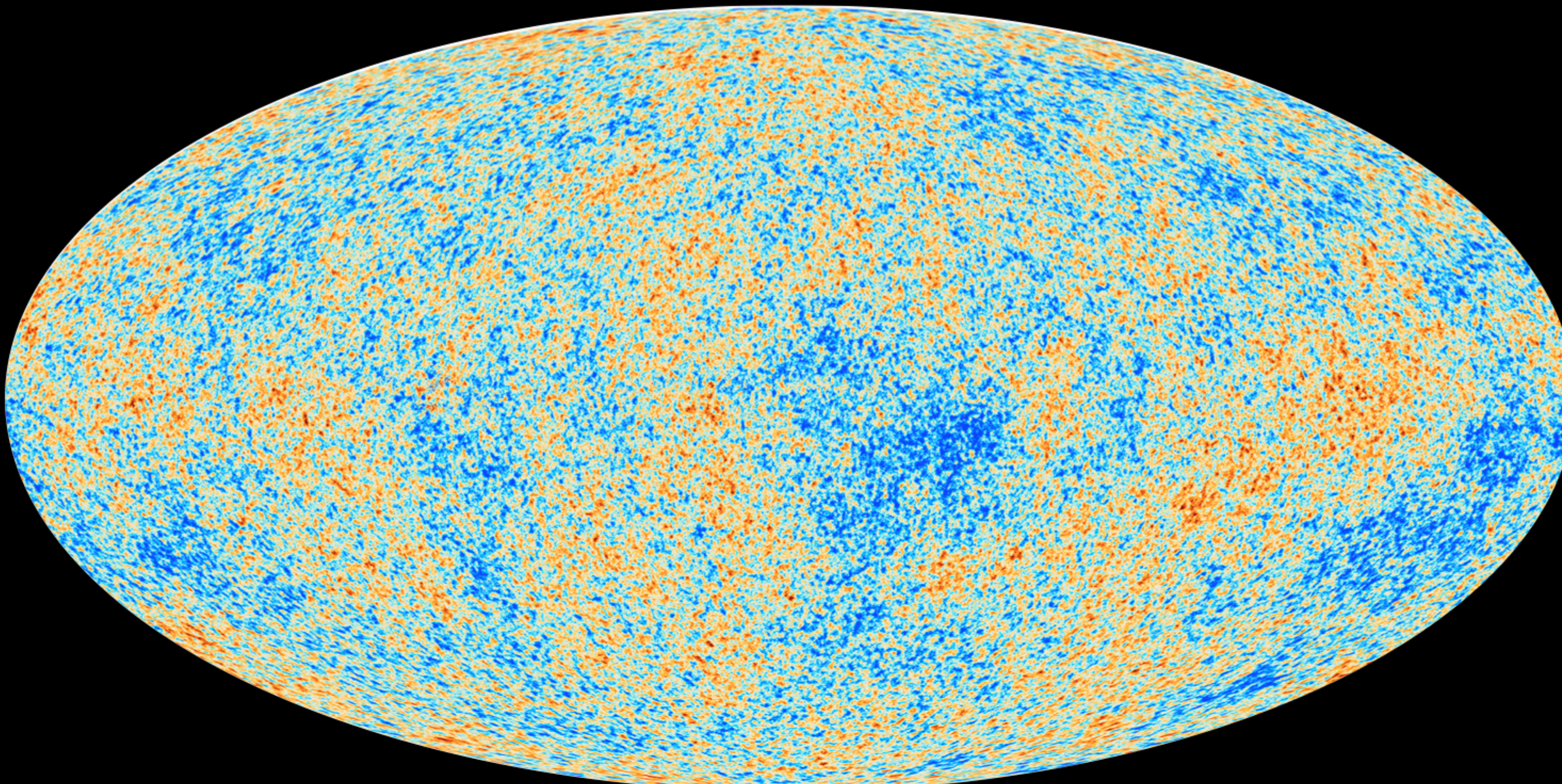
IceCube: the discovery of cosmic neutrinos
francis halzen

- 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

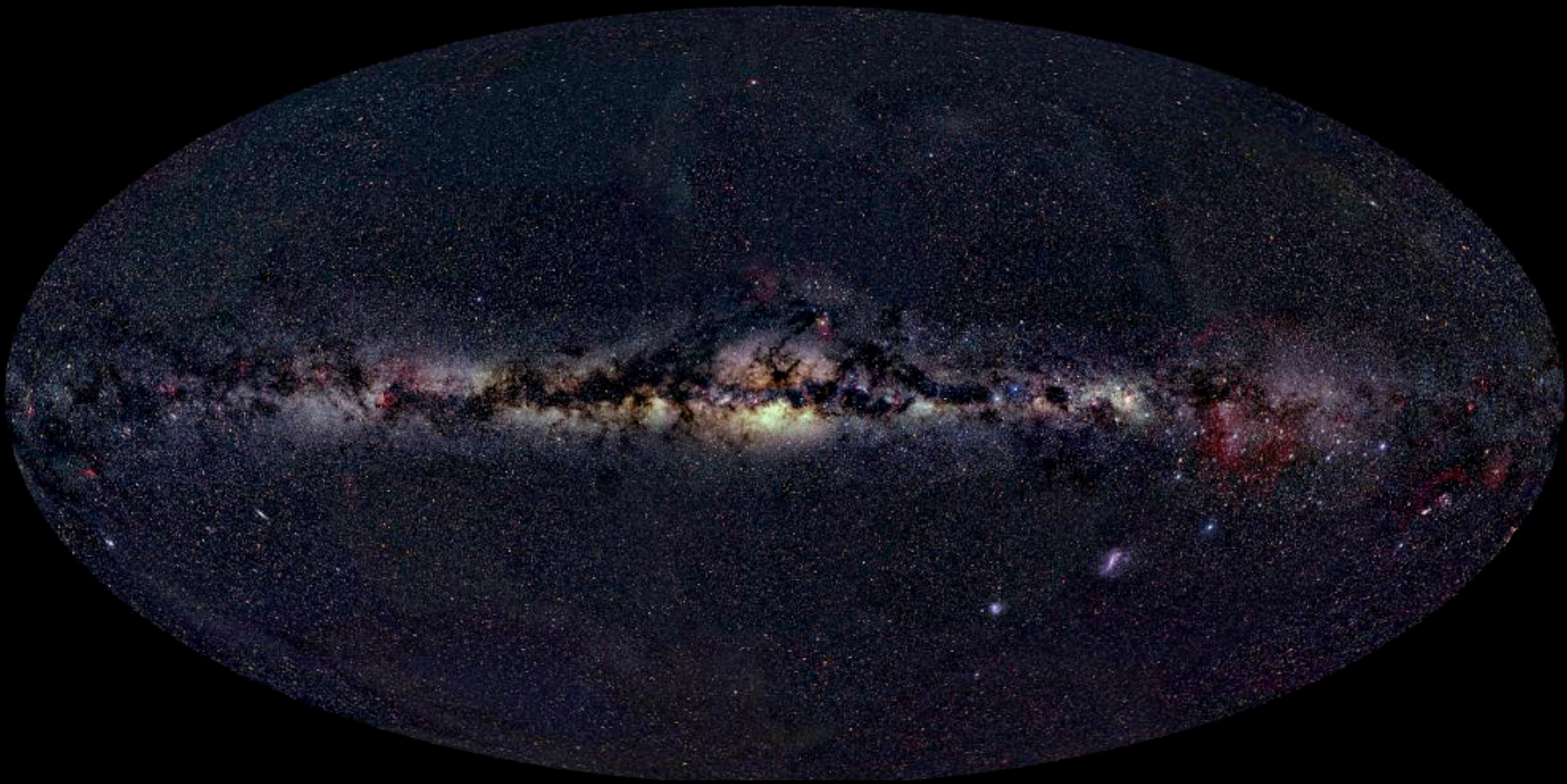
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



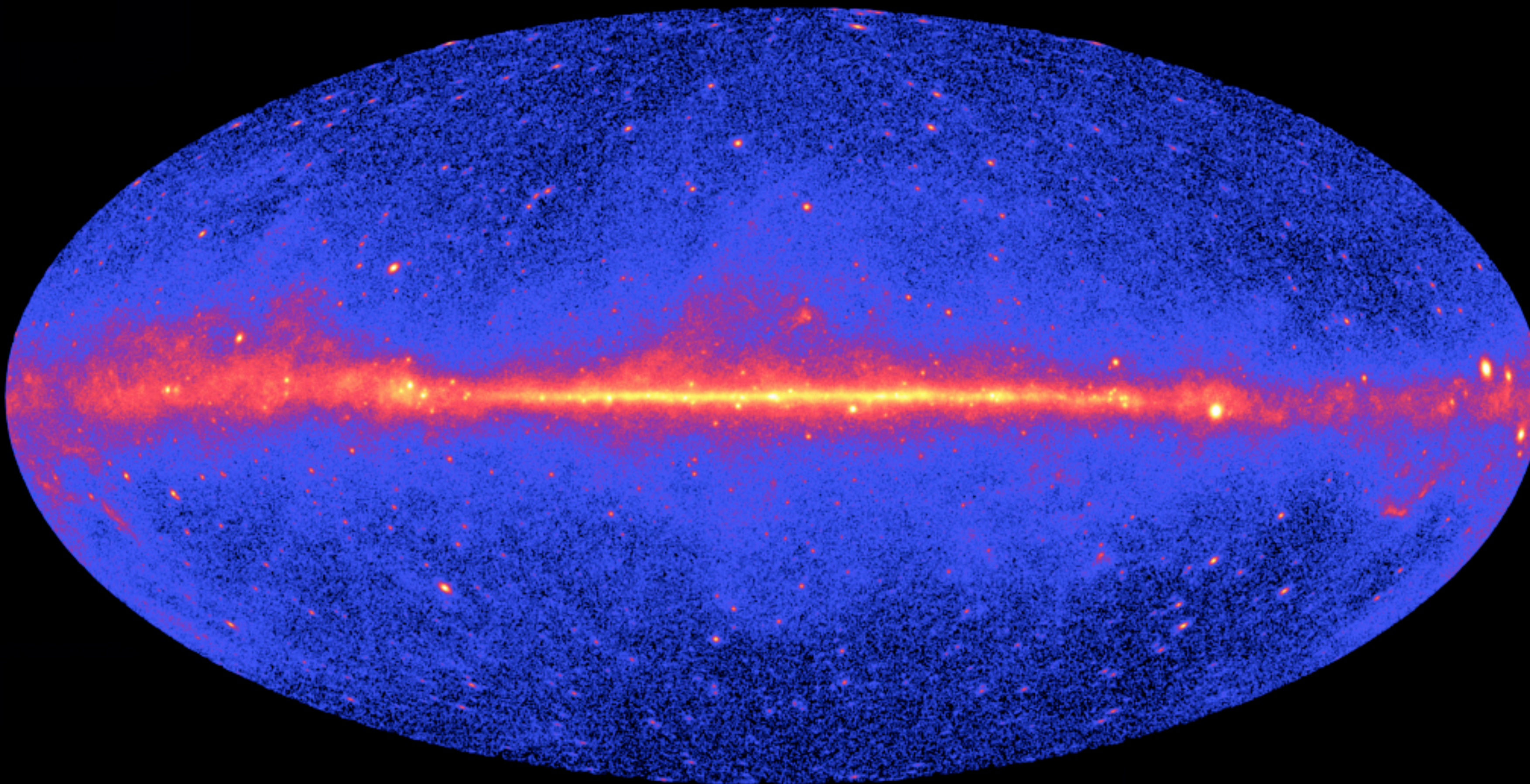
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



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

Cosmic Horizons – Gamma Radiation

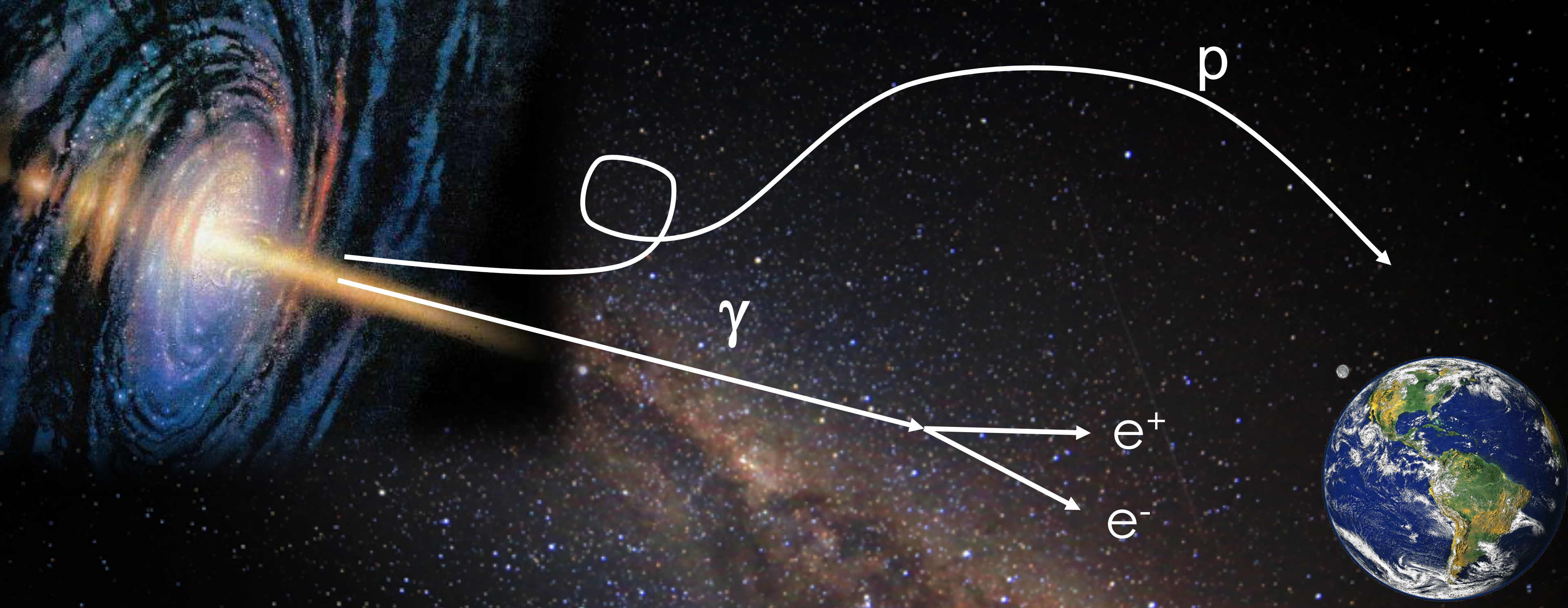


wavelength = 10^{-15} m $\Leftrightarrow$ energy = 10^{9} eV

Cosmic Horizons – Highest Energies

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

The opaque Universe

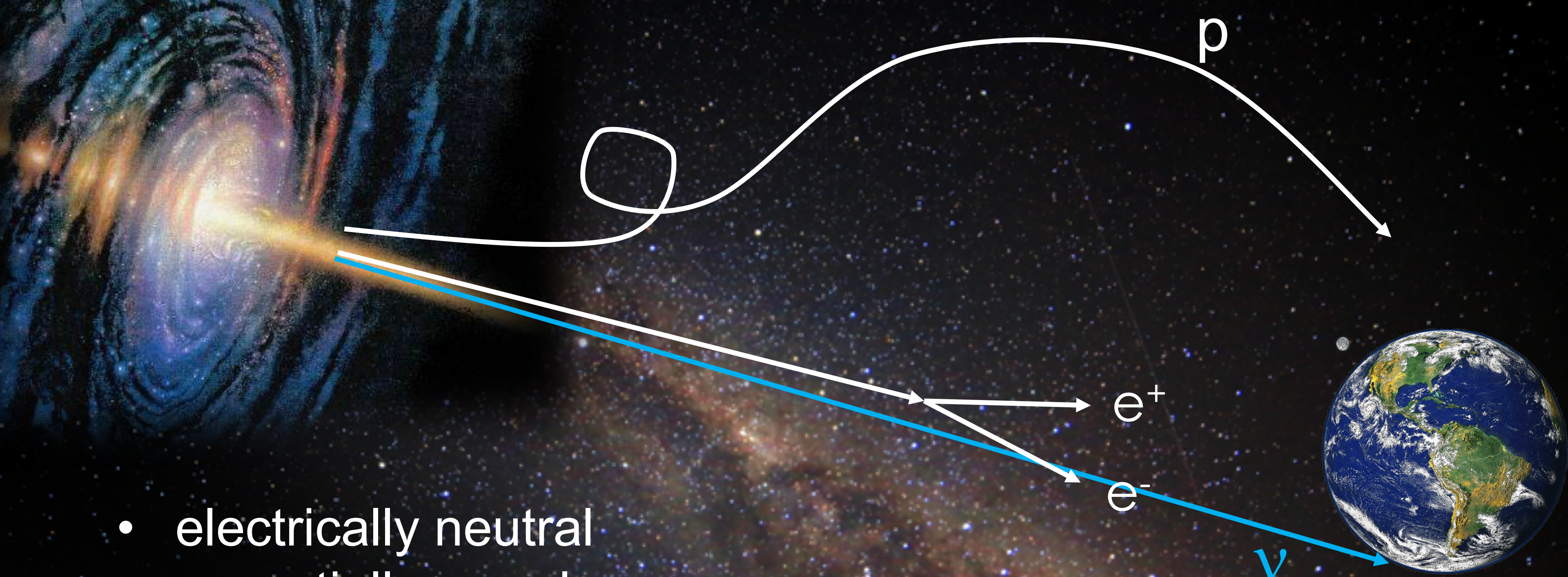


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

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

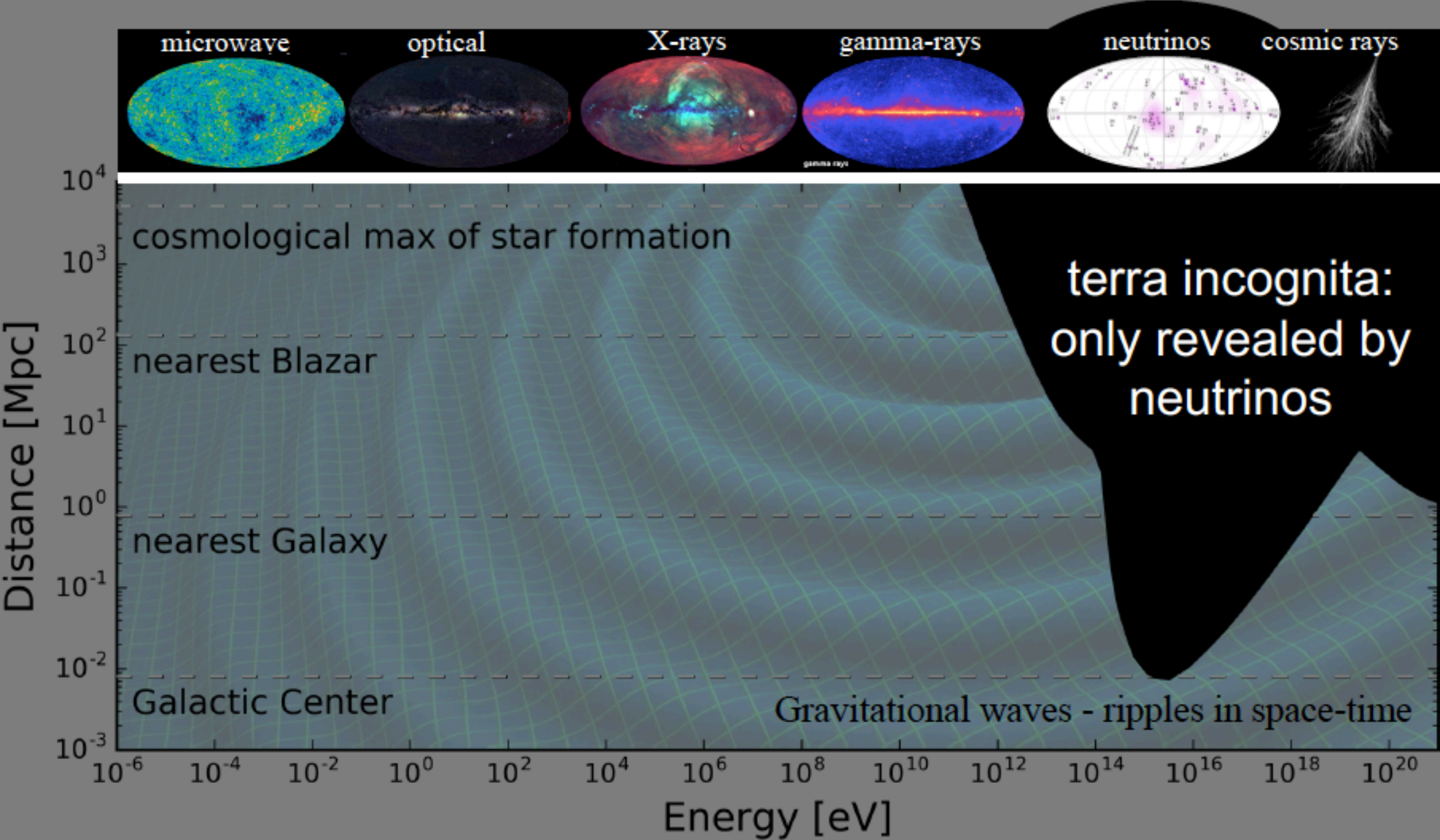
enter: neutrinos

Neutrinos? Perfect Messenger

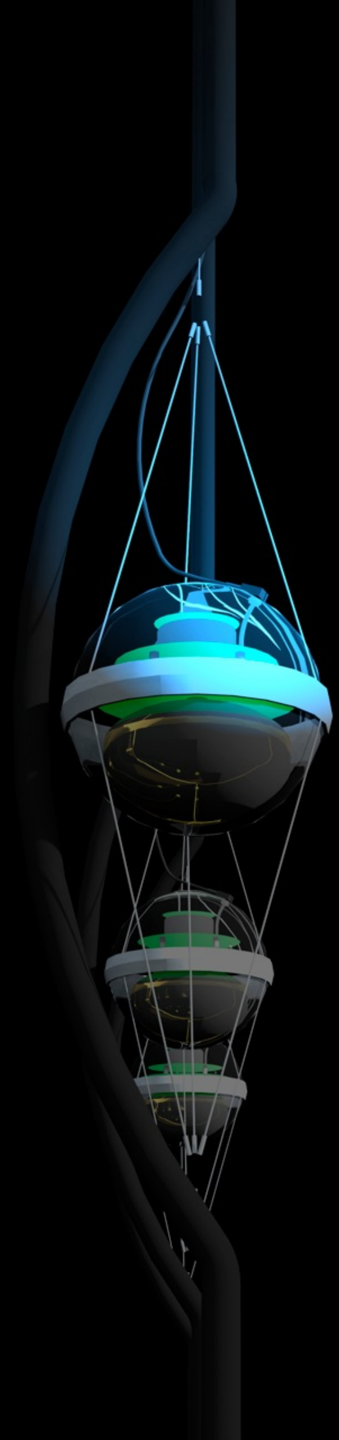


- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … 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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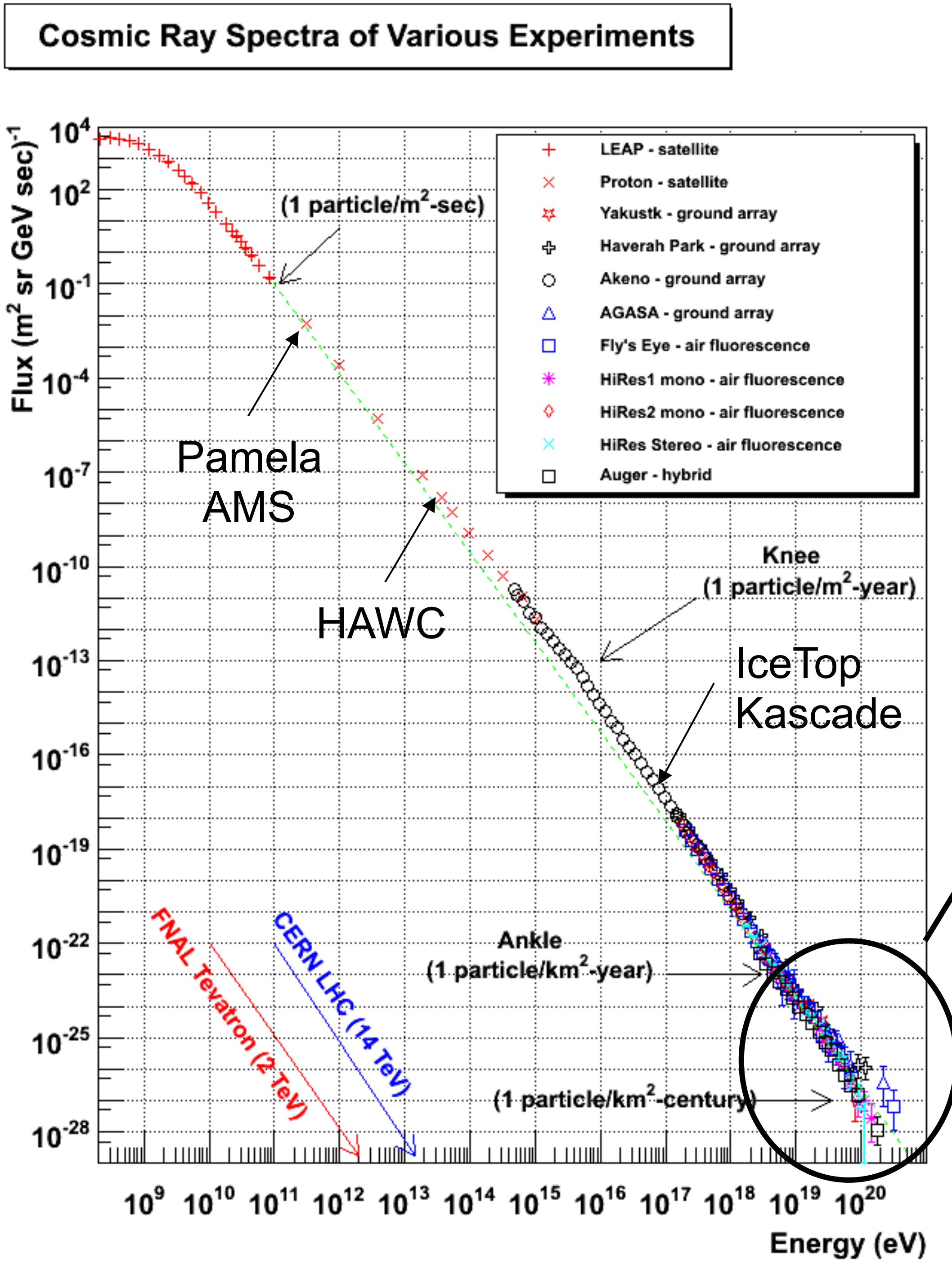
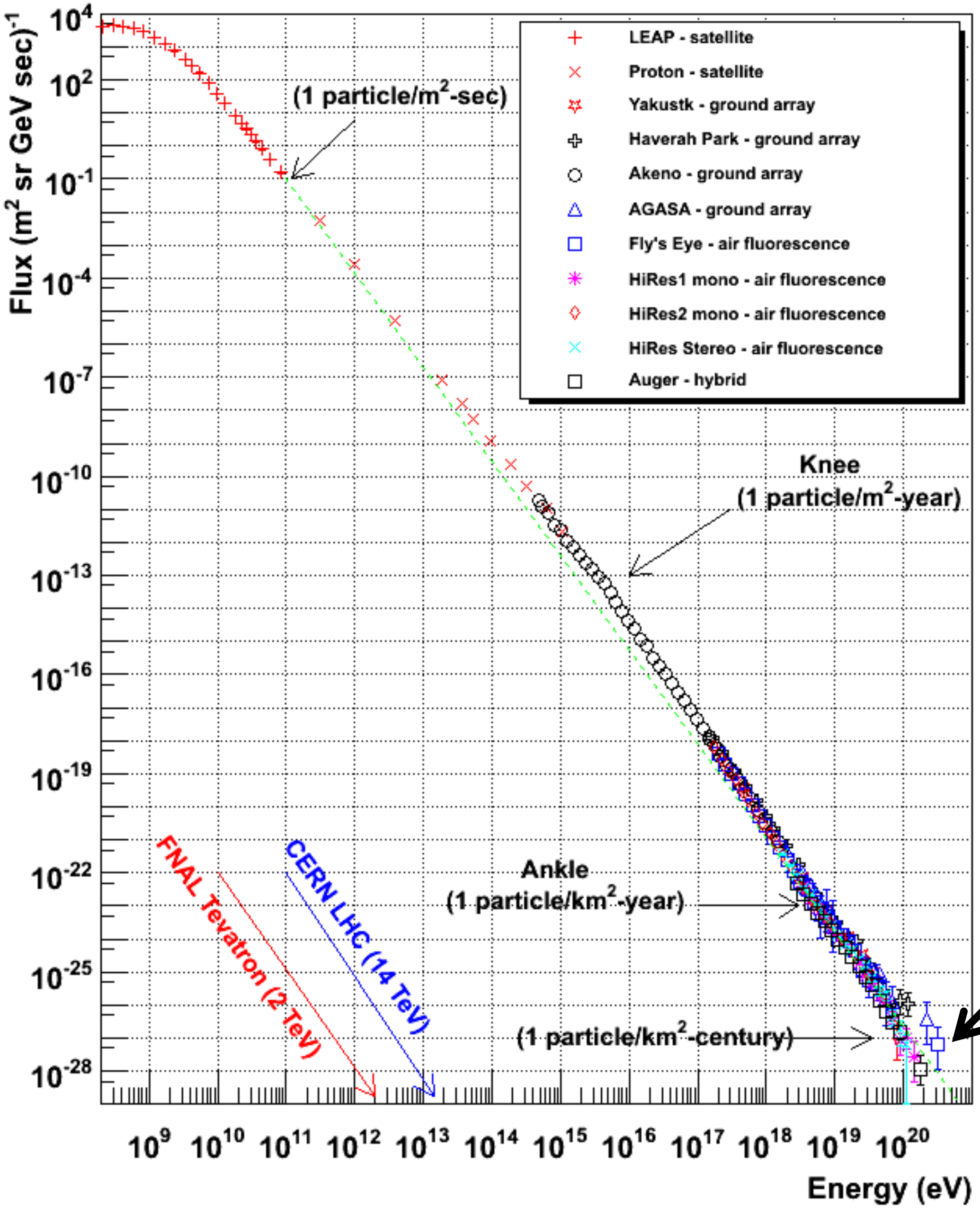


populate the
Universe

origin of cosmic rays: oldest problem in astronomy

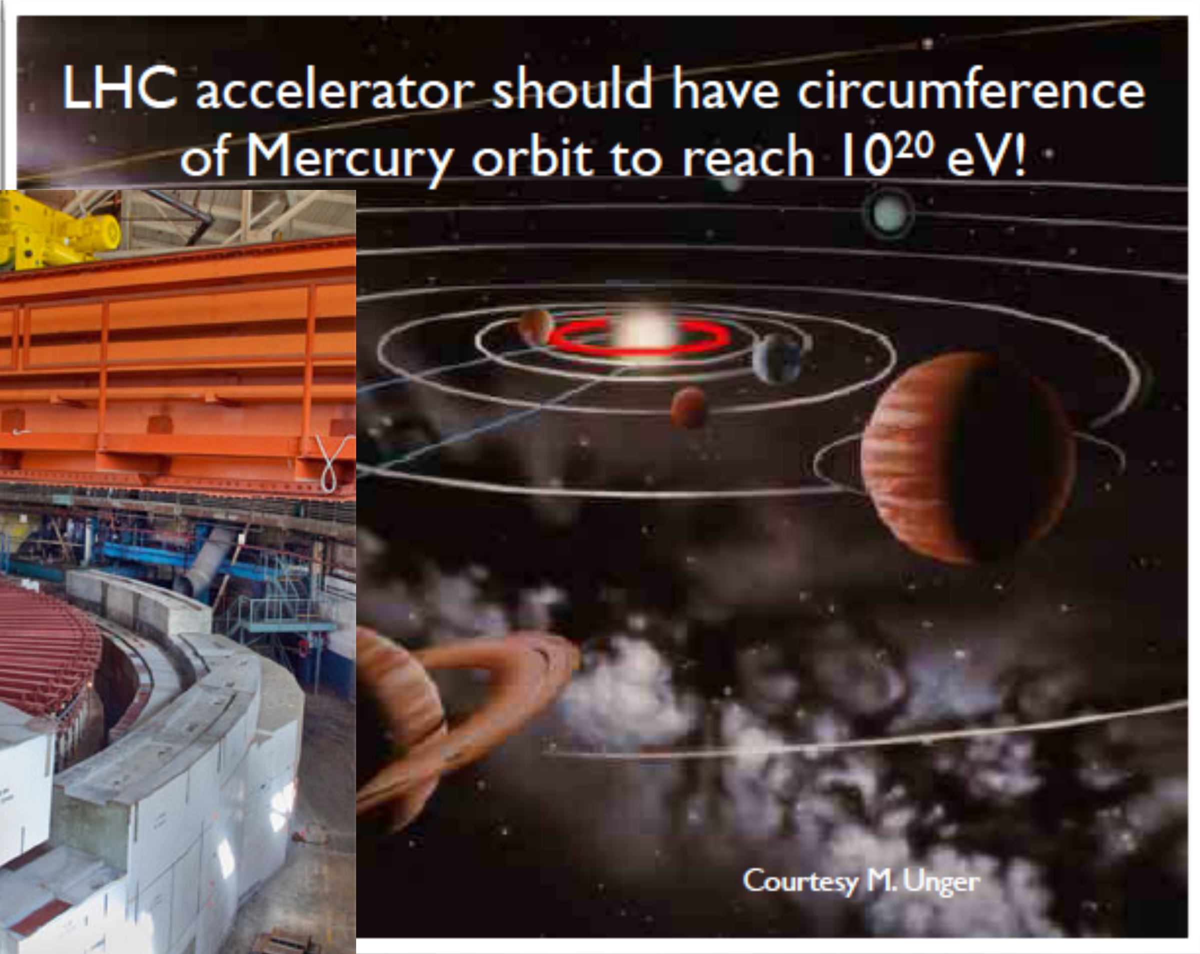


cosmic ray challenge

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

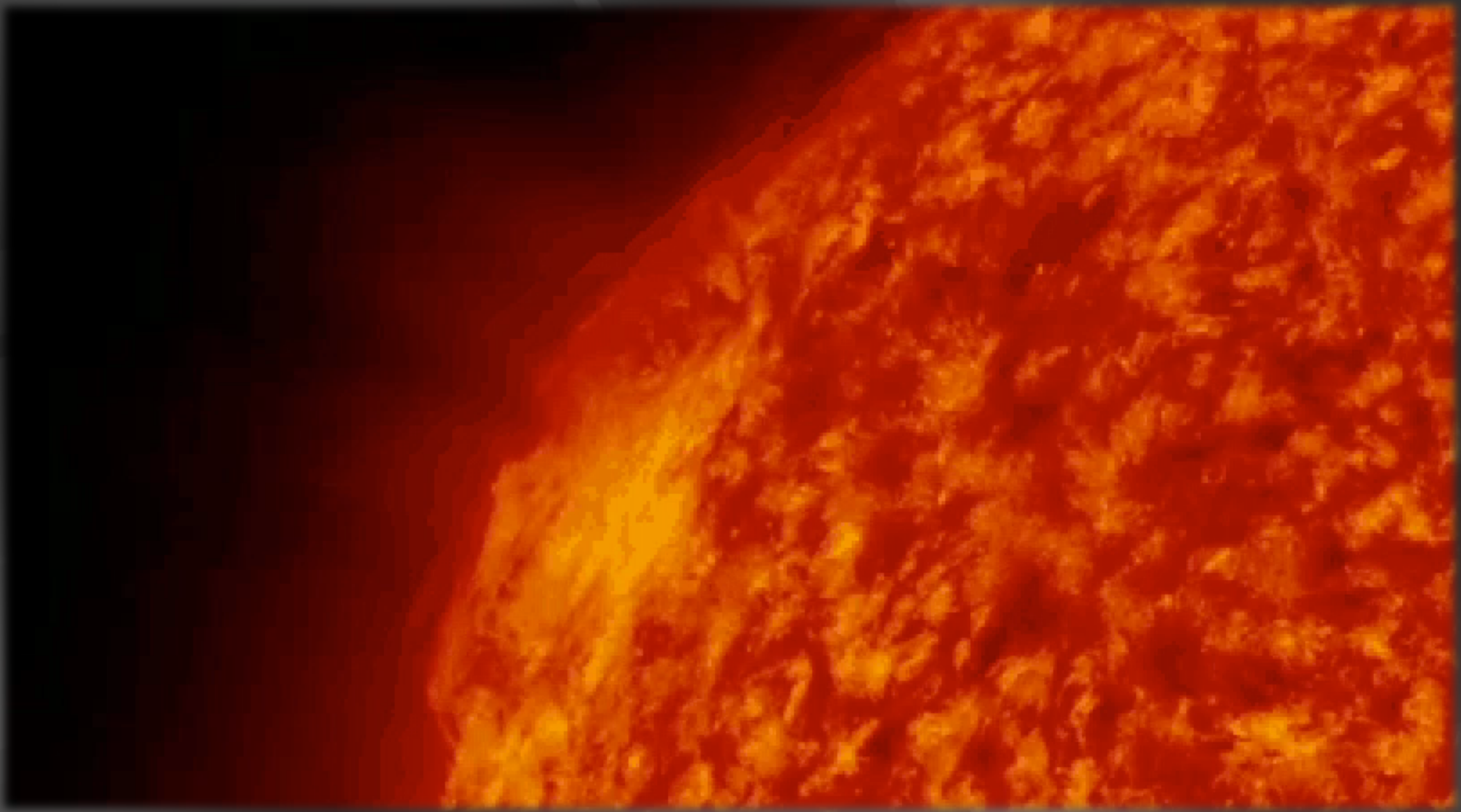
gravitational energy from collapsing stars is converted into particle acceleration?

cosmic ray accelerators

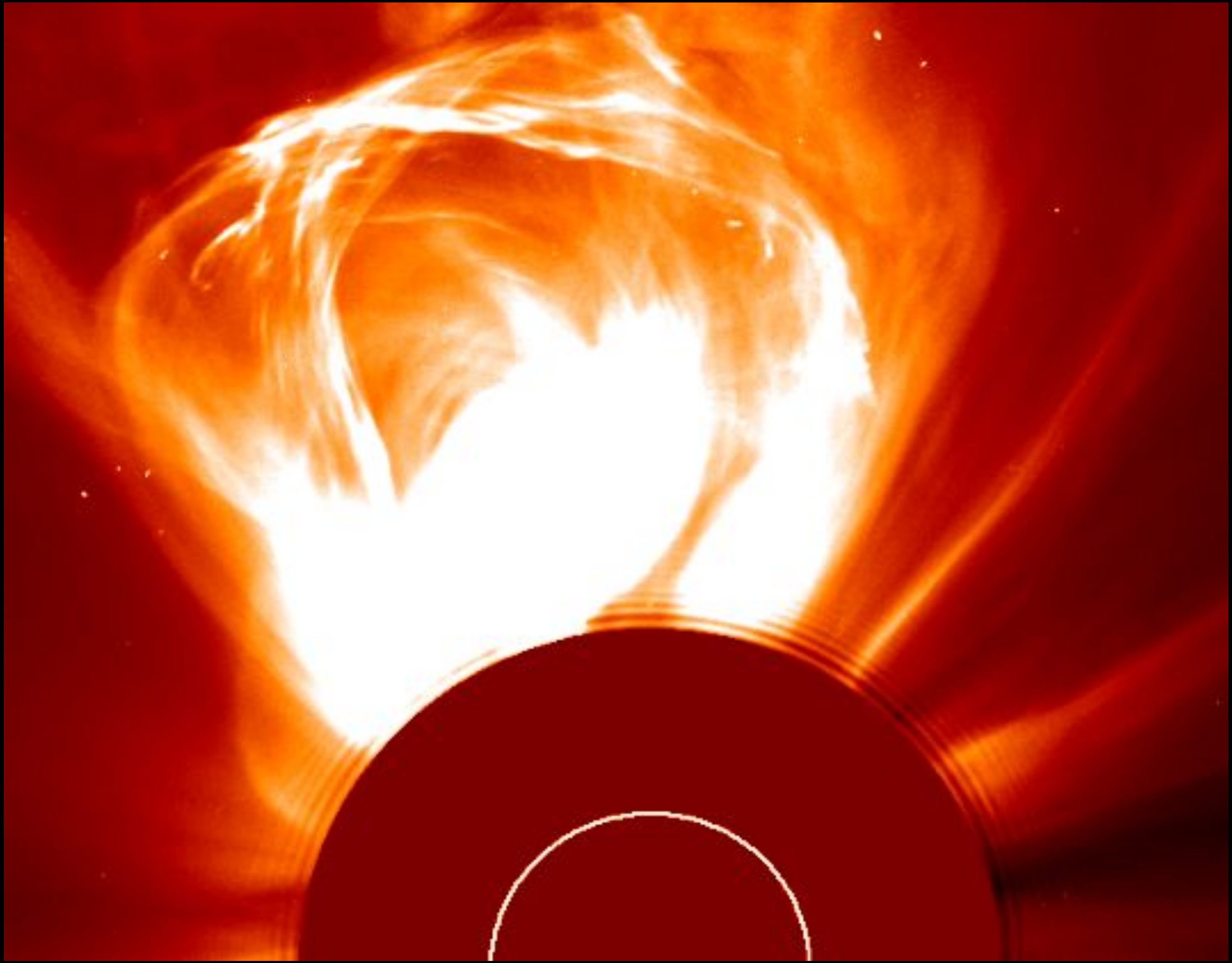


accomodating energy and luminosity are challenging

the sun constructs an accelerator



the sun constructs an accelerator



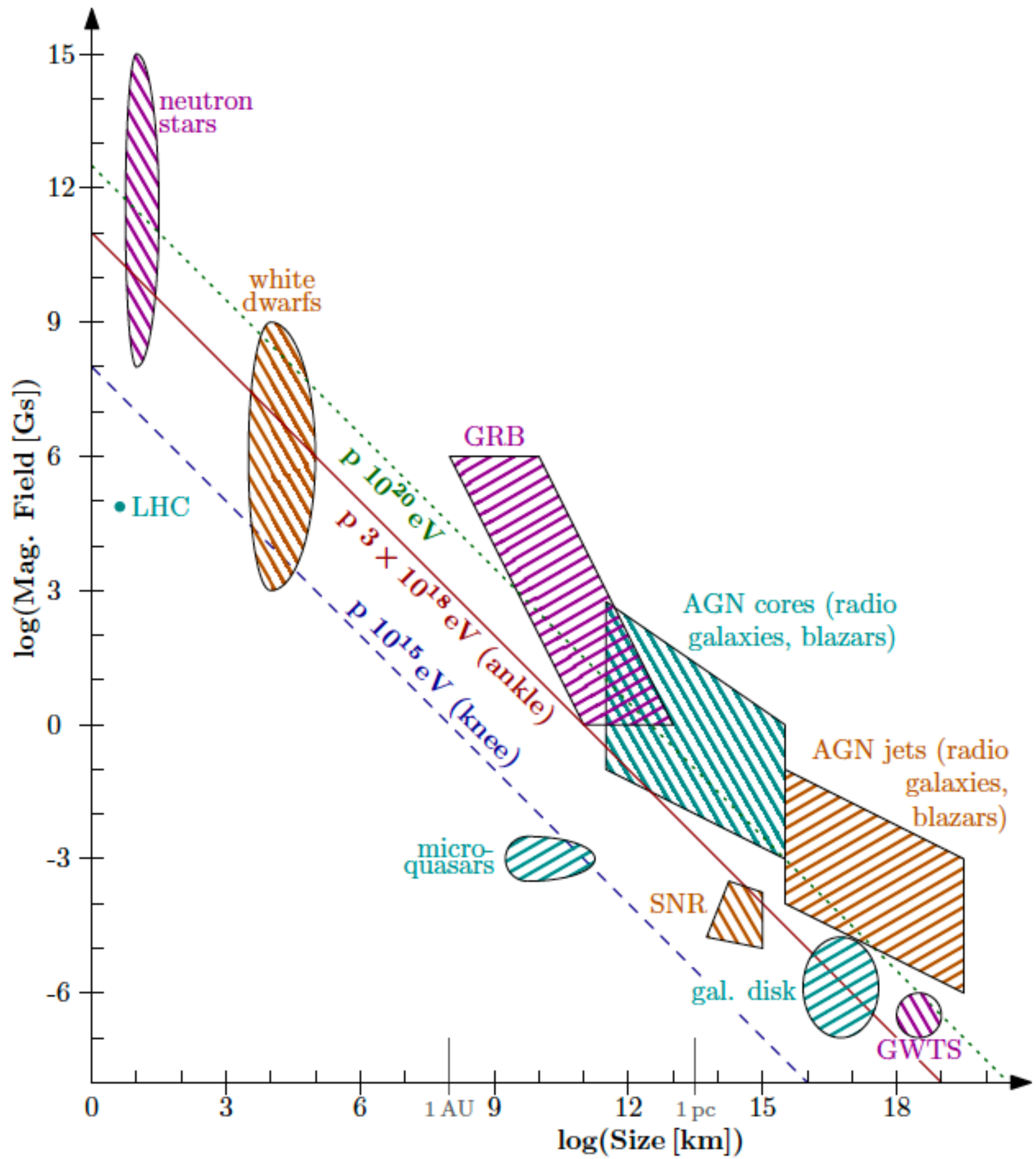
- accelerator must contain the particles

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

$$E \leq \mathrm{v}\, q B R$$

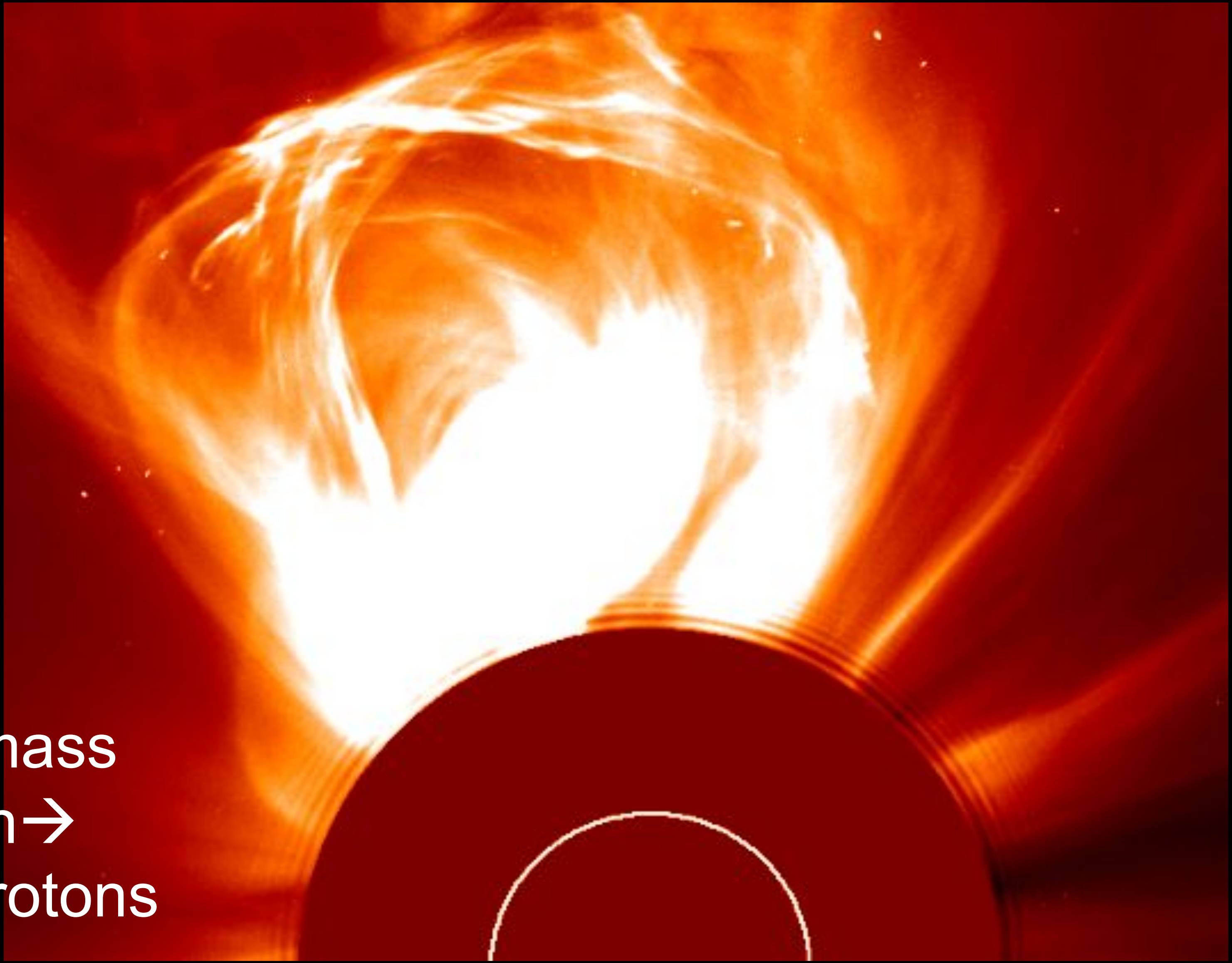
challenges of cosmic ray astrophysics:

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



log(Mag. Field [Gs])
log(Size [km])
15
12
9
6
3
0
-3
-6
0
3
6
1 AU
9
12
1 pc
15
18
neutron stars
white dwarfs
LHC
GRB
p 10^{20} eV
p 3×10^{18} eV (ankle)
p 10^{15} eV (knee)
AGN cores (radio galaxies, blazars)
AGN jets (radio galaxies, blazars)
micro-quasars
SNR
gal. disk
GWTS

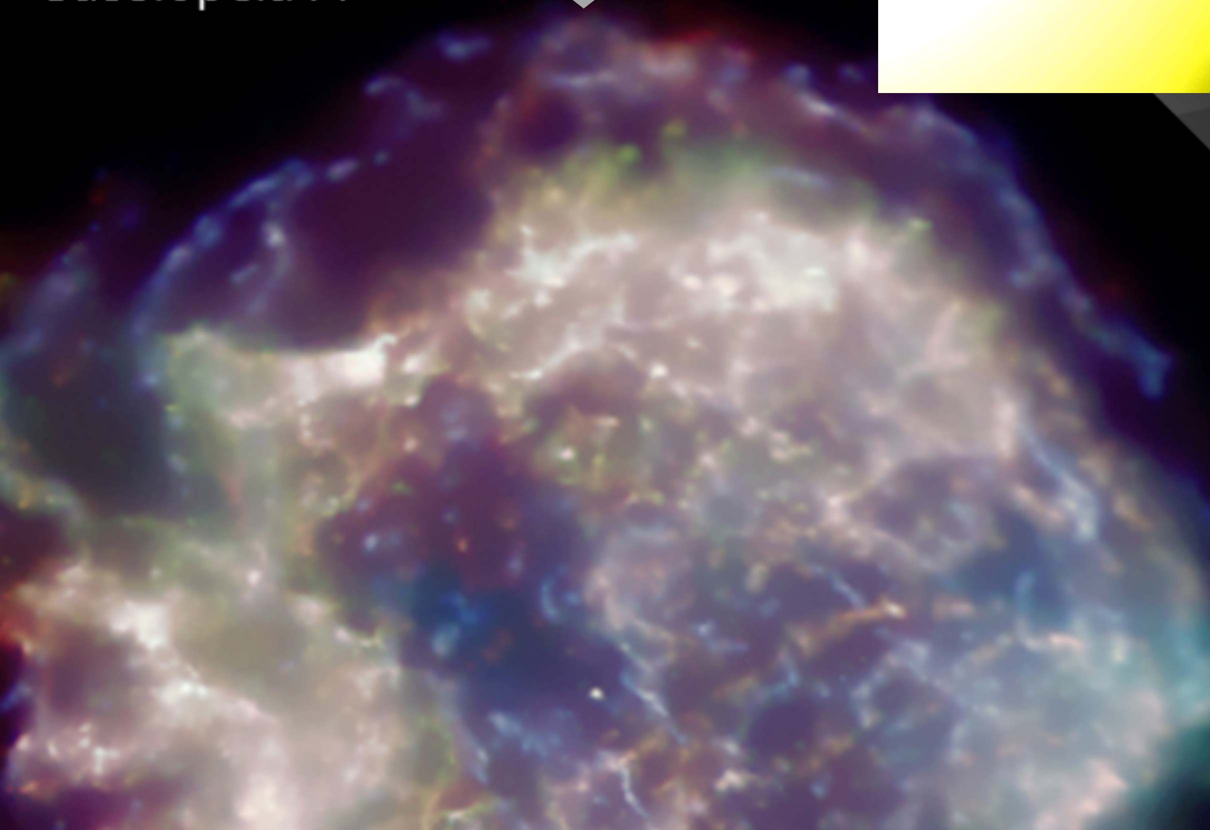
the sun constructs an accelerator

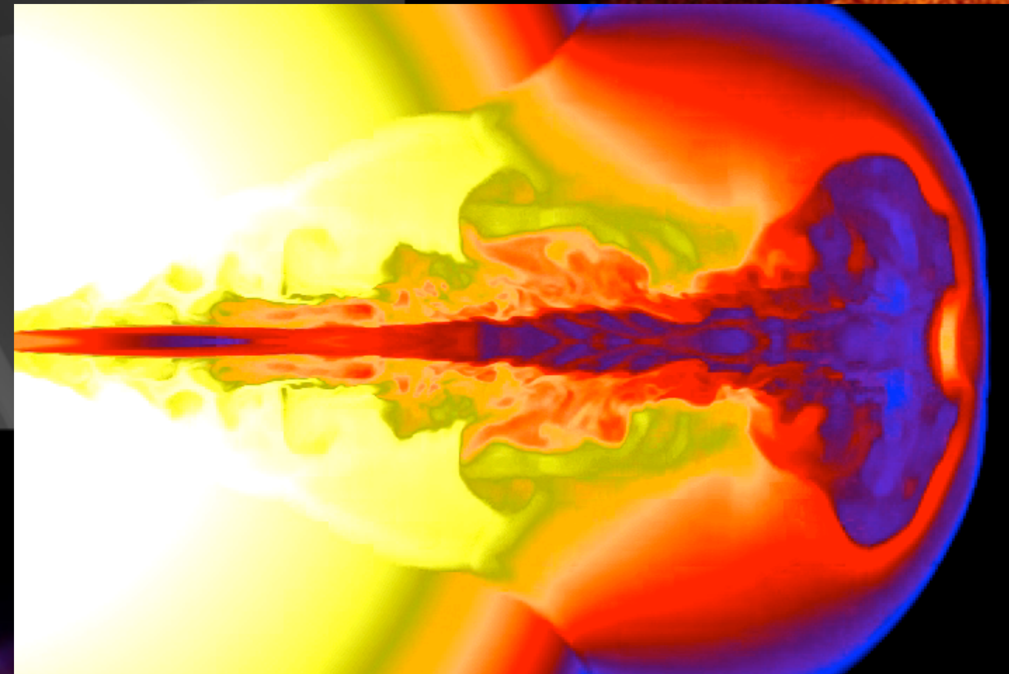


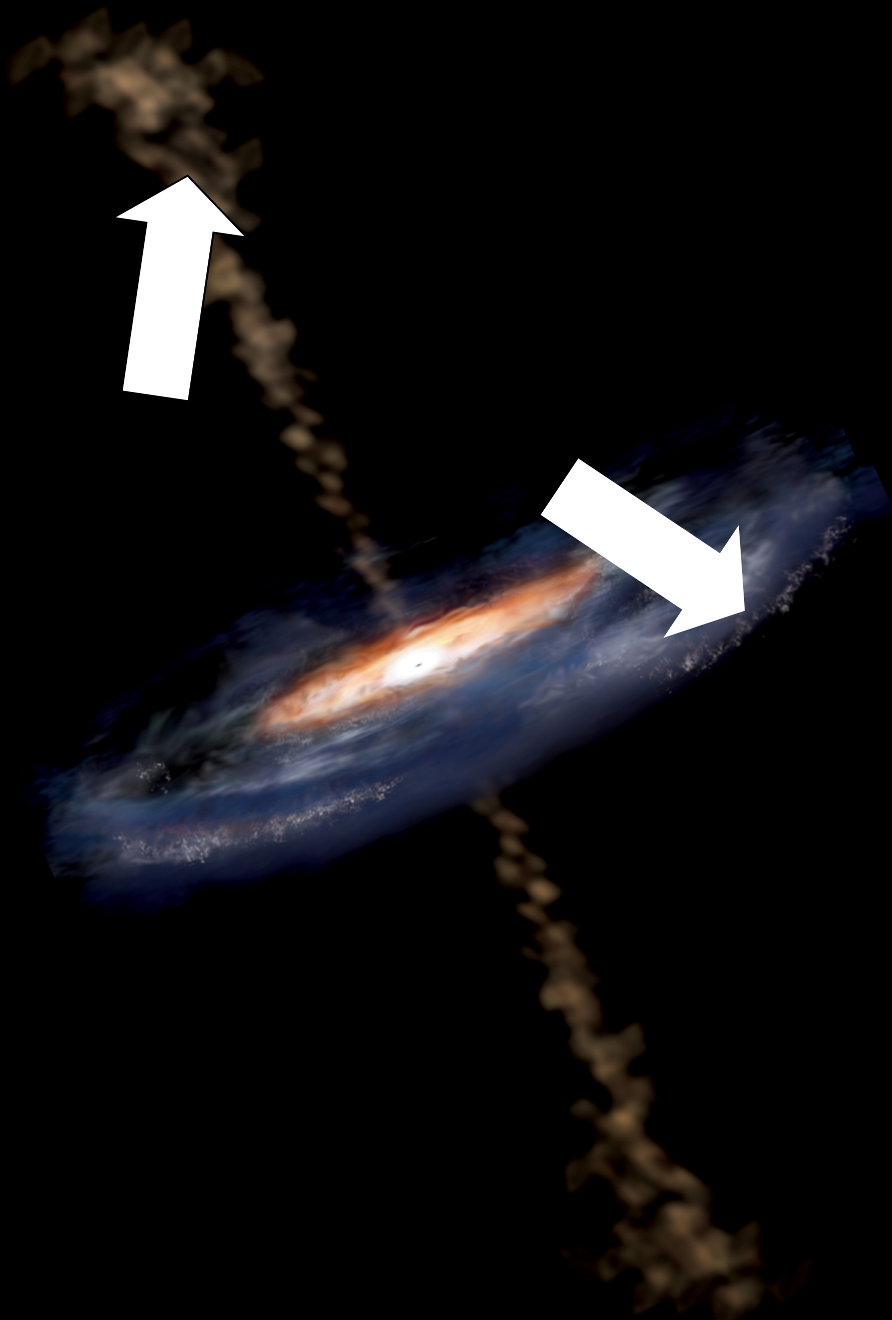
coronal mass ejection→ 10 GeV protons

supernova
remnants

Chandra
Cassiopeia A

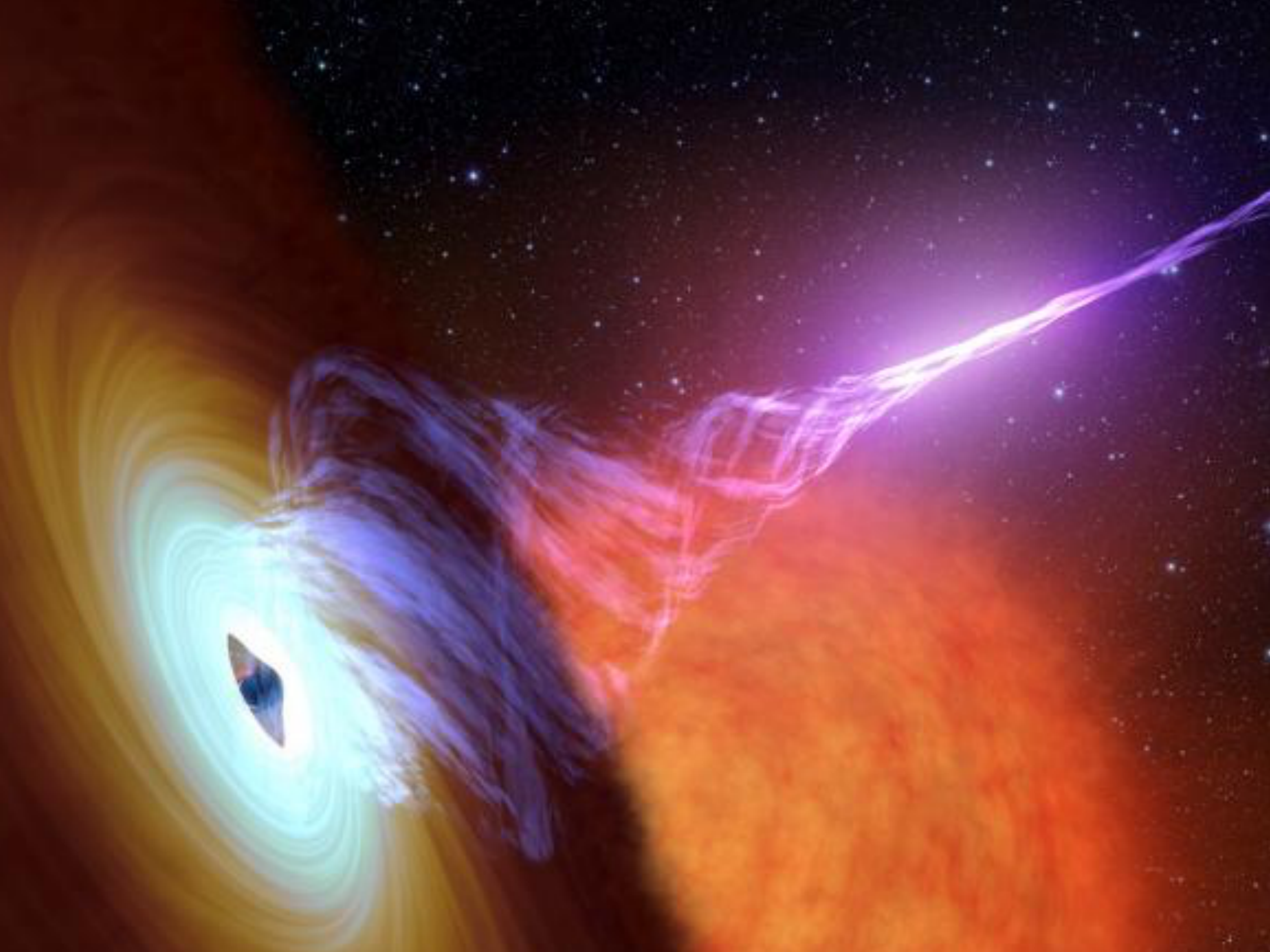


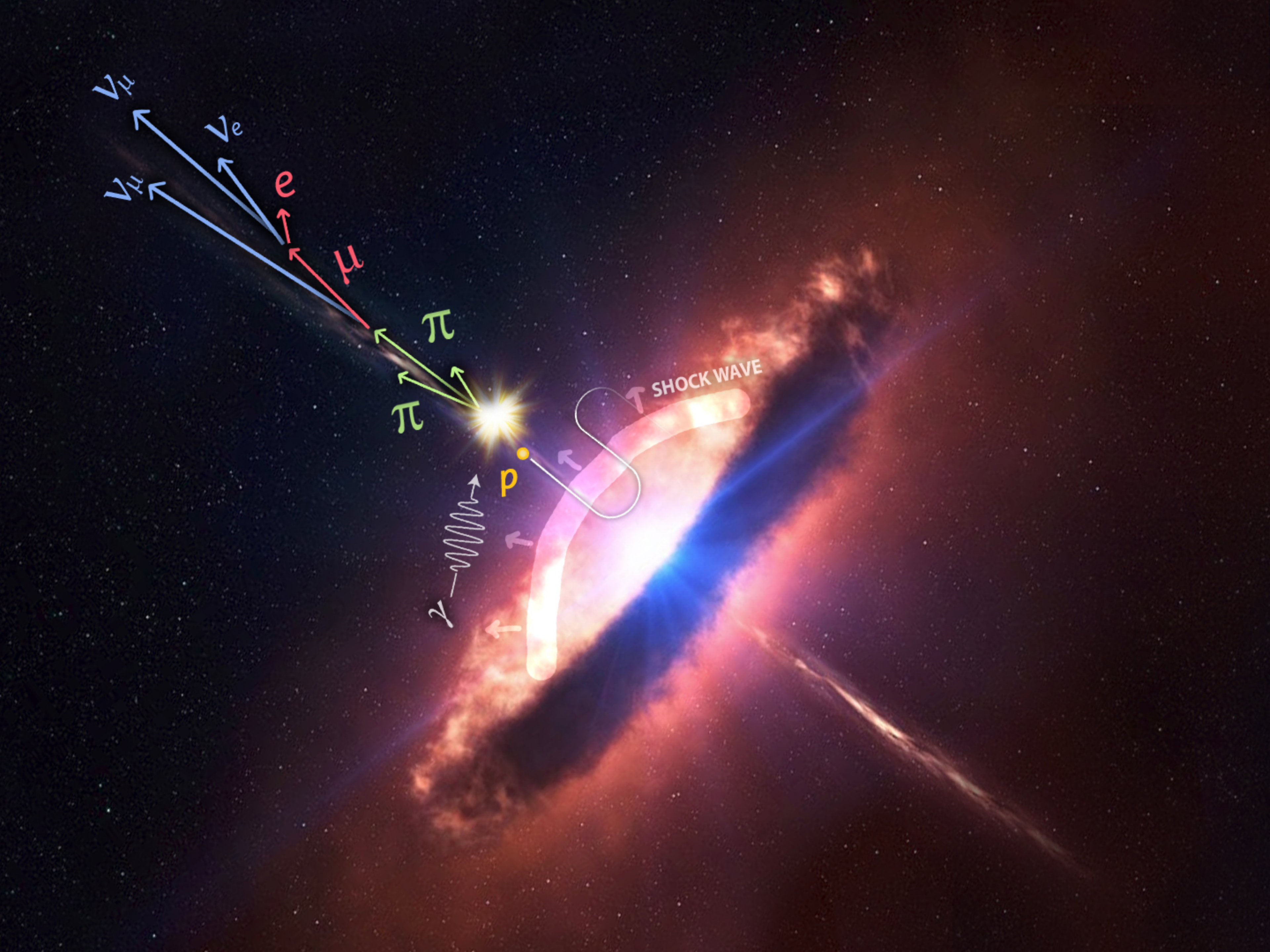




active galaxy

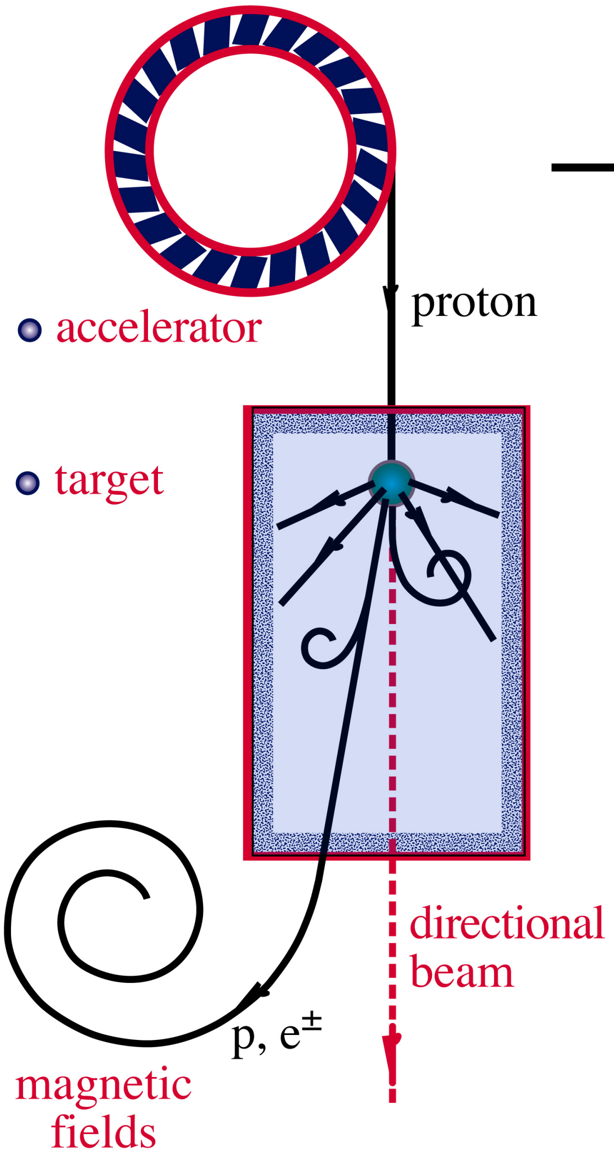
particle flows near
supermassive
black hole





νμ
νe
e
νμ
μ
π
π
SHOCK WAVE
p
γ

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

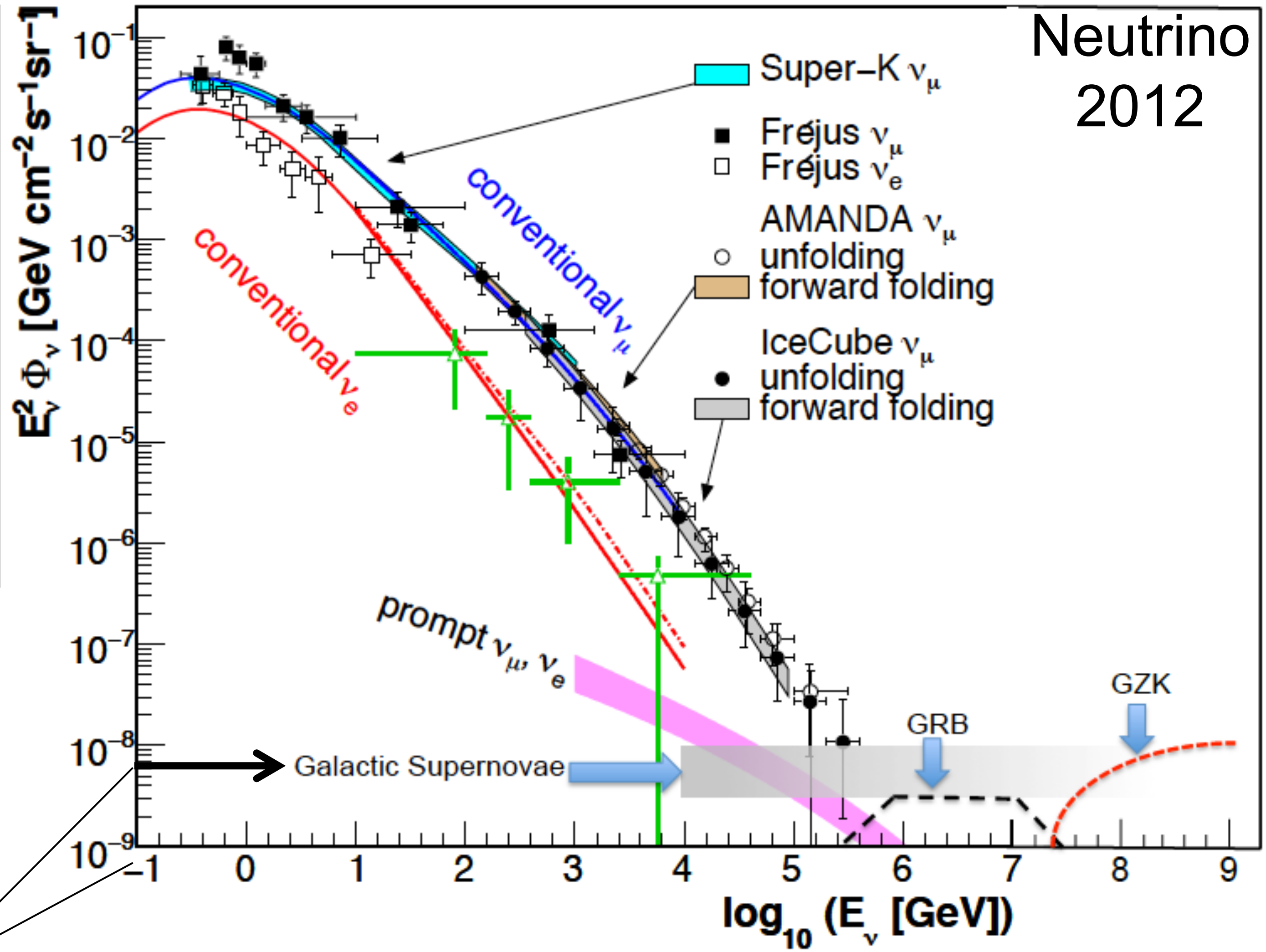
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

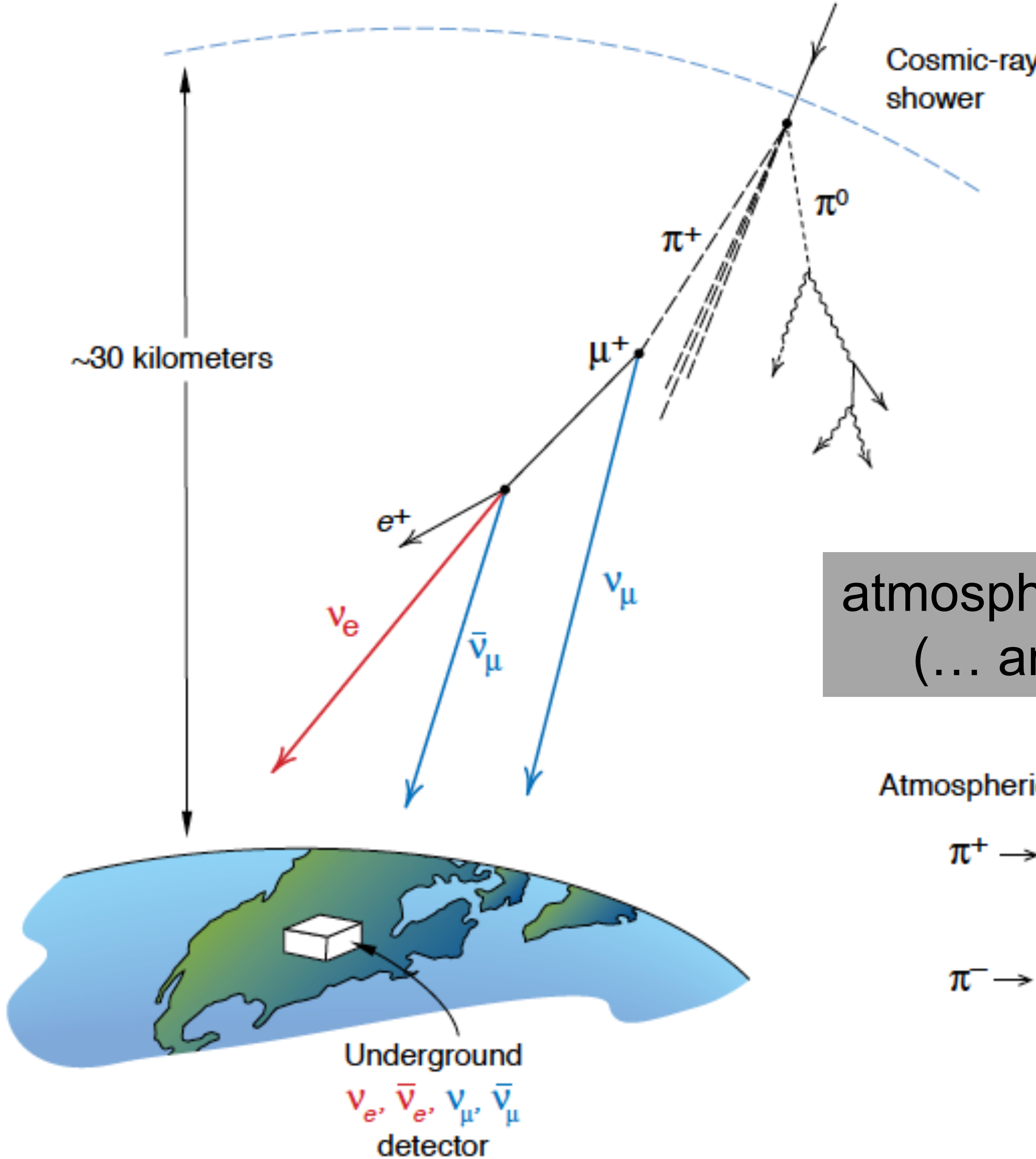
$$dN/dE \sim E^{-2}$$



10-10² events per year for a fully efficient km³ detector

atmospheric | cosmic

100 TeV

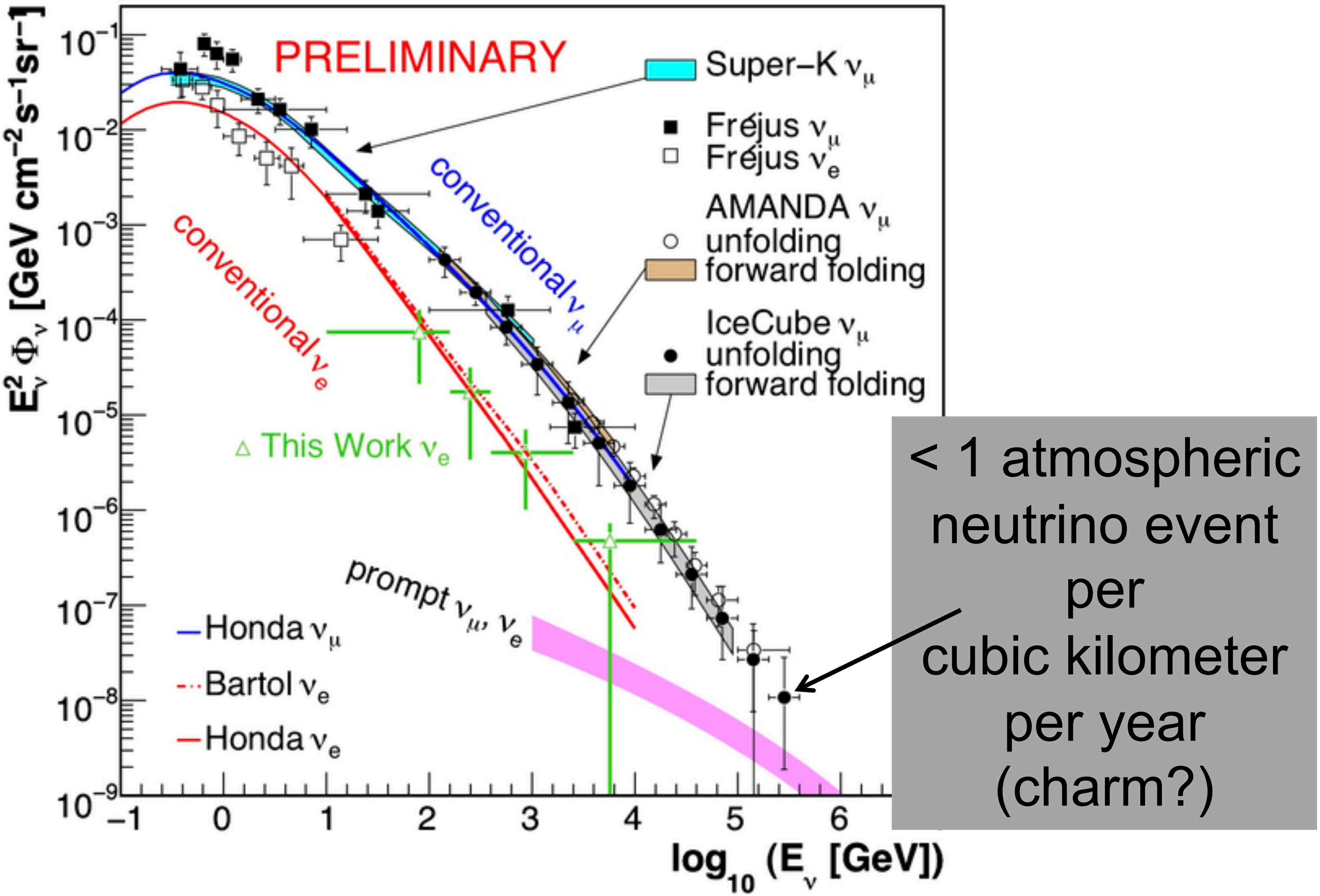


atmospheric neutrinos
(… and muons!)

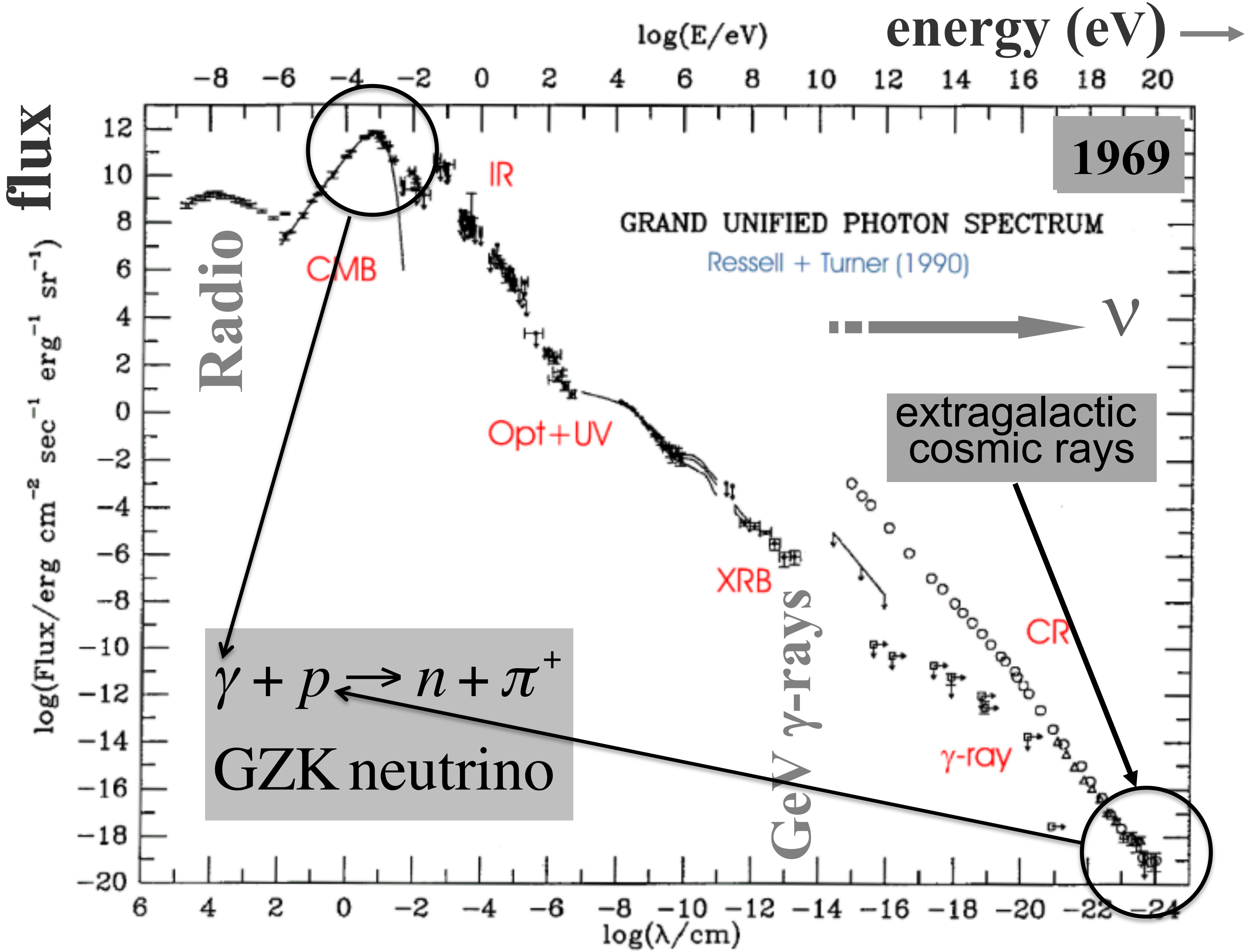
Atmospheric neutrino source

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

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



atmospheric neutrino spectrum


energy (eV)
log(E/eV)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
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
log(λ/cm)

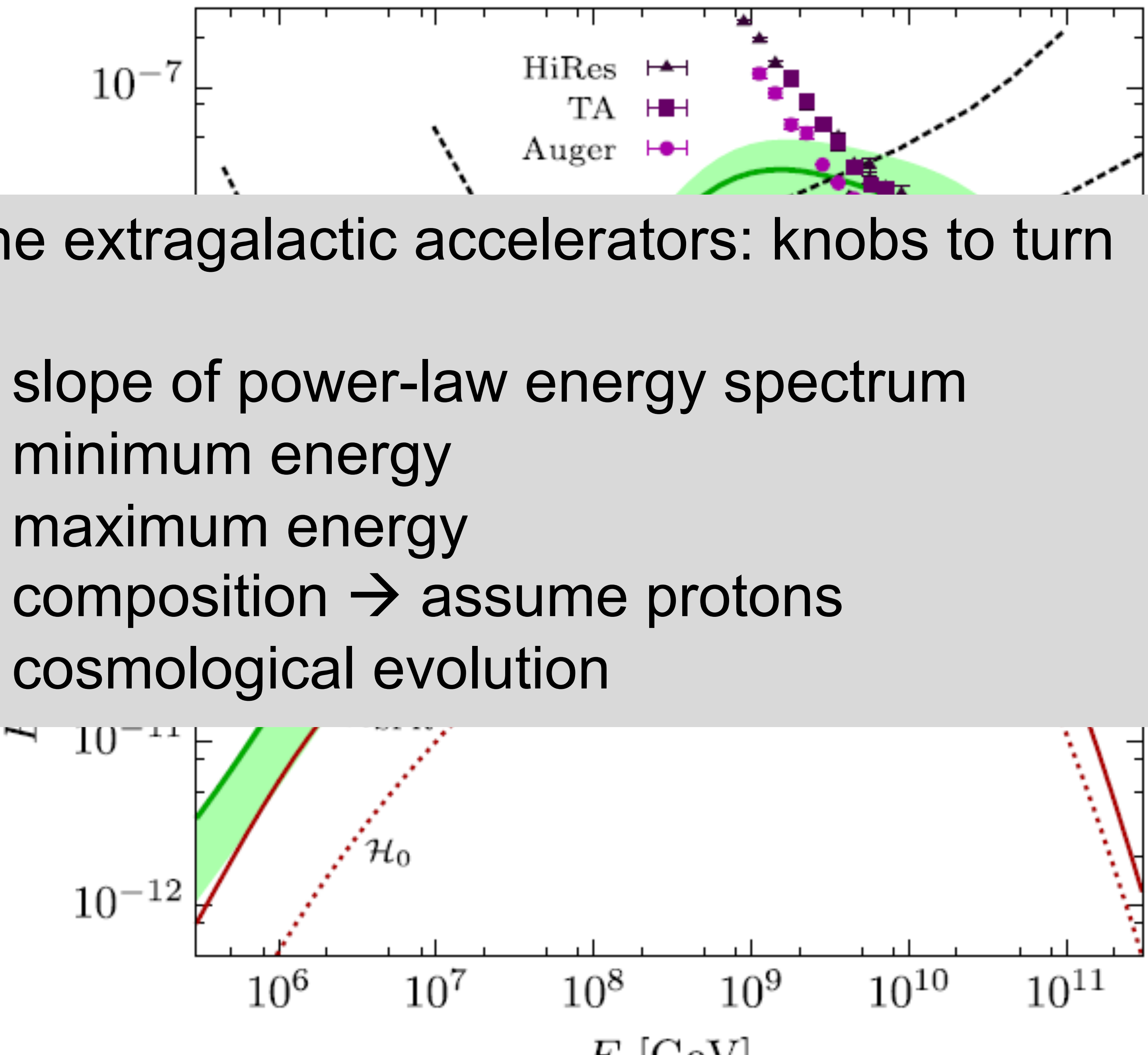
cosmic rays interact with the microwave background

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

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

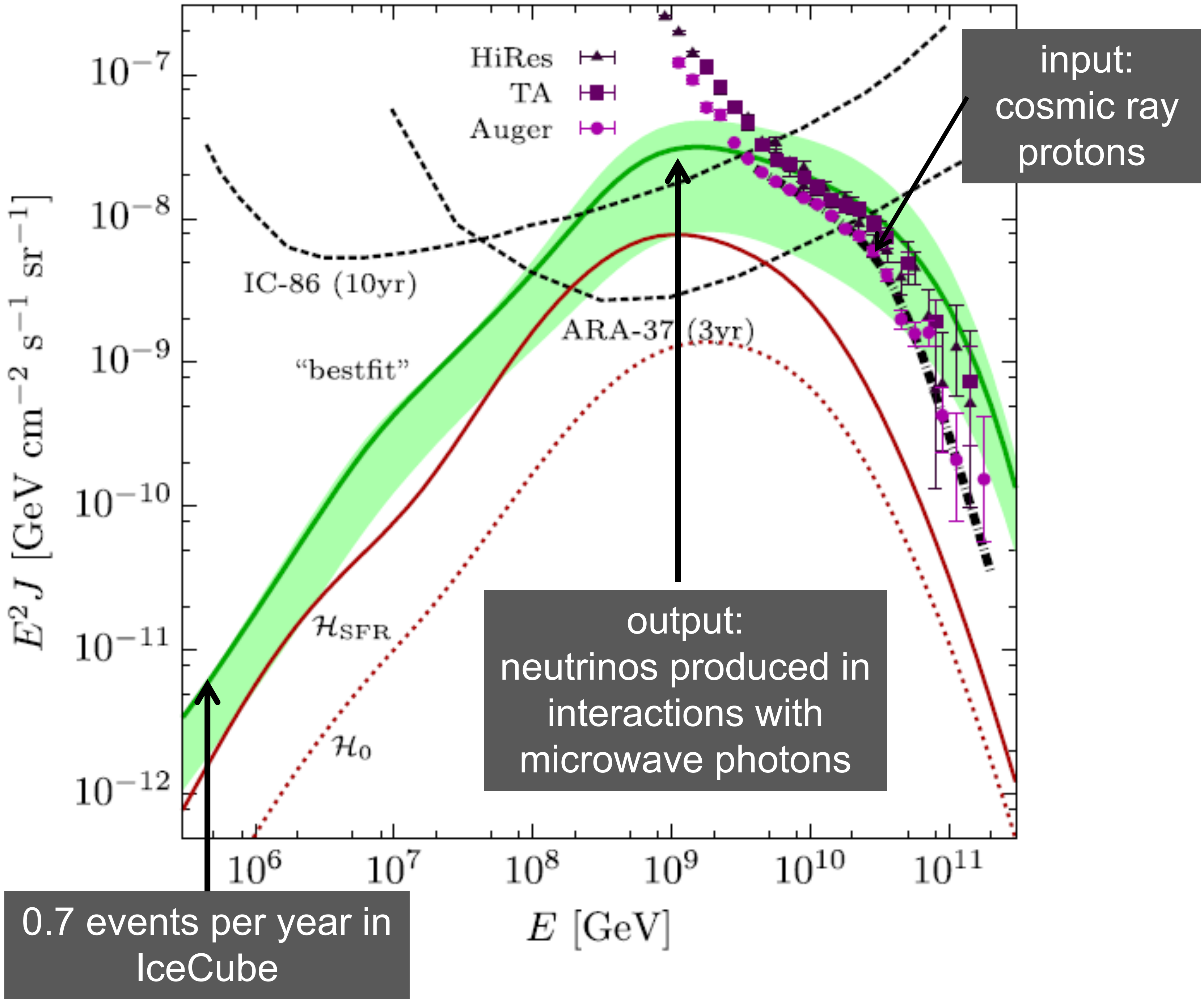
$$\pi \rightarrow \mu+\upsilon_{\mu} \rightarrow \{e+\overline{\upsilon_{\mu}}+\upsilon_{e}\}+\upsilon_{\mu}$$

1 event per cubic kilometer per year ...but it points at its source!

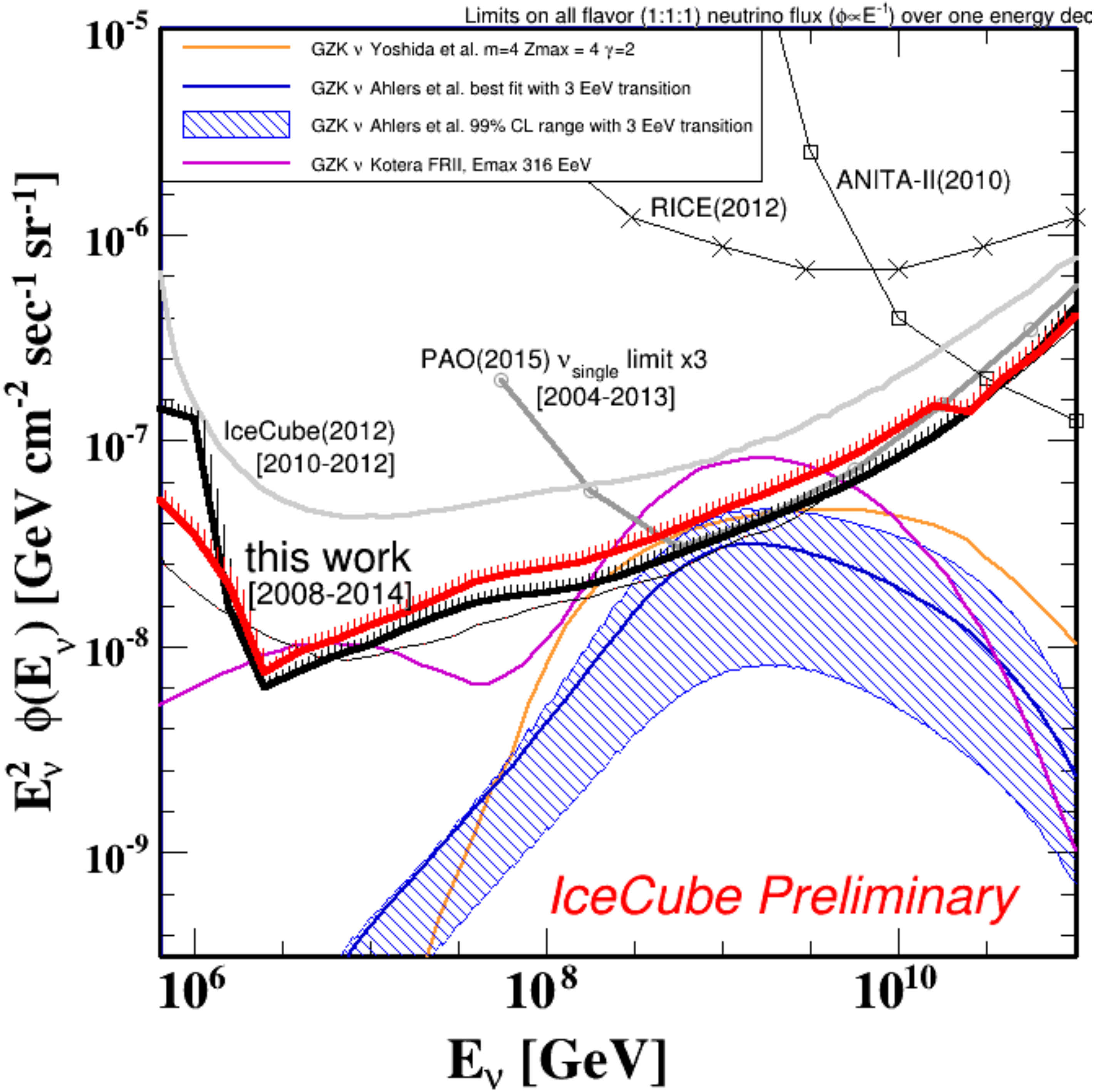


the extragalactic accelerators: knobs to turn

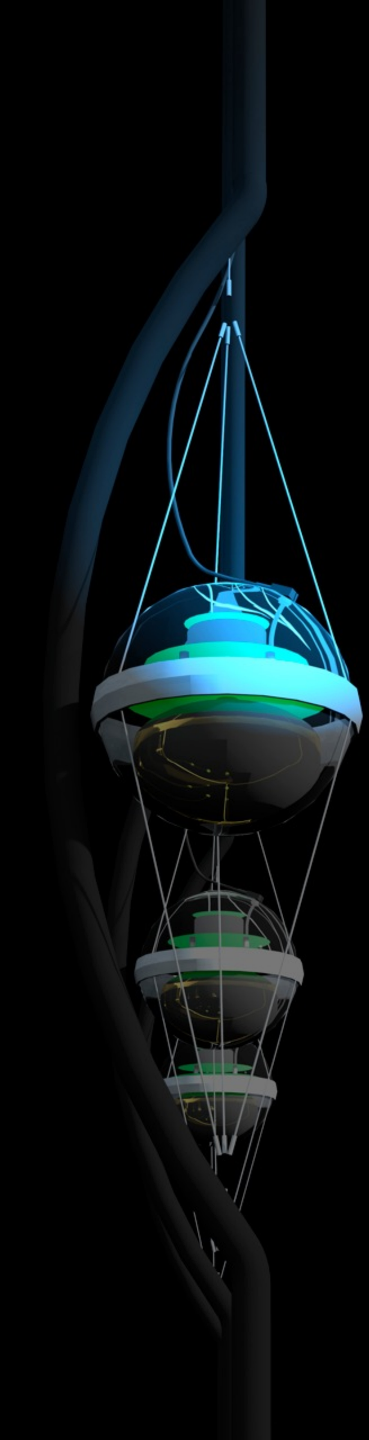
- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\mathrm{SFR}}$
$\mathcal{H}_0$
$E^2 J$ [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
E²ν φ(Eν) [GeV cm^-2 sec^-1 sr^-1]
10^-5
10^-6
10^-7
10^-8
10^-9
10^6
10^8
10^10
Eν [GeV]



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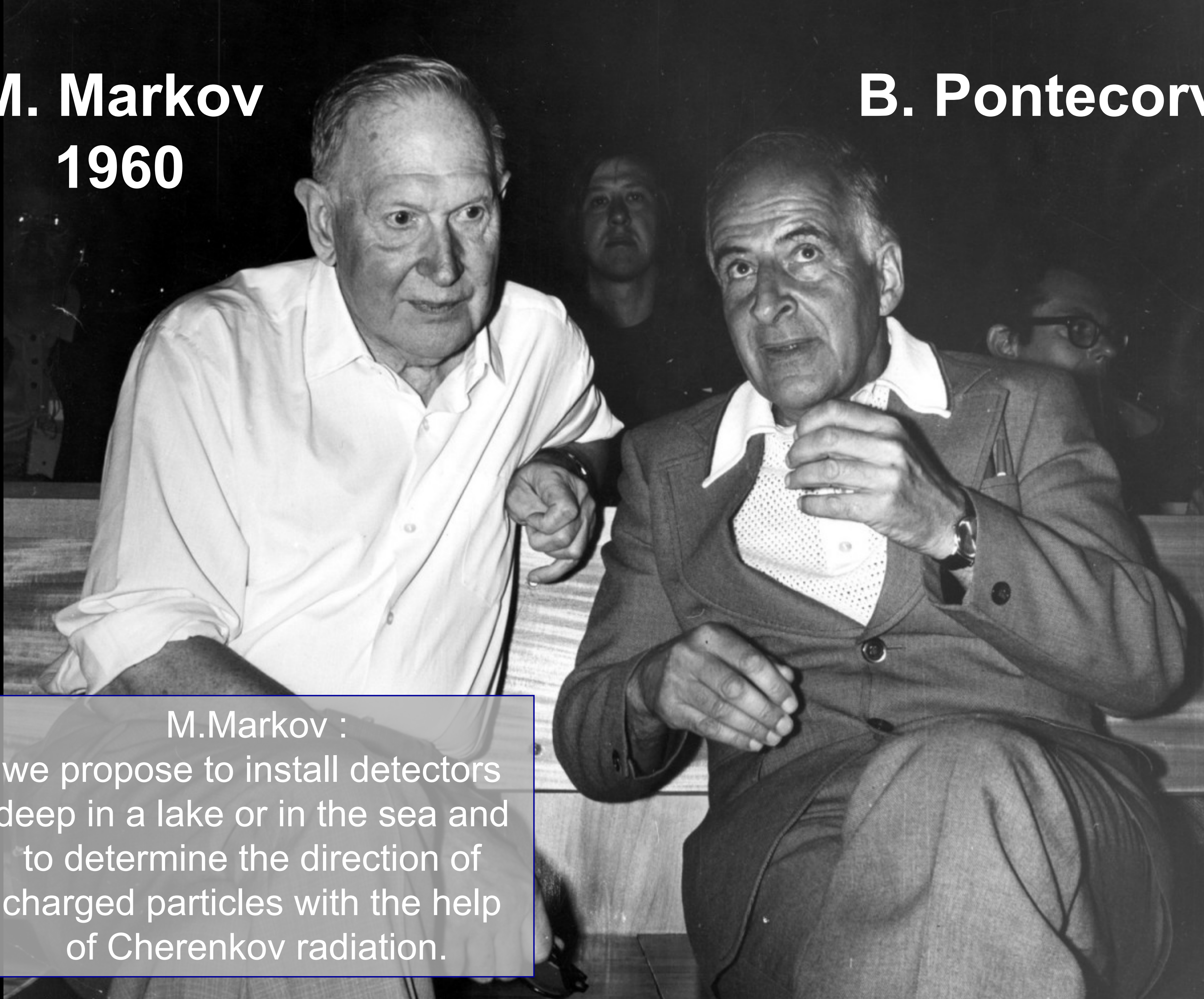
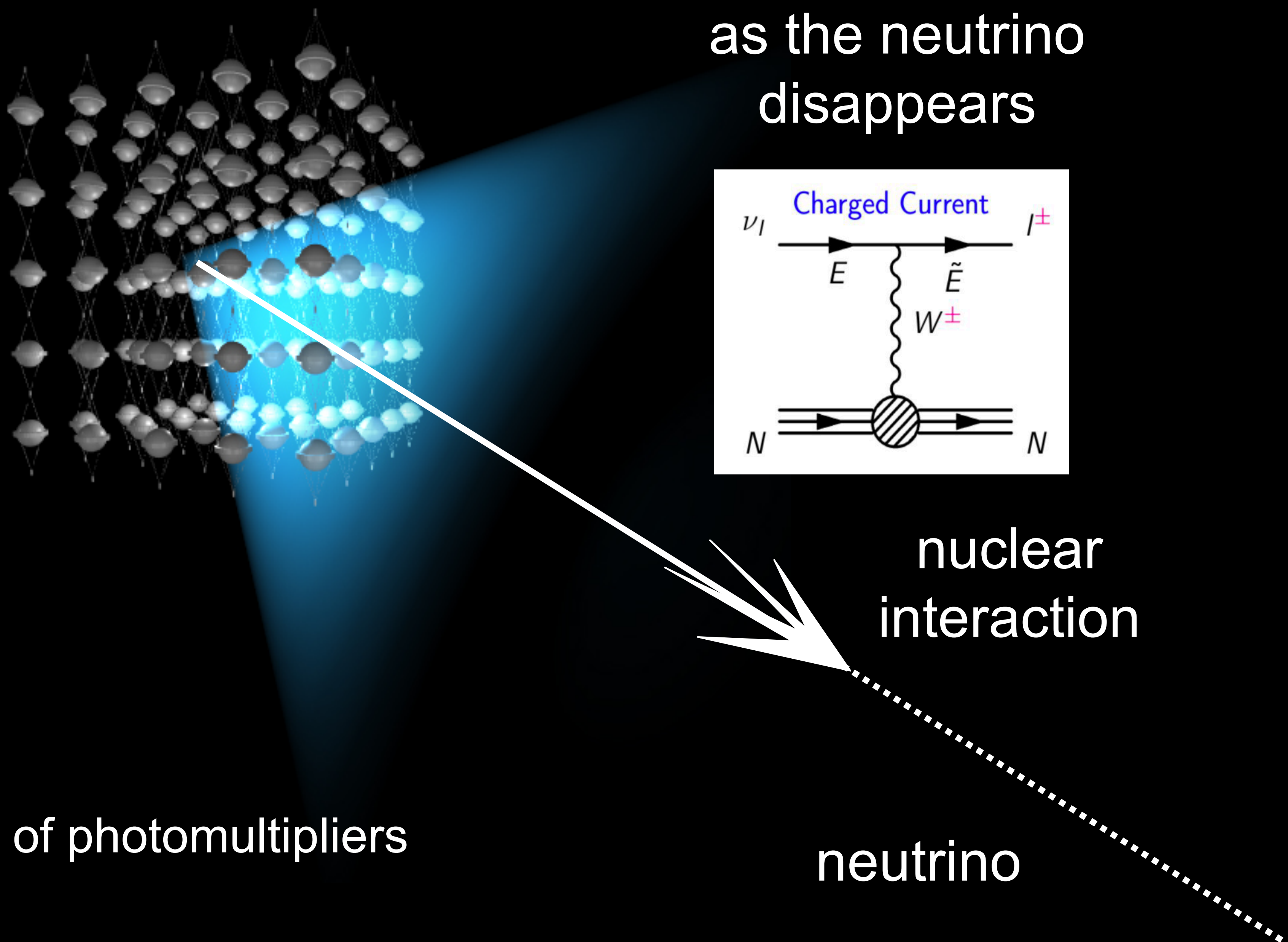
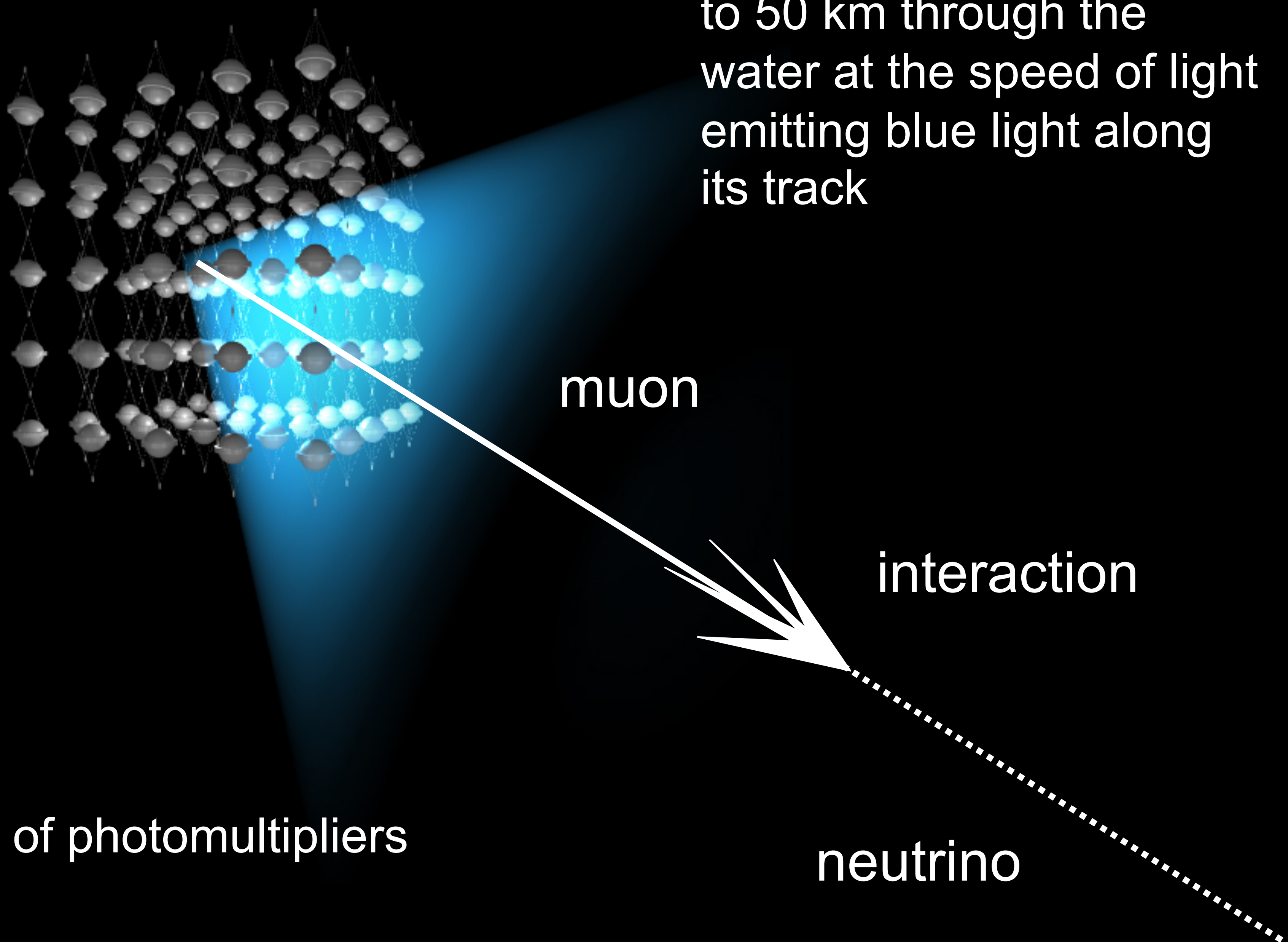

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

charged secondary particles produced as the neutrino disappears

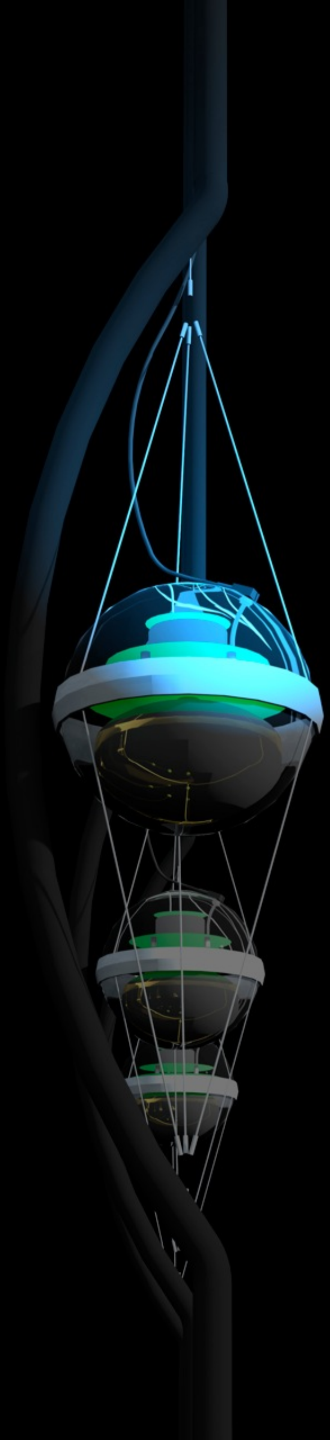


- lattice of photomultipliers

- 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



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- **intermezzo on effective area**
- the discovery of cosmic neutrinos
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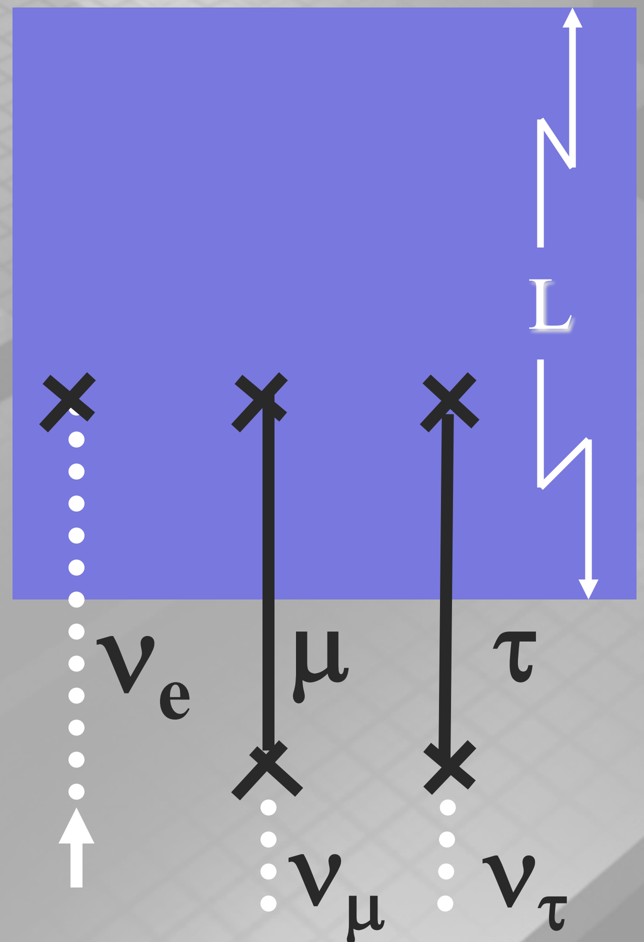
neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

$$1-e^{-\frac{L}{\lambda_\nu}} \cong \frac{L}{\lambda_\nu}$$

$$\mathit{for}\ \ \nu_\mu \quad L \rightarrow R_\mu\left[E_\mu = (1-y)E_\nu\right]$$

$$\mathit{for}\ \ \nu_\tau \quad L \rightarrow \left(E_\tau / m_\tau\right) c\tau_\tau$$

$$P_{\mathrm{det}} = n\sigma_\nu L$$

neutrino and muon area

$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu = P_{\nu\to\mu} \; A_\mu$$

neutrino and muon area

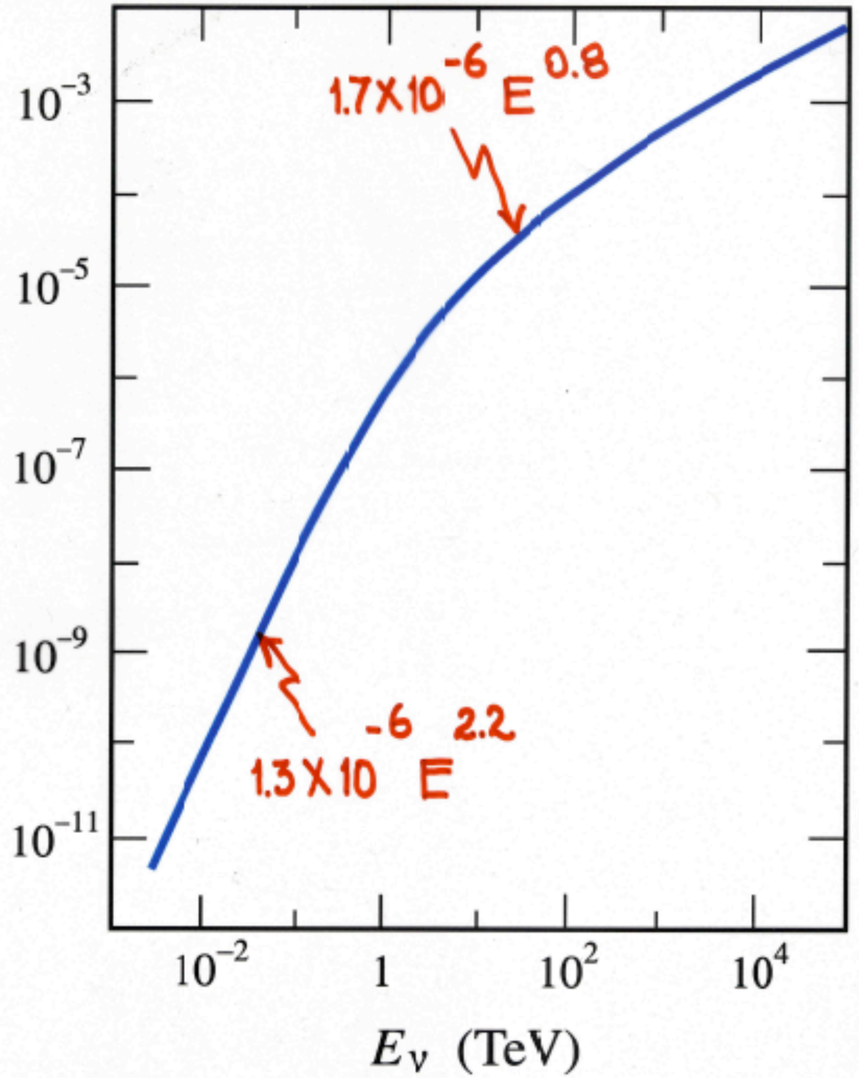
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu \to A_\nu = P_{\nu\to\mu}\, P_{survival}\, A_\mu$$

- $P_{\nu\to\mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$

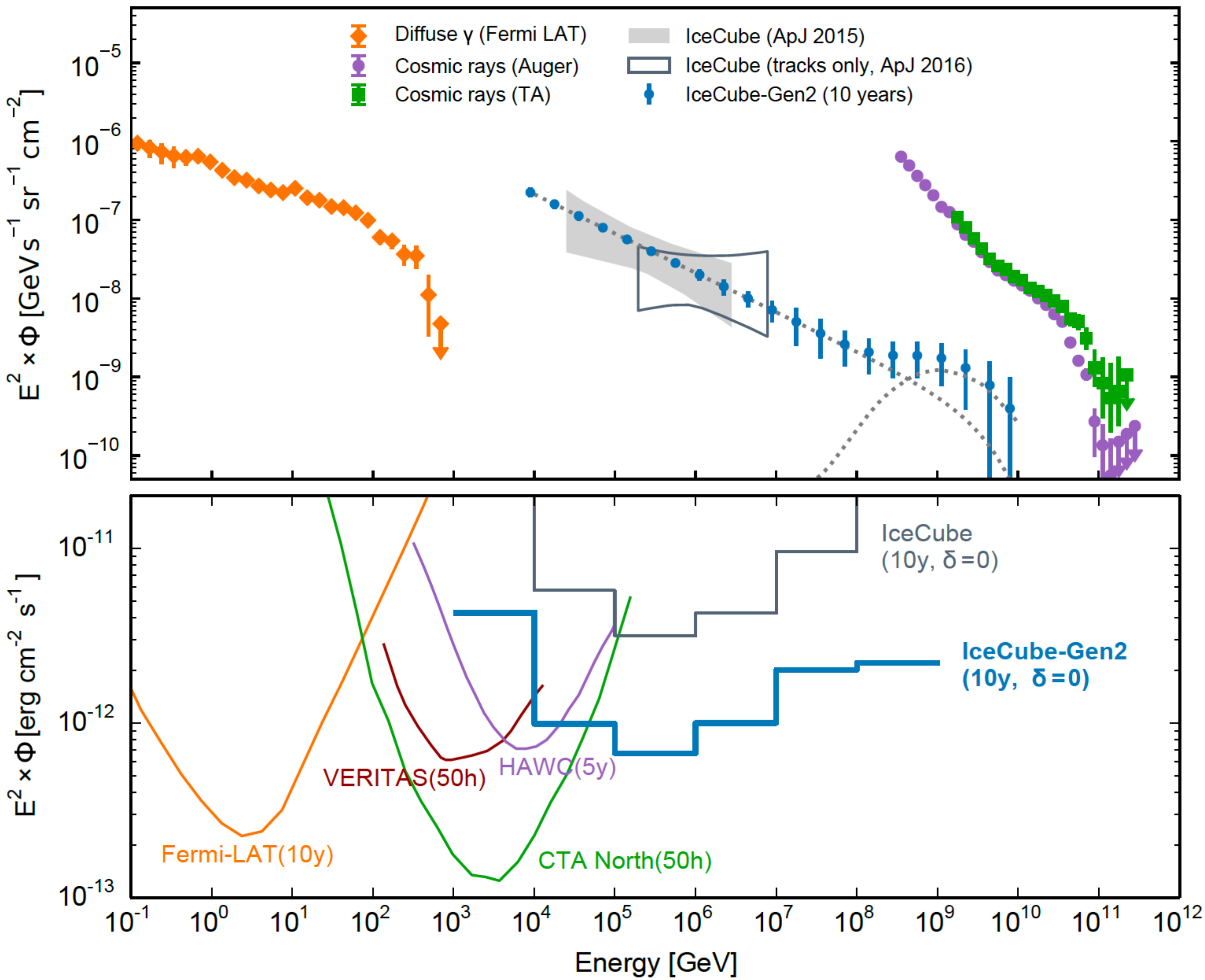


- $N_{events} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu\to\mu}\, dE$

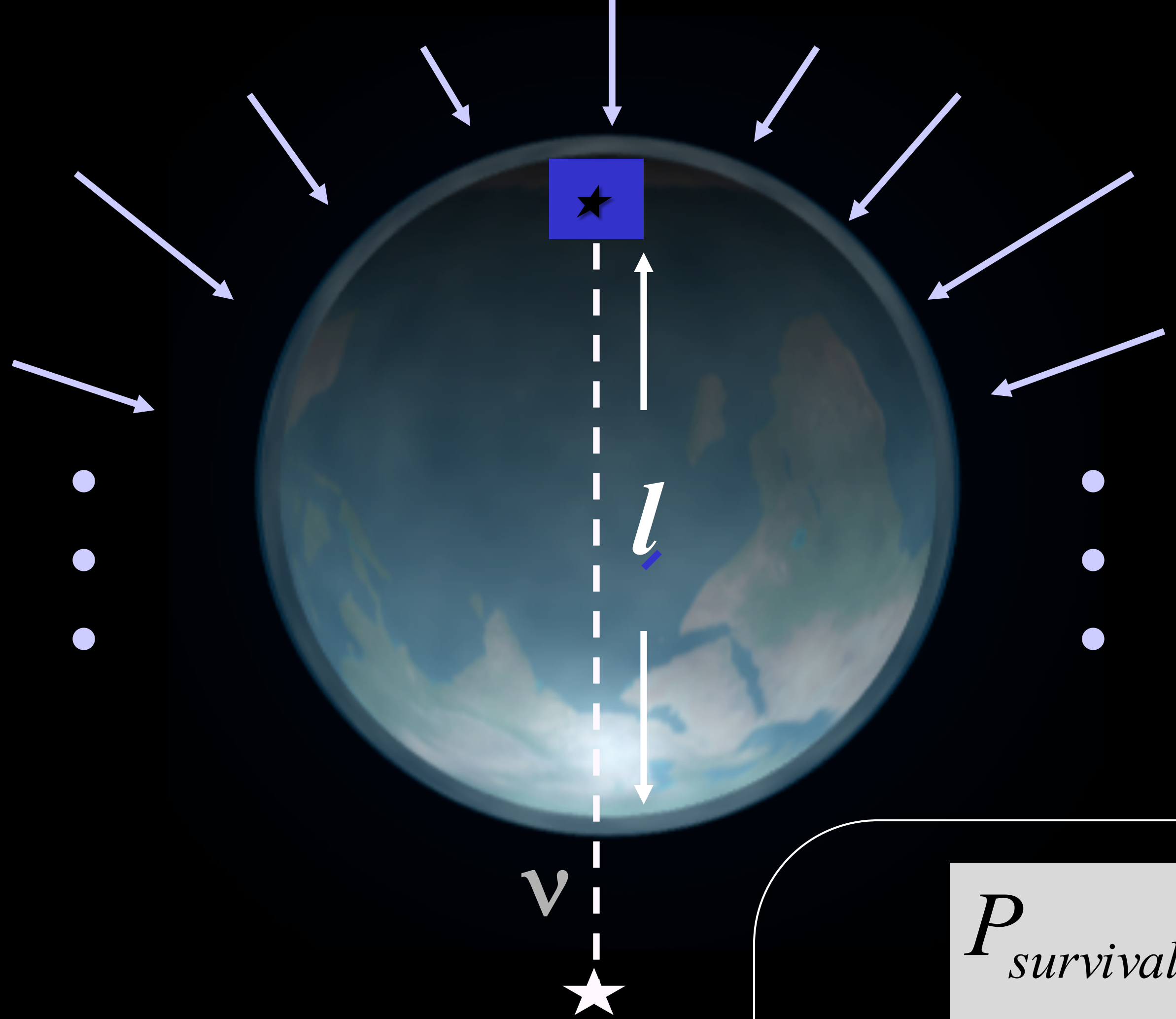
effective telescope area at 100 TeV

$$area \times P_{\mu \to \nu} \left(= \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu \sigma_\nu \cong 10^{-6}\ E_{TeV}\right)$$

- AMANDA ~ ANTARES ~ (1- 5) m^2
- IceCube 22 strings 30 m^2
- IceCube 80 strings 100 m^2



Diffuse γ (Fermi LAT)
Cosmic rays (Auger)
Cosmic rays (TA)
IceCube (ApJ 2015)
IceCube (tracks only, ApJ 2016)
IceCube-Gen2 (10 years)
E^2 × Φ [GeV s^-1 sr^-1 cm^-2]
E^2 × Φ [erg cm^-2 s^-1]
IceCube (10y, δ = 0)
IceCube-Gen2 (10y, δ = 0)
VERITAS(50h)
HAWC(5y)
Fermi-LAT(10y)
CTA North(50h)
Energy [GeV]

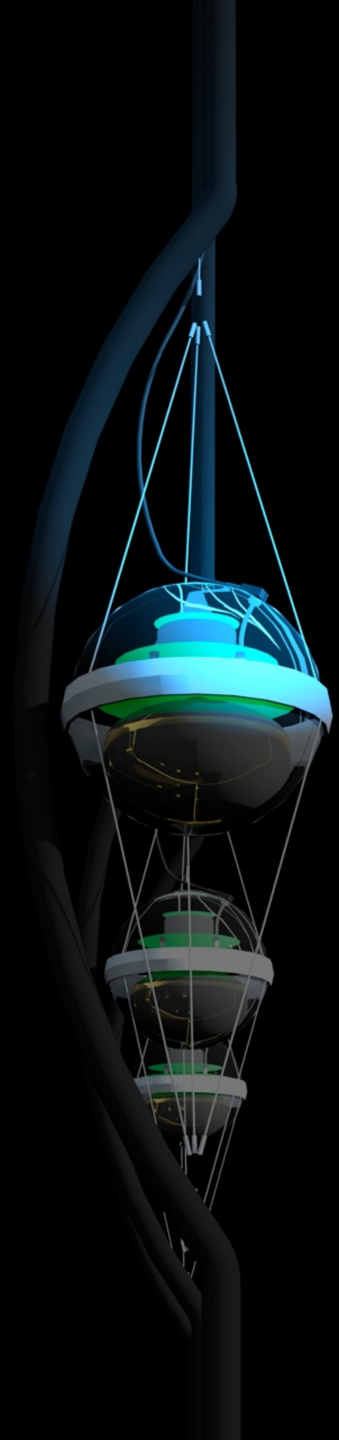


the earth as a cosmic ray muon filter

a neutrino of 70 TeV has an interaction length equal to the diameter of the earth

$$P_{survival} = \exp - \left(l / \lambda_\nu \right)$$
$$\lambda_\nu^{-1} = n \sigma_\nu \left(E_\nu \right)$$

$$n = \rho N_A$$



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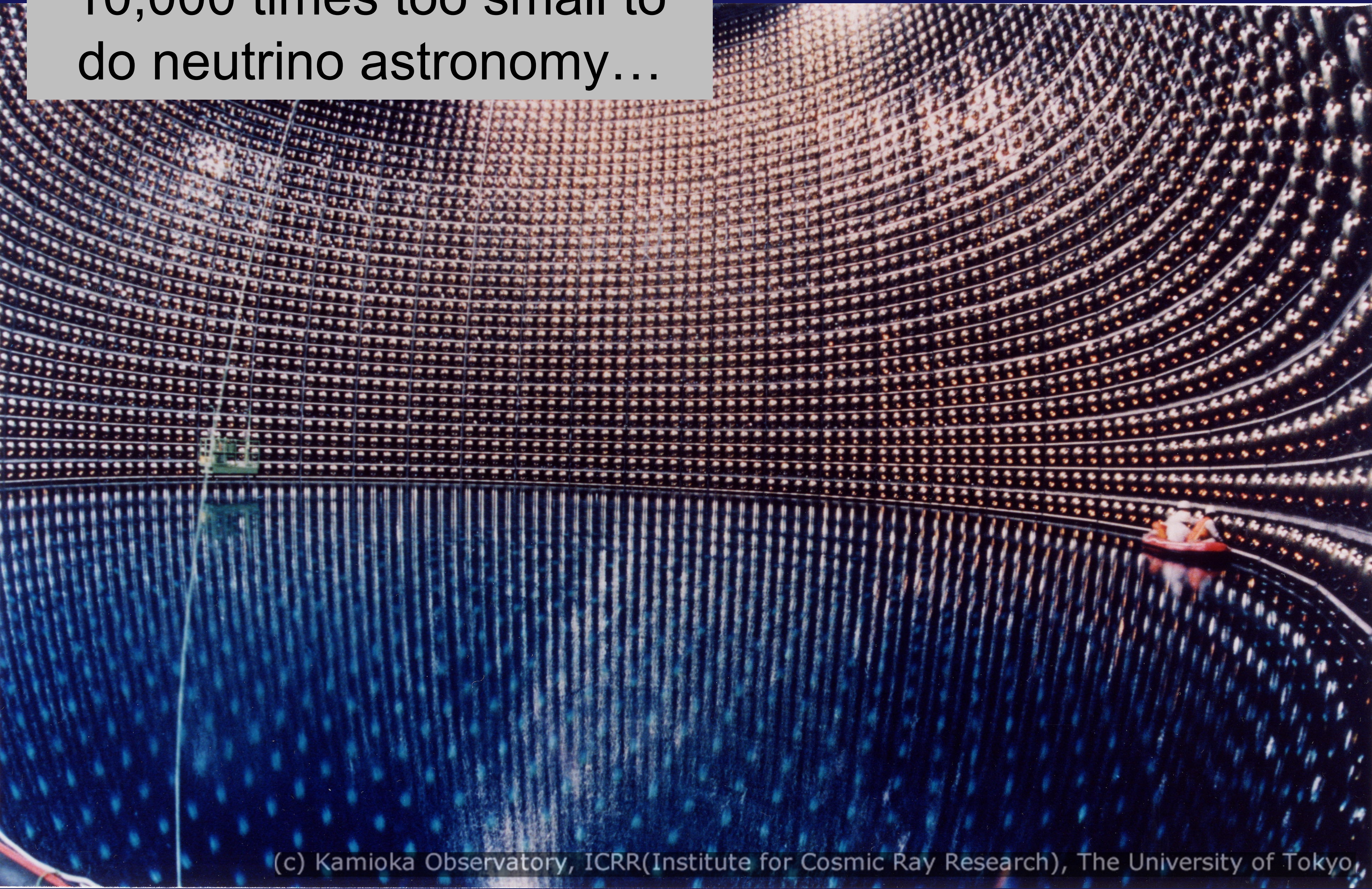
10,000 times too small to do neutrino astronomy…



standing on the shoulder of giants

1987: DUMAND test string

Lake Baikal experiment observes atmospheric neutrinos

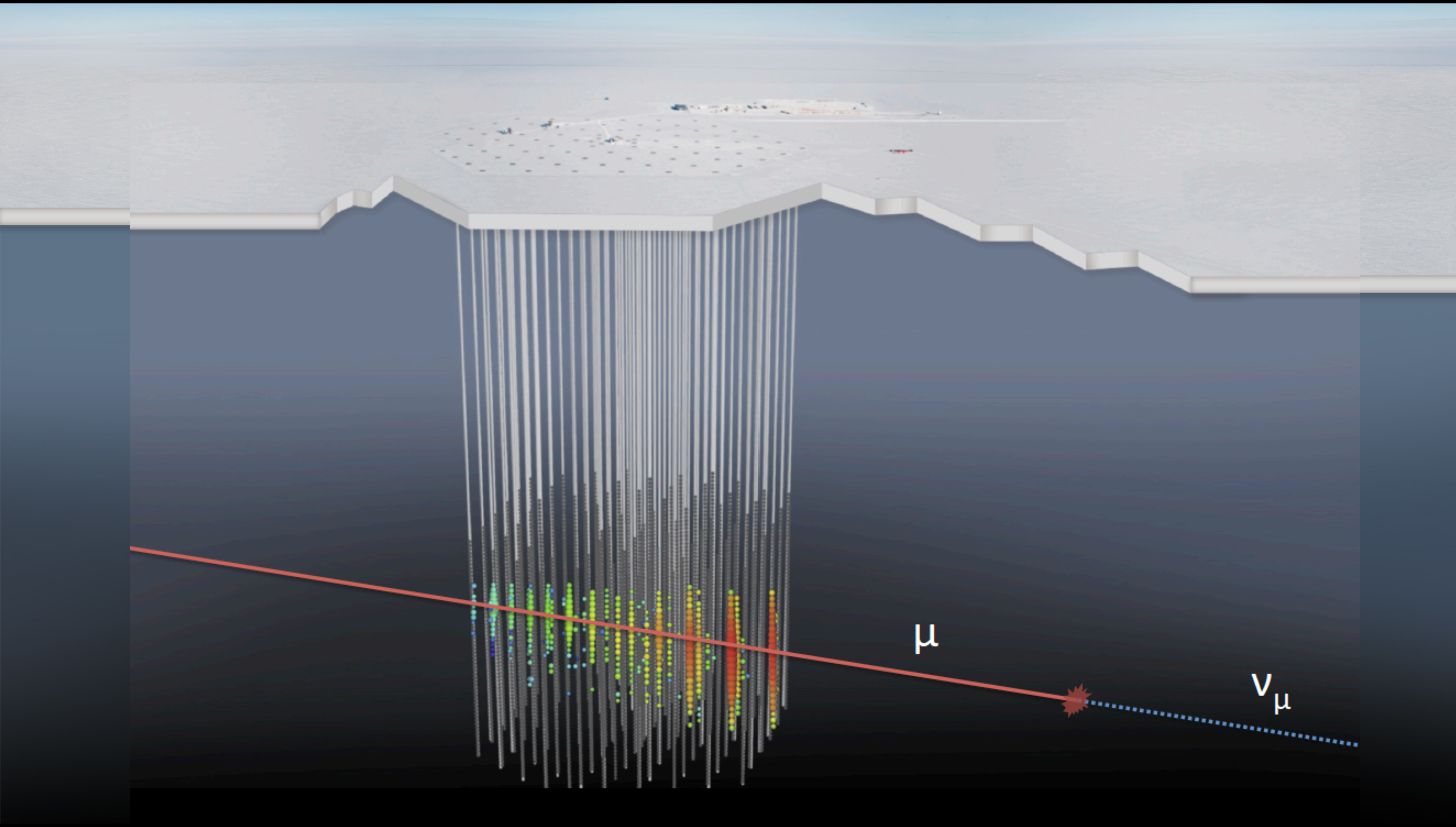
ANTARES
Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
450 m
40 km to shore
Junction Box
Interlink cables
70 m
ANTARES
France
Switzerland
Italy
Spain
Nantes
Zurich
Liechtenstein
Geneva
Lyon
Milan
Venice
Turin
Genoa
Bologna
San Marino
Toulouse
Montpellier
Marseille
Monaco
Bilbao
Andorra
Barcelona
Zaragoza
Madrid
Valencia
Palma
Murcia
Malaga
Algiers
Tunis
Gibraltar
Fes
Budapest
Google
© François Montanet

ice 1.4 kilometers below geographic South Pole

- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers


ultra-transparent ice below 1.5 km

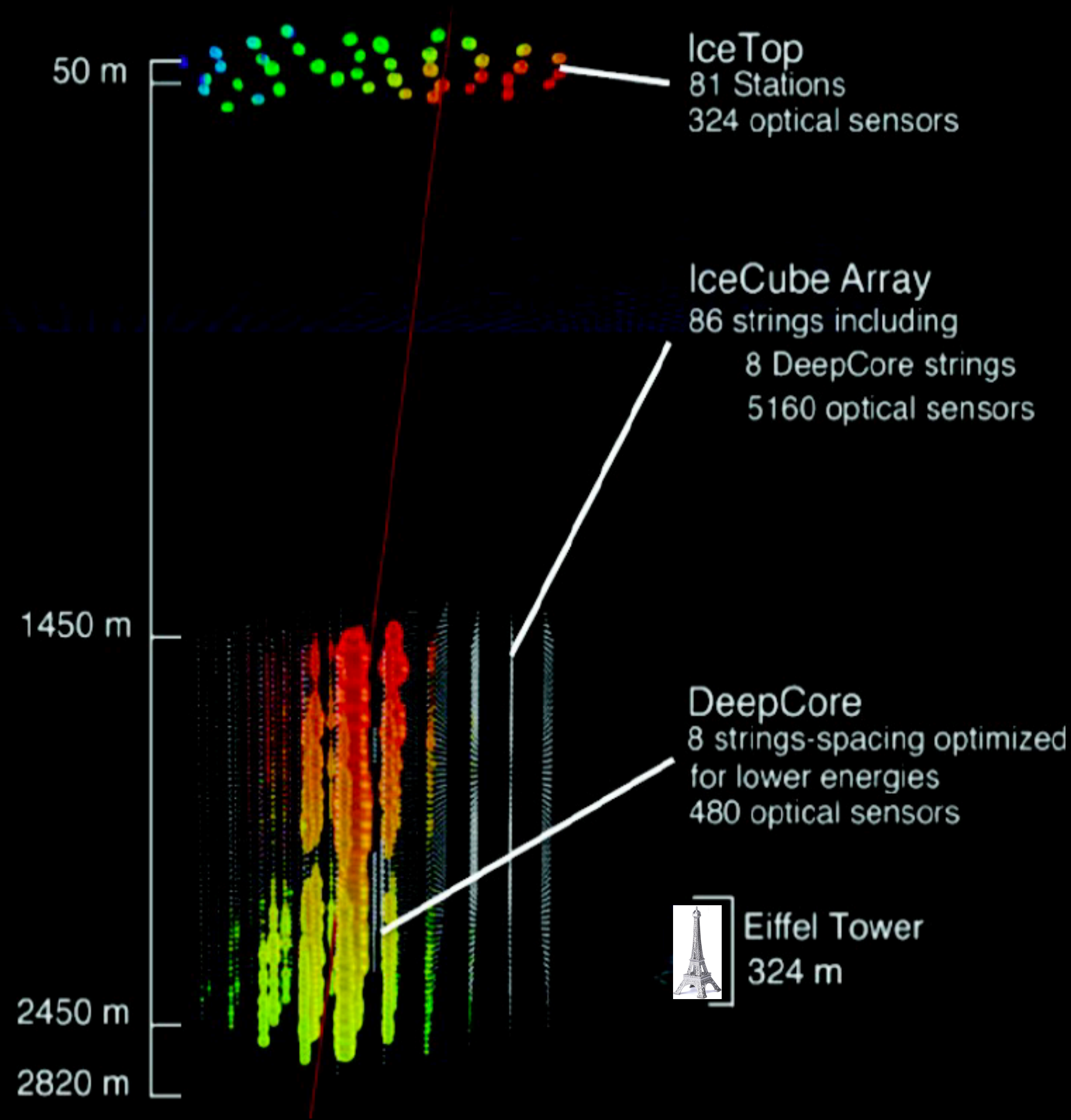
instrument 1 cubic kilometer of natural ice below 1.45 km

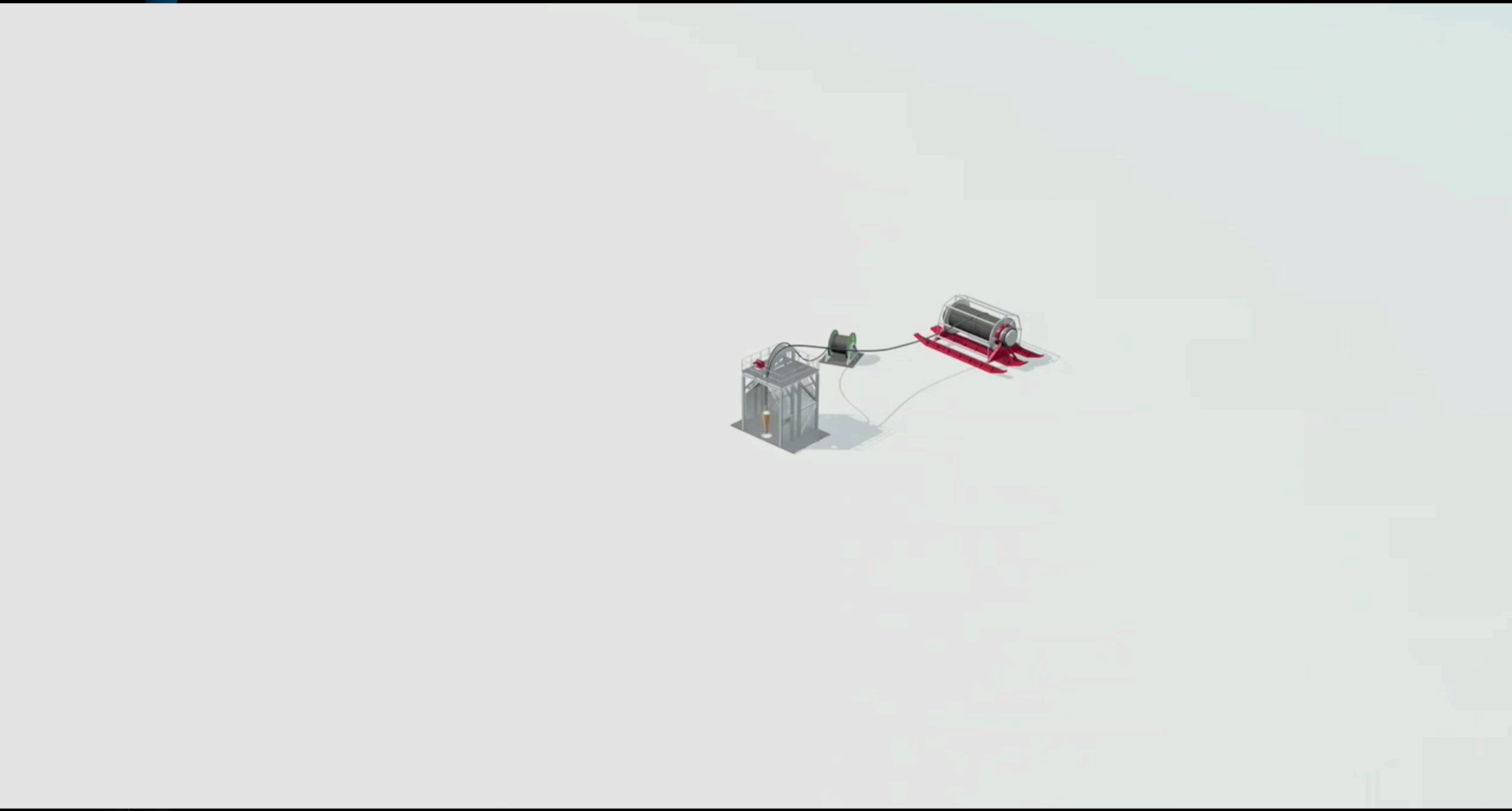


the IceCube Neutrino Observatory

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

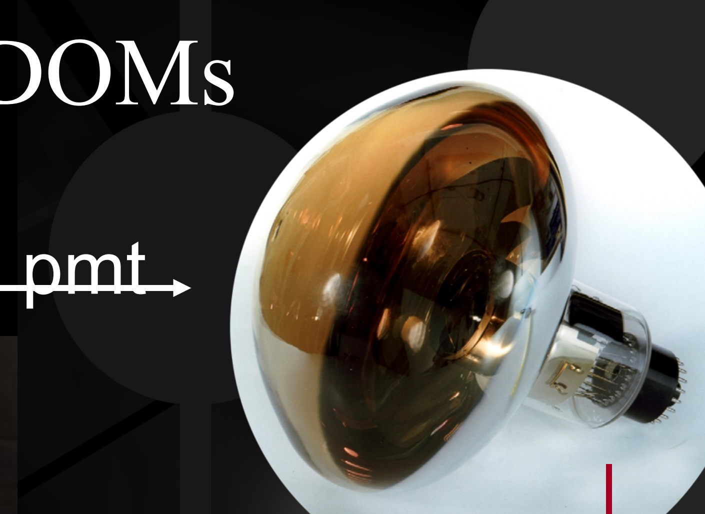
2 ns time resolution

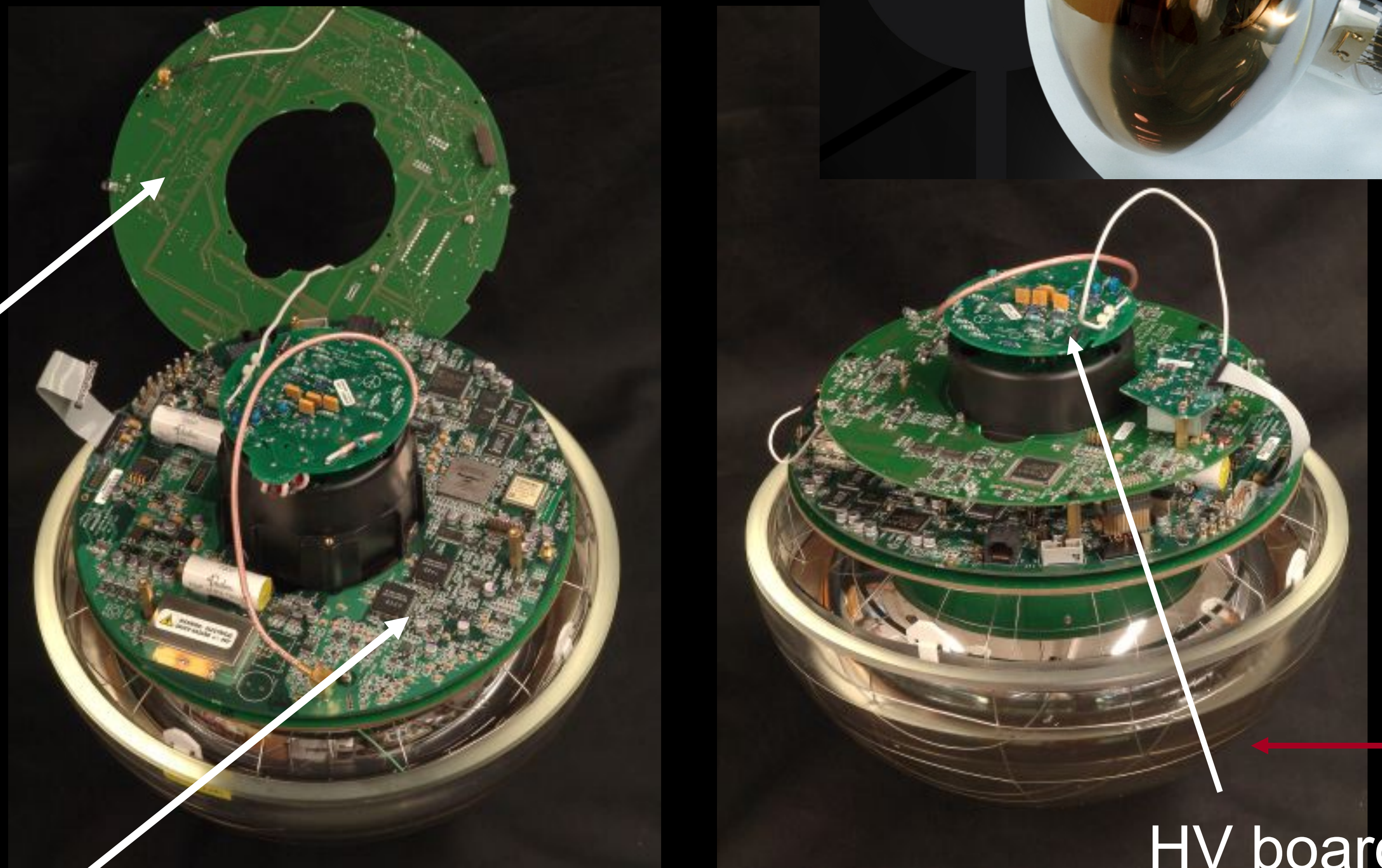




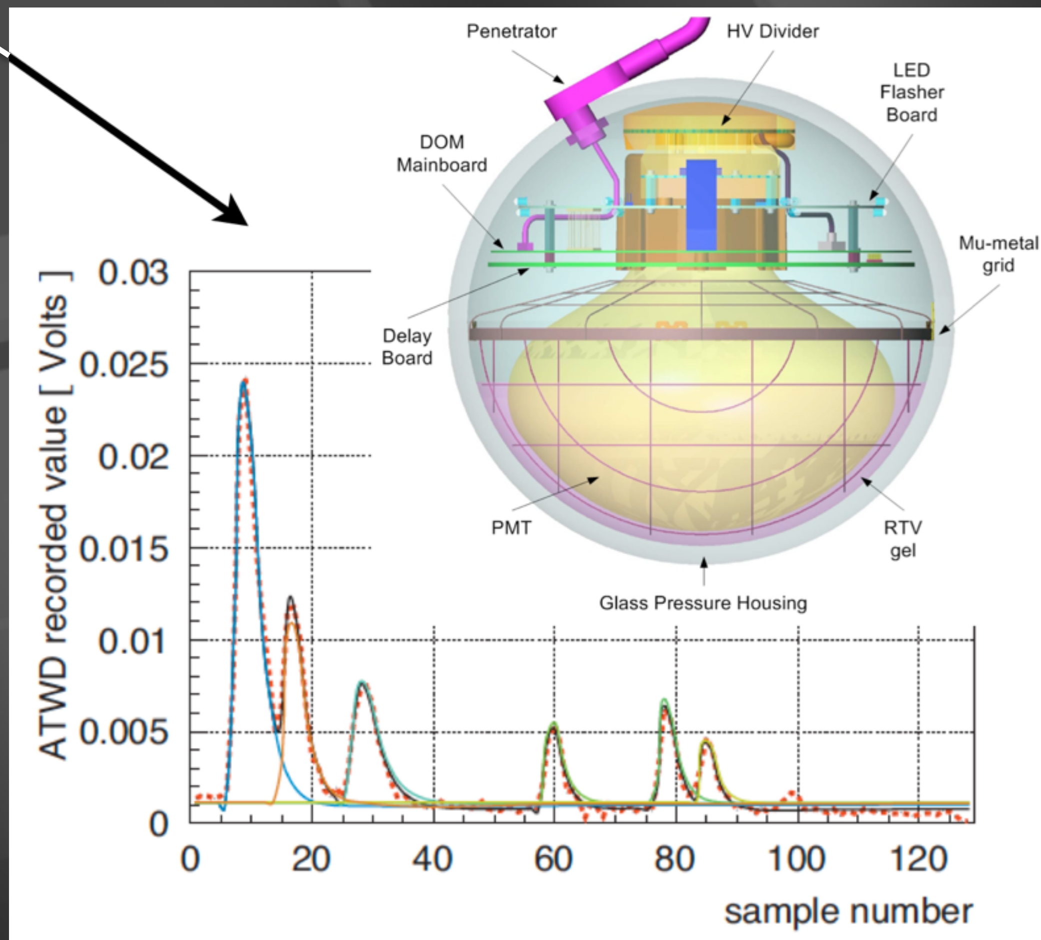
photomultiplier tube -10 inch

architecture of independent DOMs

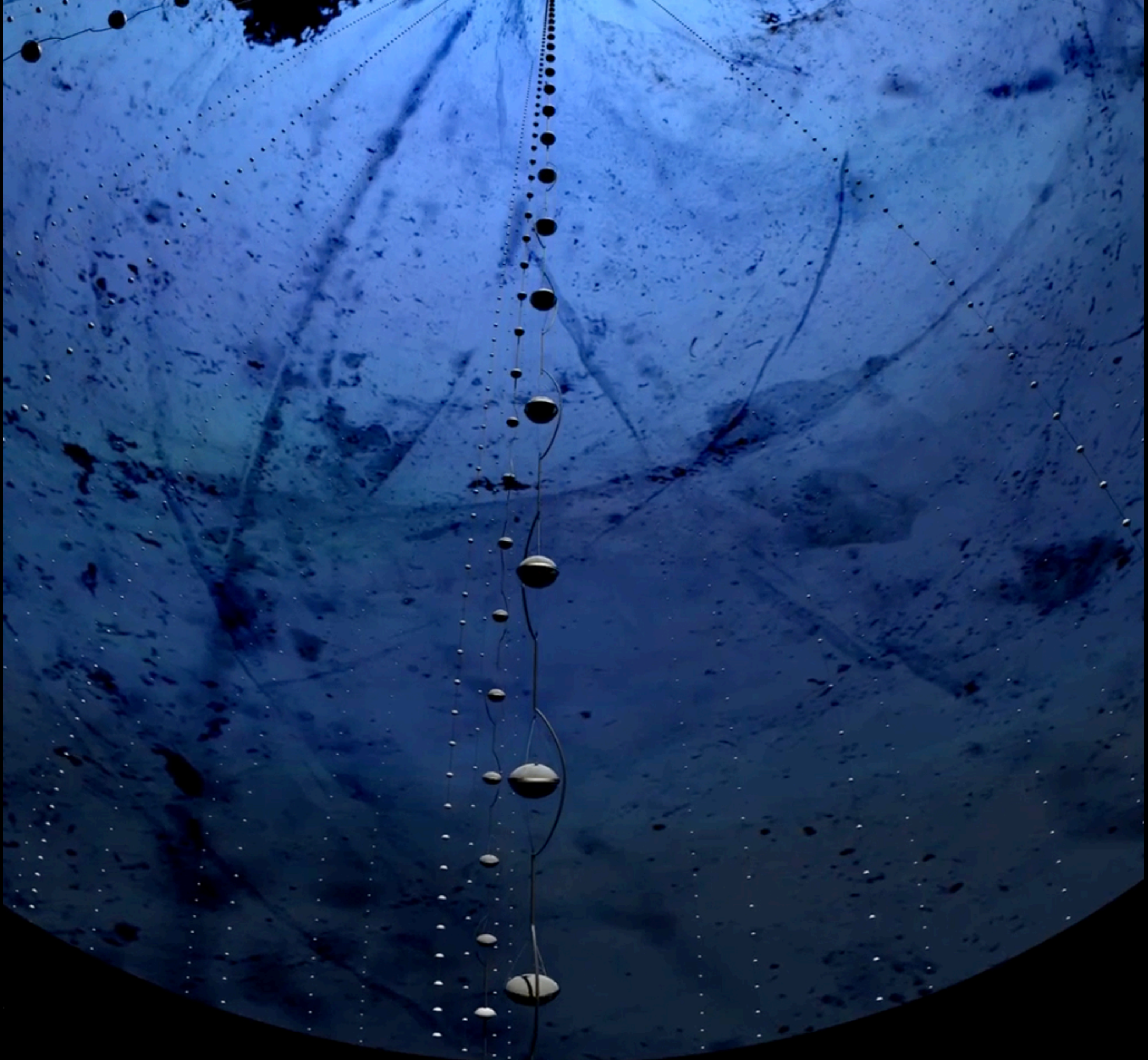


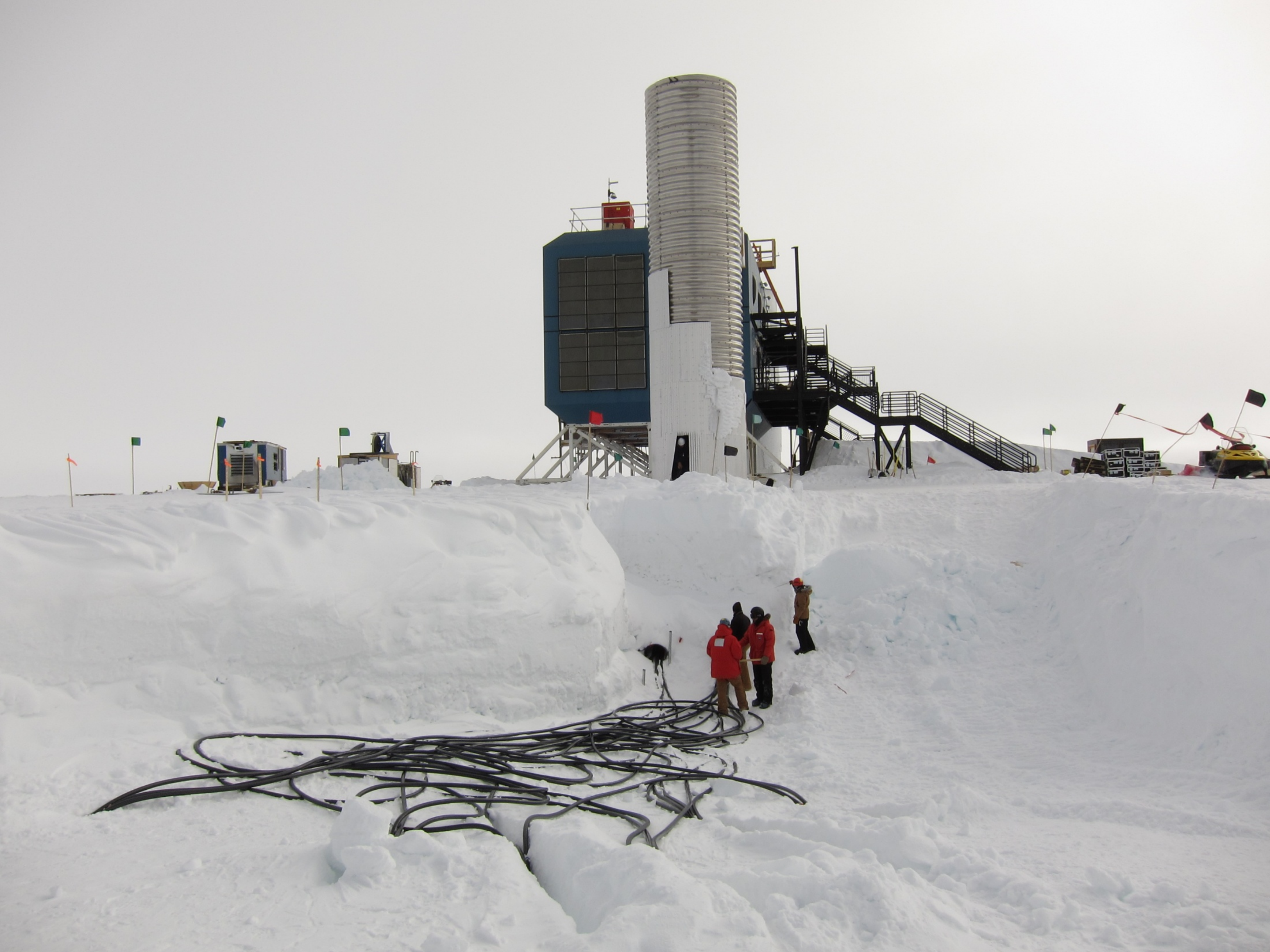


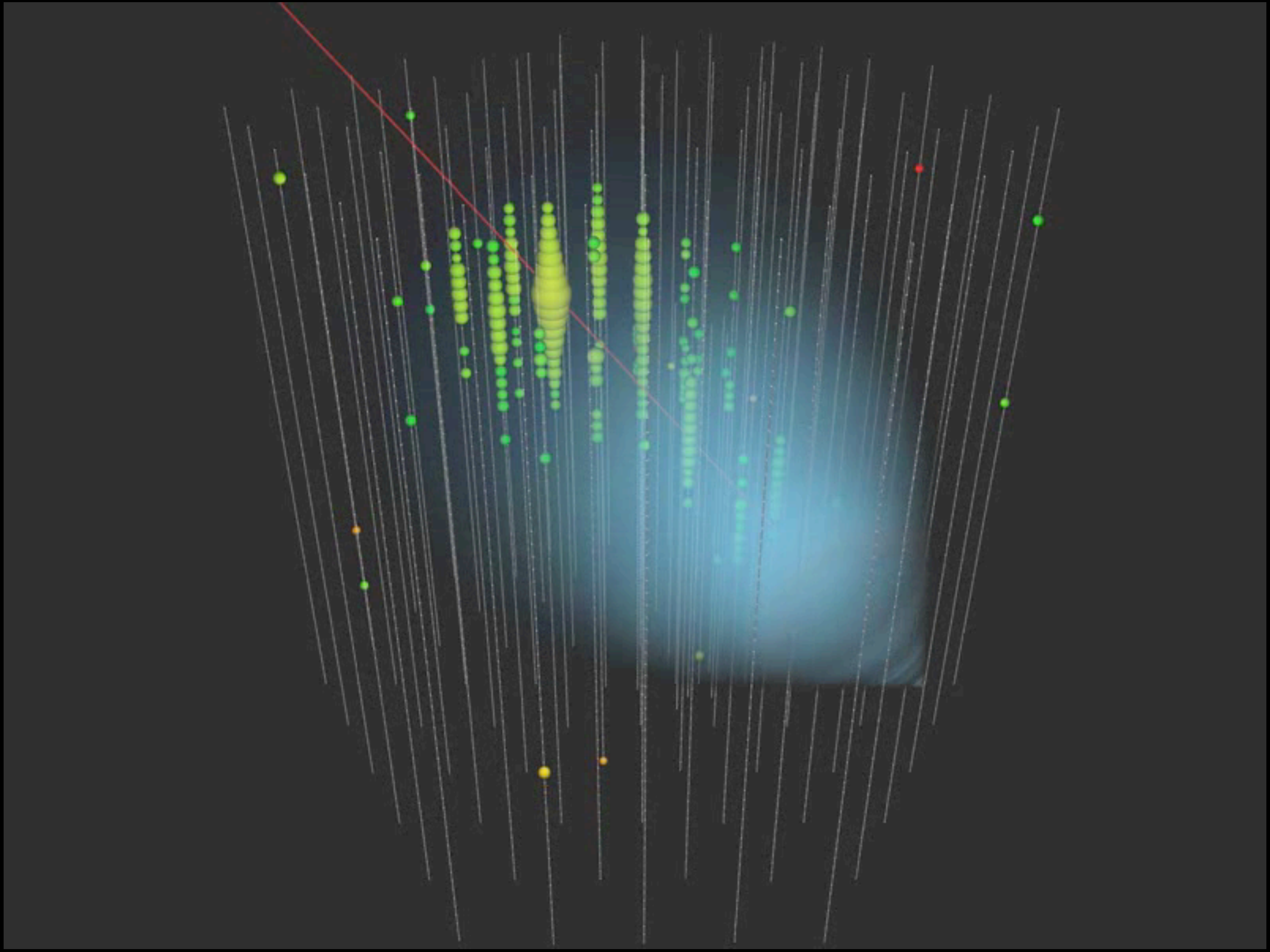
… each Digital Optical Module independently collects light signals like this, digitizes them,



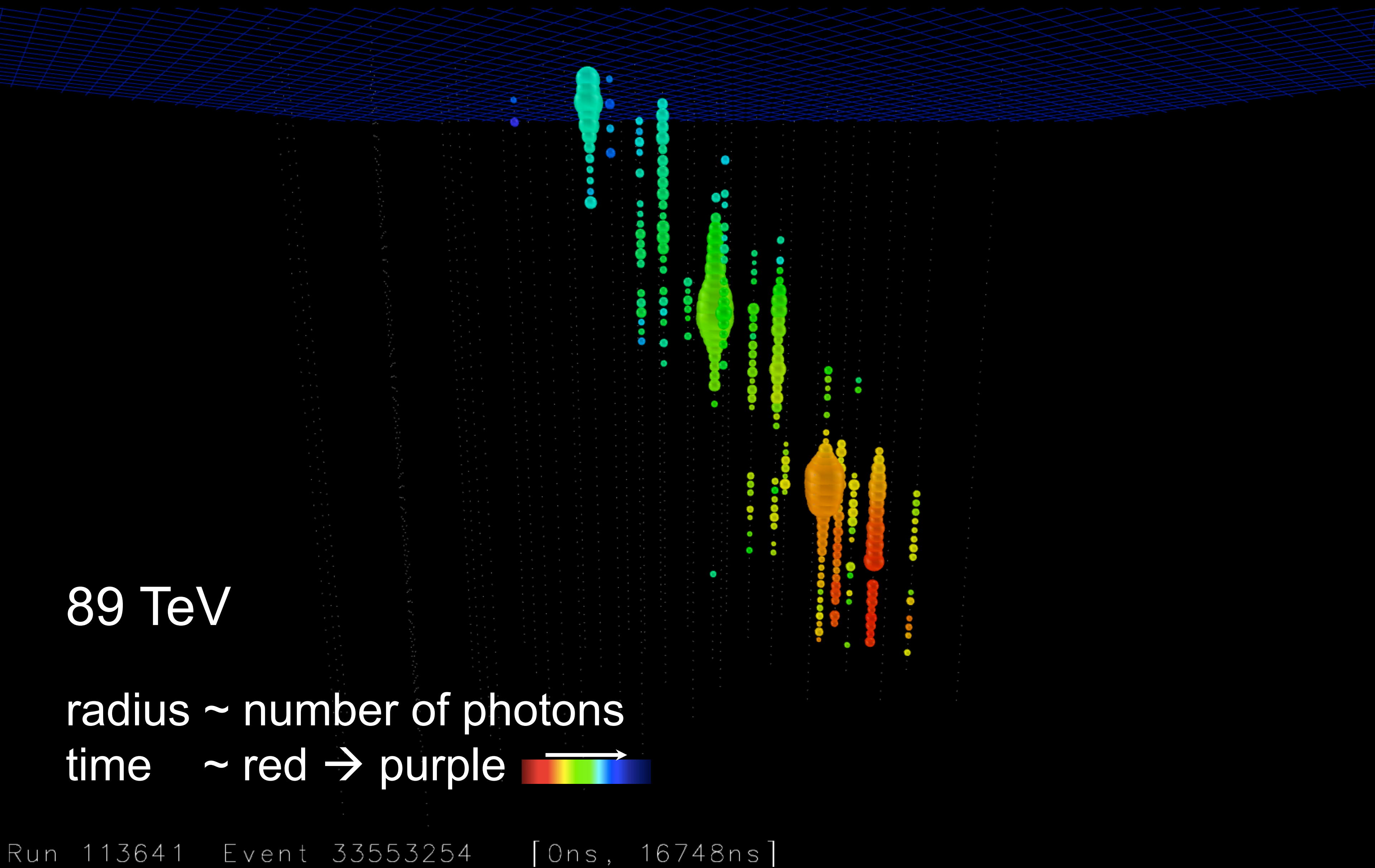
…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…



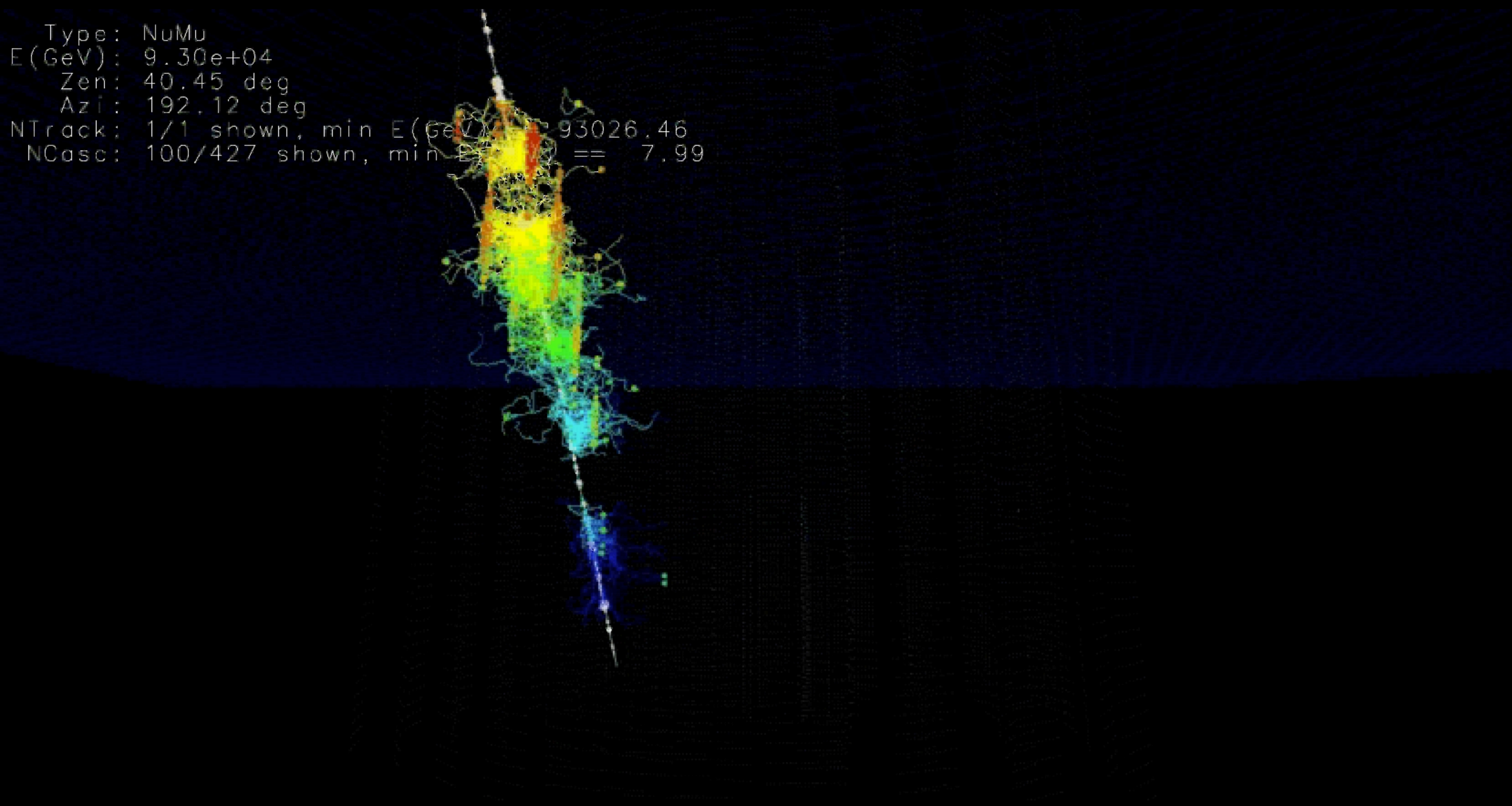




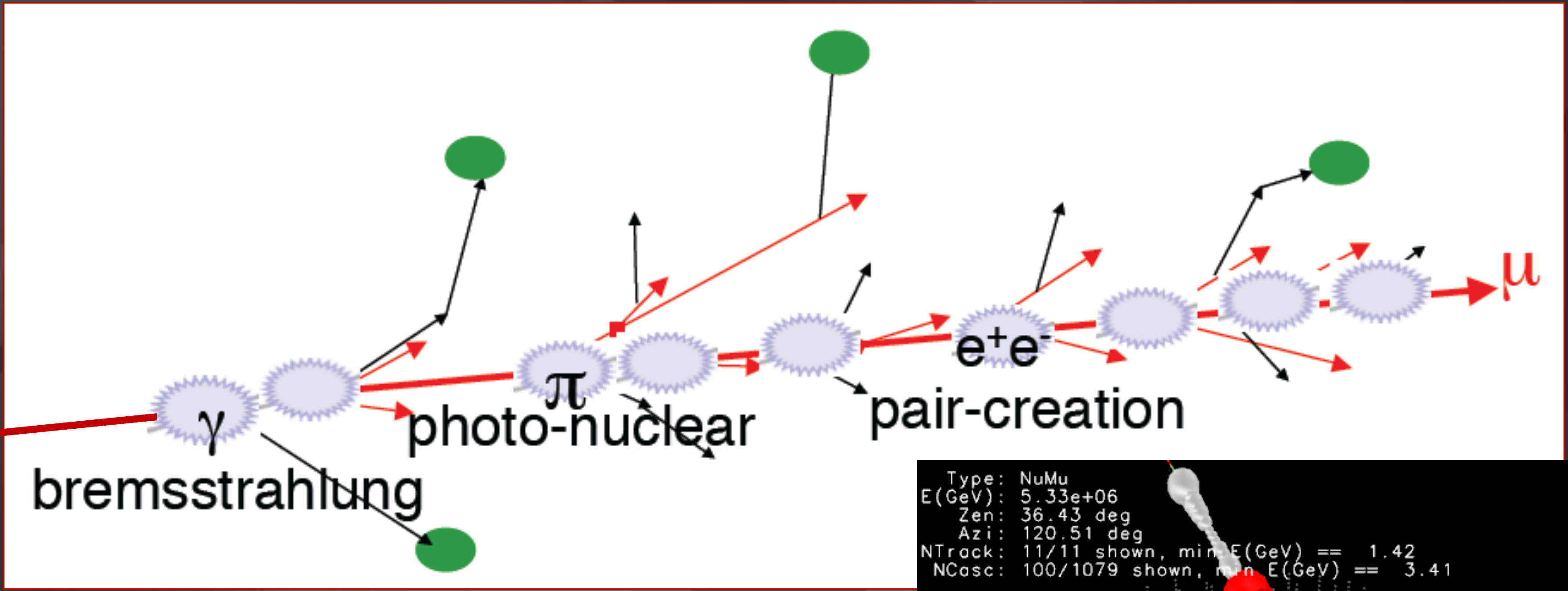
muon track: color is time; number of photons is energy

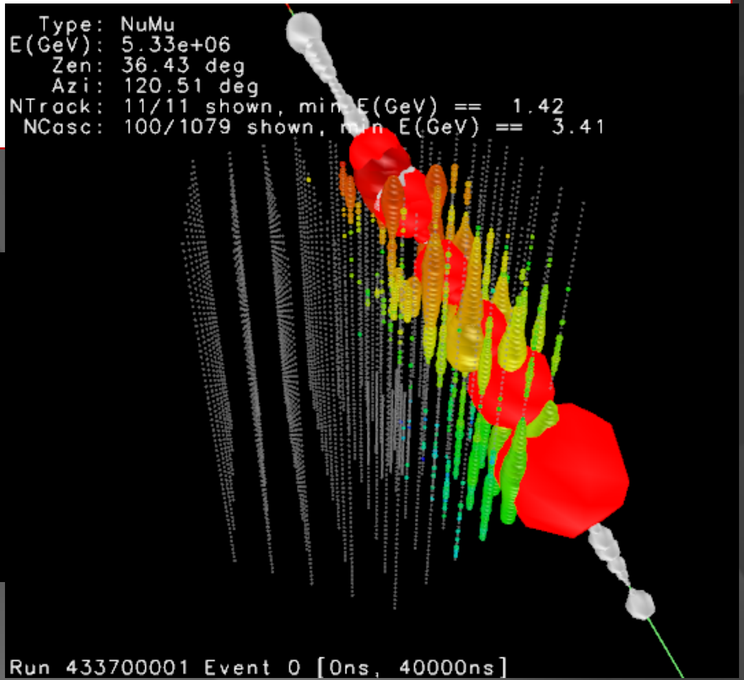

89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

93 TeV muon: light ~ energy

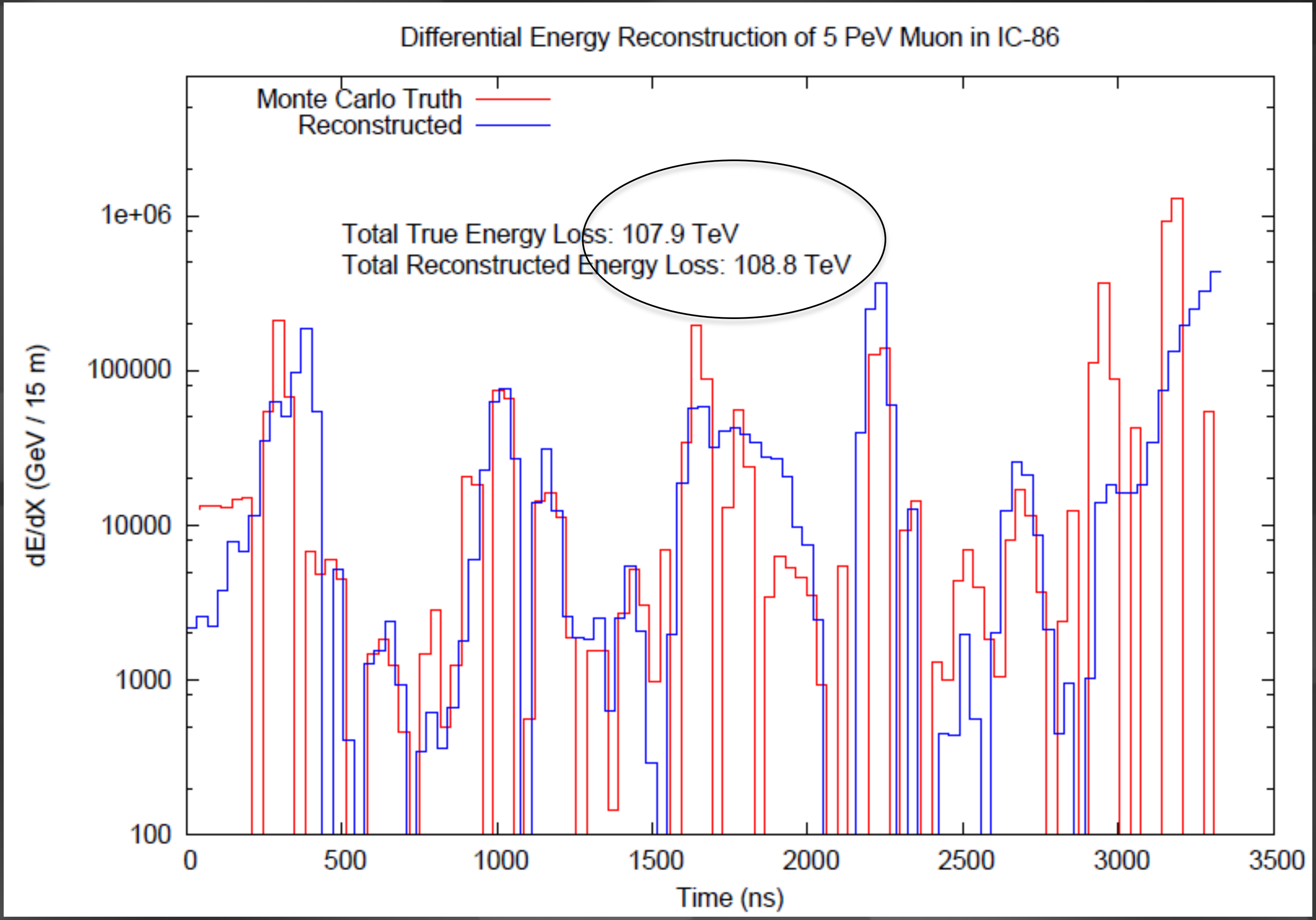


energy measurement (> 100 TeV)





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

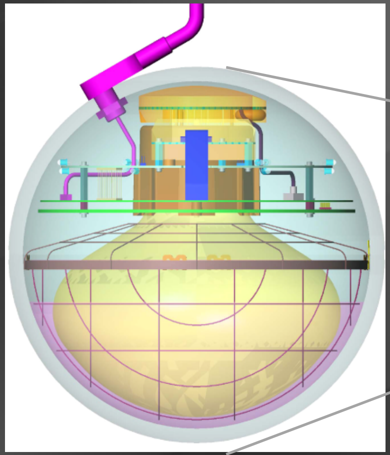


1.1 km

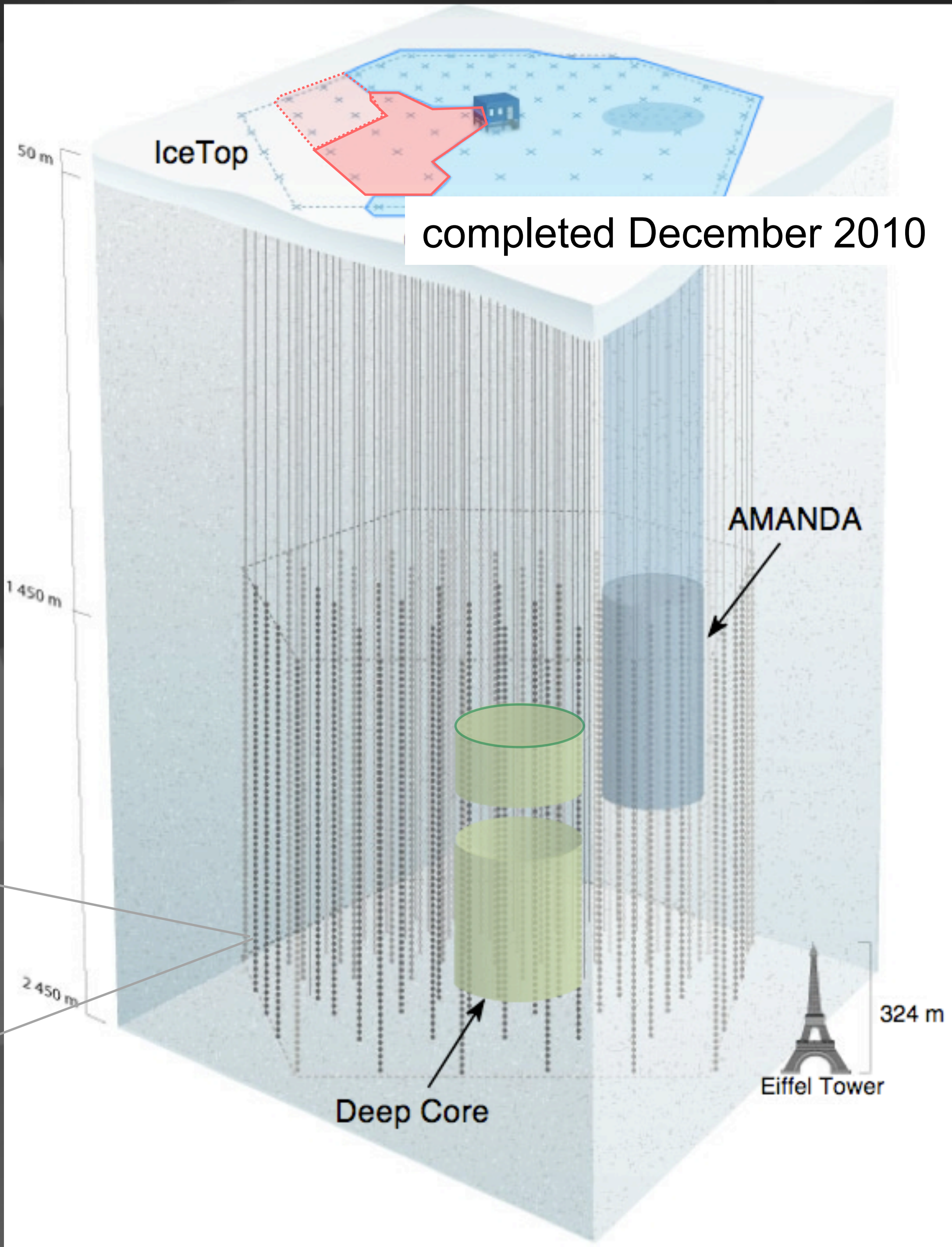
improving angular and energy resolution

IceCube / Deep Core

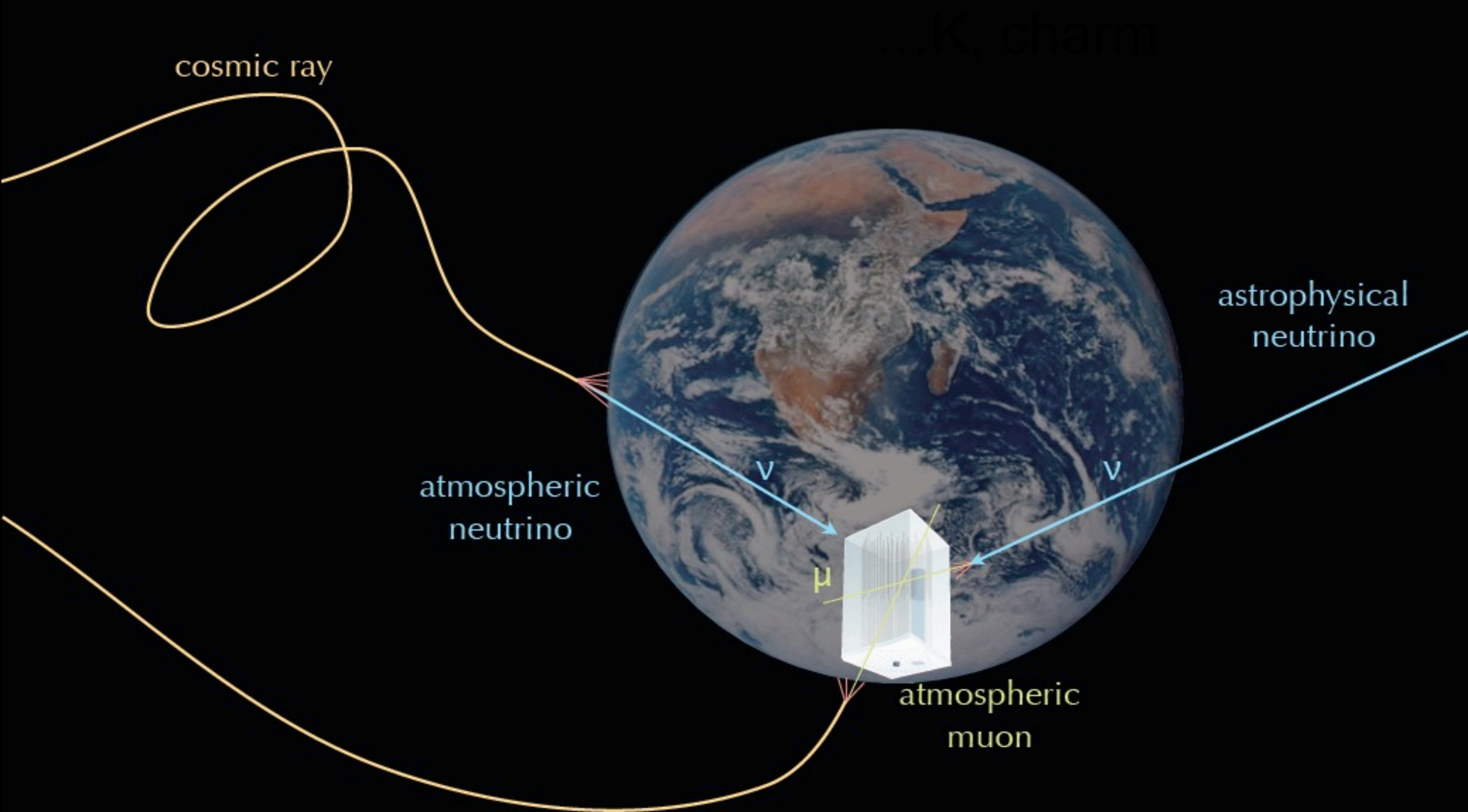
- 5160 optical sensors between 1.5 ~ 2.5 km
- 5 GeV to infinity
- < 0.4 degree muon track ~ 5 degree shower
- < 15% energy resolution

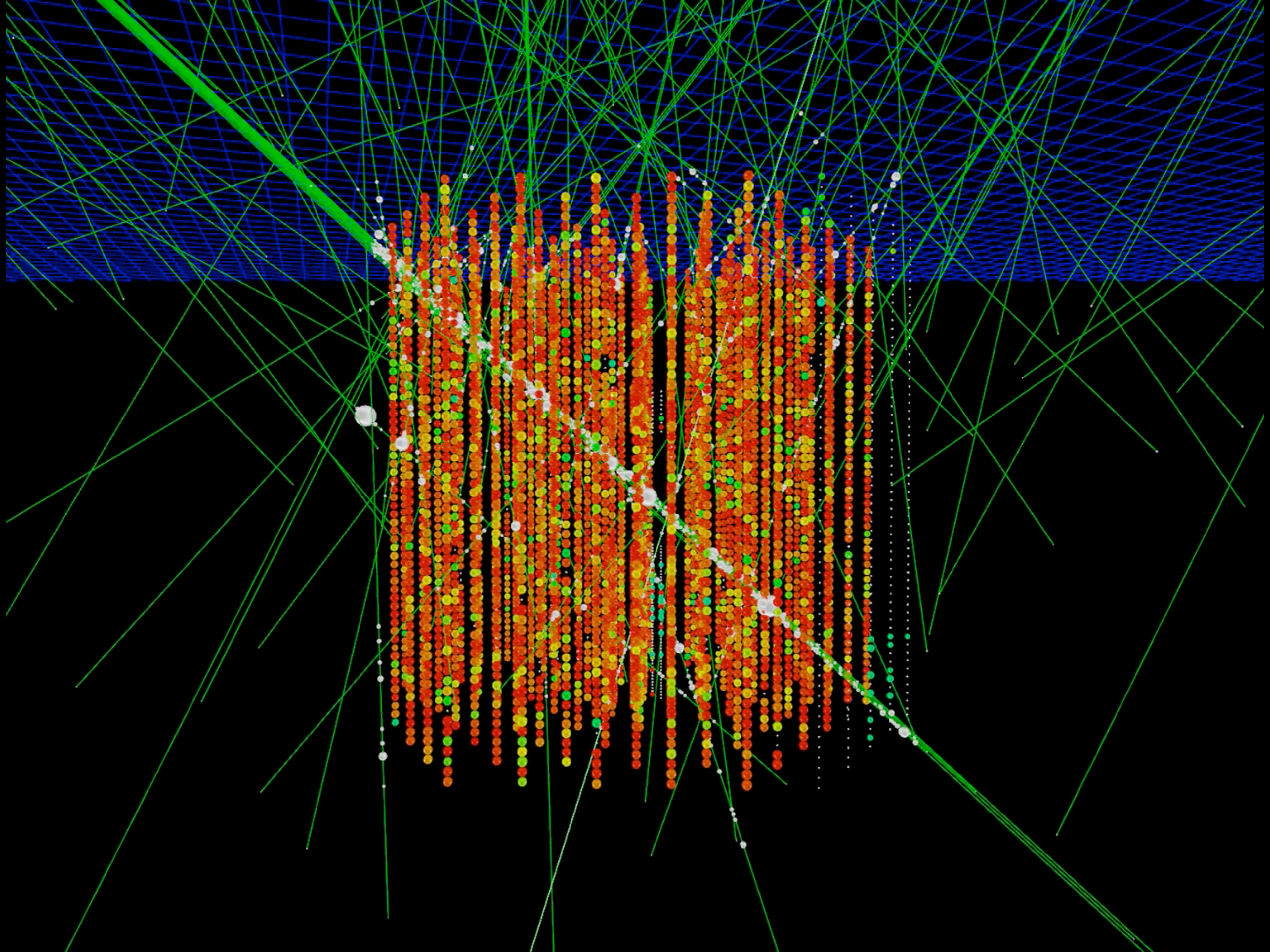


Digital Optical Module (DOM)



Signals and Backgrounds





… you looked at 10msec of data !

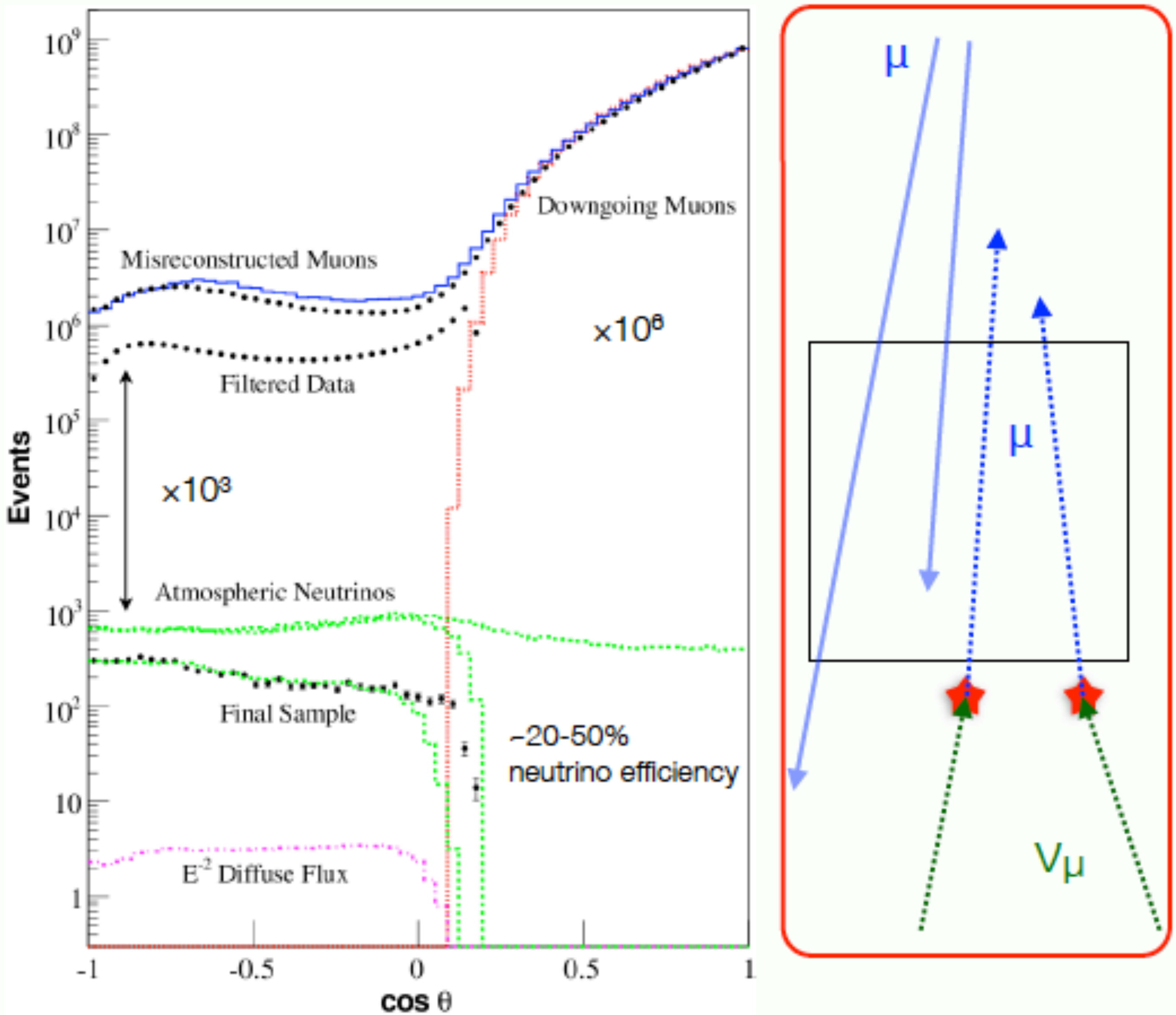
muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^{5}$
- 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	SLogL(3.5) ≤ 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

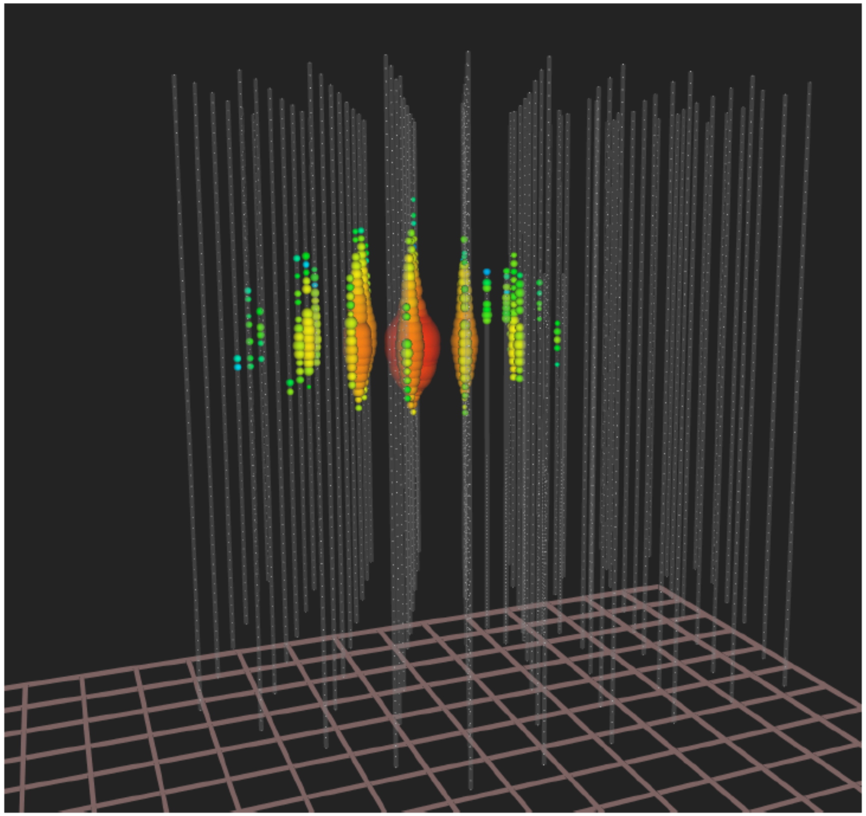
Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction 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 $dN/dE = 1 \cdot 10^{-8}\ \mathrm{GeV cm^{-2} s^{-1}} (\frac{E}{\mathrm{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)

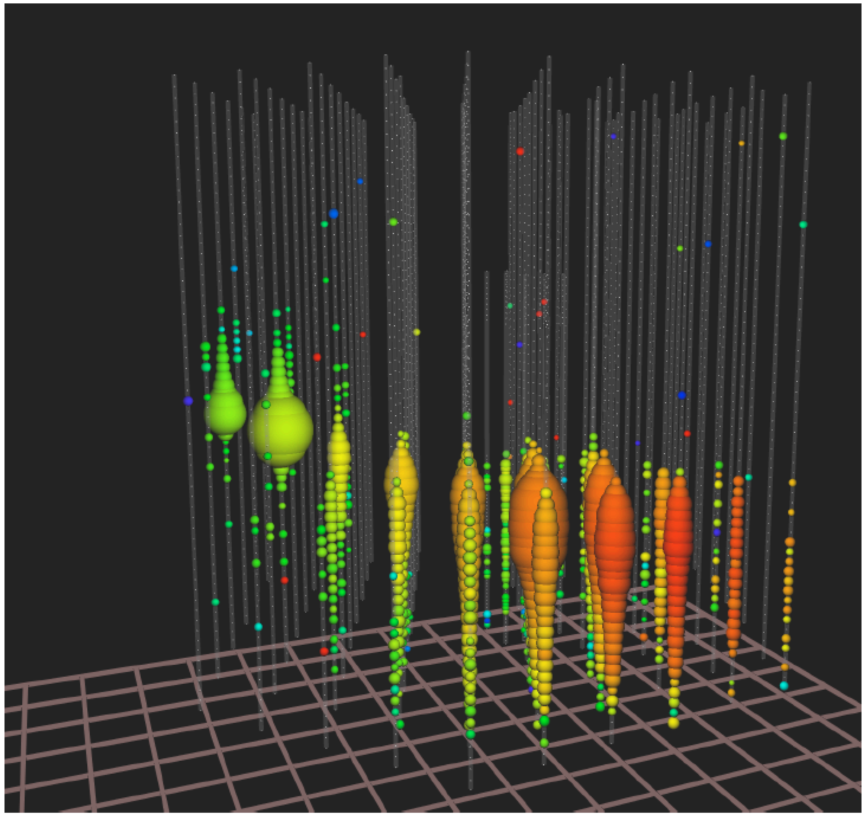
…as opposed to 35 in original AMANDA publication

Name	Precut	Summary
CoG_rhoIC	—	center of gravity, radial distance
CoG_zIC	< 500 m	center of gravity, z-component
LSepIC	> 50 m	track hits separation length
BayesLlhDiff	> 20	$\log \mathcal{L}_{\text{Bayesian}} - \log \mathcal{L}_{\text{SPE2it}}$
cosZen	≥ 82 deg	cos(SplineMPE zenith)
Plogl3p5	< 10	$\log \mathcal{L}_{\text{SplineMPE}} / (N_{Ch} - 3.5)$
LDirCIC	> 75 m	direct track length
NDirEIC	≥ 6	number of direct hits
sigma_CramerRao_deg	< 25 deg	Cramér-Rao error estimate (in degrees)
AbsSmoothnessEIC	—	|smoothness| of direct hits
AvgDistQtotDomNoCutIC	< 250 m	average charge-weighted track-to-DOM distance
LEmptyIC	< 600 m	empty track length
cos_SplineMPE_LF	< 60 deg	angle between SplineMPE and LineFit
Linefit_Speed	< 3	LineFit speed
logNChIC	≥ 6 DOMs	number of hit DOMs
DiffCosMinSplitZenith	—	$\cos \min(\theta_{\text{Split}}) - \cos \theta_{\text{SplineMPE}}$

neutrinos interacting inside the detector

muon neutrinos filtered by the Earth

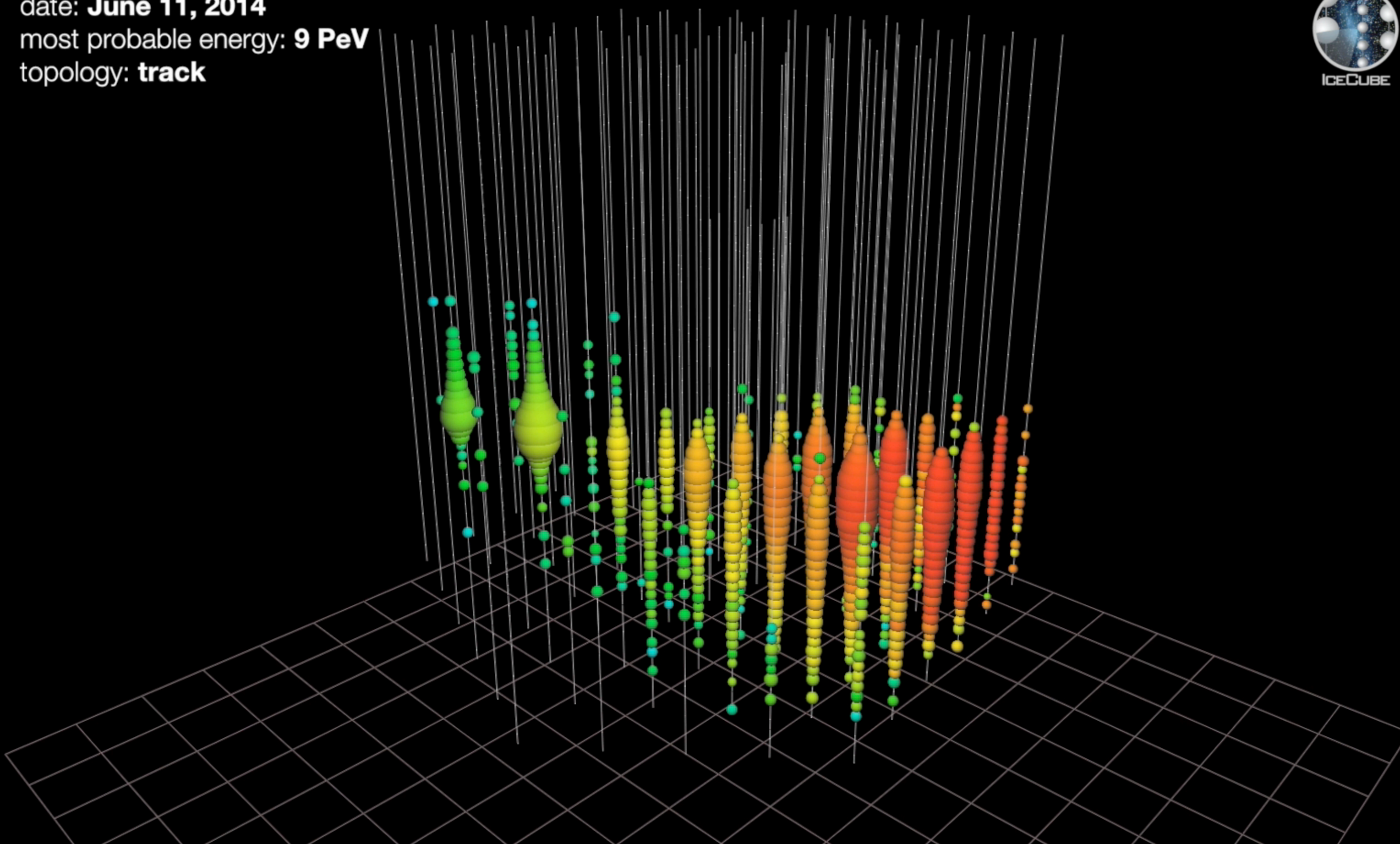


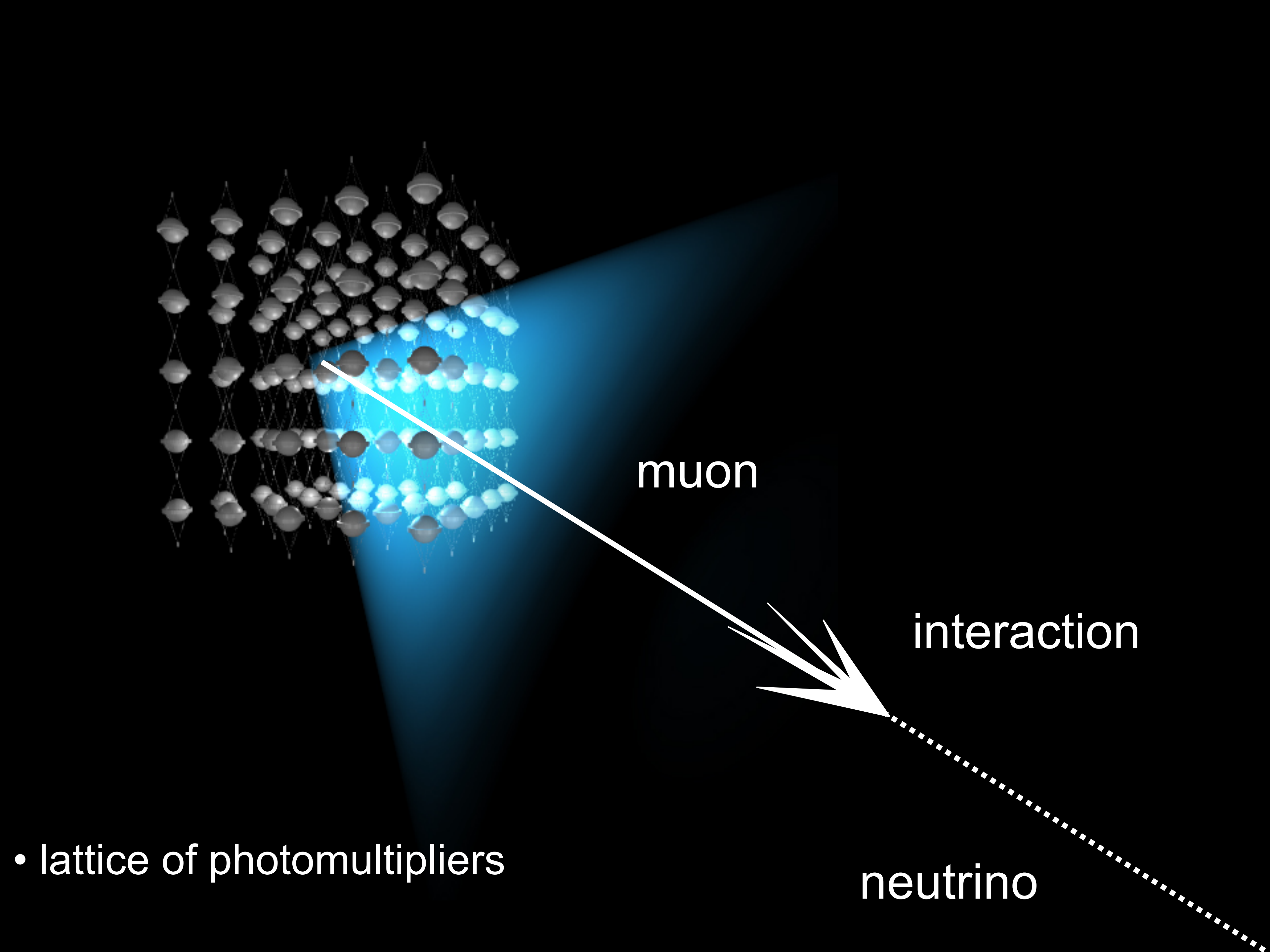


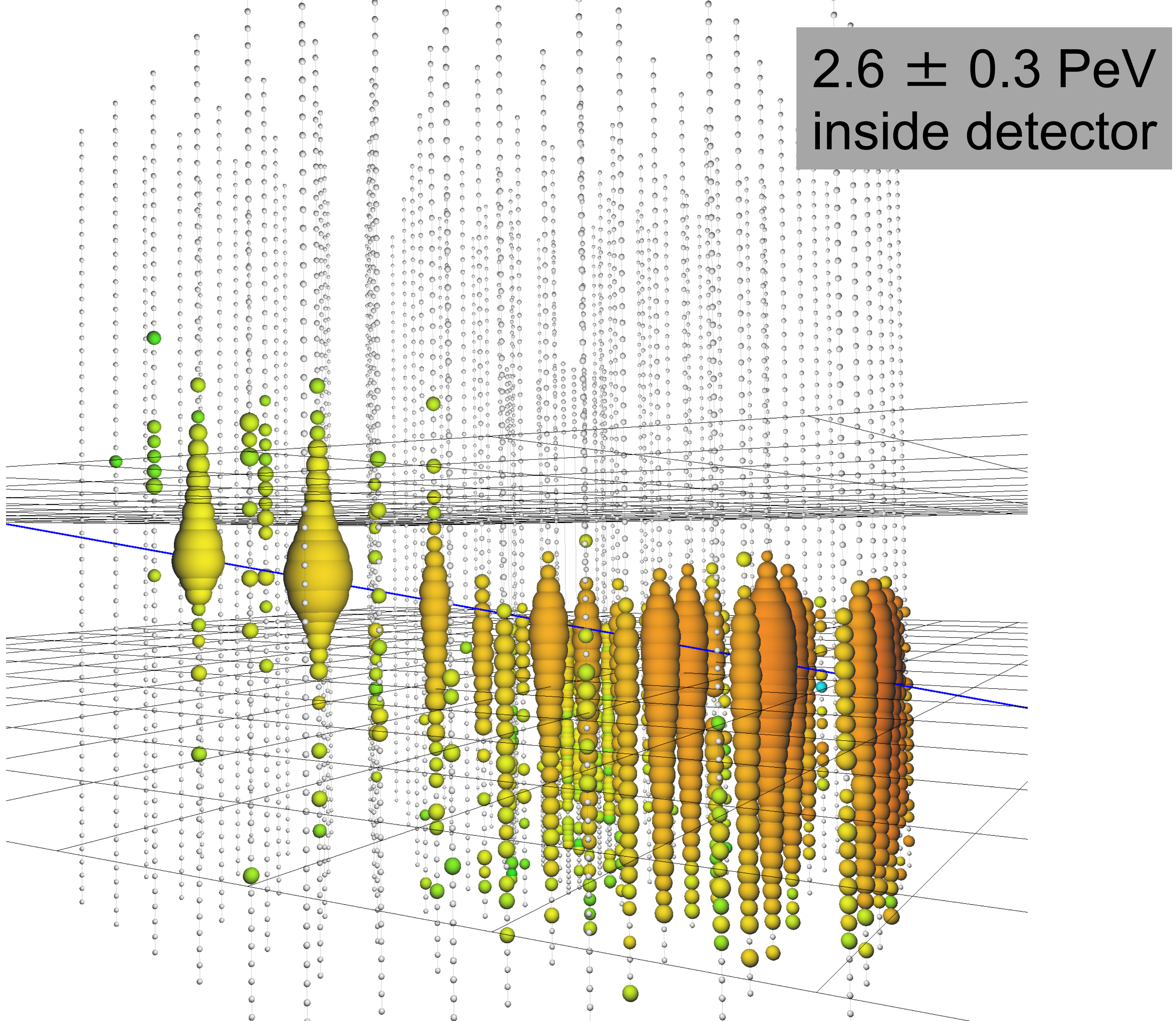
total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.4°)

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

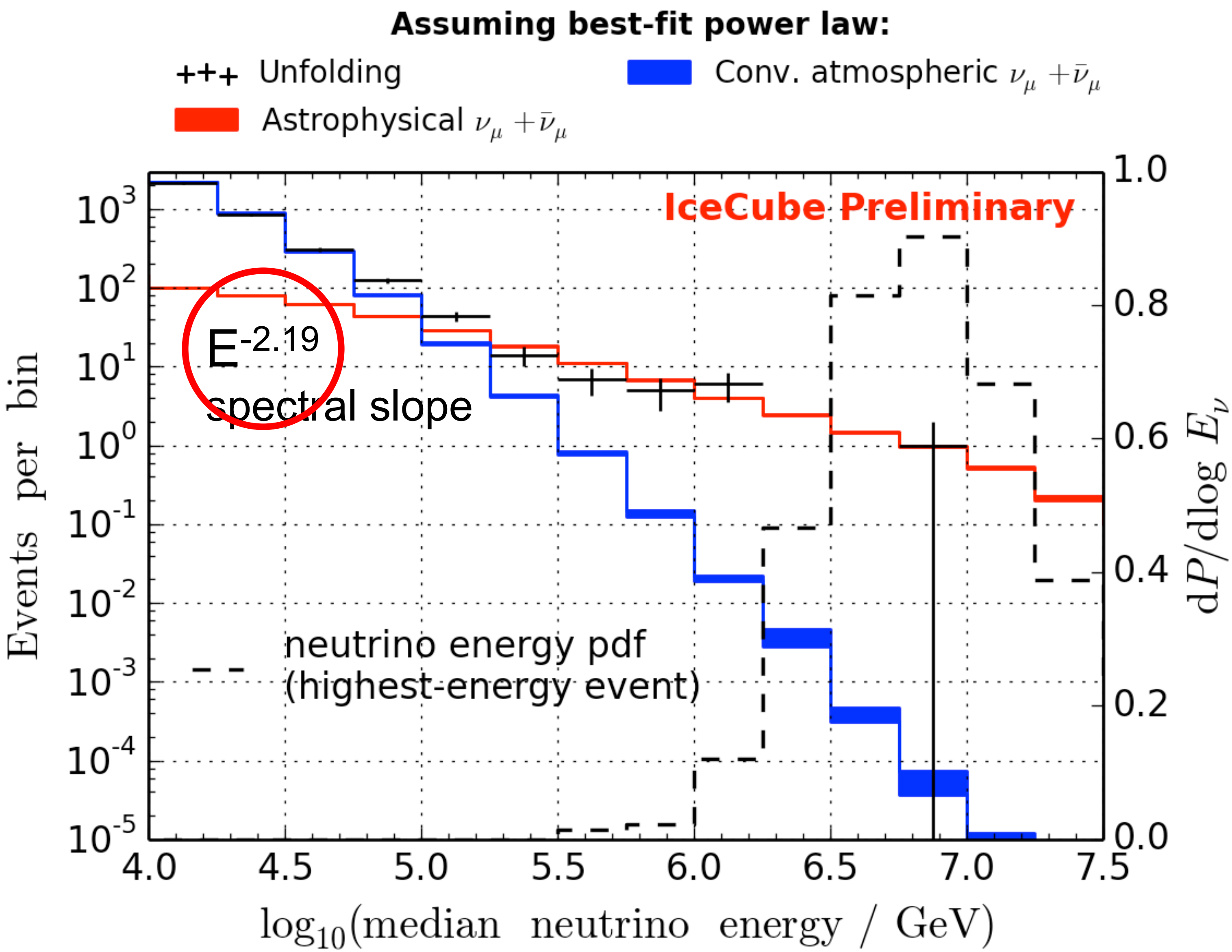



muon
interaction
neutrino
• lattice of photomultipliers


2.6 ± 0.3 PeV
inside detector

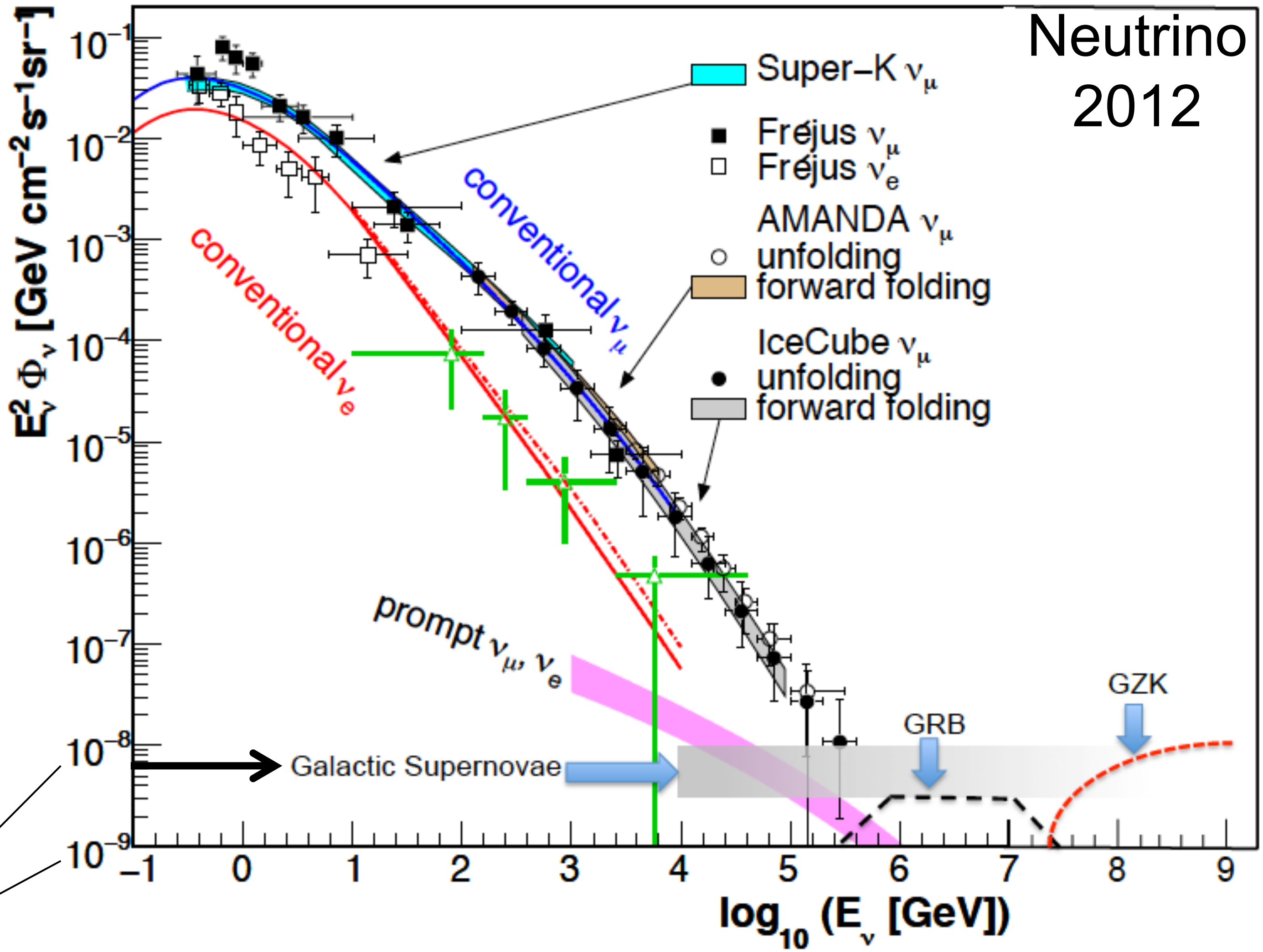
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric

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

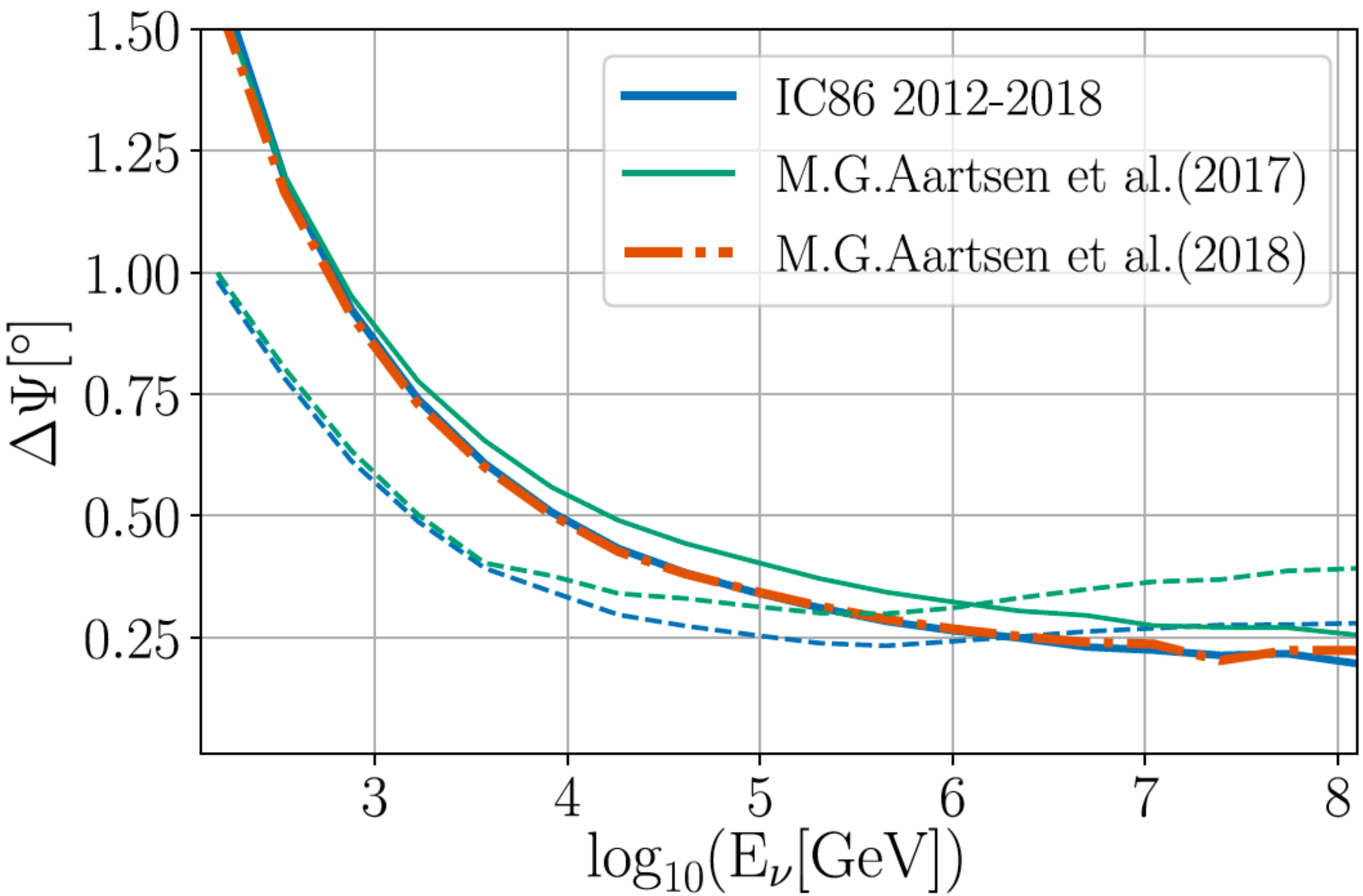
atmospheric

cosmic

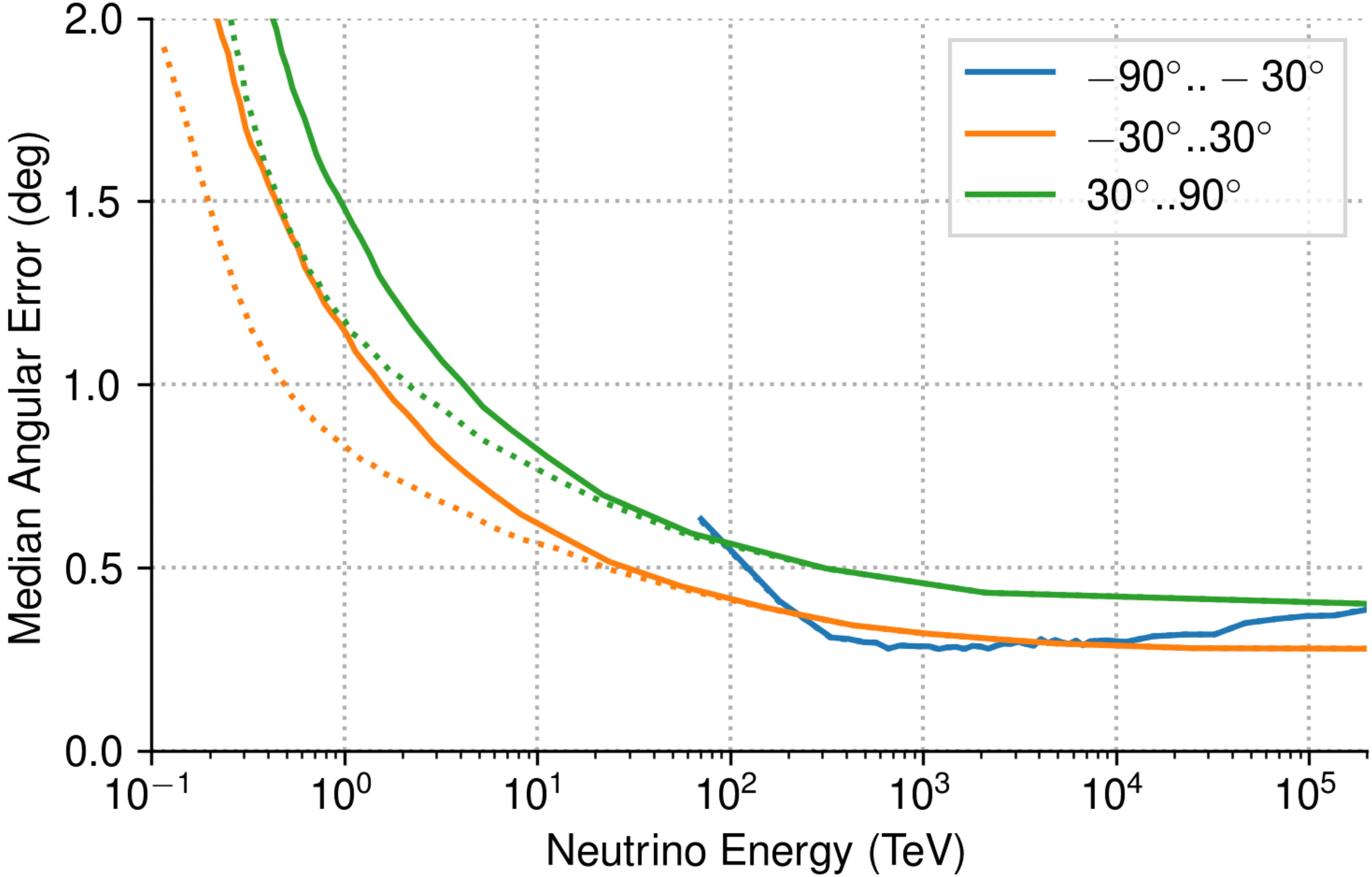
100 TeV

astronomy

- through-going muons with resolution 0.2~0.4^0
- goal 0.1^0 (IceCube upgrade 2022-23)

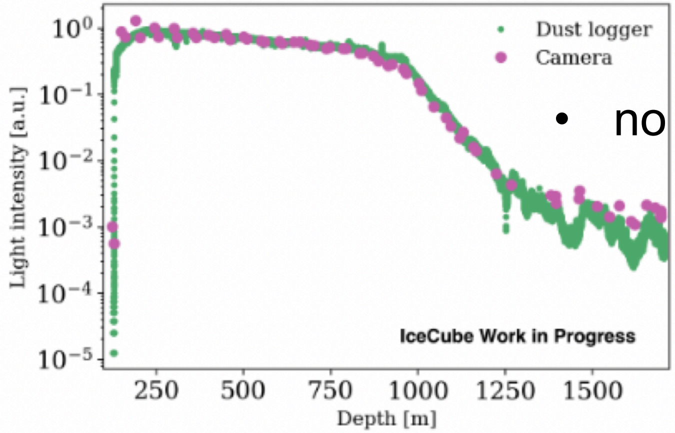


GFU 2.0 on line cuts



ice: step by step

- hole ice ?

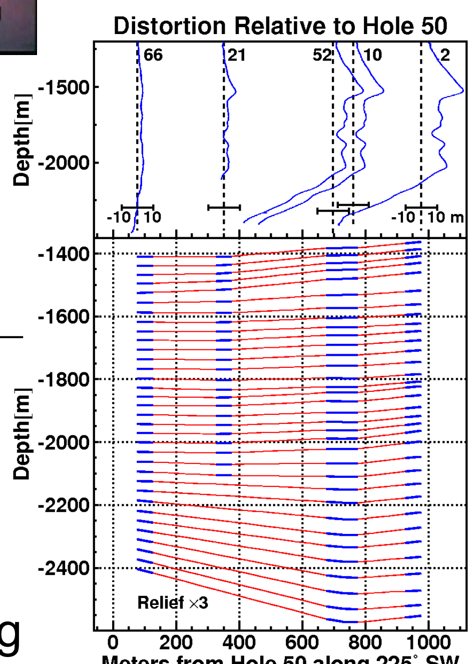


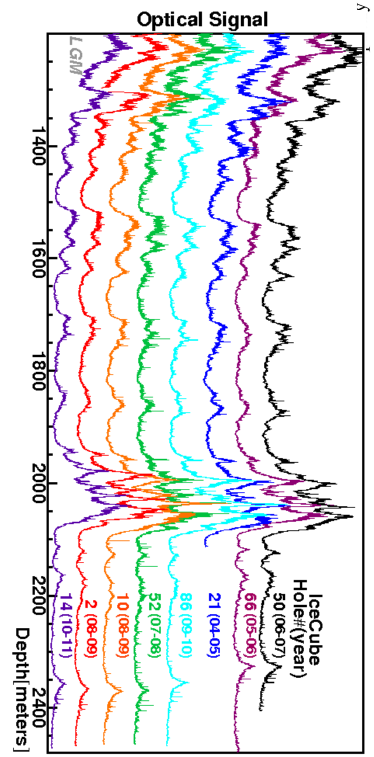
- no air bubbles/hydrates below 1350 m

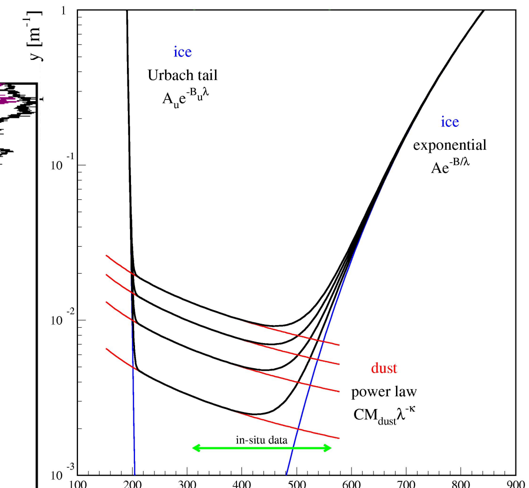
- > 100 m absorption length limited by dust

- ice layers

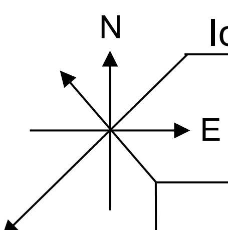
- tilted ice layers







- some birefringence ?

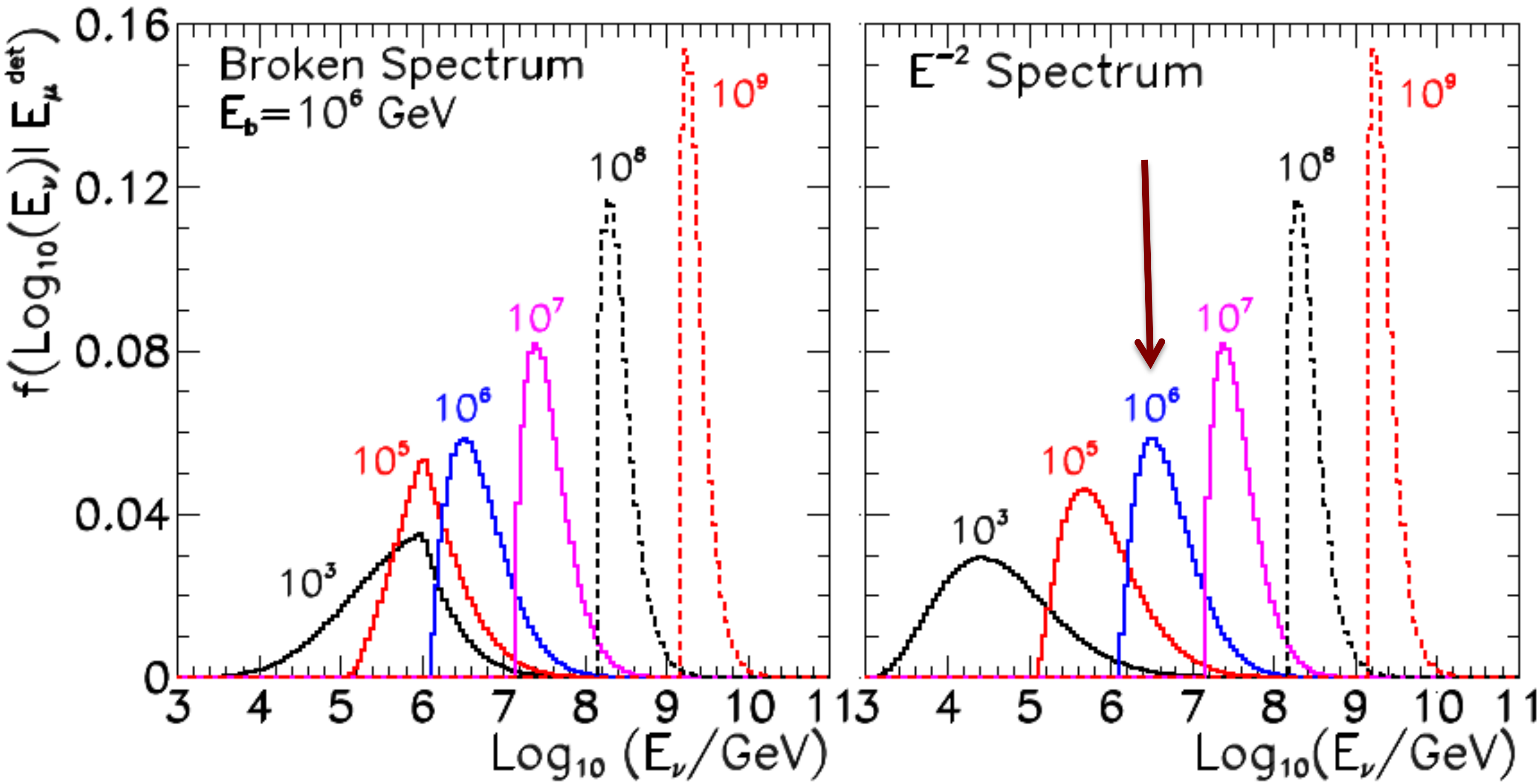


Ice Layer tilt direction
225° SW

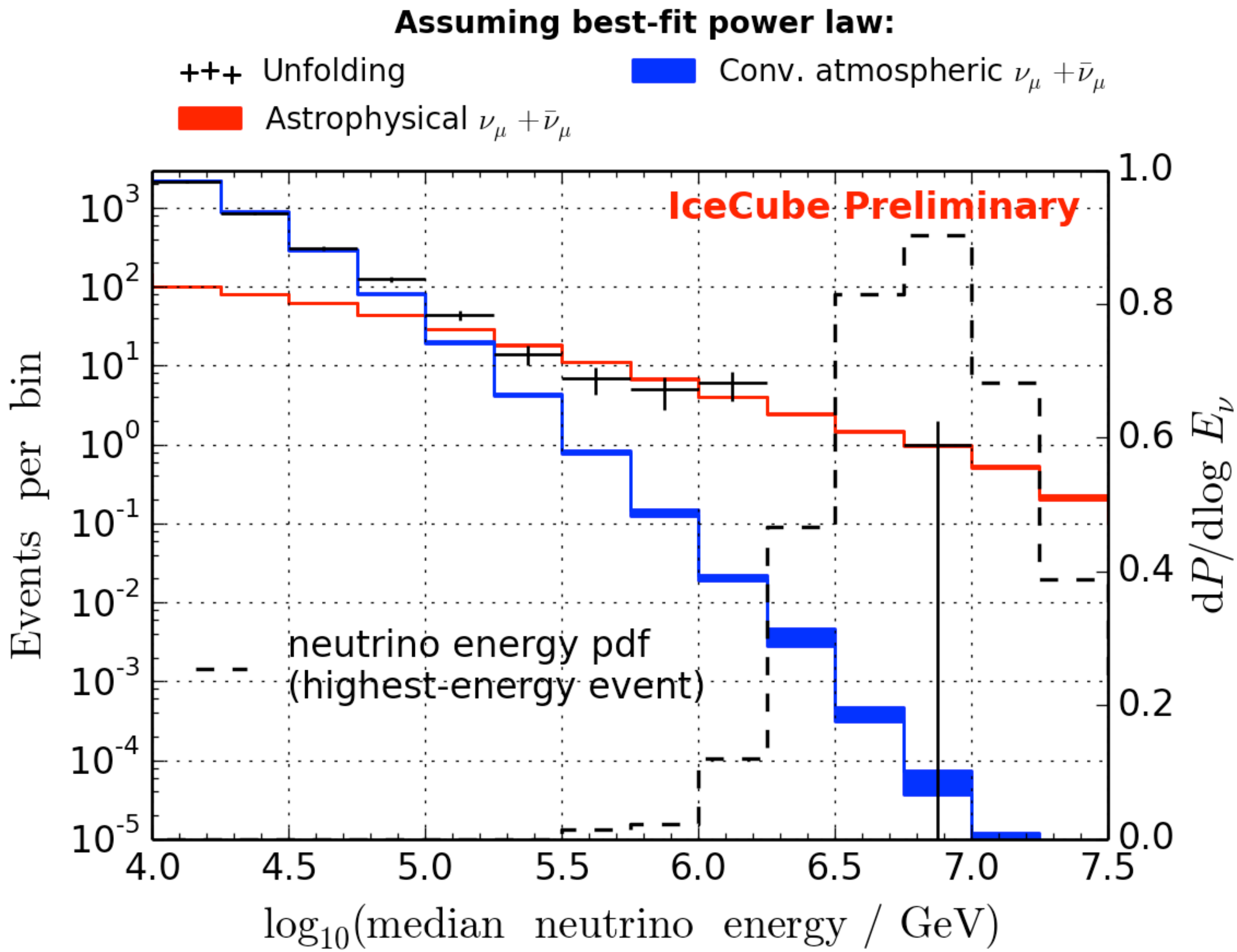
Ice flow direction
41° NW

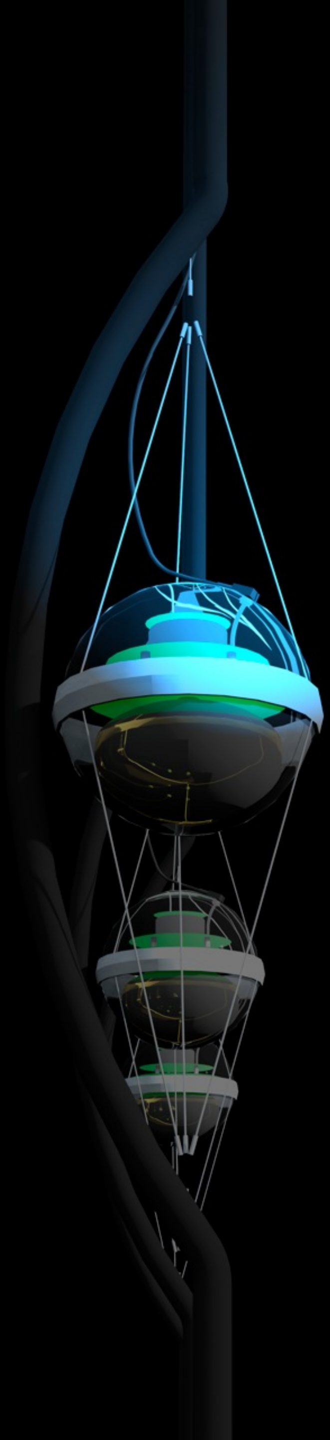
- anisotropy
~8% less scattering
41° NW

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

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

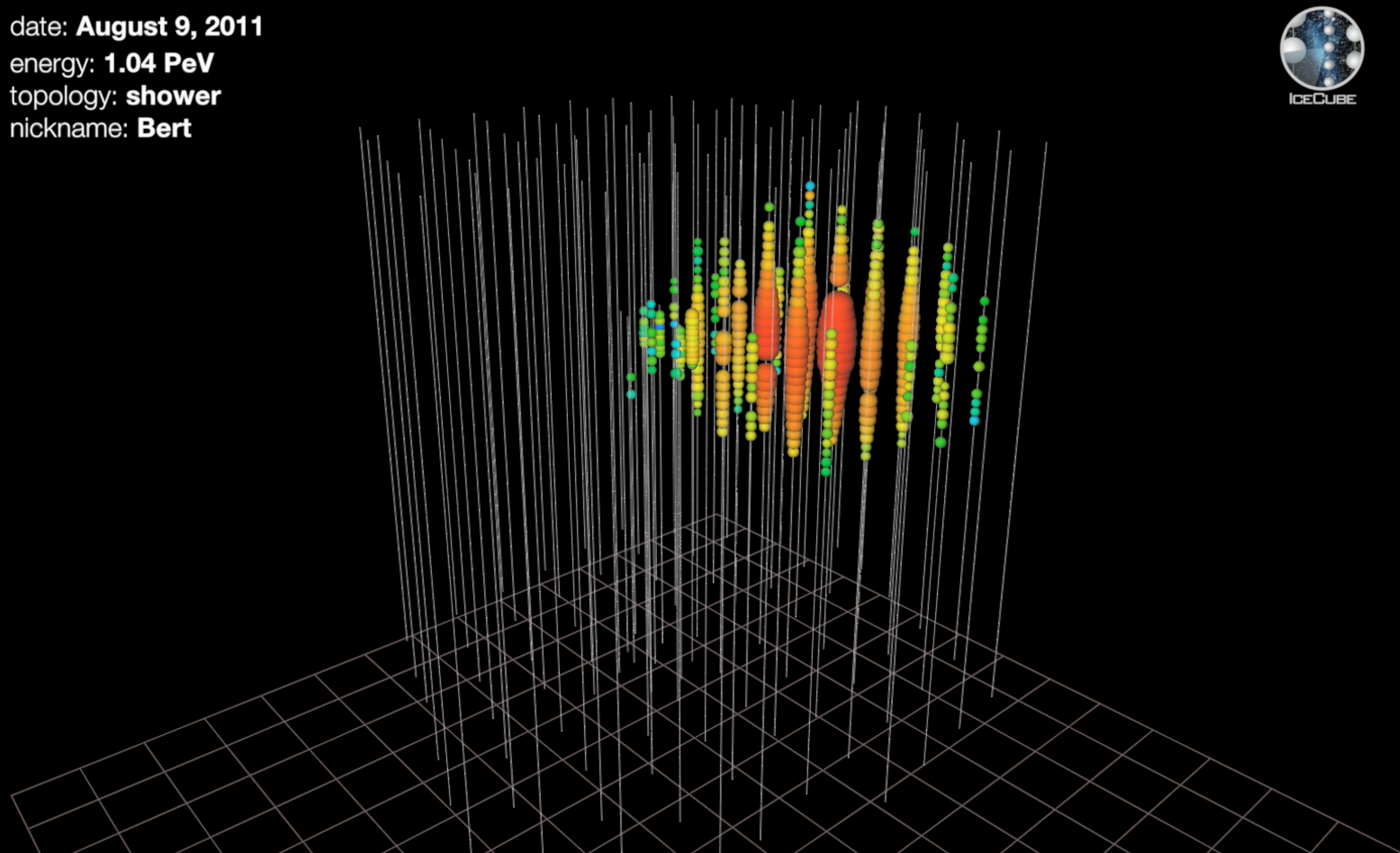
cosmic rays disappear, neutrinos with EeV $\boxed{(10^6 \text{ TeV}) \text{ energy}}$ appear

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

1 event per $\boxed{\text{cubic kilometer}}$ per year

...but it points at its source!

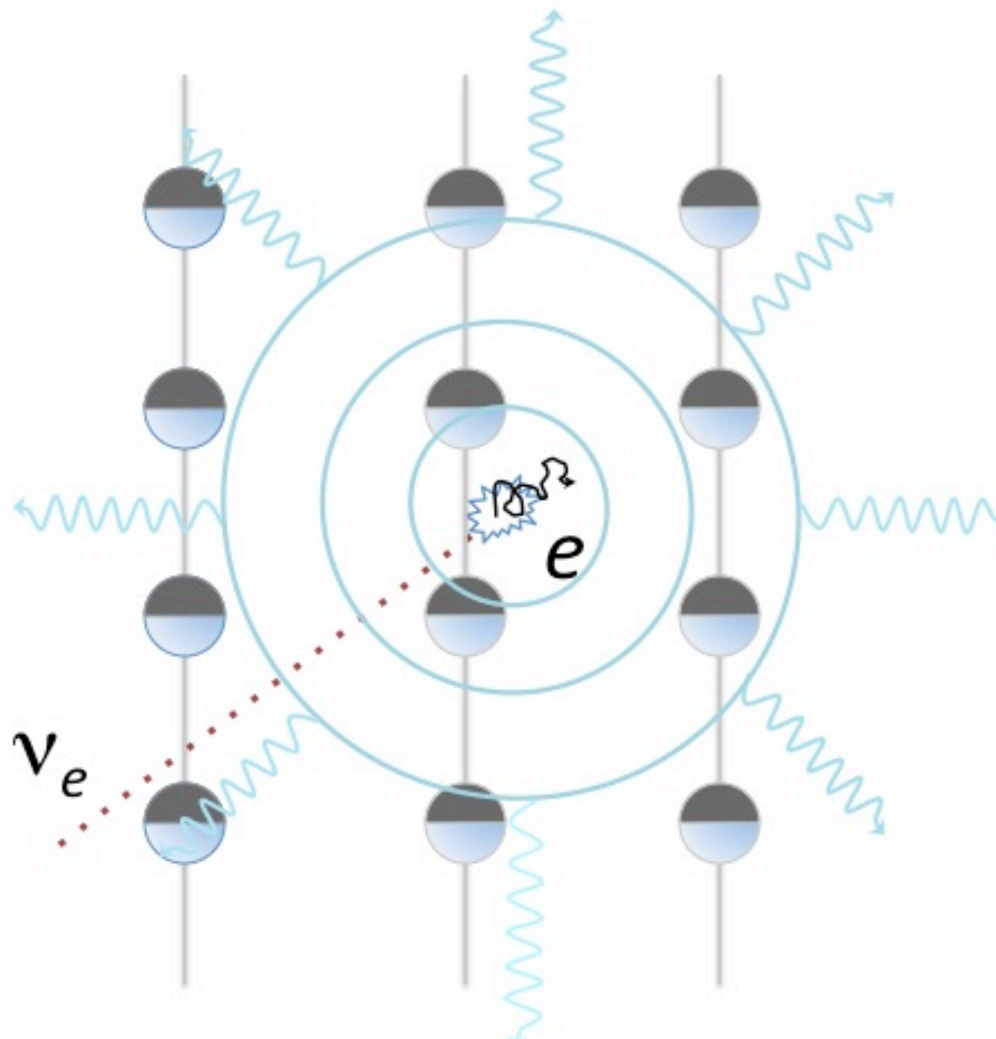
GZK neutrino search: two neutrinos with > 1,000 TeV

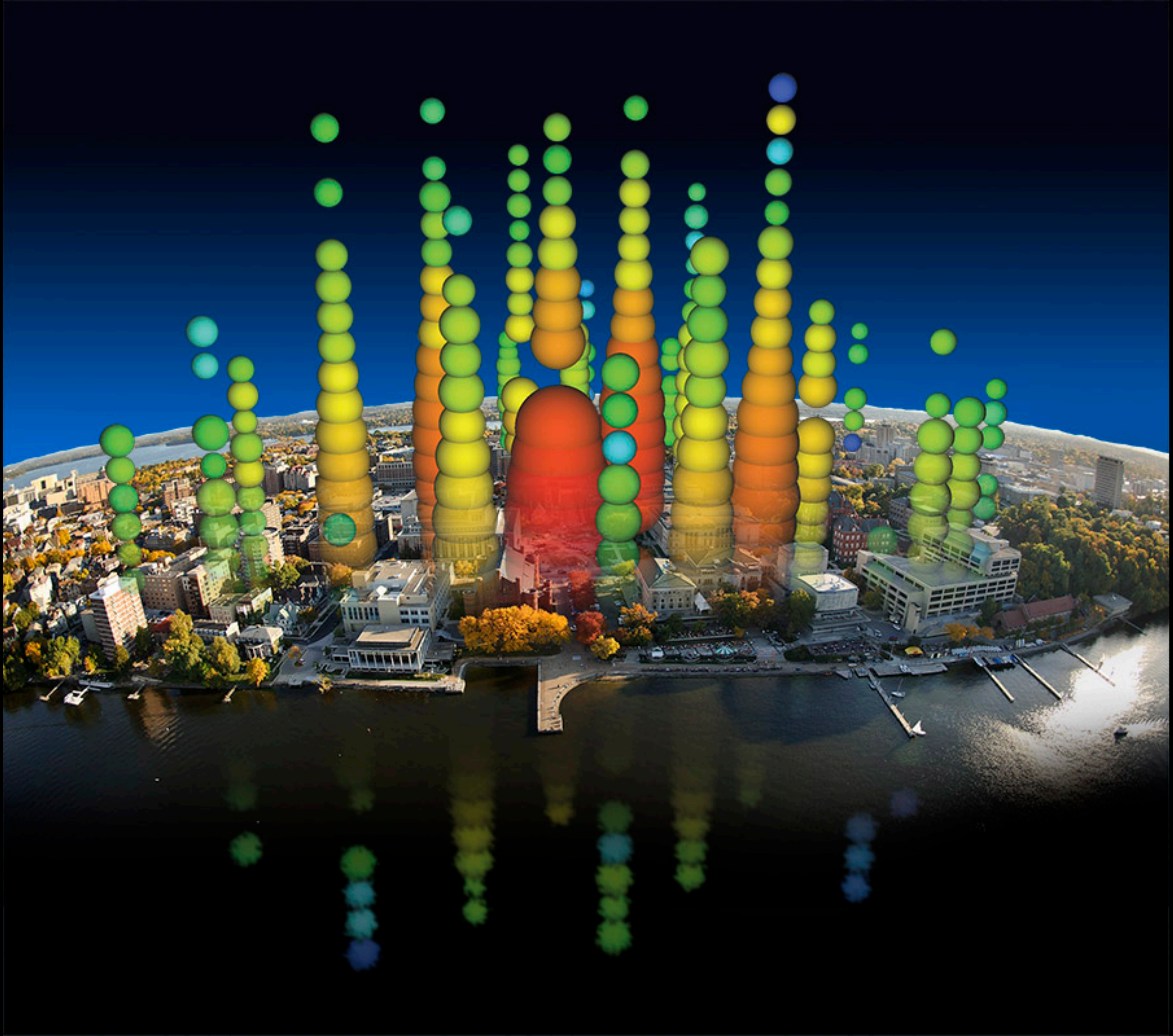


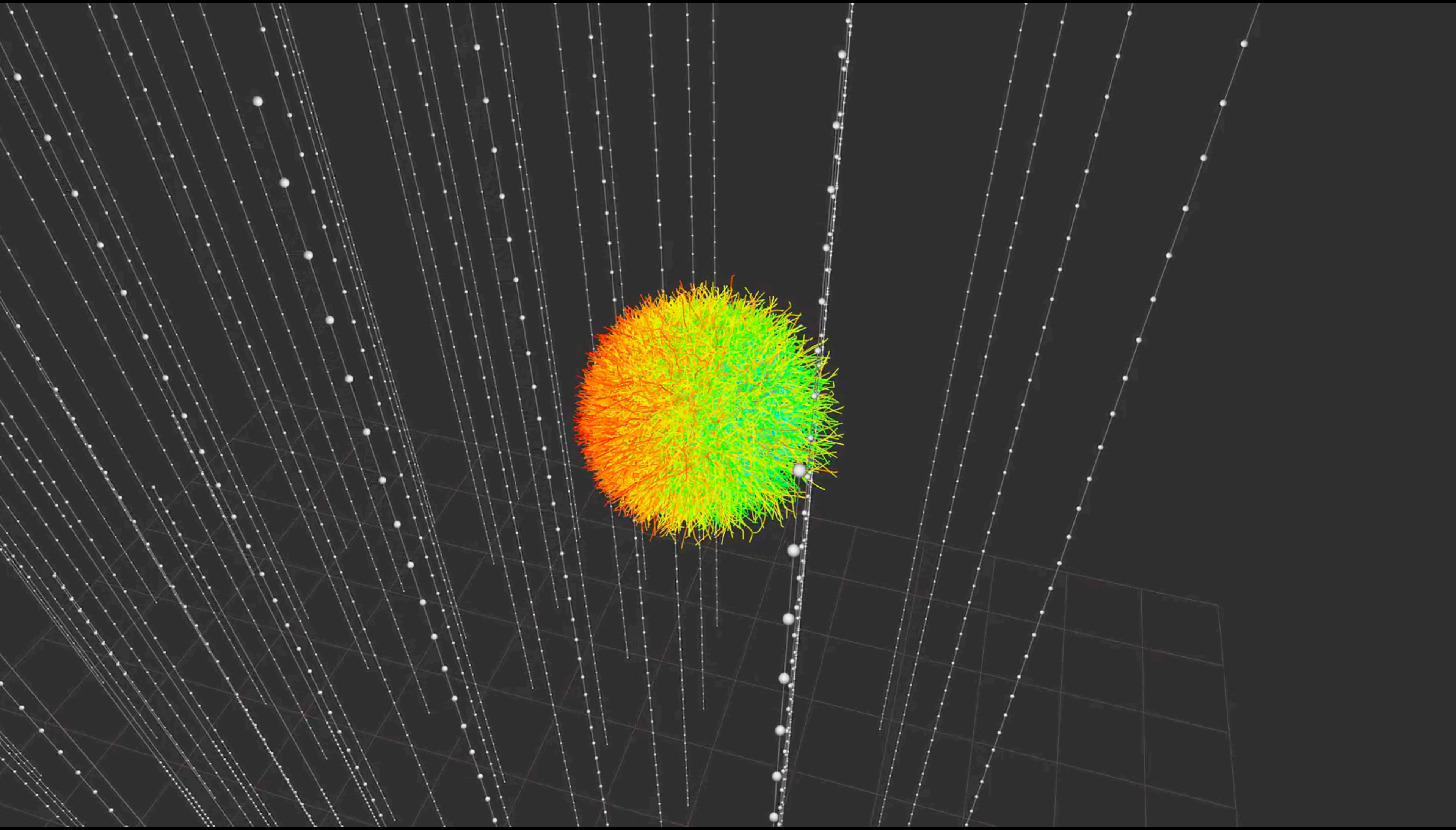
electron showers versus muon tracks

PeV ν_e and ν_τ showers:

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

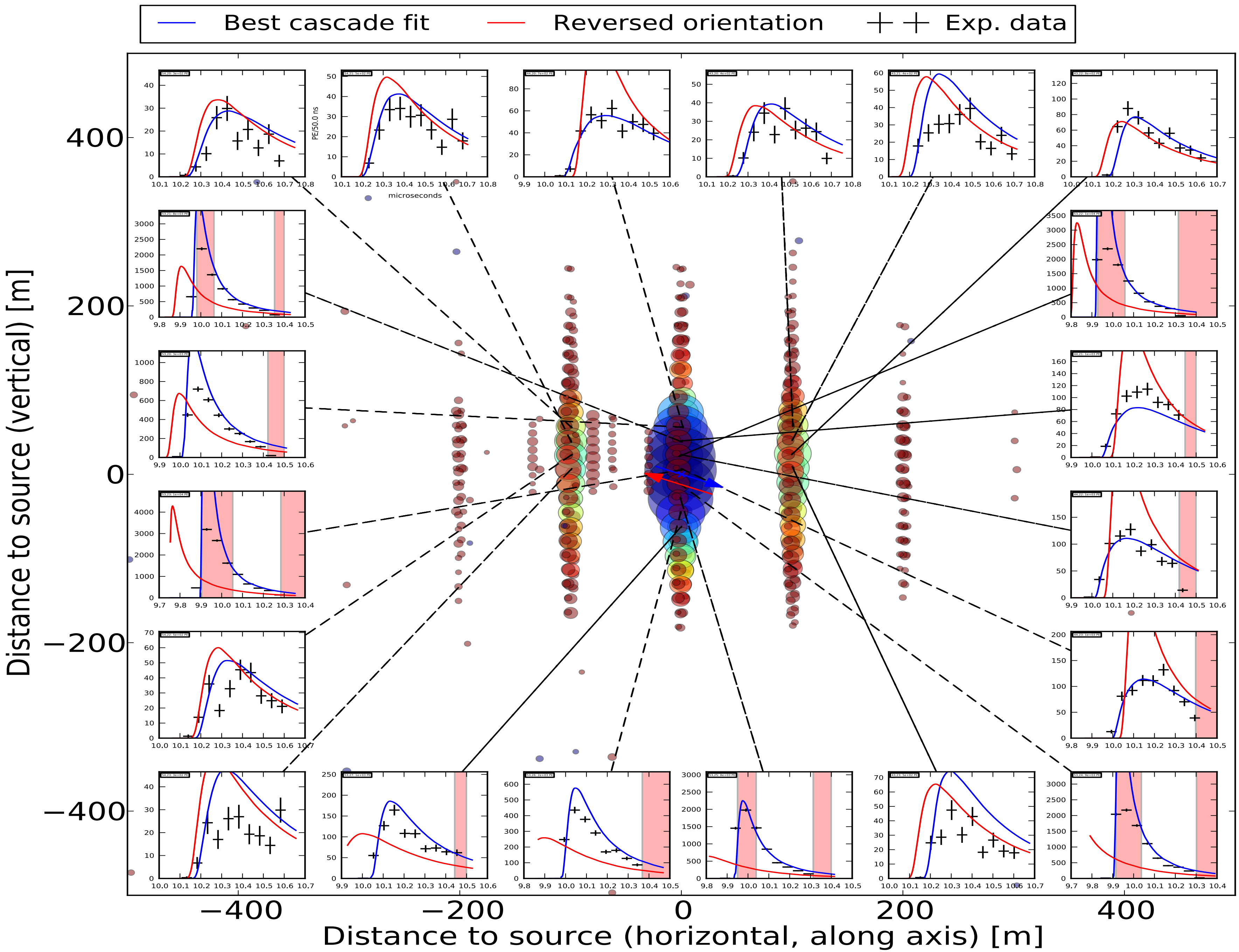






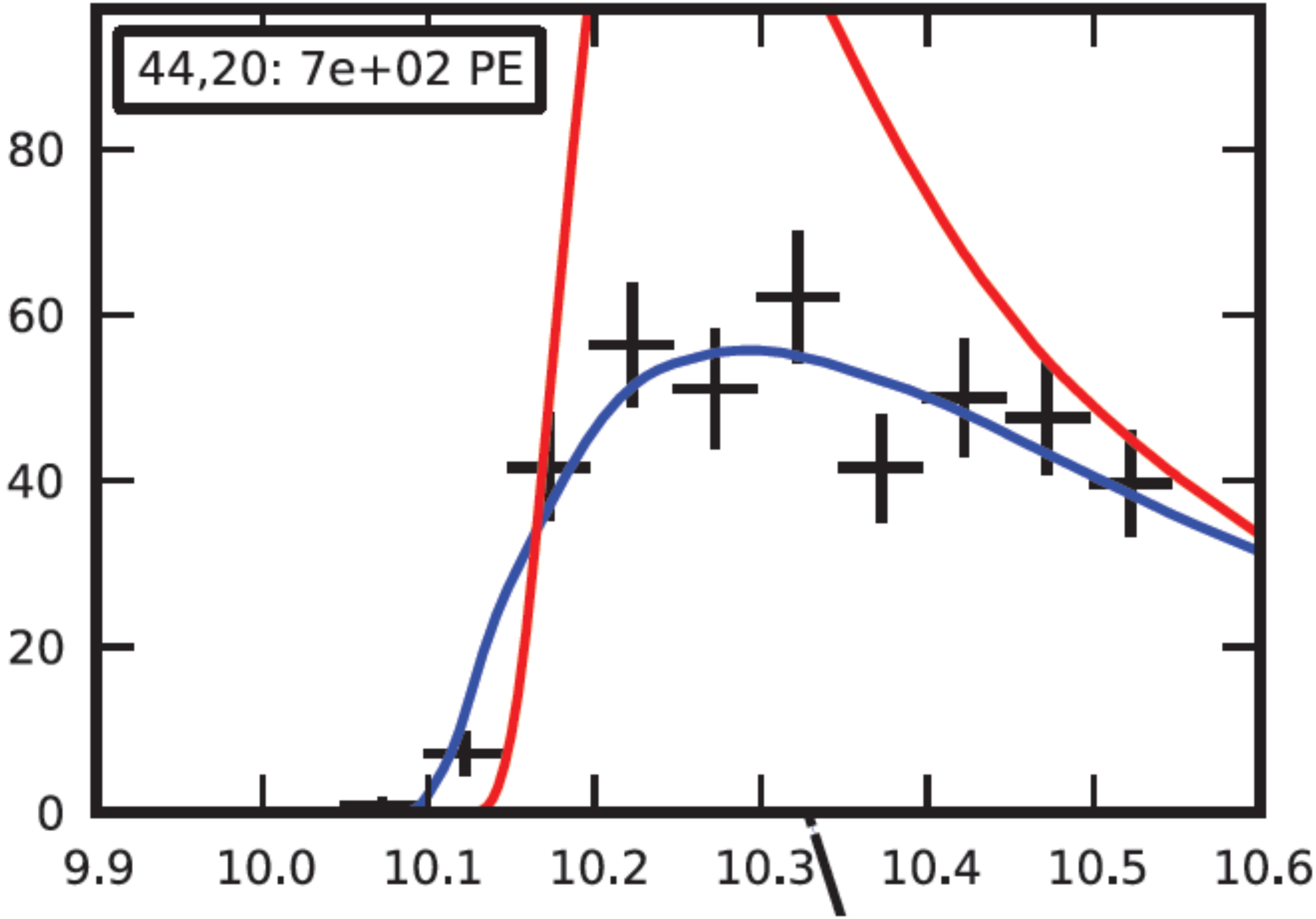
size = energy

color = time = direction

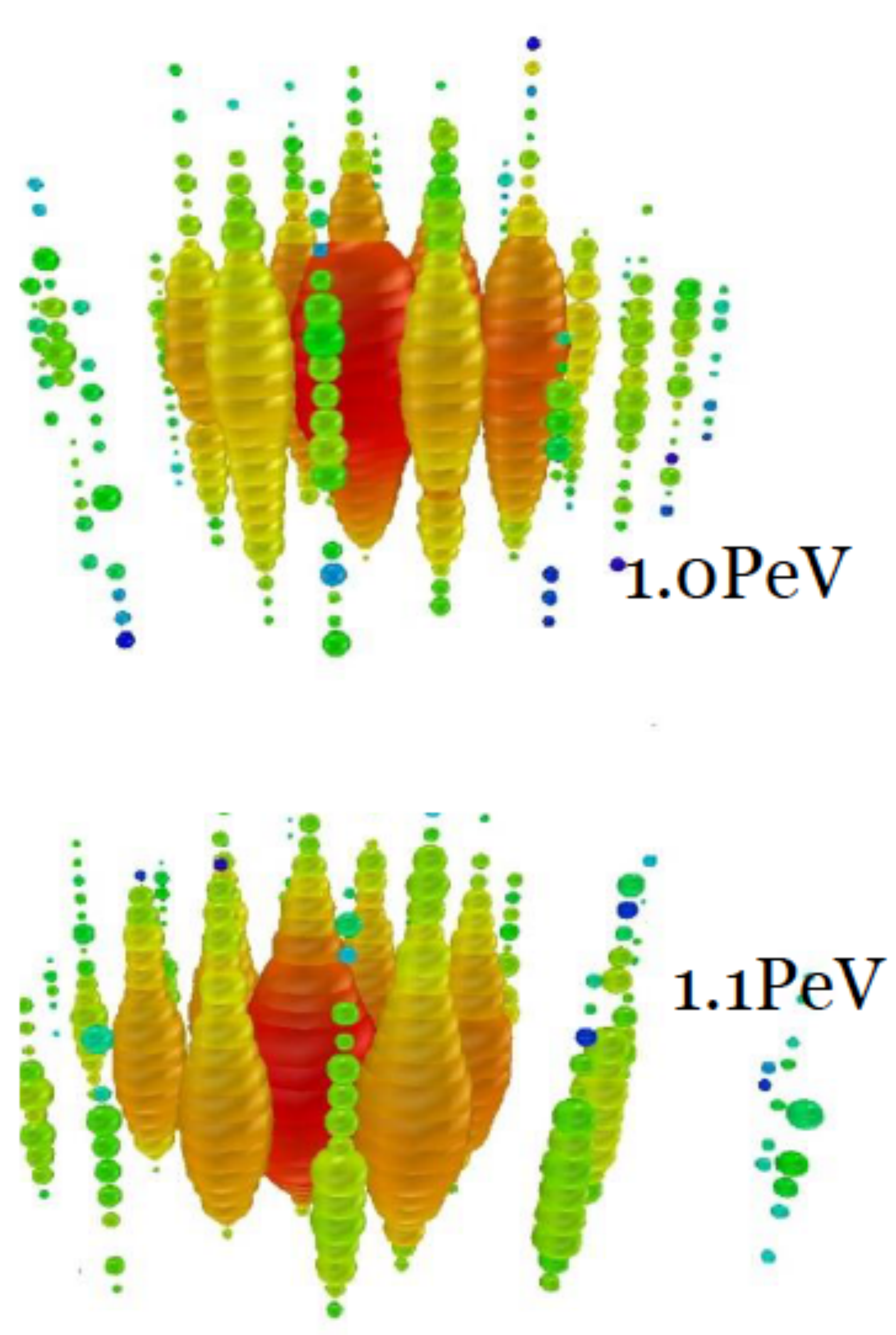


Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction

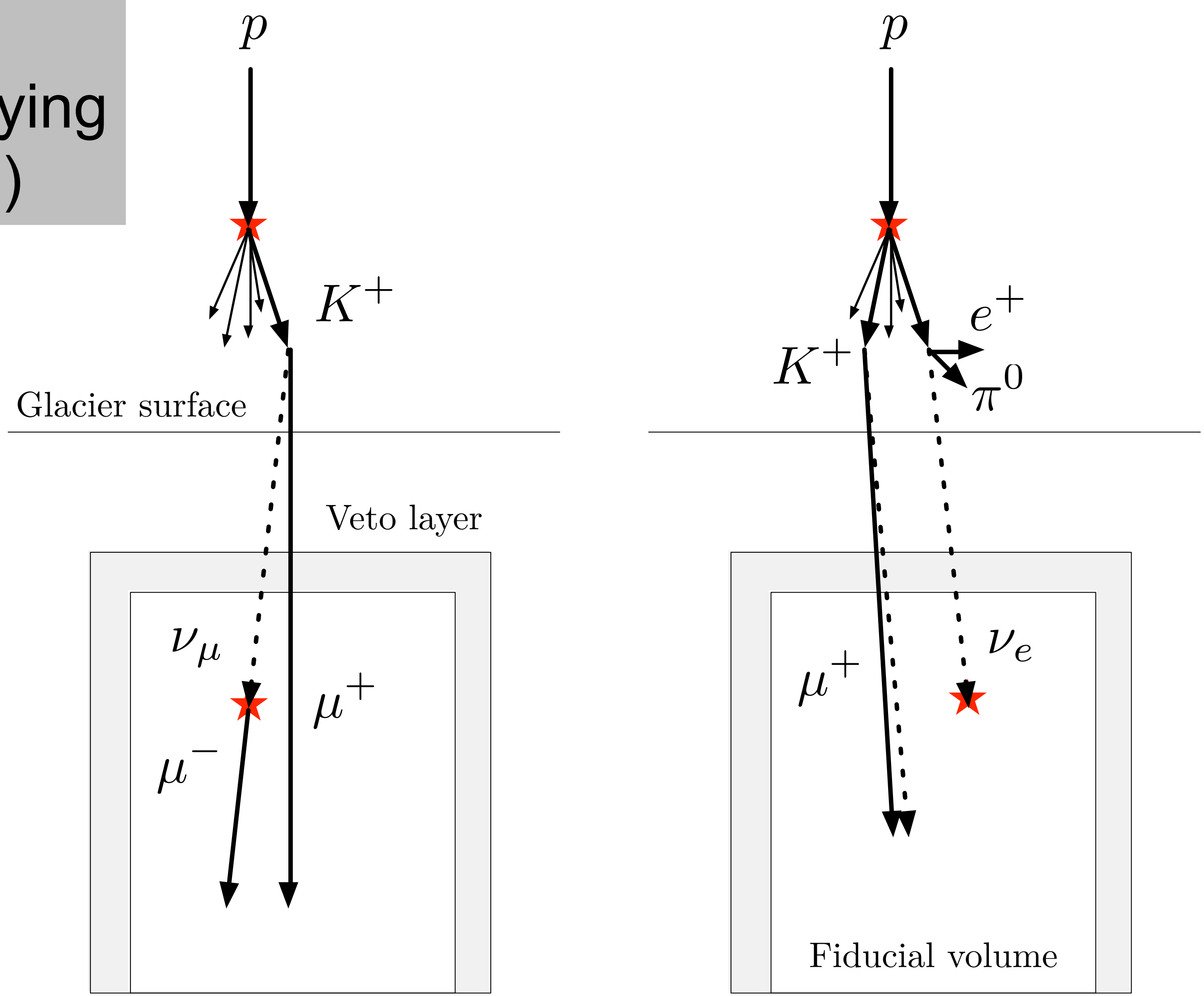


• energy

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)

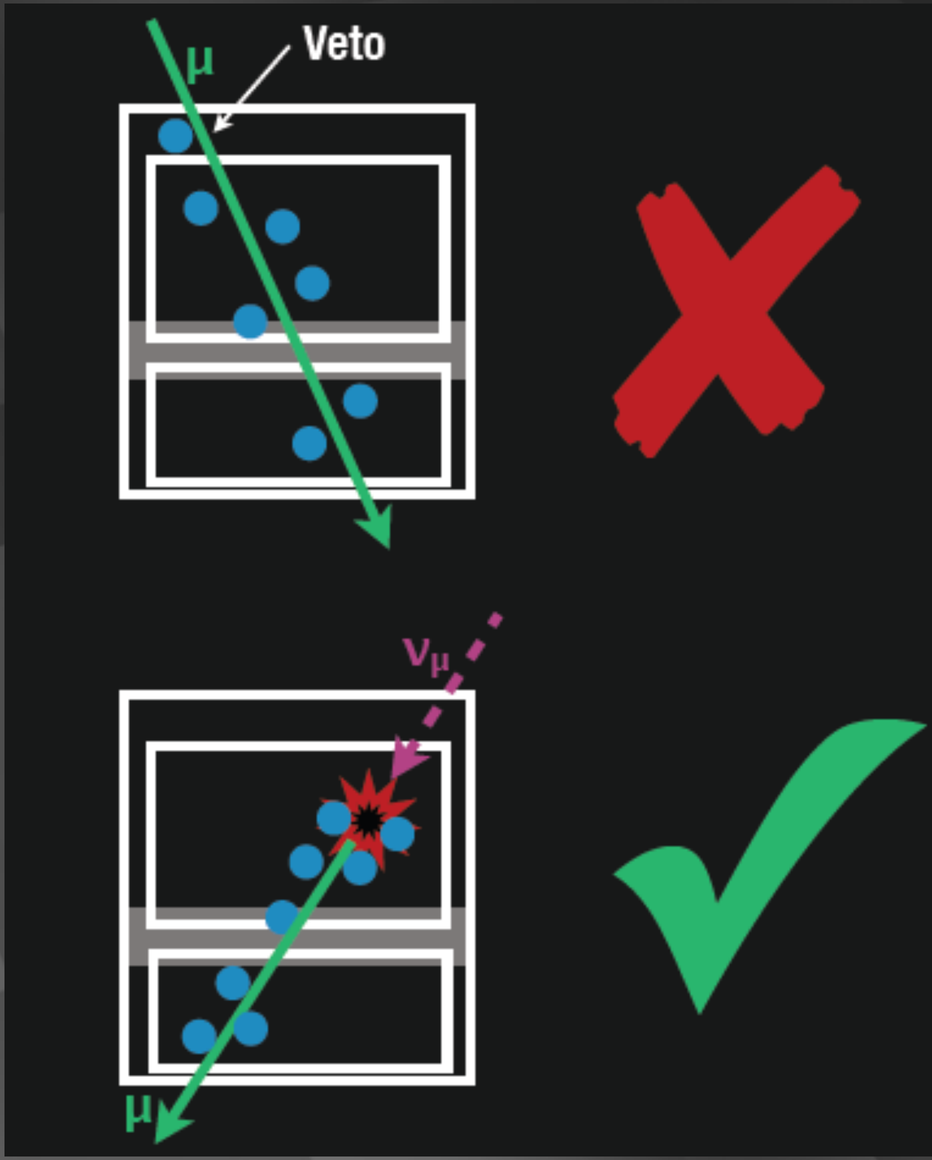


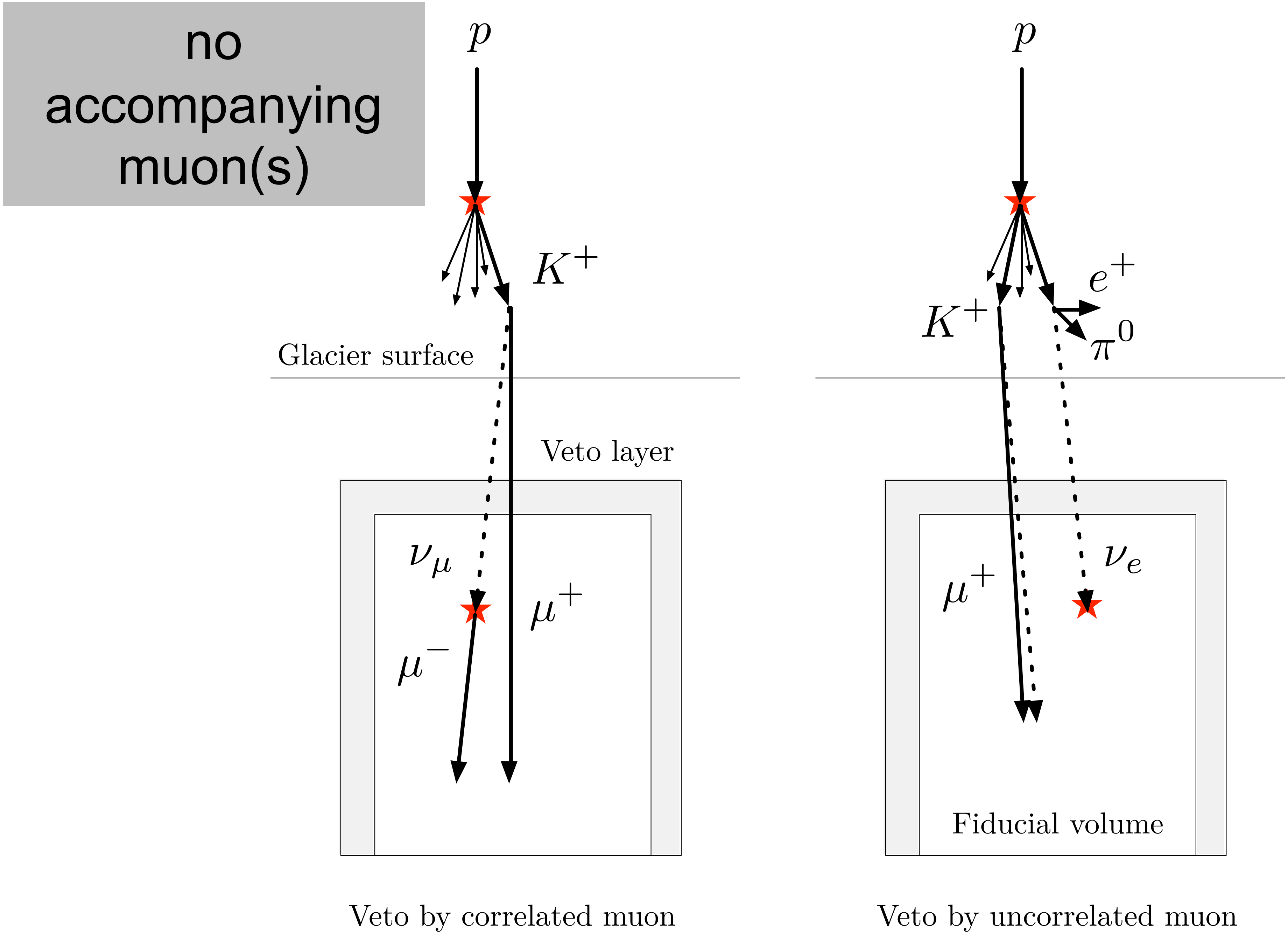
Veto by correlated muon

Veto by uncorrelated muon

events starting inside the detector

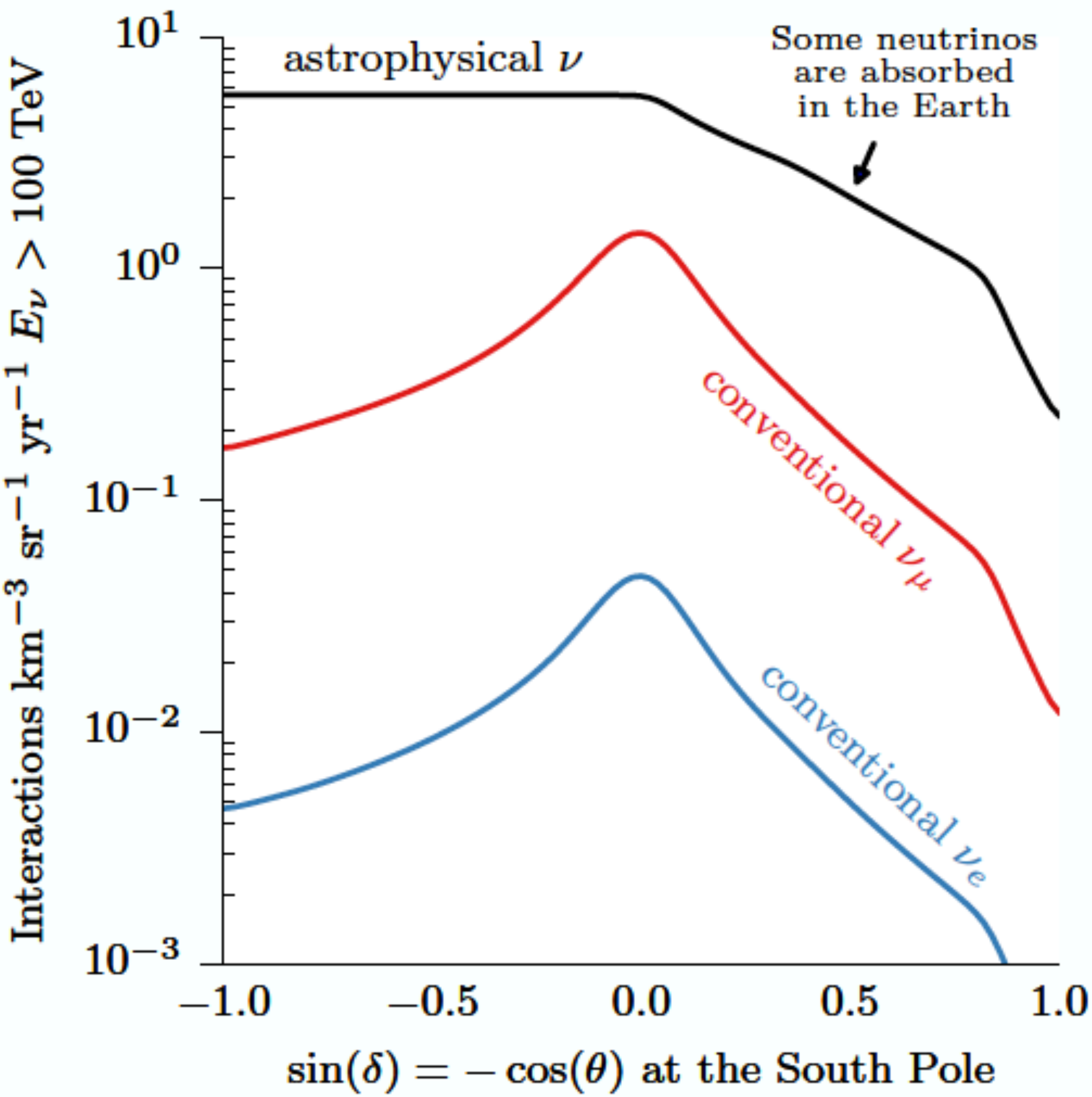
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for *atmospheric* neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



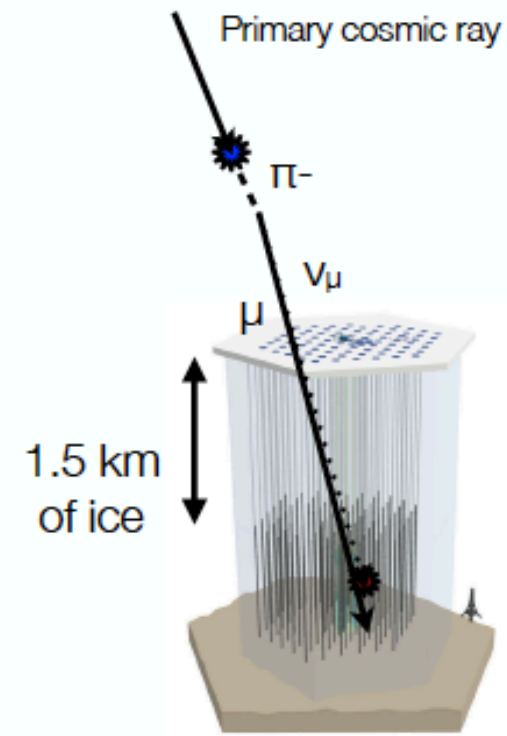


no accompanying muon(s)
p
K+
Glacier surface
Veto layer
νμ
μ+
μ−
p
e+
K+
π0
νe
μ+
Fiducial volume
Veto by correlated muon
Veto by uncorrelated muon

Atmospheric neutrino self-veto



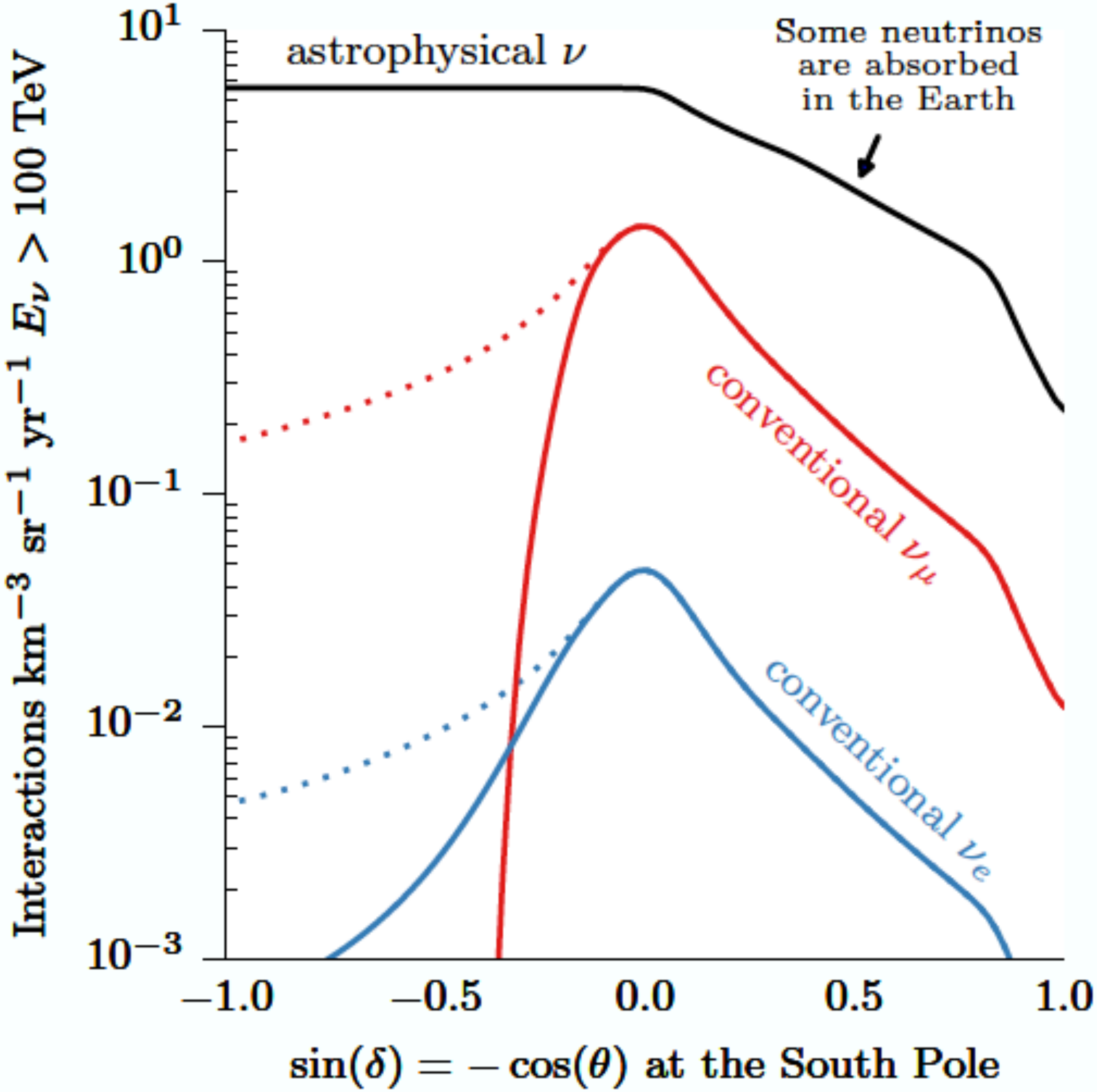
An active muon veto removes down-going atmospheric neutrinos.



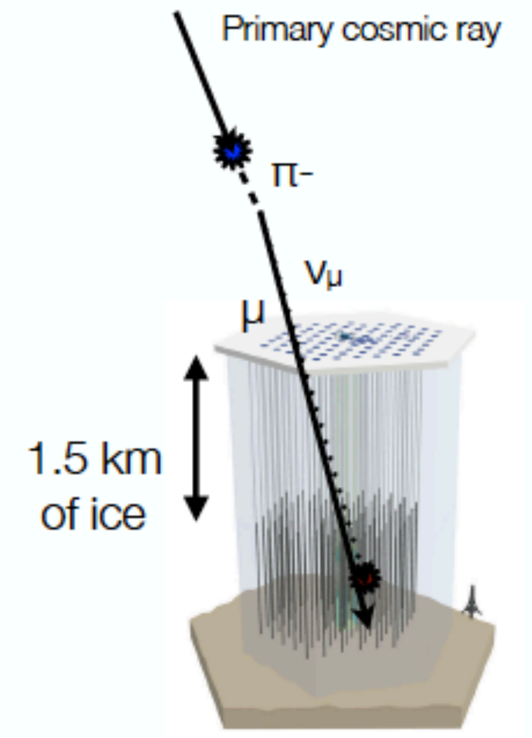
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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)

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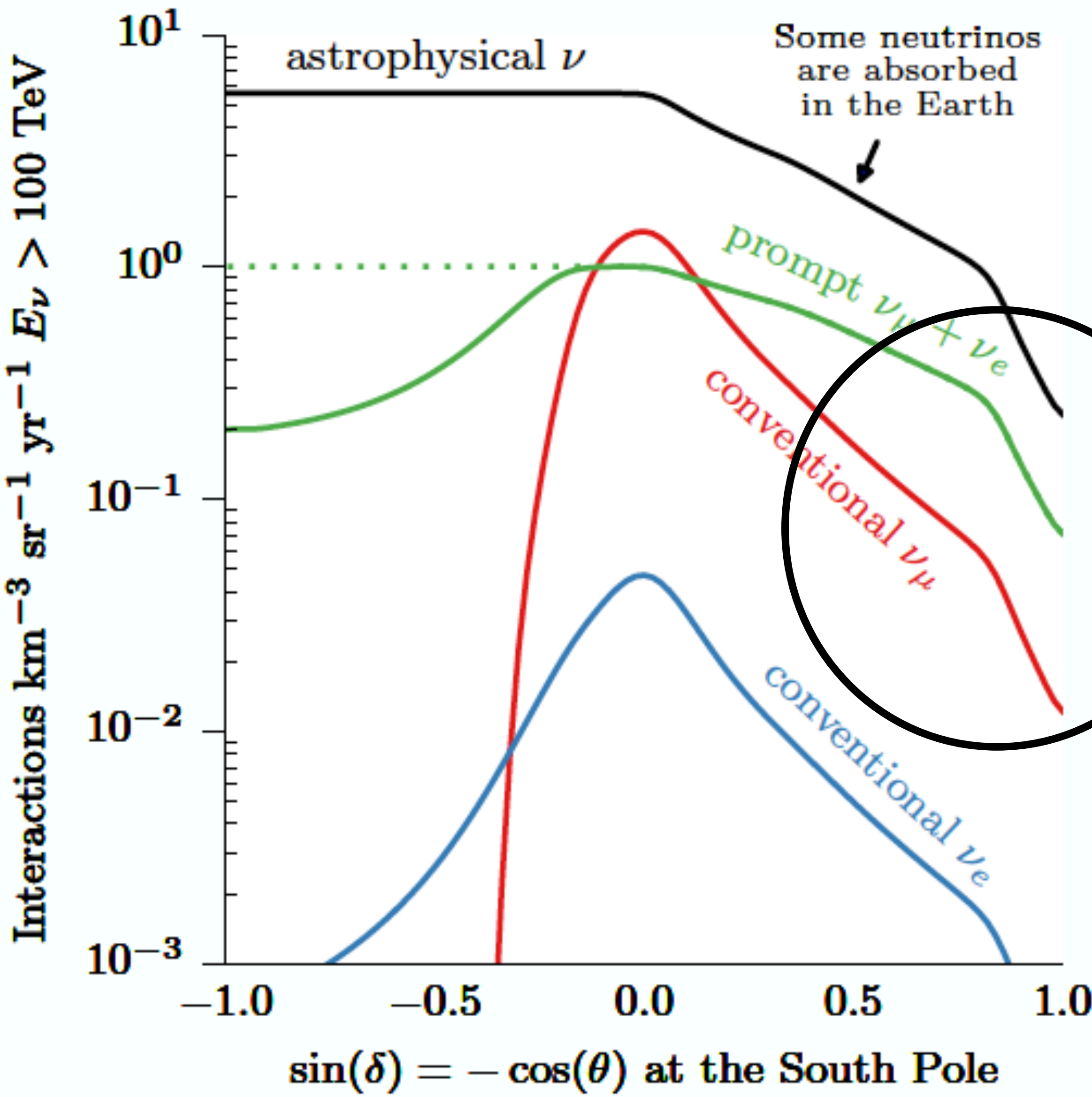
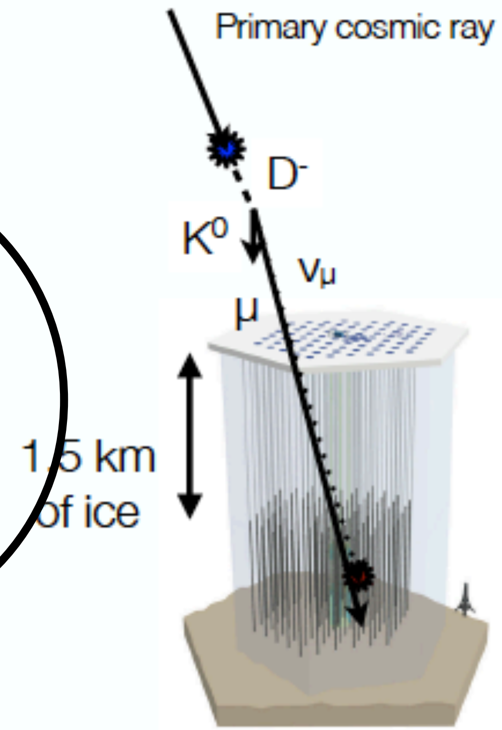
Atmospheric neutrino self-veto



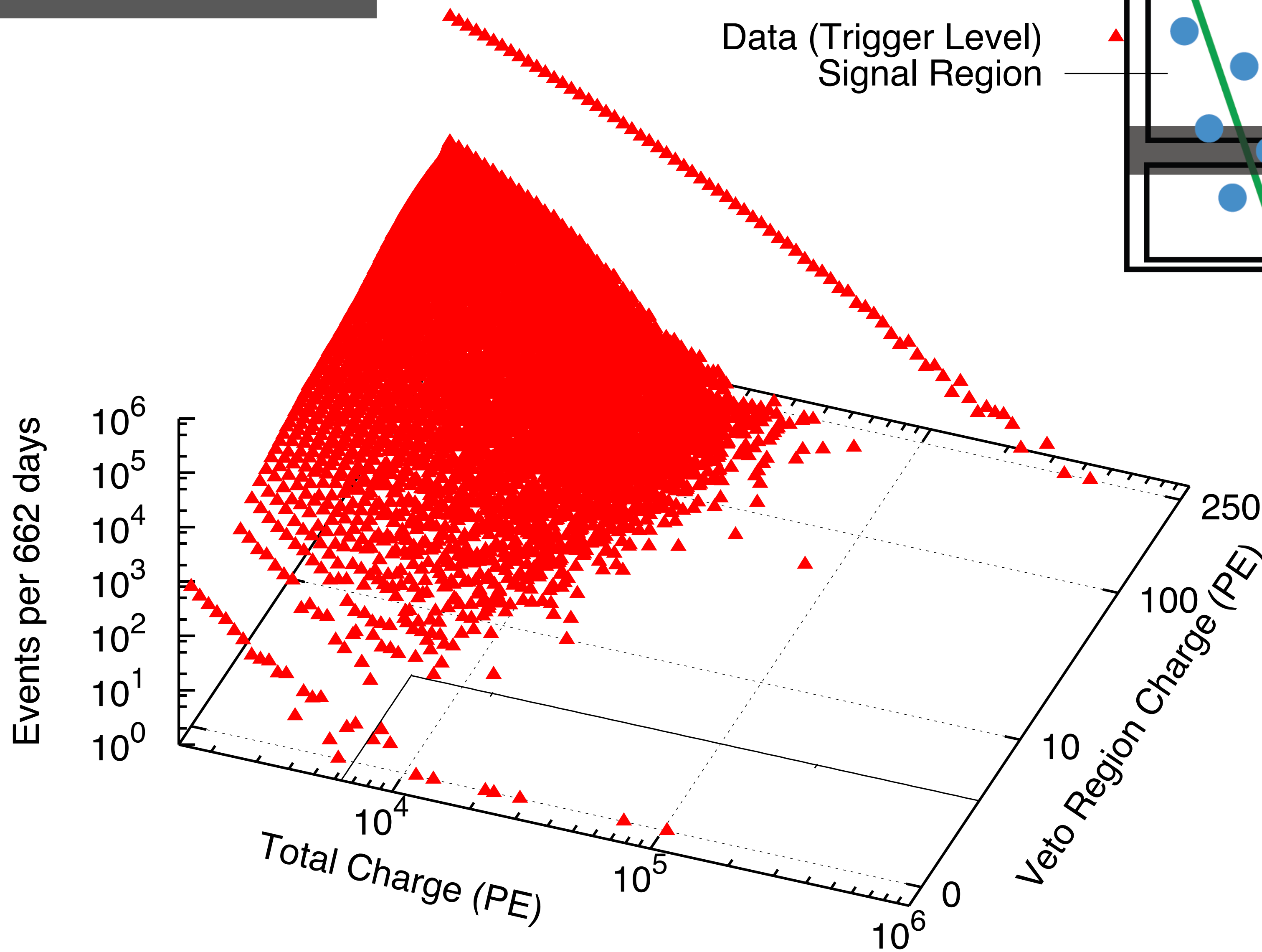
Prompt atmospheric neutrinos are vetoed, too.

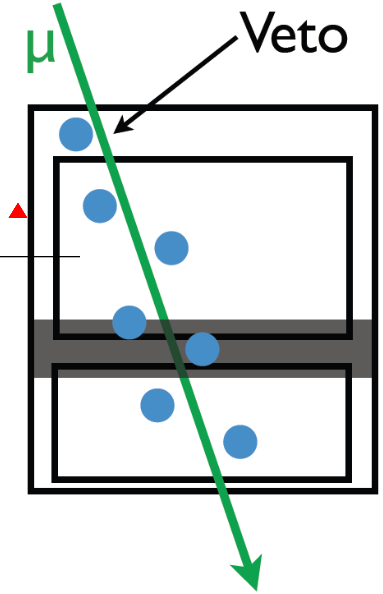


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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

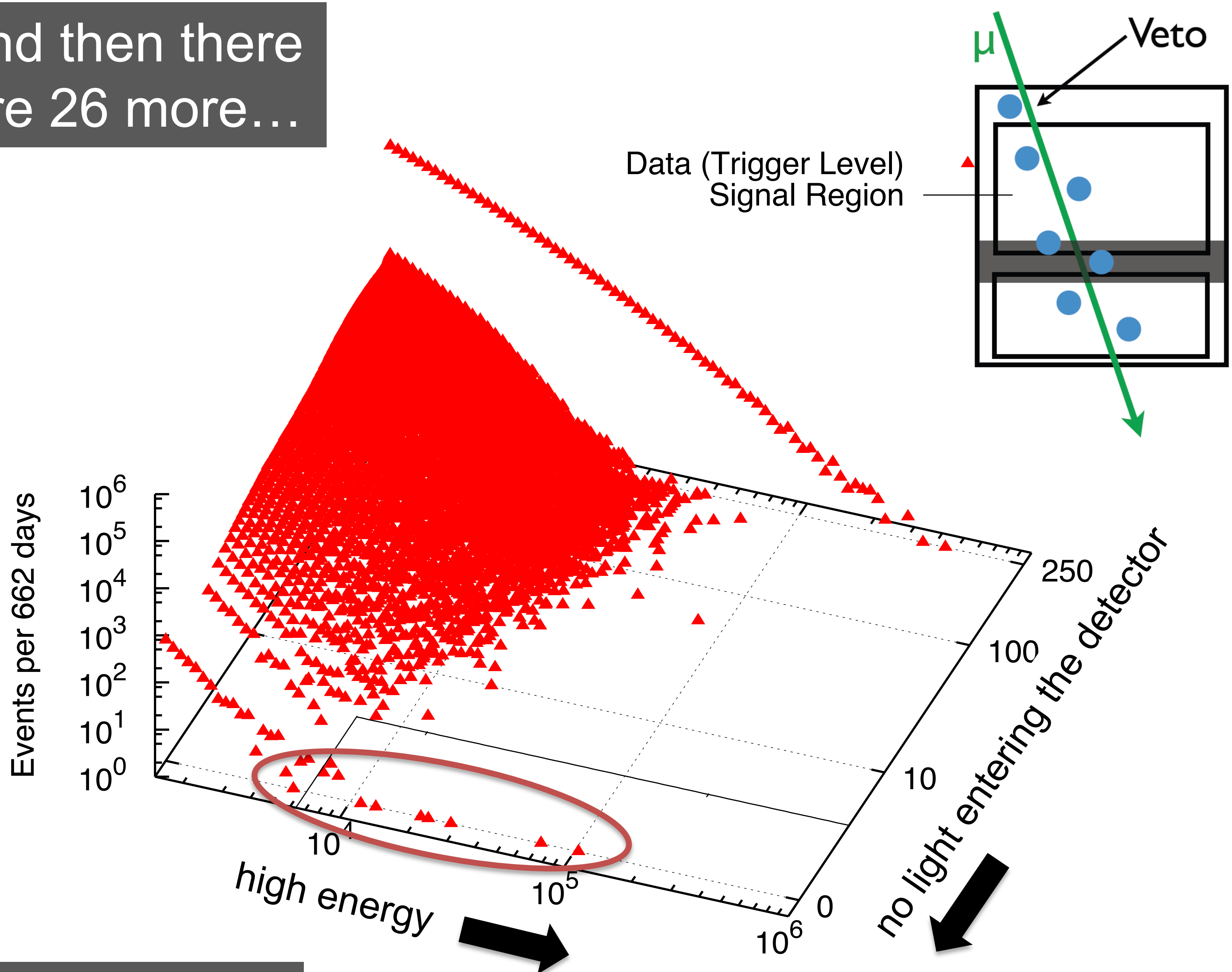
…and then there were 26 more…



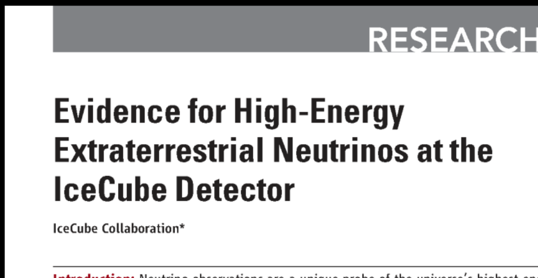


data: 86 strings one year

…and then there were 26 more…



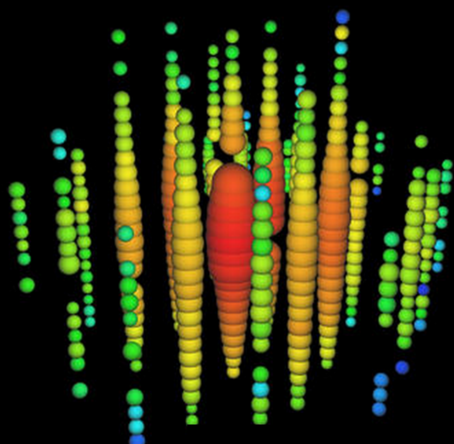
data: 86 strings one year


RESEARCH

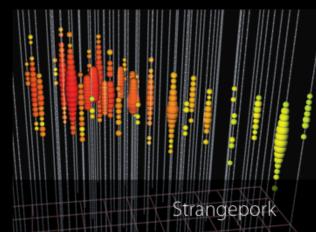
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

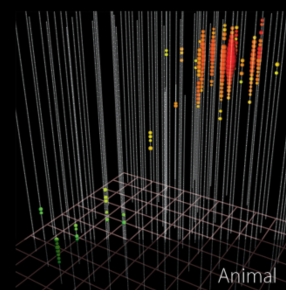
IceCube Collaboration*

Introduction: Neutrino observations are a unique probe of the universe's highest-en

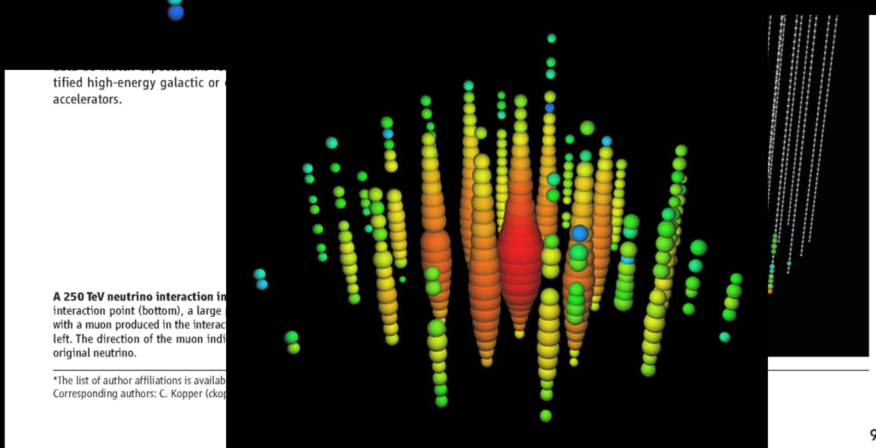


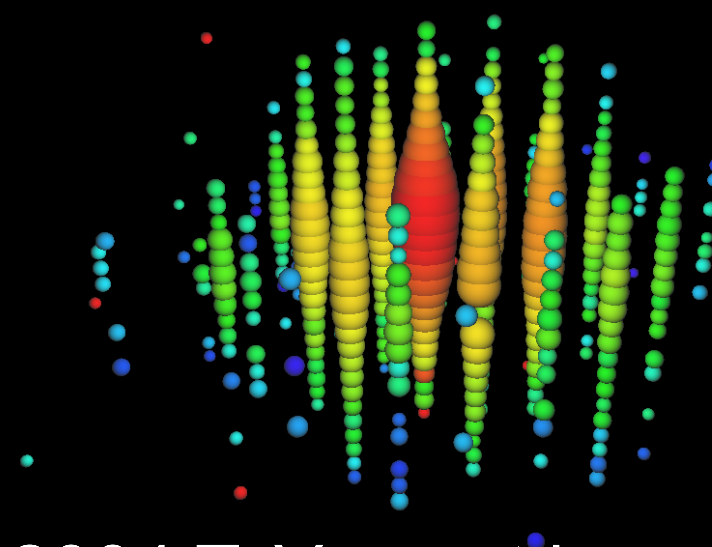
28 High Energy Events





doubled the data since 2013





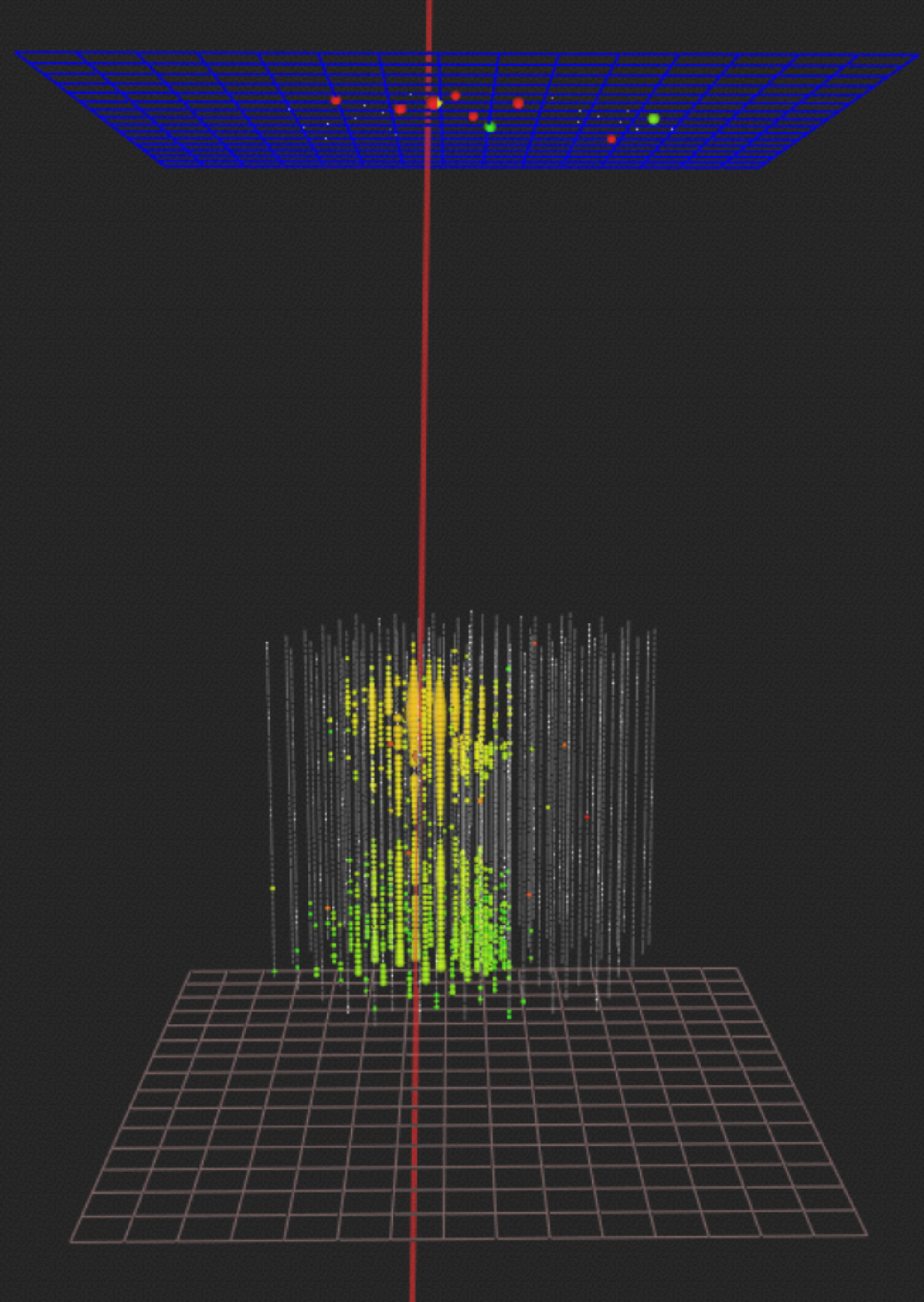
2004 TeV event in year 3

430 TeV inside detector

PeV ν_μ

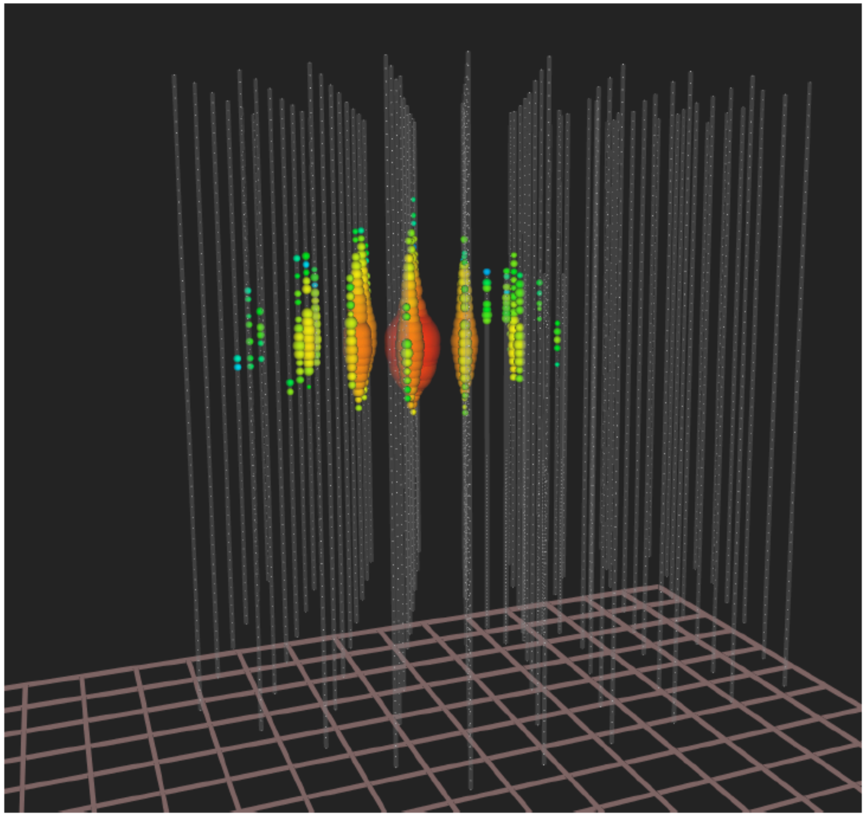
no air shower

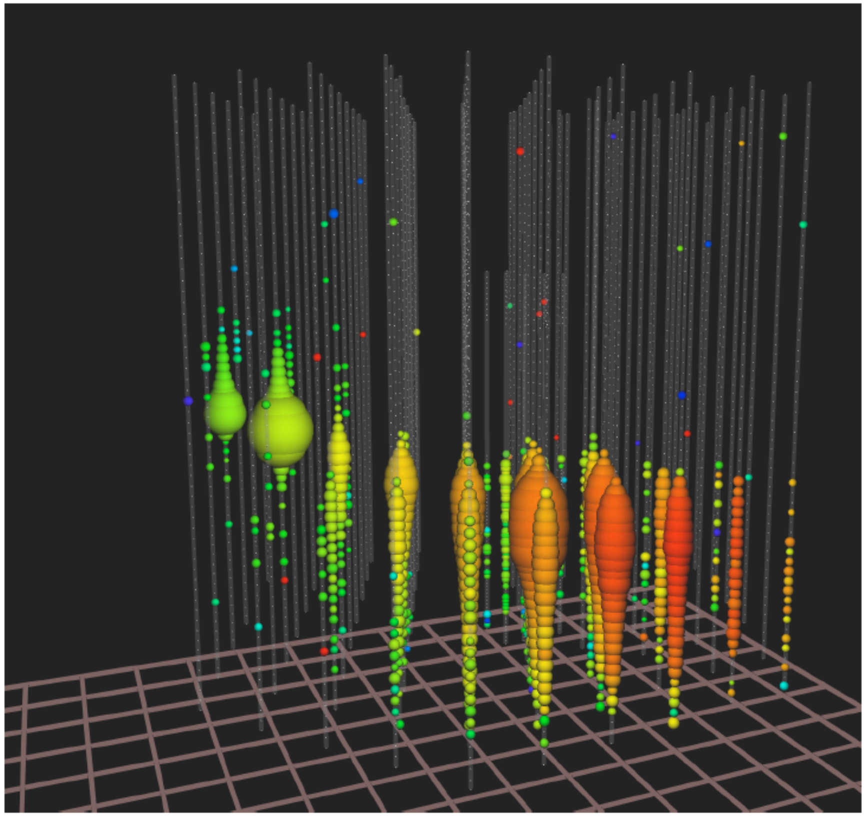
all cosmic neutrinos are isolated by self-veto



neutrinos interacting
inside the detector

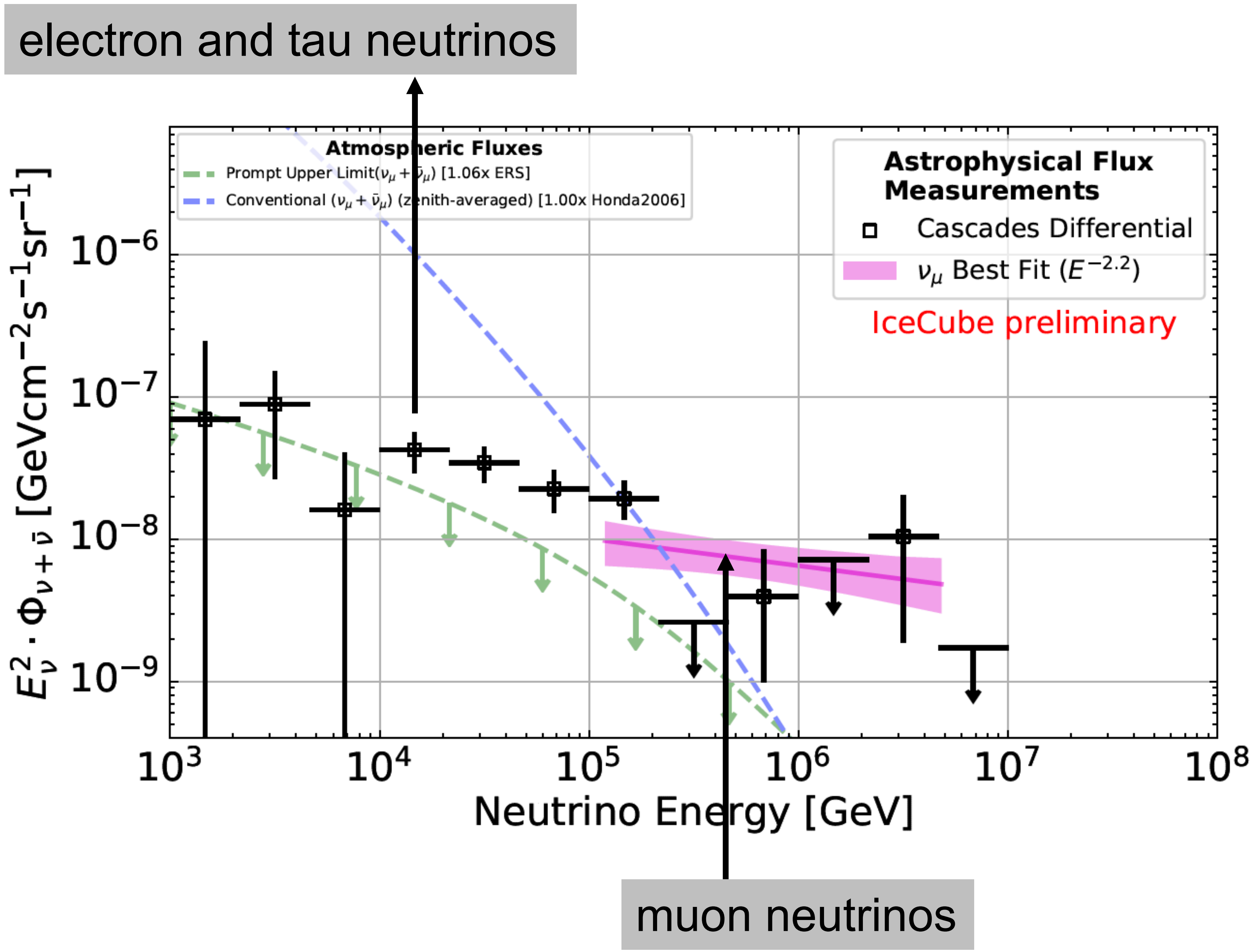
muon neutrinos
filtered by the Earth





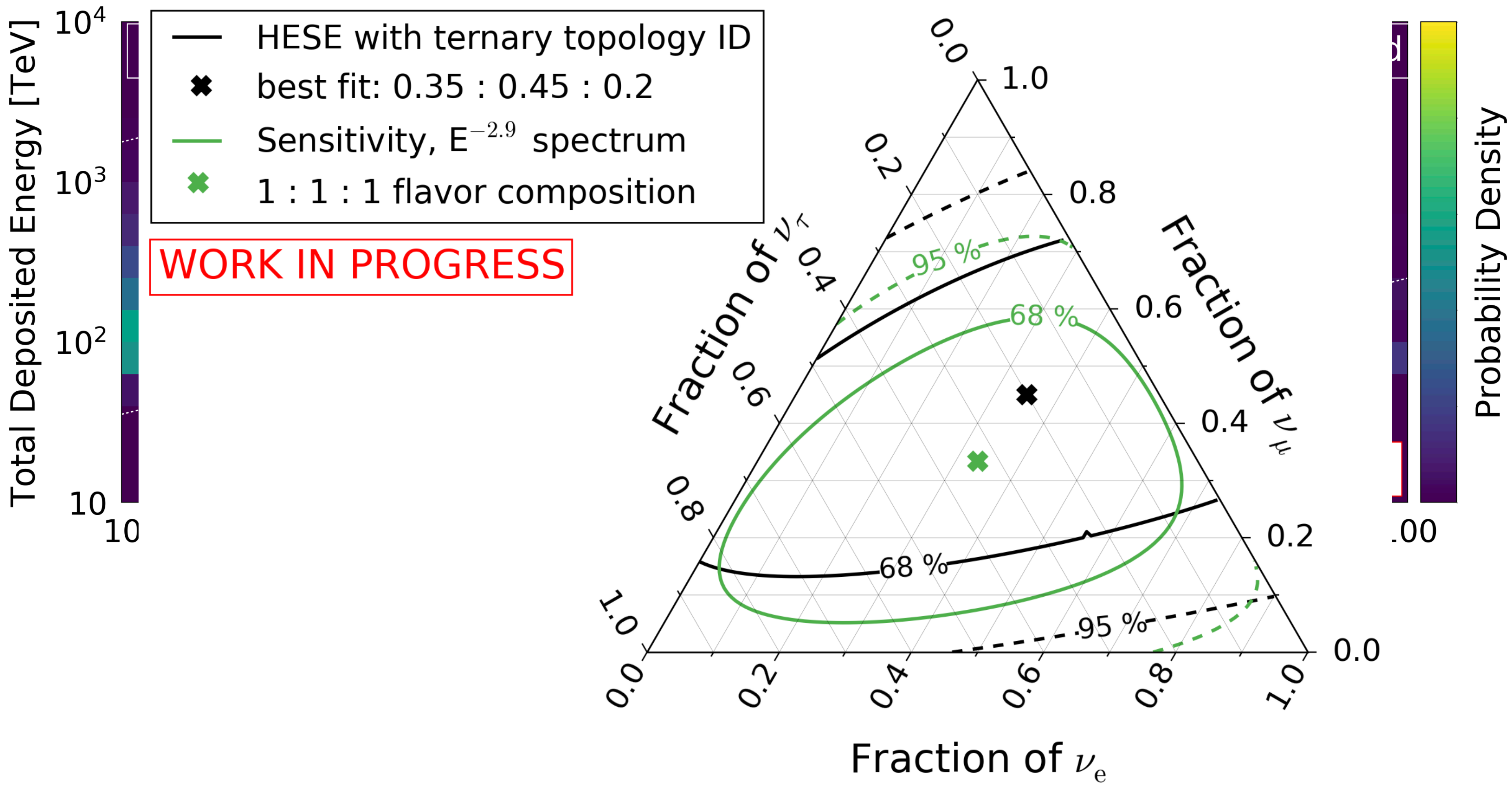
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)



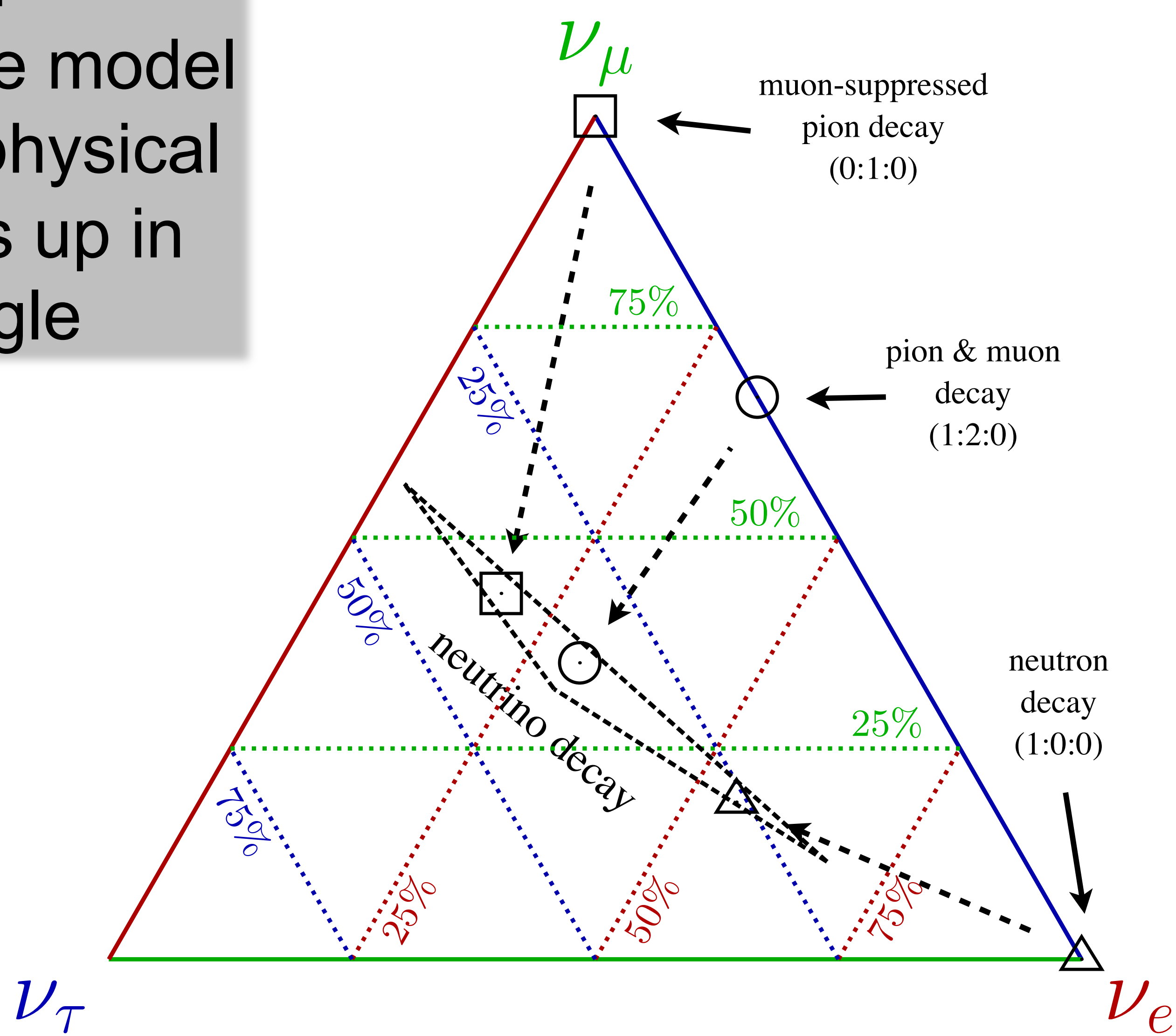
electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [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



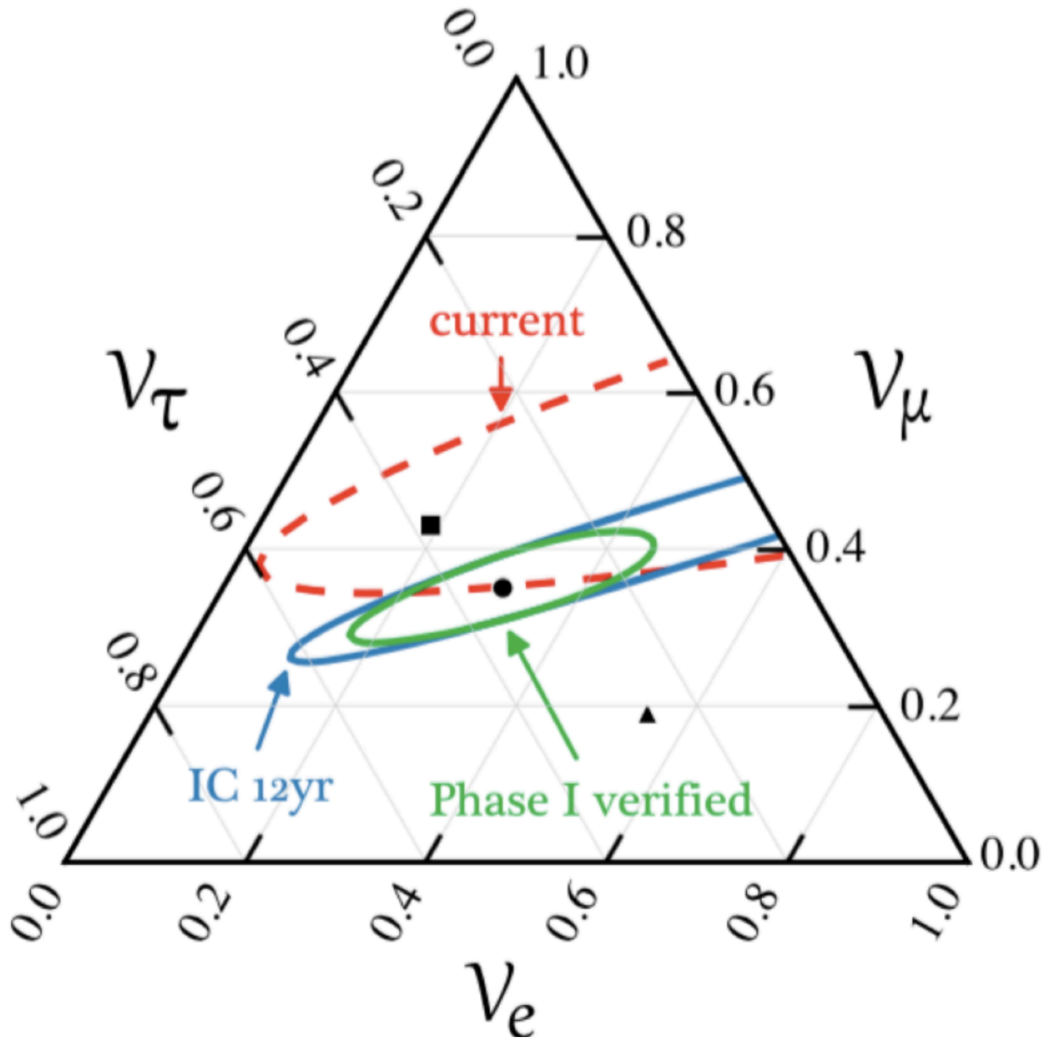
oscillations of PeV neutrinos over cosmic distances to 1:1:1

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



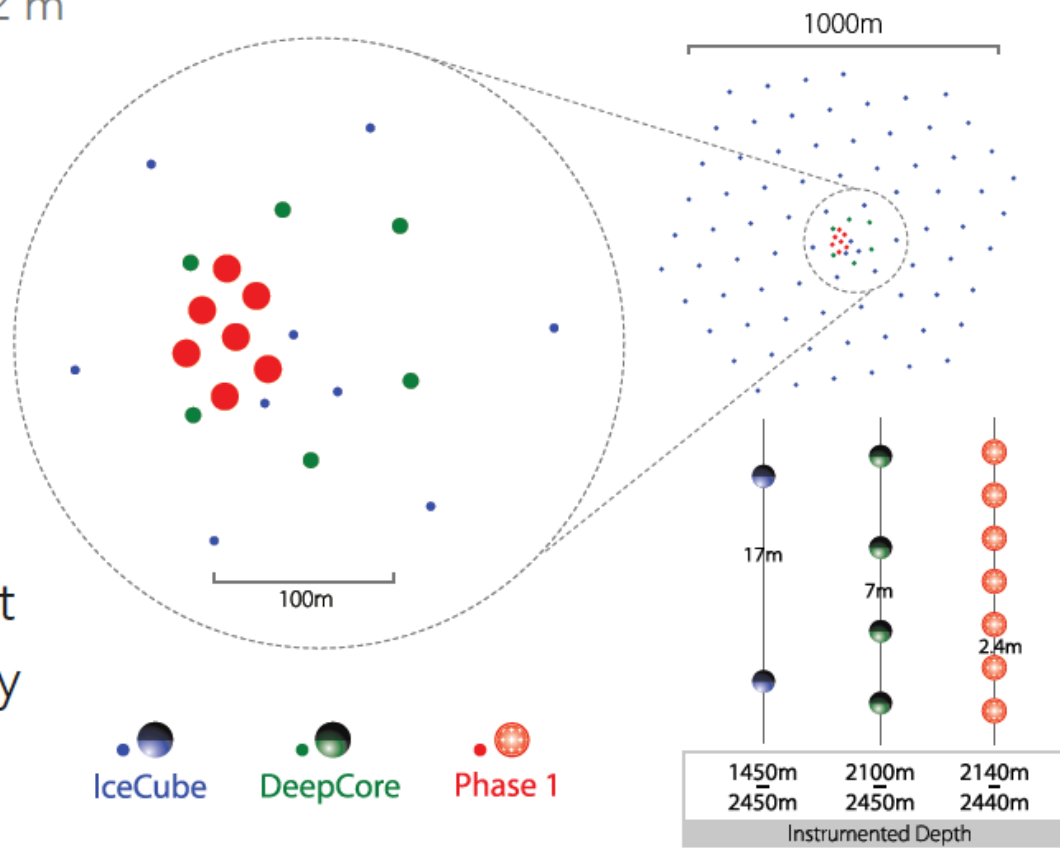
ongoing upgrade:
2022 deployment

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



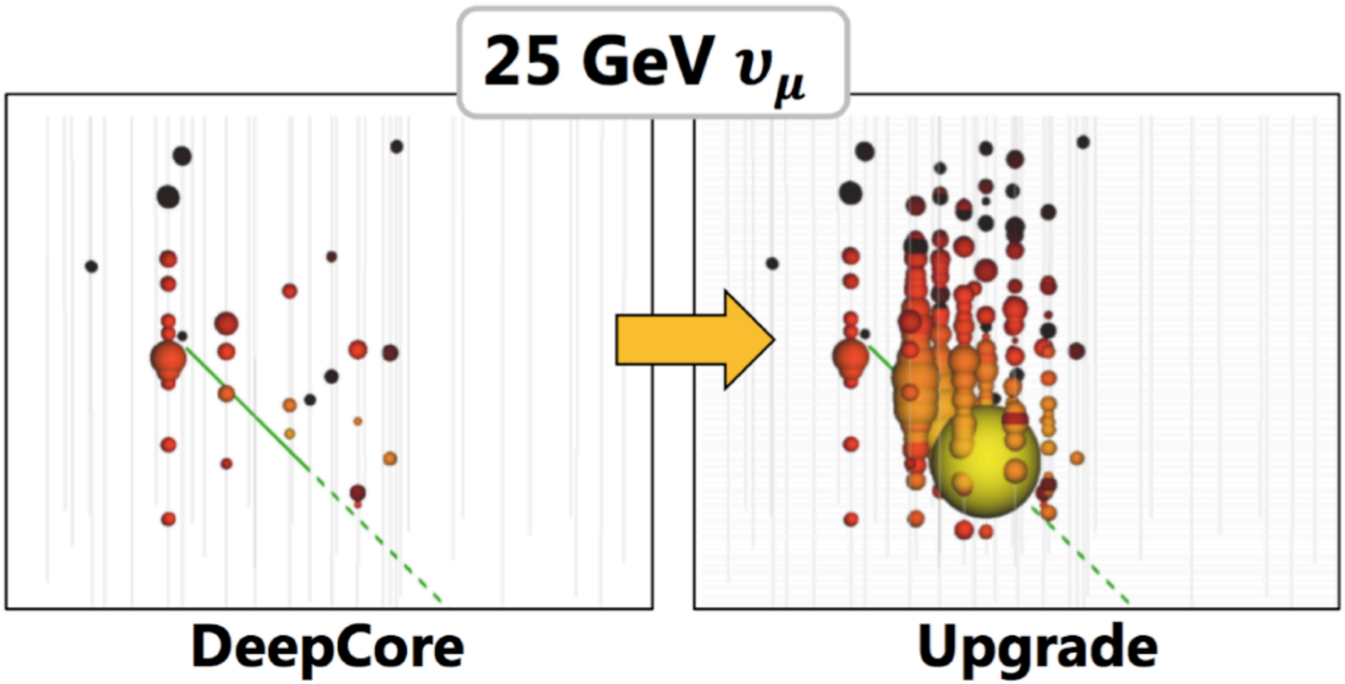
Next Step: the IceCube Upgrade (2022)

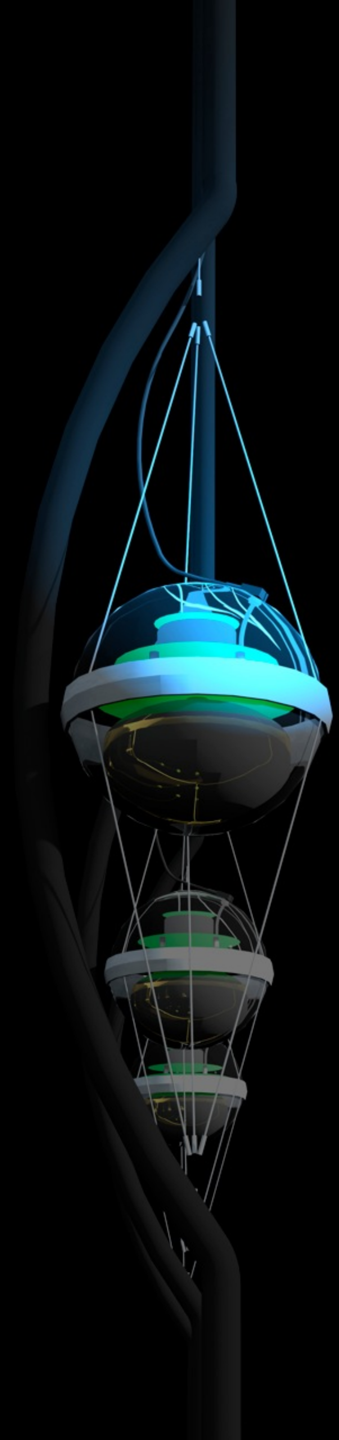
- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



→ 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

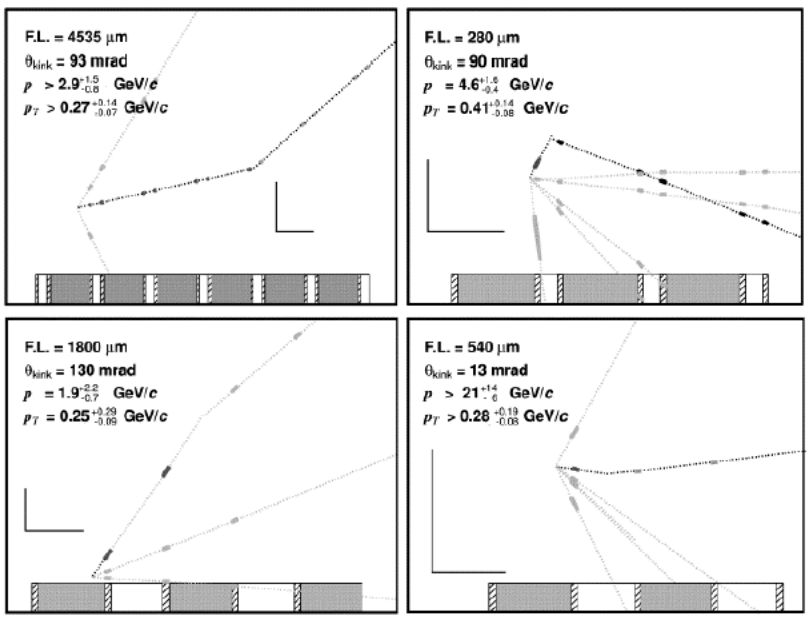
multimessenger astronomy

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

icecube.wisc.edu

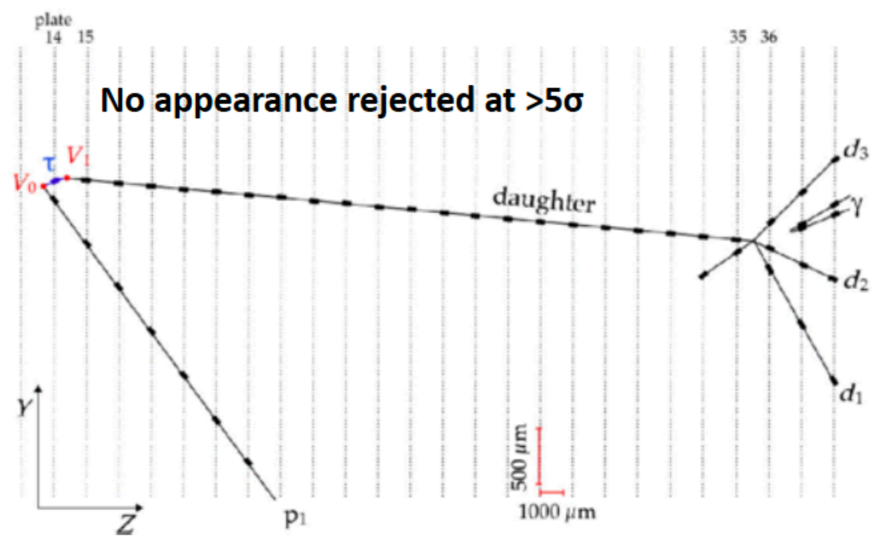
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion

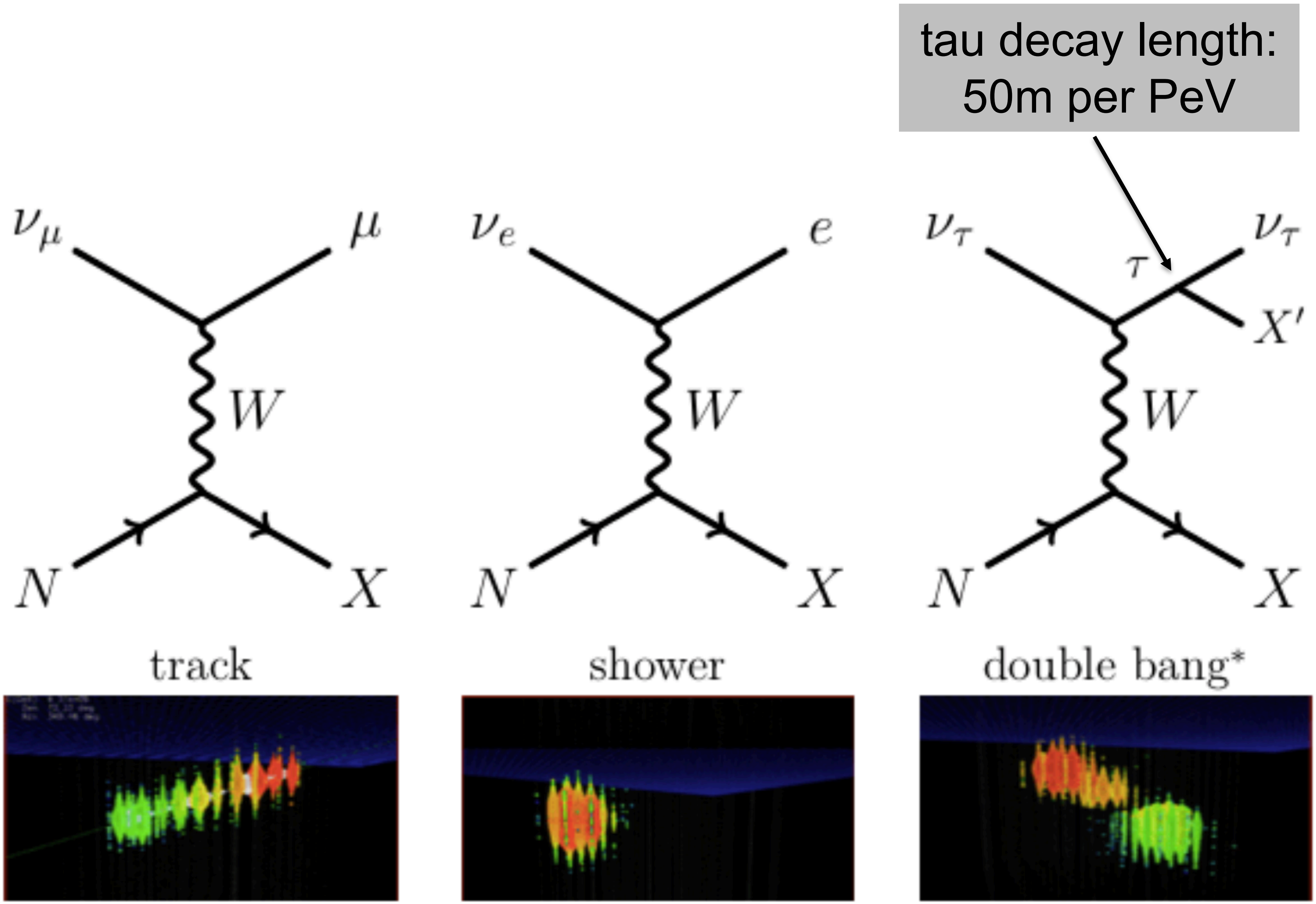


DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

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

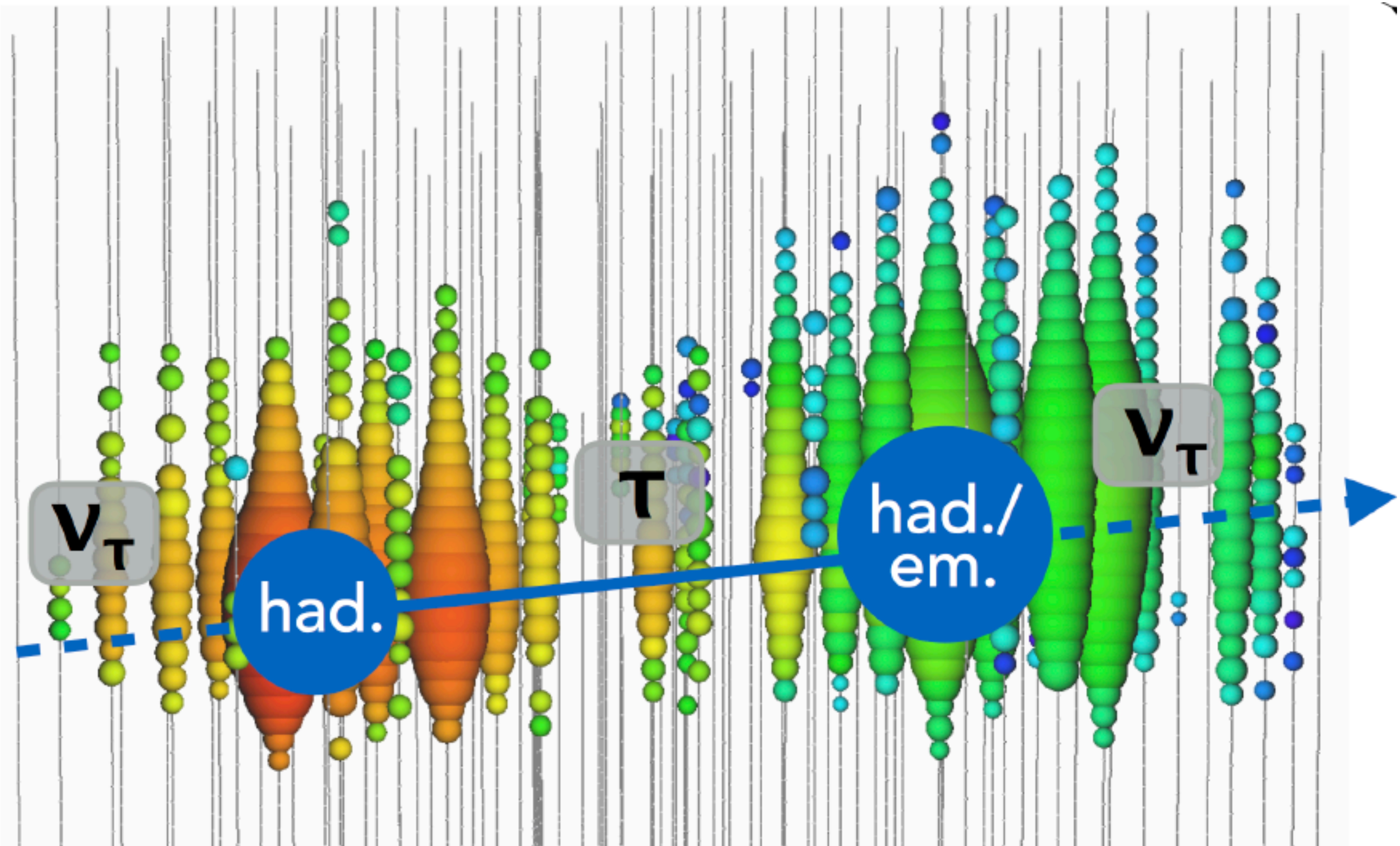


OPERA Phys. Rev. Lett. 115, 121802 (2015)

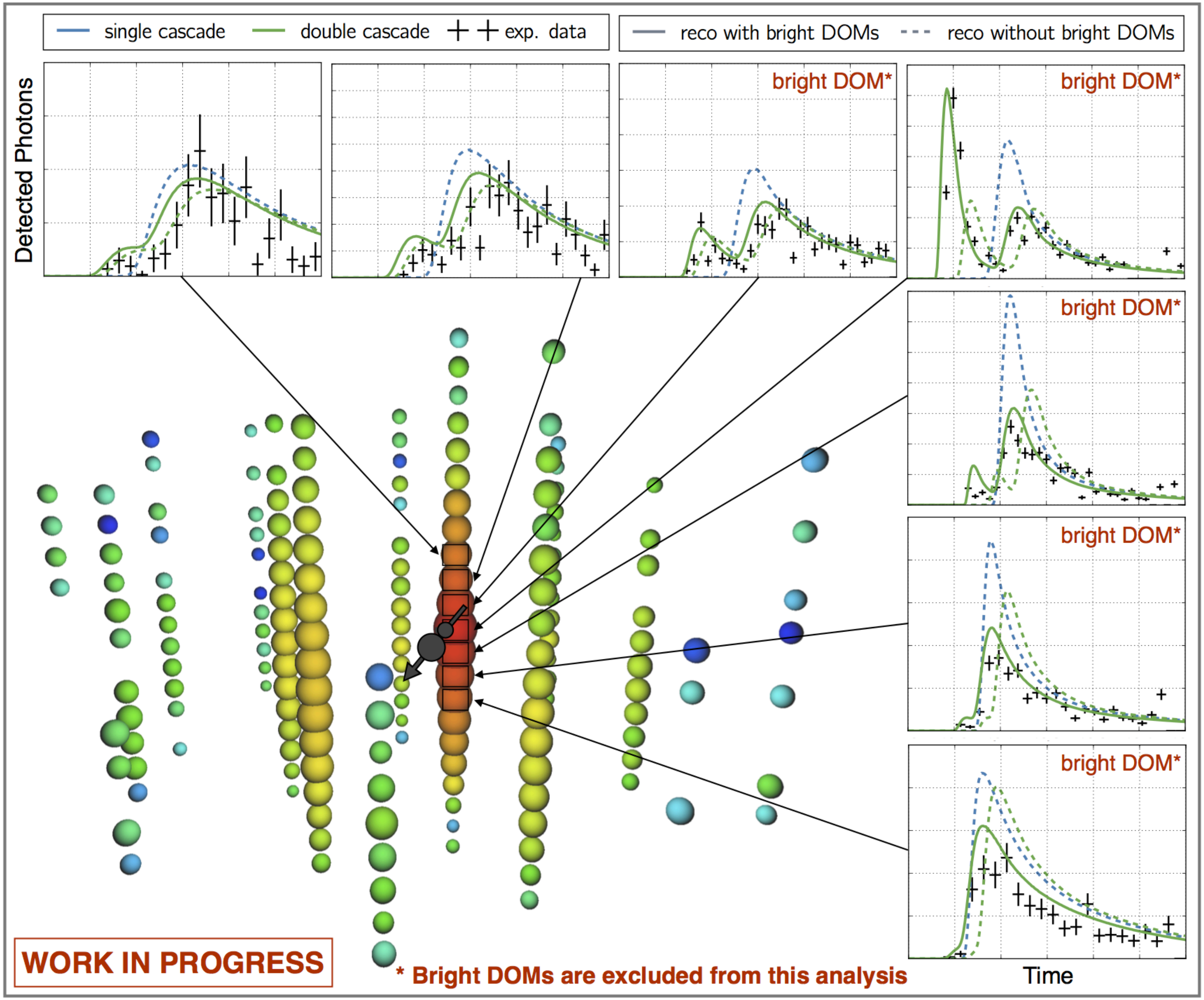

tau decay length:
50m per PeV
ν_μ
μ
W
N
X
ν_e
e
W
N
X
ν_τ
τ
ν_τ
X'
W
N
X
track
shower
double bang*

tau production and decay

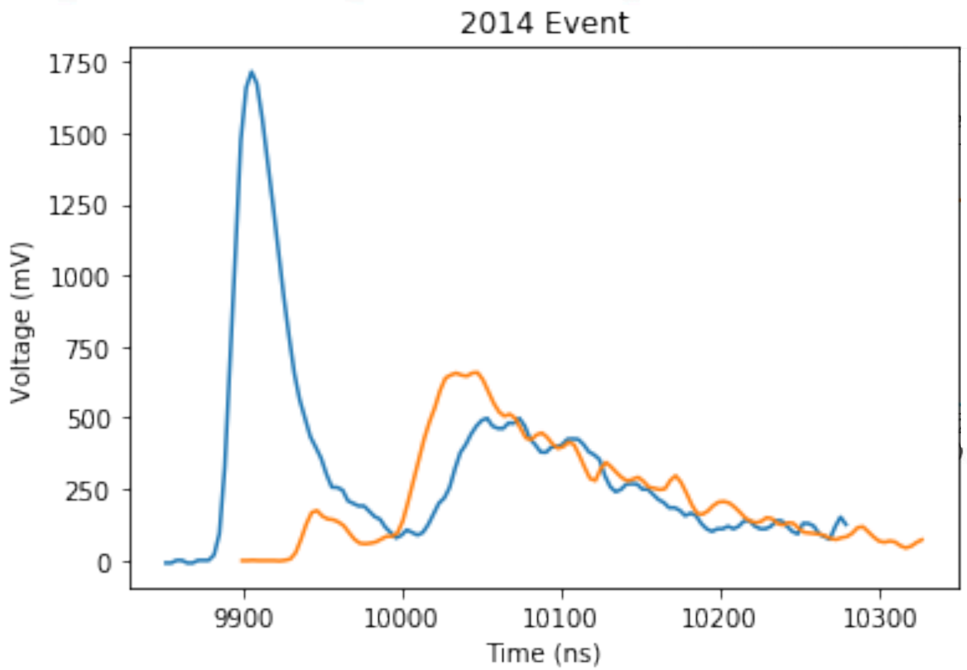
tau decay length: 50m per PeV

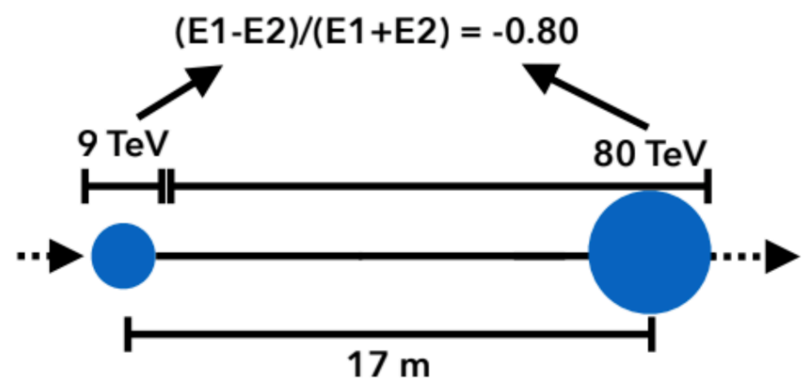


a cosmic tau neutrino: livetime 17m

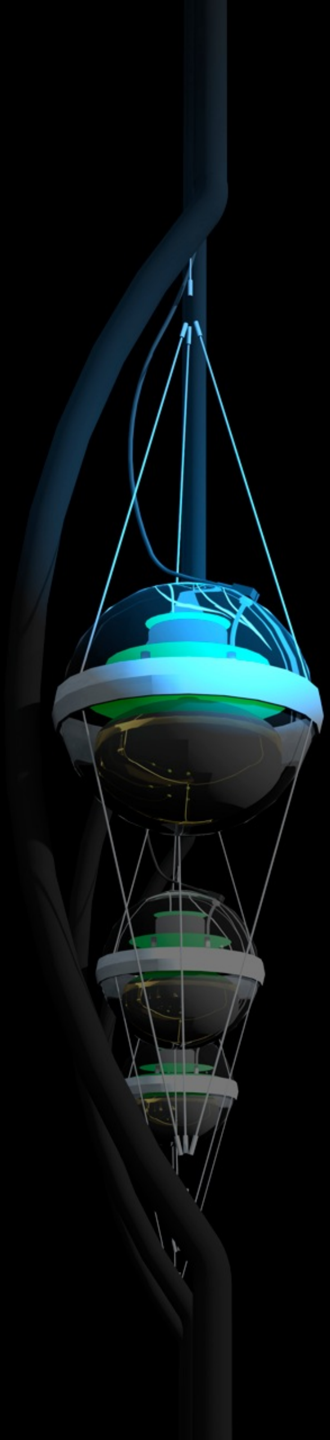


tau decay length:
50m per PeV





event found in 3 different analyses



neutrino astronomy

- cosmic neutrinos: four independent observations
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  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

multimessenger astronomy

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

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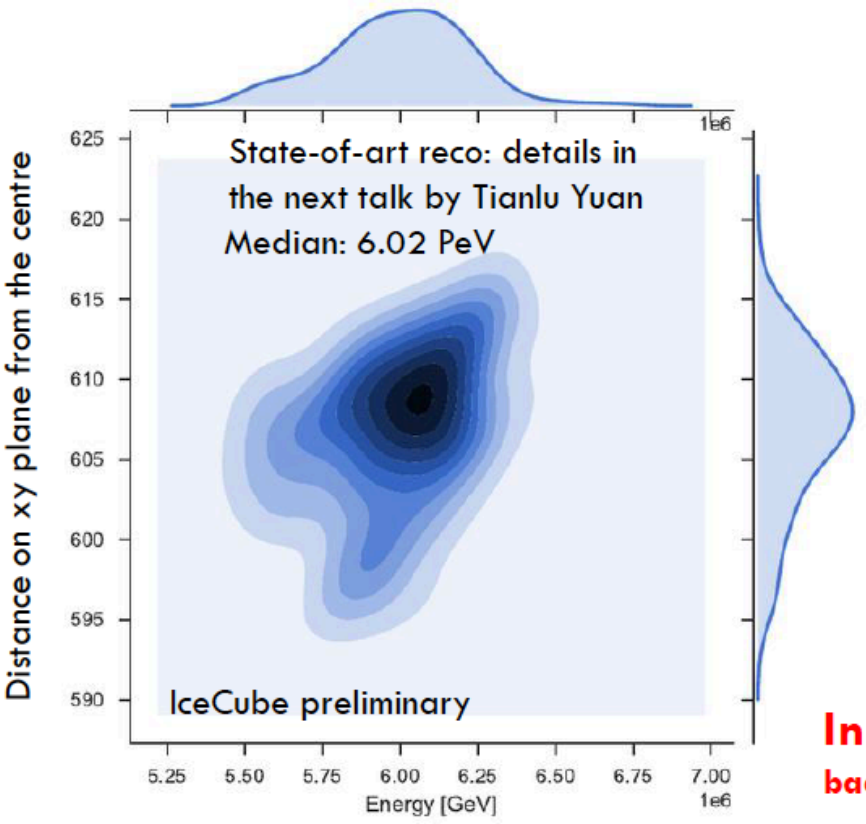
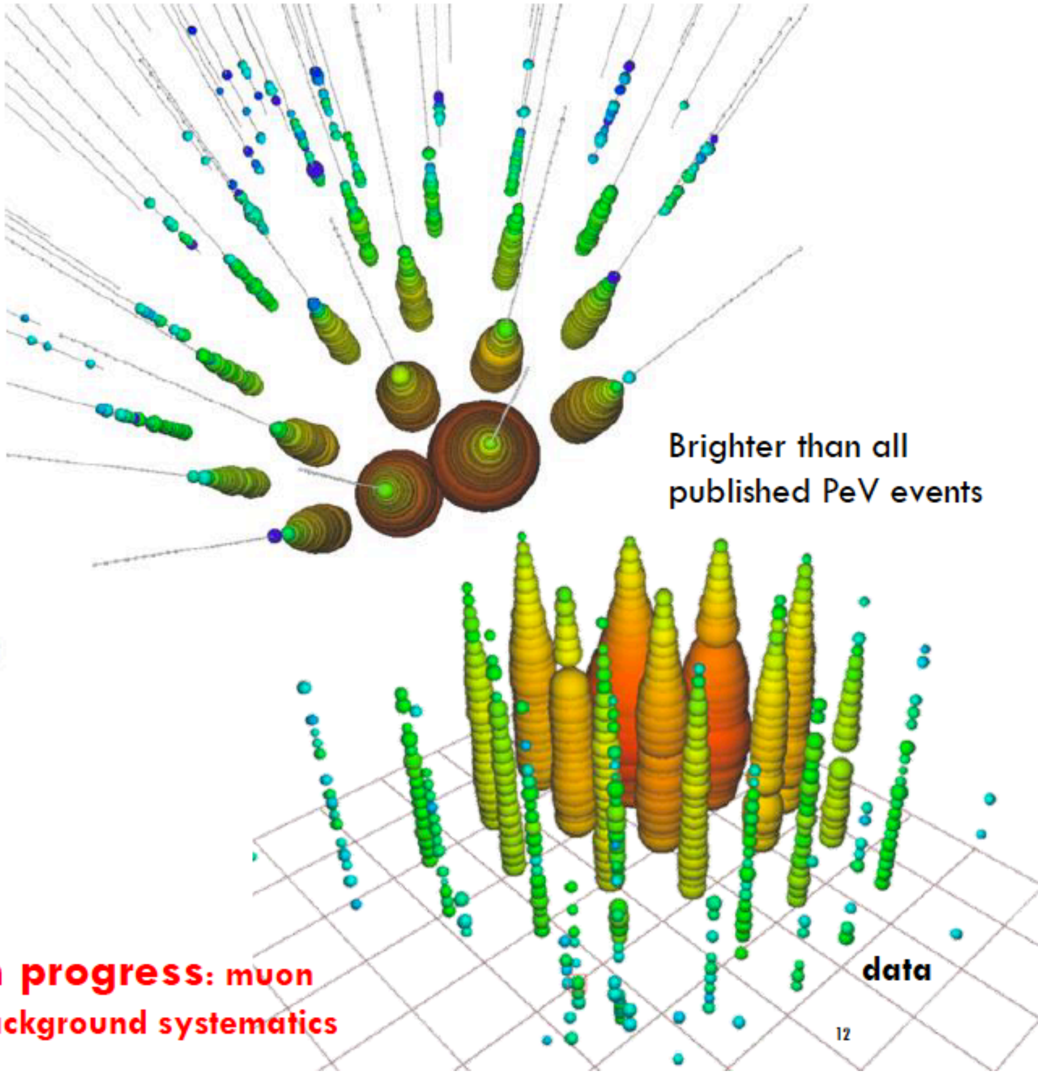
partially contained event with energy of 6.3 PeV

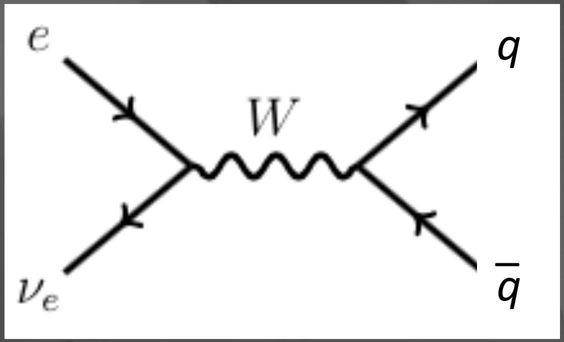
HIGHEST-ENERGY NEUTRINO CANDIDATE



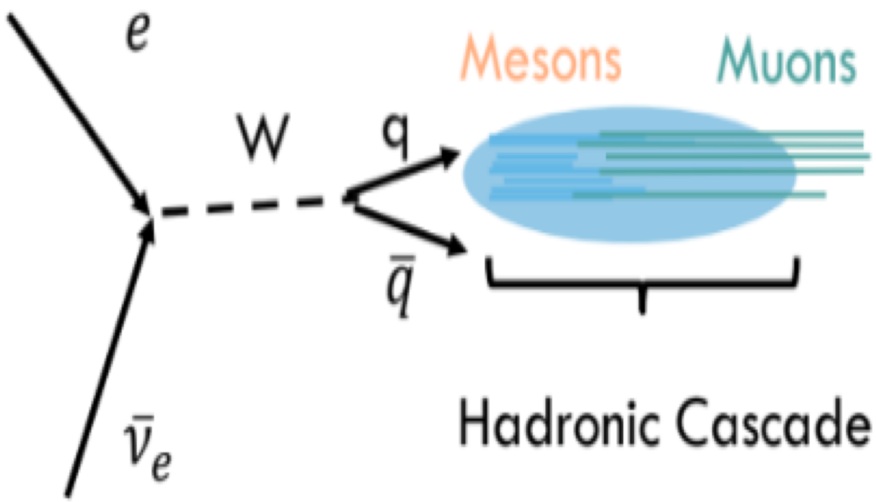


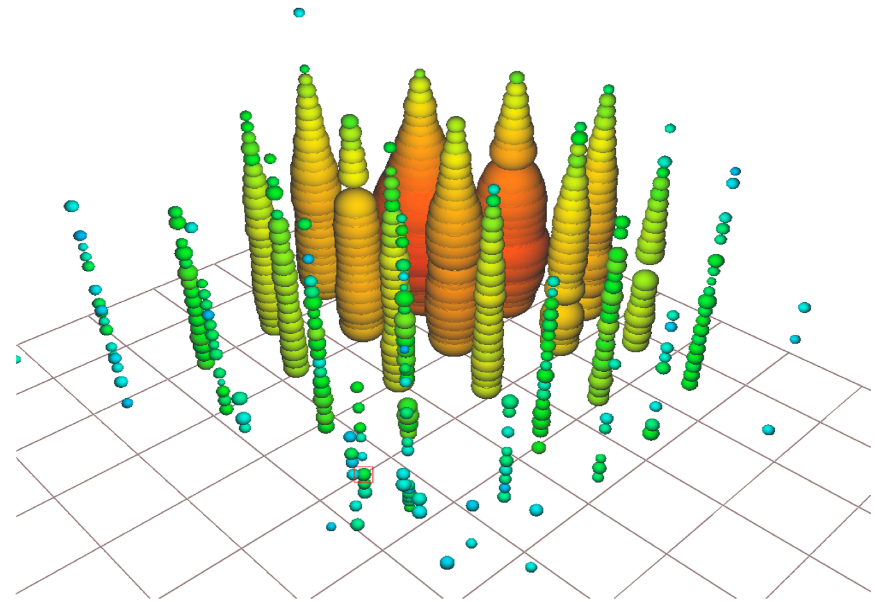
In progress: muon background systematics the first Glashow resonance event:

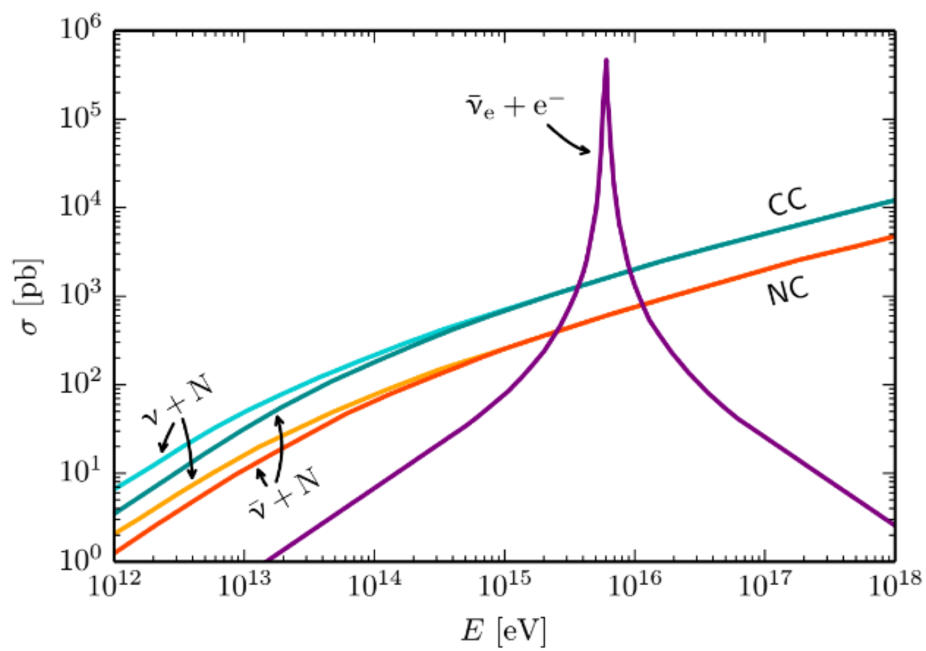
anti-ν_e + atomic electron → real W at 6.3 PeV



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





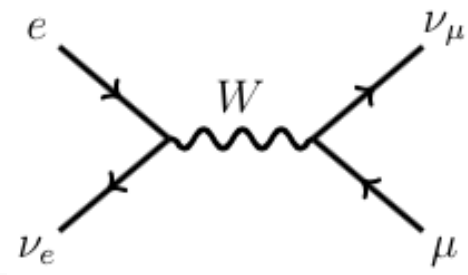


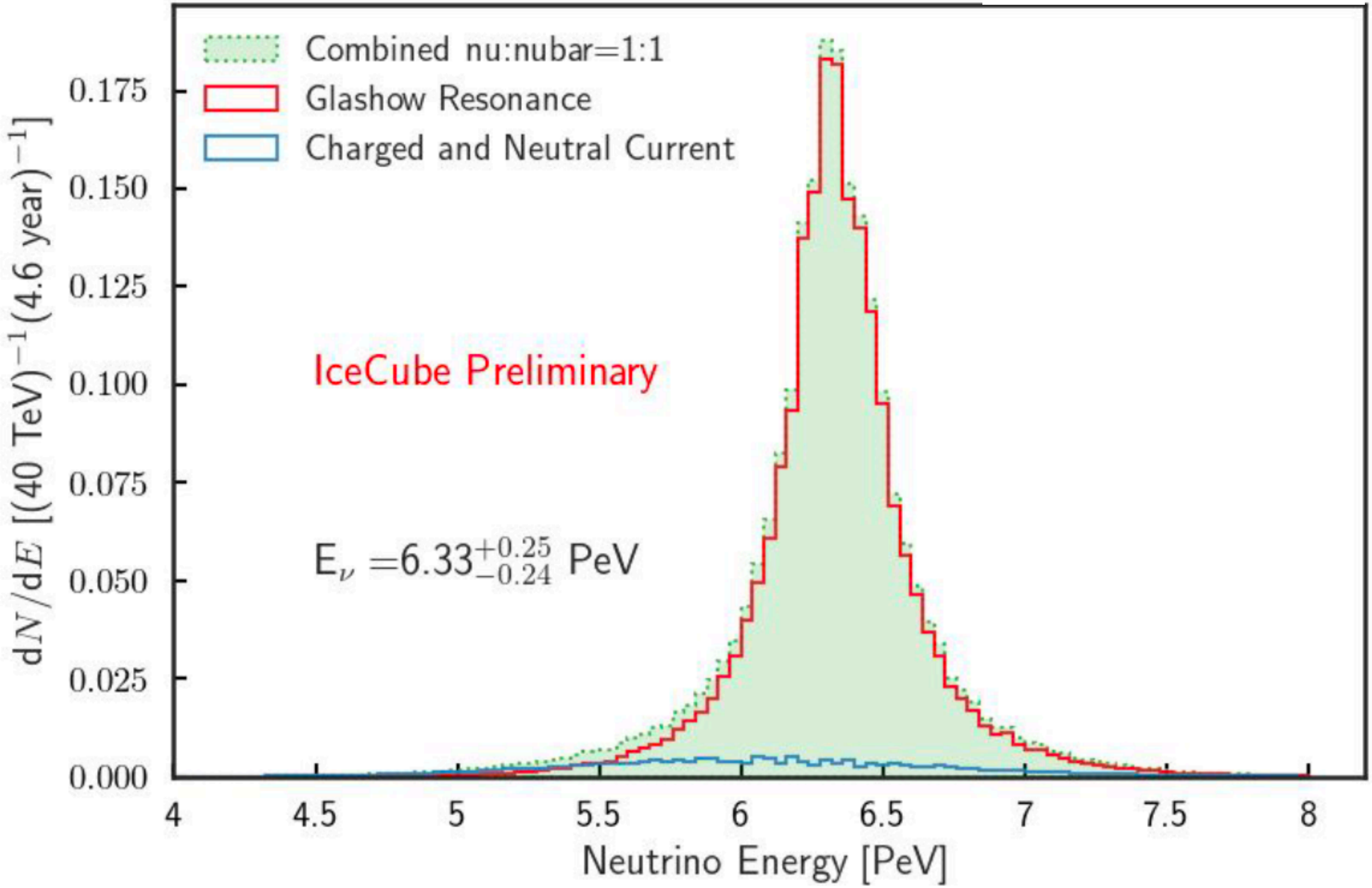
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

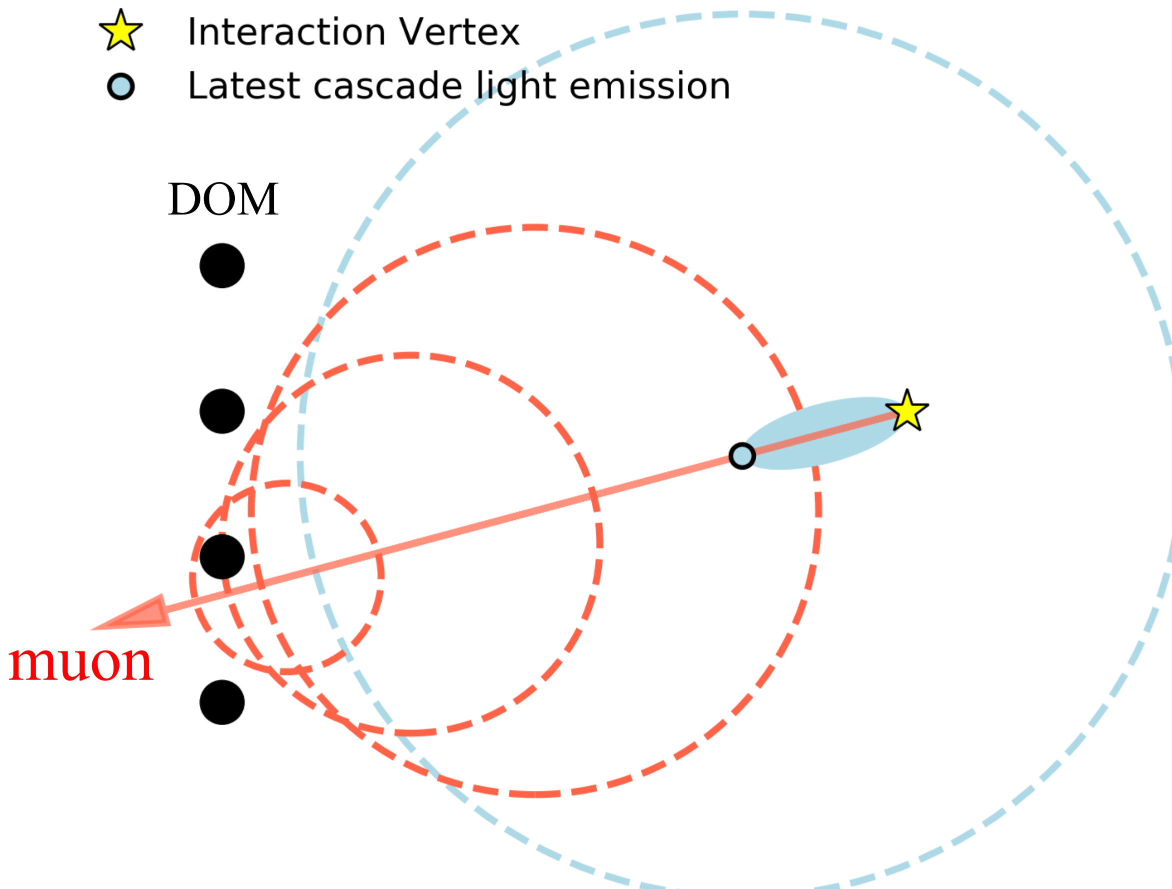
- energy measurement understood
- identification of anti-electron neutrinos

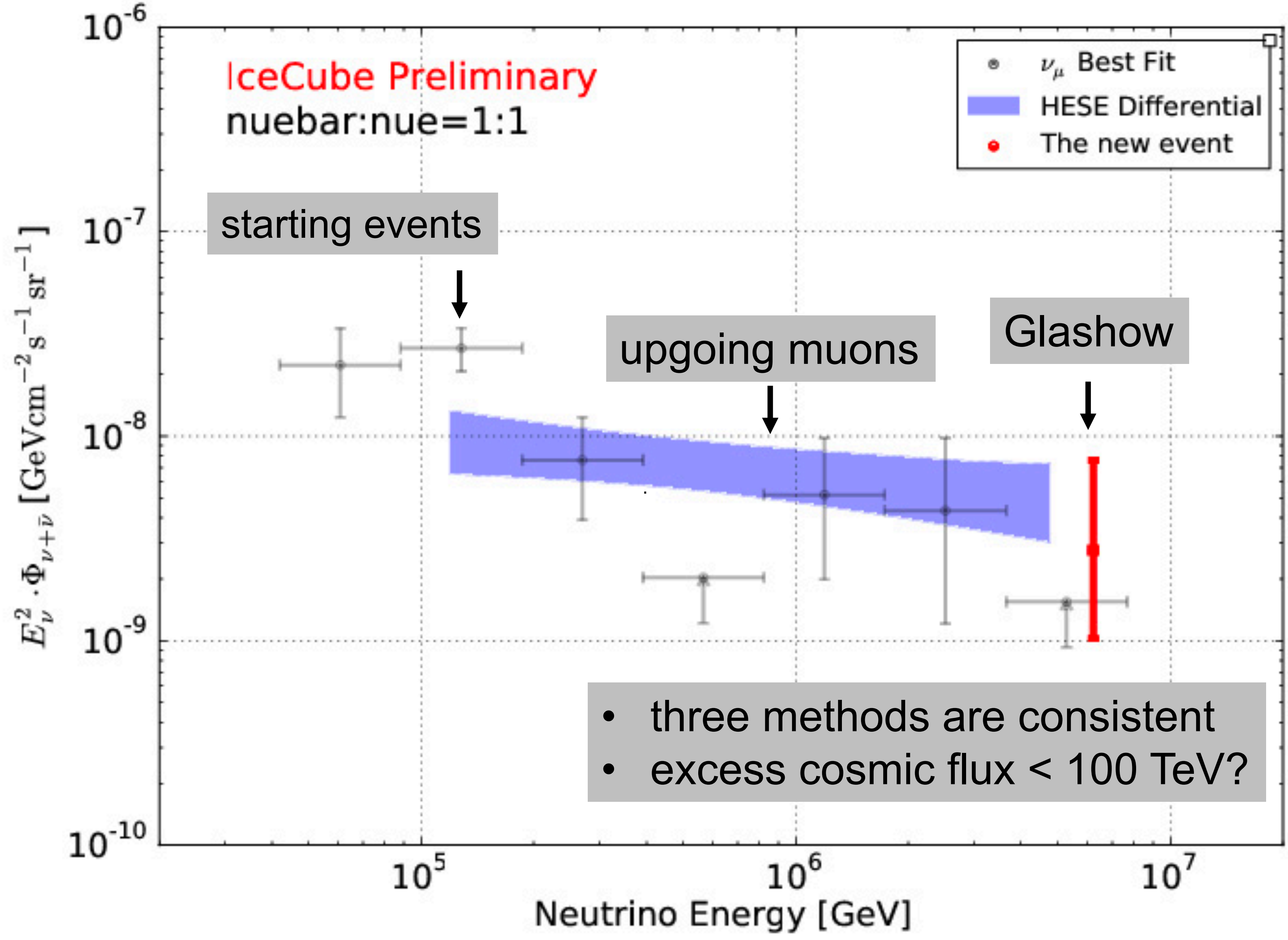




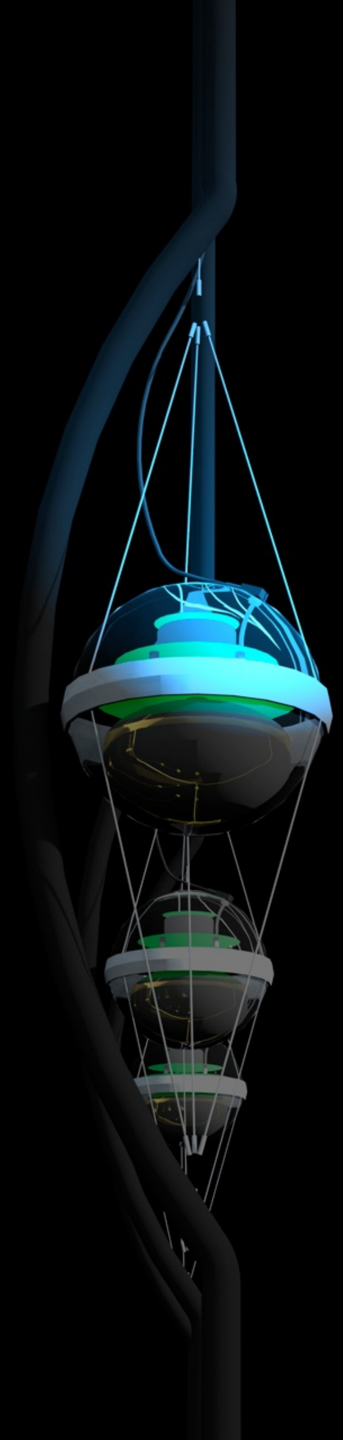
- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

- 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?
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^5
10^6
10^7



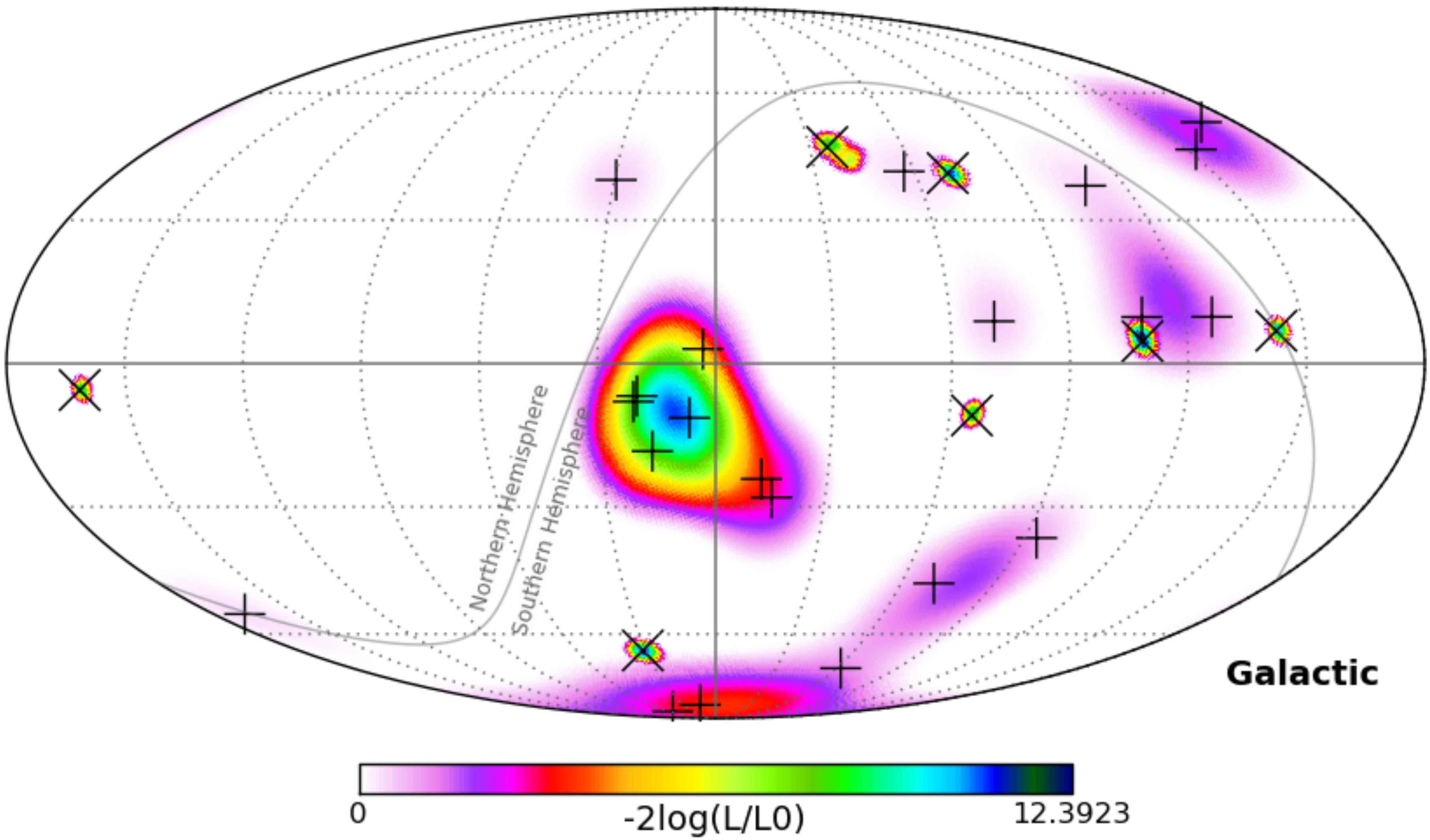
IceCube: the discovery of cosmic neutrinos

francis halzen

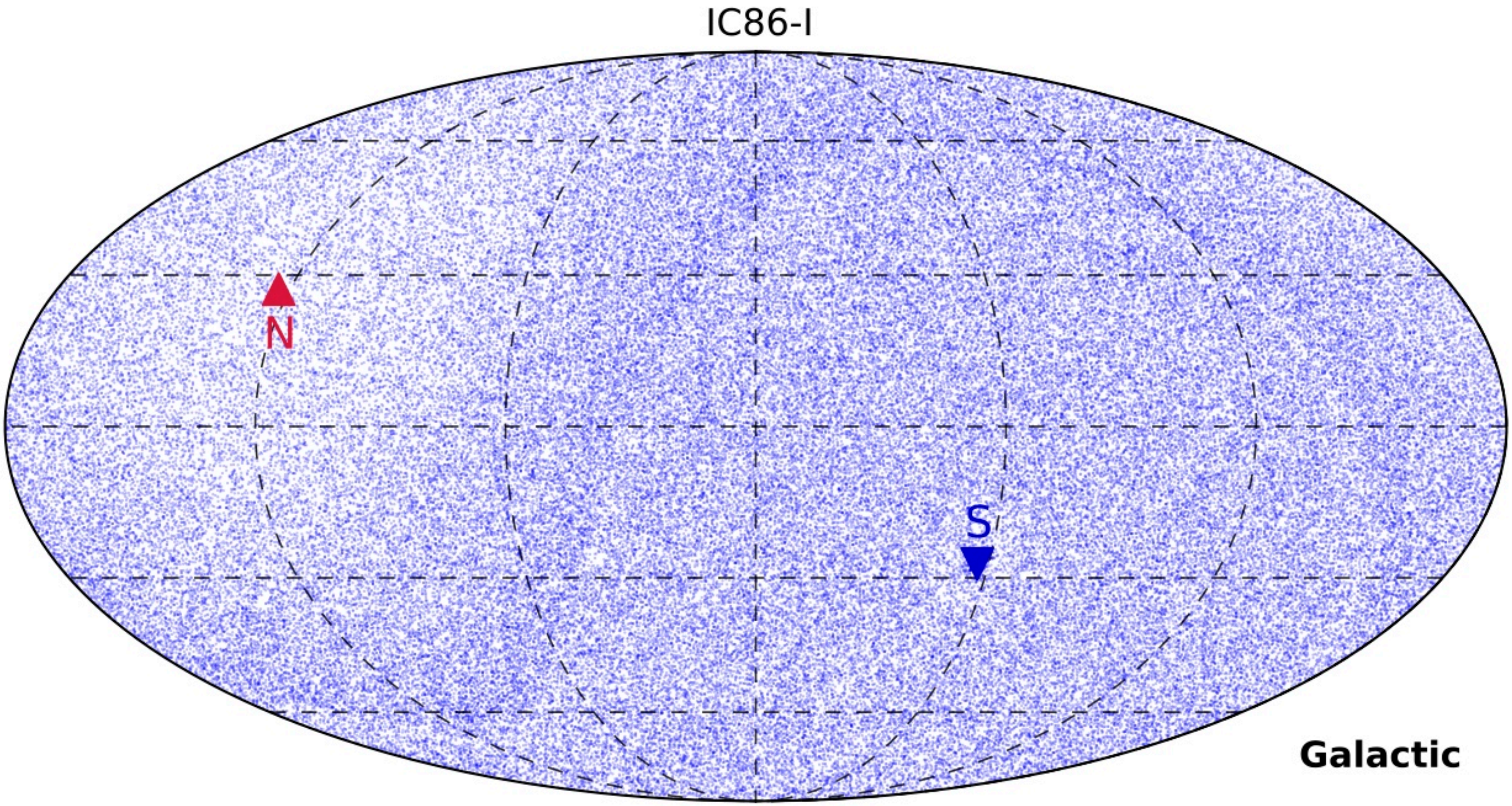
- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

2 year HESE



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

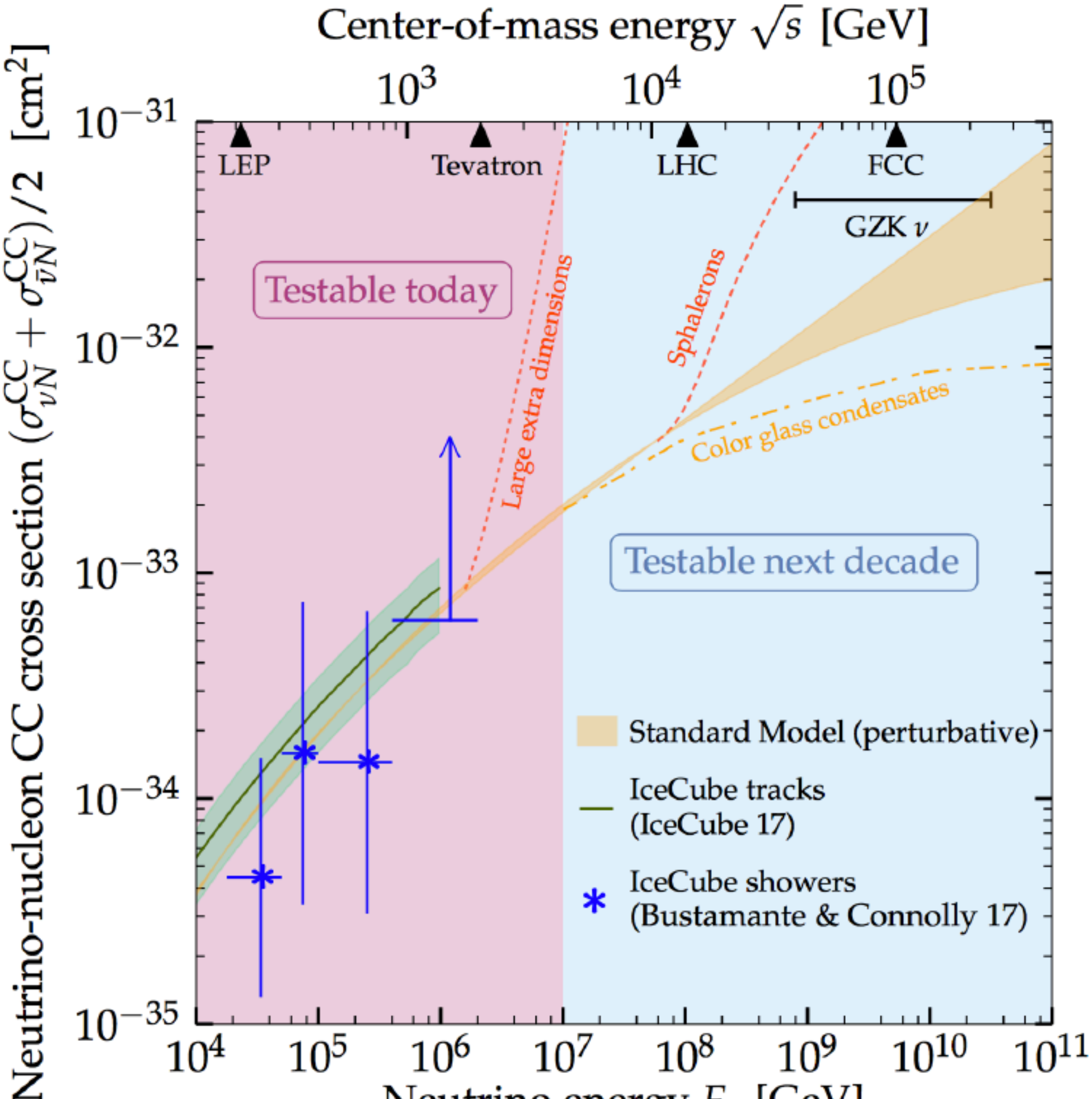


138322 neutrino candidates in one year

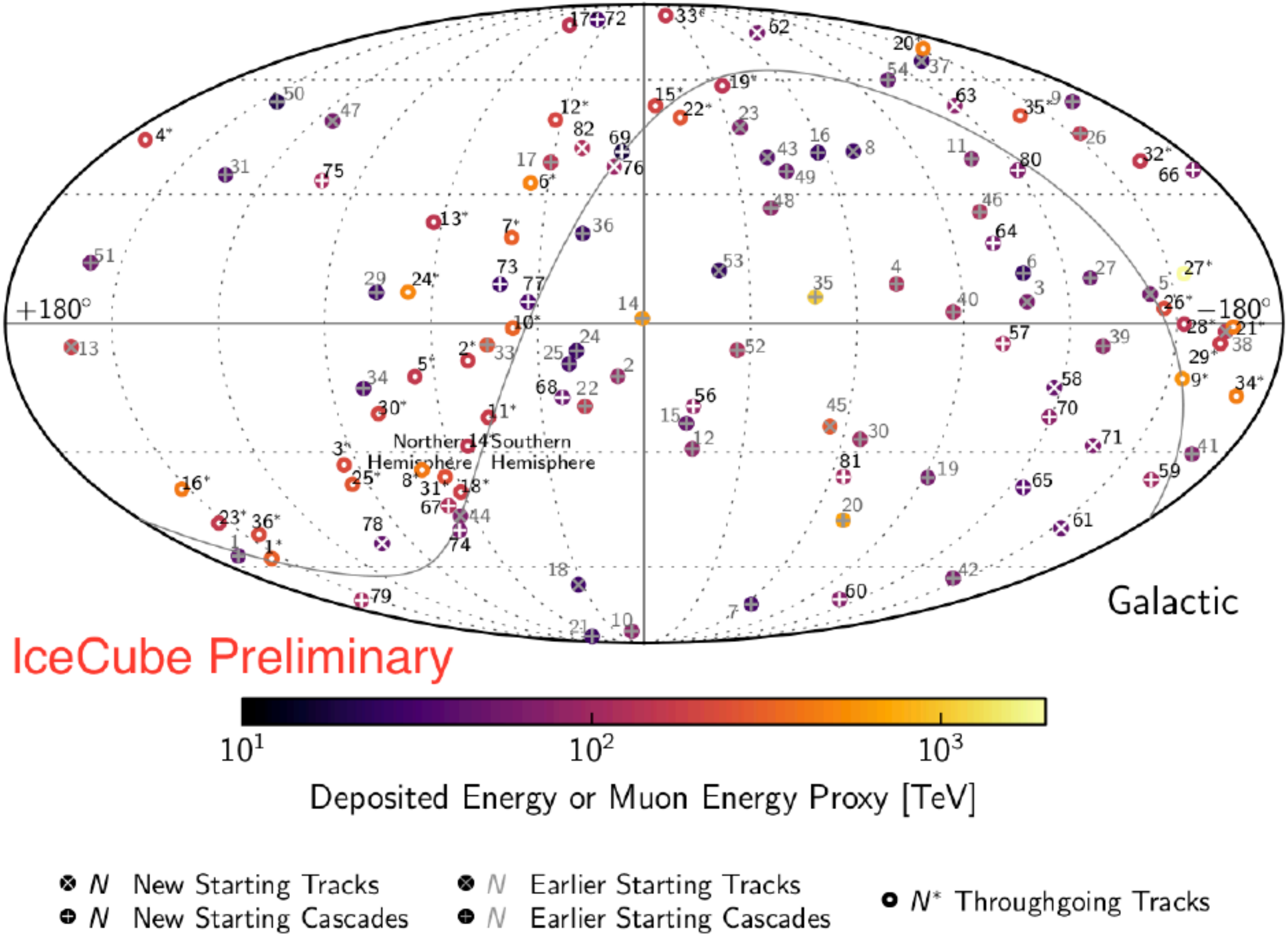
120 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

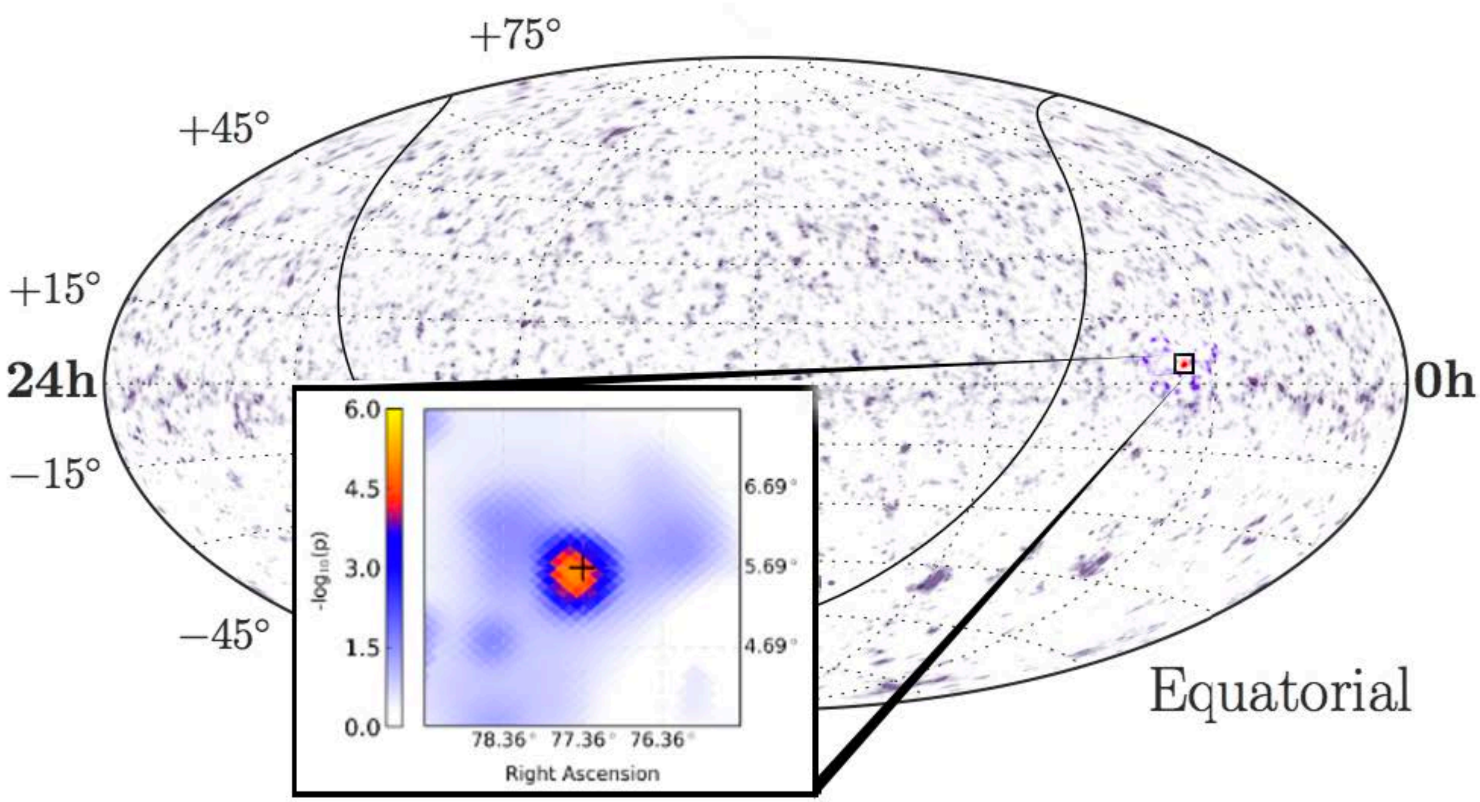
structure in the map results from neutrino absorption by the Earth



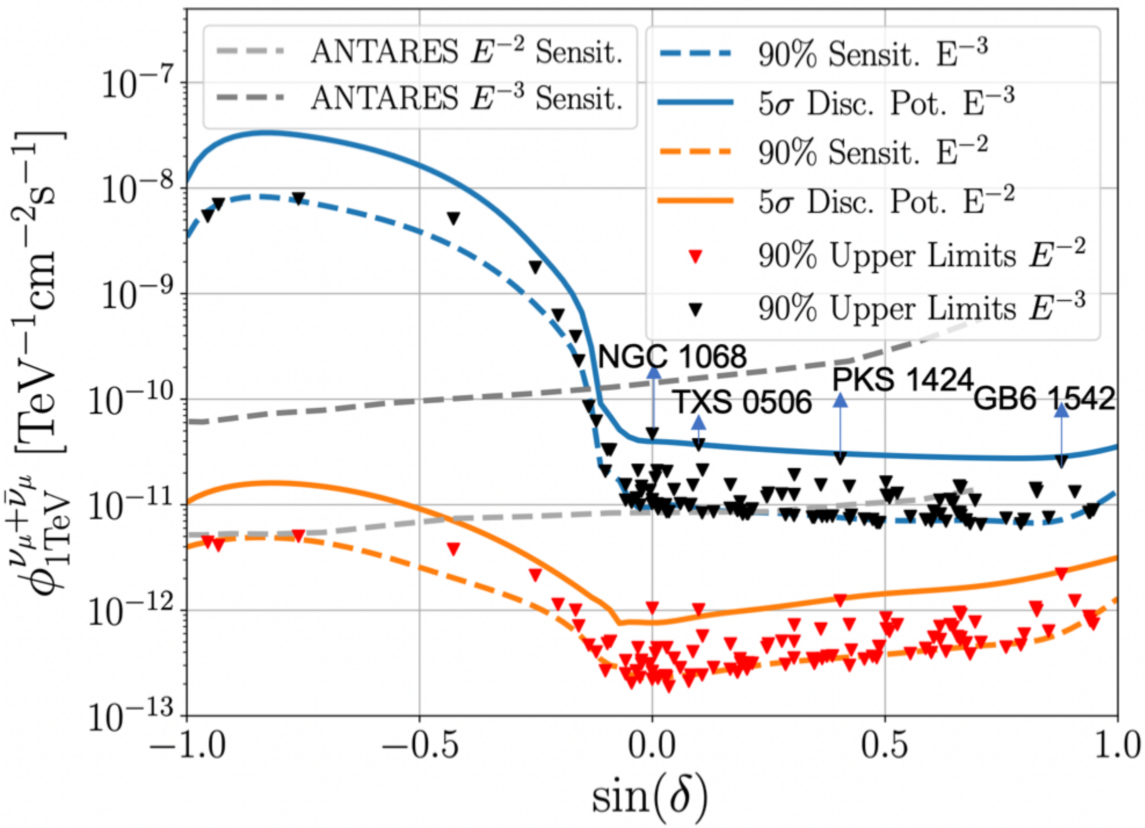
Center-of-mass energy $\sqrt{s}$ [GeV]
10^3
10^4
10^5
LEP
Tevatron
LHC
FCC
GZK ν
Testable today
Testable next decade
Large extra dimensions
Sphalerons
Color glass condensates
Standard Model (perturbative)
IceCube tracks (IceCube 17)
IceCube showers (Bustamante & Connolly 17)
Neutrino-nucleon CC cross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

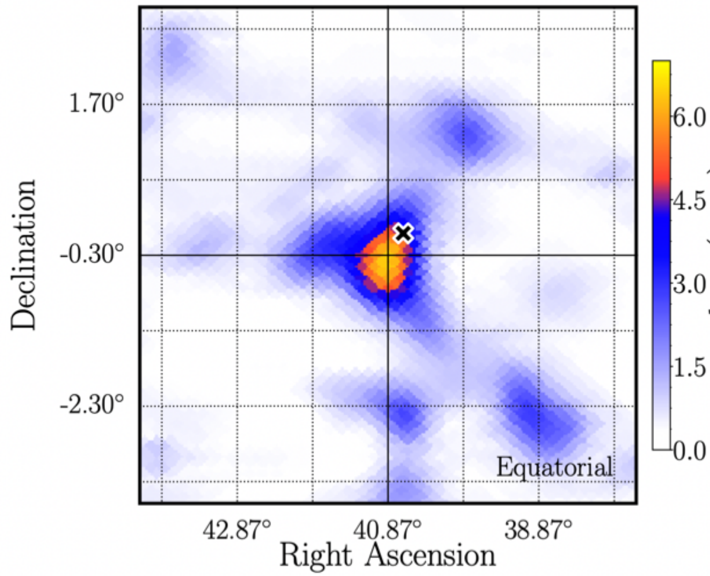

Galactic
+180°
−180°
Northern Hemisphere
Southern Hemisphere
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

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



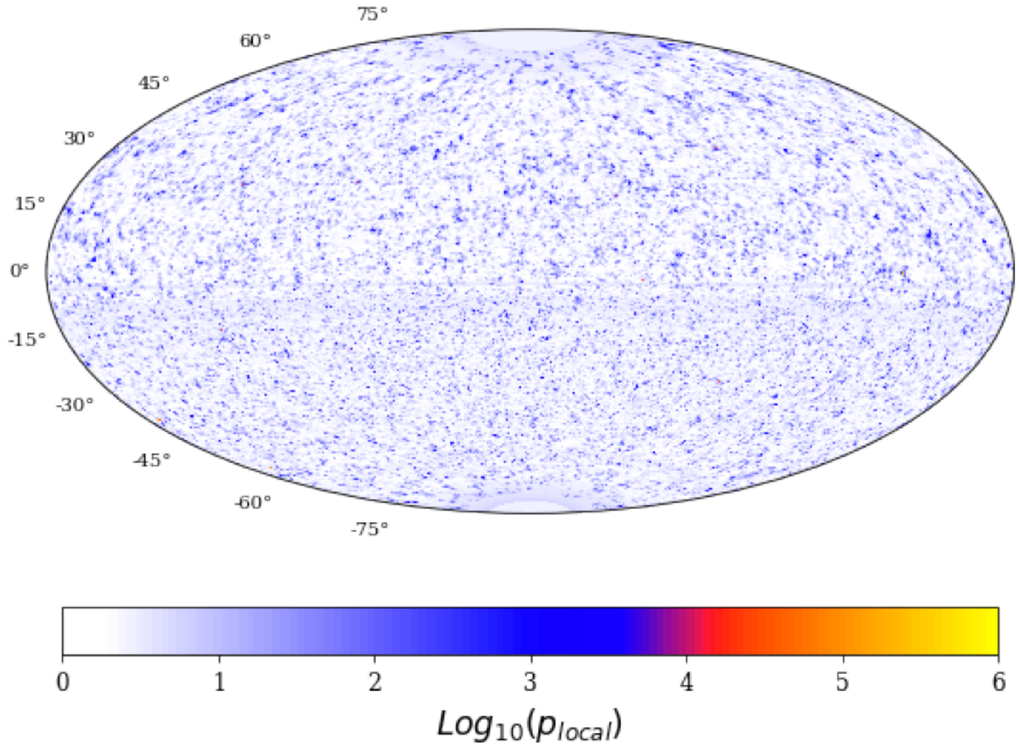
10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates

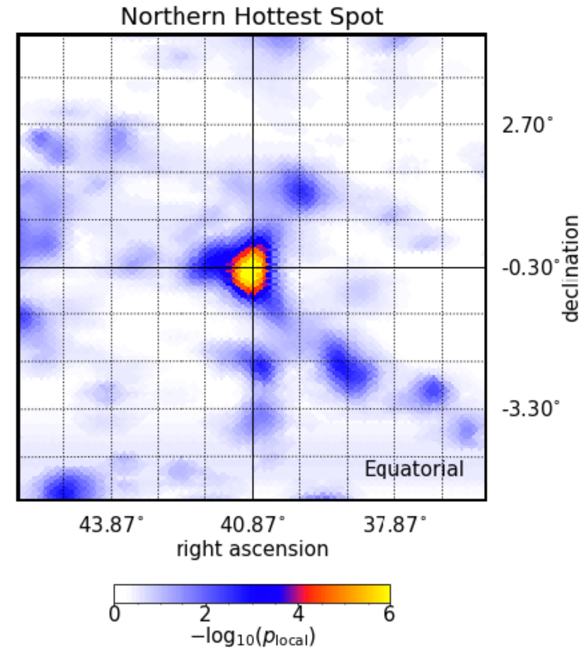




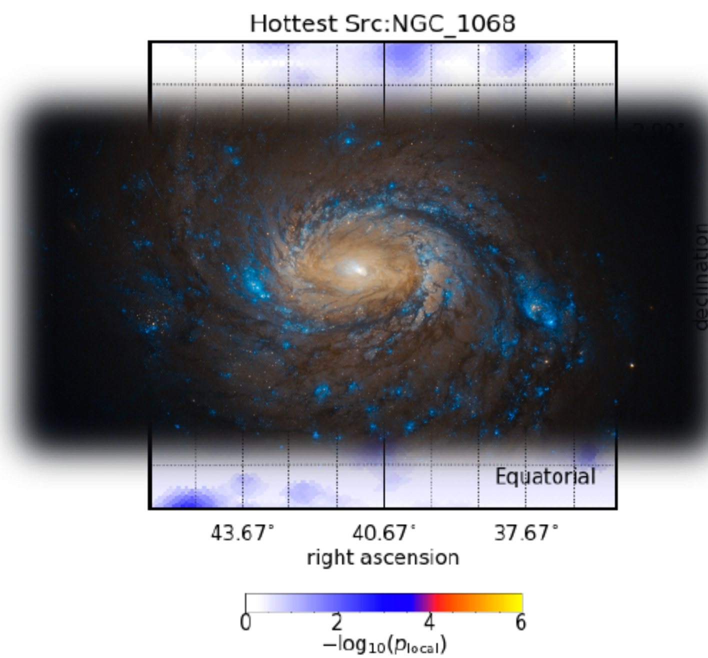
hottest spot: NGC 1068

10 years of muon neutrinos



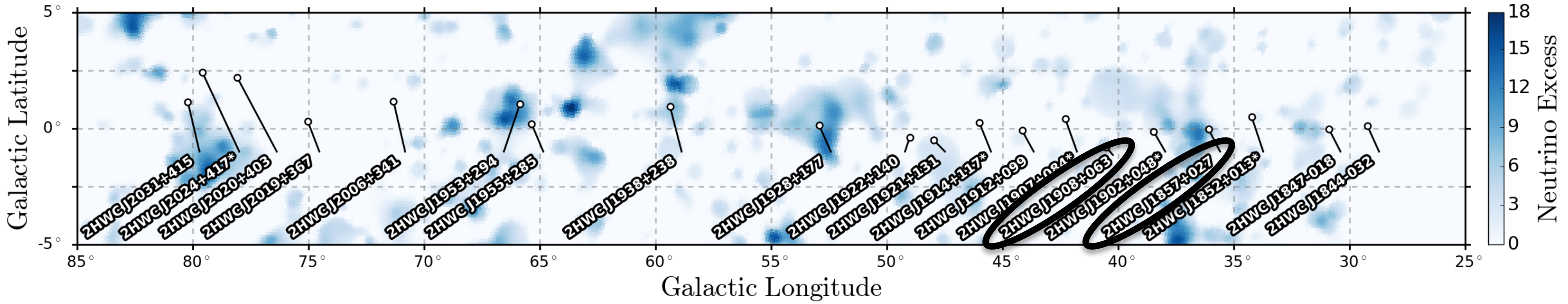


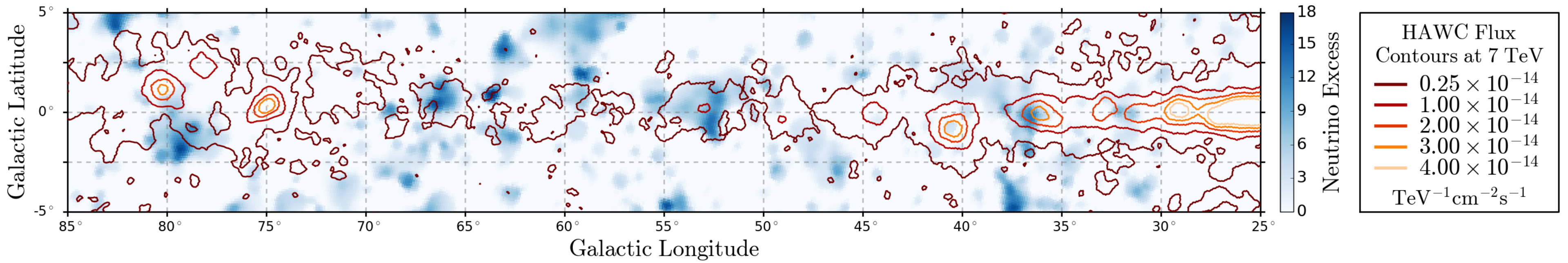
Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496



Tessa Carver

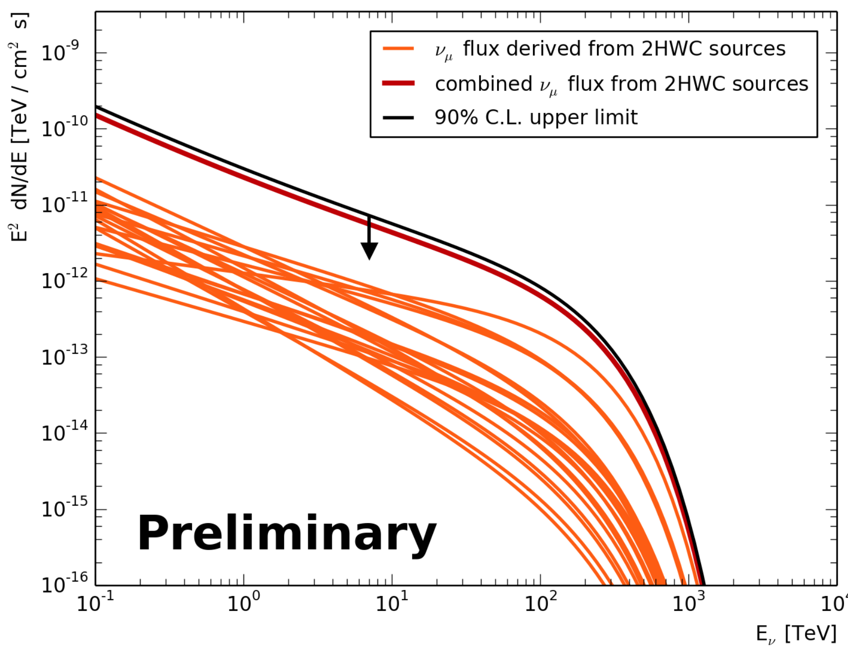
- we observe a diffuse flux of neutrinos from extragalactic sources
- skymap reveals structure at the 3σ level associated with 4 sources
- a subdominant Galactic component is emerging but does not reach 3σ level
- where are the PeV gamma rays that accompany PeV neutrinos?

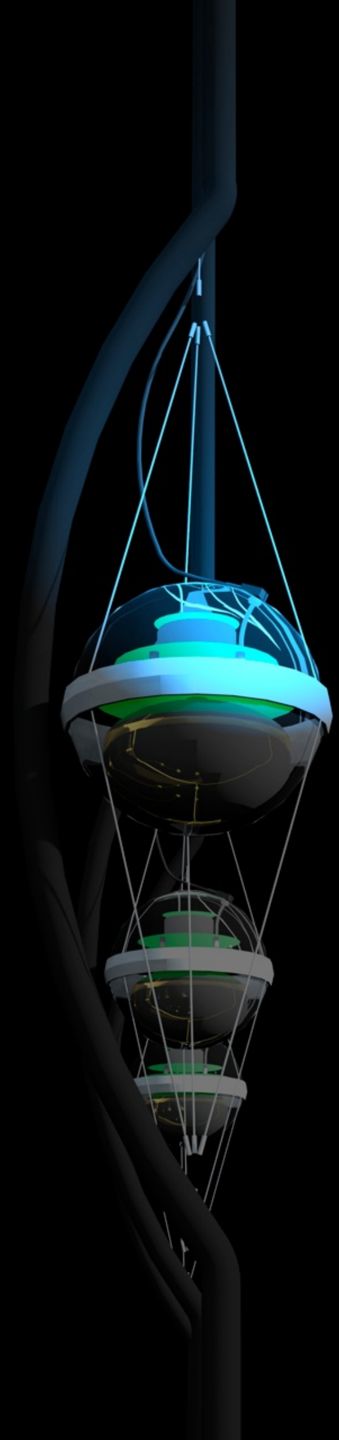




HAWC photons and IceCube neutrinos

neutrino flux at the level predicted, but not significant yet





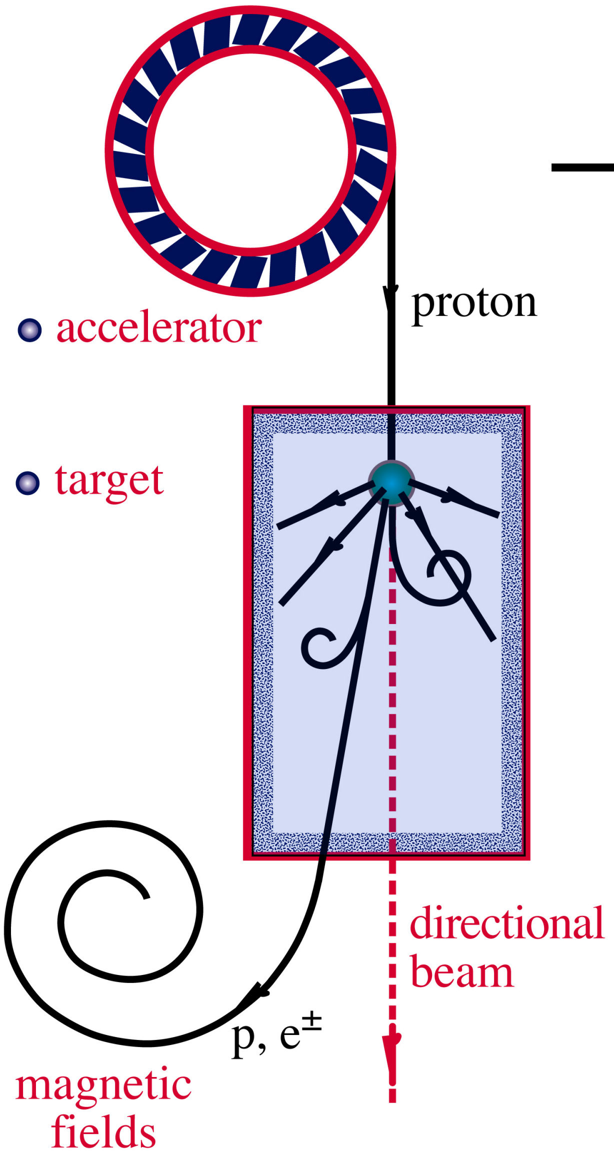
IceCube

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

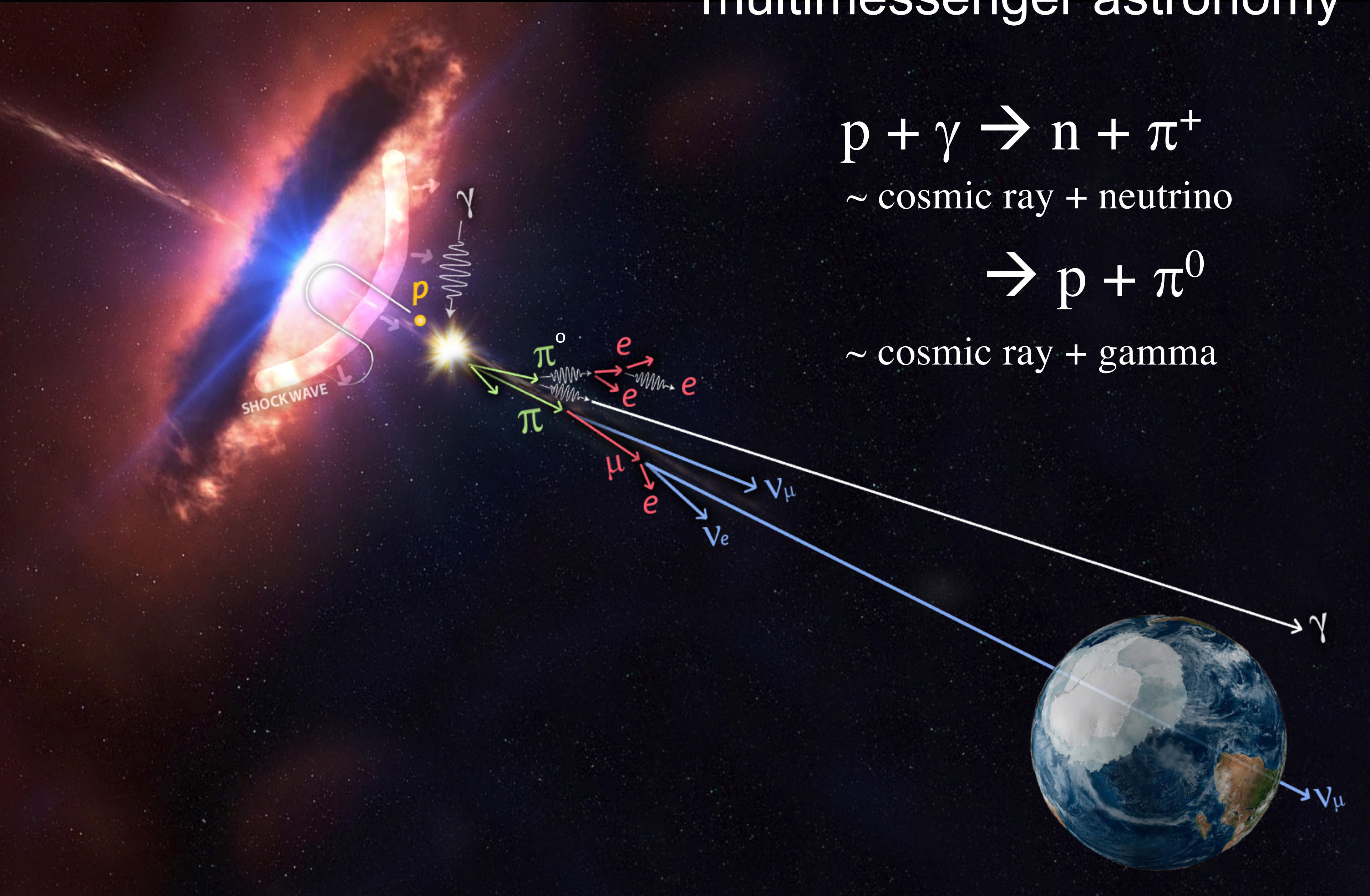
multimessenger astronomy

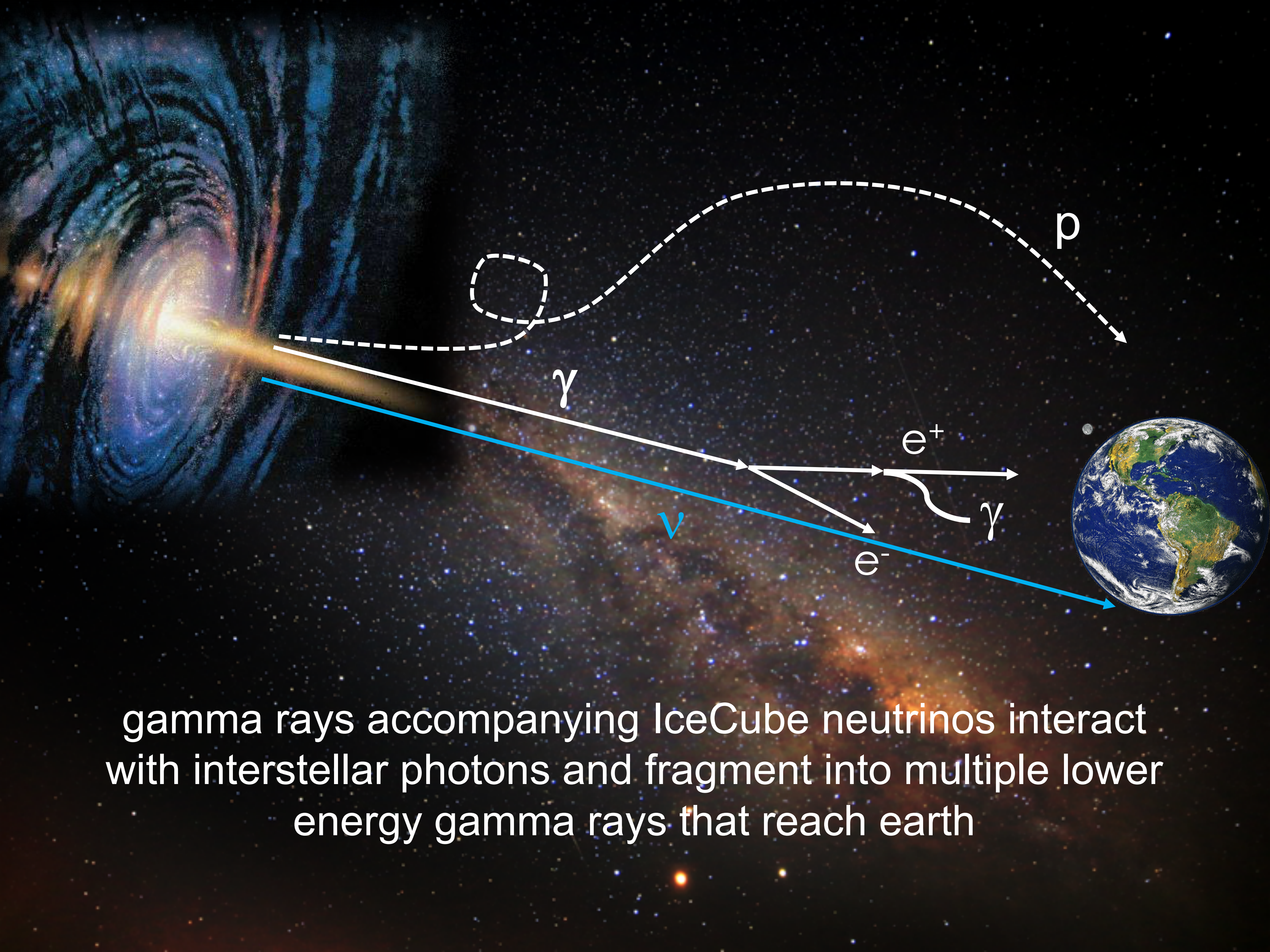
$$p + \gamma \rightarrow n + \pi^+$$

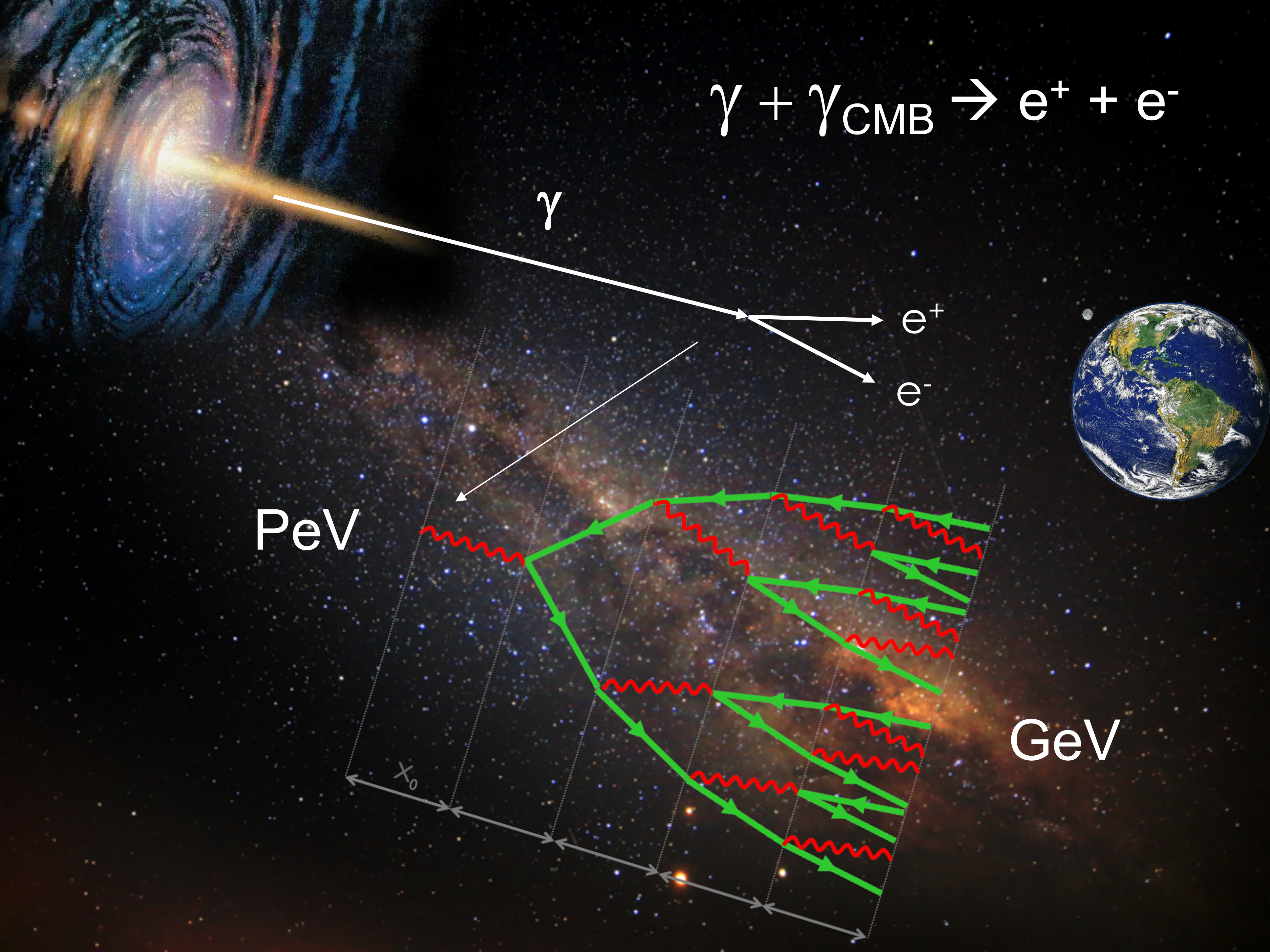
~ cosmic ray + neutrino

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

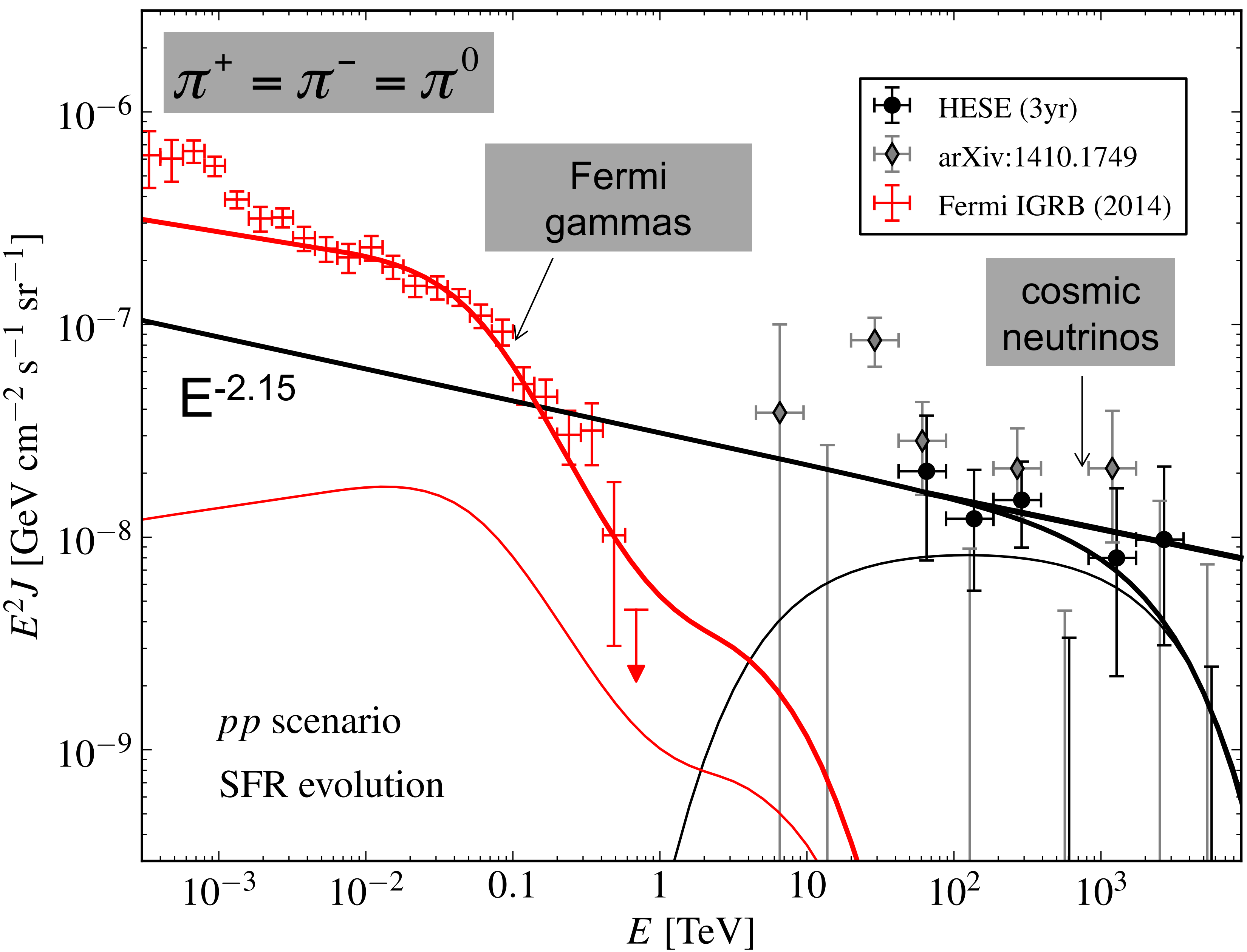
~ cosmic ray + gamma



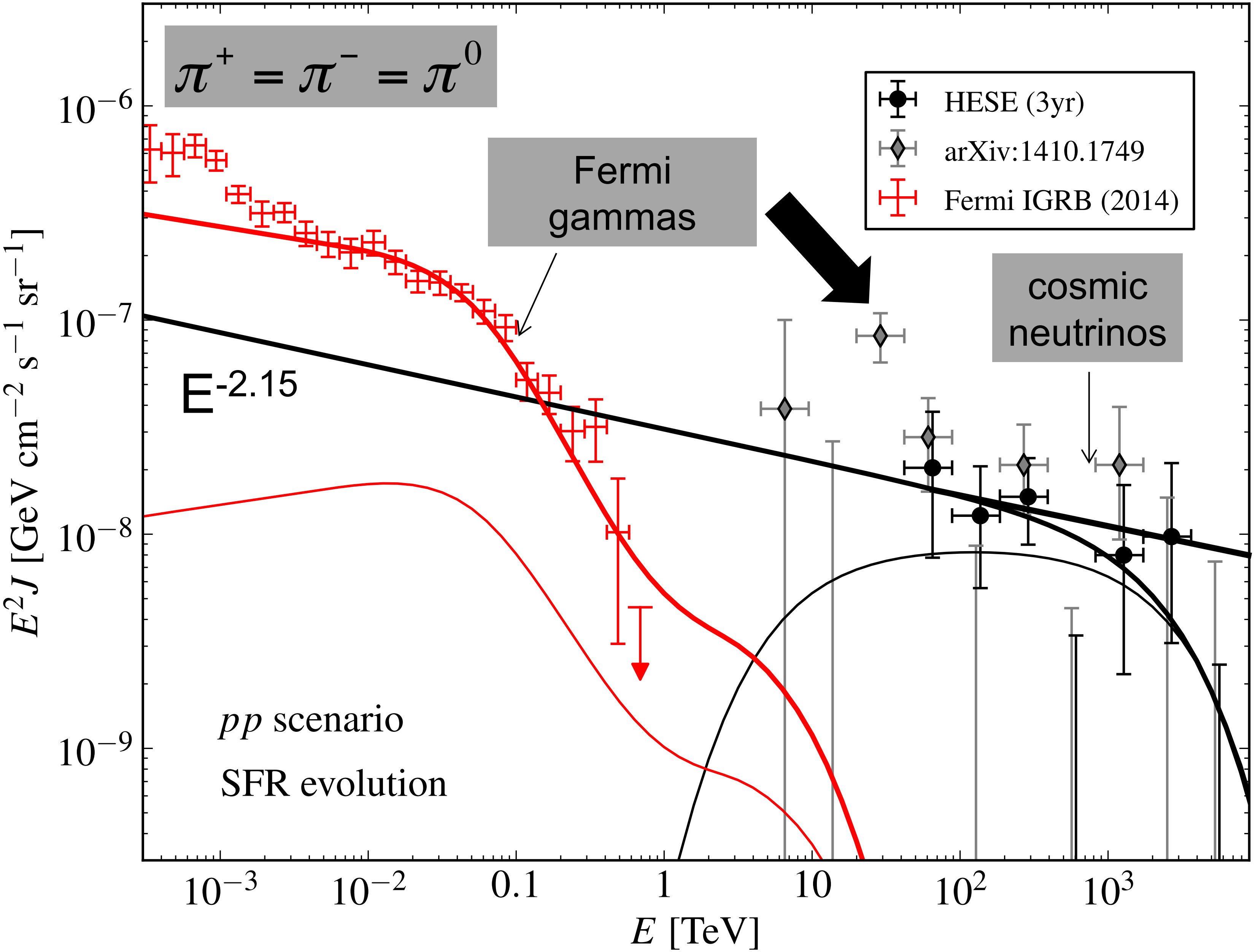

p
γ
e+
γ
ν
e-
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



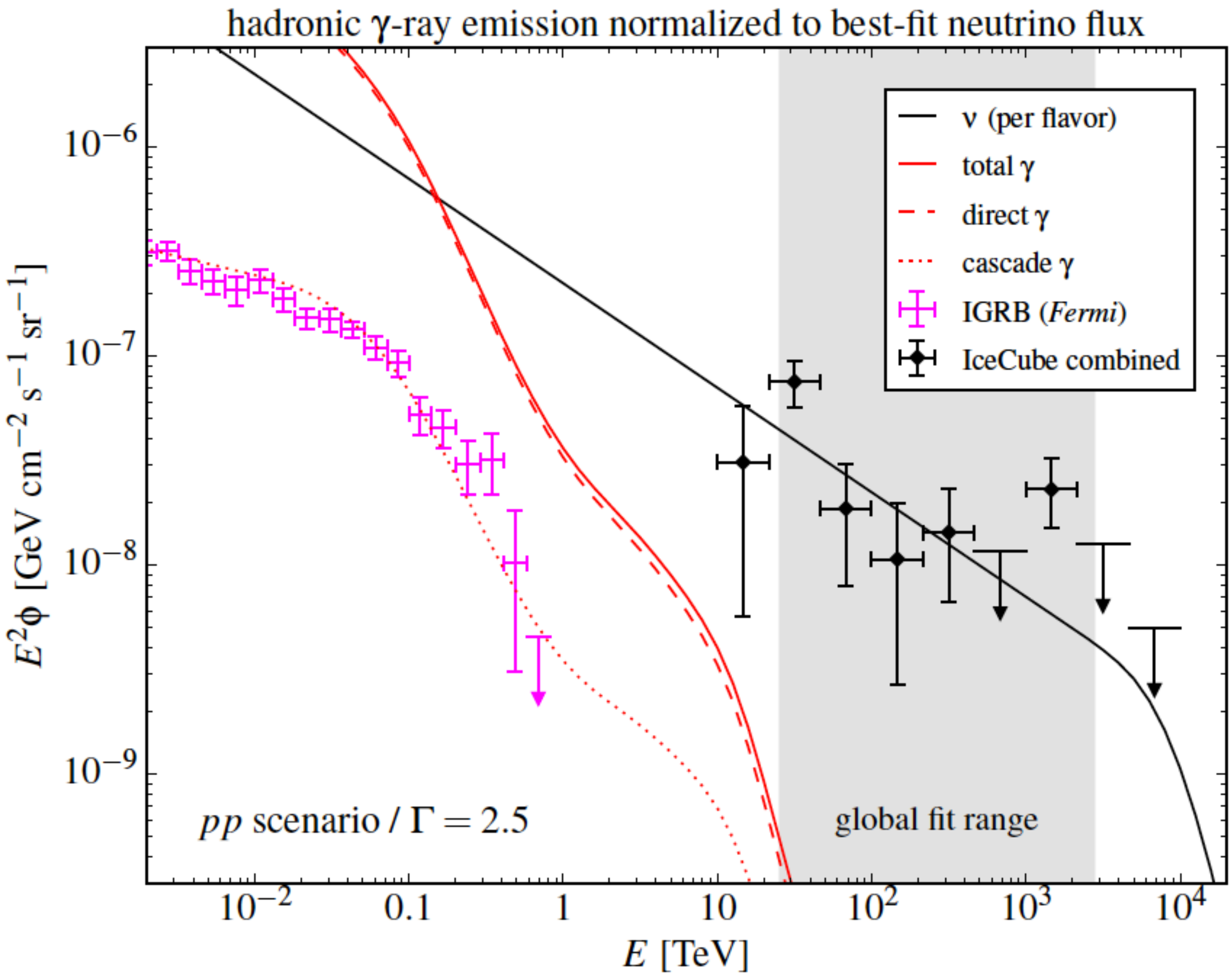
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
X_0
GeV


$\pi^+ = \pi^- = \pi^0$
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

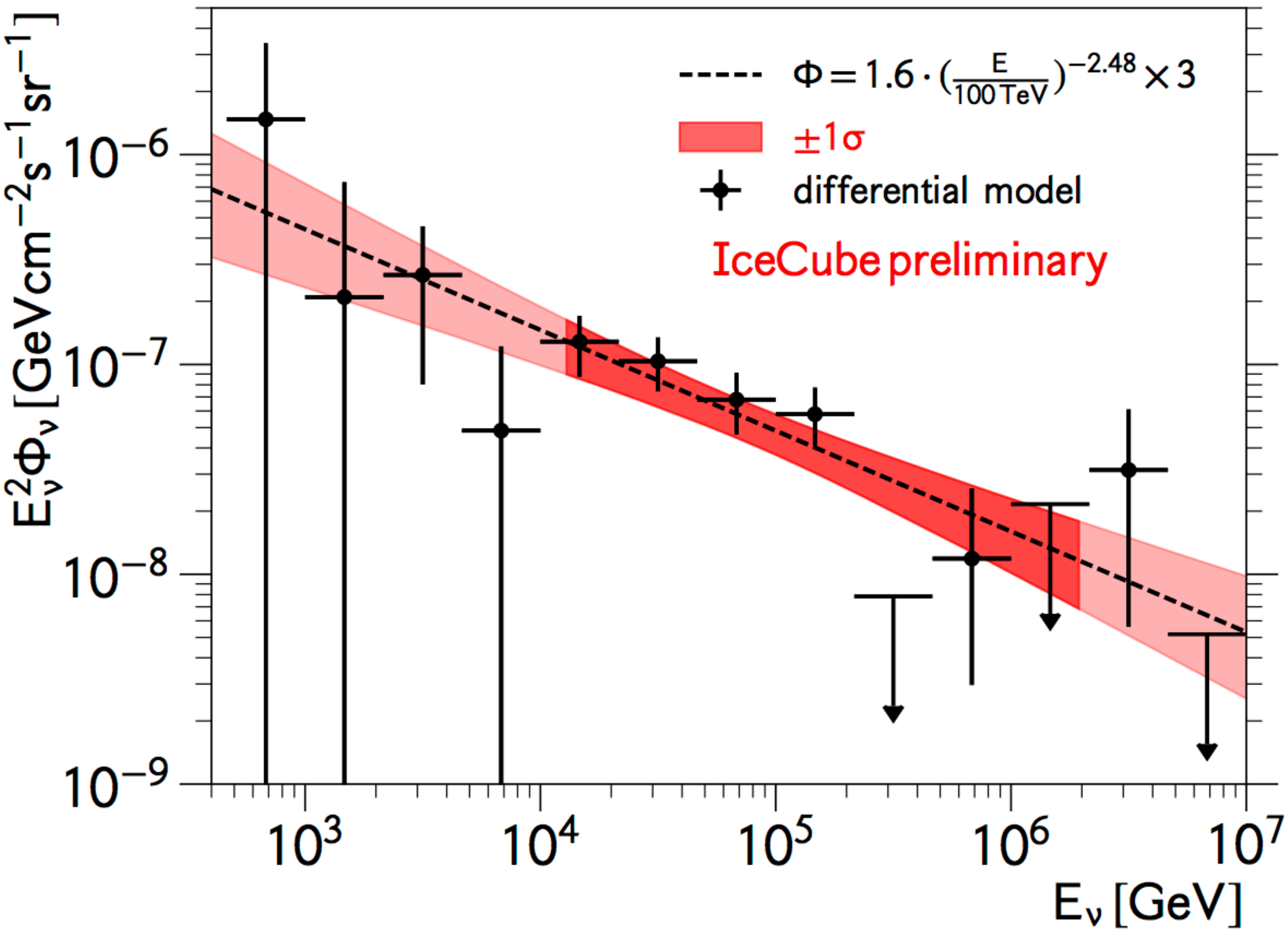


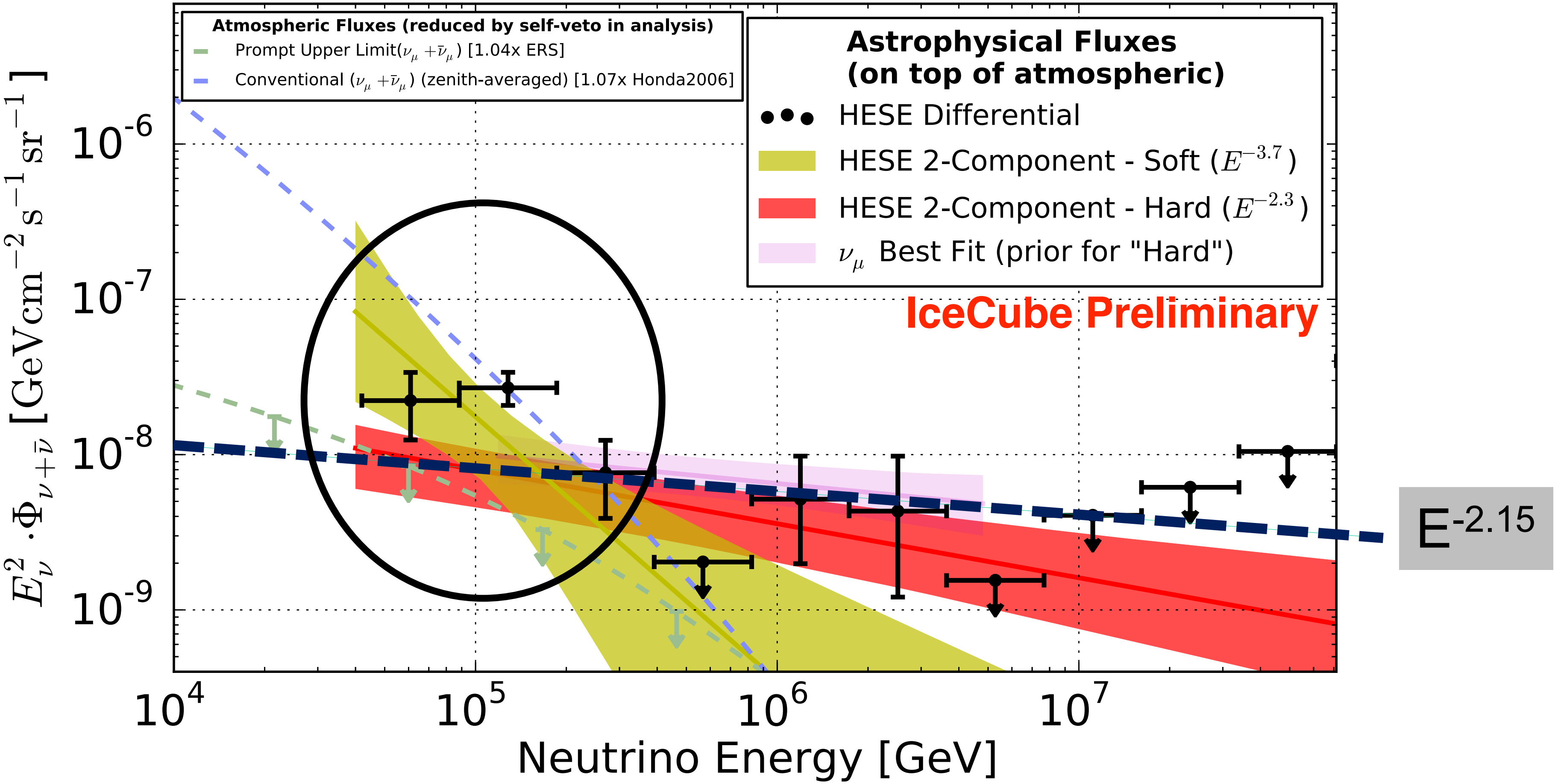
$\pi^+ = \pi^- = \pi^0$
Fermi gammas
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



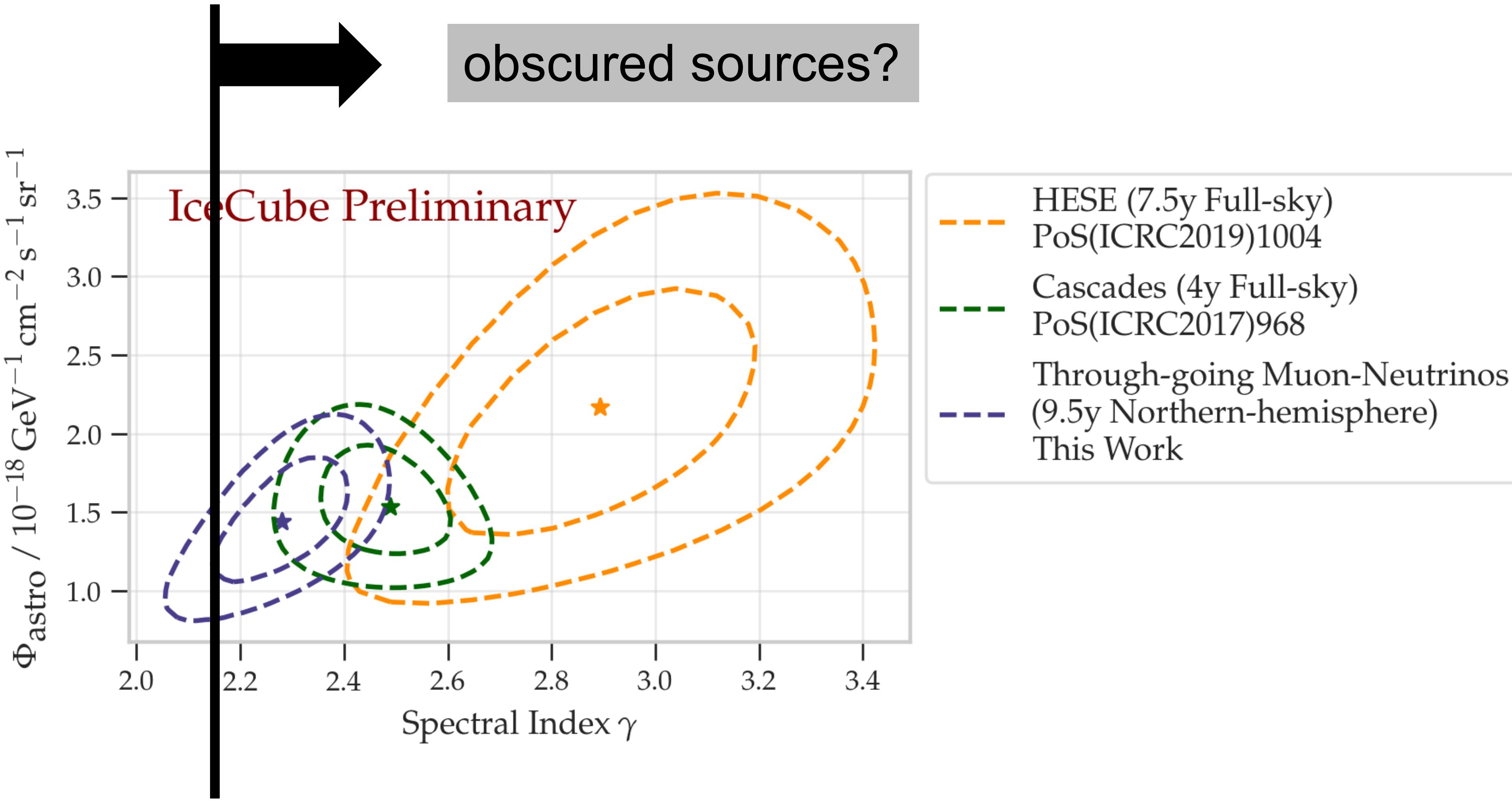
dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to lower energy

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

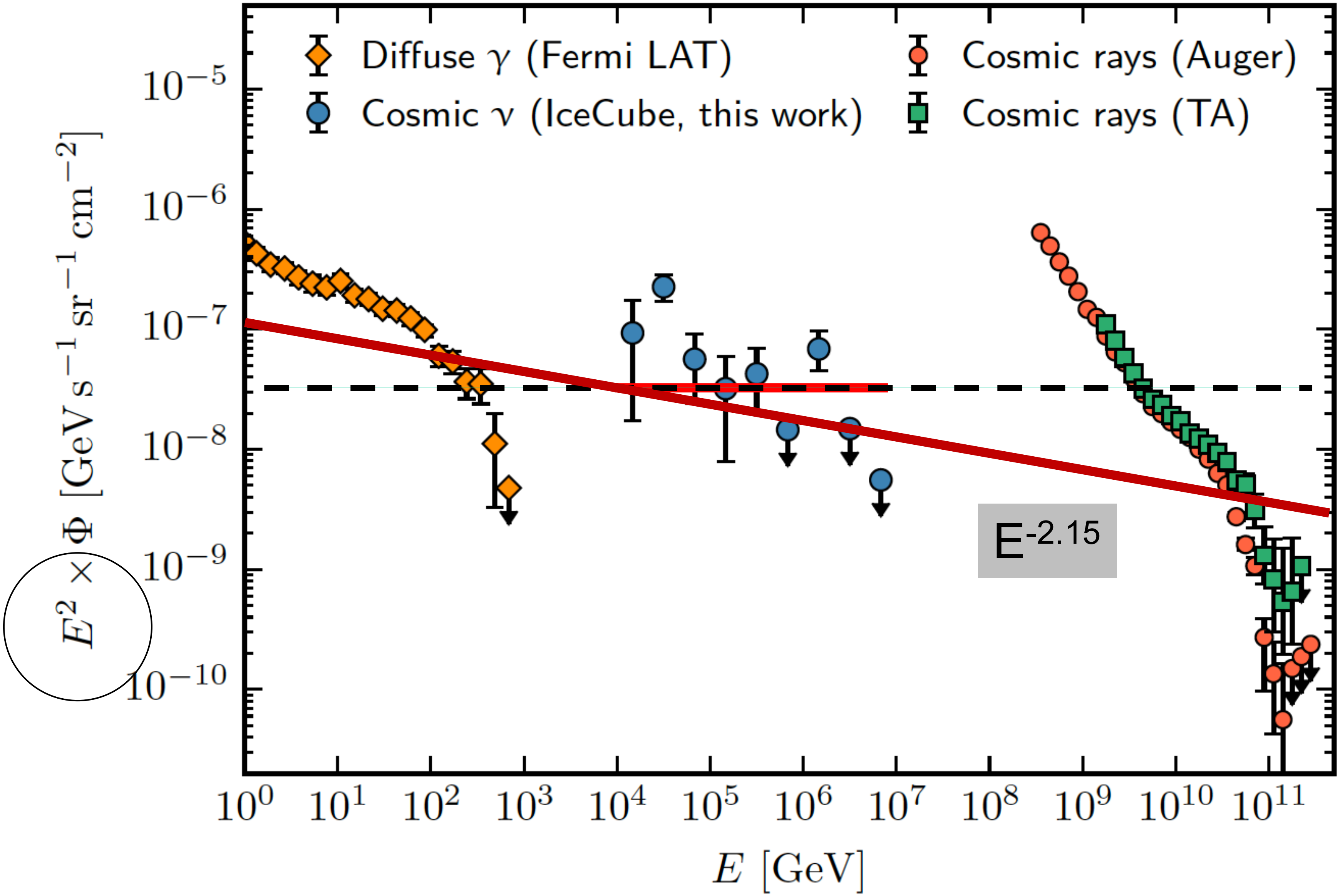




excess gamma rays relative to Fermi flux? Obscured sources?



obscured sources?
IceCube Preliminary
Φ_{astro} / 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
3.5
3.0
2.5
2.0
1.5
1.0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Spectral Index γ
HESE (7.5y Full-sky)
PoS(ICRC2019)1004
Cascades (4y Full-sky)
PoS(ICRC2017)968
Through-going Muon-Neutrinos
(9.5y Northern-hemisphere)
This Work



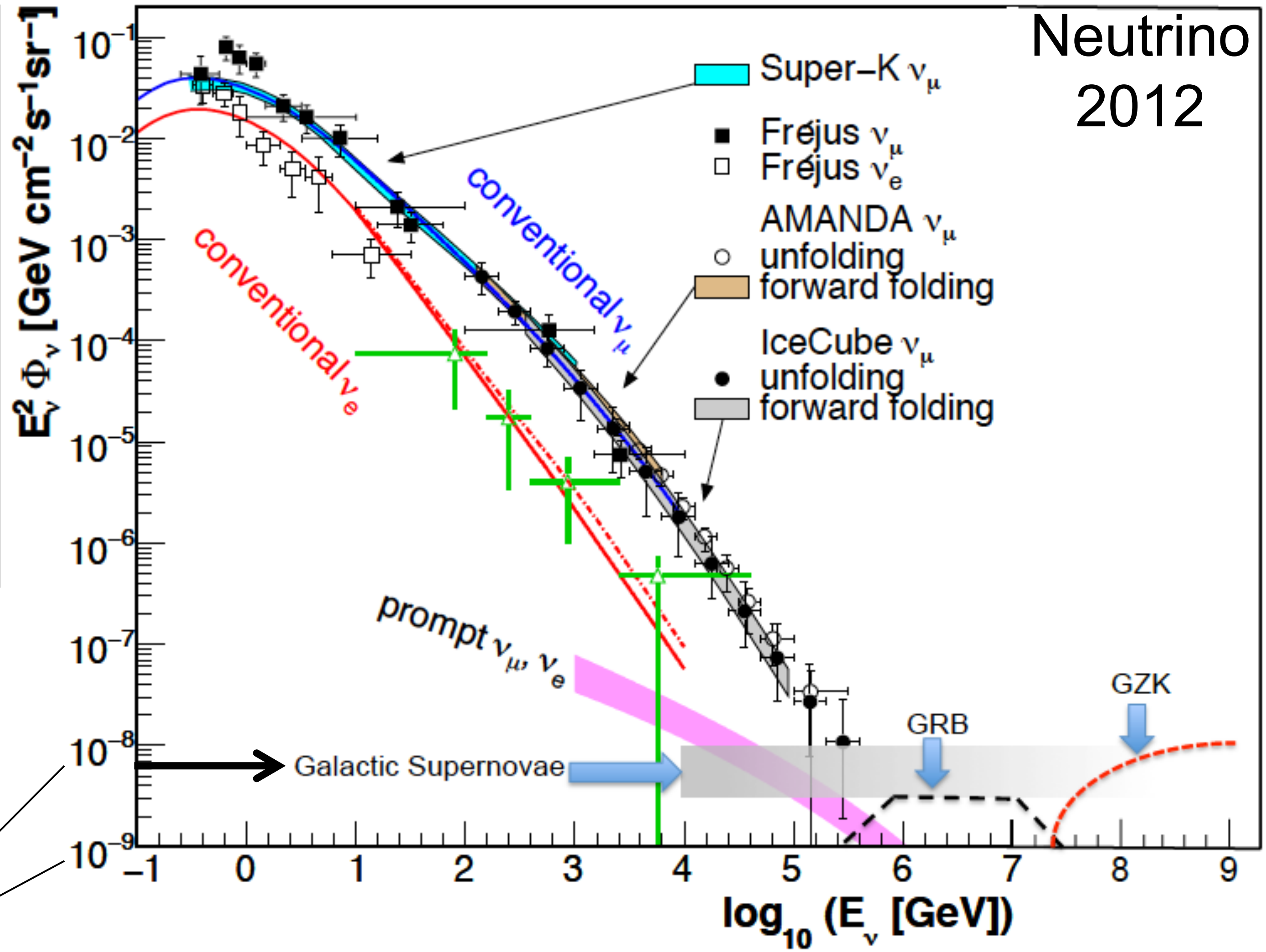
energy in the Universe in gamma rays, neutrinos and cosmic rays

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

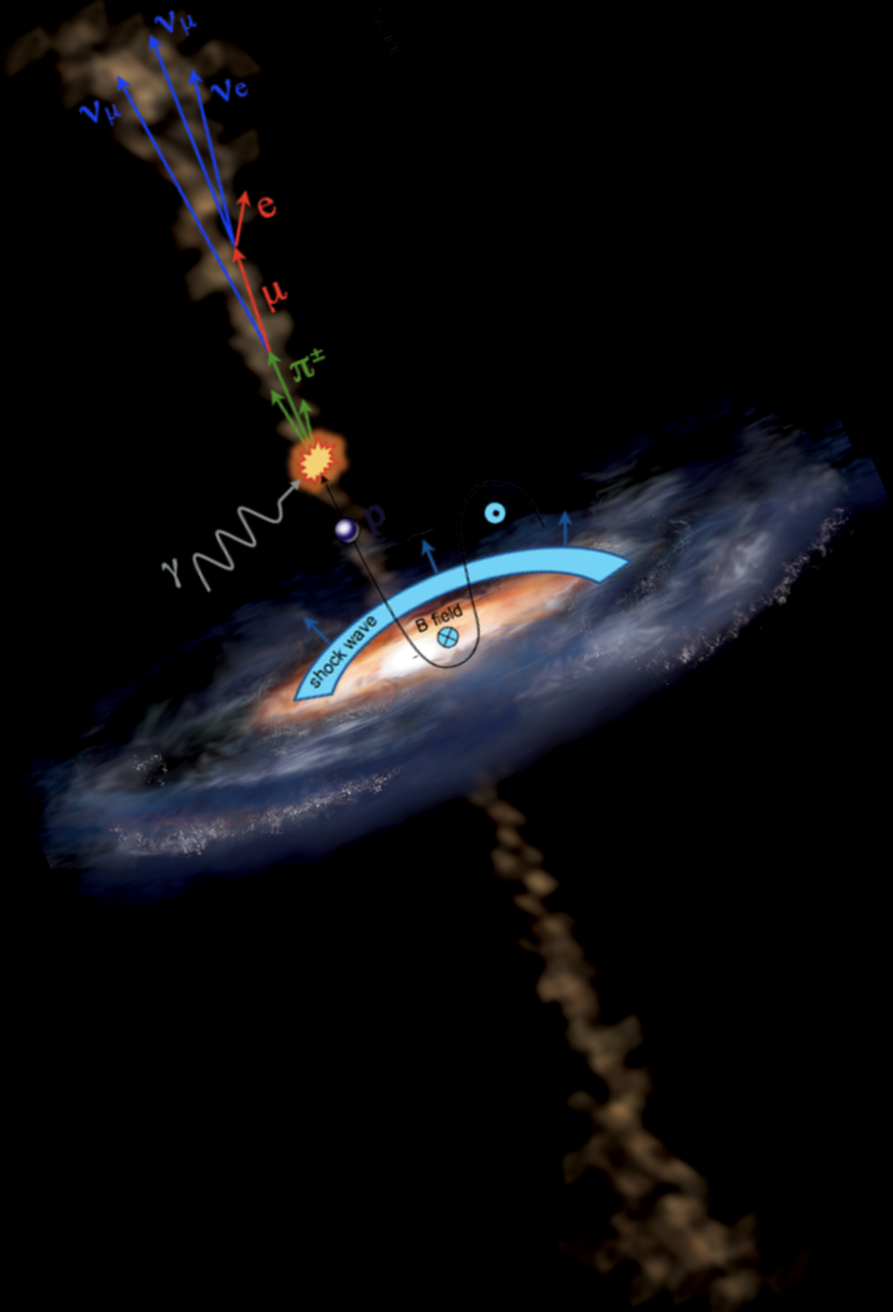
why was this a correct prediction?



atmospheric

cosmic

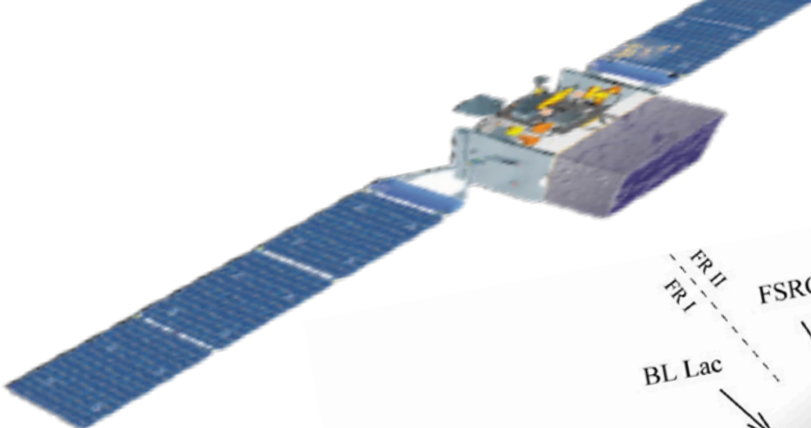
100 TeV

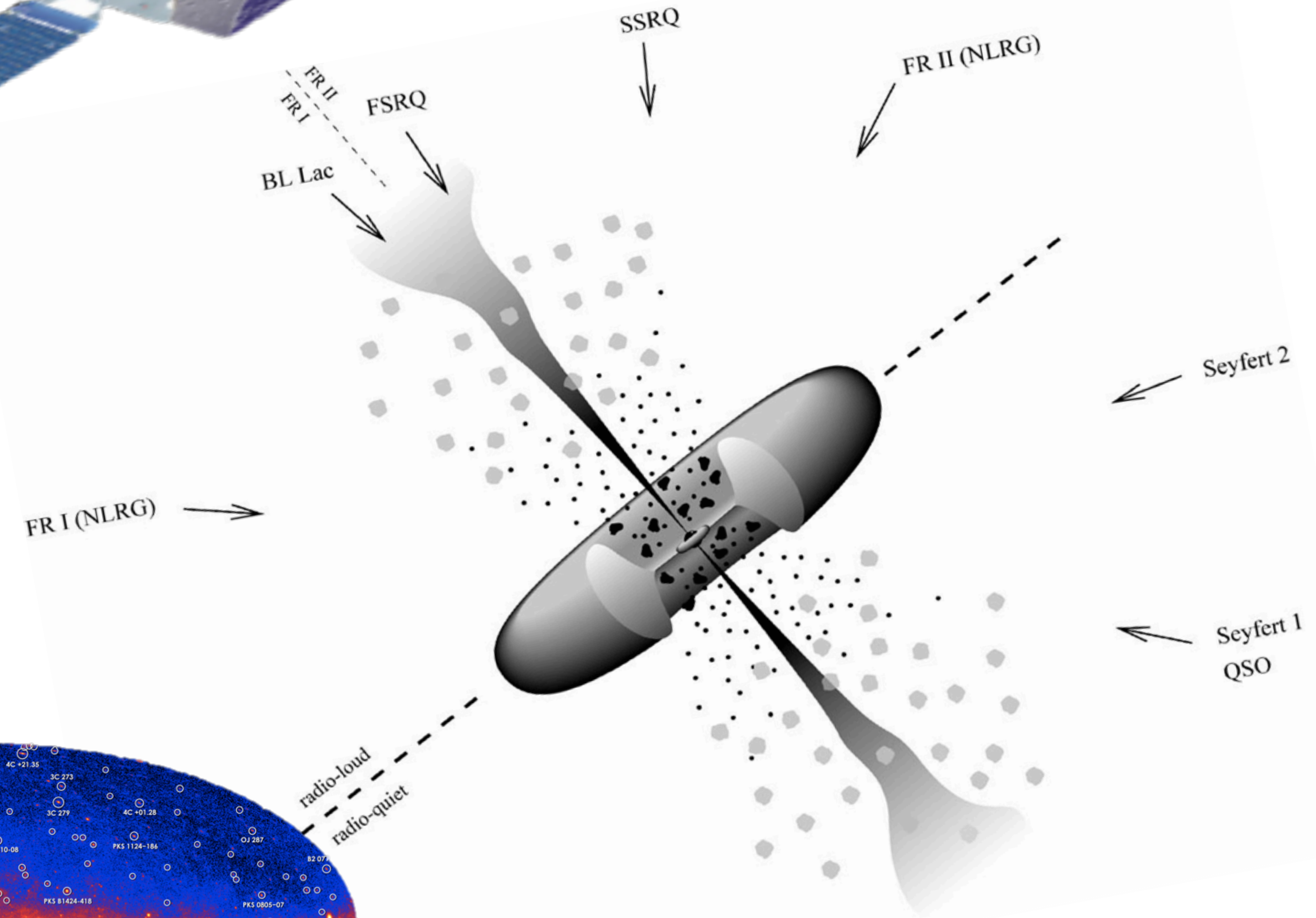


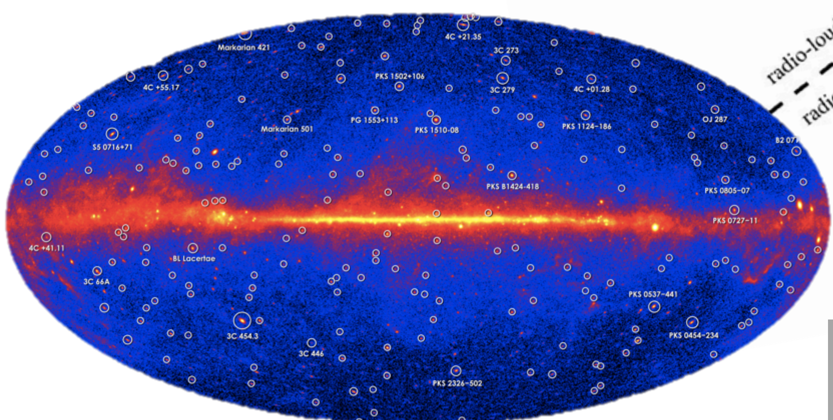
Fermi sources
are mostly
blazars

common sources?

→
multimessenger
astronomy





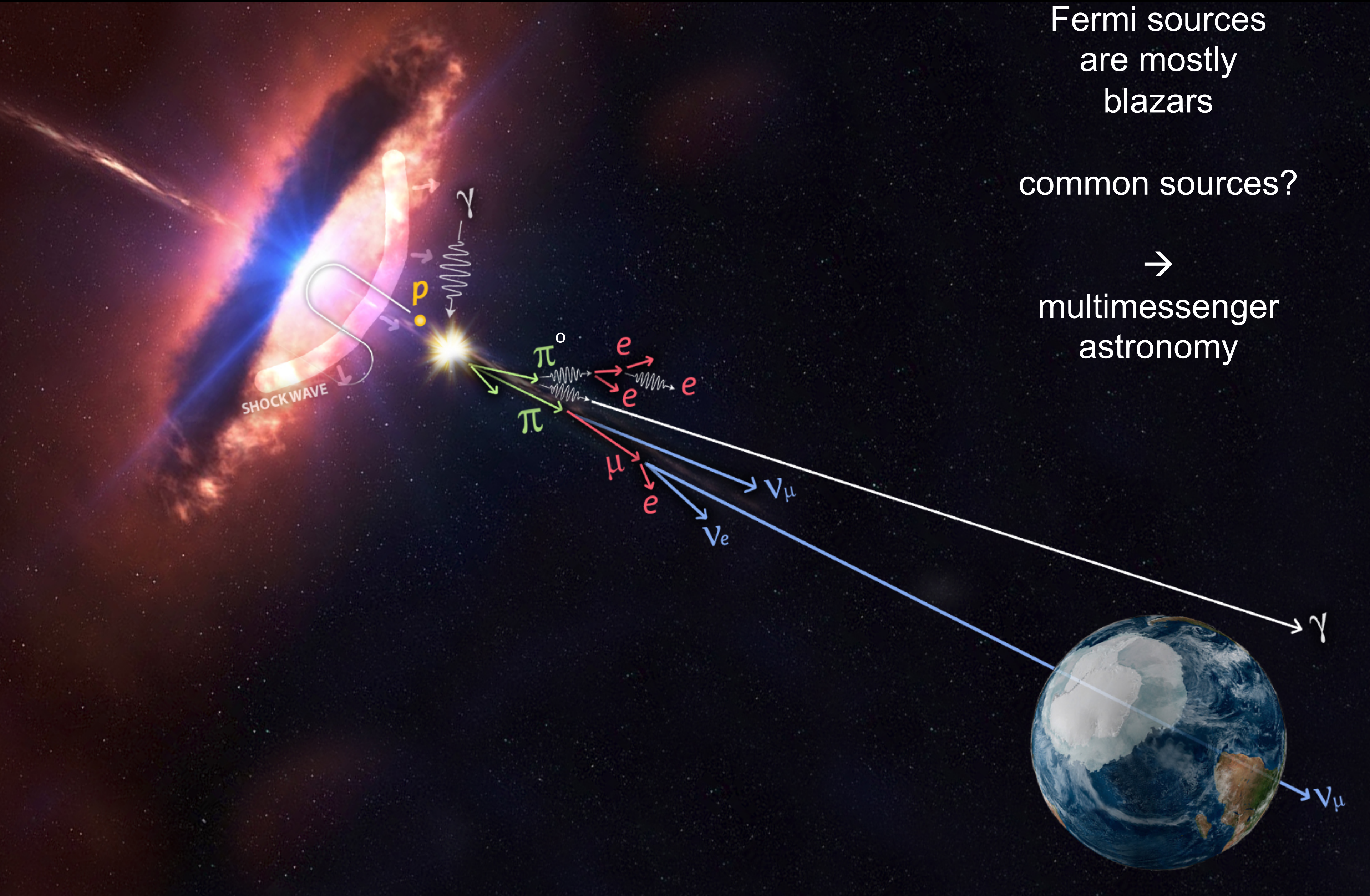


Fermi sky: mostly bazars

Fermi sources
are mostly
blazars

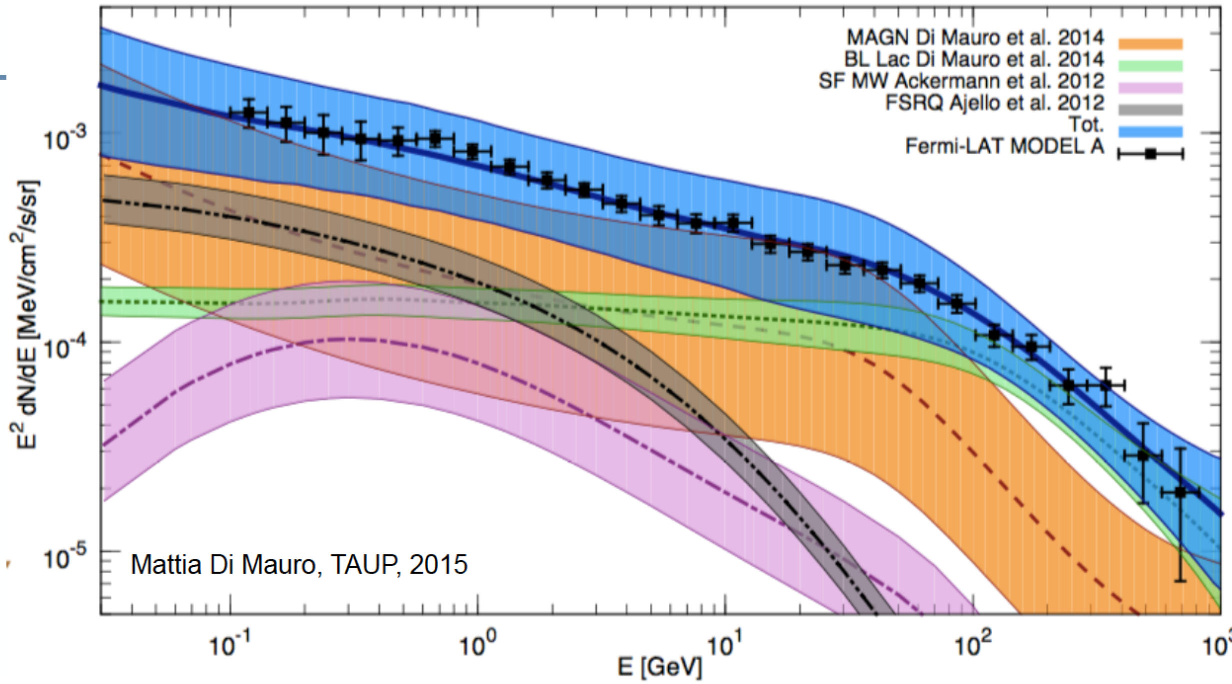
common sources?

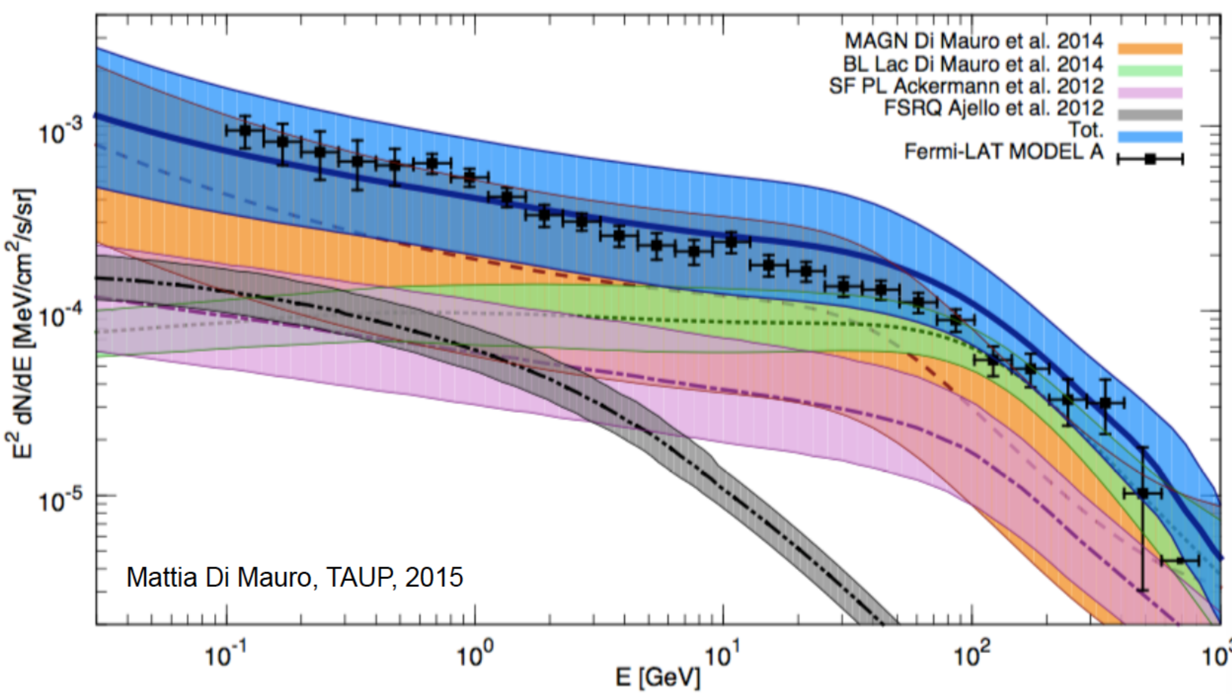
→
multimessenger
astronomy

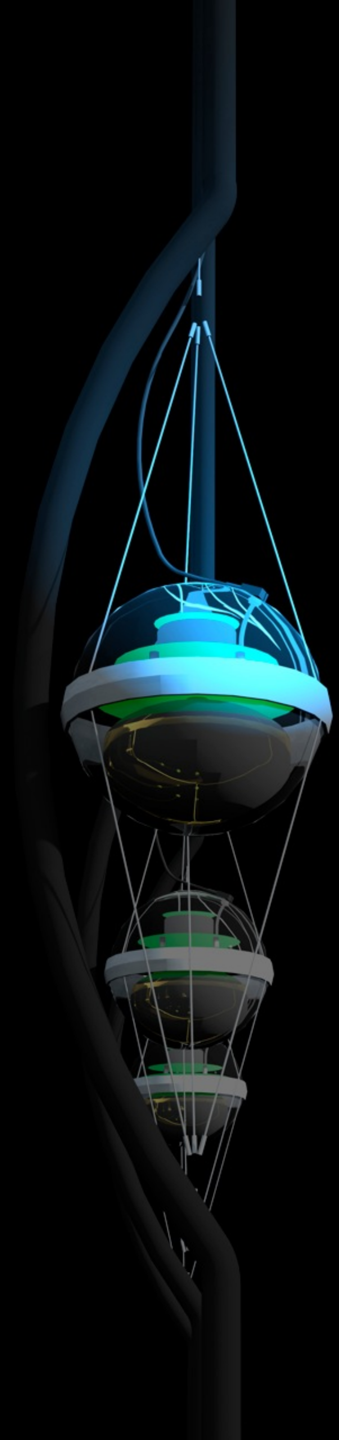


A census

- 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.







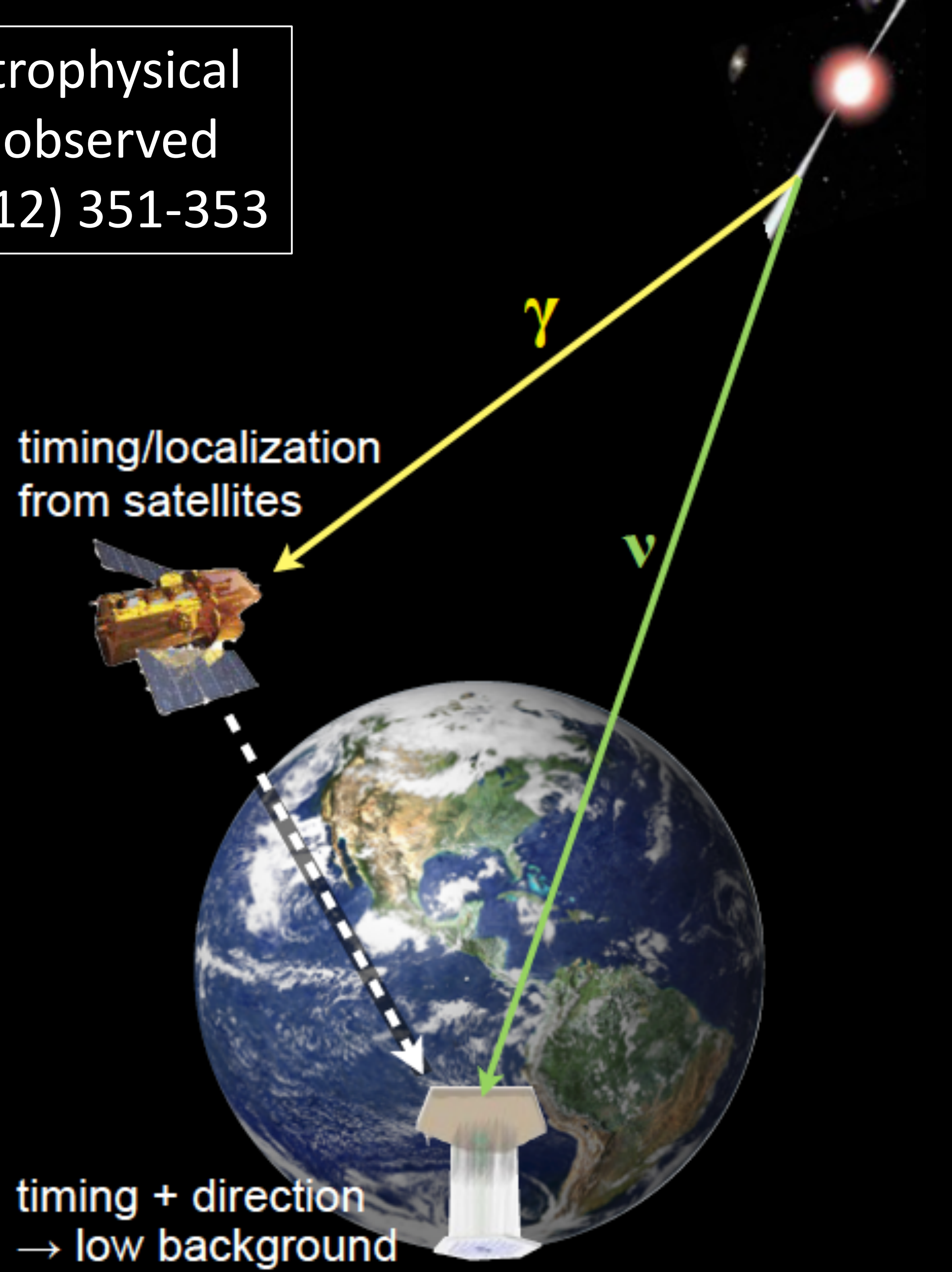
IceCube

francis halzen

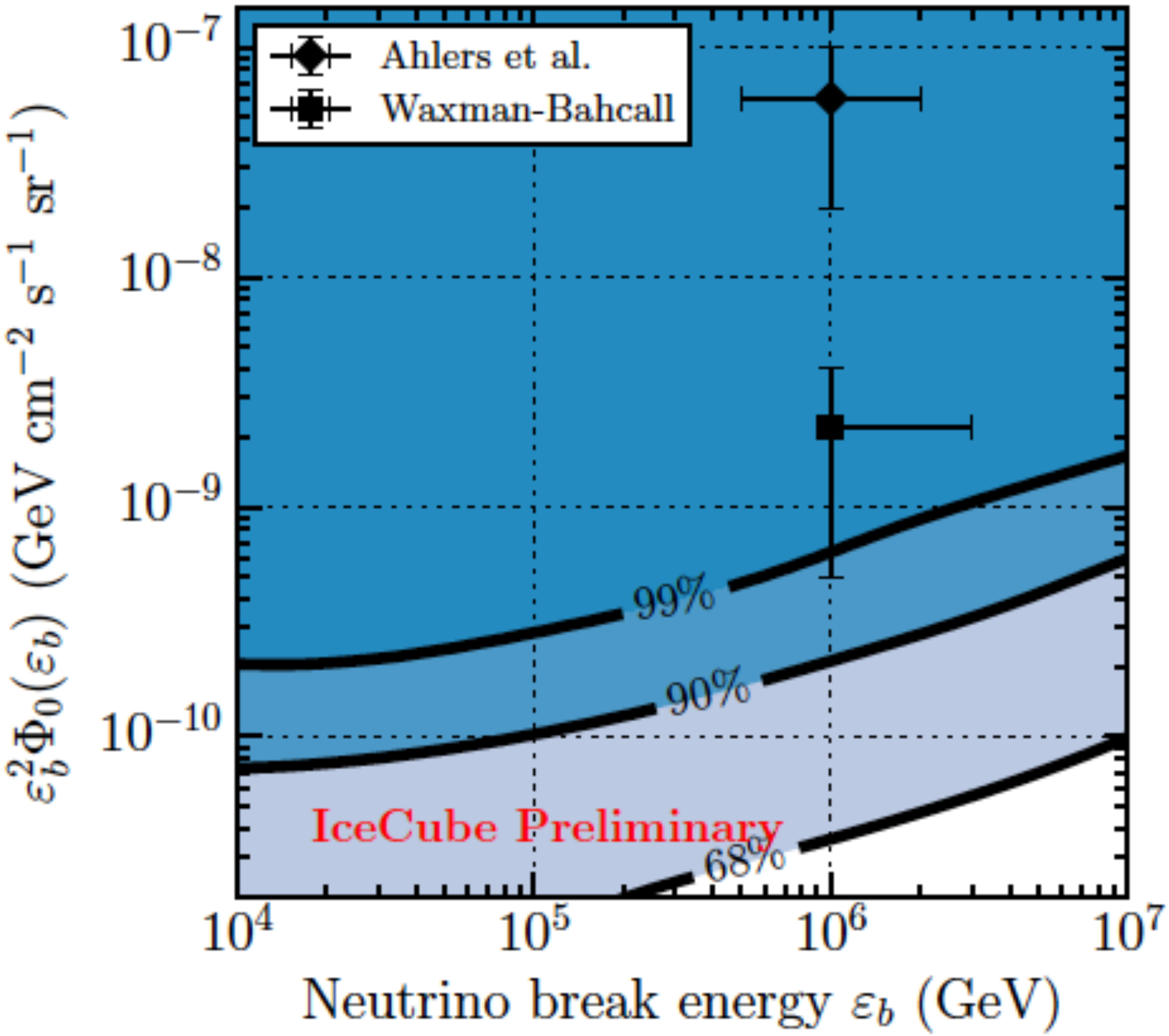
- IceCube
- cosmic neutrinos: two independent observations
    - → muon neutrinos through the Earth
    - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

iceCube.wisc.edu

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



multimessenger astronomy: wrong alerts?



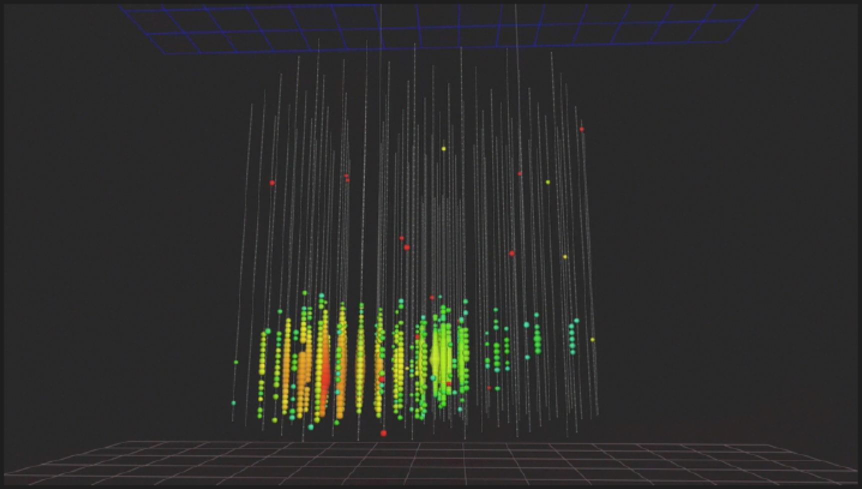
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

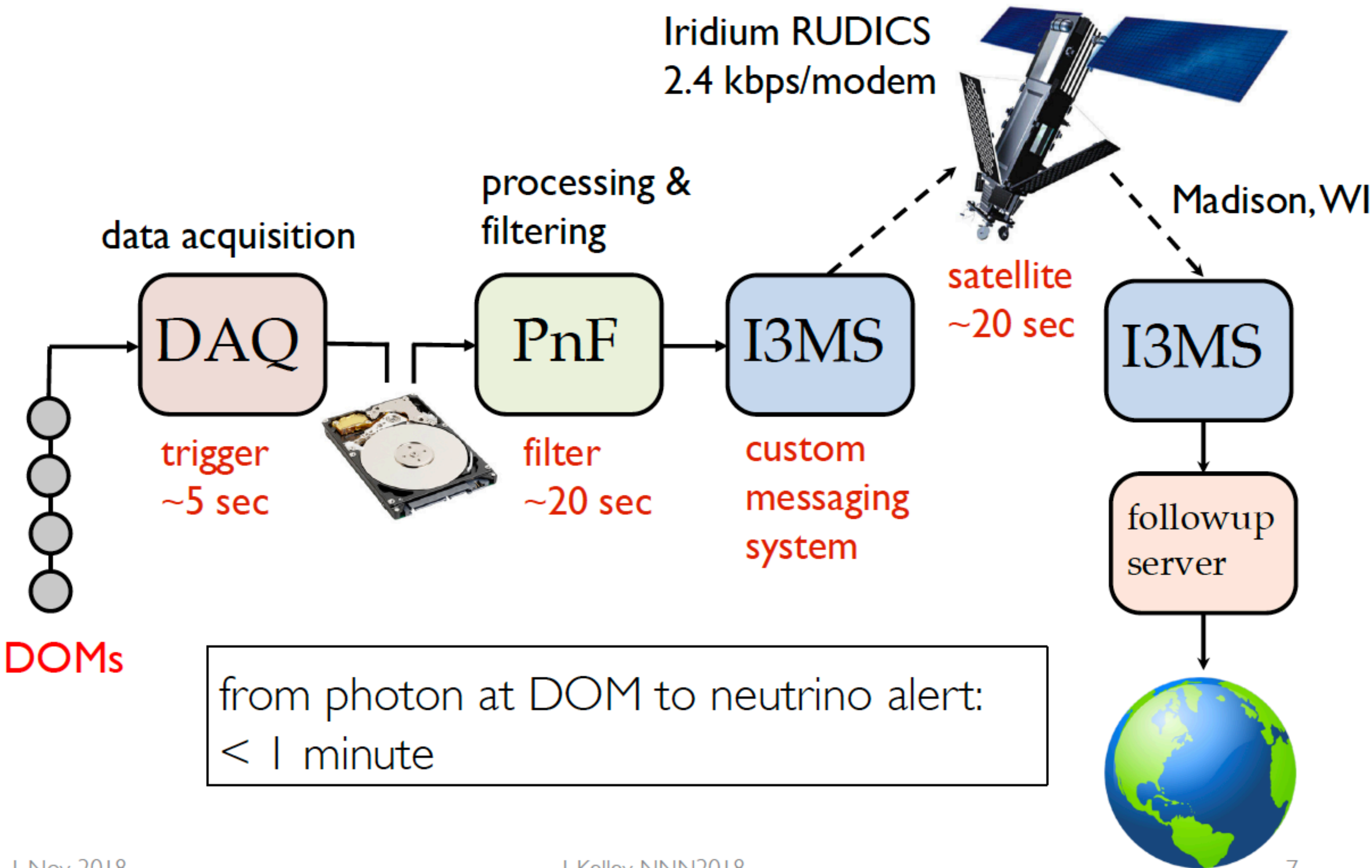
We send **rough reconstructions first** and then **update them.**

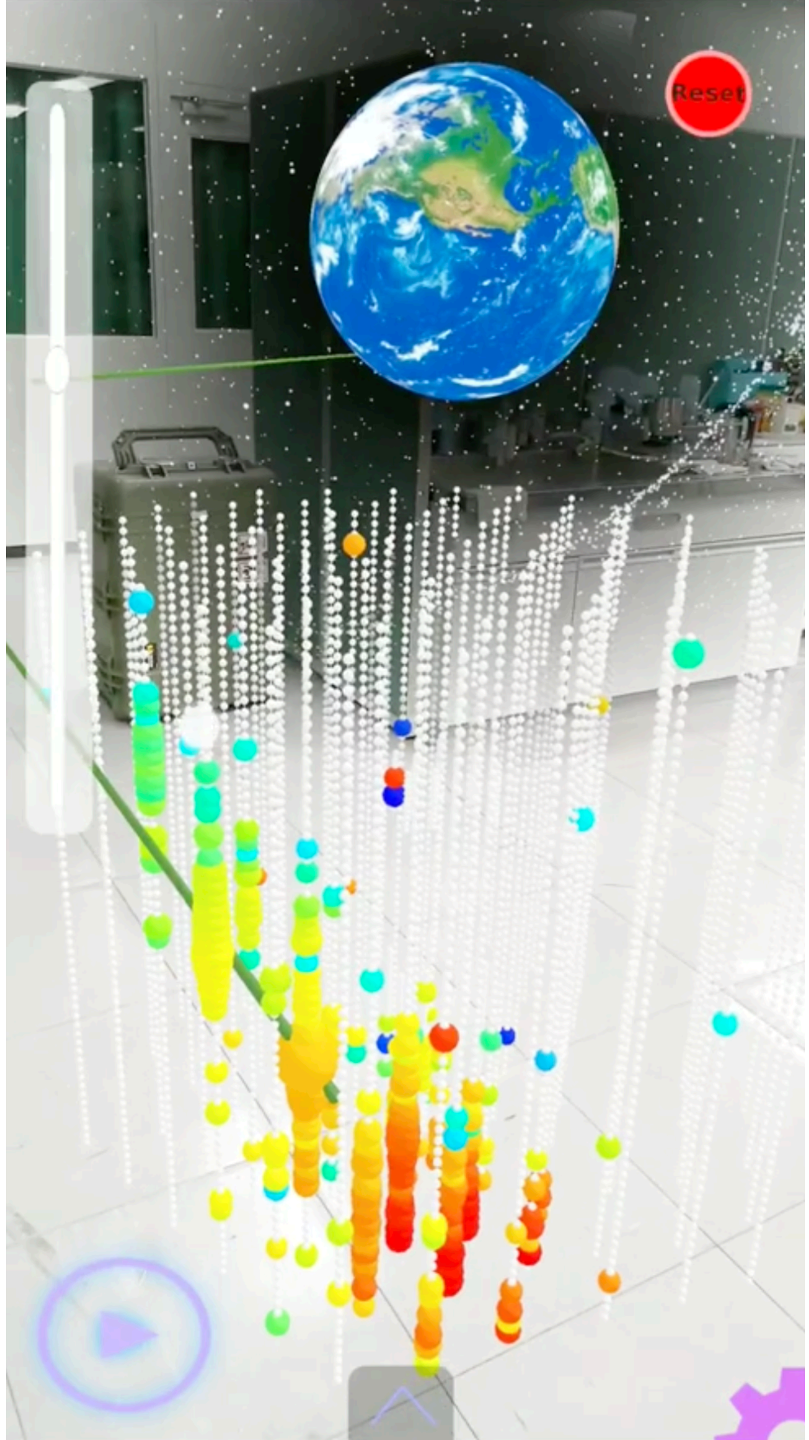


HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

M. Richman




Reset

IceCube Trigger

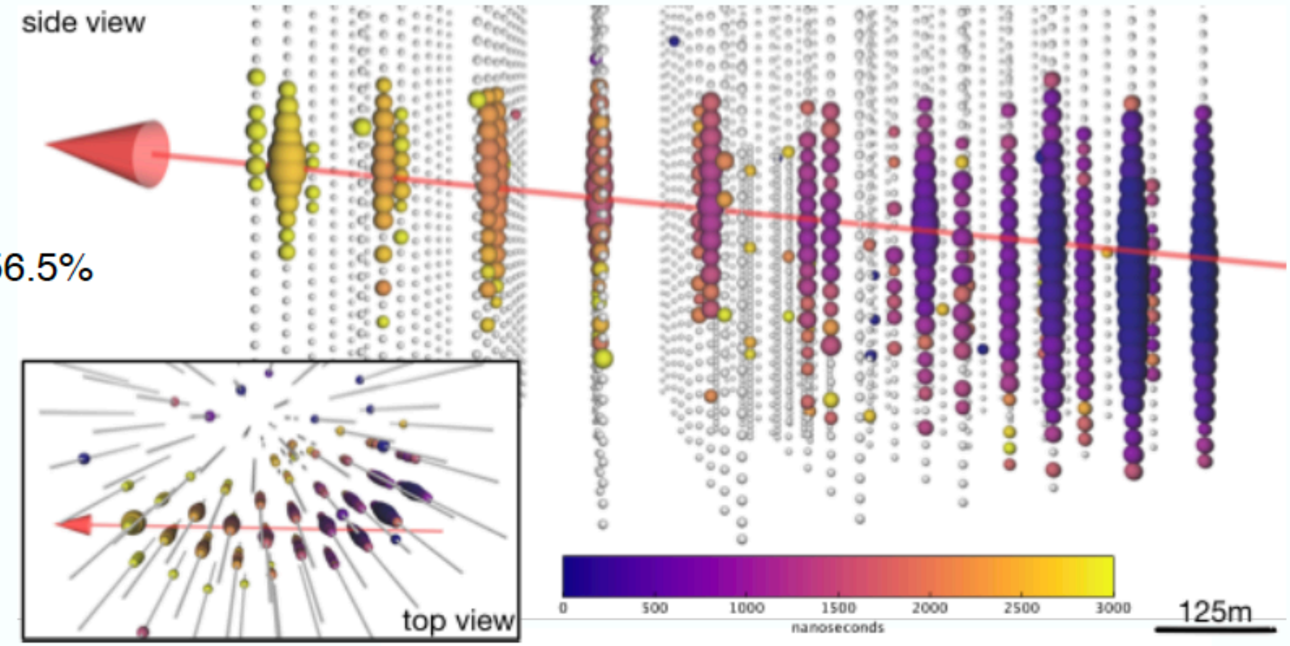
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
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]
```

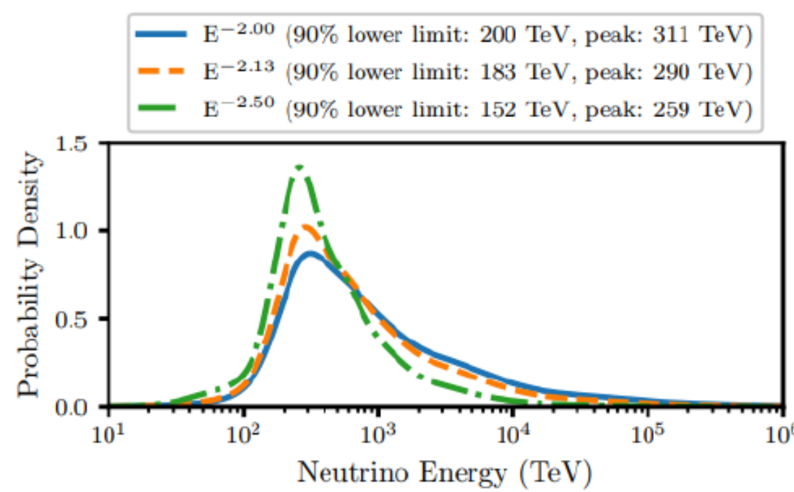
IC-170922A

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

Signalness: 56.5%



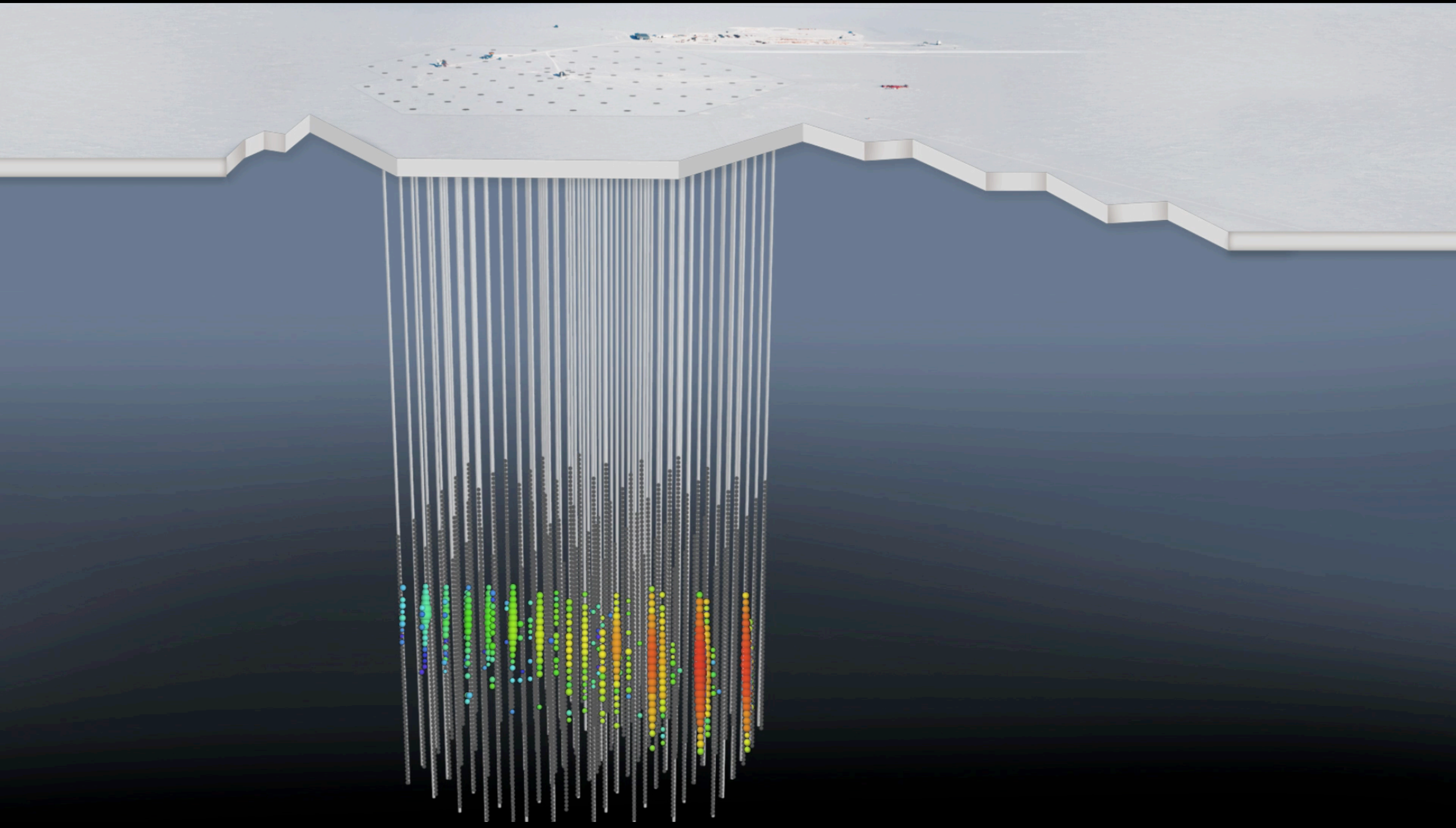
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

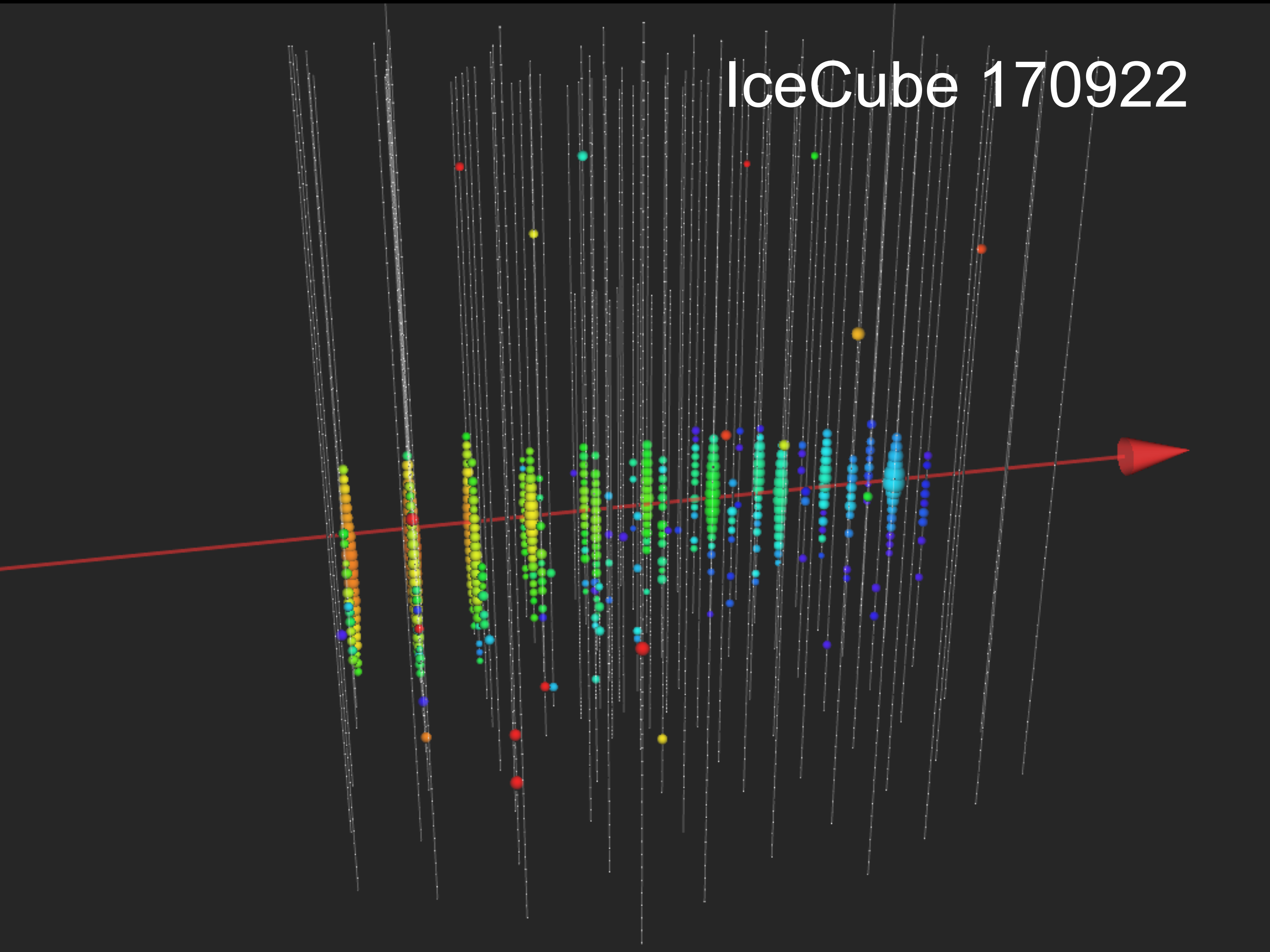


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

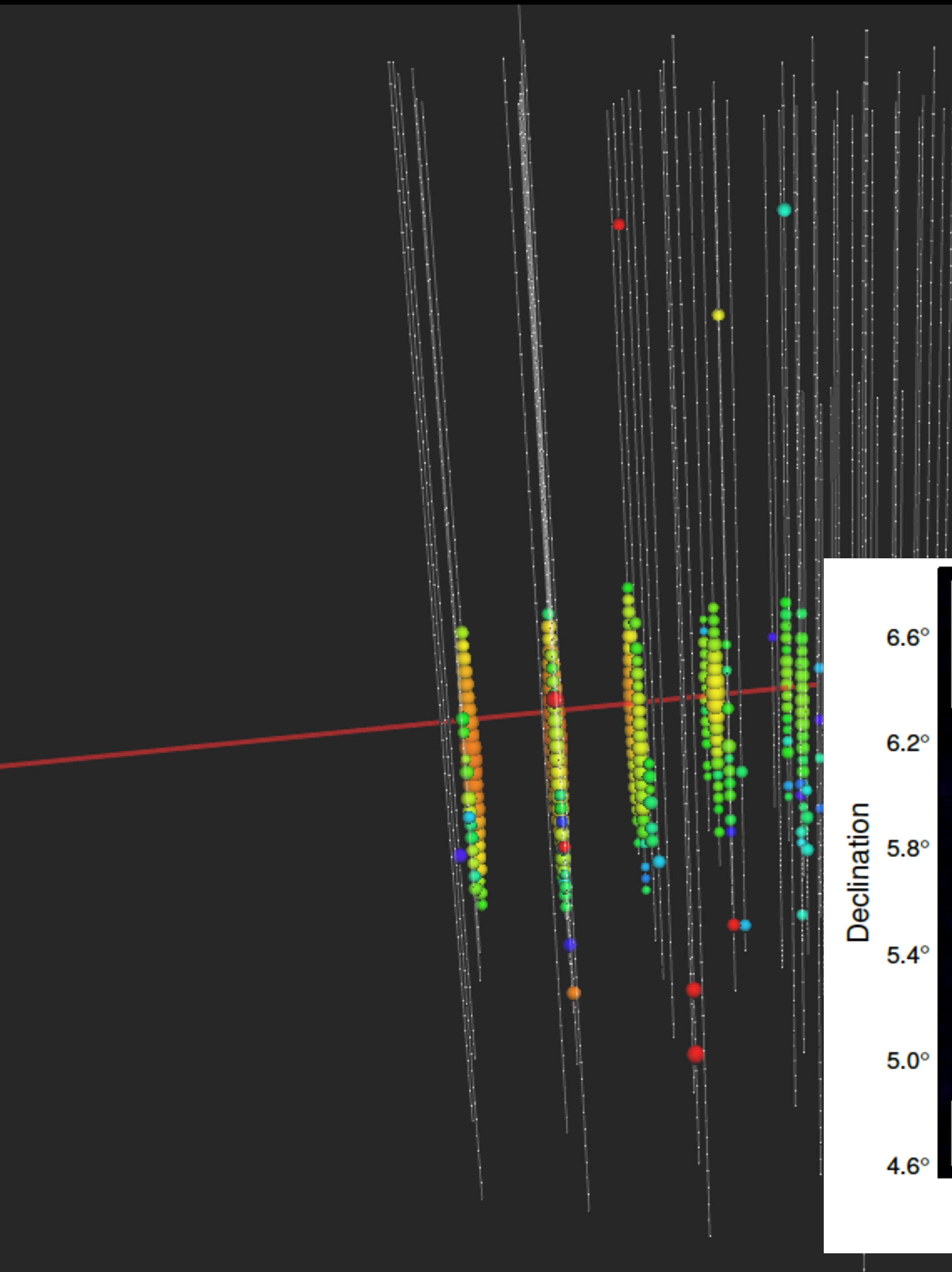
https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

multimessenger neutrinos: a new class of sources and a new class of telescopes

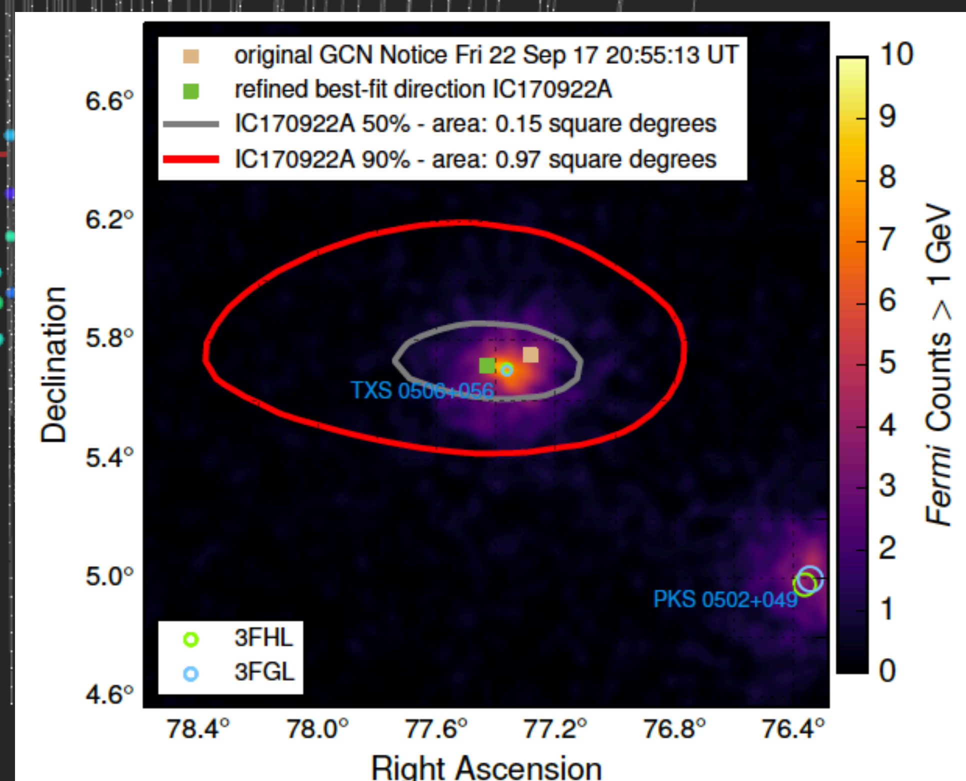



IceCube 170922

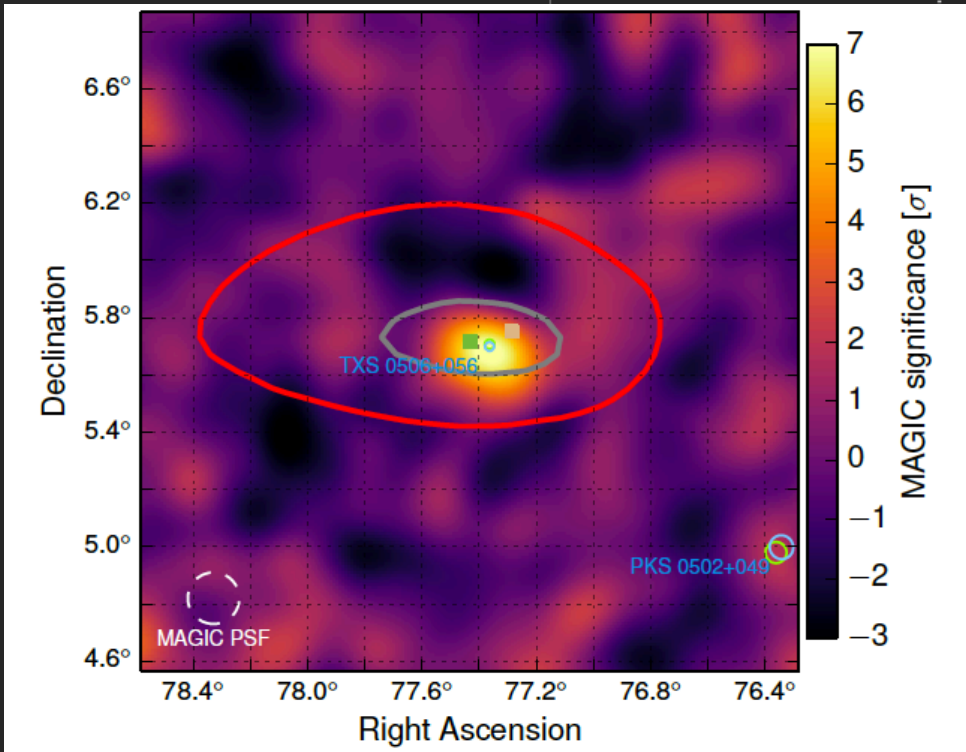
IceCube 170922



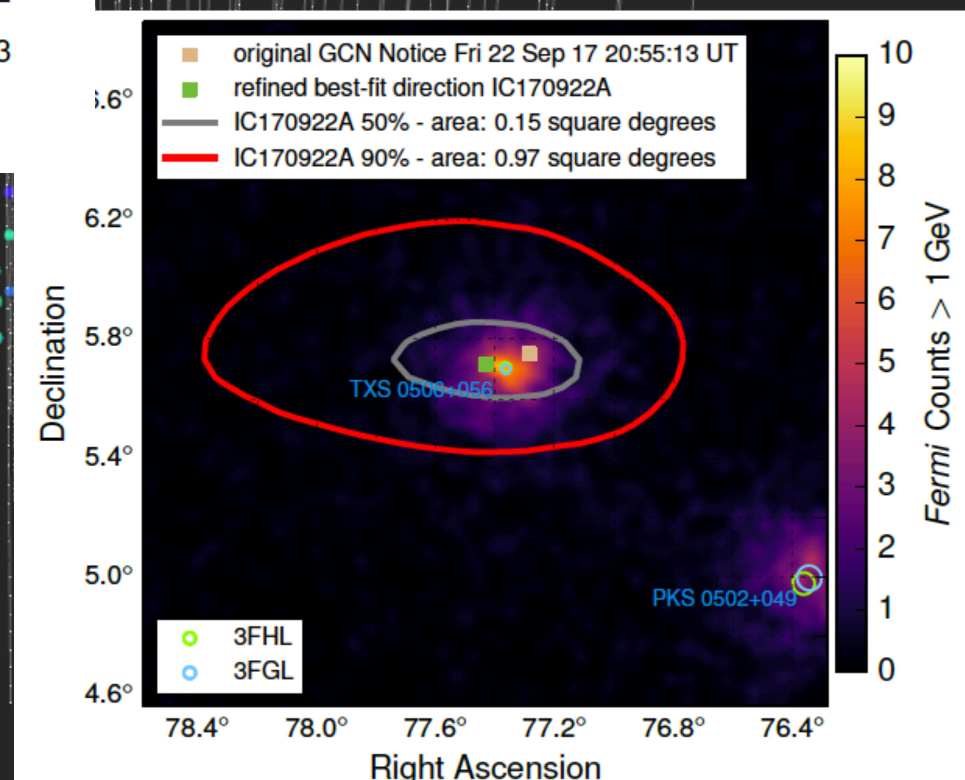
Fermi
detects a flaring
blazar within 0.1°



IceCube 170922



Fermi
detects a flaring
blazar within 0.1°

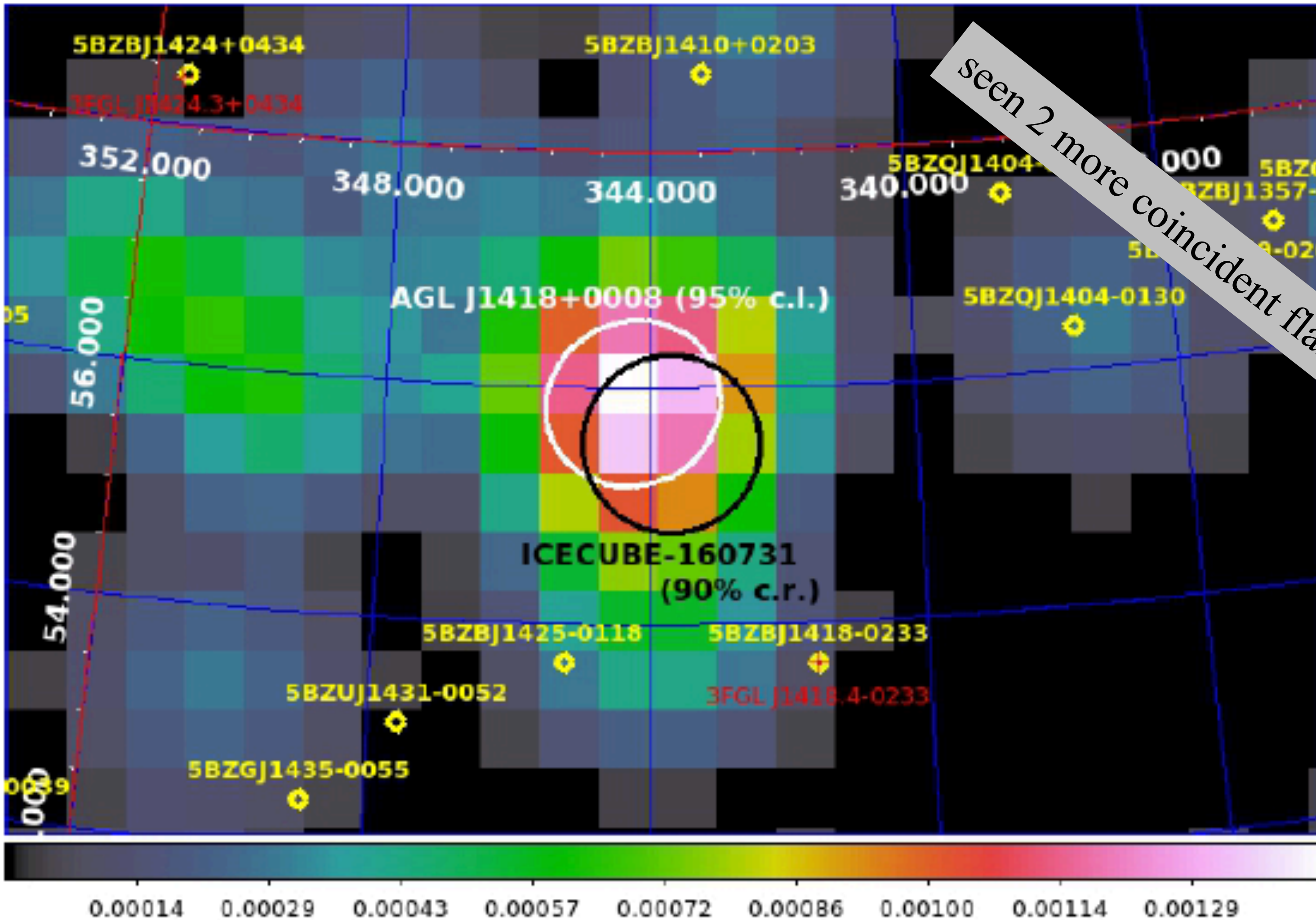


MAGIC
detects emission of
> 100 GeV gammas

MAGIC atmposheric Cherenkov telescope

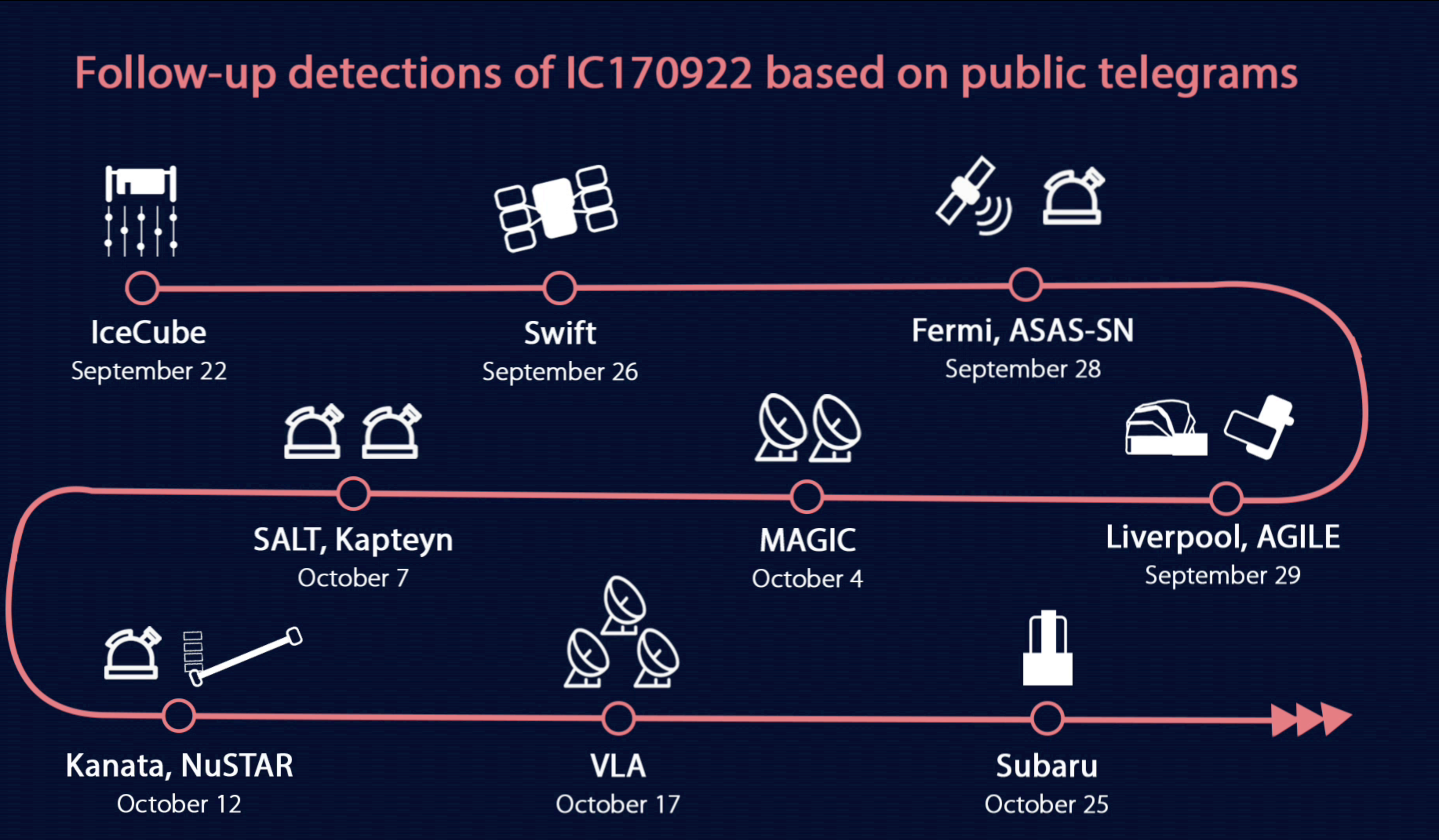
AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

F. Lucarelli,[1,2] C. Pittori,[1,2] F. Verrecchia,[1,2] I. Donnarumma,[3] M. Tavani,[4,5,6] A. Bulgarelli,[7] A. Giuliani,[8]
L. A. Antonelli,[1,2] P. Caraveo,[8] P. W. Cattaneo,[9] S. Colafrancesco,[10,2] F. Longo,[11] S. Mereghetti,[8]
A. Morselli,[12] L. Pacciani,[4] G. Piano,[4] A. Pellizzoni,[13] M. Pilia,[13] A. Rappoldi,[9] A. Trois,[13] and S. Vercellone[14]



seen 2 more coincident flashes

Corresponding author: Fabrizio Lucarelli
fabrizio.lucarelli@asdc.asi.it



Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25

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

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[2] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*
[3] *Università degli Studi dell'Insubria, Via Valleggio 11 I-22100 Como - ITALY*
[4] *INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY*
[5] *Instituto de Astrofisica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*
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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.

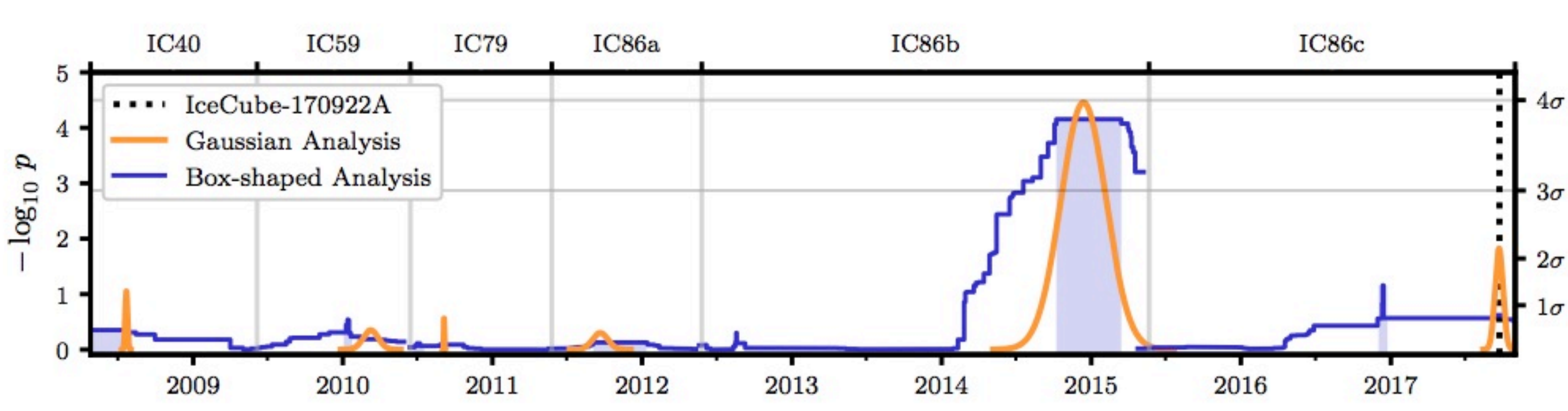
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

- 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

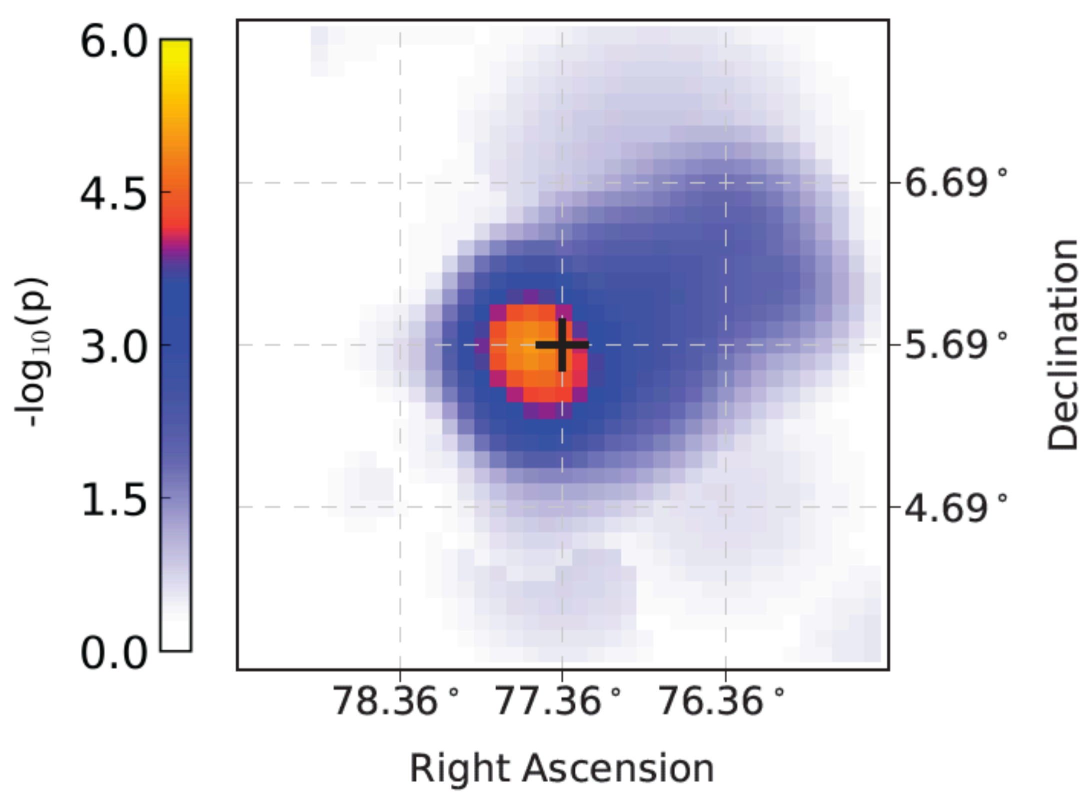
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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

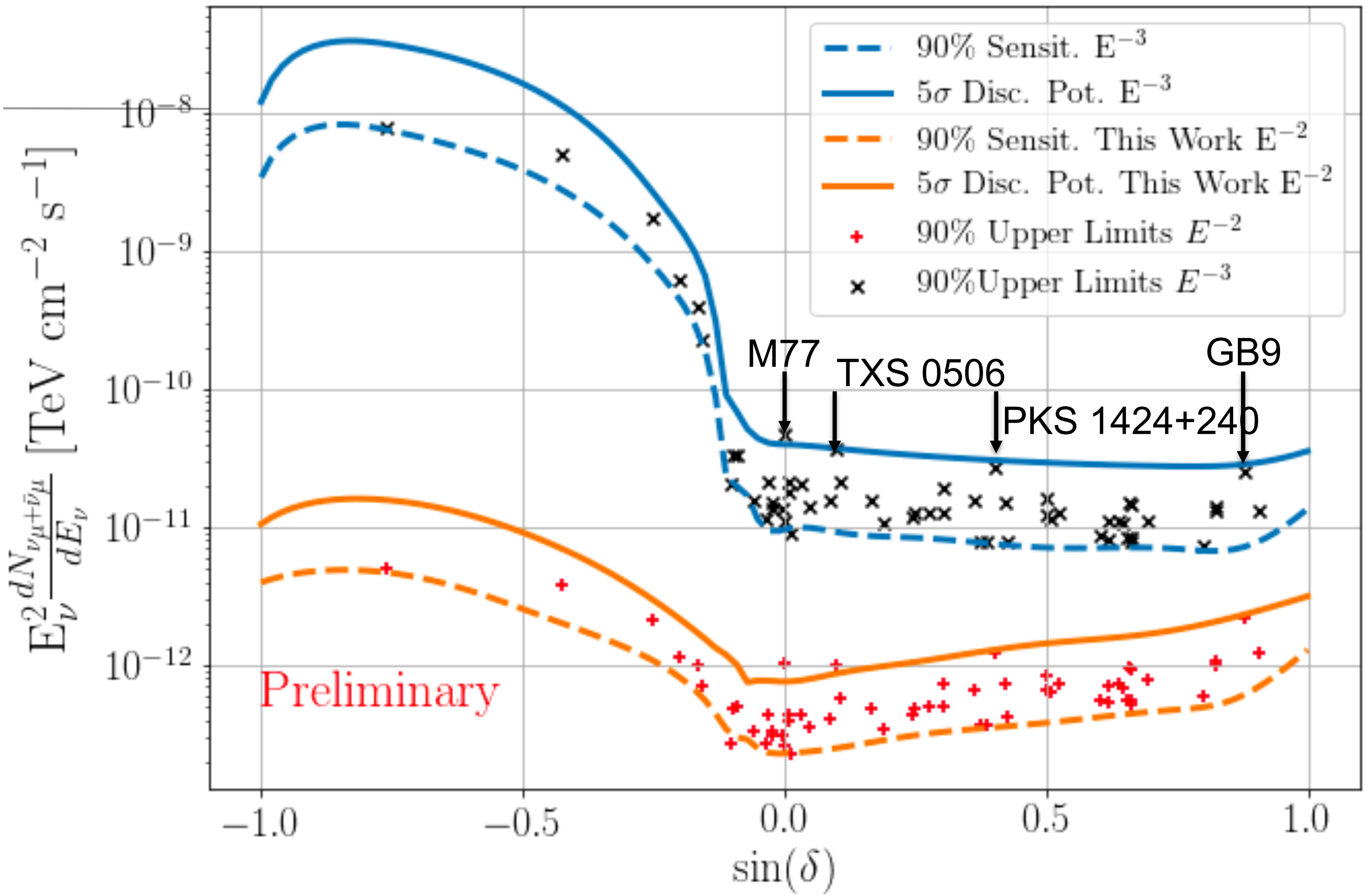


search in archival IceCube data:

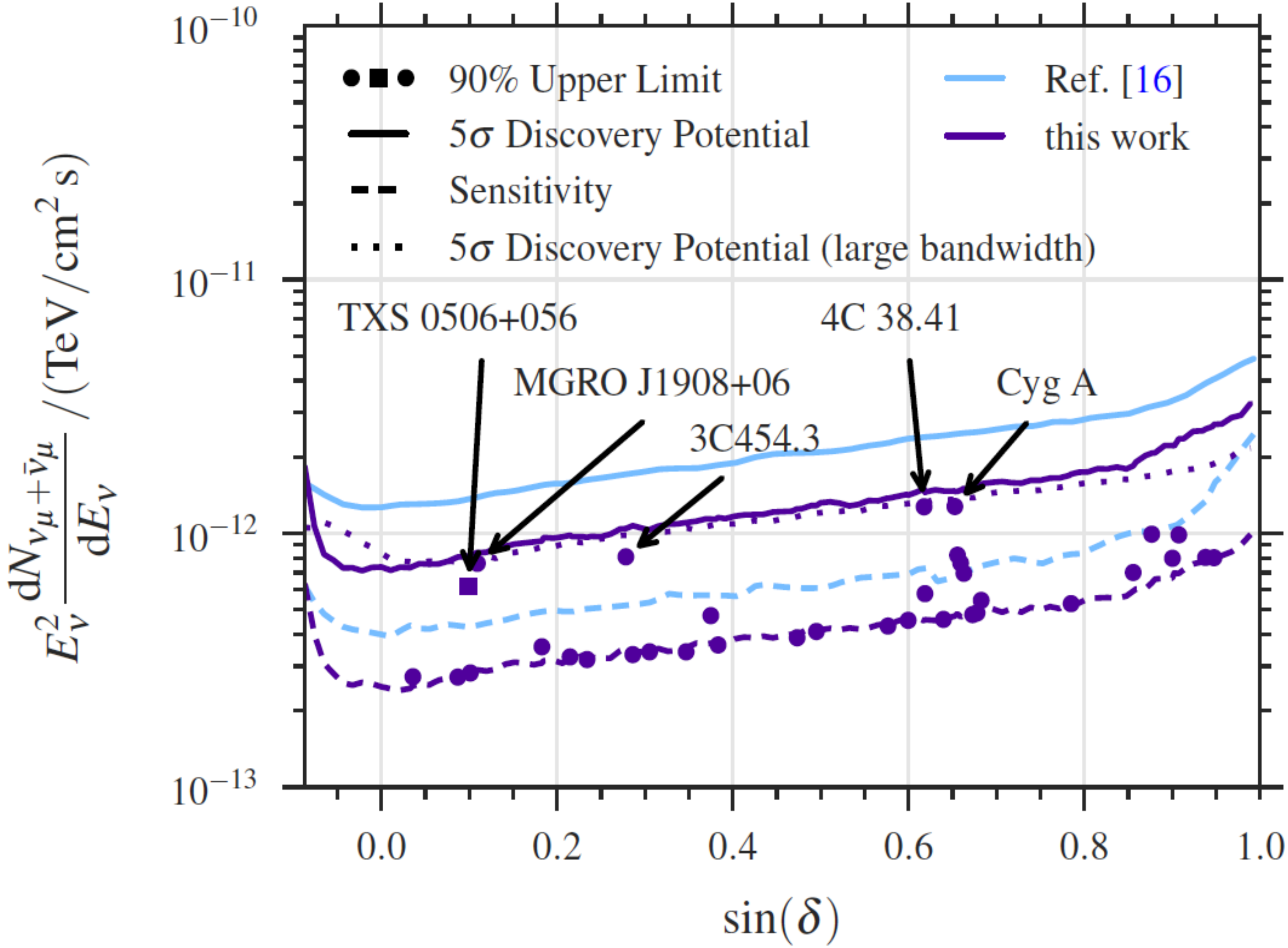
- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg.probability
- spectrum $E^{-2.1}$



Why not seen before?



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

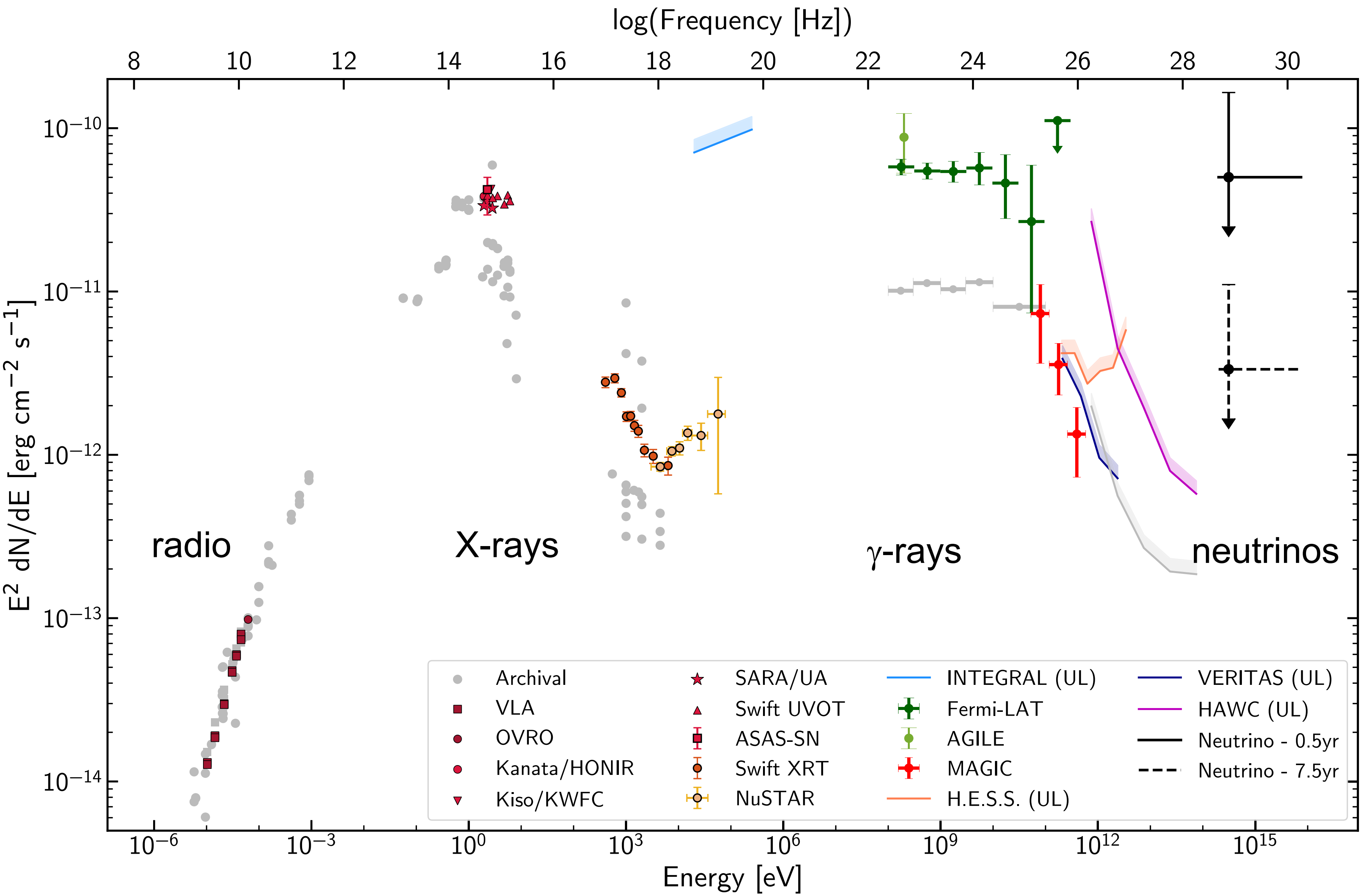


search assuming E-2.19 (diffuse) spectrum we identified a source of high energy cosmic rays:

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

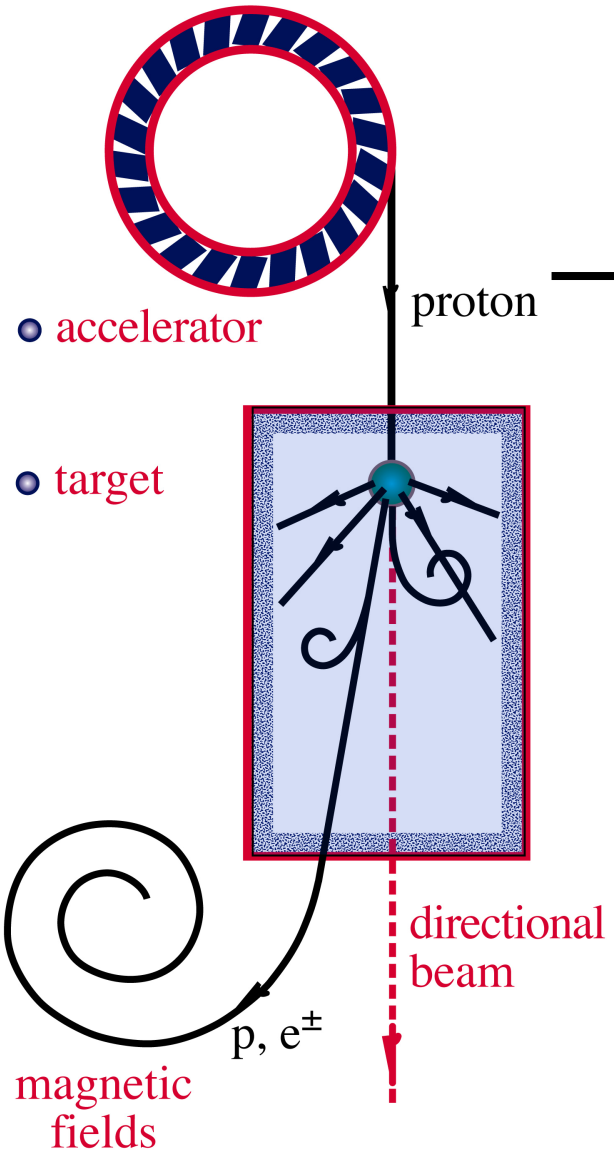
at ten times further distance, it outshines nearby active galaxies: is it special?

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



we know that this “blazar” is a cosmic ray source

ν and γ beams : heaven and earth



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

$\rightarrow$ cosmic ray + neutrino

black hole
neutron star

radiation
and dust

neutrino source
needs an accelerator
and
a target
source opacity?

some points regarding the TXS 0506+056 neutrino source:

- a blazar jet is transaparent to high energy gamma rays and therfore does not have the target density to produce neutrinos ($\sigma_{\gamma\gamma} \gg s_{p\gamma}$)

- if every “blazar” produced neutrinos at the level of TXS 0506+056, the sources would overproduce the total flux observed by IceCube by a factor of 20.

- TXS 0506+056 must indeed belong to a special subclass of sources, as already suggested by the large distance.

- a source that produces 13 neutrinos in 110 days has a target density for producing neutrinos that is large and it must therefore be opaque to high-energy gamma rays.

  It takes a major accretion event onto the black hole to accommodate the target density required to accommodate the 2014-15 observation.

  the 2014-15 burst cannot be, and is not, accompanied by a Fermi flare.

- details at arXiv:1811.07439 and arXiv:1811.07439

relation between flaring sources and the diffuse flux ?

diffuse ν_μ flux TXS luminosity

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

density of blazars

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq 7.4\times 10^{-9}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}} \simeq$$

0.05 $\longleftrightarrow$

$$\left(\frac{\mathcal{F}}{4\pi}\right)\left(\frac{c/H_0}{4.3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2\times 10^{47}\,\mathrm{erg/s}}\right)$$
$$\left(\frac{\rho}{1.5\times 10^{-8}\,\mathrm{Mpc}^{-3}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\right)\left(\frac{10\,\mathrm{yr}}{T}\right).$$

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

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

accompanying photons below Fermi threshold

proton beam normalized to the energy density in cosmic rays

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

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

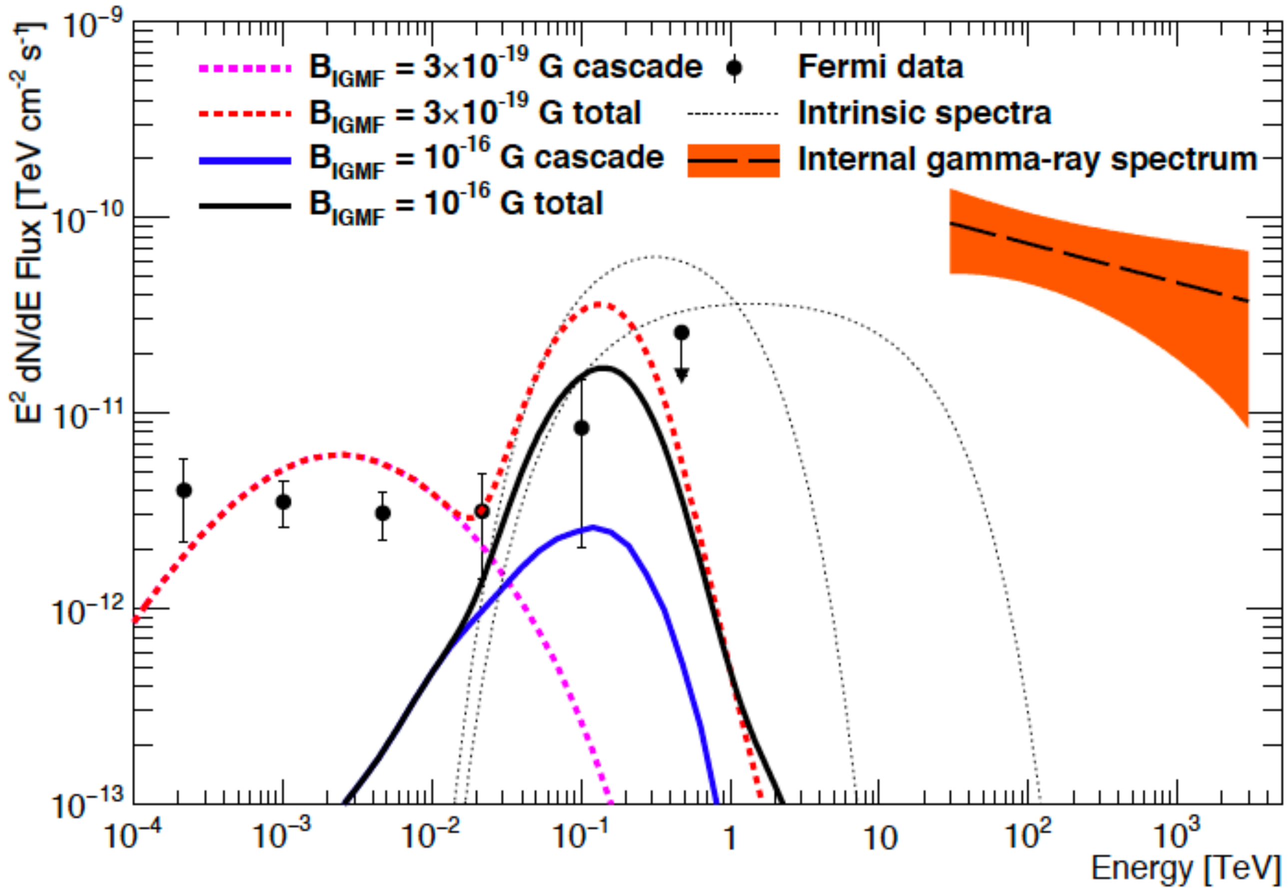
the gamma rays that accompany the neutrinos lose energy in the source

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

opacity of the gamma ray target

the multimessenger picture: gamma ray energy (mostly) below Fermi threshold

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*

Blazar Spine Sheath Model
(by Ghisellini & Tavecchio 2005)

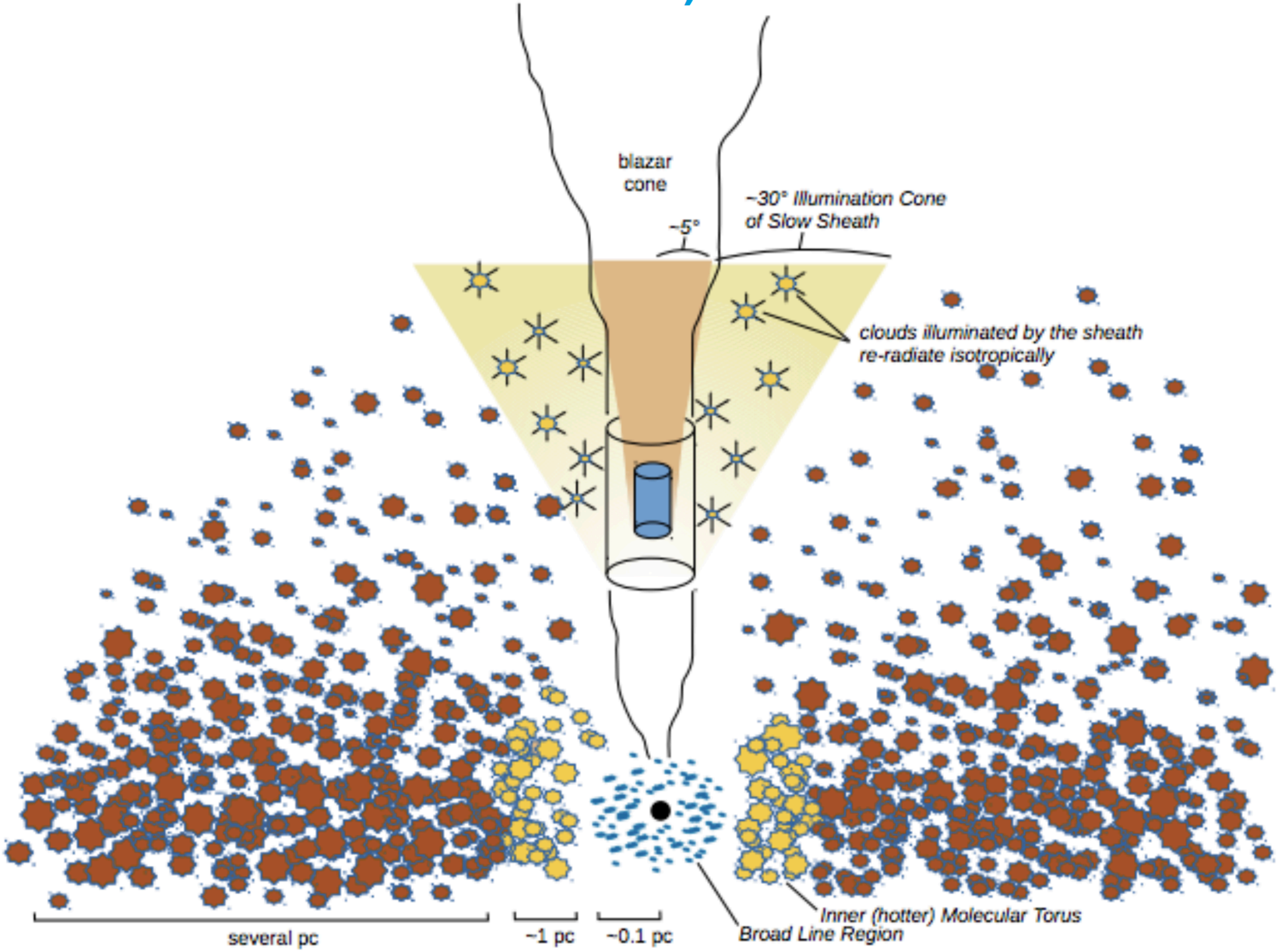
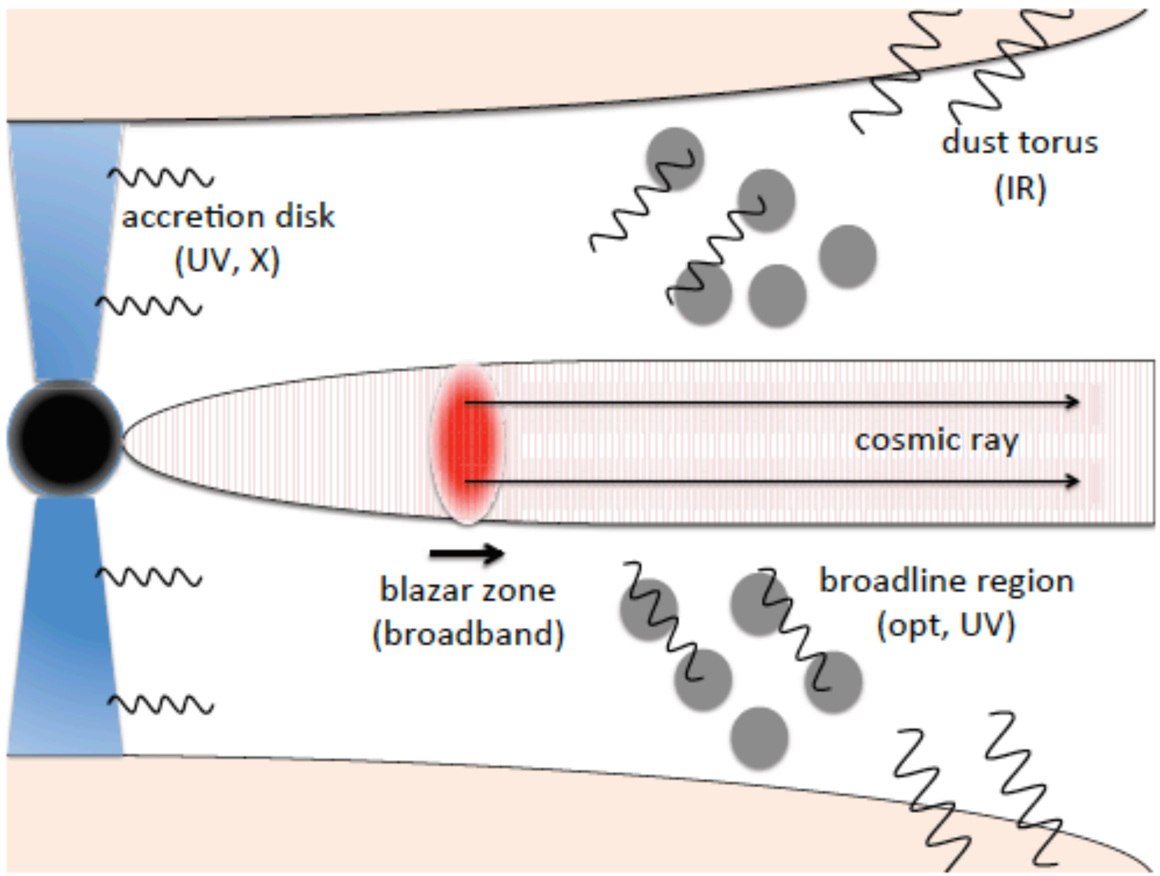


Illustration from Breiding, Georganopoulos, Meyer, 853, ApJ, 2018 interactions with photons in the broad line region of radius R, thickness ΔR (assuming a shell) and blob size $\Gamma\Delta t$. Calculations in blob frame (primed)



- accelerated protons move through a target of photons (in the broad line region BLR for instance) and interact to photoproduce pions and neutrinos by production and decay of the Δ-resonance.
- the opacity of the photon target in the BLR to $\gamma\gamma$ scattering is

$$\tau_{\gamma \mathrm{e}} = n_e \sigma_T R \simeq 0.01$$

Here R is the size of the broad line region, n_e the electron density in that region and the Thomson cross section is

$$10^{-26}\mathrm{cm}^{-2}$$

- the shock that accelerates the protons (a blob) is boosted by a Doppler factor Γ relative to the accretion disk. In the (primed) blob frame all energies are boosted by a factor Γ and all distances and times contracted by the same factor relative to the photons in the vicinity of the accretion disk and SMBH frame.
- during the time of the burst Δt it interacts with a density of photons n_γ with a cross section $\sigma_{p\gamma}$. The opacity of the photon target to the protons is:

- the energy fraction $f_{p\gamma}$ transferred by protons to pions by pγ interactions in the BLR is:

$$1 - e^{-f_{p\gamma}} = \frac{\Delta R'}{\lambda_{p\gamma}} = \sigma_{p\gamma}\, n'_\gamma\, c\Delta t'\, x_{p\to\pi}$$

where

$$n'_\gamma = \frac{u'_\gamma}{E'_\gamma} = \frac{1}{4\pi R'^2 \Delta R'}\frac{1}{E'_\gamma}\int E'_\gamma \frac{dN'_\gamma}{dE'_\gamma} dE'_\gamma$$

$$= \frac{1}{4\pi R'^2 \Delta R'}\tau_{\gamma\mathrm{e}}\frac{L'_\gamma \Delta t'}{E'_\gamma}$$

where the second equation is for the case of a fixed energy for the target photons, e.g. in the case of the blue bump with E_γ = 10 eV:

$$\frac{dN_\gamma}{dE_\gamma} = A\delta(E_\gamma - 10\,\mathrm{eV})$$

The flux at earth from the target region AE_γ required to provide an opacity of $f_{p\gamma}$ is given by:

$$AE_\gamma = E_\gamma \frac{1}{\sigma_{p\gamma}\Gamma^2\tau_{\gamma \mathrm{e}}x_{p\to\pi}} \frac{R^2}{d_L^2} \frac{1-e^{-f_{p\gamma}}}{\Delta t}$$

Here is a 110 day burst at 1.7 Gpc and $x_{p\text{->}\pi} = 0.2$. Therefore

$$= 3\times 10^{-9}\mathrm{erg\,cm^{-2}s^{-1}}\,\mathrm{R_{pc}^2}\frac{1}{\Gamma^2}(1-\mathrm{e}^{-\mathrm{f_{p\gamma}}})$$

One can verify that the time of the burst is larger than the proton acceleration time and shorter than the energyloss time.

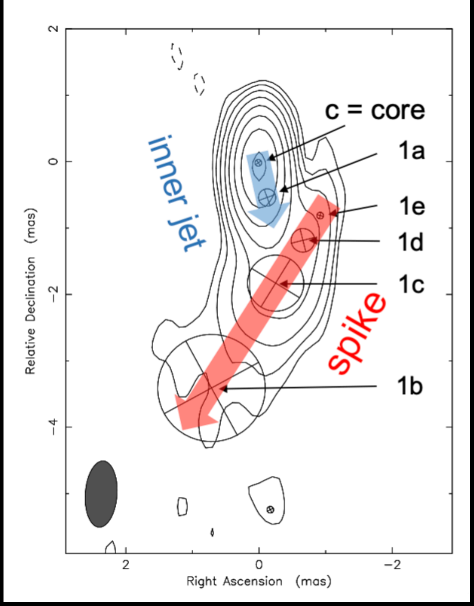
vanilla blazars cannot accommodate the 2014 burst:

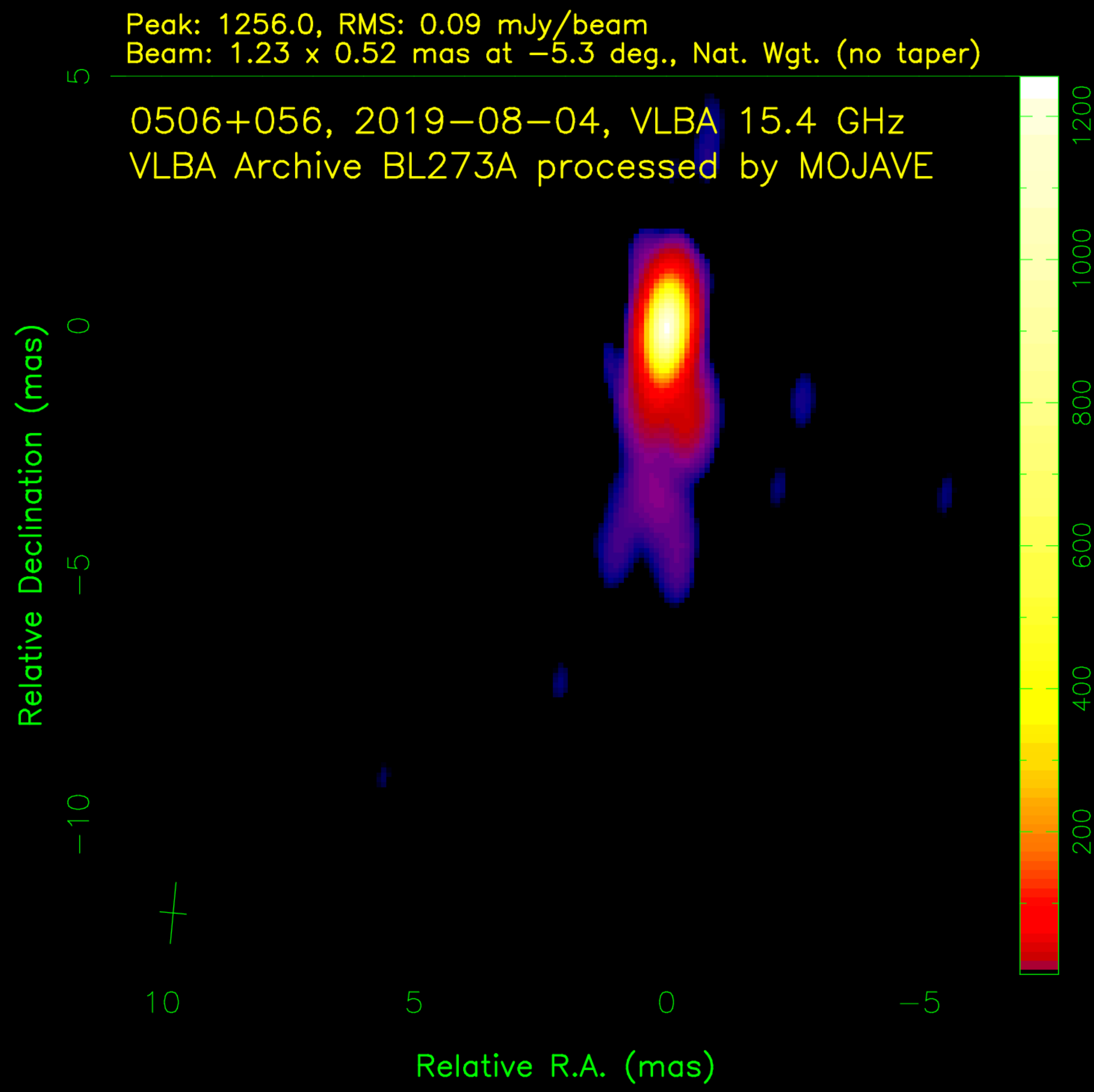
need major accretion on the black hole to provide
a target that can produce the 2014-15 neutrino burst

TXS 0506+056 is a galaxy merger?

core brightening observed in a radio burst that started 5 years ago

theory confirms observation?

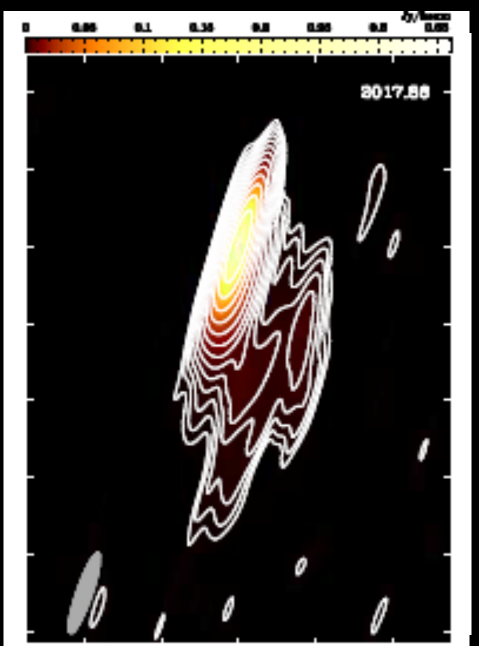




TXS 0506+056 is a galaxy merger

“We thus observe the interaction between jet features that cross each other’s paths.”

theory confirms observation



Astronomy & Astrophysics manuscript no. 0506 ©ESO 2019
December 5, 2019

Letter to the Editor

Apparent superluminal core expansion and limb brightening in the candidate neutrino blazar TXS 0506+056

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ABSTRACT

Context. IceCube has reported a very-high-energy neutrino (IceCube-170922A) in a region containing the blazar TXS 0506+056. Correlated gamma-ray activity has led to the first high-probability association of a high-energy neutrino with an extragalactic source. This blazar has been found to be in a radio outburst during the neutrino event.

Aims. Our goal is to probe the sub-milliarcsecond properties of the radio jet right after the neutrino detection and during the further evolution of the radio outburst.

Methods. We have performed target-of-opportunity very-long-baseline interferometry imaging observations at 43 GHz frequency, corresponding to 7 mm in wavelength, with the Very Long Baseline Array two and eight months, respectively, after the neutrino event.

Results. We produced two images of the radio jet of TXS 0506+056 at 43 GHz with angular resolutions of (0.2×1.1) mas and (0.2×0.5) mas, respectively. The source shows a compact, high brightness temperature core (albeit not approaching the equipartition limit, Readhead 1994) and a bright and originally very collimated inner jet. Beyond about 0.5 mas from the mm-VLBI core, the jet loses this tight collimation and expands rapidly. During the months after the neutrino event associated with this source, the overall flux density is rising. This flux density increase happens solely within the core. Notably, the core expands in size with apparent superluminal velocity during these six months so that the brightness temperature drops by a factor of three in spite of the strong flux density increase.

Conclusions. The radio jet of TXS 0506+056 shows strong signs of deceleration and/or a spine-sheath structure within the inner 1 mas (corresponding to about 70 pc to 140 pc in deprojected distance) from the mm-VLBI core. This structure is consistent with theoretical models that attribute the neutrino and gamma-ray production in TXS 0506+056 to interactions of electrons and protons in the highly-relativistic jet spine with external photons originating from a slower-moving jet region. Proton loading due to jet-star interactions in the inner host galaxy is suggested as the possible cause of deceleration.

Key words. Radiation mechanisms: non-thermal – Neutrinos – Techniques: interferometric – Radio continuum: galaxies – Galaxies: quasars: individual: TXS 0506+056

Mon. Not. R. Astron. Soc. **000**, 1–?? (0000) Printed 14 November 2018 (MN LaTeX style file v2.2)

VLBI radio structure and radio brightening of the high-energy neutrino emitting blazar TXS 0506+056

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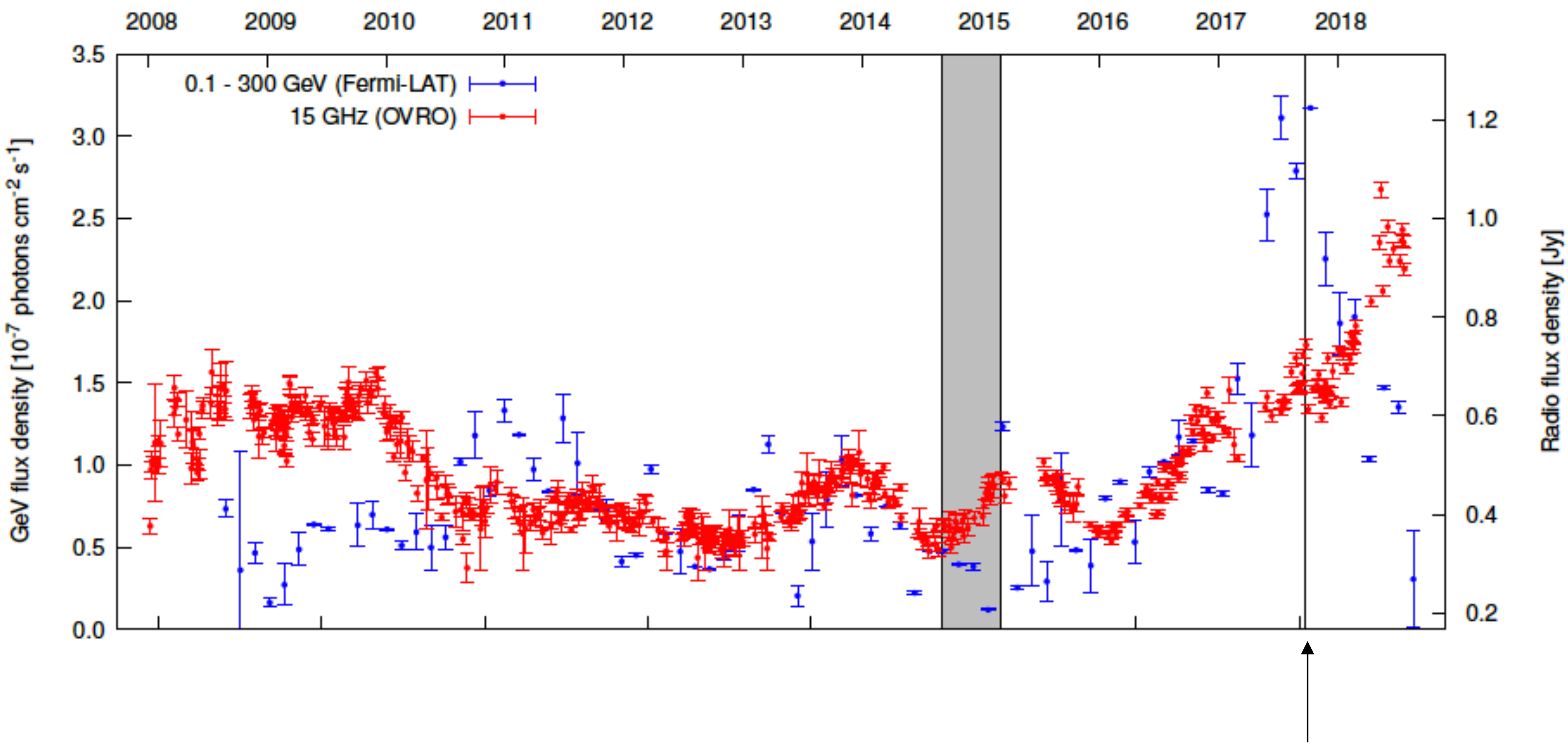
Accepted . Received ; in original form

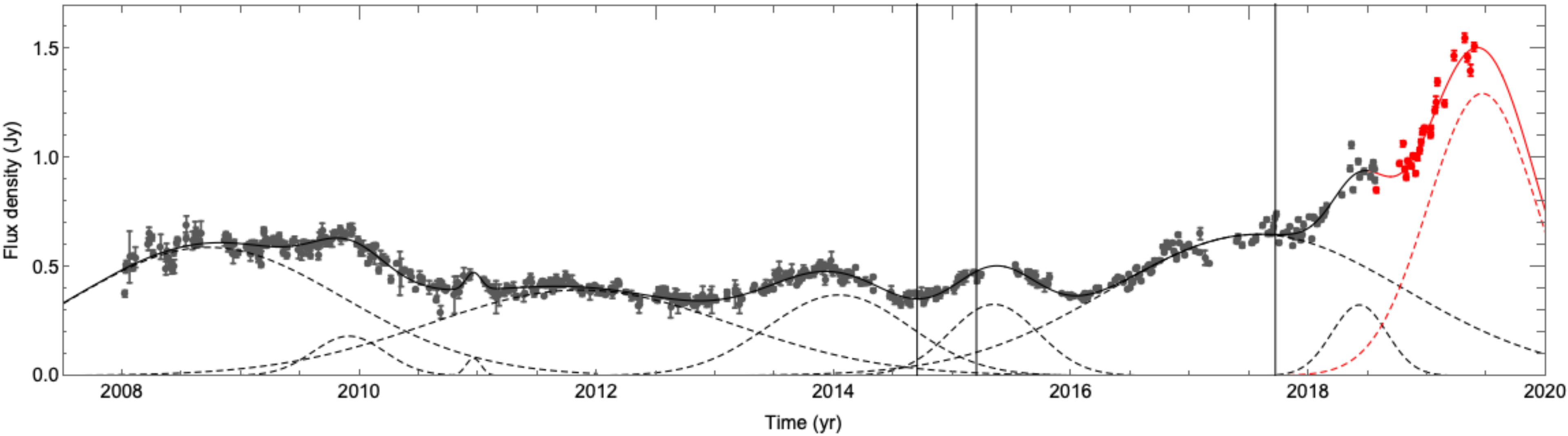
ABSTRACT
We report on the radio brightening of the blazar TXS 0506+056 (at $z = 0.3365$), supporting its identification as source of the high-energy (HE) neutrino IC-170922A by the IceCube Neutrino Observatory. MOJAVE/VLBA data indicate its radio brightness abruptly increasing since January 2016. When decomposing the total radio flux density curve (January 2008 - July 2018) provided by the Owens Valley Radio Observatory into eight Gaussian flares, the peak time of the largest flare overlaps with the HE neutrino detection, while the total flux density exhibits a threefold increase since January 2016. We reveal the radio structure of TXS 0506+056 by analysing VLBI data from the MOJAVE/VLBA Survey. The jet-components maintain quasi-stationary core separations. The structure of the ridge line is indicative of a jet curve at the region $0.5 \div 2$ mas ($2.5 \div 9.9$ pc projected) from the VLBI core. The brightness temperature of the core and the pc-scale radio morphology support a helical jet structure at small inclination angle ($< 8\overset{\circ}{.}2$). The jet pointing towards the Earth is key property facilitating multimessenger observations (HE neutrinos, γ- and radio flares). The radio brightening preceding the detection of a HE neutrino is similar to the one reported for the blazar PKS 0723–008 and IceCube event ID5.

Key words: galaxies: BL Lacertae objects: individual: TXS 0506+056 – physical data and processes: neutrinos –radio continuum: galaxies – techniques: interferometric

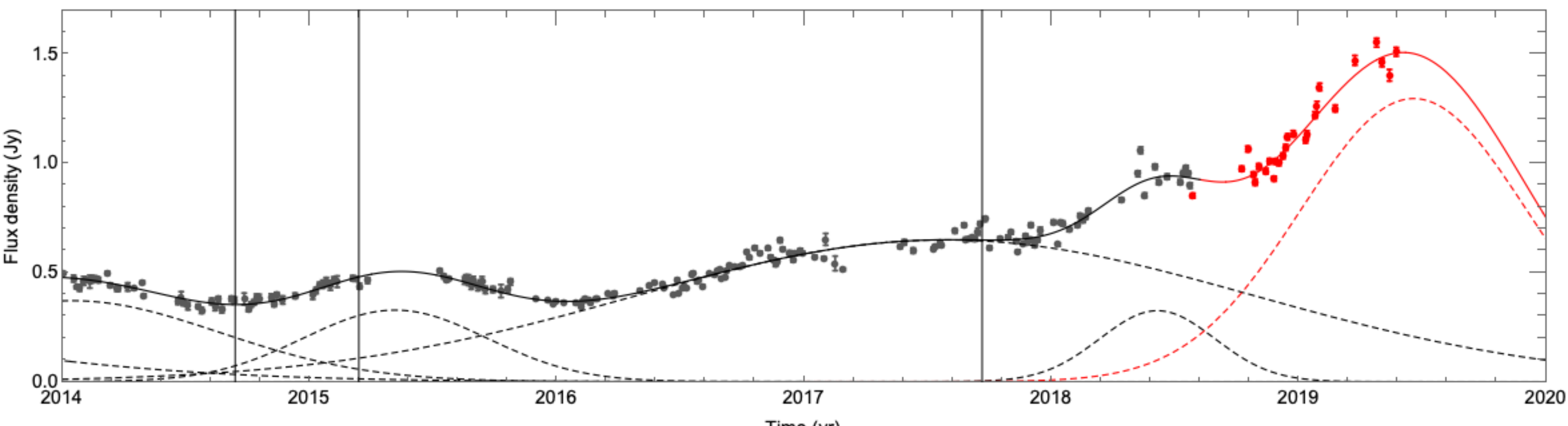


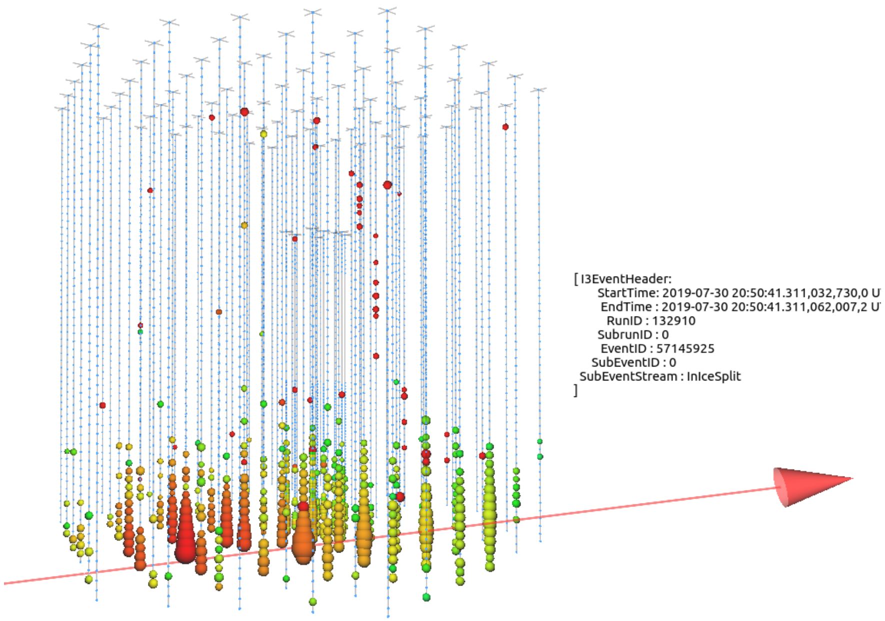
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
0.1 - 300 GeV (Fermi-LAT)
15 GHz (OVRO)
GeV flux density [10^{-7} photons cm^{-2} s^{-1}]
Radio flux density [Jy]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.2
0.4
0.6
0.8
1.0
1.2

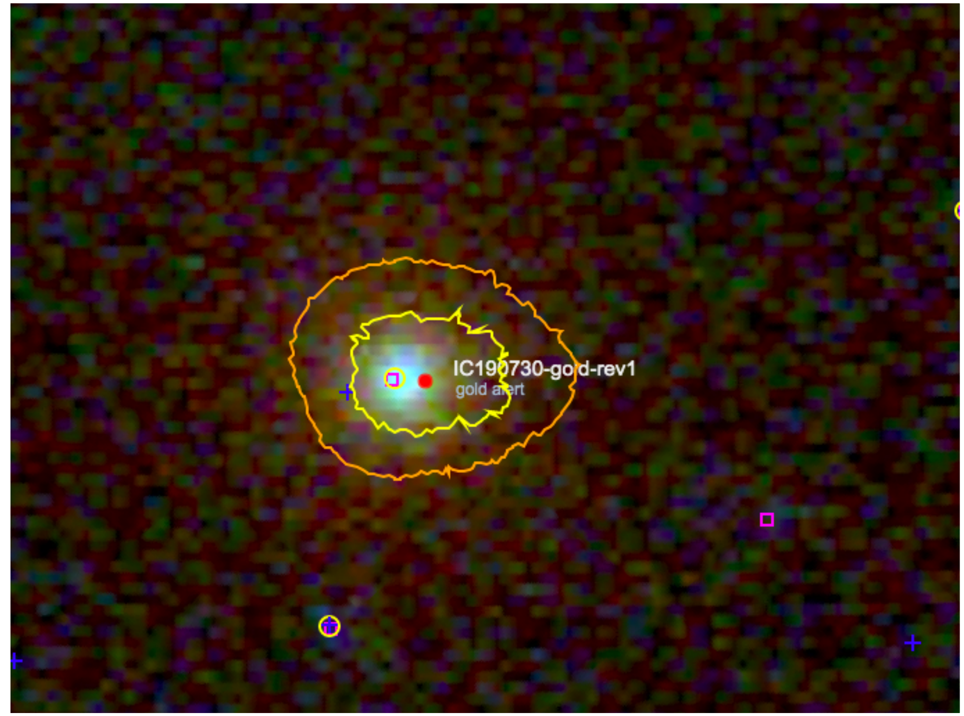
TXS 0506+056



upper: OVRO data for TXS 0506+056
lower: interferometric VLBA data at 15 GHz







IC 190730: 300 TeV

- coincident with PKS 1502+106
- galaxy merger

[Previous | Next]

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

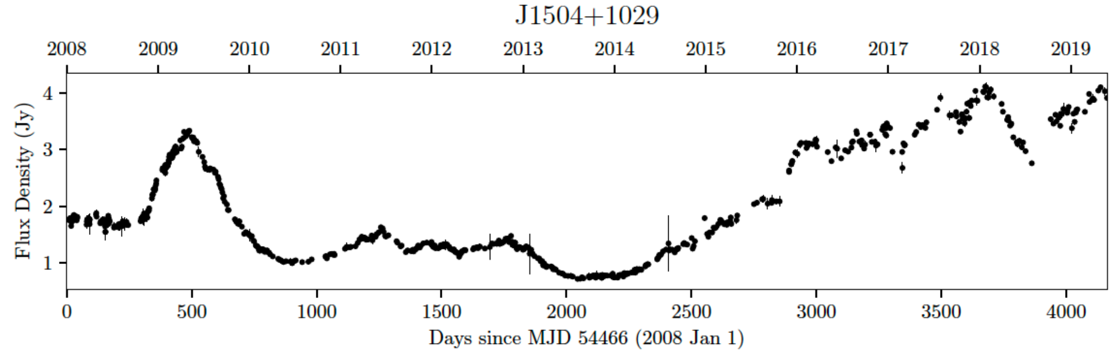
Tweet

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.

Related

- **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

OVRO Radio Flare



OVRO Montitoring (http://www.astro.caltech.edu/ovroblazars/)

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)*
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No evidence of short-term flaring activity in any wavelengths.

Long-term radio flare reported by OVRO, also reported for TXS 0506+056.

the two highest energy IceCube alerts are coincident with radio flares

are blazars the sources of the cosmic neutrinos?

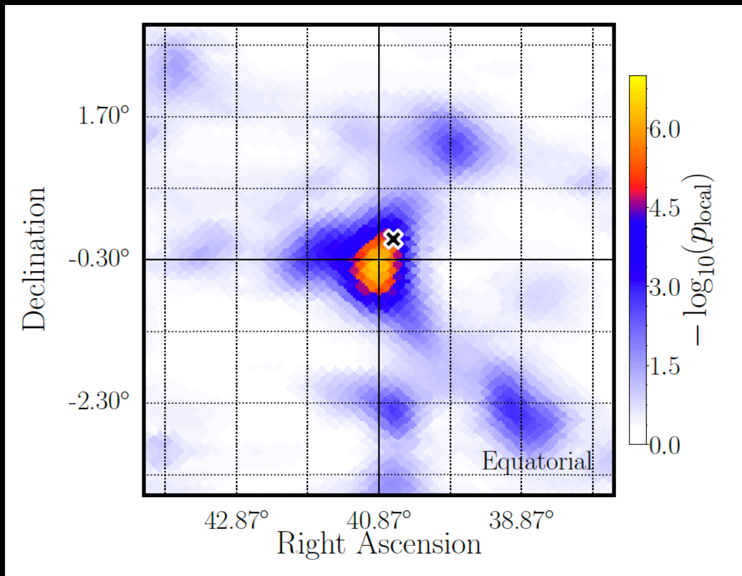
a special class of gamma ray sources that undergo 110-day duration flares like TXS 0506+056 once every 10 years accommodates the observed diffuse flux of high-energy cosmic neutrinos

- selected by redshift evolution ?
- galaxy mergers (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



evidence for M77 (NGC1086)

- agn activity
- merger (with a star-forming region or satellite galaxy)
- nearby!

A&A 567, A125 (2014)
DOI: 10.1051/0004-6361/201423843

Astronomy & Astrophysics

Molecular line emission in NGC 1068 imaged with ALMA★

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

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Received 19 March 2014 / Accepted 4 June 2014

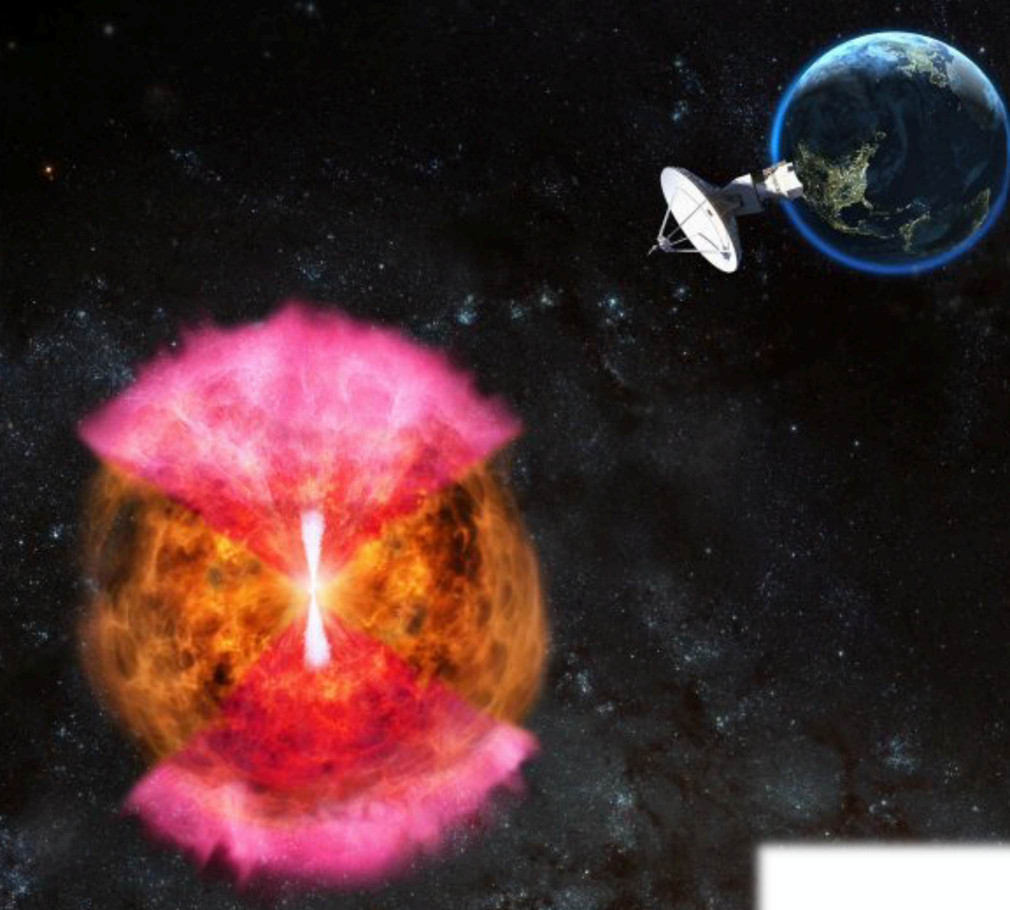
ABSTRACT

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 ($M_{\rm mol} \sim 2.7^{+0.9}_{-1.2} \times 10^7$ $M_\odot$) 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.

neutron star-neutron star merger

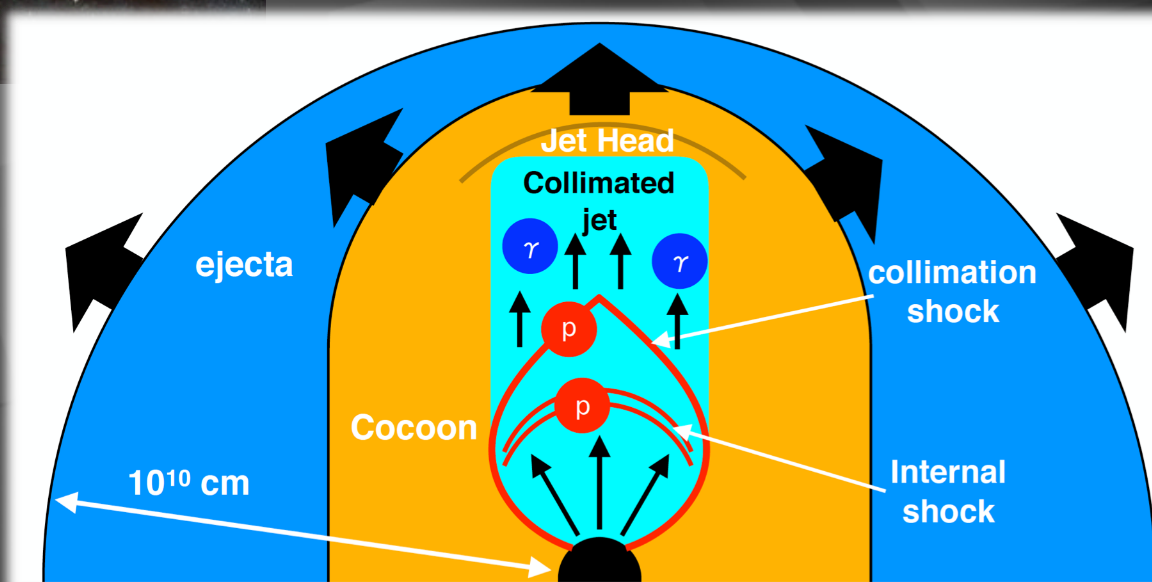
LIGO-VIRGO

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)



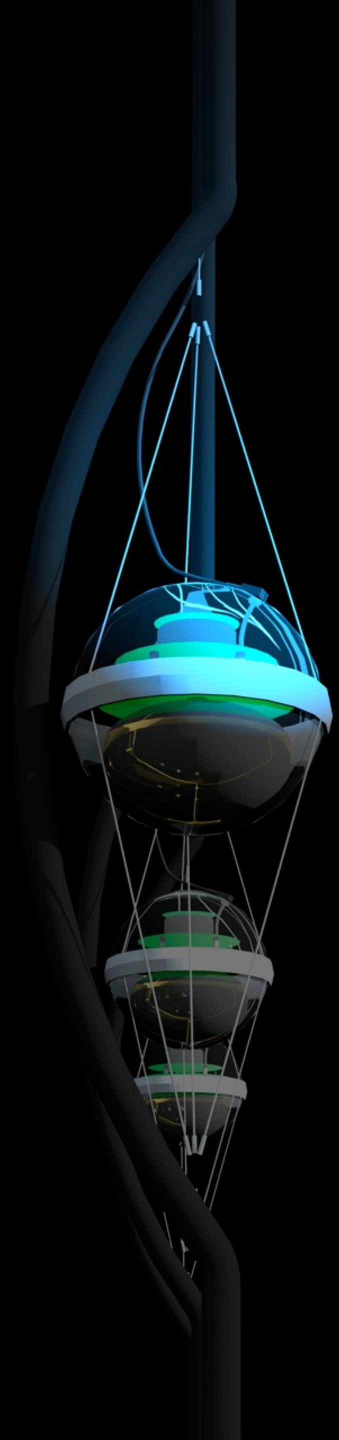
Kimura et al.

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

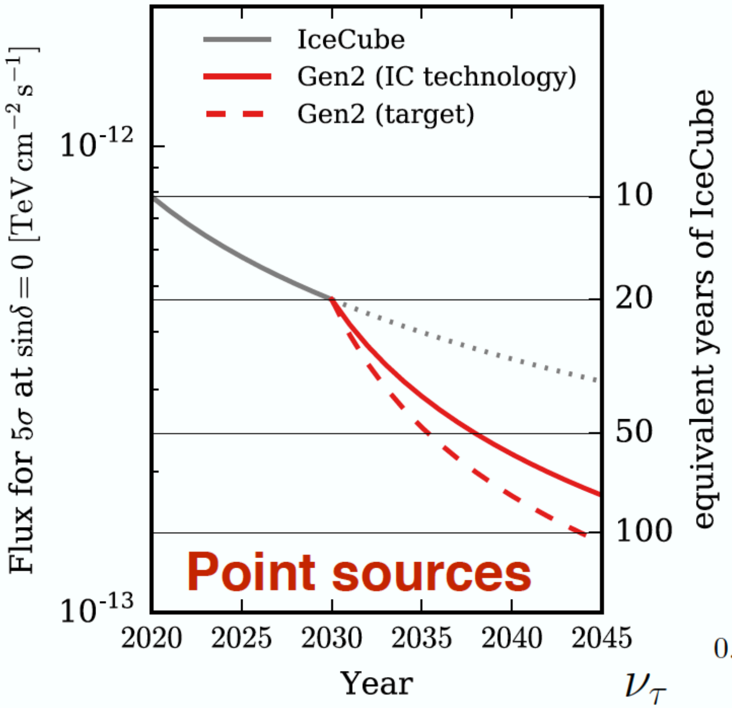
IceCube.wisc.edu

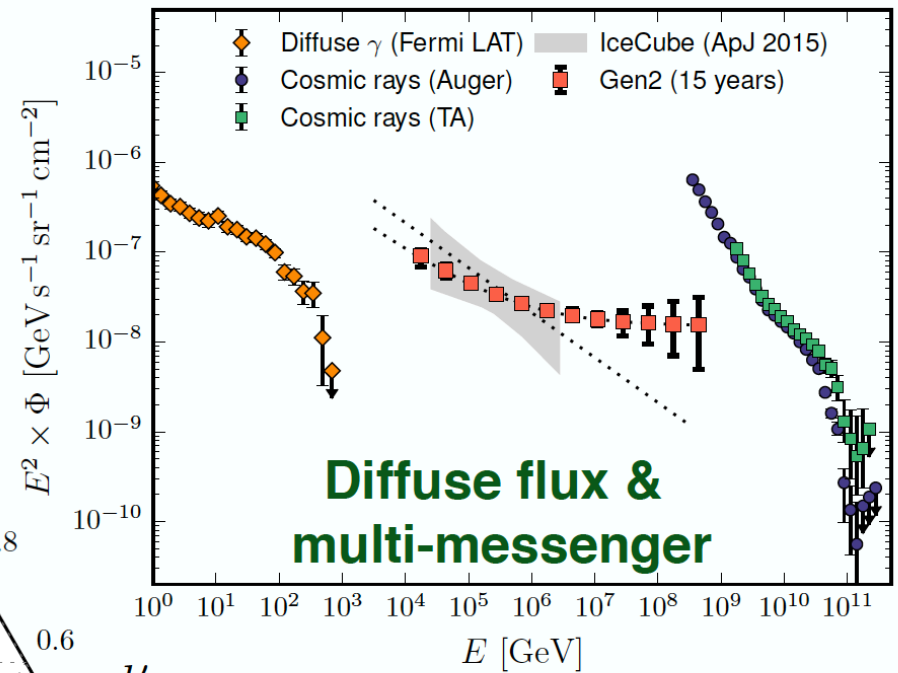
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

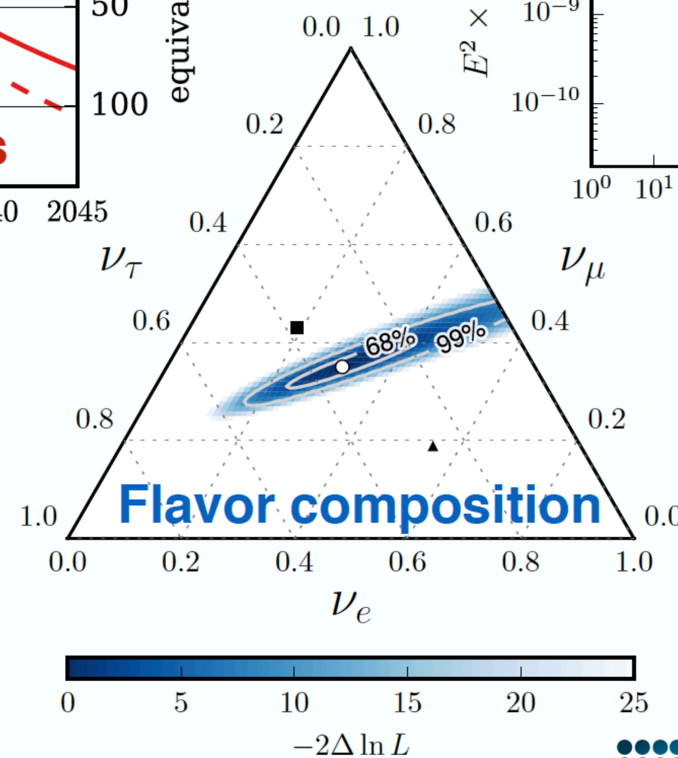
- need 1,000 events versus 100 now in a few years

- discovery instrument → astronomical telescope

IceCube-Gen2: Science Case



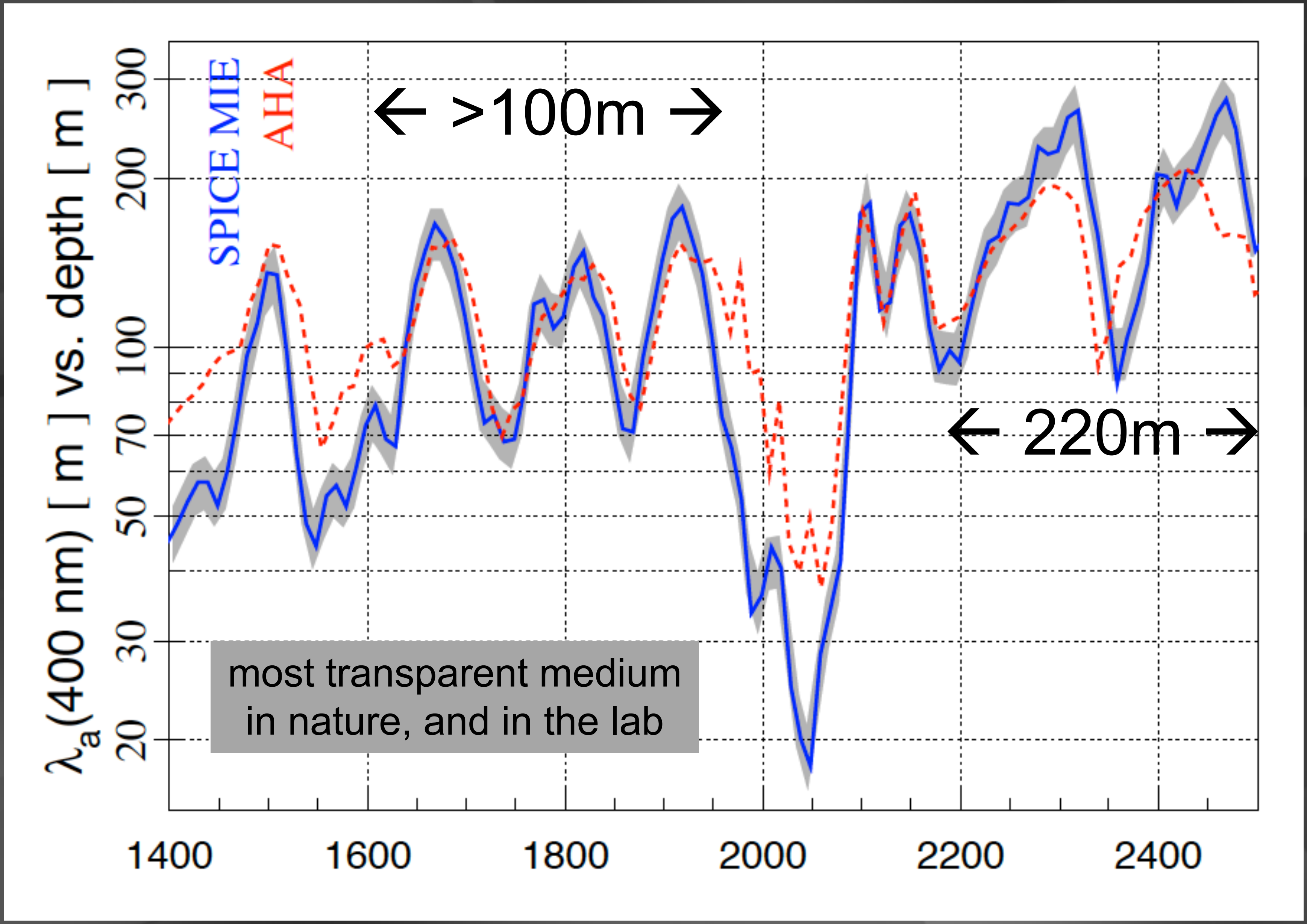




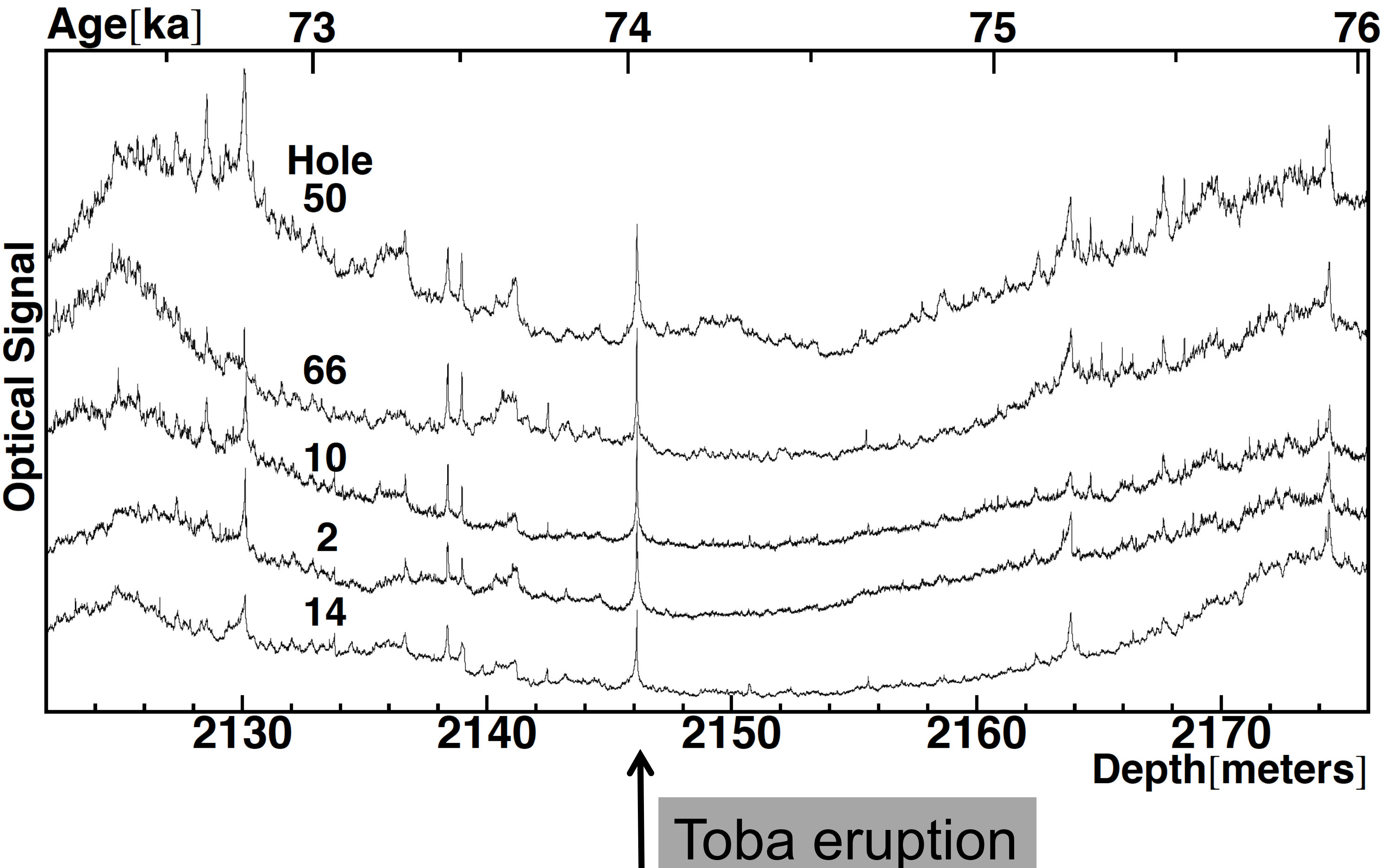
WIPAC
Wisconsin IceCube Particle Astrophysics Center

IceCube
South Pole Neutrino Observatory

absorption length of Cherenkov light



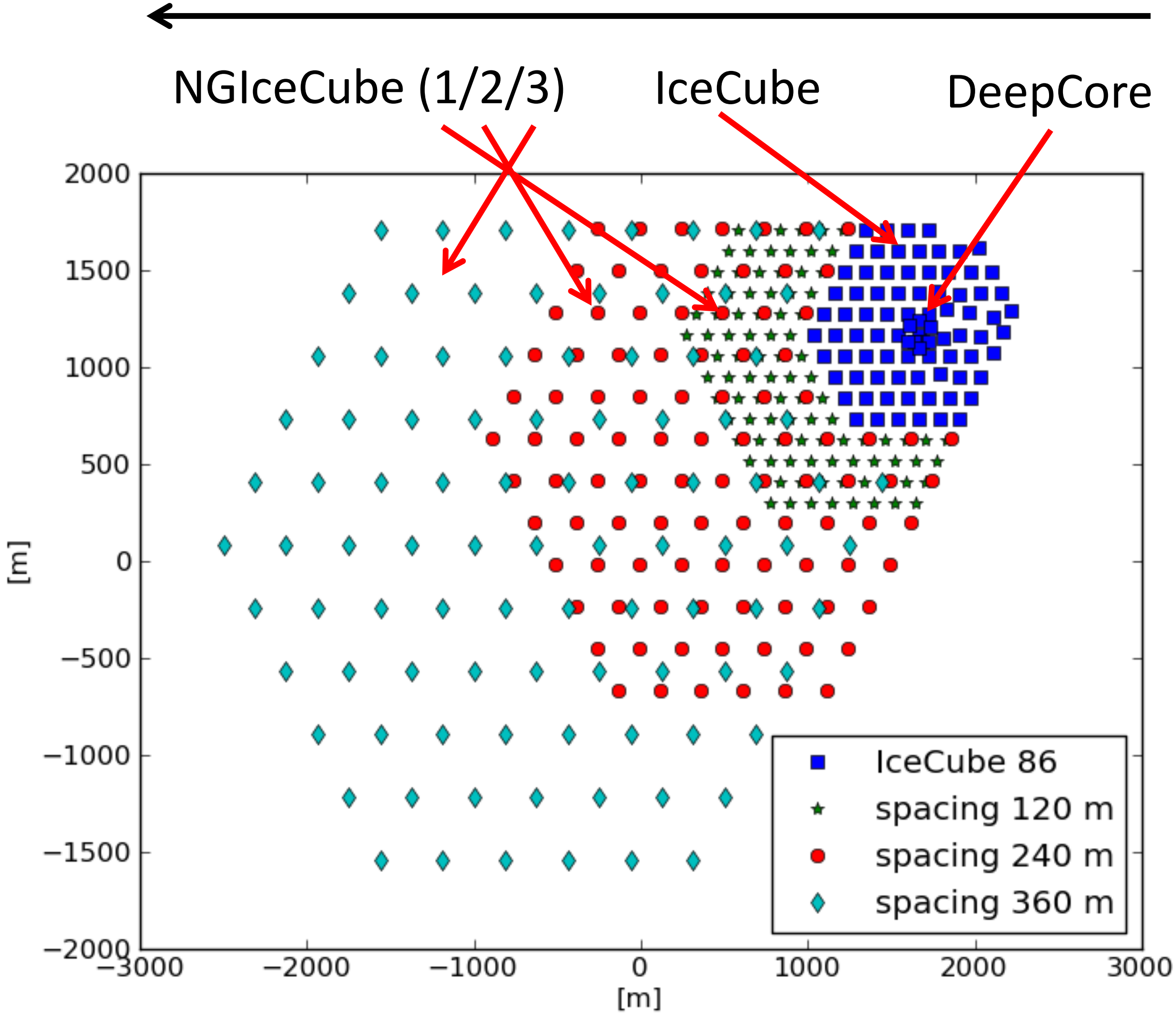
we are limited by computing, not the optics of the ice



Toba eruption

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 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

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

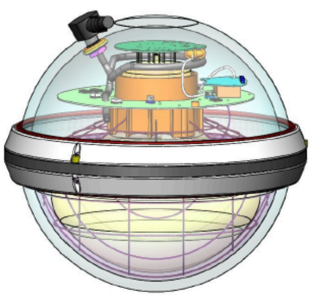
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

New technologies

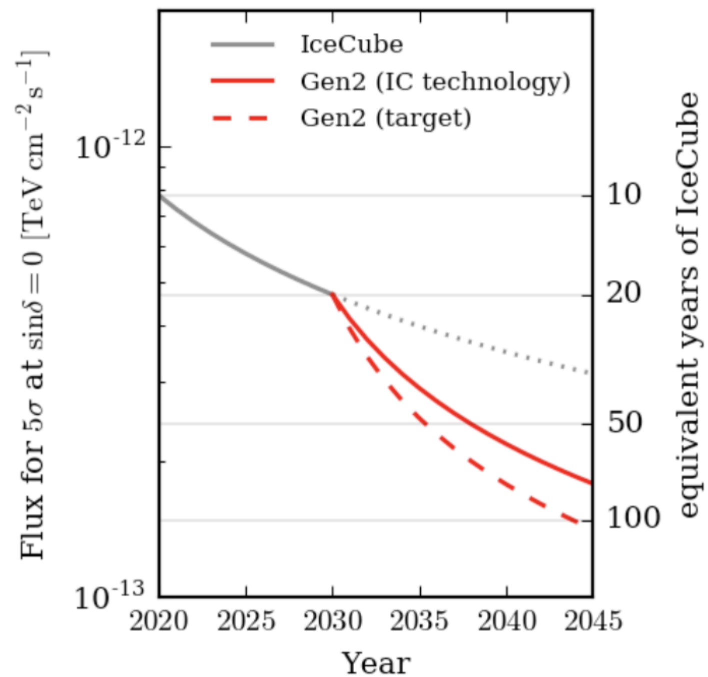
- more PMTs
- wavelength shifters
- narrow profile
- better glass, gel

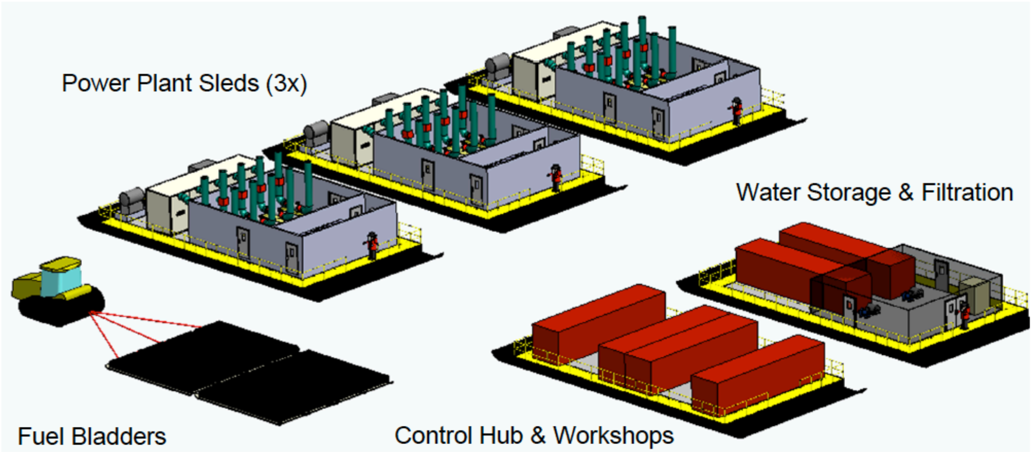
Baseline Gen2 DOM

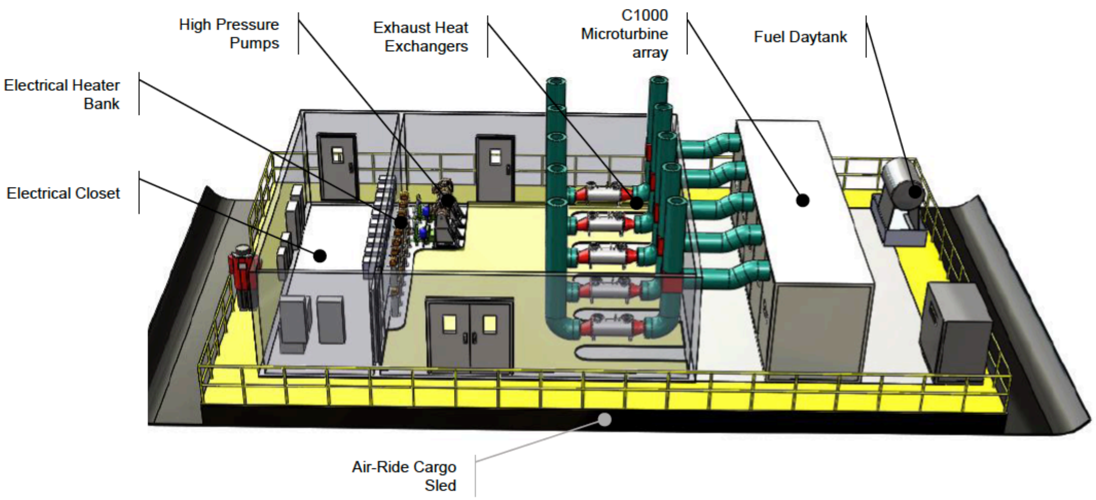
- updated electronics



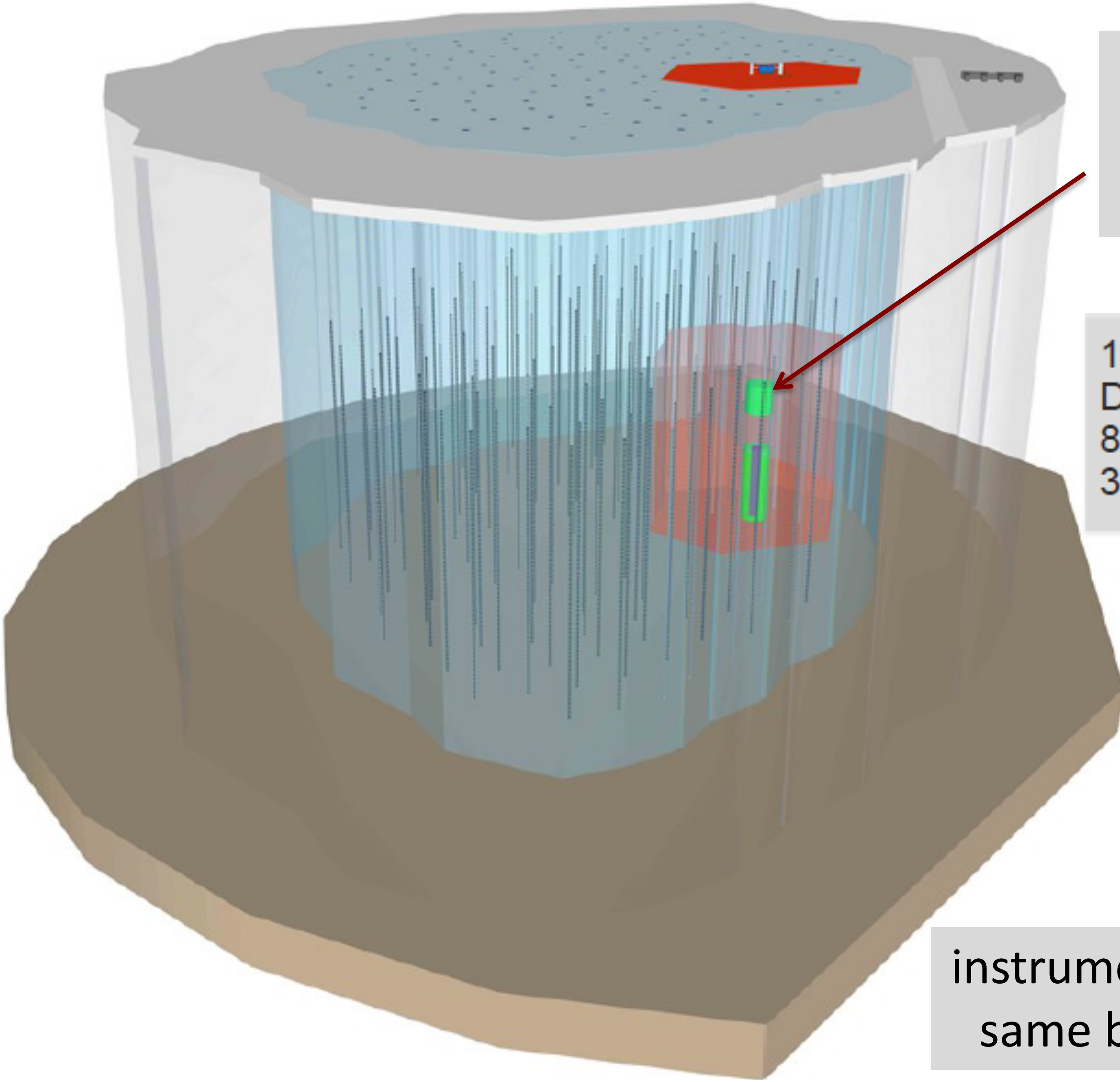
Point source sensitivity







- 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

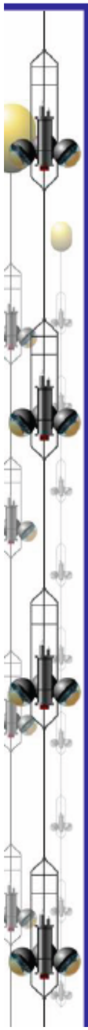


PINGU infill
40 strings
GeV threshold

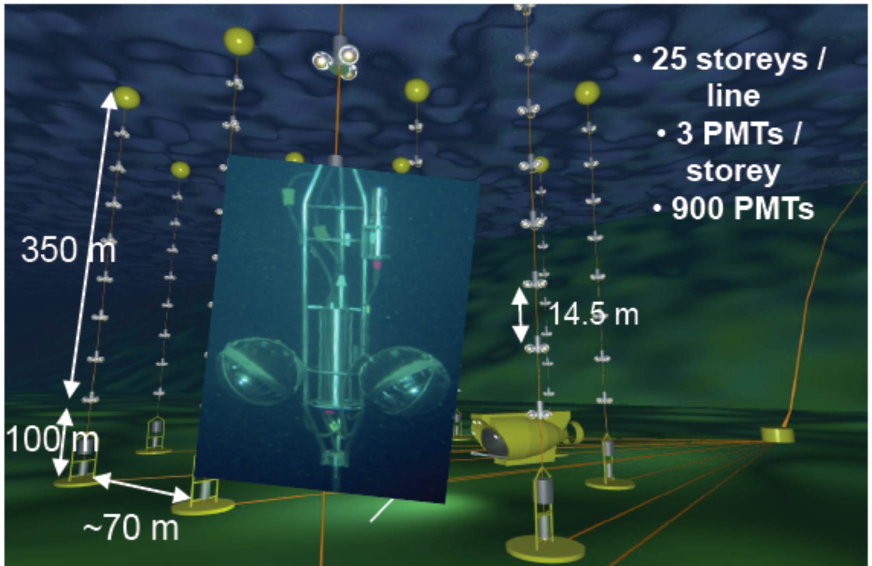
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 10
same budget as IceCube

Mediterranean Detectors



ANTARES Complete since 2008



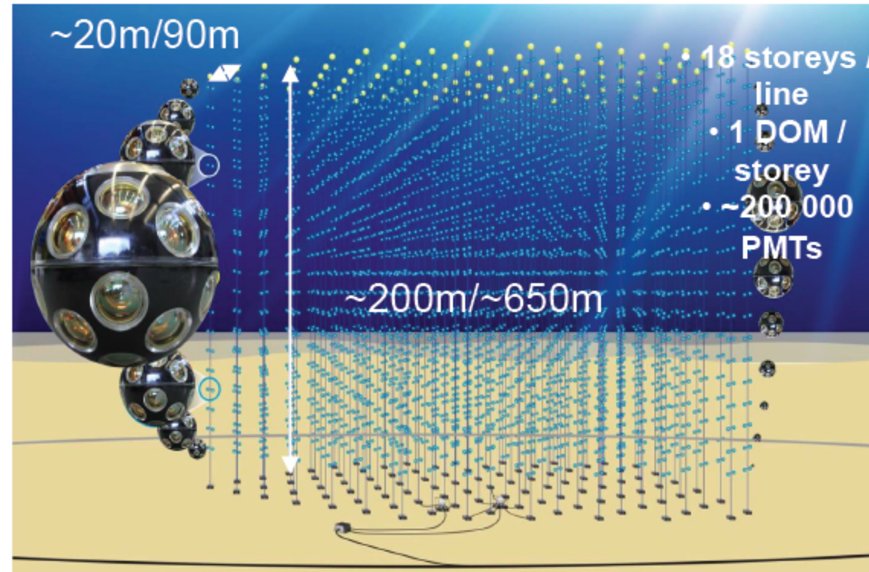
~10 Mton

12 lines

First Generation

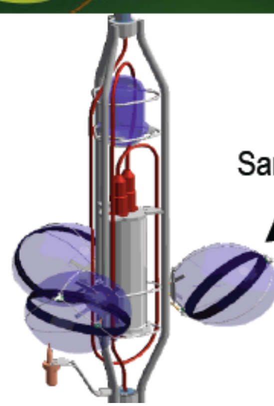
First line since 10 years

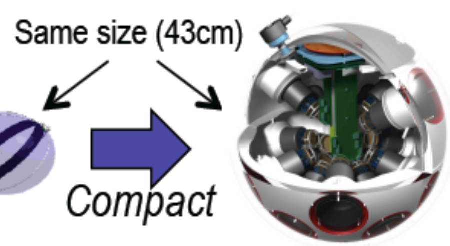
KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton

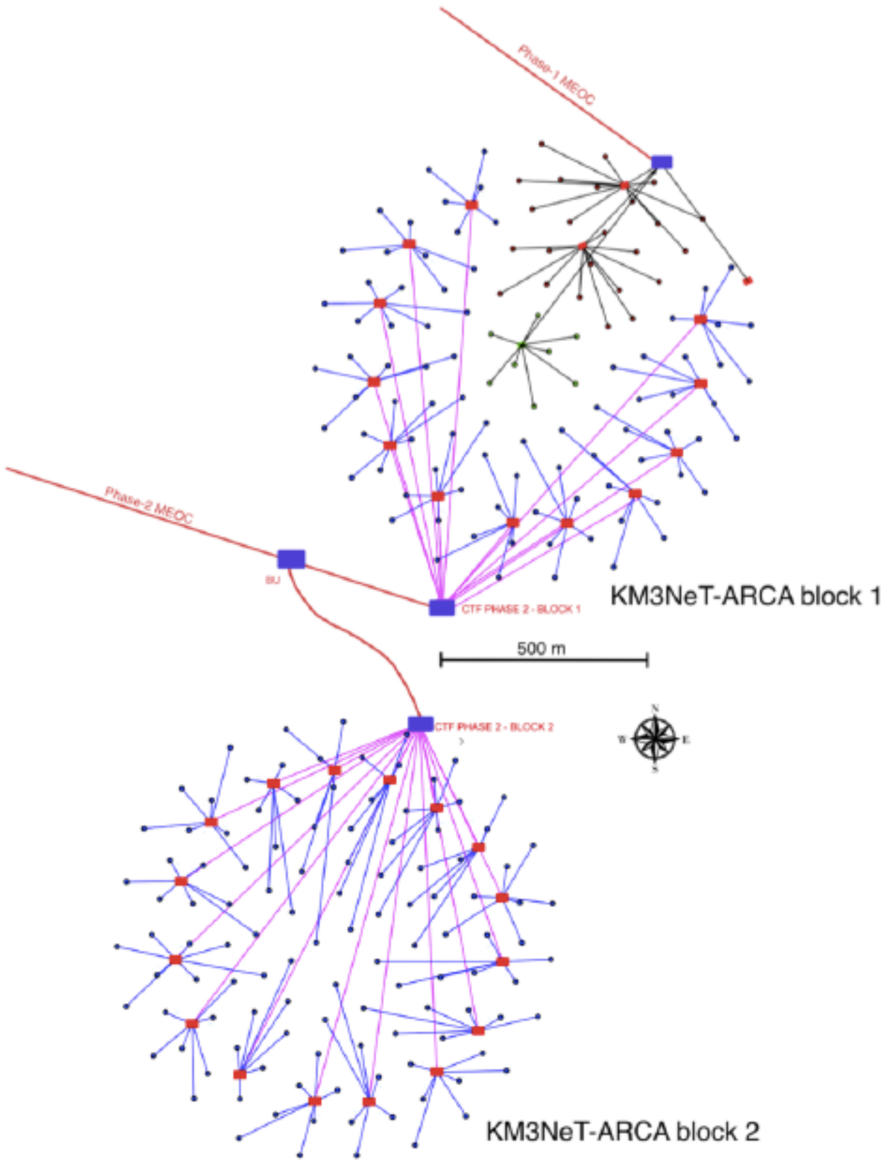


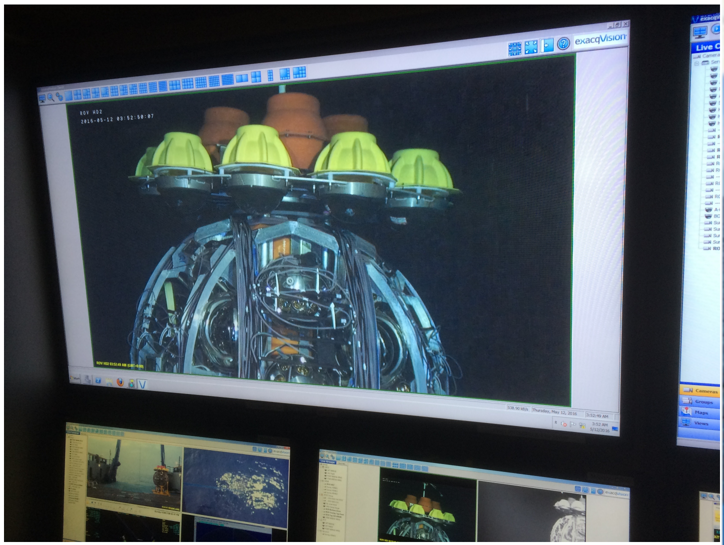


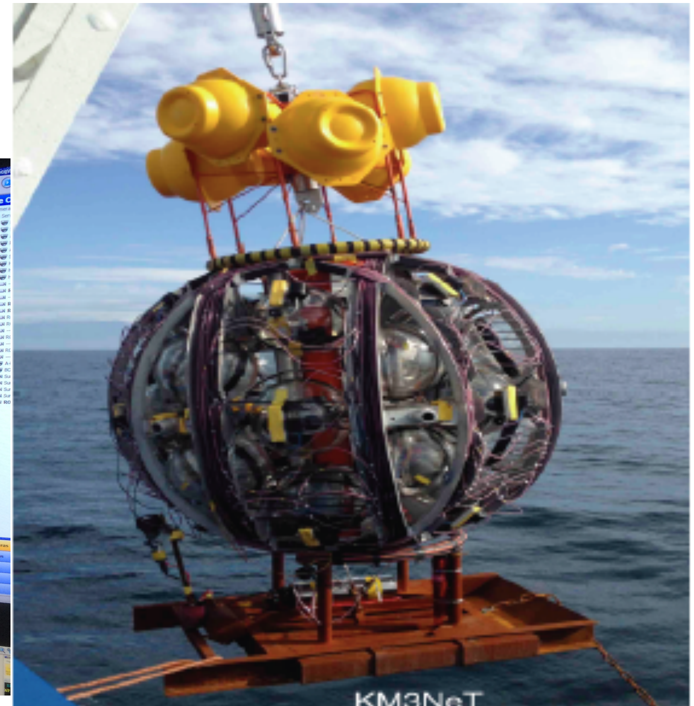
- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

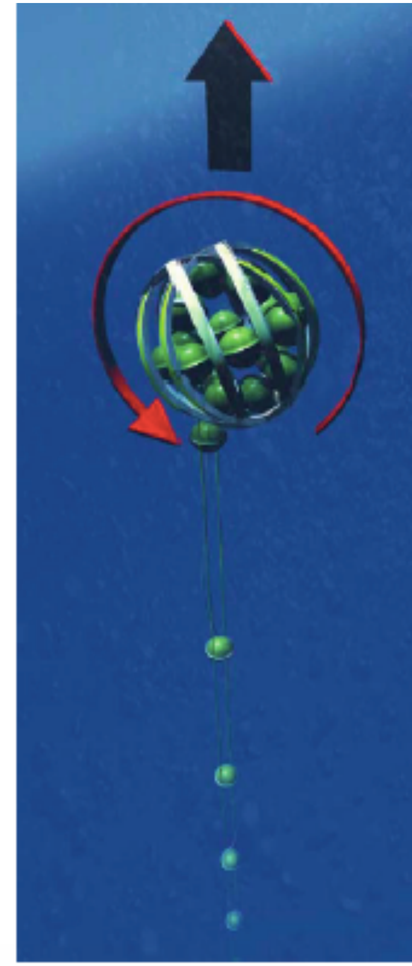
High energies ARCA







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)

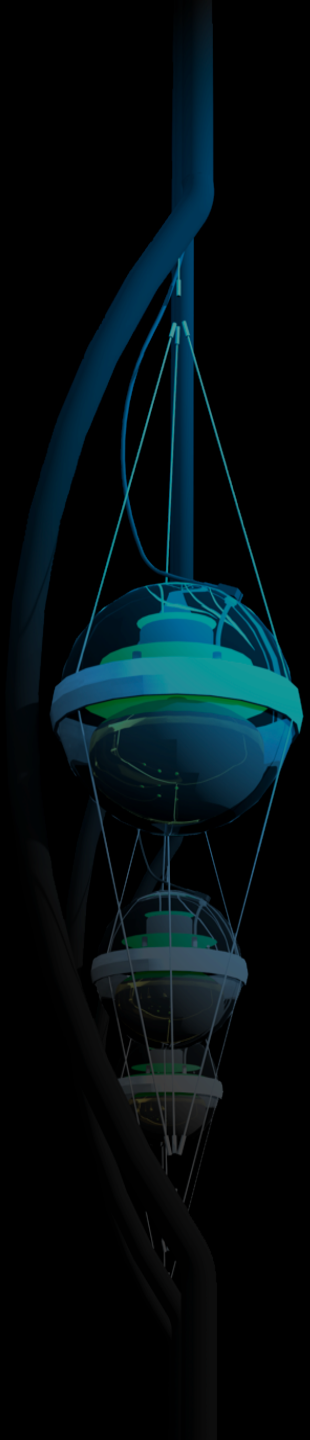
THE ICECUBE COLLABORATION

ISTRALIA 1

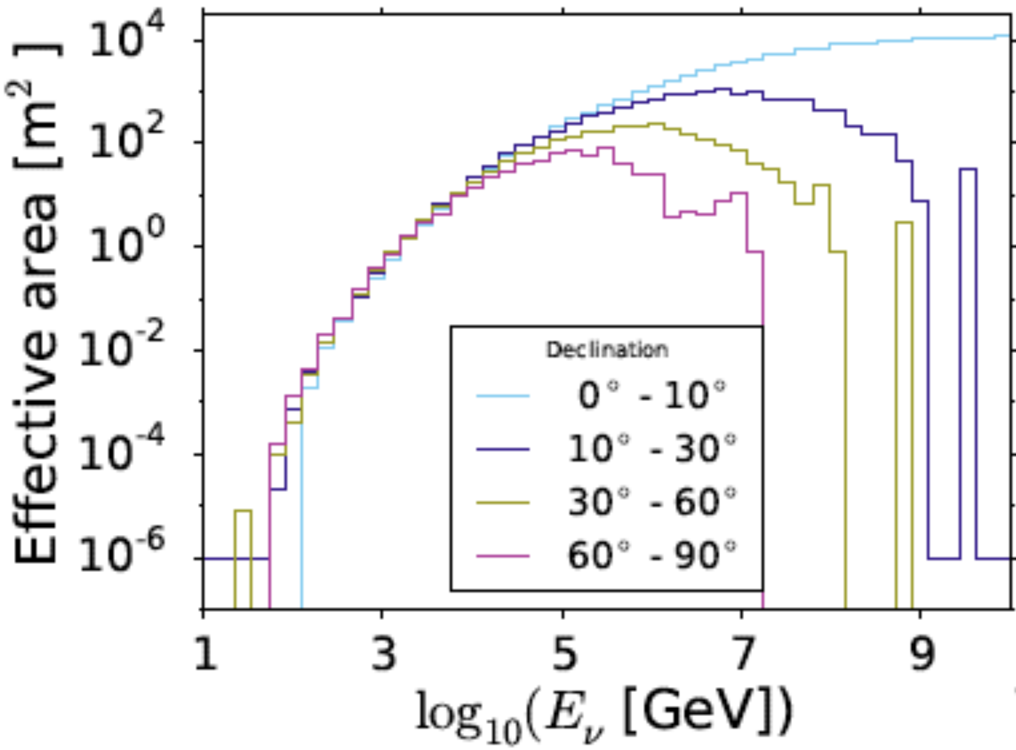
NGDOM 1

UNITED STATES 25

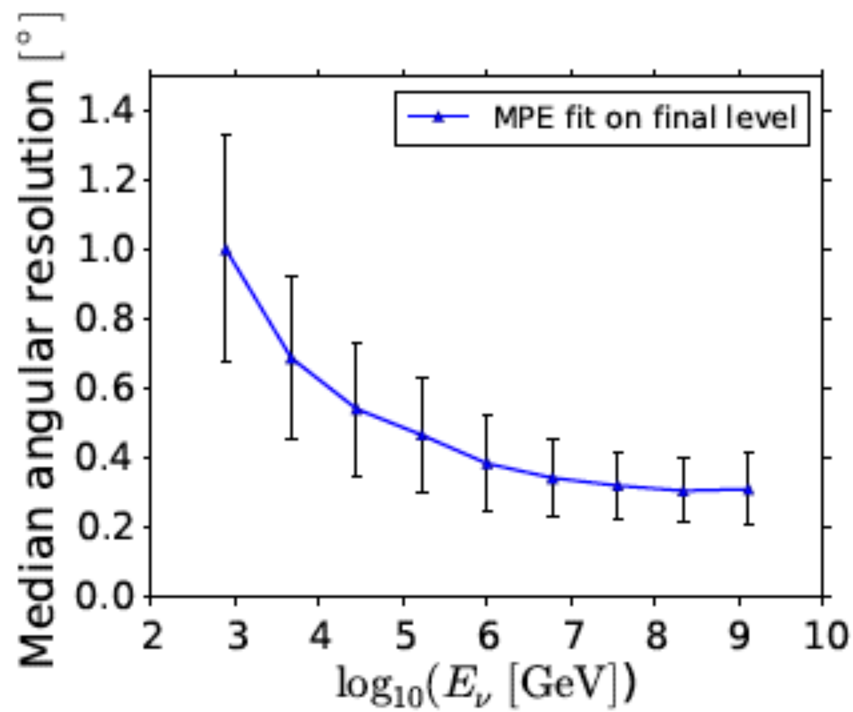
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



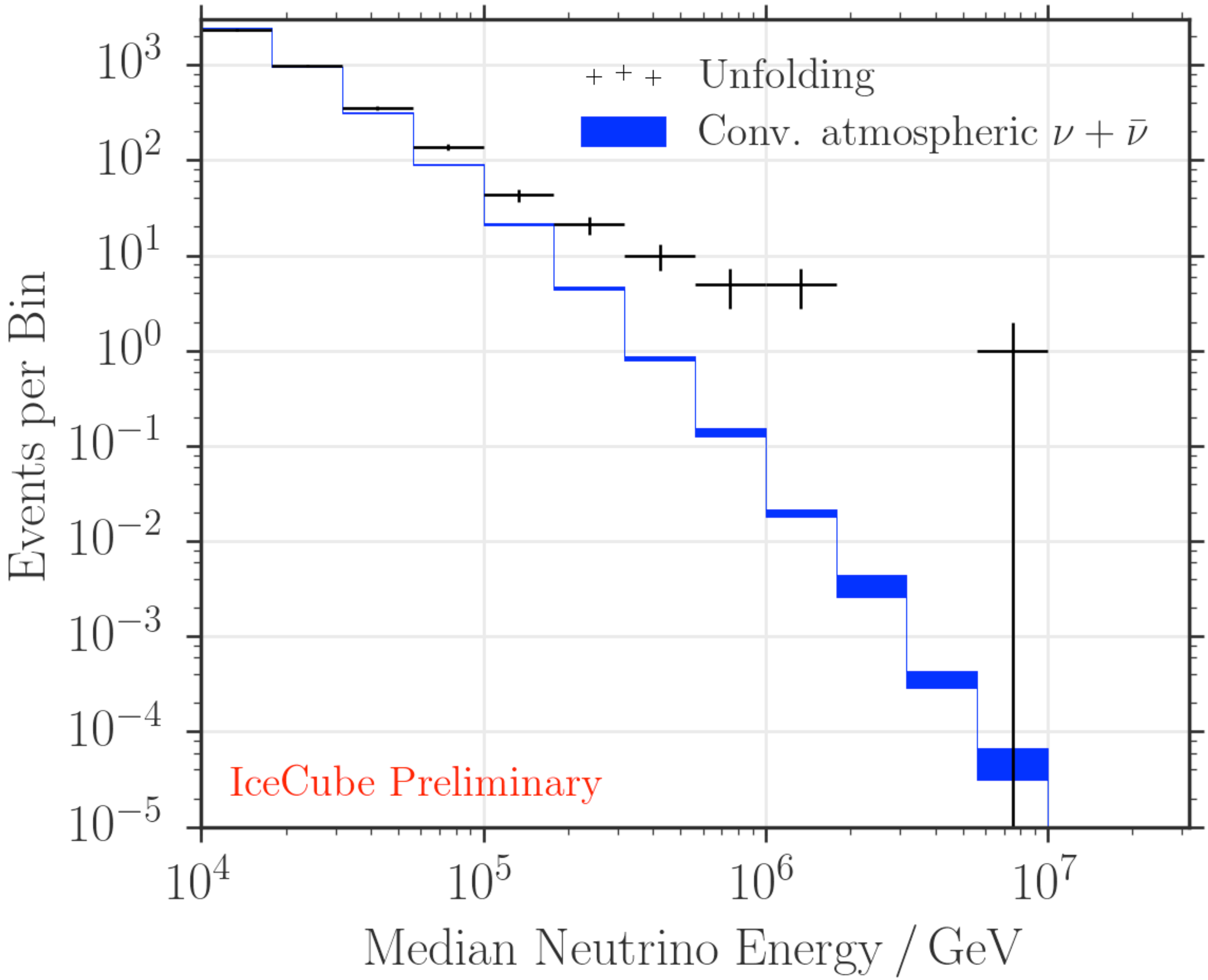
overflow slides



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])

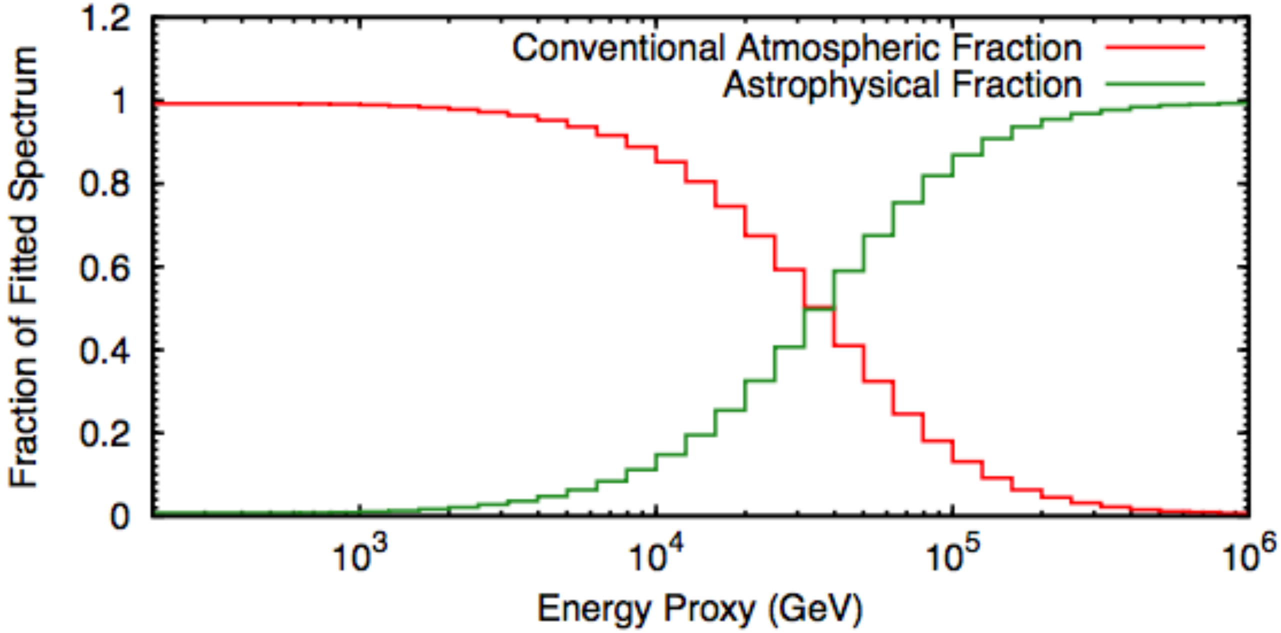


Median angular resolution [°]
MPE fit on final level
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])



Unfolding
Conv. atmospheric $\nu + \bar{\nu}$
IceCube Preliminary
Events per Bin
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
Median Neutrino Energy / GeV

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



equal energy in cosmic rays and neutrinos

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

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

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

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

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

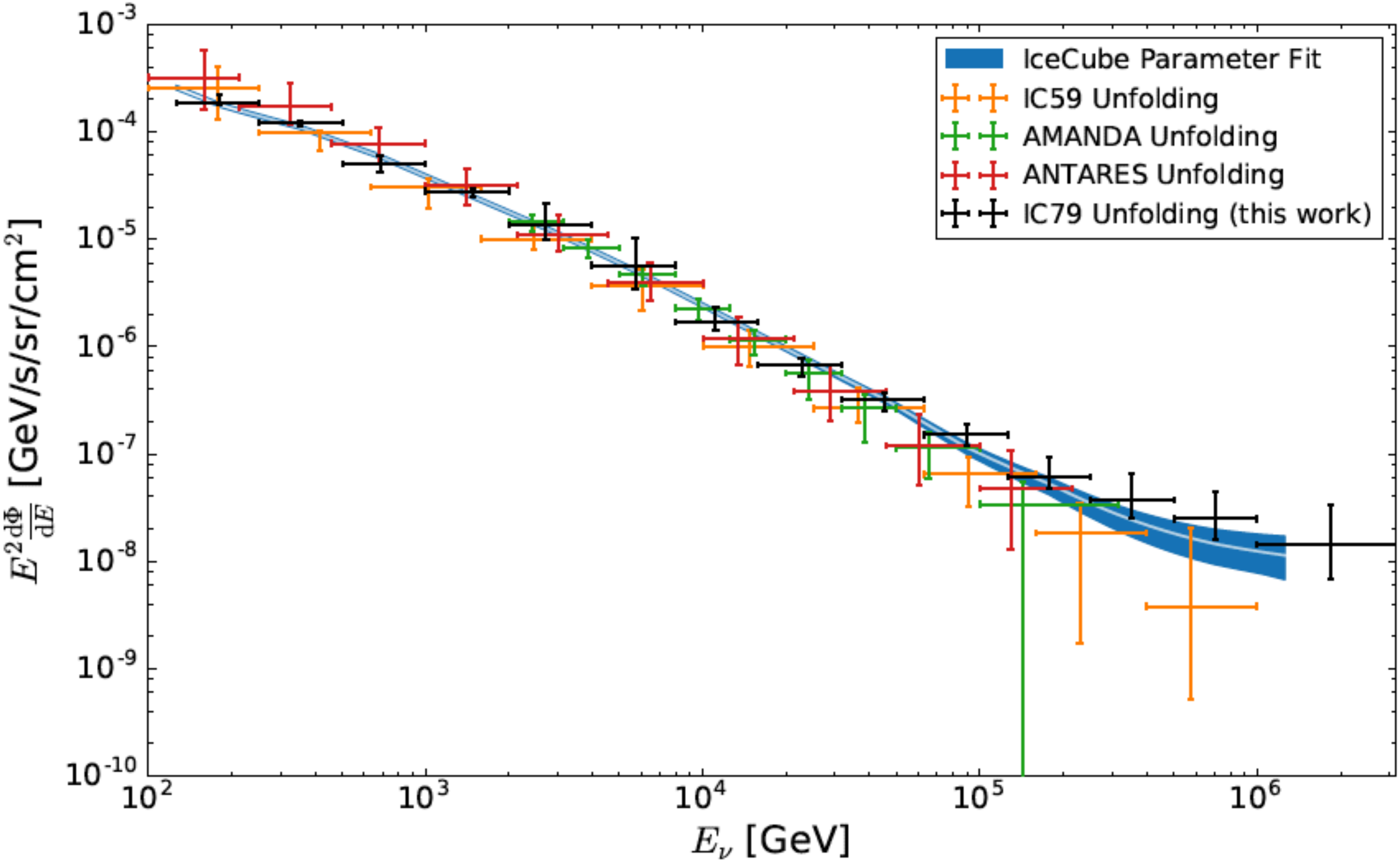
equal energy in cosmic rays and neutrinos

actually…

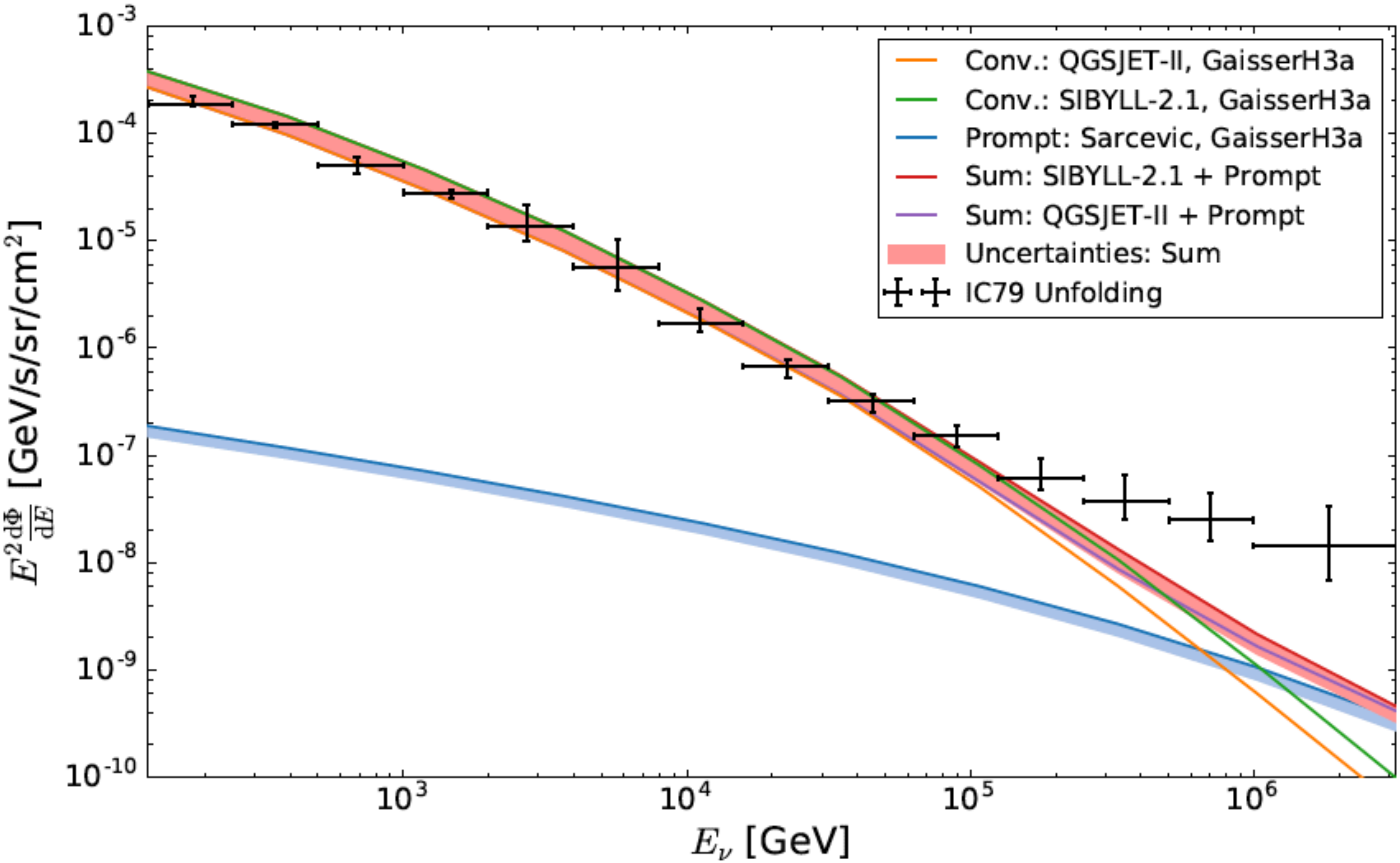
$$\rho_{\nu+\bar{\nu}}(E) = f_\pi \frac{E}{E_p}\left[\xi_z t_H\right]\left[c\dot{\rho}_{cr}\right]$$

- $f_\pi \leq 1$ 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

unfolded "atmospheric" neutrino flux

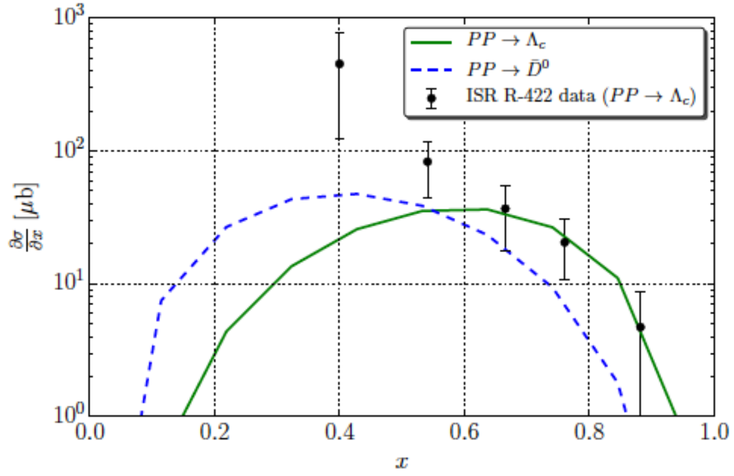


unfolded “atmospheric” neutrino flux

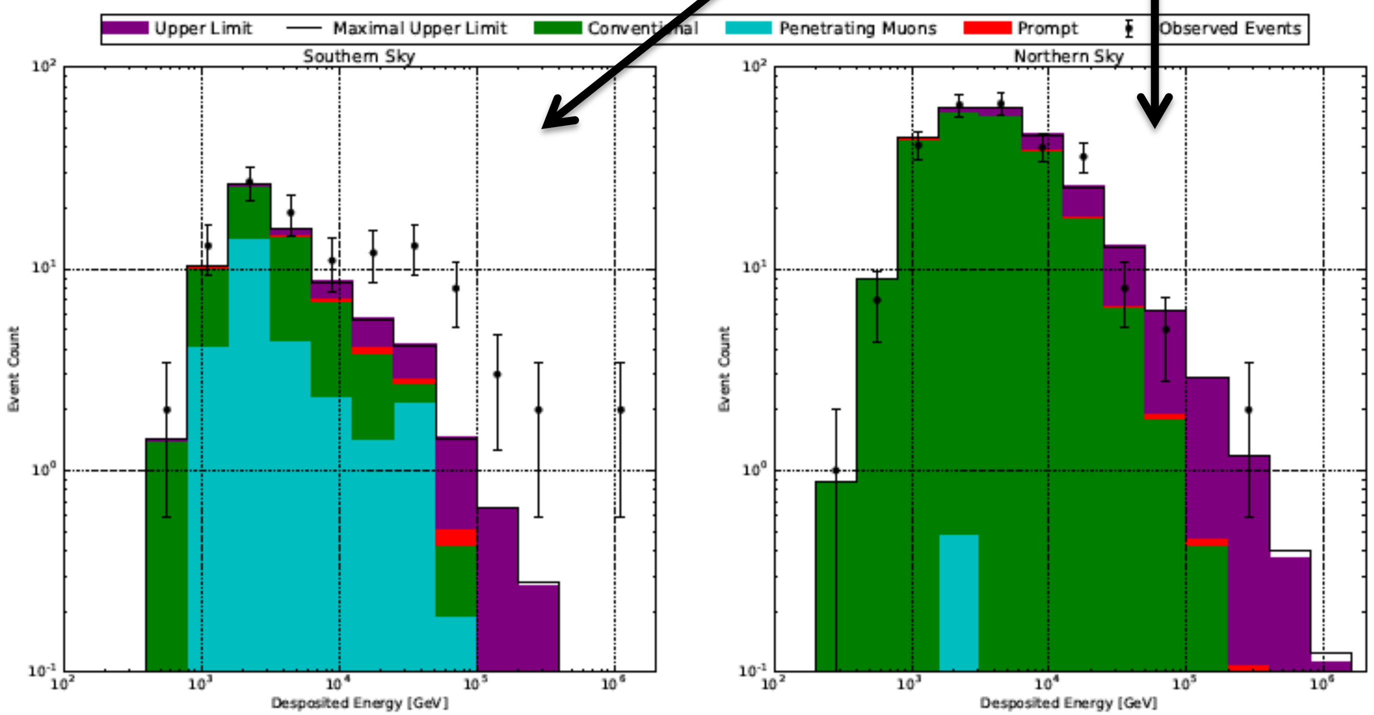


not forward charm production

analogous to pp→($K^+\Lambda$)p

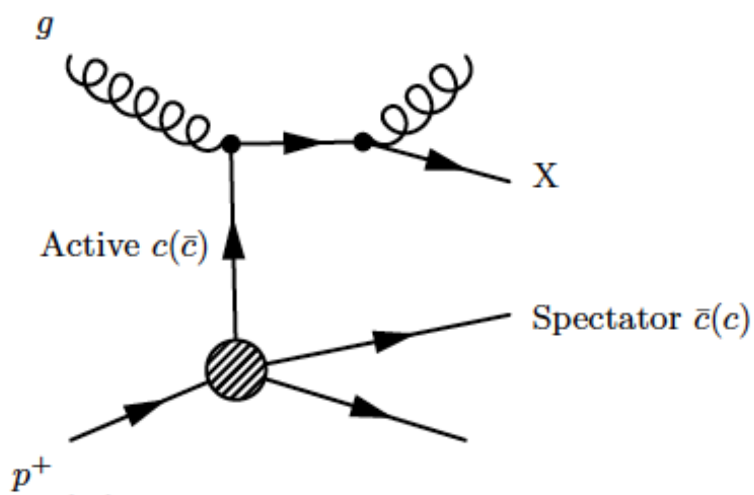


upcoming events:
"extreme" charm model can fit the northern, not the southern hemisphere

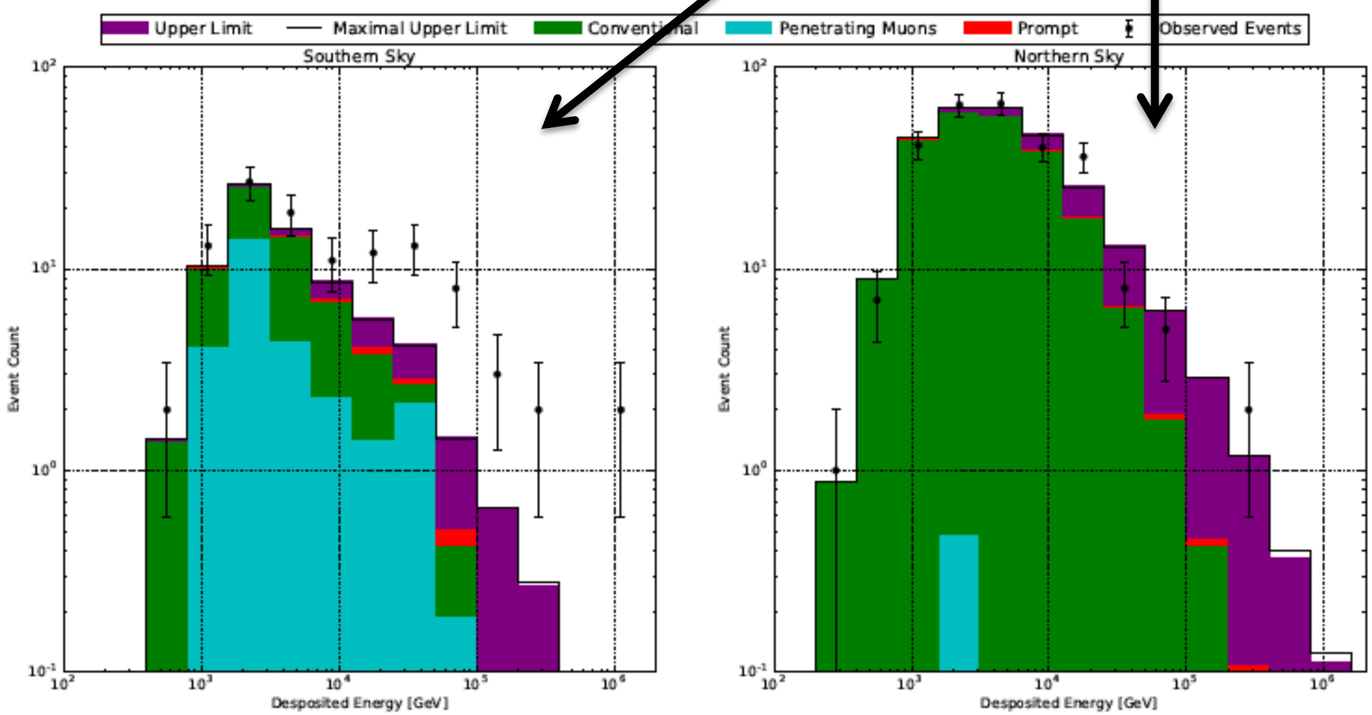


LHC: charm pairs in proton

analogous to pp→($K^+\Lambda$)p



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



```
//////////////////////////////////////////////////////////////////////
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 High Neutrino.
9440 Search for counte IceCube-160814A ANTARES
9425 MASTER: OT disc during inspection 58537957 trigger
9391 INTEGRAL follow- IceCube HESE 12 58537957

HESE ALERT

- 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?

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

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

$$L_\nu \rho = \frac{4\times 10^{43}}{\zeta}\frac{erg}{Mpc^3 yr}$$ 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:

$$F_{ns} = \frac{L_\nu}{4\pi d^2} \le 2\times 10^{-9}\,\frac{\text{GeV}}{\text{cm}^2\text{sec}} \quad \text{with} \quad d = (4\pi\rho)^{\frac{1}{3}} \leftarrow V_1 \propto \frac{1}{\rho}$$

and

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

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

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

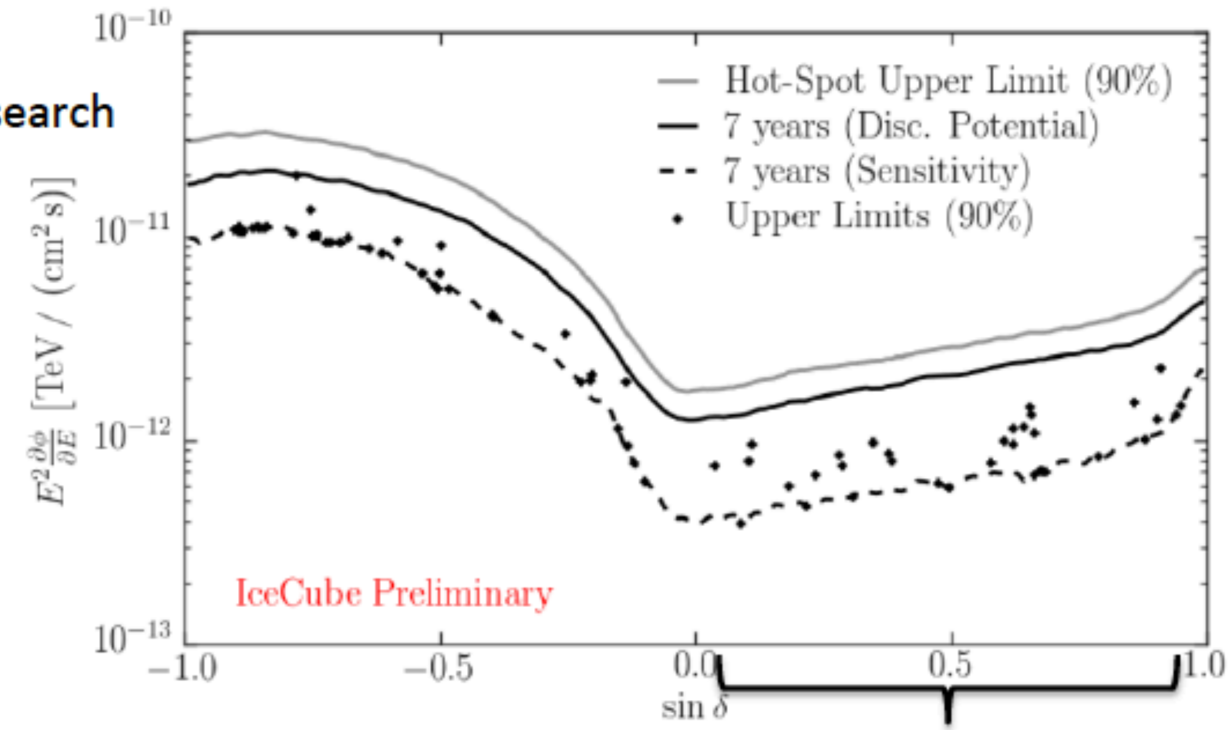
$\#$ of events from the whole sky : $\zeta L_\nu \rho R_H \otimes Area$

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

Point source limits

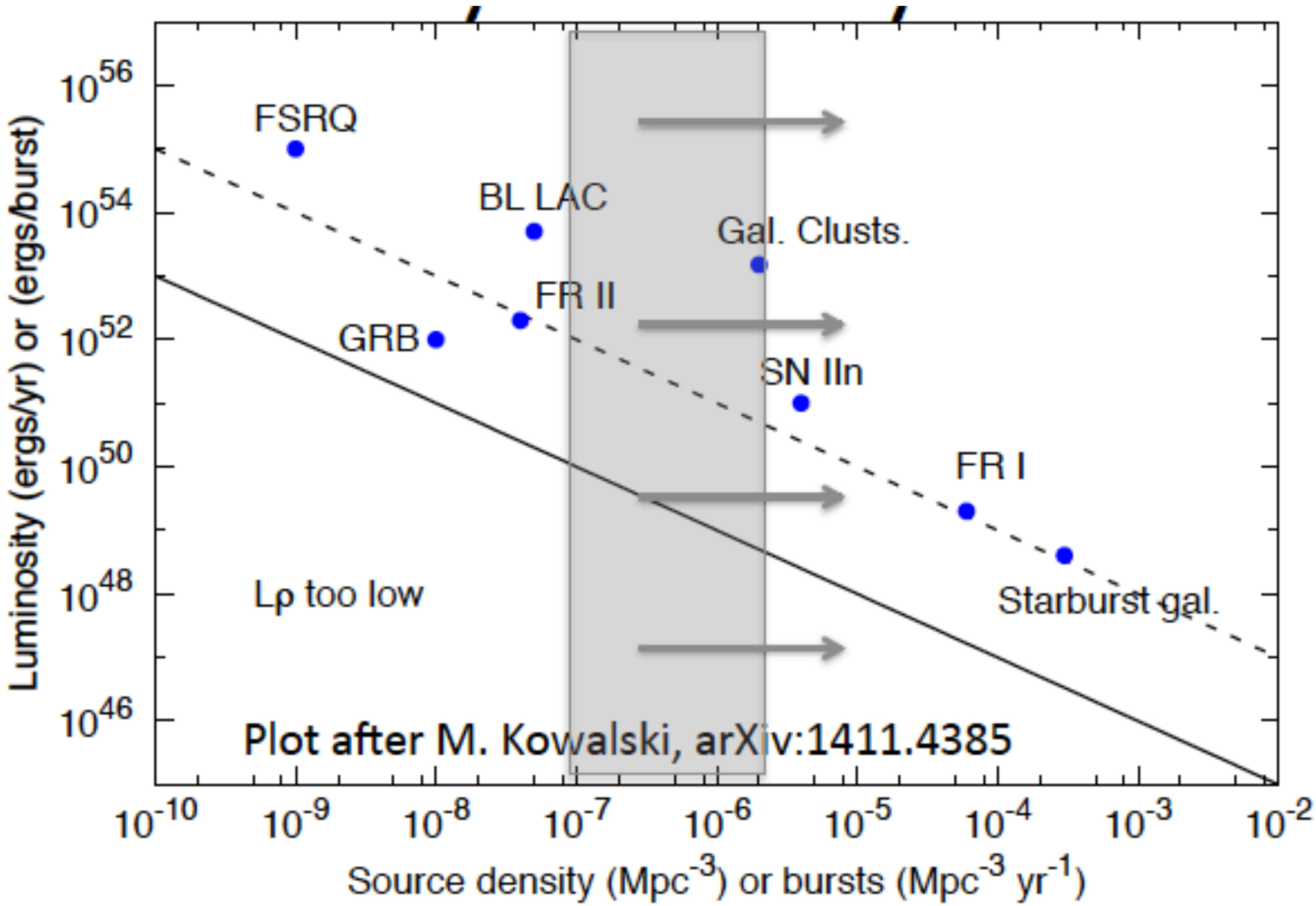
Relation between flux from whole sky and number/intensity of individual sources
P. Lipari, PR D78 (2008) 083001 … Murase & Waxman, arXiv:1607.01601

IceCube 7 yr pt src search



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

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



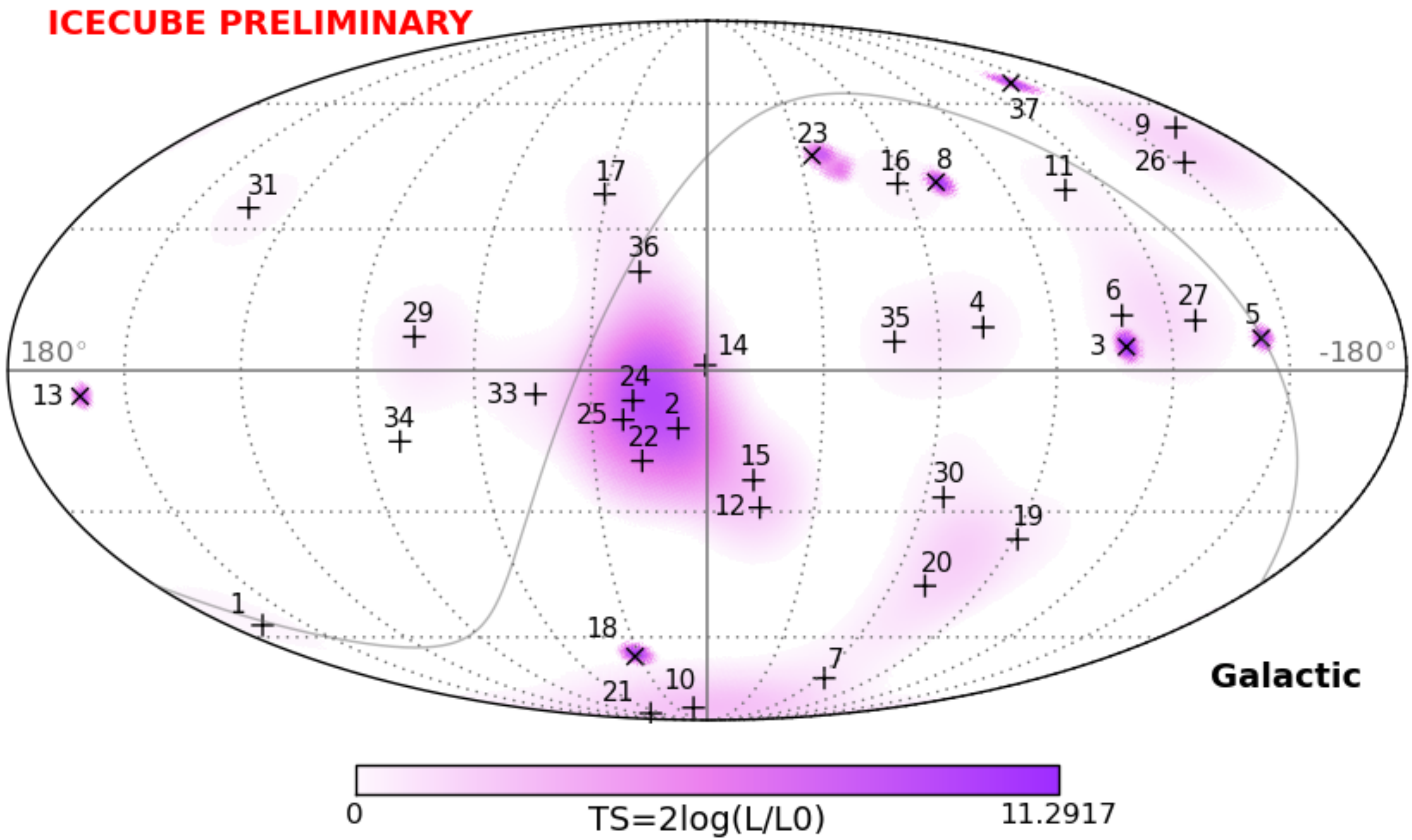
FSRQ
BL LAC
Gal. Clusts.
FR II
GRB
SN IIn
FR I
Starburst gal.
Lρ too low
Plot after M. Kowalski, arXiv:1411.4385
Luminosity (ergs/yr) or (ergs/burst)
Source density (Mpc-3) or bursts (Mpc-3 yr-1)

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

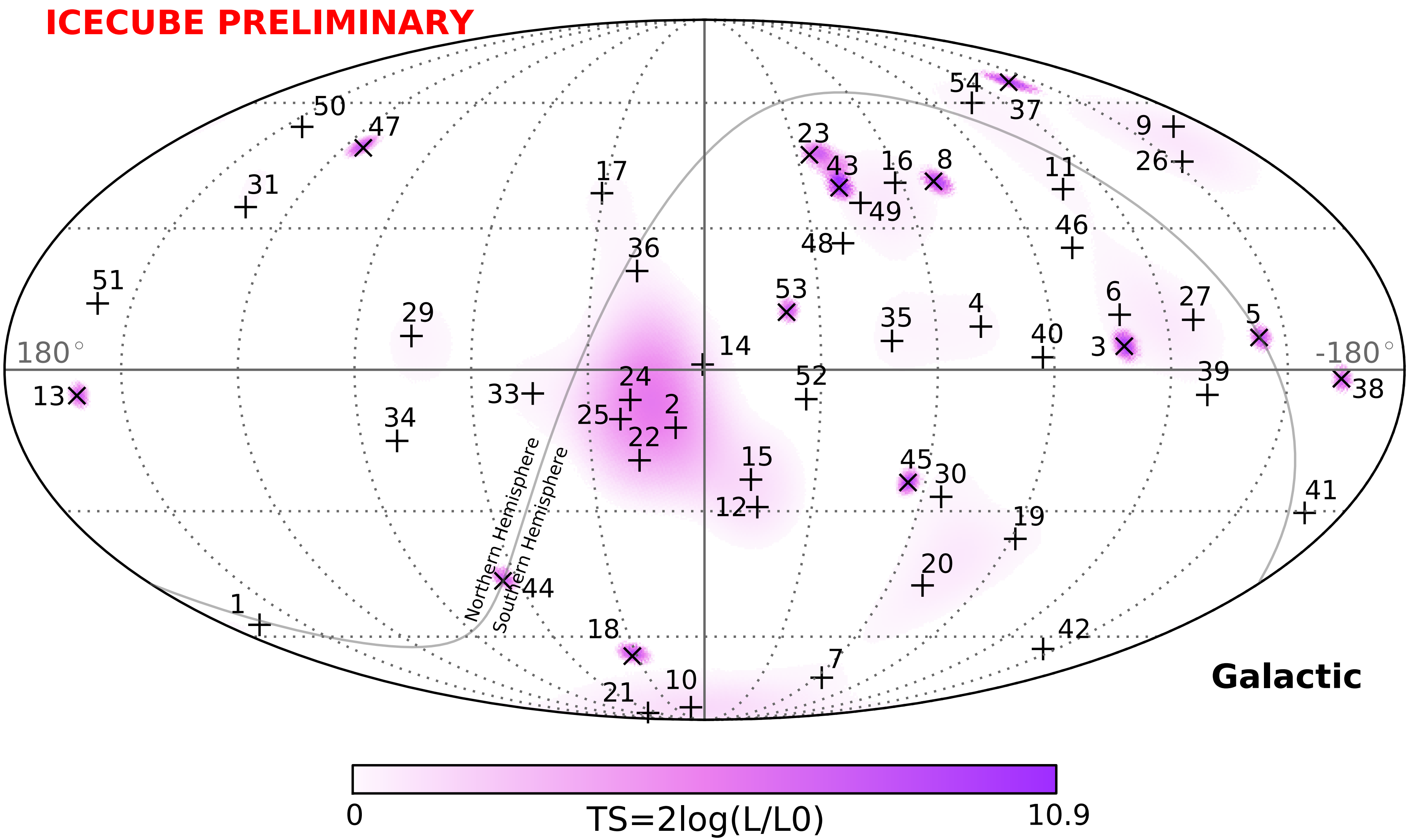
Φ_{ν_e} $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	interaction type	pp source IC-86	240m	360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$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

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

3 year HESE

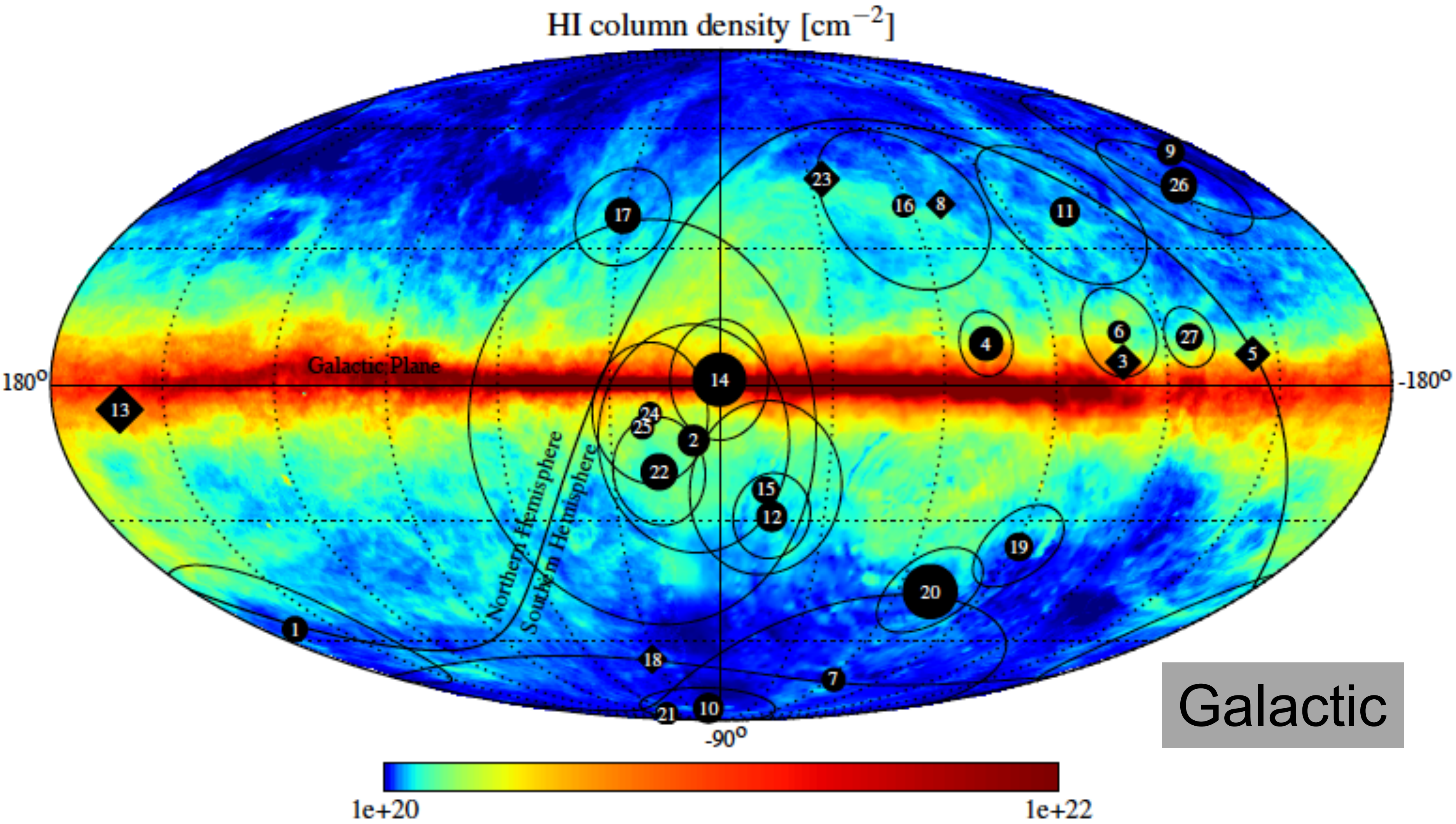


4 year HESE



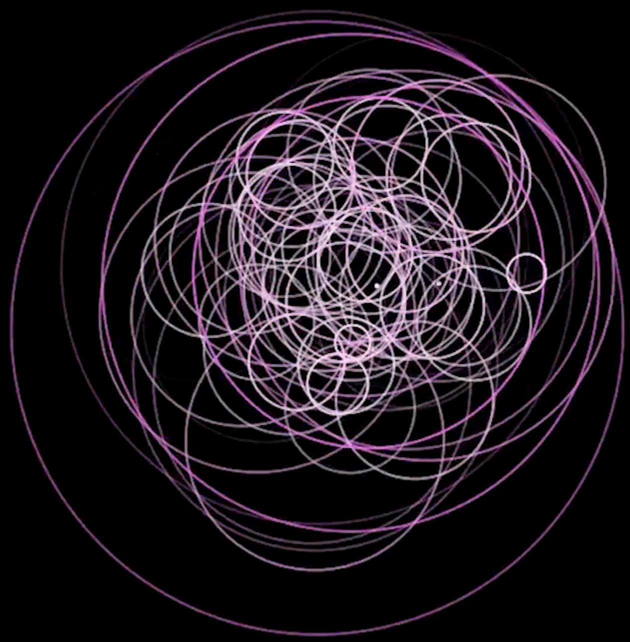
where do they come from?

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



Galactic

11 Sep 2017



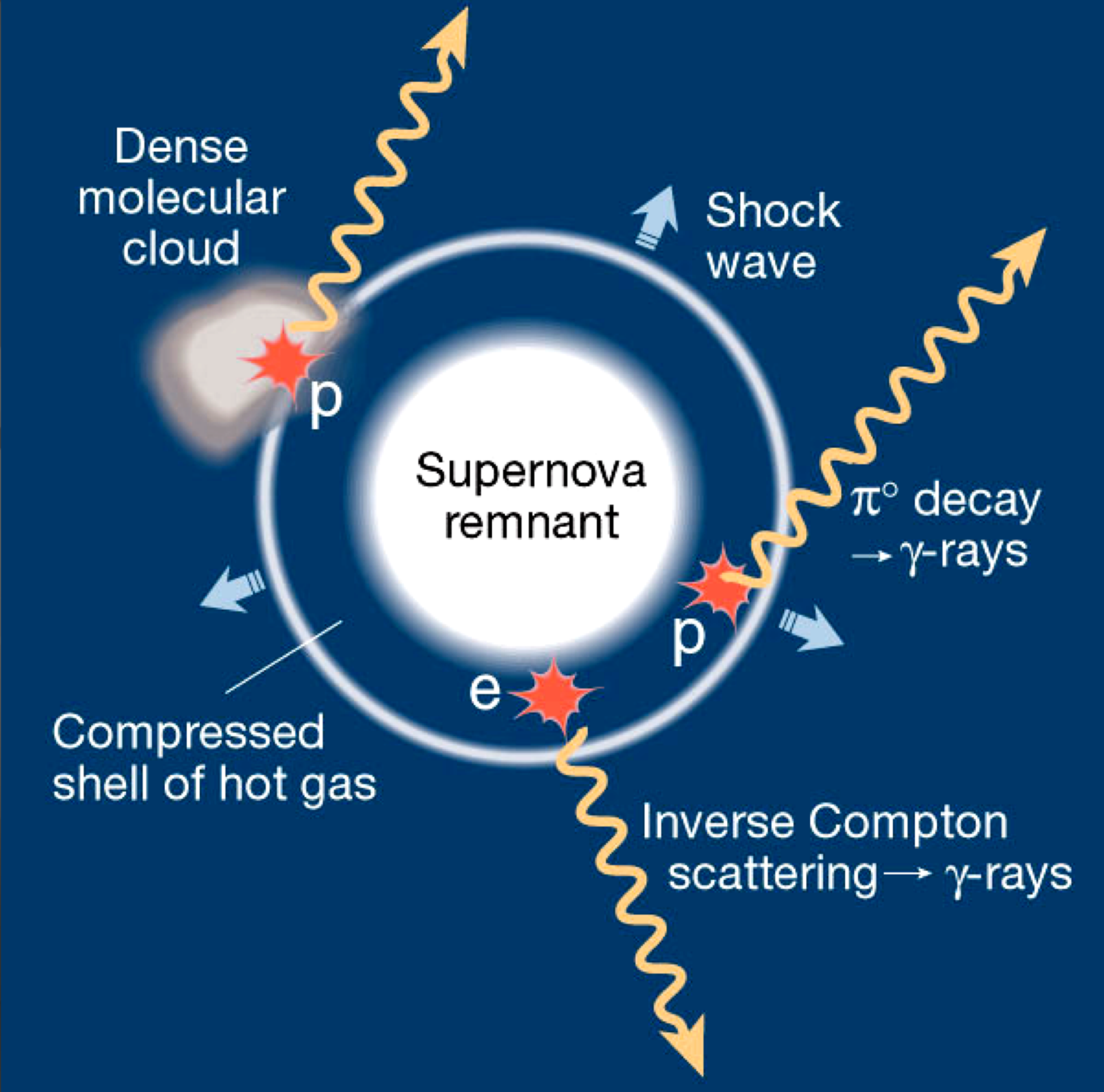
IceCube Neutrino Flare

2014 - 2015

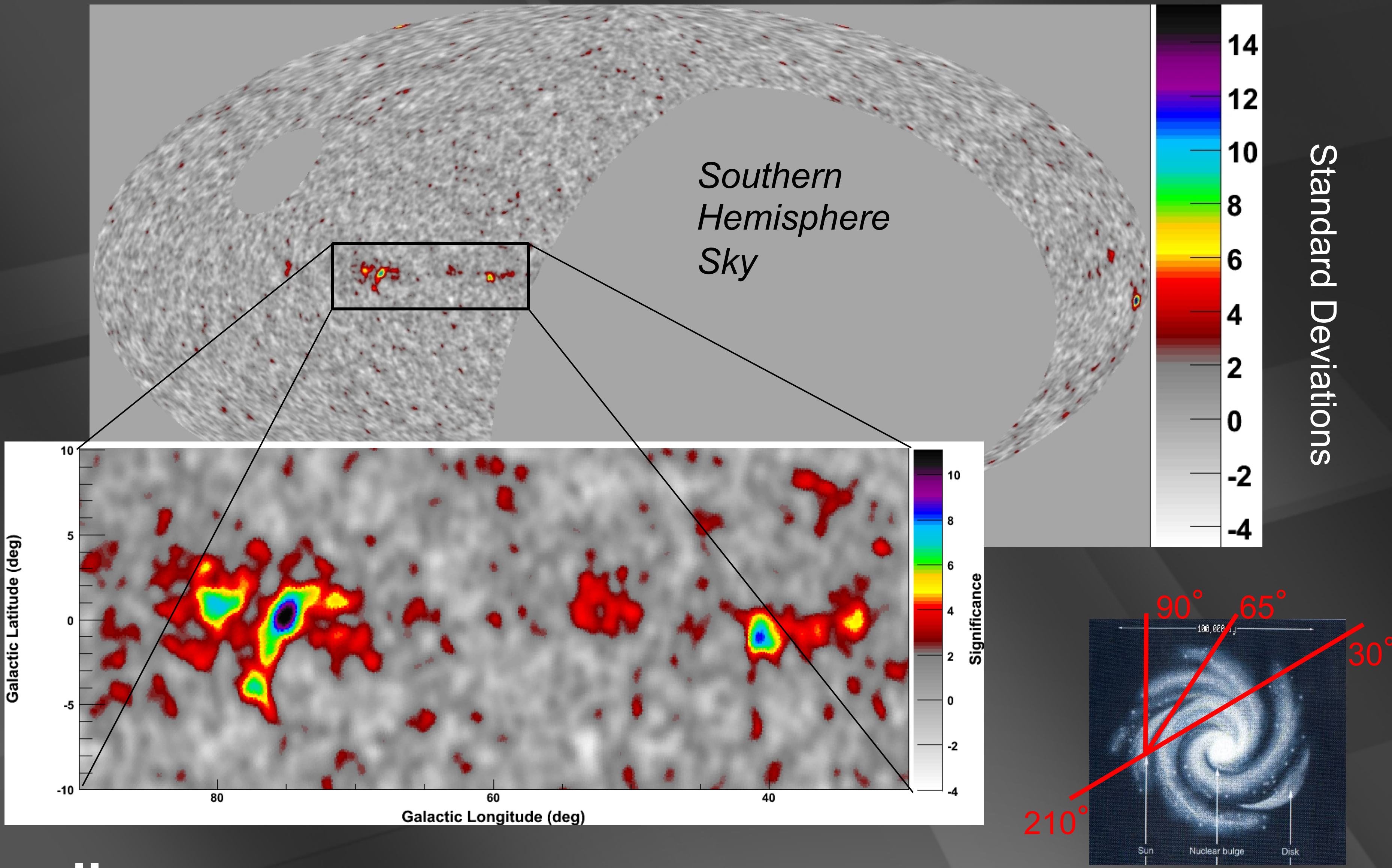
Galactic sources?

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

10^{-12} erg/cm^3

energy in >TeV photons produced by cosmic rays per cm^3 per sec

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

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

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

should be observed by present TeV gamma-ray telescopes

Milagro sources ?
RX J1713.7-3946??

neutral pions

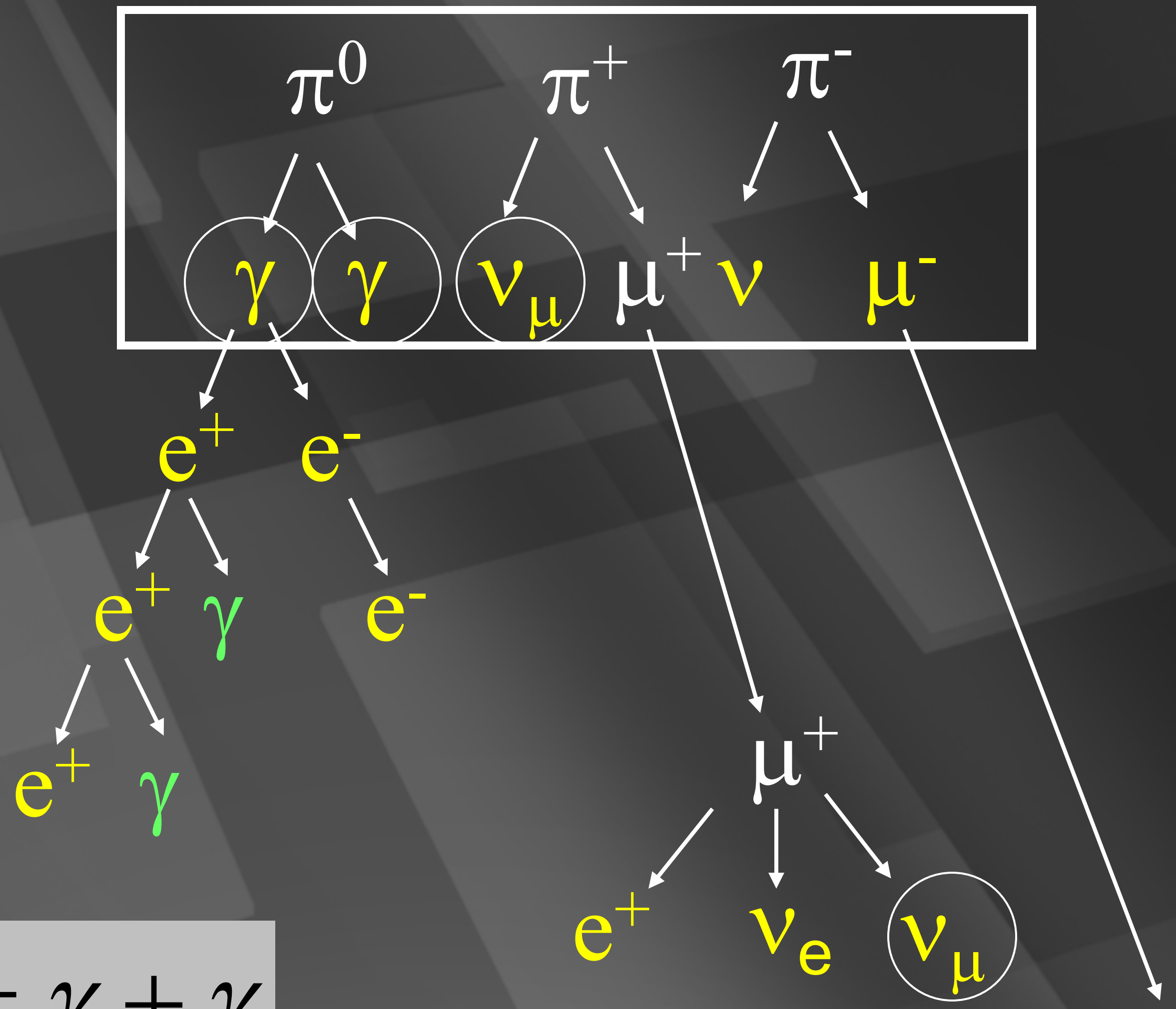
are observed as

gamma rays

charged pions

are observed as

neutrinos



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

ν flux accompanying TeV gammas

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

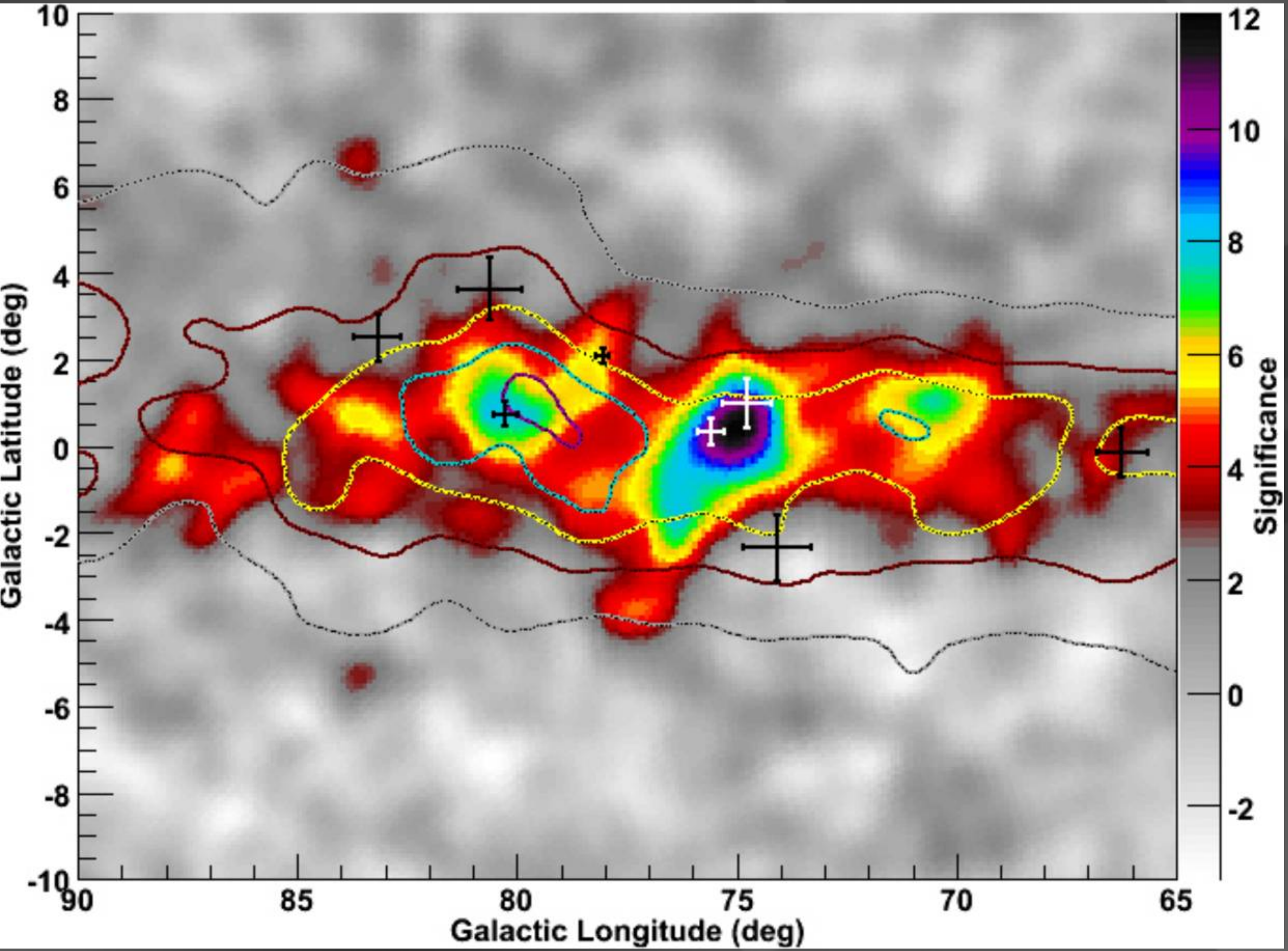
$$\text{number of events} = \text{Area Time} \int dE \, \frac{dN_\nu}{dE} P_{\nu \to \mu}$$

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

reject background

$\rightarrow E \geq 40\, TeV$

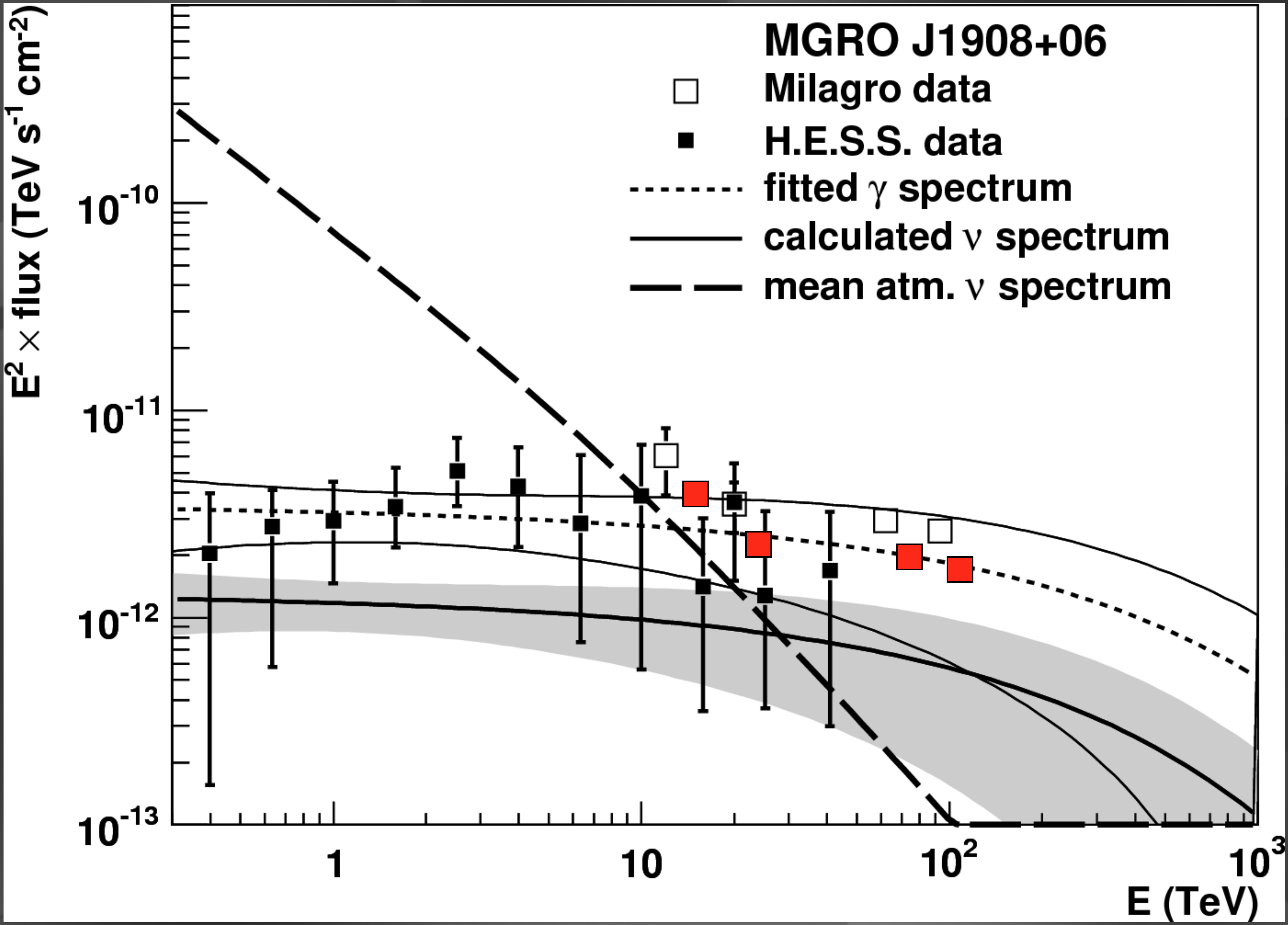
Cygnus region at ~ 1kpc : Milagro



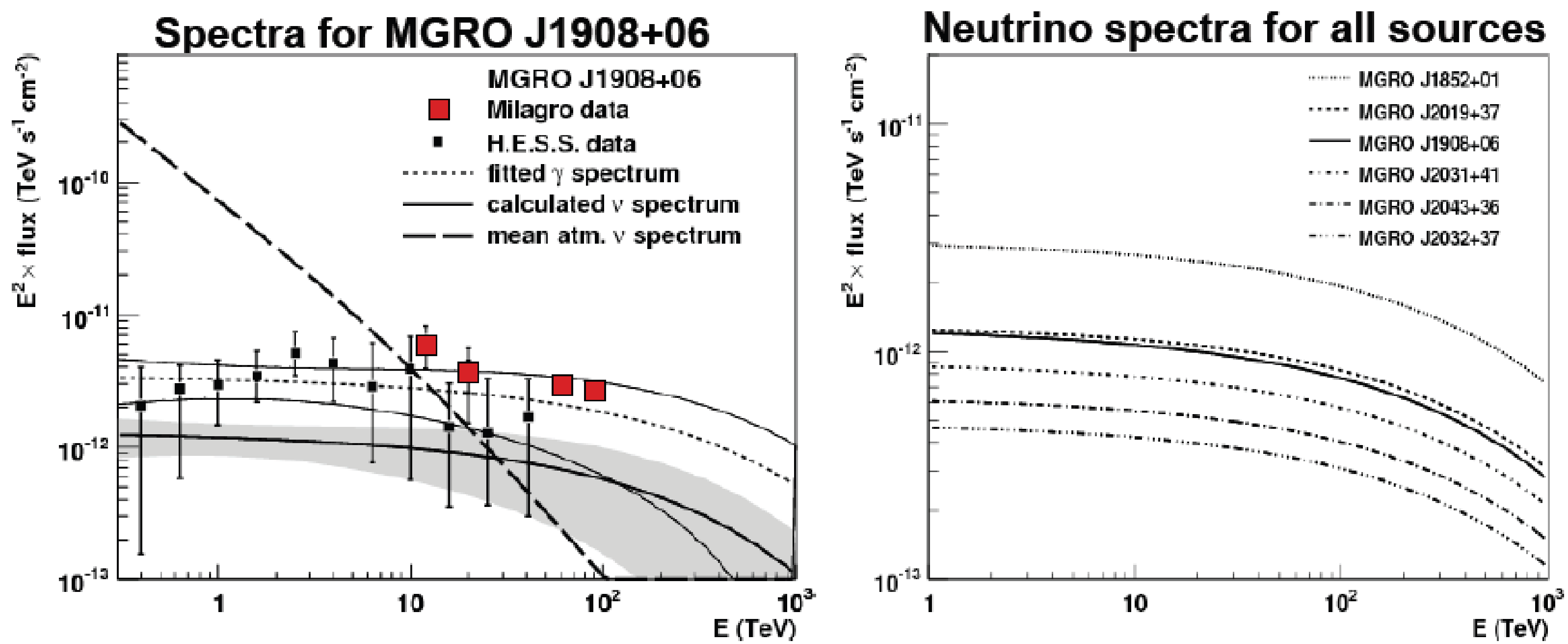
translation of
TeV gamma rays
into
TeV neutrinos
yields:

3 ± 1 ν per year in IceCube per source

MGRO J1908+06: the first Pevatron?



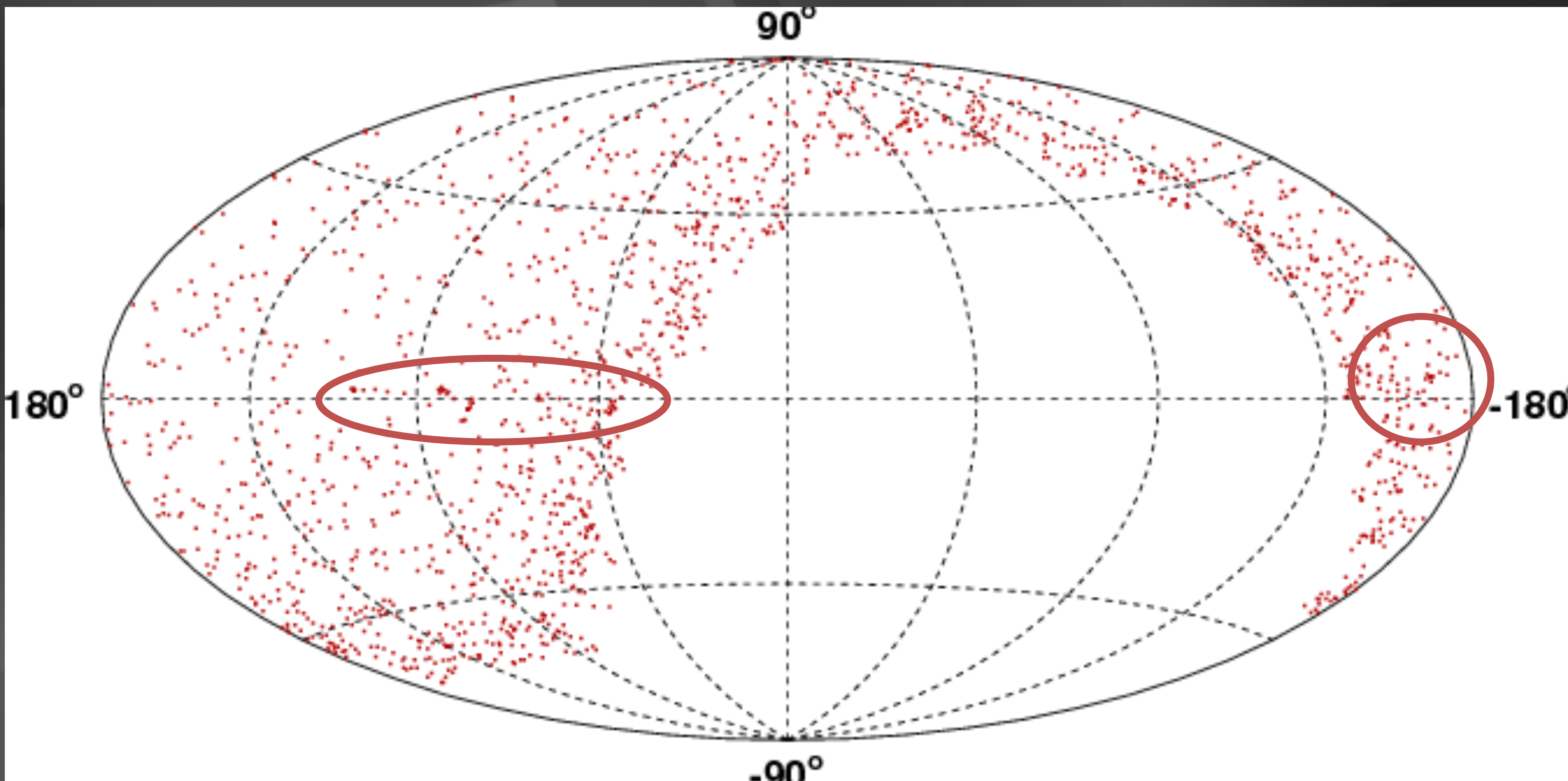
Gamma and Neutrino Spectra



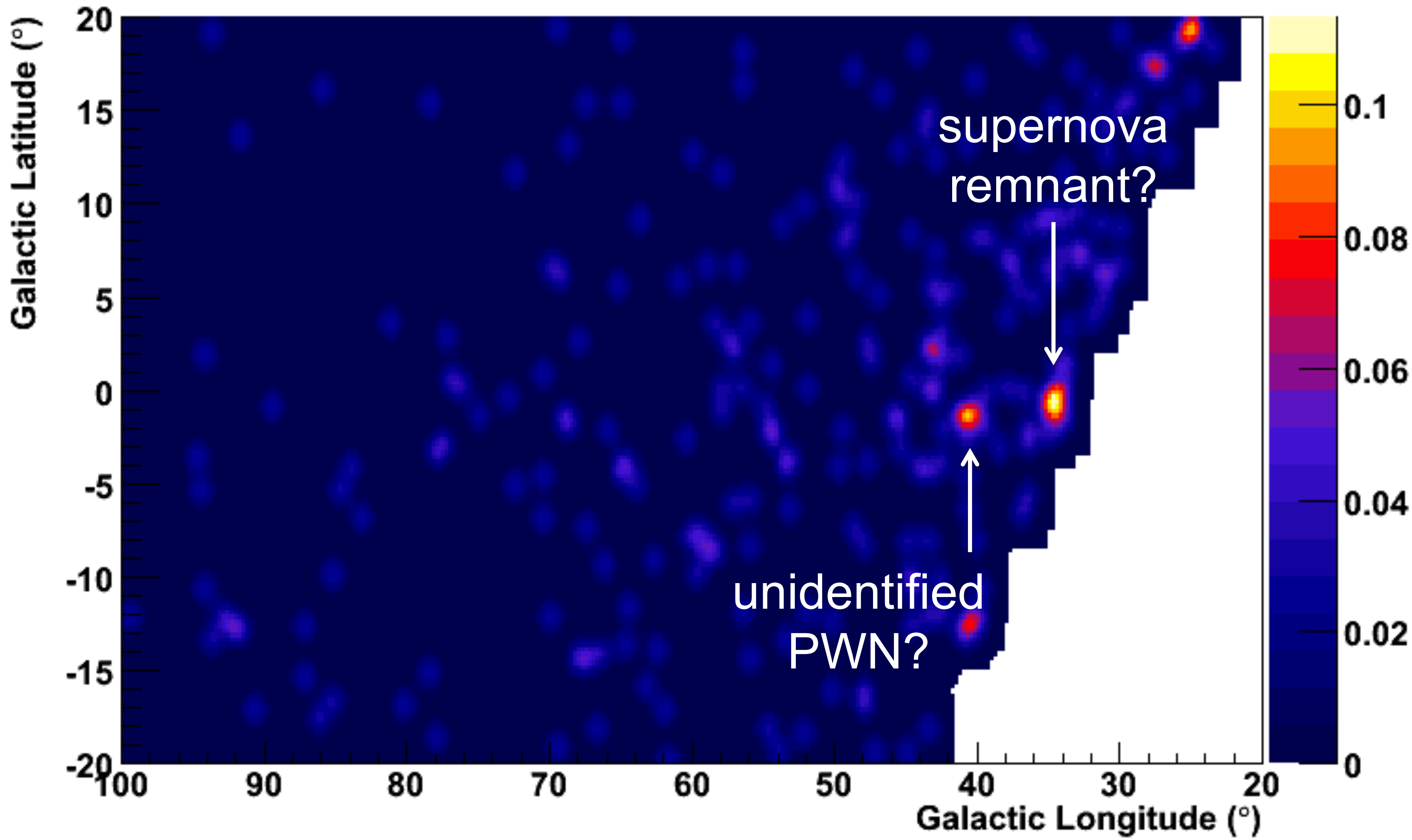
Halzen, Kappes, O'Murchadha: arXiv:0803.0314

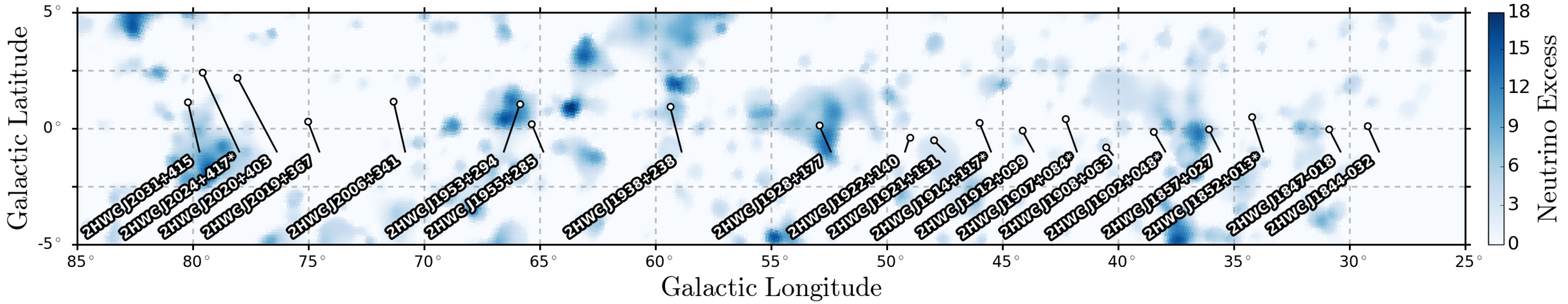
- Assumed E^{-2} with Milagro normaliztion (MGRO J1908 index = 2.1)
- ν spectrum cutoff @ 180 TeV

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

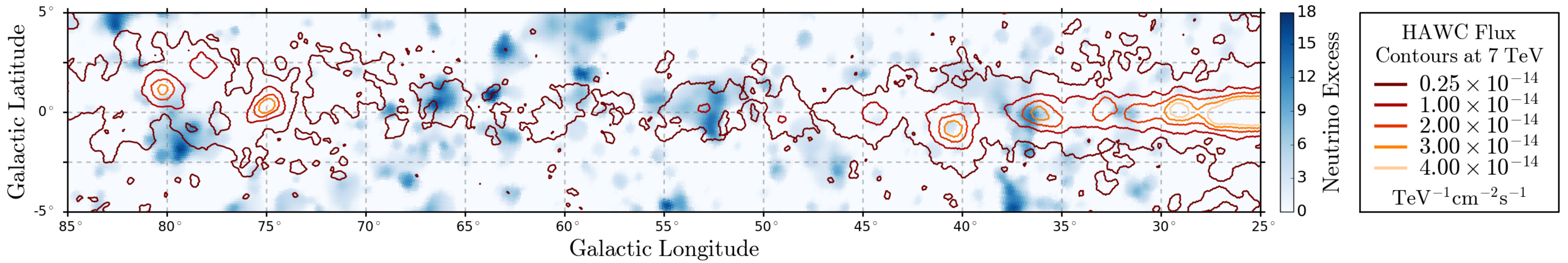


Simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.

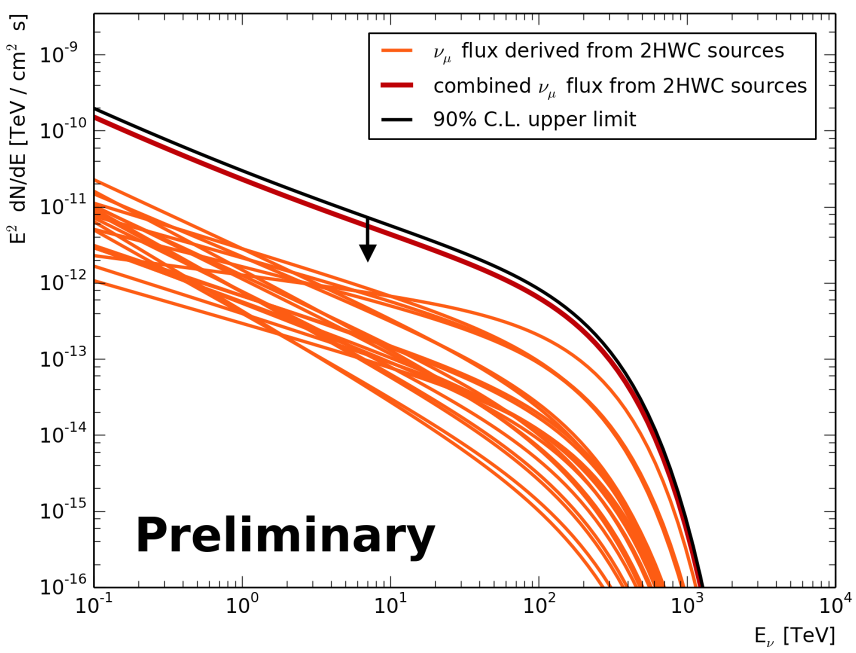




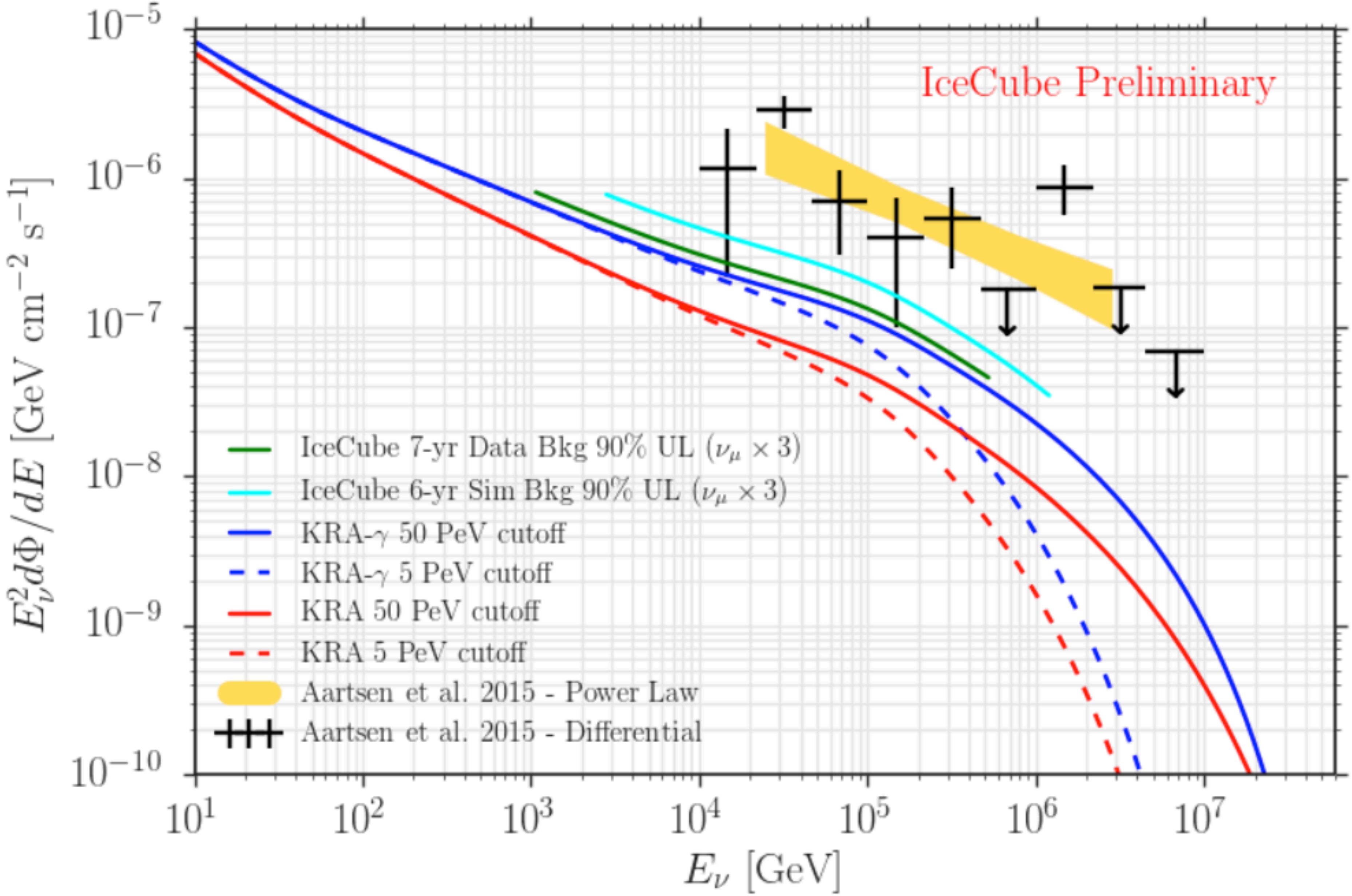
Galactic Latitude
Galactic Longitude
Neutrino Excess
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1847-018
2HWC J1844-032



Galactic Latitude
Galactic Longitude
Neutrino Excess
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}
$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$

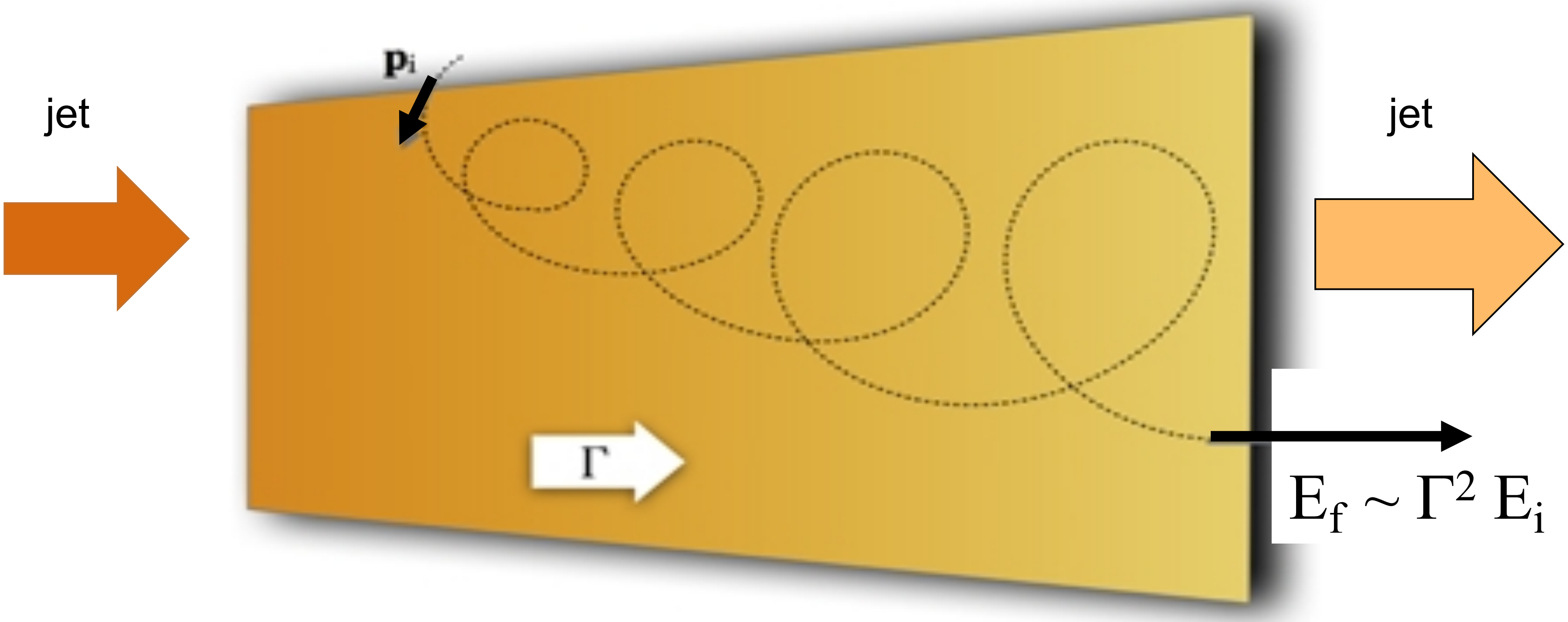


ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
Preliminary
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]



IceCube Preliminary
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
$E_\nu^2 d\Phi/dE$ [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

espresso mechanism: one-shot acceleration



consistent with the expectation for individual sources

blobs in agn jets: protons interact with synchrotron photons produced by co-accelerated electrons

$$1 - e^{-\tau_{p\gamma}} = \frac{aL_\gamma}{E_\gamma} \frac{1}{\Gamma^2 \Delta t} \frac{3\,\sigma_{p\gamma}}{4\pi c^2}$$

$$1 - e^{-\tau_{p\gamma}} \geq 0.4$$

$$\simeq \left[\frac{a}{10\%}\right]\left[\frac{L_\gamma}{2\times 10^{46}\mathrm{erg\,s^{-1}}}\right]\left[\frac{10\,\mathrm{eV}}{E_\gamma}\right]\left[\frac{1}{\Gamma^2}\right]\left[\frac{110\,\mathrm{d}}{\Delta t}\right]\left[\frac{3\,\sigma_{p\gamma}}{4\pi c^2}\right]$$

- a: efficiency to convert gamma ray luminosity L_γ to synchrotron target photons of energy 10 eV

- Δt: duration of the burst.