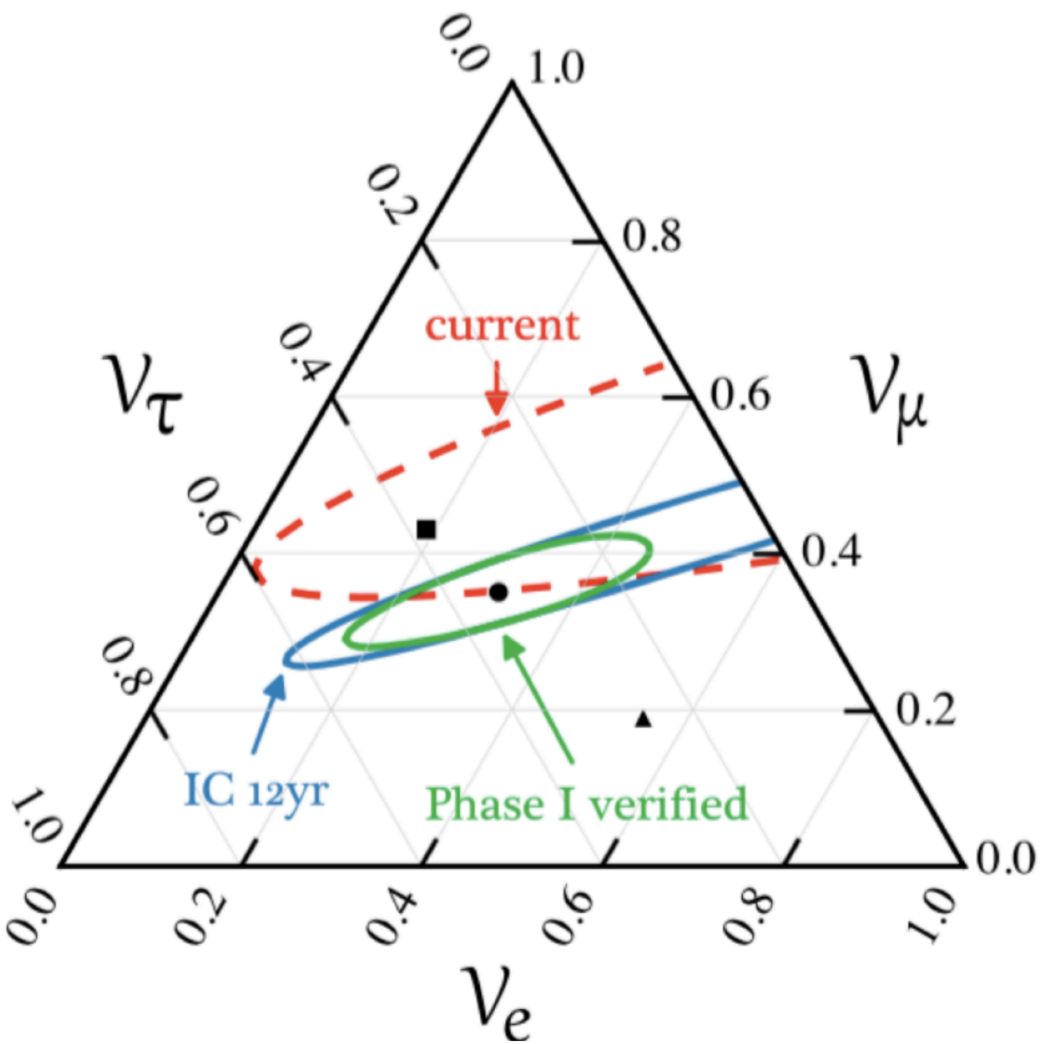
oscillations of PeV neutrinos over cosmic distances to 1:1:1

new physics ?
if not…
every possible model
for the astrophysical
source ends up in
the triangle



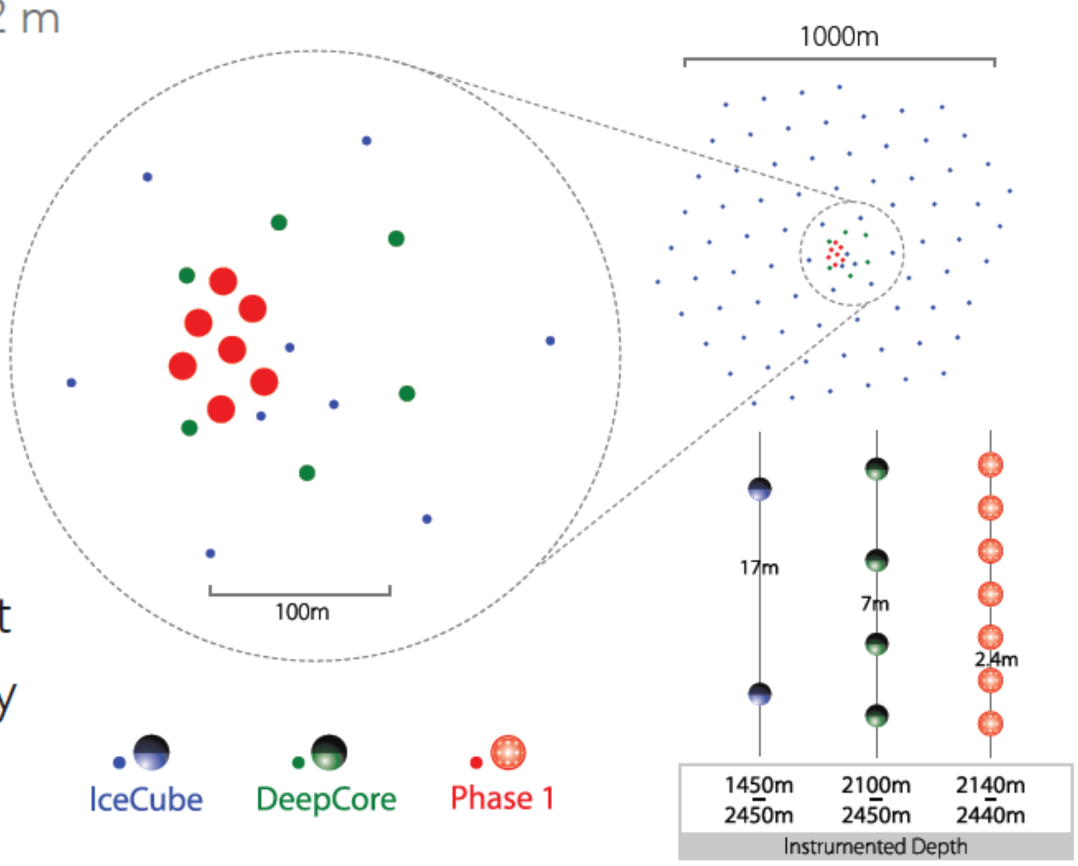
ongoing upgrade:
2022 deployment

- neutrino oscillation at PeV energy
- nutau: test of the 3-neutrino scenario
- neutrino physics BSM
- IceCube Gen2 pathfinder



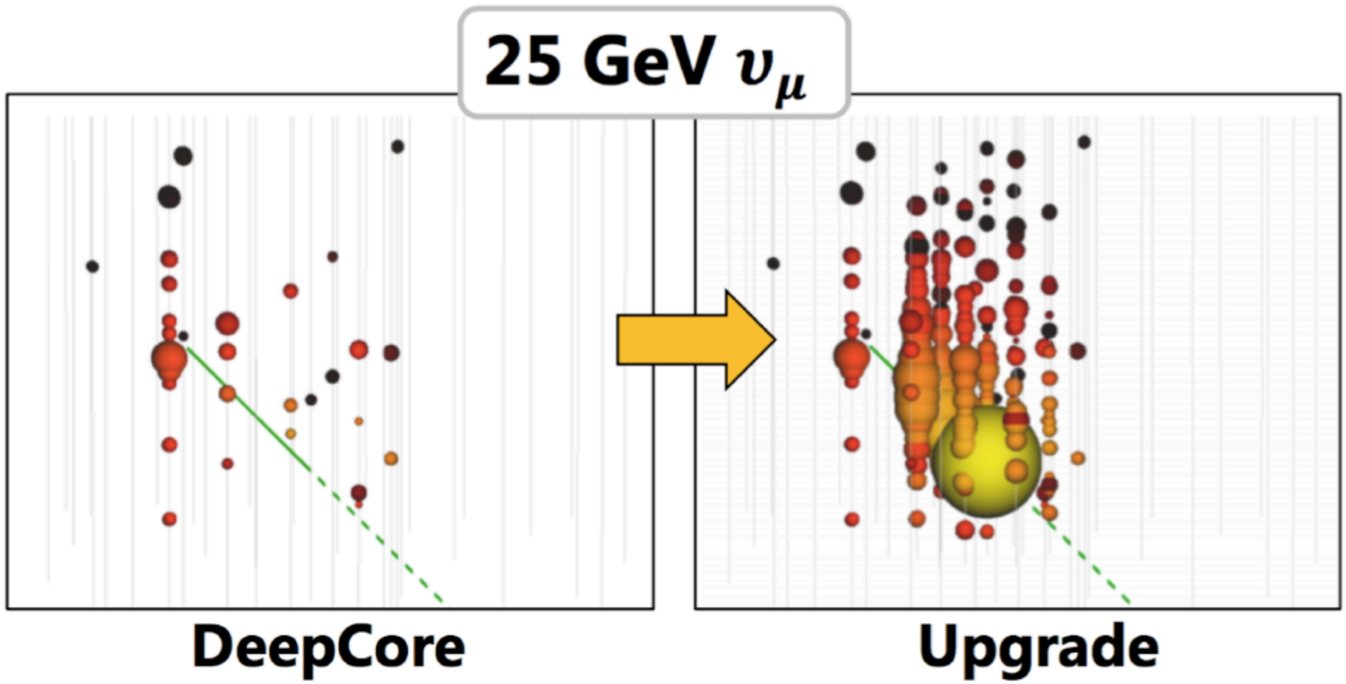
Next Step: the IceCube Upgrade (2022)

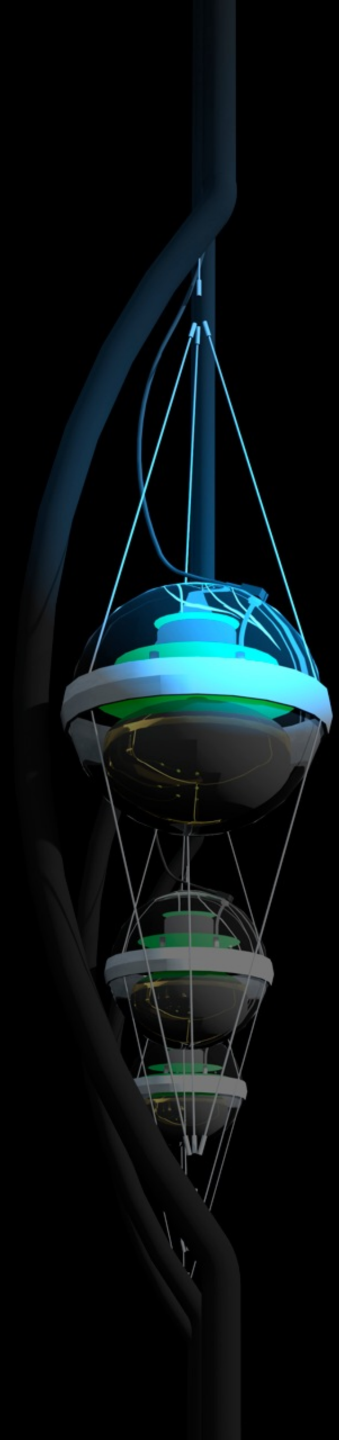
- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



→ recalibration IceCube to reach 0.1^0 degree ang.res.

Low energy neutrinos in the Upgrade





neutrino astronomy

- cosmic neutrinos: four independent observations
  → muon neutrinos through the Earth
  → starting neutrinos: all flavors
  → tau neutrinos
  → Glashow event

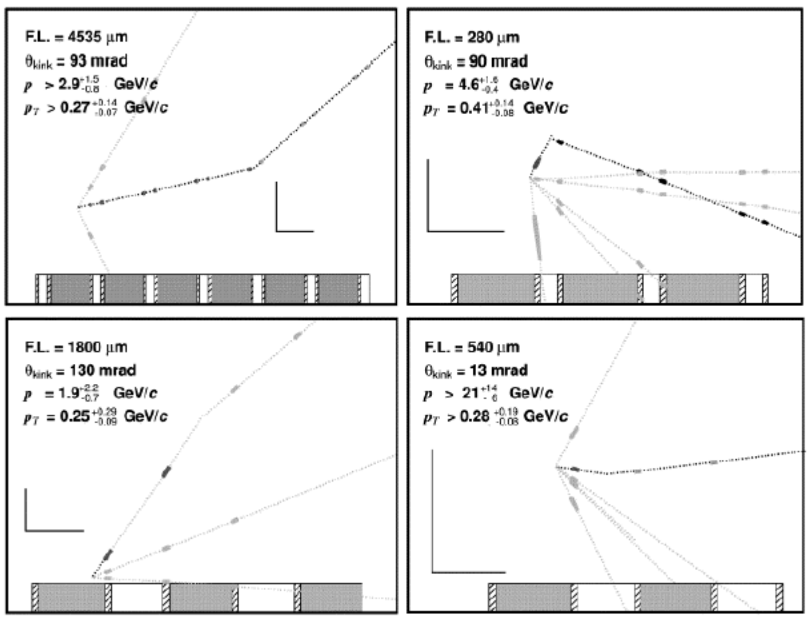
multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

icecube.wisc.edu

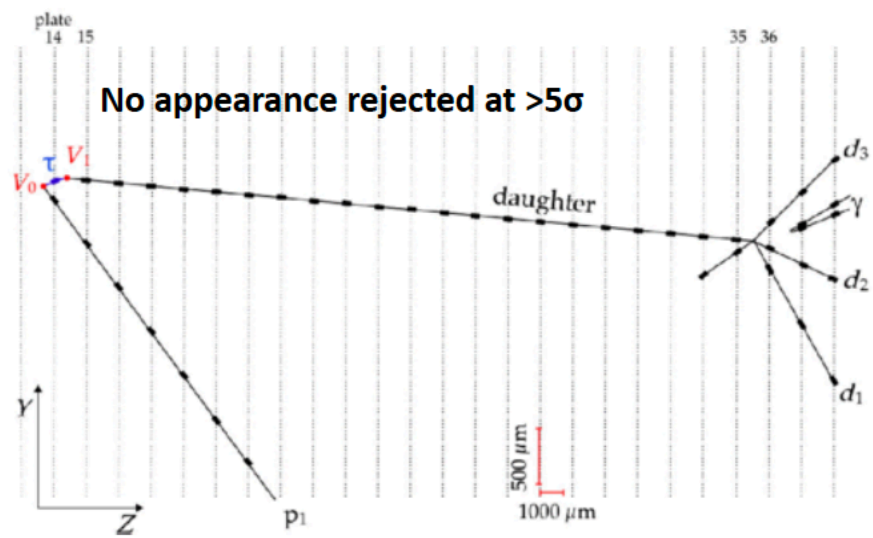
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion

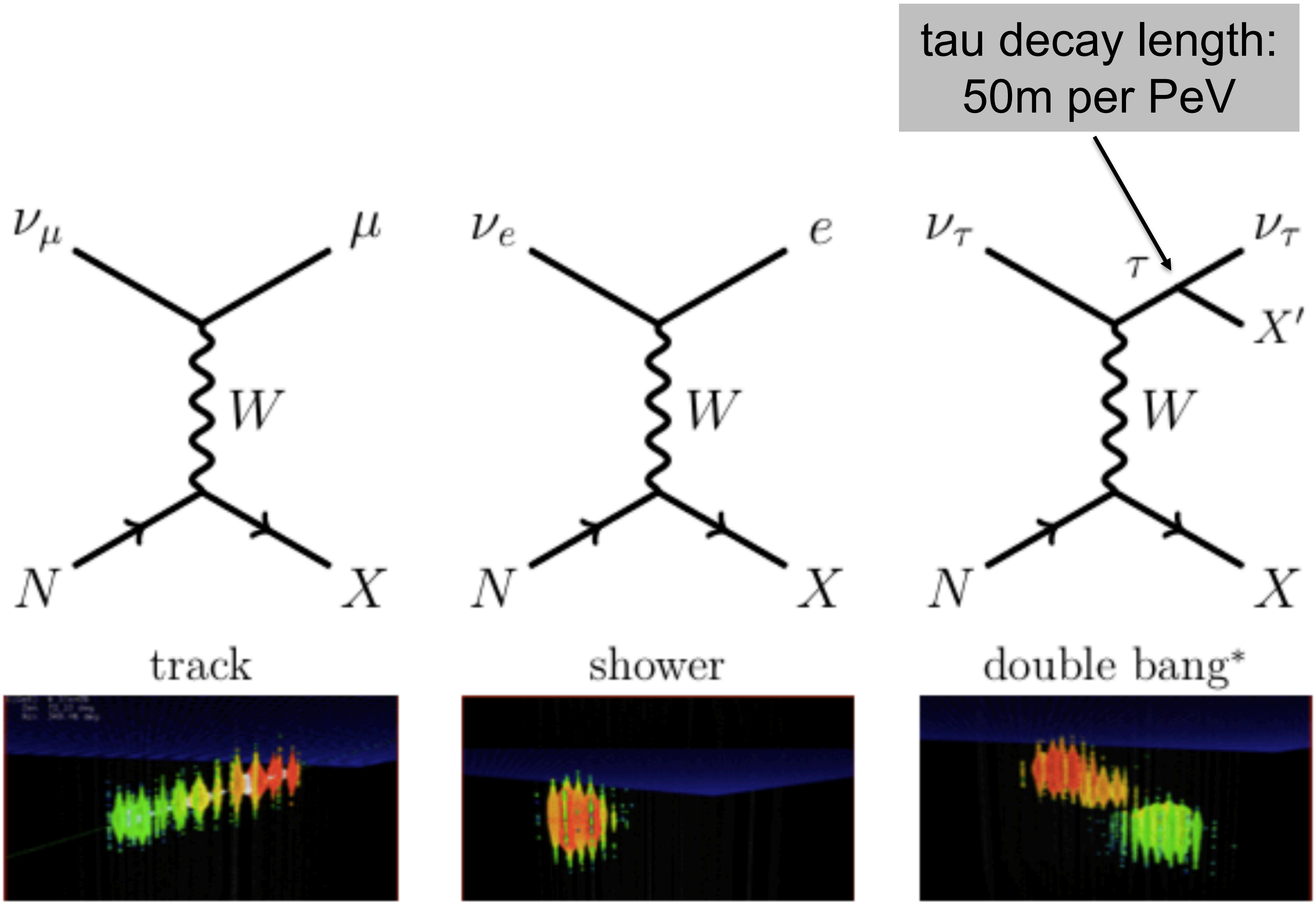


DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion

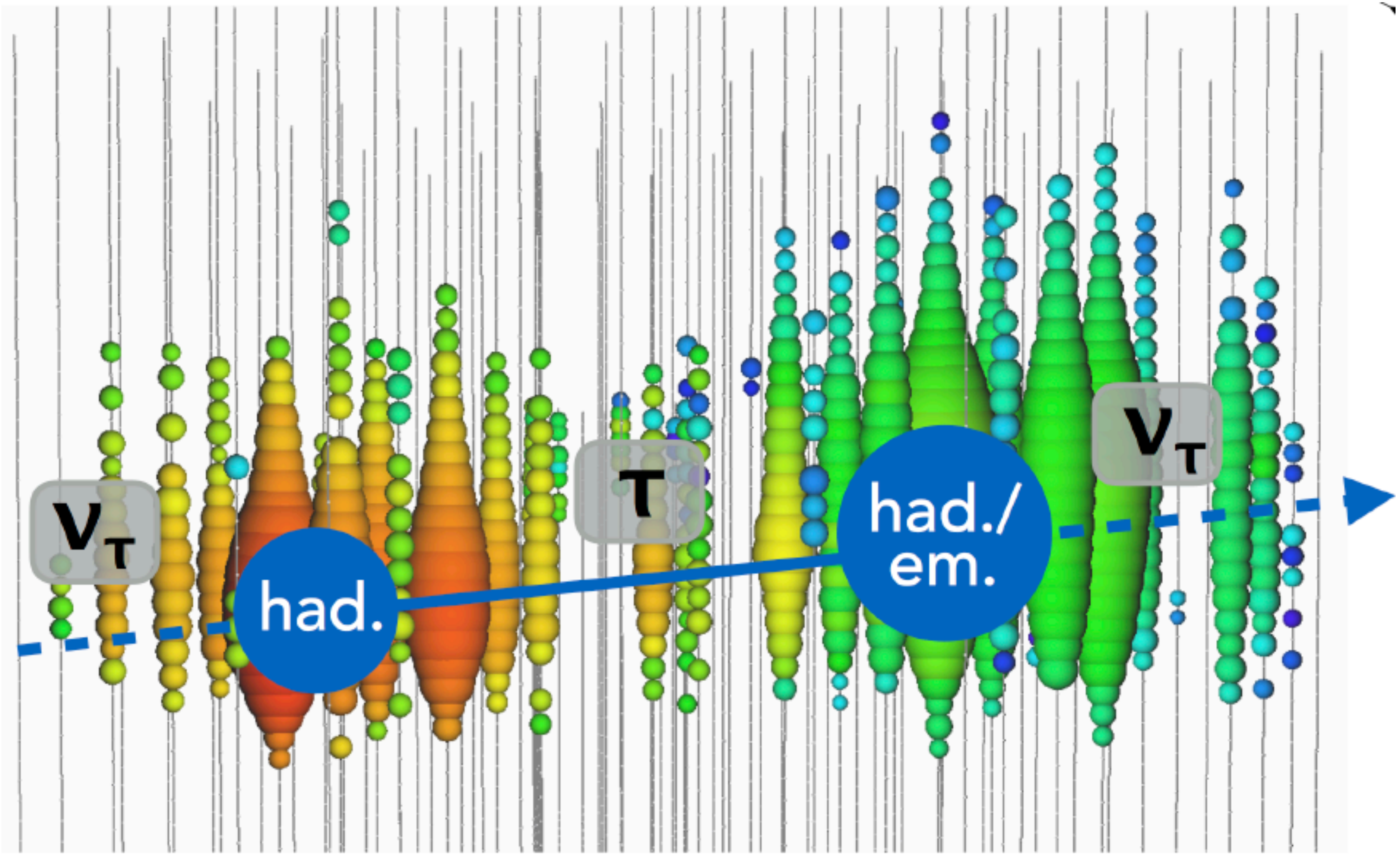


OPERA Phys. Rev. Lett. 115, 121802 (2015)

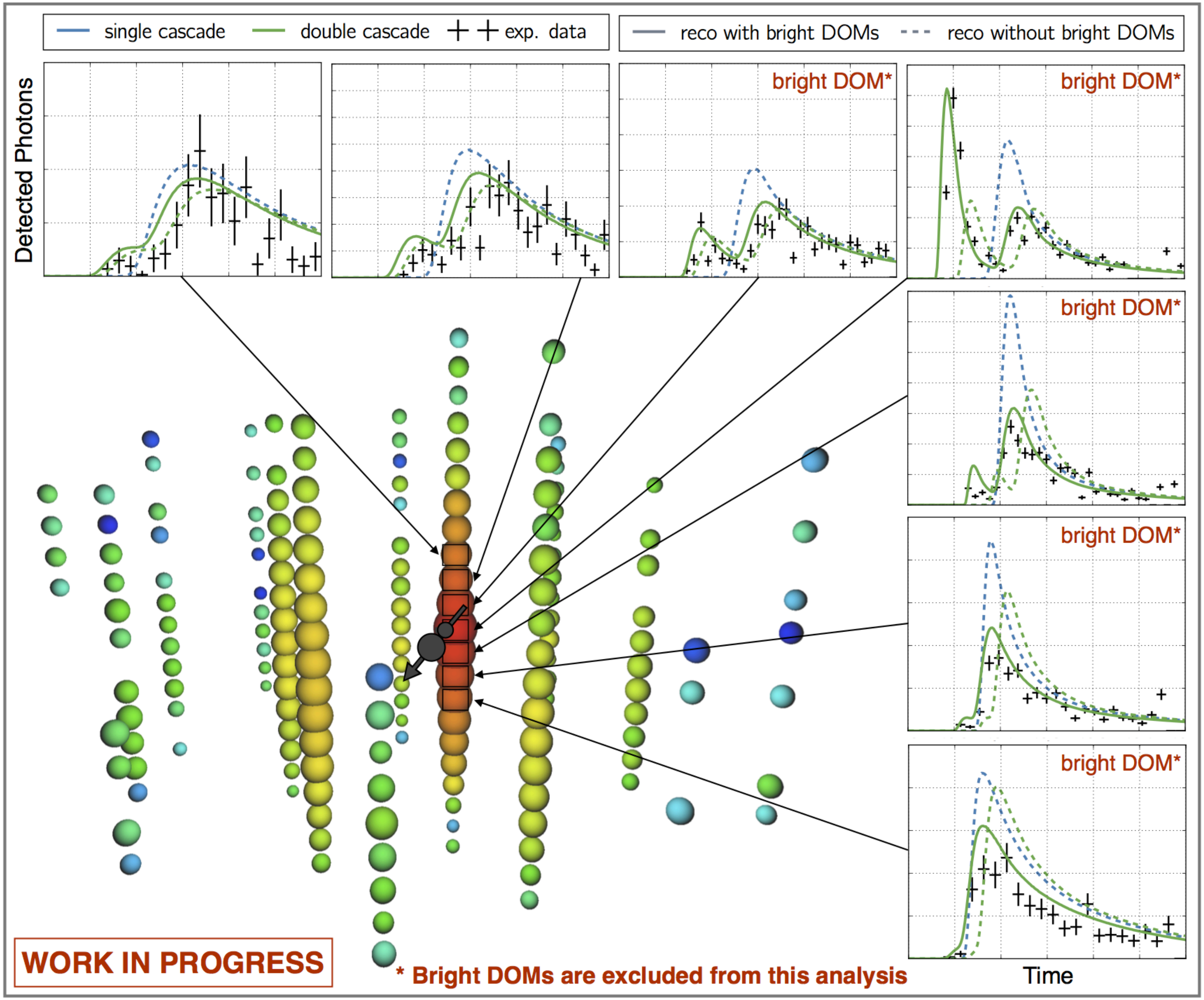

tau decay length:
50m per PeV
ν_μ
μ
W
N
X
ν_e
e
W
N
X
ν_τ
τ
ν_τ
X'
W
N
X
track
shower
double bang*

tau production and decay

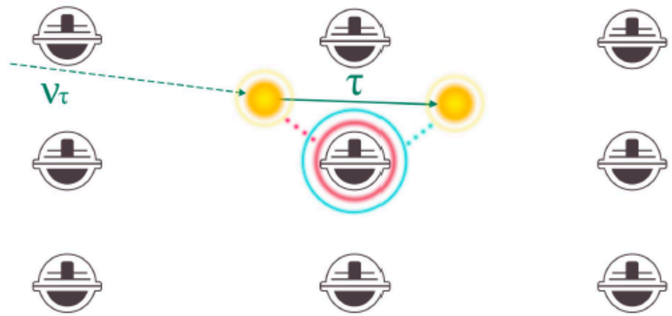
tau decay length:
50m per PeV

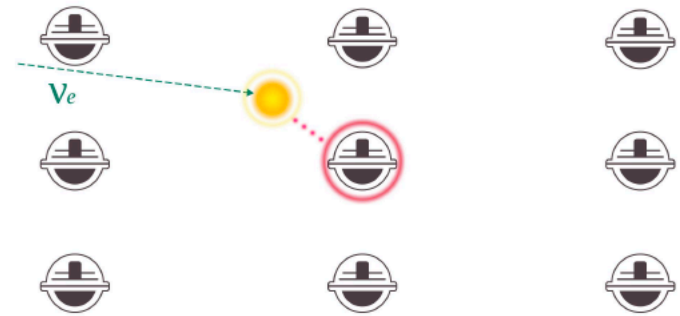


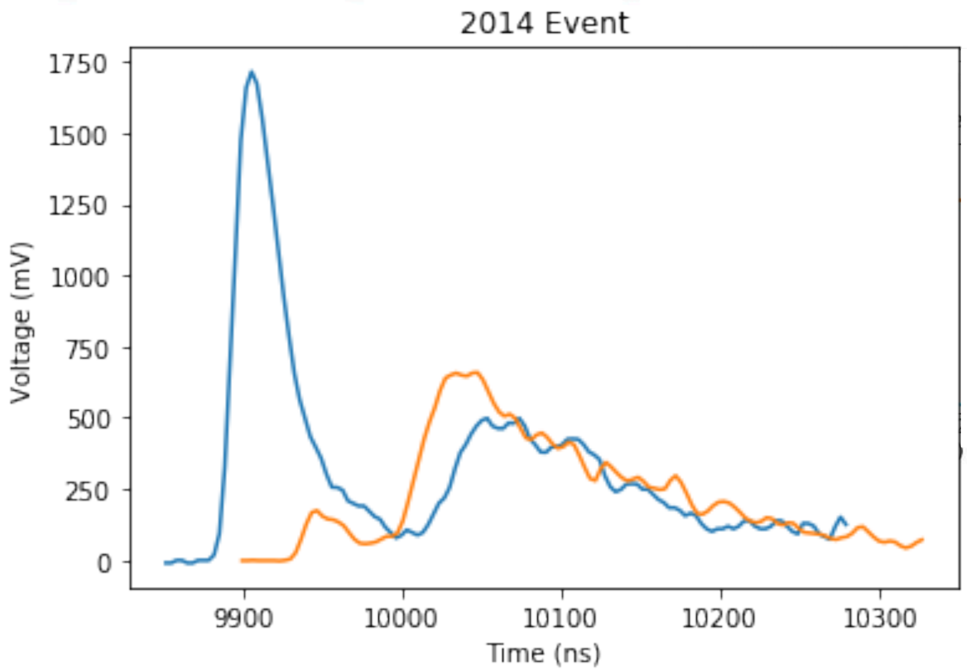
a cosmic tau neutrino: livetime 17m

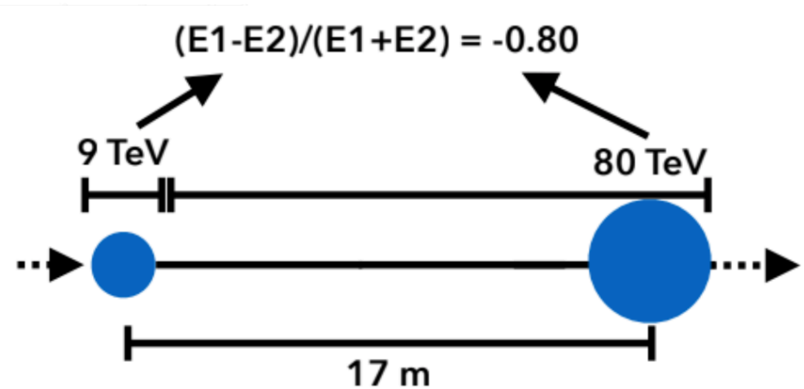


tau decay length:
50m per PeV

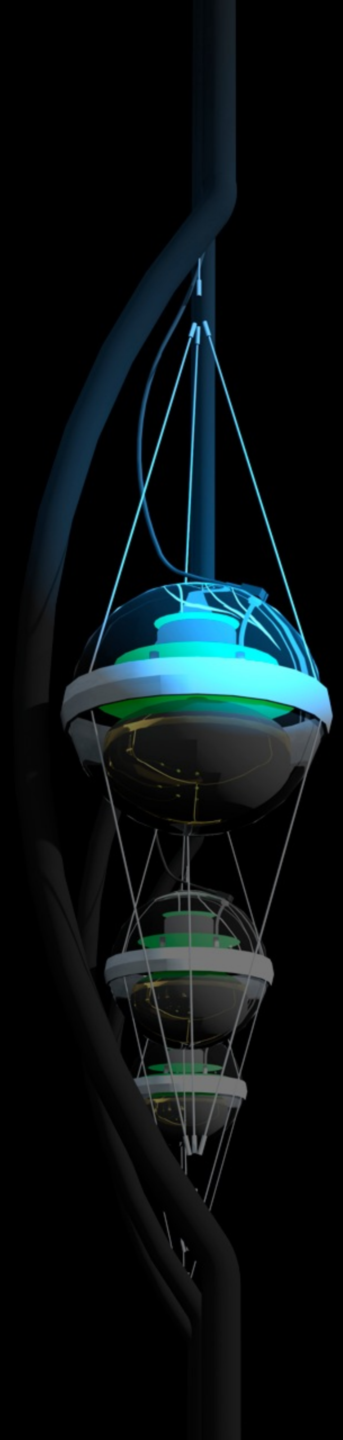








event found in 3 different analyses



neutrino astronomy

- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

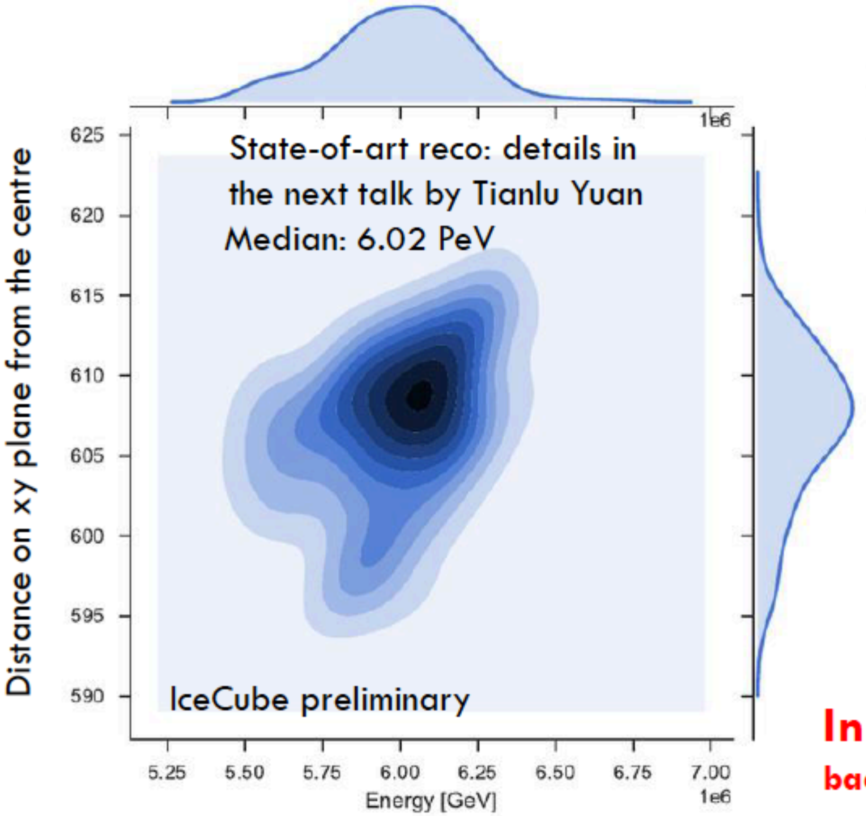
multimessenger astronomy

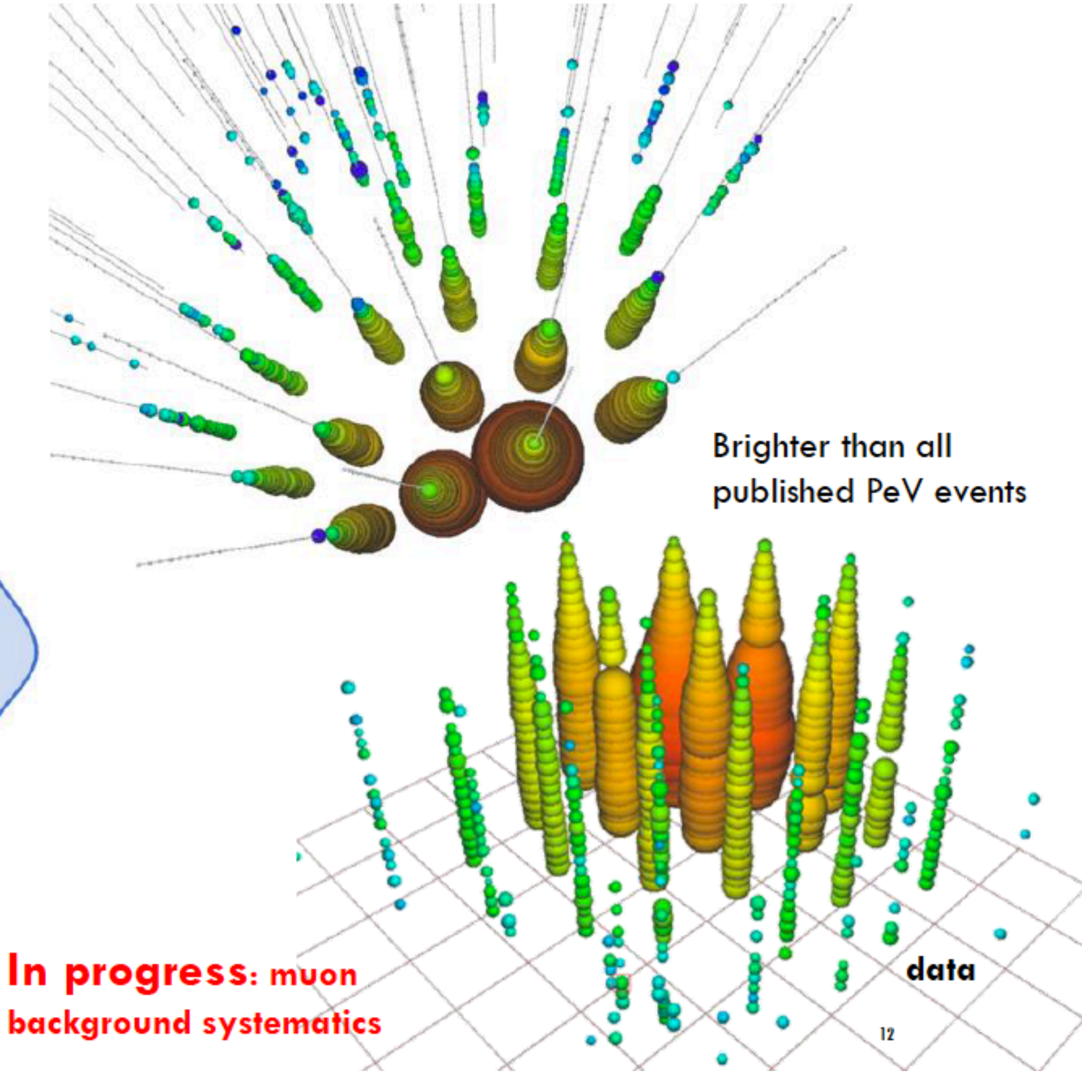
- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

icecube.wisc.edu

partially contained event with energy of 6.3 PeV

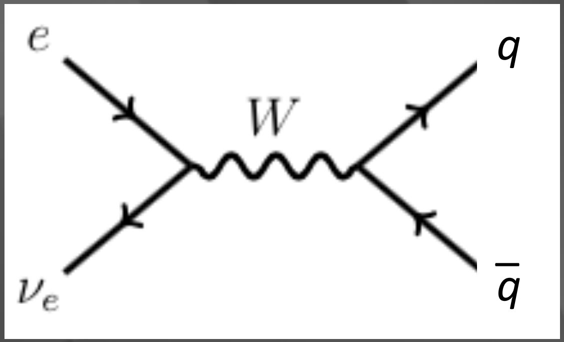
HIGHEST-ENERGY NEUTRINO CANDIDATE



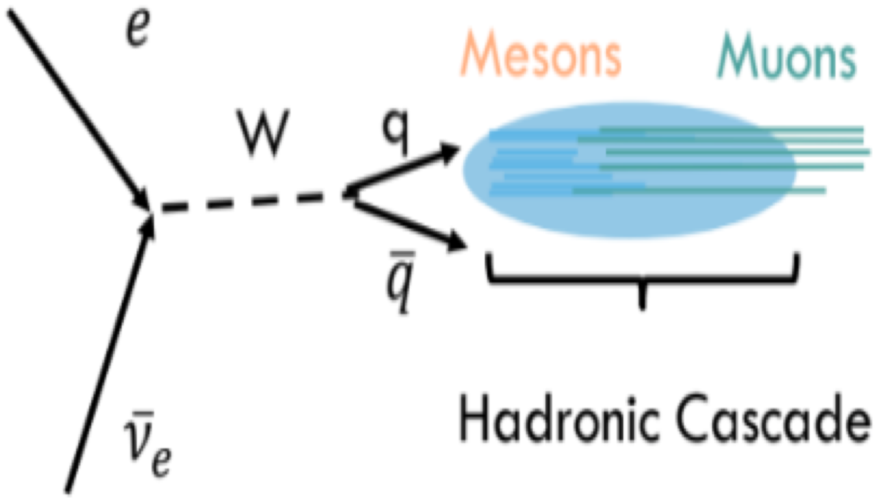


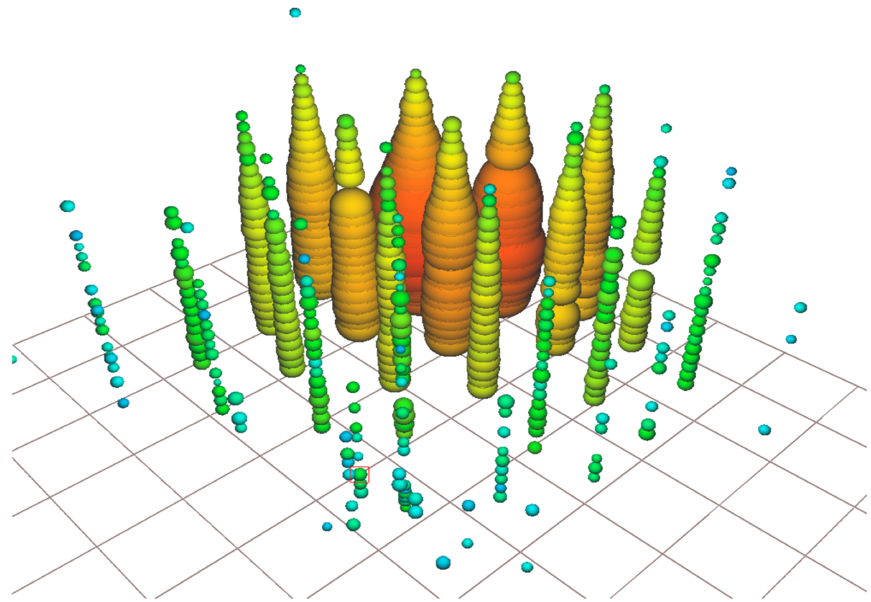
the first Glashow resonance event:

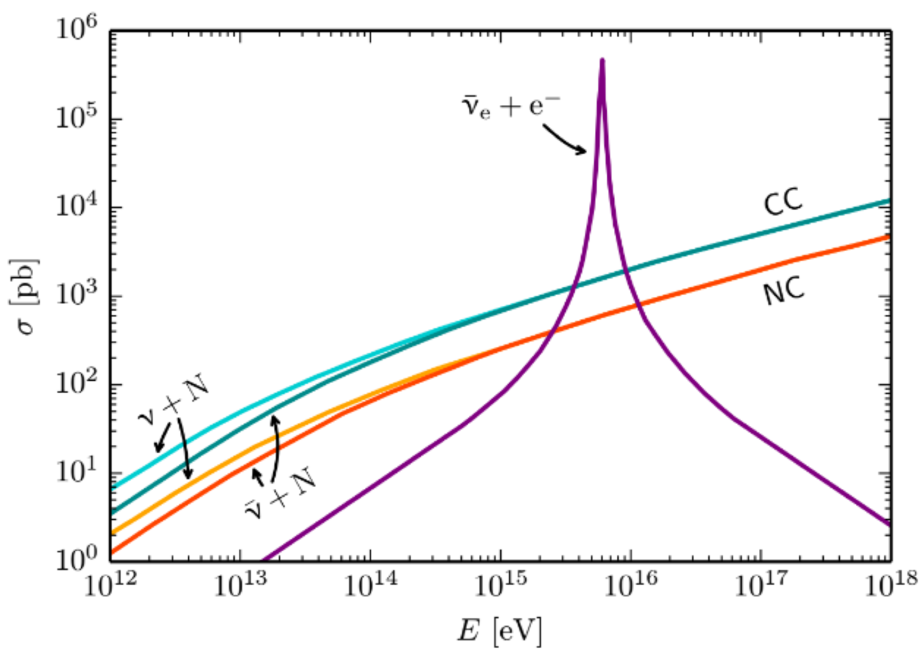
anti-ν_e + atomic electron → real W at 6.3 PeV



Glashow resonance: anti-ν_e + atomic electron → real W





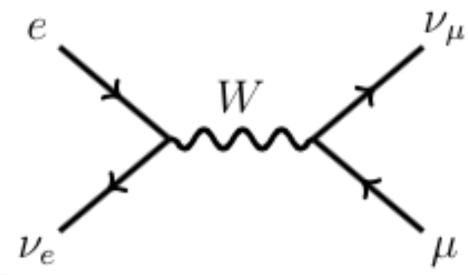


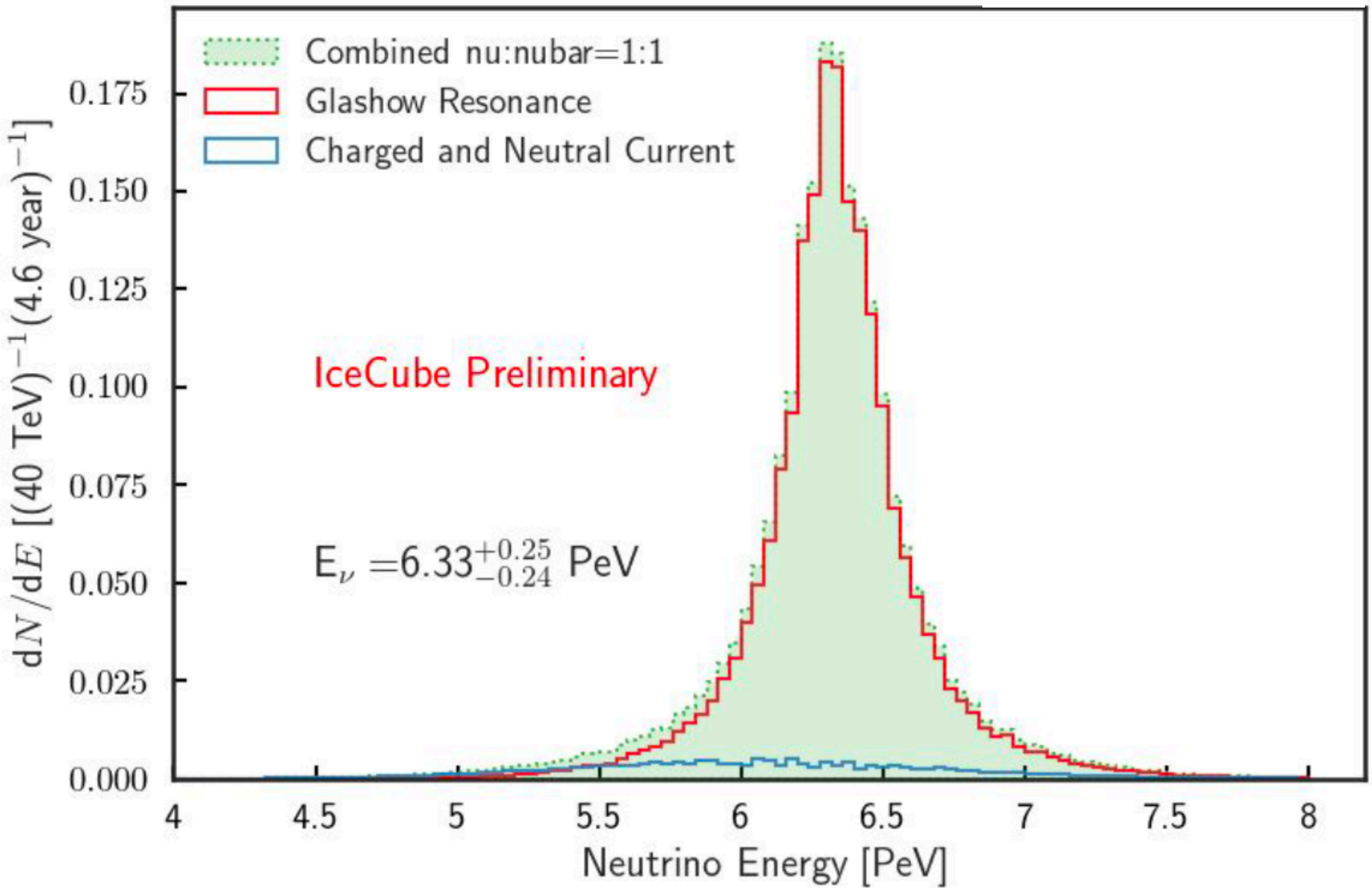
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

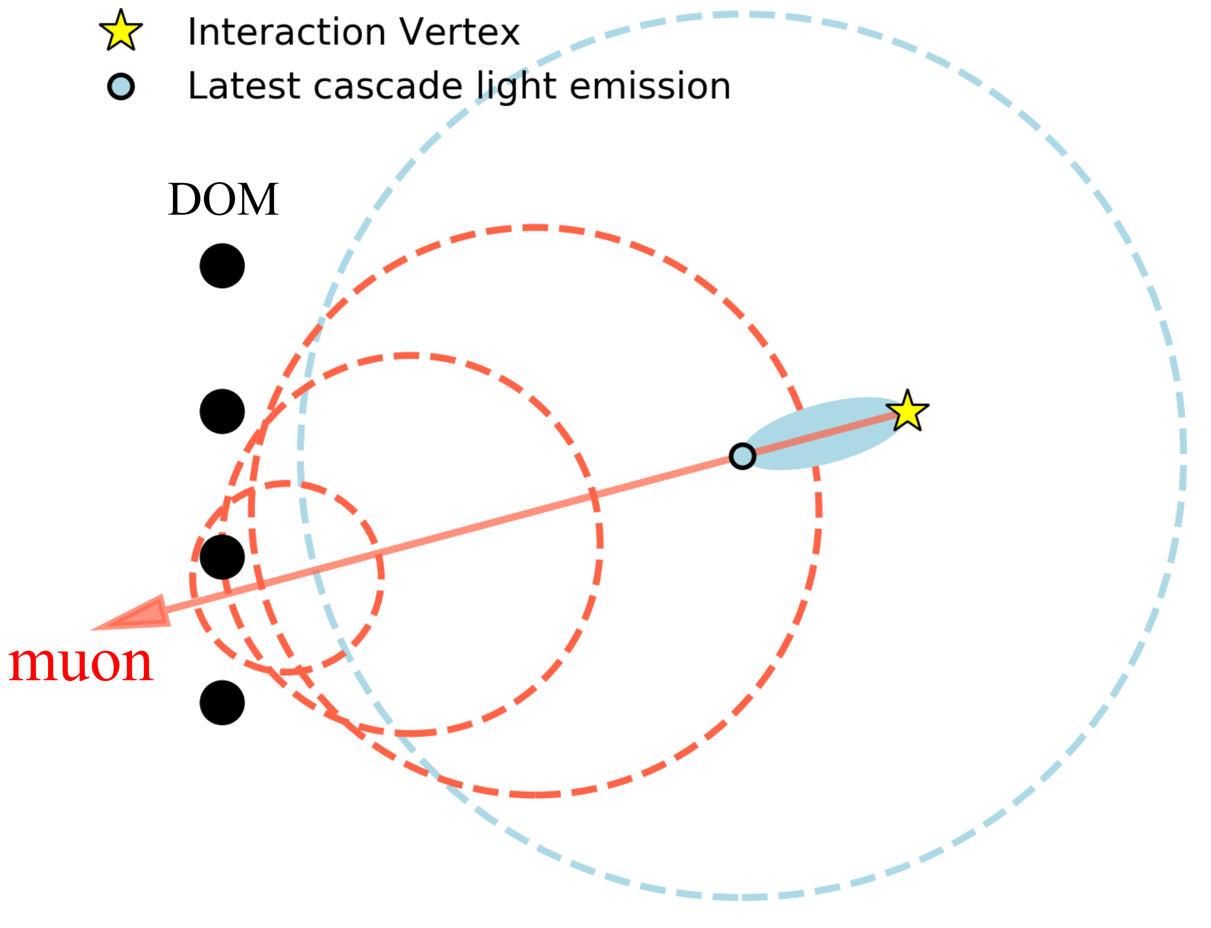
- energy measurement understood
- identification of anti-electron neutrinos

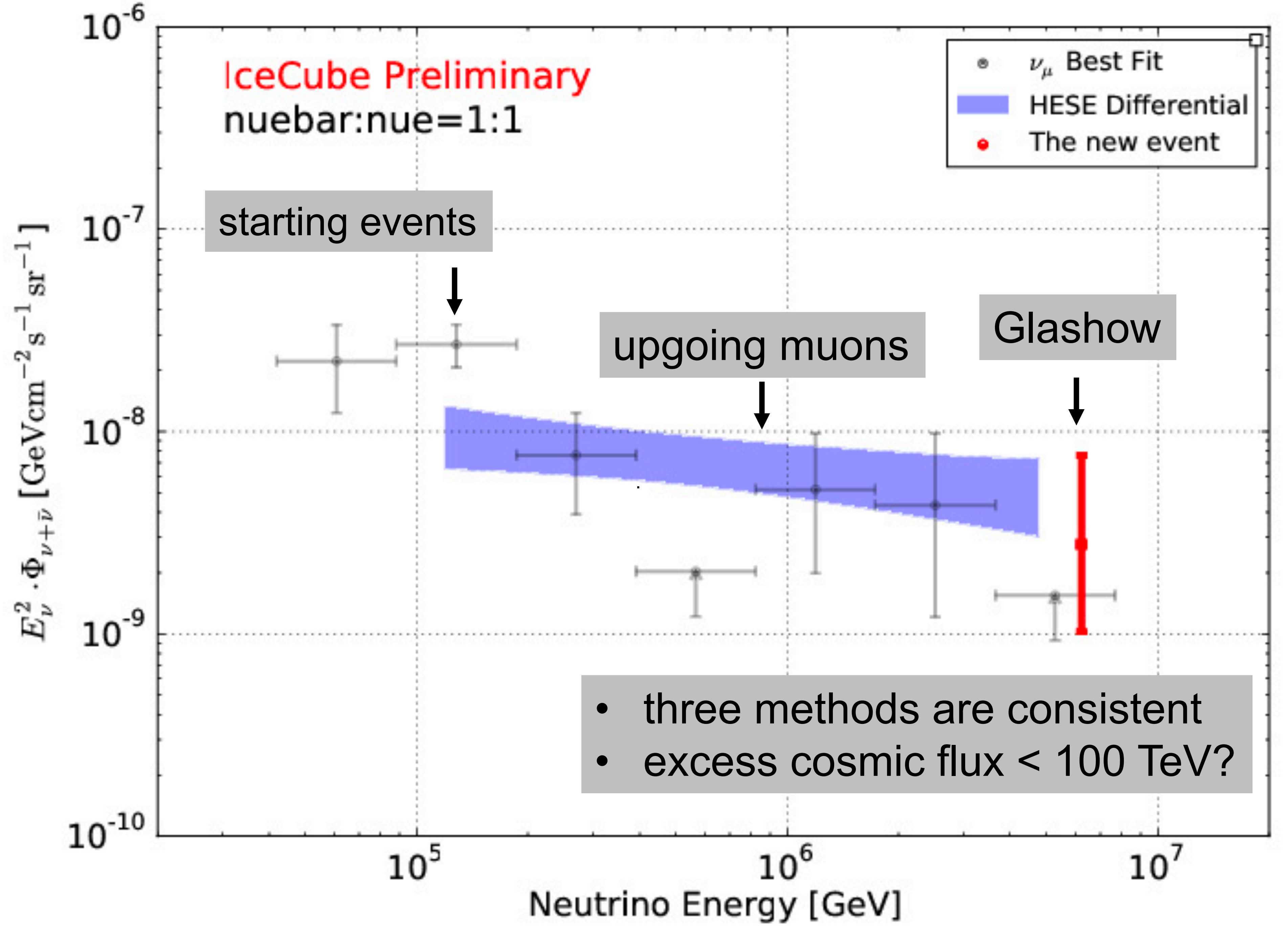


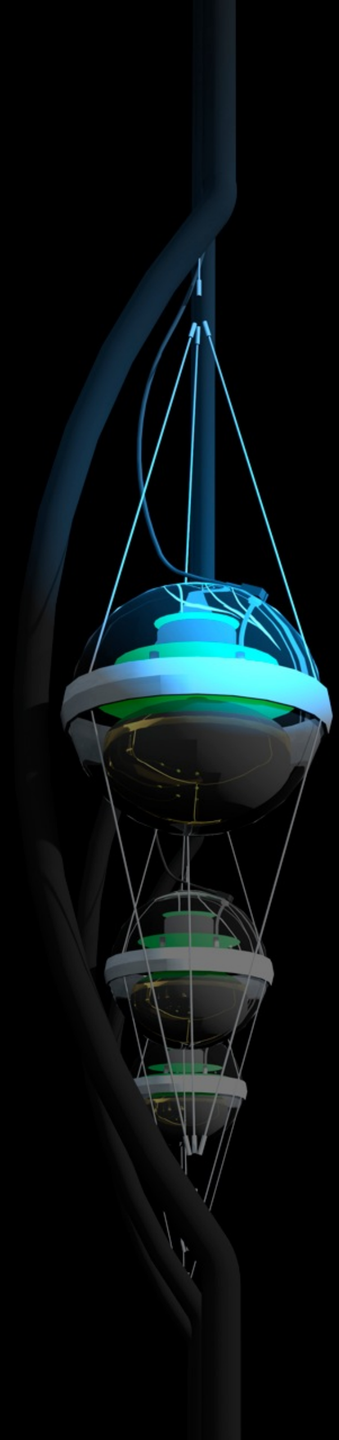


- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)




IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
starting events
upgoing muons
Glashow
• three methods are consistent
• excess cosmic flux < 100 TeV?
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^5
10^6
10^7



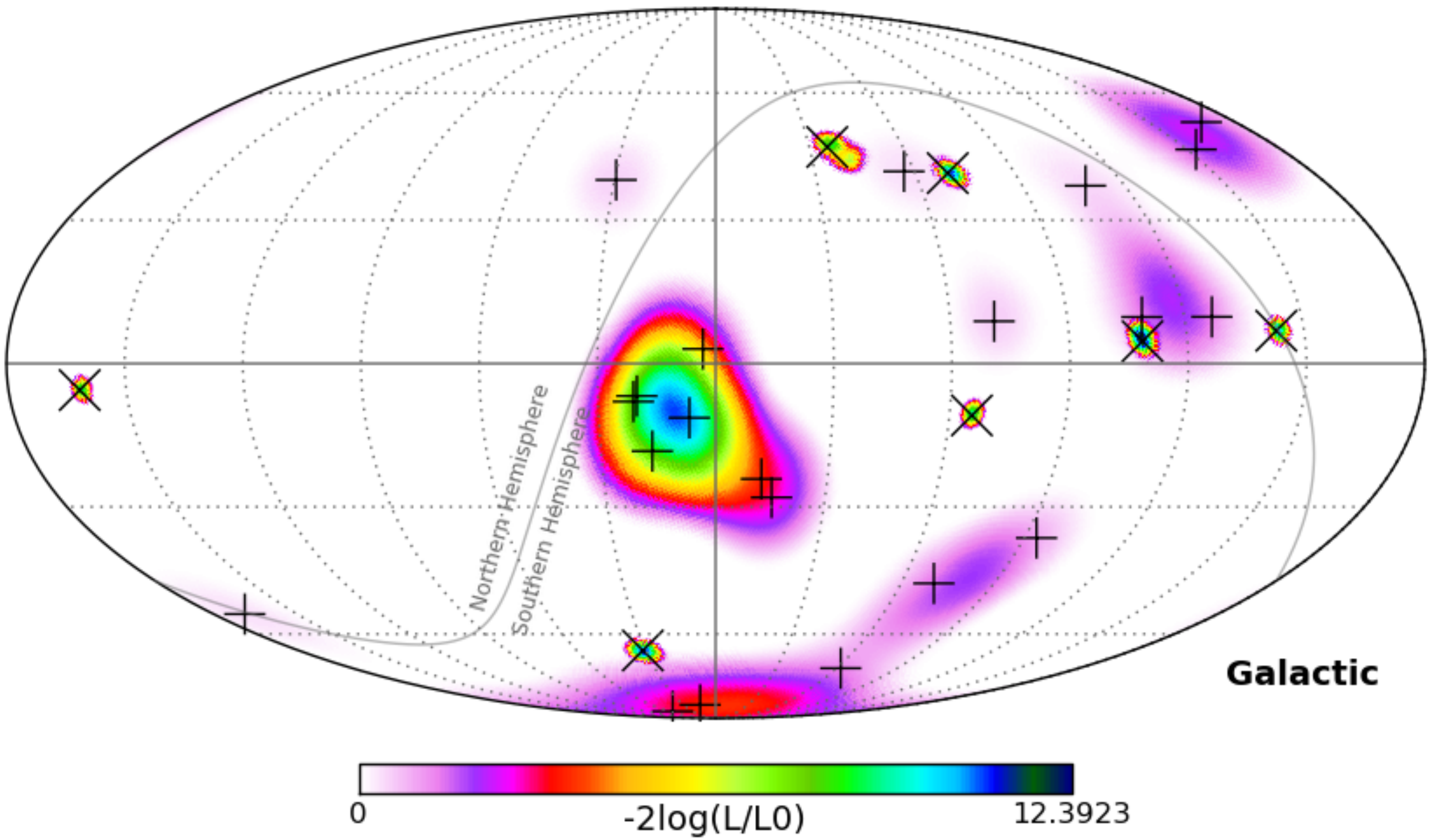
IceCube: the discovery of cosmic neutrinos

francis halzen

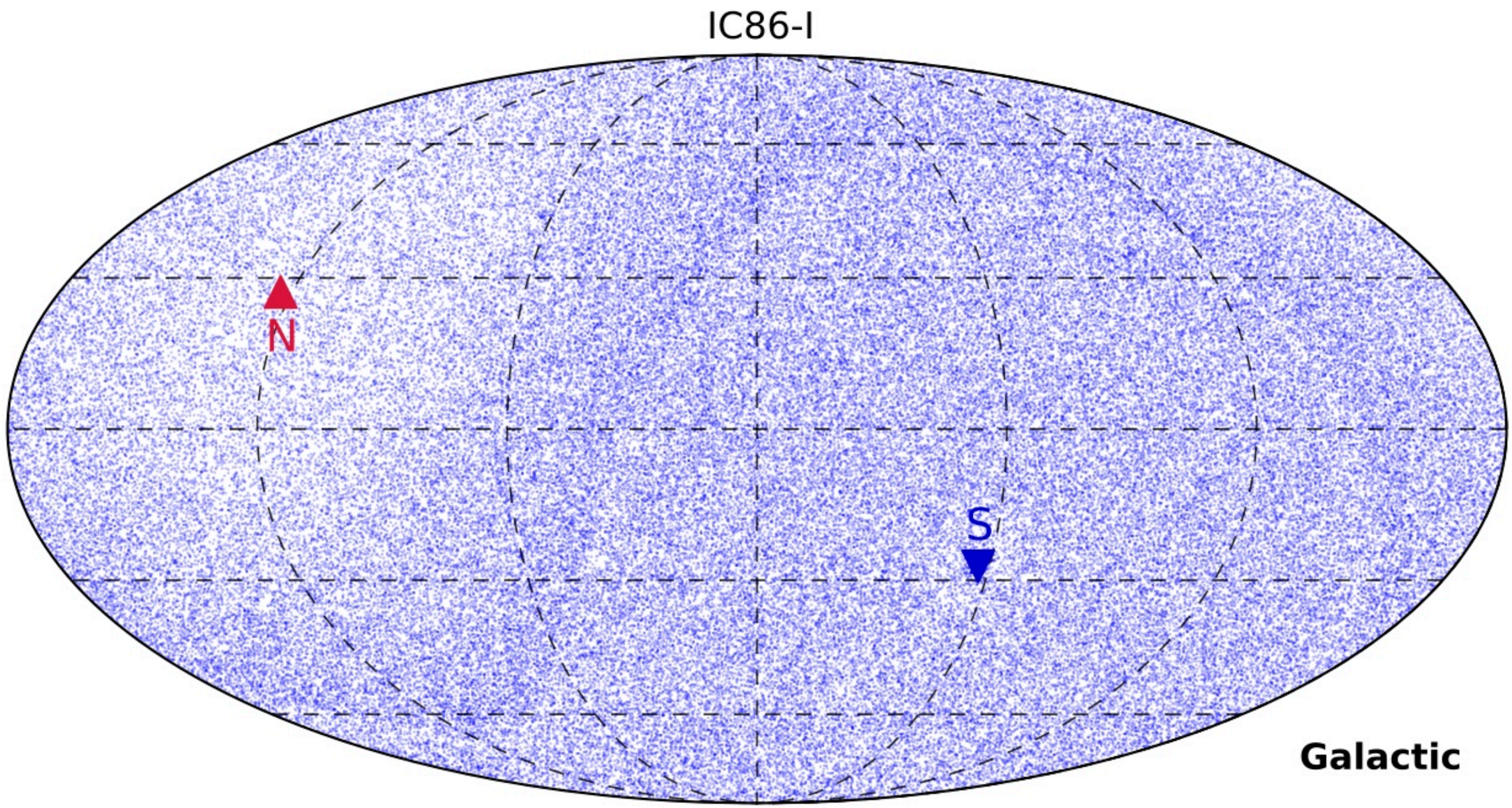
- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

2 year HESE



Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

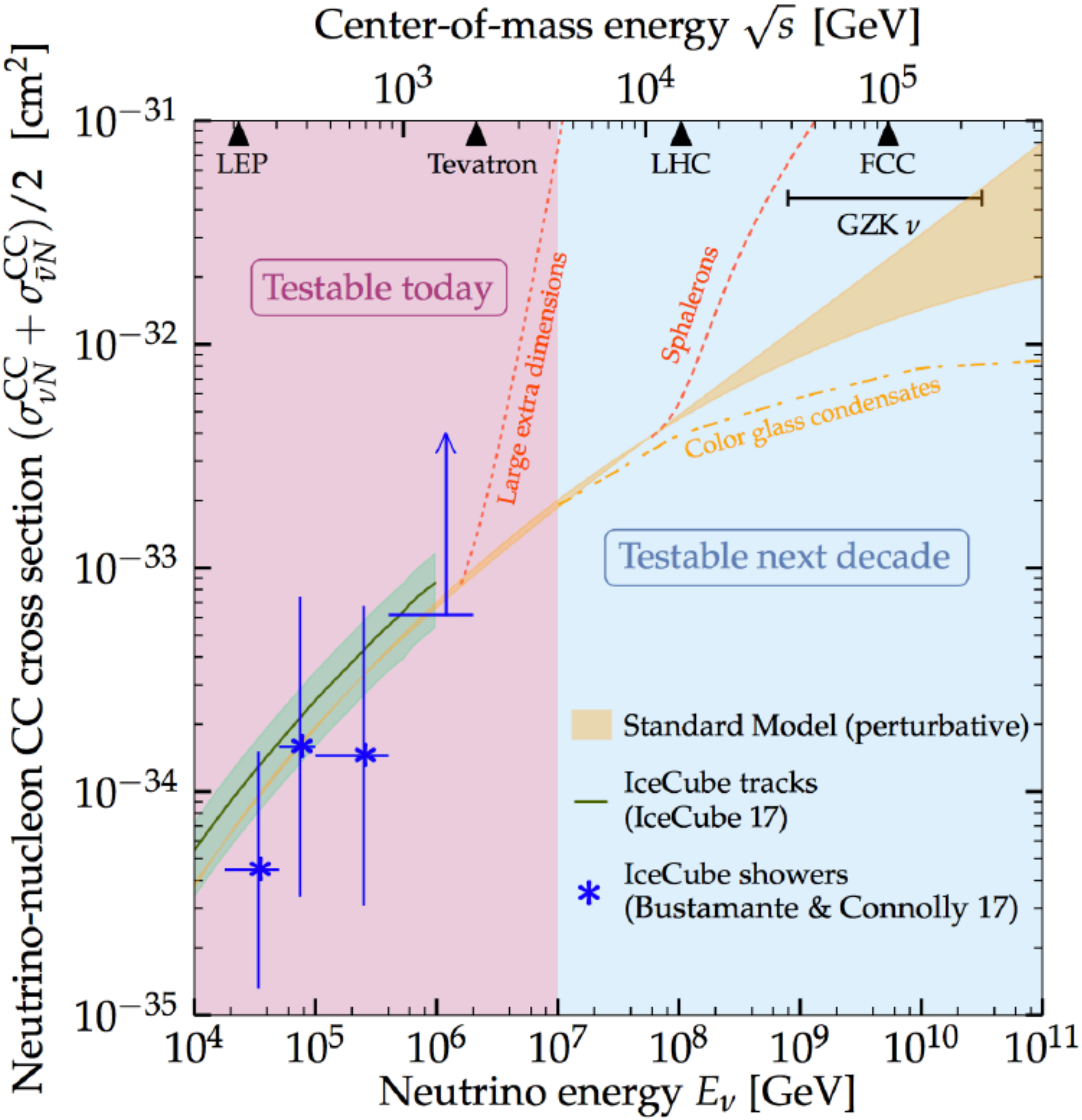


138322 neutrino candidates in one year

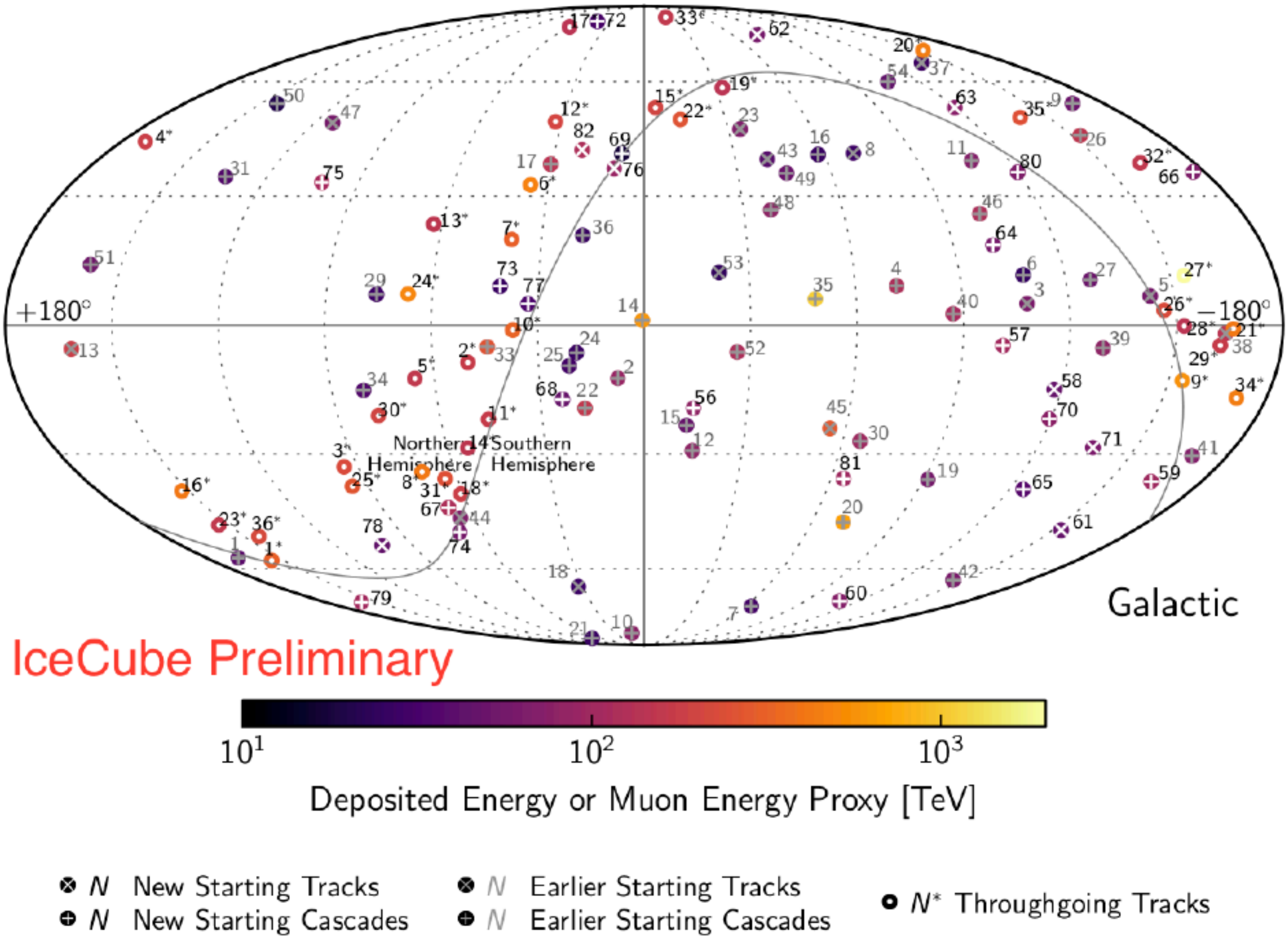
120 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

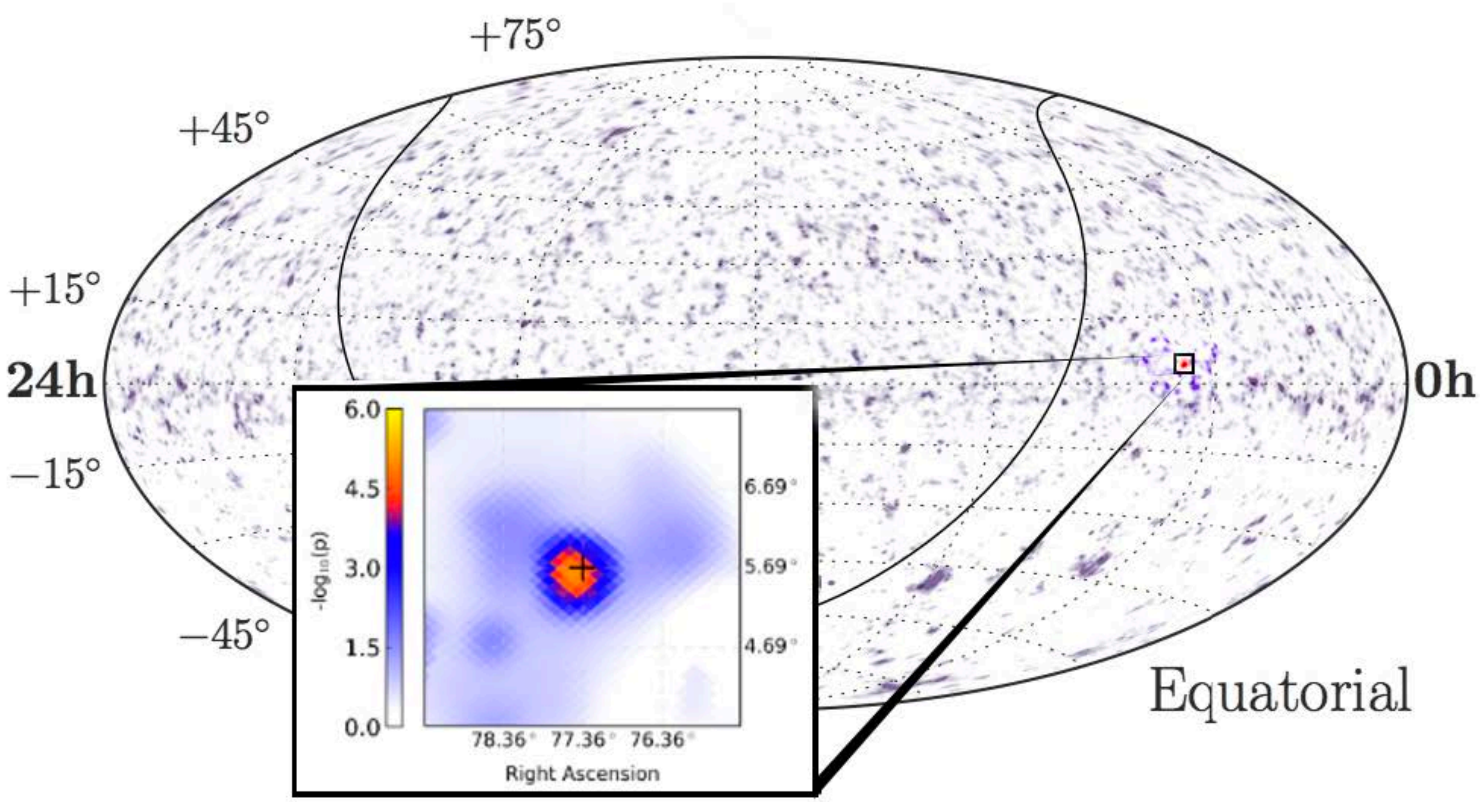
structure in the map results from neutrino absorption by the Earth



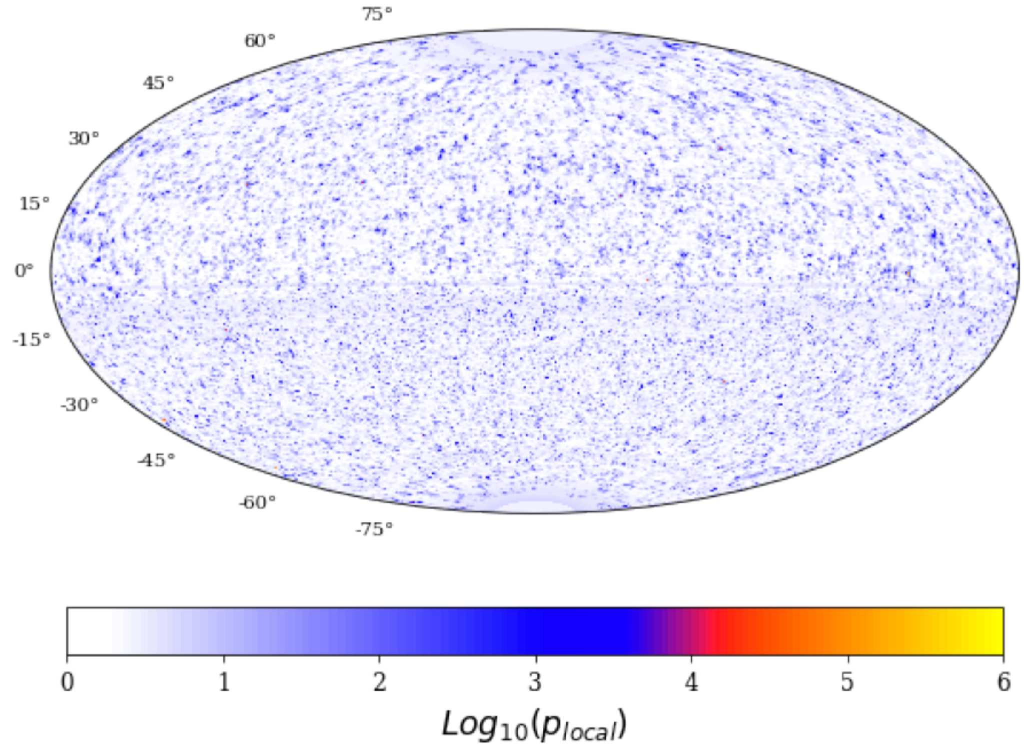
Center-of-mass energy $\sqrt{s}$ [GeV]
10^3
10^4
10^5
Neutrino-nucleon CC cross section $(\sigma_{\nu N}^{CC} + \sigma_{\bar{\nu} N}^{CC})/2$ [cm^2]
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
LEP
Tevatron
LHC
FCC
GZK ν
Testable today
Testable next decade
Large extra dimensions
Sphalerons
Color glass condensates
Standard Model (perturbative)
IceCube tracks
(IceCube 17)
IceCube showers
(Bustamante & Connolly 17)
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy E_ν [GeV]

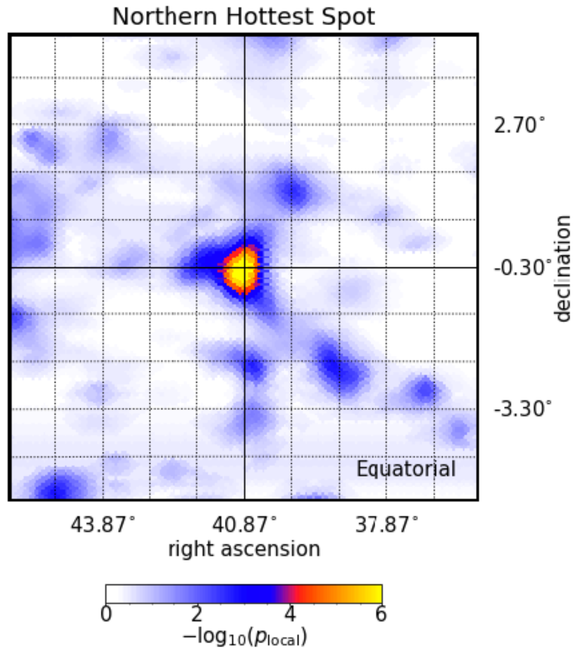

+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates

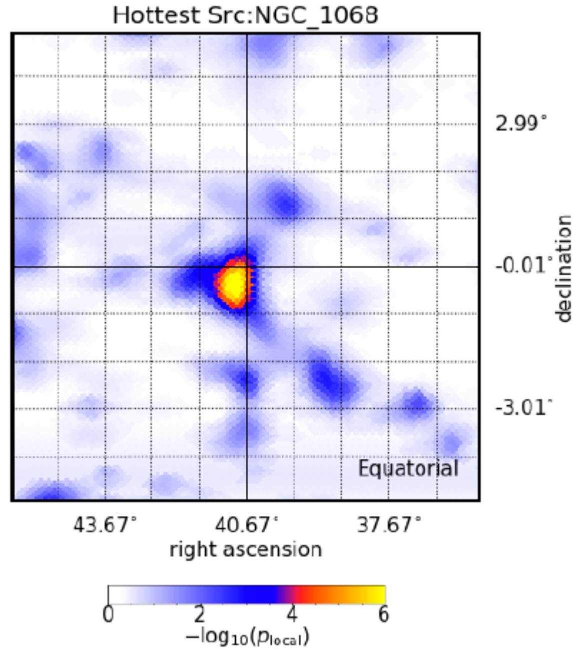


10 years of muon neutrinos

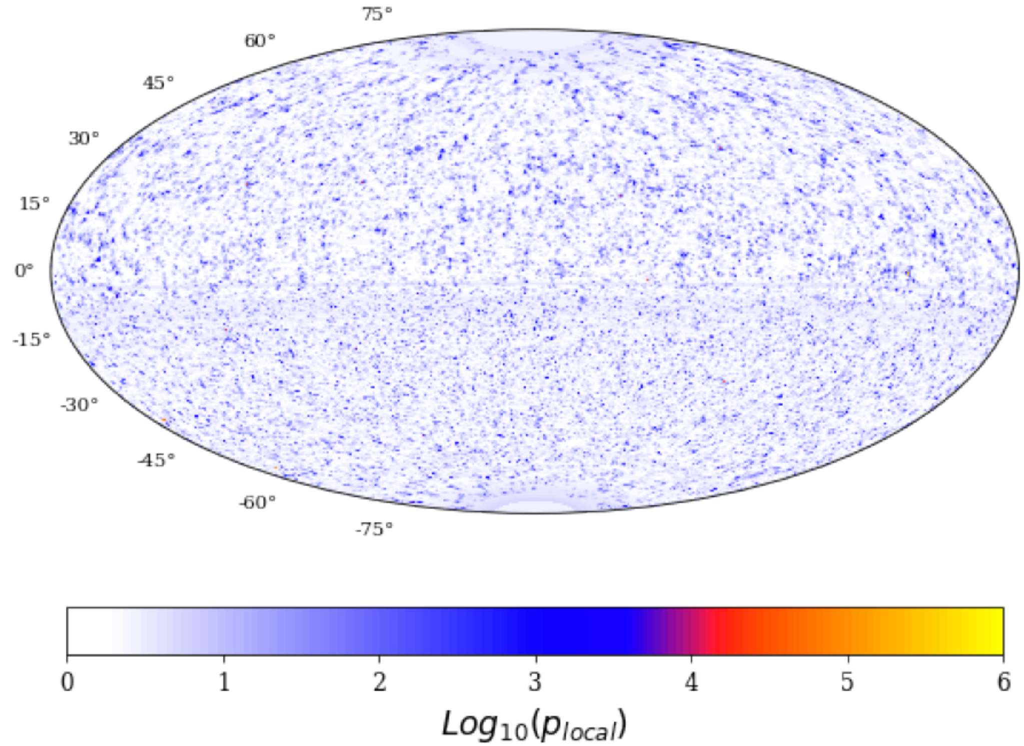


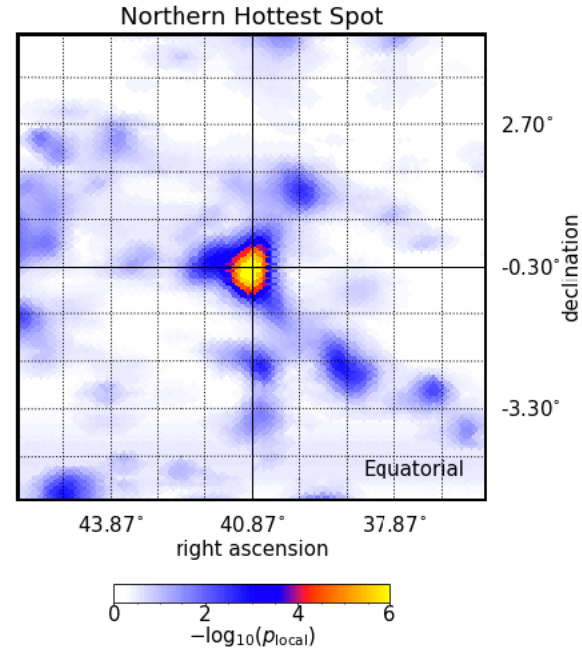


Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496



10 years of muon neutrinos





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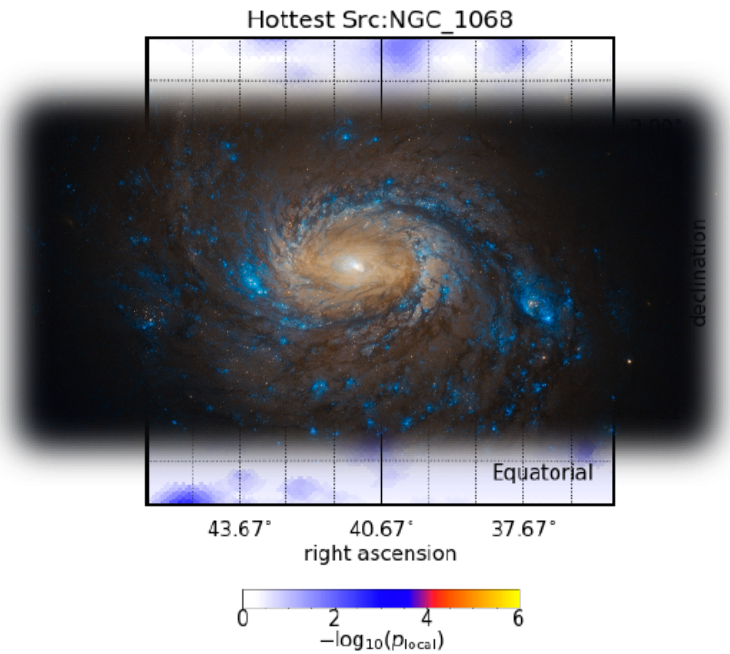
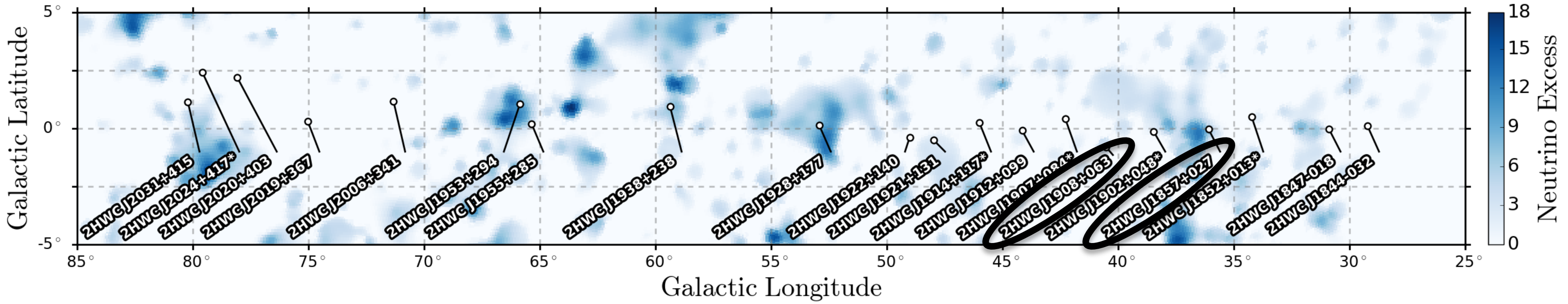
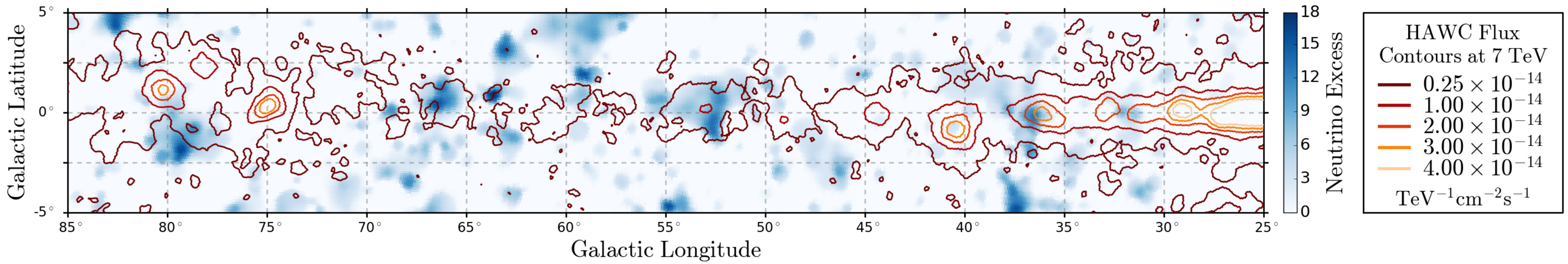


Tessa Carver

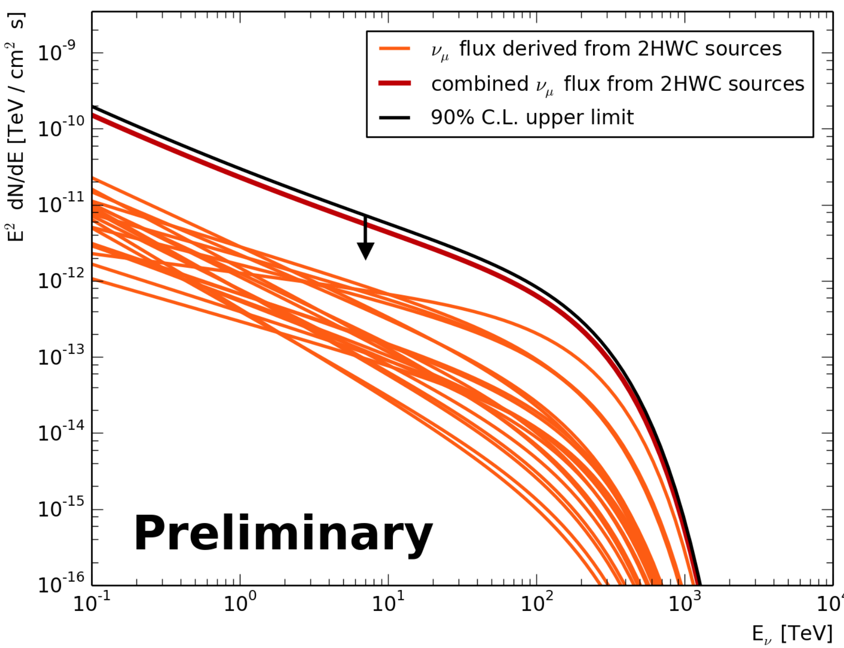
- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

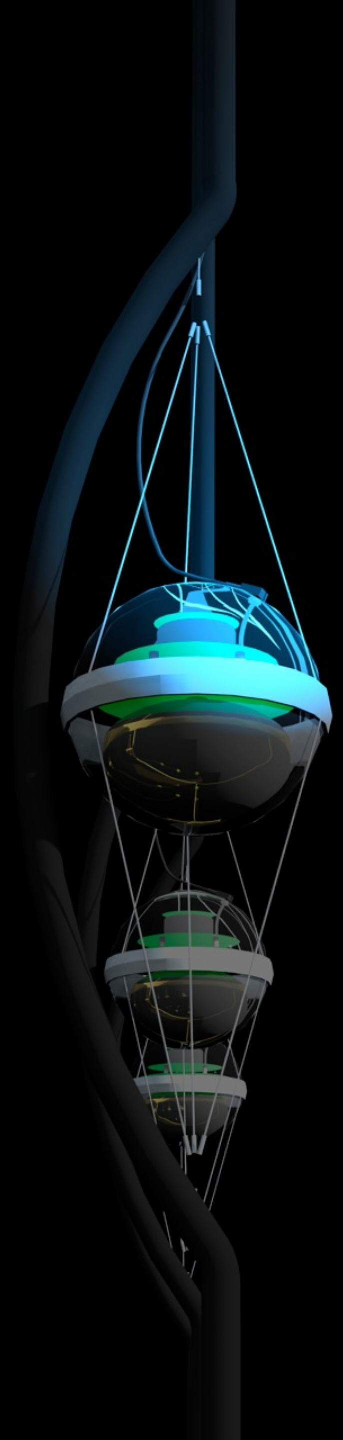




HAWC photons and IceCube neutrinos

neutrino flux at the level predicted, but not significant yet





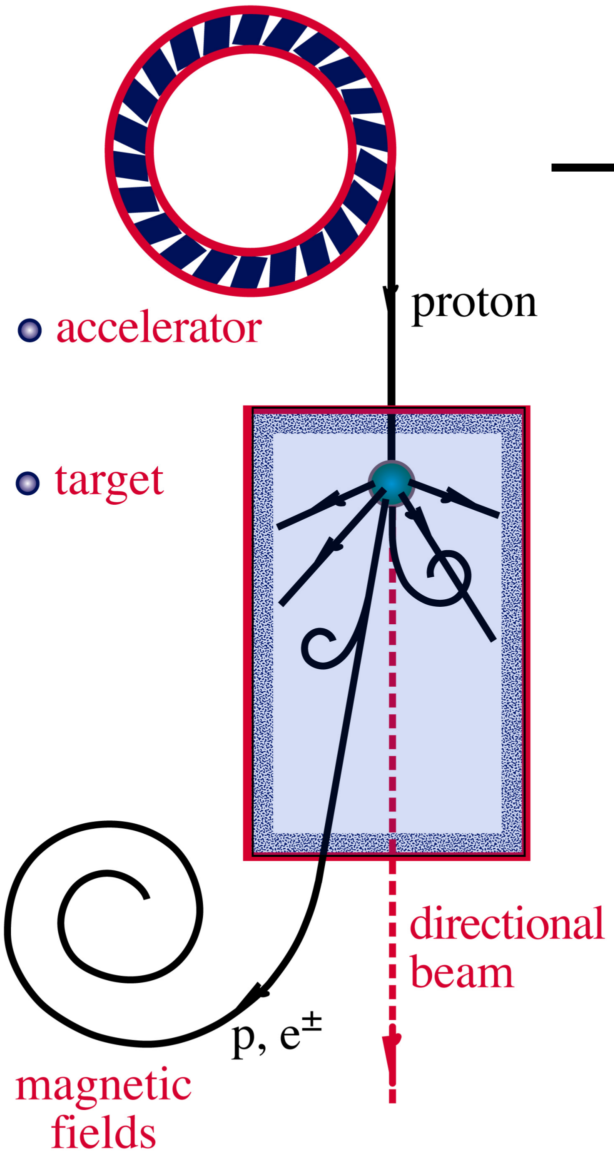
IceCube

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- **Fermi photons and IceCube neutrinos**
- the first high-energy cosmic ray accelerator
- cosmic neutrinos below 100 TeV?

iceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation
and dust

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

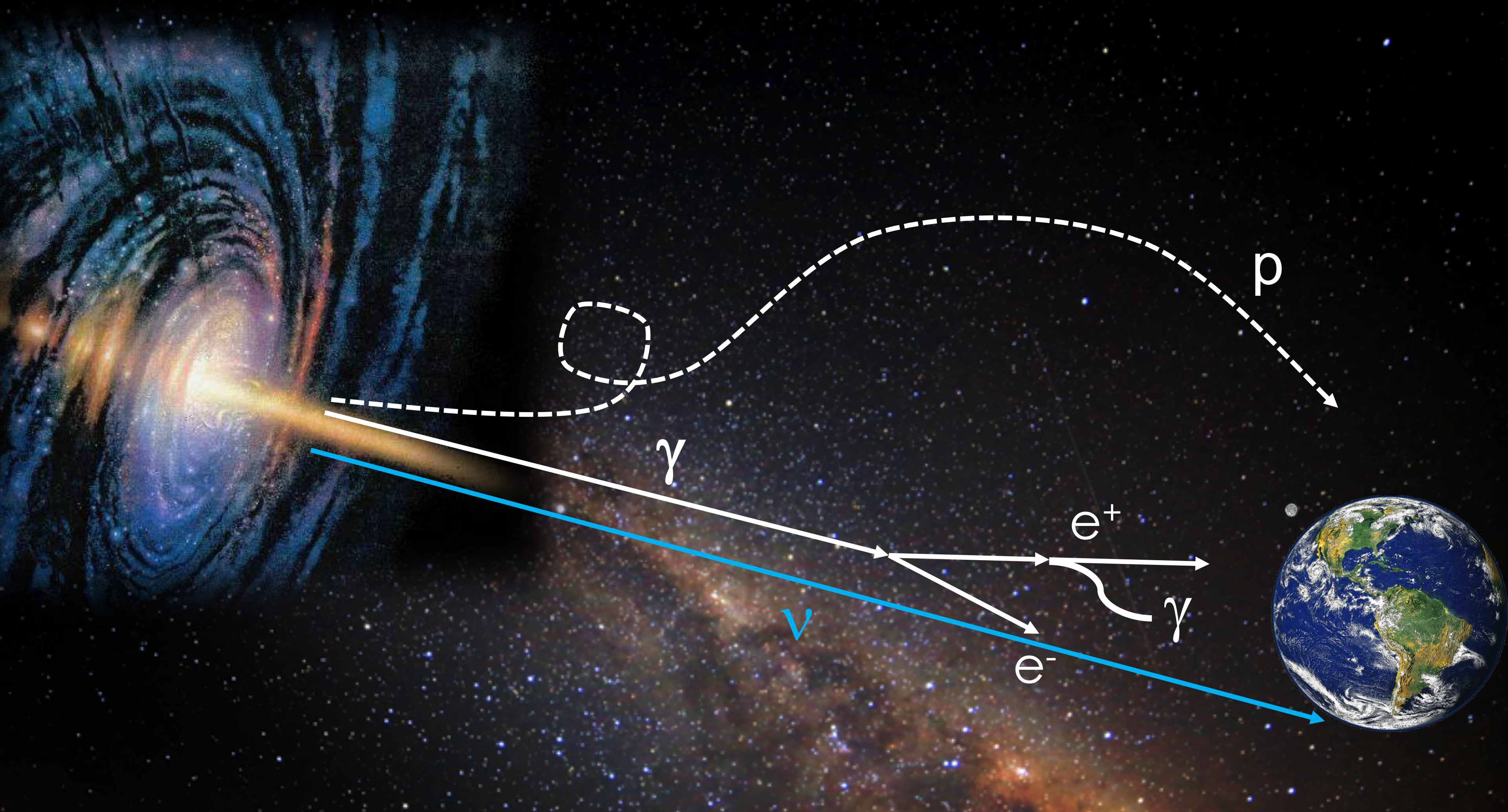
multimessenger astronomy

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

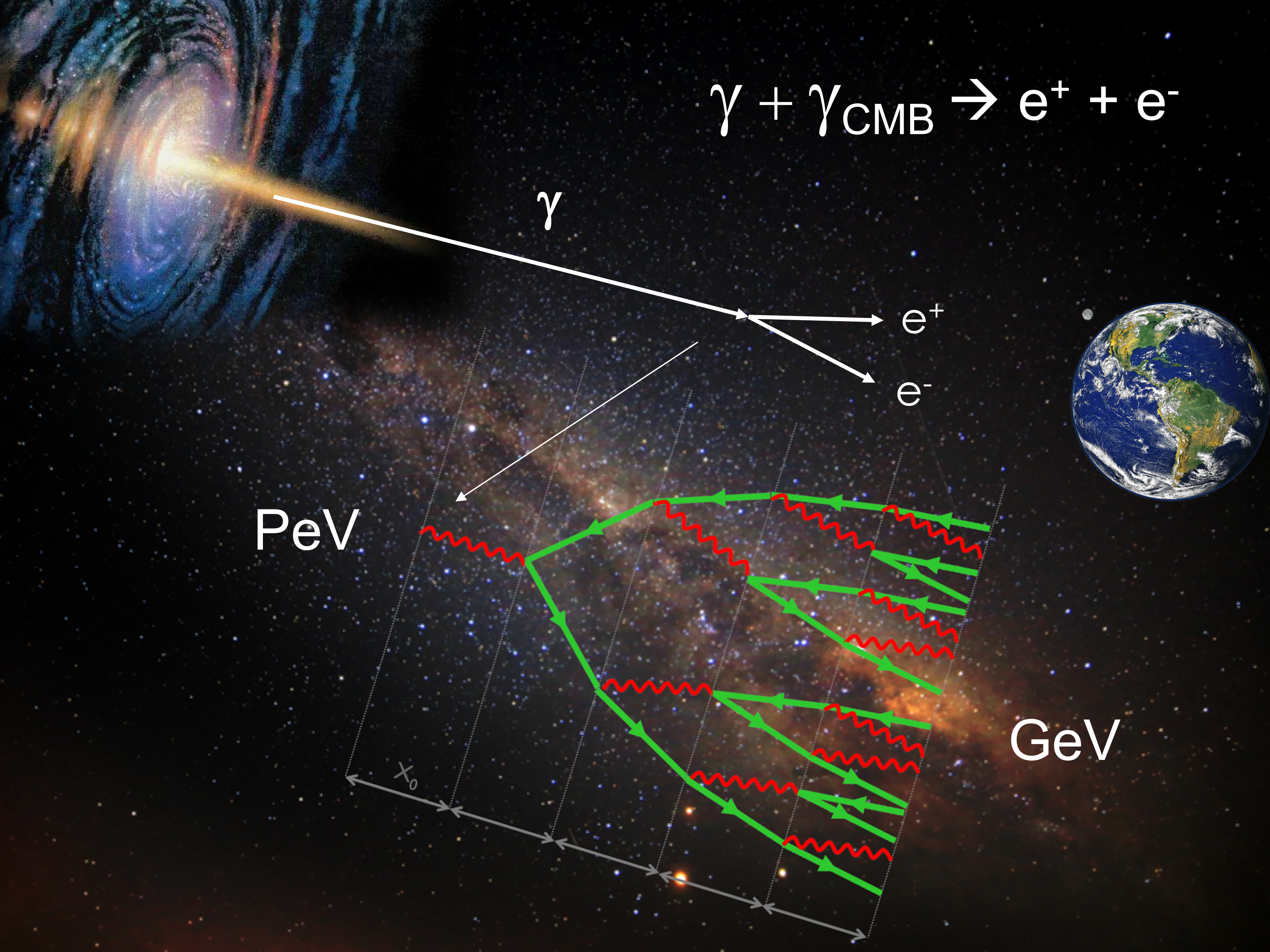
~ cosmic ray + neutrino

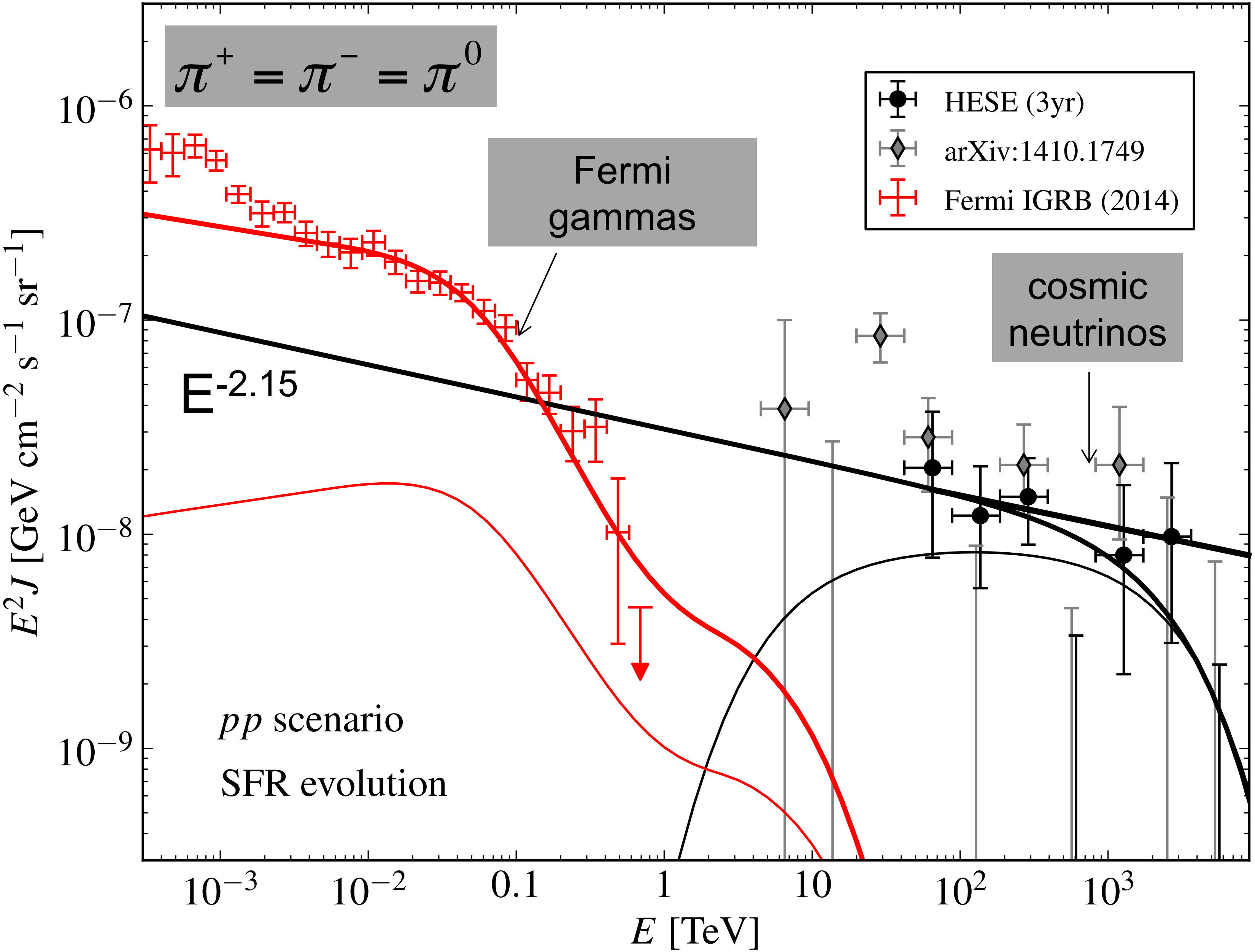
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma



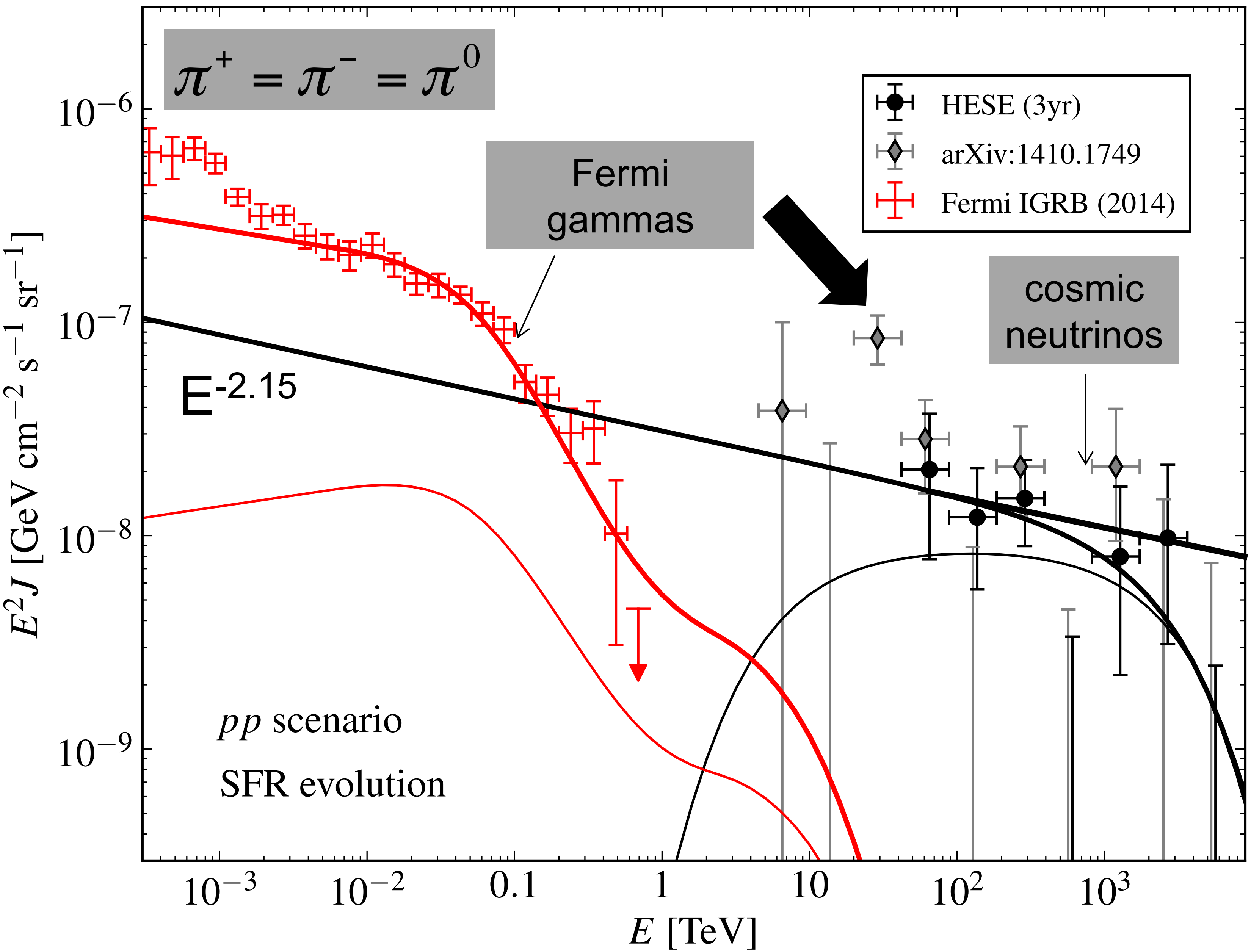
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
X_0
GeV



$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



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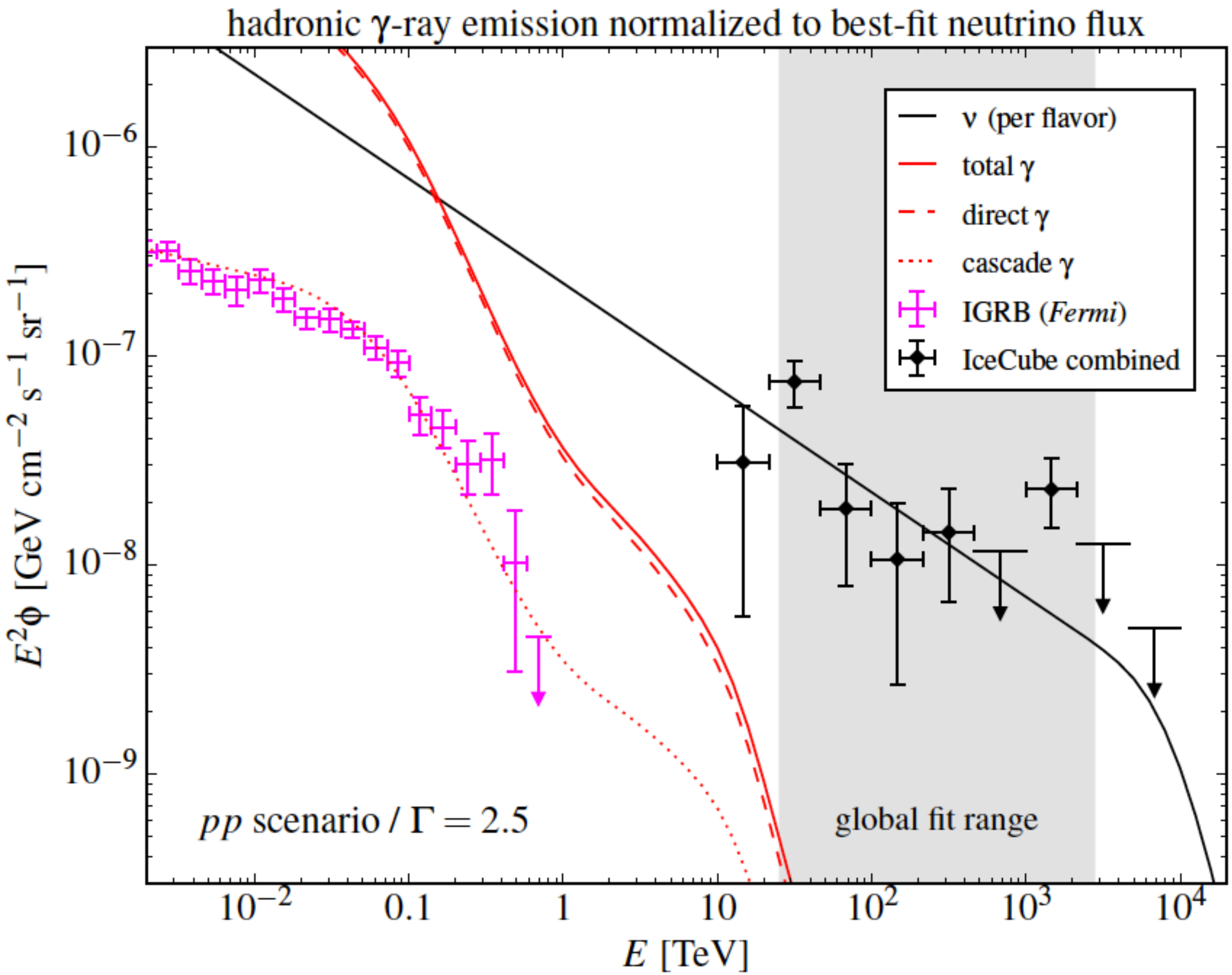
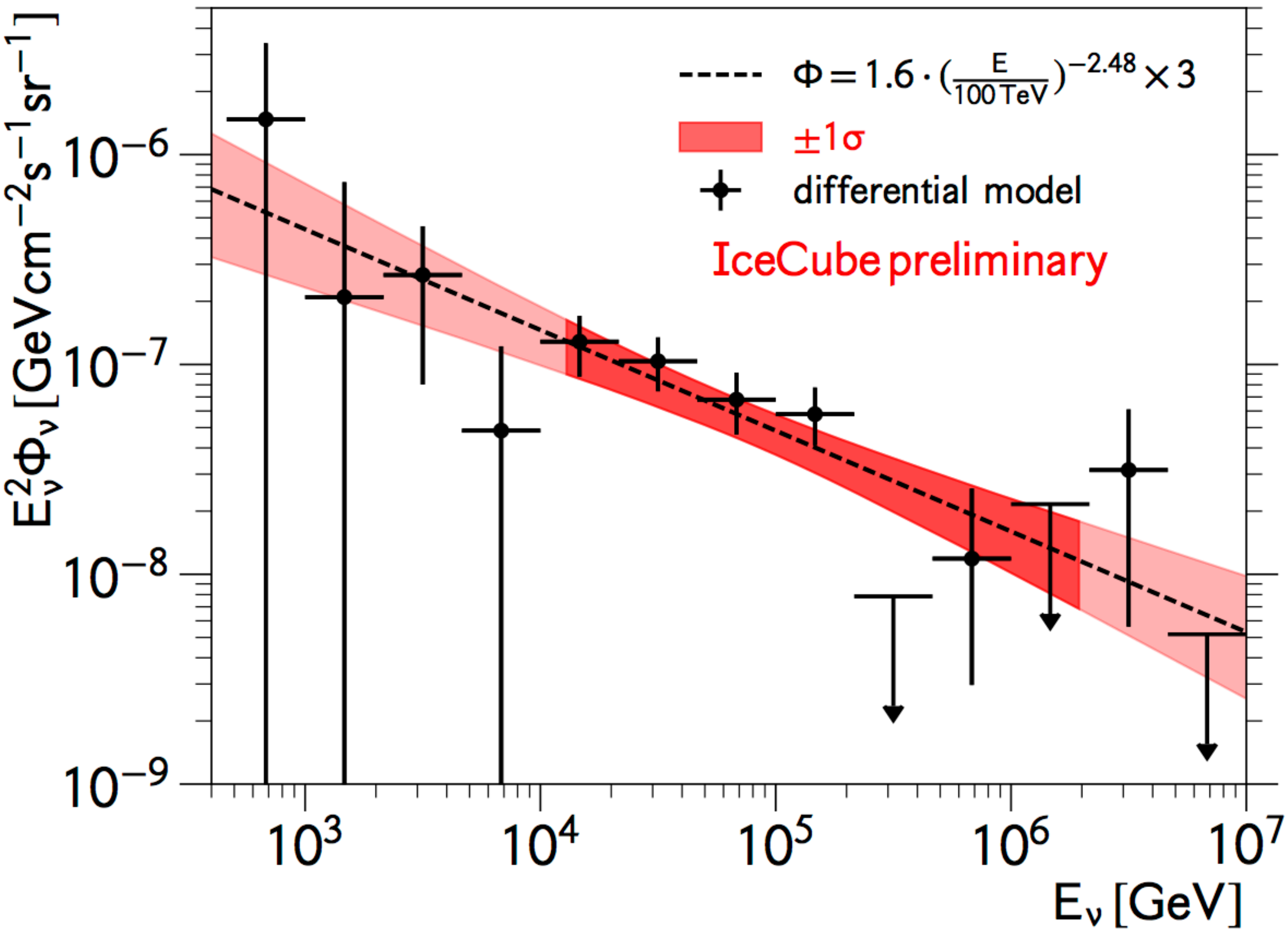
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

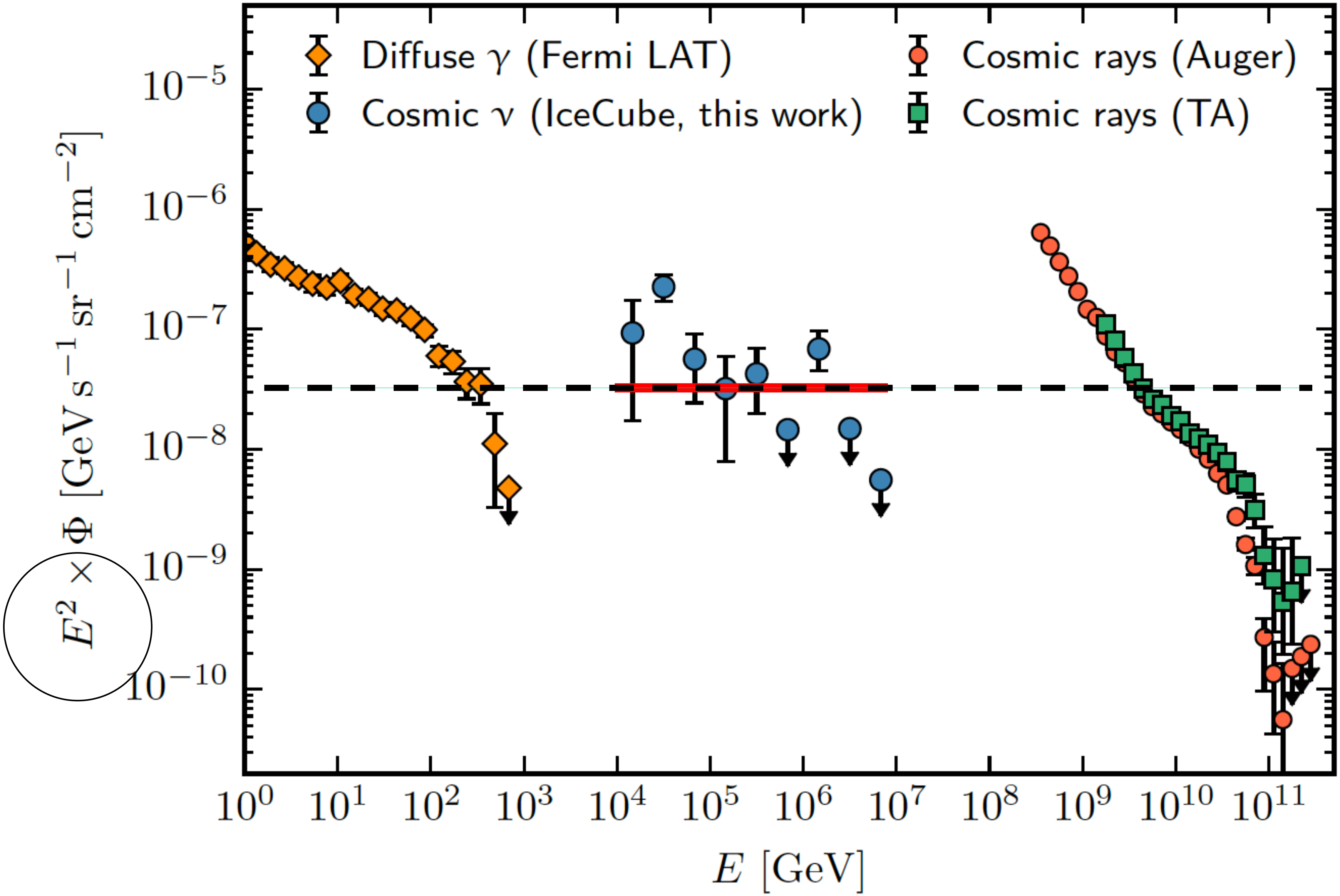


dark sources below 100 TeV not seen in γ's ?

gamma rays cascade in the source to lower energy

Multi-year cascade ($\nu_e+\nu_\tau$) analysis: dark sources ?





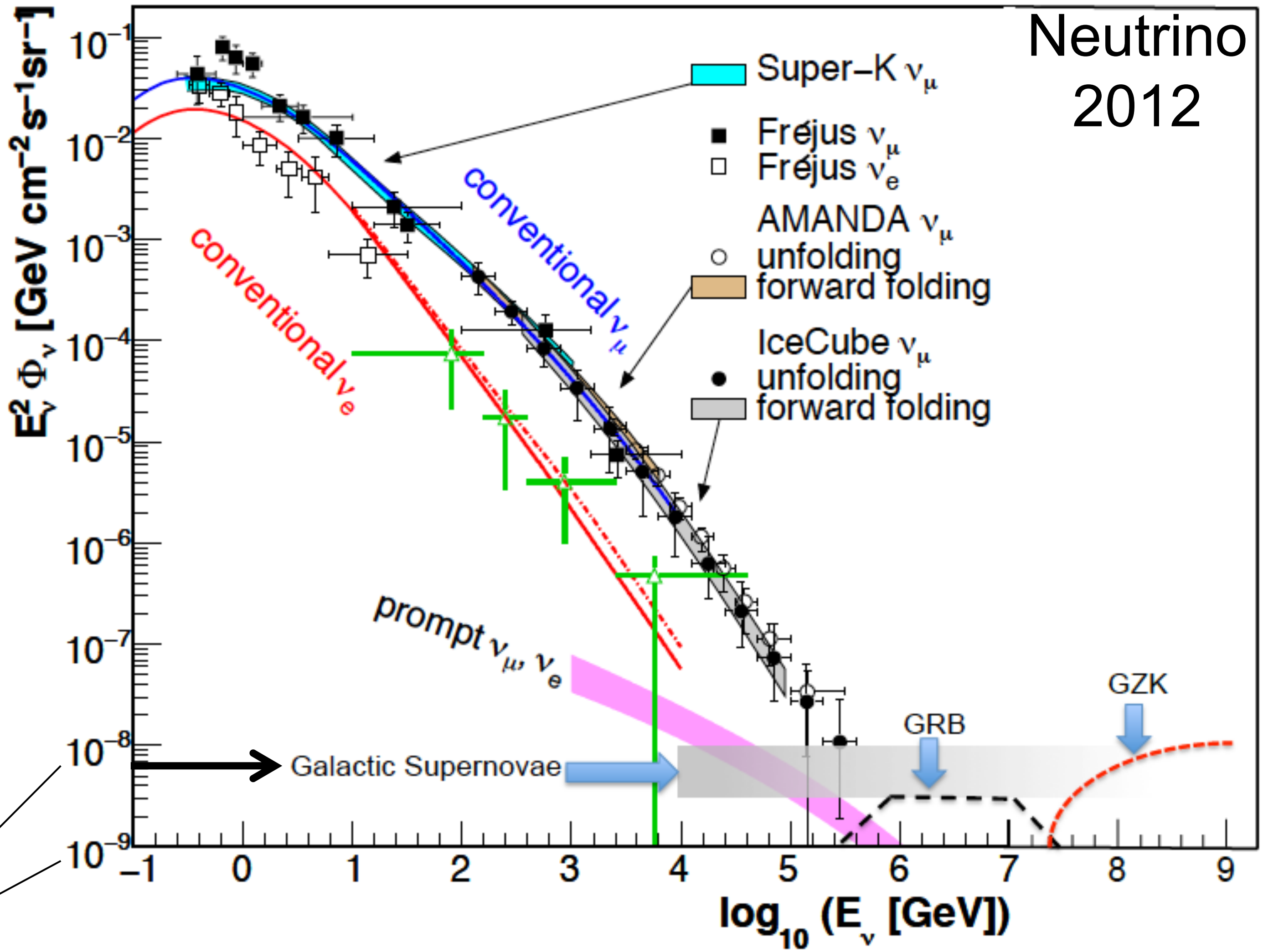
energy in the Universe in gamma rays, neutrinos and cosmic rays

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

$dN/dE \sim E^{-2}$

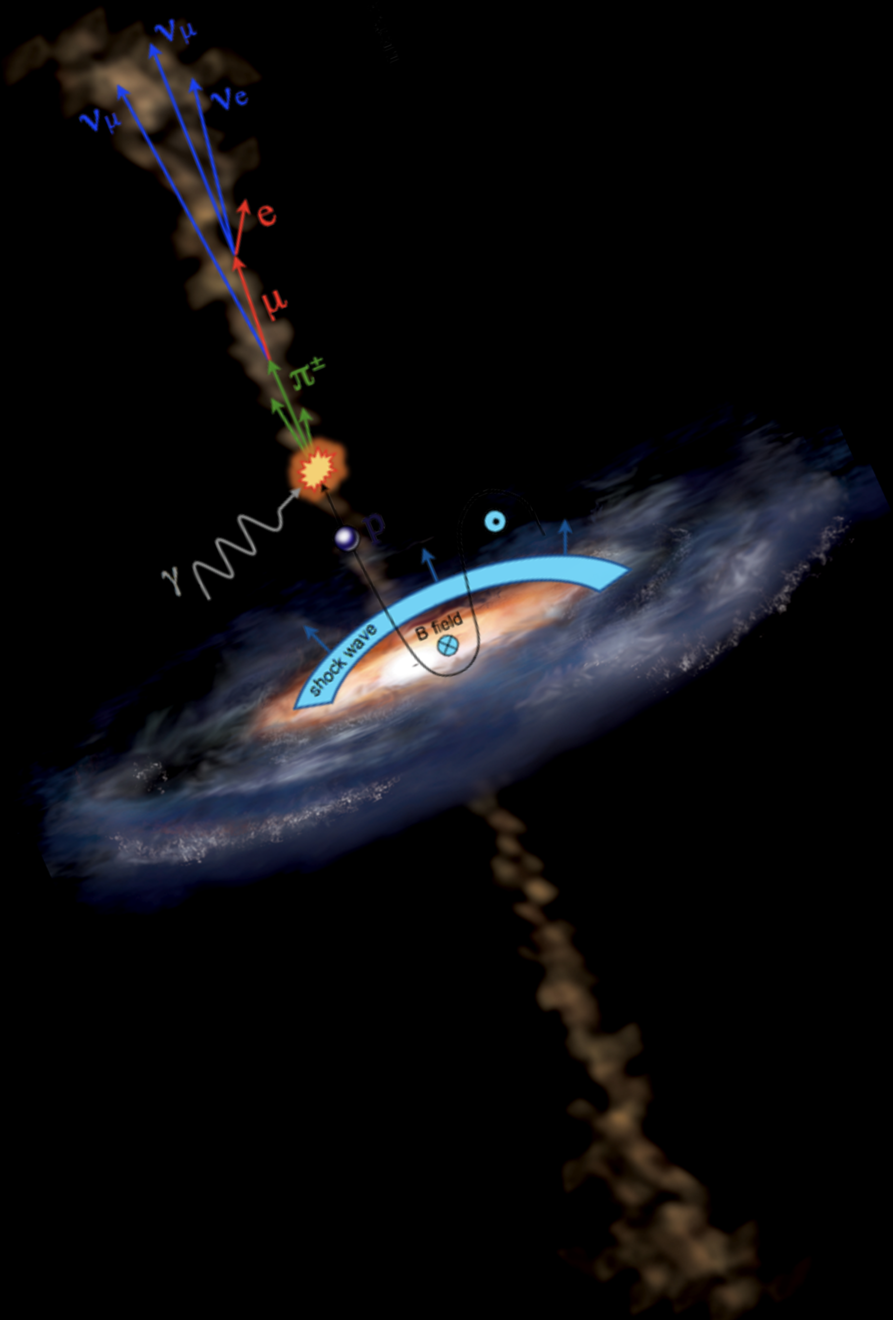
10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV

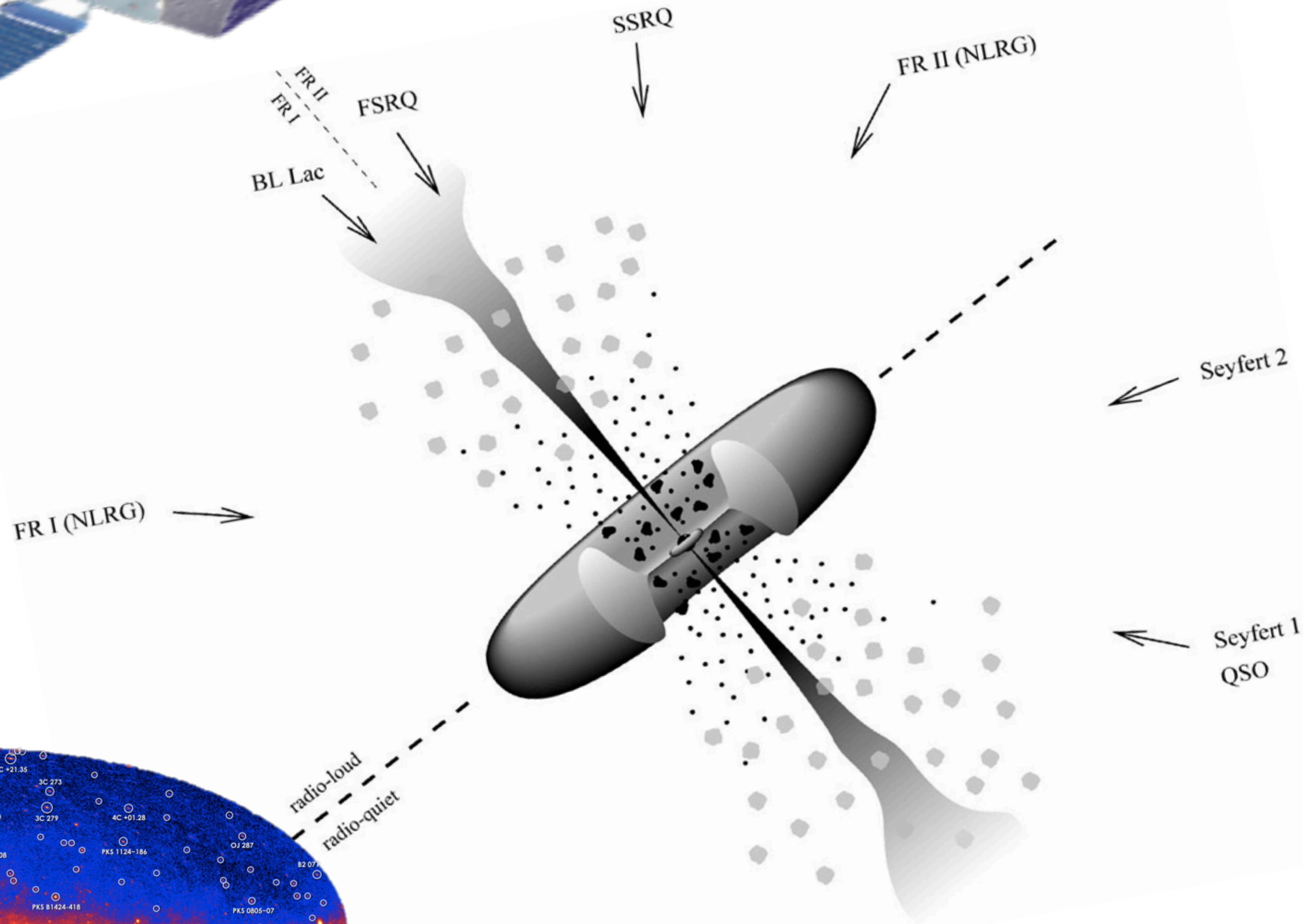


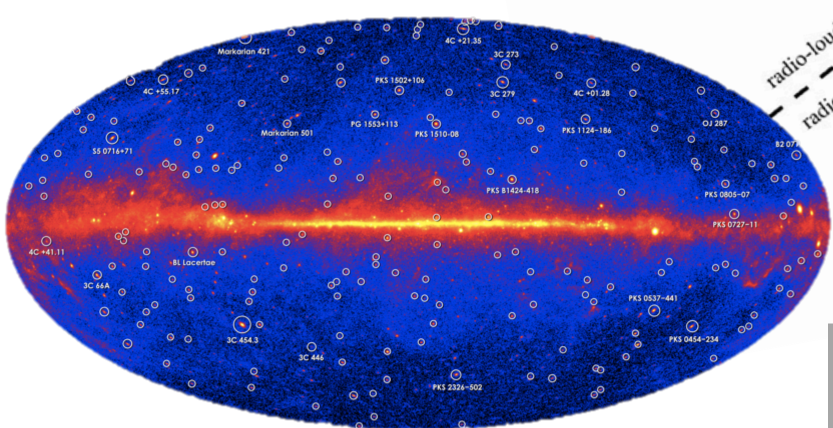
Fermi sources are mostly blazars

common sources?

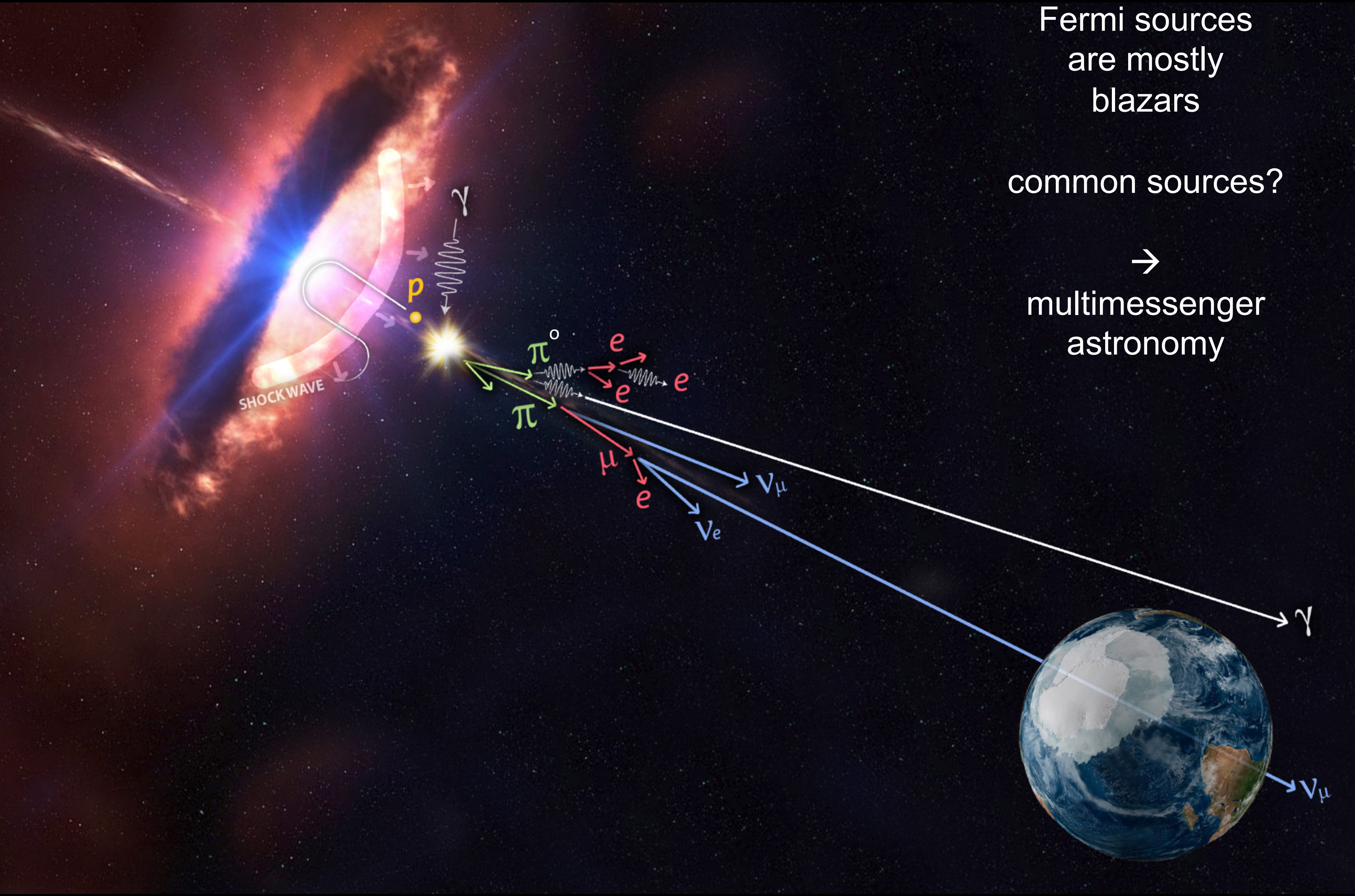
→

multimessenger astronomy





Fermi sky: mostly bazars



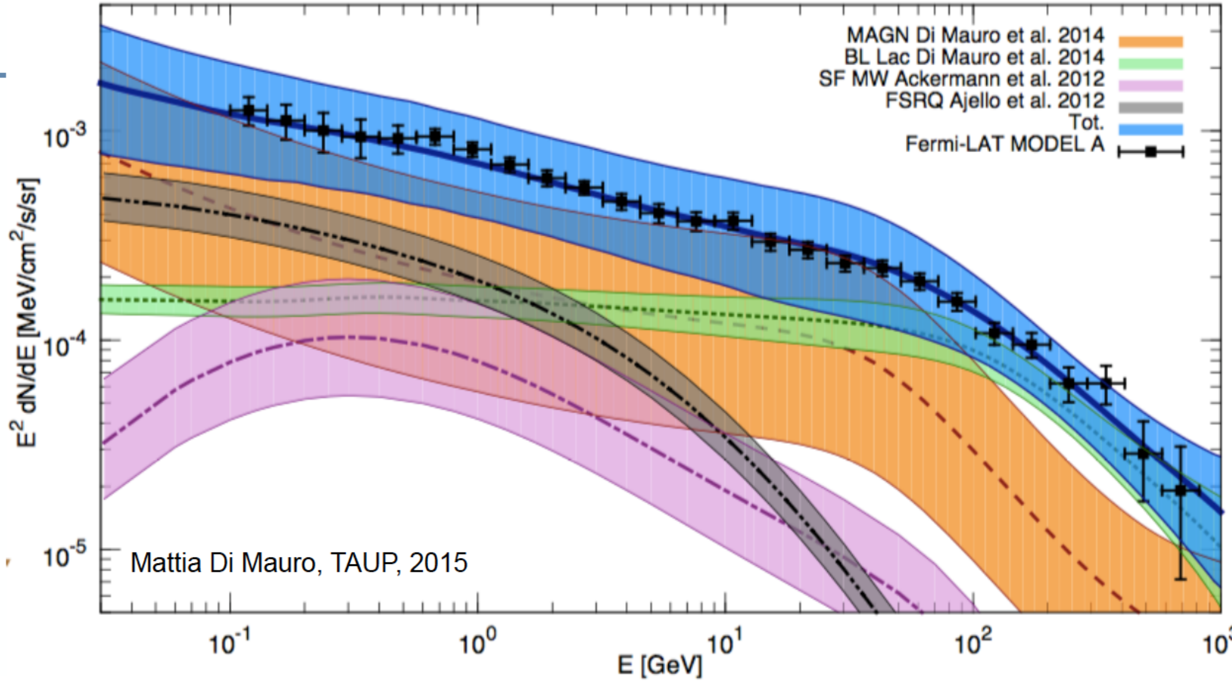
Fermi sources are mostly blazars

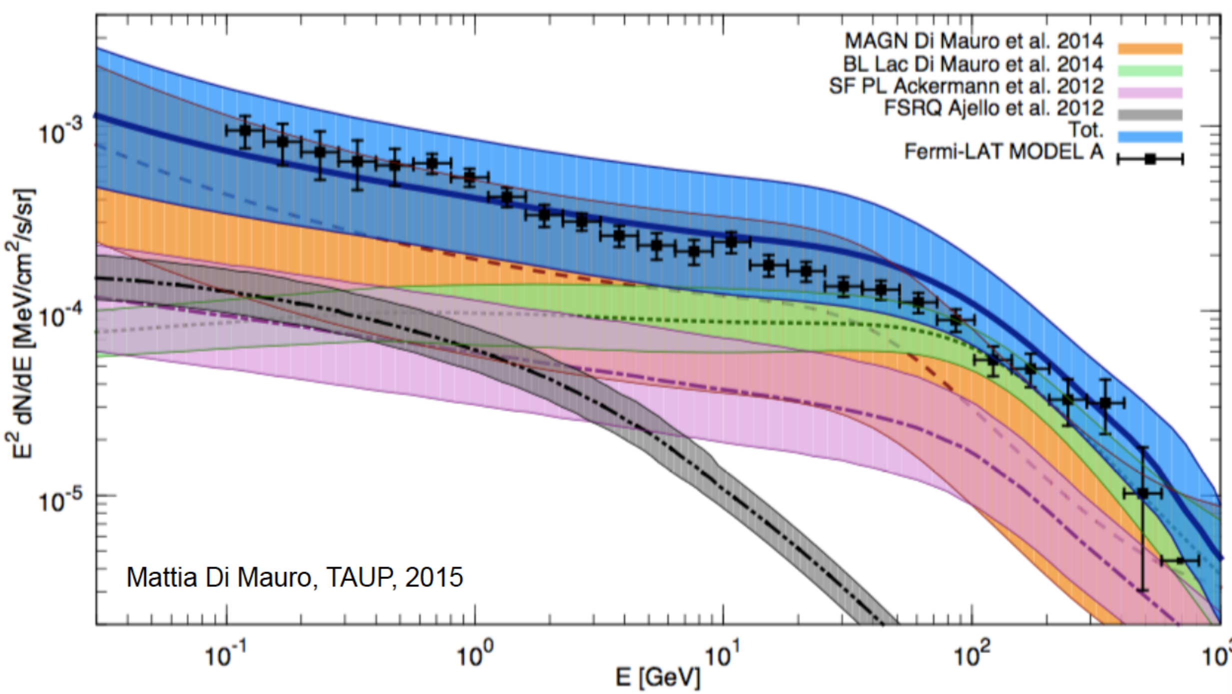
common sources?

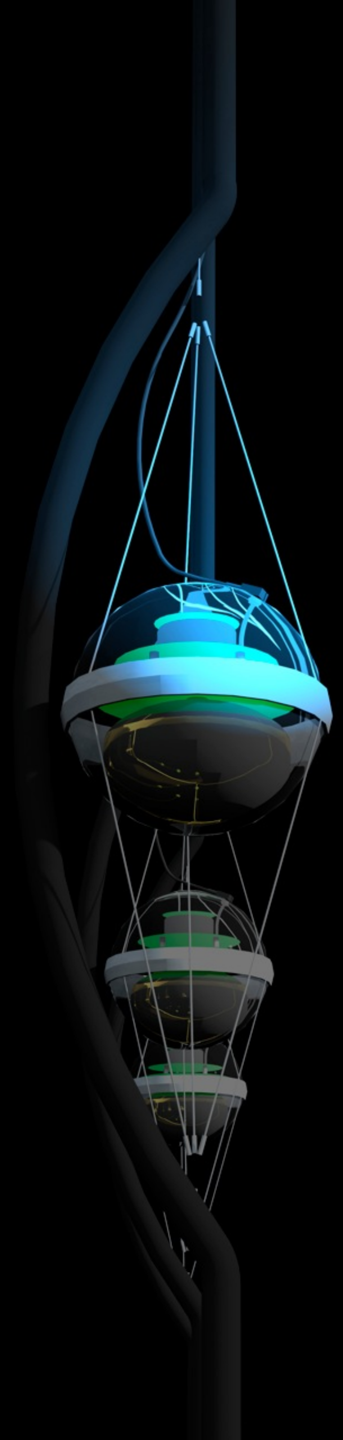
→ multimessenger astronomy

A census

- **BL Lac class of Blazars dominates the high-energy gamma-ray emission**
  - 86% (+16%/-14%) above 50 GeV
- **Large uncertainties in radio-galaxy and star-forming galaxy contributions**
- **Real diffuse contributions must be small**
  - UHECR interactions
  - WIMP annihilation
  - etc.







IceCube

francis halzen

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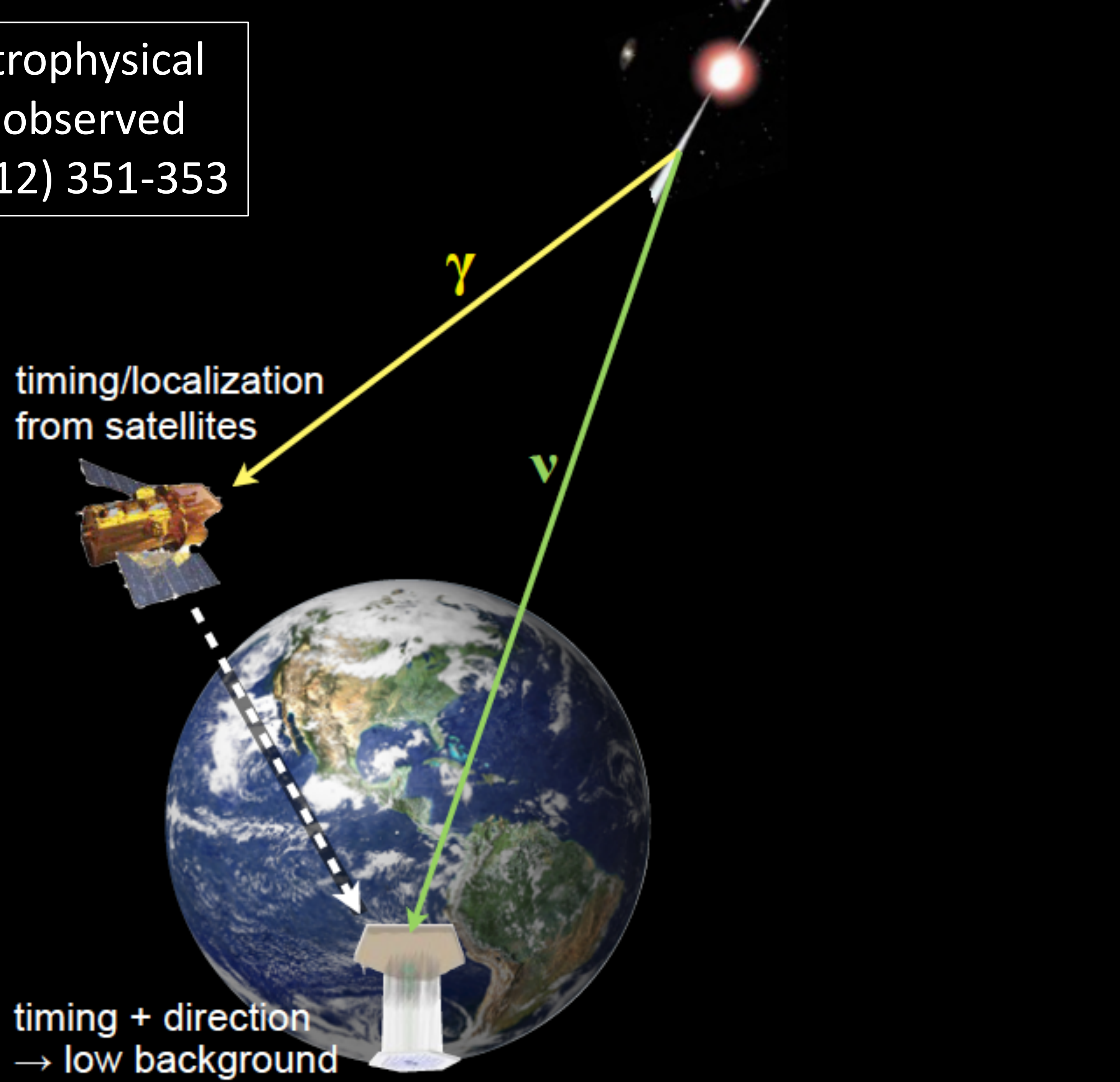
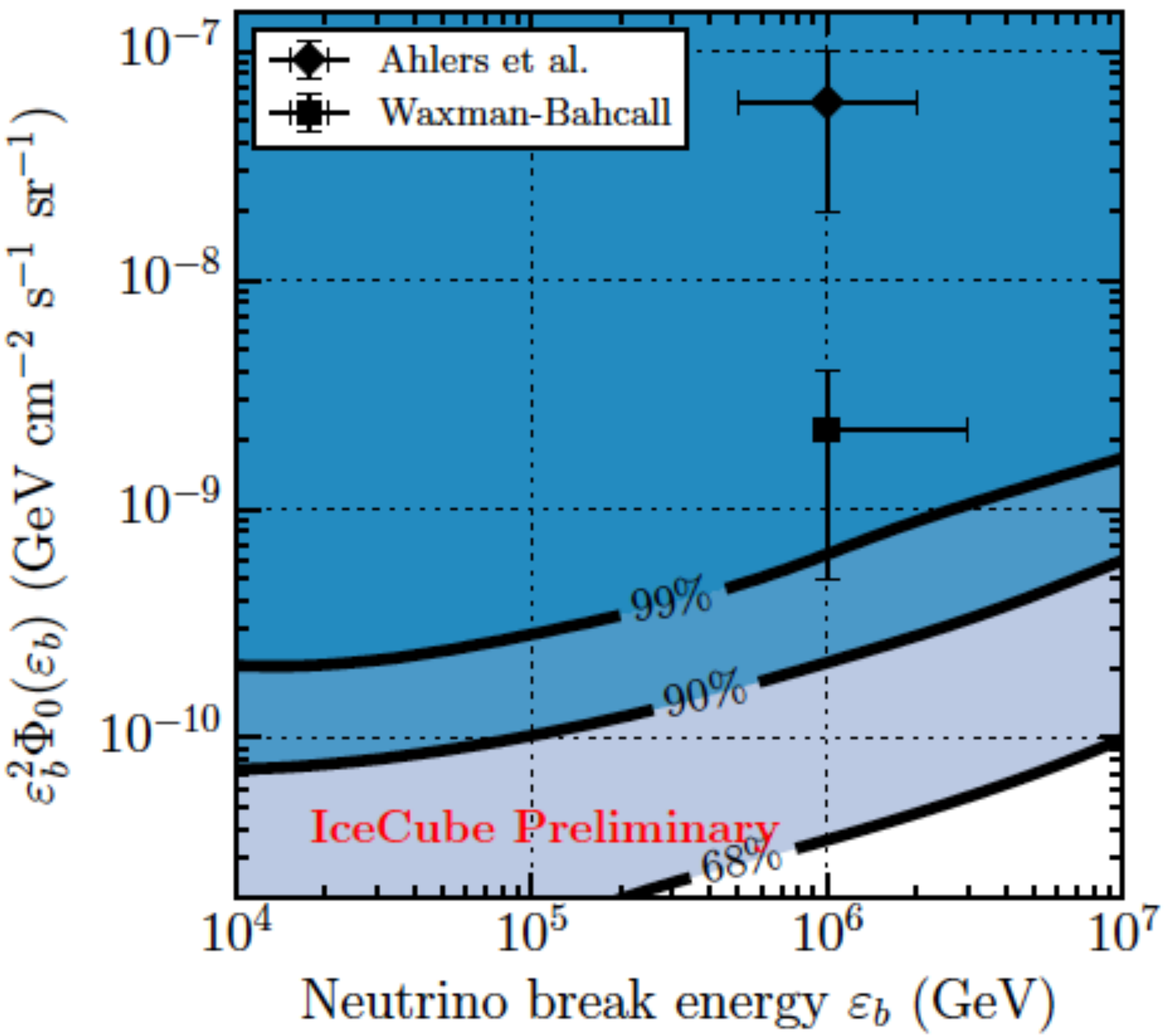
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

iceCube.wisc.edu

flux < 1% of astrophysical neutrino flux observed Nature 484 (2012) 351-353



multimessenger astronomy: wrong alerts?



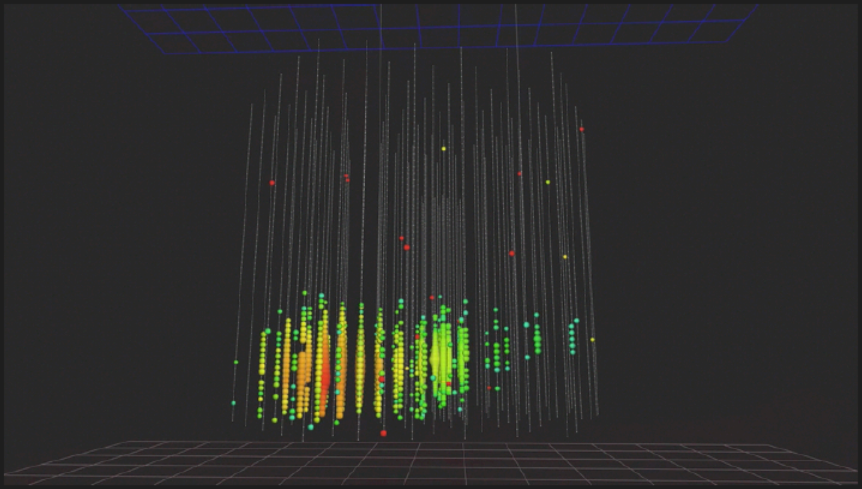
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

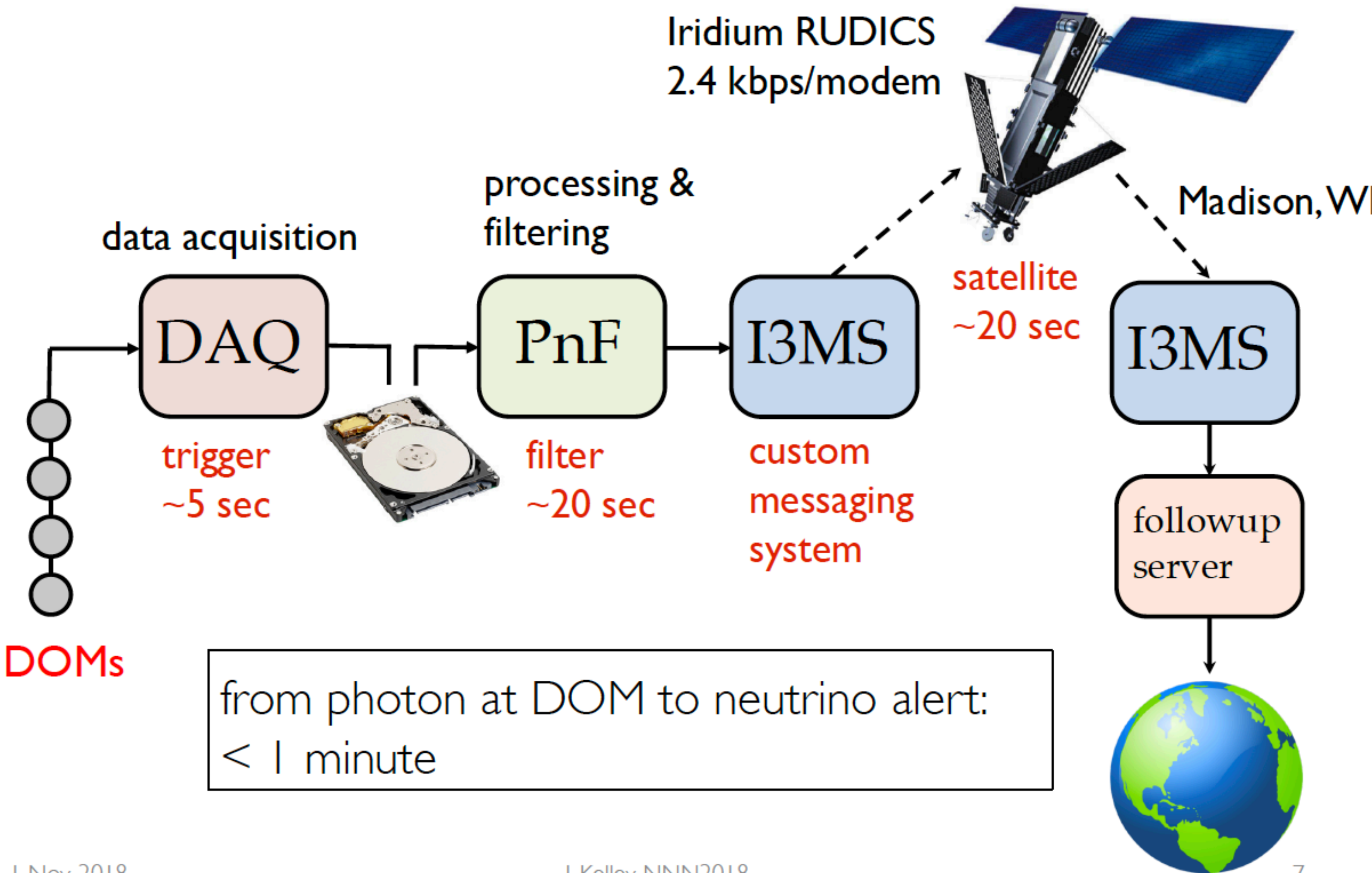
GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them.**



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!



IceCube Trigger

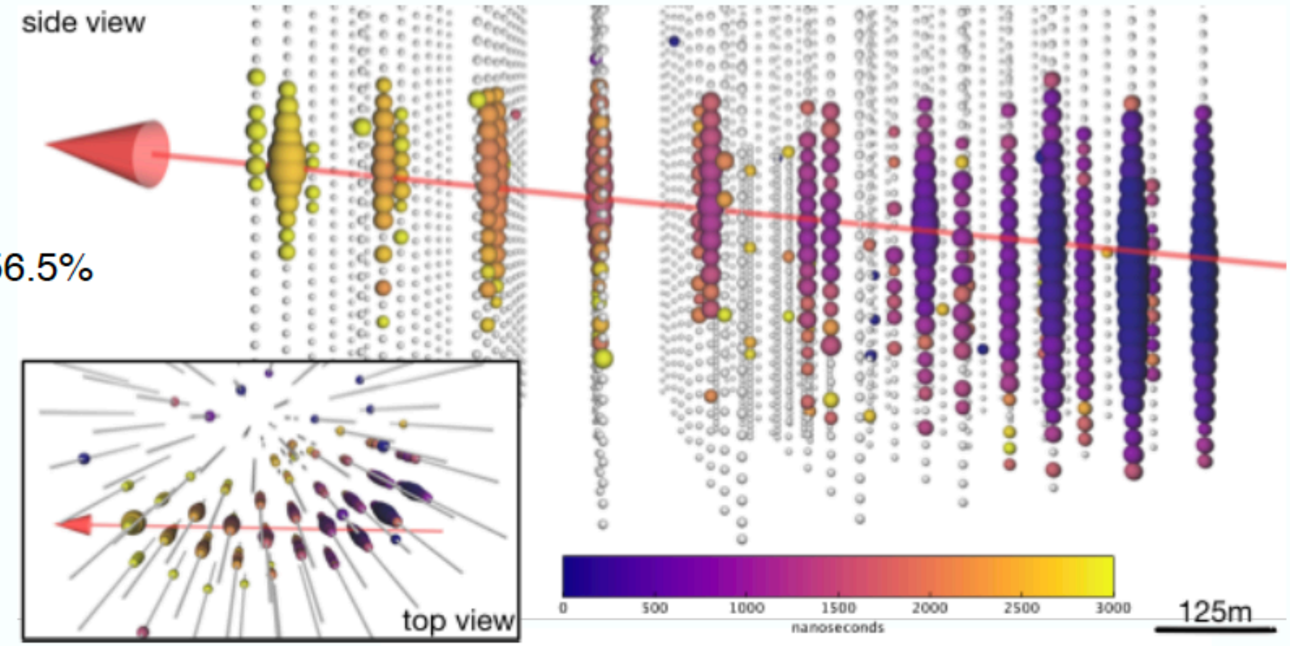
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

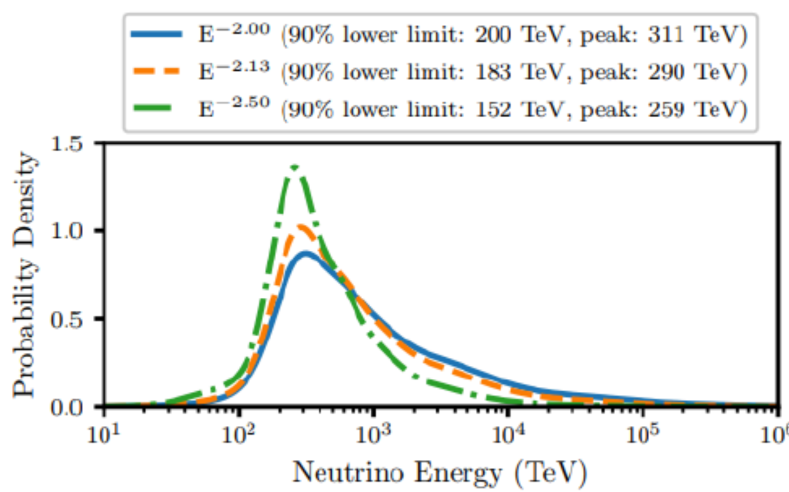
IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%



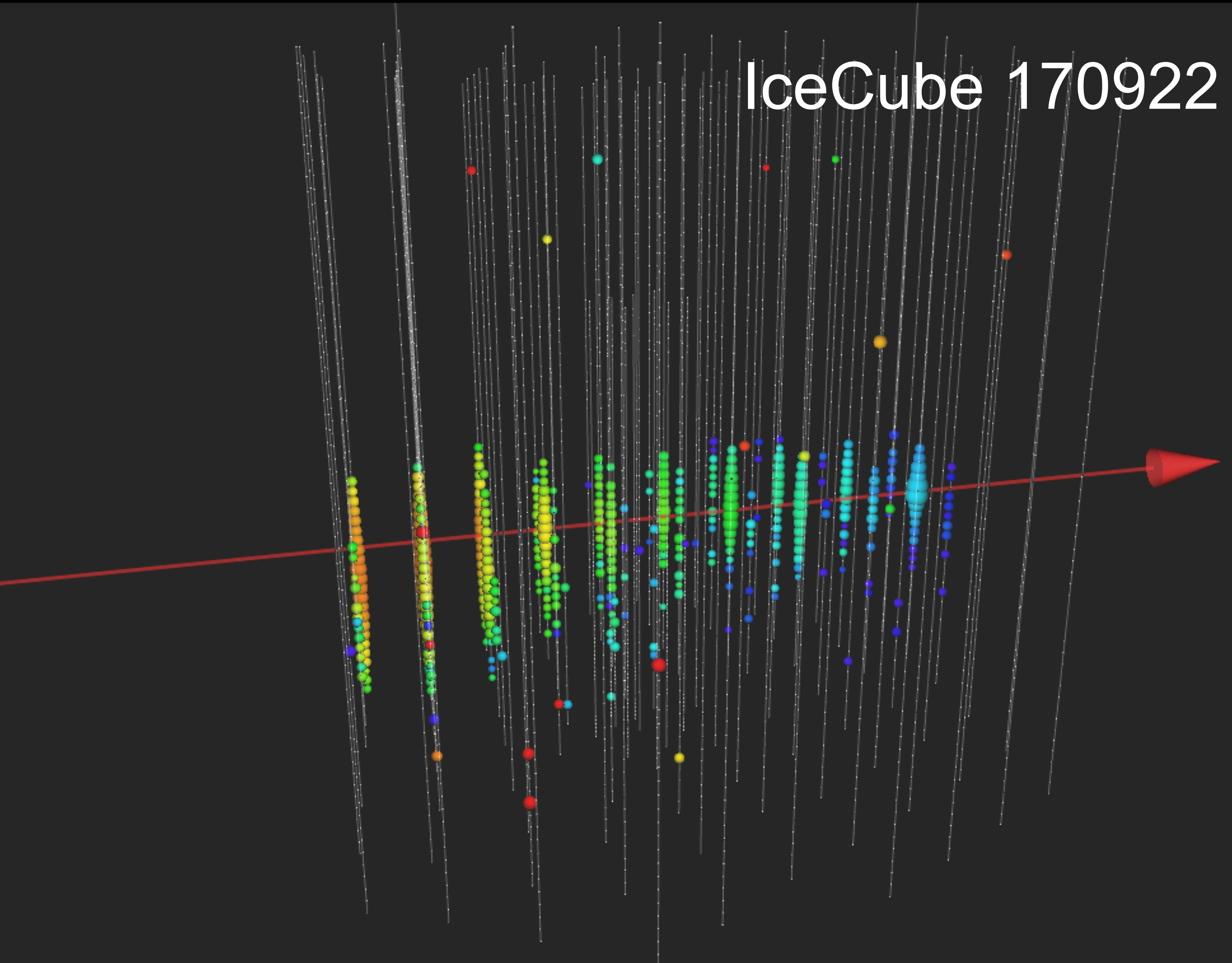
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

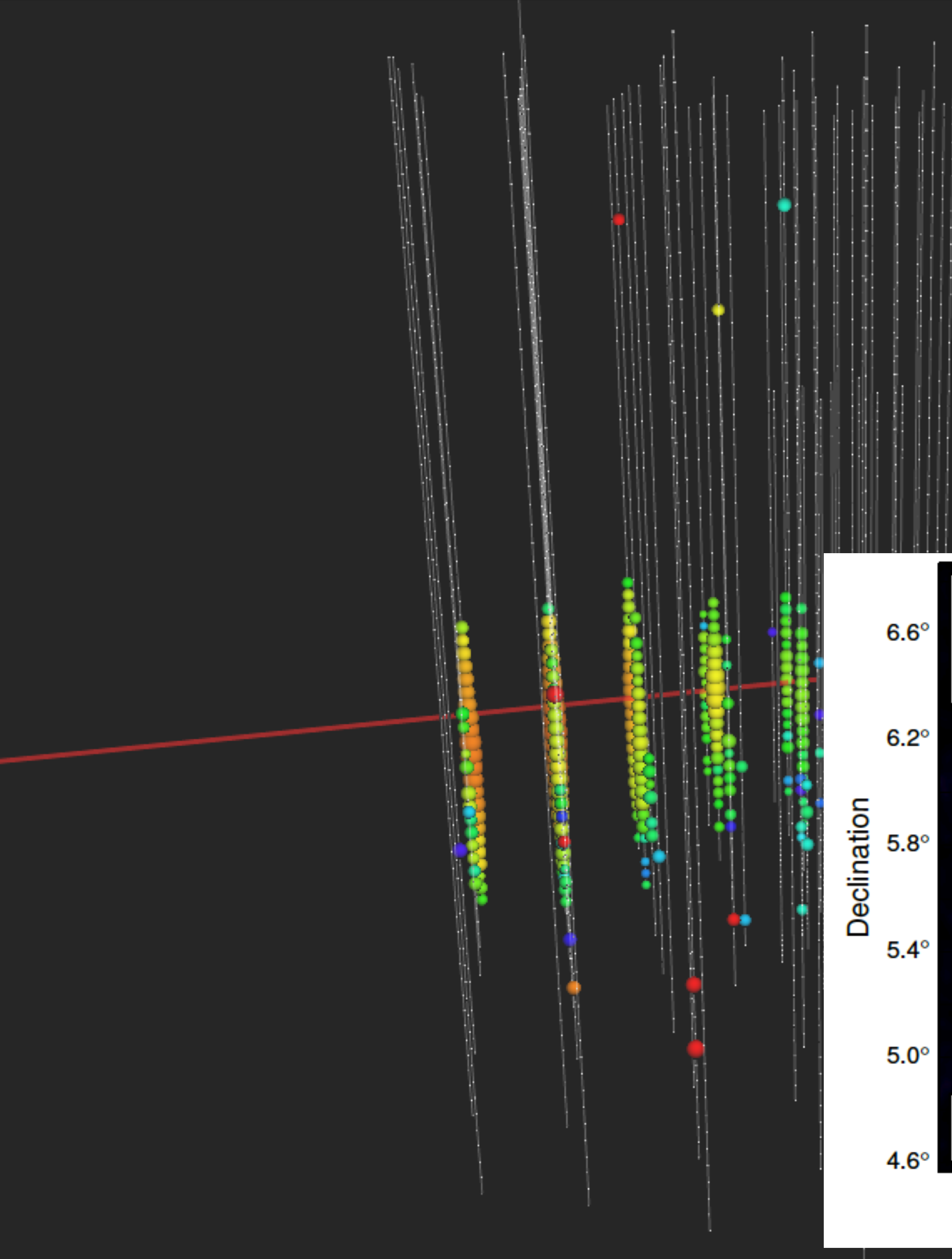
https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

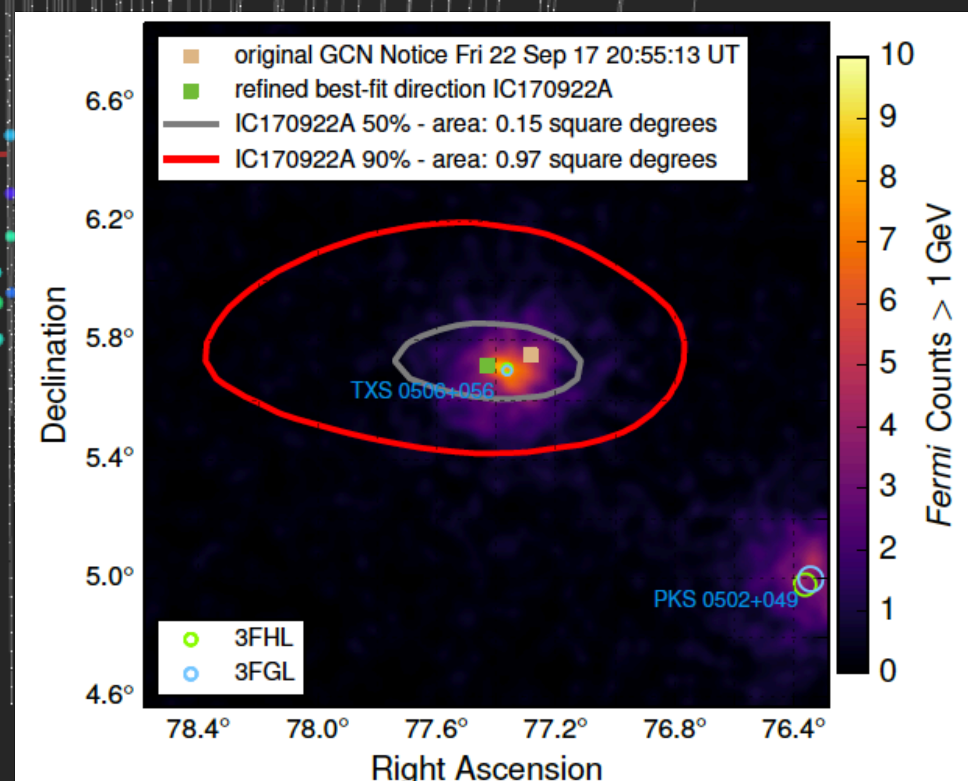
IceCube 170922



IceCube 170922

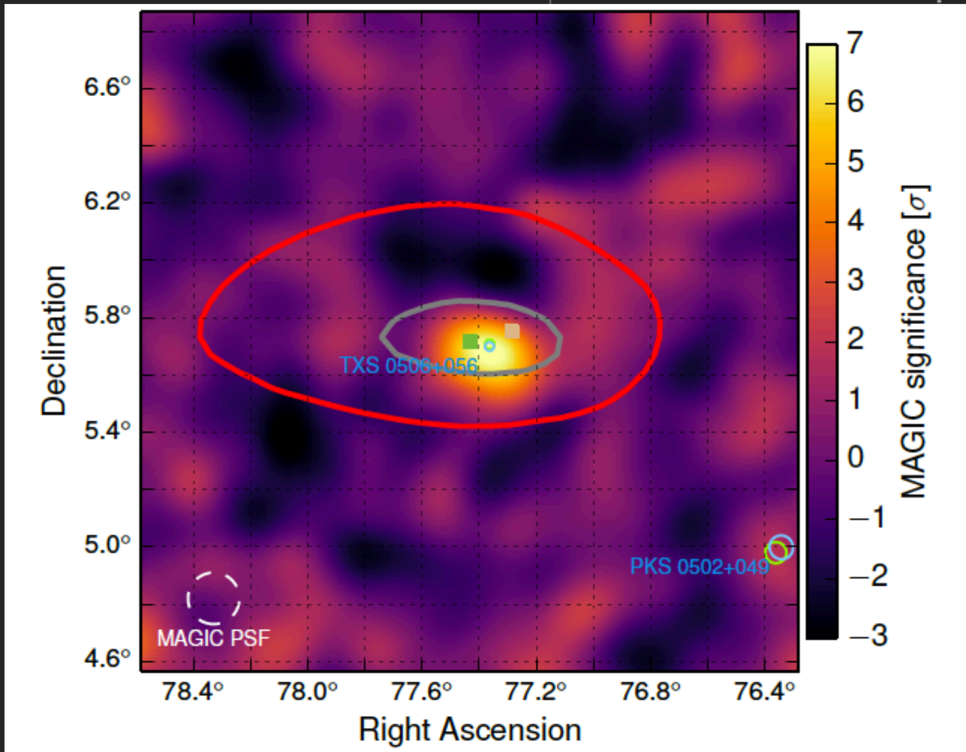
Fermi detects a flaring blazar within 0.1°



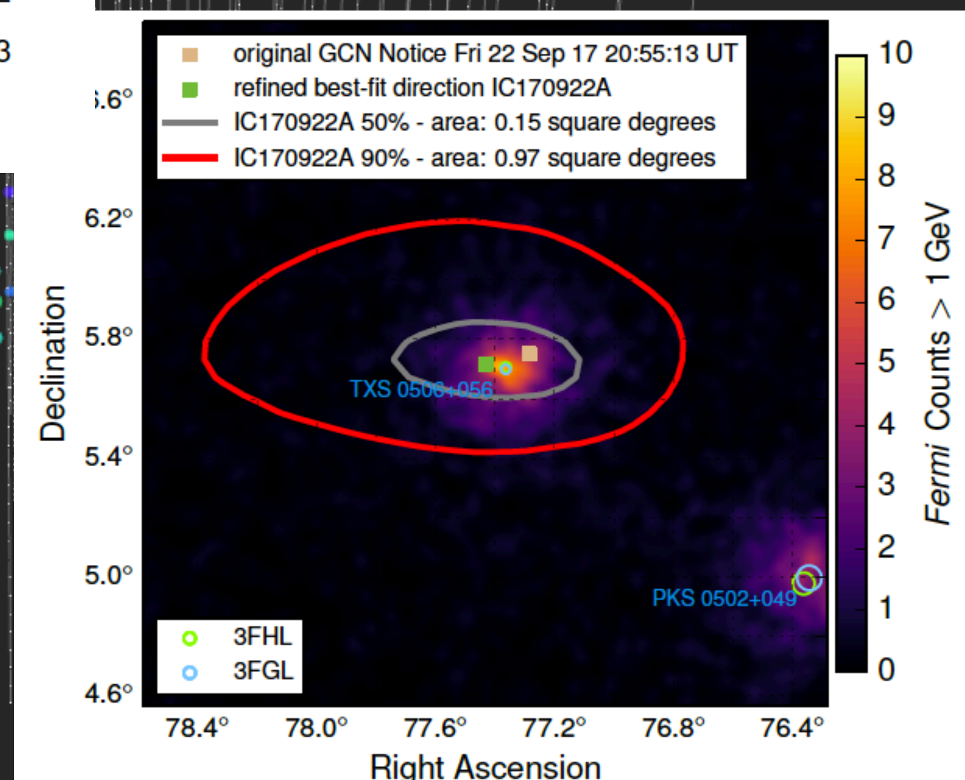


IceCube 170922

Fermi
detects a flaring blazar within 0.1°



MAGIC
detects emission of
> 100 GeV gammas



MAGIC atmposheric Cherenkov telescope

Follow-up detections of IC170922 based on public telegrams

THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

Simona Paiano,[1,2] Renato Falomo,[1] Aldo Treves,[3,4] and Riccardo Scarpa[5,6]

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(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365±0.0010.

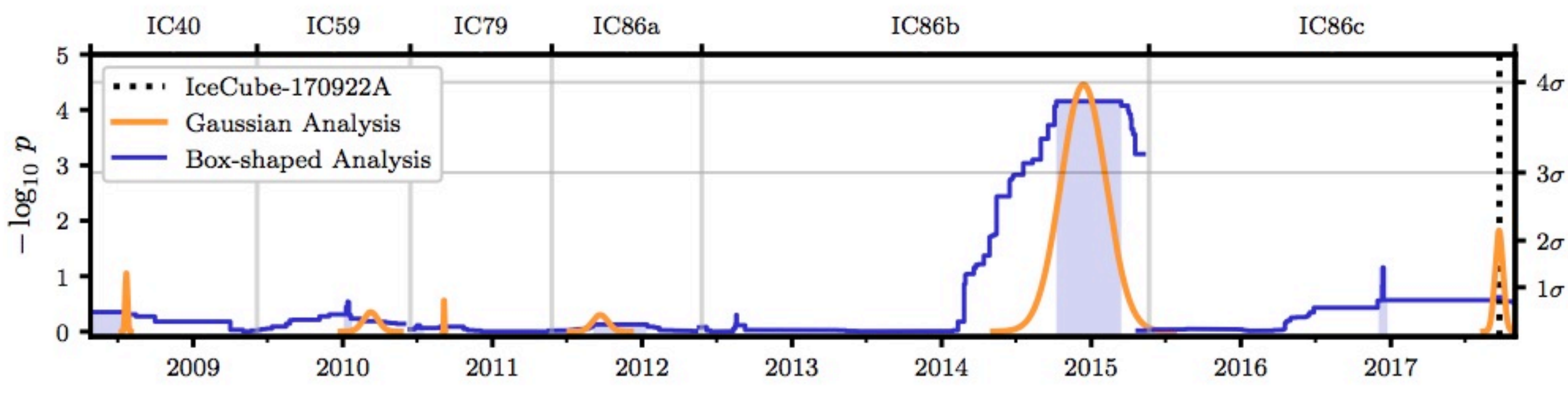
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

- we do not see our own Galaxy
- we do not see the nearest extragalactic sources
- we find a blazar at 4 billion lightyears!

multiwavelength campaign launched by IC 170922

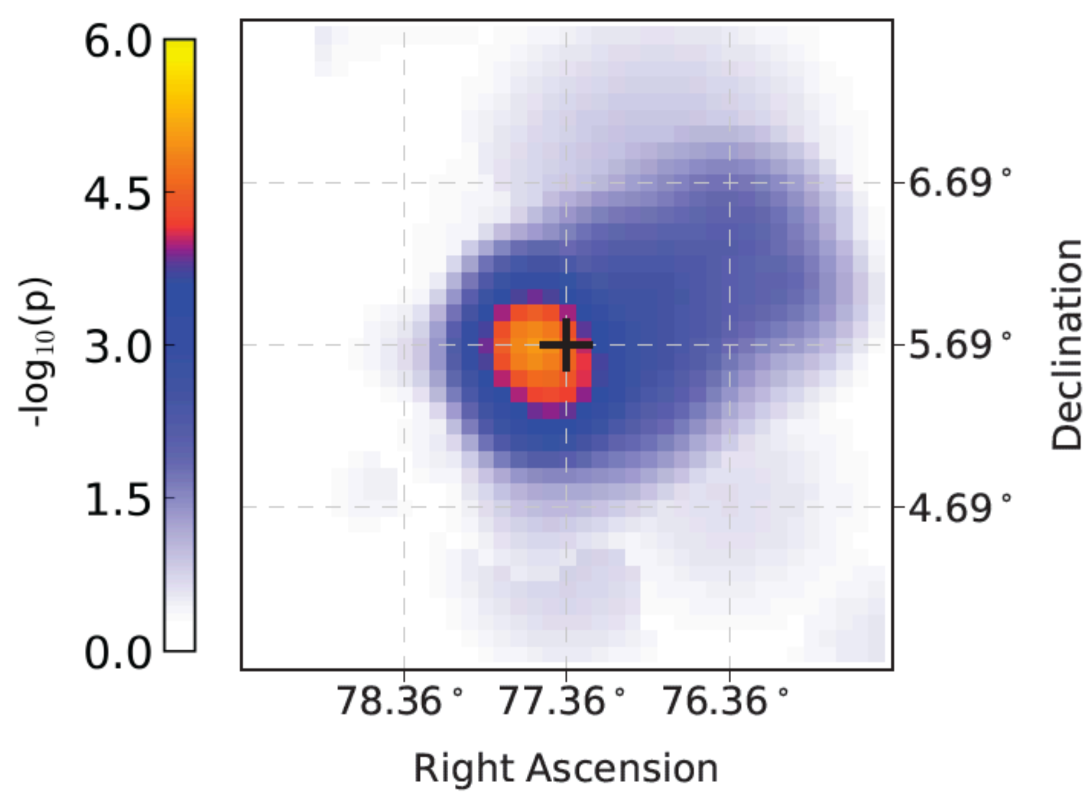
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^o Dec 5.72^o
- Fermi-LAT: flaring blazar within 0.1^o (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

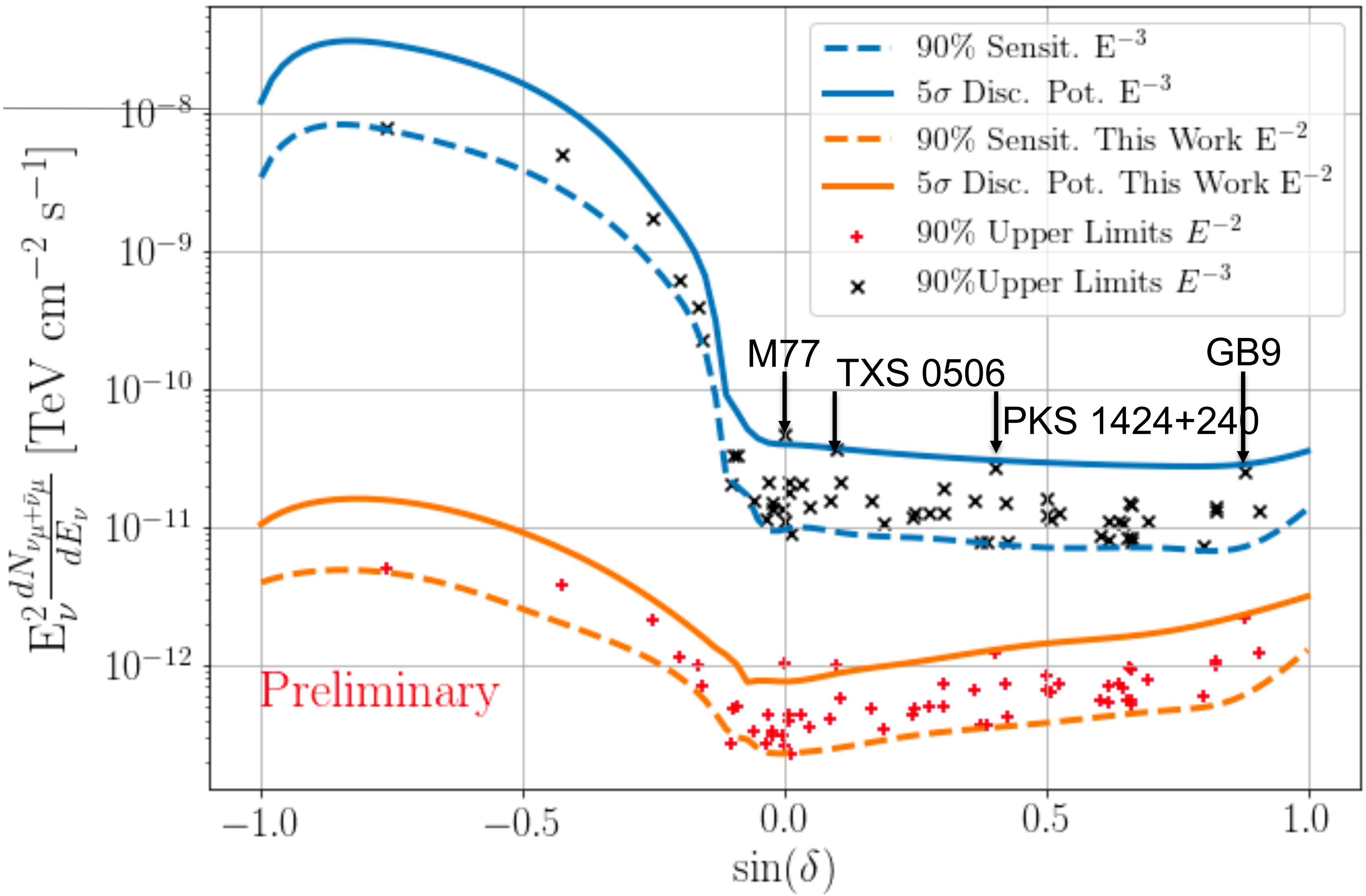


search in archival IceCube data:

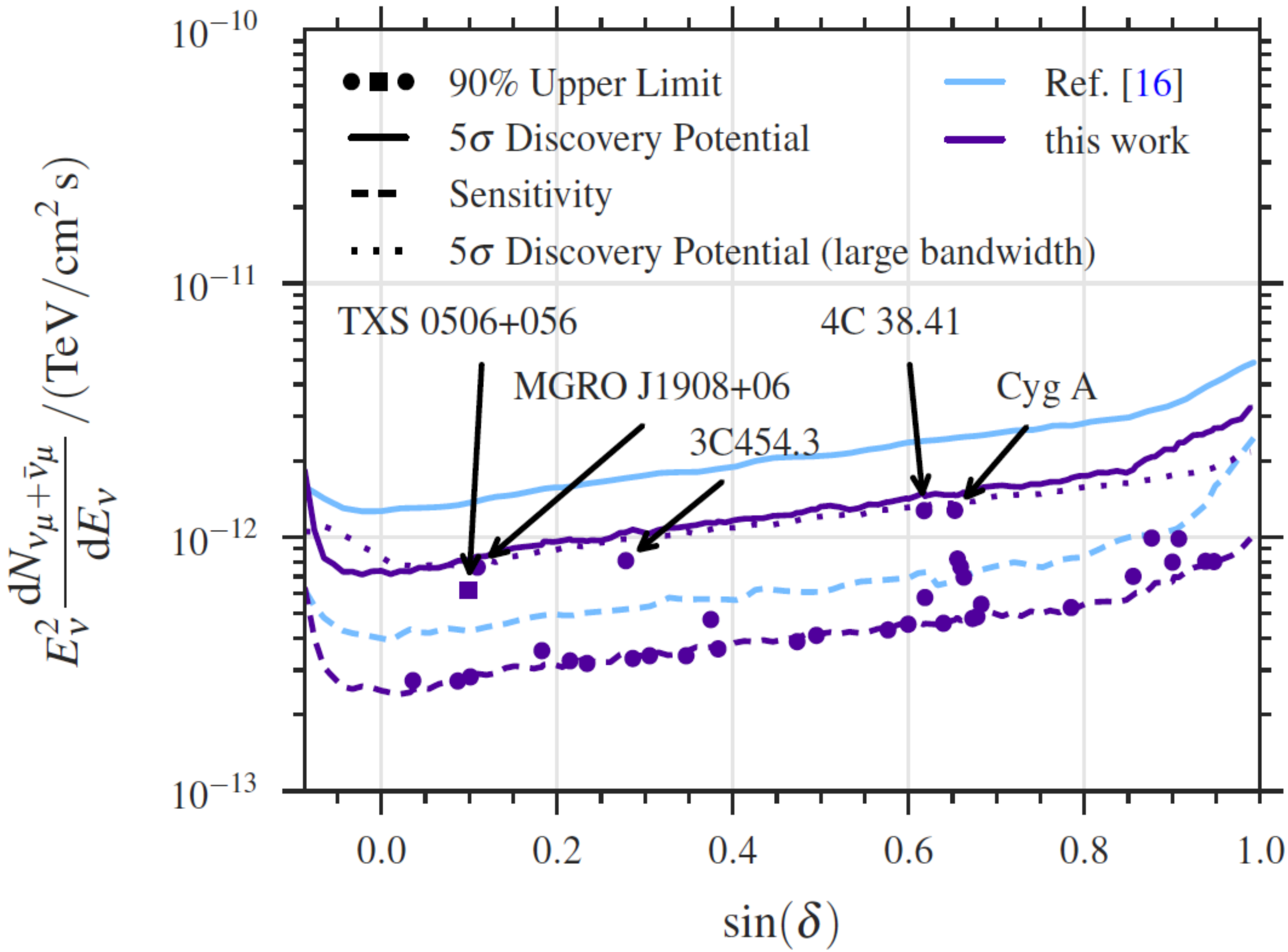
- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg.probability
- spectrum E$^{-2.1}$



Why not seen before?



this is the case for larger detectors with better angular resolution!

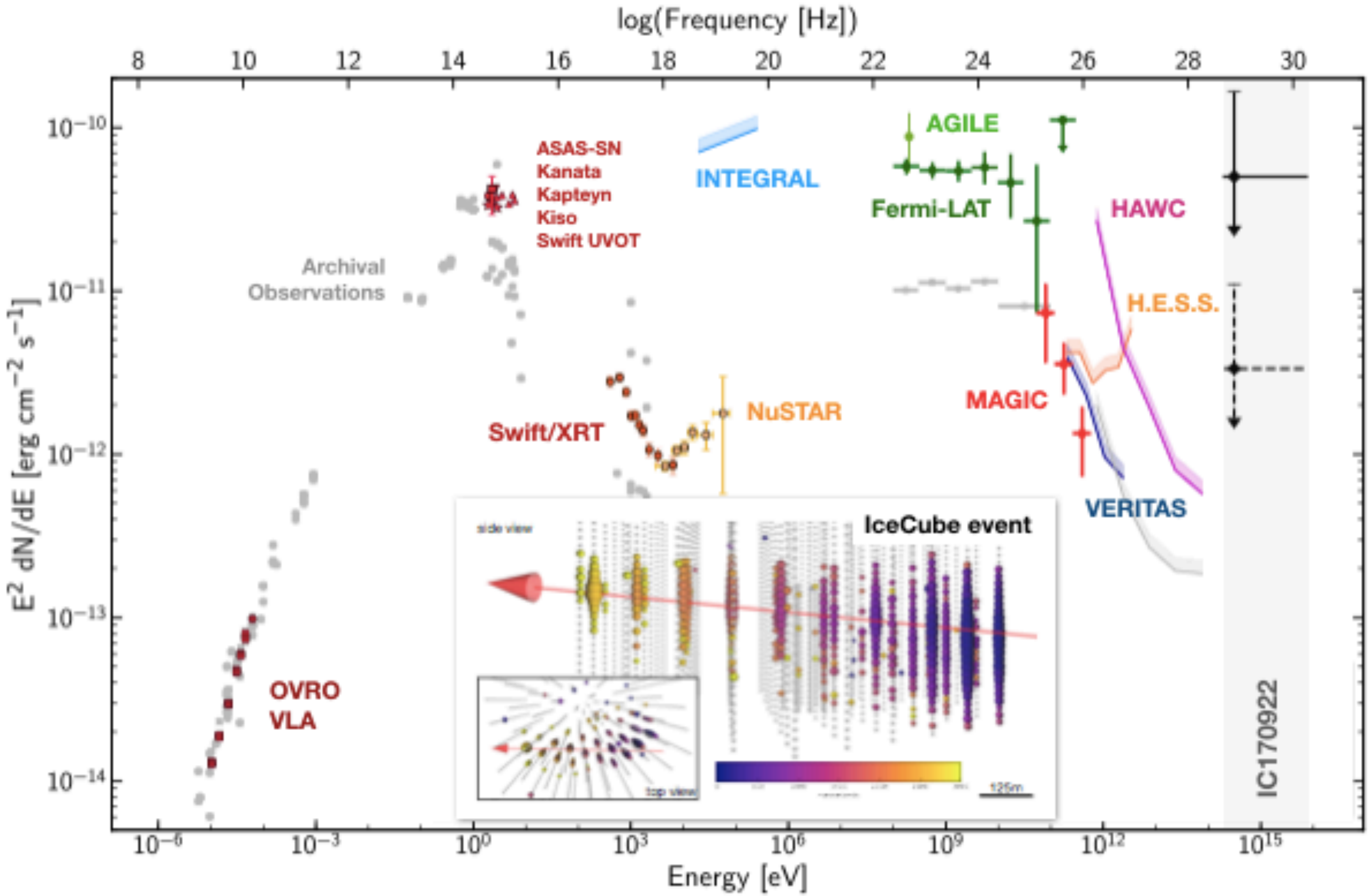


search assuming E-2.19 (diffuse) spectrum we identified a source of high energy cosmic rays:

the active galaxy (blazar) TXS 0506+056 at a redshift of 0.33

at ten times further distance, it outshines nearby active galaxies: is it special?

extensive multiwavelength campaign will allow us to study the first cosmic accelerator



we know that this one is a cosmic ray source

are blazars the sources

of the cosmic neutrinos?

a special class of blazars that undergo 110-day duration flares like TXS 0506+056 once every 10 years accommodates the observed diffuse flux of high-energy cosmic neutrinos
selected by evolution?) selected by redshift evolution ?
a galaxy merger (VLA observations during 2014 burst) ?

of the highest energy cosmic rays?

measured flux satisfies the energy requirement

arXiv:1812.05654 -- arXiv:1811.07439 -- arXiv:1811.06356 -- arXiv:1807.07942

relation between flaring sources and the diffuse flux ?

diffuse ν_μ flux — TXS luminosity

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{c}{H_0}\xi_z L_\nu \rho \mathcal{F} \frac{\Delta t}{T}$$

density of blazars

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq 7.4 \times 10^{-9}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}} \times \left(\frac{\mathcal{F}}{4\pi}\right)\left(\frac{c/H_0}{4.3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2\times 10^{47}\,\mathrm{erg/s}}\right)\left(\frac{\rho}{1.5\times 10^{-8}\,\mathrm{Mpc}^{-3}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\right)\left(\frac{10\,\mathrm{yr}}{T}\right).$$

vanilla blazars cannot accommodate the 2014 burst

- need a major accretion on the black hole to create a target that can produce the 2014-15 neutrino burst
- a target that produces > 12 neutrinos in 110 days is opaque to gamma rays that lose energy in the source even before entering the EBL
- the coincident gamma ray flux can be accommodated

a target that produces > 12 neutrinos in 110 days is opaque to gamma rays that lose energy in the source even before entering the EBL

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{8\pi}\,\tau_{p\gamma}\,\xi_z\,t_H \left(\frac{dE}{dt}\right)_{\rm CR}$$

proton beam normalized to the energy density in cosmic rays

$$\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$$

$$\tau_{p\gamma} \gtrsim 0.4$$

opacity of the gamma ray target

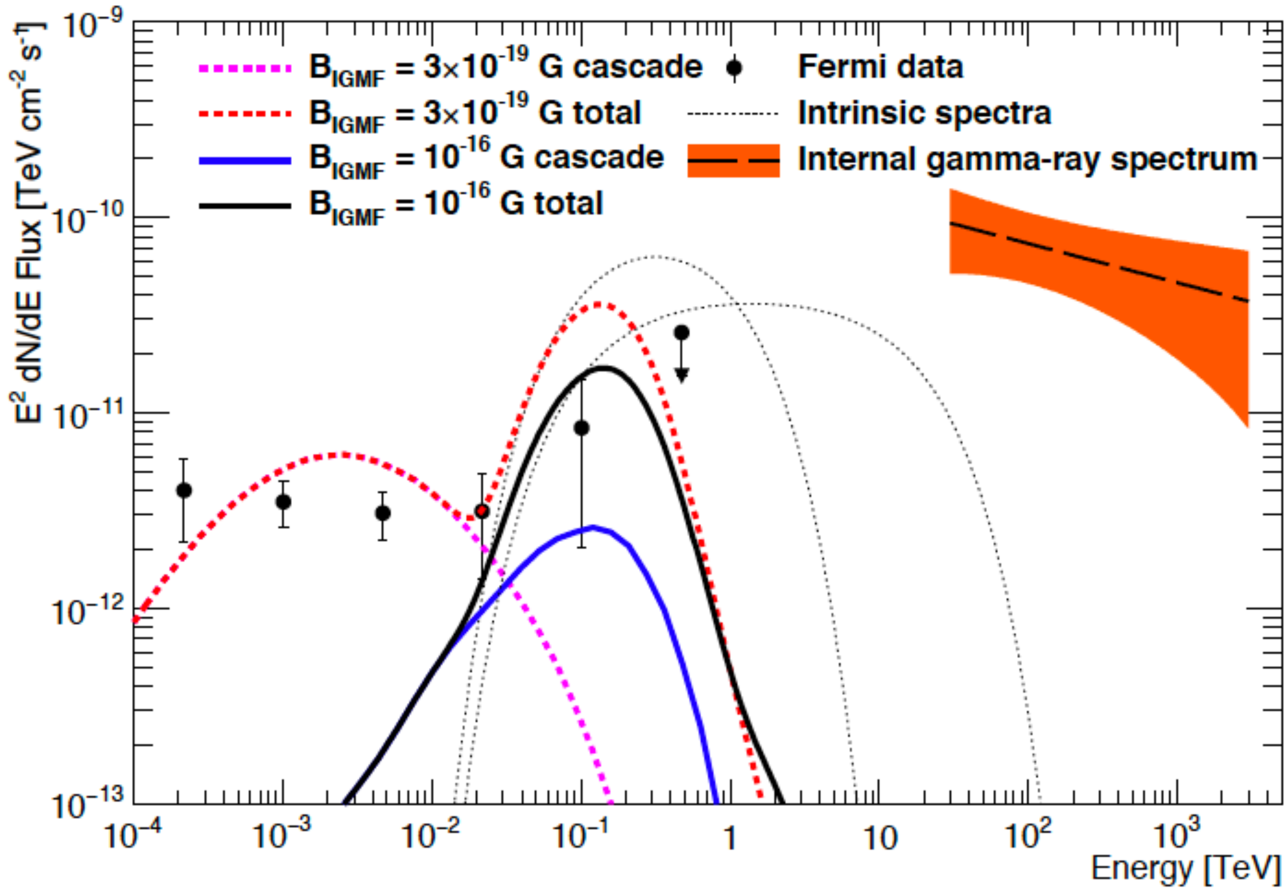
$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}}\tau_{p\gamma}$$

the gamma rays that accompany the neutrinos lose energy in the source

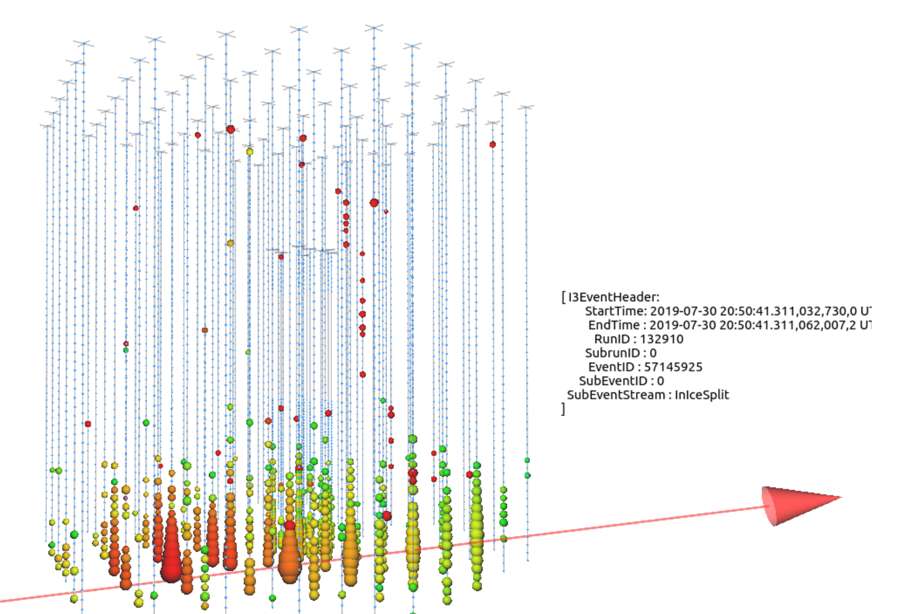
accompanying photons below Fermi threshold

the multimessenger picture

neutrino flux → (multimessenger relation) → gamma ray flux cascades to lower energy in the source → (EBL absorption) → observed flux @ Fermi



**Fermi data from S. Garrappa+, TeVPA2018*



Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on *7 Aug 2019; 12:31 UT*
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

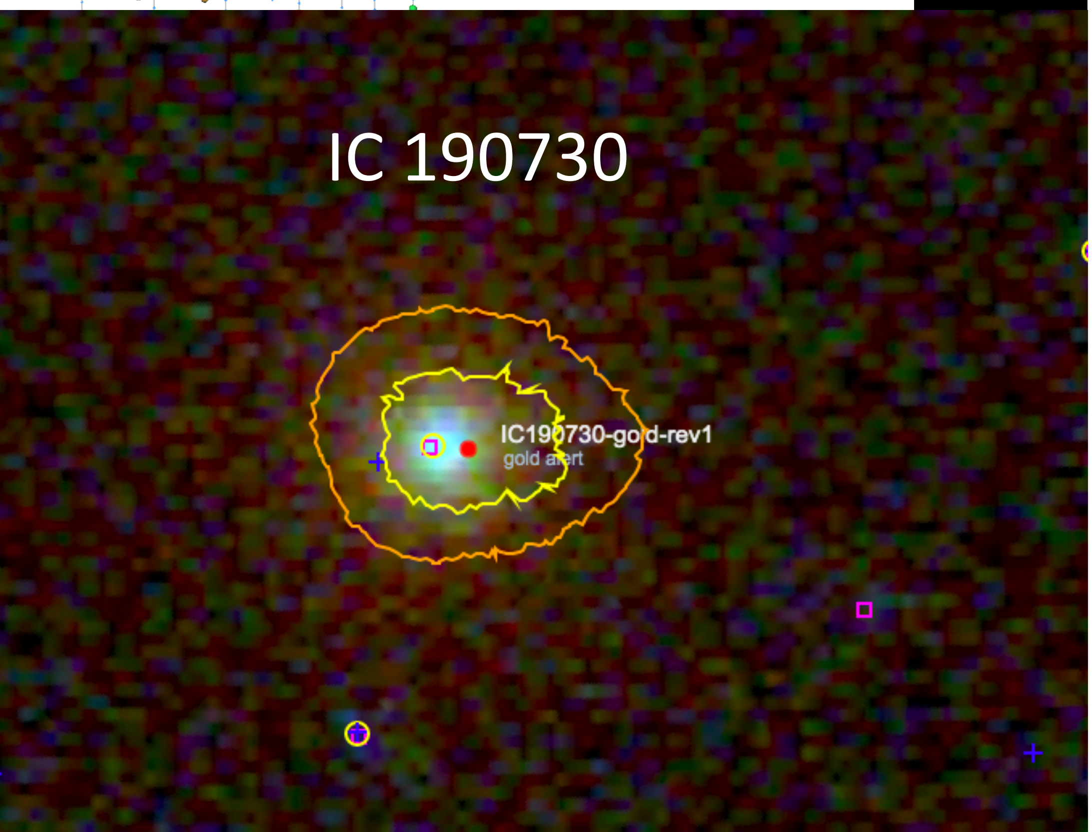
Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

12996 Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985 IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983 Optical fluxes of candidate neutrino blazar PKS 1502+106
12981 ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974 Optical follow-up of IceCube-190730A with ZTF
12971 IceCube-190730A: MASTER alert observations and analysis
12967 IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926 VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

galaxy mergers?



Molecular line emission in NGC 1068 imaged with ALMA★

I. An AGN-driven outflow in the dense molecular gas

S. García-Burillo[1], F. Combes[2], A. Usero[1], S. Aalto[3], M. Krips[4], S. Viti[5], A. Alonso-Herrero[6,★★], L. K. Hunt[7], E. Schinnerer[8], A. J. Baker[9], F. Boone[10], V. Casasola[11], L. Colina[12], F. Costagliola[13], A. Eckart[14], A. Fuente[1], C. Henkel[15,16], A. Labiano[1,17], S. Martín[4], I. Márquez[13], S. Muller[3], P. Planesas[1], C. Ramos Almeida[18,19], M. Spaans[20], L. J. Tacconi[21], and P. P. van der Werf[22]

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Received 19 March 2014 / Accepted 4 June 2014

ABSTRACT

Aims. We investigate the fueling and the feedback of star formation and nuclear activity in NGC 1068, a nearby (D = 14 Mpc) Seyfert 2 barred galaxy, by analyzing the distribution and kinematics of the molecular gas in the disk. We aim to understand if and how gas accretion can self-regulate.
Methods. We have used the Atacama Large Millimeter Array (ALMA) to map the emission of a set of dense molecular gas ($n(H_2) \simeq 10^{5-6}$ cm^{-3}) tracers (CO(3–2), CO(6–5), HCN(4–3), HCO^+(4–3), and CS(7–6)) and their underlying continuum emission in the central $r \sim 2$ kpc of NGC 1068 with spatial resolutions ~0.3″–0.5″ (~20–35 pc for the assumed distance of D = 14 Mpc).
Results. The sensitivity and spatial resolution of ALMA give an unprecedented detailed view of the distribution and kinematics of the dense molecular gas ($n(H_2) \geq 10^{5-6}$cm^{-3}) in NGC 1068. Molecular line and dust continuum emissions are detected from a $r \sim 200$ pc off-centered circumnuclear disk (CND), from the 2.6 kpc-diameter bar region, and from the $r \sim 1.3$ kpc starburst (SB) ring. Most of the emission in HCO^+, HCN, and CS stems from the CND. Molecular line ratios show dramatic order-of-magnitude changes inside the CND that are correlated with the UV/X-ray illumination by the active galactic nucleus (AGN), betraying ongoing feedback. We used the dust continuum fluxes measured by ALMA together with NIR/MIR data to constrain the properties of the putative torus using CLUMPY models and found a torus radius of 20^{+6}_{-10} pc. The Fourier decomposition of the gas velocity field indicates that rotation is perturbed by an inward radial flow in the SB ring and the bar region. However, the gas kinematics from $r \sim 50$ pc out to $r \sim 400$ pc reveal a massive ($M_{mol} \sim 2.7^{+0.9}_{-1.2} \times 10^7\ M_\odot$) outflow in all molecular tracers. The tight correlation between the ionized gas outflow, the radio jet, and the occurrence of outward motions in the disk suggests that the outflow is AGN driven.
Conclusions. The molecular outflow is likely launched when the ionization cone of the narrow line region sweeps the nuclear disk. The outflow rate estimated in the CND, $dM/dt \sim 63^{+21}_{-37}\ M_\odot$ yr^{-1}, is an order of magnitude higher than the star formation rate at these radii, confirming that the outflow is AGN driven. The power of the AGN is able to account for the estimated momentum and kinetic luminosity of the outflow. The CND mass load rate of the CND outflow implies a very short gas depletion timescale of ≤1 Myr. The CND gas reservoir is likely replenished on longer timescales by efficient gas inflow from the outer disk.

TXS 0506+056

"We thus observe the interaction between jet features that cross each other's paths."

Astronomy & Astrophysics manuscript no. output ©ESO 2019
July 31, 2019

A Cosmic Collider: IceCube neutrino generated in a precessing jet-jet interaction in TXS 0506+056?

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Received September 15, 1996; accepted March 16, 1997

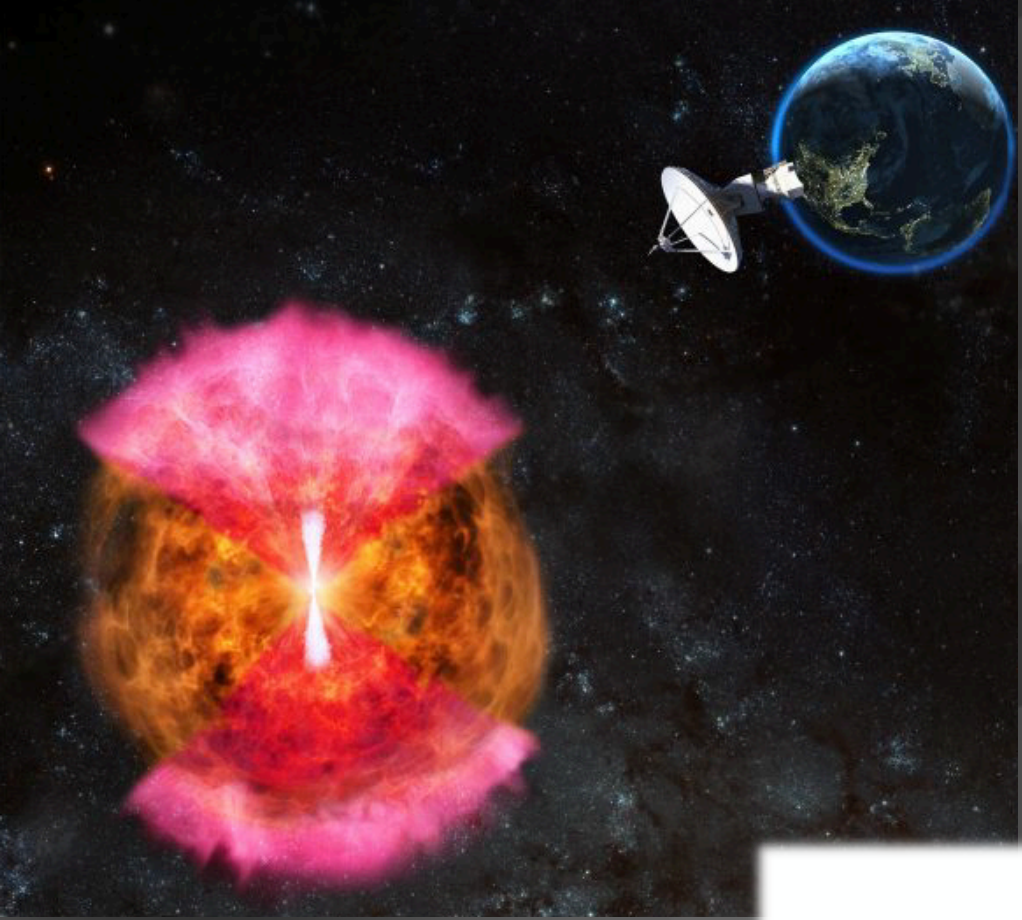
ABSTRACT

Context. The neutrino event IceCube-170922A appears to originate from the BL Lac object TXS 0506+056. To understand the neutrino creation process and localize the emission site, we studied the radio images of the jet at 15 GHz.
Aims. Other BL,Lac objects show similar properties as TXS 0506+056, such as multi-wavelength variability or a curved jet. However, so far, only TXS 0506+056 has been identified as neutrino emitter. This paper aims to figure out, what makes the pc-scale jet of TXS 0506+056 specific in this respect.
Methods. We re-analyzed and re-modeled 16 VLBA 15 GHz observations between 2009 and 2018. We thoroughly examined the jet kinematics and flux-density evolution of individual jet components during the time of enhanced neutrino activity between Sept,2014 and March 2015, and in particular before and after the neutrino event.
Results. Our results suggest that the jet is very strongly curved and most likely observable under a special viewing angle of close to zero. We thus may observe the interaction between jet features which cross each others' paths. We find subsequent flux-density flaring of six components passing the likely collision site. In addition, we find strong indication for precession of the inner jet and model a precession period of about 10 yrs by the Lense-Thirring effect. We discuss an alternative scenario that is the interpretation of observing the signature of *two* jets within TXS 0506+056, again hinting towards a collision of jetted material. We essentially suggest that the neutrino emission may result from the interaction of jetted material in combination with a special viewing angle and jet precession.
Conclusions. We propose that the enhanced neutrino activity during the neutrino flare in 2014 - 2015 and the single EHE neutrino IceCube-170922A could be generated by a cosmic collision within TXS 0506+056. Our findings seem capable of explaining the neutrino generation at the time of a low gamma-ray flux and also indicate that TXS 0506+056 might be an atypical blazar. It seems to be the first time that (i) a potential collision of two jets on pc-scales is reported and that (ii) the detection of a cosmic neutrino might be traced back to a cosmic jet-collision.

neutron star-neutron star merger

LIGO-VIRGO

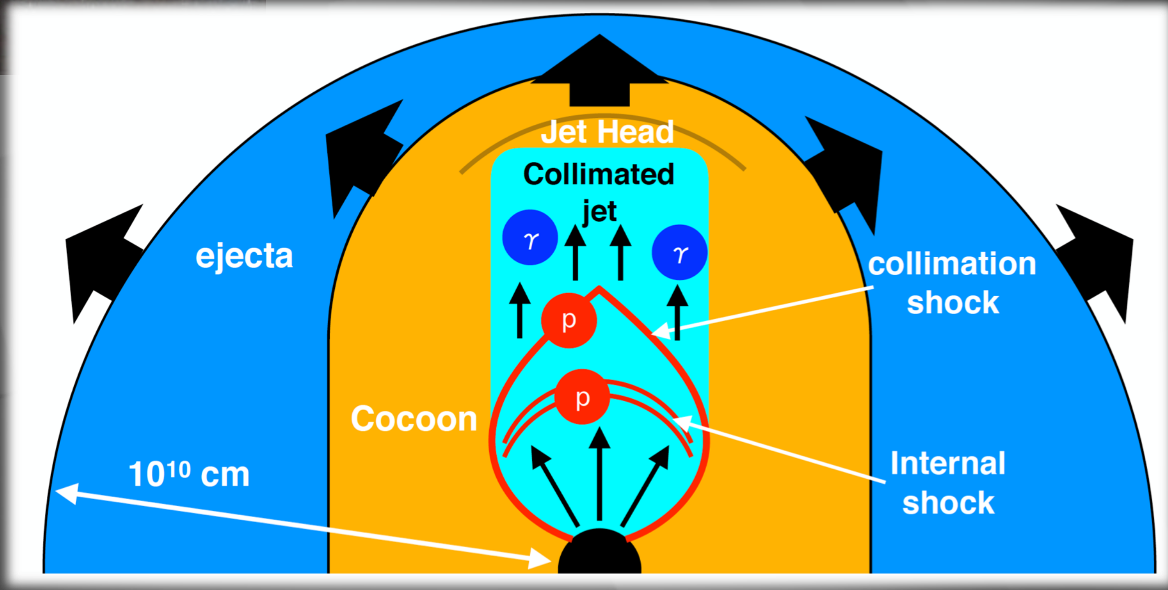
merger of neutron stars about to launch a jet



high-energy neutrinos: from collimation (TeV) and internal shocks (PeV):

protons photoproduce neutrinos

- on photons from leakage of the collimated jet
- on synchrotron photons from electrons (internal shock)



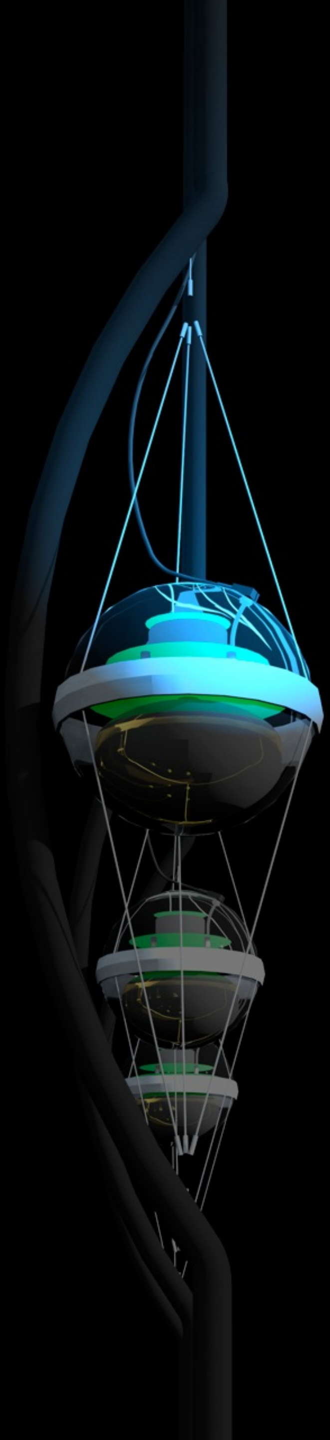
Kimura et al.

TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28



IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

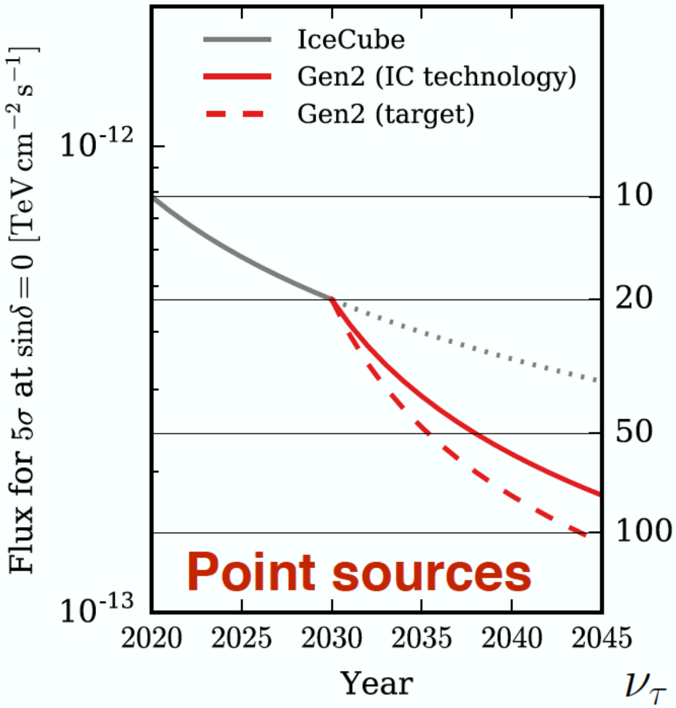
IceCube.wisc.edu

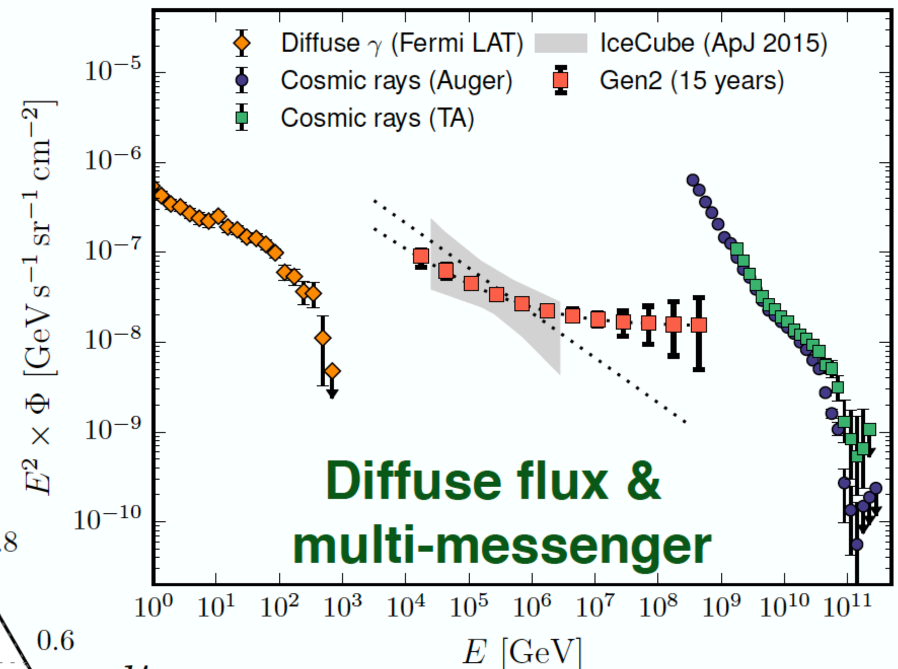
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

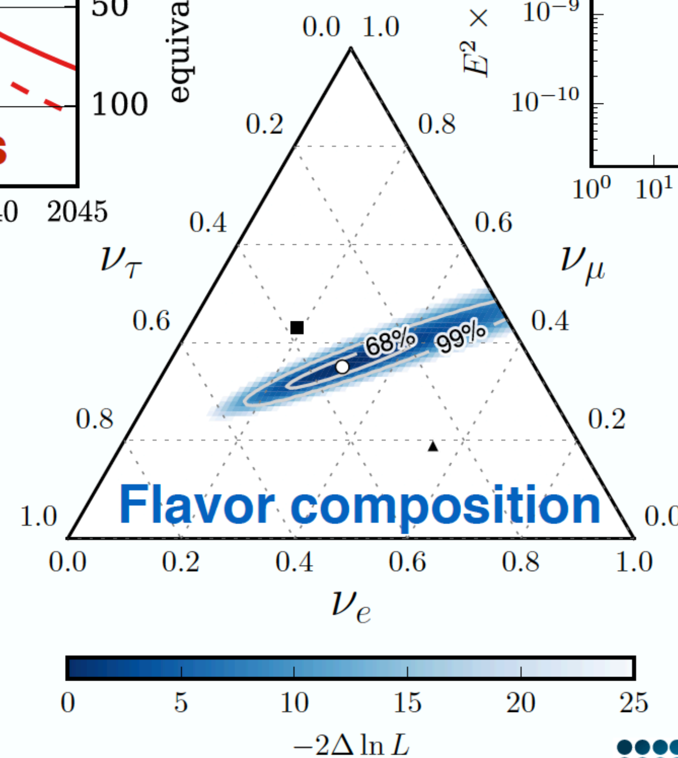
- need 1,000 events versus 100 now in a few years

- discovery instrument → astronomical telescope

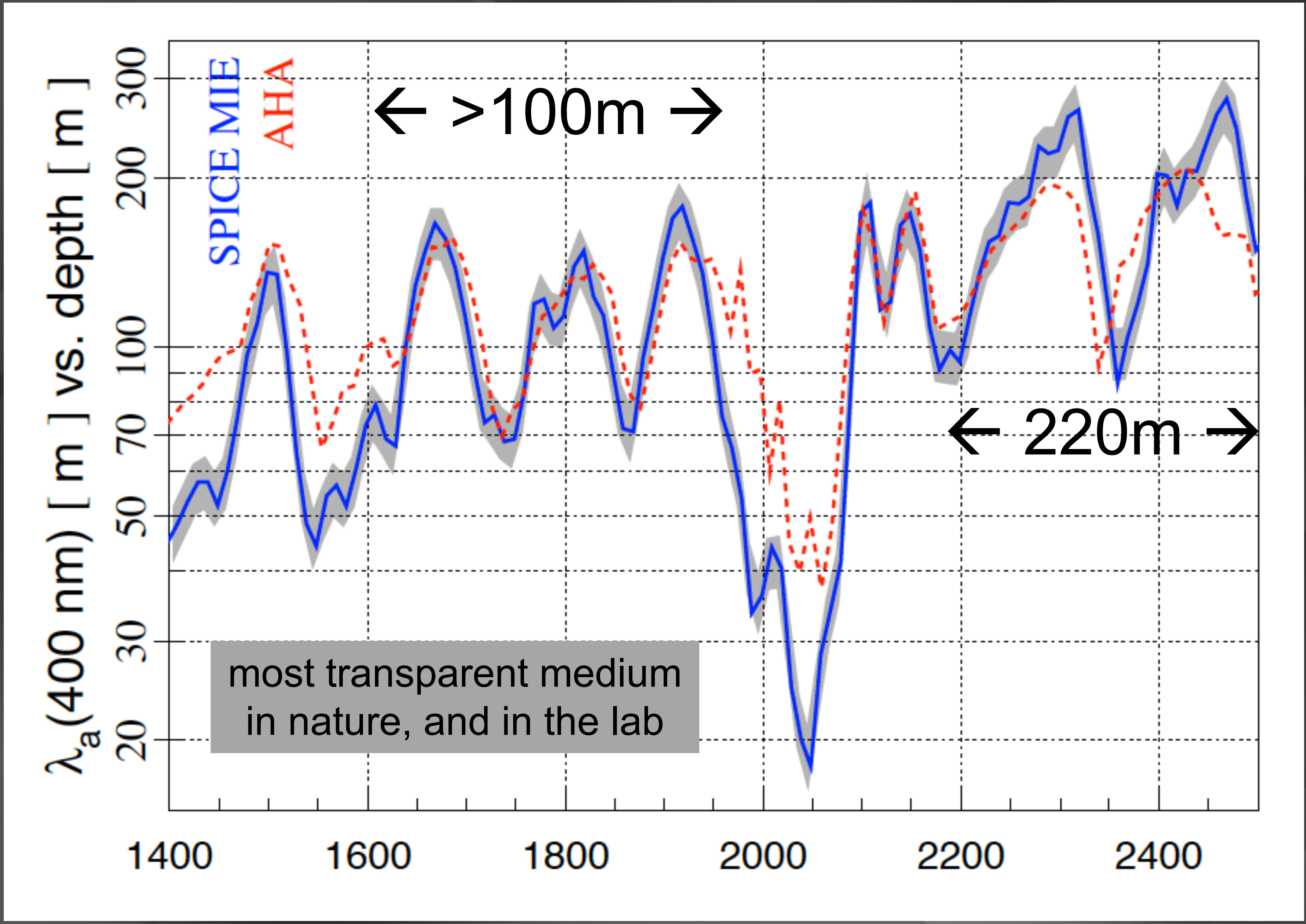
IceCube-Gen2: Science Case



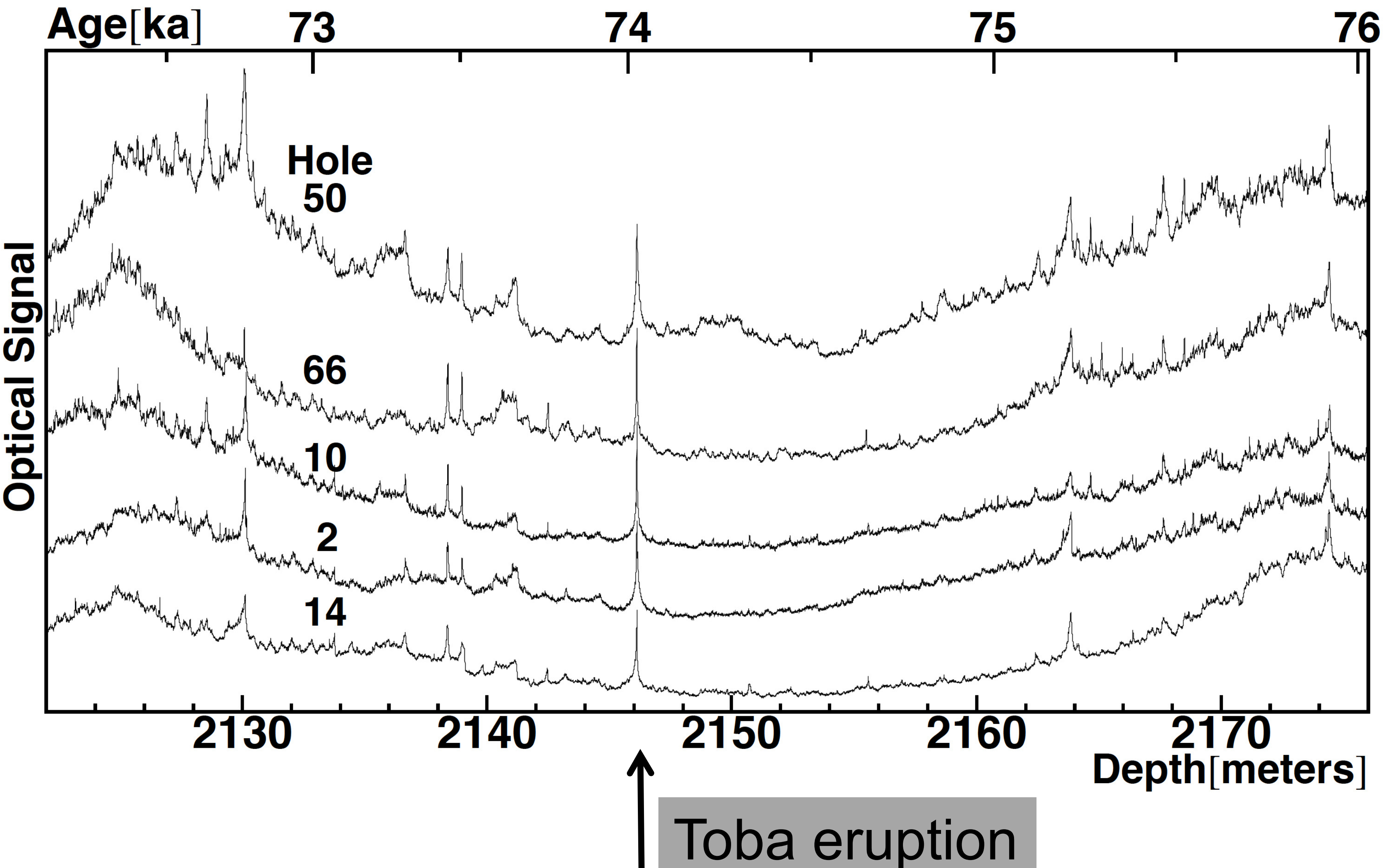




absorption length of Cherenkov light

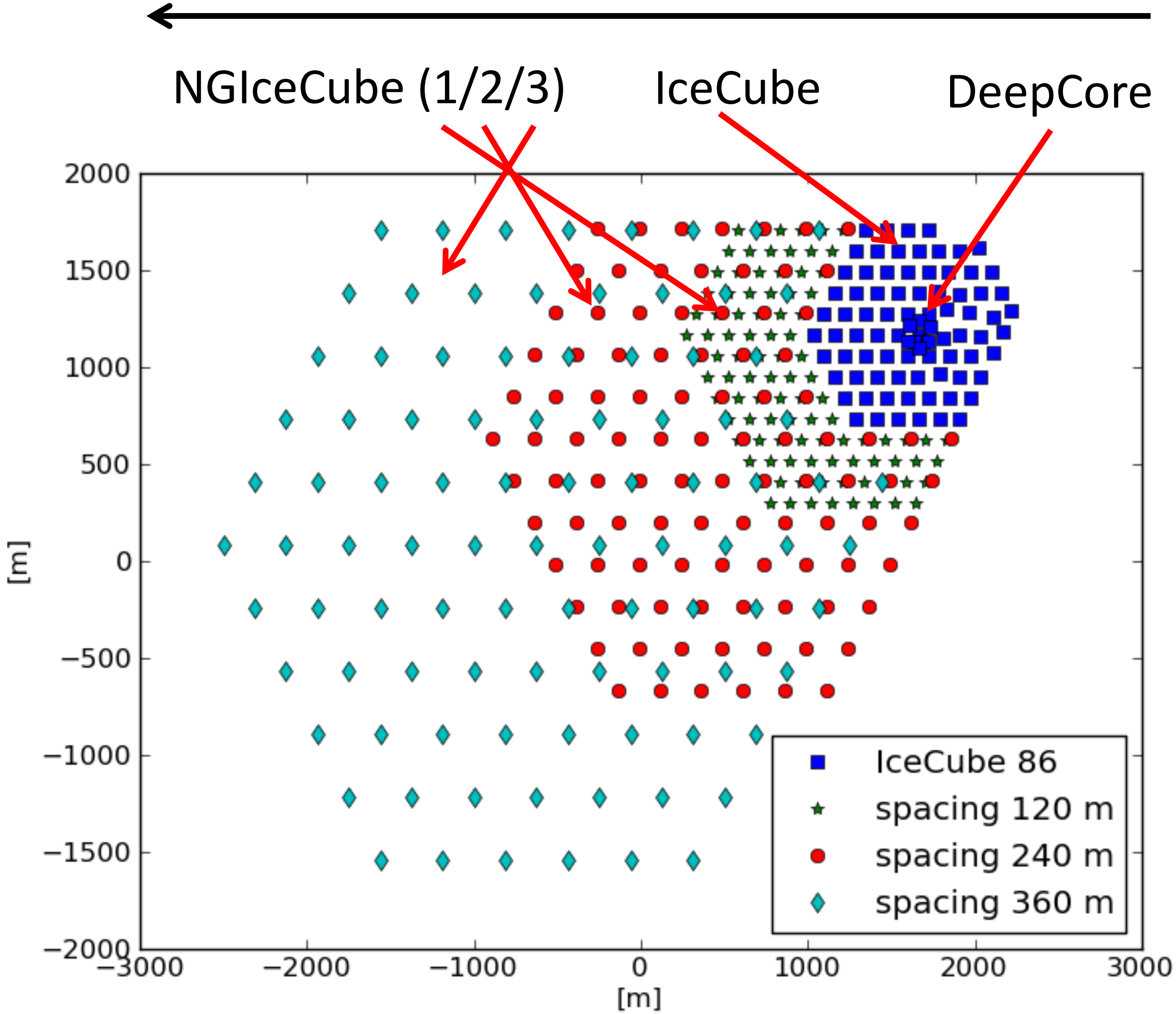


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³

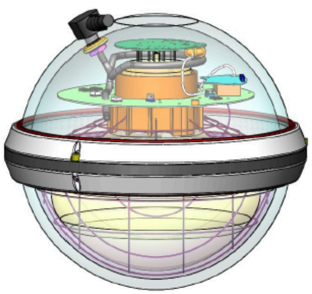
Baseline Gen2 DOM

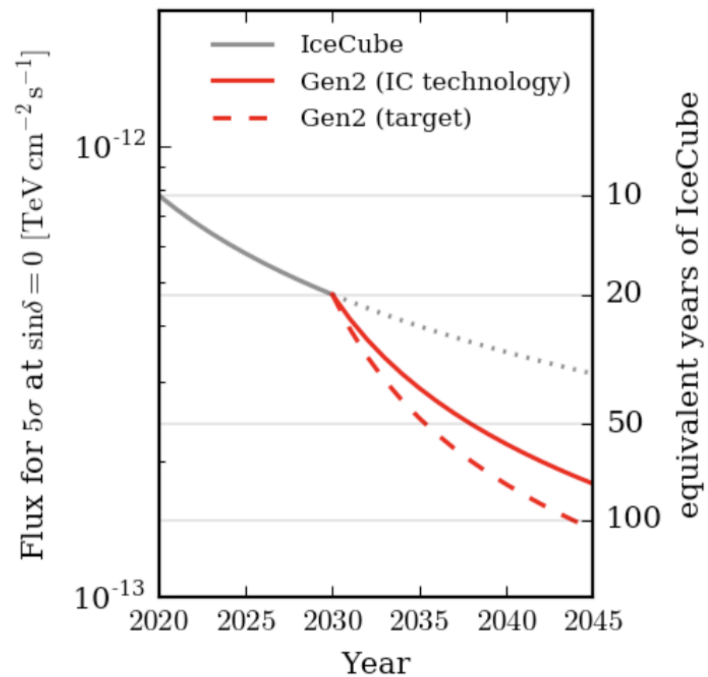
- updated electronics

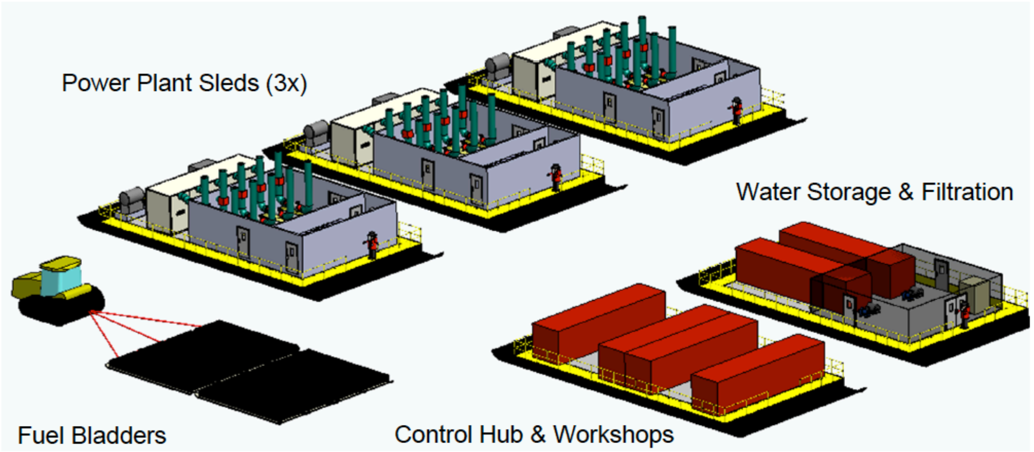
New technologies

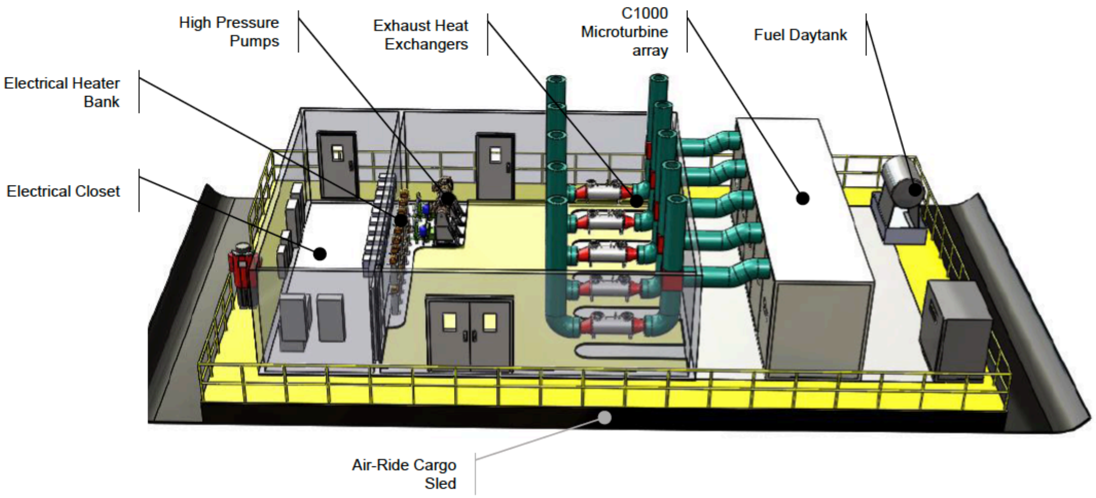
- more PMTs
- wavelength shifters
- narrow profile
- better glass, gel

Point source sensitivity

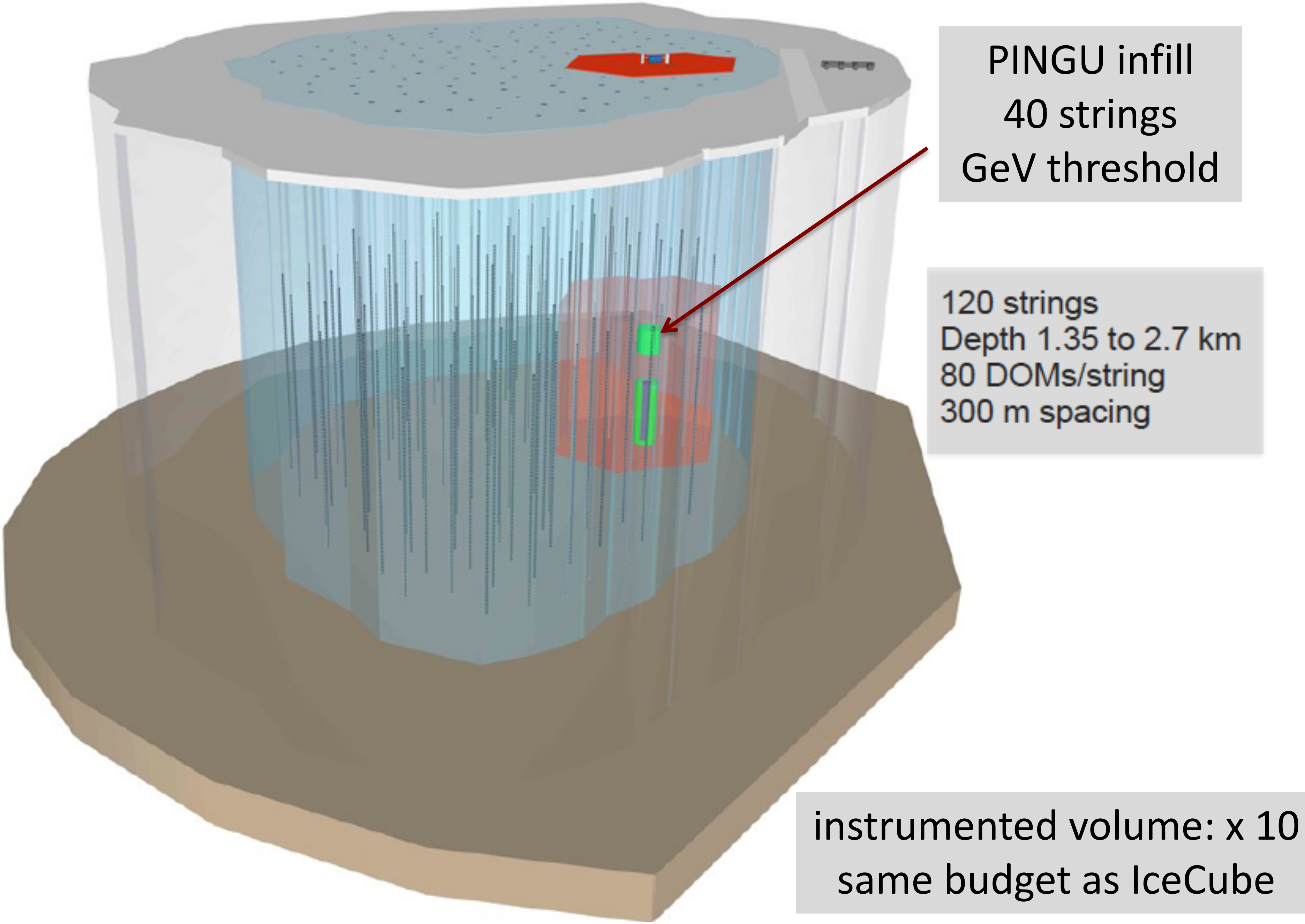






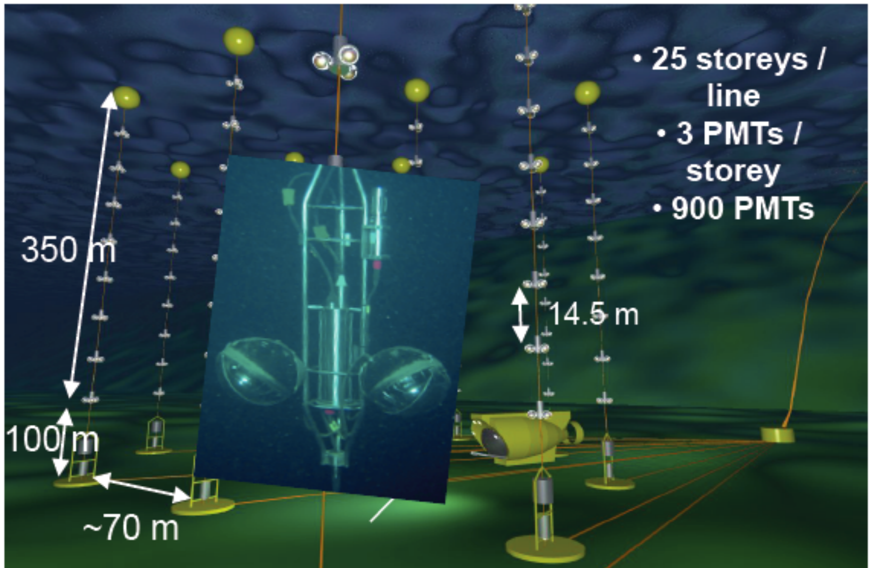


- Next-generation Enhanced Hot Water Drill
  - reduced footprint
  - smaller crew
- Transport equipment and fuel using South Pole Traverse
  - fewer flights needed
- May also reduce hole diameter
  - reduced fuel usage


PINGU infill
40 strings
GeV threshold
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing
instrumented volume: x 10
same budget as IceCube

Mediterranean Detectors

ANTARES Complete since 2008



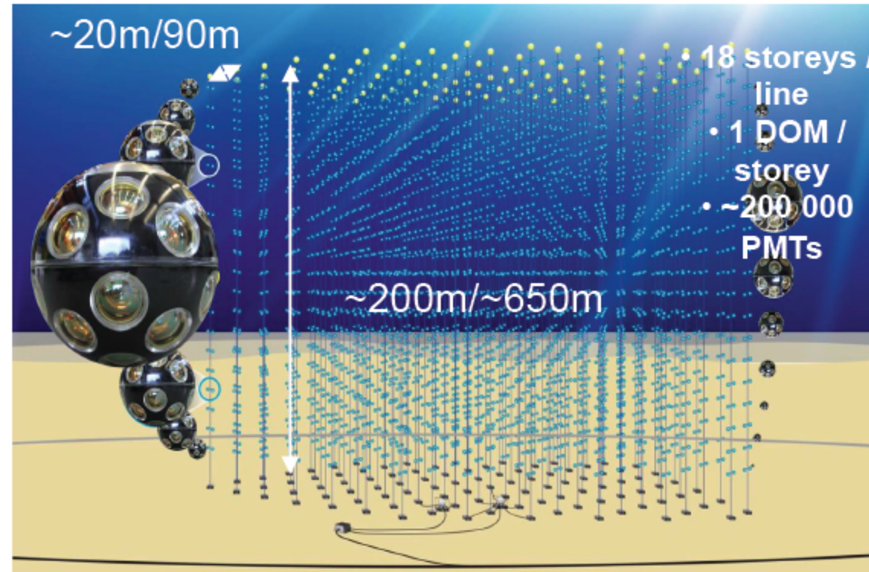
~10 Mton

12 lines

First Generation

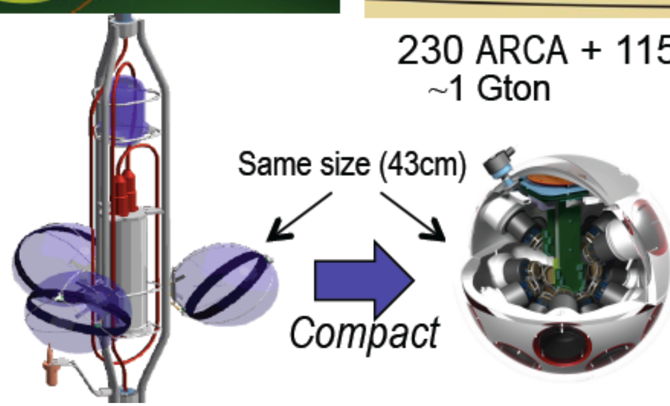
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

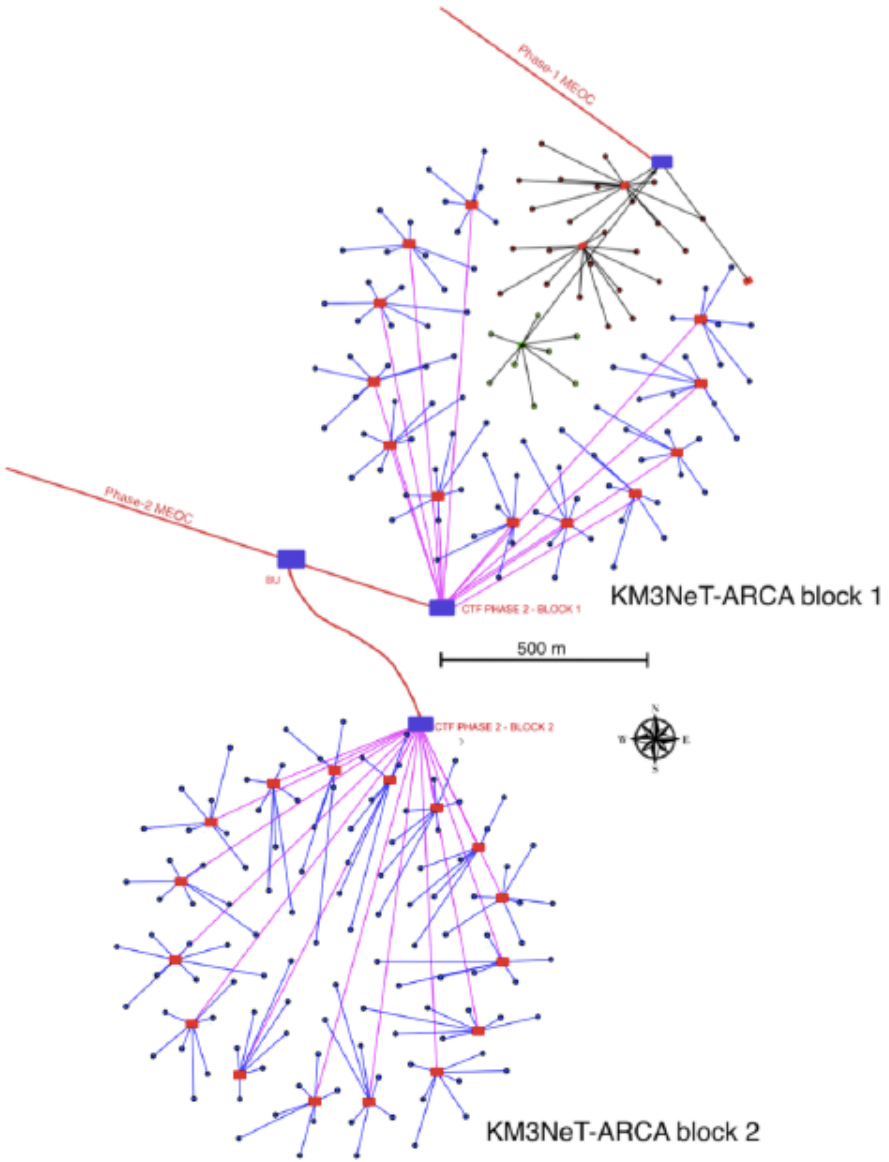
~1 Gton ~6 Mton

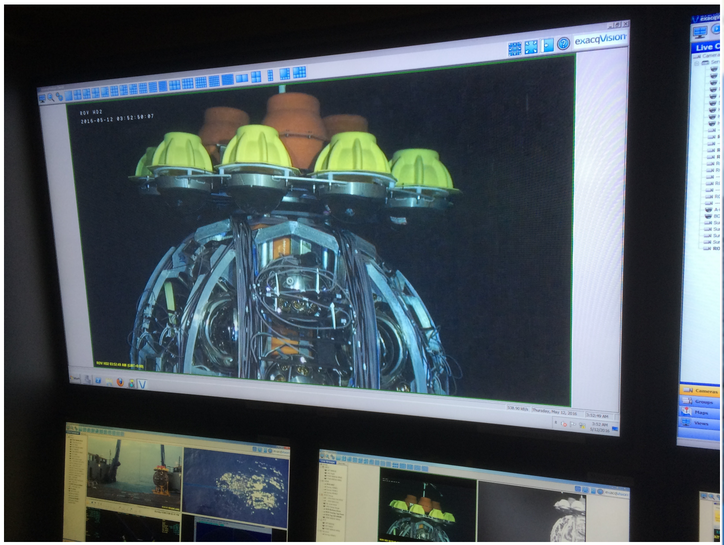


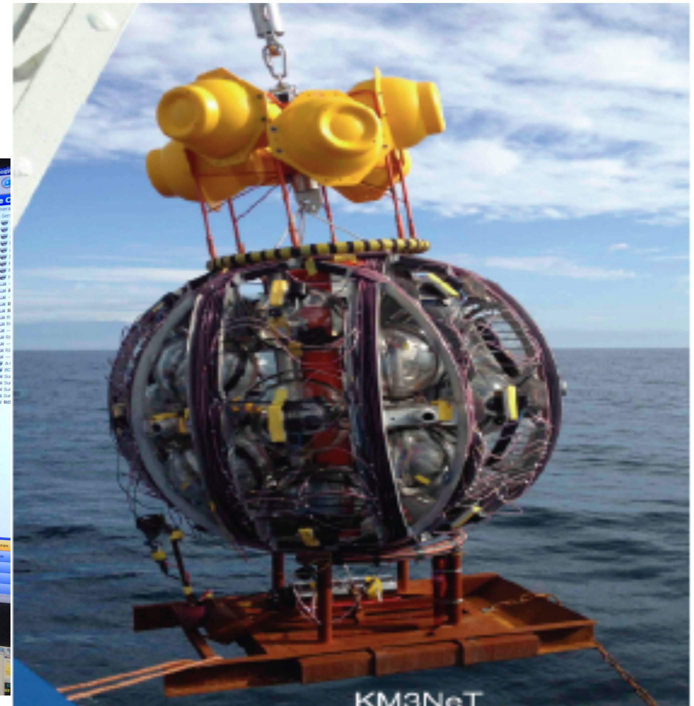
• DOM: 31 3" PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

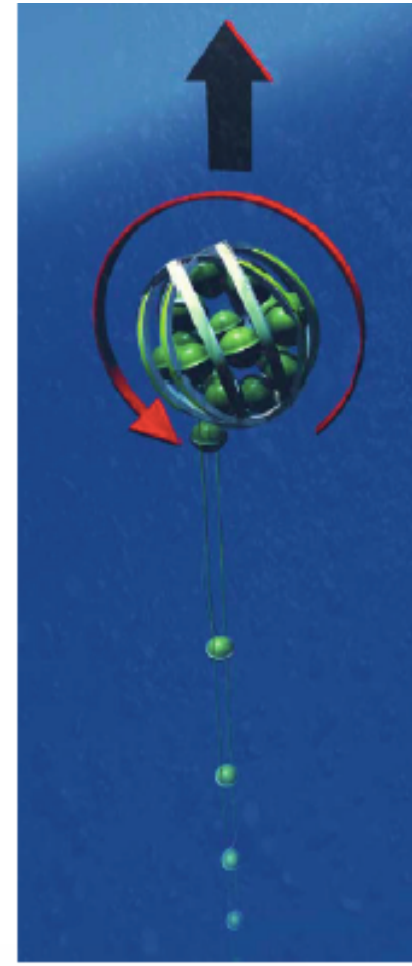
High energies ARCA







rapid deployment
autonomous unfurling
recoverable



KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf did not talk about:

- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- cosmic ray physics, muon maps,…
- PINGU/ORCA
- ….

Conclusions

- more to come from IceCube: many analyses have not exploited more than one year of data
- analyses are not in the background-dominated regime
- next-generation detector(s):
    1. discovery → astronomy (also KM3NeT, GVD)
    2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
    3. potential for discovery
- neutrinos are never boring!

The IceCube–PINGU Collaboration

International 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)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

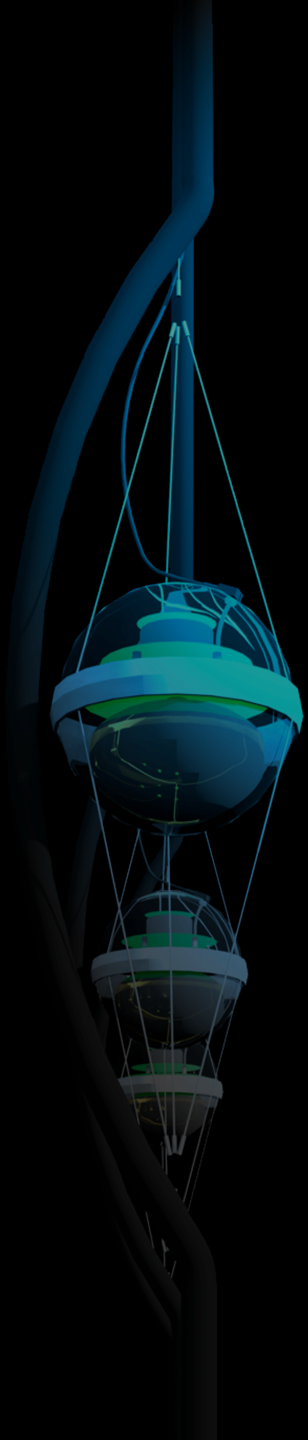
THE ICECUBE COLLABORATION

STRALIA 1

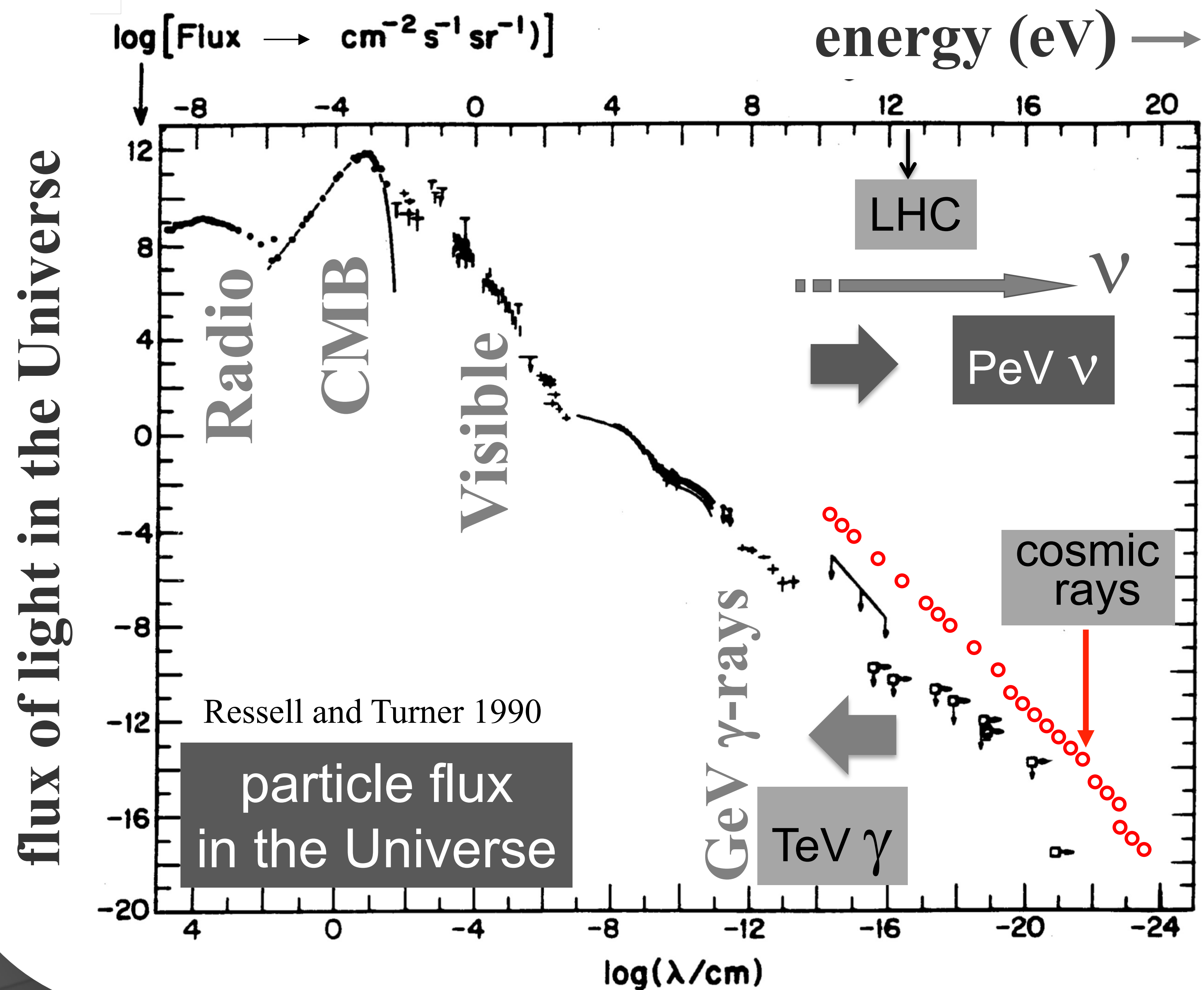
NGDOM 1

UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



overflow slides



energy (eV)
log[Flux → cm⁻² s⁻¹ sr⁻¹)]
flux of light in the Universe
Radio
CMB
Visible
GeV γ-rays
LHC
ν
PeV ν
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe
log(λ/cm)

IceCube Weekly Report 29, 2016

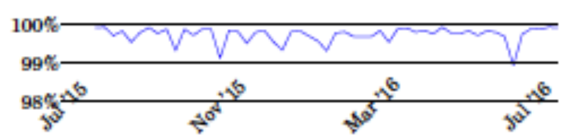
July 18 through July 24

Christian is getting quite good at these aurora shots, don't you think? Hard to remember its night time here...

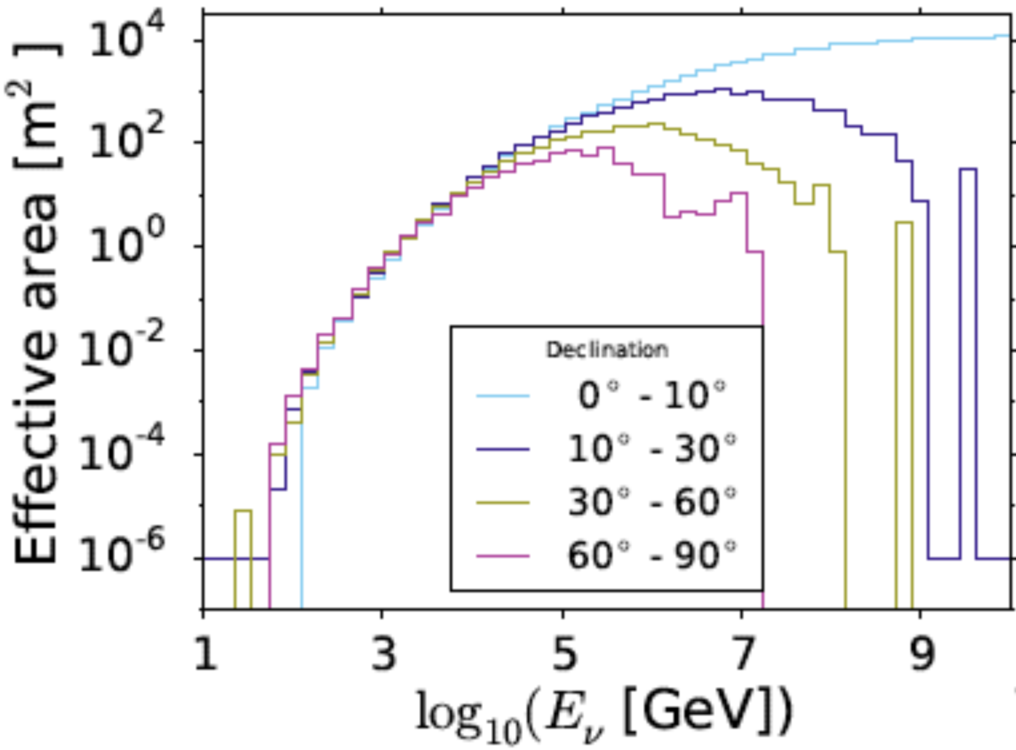
Another perfect week for IceCube! Hooray! A few minor hardware issues such as a predicted harddrive failure in ARA, and a misbehaving piece of RAM in the *i3live* machine, gave the winterovers something to do, but nothing serious, and nothing that impacted data-taking.

Station life was nice this week as we celebrated Christmas in July with a Christmas dinner on Sunday. We also had our monthly full-station ERT drill, where one of the UTs came across a fire in the Rod well. With the aid of a smoke machine, it was given an extra edge of realism.

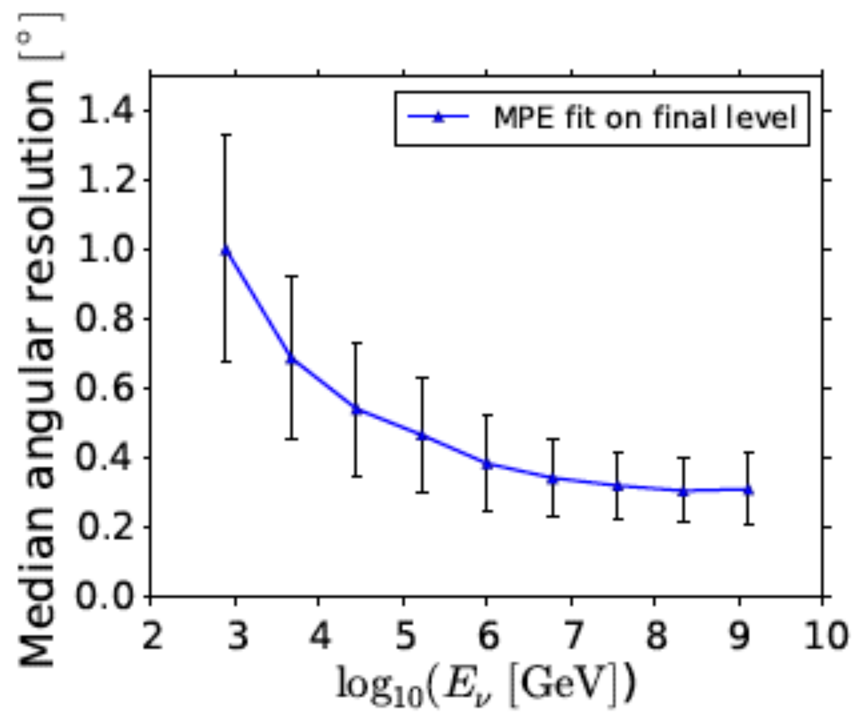
Uptime



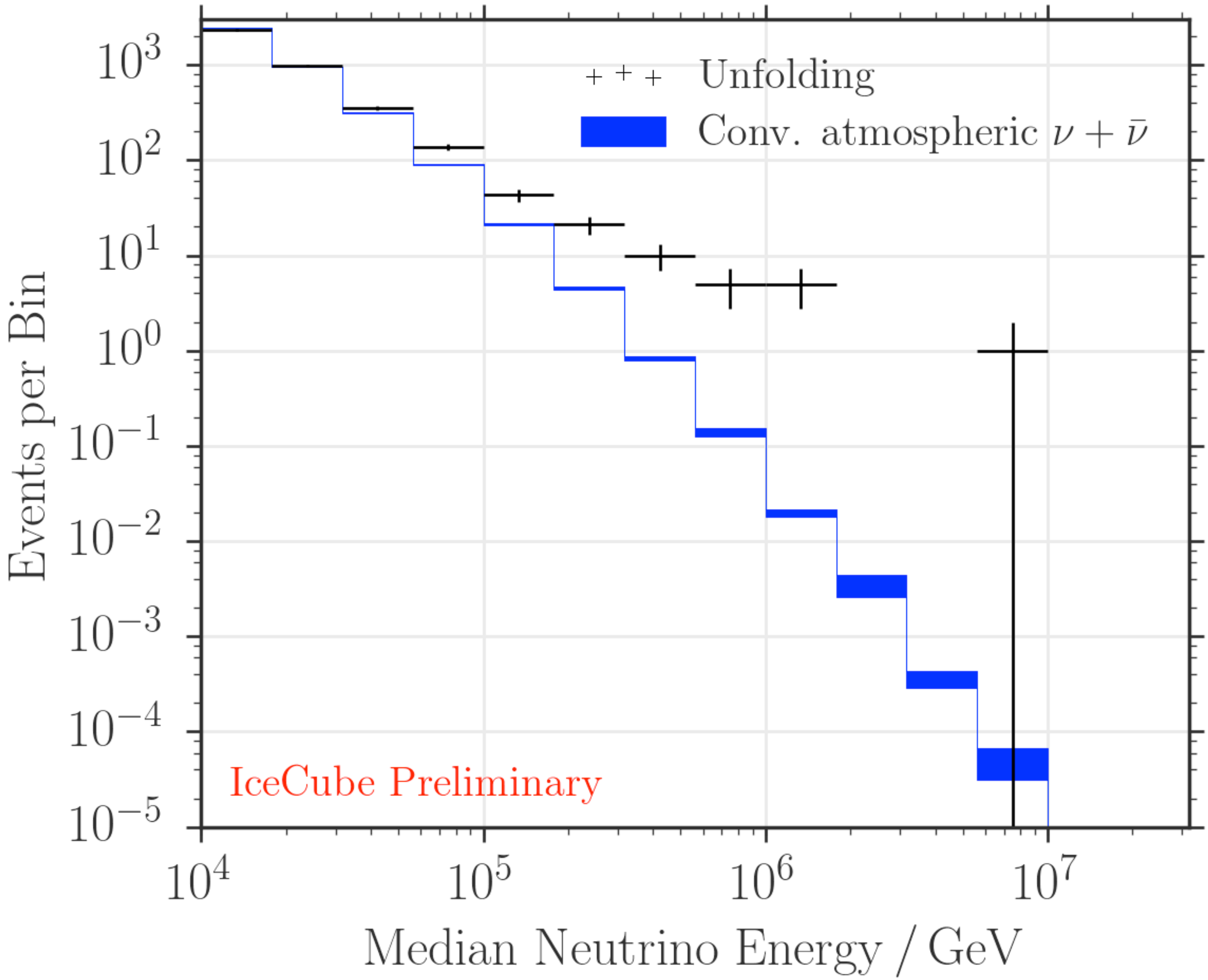
99.94%



Effective area [m^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Declination
0° - 10°
10° - 30°
30° - 60°
60° - 90°
1
3
5
7
9
$\log_{10}(E_\nu$ [GeV])

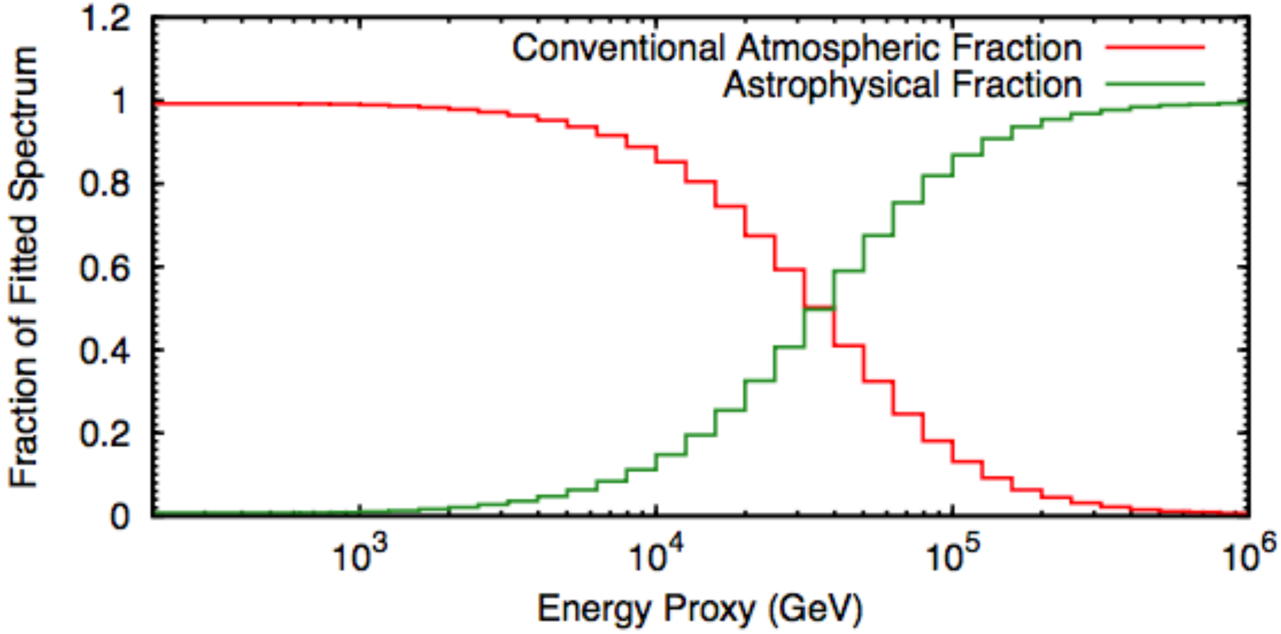


Median angular resolution [°]
MPE fit on final level
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])

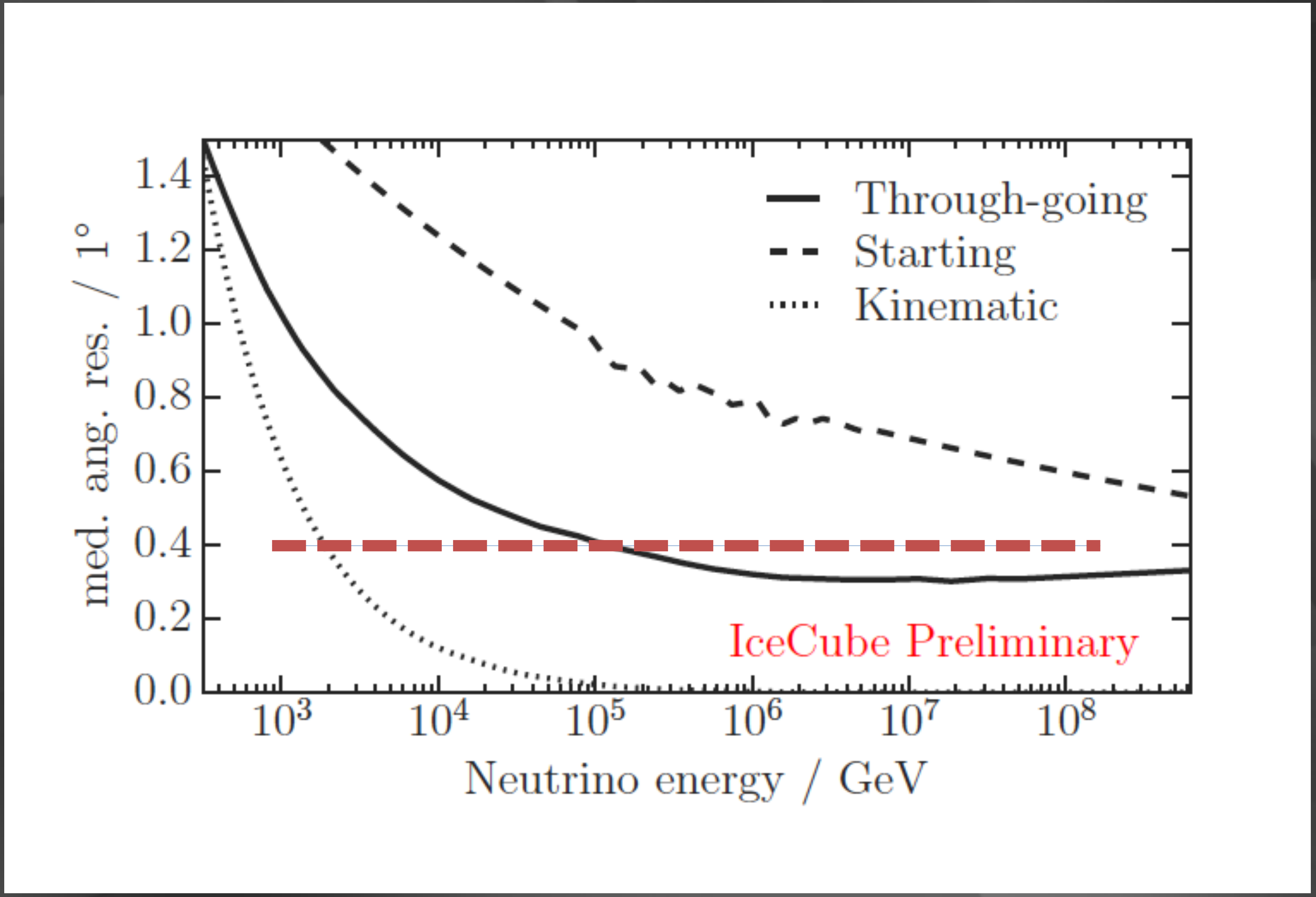


Unfolding
Conv. atmospheric $\nu + \bar{\nu}$
IceCube Preliminary
Events per Bin
Median Neutrino Energy / GeV
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{4}
10^{5}
10^{6}
10^{7}

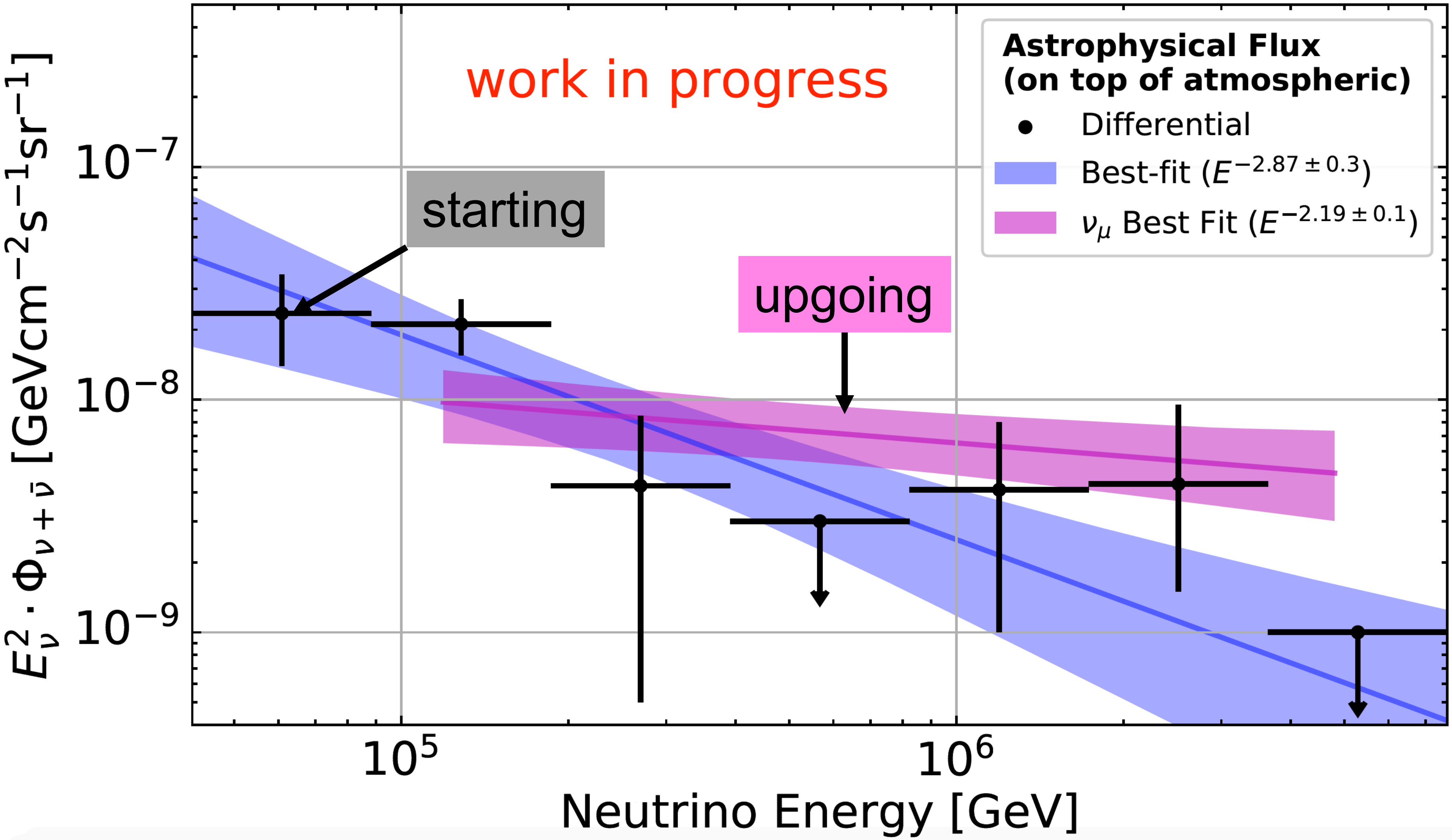
Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5



astronomy here: through-going muons with resolution 0.2~0.4^0



high-energy starting events – 7.5 yr



two methods are consistent

- Different event signatures allow flavor separation → primarily μ vs. e, τ

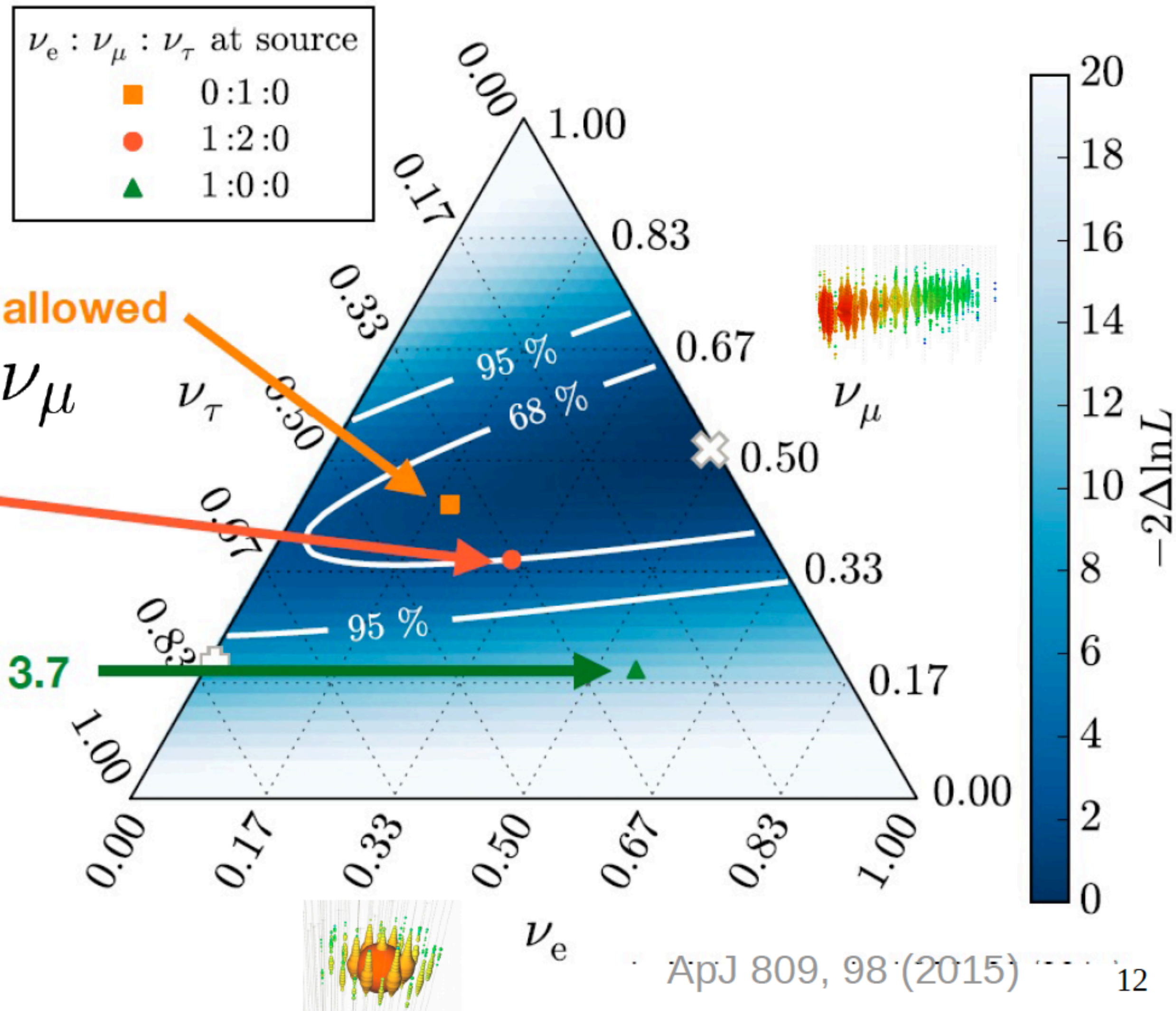
Muon-damped pion decay: allowed

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

Pion decay: allowed

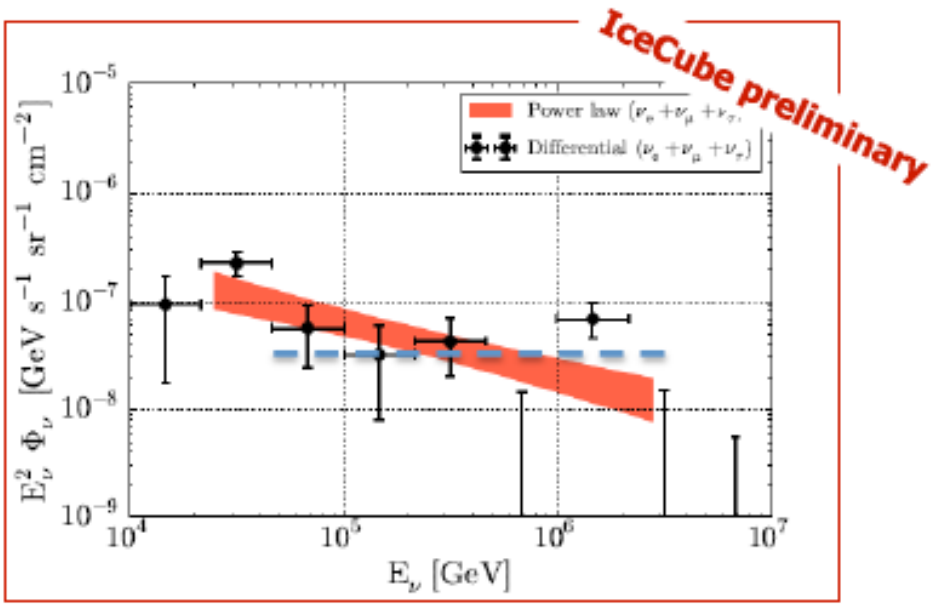
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

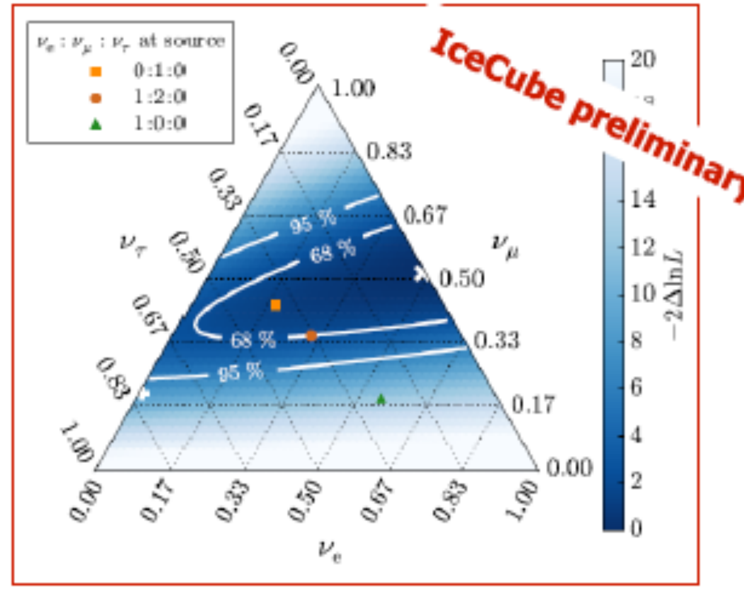
Neutron decay: rejected at 3.7



ApJ 809, 98 (2015)

- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events





assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 at Earth →

unbroken power-law between 25 TeV and 2.8 PeV
spectral index – 2.5 ± 0.09 (-2 disfavored at 3.8 σ)
flux at 100 TeV $(6.7 \pm 1.2)\times10^{-18}$ (GeV · cm^2 · s · sr)$^{-1}$

the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

equal energy in cosmic rays and neutrinos

$$\rho_{\nu+\bar{\nu}}(E) = \frac{E}{E_p}\left[\xi_z t_H\right]\left[c\dot{\rho}_p\right]$$

$$\rho_{\nu+\bar{\nu}}(E) = 4\pi E^2 \frac{dN_\nu}{dE}$$

$$\dot{\rho}_p(E_p) = E_p^2 \frac{d\dot{N}_p}{dE_p} \approx 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

$$\xi_z t_H = \text{evolution of sources} \times \text{Hubble time}$$

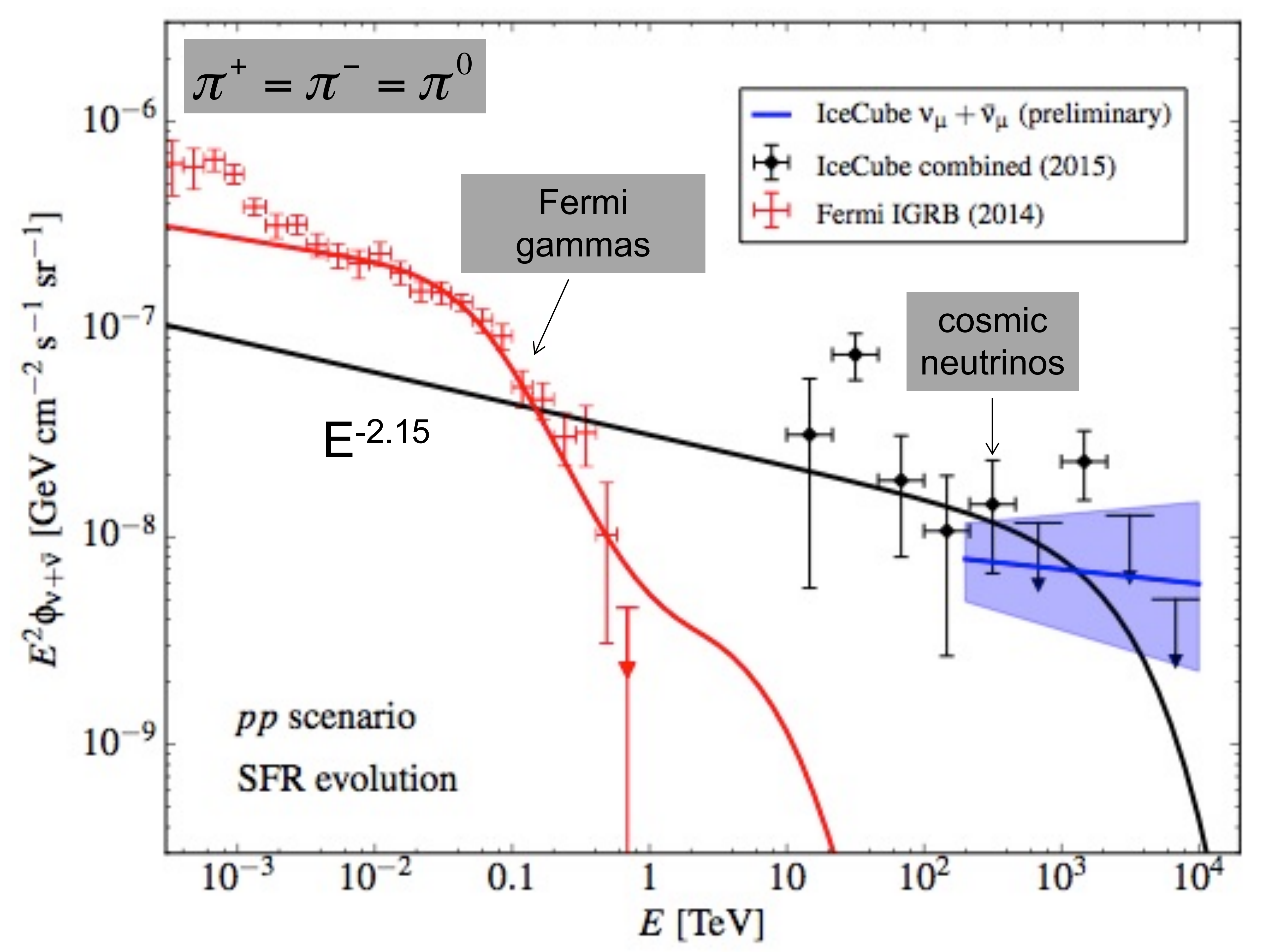
$$\Rightarrow E^2 \frac{dN_\nu}{dE} \approx 10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

equal energy in cosmic rays and neutrinos

actually…

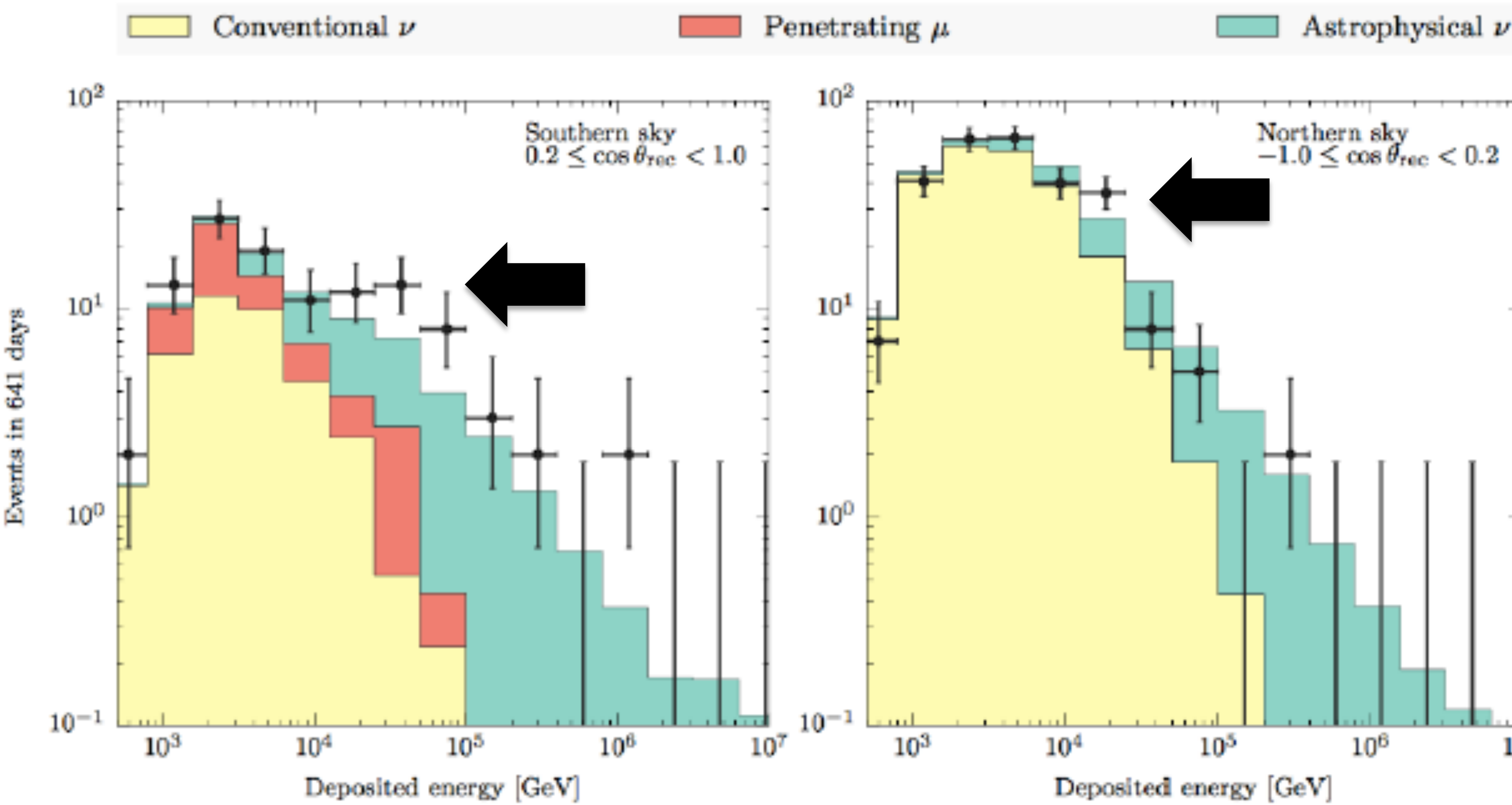
$$\rho_{\nu+\bar{\nu}}(E) = f_{\pi} \frac{E}{E_p}\left[\xi_z t_H\right]\left[c\dot{\rho}_{cr}\right]$$

- $f_{\pi} \leq 1$ transparent (to photons) source; equality is the WB bound
- $f_{\pi} \geq 1$ obscured source
- observed flux is well below the WB bound (at $20 \sim 100$ PeV); have to observe PeV photons



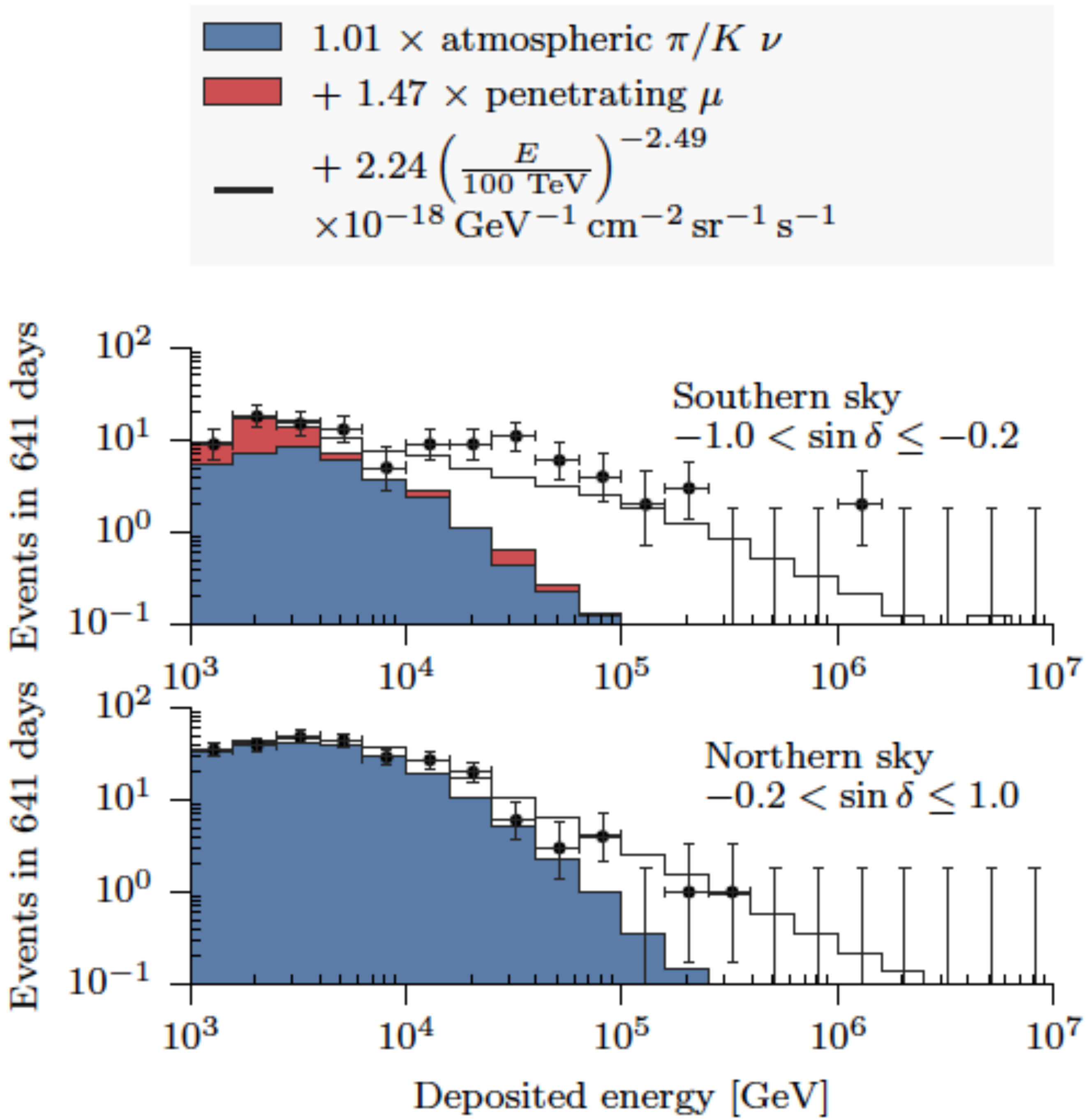
$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]

towards lower energies: a second component?



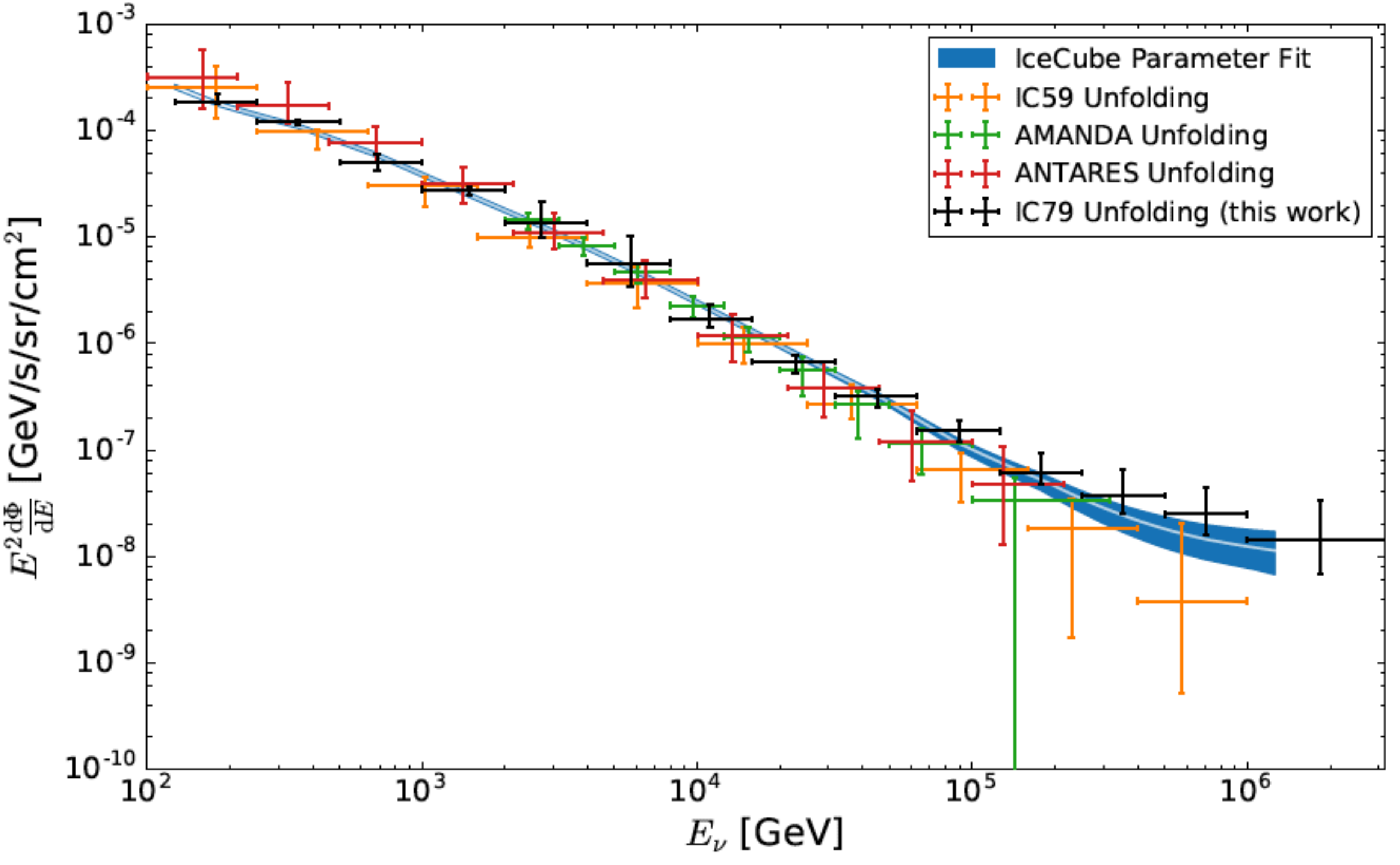
warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

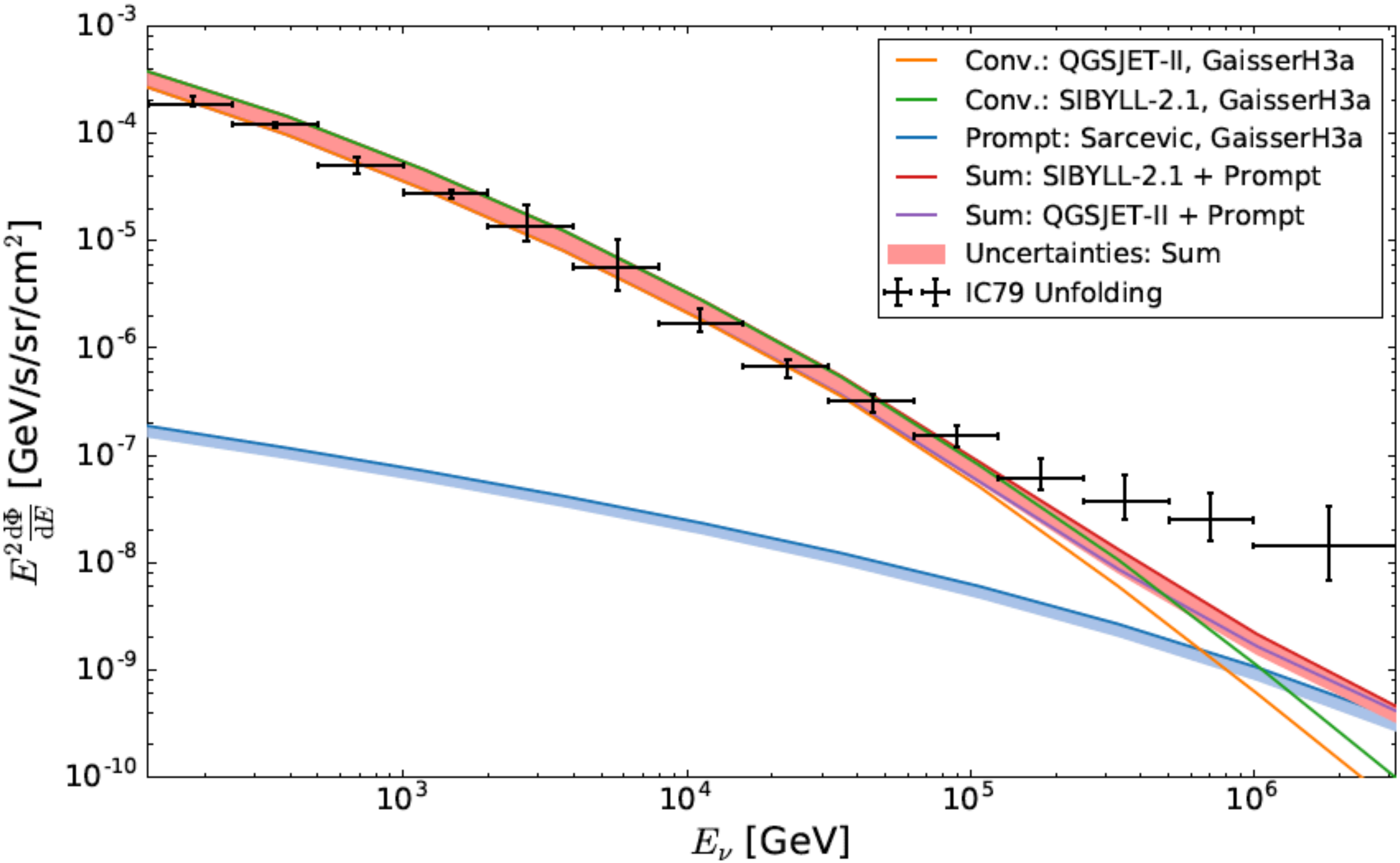


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
+ 2.24 (E/100 TeV)^−2.49 ×10^−18 GeV^−1 cm^−2 sr^−1 s^−1
Events in 641 days
Southern sky
−1.0 < sin δ ≤ −0.2
Northern sky
−0.2 < sin δ ≤ 1.0
Deposited energy [GeV]

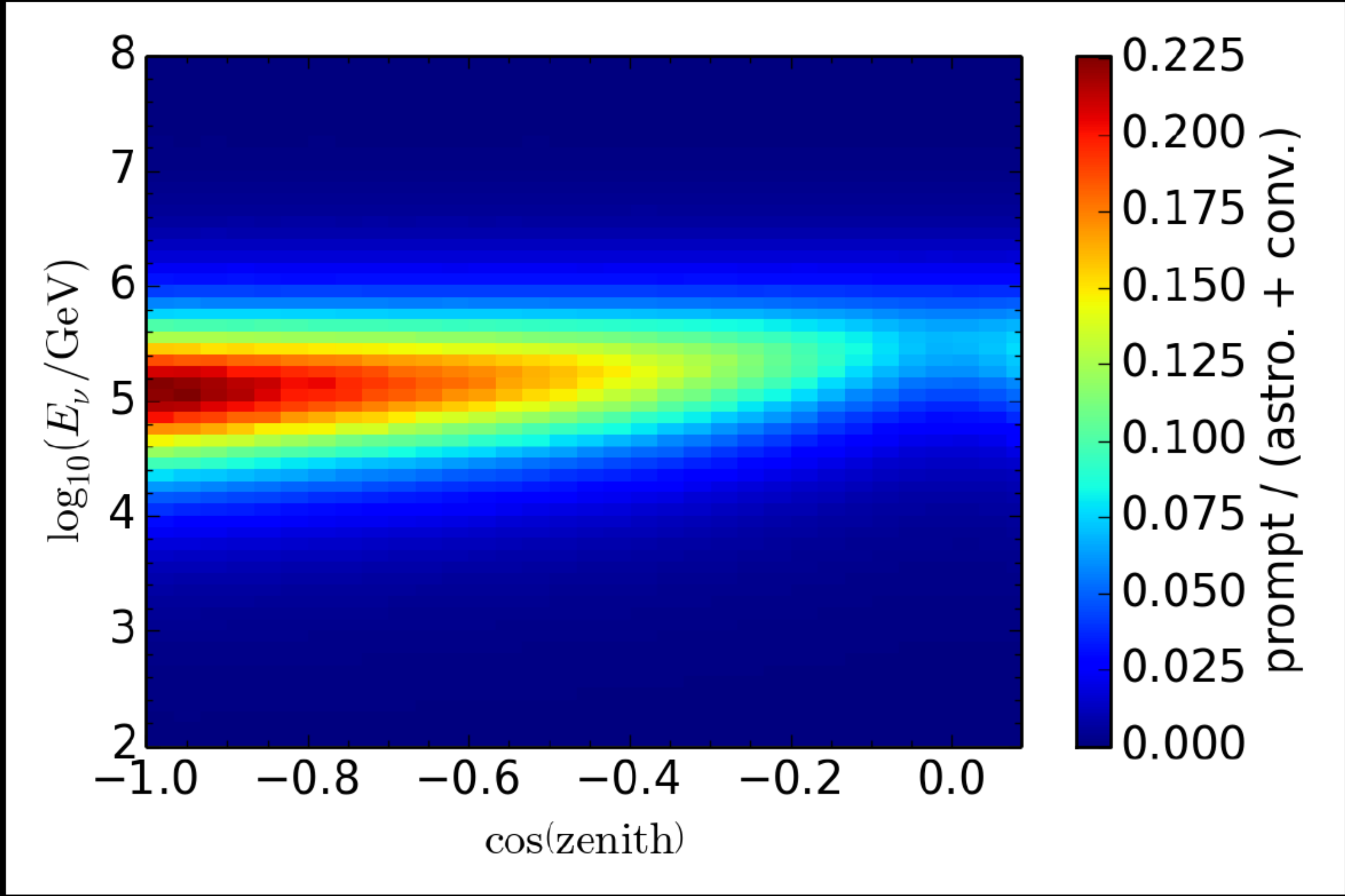
unfolded “atmospheric” neutrino flux



unfolded “atmospheric” neutrino flux



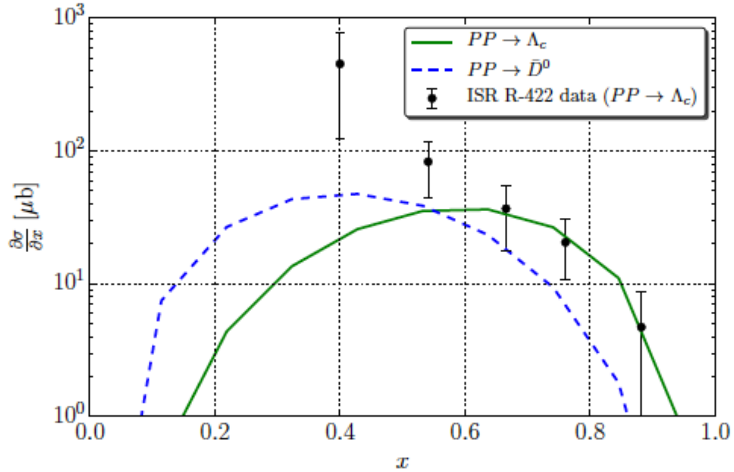
not atmospheric charm



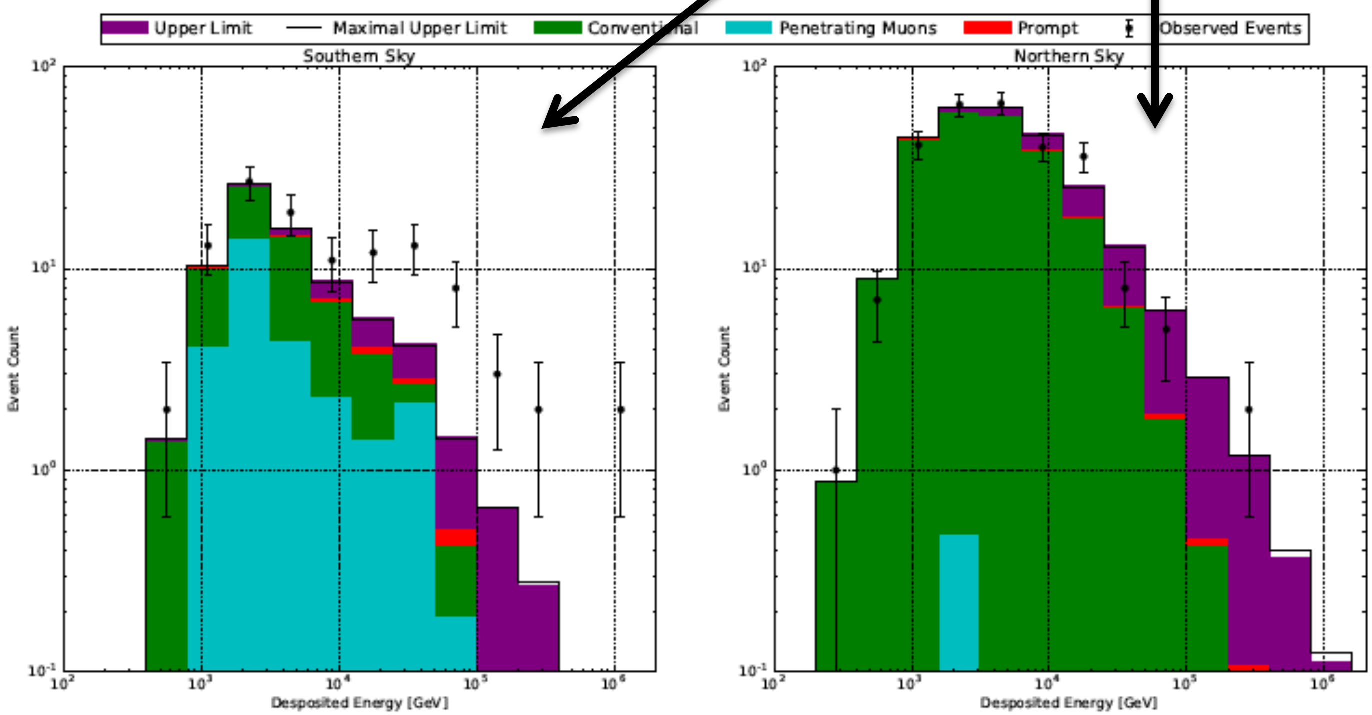
- Prompt flux would appear @ around 100 TeV
  → ~ 20% effect in straight up-going region

not forward charm production

analogous to pp→($K^+\Lambda$)p

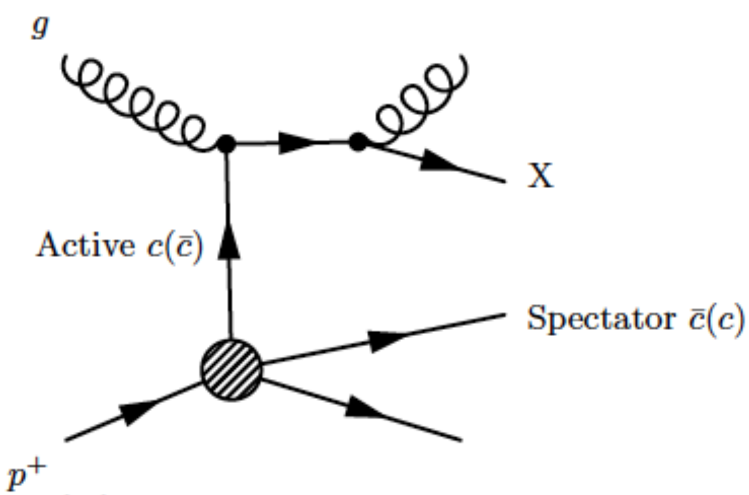


upcoming events:
"extreme" charm model can fit the northern, not the southern hemisphere

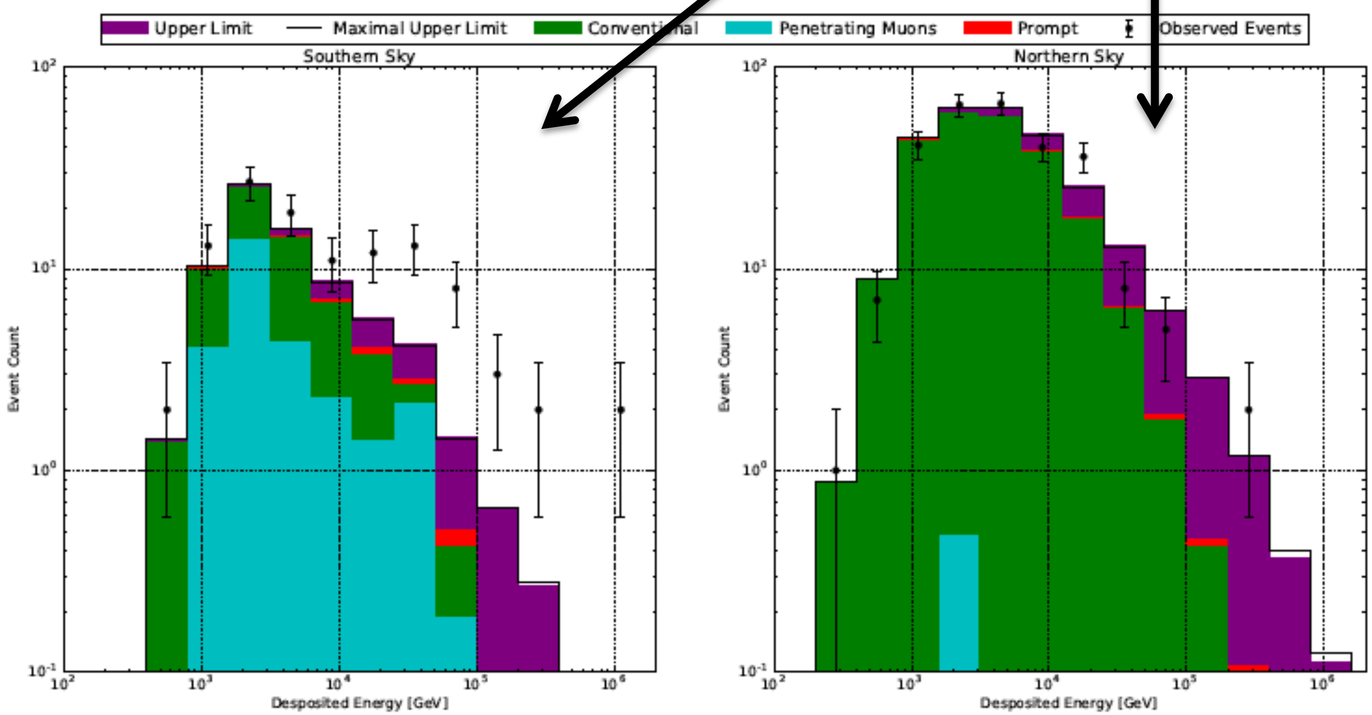


LHC: charm pairs in proton

analogous to pp→($K^+\Lambda$)p

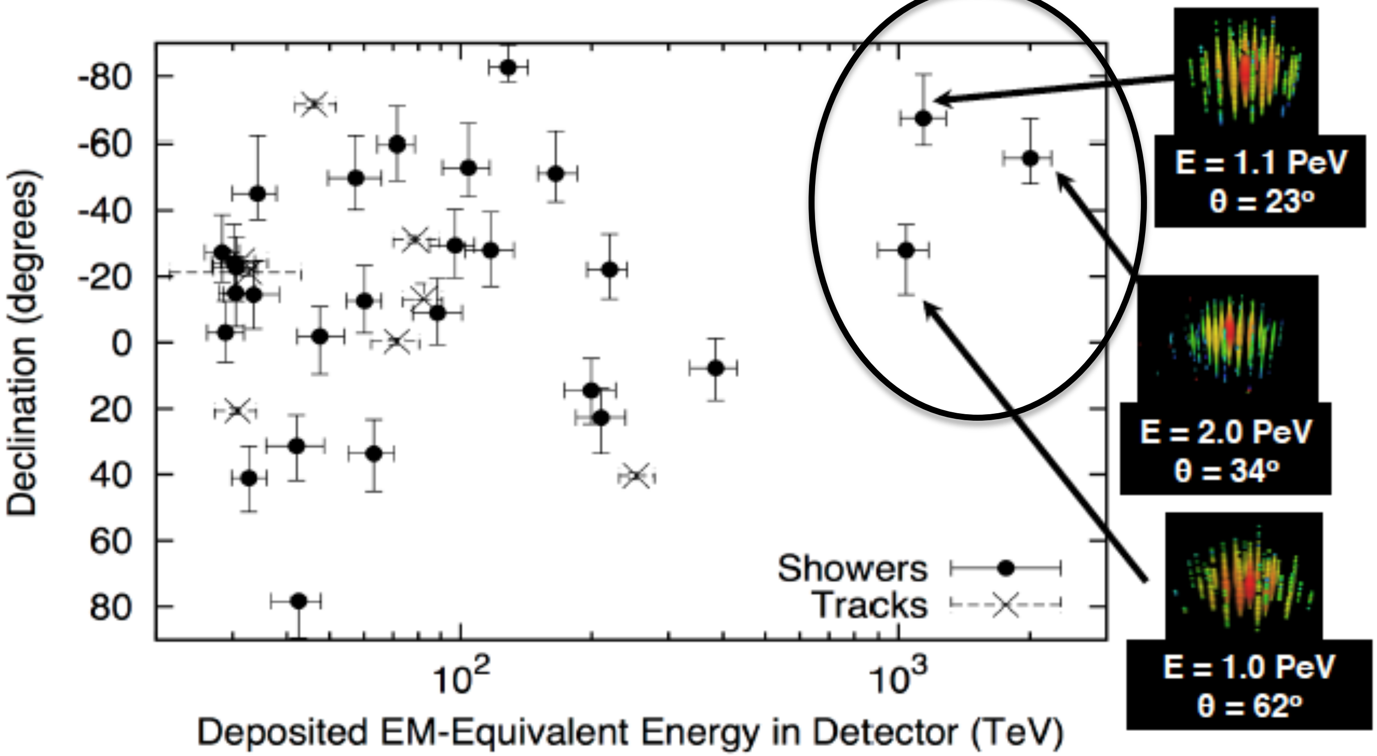


upcoming events:
"extreme" charm model
can fit the northern, not
the southern hemisphere

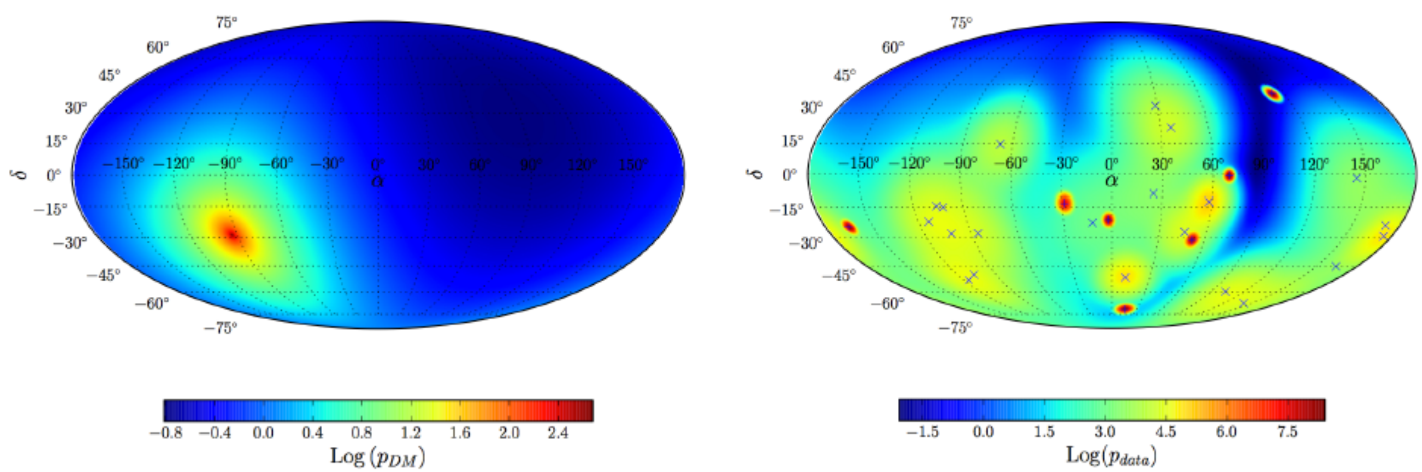


- dark matter?

expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle



- we observe a diffuse extragalactic flux
- active galaxies, most likely some form of AGN?
- correlation to catalogues should confirm this
- correlation in time with a AGN flare can be a smoking gun
- …. but correlation of cosmic neutrinos to < 30% of all Fermi blazars (different subsets produce highest energy neutrinos and gamma rays)

HESE ALERT

```
////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Sun 14 Aug 16 21:46:36 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          128340
EVENT_NUM:        58537957
SRC_RA:           199.3100d {+13h 17m 14s} (J2000),
                  199.5422d {+13h 18m 10s} (current),
                  198.6132d {+13h 14m 27s} (1950)
SRC_DEC:          -32.0165d {-32d 00' 58"} (J2000),
                  -32.1038d {-32d 06' 13"} (current),
                  -31.7532d {-31d 45' 11"} (1950)
SRC_ERROR:        89.39 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      28.79 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17614 TJD;    227 DOY;    16/08/14 (yy/mm/dd)
DISCOVERY_TIME:   78354 SOD {21:45:54.00} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           10431.02 [pe]
SIGNAL_TRACKNESS: 0.12 [dn]
SUN_POSTN:        144.87d {+09h 39m 29s}  +14.01d {+14d 00' 24"}
SUN_DIST:          69.72 [deg]   Sun_angle= -3.6 [hr] (East of Sun)
MOON_POSTN:       279.69d {+18h 38m 45s}  -18.41d {-18d 24' 37"}
MOON_DIST:         72.22 [deg]
GAL_COORDS:       309.28, 30.54 [deg] galactic lon,lat of the event
ECL_COORDS:       210.33,-22.02 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_HESE.
```

http://gcn.gsfc.nasa.gov/notices_amon/

MASTER: OT discovered during inspection of HESE 58537957 trigger

'el #9425; *N. Tyurina, V. Lipunov (Lomonosov MSU), D. Buckley (SAAO), E. Gorbovskoy, P. Balanutsa, A. Kuznetsov, V. Kornilov, D. Kuvshinov, D. Vlasenko, O. Gress, K. Ivanov, V. humkov (Lomonosov Moscow State University, SAI), S. Potter (South African Astronomical Observatory)*

on ***30 Aug 2016; 00:37 UT***

Credential Certification: Nataly Tyurina (tiurina@sai.msu.ru)

bjects: Optical, Neutrinos, Request for Observations, Transient

ferred to by ATel #: 9456

Tweet | Recommend | 2

ASTER OT J130845.02-323254.9 - optical transient detection during inspection of HESE 537957_128340 alert

ASTER-SAAO auto-detection system (Lipunov et al., "MASTER Global Robotic Net", vances in Astronomy, 2010, 349171) discovered OT source at (RA, Dec) = 13h 08m 45.02s 'd 32m 54.9s on 2016-08-24.73811 UT during inspection of HESE alert (58537957 trigger mber) http://gcn.gsfc.nasa.gov/notices_amon/58537957_128340.amon .
e OT unfiltered magnitude is 19.6m (limit 20.5m).
e OT is seen in 12 images. There is no minor planet at this place.

9456 MASTER OT J130 323254.9: Variable Source of the Hig Neutrino.
9440 Search for counte IceCube-160814A ANTARES
9425 MASTER: OT disc during inspection 58537957 trigger
9391 INTEGRAL follow- IceCube HESE 12 58537957

- An HESE alert was launched on 14 Aug. 2016 for 1 event with exceptionally high charge of 10’431 pe in the detector from the direction centered at RA=199.3100 Dec=-32.0165 and error circle of 1.5° error (90% containment)
- INTEGRAL set an upper limit between 20-200 keV
- ANTARES did not find other neutrinos
- Inside about 1σ error box MASTER detected an Optical Transient
- Another was detected on Sep.4
- Hypothesis: a pulsing white dwarf, remaining out of a binary system. Possible scenario for neutrino production? intense enough B-fields and disintegration of binary companion or accretion of matter?
- Recent discovery of A pulsing, radio emitting white dwarf". Nature doi:10.1038/nature18620,16 (2016)

http://www.astronomerstelegram.org/?read=9456

auto correlation: multiple neutrinos from the same source

total number of events required to observe n-events multiplets from the closest sources is

$$740 \times \left[\frac{n}{2}\right] \times \left[\frac{\rho_0}{10^{-5}}\right]^{\frac{1}{3}} \text{ events}$$

for a observed diffuse cosmic flux and 0.4 degrees angular resolution

examples of local source densities (per Mpc^3):

- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

Is the nearest source of the extragalactic IceCube flux F_ν observable?

$$F_\nu \equiv E^2 \frac{dN}{dE\,d\Omega\,dt} = \int d^3r \frac{L_\nu}{4\pi r^2}\rho = \frac{L_\nu \rho}{4\pi}\int d\Omega\,dr = \frac{L_\nu \rho}{4\pi}\zeta R_H$$

$$\approx 3\times 10^{-8}\,\frac{\text{GeV}}{\text{cm}^2\,\text{sec}\,\text{sr}},\ \text{therefore}$$

$$L_\nu \rho = \frac{4\times 10^{43}}{\zeta}\frac{erg}{Mpc^3\,yr}$$ should be ~1% of the sources. This is the minumum power density to produce the neutrinos.

Flux of the nearest source $(F_{ns}) <$ the IceCube ps limit:

$$F_{ns} = \frac{L_\nu}{4\pi d^2} \leq 2\times10^{-9}\ \frac{\text{GeV}}{\text{cm}^2\text{sec}} \quad \text{with} \quad d = (4\pi\rho)^{\frac{1}{3}} \leftarrow V_1 \propto \frac{1}{\rho}$$

and

$$F_{ns} = \frac{L_\nu d}{4\pi d^3} = \rho L_\nu d.$$ Combined with the result for ρL_ν:

$d \leq 100\text{Mpc}$ and $\rho \geq \dfrac{10^{-7}}{\text{Mpc}^3}$ for ζ=3.

$$\# \text{ of events from the nearest source: } \frac{L_\nu}{4\pi d^2} \otimes Area$$

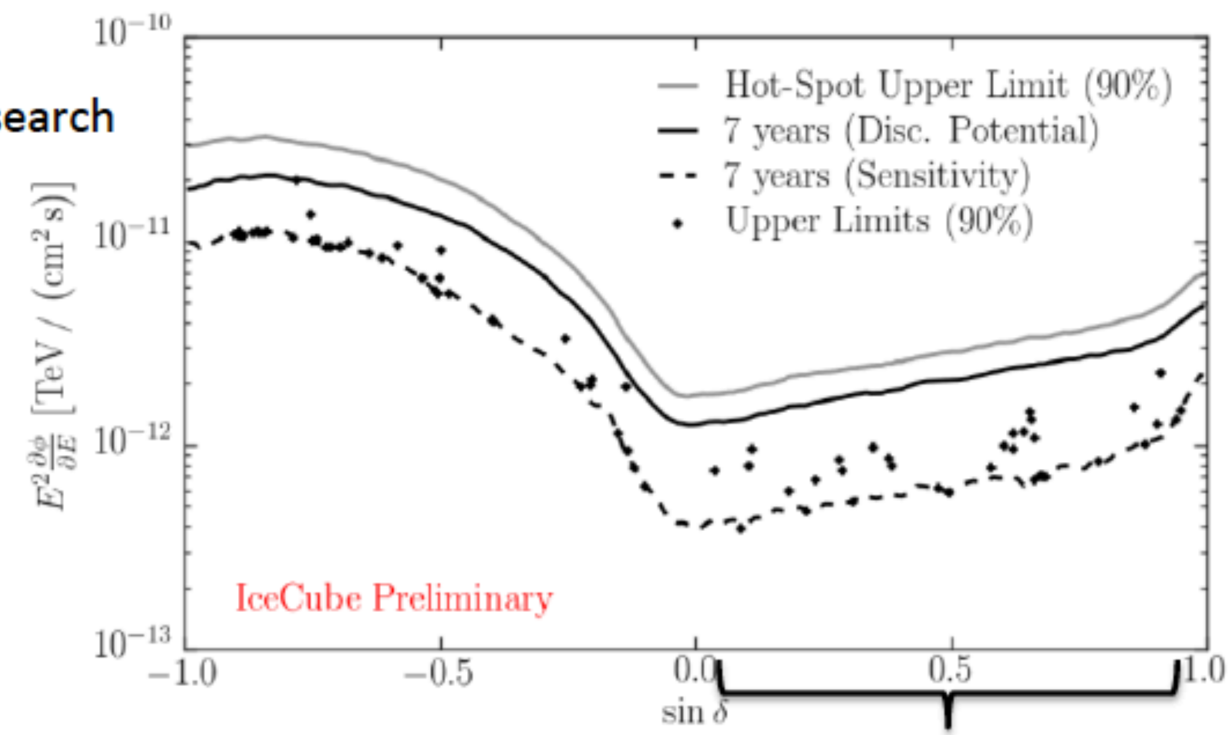
$$\# \text{ of events from the whole sky } : \zeta L_\nu \rho R_H \otimes Area$$

$$\text{ratio} = \frac{d}{\zeta R_H} = \frac{1}{\zeta R_H (4\pi\rho)^{1/3}} = 10^{-2} \text{ for } \rho = 10^{-7}. \text{ Soon!}$$

Point source limits

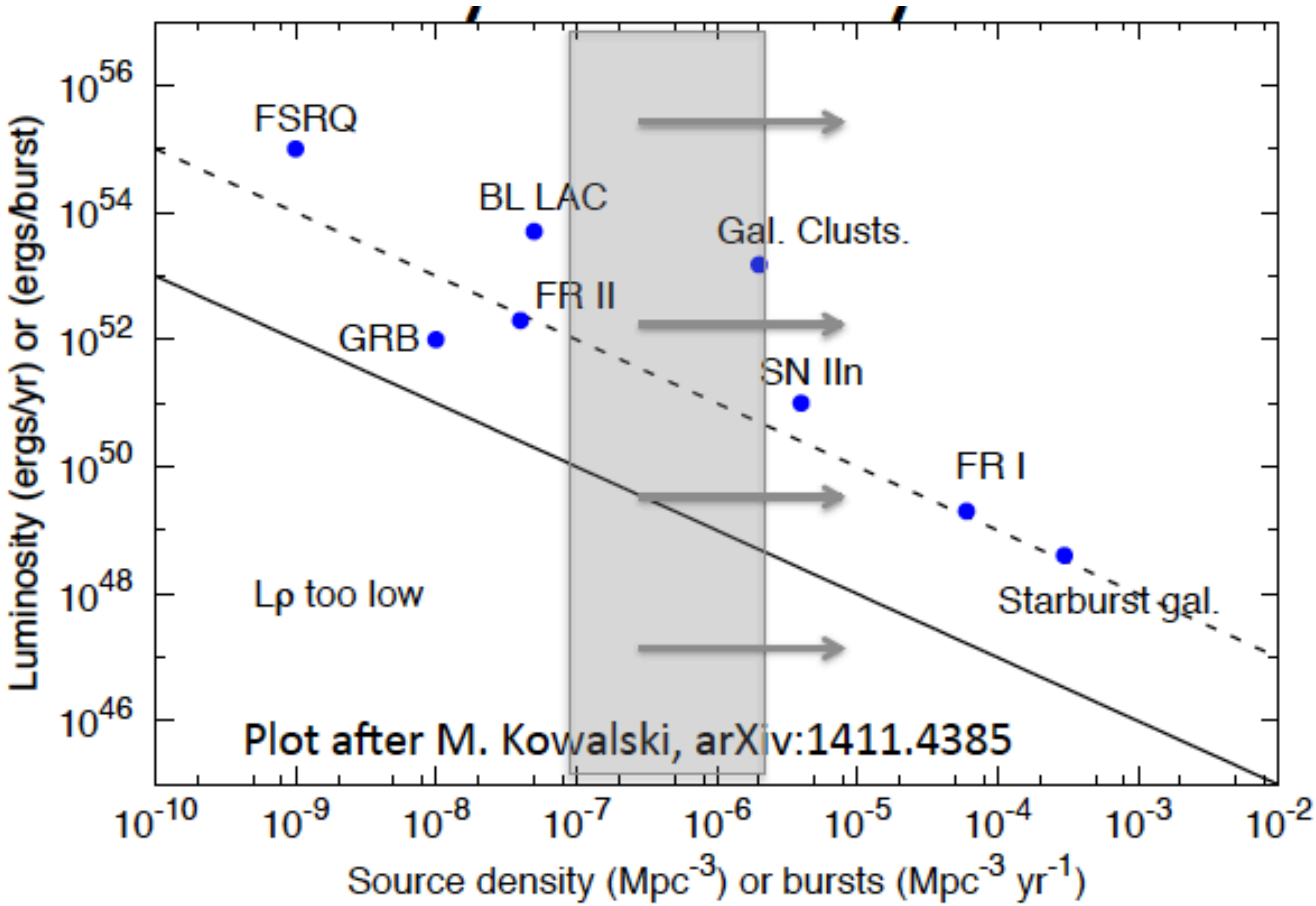
Relation between flux from whole sky and number/intensity of individual sources
P. Lipari, PR D78 (2008) 083001 … Murase & Waxman, arXiv:1607.01601

IceCube 7 yr pt src search



Northern hemisphere, good pointing with ν_μ-induced μ, limits

$$< 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$$

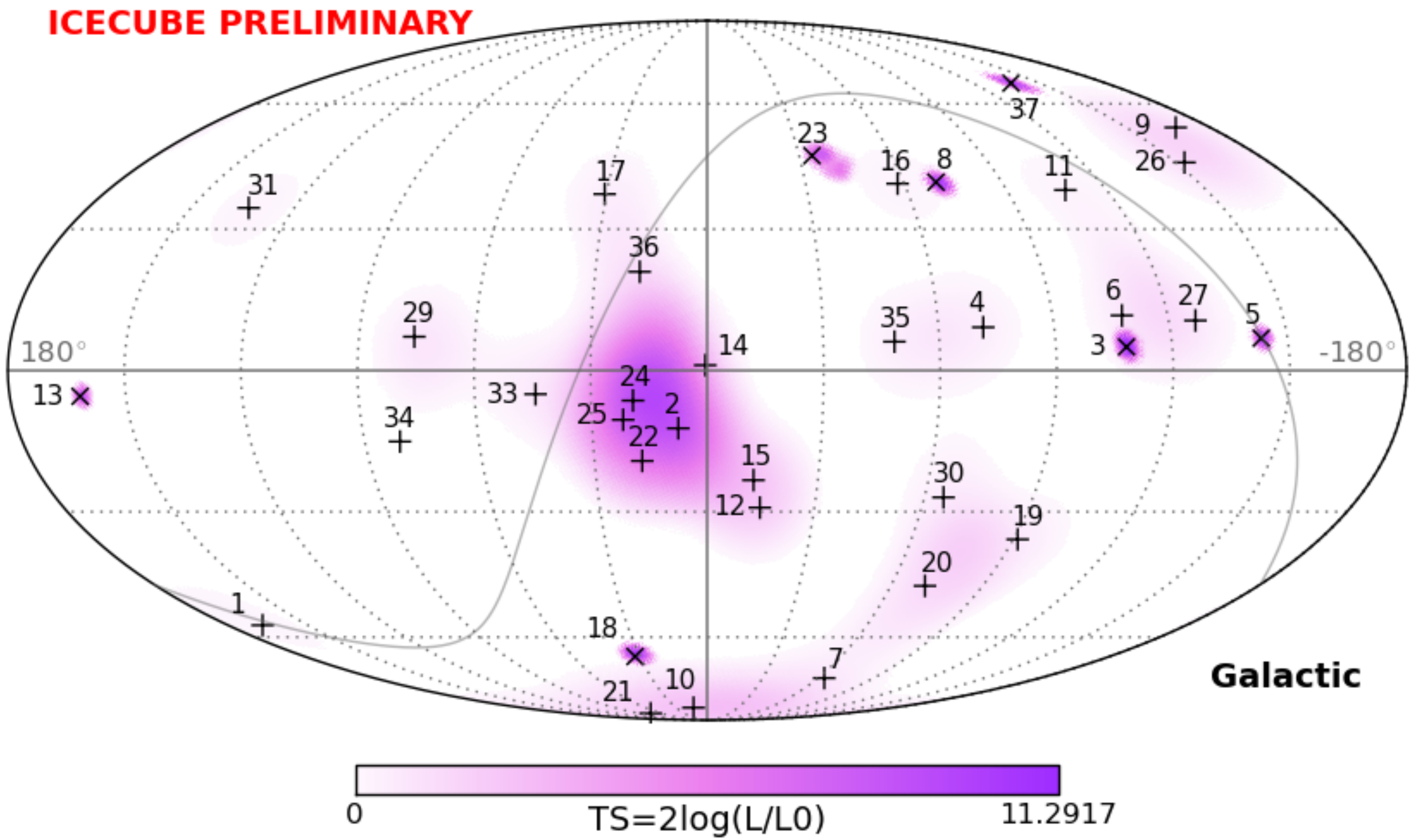

FSRQ
BL LAC
Gal. Clusts.
FR II
GRB
SN IIn
FR I
Starburst gal.
Lρ too low
Plot after M. Kowalski, arXiv:1411.4385
Luminosity (ergs/yr) or (ergs/burst)
Source density (Mpc-3) or bursts (Mpc-3 yr-1)
10^56
10^54
10^52
10^50
10^48
10^46
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2

Glashow resonance dictates $\nu_e - \nu_\tau$ mixture events per year:

Φ_{ν_e} $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	interaction type	pp source IC-86	240m	360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$	GR	0.12	0.9	2.1
	DIS	0.01	0.1	0.2

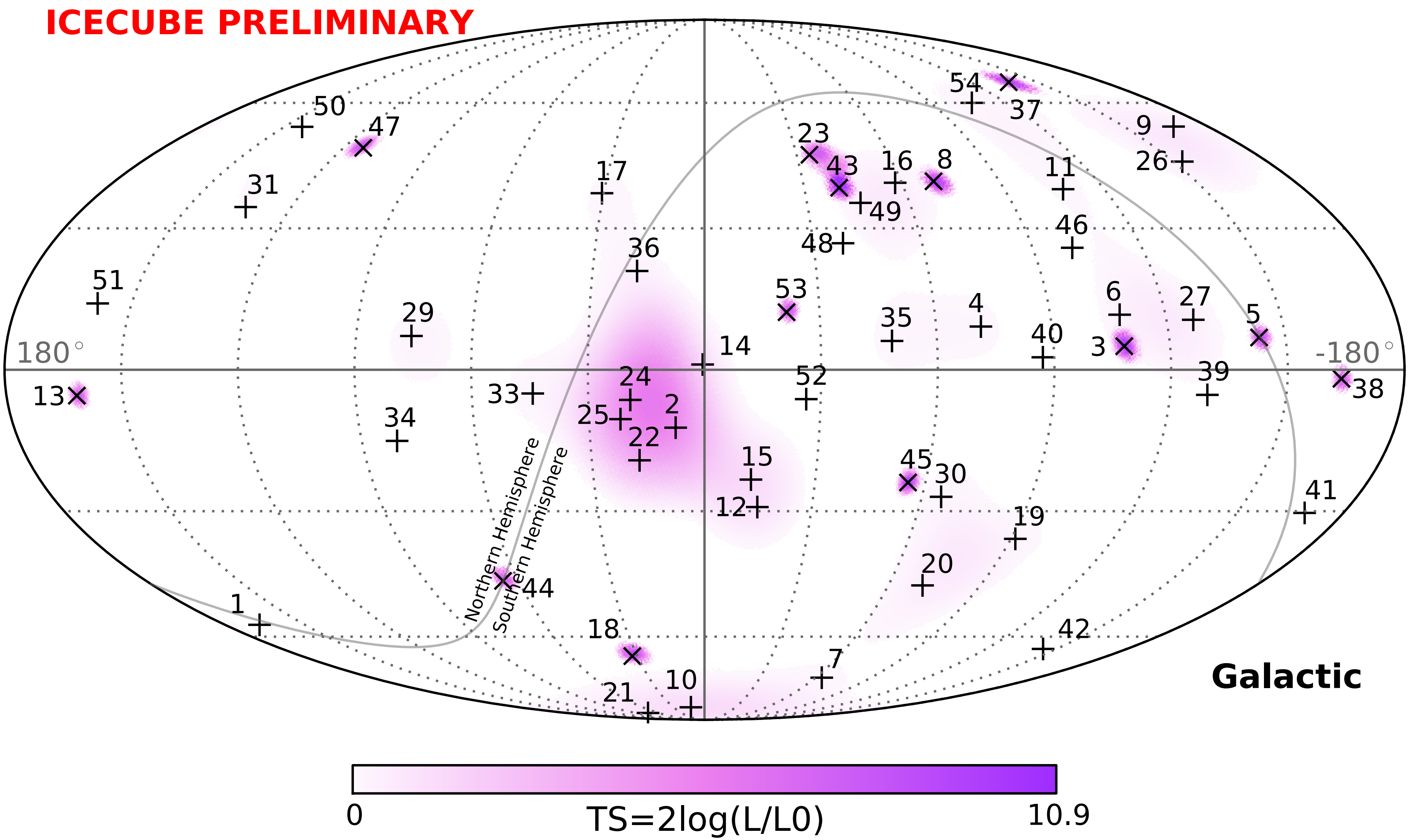
$$\overline{\nu}_e + e^- \rightarrow W$$

3 year HESE



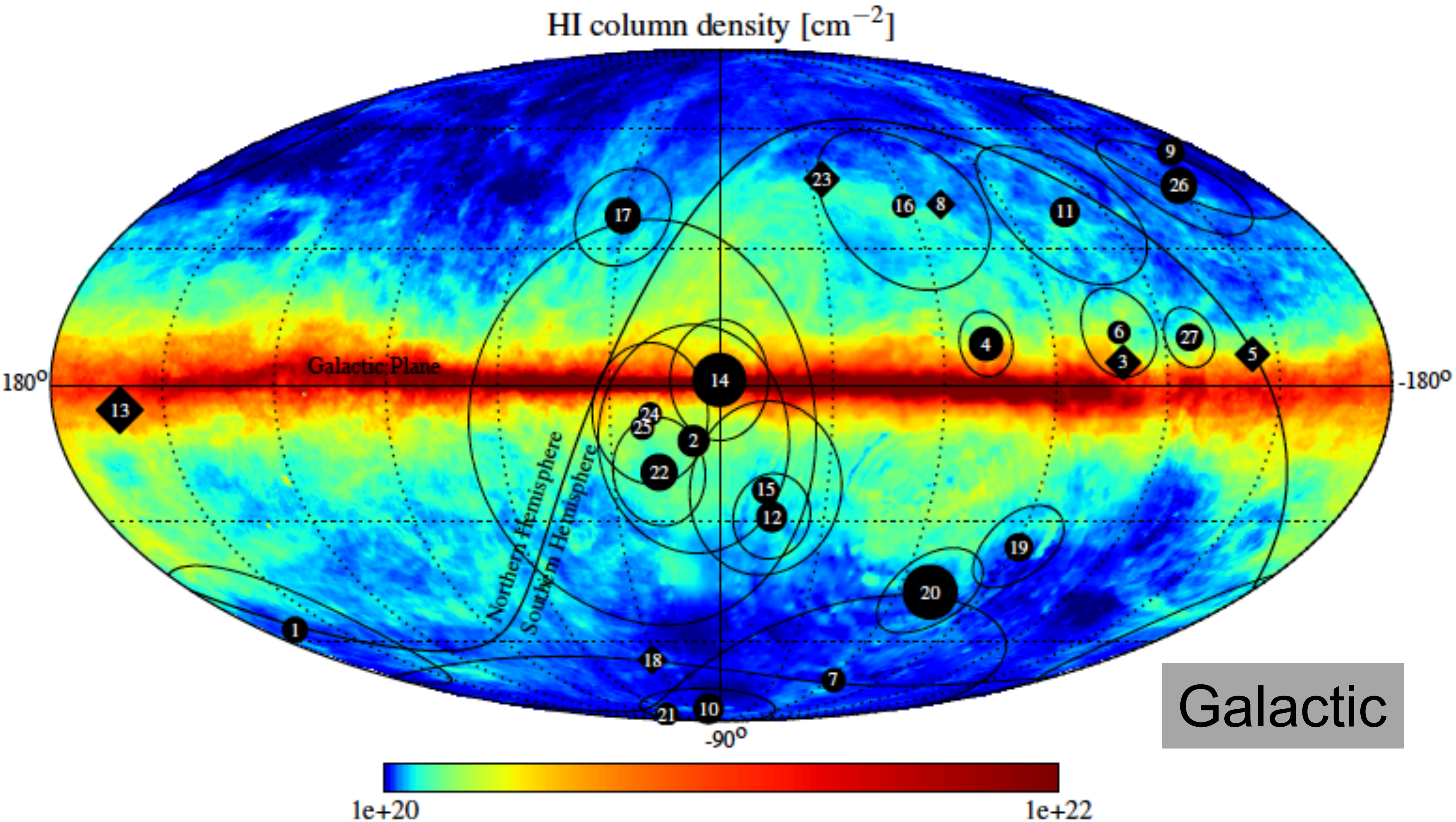
ICECUBE PRELIMINARY
180°
-180°
Galactic
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
33
34
35
36
37
0
TS=2log(L/L0)
11.2917

4 year HESE



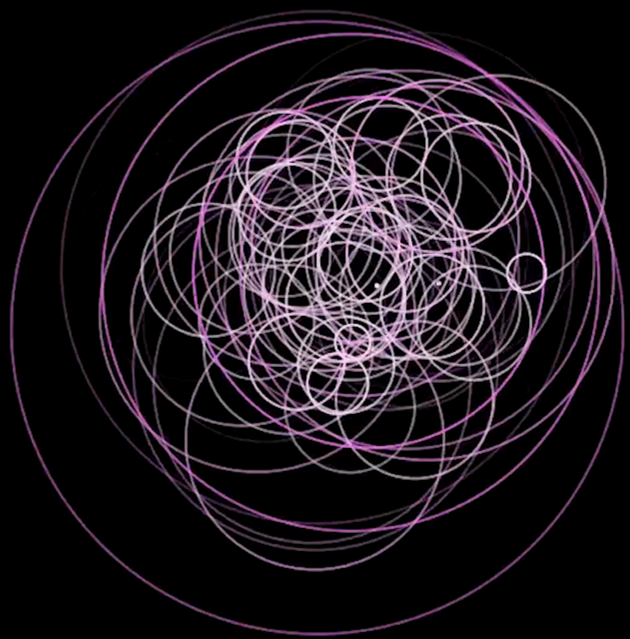
where do they come from?

correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg



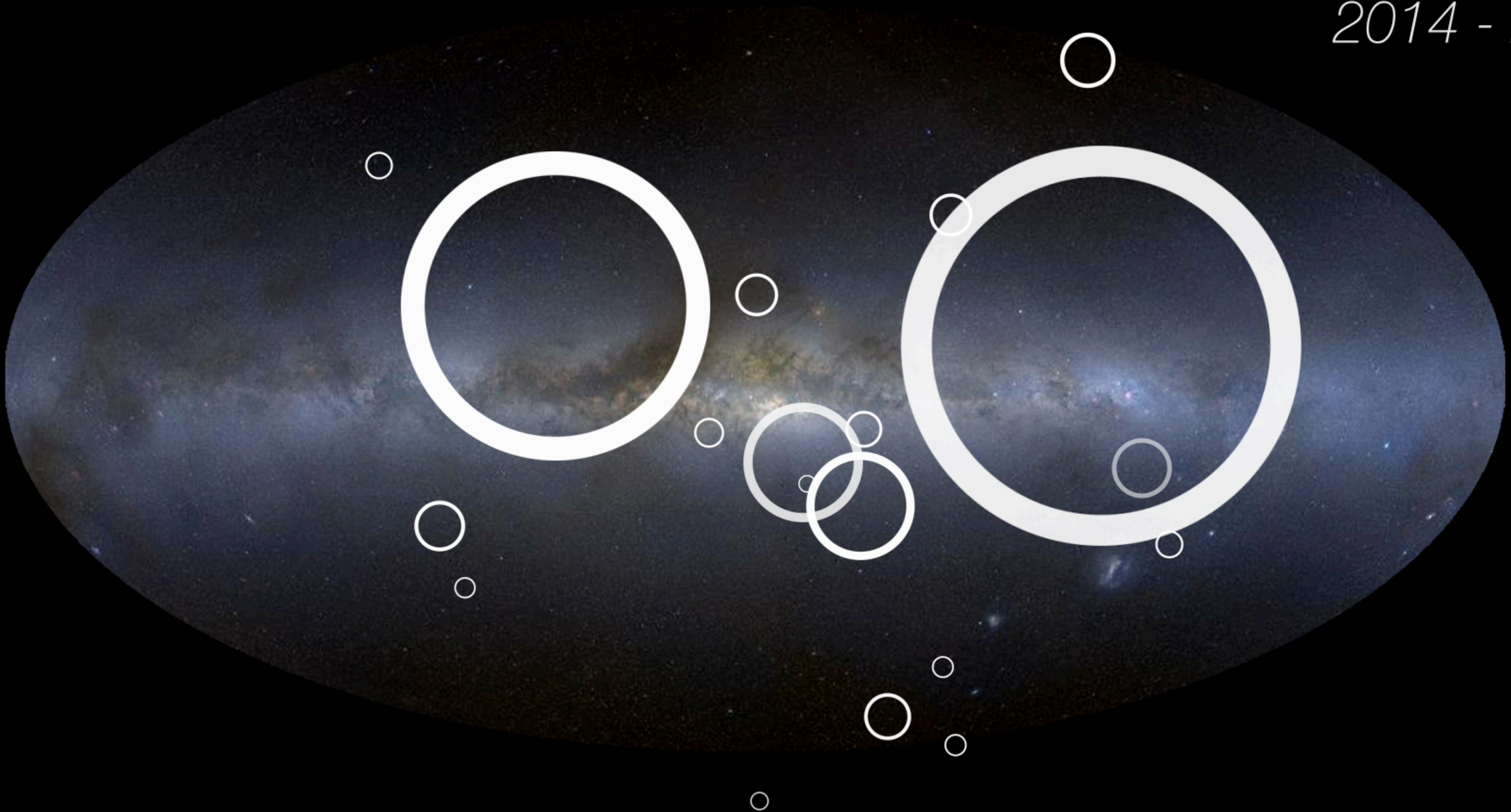
Galactic

11 Sep 2017



IceCube Neutrino Flare

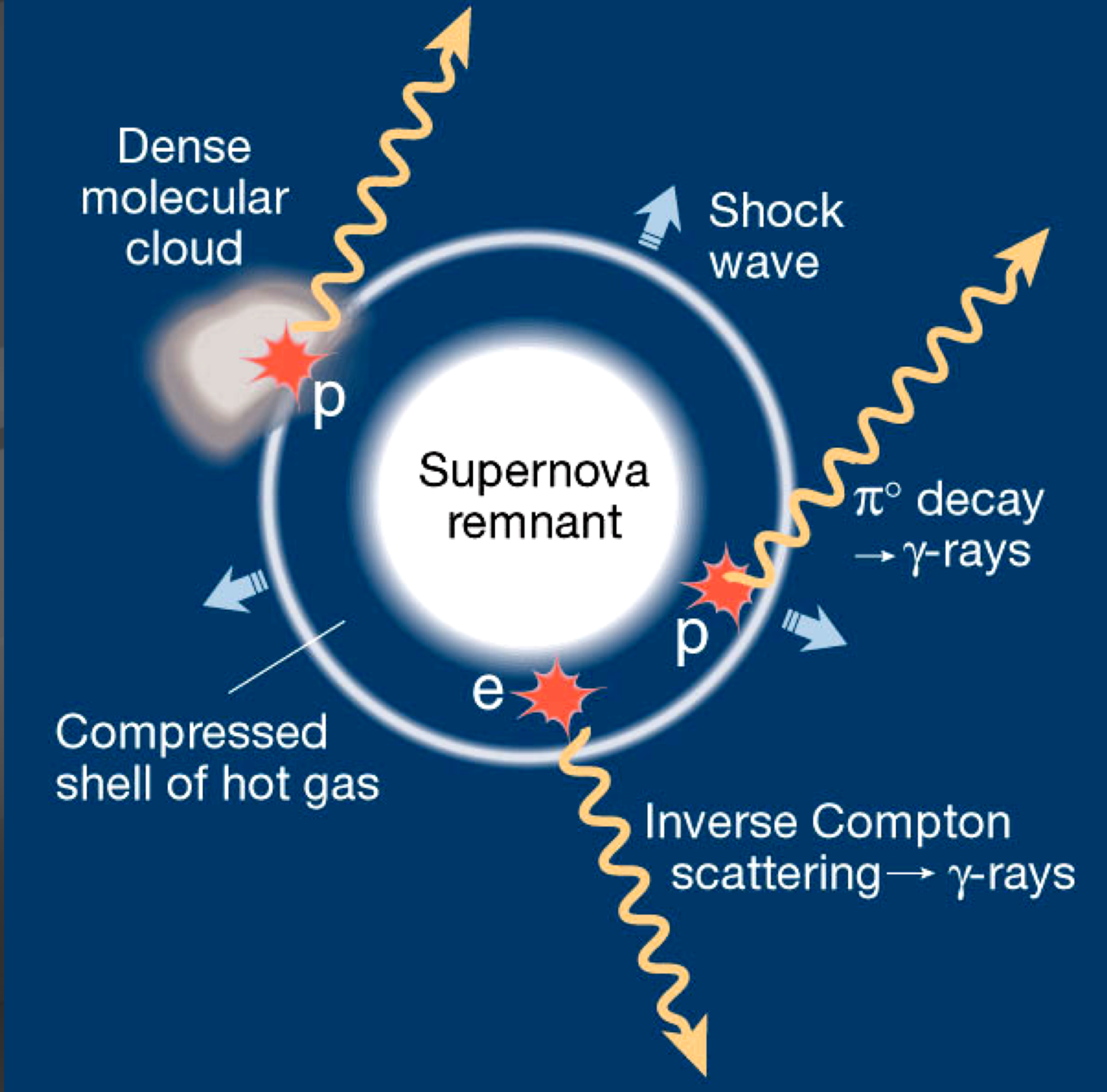
2014 - 2015



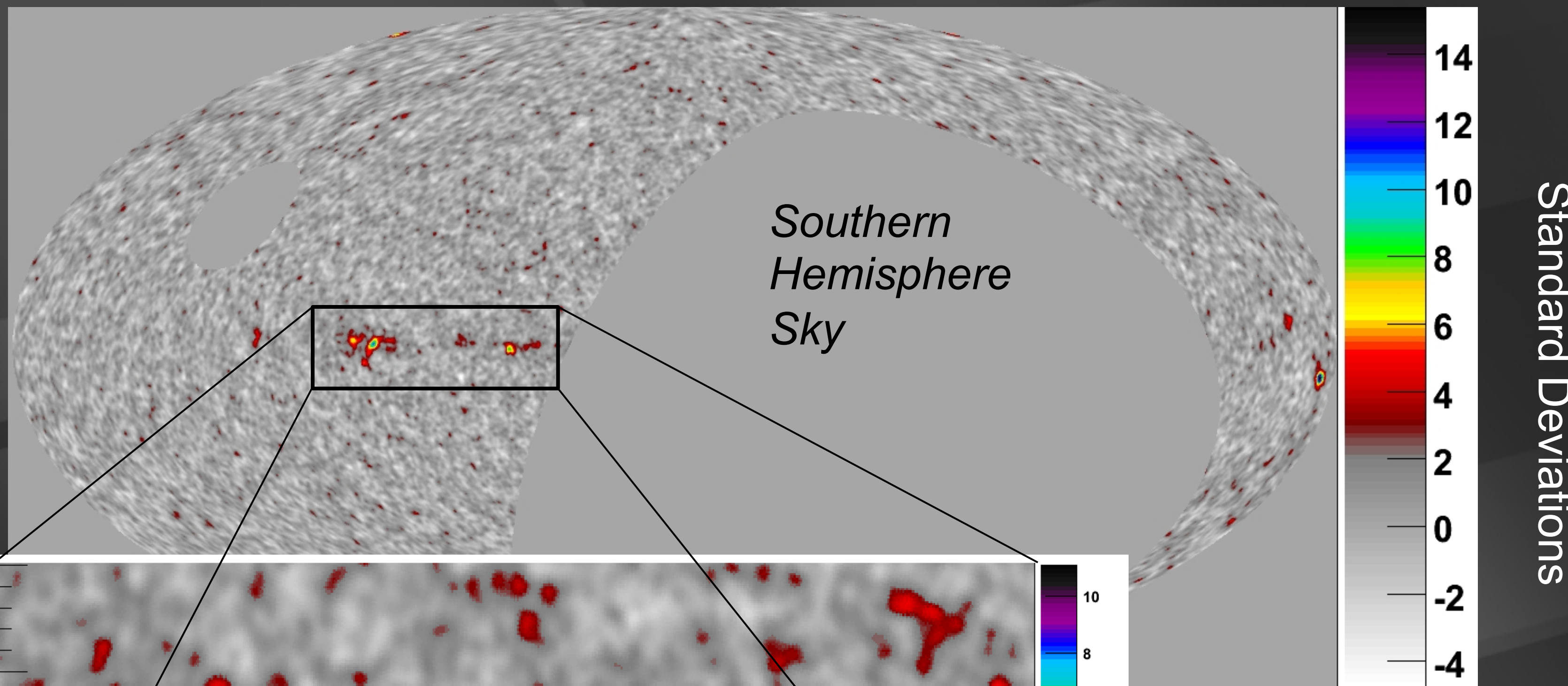
Galactic sources?

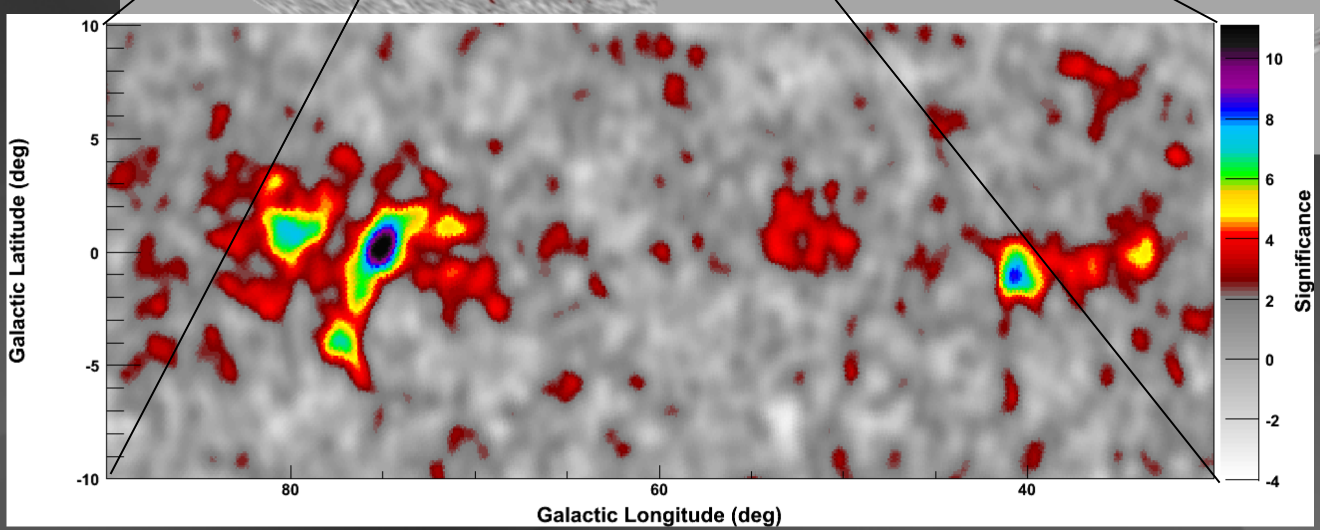
neutrinos from supernova remnants :

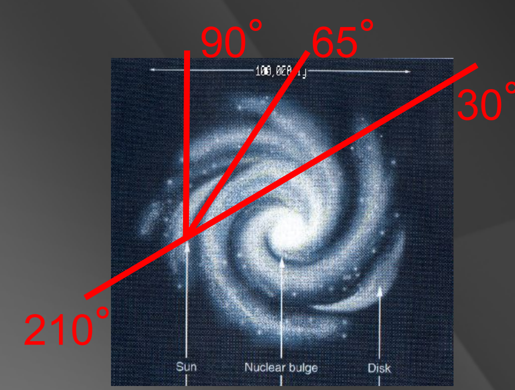
molecular clouds as beam dumps → pion production



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







milagro

emissivity (units: (note!) per unit volume per GeV per second) in photons produced by a number density of cosmic rays N_p interacting with a target density n_{gas} per cm^3

production rate

total cross section

$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$

$$\mathrm{f}_{\pi^0}\left(\equiv K_p\right) = < \frac{E_\pi}{E_p} > \text{ and } \mathrm{q}_\gamma\left(E_\gamma\right) = 2q_\pi\left(\frac{E_\pi}{2}\right)$$

$$\int_{1\mathrm{TeV}} dE_\gamma \, E_\gamma \, \frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi \, d^2} L_\gamma$$

$$L_\gamma = V \, Q_\gamma = \frac{W}{\rho_{cr}} Q_\gamma$$

volume of the remnant

energy in >TeV photons produced by cosmic rays per cm³ per sec

10^{-12} erg/cm³

γ, ν flux of galactic cosmic rays

a SNR at d = 1 kpc transferring W = 10^{50} erg to cosmic rays interacting with interstellar gas (or molecular clouds) with density n > 1 cm^{-3} produces a gamma-ray flux of

$$E\frac{dN_\gamma}{dE}(>1\,TeV) =$$

$$\geq 10^{-11} cm^{-2} s^{-1} \frac{W}{10^{50}\,erg}\frac{n}{1\,cm^3}\left(\frac{d}{1\,kpc}\right)^{-2}$$

should be observed by present TeV gamma-ray telescopes

Milagro sources ?
RX J1713.7-3946??

neutral pions

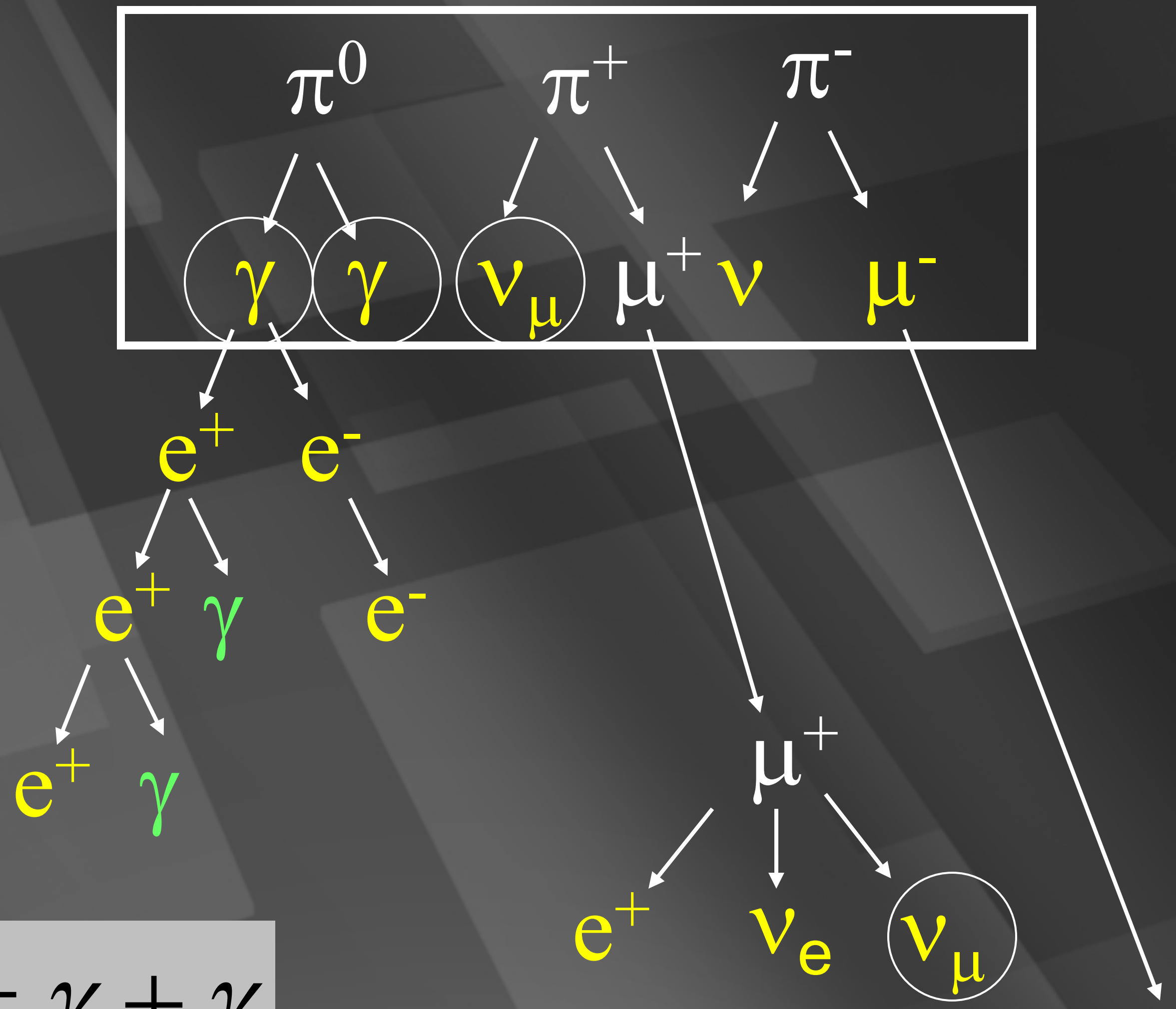
are observed as

gamma rays

charged pions

are observed as

neutrinos



$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

ν flux accompanying TeV gammas

$$\frac{dN_\nu}{dE} \cong \frac{1}{2}\frac{dN_\gamma}{dE}$$

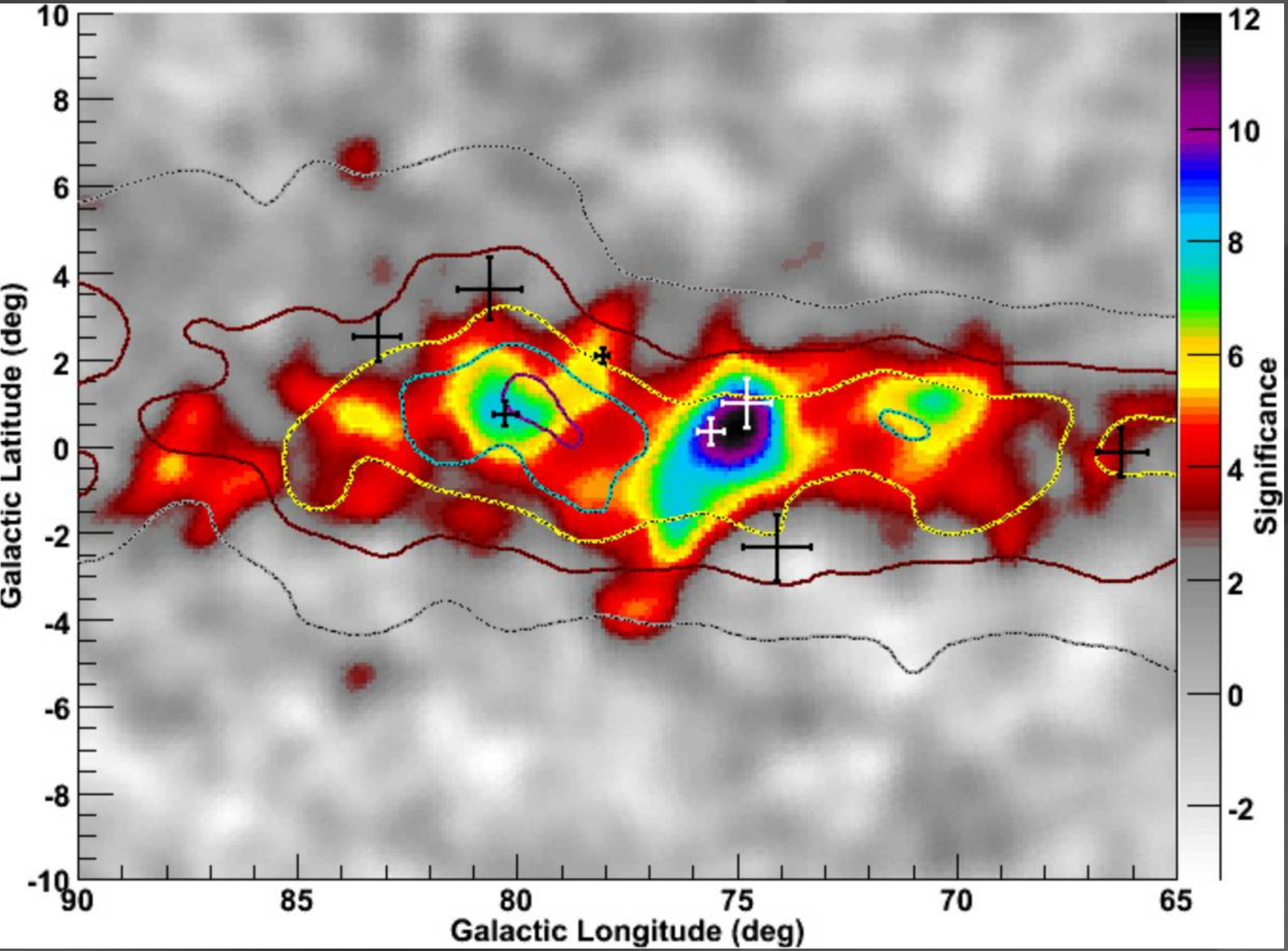
$$\text{number of events} = \text{Area Time} \int dE \, \frac{dN_\nu}{dE} P_{\nu \to \mu}$$

$$= 1.5 \ln\left(\frac{E_{\max}}{E_{\min}}\right) \text{ events per km}^2 \text{ per year per source!}$$

reject background

$\rightarrow E \geq 40 \, TeV$

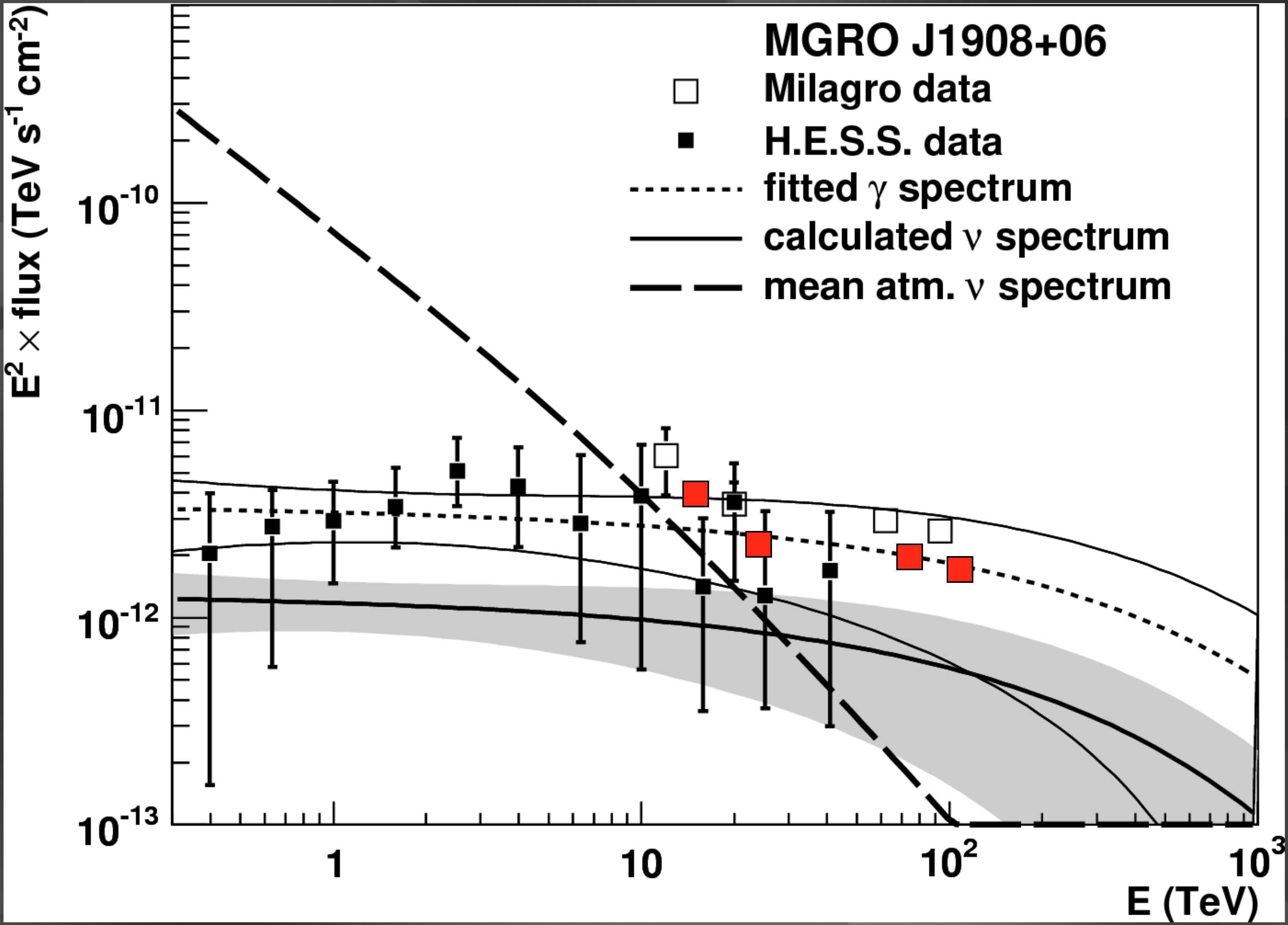
Cygnus region at ~ 1kpc : Milagro



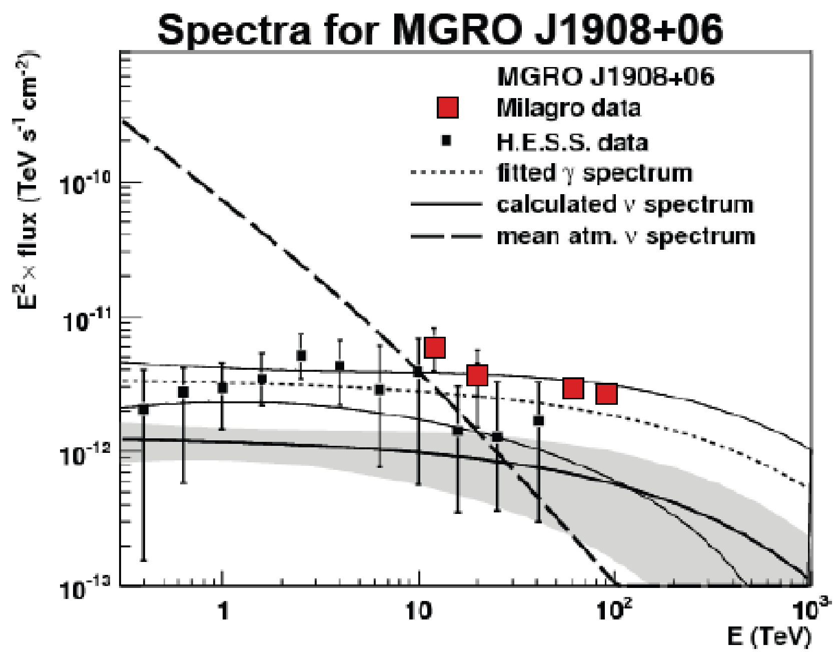
translation of TeV gamma rays into TeV neutrinos yields:

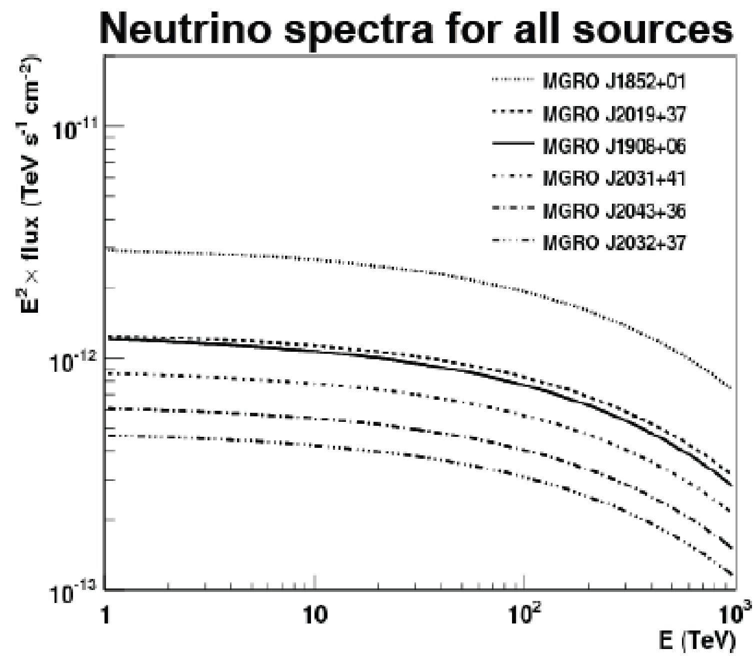
3 ± 1 ν per year in IceCube per source

MGRO J1908+06: the first Pevatron?



Gamma and Neutrino Spectra

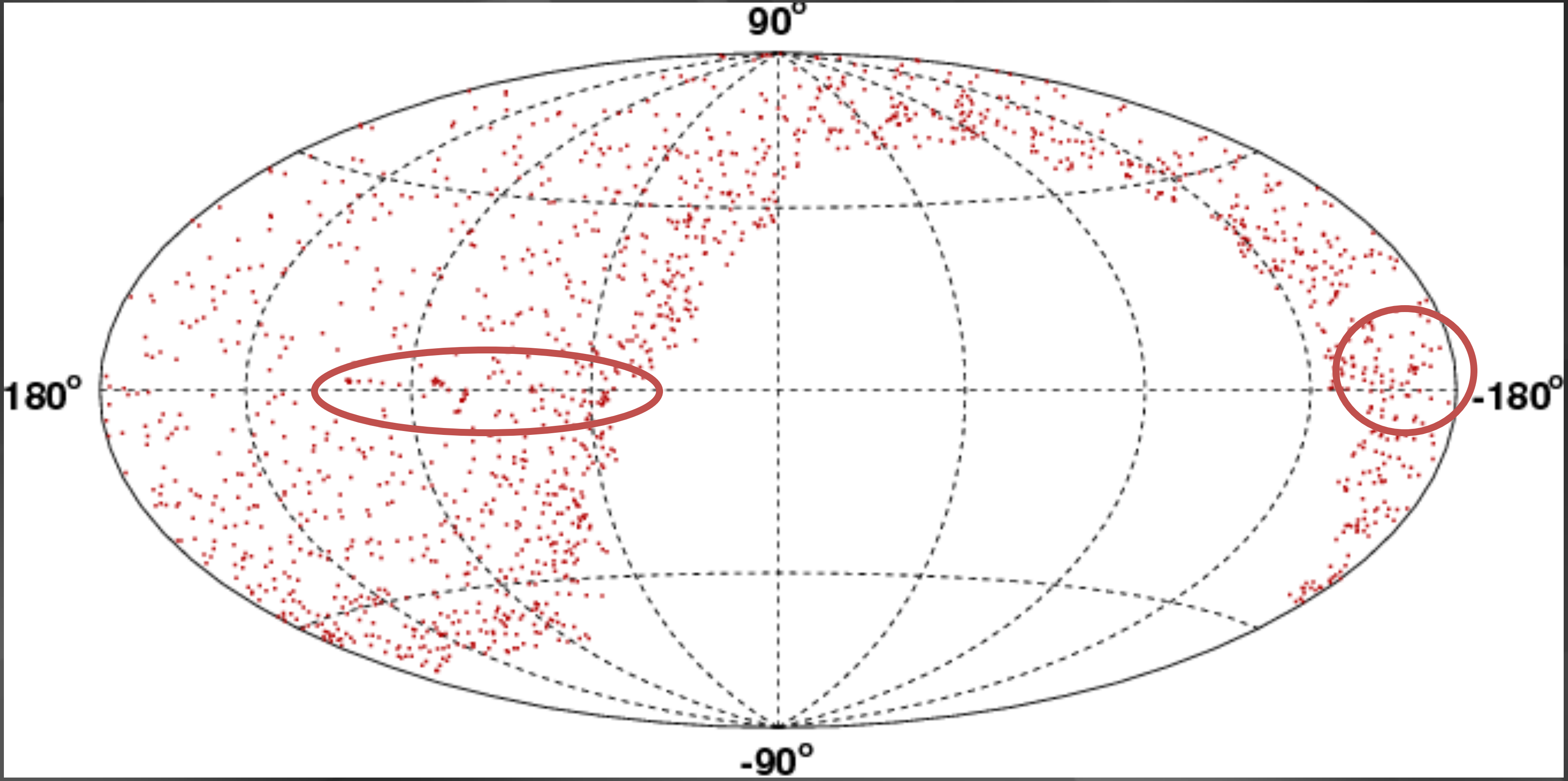




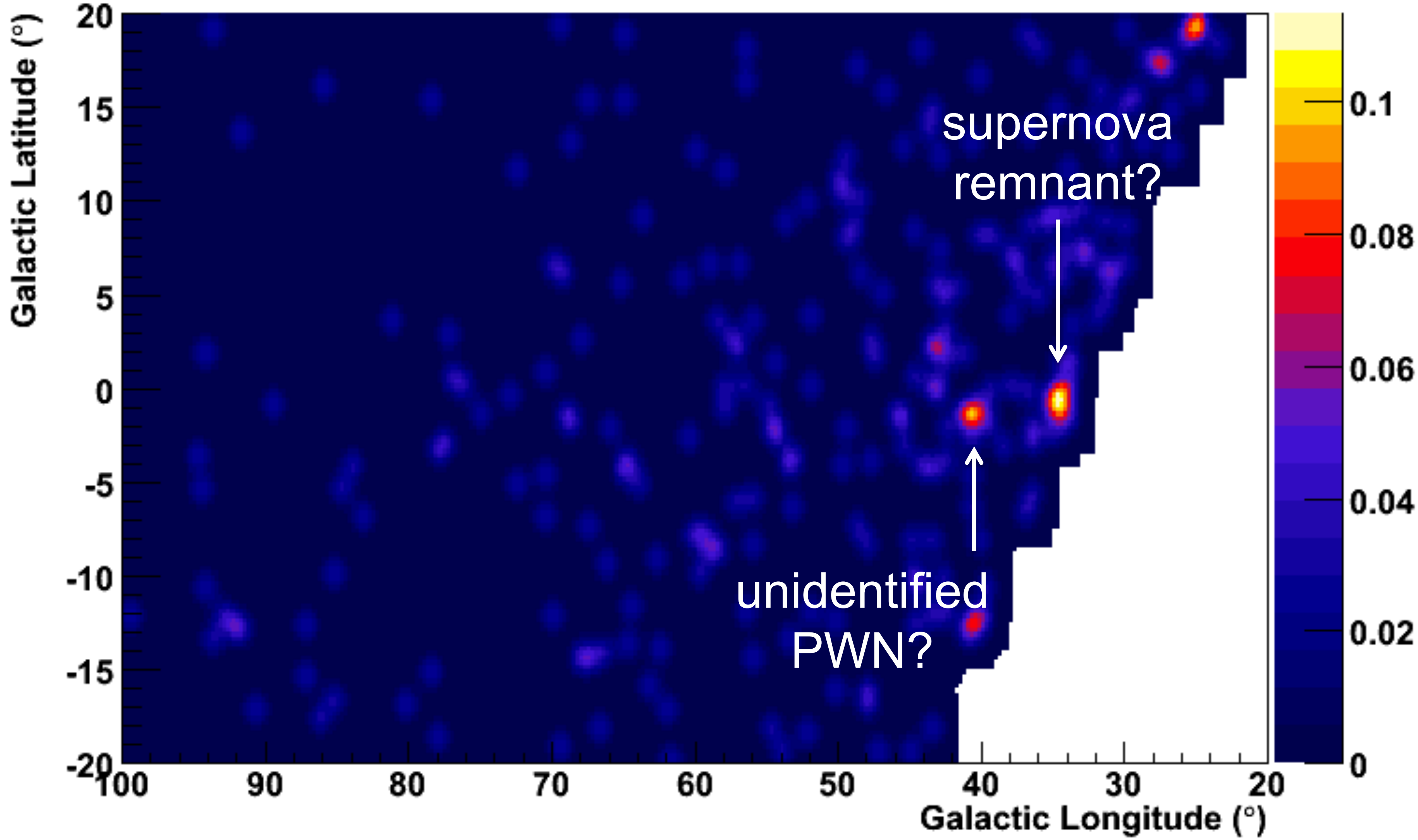
Halzen, Kappes, O'Murchadha: arXiv:0803.0314

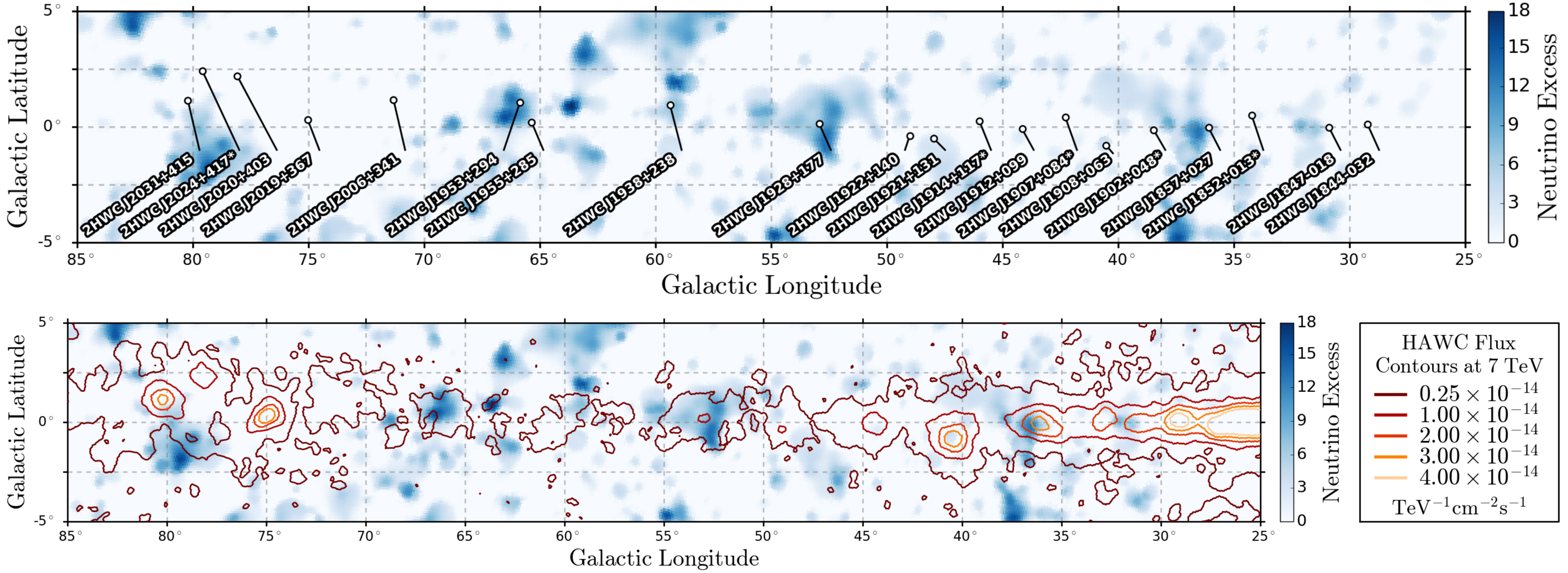
- Assumed E^{-2} with Milagro normaliztion (MGRO J1908 index = 2.1)
- ν spectrum cutoff @ 180 TeV

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

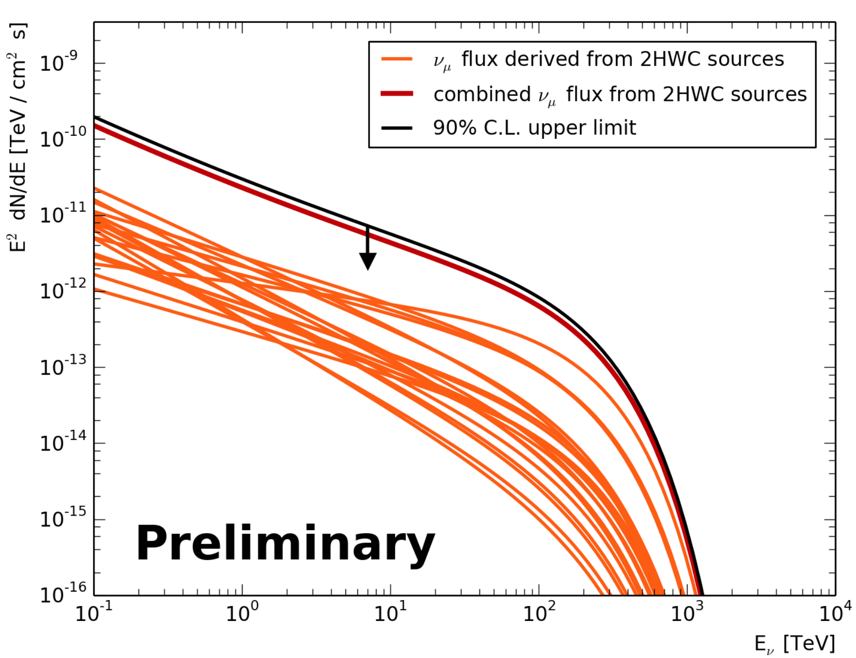


Simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.

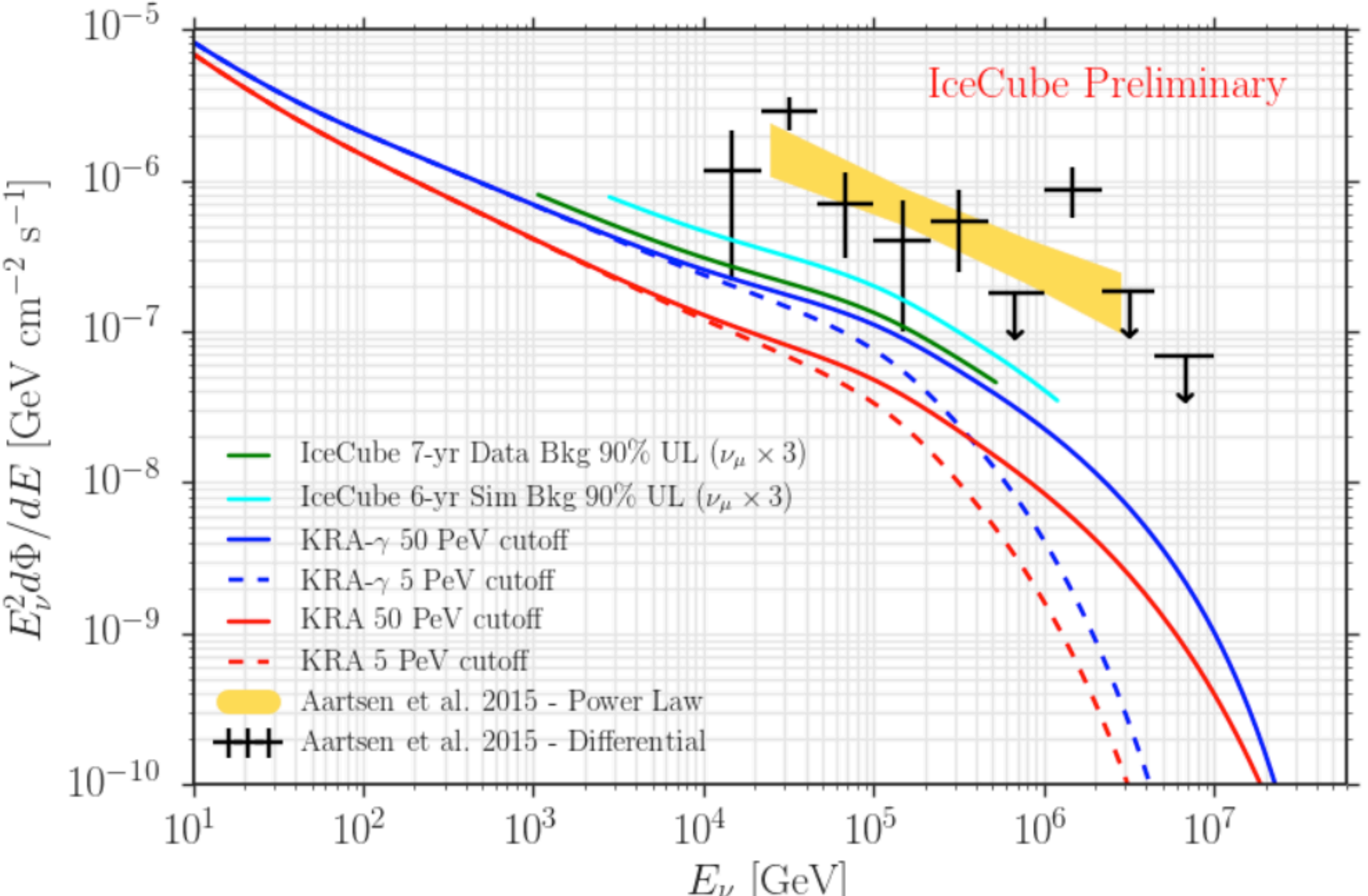




Galactic Latitude
Galactic Longitude
Neutrino Excess
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1847-018
2HWC J1844-032
HAWC Flux Contours at 7 TeV
0.25×10^{-14}
1.00×10^{-14}
2.00×10^{-14}
3.00×10^{-14}
4.00×10^{-14}
$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$



ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]
Preliminary



IceCube Preliminary
$E_\nu^2 d\Phi/dE$ [GeV cm^{-2} s^{-1}]
E_ν [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
IceCube 7-yr Data Bkg 90% UL ($\nu_\mu \times 3$)
IceCube 6-yr Sim Bkg 90% UL ($\nu_\mu \times 3$)
KRA-γ 50 PeV cutoff
KRA-γ 5 PeV cutoff
KRA 50 PeV cutoff
KRA 5 PeV cutoff
Aartsen et al. 2015 - Power Law
Aartsen et al. 2015 - Differential