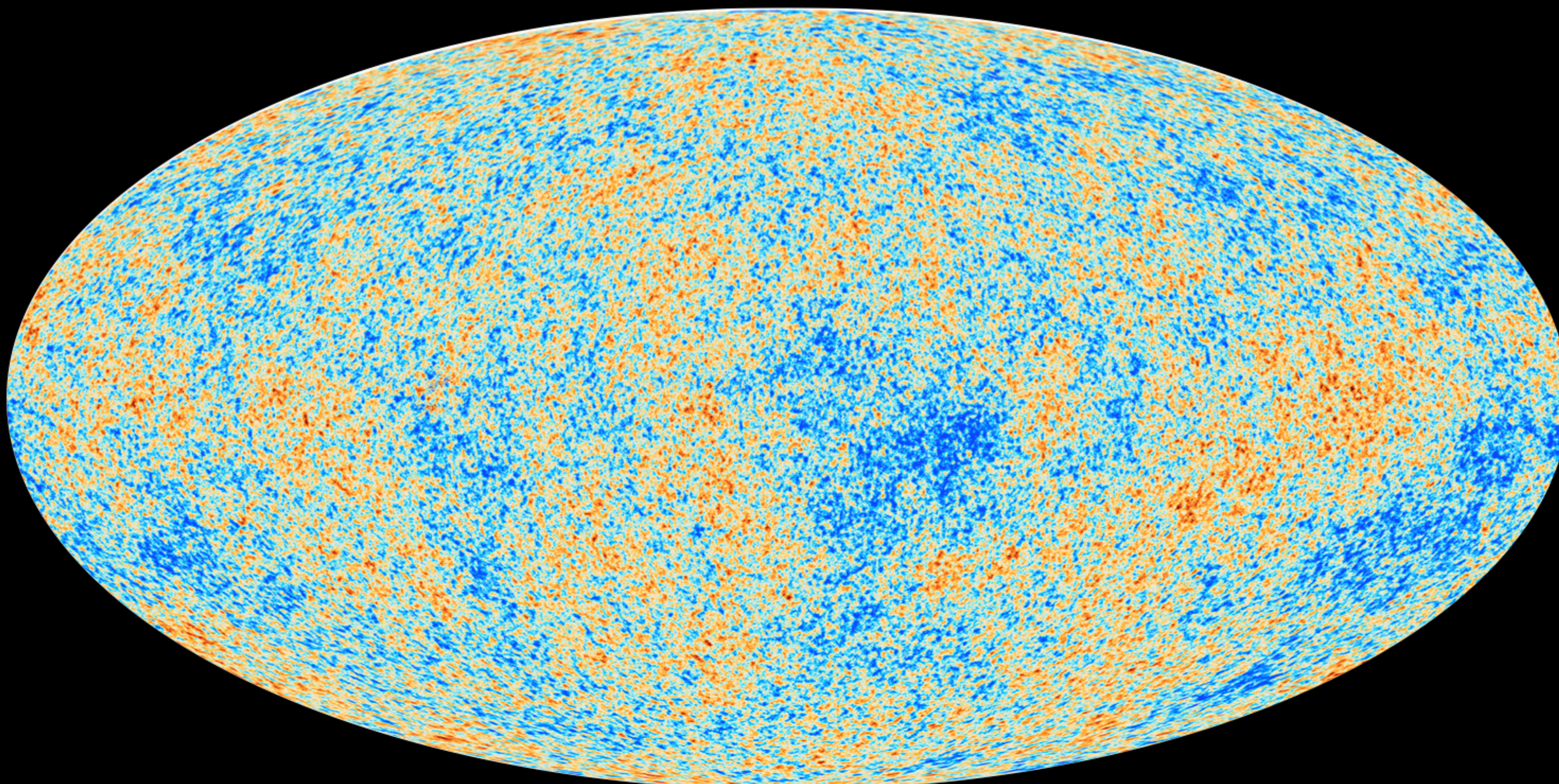
IceCube: the discovery of cosmic neutrinos
francis halzen

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

IceCube.wisc.edu

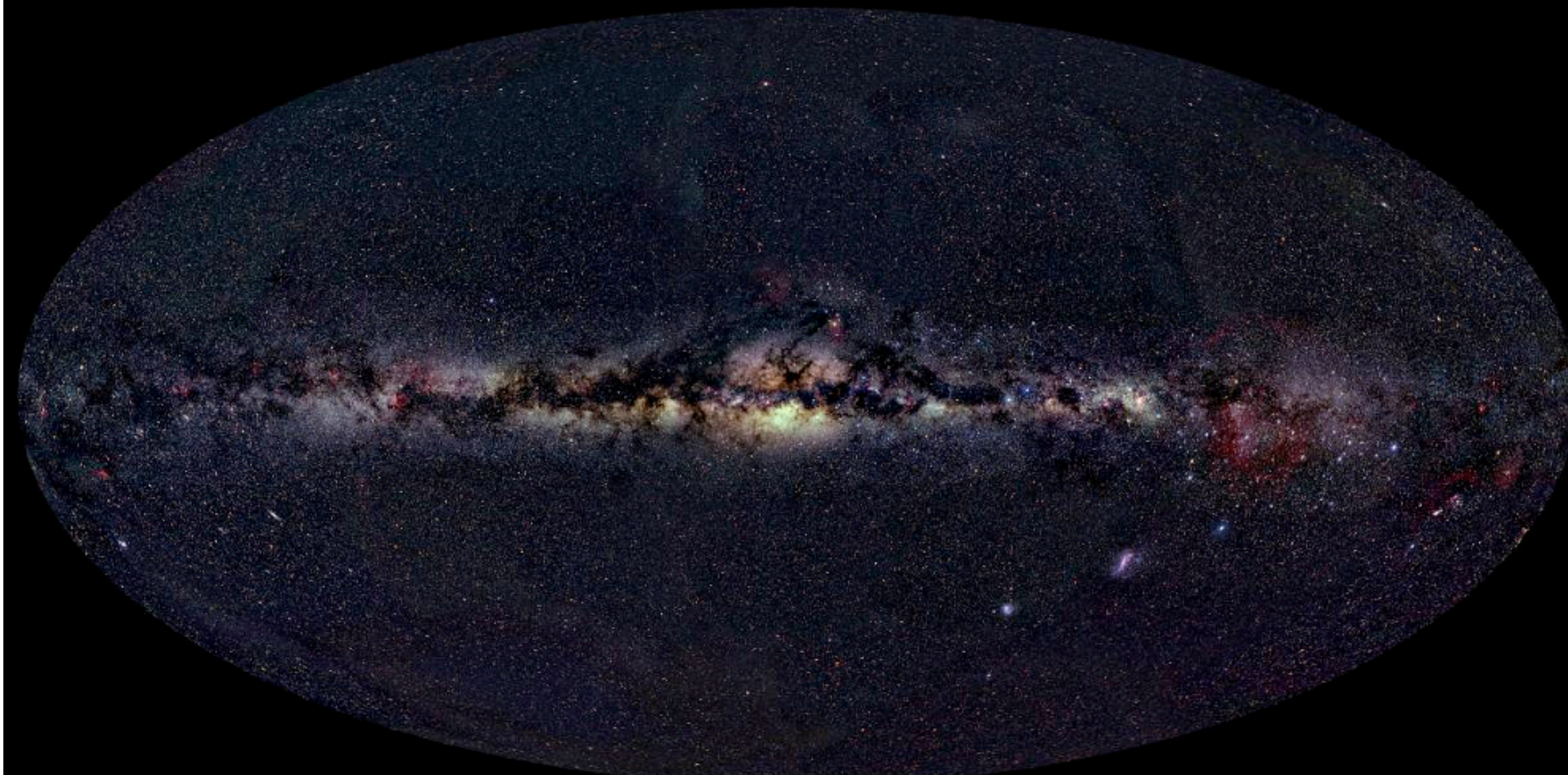
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



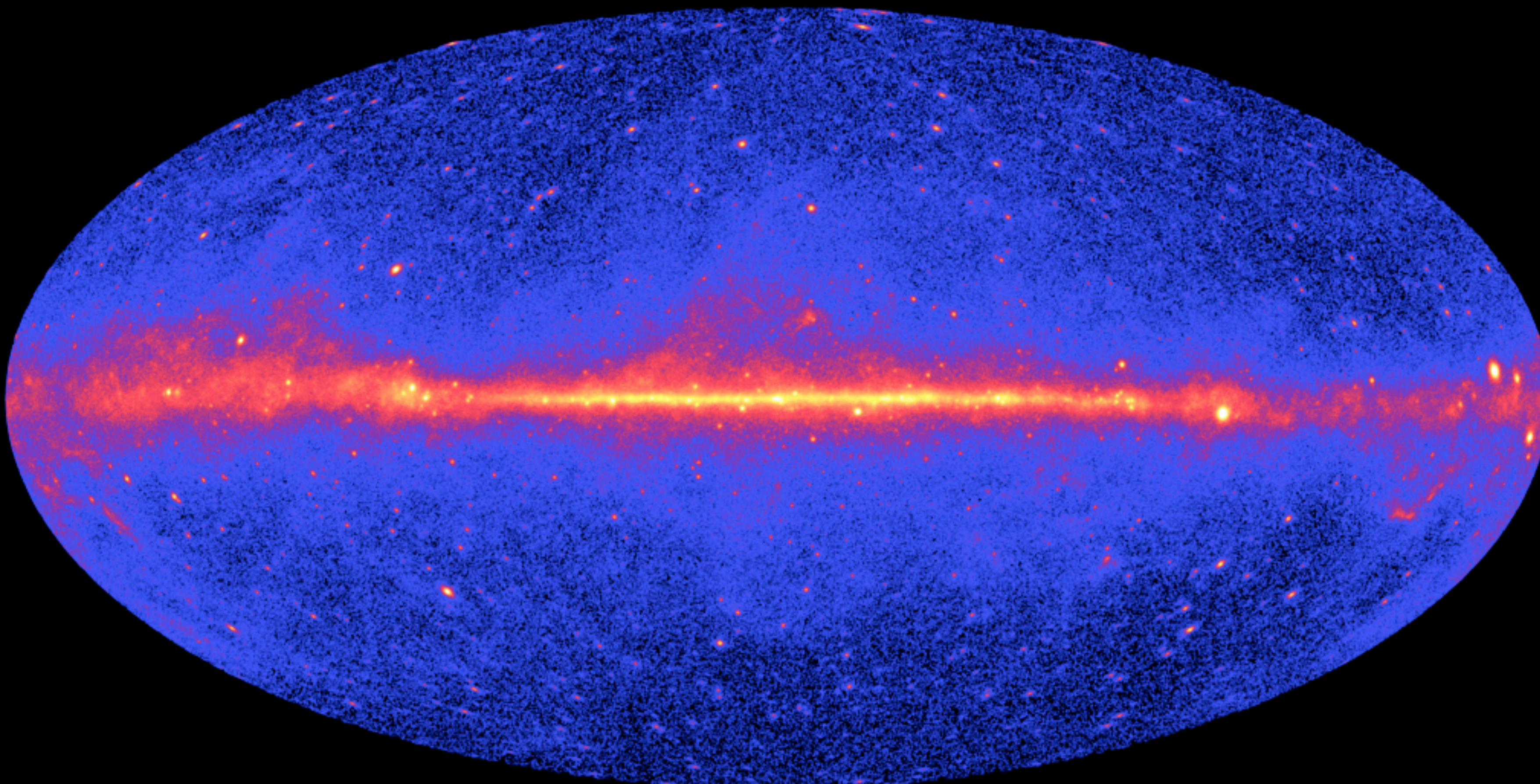
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m ⇔ energy = 1 eV

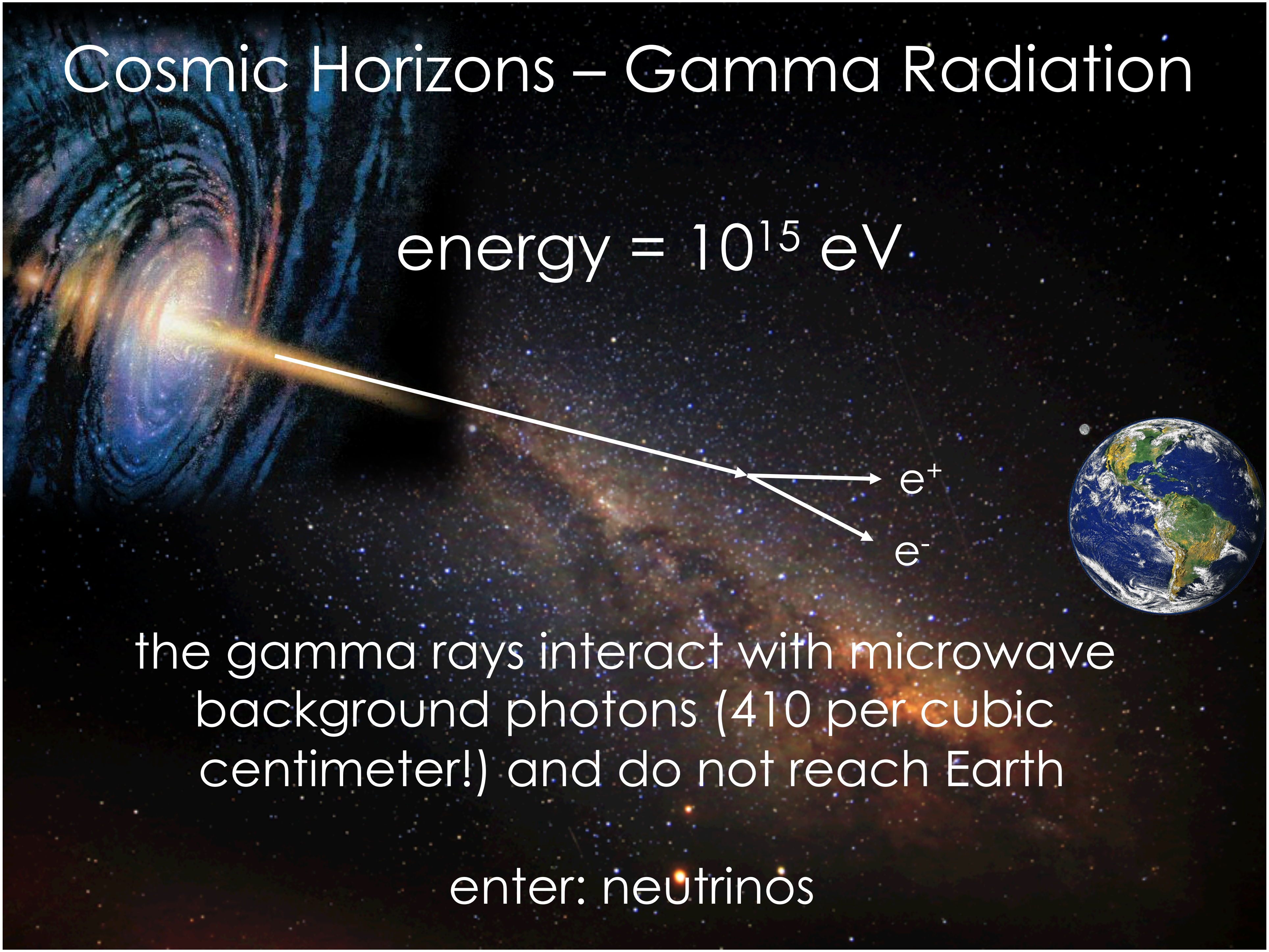
Cosmic Horizons – Gamma Radiation



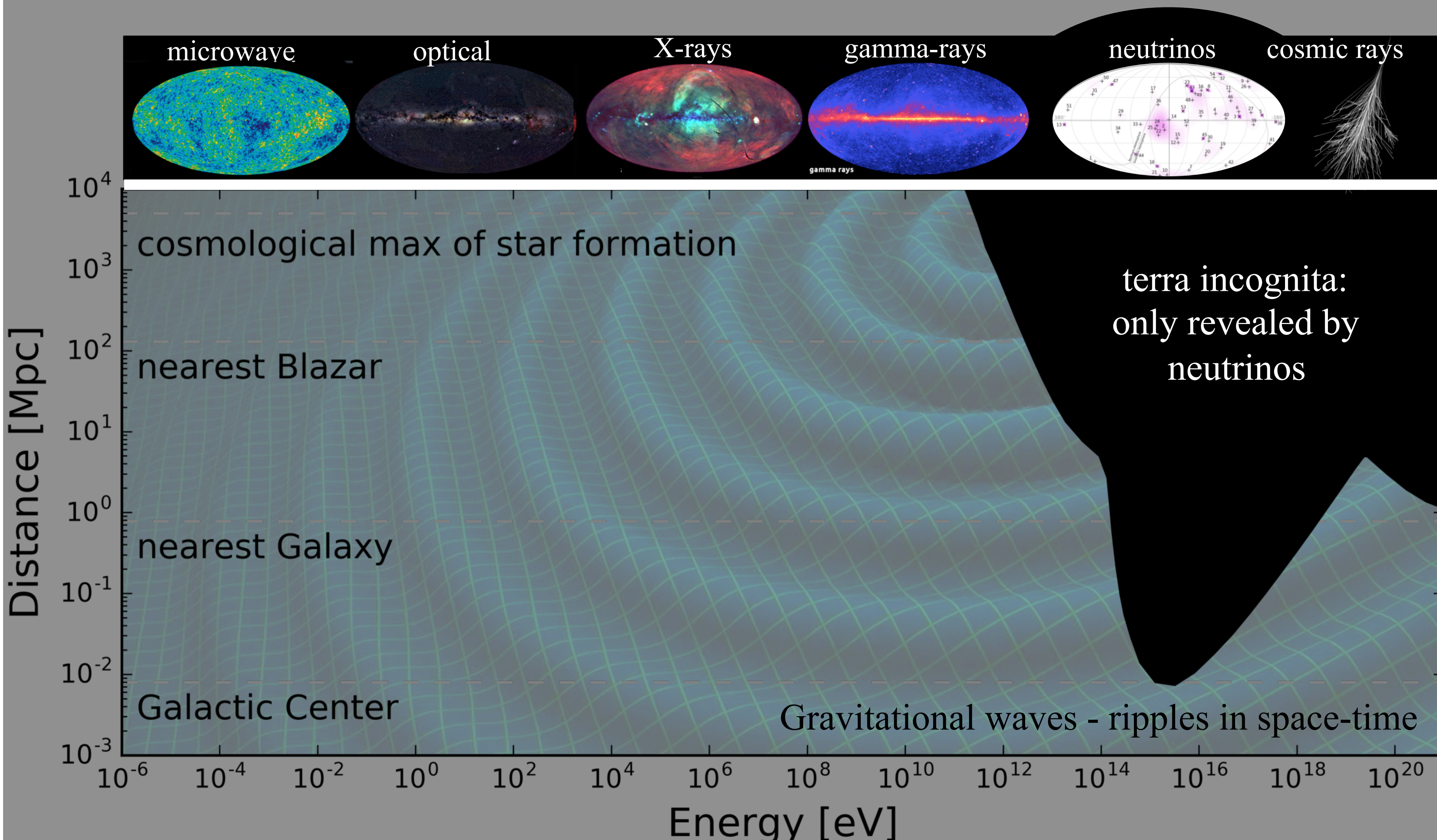
wavelength = 10^{-15} m ⇔ energy = 10^{9} eV

Cosmic Horizons – Gamma Radiation

energy = 10^{15} eV

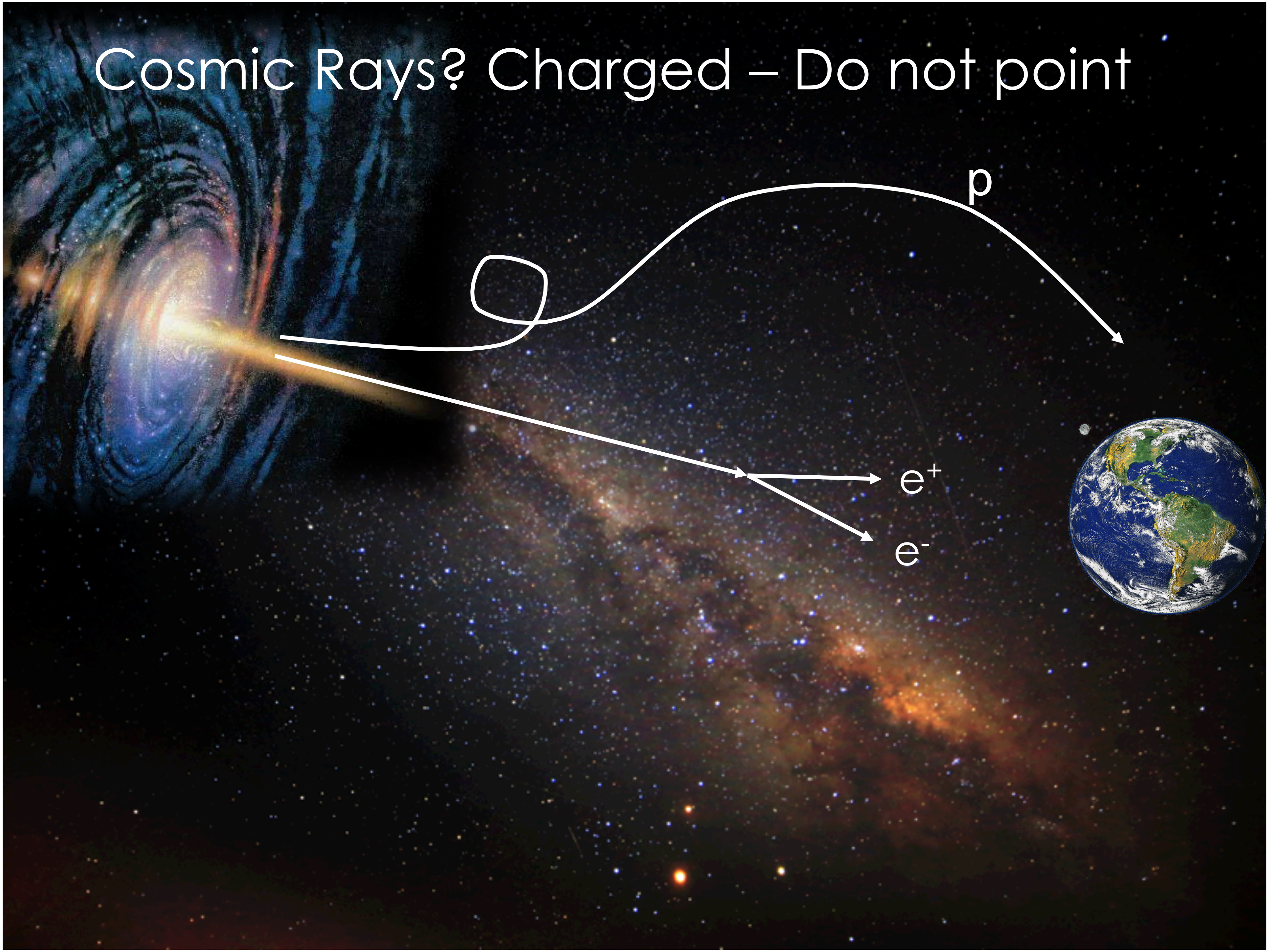

Cosmic Horizons – Gamma Radiation
energy = 10^{15} eV
e^+
e^-
the gamma rays interact with microwave background photons (410 per cubic centimeter!) and do not reach Earth
enter: neutrinos

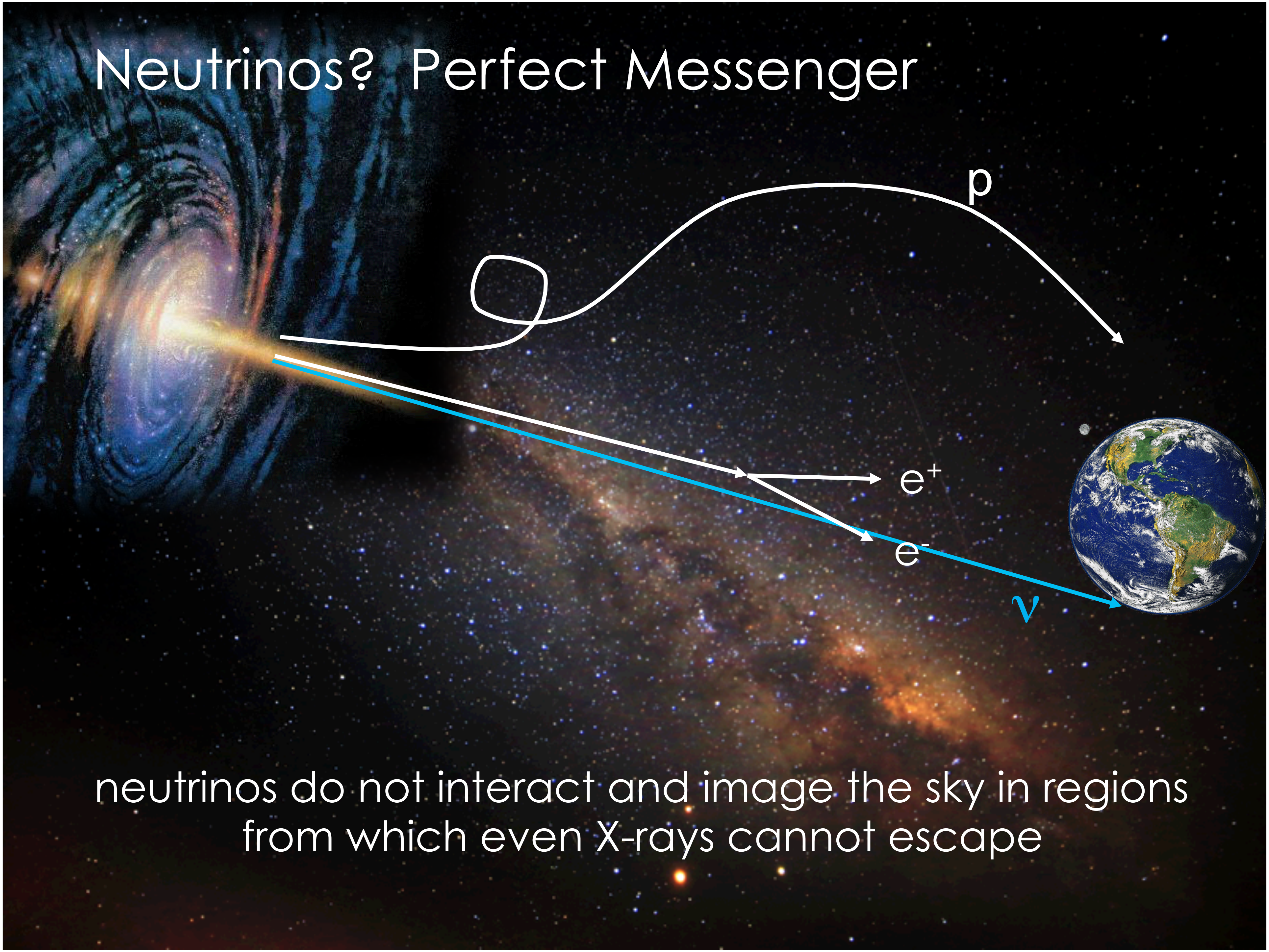
Multi-Messenger Astronomy

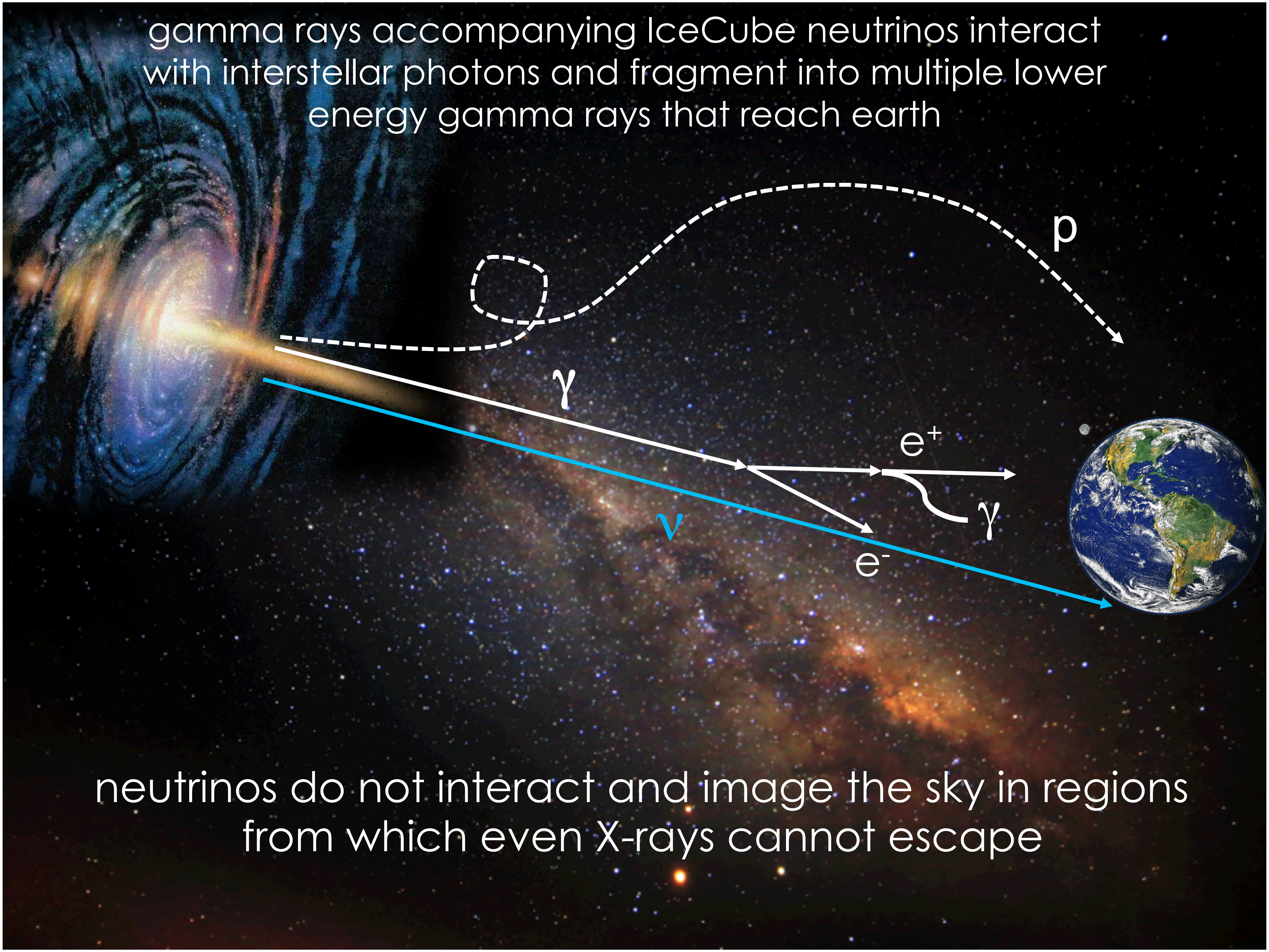


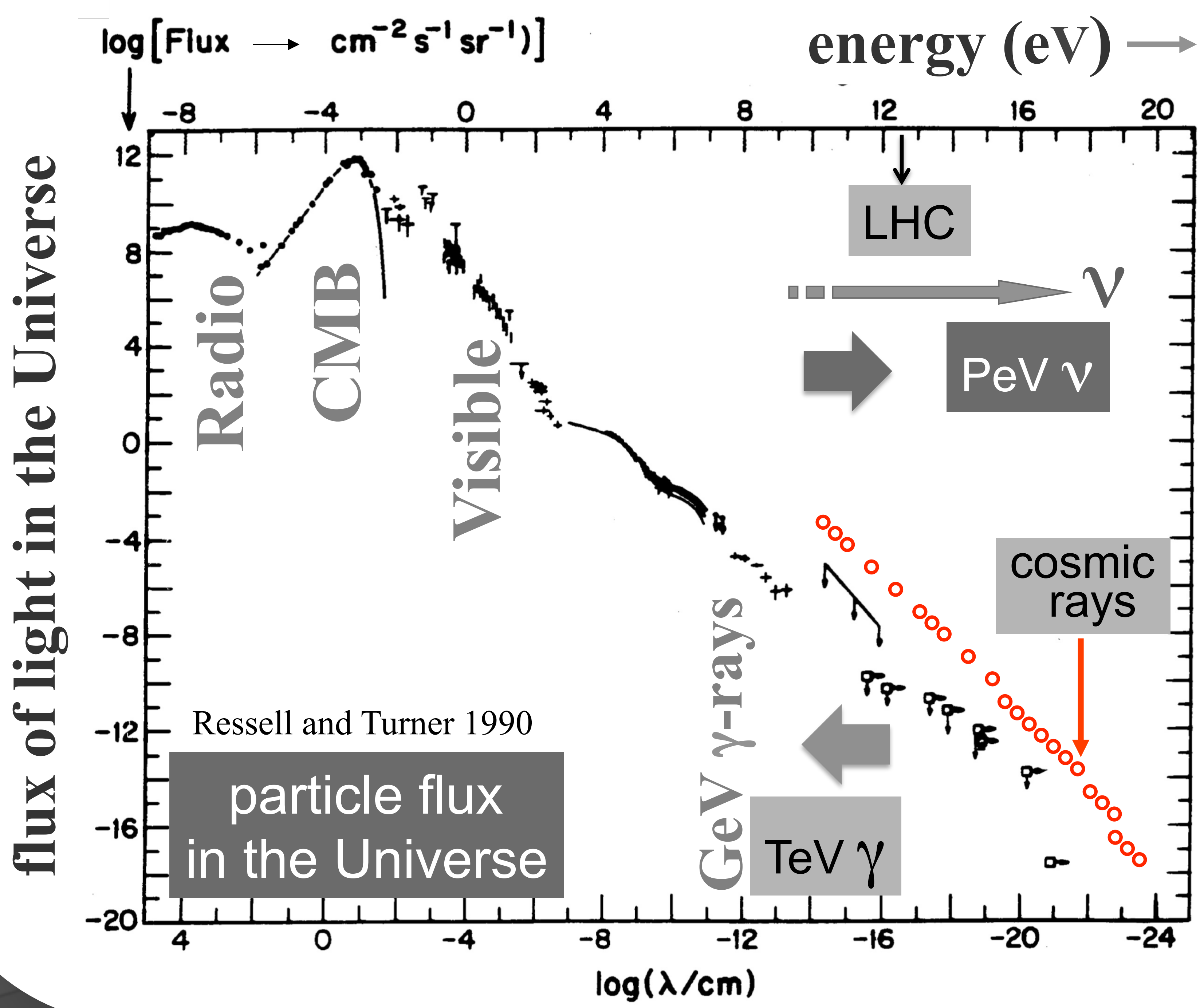
20% of the Universe is opaque to the EM spectrum

Cosmic Rays? Charged – Do not point




Neutrinos? Perfect Messenger
p
e+
e-
ν
neutrinos do not interact and image the sky in regions
from which even X-rays cannot escape

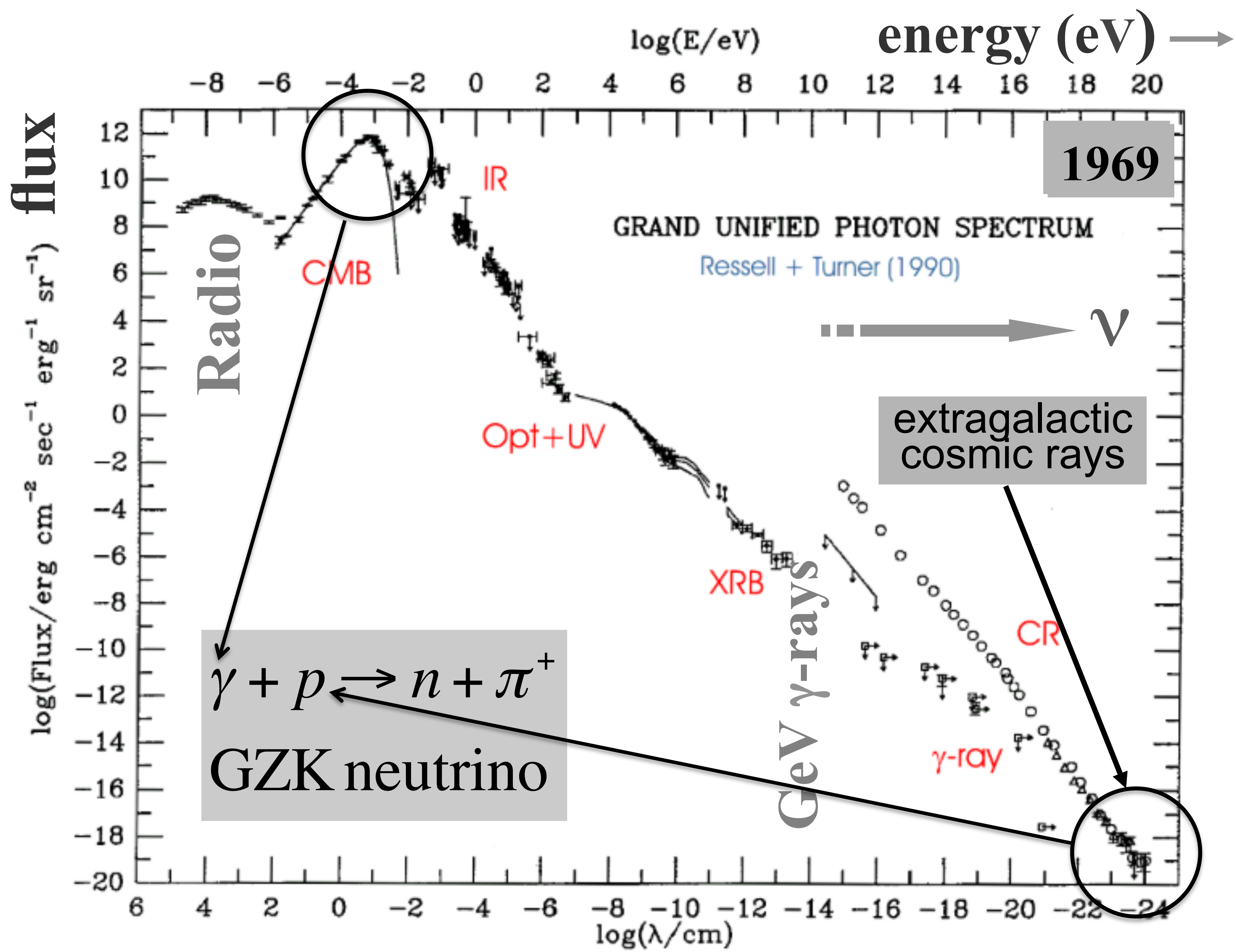

gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth
p
γ
e^+
γ
ν
e^-
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape



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

neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
  ($n \rightarrow p + e + \nu_e$)
- … but difficult to detect



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

cosmic rays interact with the microwave background

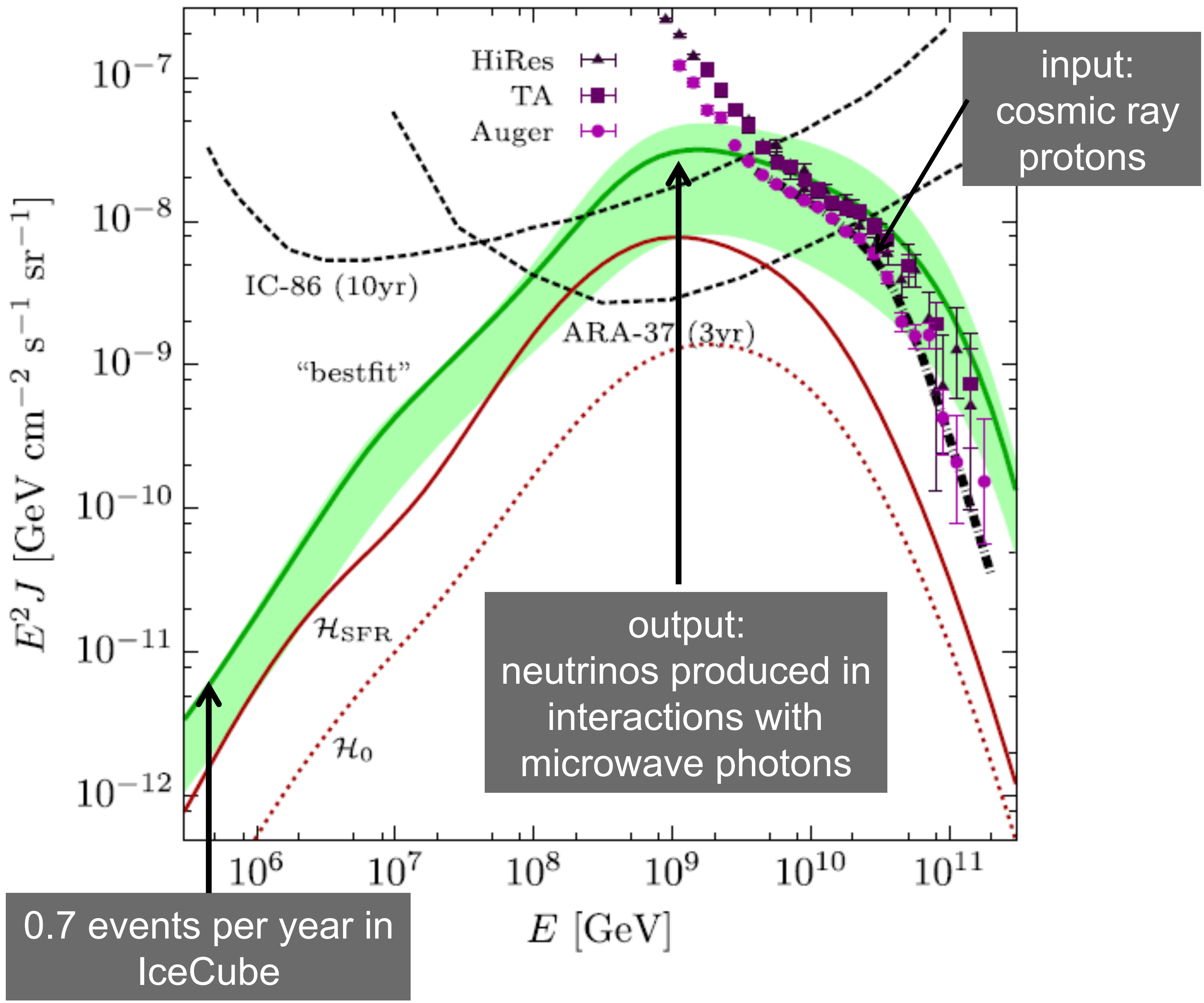
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

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

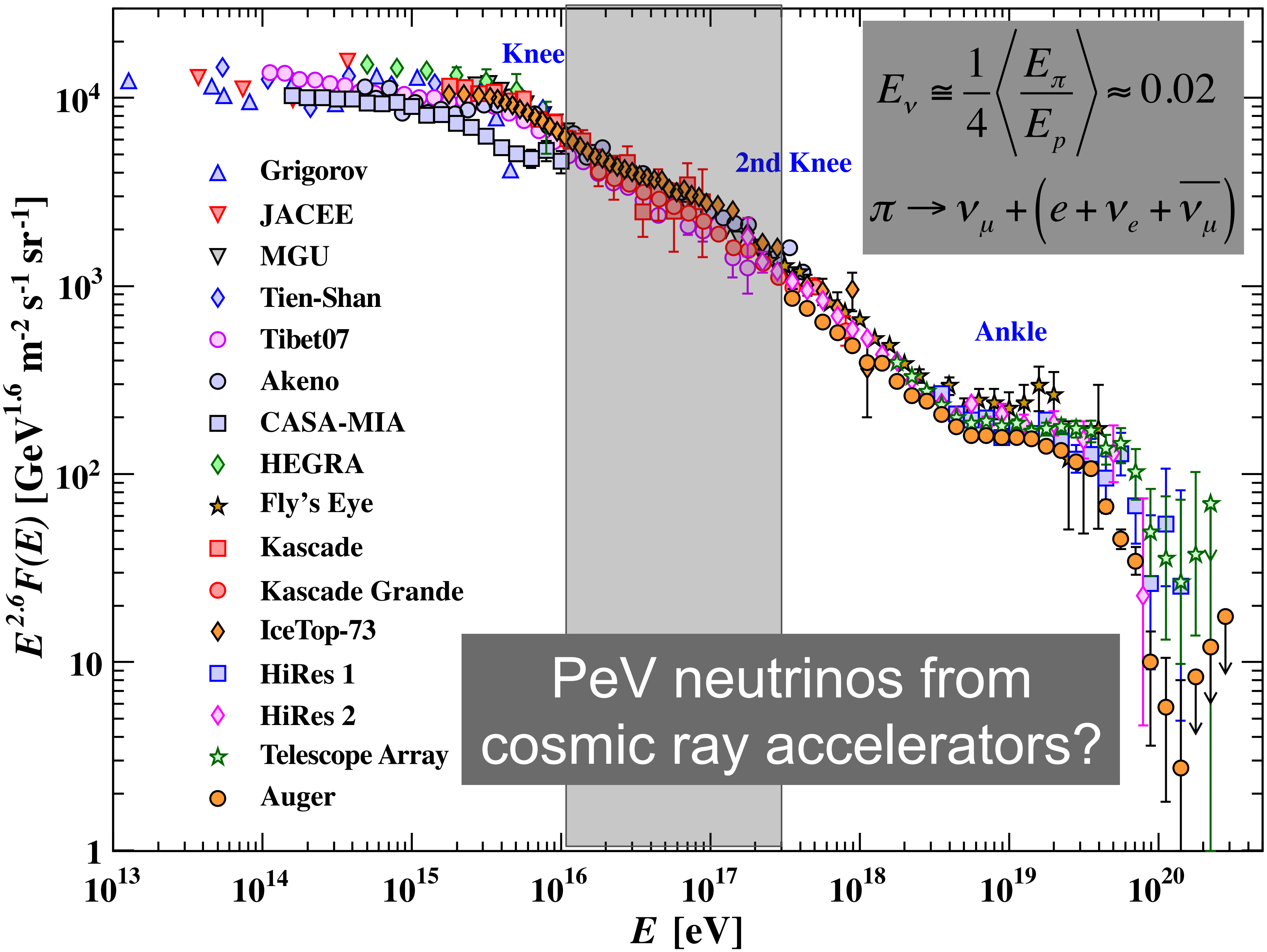
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source!



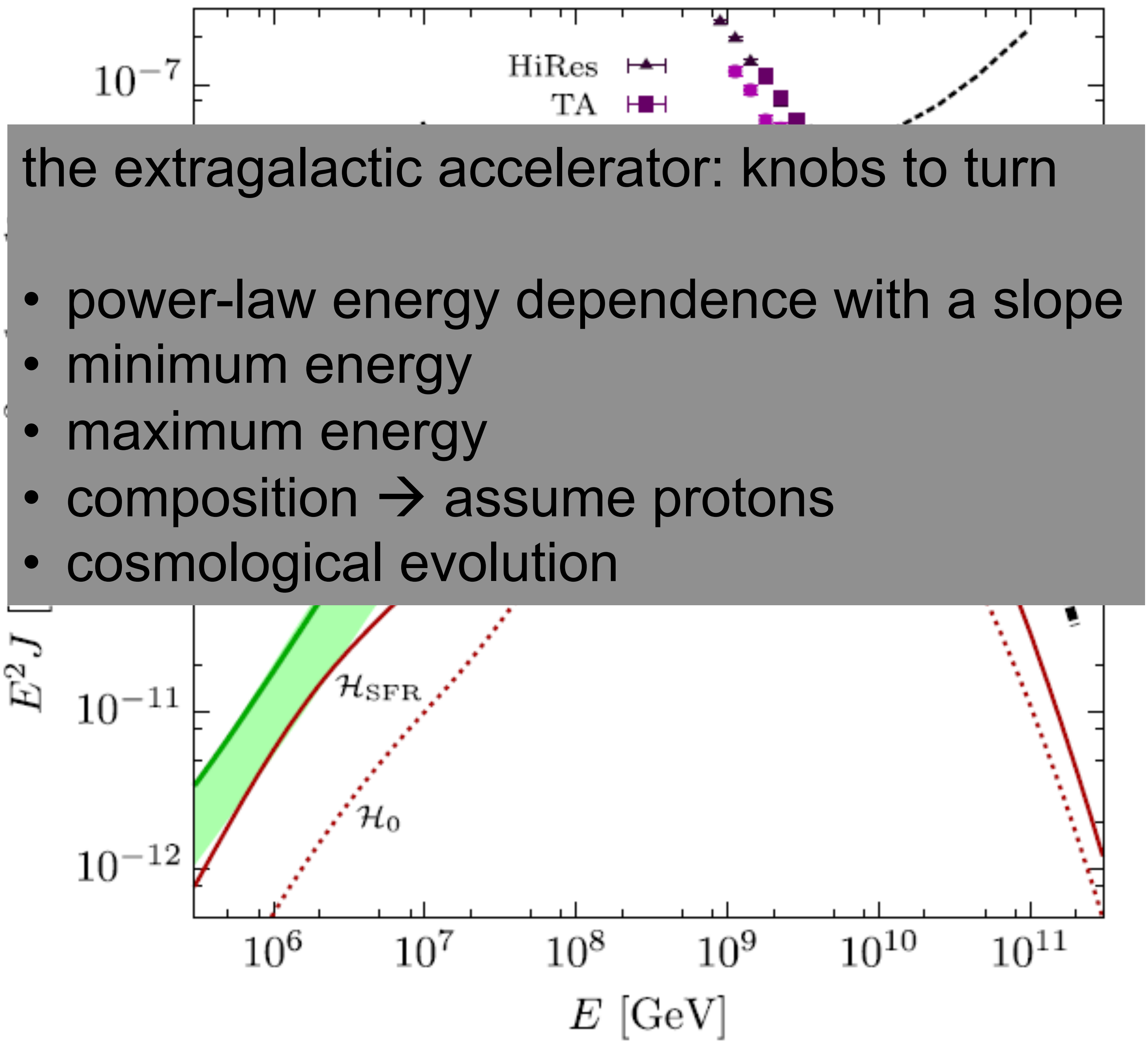
HiRes
TA
Auger
input: cosmic ray protons
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
output: neutrinos produced in interactions with microwave photons
0.7 events per year in IceCube
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}



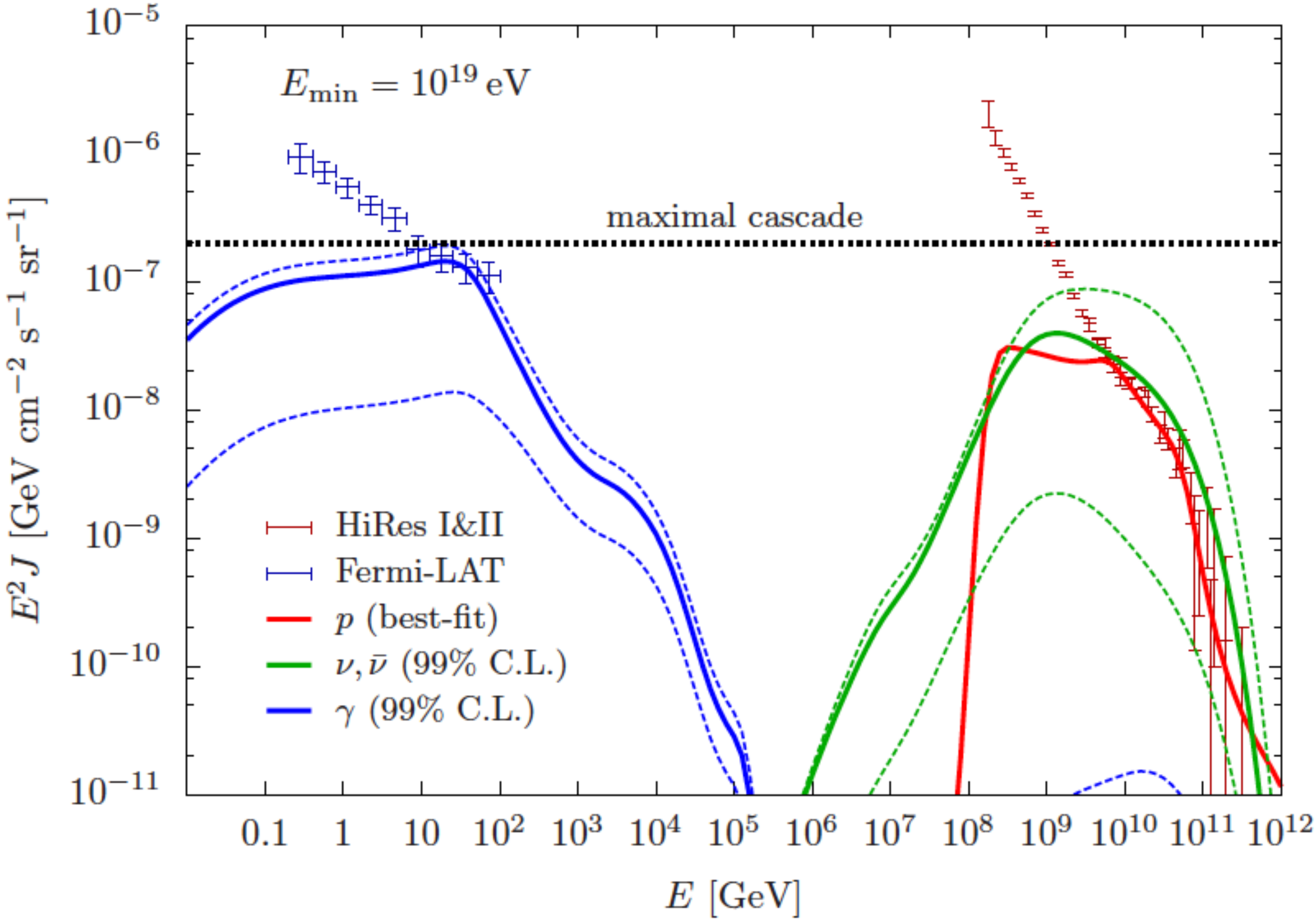
Knee
2nd Knee
Ankle
$E_\nu \cong \frac{1}{4}\left\langle \frac{E_\pi}{E_p} \right\rangle \approx 0.02$
$\pi \rightarrow \nu_\mu + \left(e + \nu_e + \overline{\nu_\mu}\right)$
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
PeV neutrinos from cosmic ray accelerators?
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]

the extragalactic accelerator: knobs to turn

- power-law energy dependence with a slope
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution

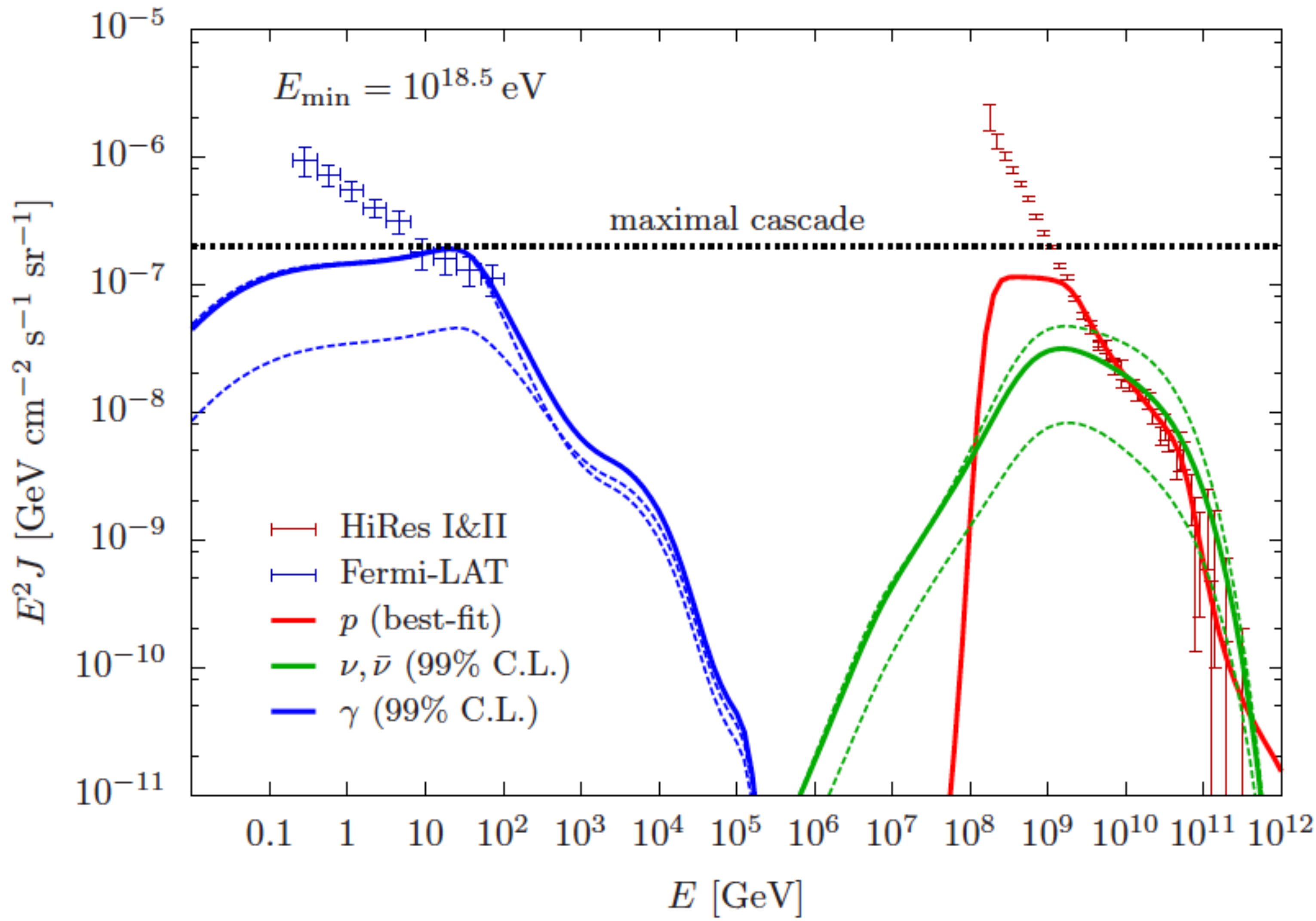


Cosmogenic neutrinos from CR protons



[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons



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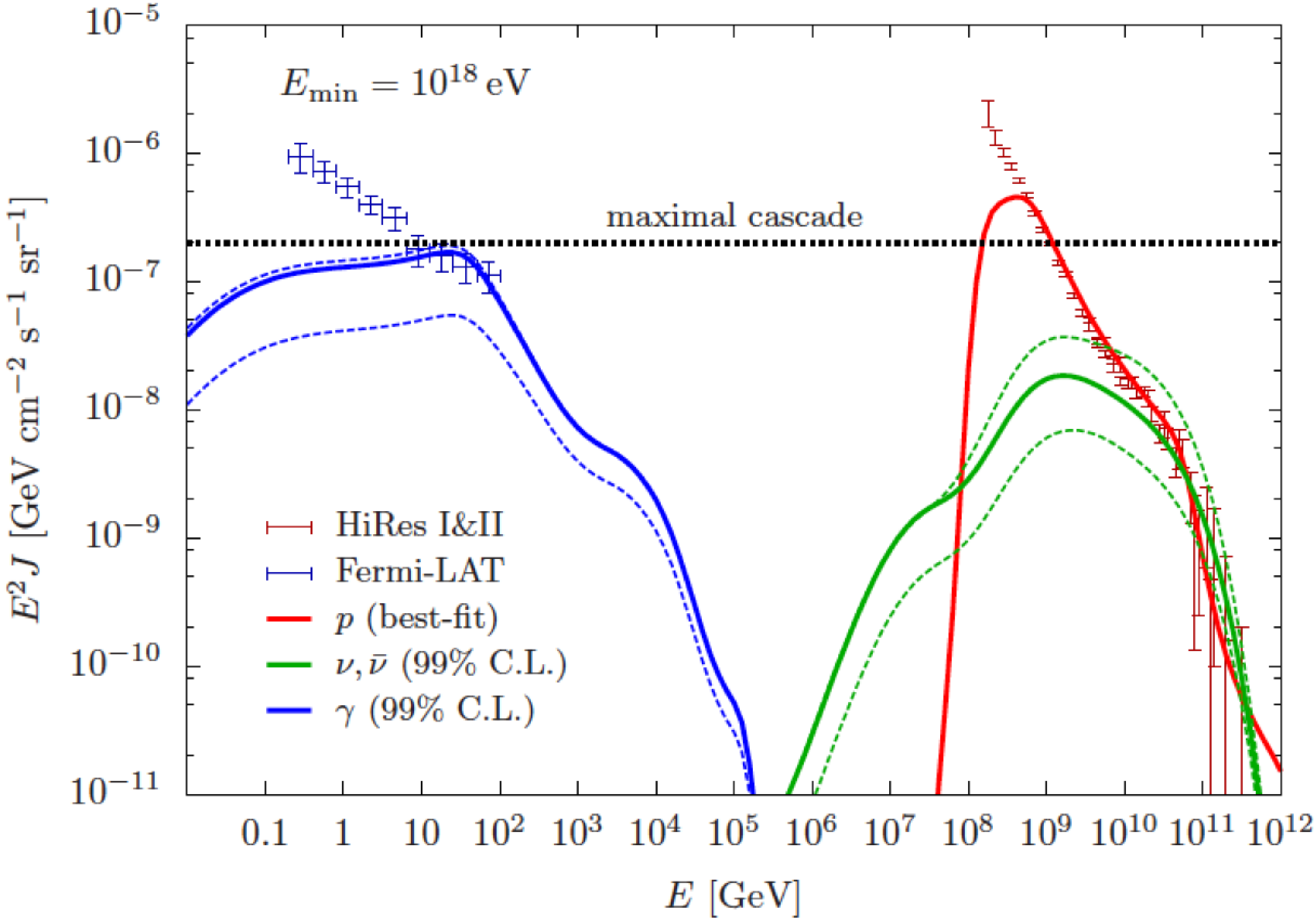
Cosmogenic neutrinos from CR protons



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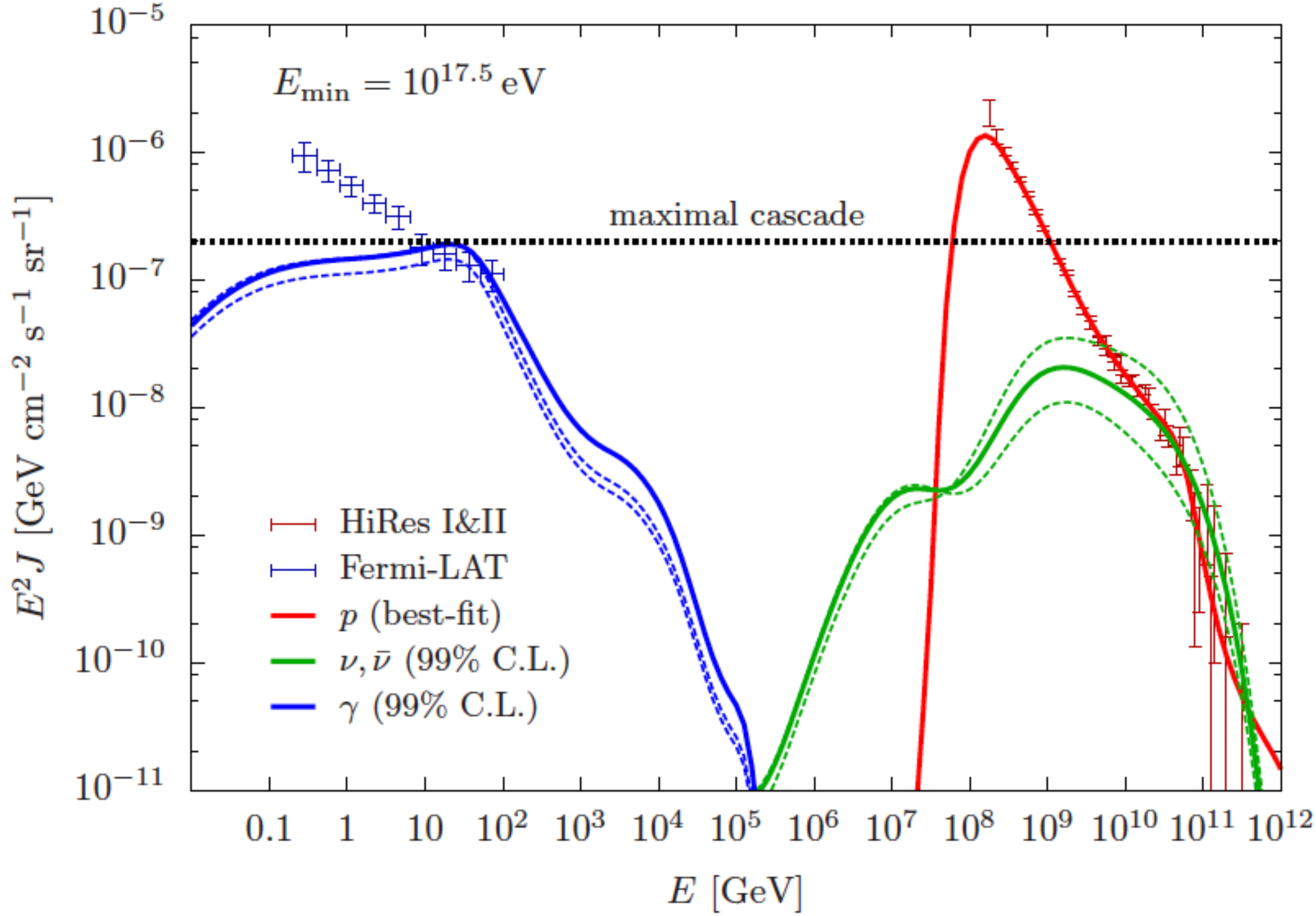
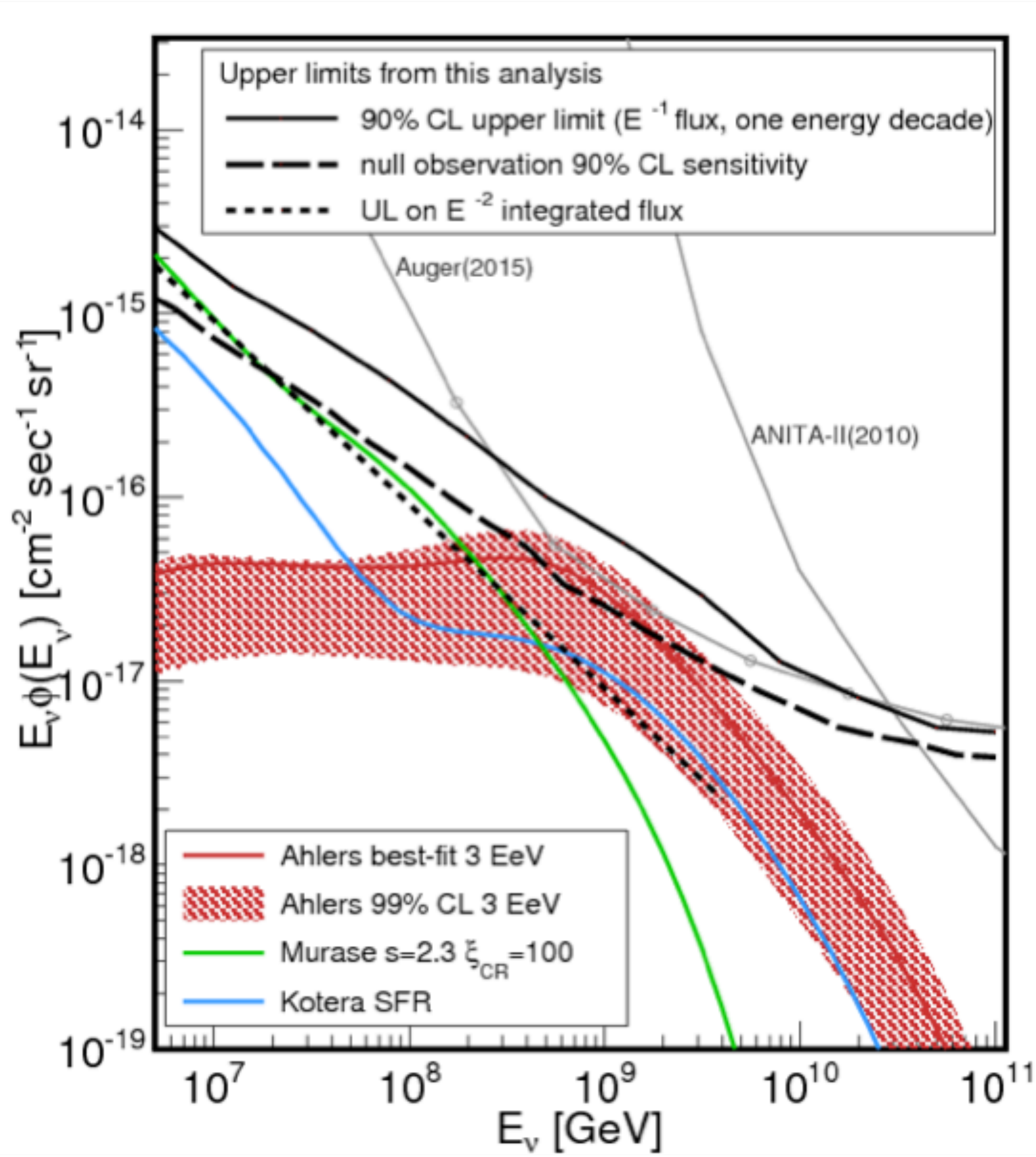
Cosmogenic neutrinos from CR protons



knobs to turn: inject accelerator slope, minimum and maximum energy, evolution with z

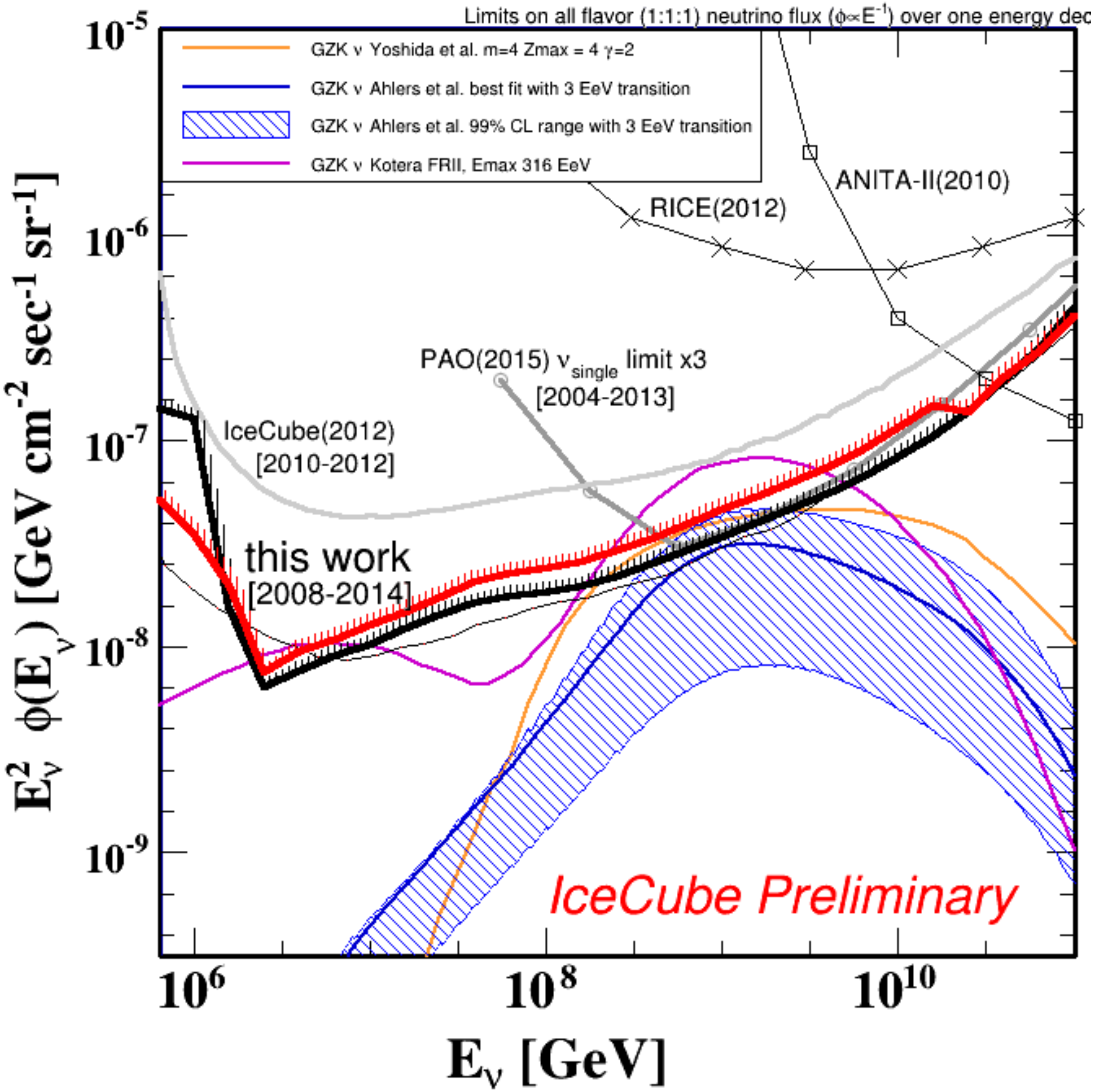
Ahlers *et al.* [22] best fit, 1 EeV	$2.8^{+0.4}_{-0.4}$	$9.5^{+6.5}_{-1.6}\%$	1.17
Ahlers *et al.* [22] best fit, 3 EeV	$4.4^{+0.6}_{-0.7}$	$2.2^{+1.3}_{-0.9}\%$	0.66
Ahlers *et al.* [22] best fit, 10 EeV	$5.3^{+0.8}_{-0.8}$	$0.7^{+1.6}_{-0.2}\%$	0.48

TABLE I. Cosmogenic neutrino model tests: Expected number of events in 2426 days of effective livetime, p-values from model hypothesis test, and 90%-CL model-dependent limits in terms of the model rejection factor (MRF) [52], defined as the ratio between the flux upper limit and the predicted flux.

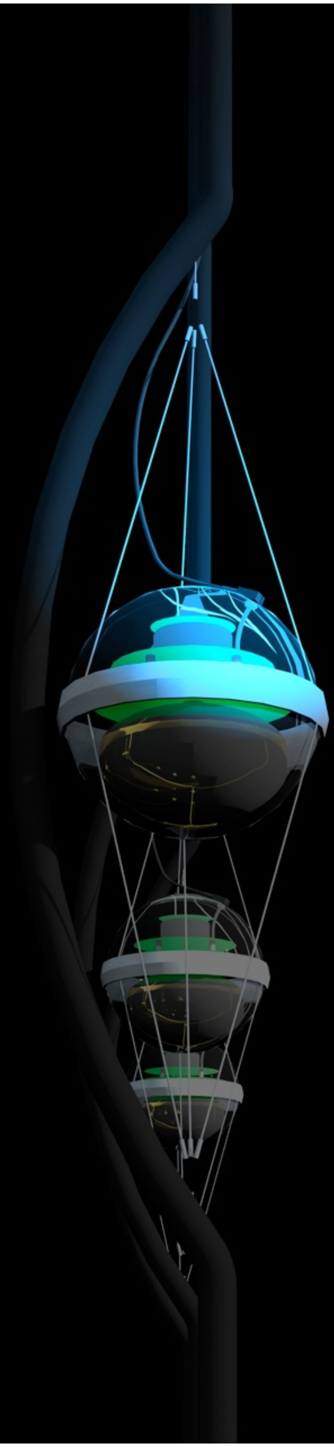


Upper limits from this analysis
90% CL upper limit (E -1 flux, one energy decade)
null observation 90% CL sensitivity
UL on E -2 integrated flux
Auger(2015)
ANITA-II(2010)
Ahlers best-fit 3 EeV
Ahlers 99% CL 3 EeV
Murase s=2.3 ξCR=100
Kotera SFR
Eνφ(Eν) [cm-2 sec-1 sr-1]
Eν [GeV]

1607.05886



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



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- cosmogenic neutrinos
- **cosmic ray accelerators**
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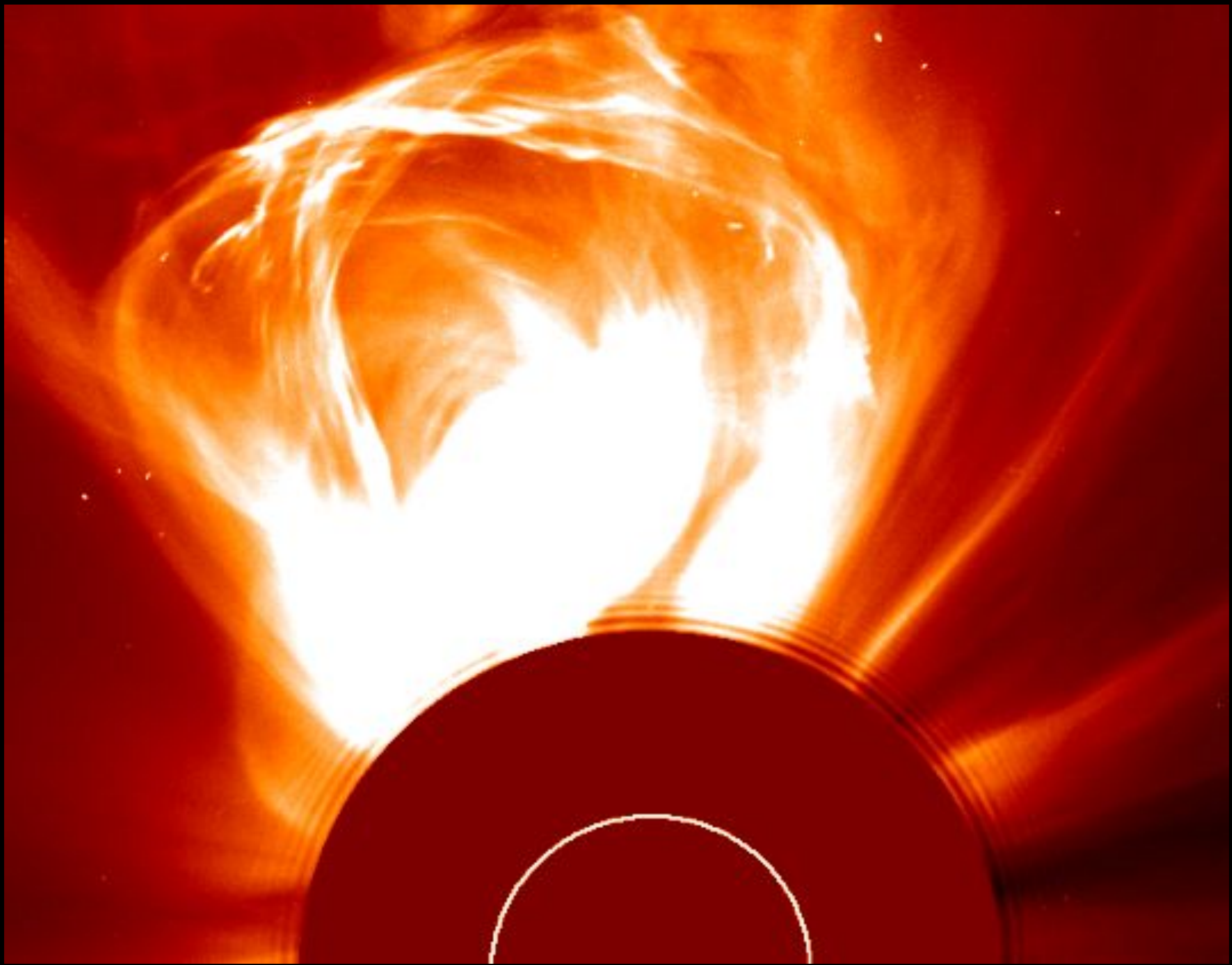
IceCube.wisc.edu

the sun constructs an accelerator



- accelerator must contain the particles

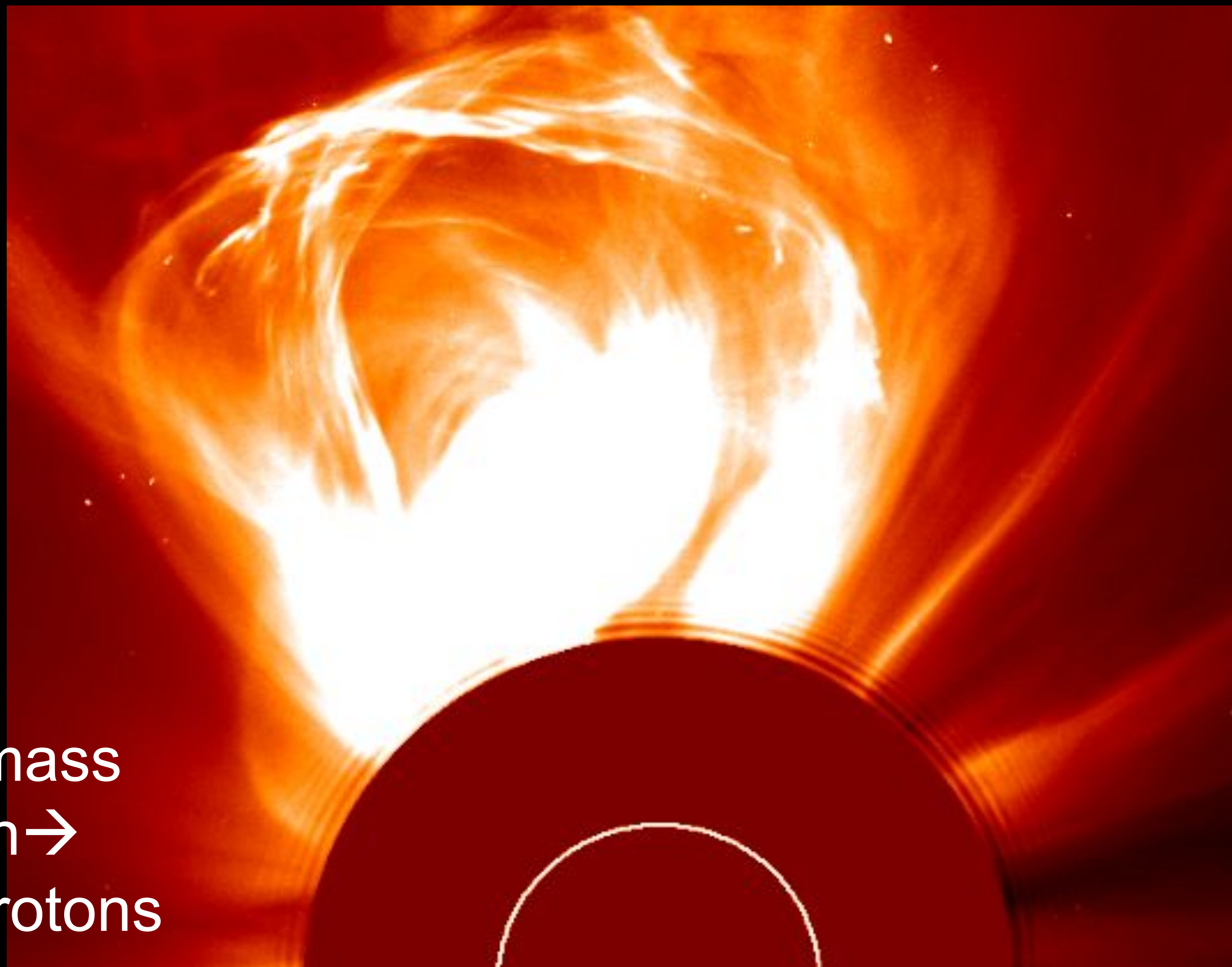
$$R_{gyro} \left(= \frac{E}{\mathrm{v} q B}\right) \le R$$

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

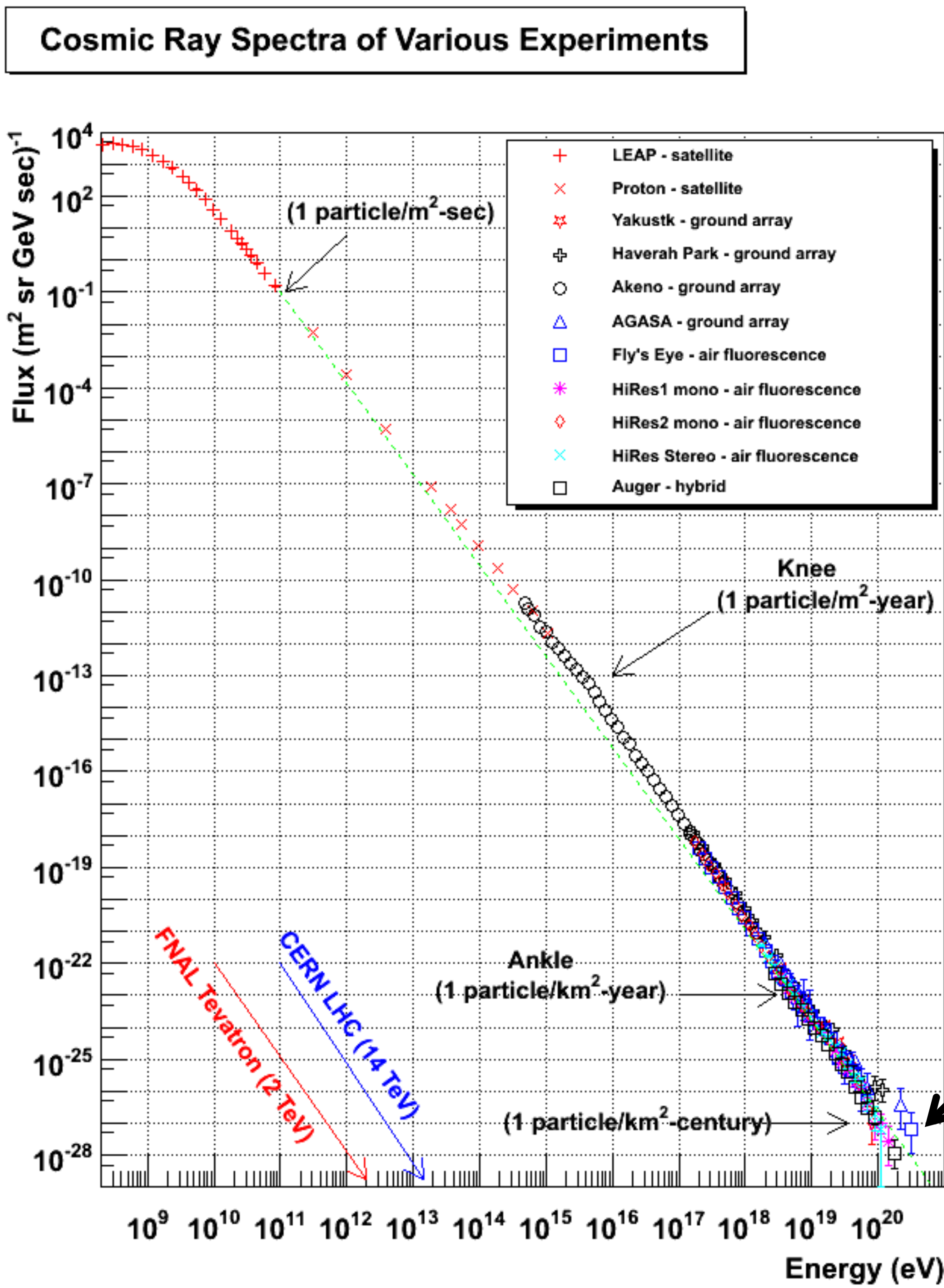
challenges of cosmic ray astrophysics:

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

the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

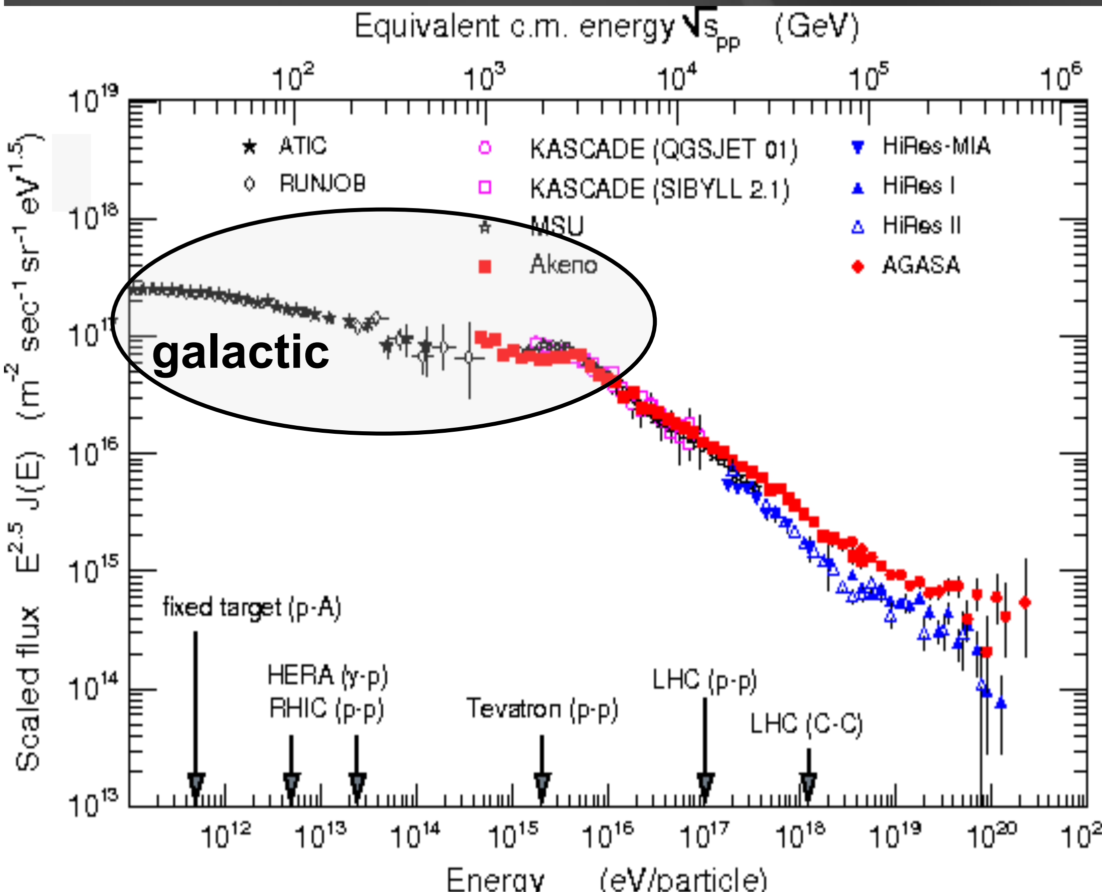


cosmic ray accelerators:
where, how?

gravitational energy from collapsing star converted into particle acceleration

LHC filling the orbit of Mercury

Cosmic Rays & SNRs



observed energy density of galactic CR:

~ 10^{-12} erg/cm^3

supernova remnants: 10^{50} ergs every 30 years

~10^{-12} erg/cm^3

for steady state of CR with lifetime 10^6 years

SNRs provide the environment and energy to explain the galactic cosmic rays!

flux of extragalactic cosmic rays

ankle → one 10^{19} eV particle per km squared per year per sr

$$E^2 \frac{dN}{dE} = \frac{10^{19}\, eV}{(10^{10}\, cm^2)(3\times 10^7 \sec)\ sr}$$

cosmic accelerator E^{-2}

$$= 3\times 10^{-11}\, TeV\, cm^{-2} \sec^{-1} sr^{-1}$$

total flux = velocity x density

$$4\pi \int dE \left(E \frac{dN}{dE}\right) = c\,\rho_E$$

$$\rho_E = \frac{4\pi}{c} \int \frac{3\times 10^{-11}}{E}\, dE \; \frac{TeV}{cm^3}$$

$$= \cdots \log \frac{E_{\max}}{E_{\min}} \cong 10^{-19}\, \frac{TeV}{cm^3}$$

$$1\,TeV \cong 1.6\,erg$$

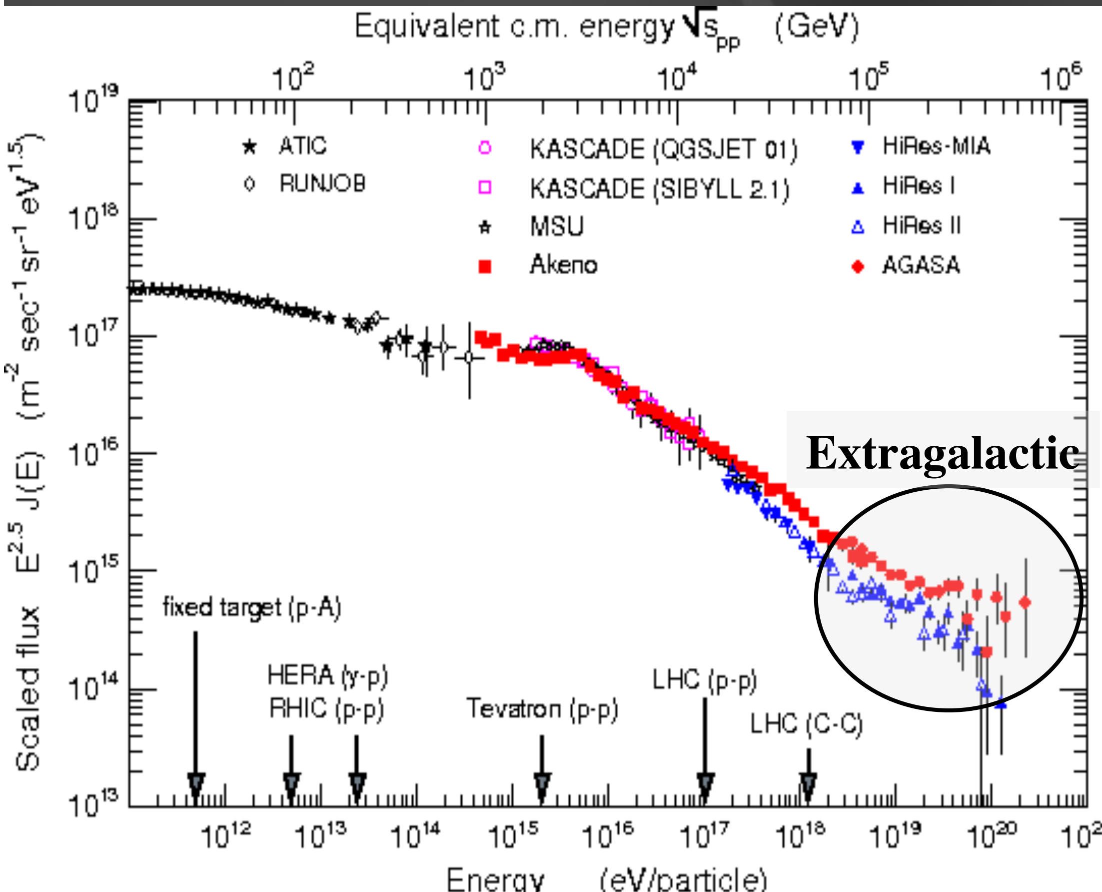
300 GRB per Gigaparsec^3 per year
for 10^{10} years (Hubble time)

$$2\times10^{51}\,erg\times\frac{300}{Gpc^3\;yr}\times10^{10}\,yr=3\times10^{-19}\,\frac{erg}{cm^3}$$

- correct cosmology: same answer
- Fermi: photon (electron) energy less than this ?
- challenged by IceCube limits

$$1Gpc^3=2.9\times10^{82}\,cm^3\qquad Hubble\;time=10^{10}\;years$$

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

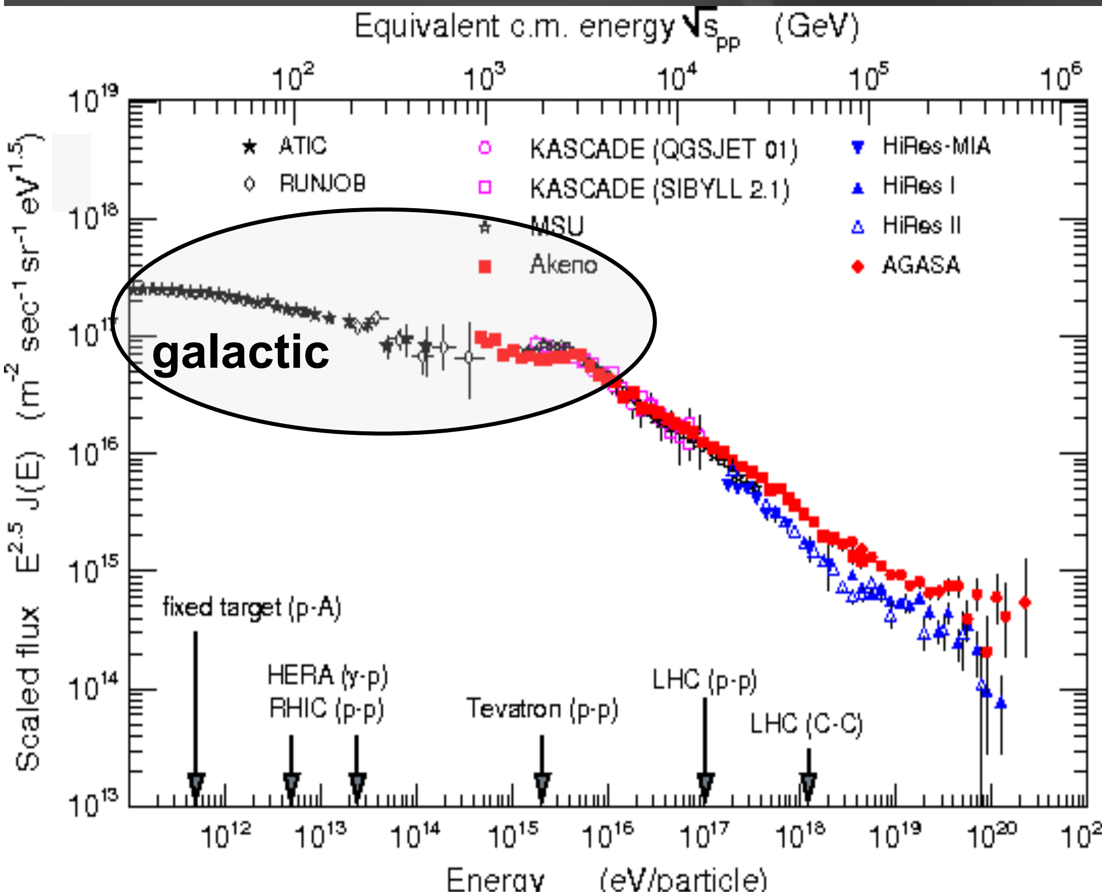
~ 10^{-19} erg / cm^3

Gamma-Ray Bursts:
$2x10^{51}$ ergs x 300/Gpc^3 x 10^{10} yr

~ 10^{-19} erg / cm^3

GRBs provide environment and energy to explain the extragalactic cosmic rays!

Cosmic Rays & SNRs



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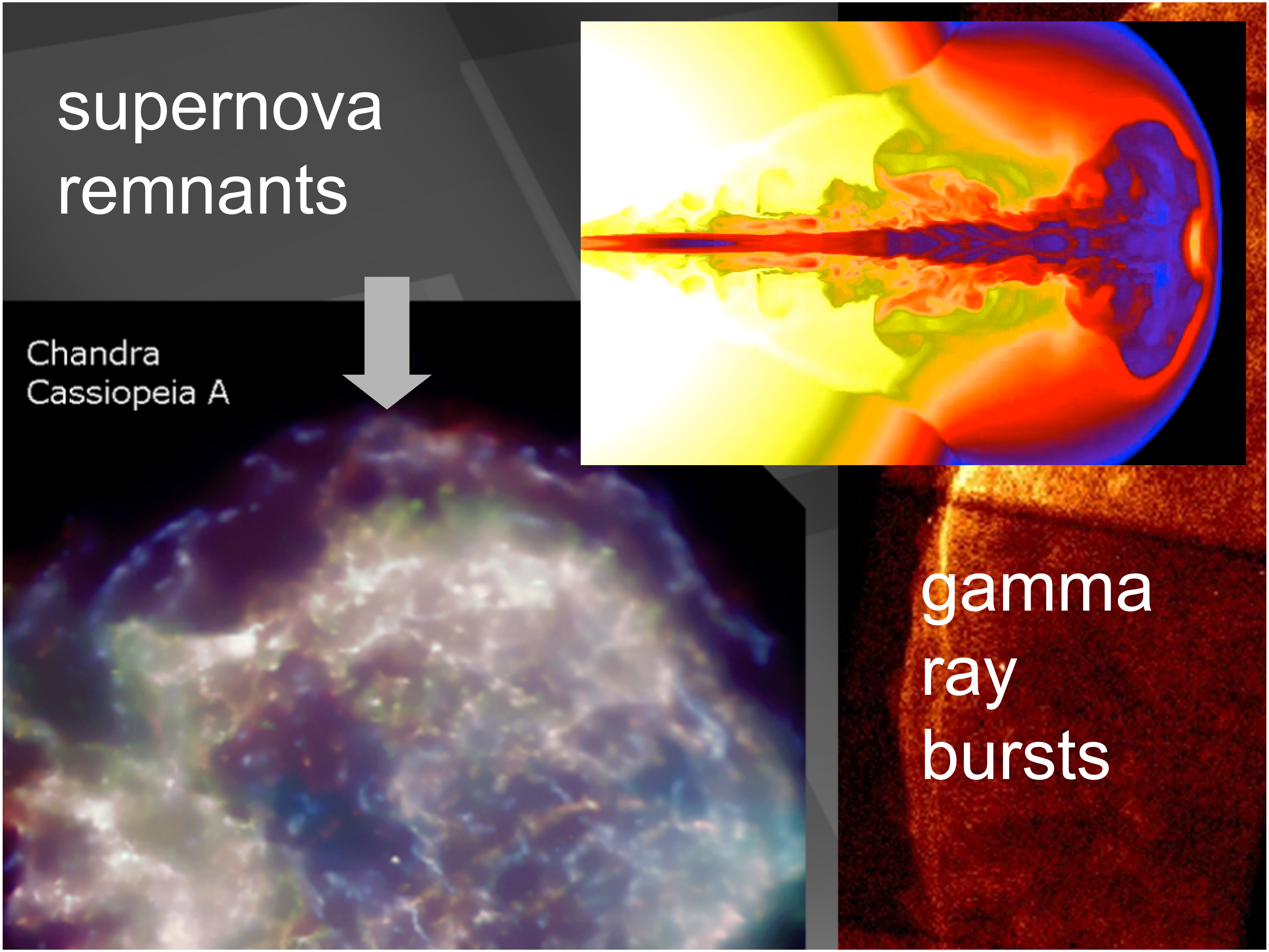
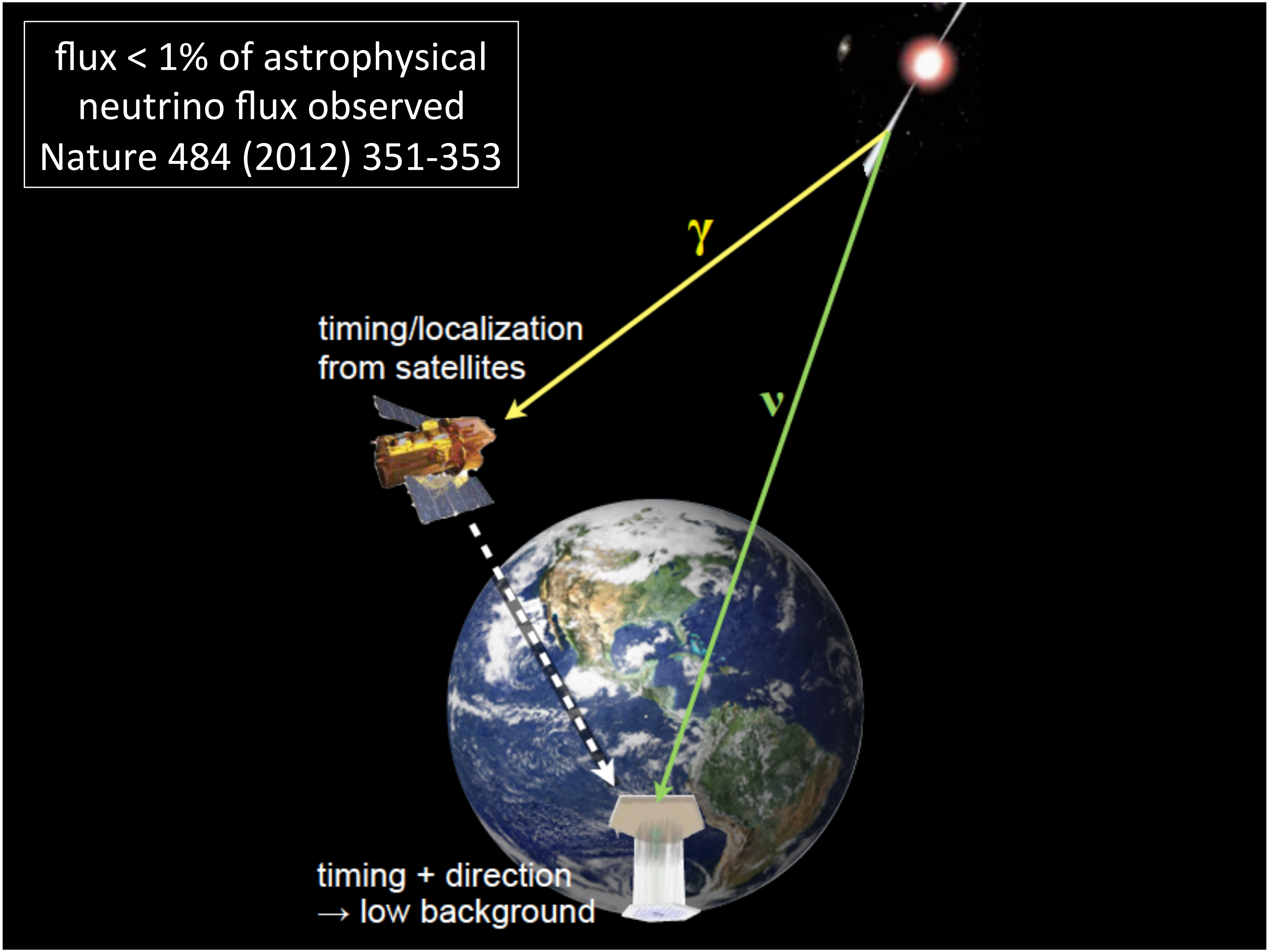
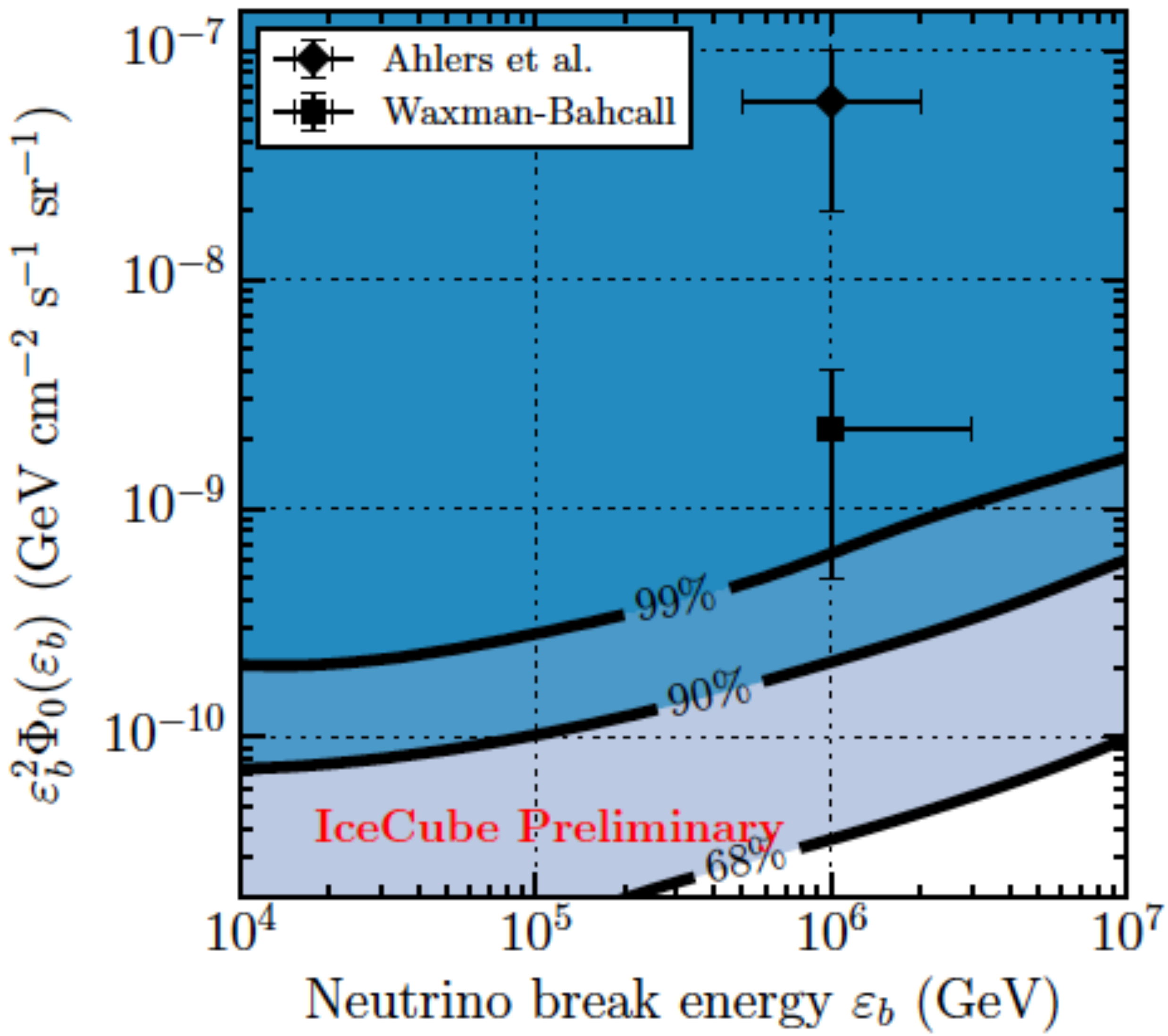
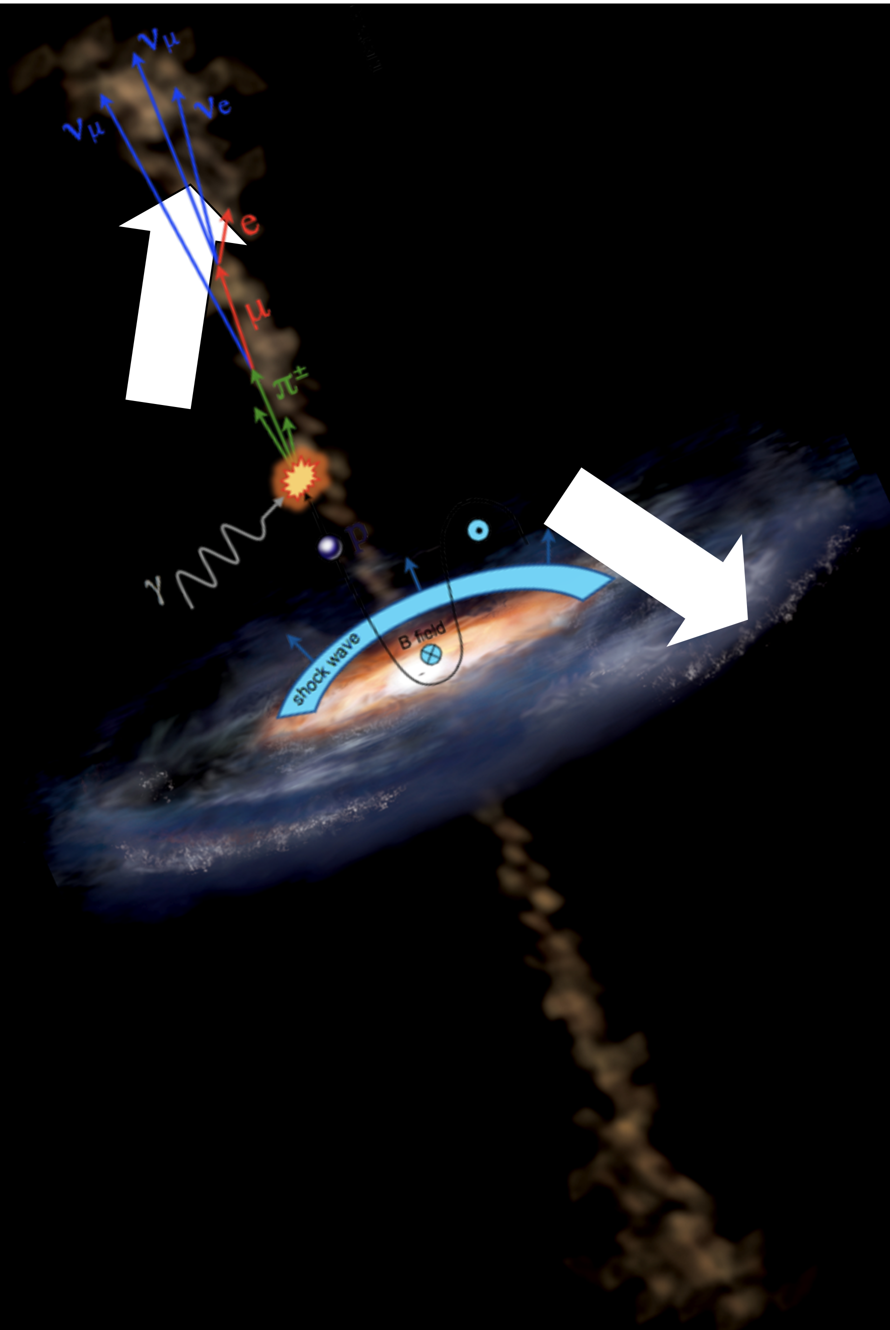

supernova
remnants
Chandra
Cassiopeia A
gamma
ray
bursts


flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353
γ
ν
timing/localization
from satellites
timing + direction
→ low background

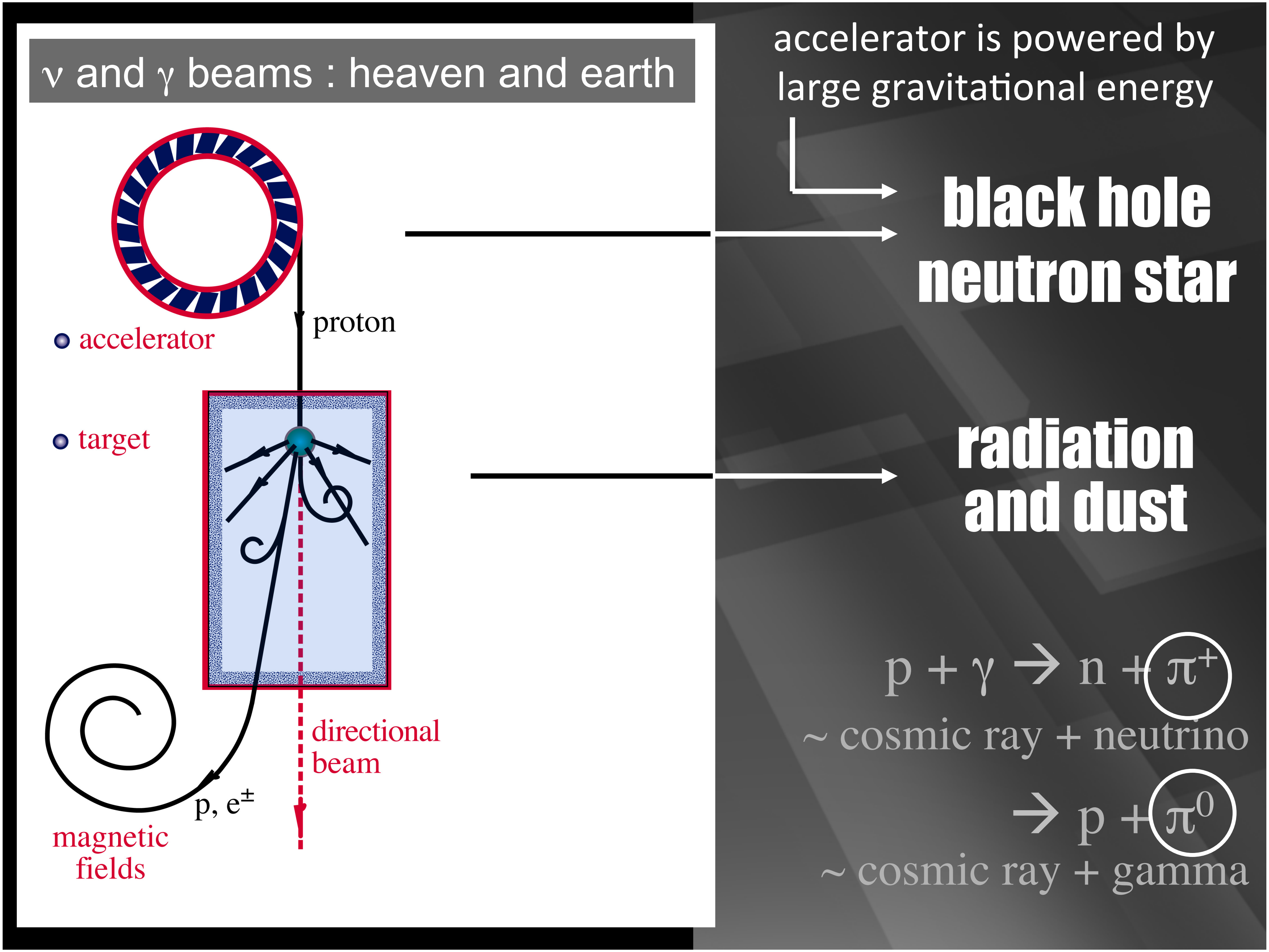


Ahlers et al.
Waxman-Bahcall
99%
90%
68%
IceCube Preliminary
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^4
10^5
10^6
10^7
$\varepsilon_b^2\Phi_0(\varepsilon_b)$ (GeV cm^{-2} s^{-1} sr^{-1})
Neutrino break energy ε_b (GeV)



active galaxy

particle flows near
supermassive
black hole

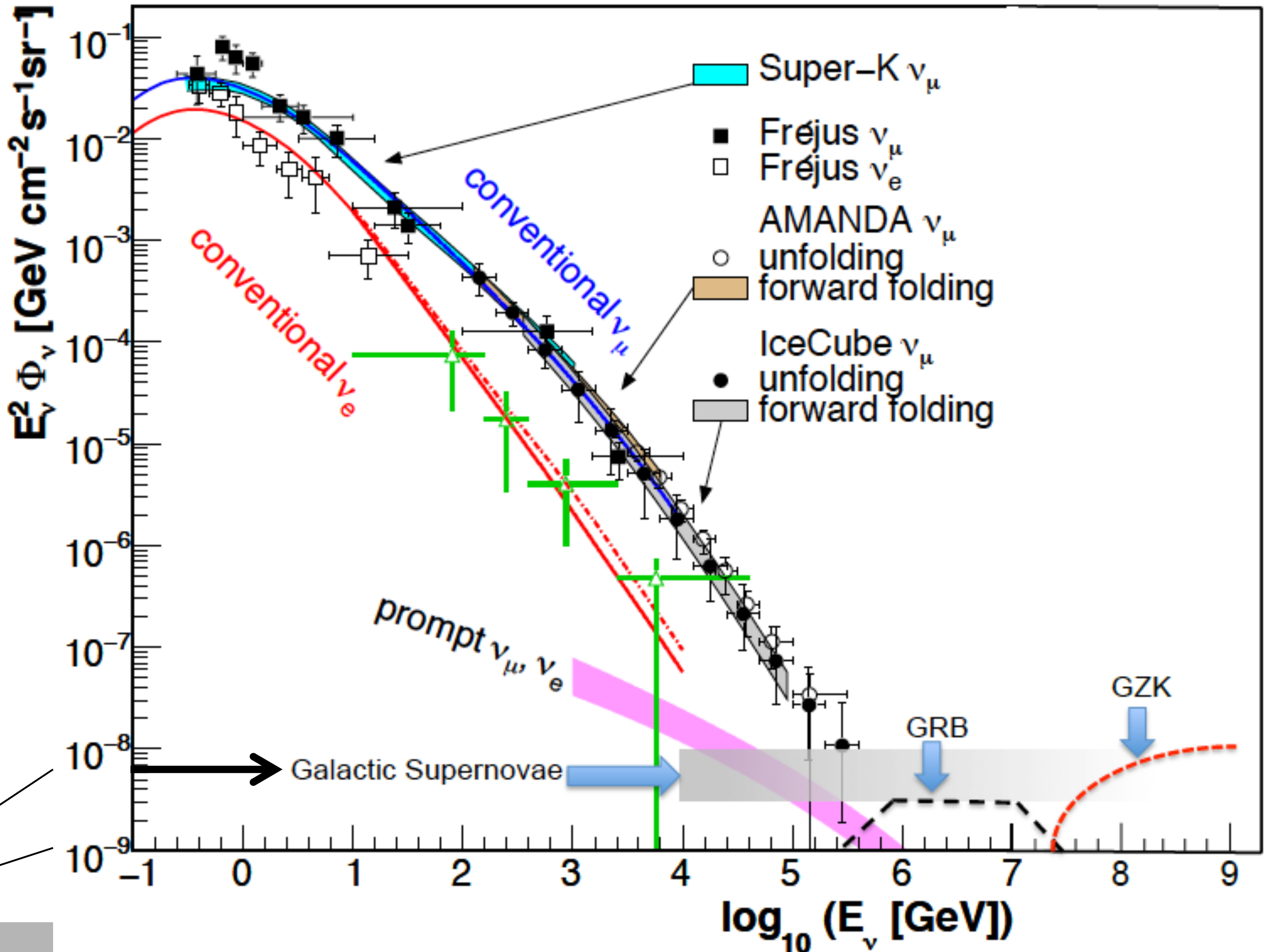

ν and γ beams : heaven and earth
accelerator is powered by large gravitational energy
black hole
neutron star
radiation and dust
proton
accelerator
target
directional beam
magnetic fields
p, e±
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient 1 km^3 detector

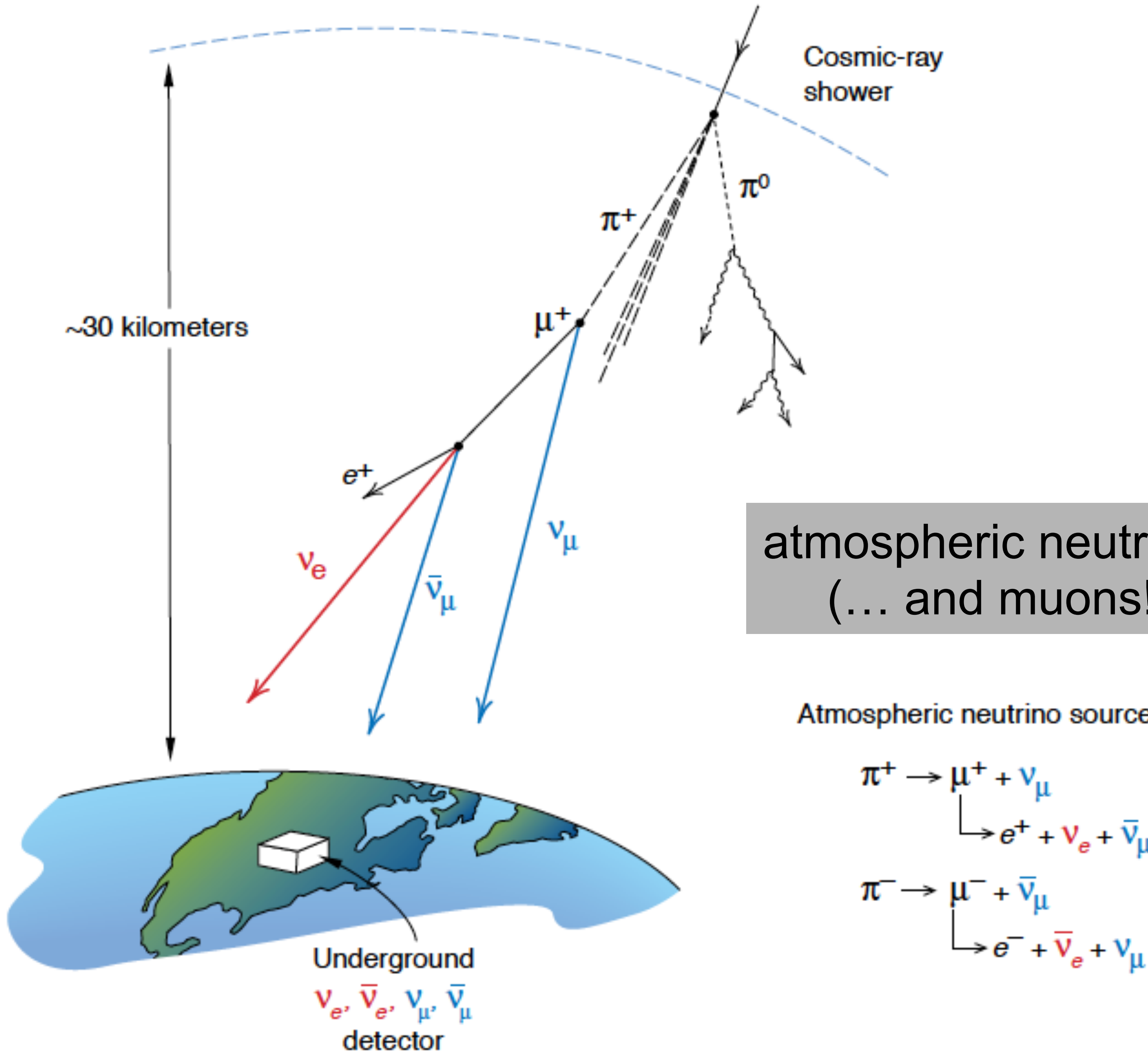


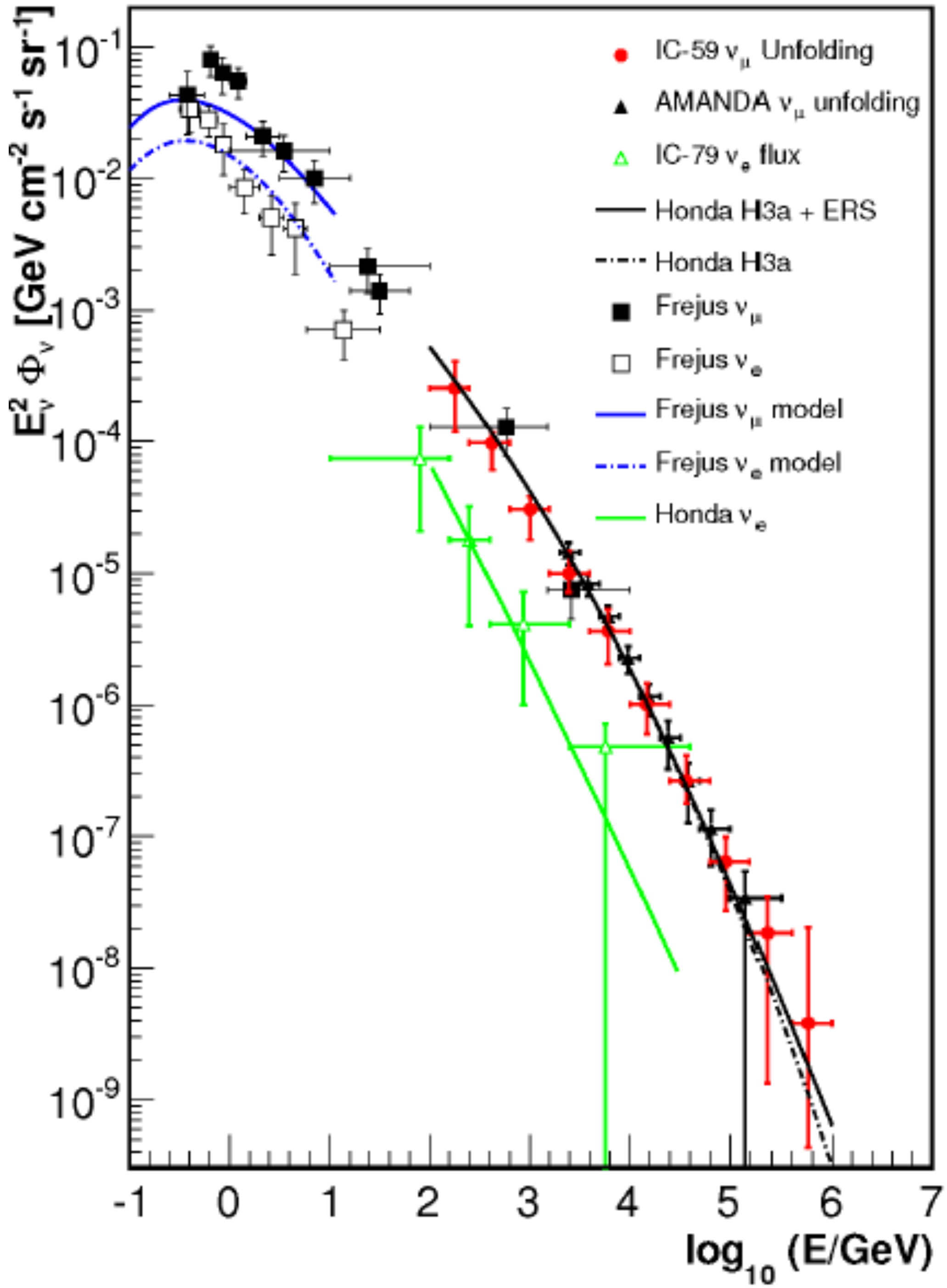
atmospheric

cosmic

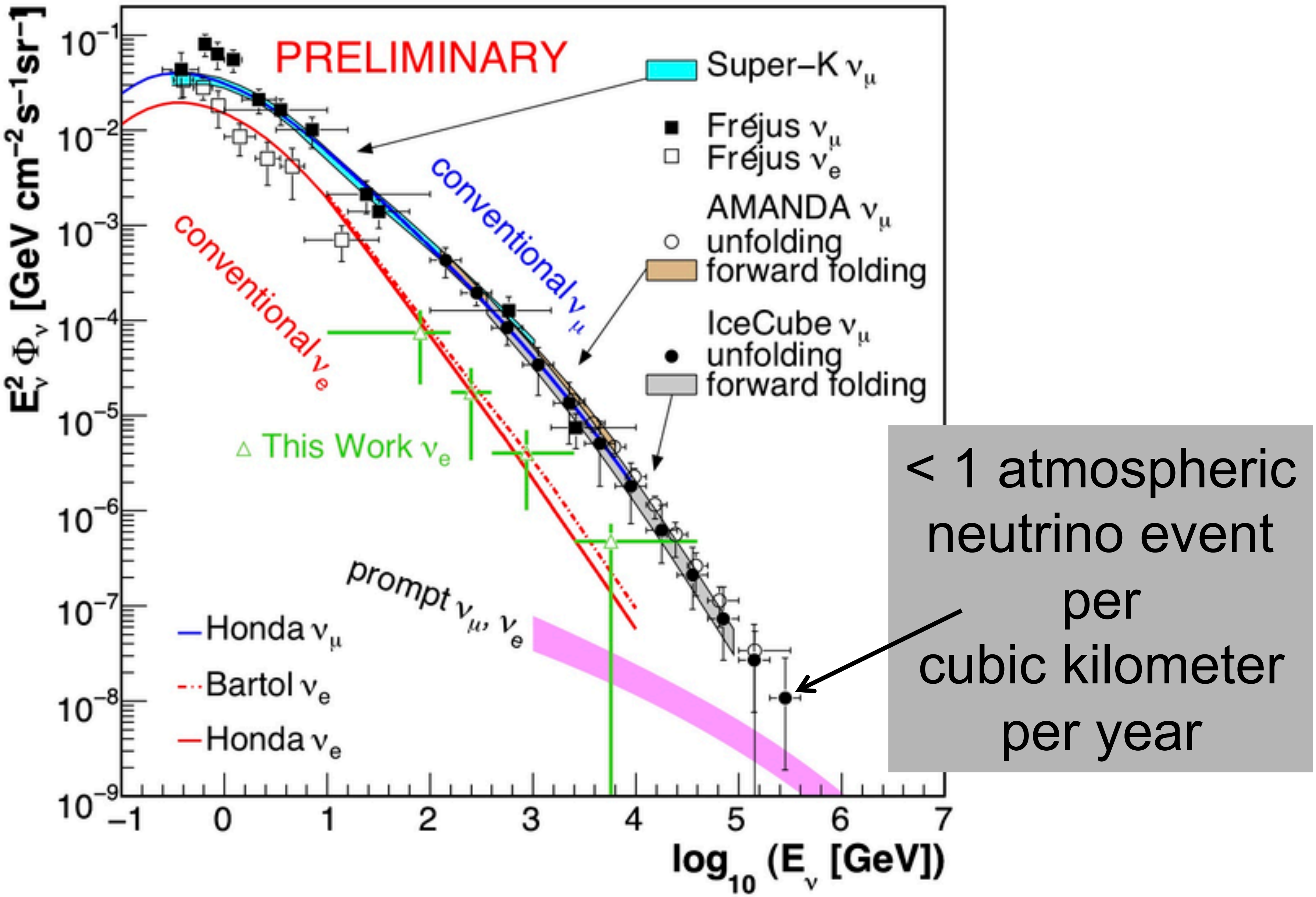
100 TeV

atmospheric neutrinos
(… and muons!)

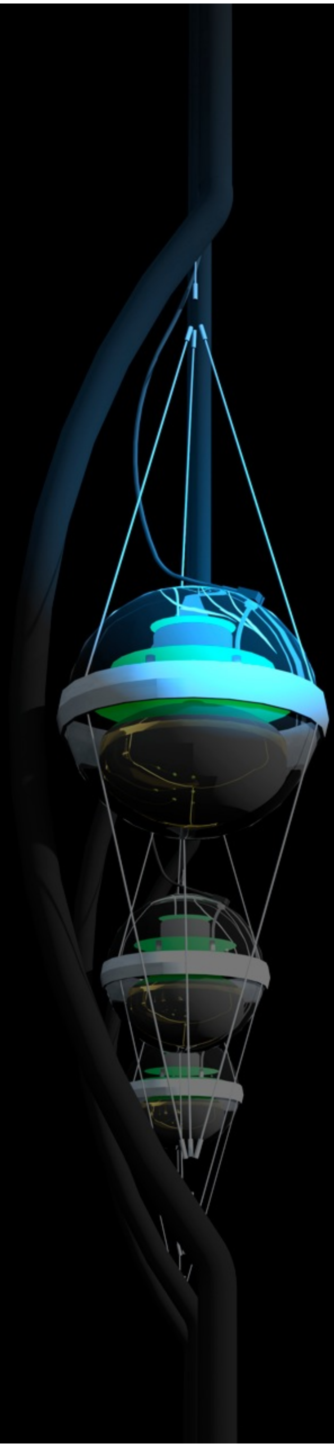




$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-1
0
1
2
3
4
5
6
7
$\log_{10}$ (E/GeV)
IC-59 ν_μ Unfolding
AMANDA ν_μ unfolding
IC-79 ν_e flux
Honda H3a + ERS
Honda H3a
Frejus ν_μ
Frejus ν_e
Frejus ν_μ model
Frejus ν_e model
Honda ν_e



atmospheric neutrino spectrum



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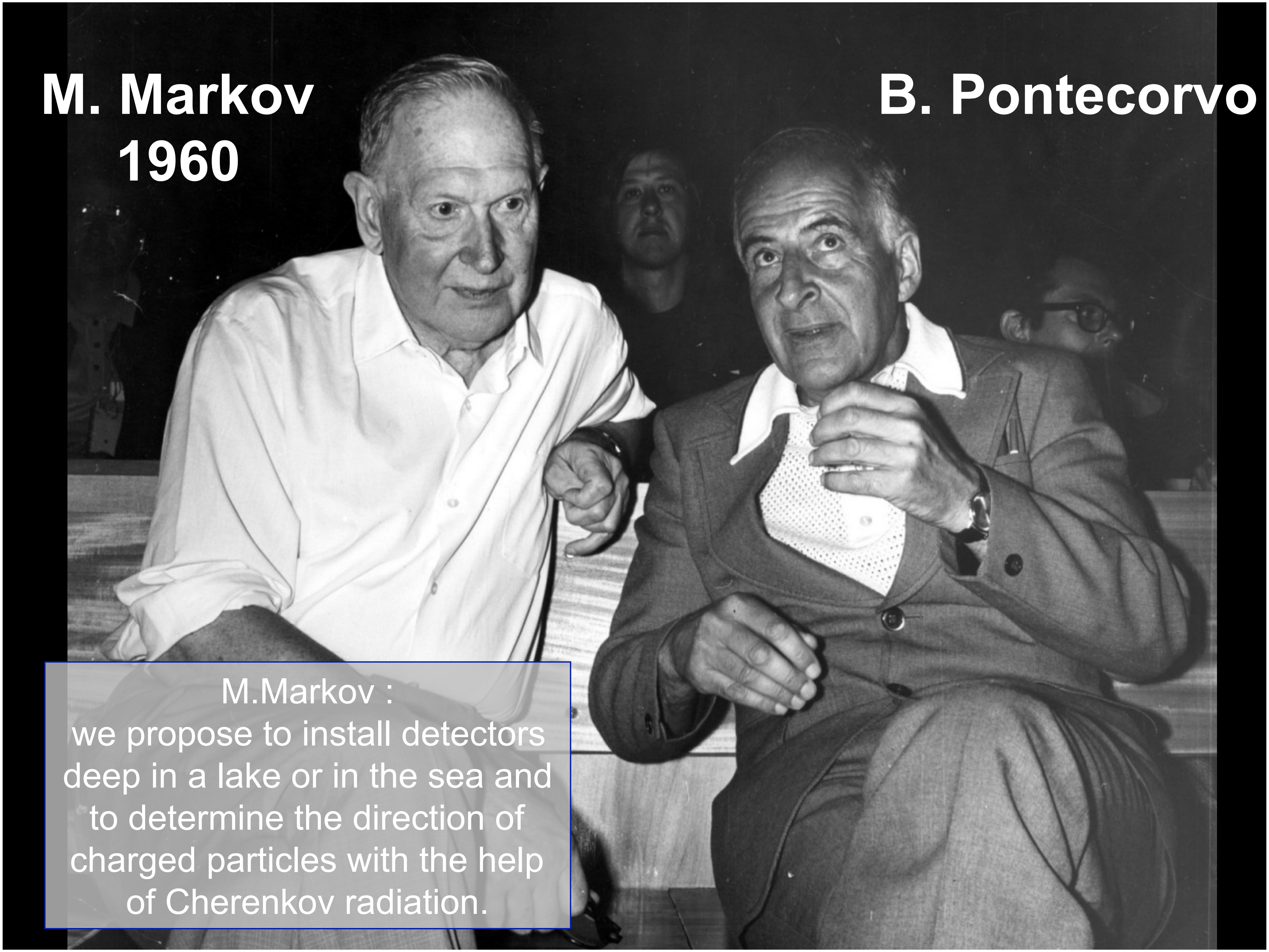
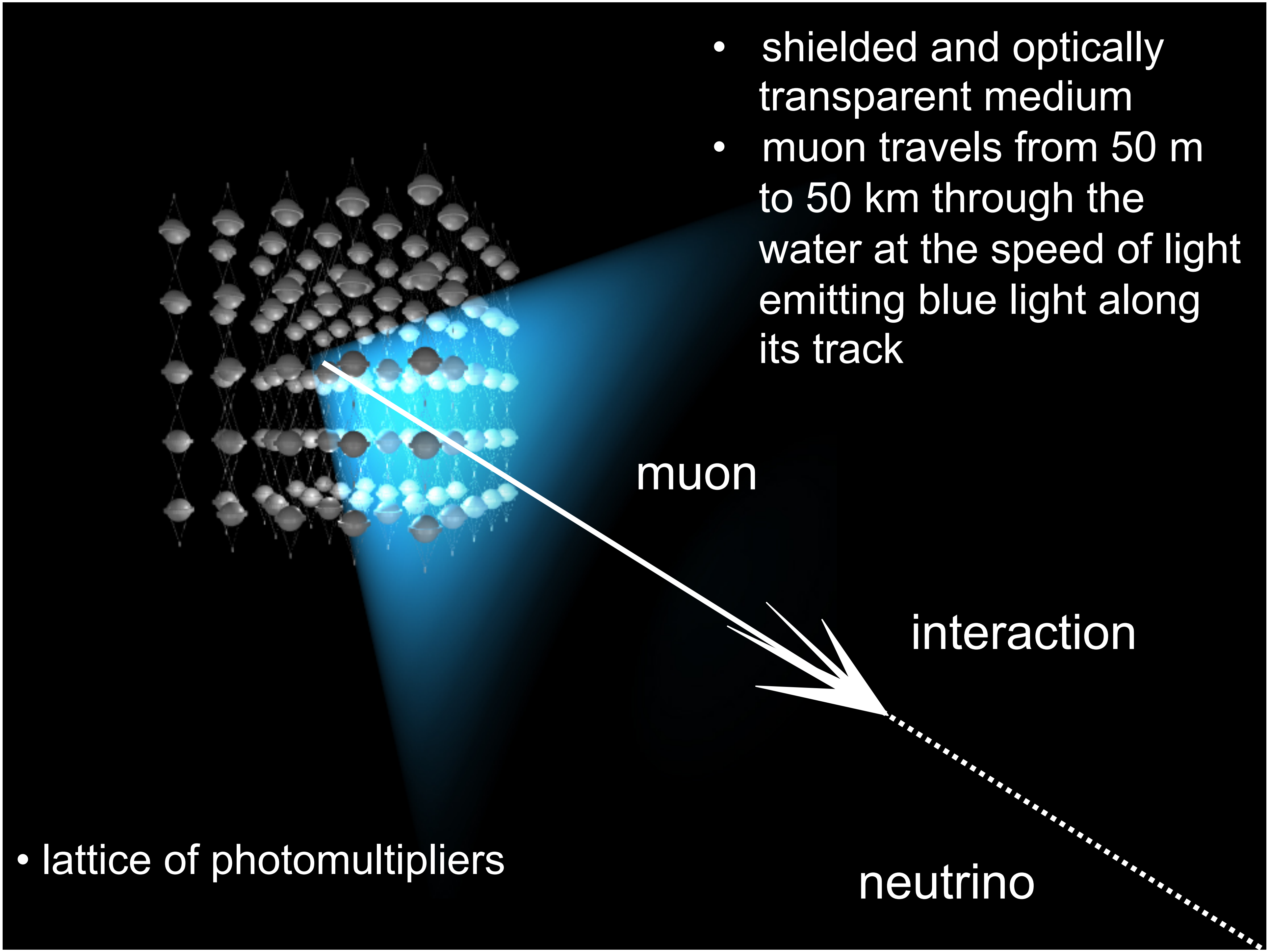
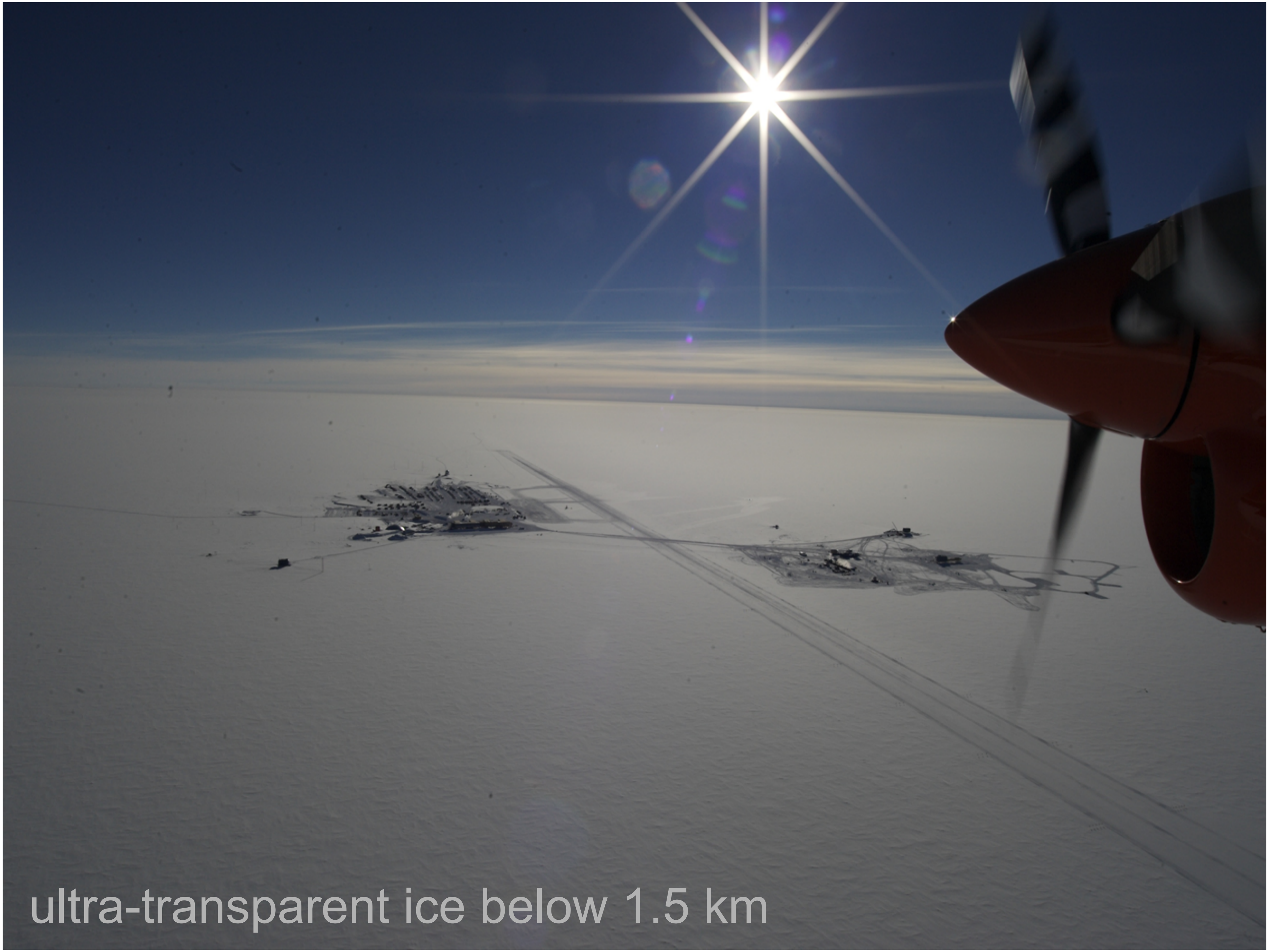
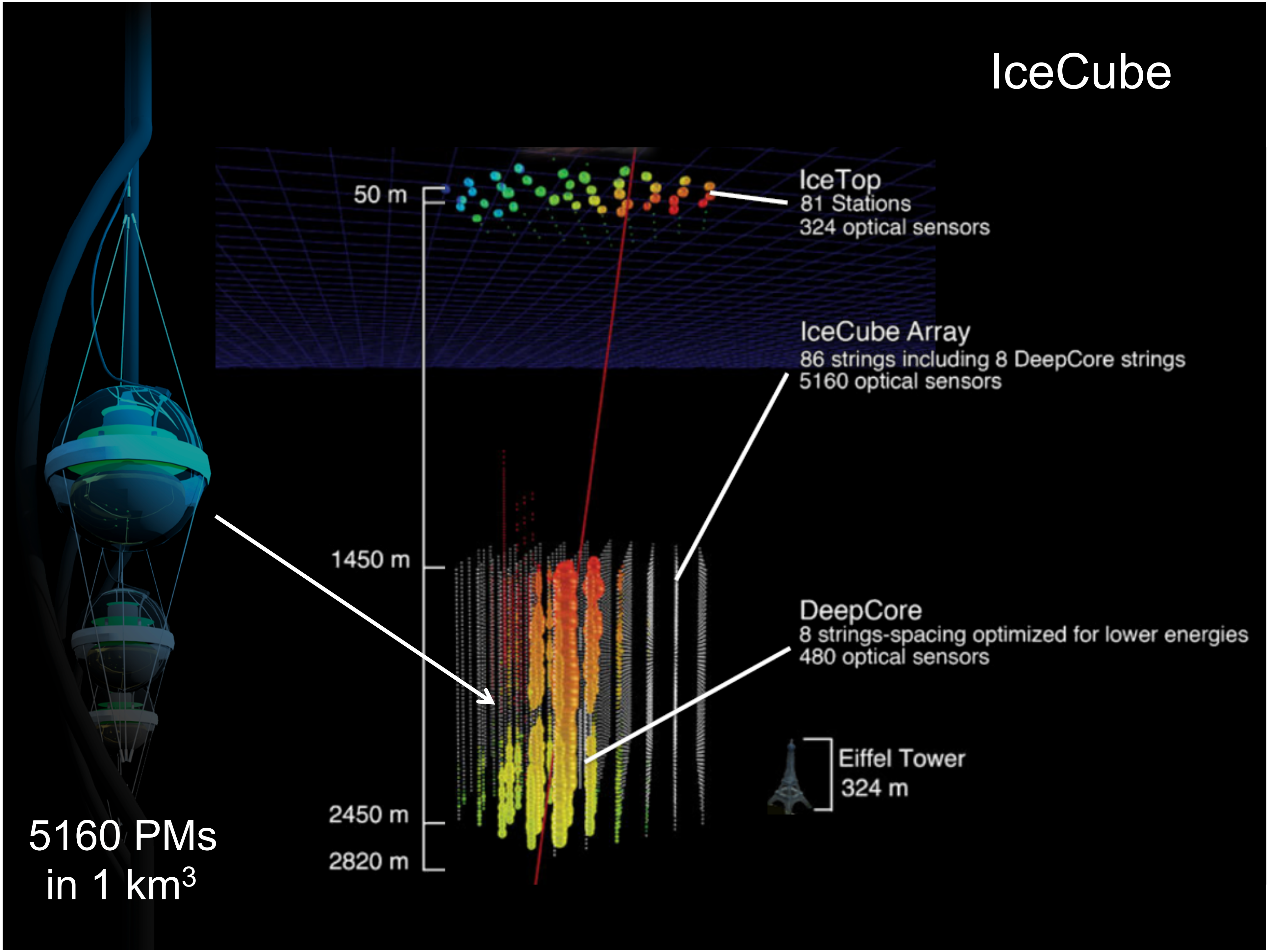

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

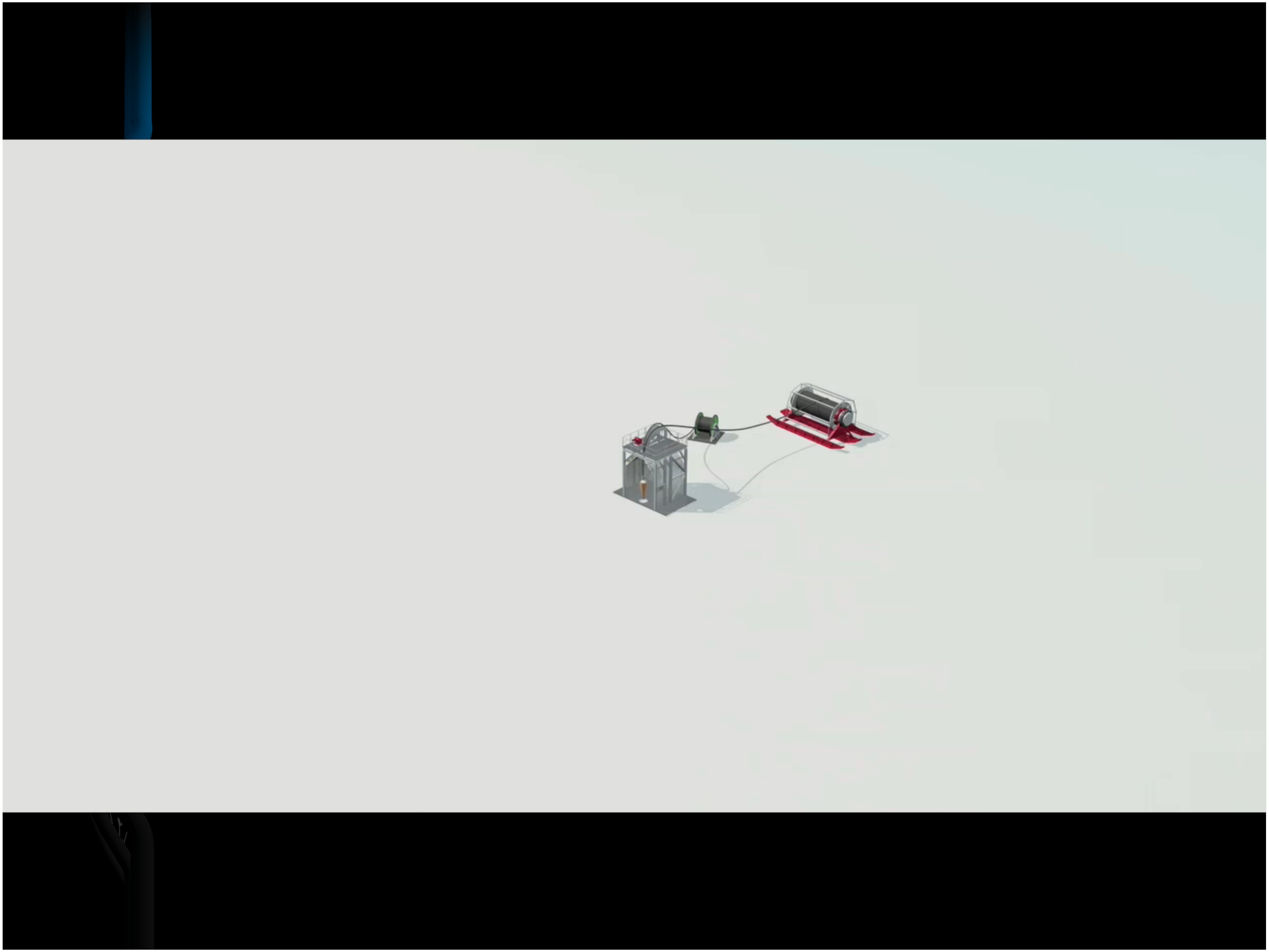

• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
neutrino
• lattice of photomultipliers


ultra-transparent ice below 1.5 km

IceCube

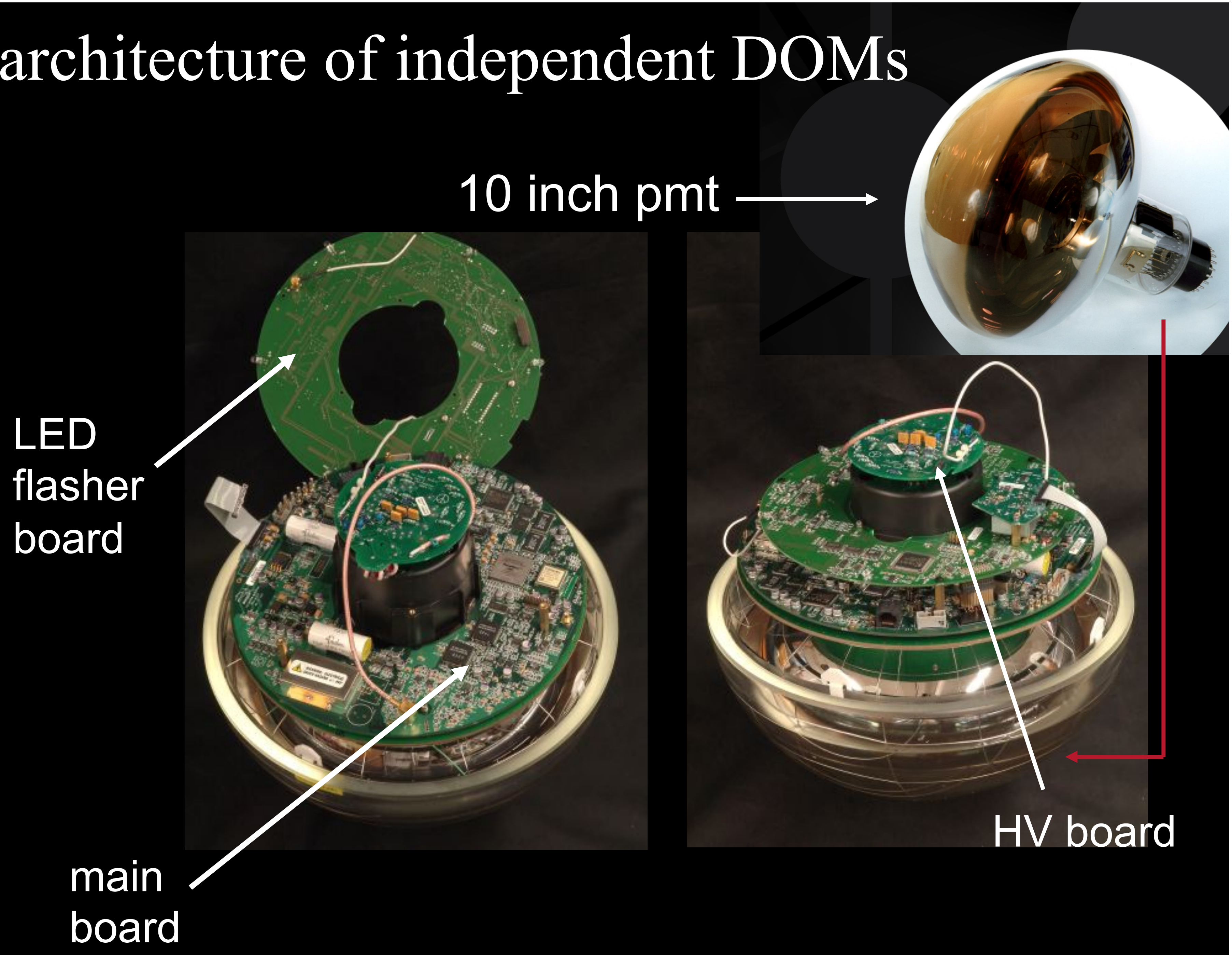


5160 PMs in 1 km^3

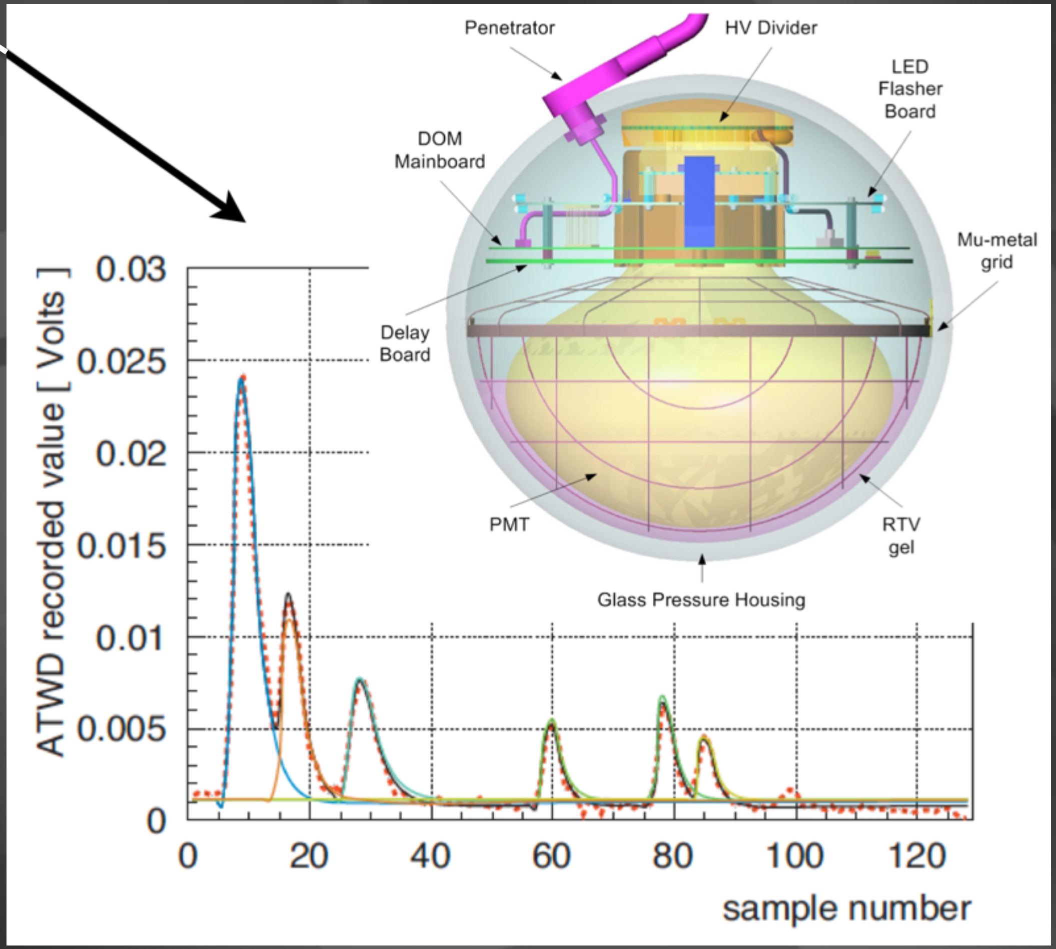


photomultiplier tube -10 inch

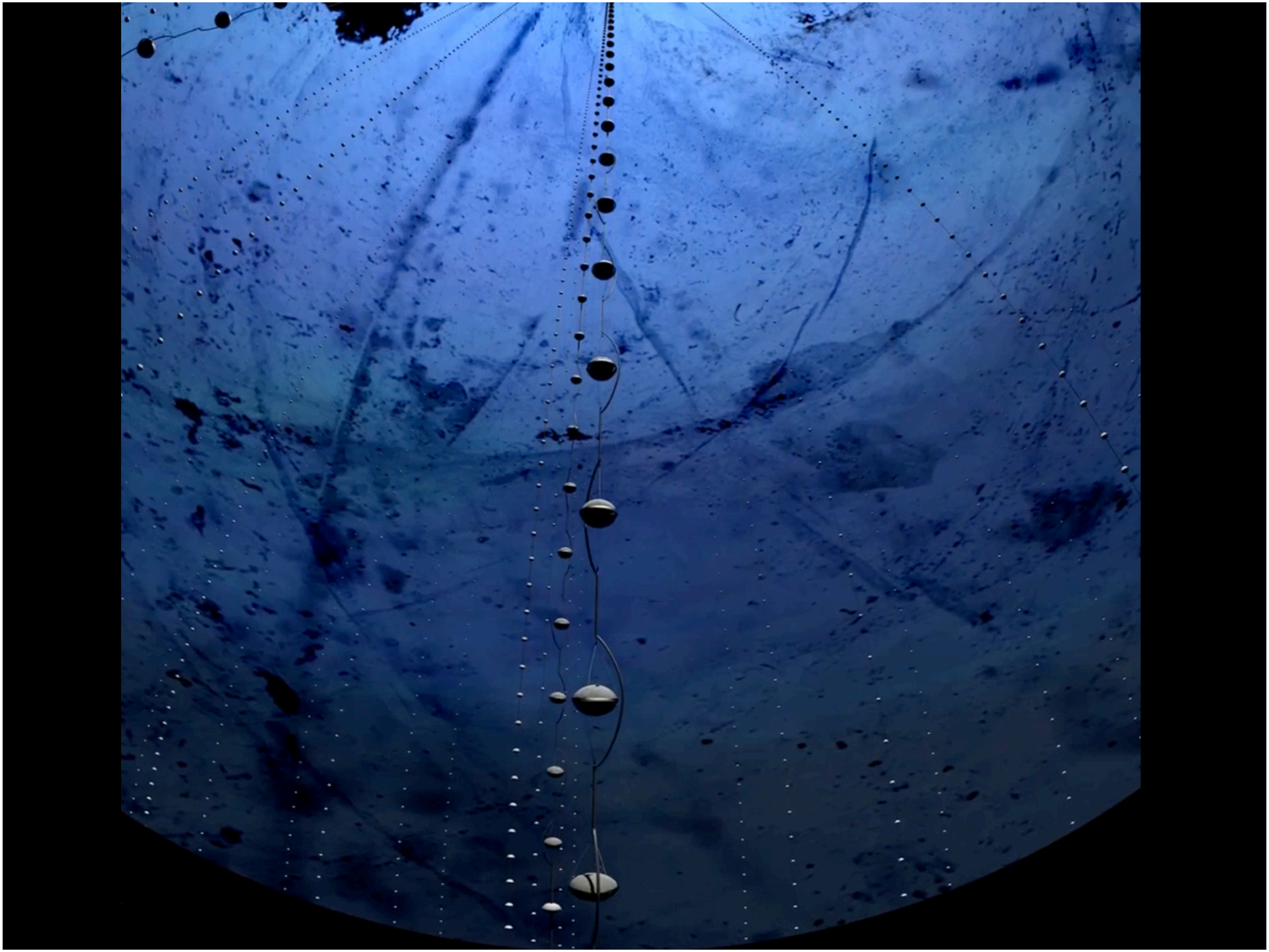
architecture of independent DOMs

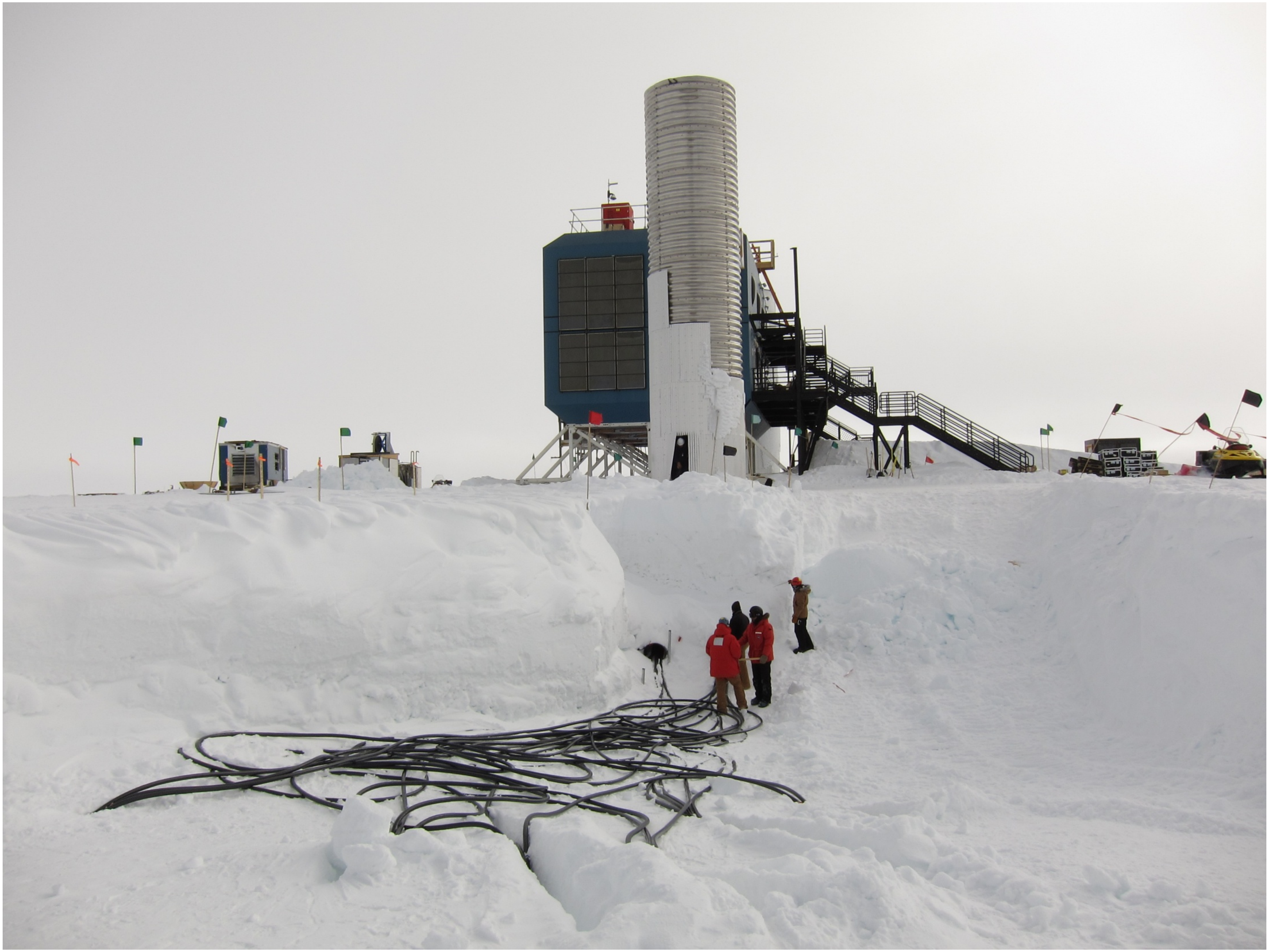


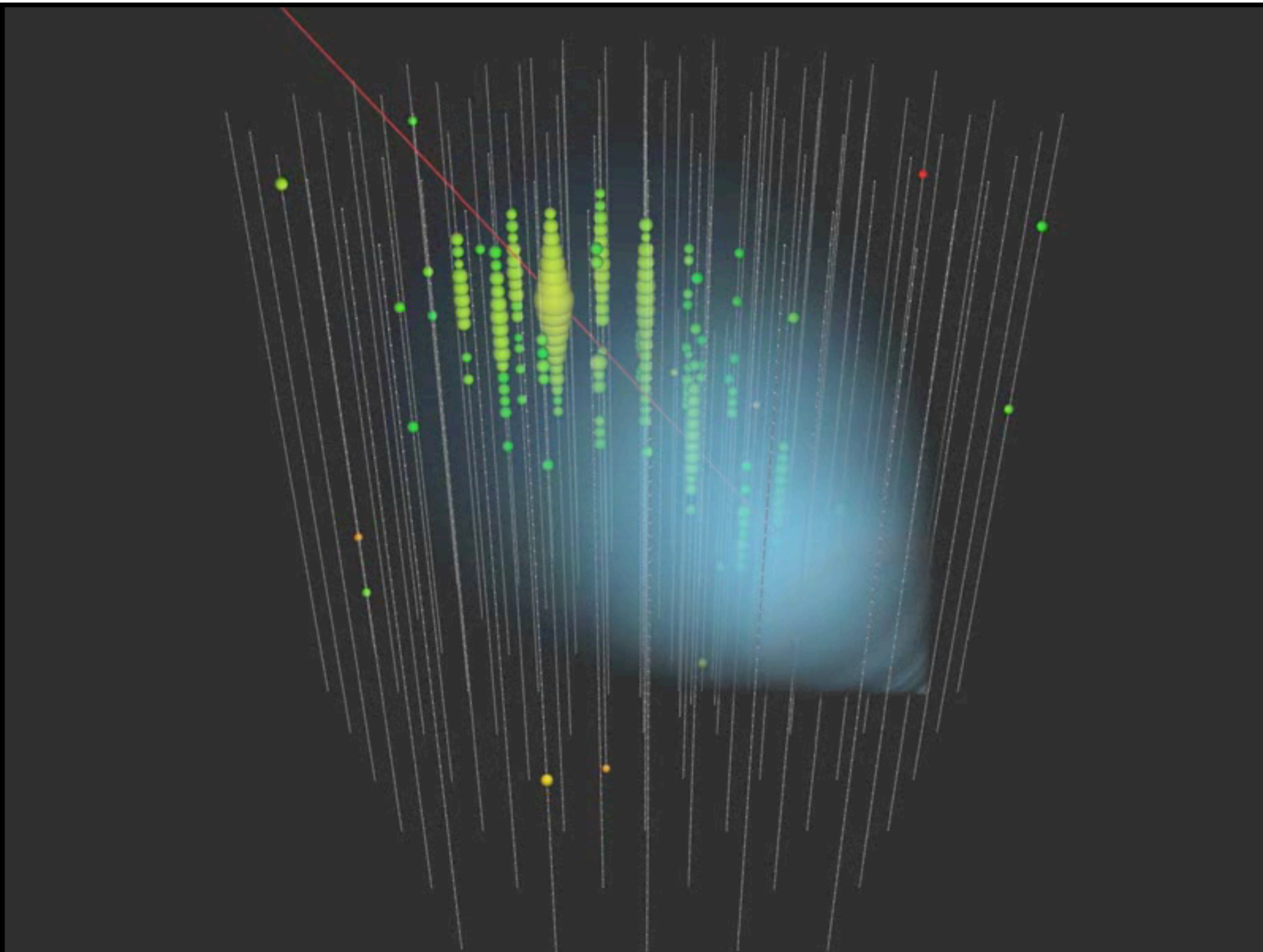
… each Digital Optical Module independently collects light signals like this, digitizes them,



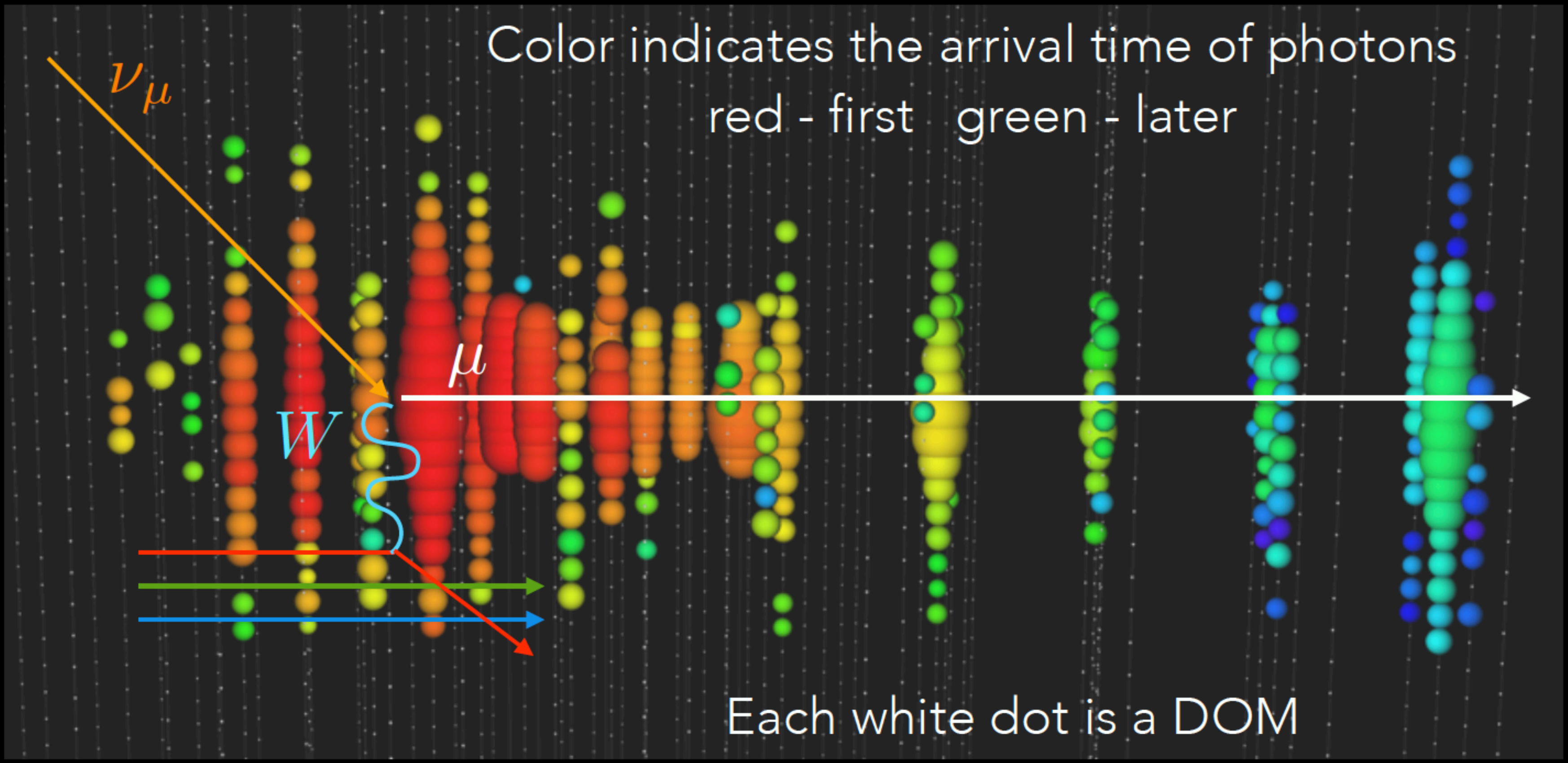
…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…





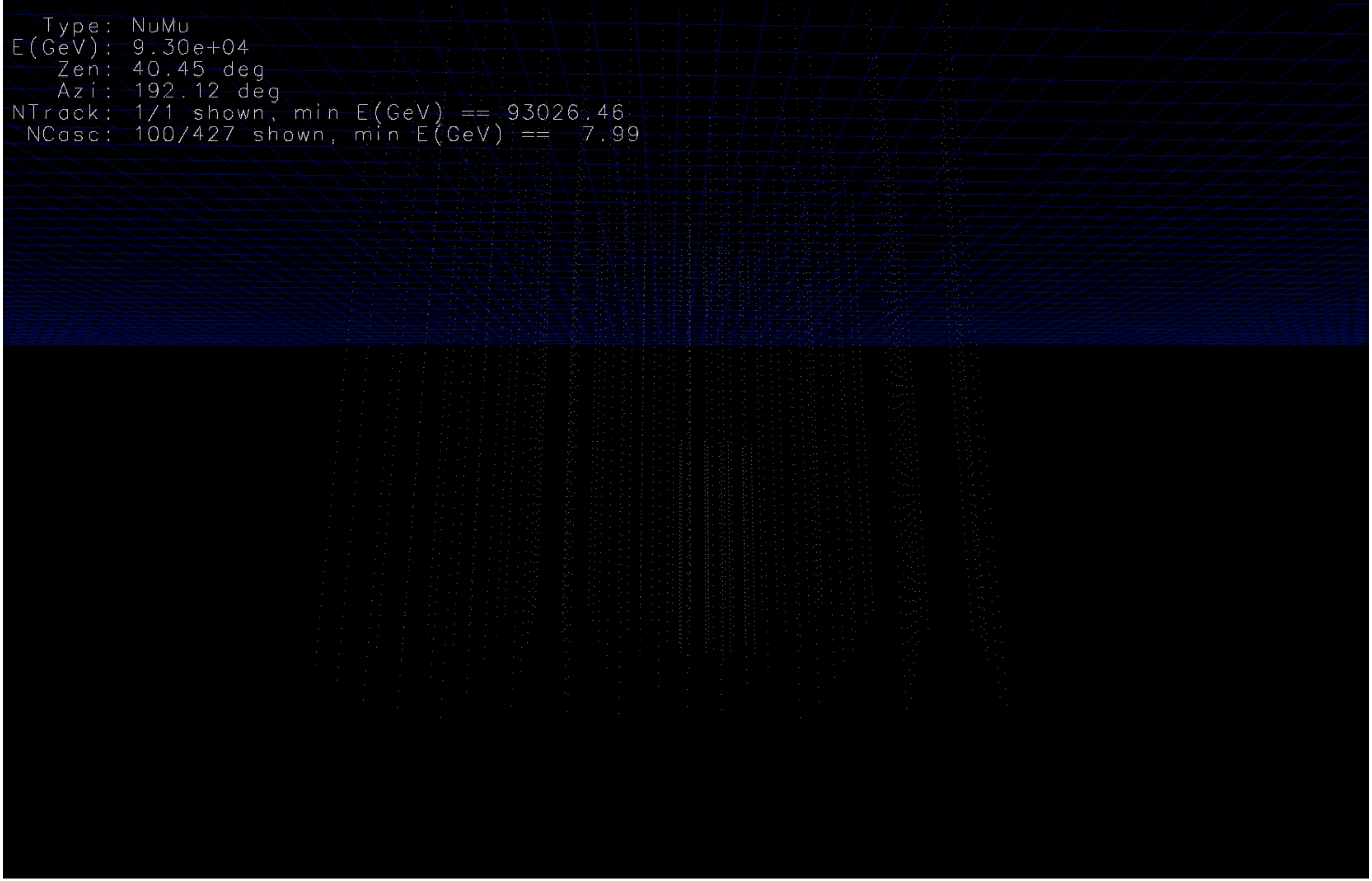


muon track: color is time; number of photons is energy

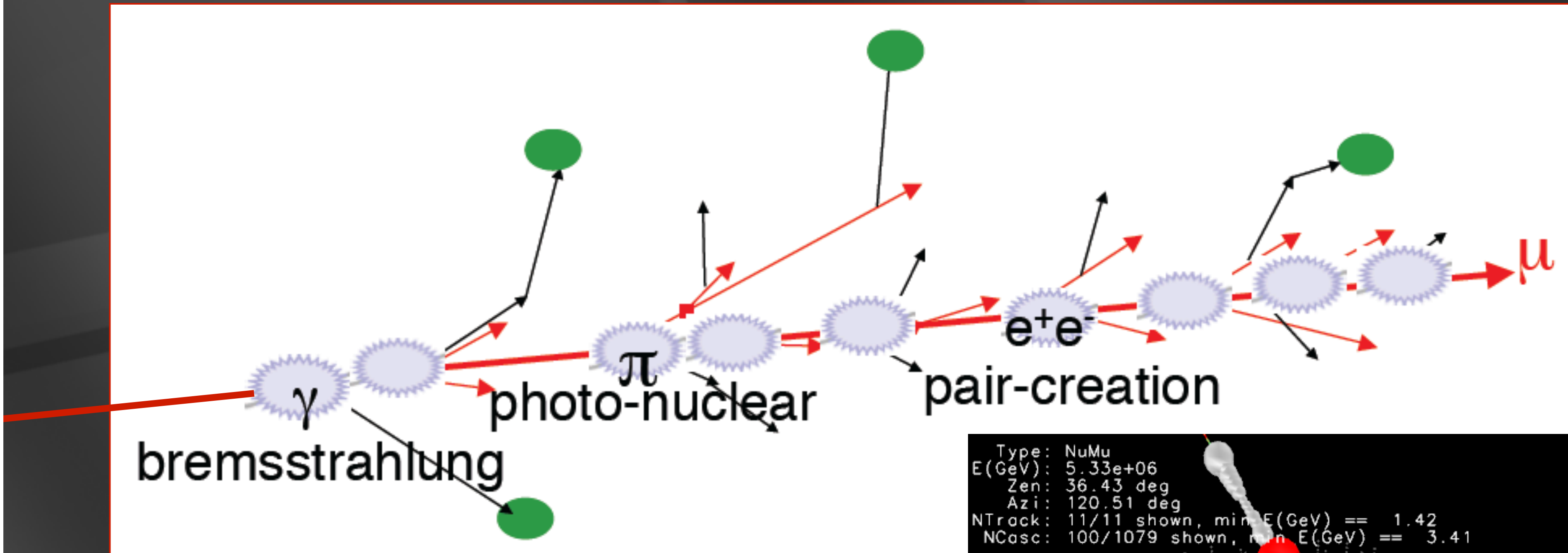


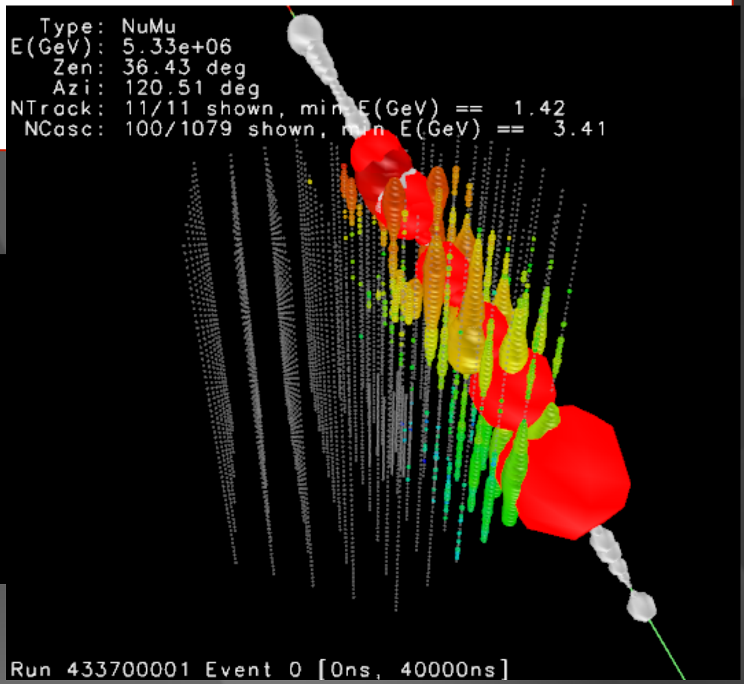
Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

93 TeV muon: light ~ energy

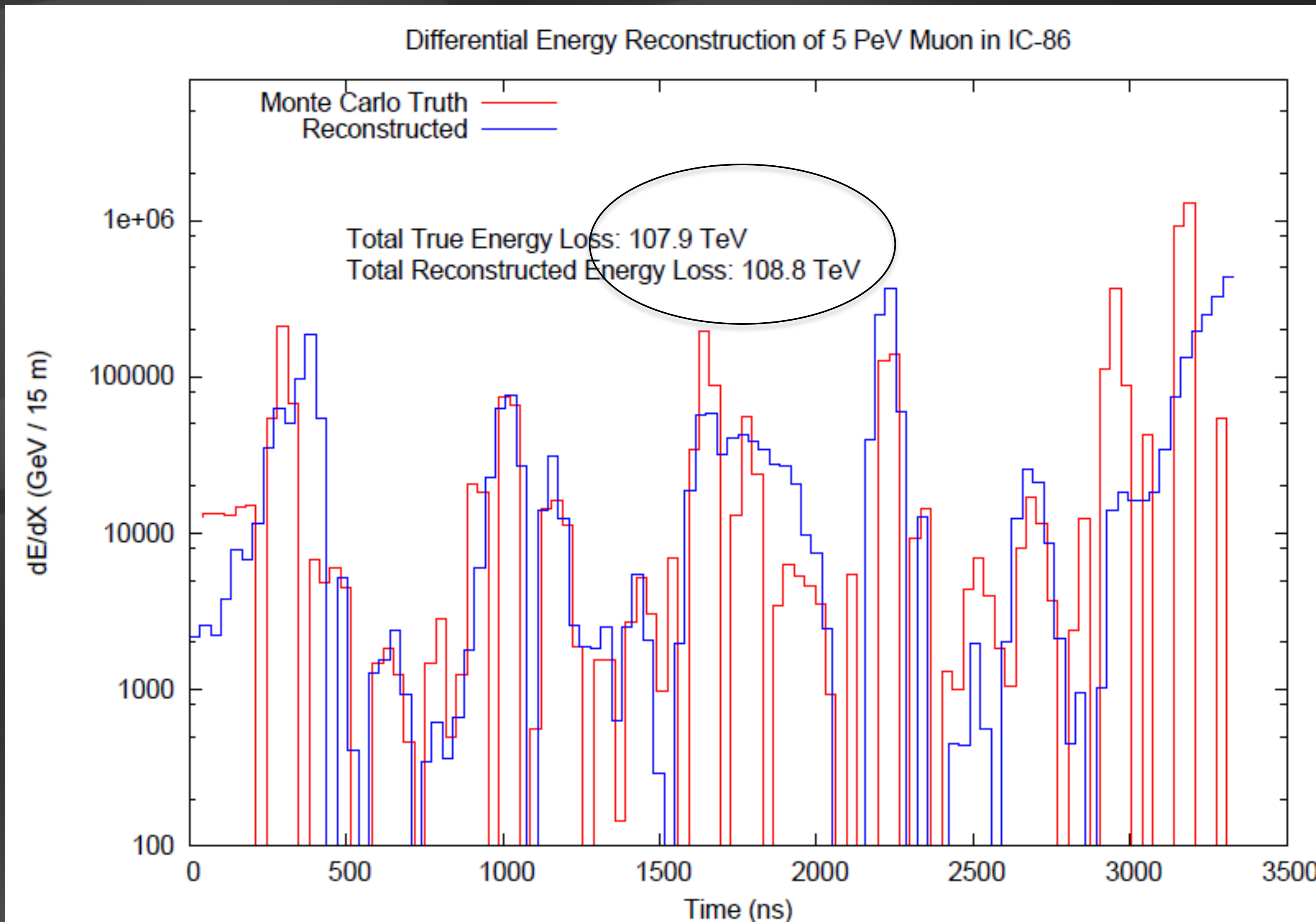


energy measurement (> 1 TeV)





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

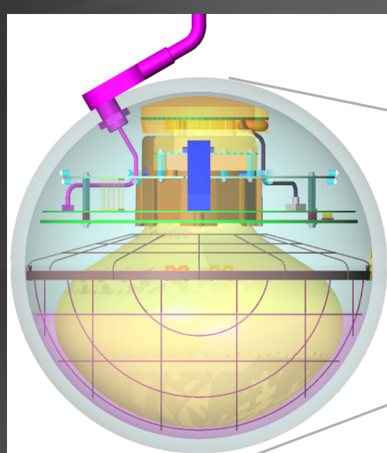


1.1 km

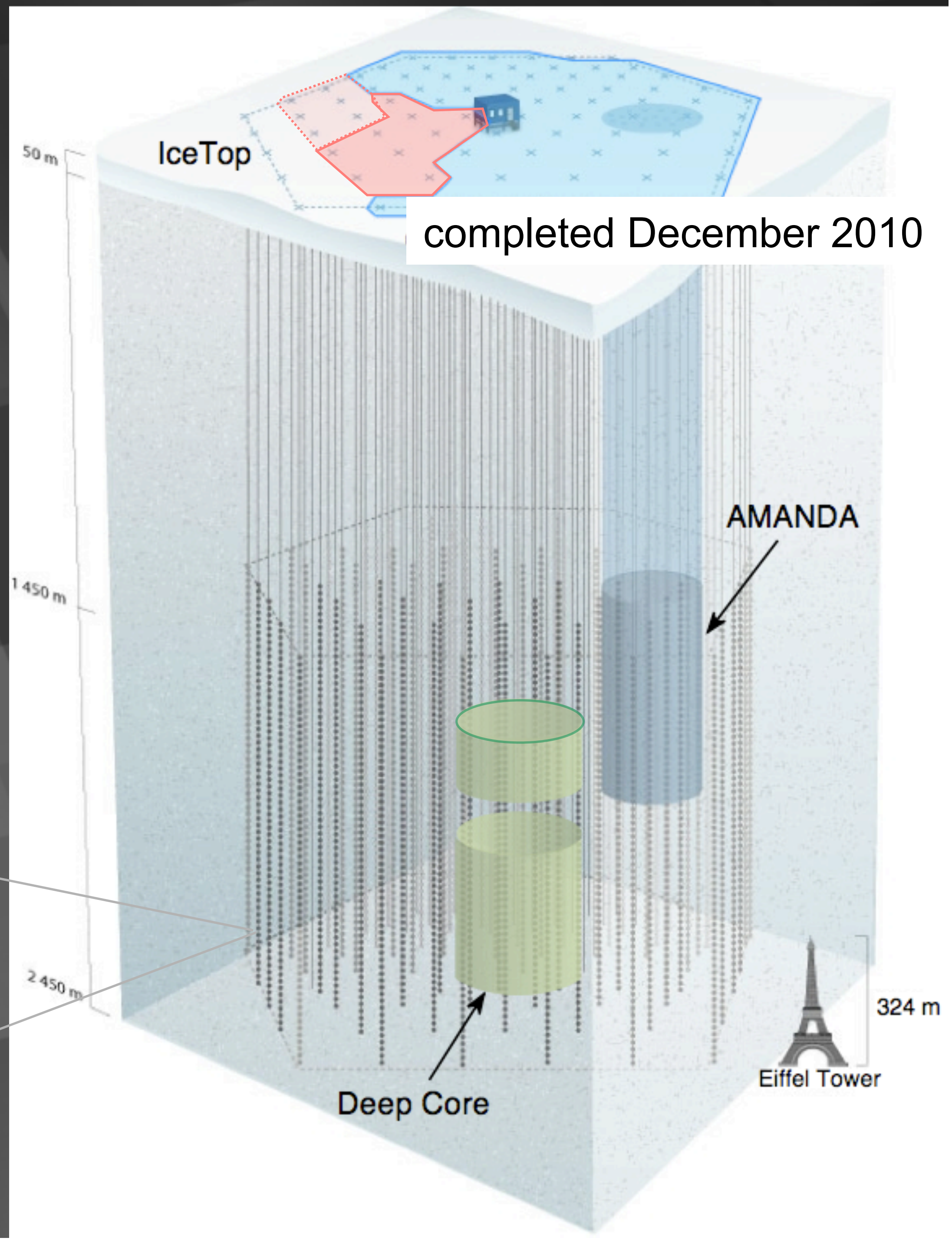
improving angular and energy resolution

IceCube / Deep Core

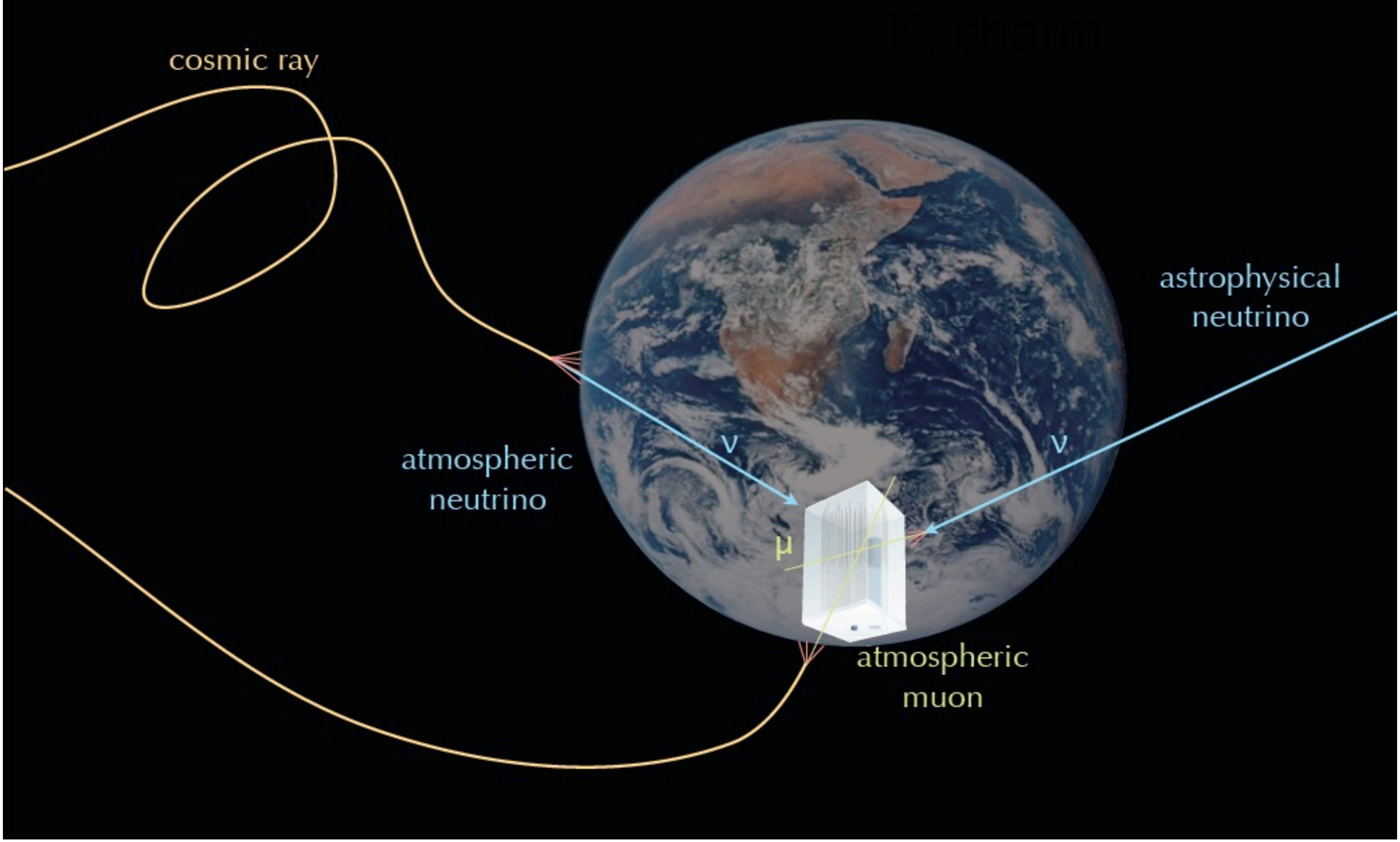
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.4 degree muon track ~ 10 degree shower
- < 15% energy resolution

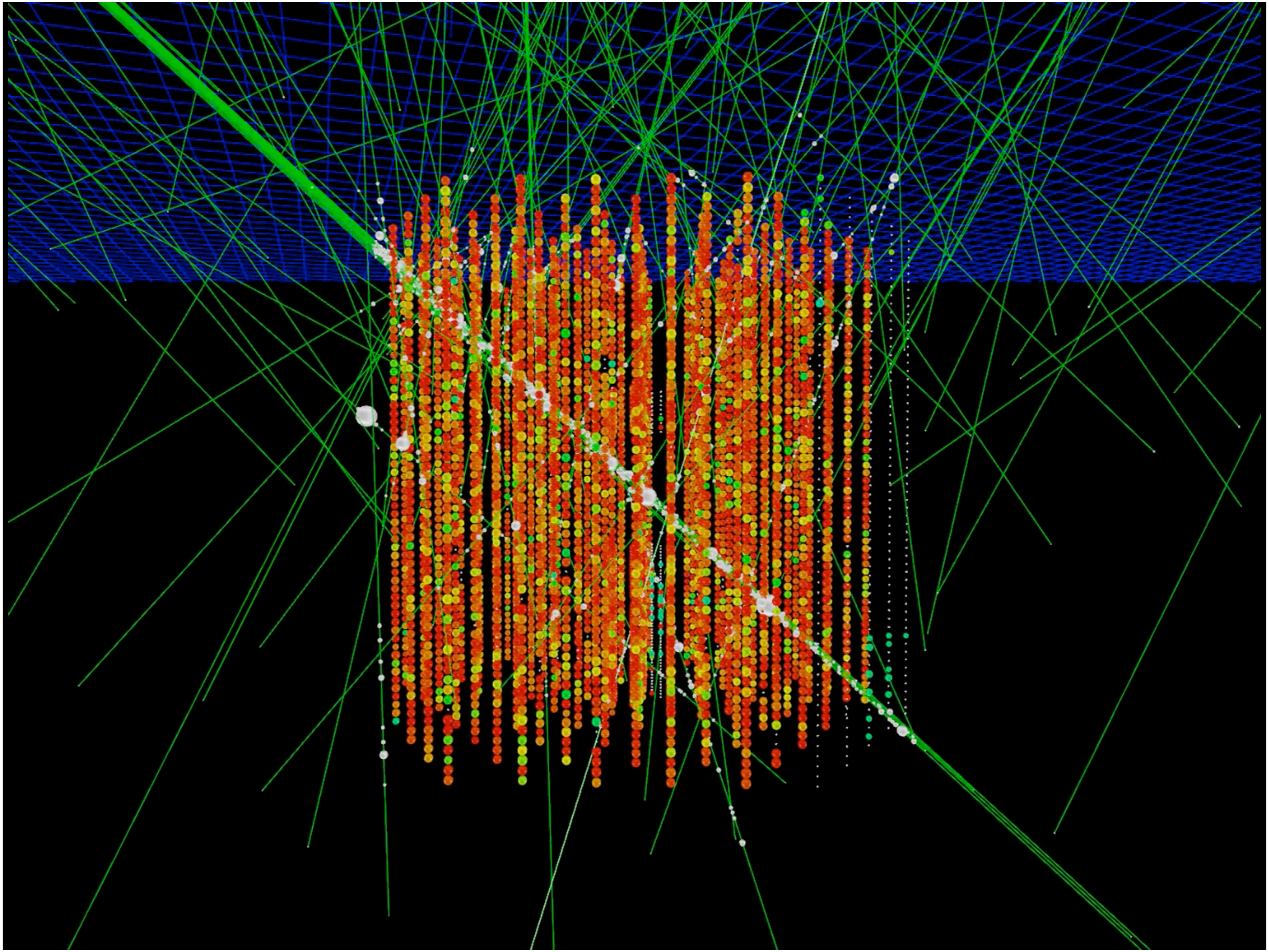


Digital Optical Module (DOM)



Signals and Backgrounds





… you looked at 10msec of data !

muons detected per year:

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

* 3000 per second ** 1 every 6 minutes

IceCube Weekly Report 29, 2016

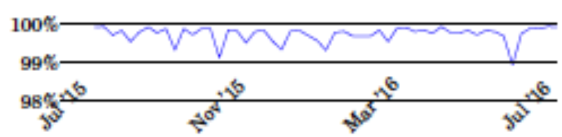
July 18 through July 24

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

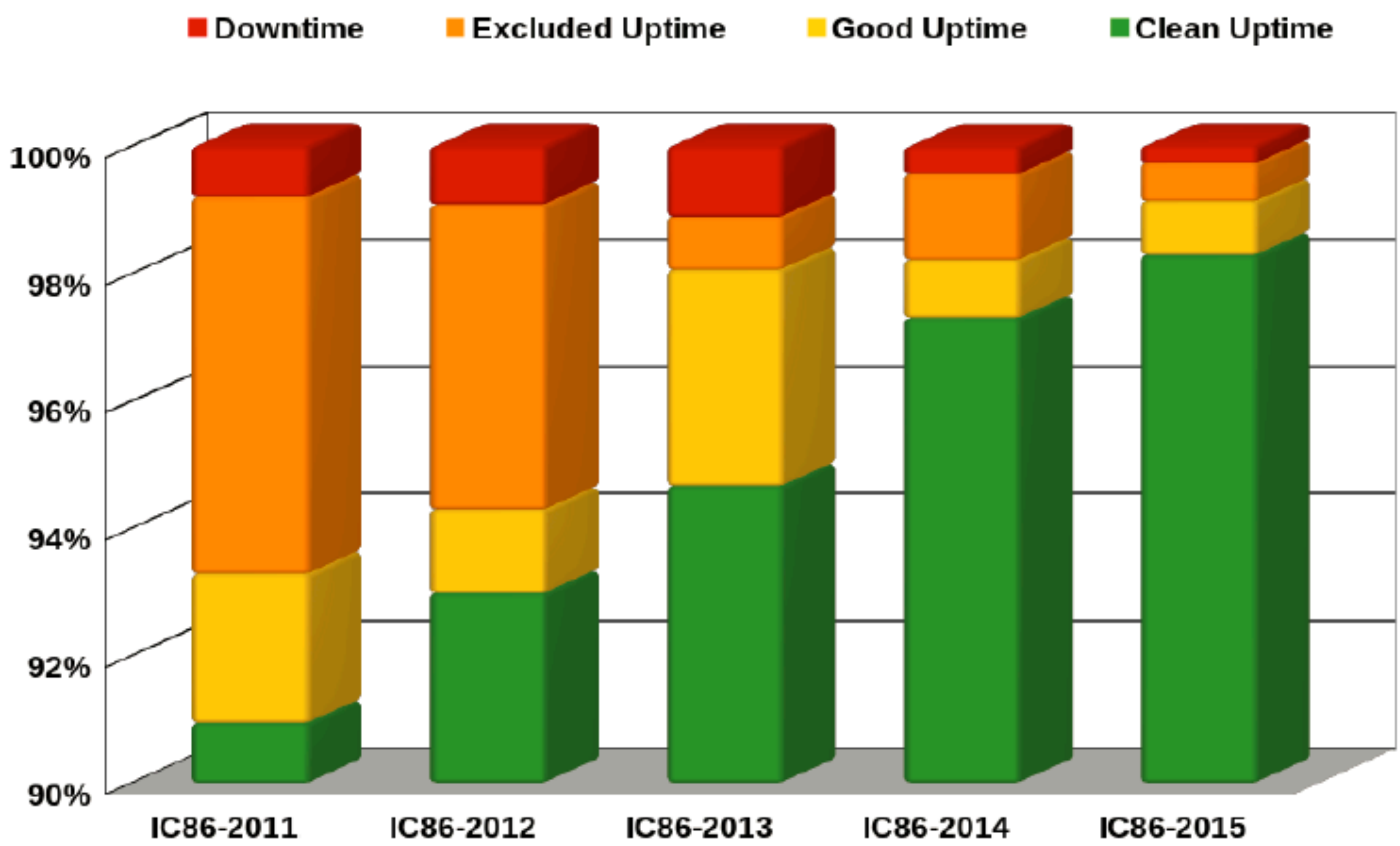
Another perfect week for IceCube! Hooray! A few minor hardware issues such as a predicted harddrive failure in ARA, and a misbehaving piece of RAM in the *i3live* machine, gave the winterovers something to do, but nothing serious, and nothing that impacted data-taking.

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

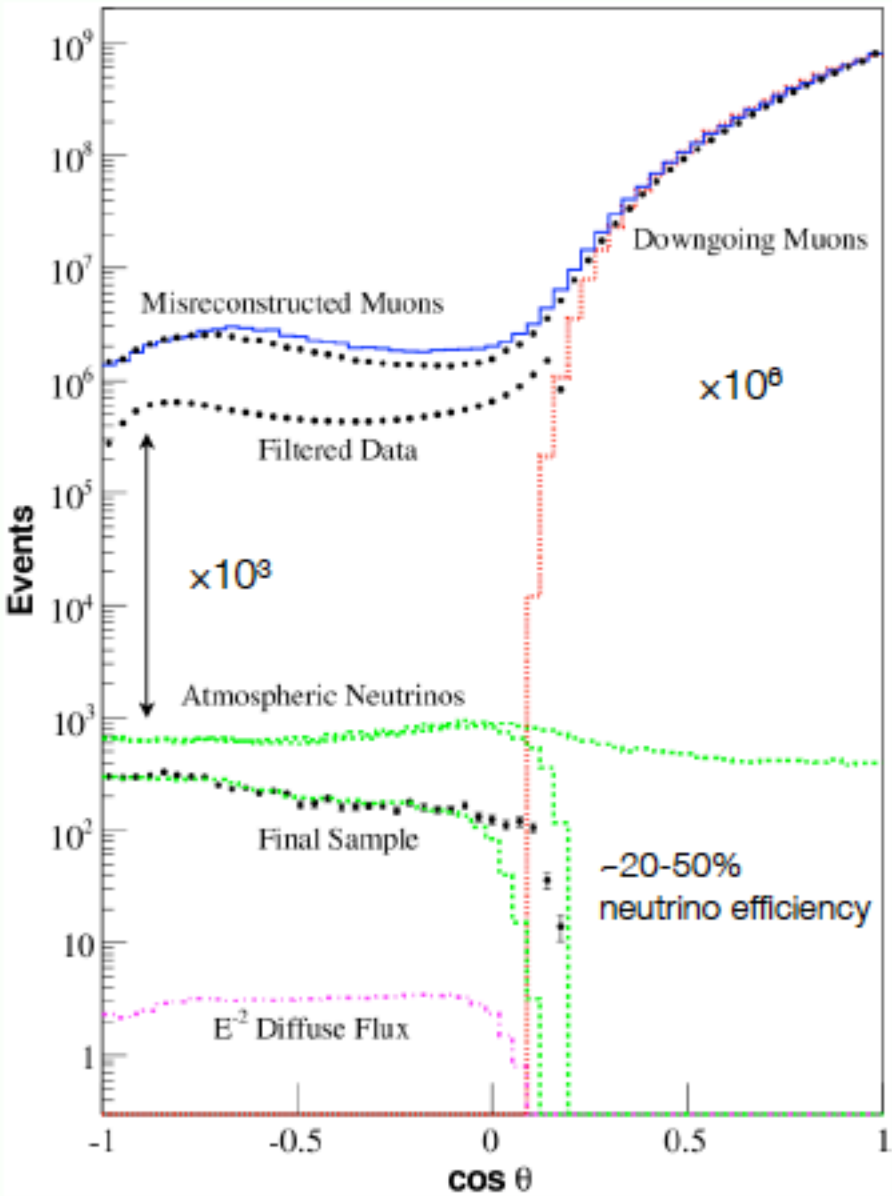
Uptime

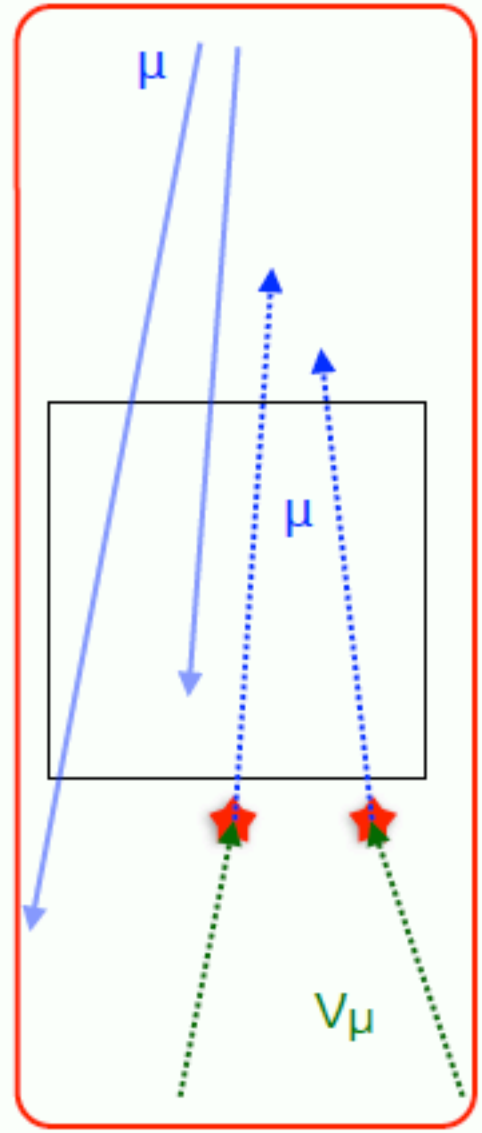


99.94%


Downtime
Excluded Uptime
Good Uptime
Clean Uptime
100%
98%
96%
94%
92%
90%
IC86-2011
IC86-2012
IC86-2013
IC86-2014
IC86-2015

through-going (tracks)

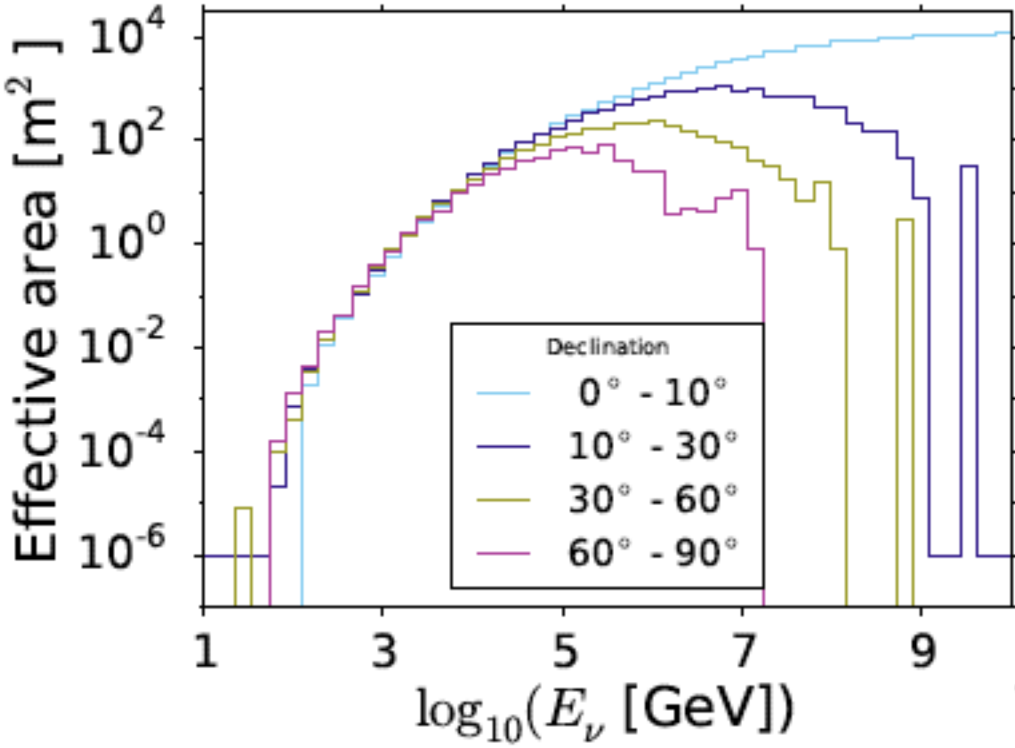




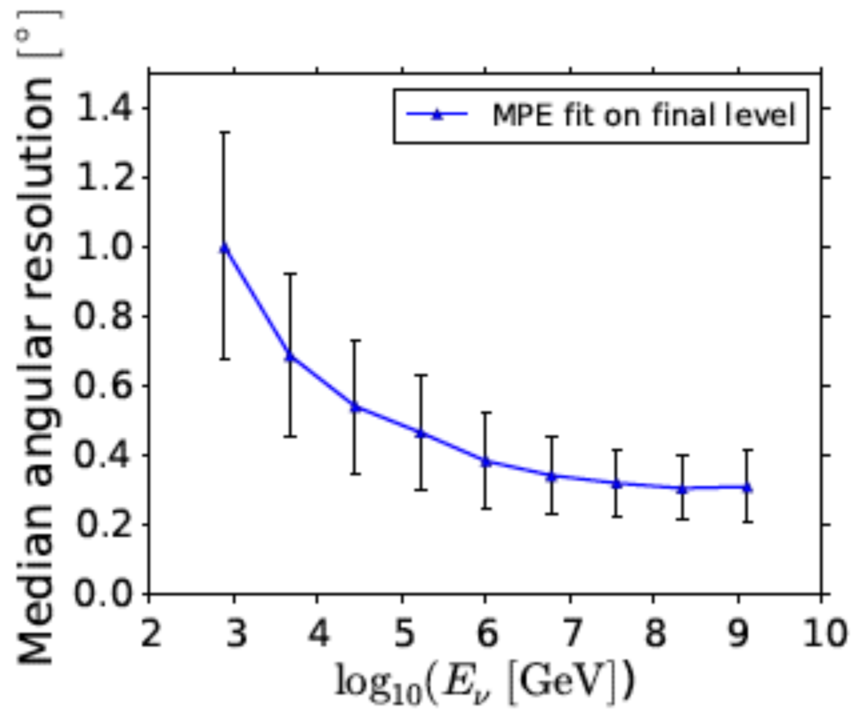
selection cuts for on-line numu extraction

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

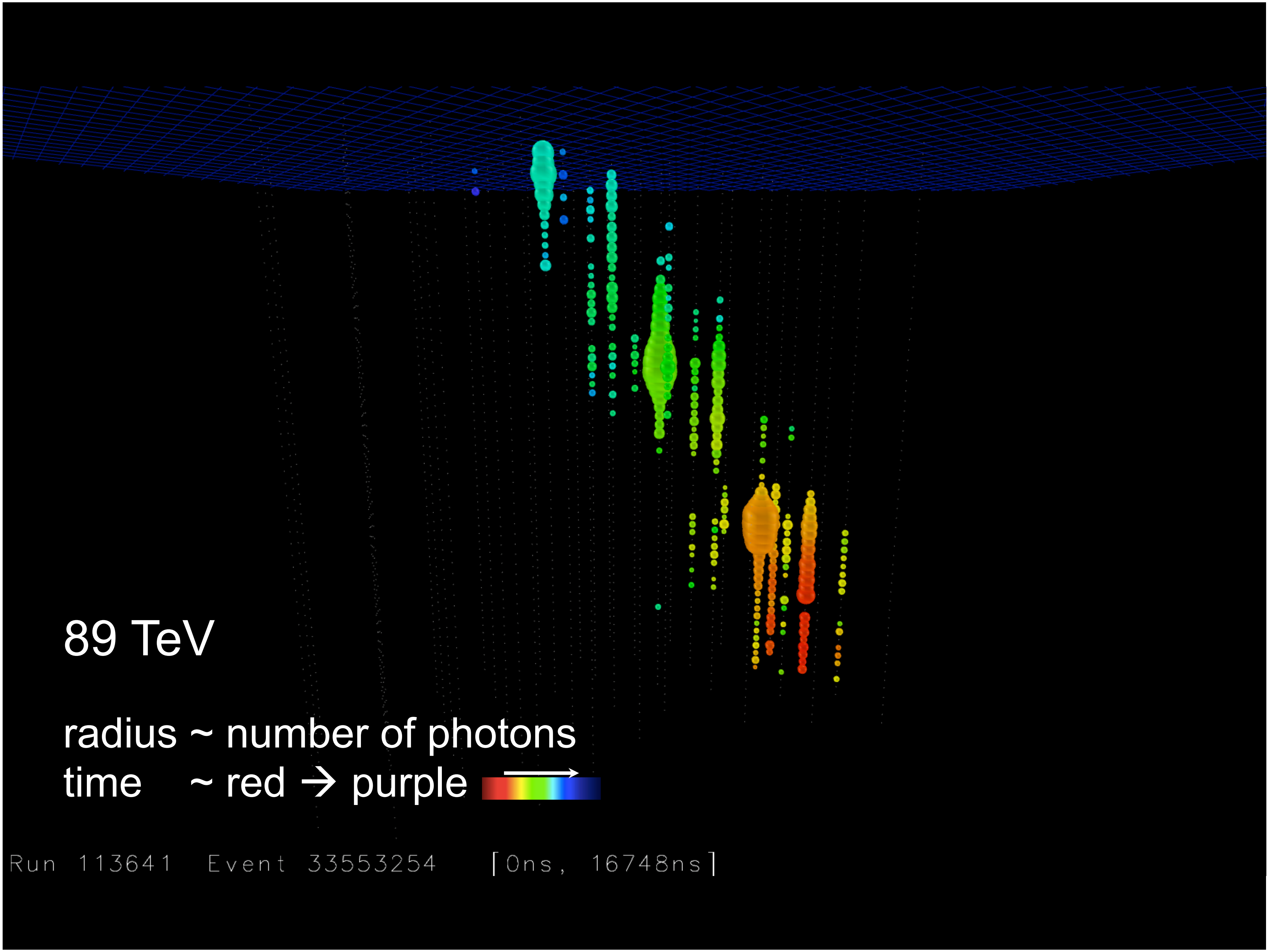
Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction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

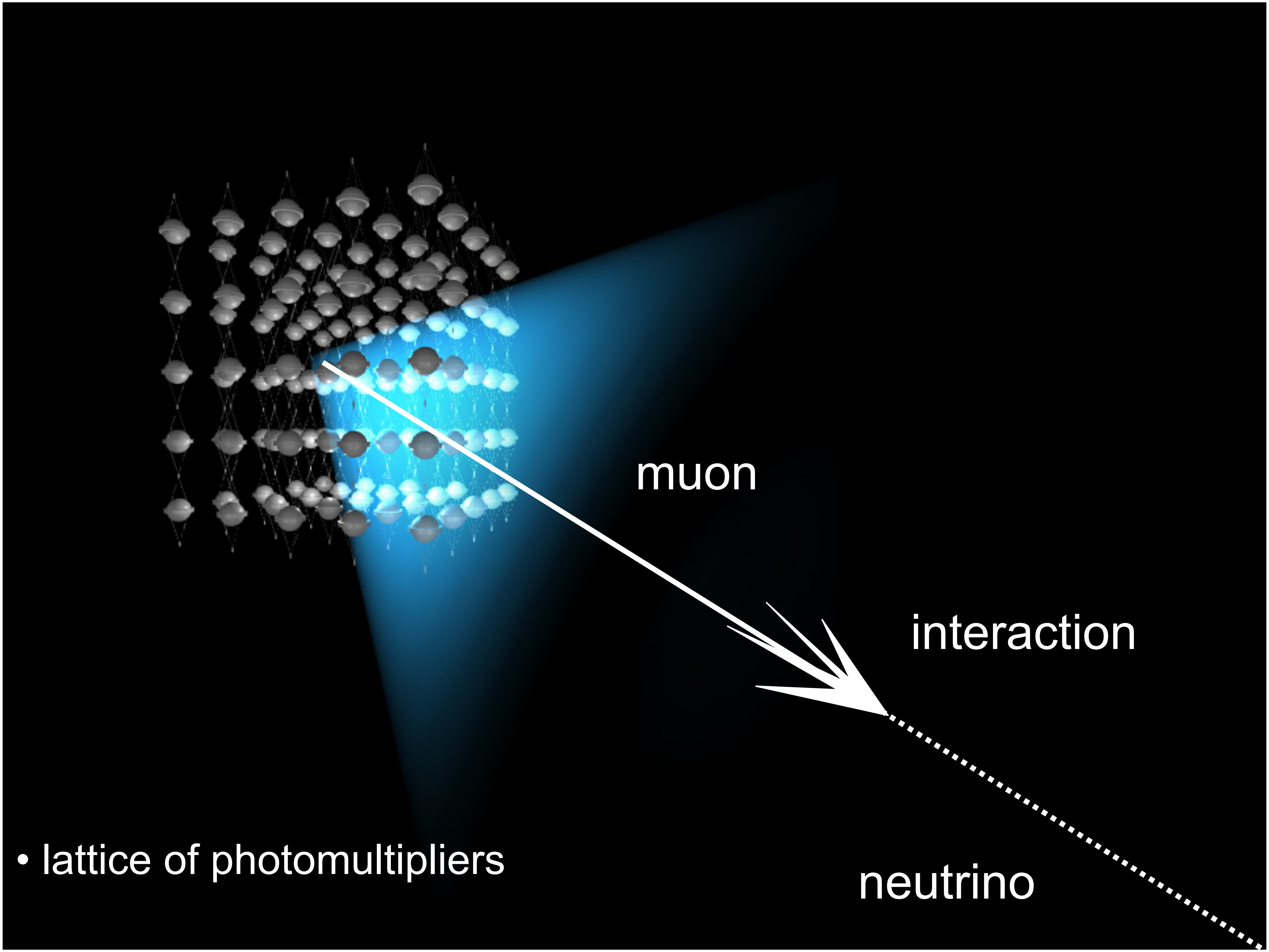


Effective area [m^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Declination
0° - 10°
10° - 30°
30° - 60°
60° - 90°
1
3
5
7
9
$\log_{10}(E_\nu$ [GeV])

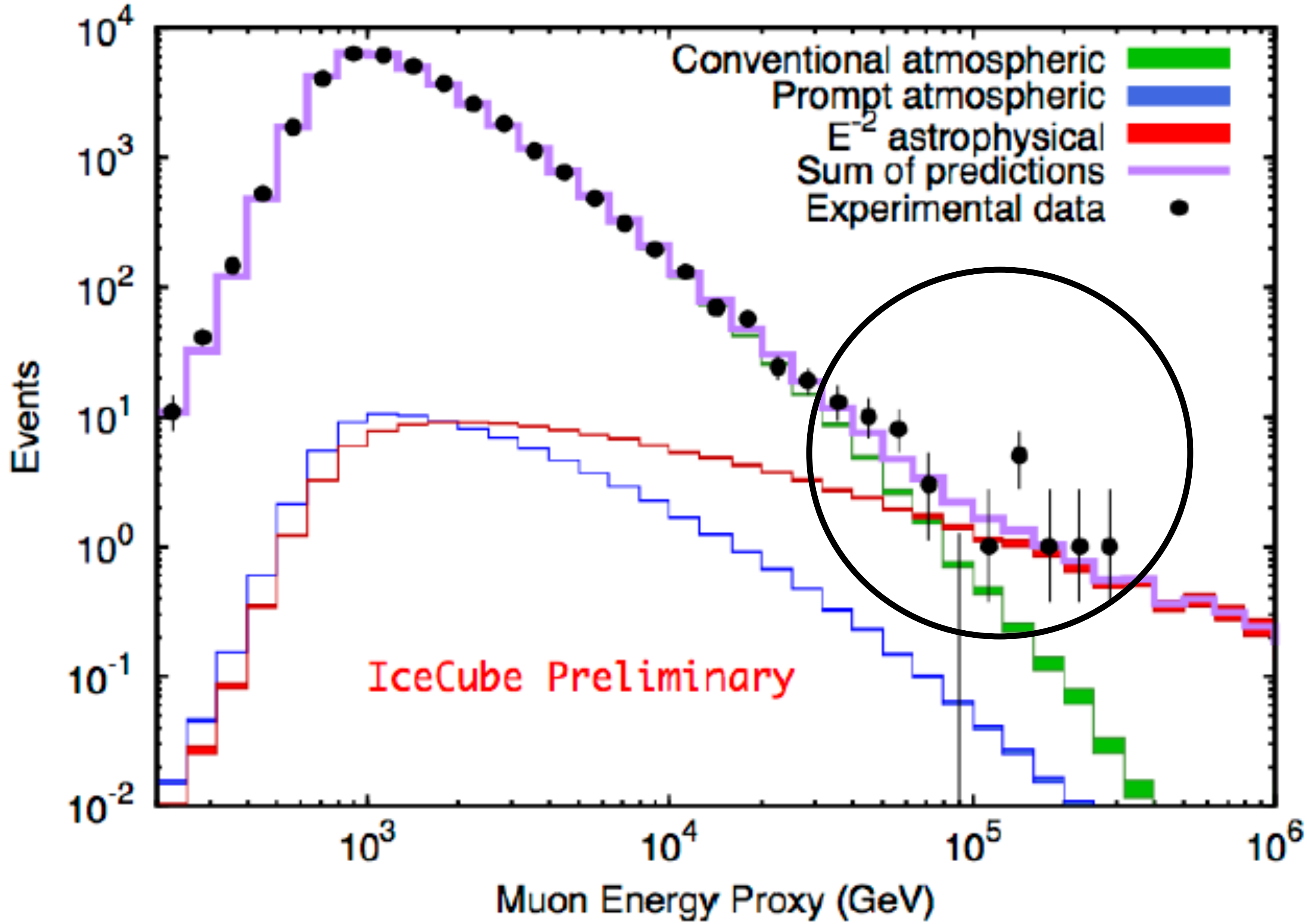


Median angular resolution [°]
MPE fit on final level
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])


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


muon
interaction
neutrino
• lattice of photomultipliers

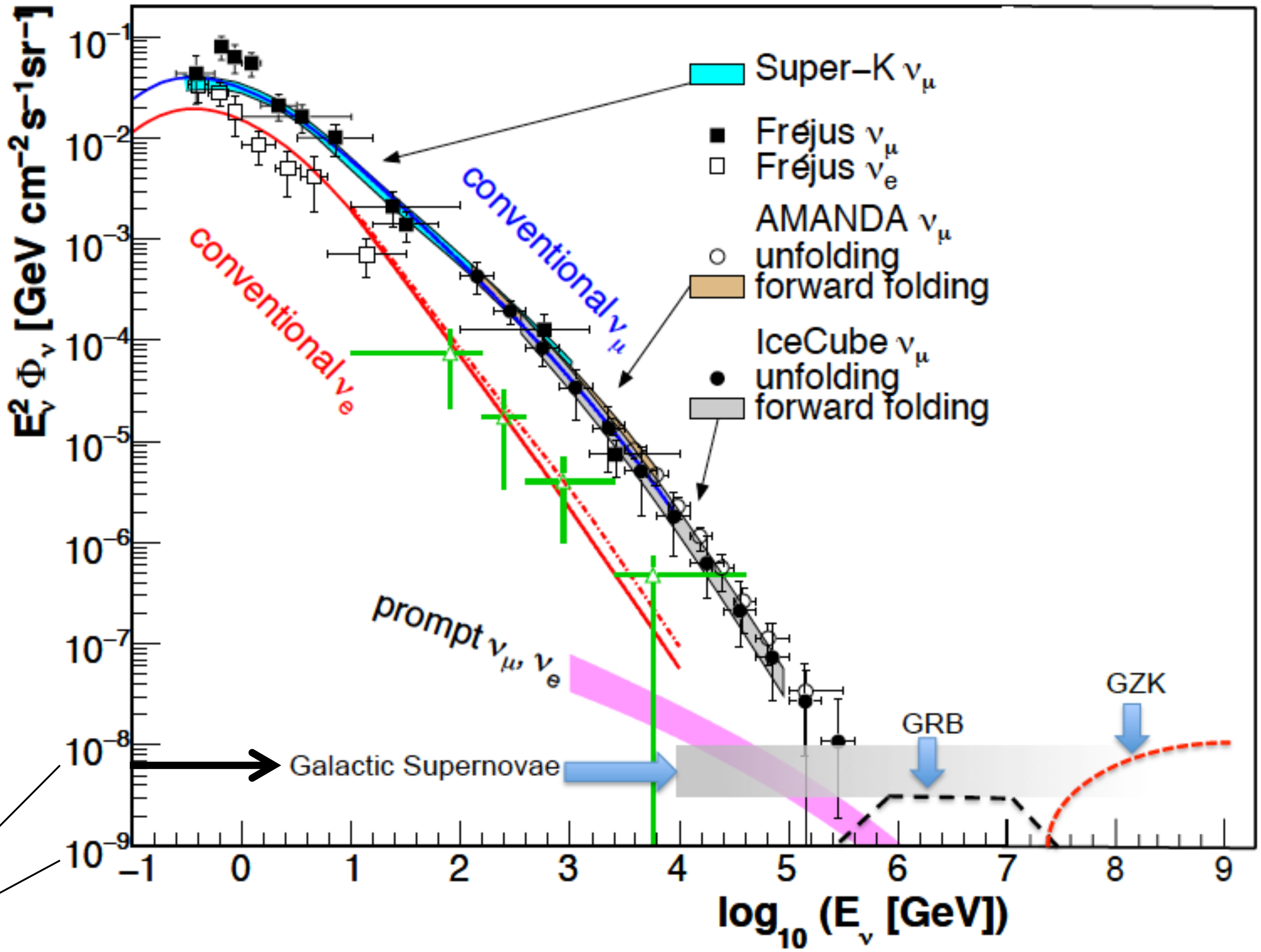
cosmic neutrinos in 2 years of data at 3.7 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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



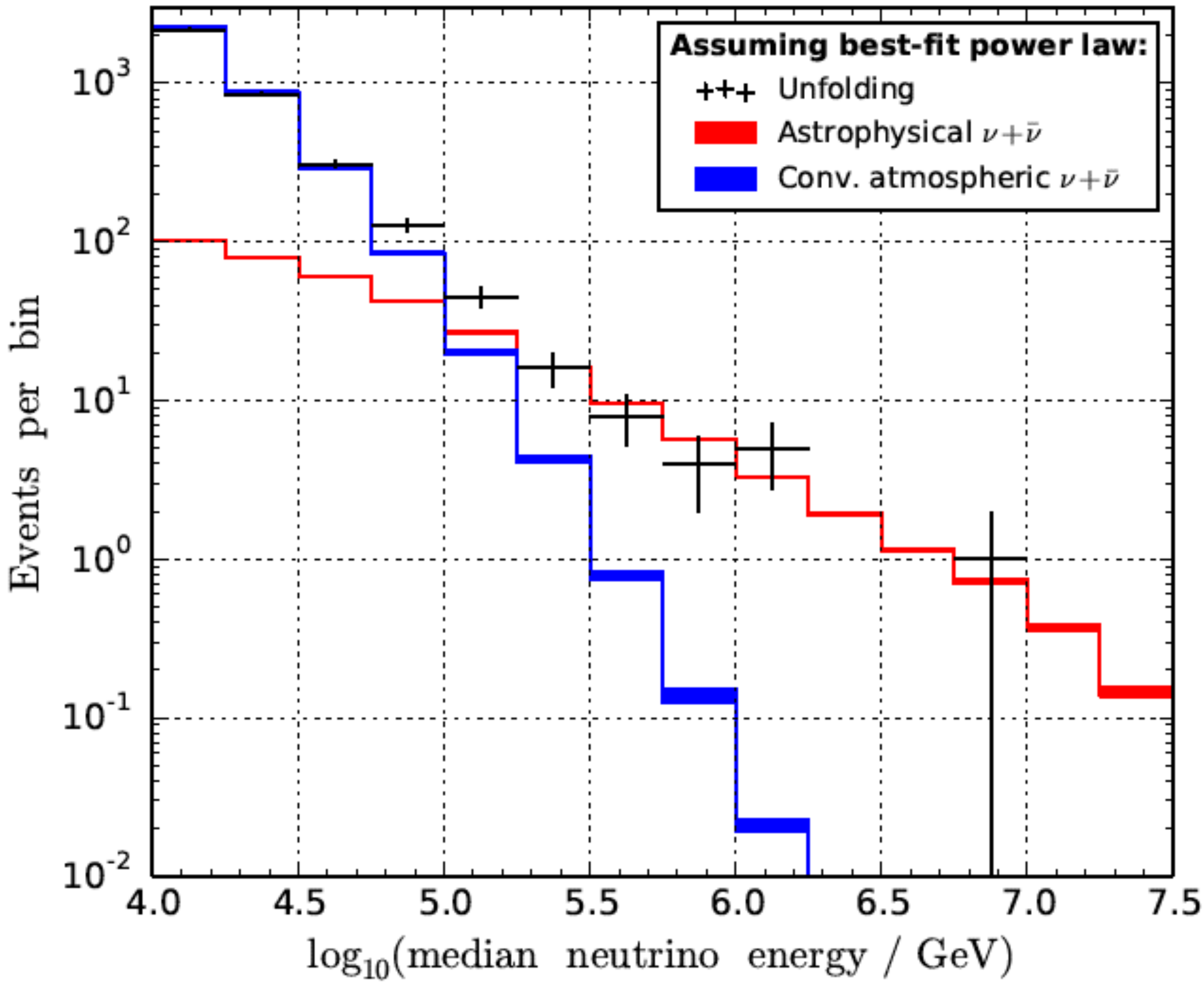
10—100 events per year for fully efficient detector

atmospheric

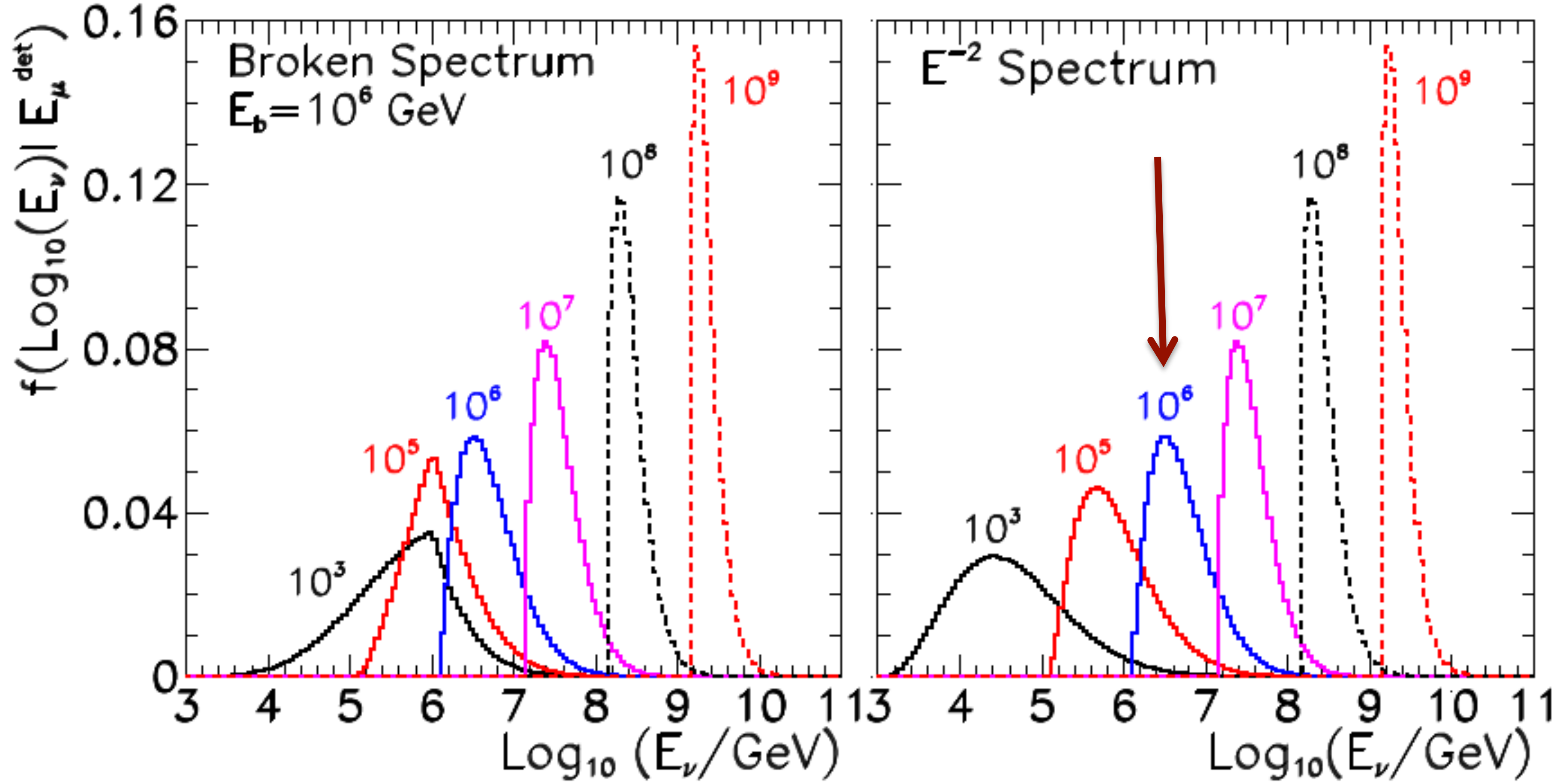
cosmic

100 TeV

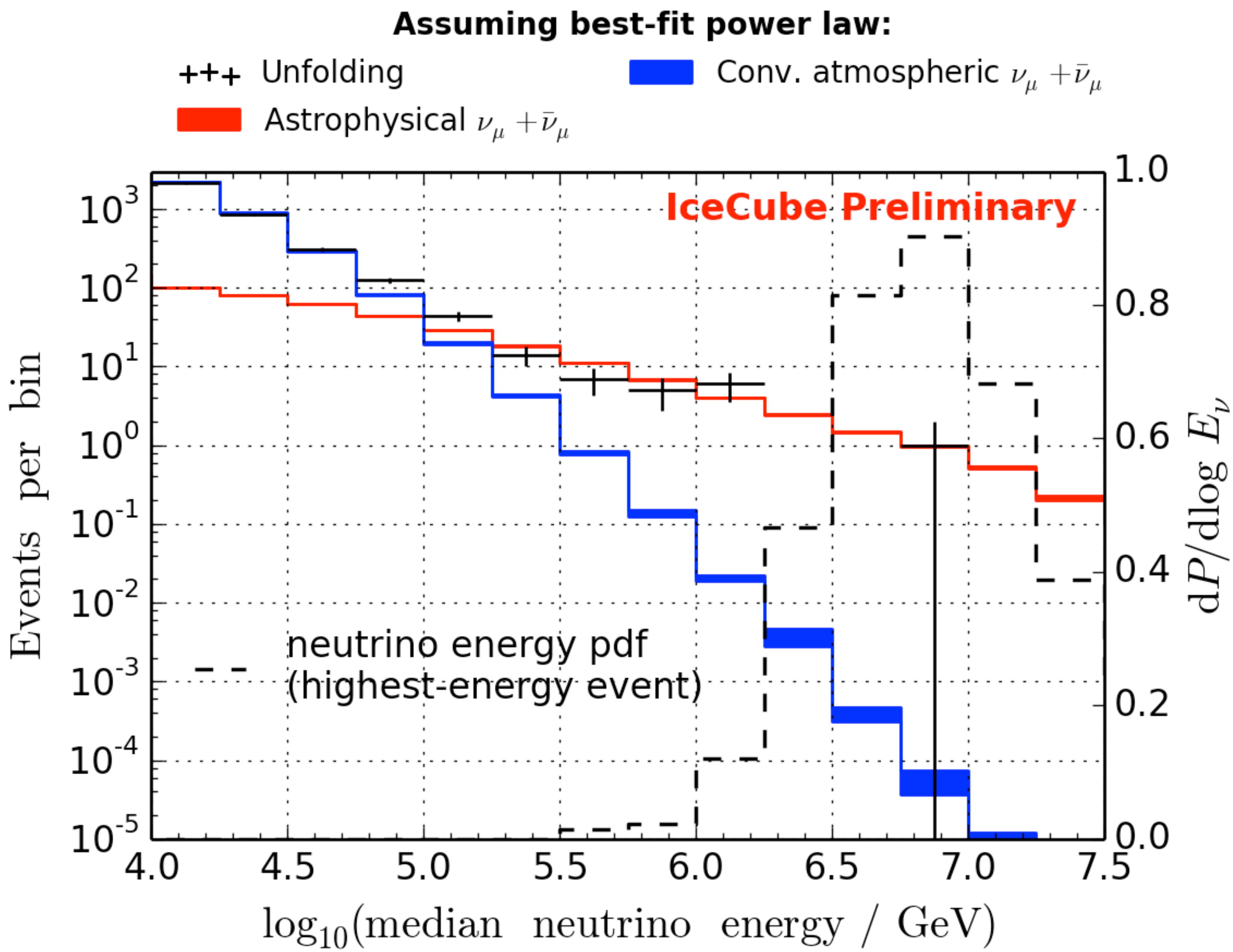
muon neutrinos through the Earth → 5.6 sigma

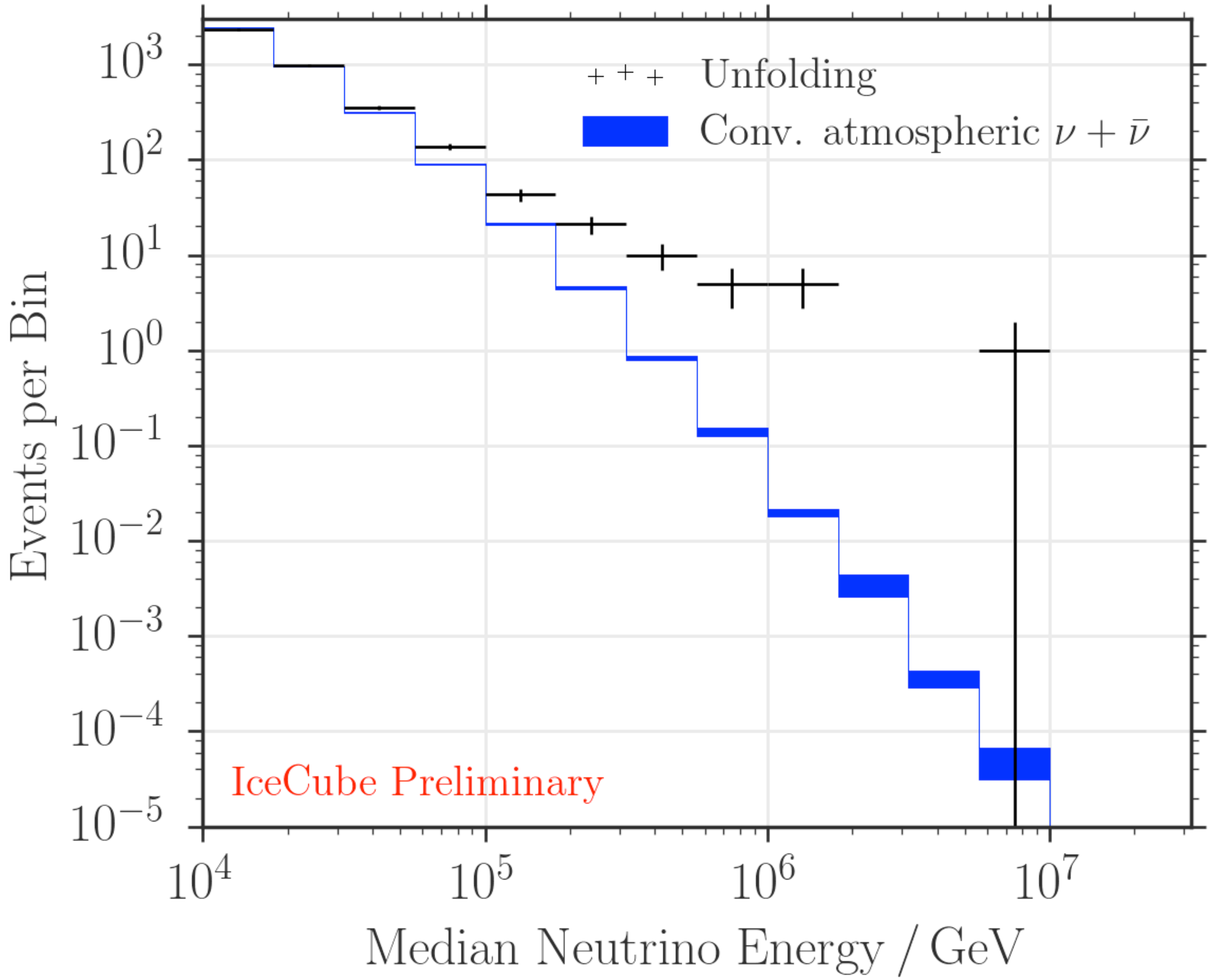


distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube

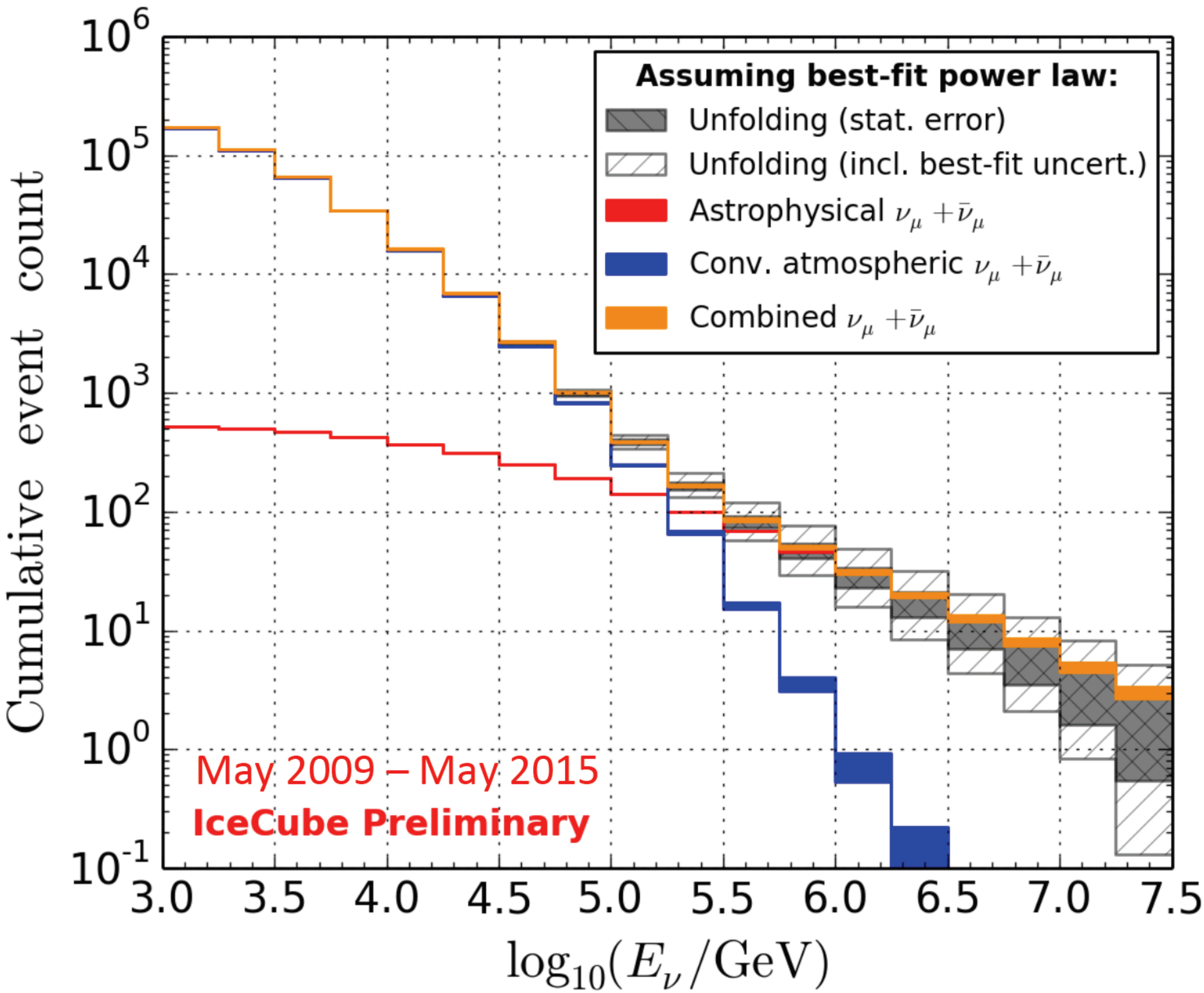


muon neutrinos through the Earth → 5.6 sigma



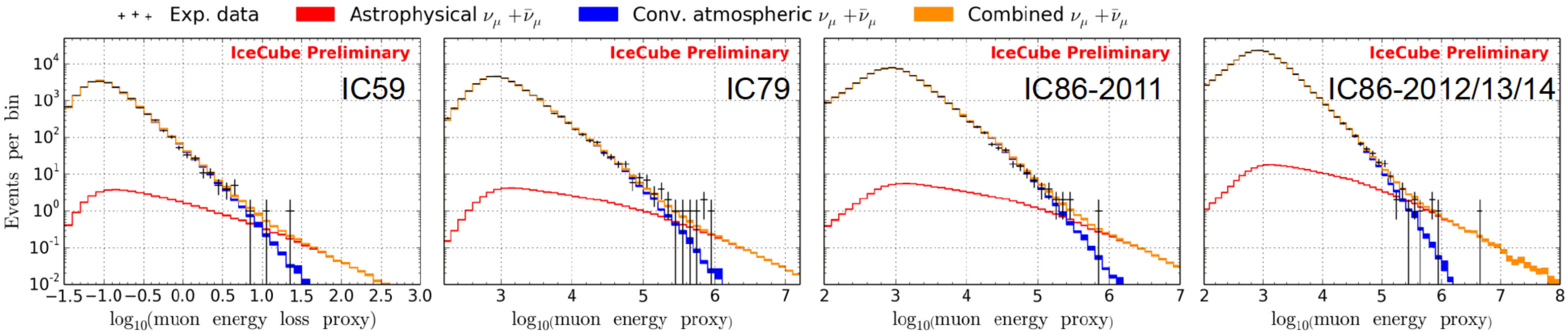


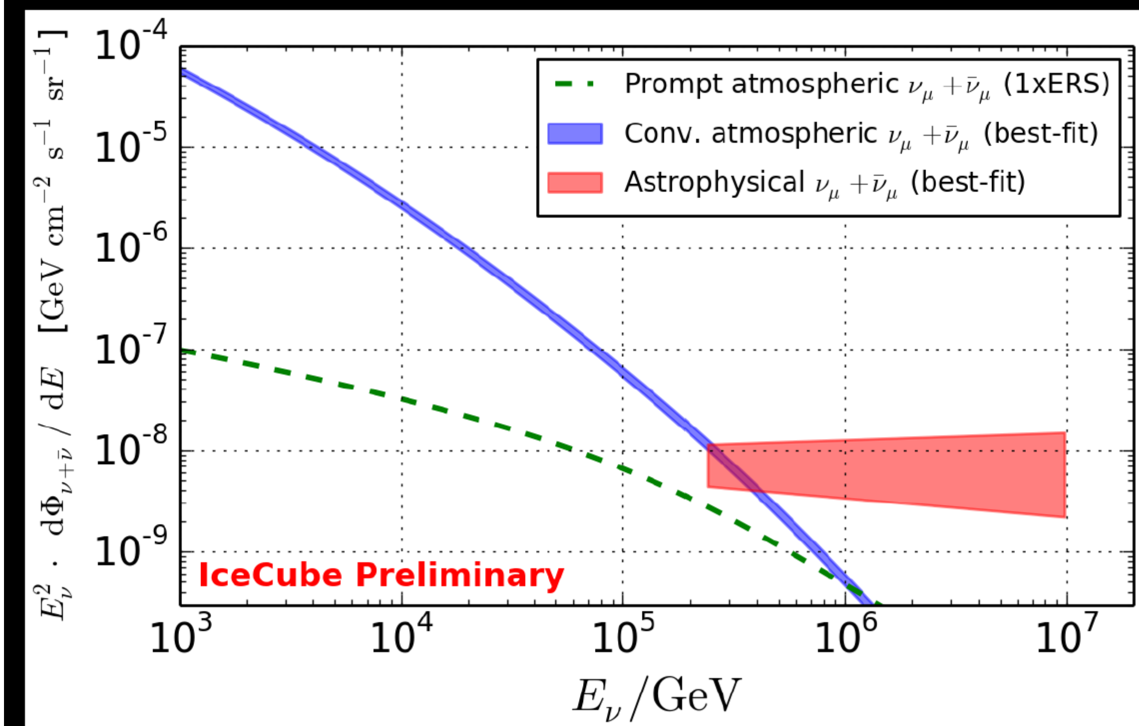
Unfolding
Conv. atmospheric $\nu + \bar{\nu}$
IceCube Preliminary
Events per Bin
Median Neutrino Energy / GeV
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^4
10^5
10^6
10^7



Assuming best-fit power law:
Unfolding (stat. error)
Unfolding (incl. best-fit uncert.)
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
Combined $\nu_\mu + \bar{\nu}_\mu$
May 2009 – May 2015
IceCube Preliminary
Cumulative event count
$\log_{10}(E_\nu/\mathrm{GeV})$
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5

after 7 years: 3.7 → 6 sigma





- **Best-fit astrophysical normalization:**

  0.97+.27-.25 $\times 10^{-18}\ \mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$

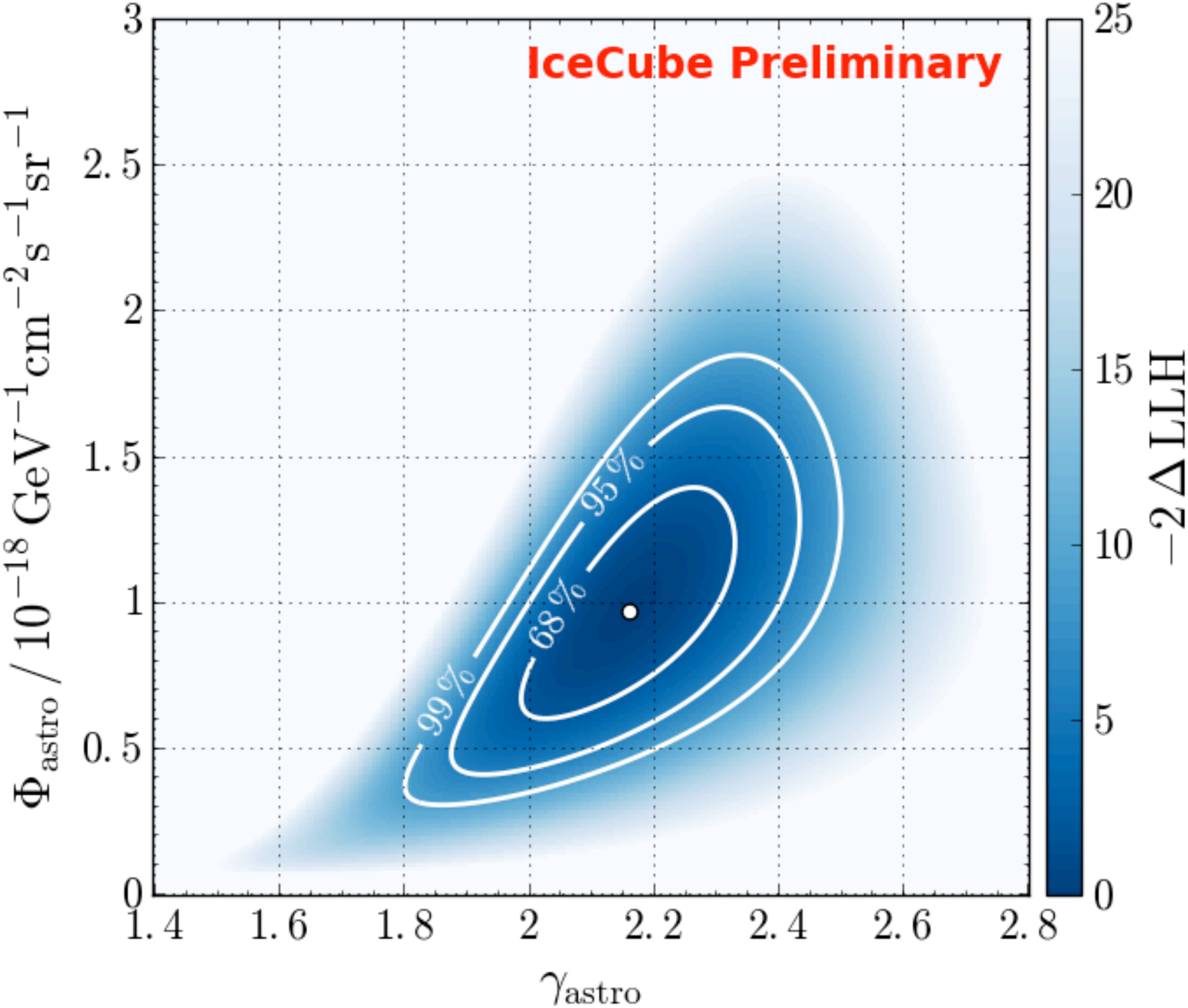
- **Best-fit spectral index:**

  γ_{astro} = 2.16 ± 0.11

- **Energy ranges:**

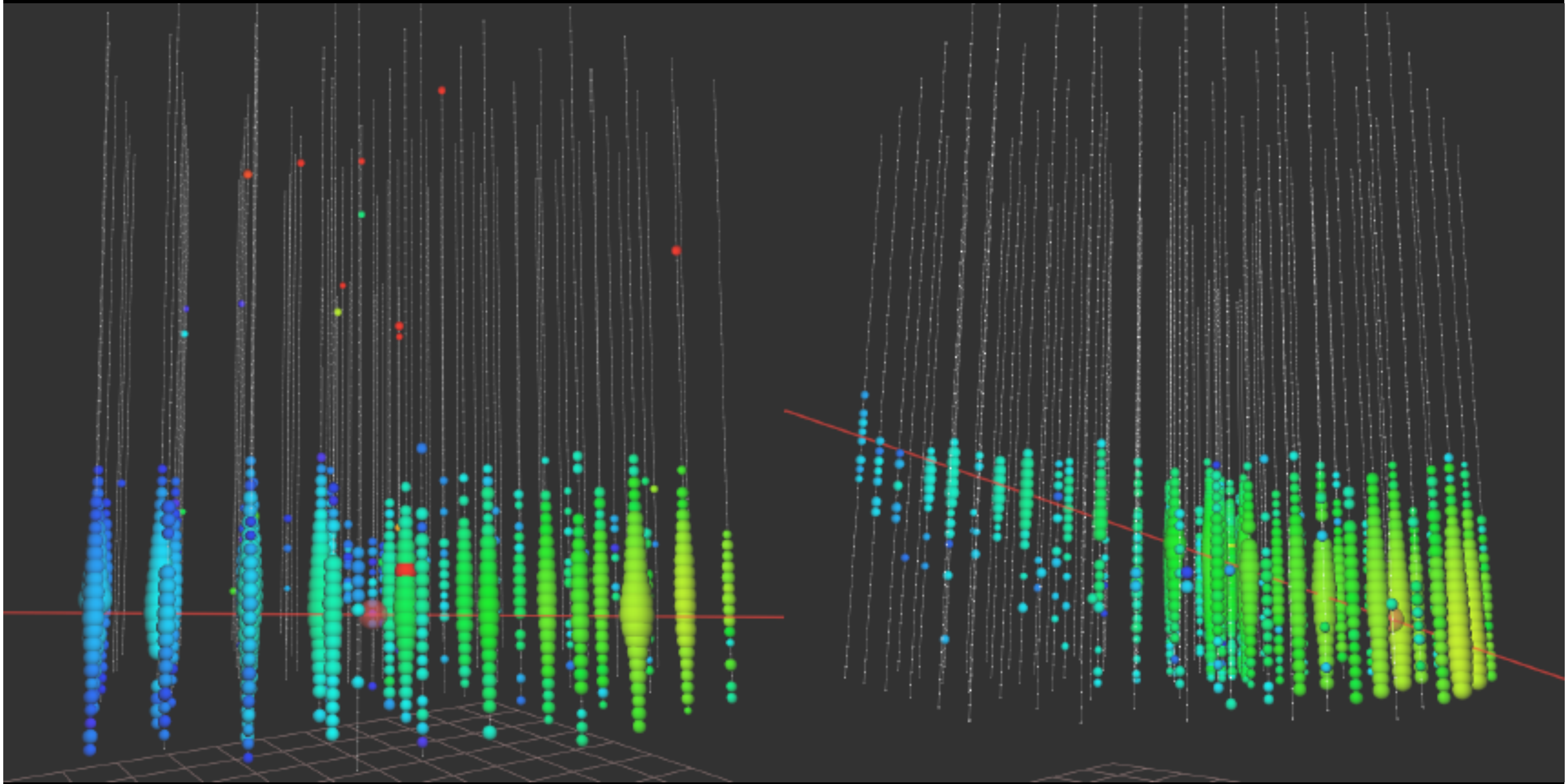
  240 TeV – 10 PeV

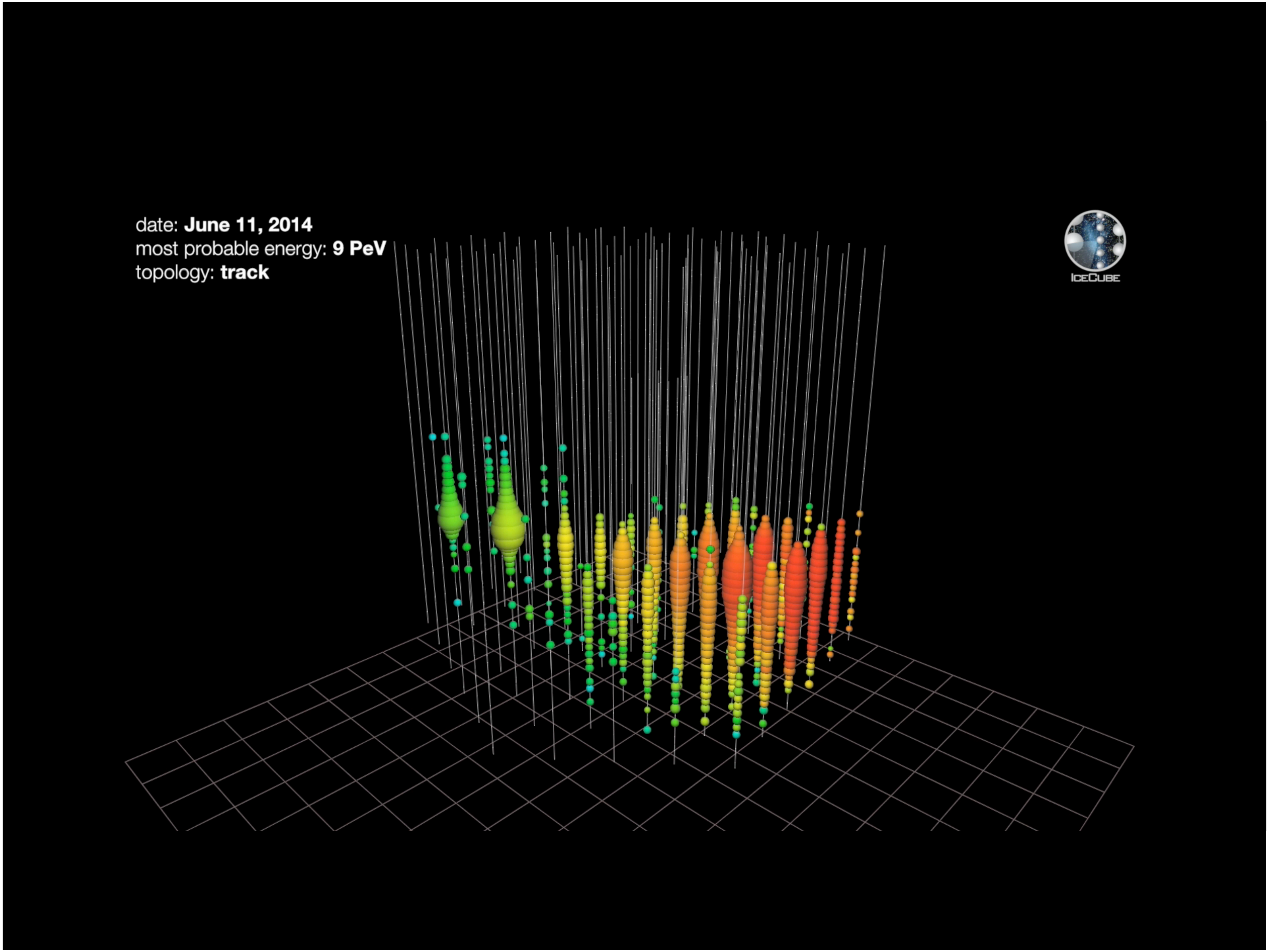
- Atmospheric-only hypothesis excluded by 6.0σ

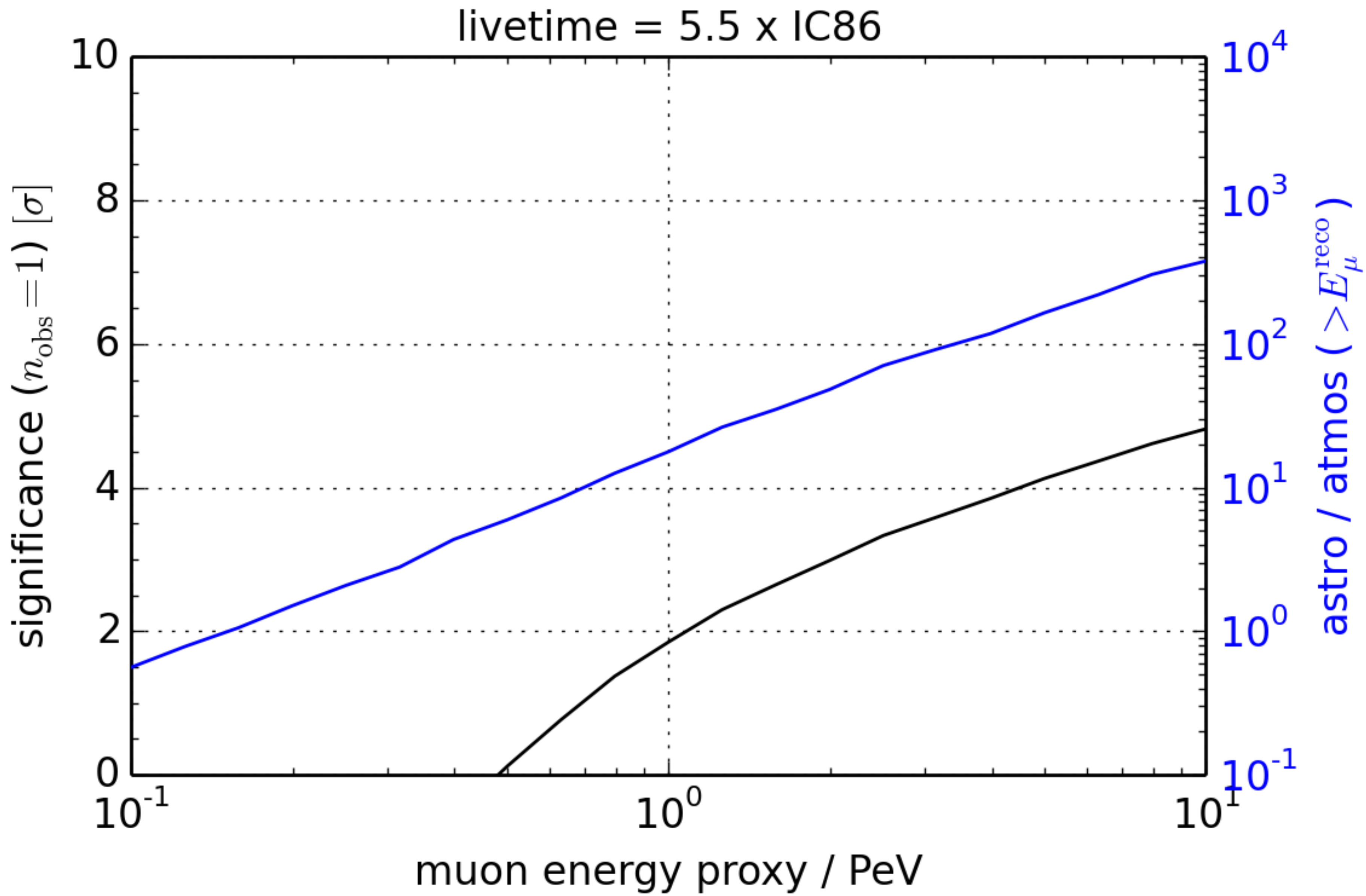

IceCube Preliminary
99 %
95 %
68 %
$\Phi_{\mathrm{astro}}\,/\,10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
γ_{astro}
$-2\,\Delta\,\mathrm{LLH}$
0
0.5
1
1.5
2
2.5
3
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
0
5
10
15
20
25

highest energy muon energy observed: 560 TeV

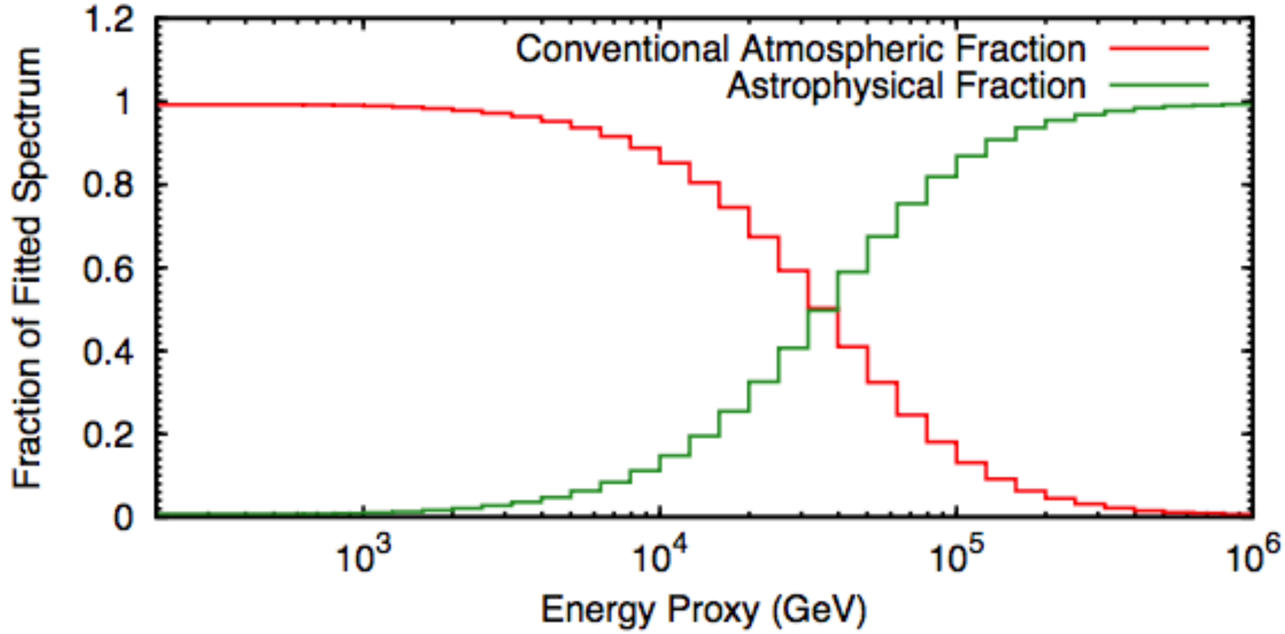
→ PeV ν_μ



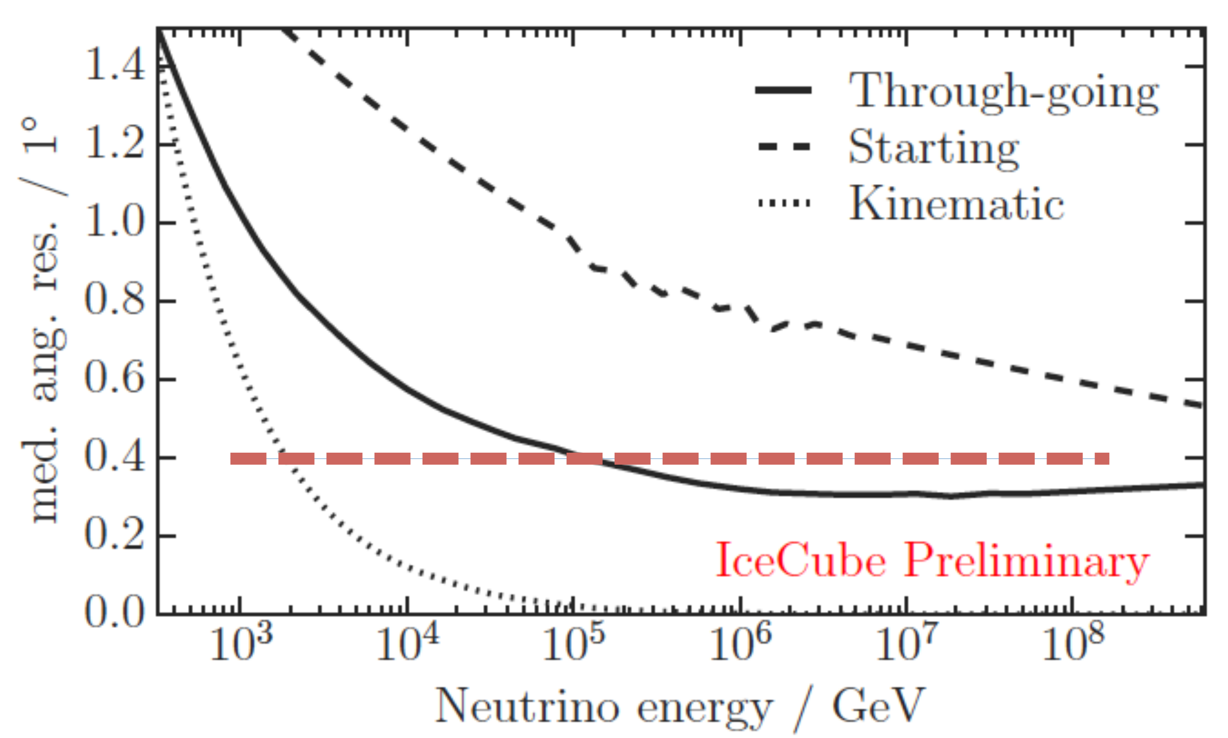

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube


livetime = 5.5 x IC86
significance ($n_{\mathrm{obs}}=1$) [σ]
astro / atmos ($>E_\mu^{\mathrm{reco}}$)
muon energy proxy / PeV
0
2
4
6
8
10
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

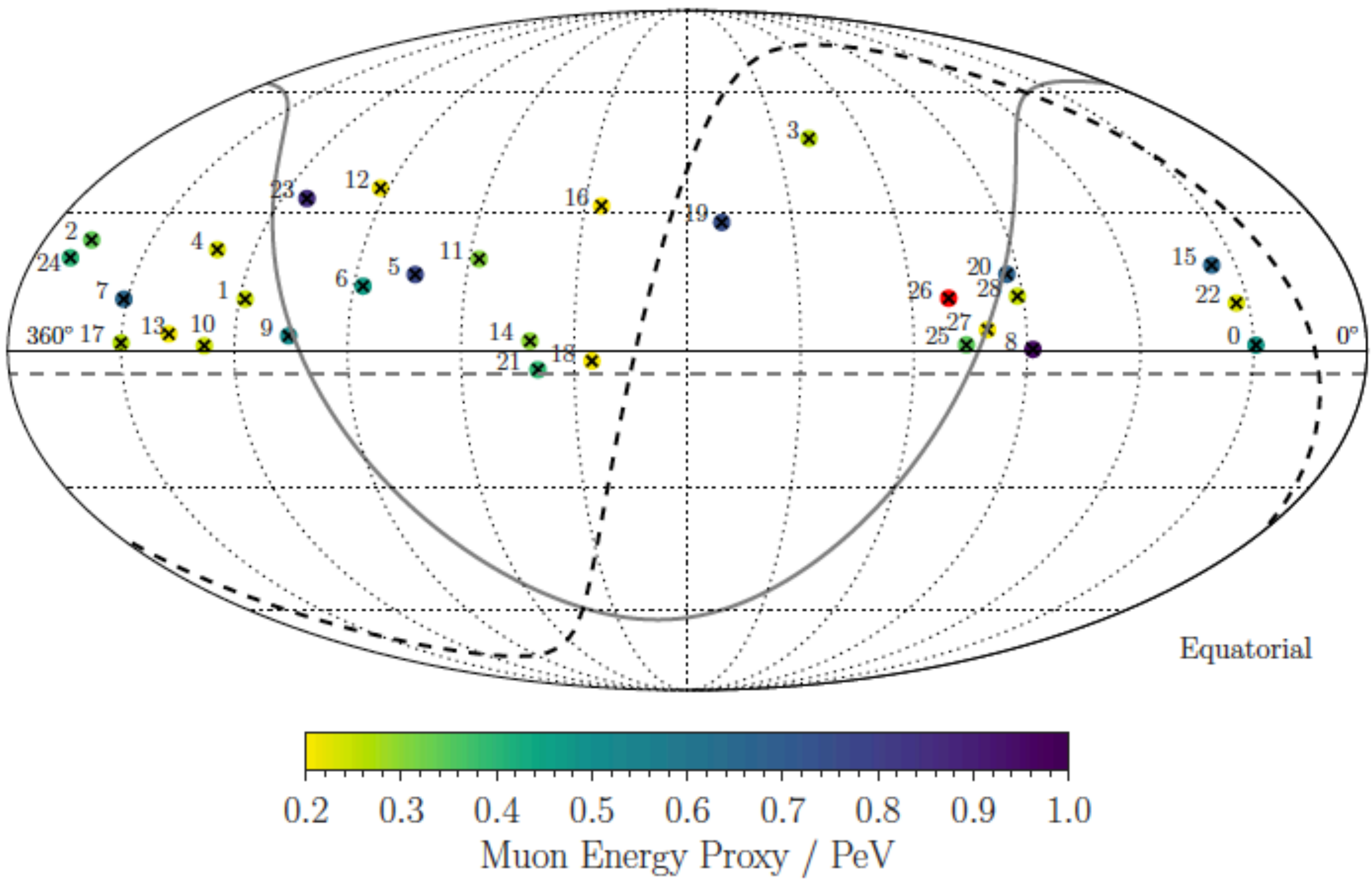
Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5

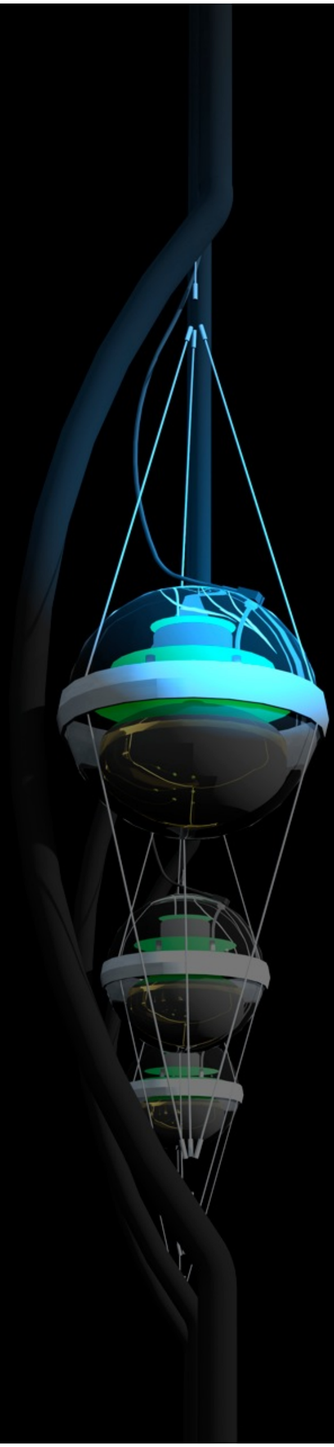


astronomy here: through-going muons with resolution 0.2~0.4^0



highest energy ν_μ: astronomy with best resolution !





IceCube: the discovery of cosmic neutrinos

francis halzen

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

IceCube.wisc.edu

cosmic rays interact with the microwave background

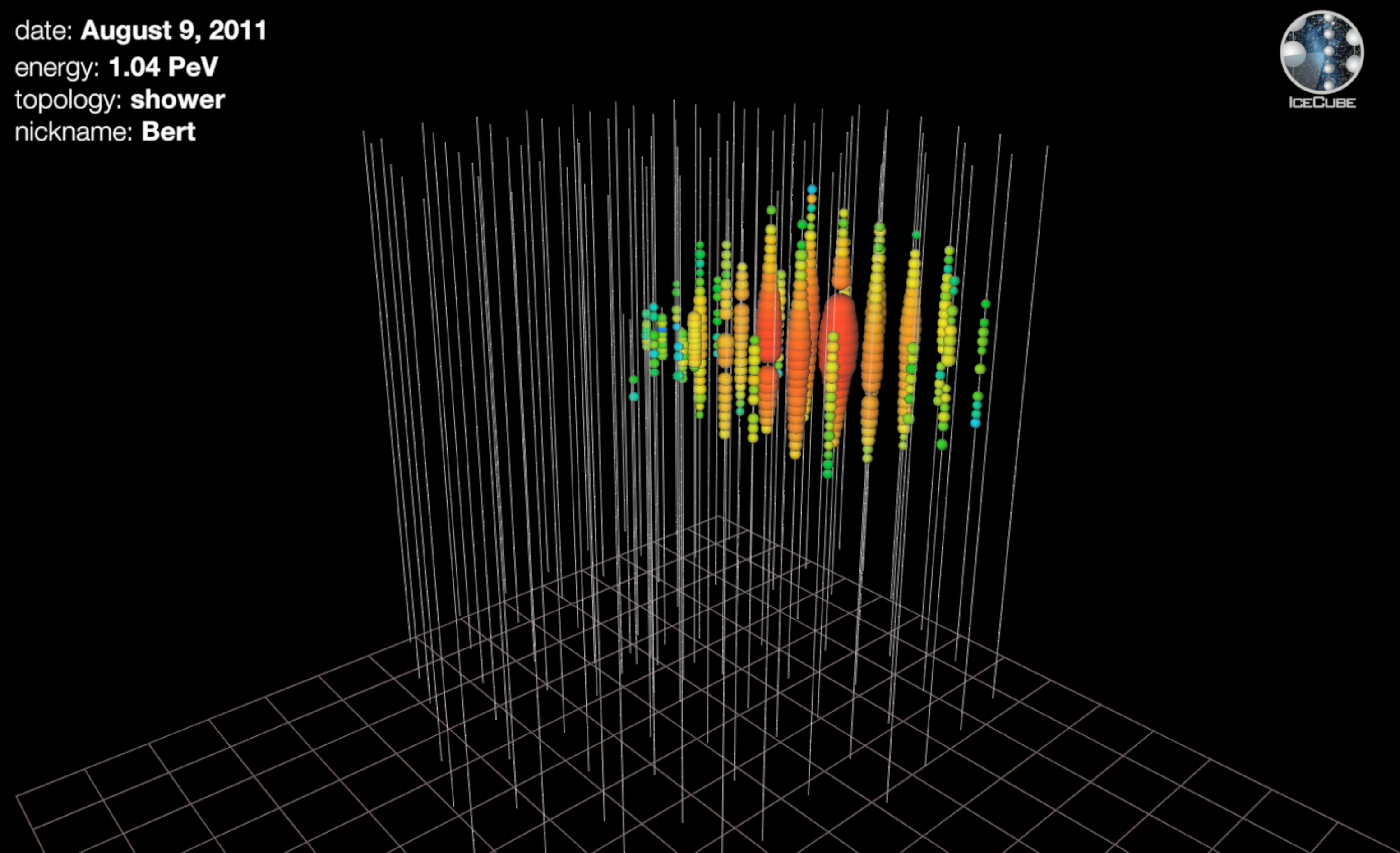
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

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

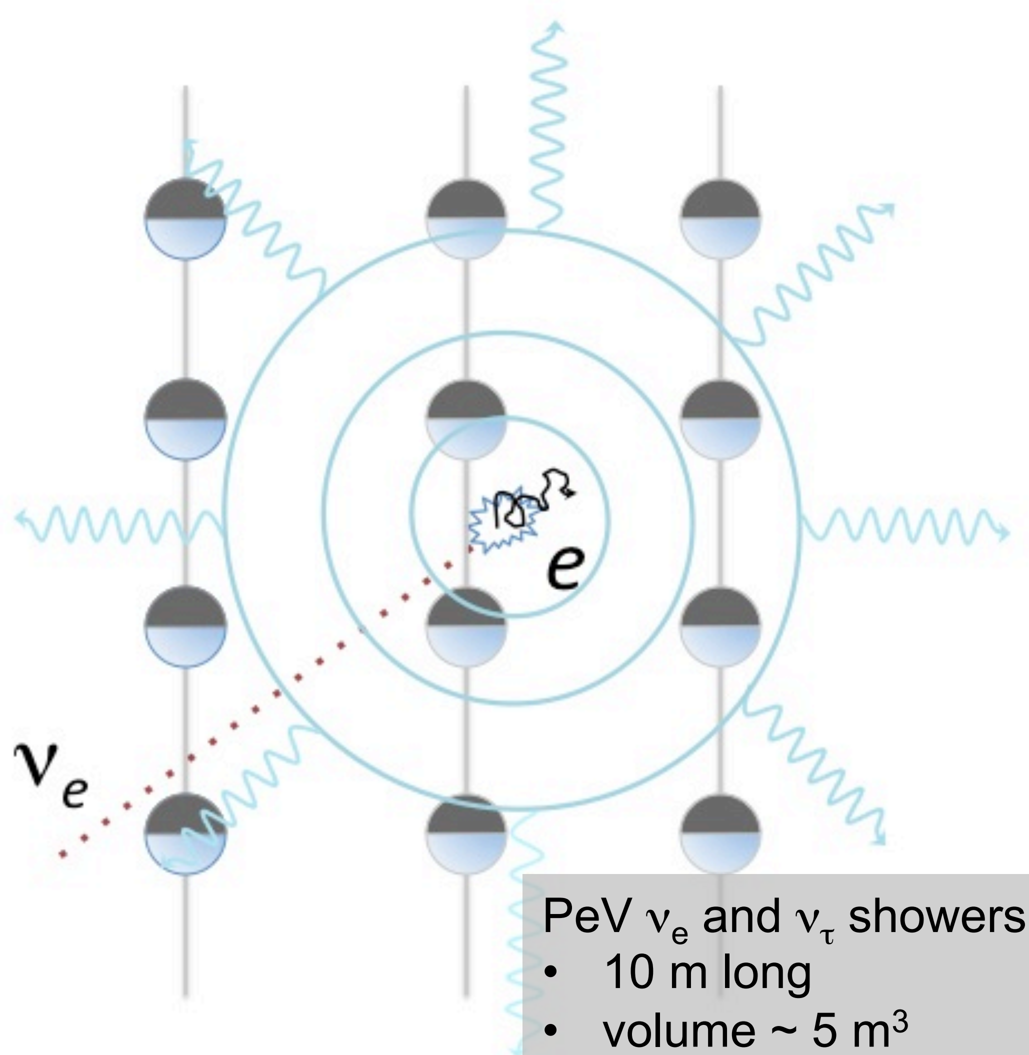
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

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

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

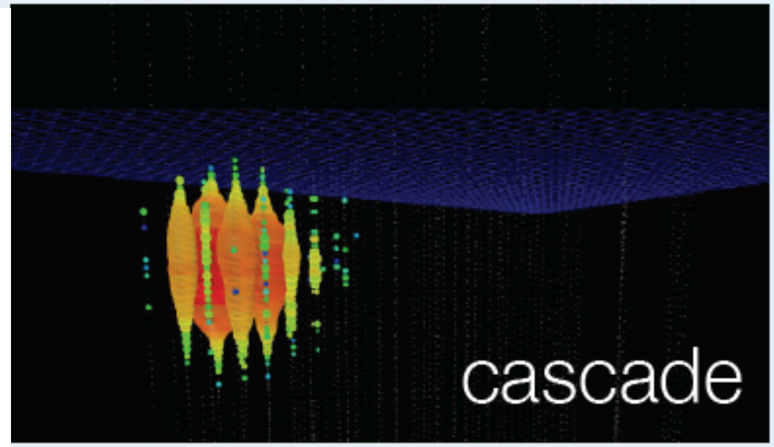


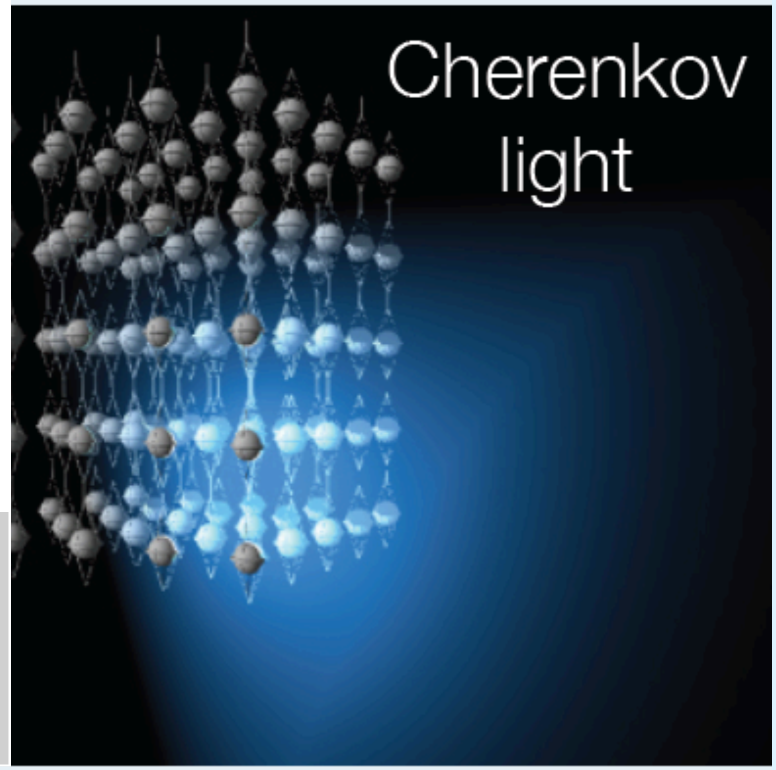
tracks and showers

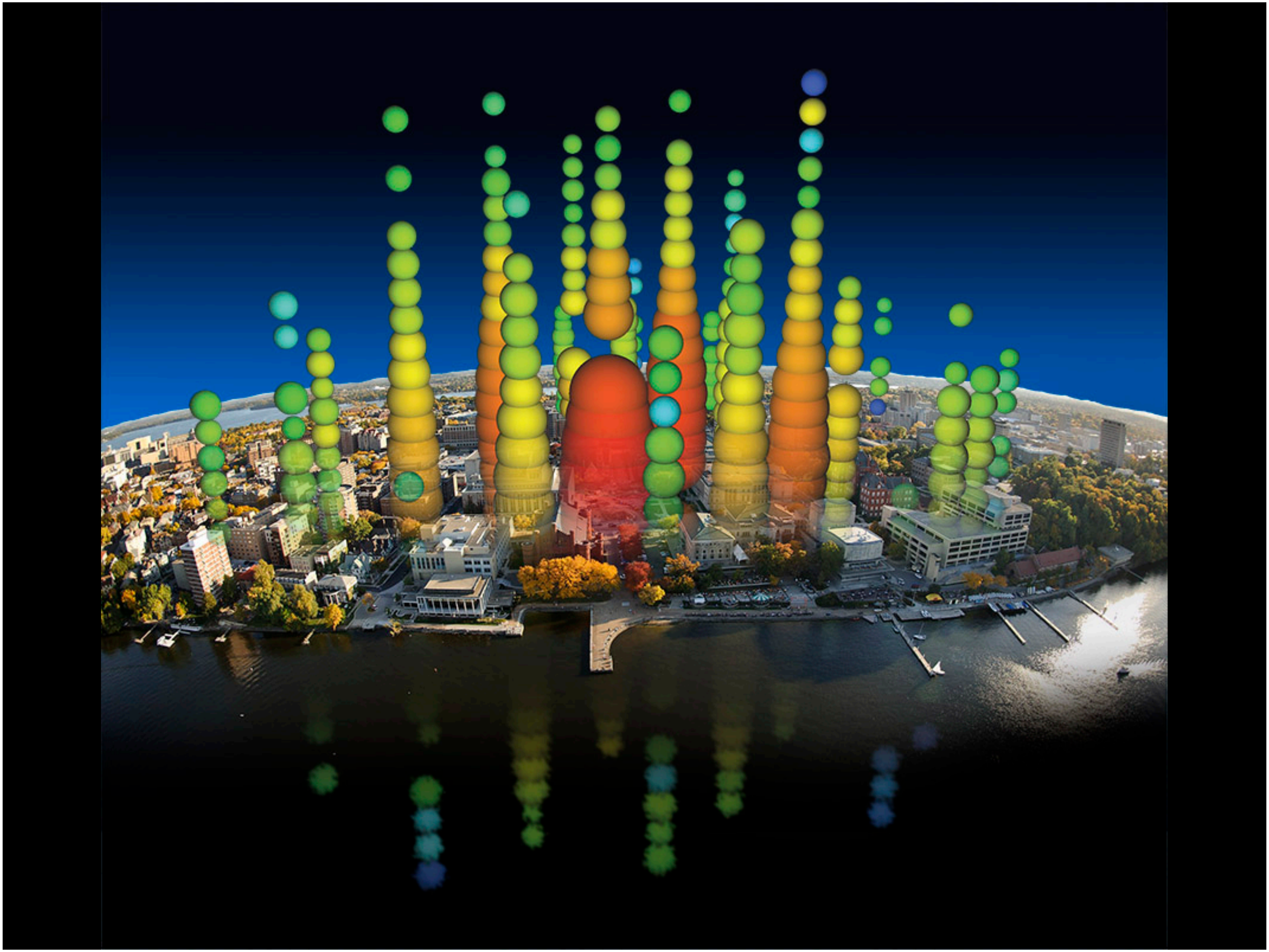


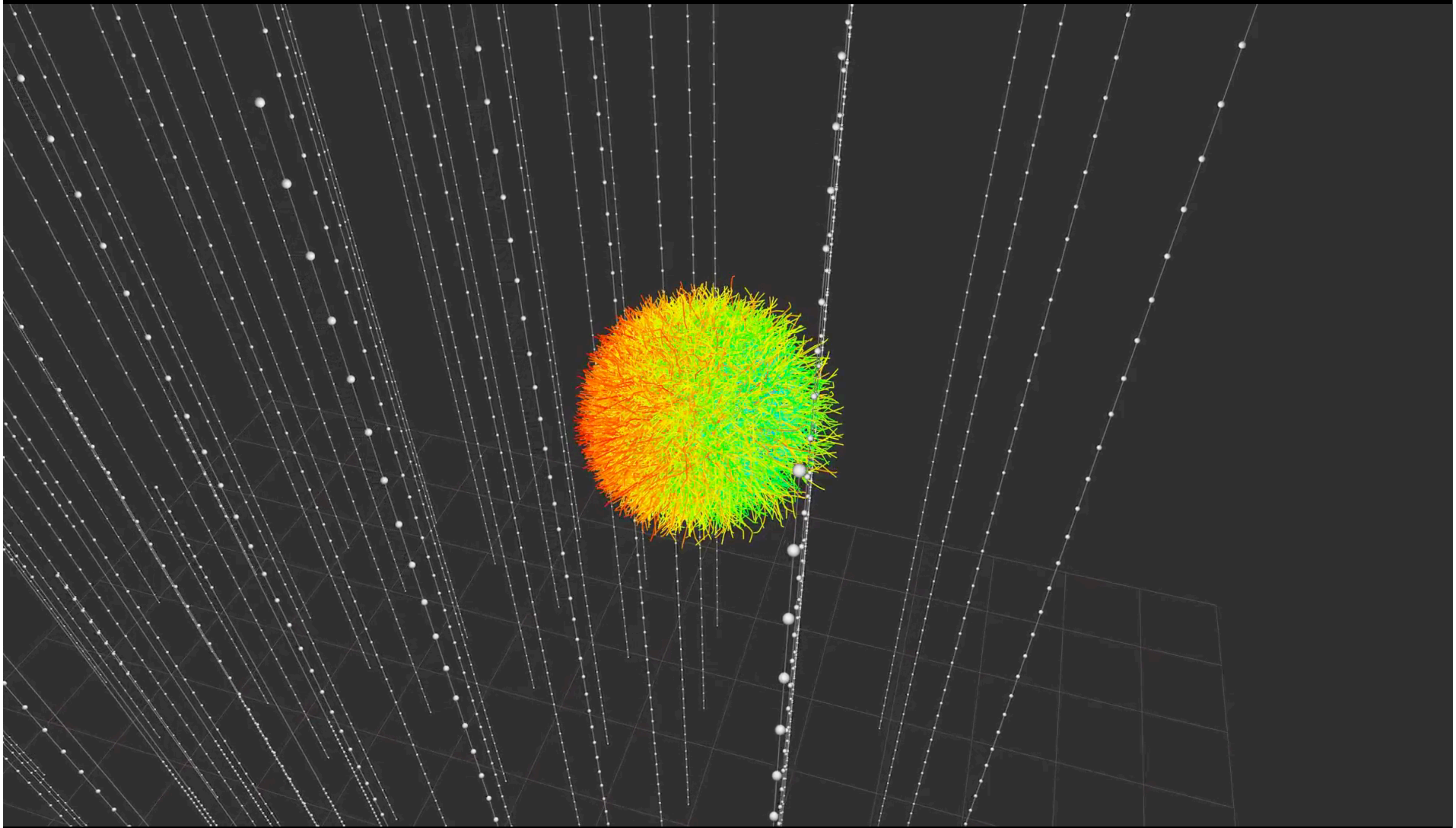
PeV ν_e and ν_τ showers:

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



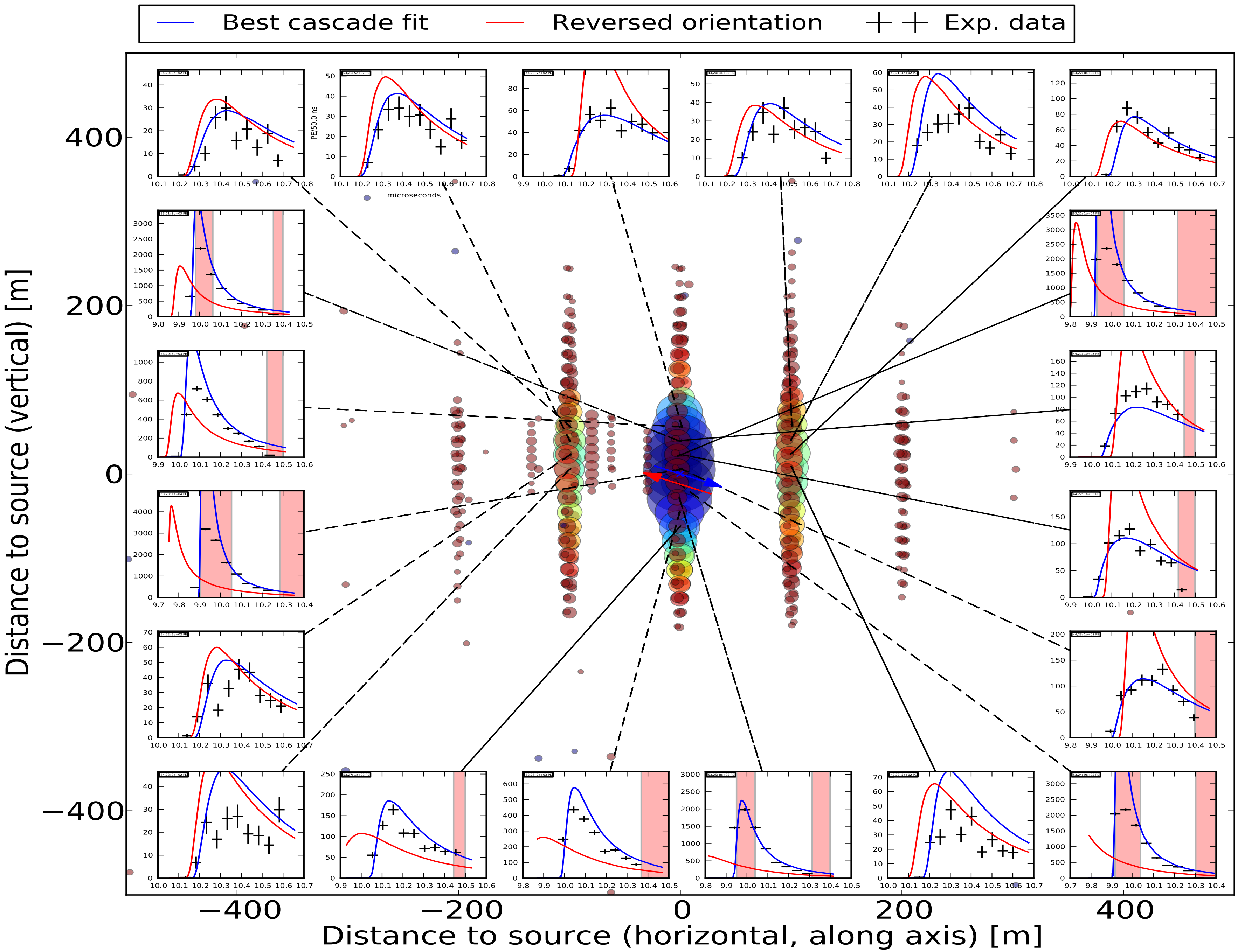






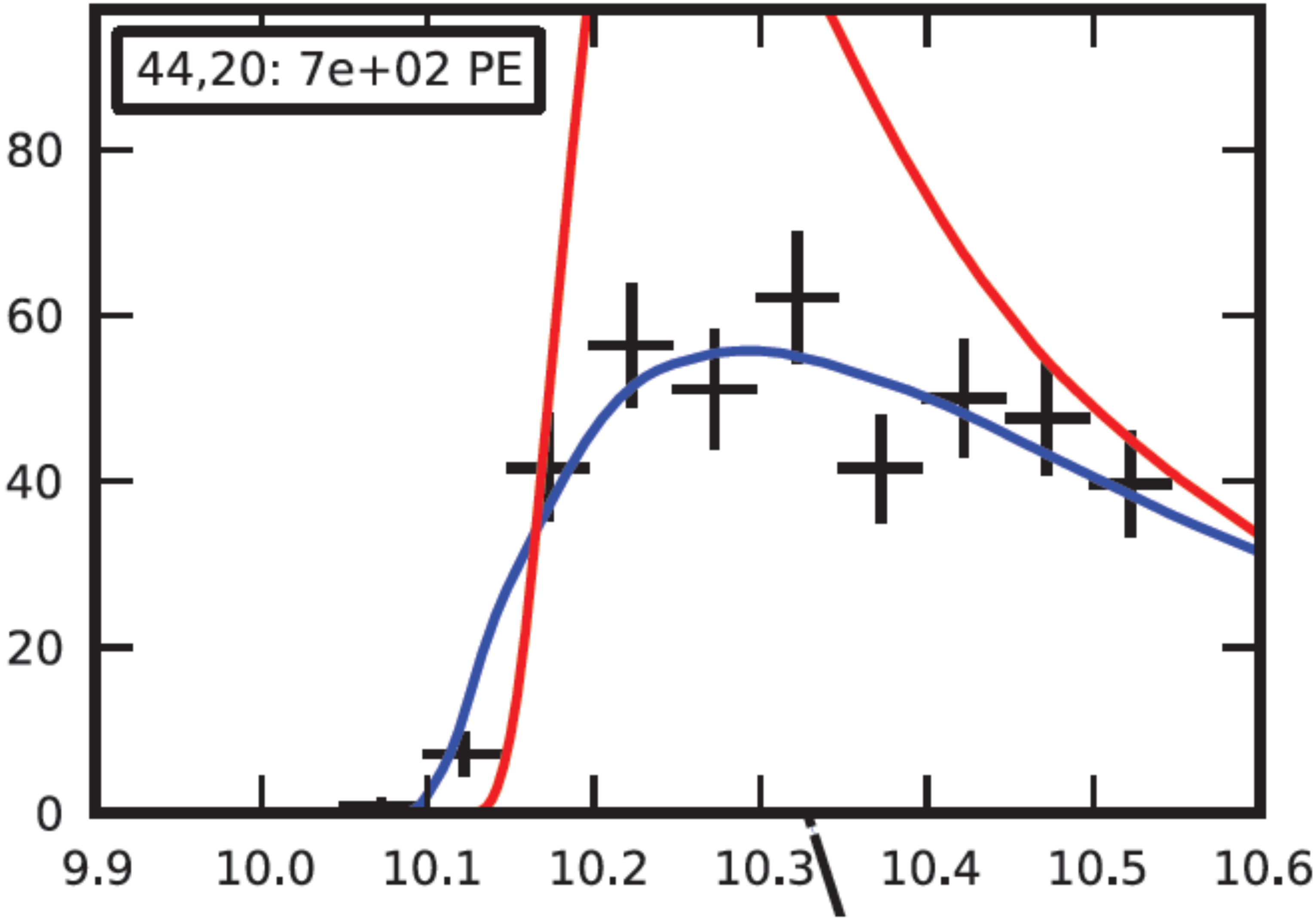
size = energy

color = time = direction

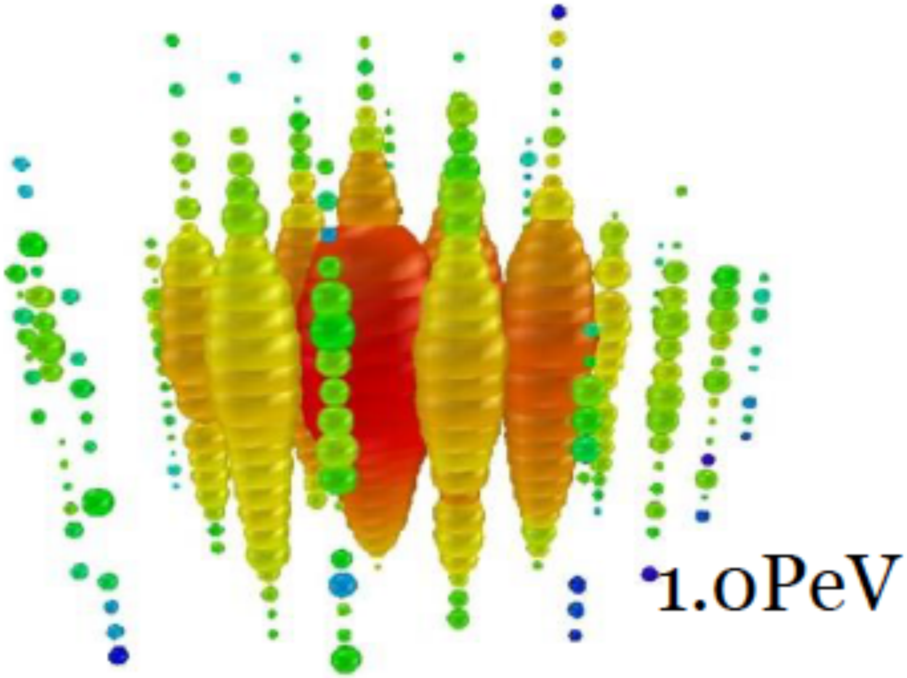


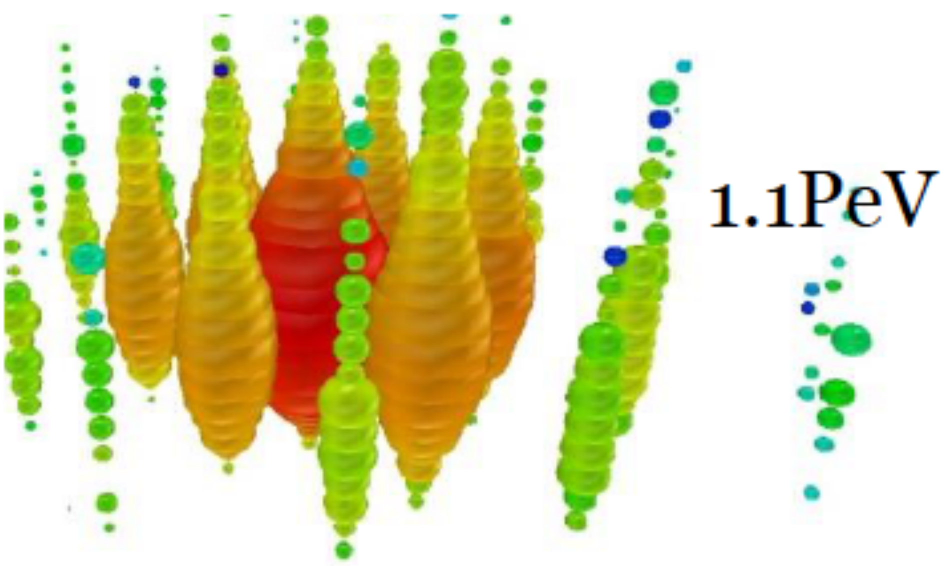
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction



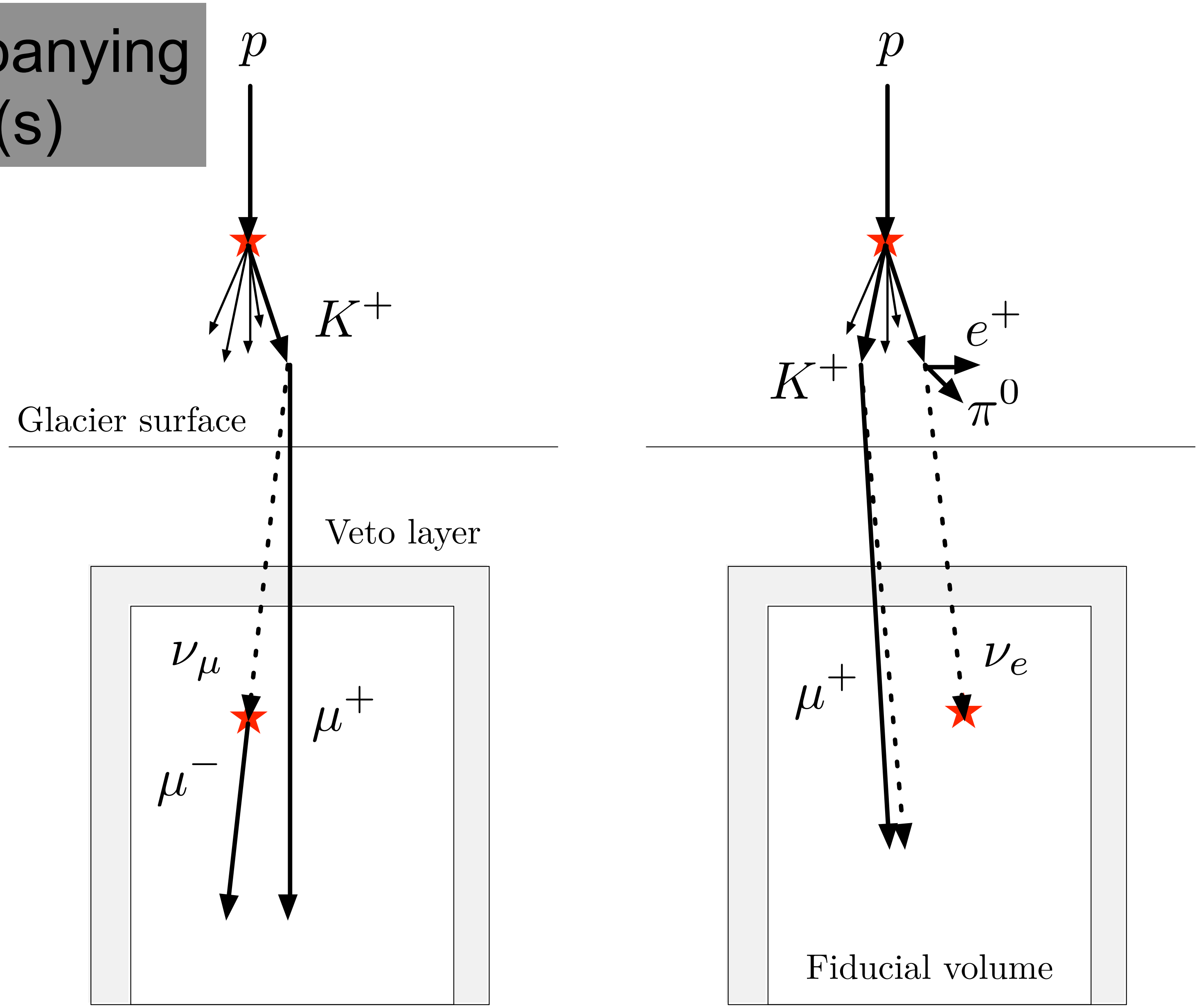


- energy

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

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

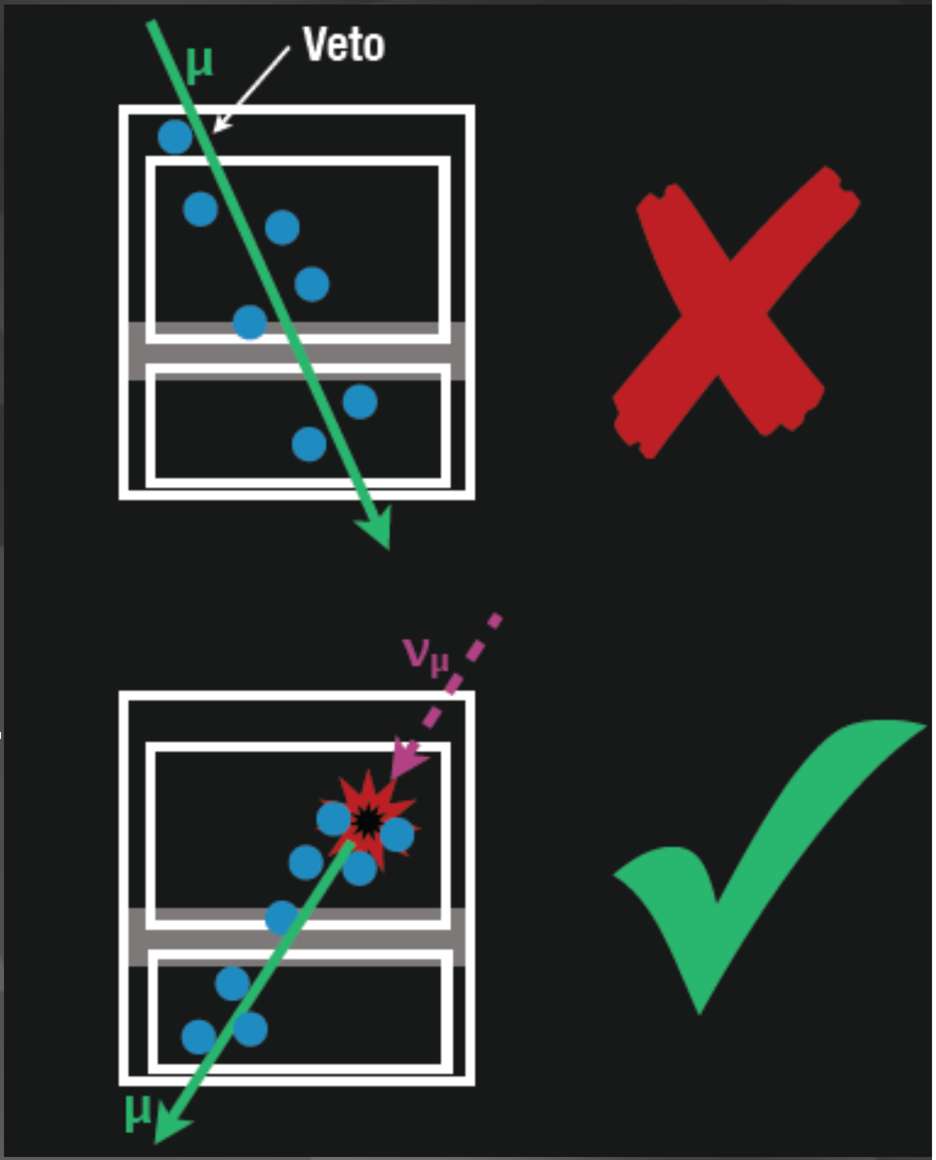
→ flux at present level of diffuse limit no accompanying muon(s)



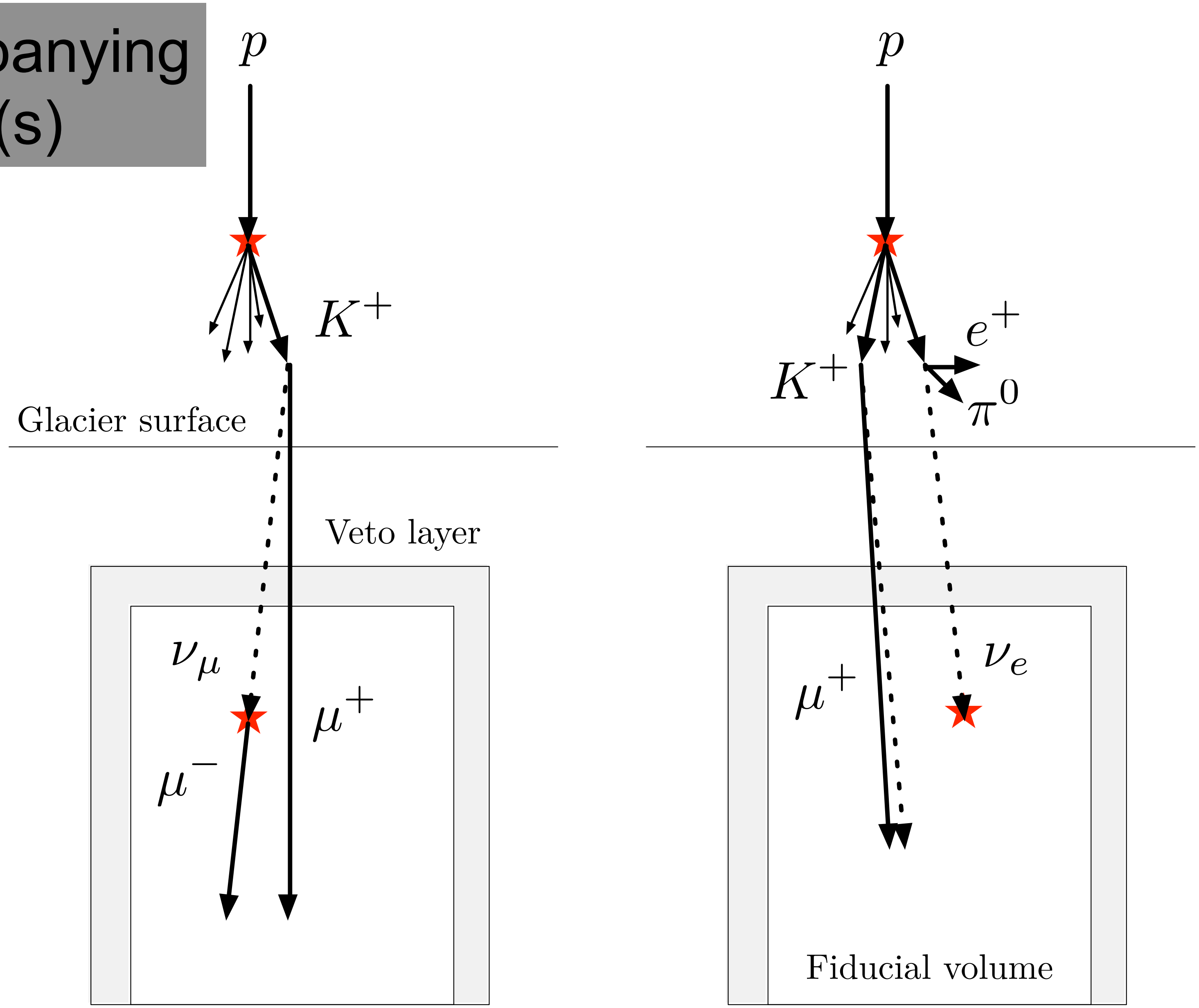
Veto by correlated muon

Veto by uncorrelated muon

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



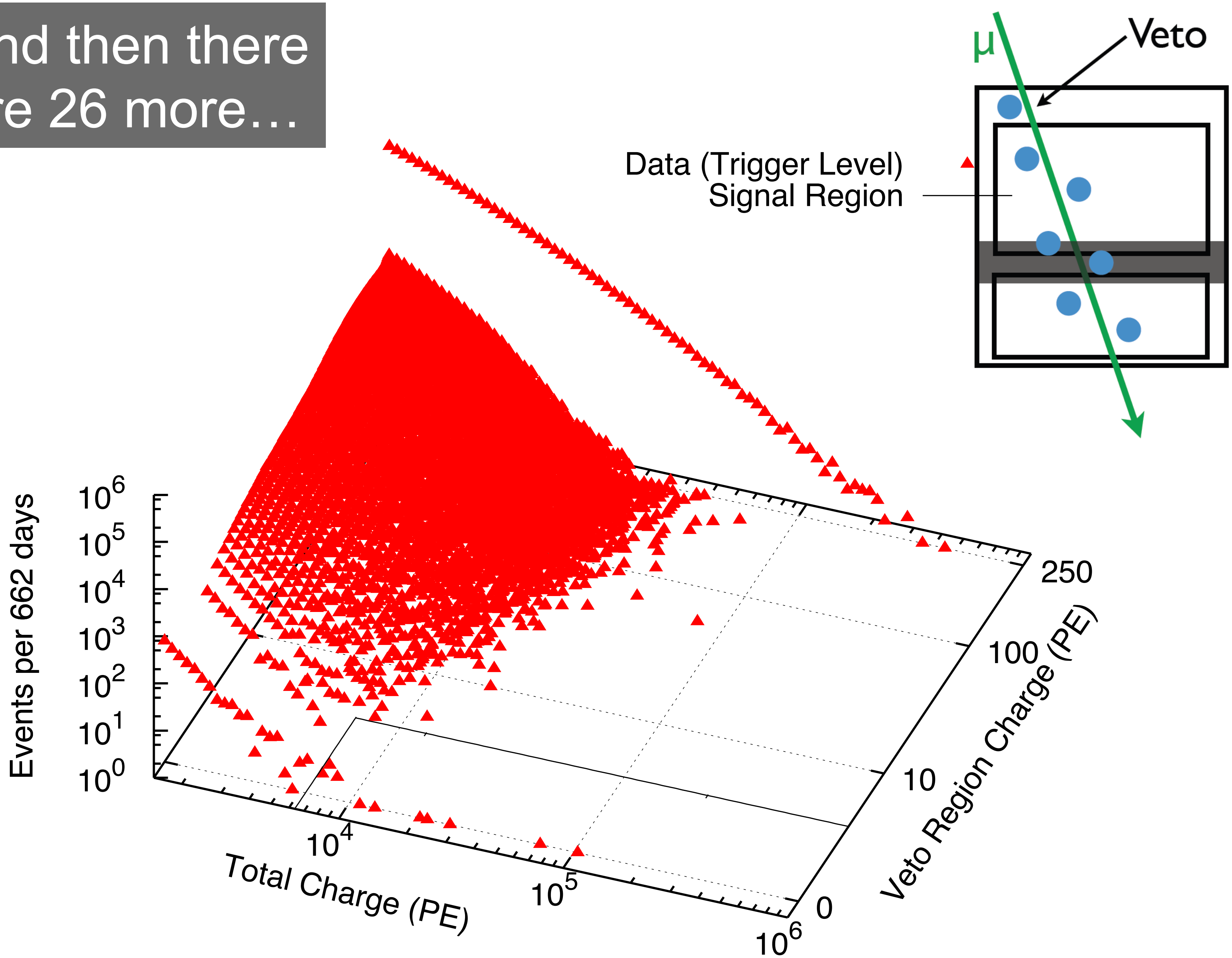
no accompanying muon(s)



Veto by correlated muon

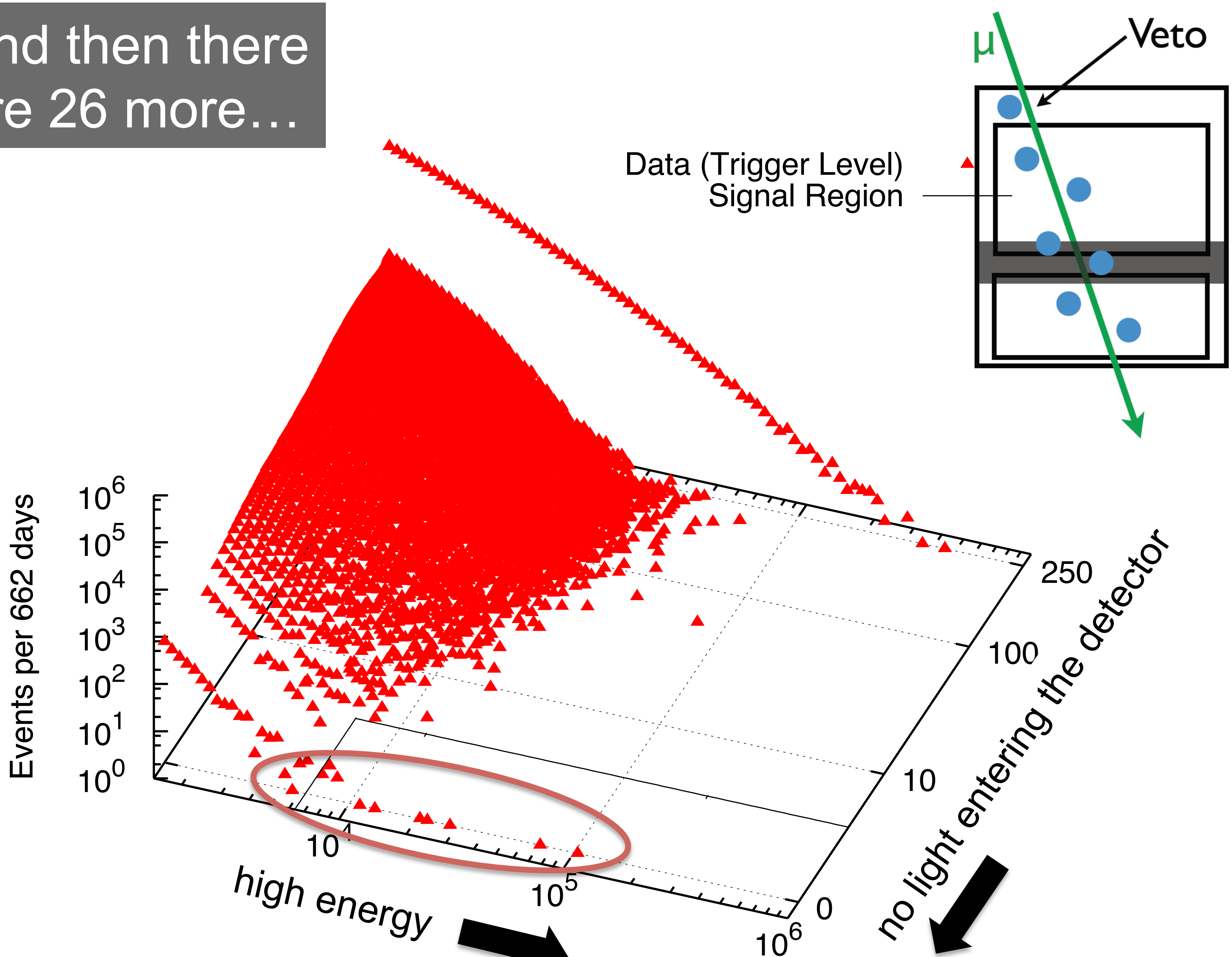
Veto by uncorrelated muon

...and then there were 26 more...

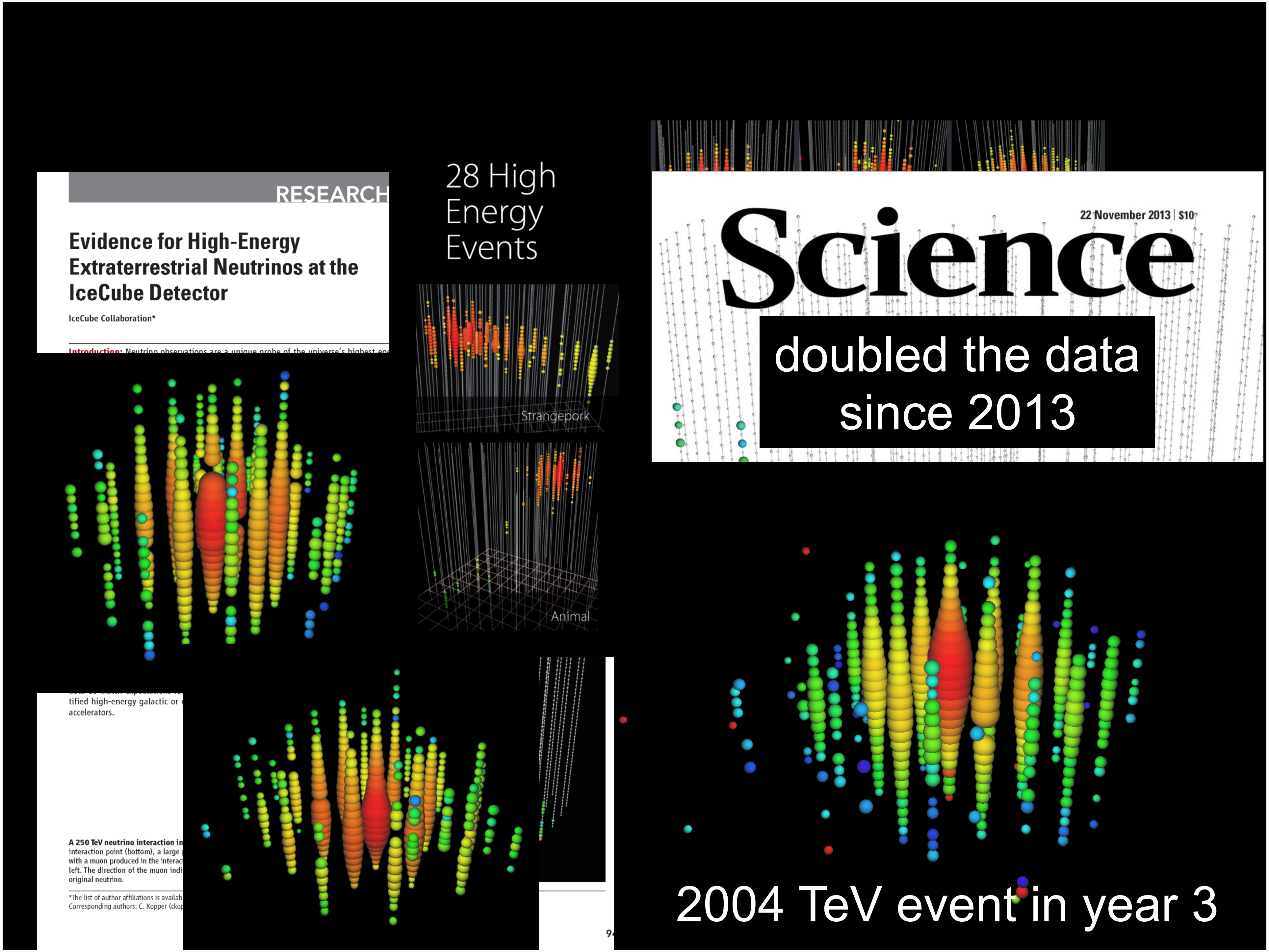


data: 86 strings one year

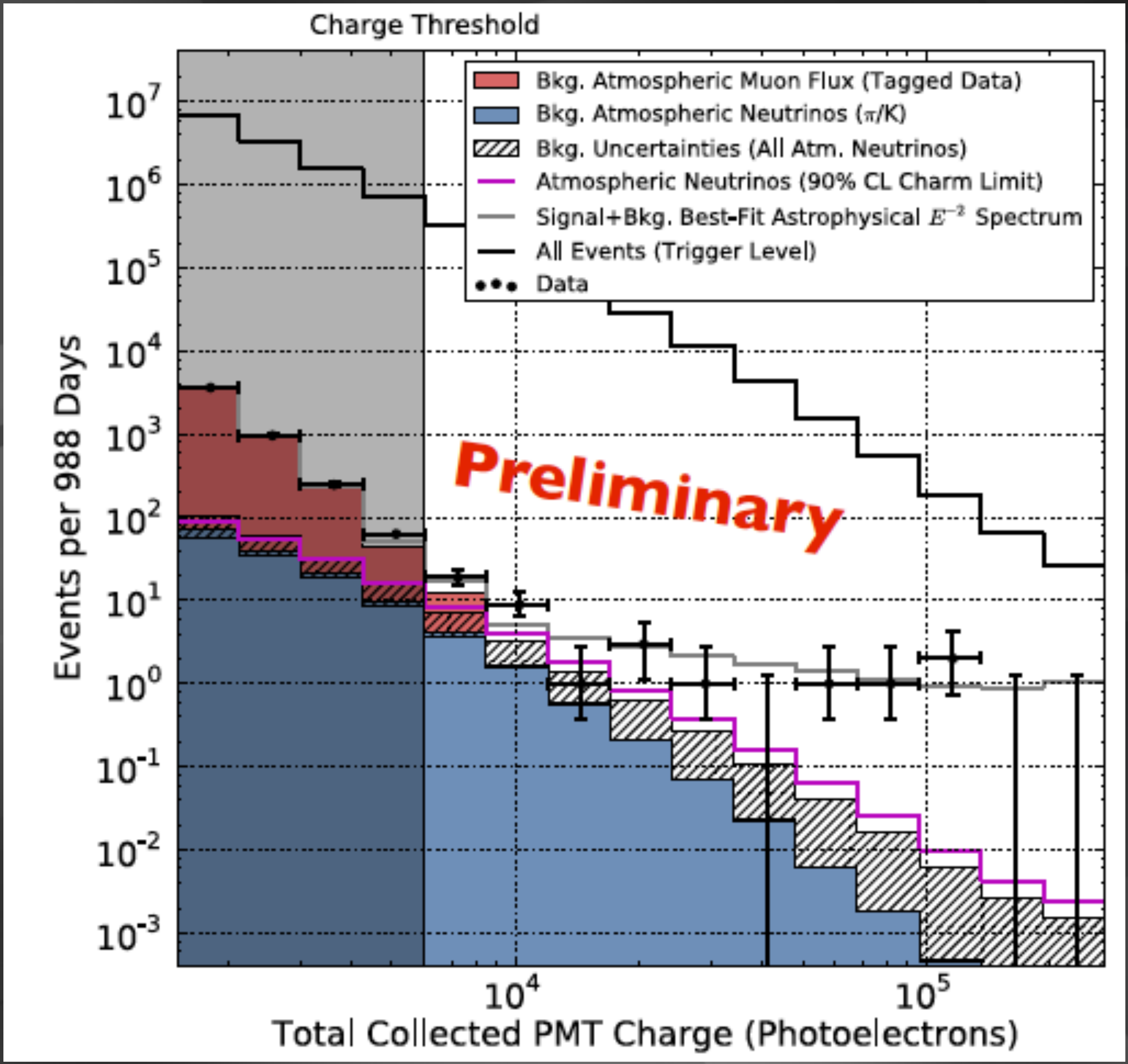
…and then there were 26 more…



data: 86 strings one year

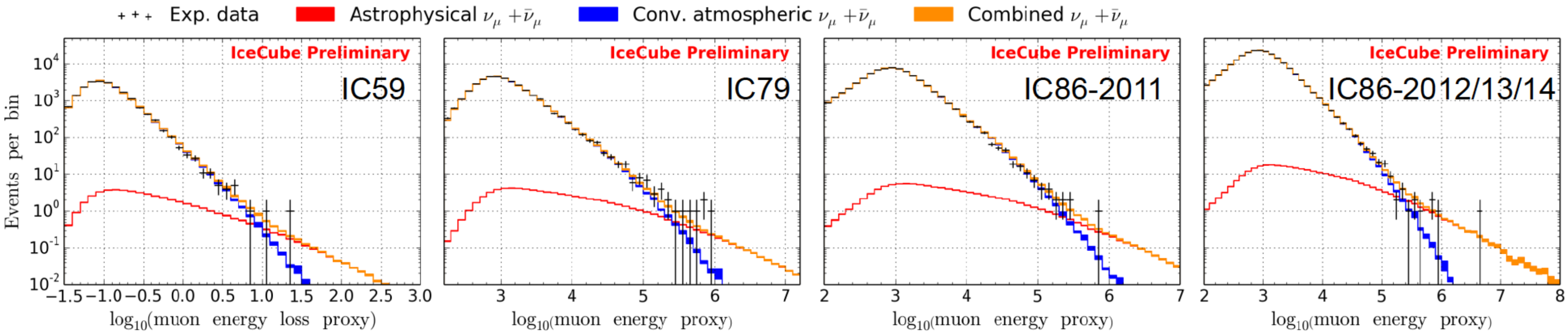

RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
doubled the data since 2013
2004 TeV event in year 3

total charge collected by PMTs of events with interaction inside the detector



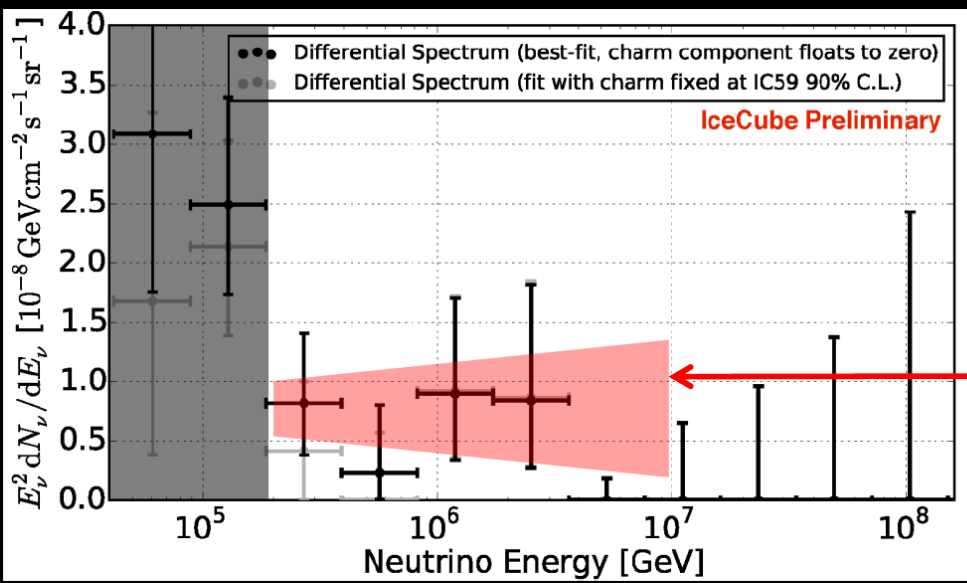
Science 342 (2013) 1242856

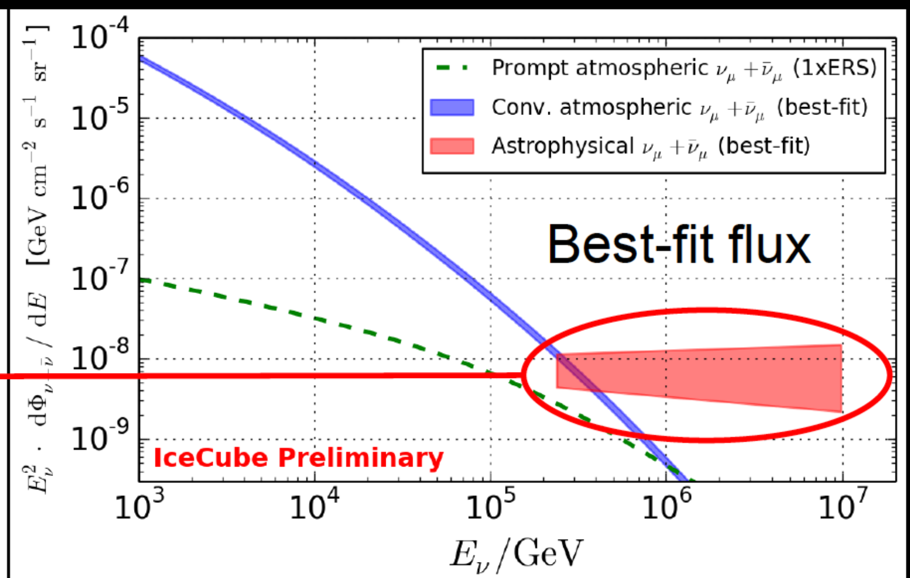
after 6 years: 3.7→ 6.0 sigma

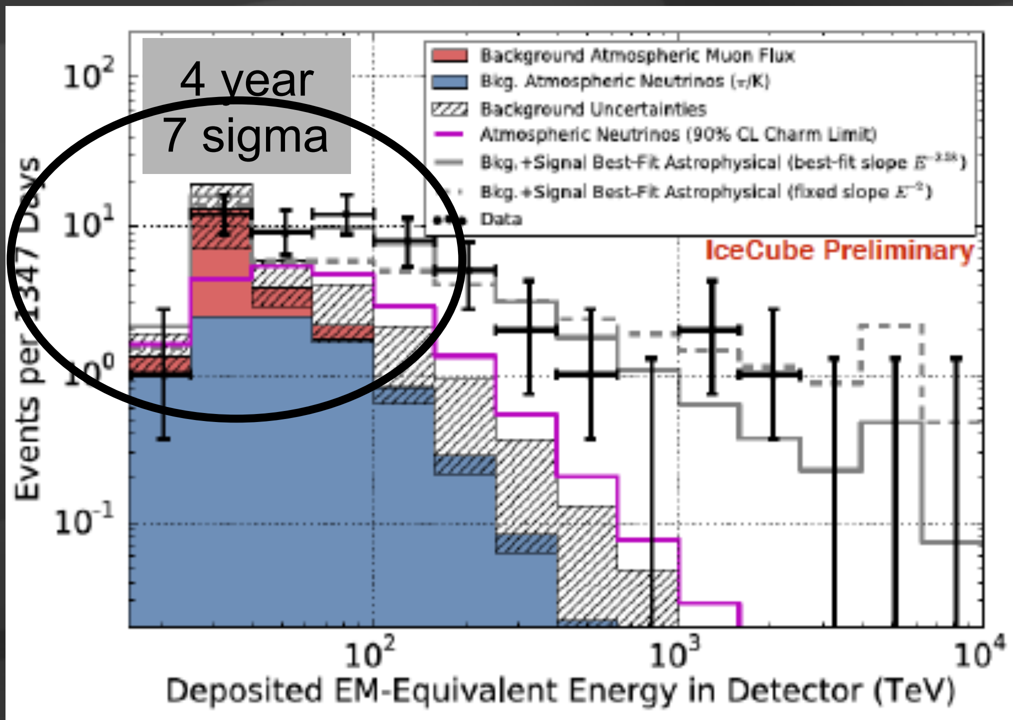


HESE 4 year unfolding
(→ dominated by shower-like events)

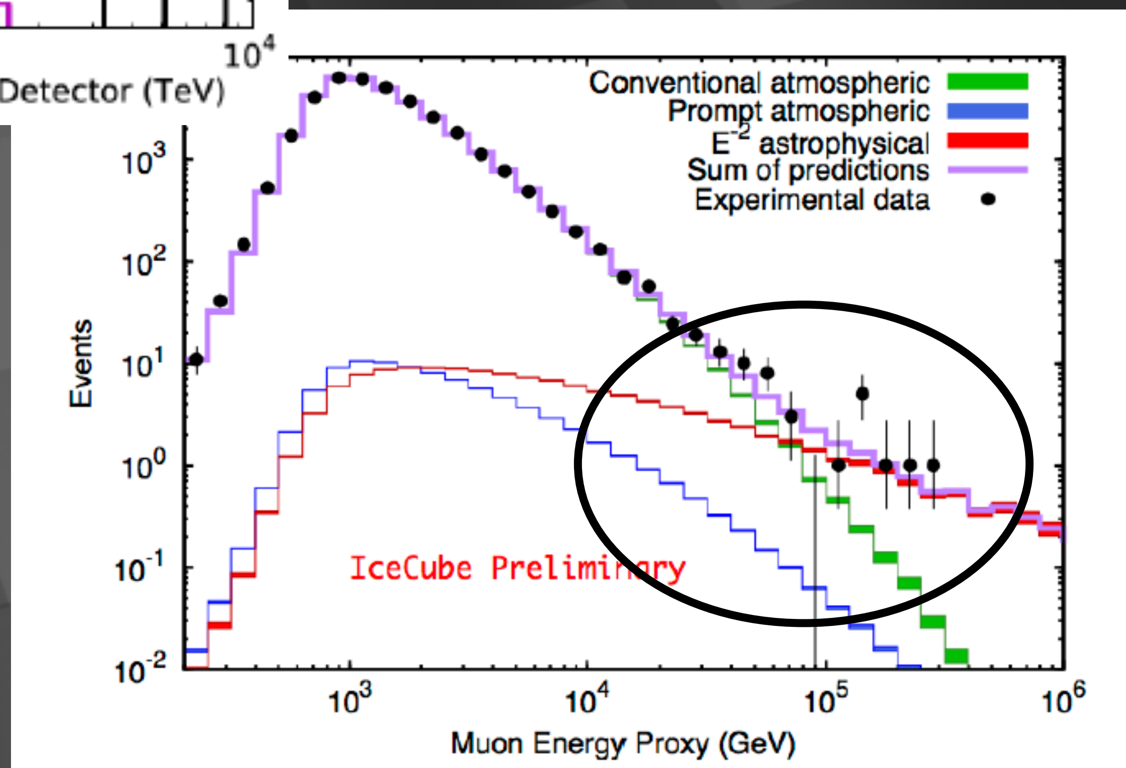
6 year up-going numu analysis







confirmation!
flux of muon neutrinos
through the Earth

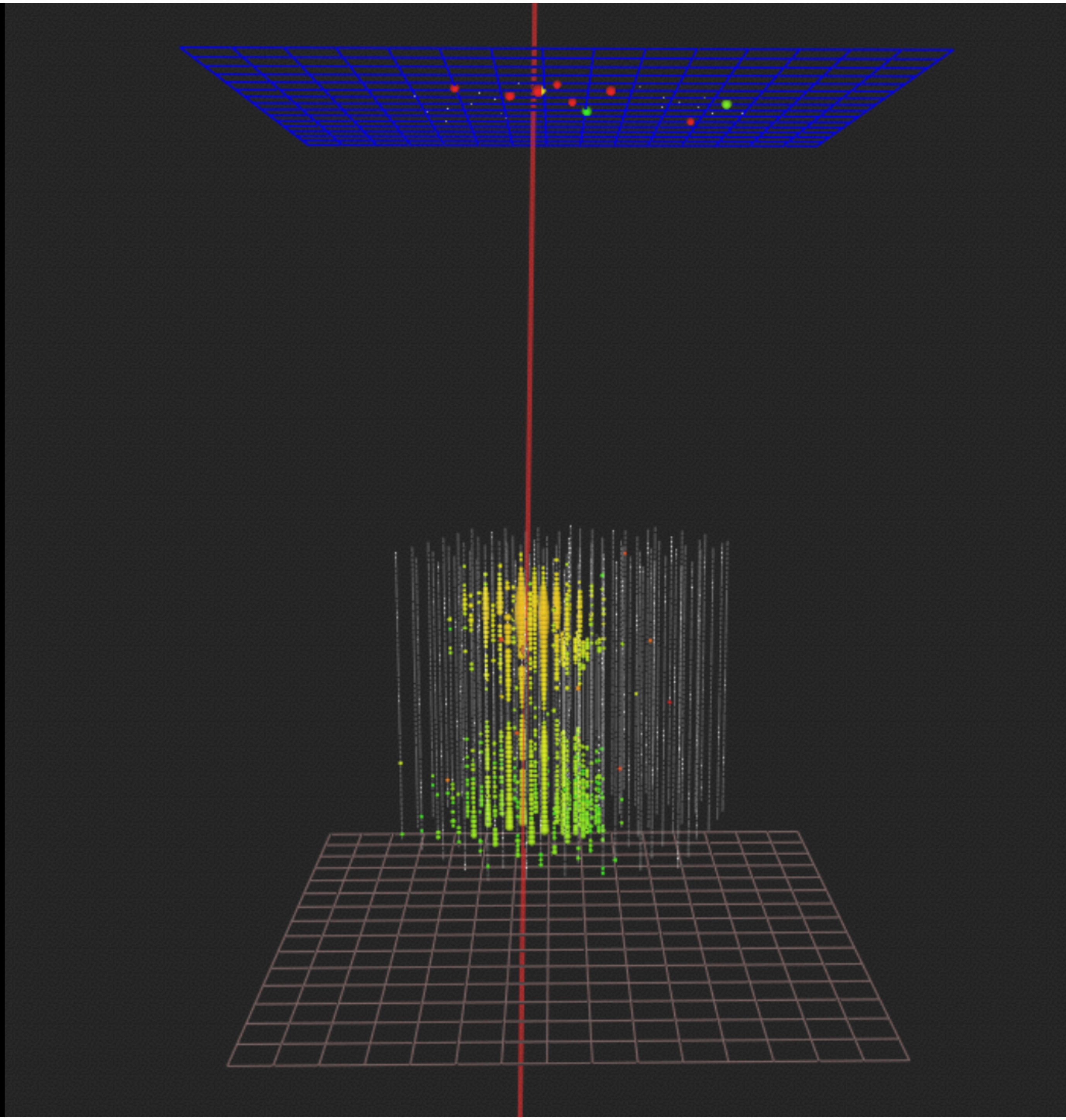


neutrinos of all flavors
interacting inside
IceCube

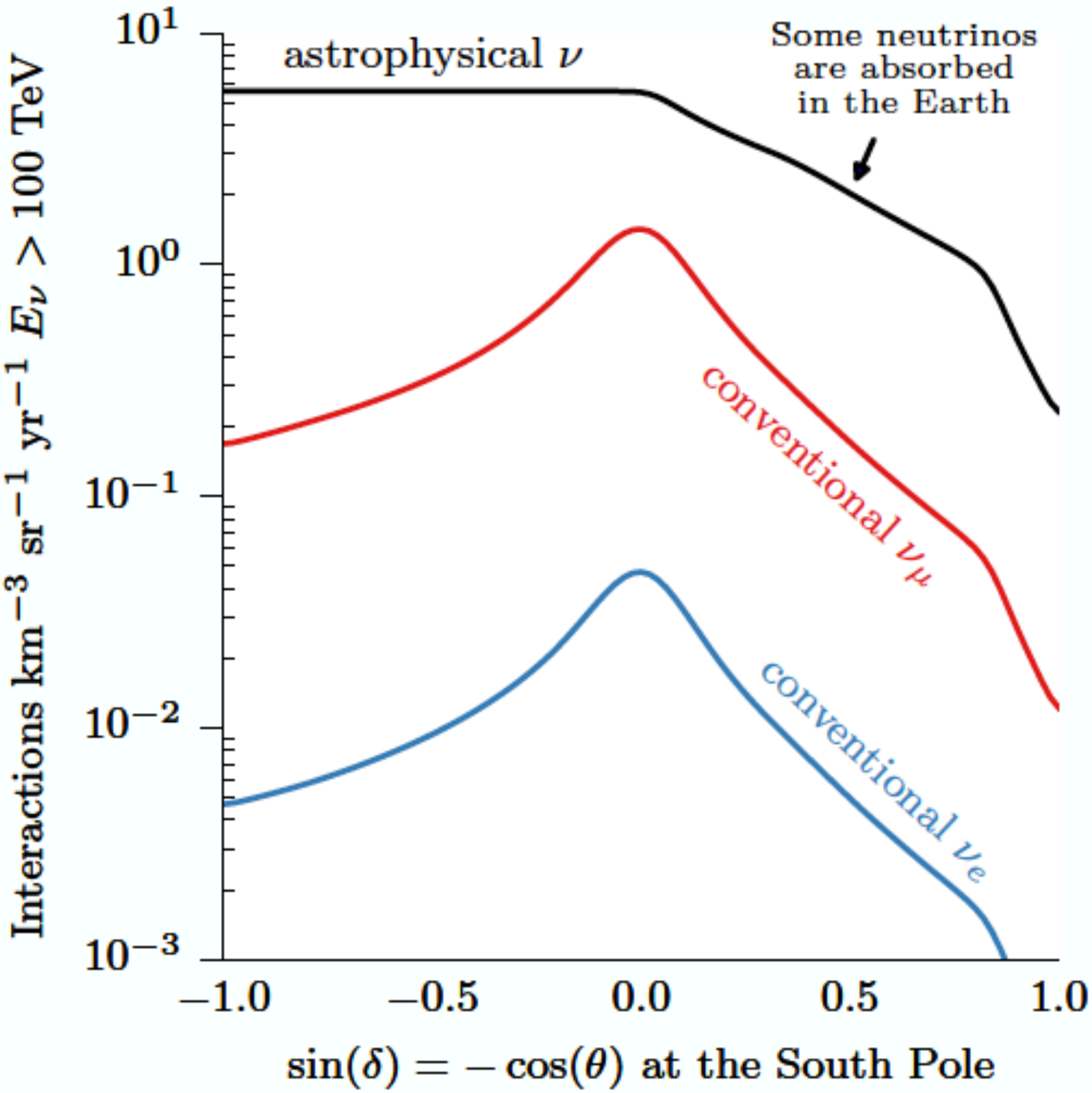
430 TeV

1 event:
~ 5 sigma
discovery

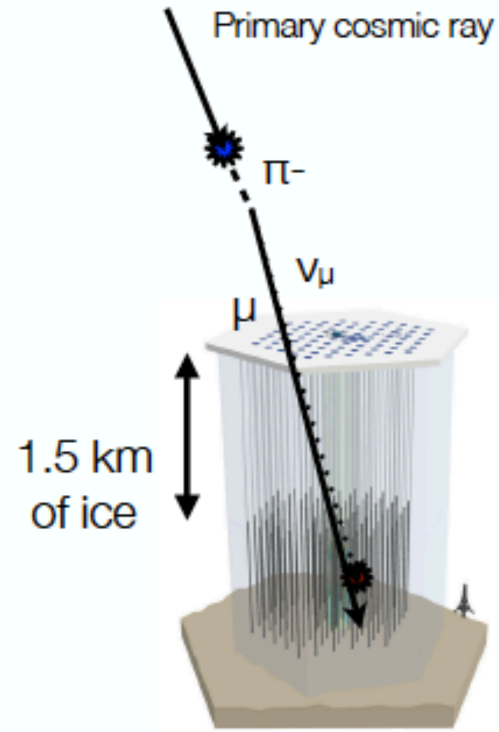
> PeV ν_μ



Atmospheric neutrino self-veto



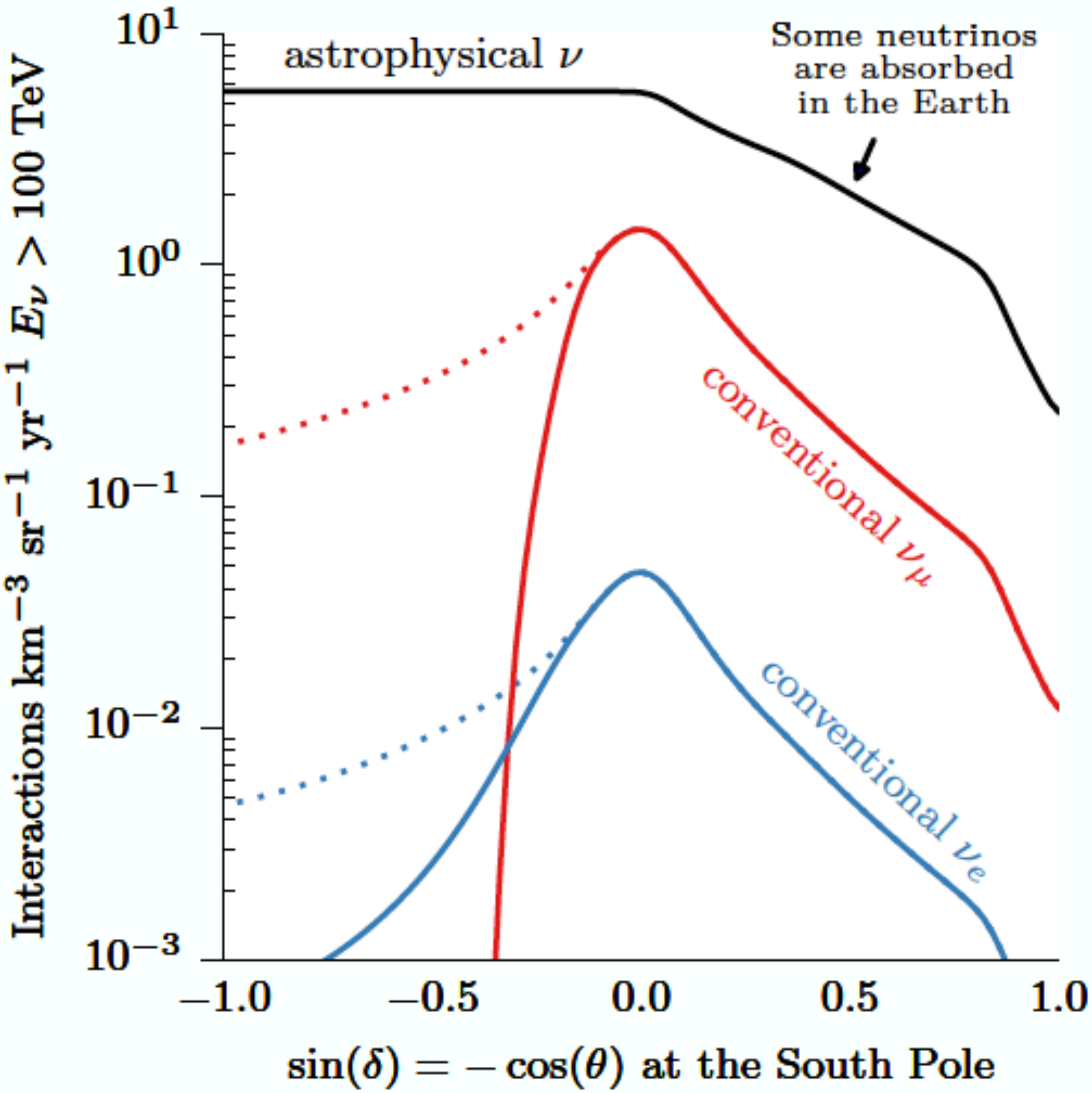
An active muon veto removes down-going atmospheric neutrinos.



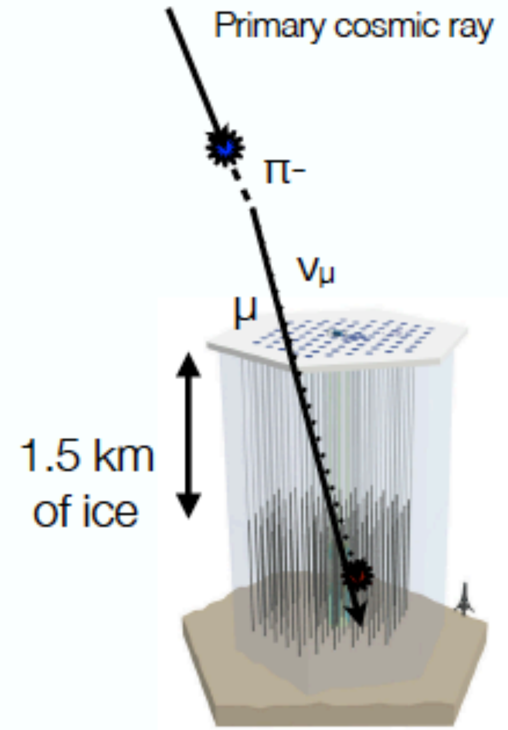
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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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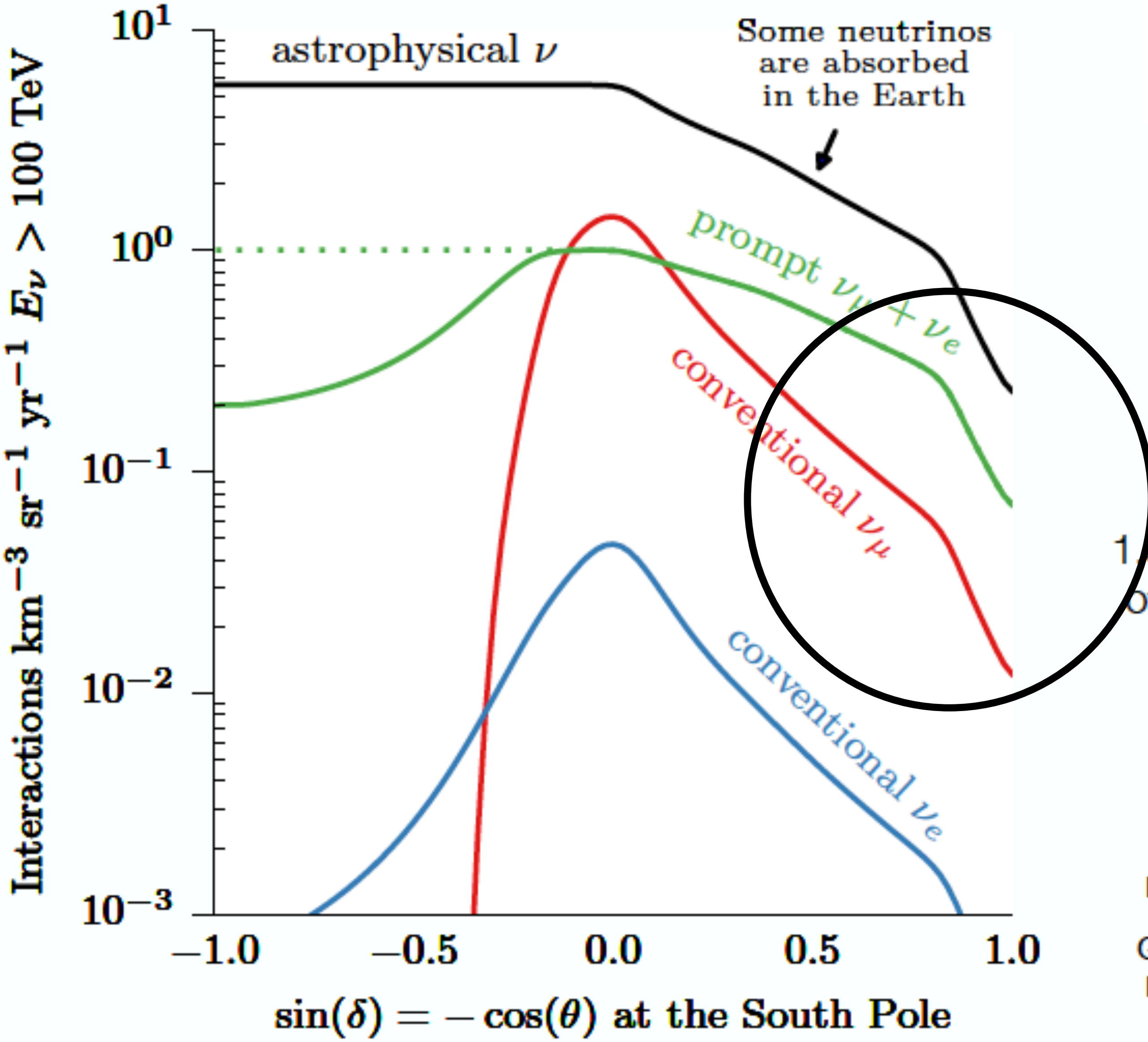
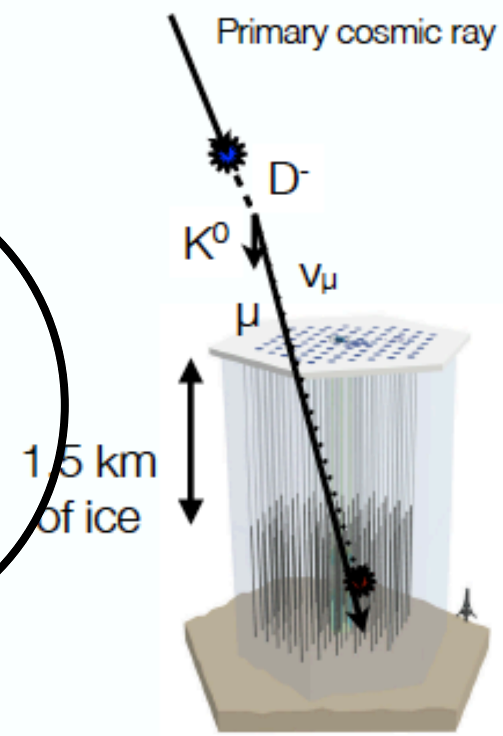
Atmospheric neutrino self-veto

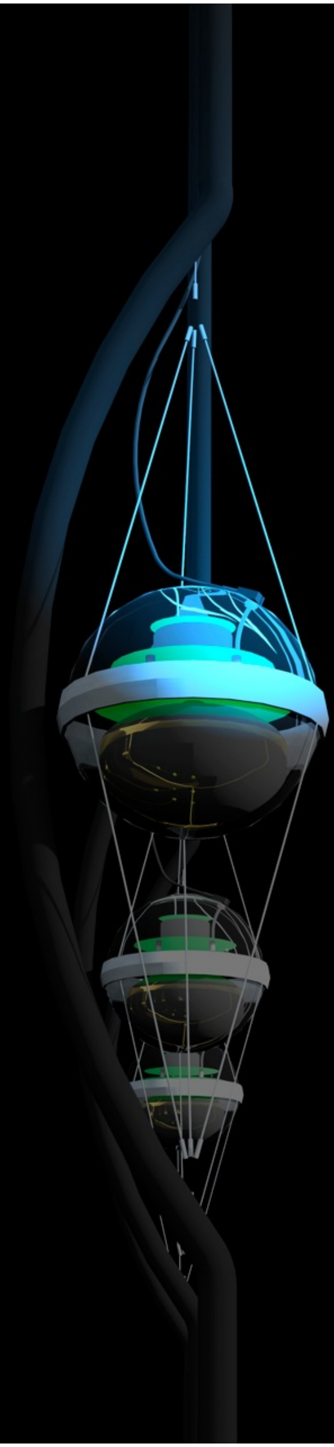


Prompt atmospheric neutrinos are vetoed, too.



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

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



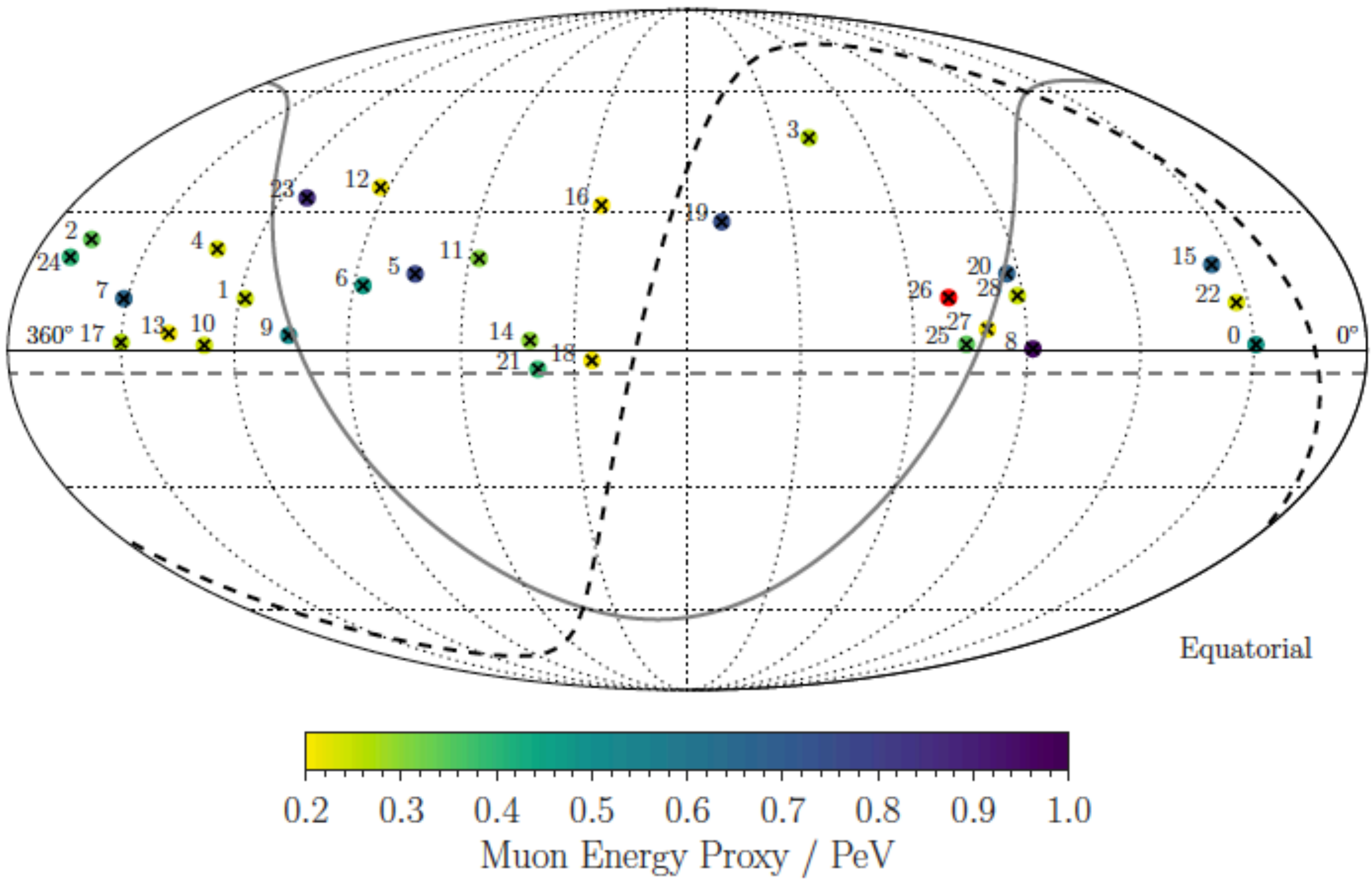
IceCube: the discovery of cosmic neutrinos

francis halzen

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

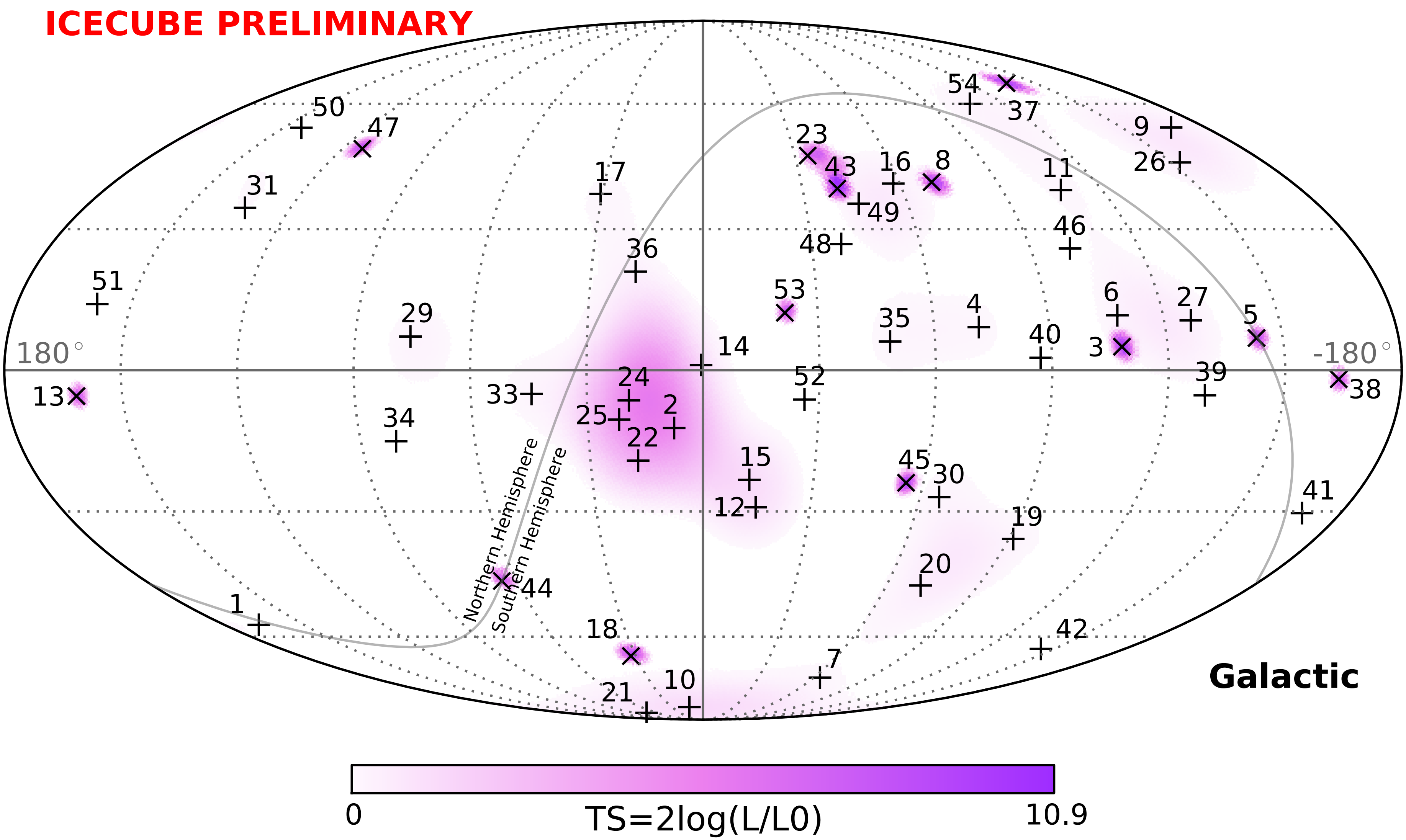
IceCube.wisc.edu

[redacted]



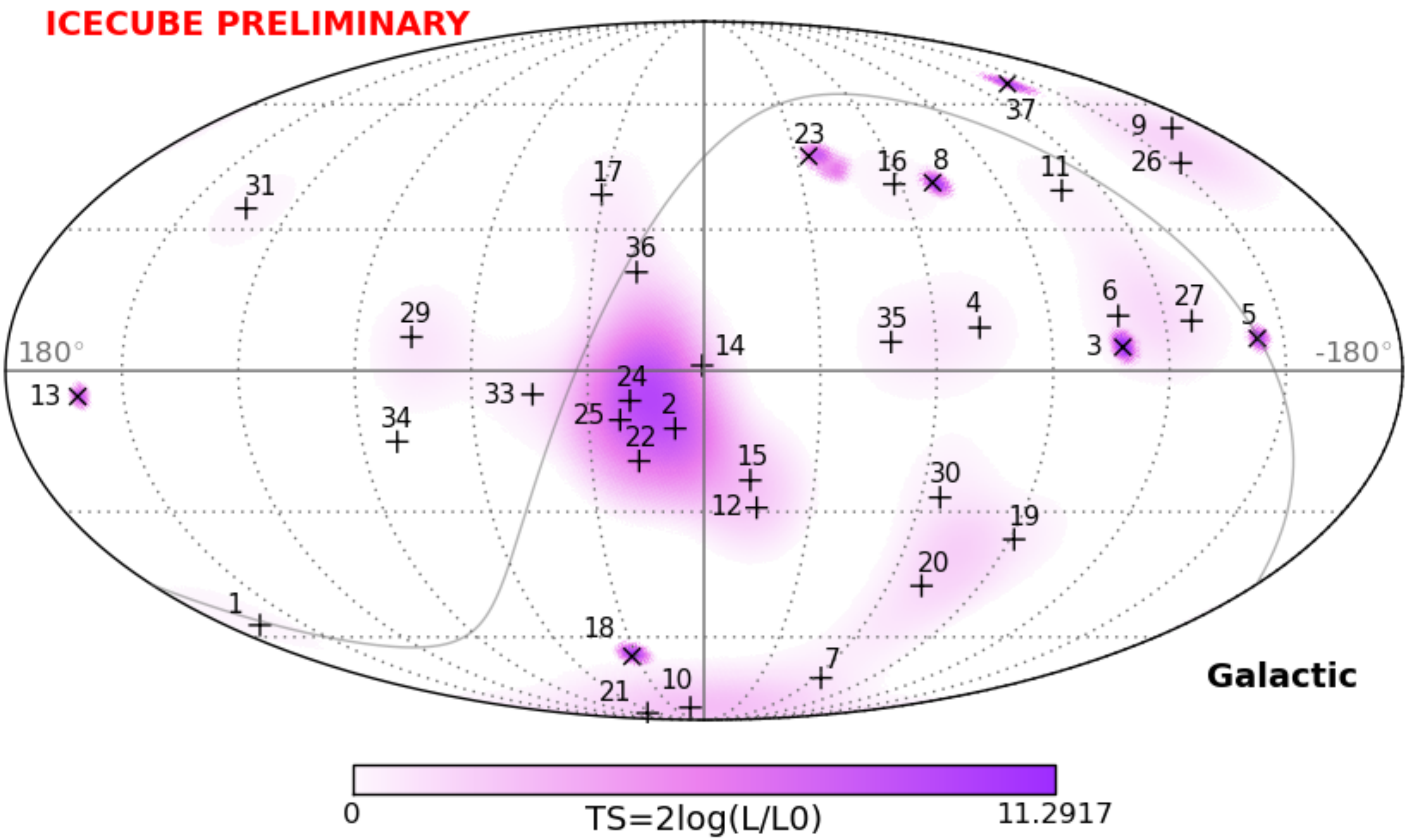
[redacted]

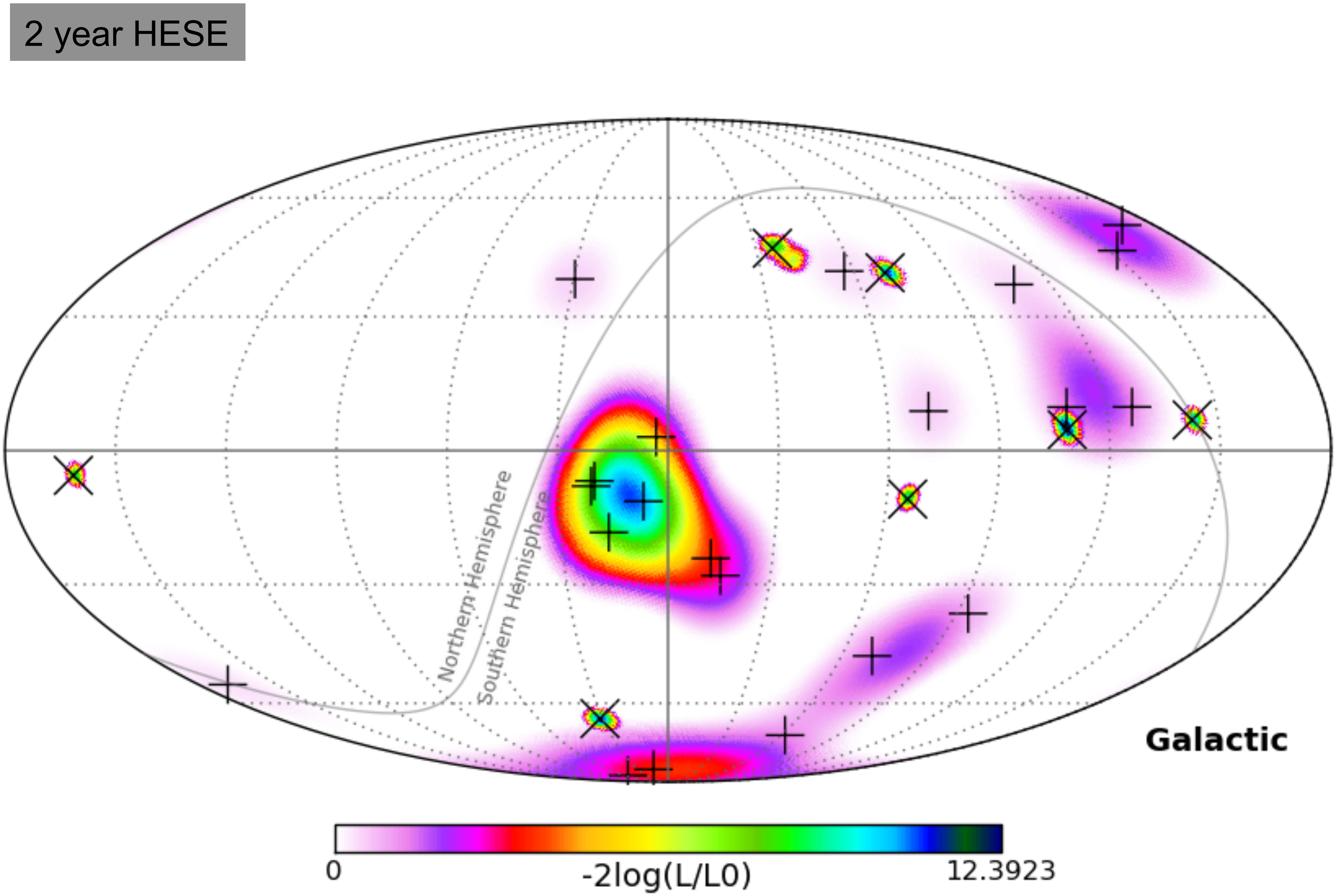
4 year HESE



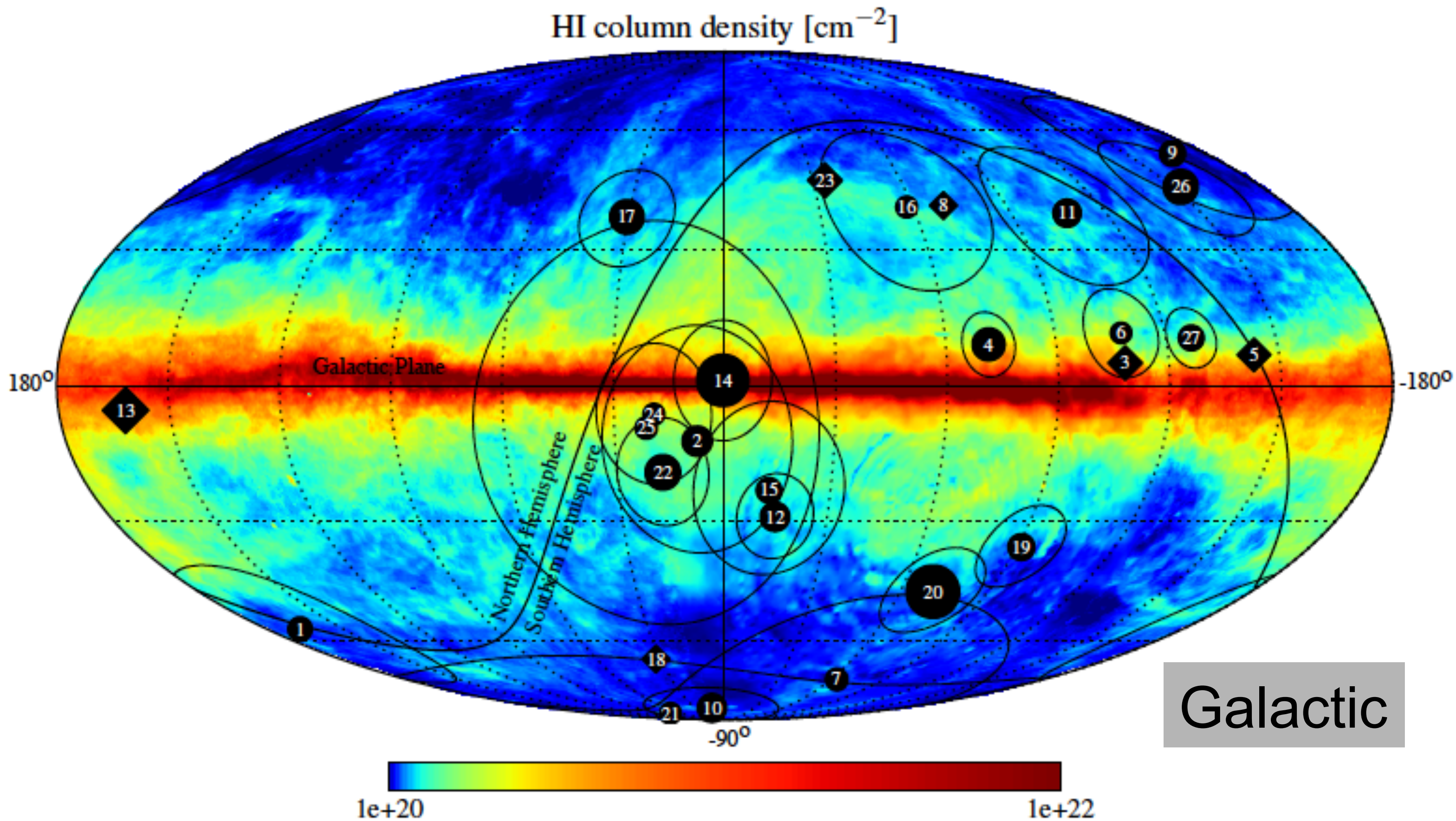
where do they come from?

3 year HESE


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

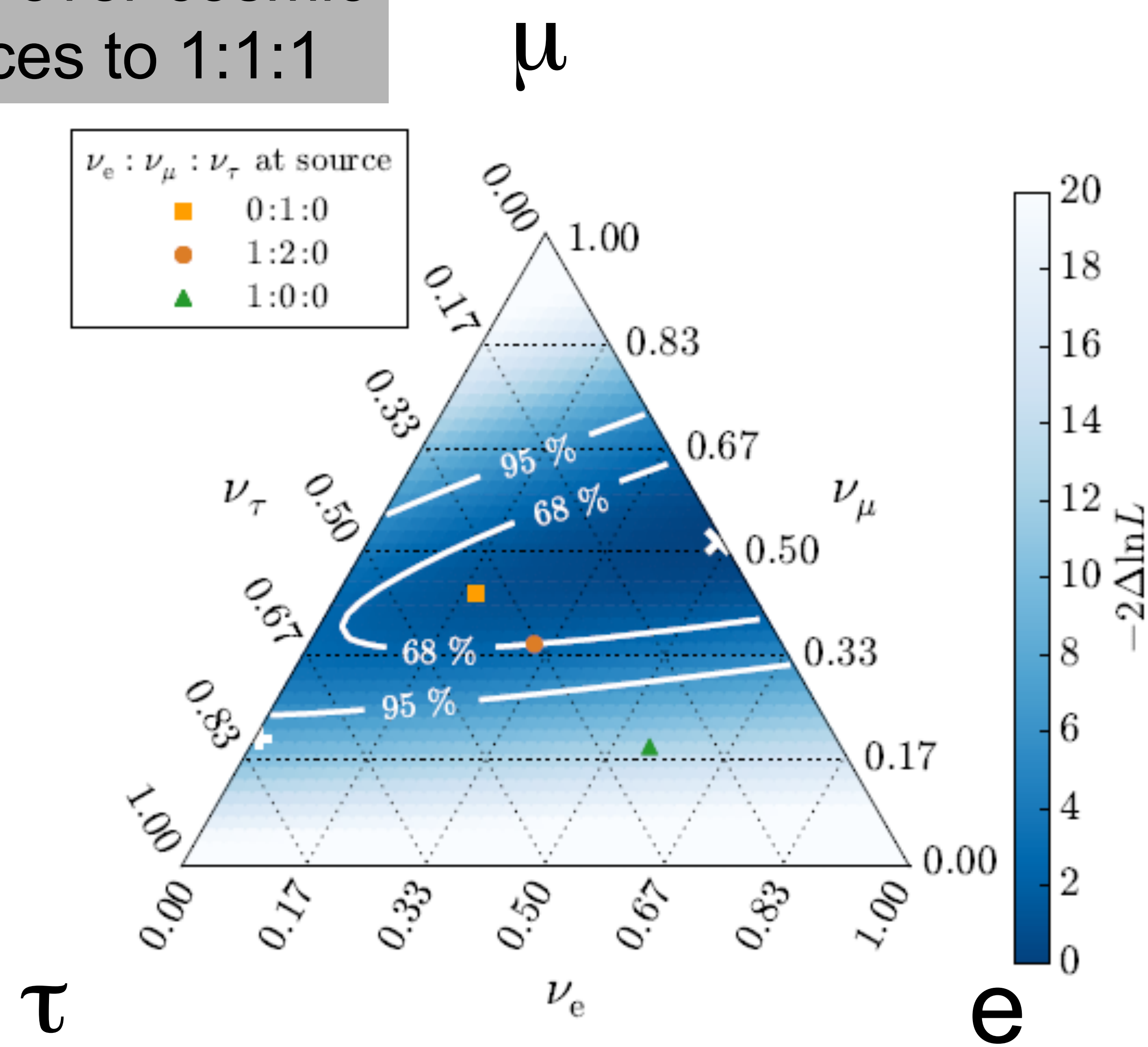

2 year HESE
Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

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



Galactic

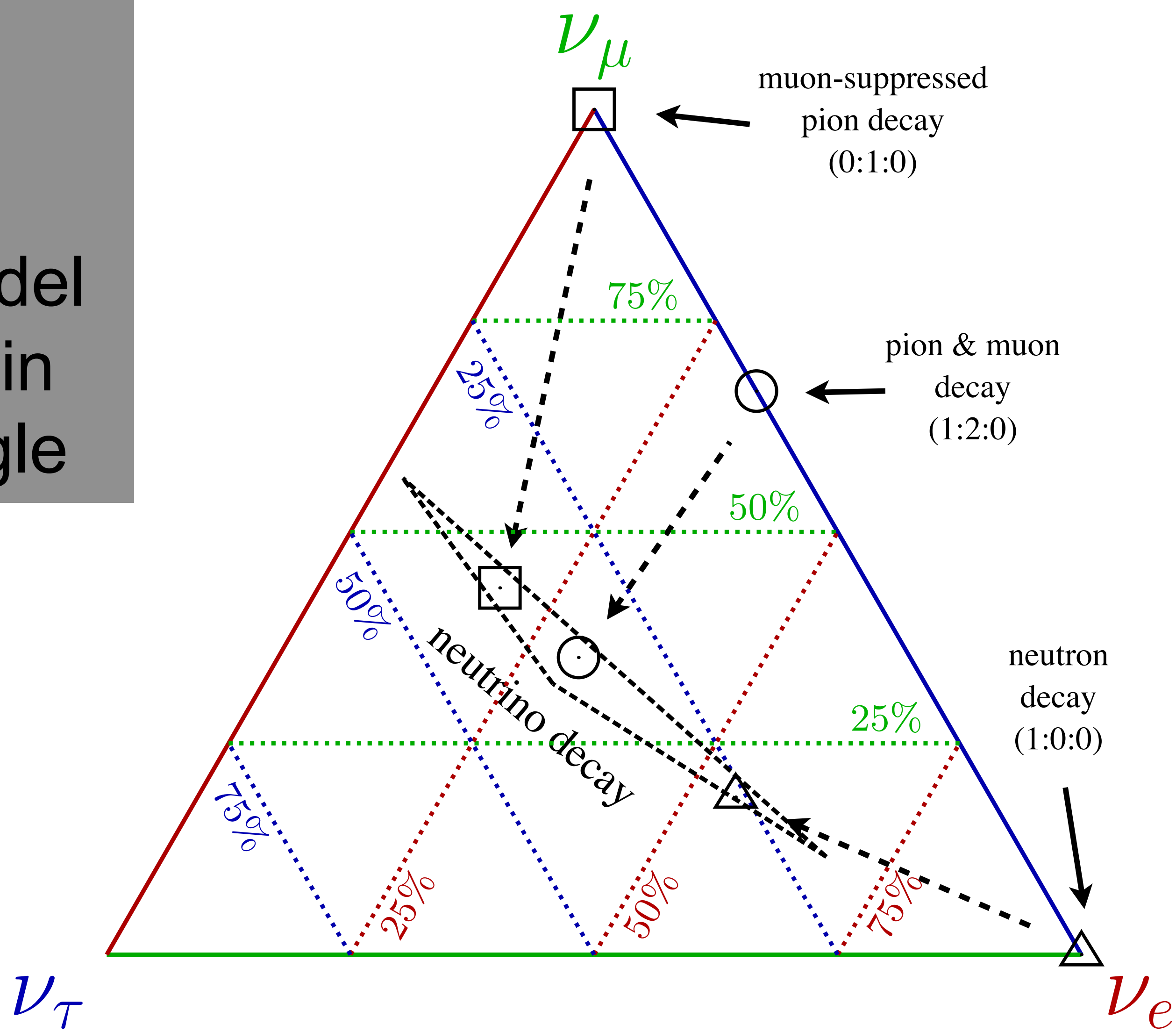
oscillate over cosmic distances to 1:1:1



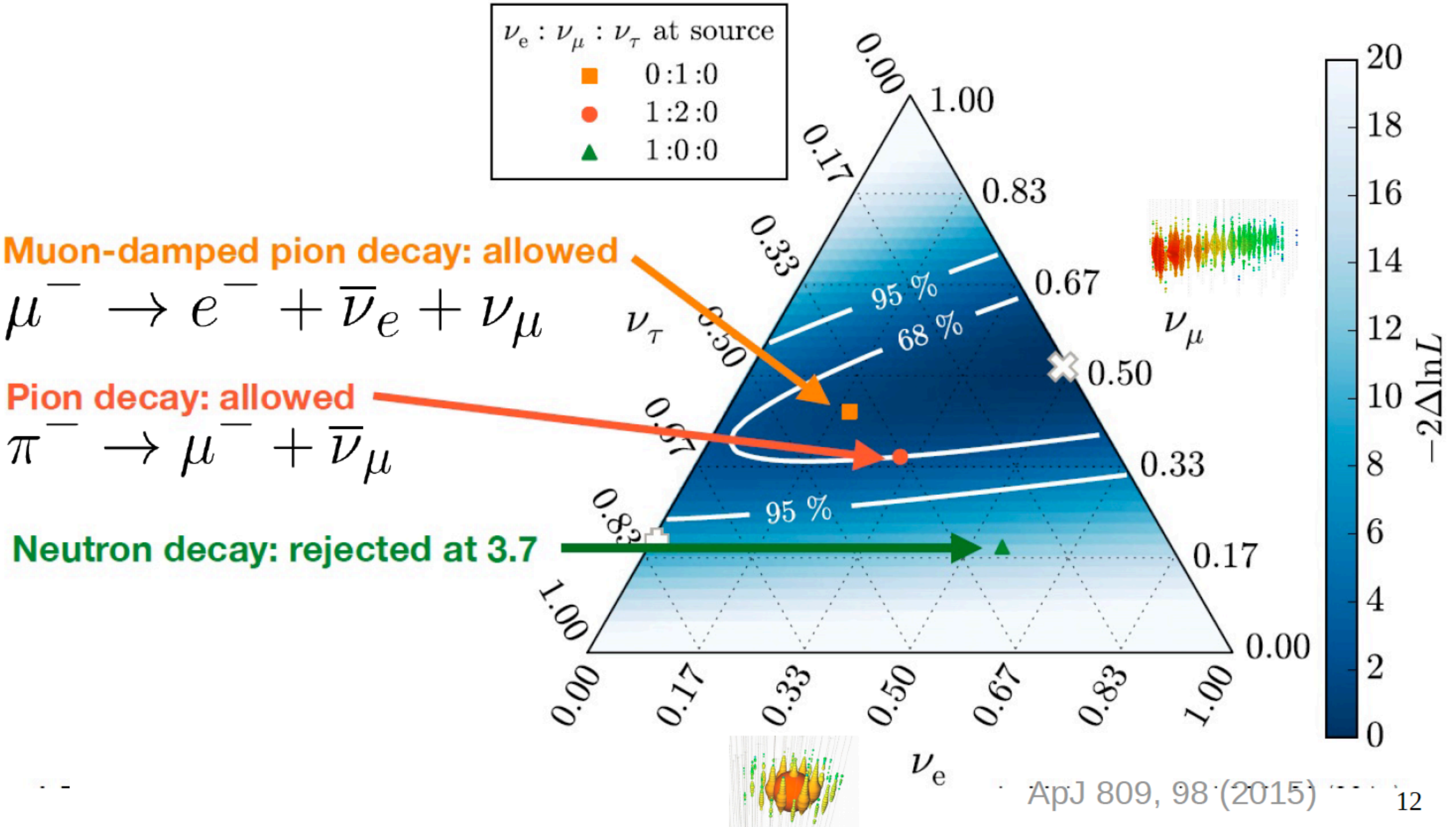
new physics ?

if not…

every model ends up in the triangle

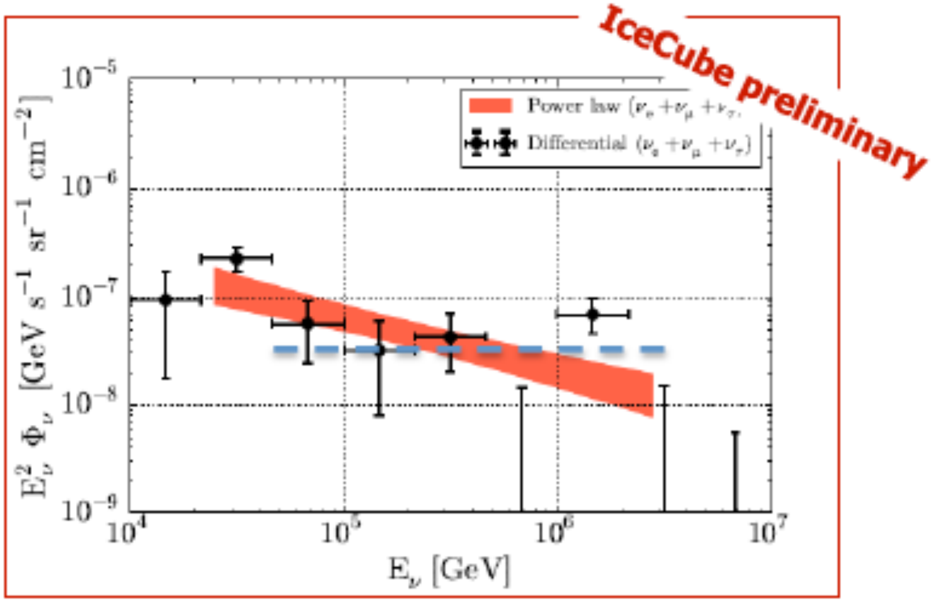


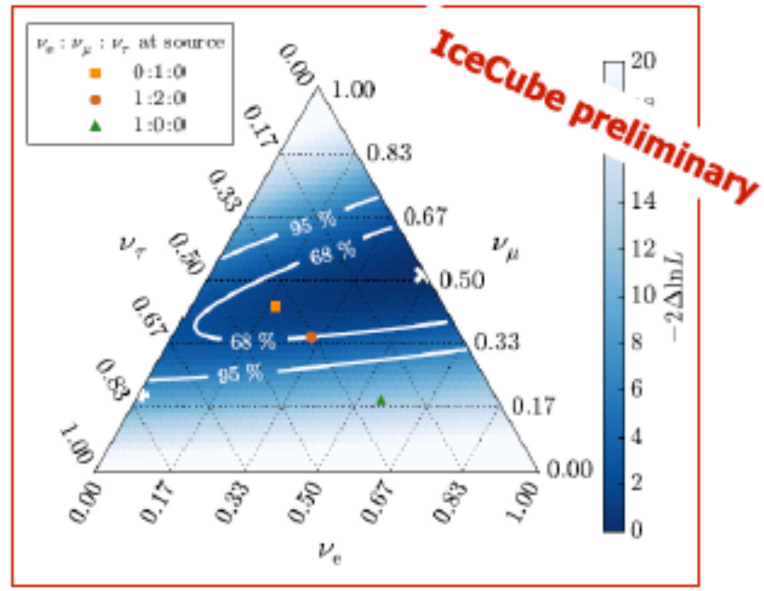
- Different event signatures allow flavor separation → primarily μ vs. e, τ



ApJ 809, 98 (2015)

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





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

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

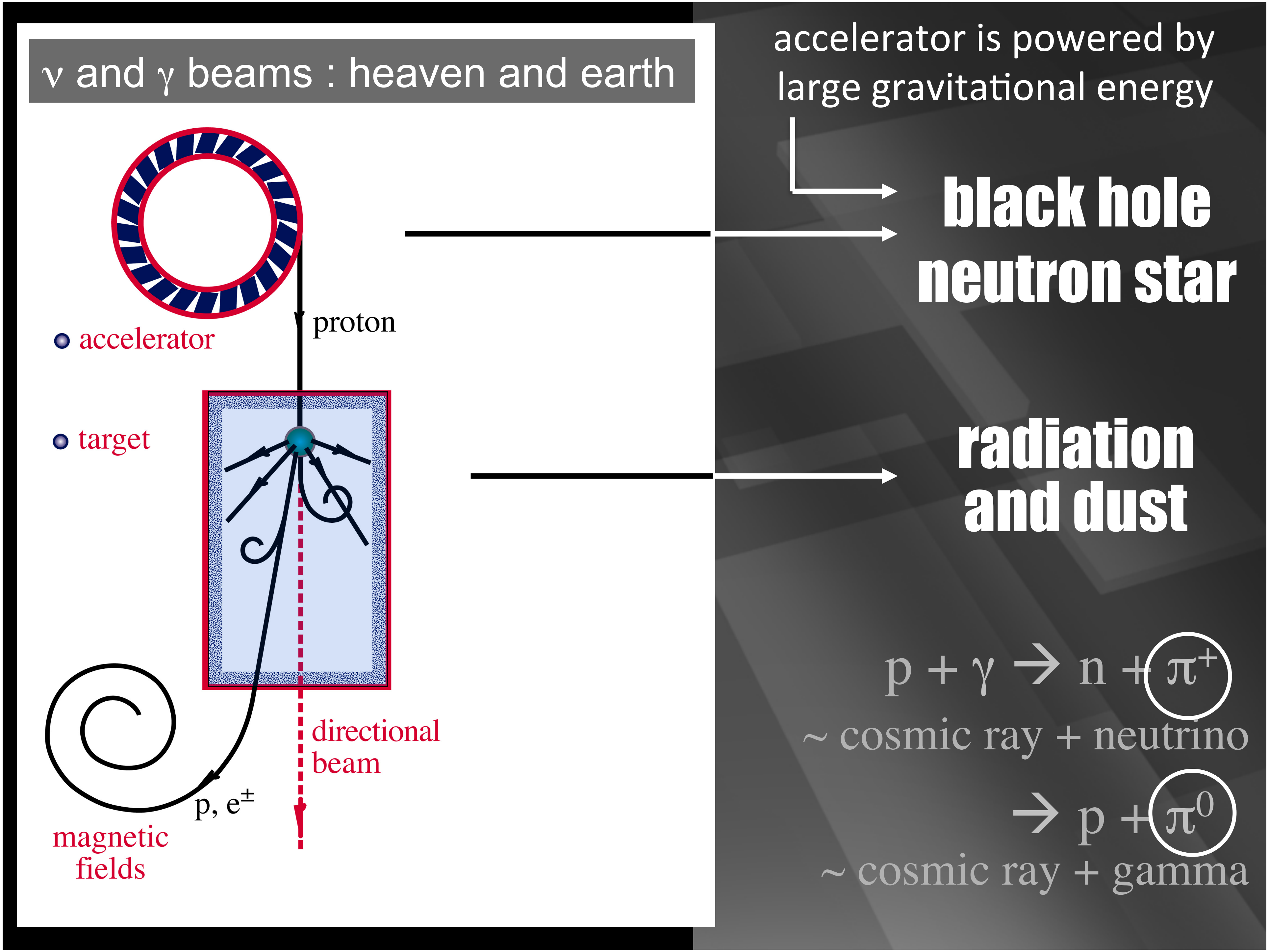
the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

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

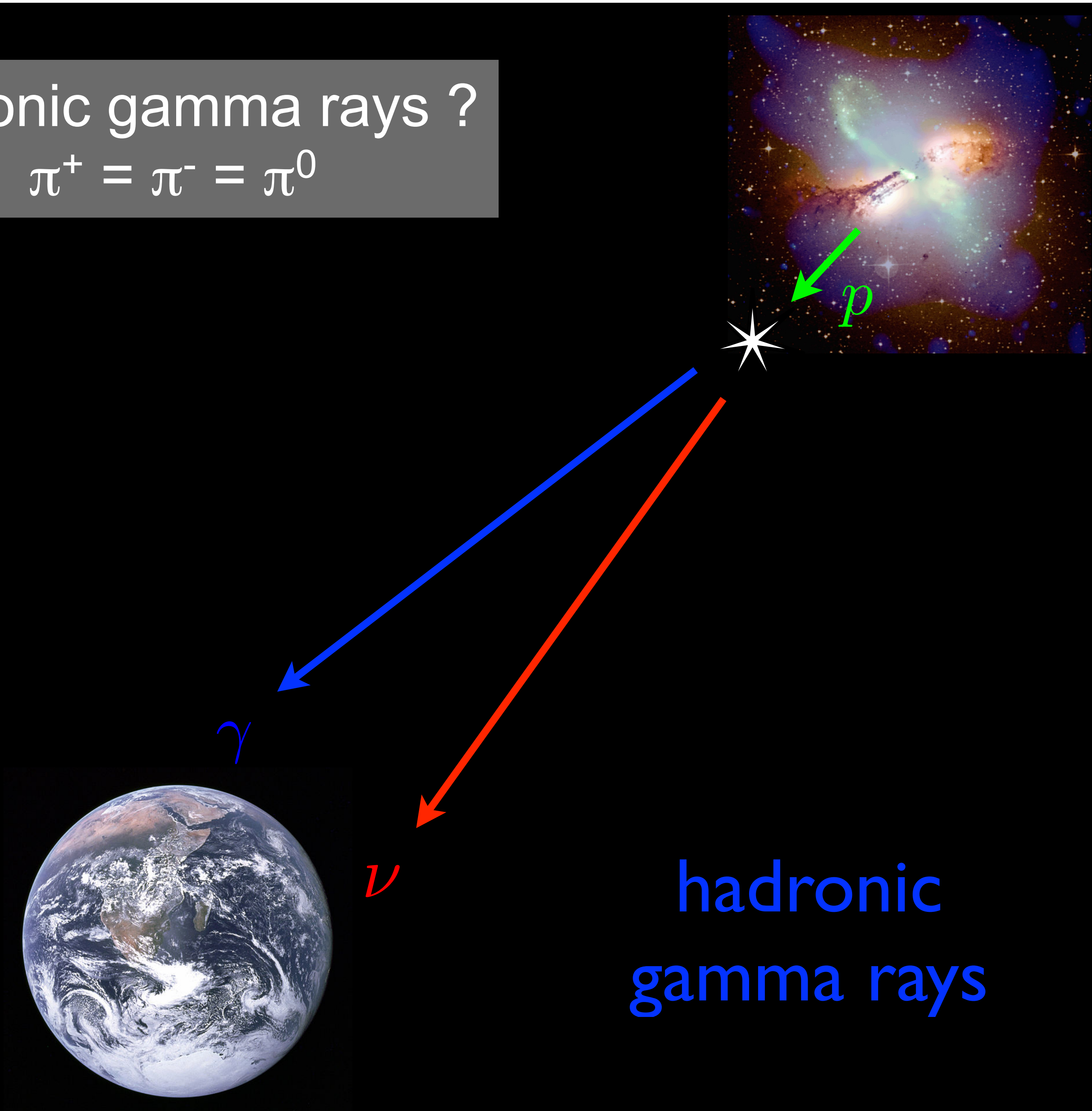
$$\overline{\nu}_e + e^- \rightarrow W$$

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

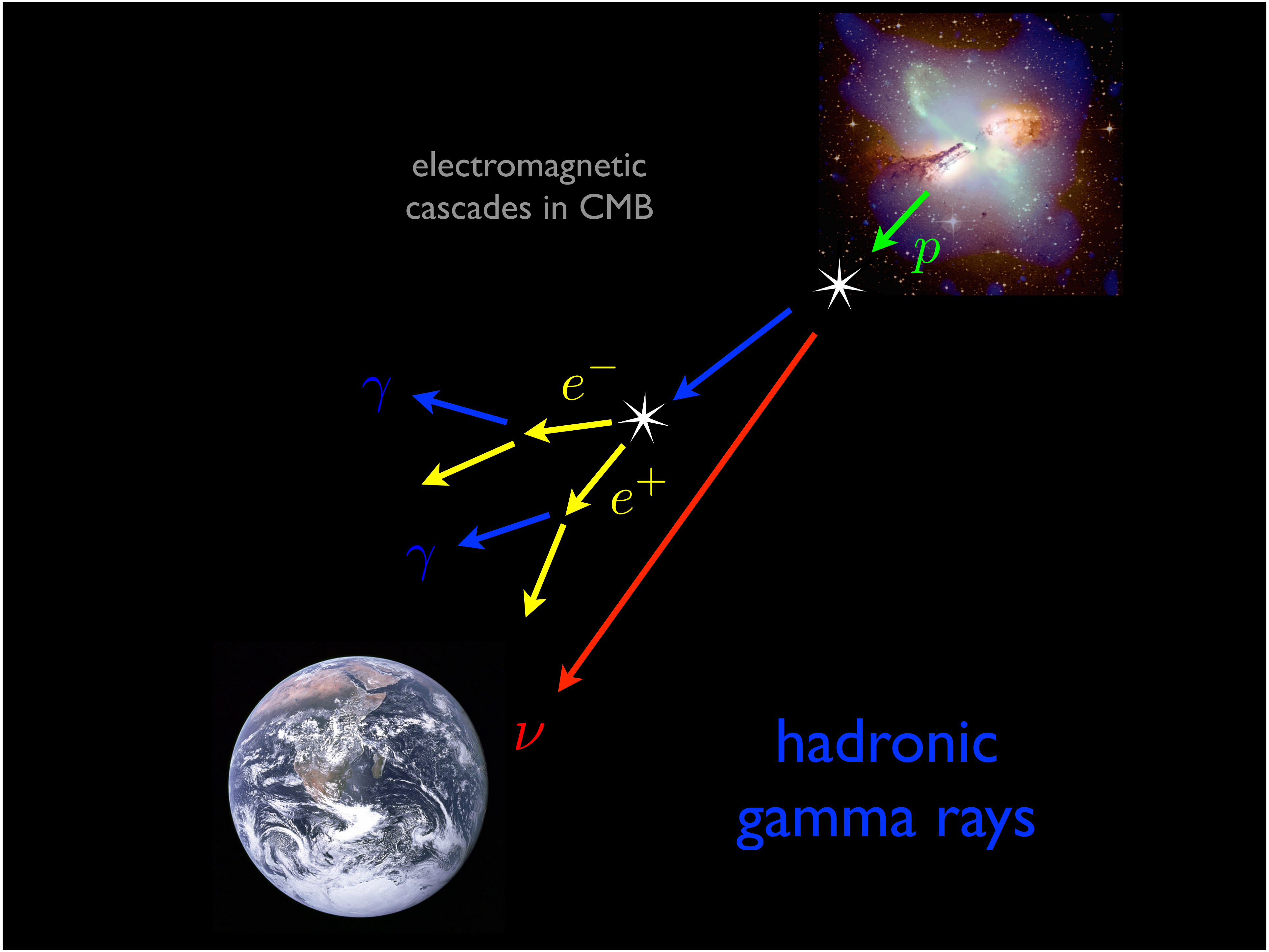

ν and γ beams : heaven and earth
accelerator is powered by
large gravitational energy
black hole
neutron star
proton
accelerator
target
radiation
and dust
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma
directional
beam
p, e±
magnetic
fields

hadronic gamma rays ?

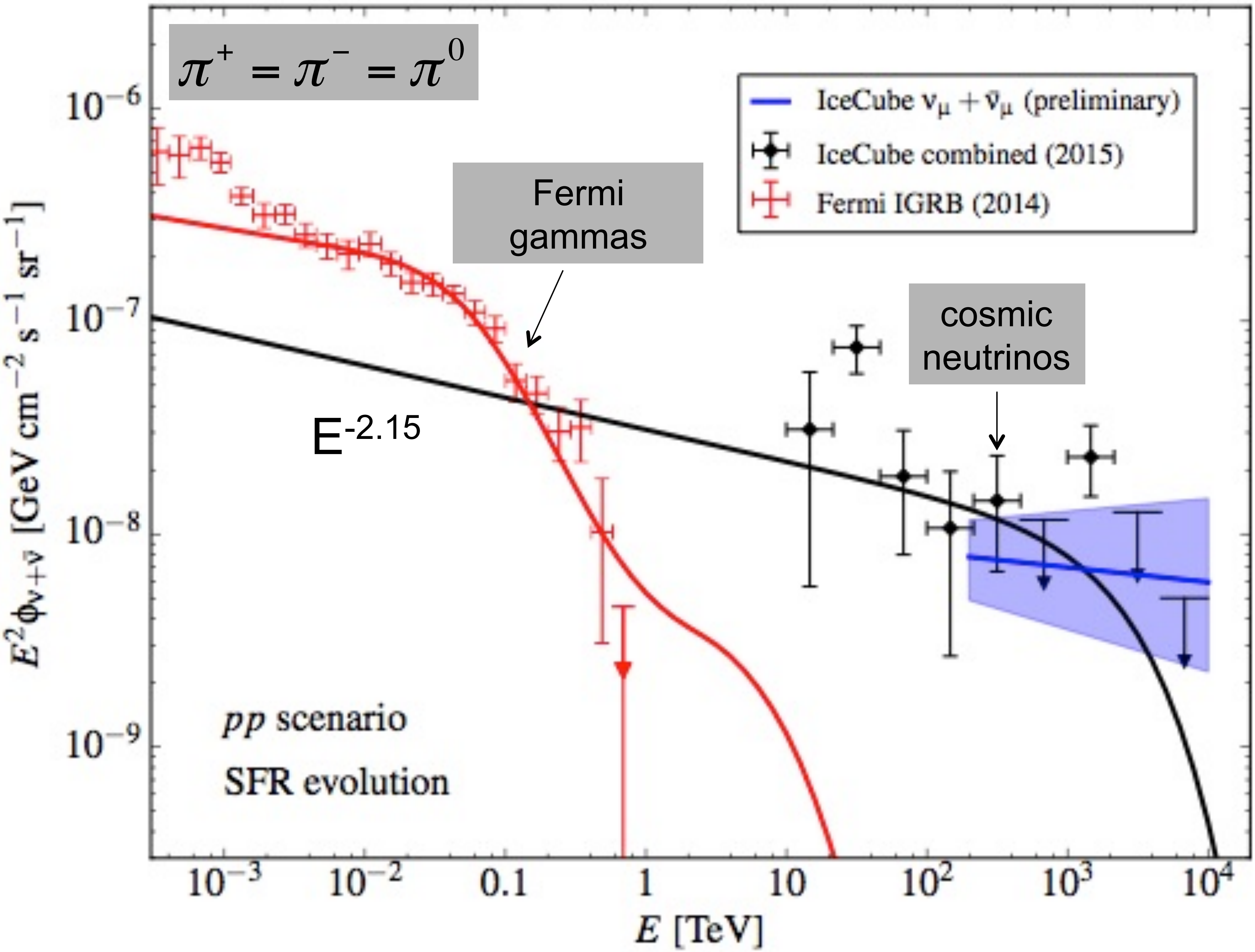
$\pi^+ = \pi^- = \pi^0$



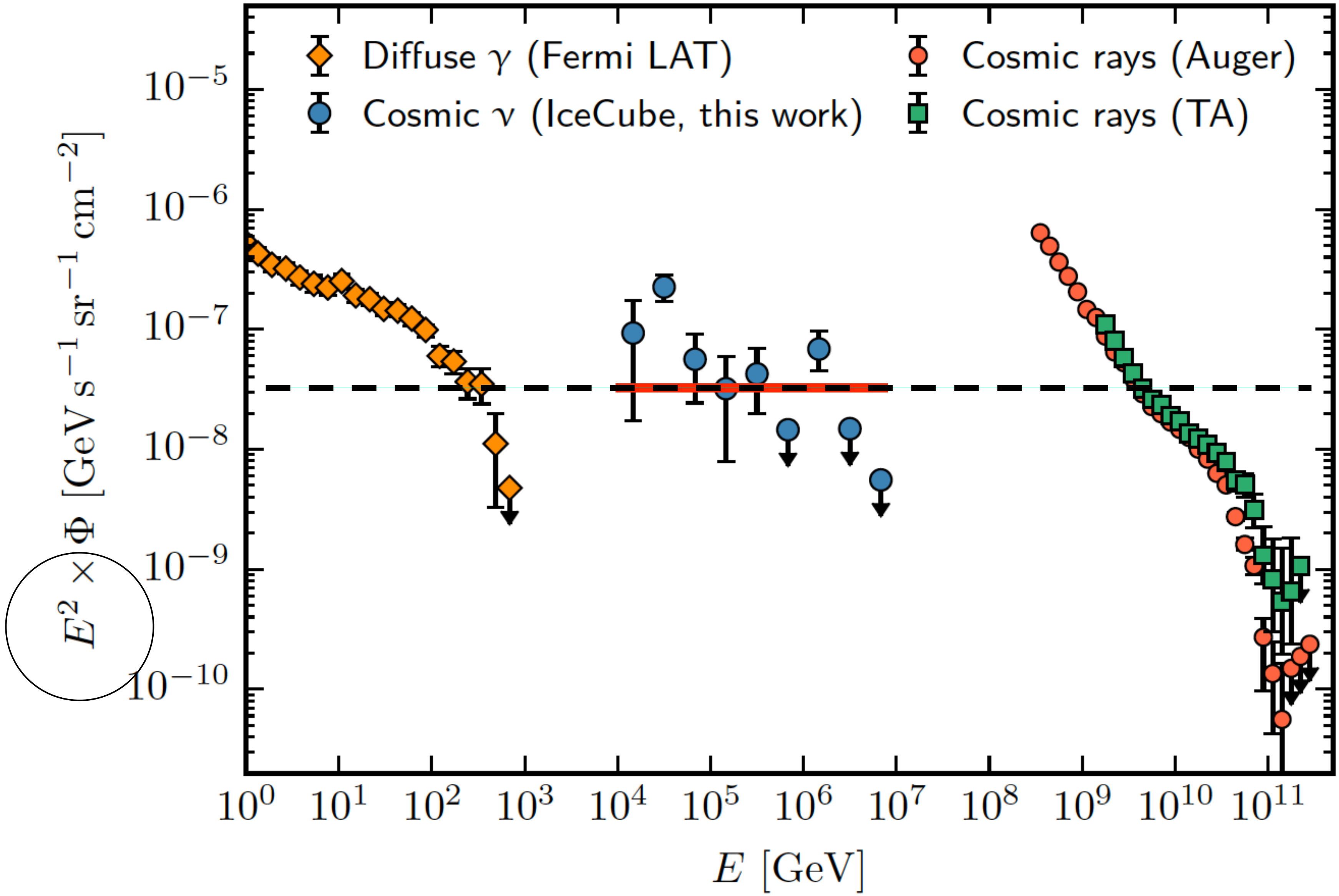
hadronic
gamma rays



electromagnetic
cascades in CMB
p
e^-
γ
e^+
γ
ν
hadronic
gamma rays



$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
10^4



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

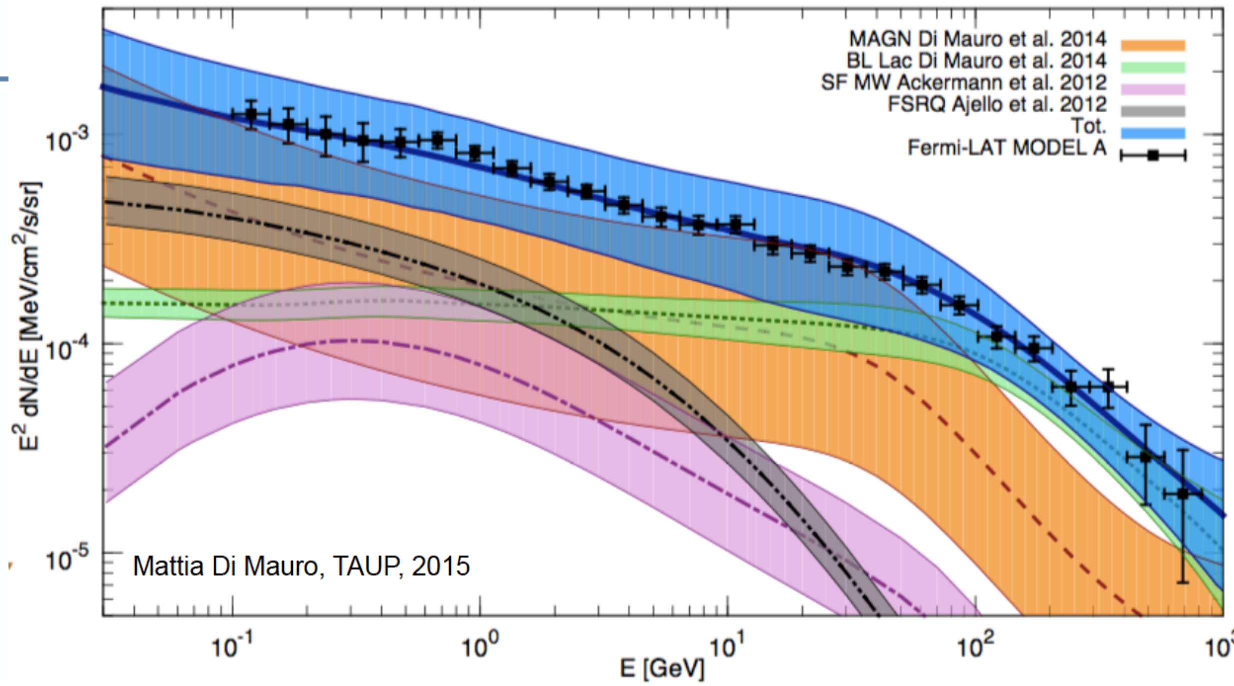
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

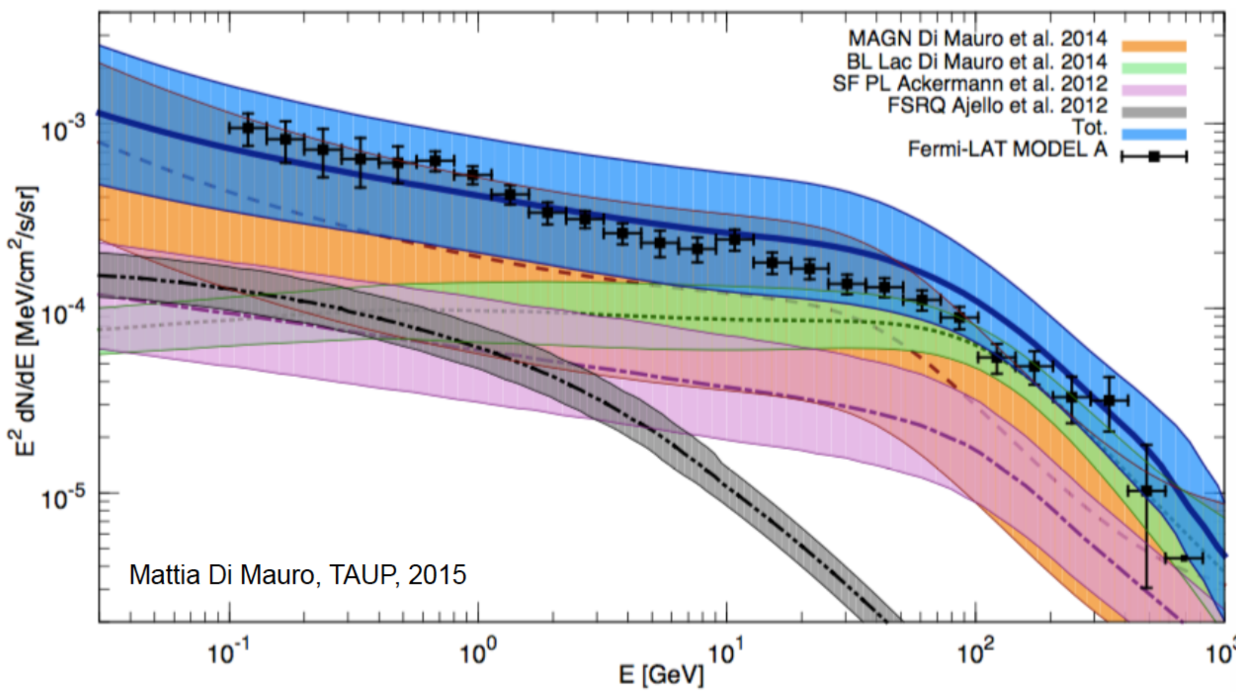
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)

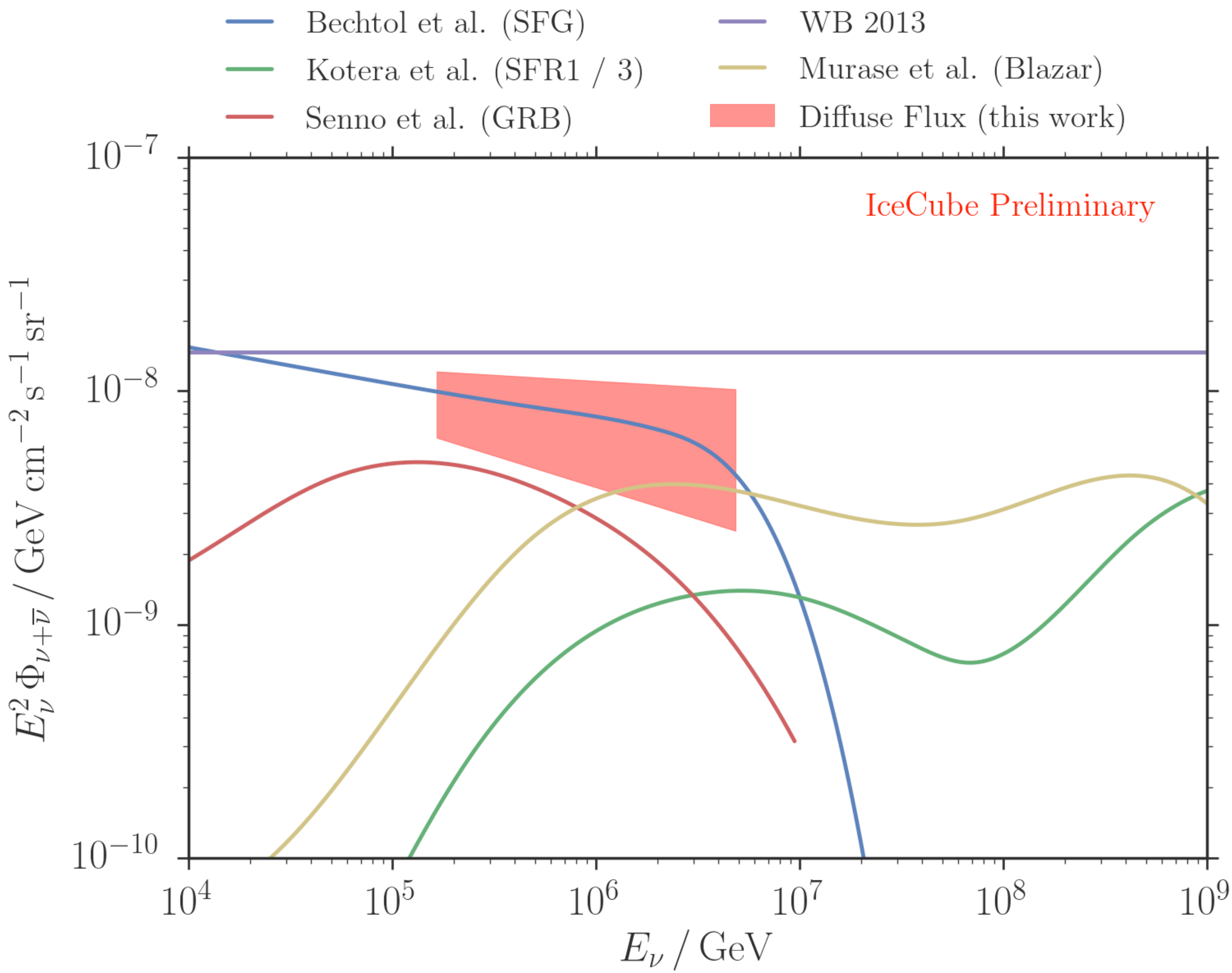
- at some level common Fermi-IceCube sources?

A census

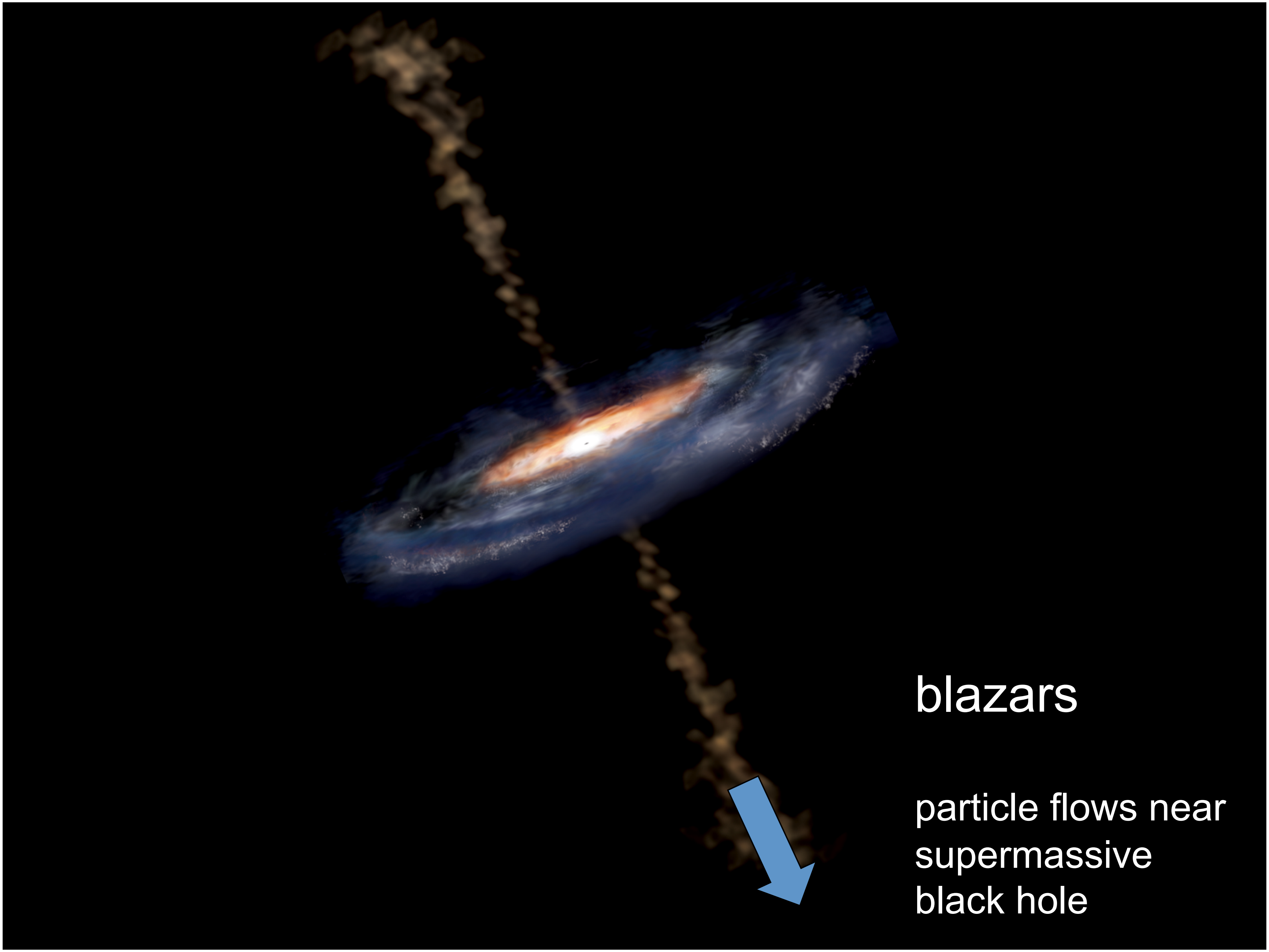
- BL Lac class of Blazars dominates the high-energy gamma-ray emission
  - 86% (+16%/-14%) above 50 GeV
- Large uncertainties in radio-galaxy and star-forming galaxy contributions
- Real diffuse contributions must be small
  - UHECR interactions
  - WIMP annihilation
  - etc.

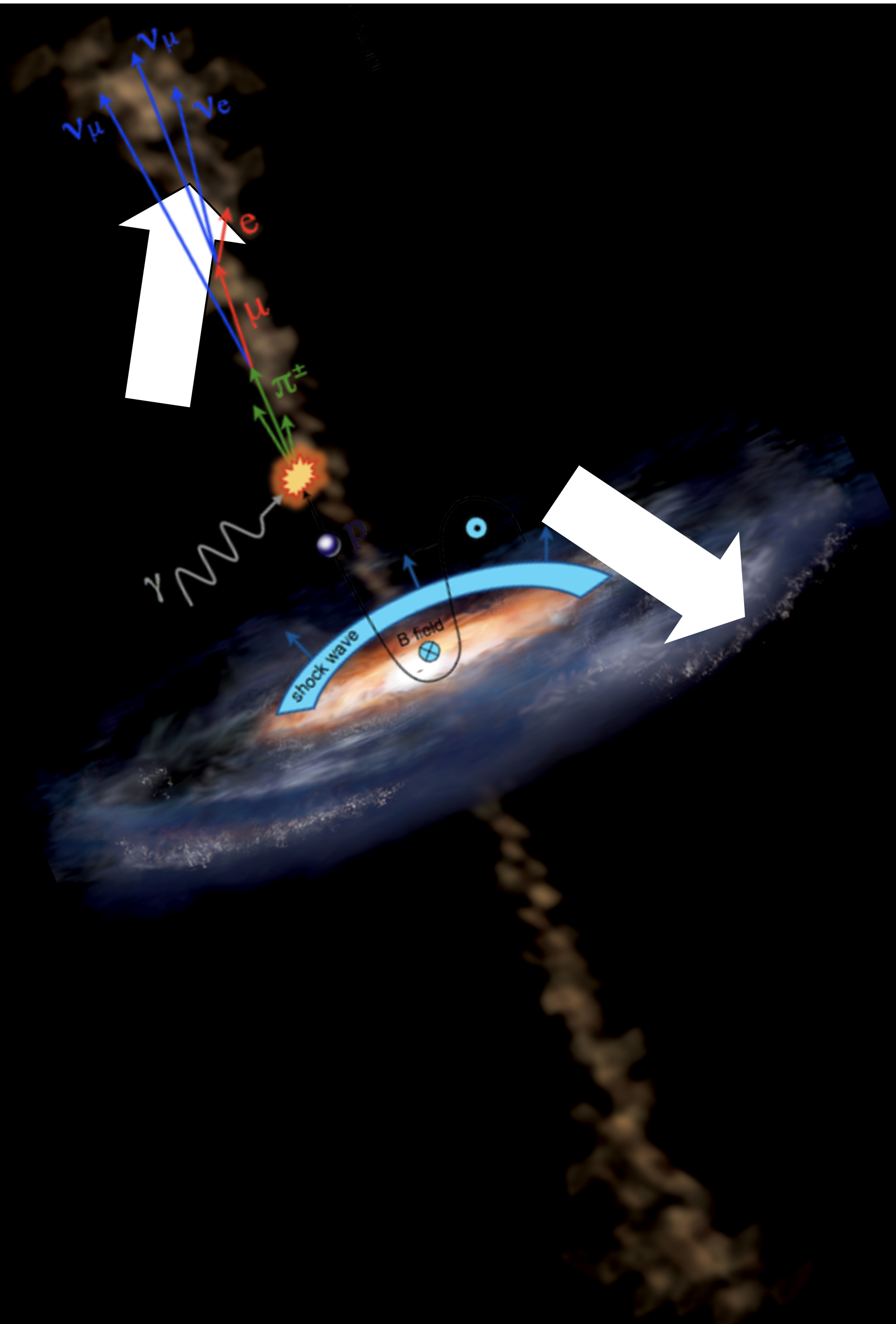






Bechtol et al. (SFG)
Kotera et al. (SFR1 / 3)
Senno et al. (GRB)
WB 2013
Murase et al. (Blazar)
Diffuse Flux (this work)
IceCube Preliminary
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$E_\nu^2\,\Phi_{\nu+\bar{\nu}}$ / GeV cm^{-2} s^{-1} sr^{-1}
10^4
10^5
10^6
10^7
10^8
10^9
E_ν / GeV


blazars
particle flows near supermassive black hole

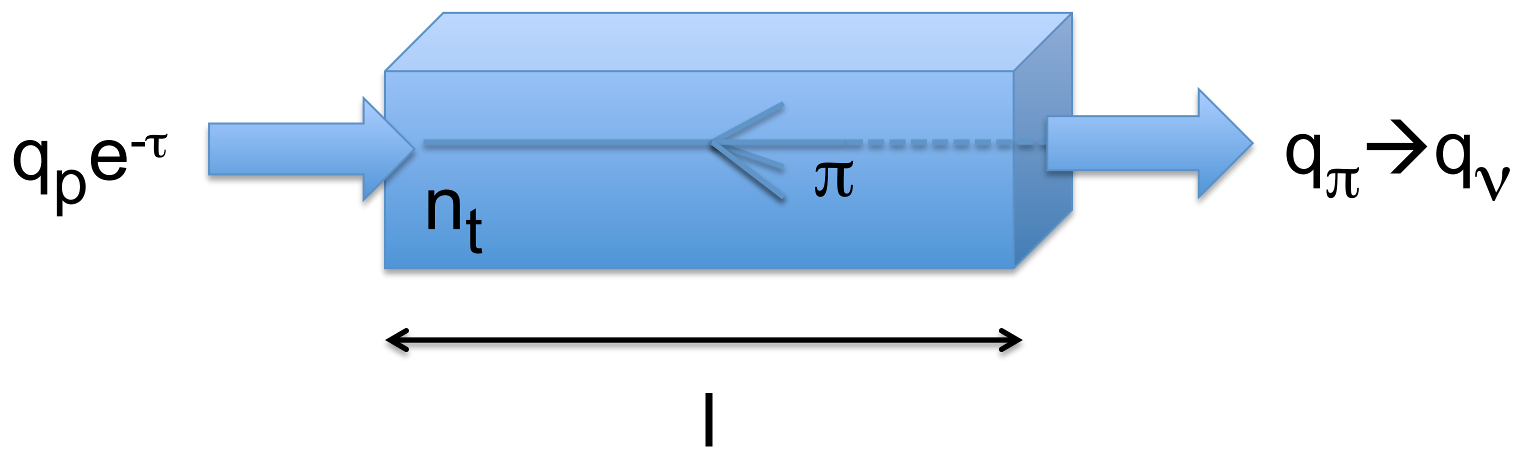


active galaxy

particle flows near
supermassive
black hole

neutrino-producing beam dump

$K_p E_p = n_\pi \langle E_\pi \rangle$



$$\pi \rightarrow \mu + \upsilon_\mu \rightarrow \{e + \overline{\upsilon_\mu} + \upsilon_e\} + \upsilon_\mu \quad \text{and} \quad \pi^0 \rightarrow \gamma + \gamma$$

3.1 Extragalactic Neutrino-Producing Beam Dumps

An active galaxy presents multiple opportunities for accelerating particles in the in- and outflows associated with the supermassive black hole. The high energy particles may subsequently produce neutrinos in interactions with multiple targets such as the dense matter near the black hole, the galactic disk of the galaxy associated with the black hole, photons produced in the jet or radiated from the accretion disk. It is therefore useful to start by considering a generic beam dump where a beam of protons an initial flux $j_{\rm p}\,(E_{\rm p})$ interacts with a target of density n over a distance l. The optical depth target after the proton travels a distance l' is given by:

$$\tau' = \frac{l'}{\lambda} = n l' \sigma_{pp}. \tag{8}$$

Each time a proton interacts it deposits $K_p E_p$ energy into $\langle n_\pi \rangle$ pions of average energy $\langle E_\pi \rangle$; here $K_p \simeq 0.2$ is the proton inelasticity. Energy conservation implies that

$$K_p E_p = E_\pi = \langle n_\pi \rangle \langle E_\pi \rangle . \tag{9}$$

The flux of pions produced per energy and time interval $q_{\pi^\pm}(E_\pi)$ is related to the proton interaction rate in the target $q_{\rm p}(E_{\rm p}, \tau)$ by

$$q_{\pi^\pm} = \int_{E_{\rm th}}^{\infty} dE_p \int_0^l dl'\, q_p\left(E_p, \tau'\right) \delta\left(E_\pi - \langle E_\pi \rangle\right) , \tag{10}$$

where $q_p\,(E_p\,, \tau) = j_p\,(E_p)\,\exp(-\tau)$ and $j_p\,(E_p)$ the incident proton flux entering the target. The delta function expresses the fact that all pions are produced with the same average energy $\langle E_\pi \rangle$.

Typically, one makes the approximations that the proton cross section is independent of energy, $\sigma_{pp} \approx 3 \cdot 10^{-26}$ cm^2, and as a result

$$q_{\pi^\pm} = \int_{E_{\rm th}}^{\infty} dE_{\rm p} \left(1 - \exp(-\tau)\right) \, j_p(E_p) \, \delta \left(E_\pi - \langle E_\pi \rangle\right) \, . \tag{11}$$

Two limiting cases are often relevant. When all protons interact $(1 - \exp(-\tau)) \rightarrow 1$. In other cases, the optical depth is small and $(1 - \exp(-\tau)) \rightarrow \tau$, with $\tau \simeq l \, n \, \sigma_{pp}$,

$$q_{\pi^\pm} = n \, l \, \sigma_{pp} \int_{E_{\rm th}}^{\infty} dE_p \, j_p \left(E_p\right) \, \delta \left(E_\pi - \langle E_\pi \rangle\right) \, . \tag{12}$$

The integral can be performed by rewriting the delta function as

$$\delta \left(E_\pi - \frac{K_p}{\langle n_\pi \rangle} E_p \right) = \frac{\langle n_\pi \rangle}{K_p} \delta \left(E_p - \frac{\langle n_\pi \rangle \langle E_\pi \rangle}{K_p} \right) \tag{13}$$

using Eq. 9. We thus obtain the result that

$$q_{\pi^\pm} = n \, l \, \sigma_{pp} \, \langle n_\pi \rangle \, \frac{1}{f_\pi} \, j_p \left(E_p\right) \, , \tag{14}$$

with $f_\pi = K_p = E_\pi / E_p$, the fraction of the incident proton energy going into pions, using a more common notation. Note that in the case of a target where all protons interact, i.e. $(1 - \exp(-\tau)) \rightarrow 1$, we obtain the relations that reflect particle and energy conservation:

summary: emissivity (units: per GeV per second) in pions produced by accelerated cosmic rays interacting with a target density *n* per cm^3 per second over a distance of target *l*

$$q_{\pi^\pm} = \int_{E_{\rm th}}^{\infty} dE_p \int_0^l dl' \, q_p\left(E_p, \tau'\right) \, \delta\left(E_\pi - \langle E_\pi \rangle\right)$$

$$q_\pi \cong n_{cr} \left(\frac{l}{\lambda_{\rm int}}\right) \cong \frac{1}{K_\pi} < n_\pi > n_{cr} \, n \, l \, \sigma_{pp}$$

generic beam dump formula

neutral pions

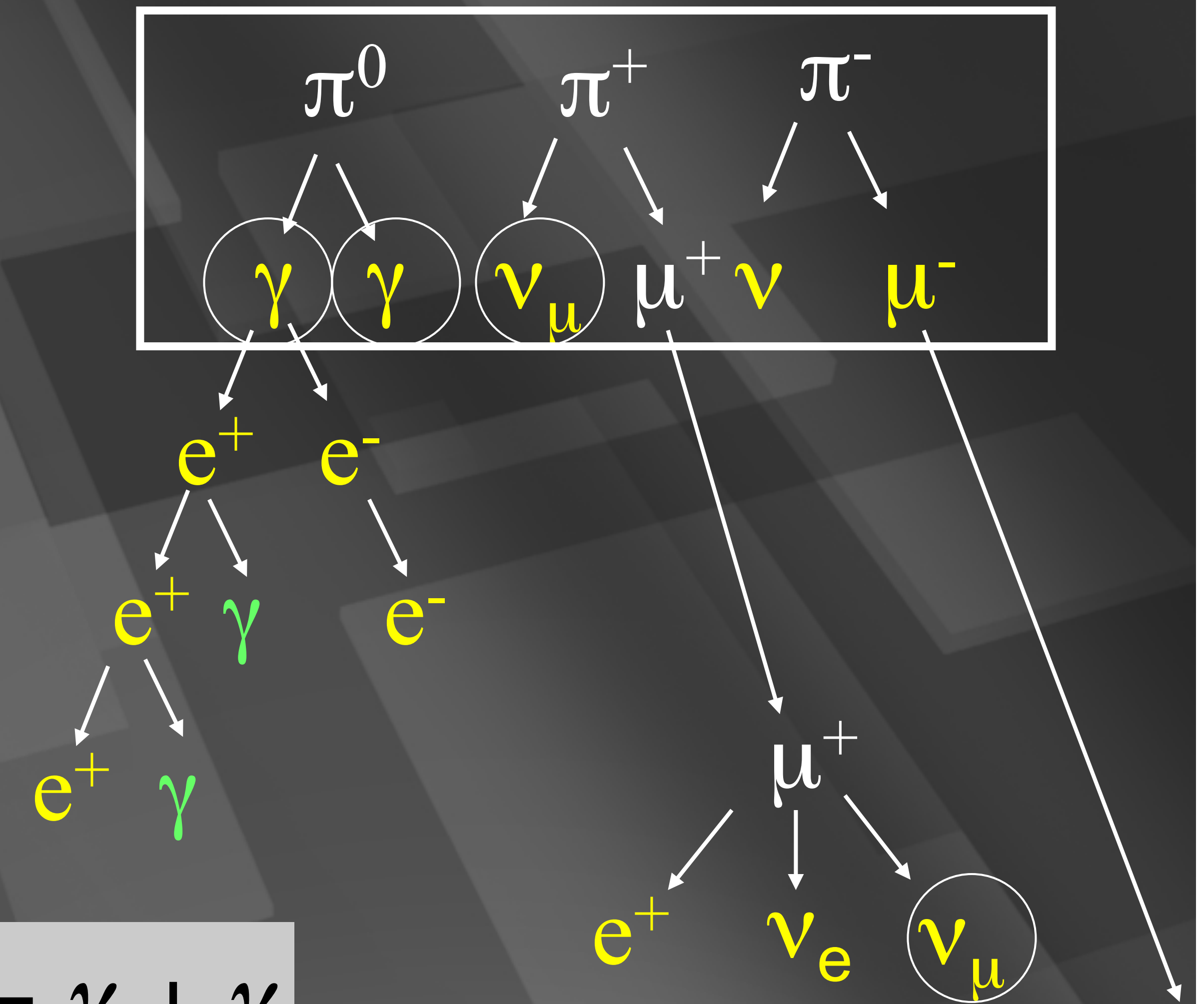
are observed as

gamma rays

charged pions

are observed as

neutrinos



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

AGN as plausible cosmic beam dump:

beam | target

- *arXiv:1406.0506 [astro-ph.HE] Tjus et al.*

beam	target
protons normalized to total radio flux	high column density of FR-I near black hole

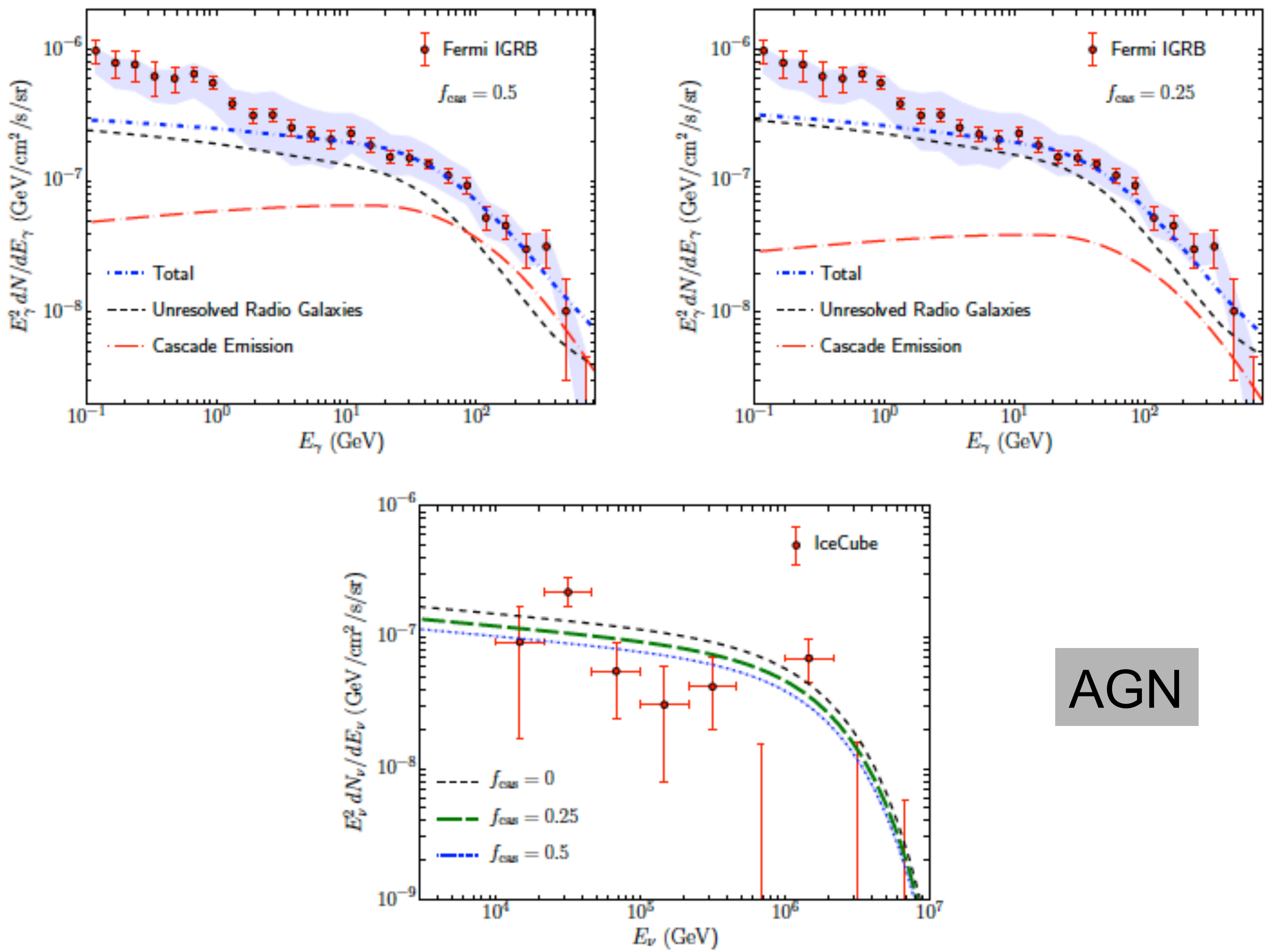
- *arXiv:1604.08505 [astro-ph.HE] Hooper*

beam	target
protons normalized to Fermi diffuse extragalactic flux	diffusion in the galactic plane of the galaxy

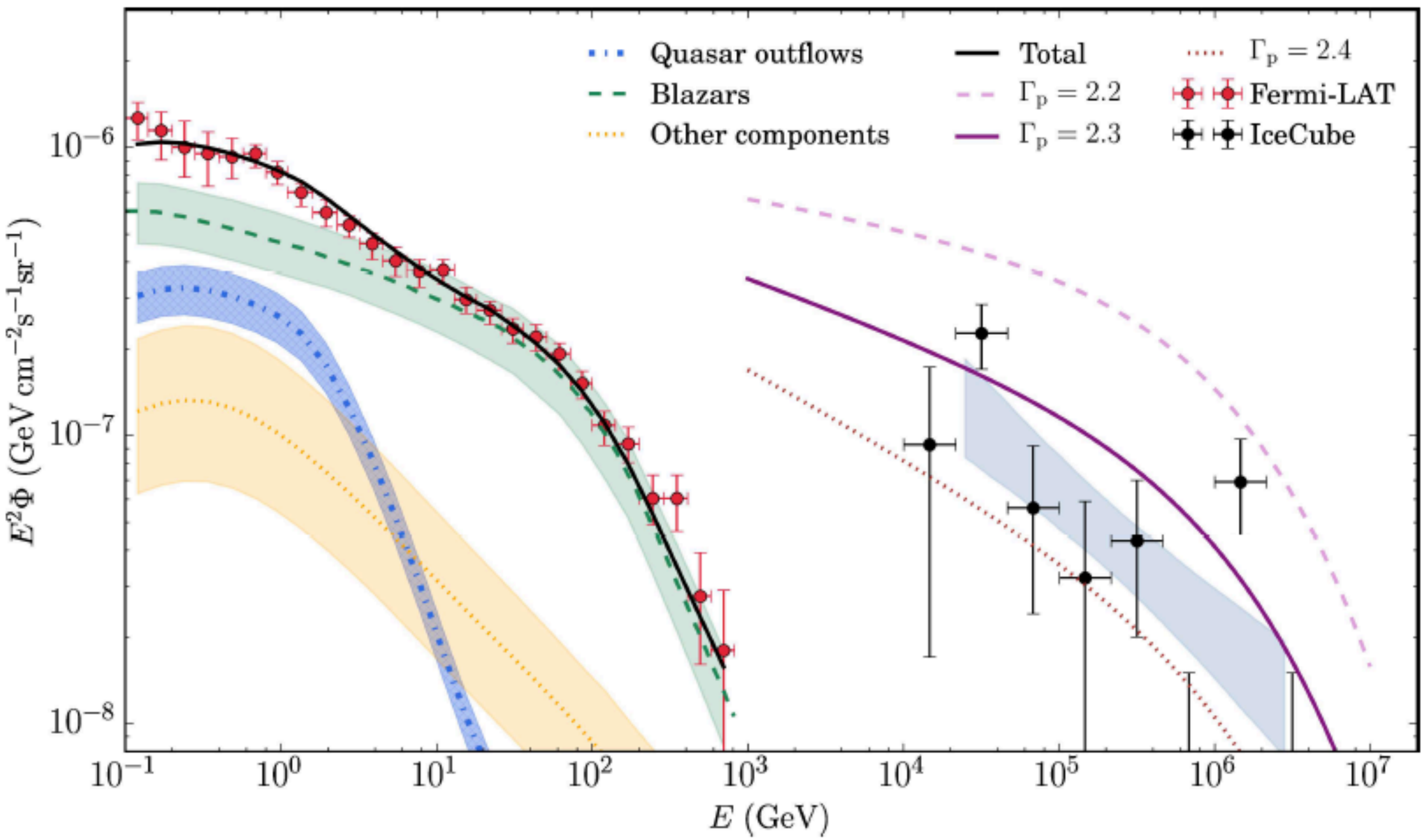
- *arXiv:1607.06476 [astro-ph.HE] Loeb*

beam	target
quasar outflows normalized to Fermi extragalactic flux	interstellar protons

"I can paint like Titian, only the details are missing" W. Pauli


Fermi IGRB
$f_{cas} = 0.5$
Total
Unresolved Radio Galaxies
Cascade Emission
$E_\gamma^2\, dN/dE_\gamma$ (GeV/cm^2/s/sr)
E_γ (GeV)
Fermi IGRB
$f_{cas} = 0.25$
Total
Unresolved Radio Galaxies
Cascade Emission
$E_\gamma^2\, dN/dE_\gamma$ (GeV/cm^2/s/sr)
E_γ (GeV)
IceCube
$f_{cas} = 0$
$f_{cas} = 0.25$
$f_{cas} = 0.5$
$E_\nu^2\, dN_\nu/dE_\nu$ (GeV/cm^2/s/sr)
E_ν (GeV)

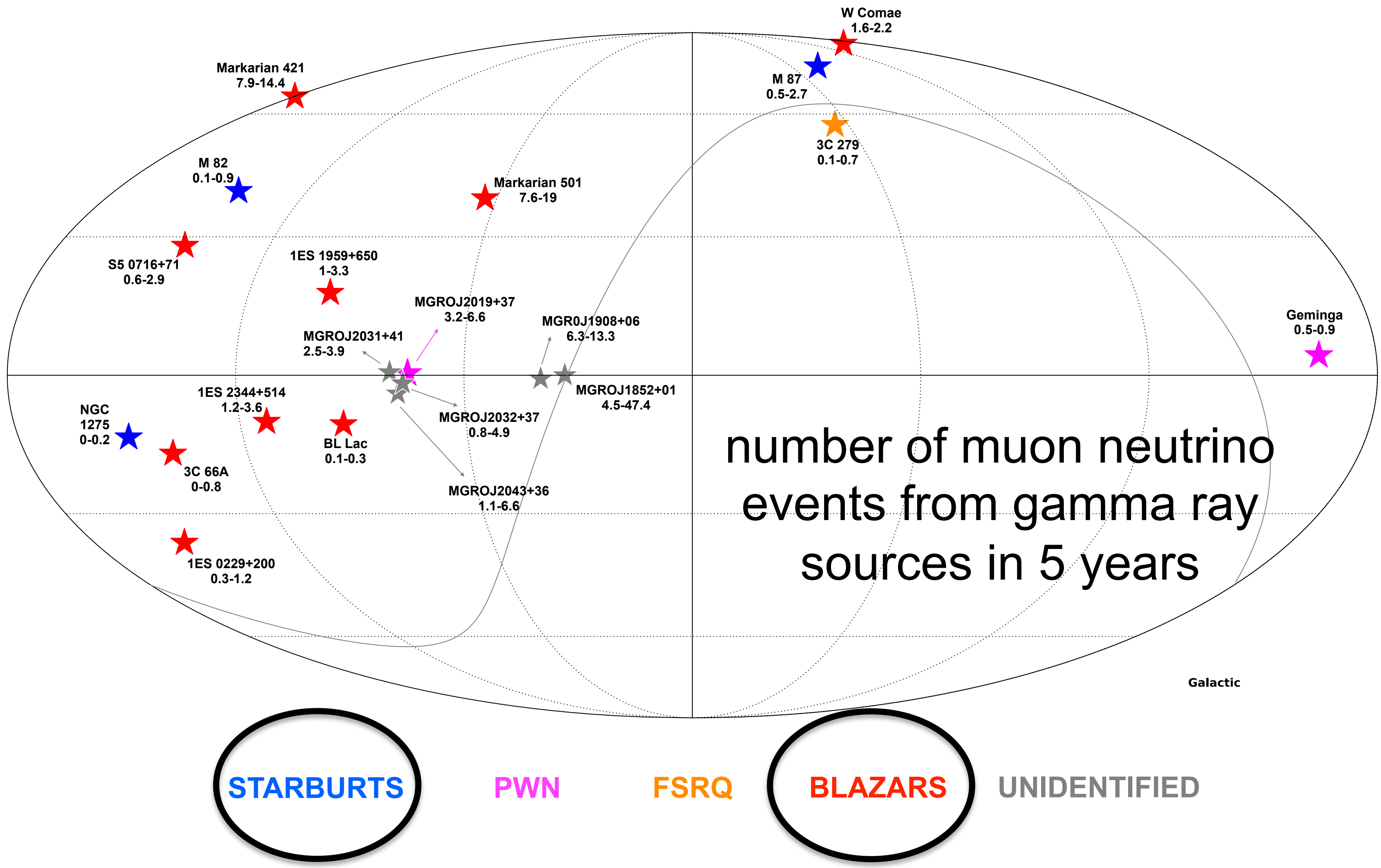
AGN



Quasar outflows
Blazars
Other components
Total
$\Gamma_p = 2.2$
$\Gamma_p = 2.3$
$\Gamma_p = 2.4$
Fermi-LAT
IceCube
$E^2\Phi$ (GeV cm^{-2}s^{-1}sr^{-1})
E (GeV)
10^{-6}
10^{-7}
10^{-8}
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7

QUASARS

photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters

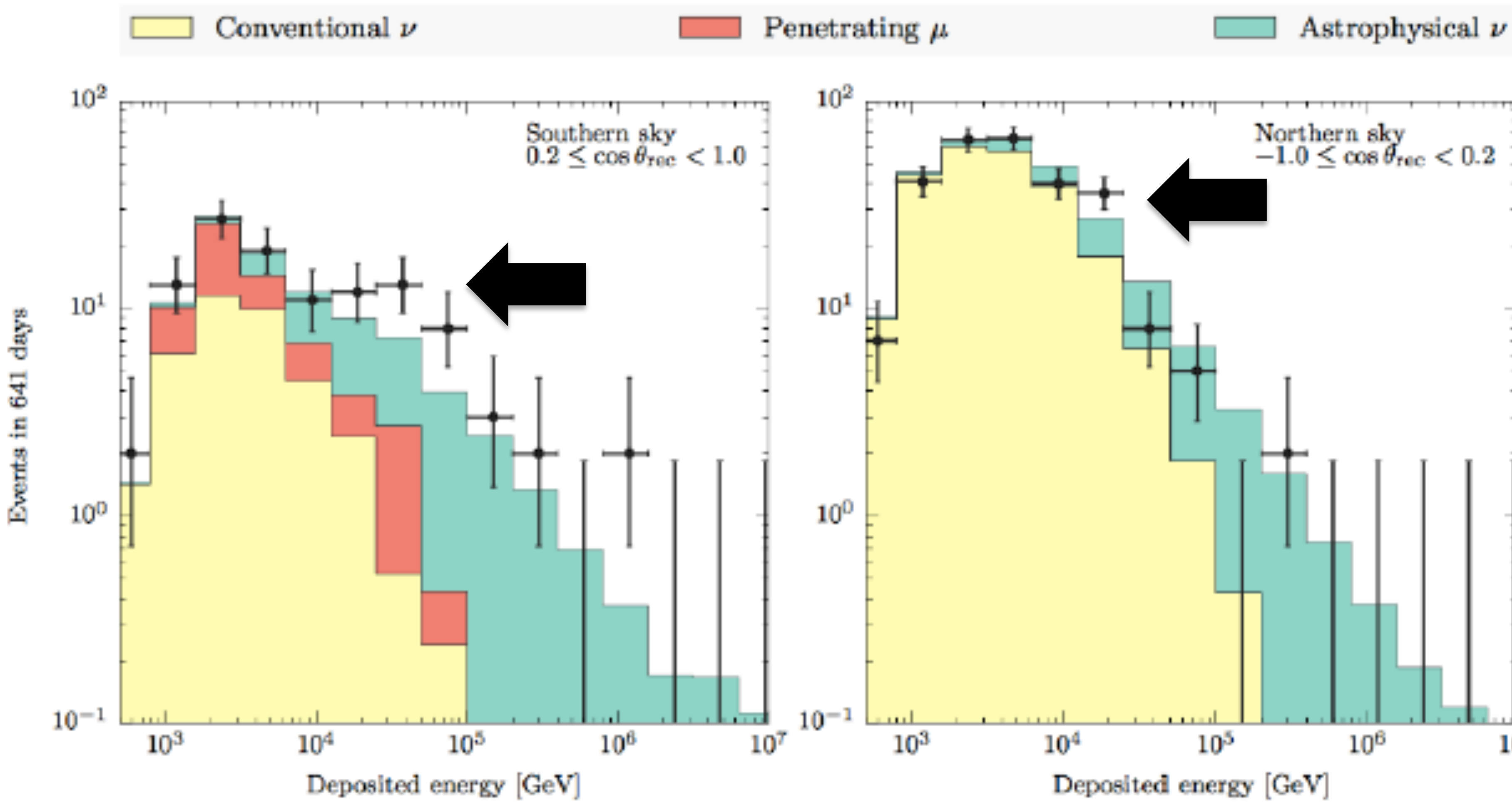


	Type	Origin	Flux Seen by	Min #Events	Max #Events	flux ratio	Integration bound [TeV]	cut off
MGRO J2031+41	UNID	Galactic	MILAGRO	2.5	3.9	-	$1\text{-}10^3$	✓
MGRO J2019+37	PWN	Galactic	MILAGRO	3.2	6.6	-	$1\text{-}10^3$	✓
MGRO J1908+06	UNID	Galactic	MILAGRO	6.3	13.3	-	$1\text{-}10^3$	✓
MGRO J1852+01	UNID	Galactic	MILAGRO	4.5	47.4	-	$1\text{-}10^3$	✓
MGRO J2032+37	UNID	Galactic	MILAGRO	0.8	4.9	-	$1\text{-}10^3$	✓
MGRO J2043+36	UNID	Galactic	MILAGRO	1.1	6.6	-	$1\text{-}10^3$	✓
Markarian 421	Blazar	Extragalactic	MAGIC	7.9	14.4	2.1	$0.25\text{-}10^3$	✓
M 87	Starburst	Extragalactic	MAGIC	0.5	2.7	0.13	0.1-Infinity	-
Geminga	PWN	Galactic	MILAGRO	0.5	0.9	0.08	17.5-Infinity	-
S5 0716+71	Blazar	Extragalactic	MAGIC	0.6	2.9	0.3	0.2-Infinity	-
1ES 1959+650	Blazar	Extragalactic	MAGIC	1.0	3.3	0.4	0.3-Infinity	-
1ES 2344+514	Blazar	Extragalactic	VERITAS/MAGIC	1.2	3.6	0.8	0.175-Infinity	-
3C 66A	Blazar	Extragalactic	MAGIC	0	0.8	0.4	0.1-Infinity	-
BL Lac	Blazar	Extragalactic	MAGIC	0.1	0.3	0.2	0.1-Infinity	-
W Comae	Blazar	Extragalactic	VERITAS	1.6	2.2	1.9	0.2-Infinity	-
Markarian 501	Blazar	Extragalactic	AGRO	7.6	19	1.7	0.15-Infinity	-
3C 279	FSRQ	Extragalactic	MAGIC	0.1	0.7	1.5	0.25-Infinity	-
1ES 0229+200	Blazar	Extragalactic	HESS	0.3	1.2	0.1	0.58-Infinity	-
M 82	Starburst	Extragalactic	VERITAS	0.1	0.9	0.02	0.35-Infinity	-
NGC 1257	Starburst	Extragalactic	MAGIC	0	0.2	0.18	0.1-Infinity	-

The minimum and maximum expected number of events from interesting sources in 5 years of IC86. The neutrino fluxes are estimated from Gamma ray flux assuming pp interaction at the source. The flux ratio is Integrated Gamma ray flux above threshold energy divided by 90% confidence level neutrino flux limit from 4-year point search of IceCube with a factor 2. The flux used for the W Comae is based on the fitted flux of the flares in different years.

- there is more

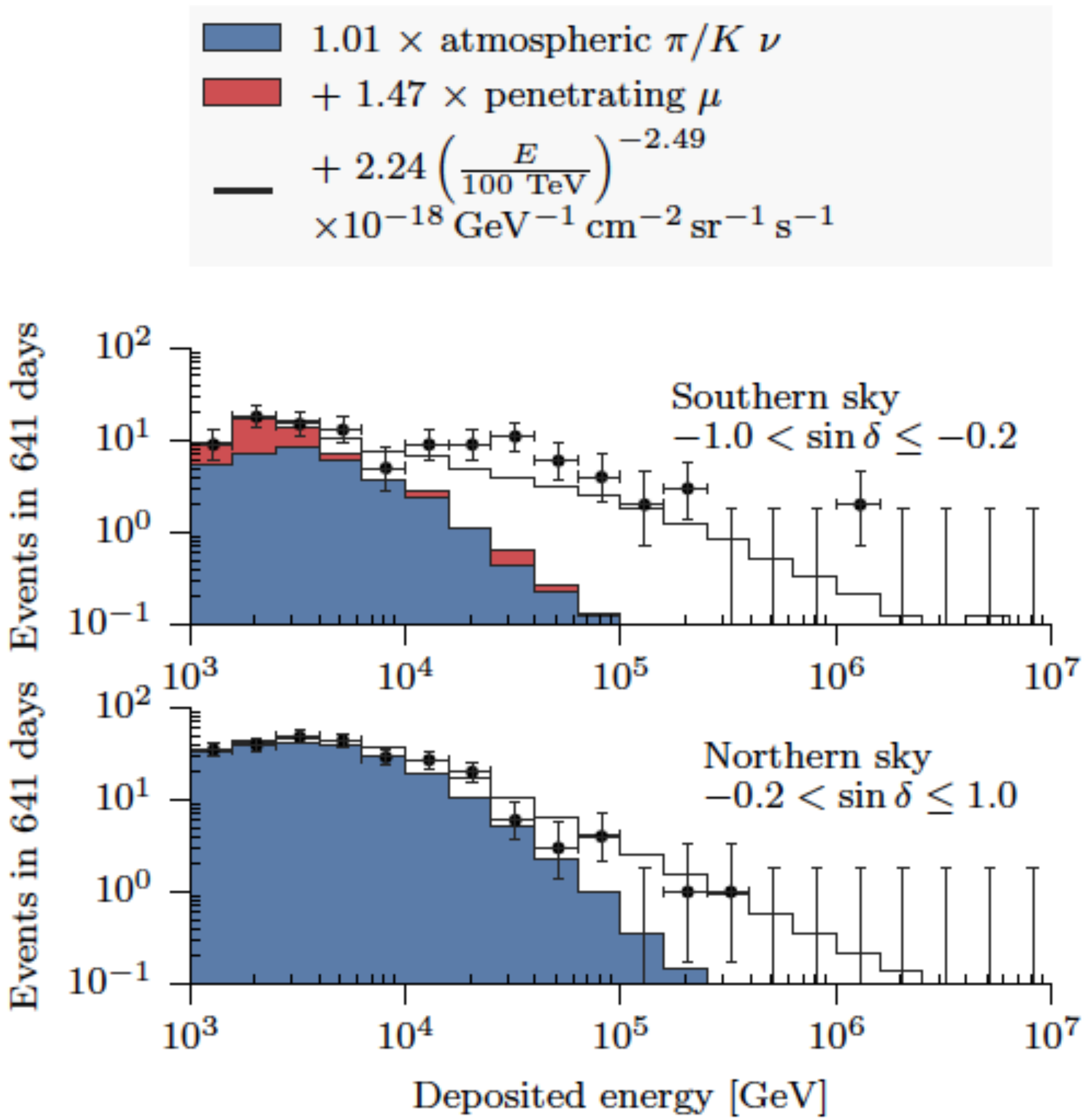
towards lower energies: a second component?



warning:

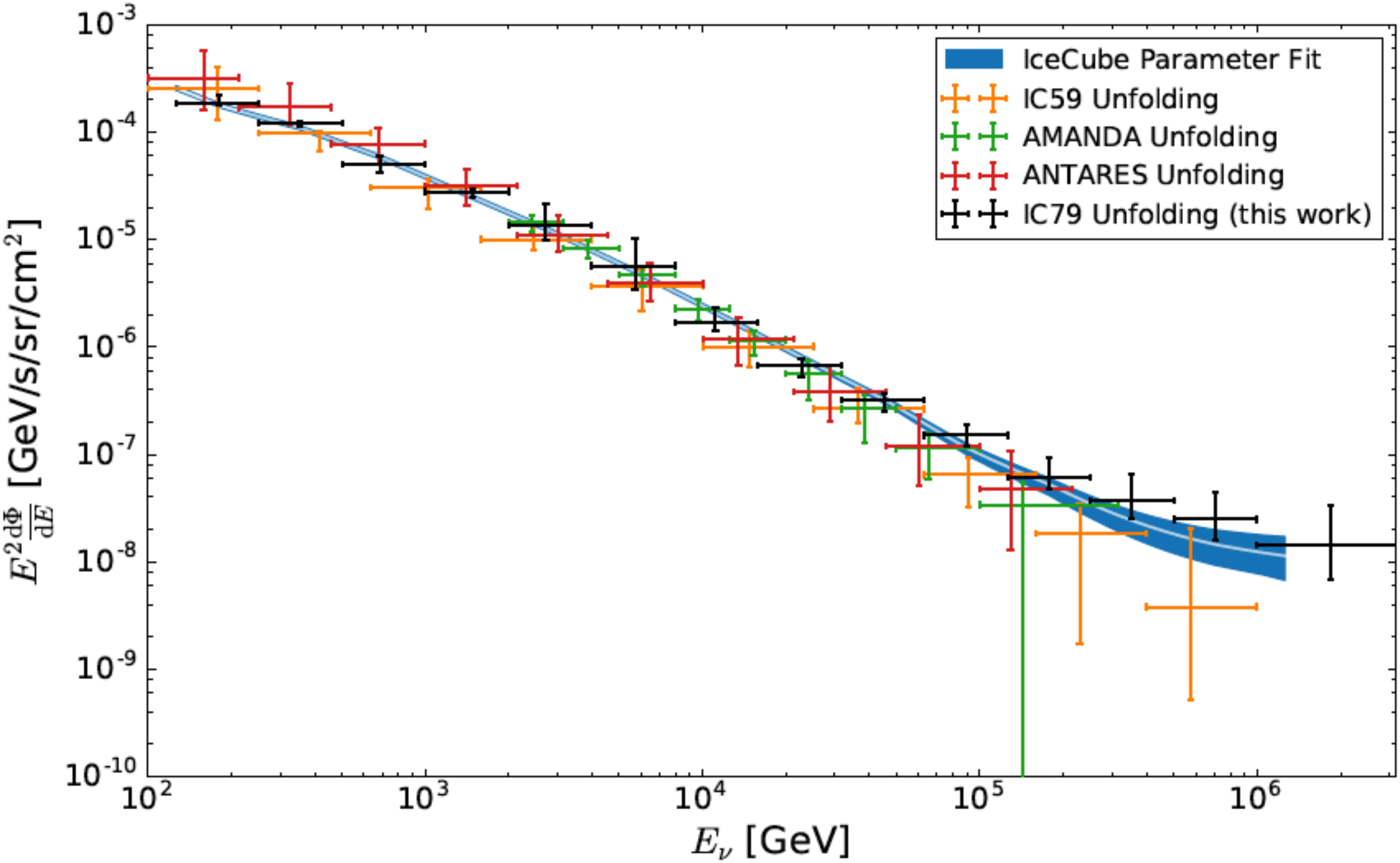
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

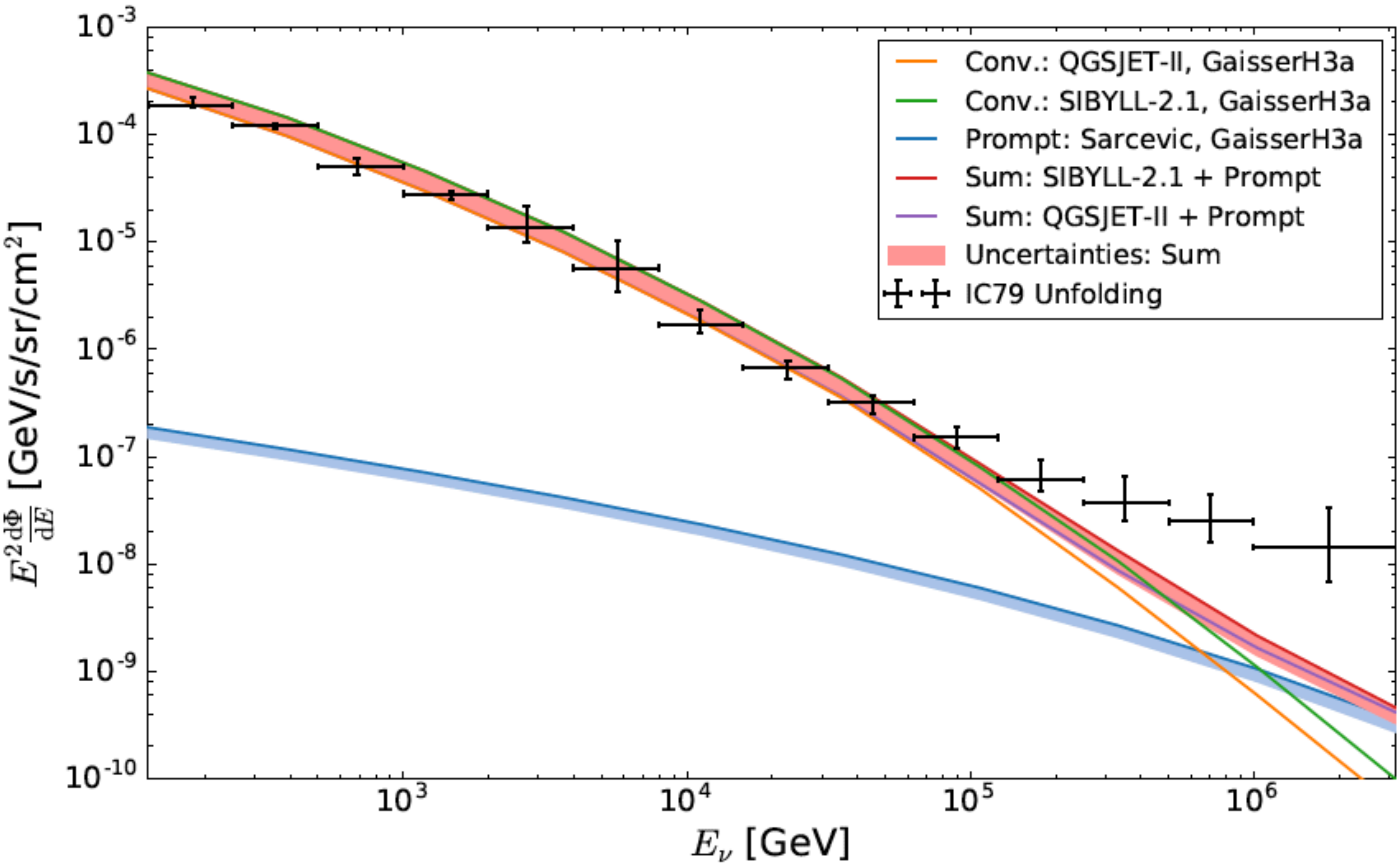


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
$+ 2.24 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.49} \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$
Southern sky
$-1.0 < \sin\delta \leq -0.2$
Northern sky
$-0.2 < \sin\delta \leq 1.0$
Events in 641 days
Deposited energy [GeV]

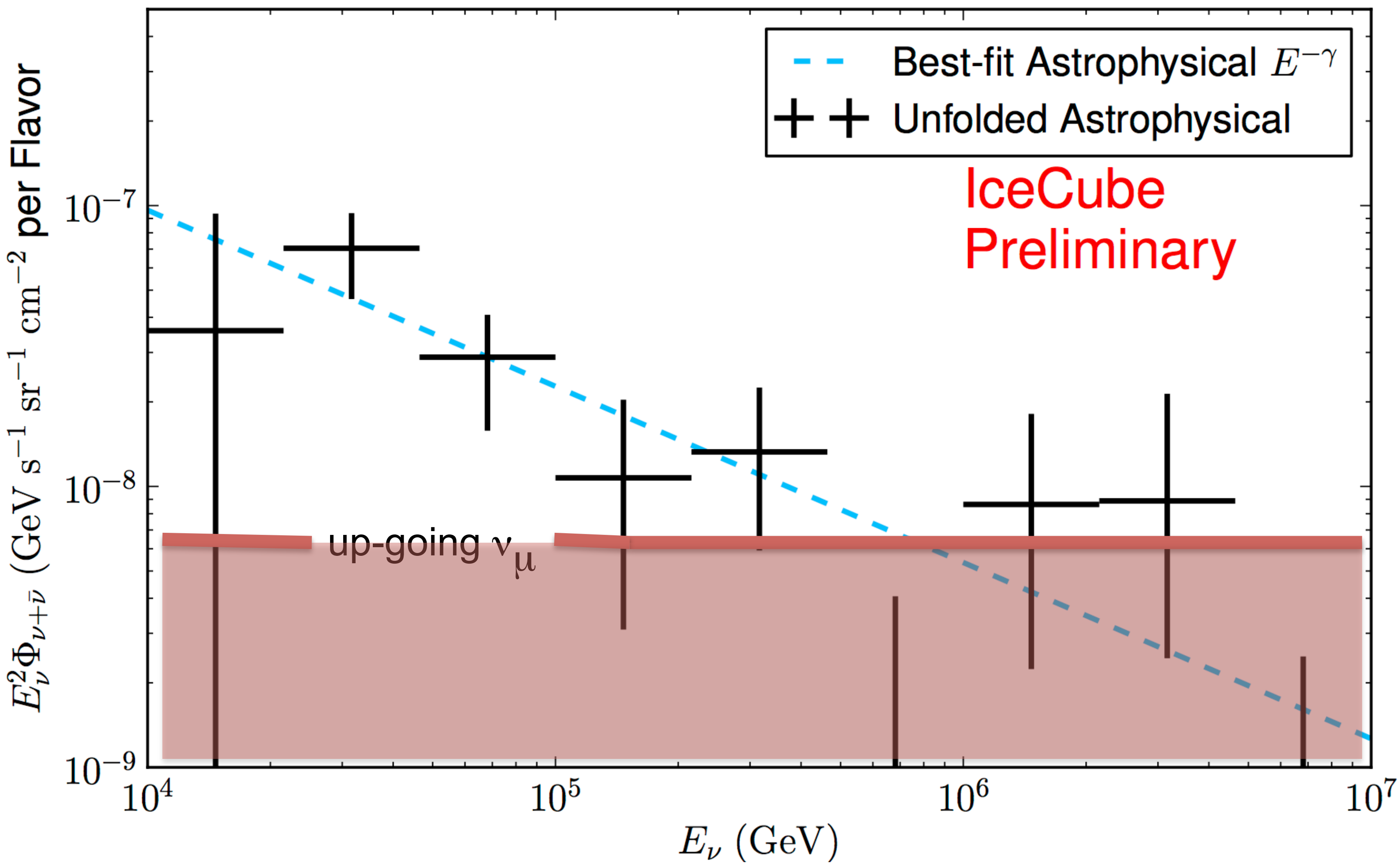
unfolded “atmospheric” neutrino flux



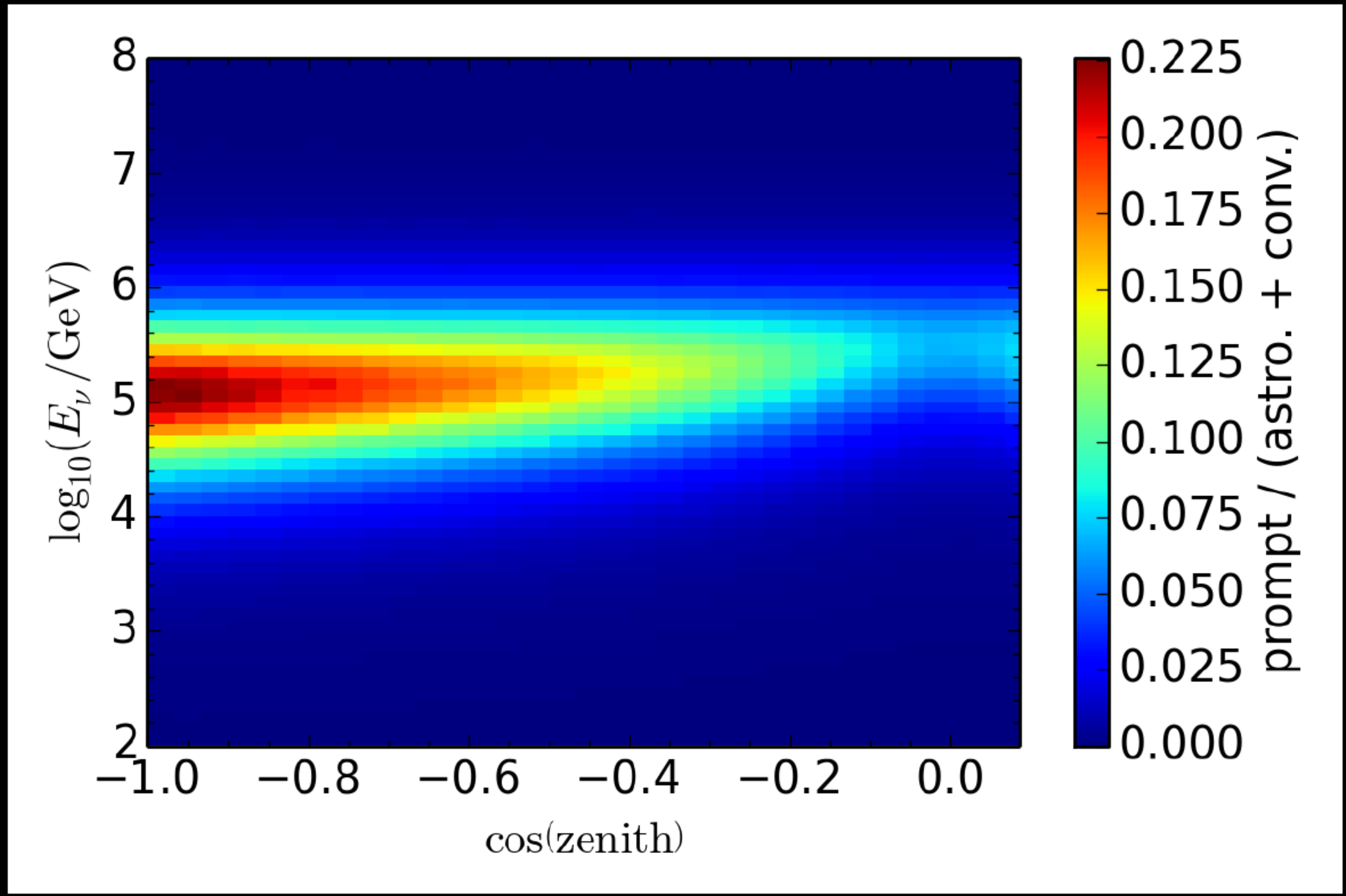
unfolded "atmospheric" neutrino flux



yet lower energies….



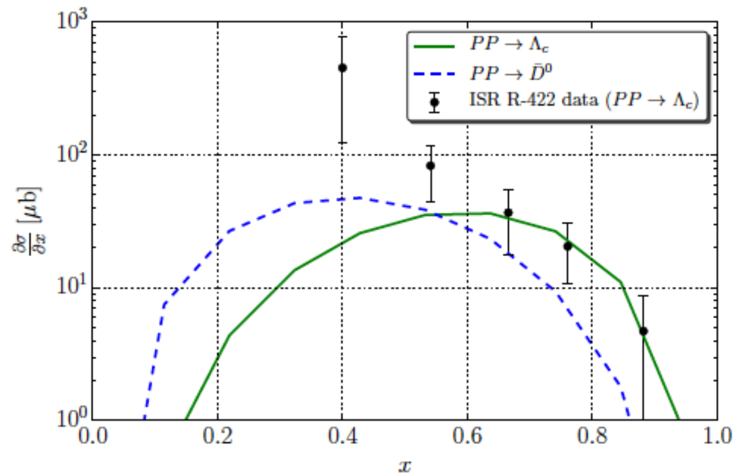
not atmospheric charm



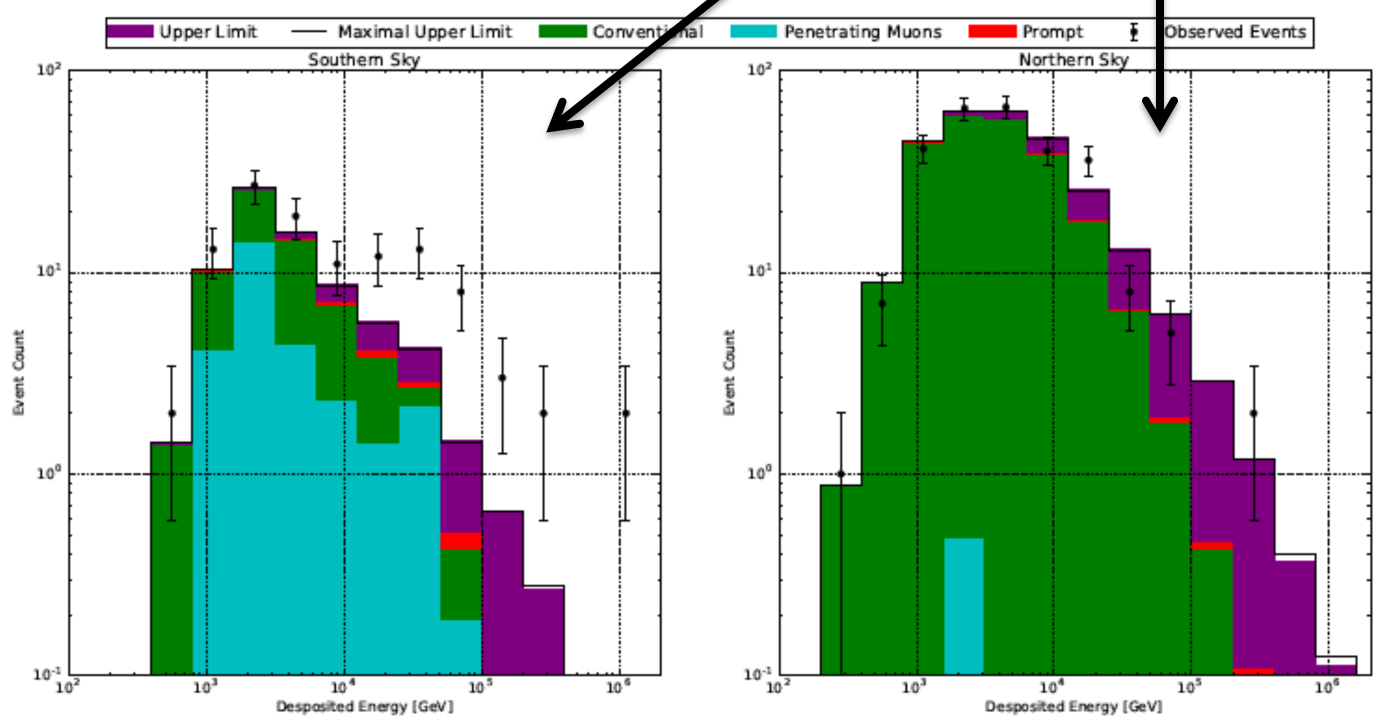
- Prompt flux would appear @ around 100 TeV
  → ~ 20% effect in straight up-going region

not forward charm production

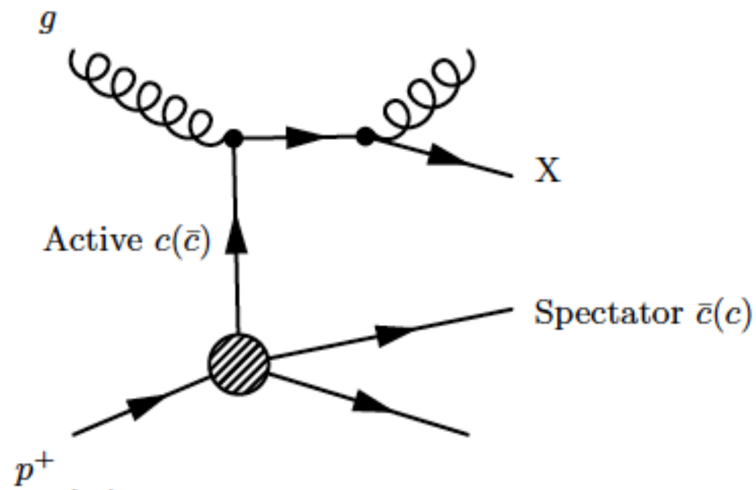
analogous to pp→(K⁺Λ)p



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

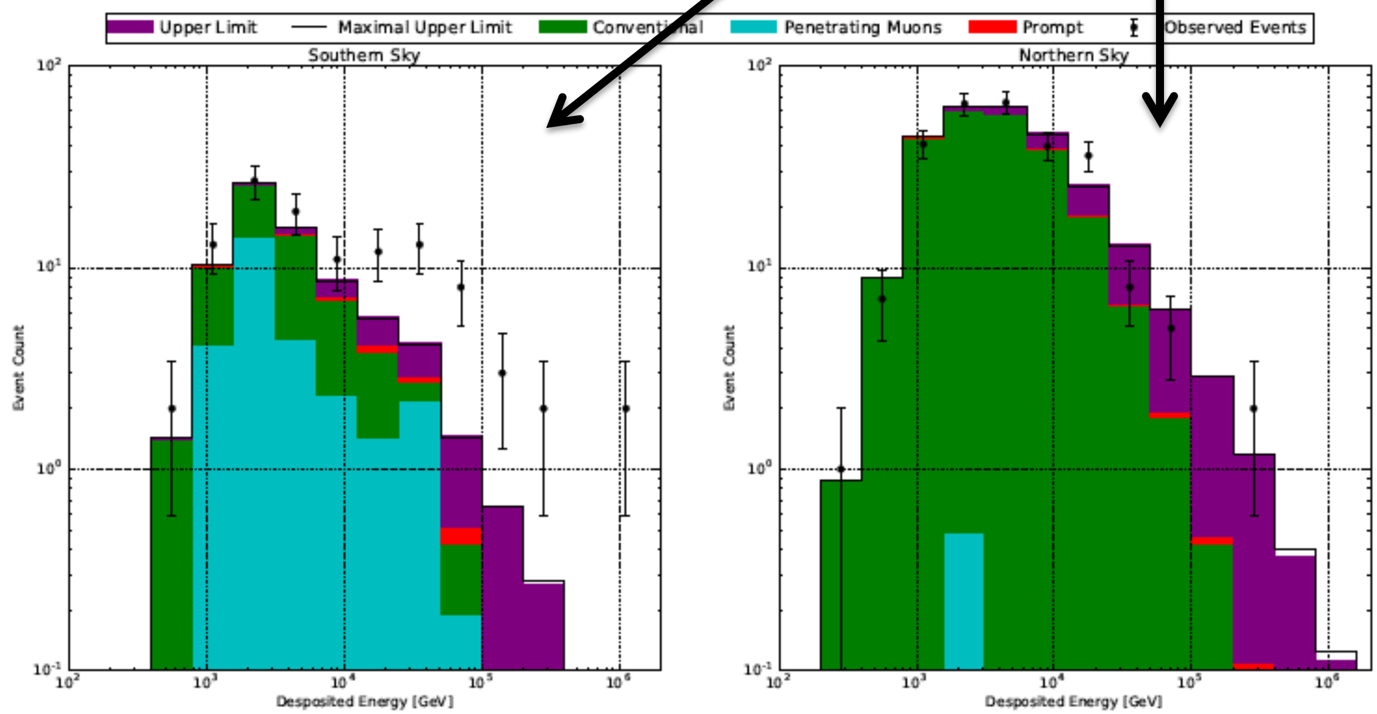


LHC: charm pairs in proton

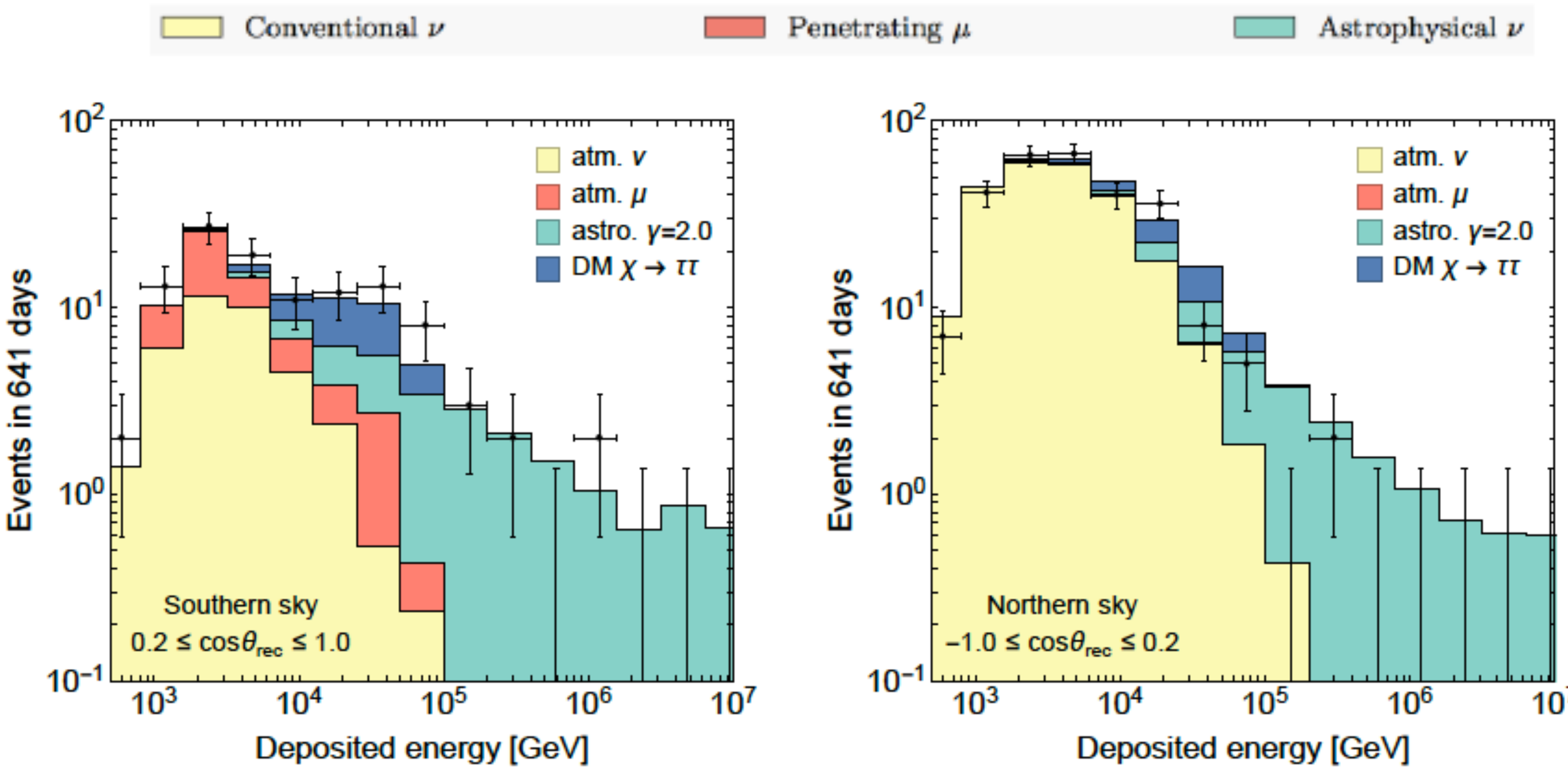


analogous to pp→($K^+\Lambda$)p

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



towards lower energies: a second component?



warning:

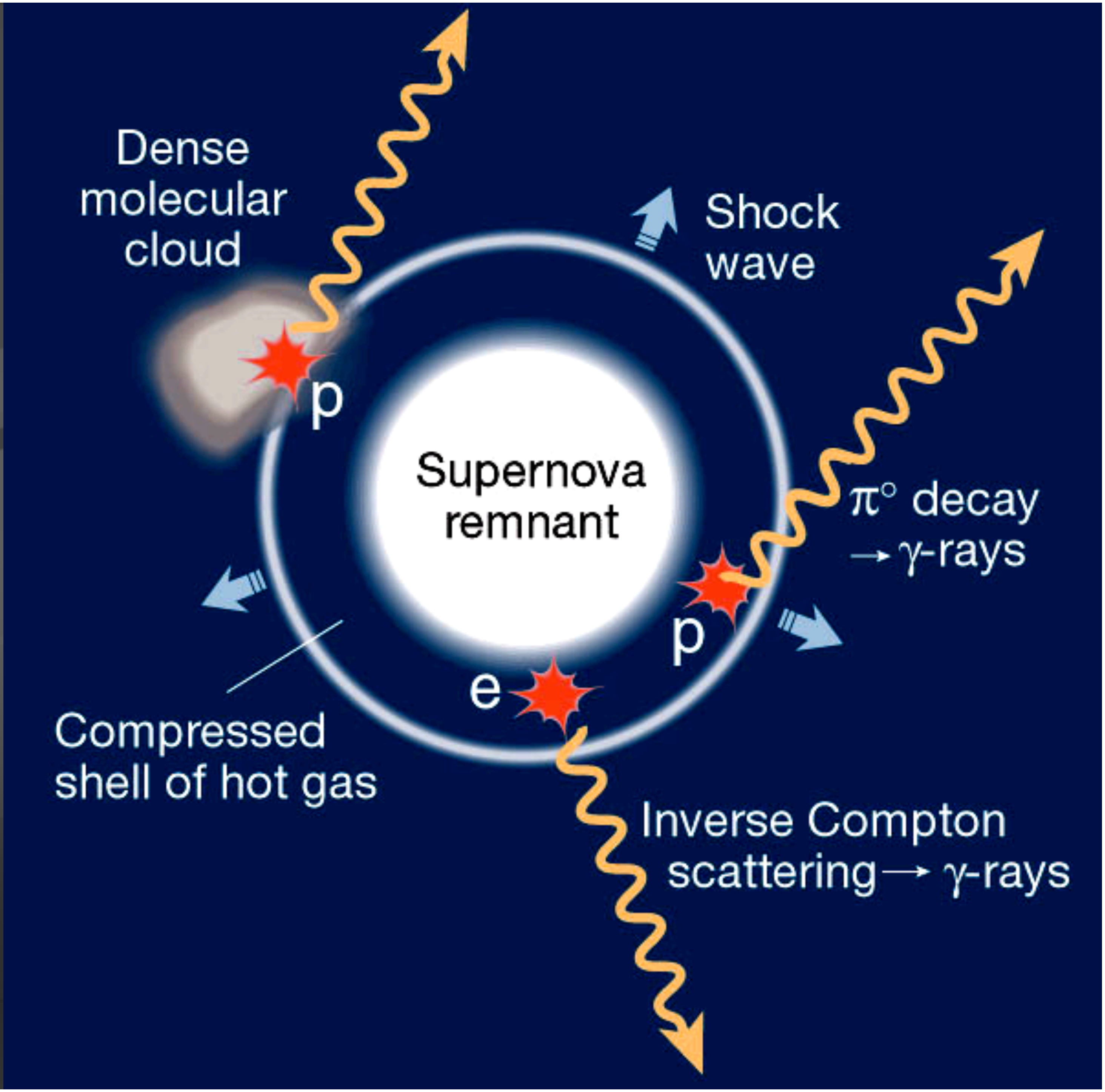
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

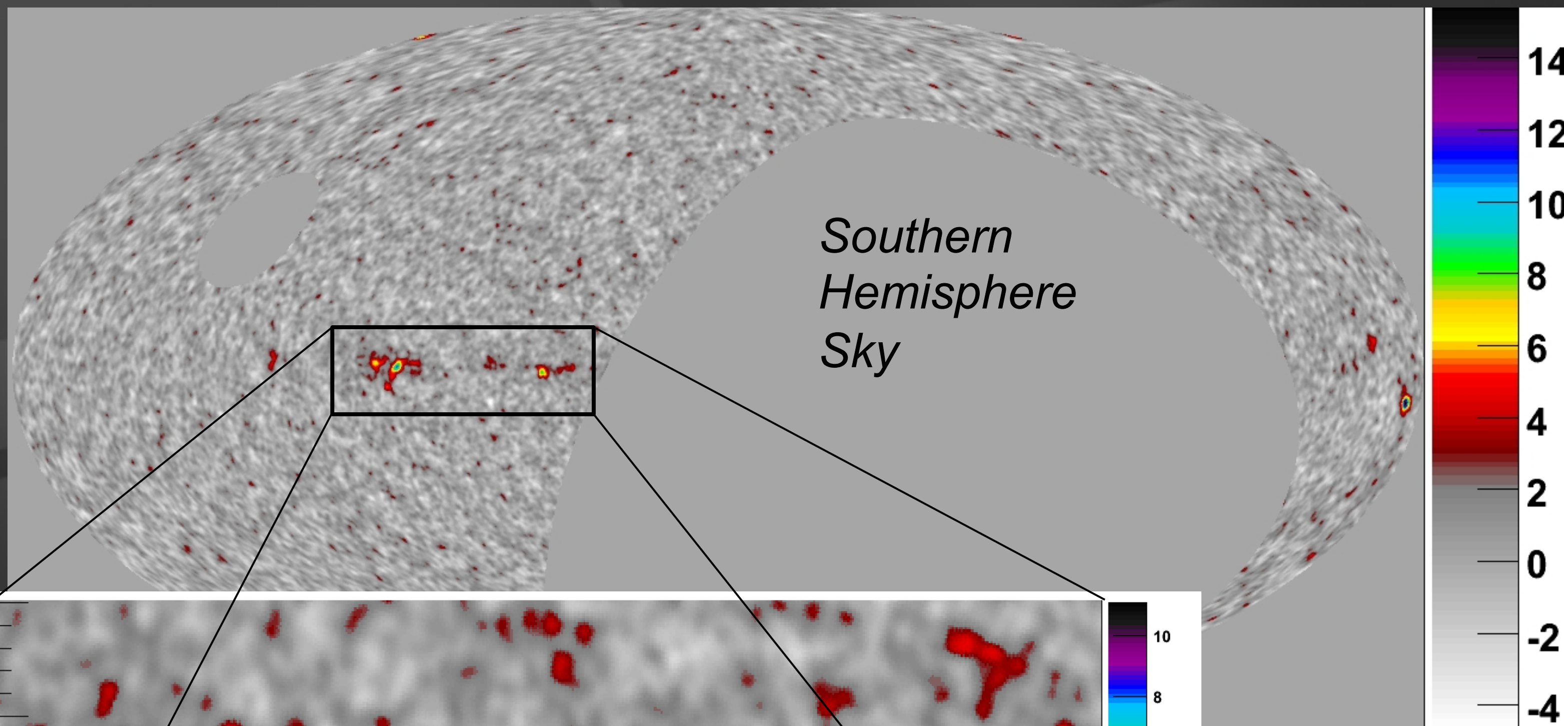
- Galactic?

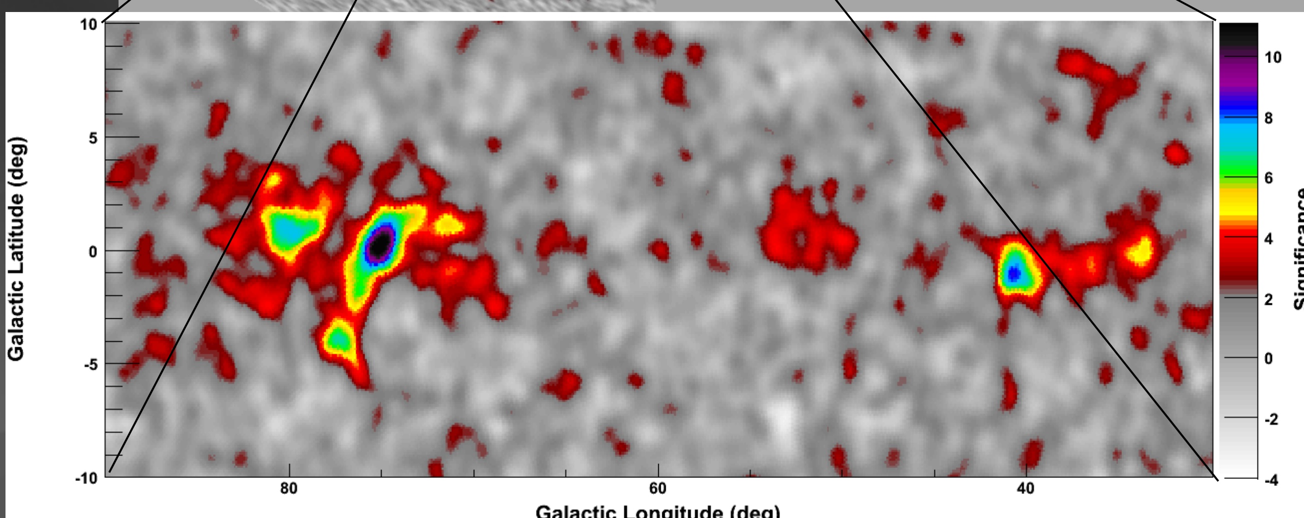
neutrinos from supernova remnants :

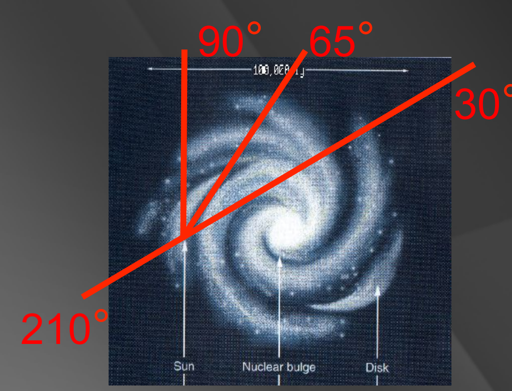
molecular clouds as beam dumps
→
pion production



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

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

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

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

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

volume of the remnant (V)

10^{-12} erg/cm^3 (ρ_{cr})

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

γ, ν flux of galactic cosmic rays

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

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

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

should be observed by present TeV gamma-ray telescopes

Milagro sources ?
RX J1713.7-3946??

neutral pions

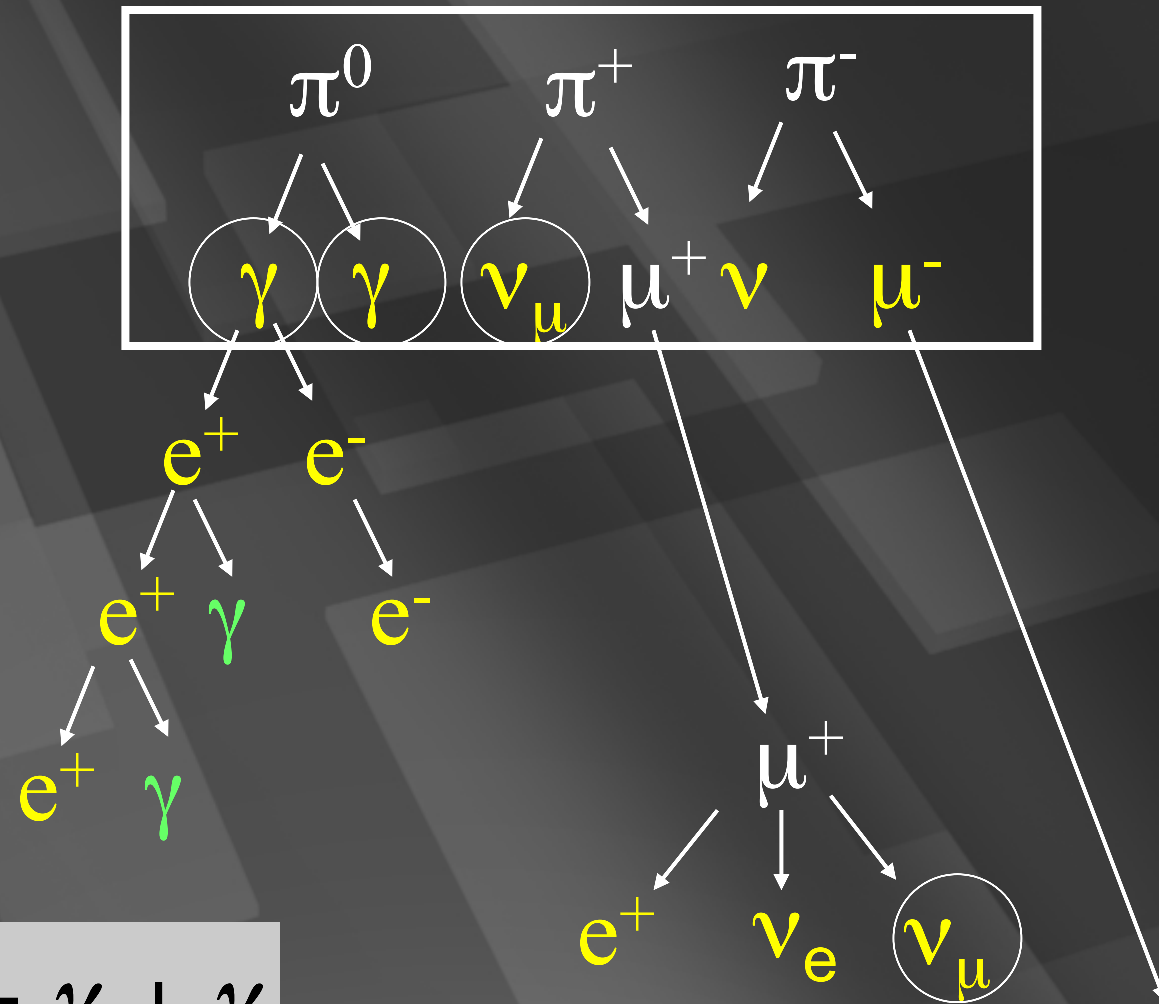
are observed as

gamma rays

charged pions

are observed as

neutrinos



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

ν flux accompanying TeV gammas

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

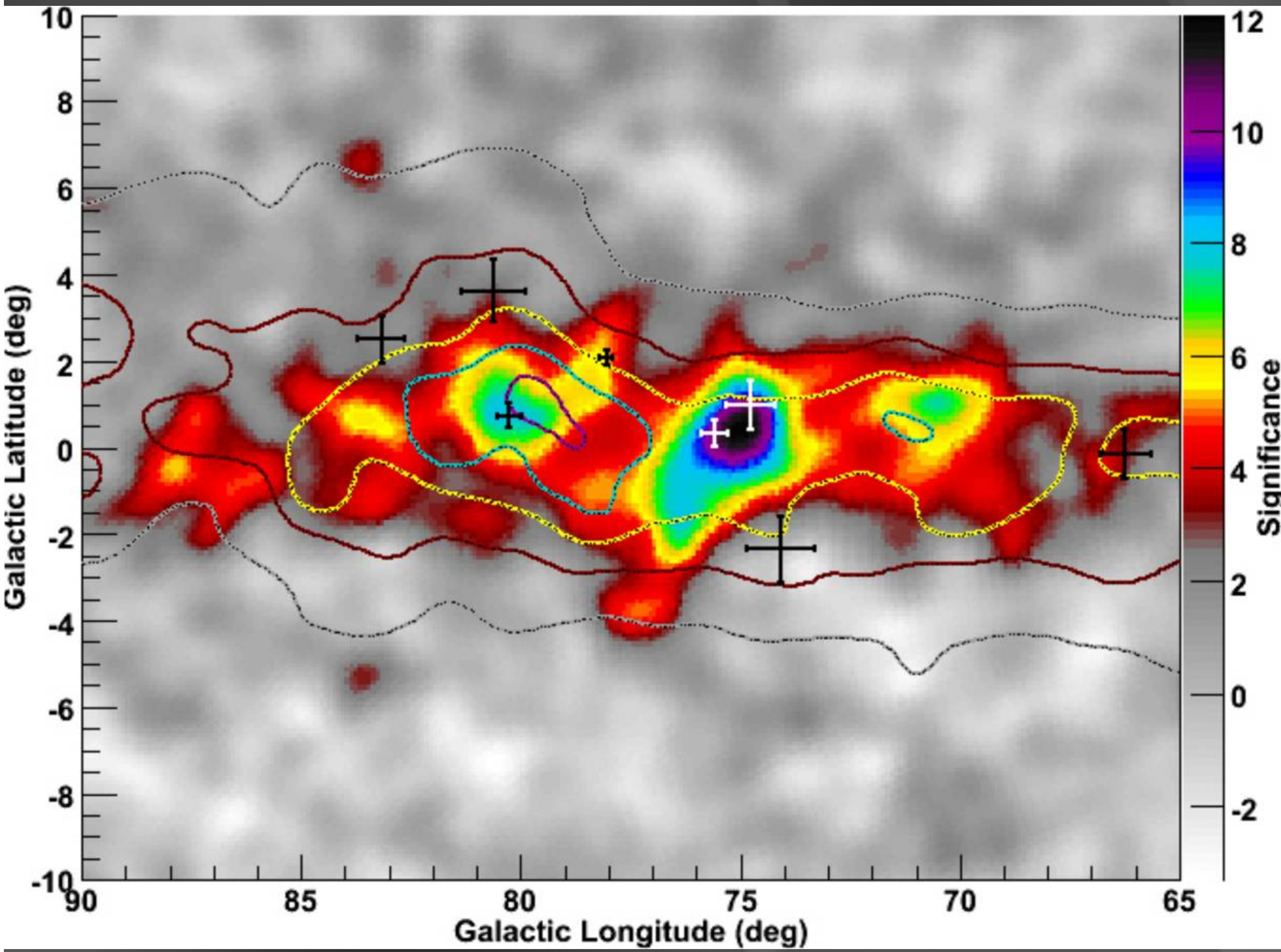
$$\text{number of events} = \text{Area Time} \int dE \, \frac{dN_\nu}{dE} P_{\nu\to\mu}$$

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

$$\textit{reject background}$$

$$\rightarrow E \geq 40\, TeV$$

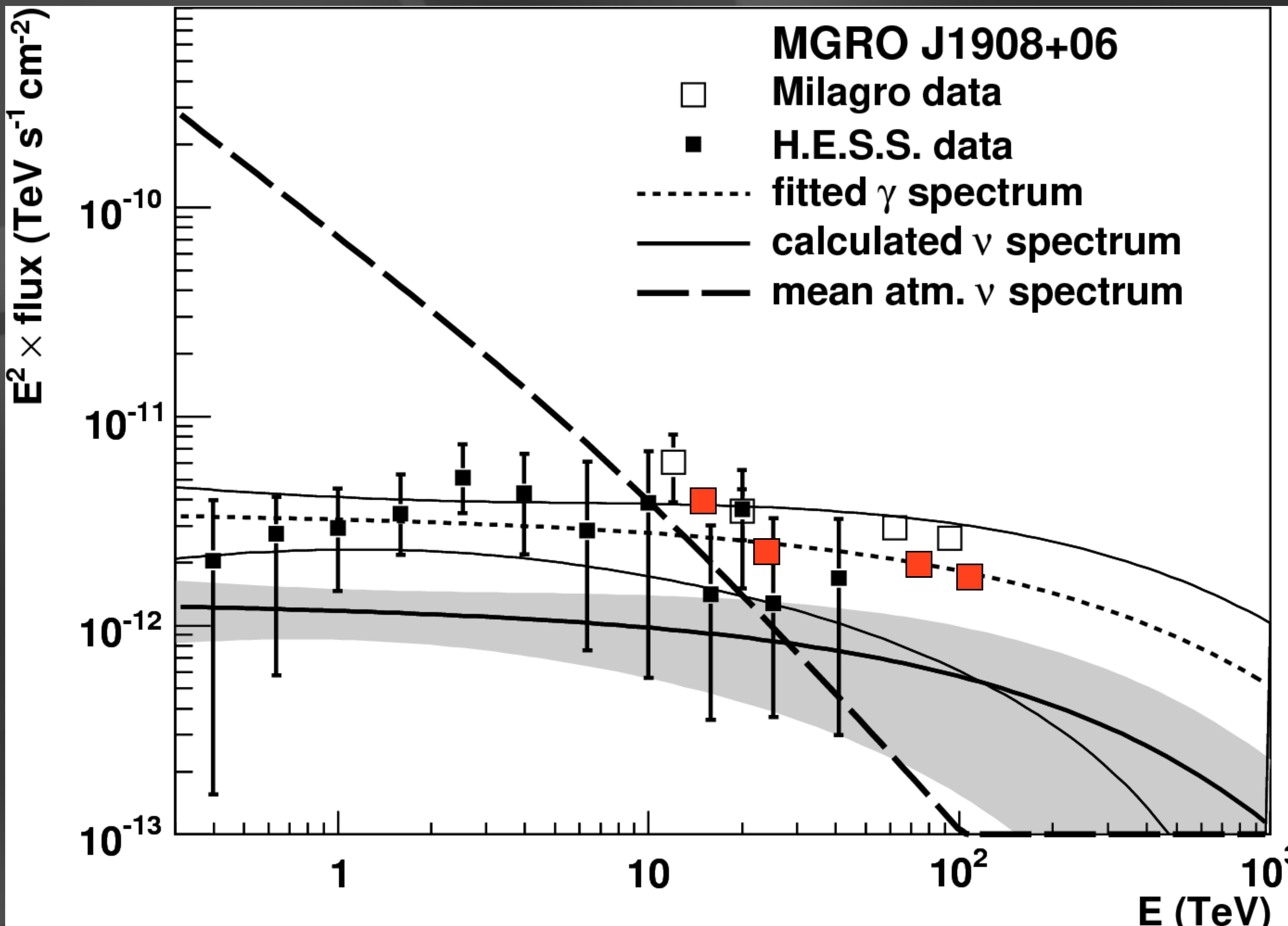
Cygnus region at ~ 1kpc : Milagro



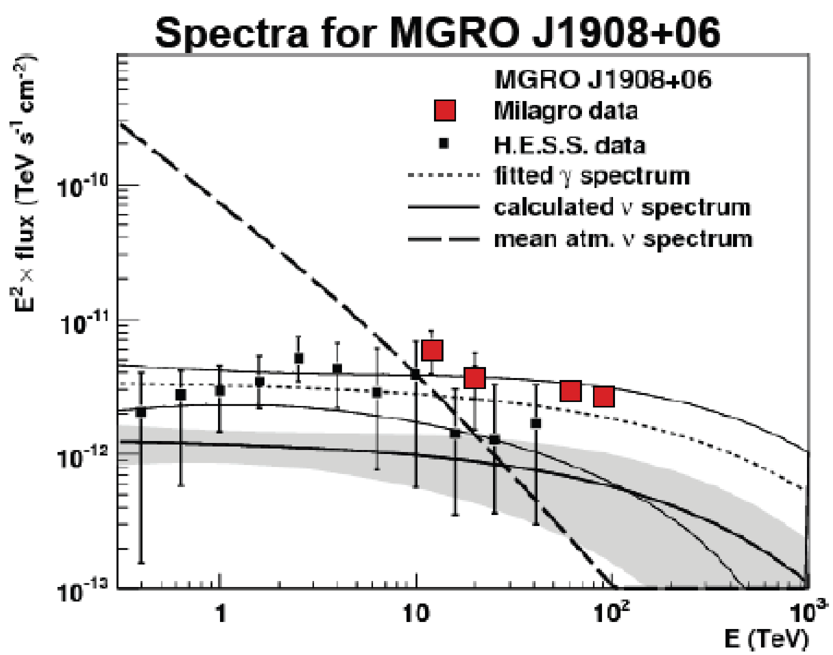
translation of
TeV gamma rays
into
TeV neutrinos
yields:

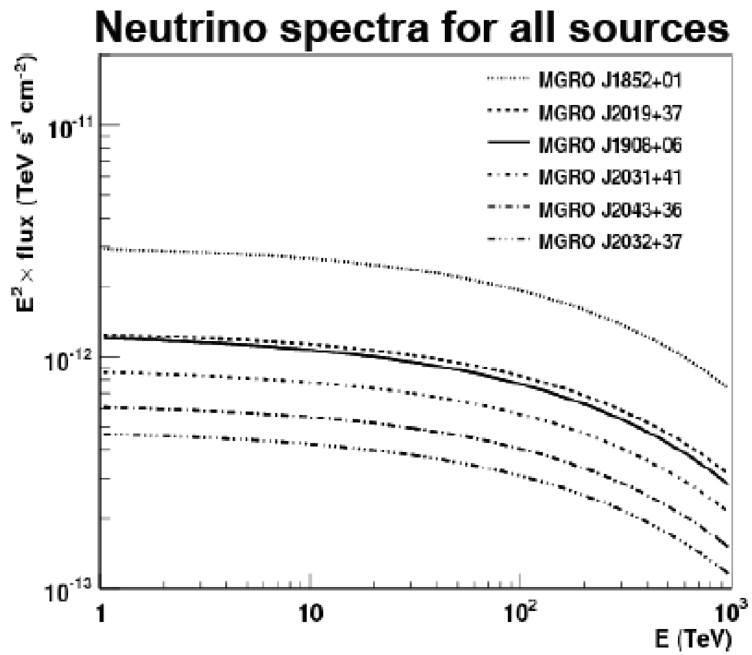
3 ± 1 ν per year in IceCube per source

MGRO J1908+06: the first Pevatron?



Gamma and Neutrino Spectra

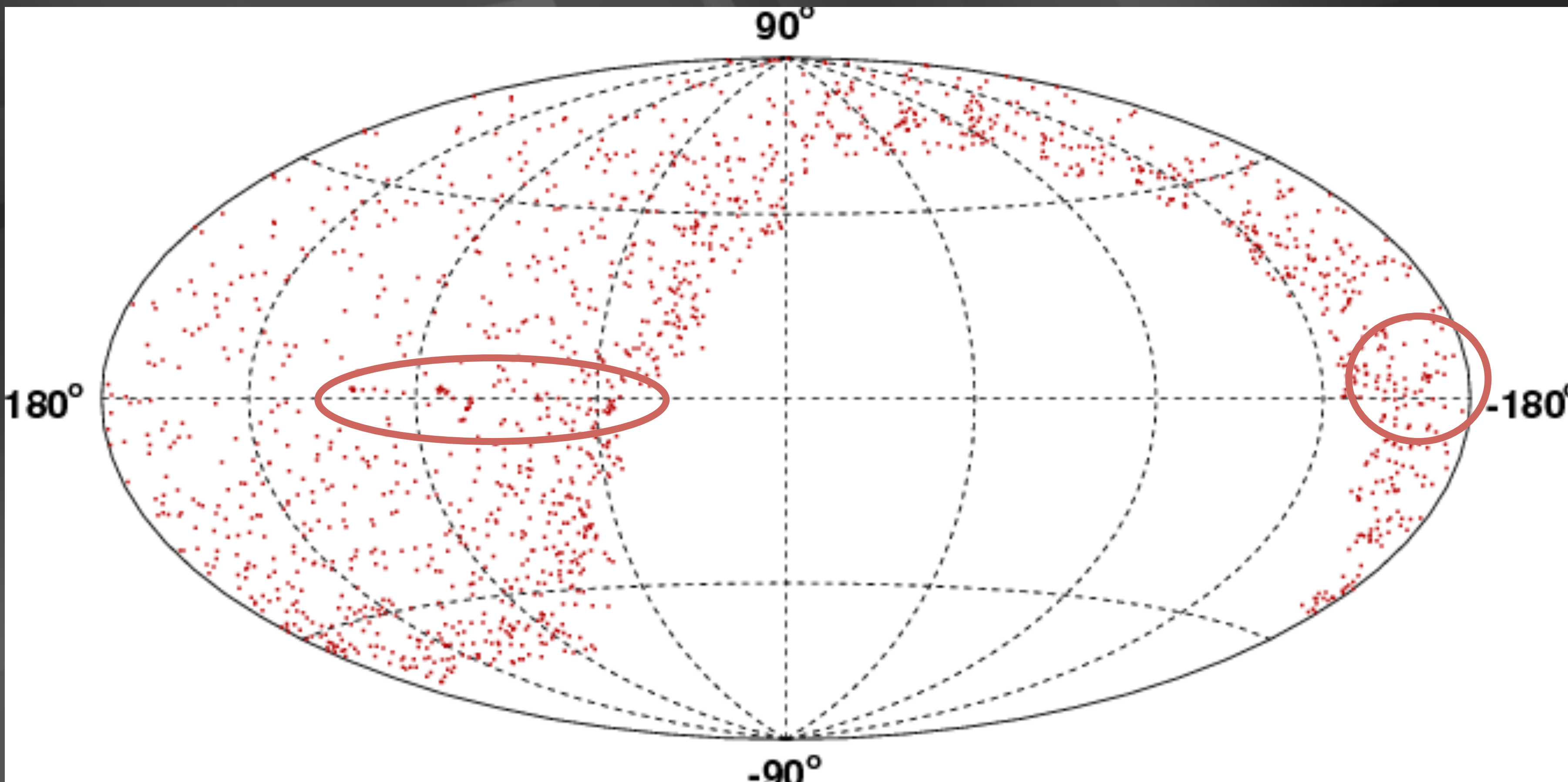




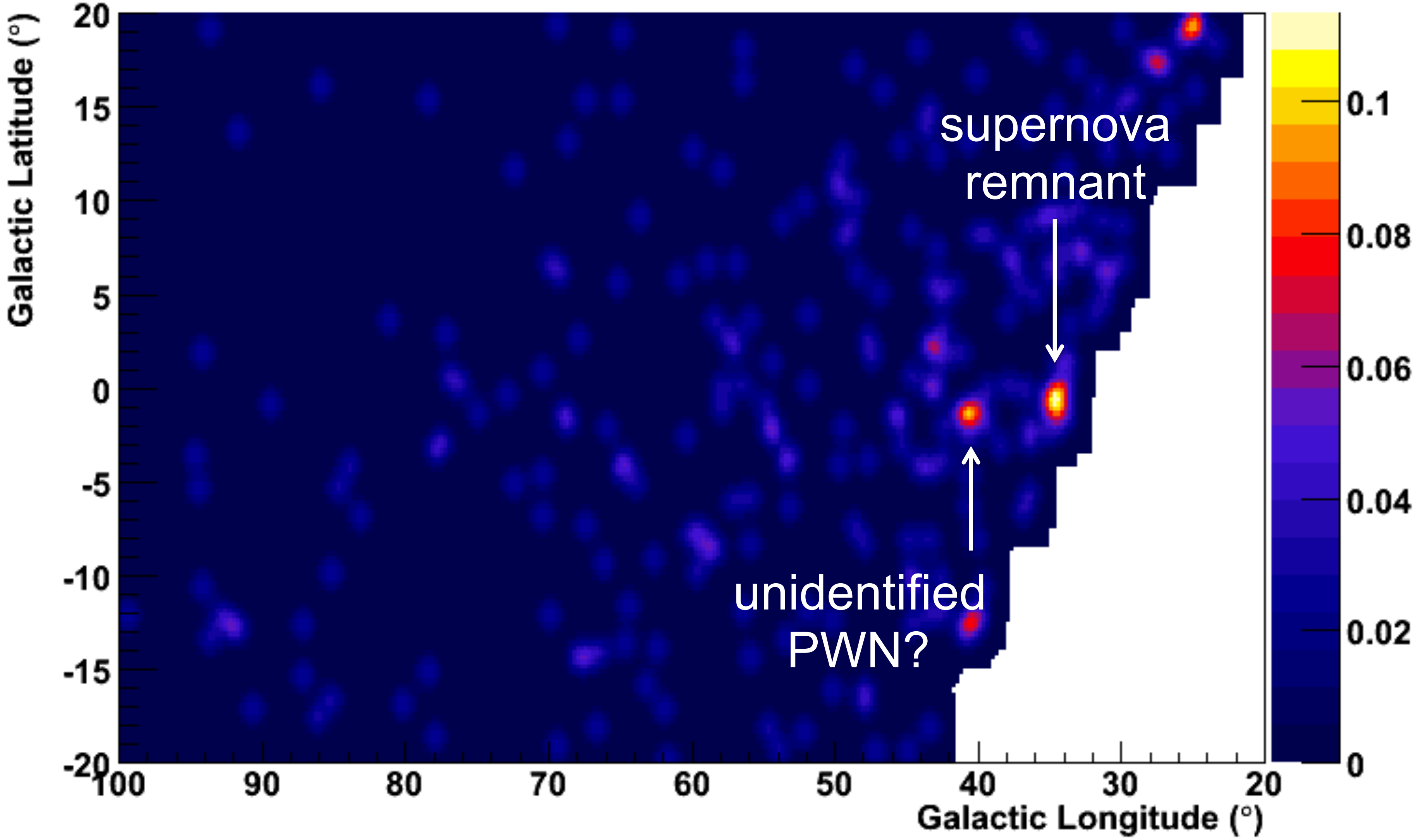
Halzen, Kappes, O'Murchadha: arXiv:0803.0314

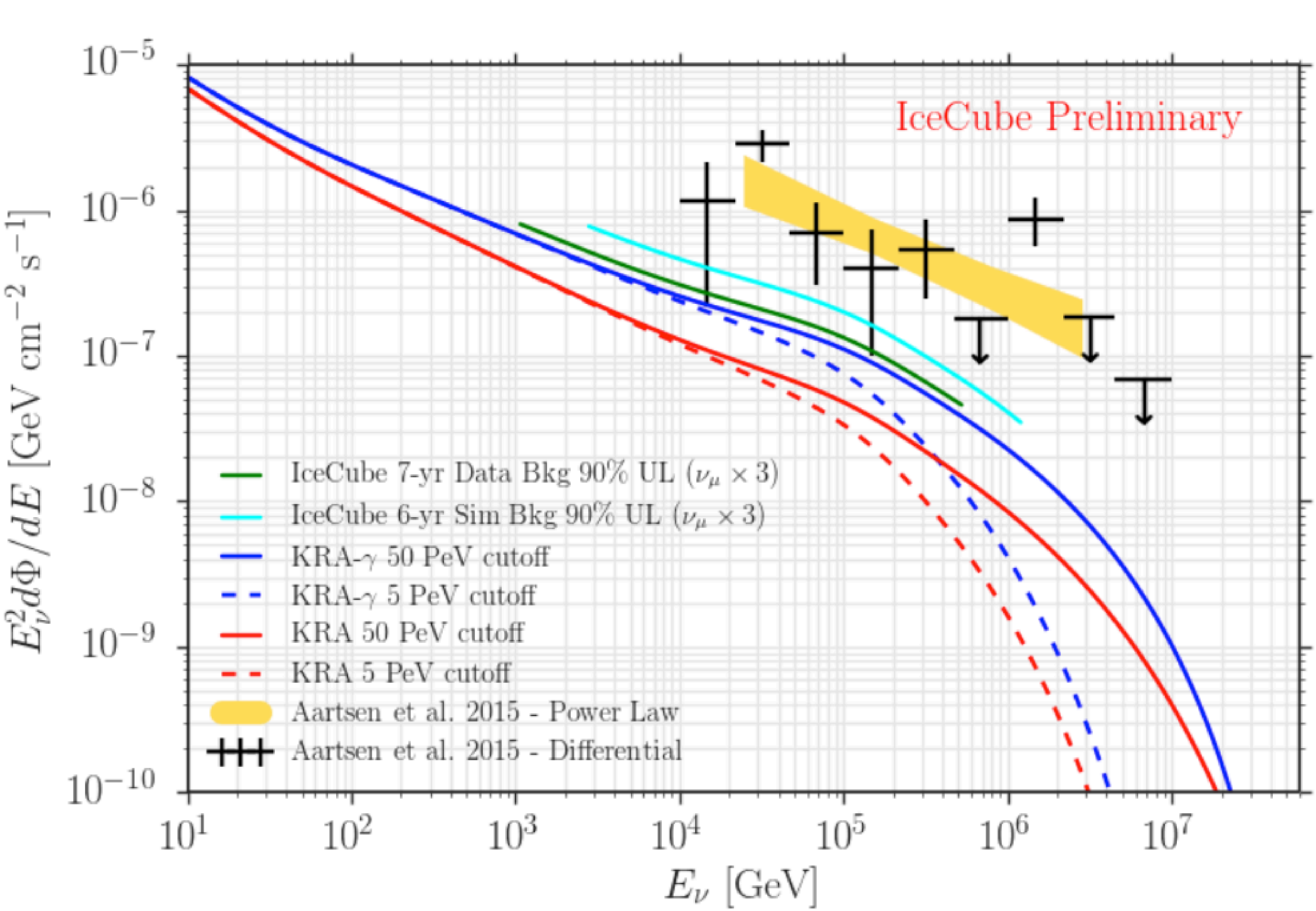
- Assumed E^{-2} with Milagro normaliztion (MGRO J1908 index = 2.1)
- ν spectrum cutoff @ 180 TeV

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.

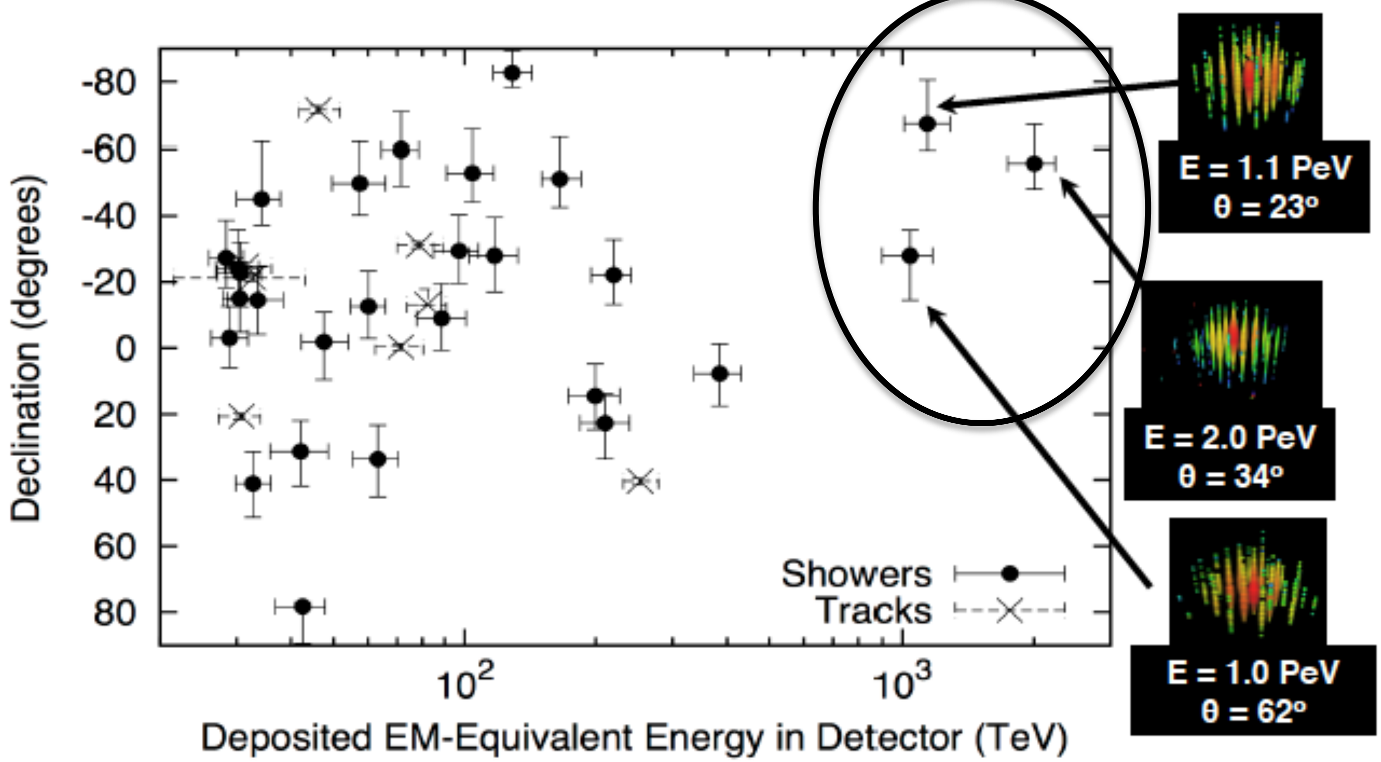




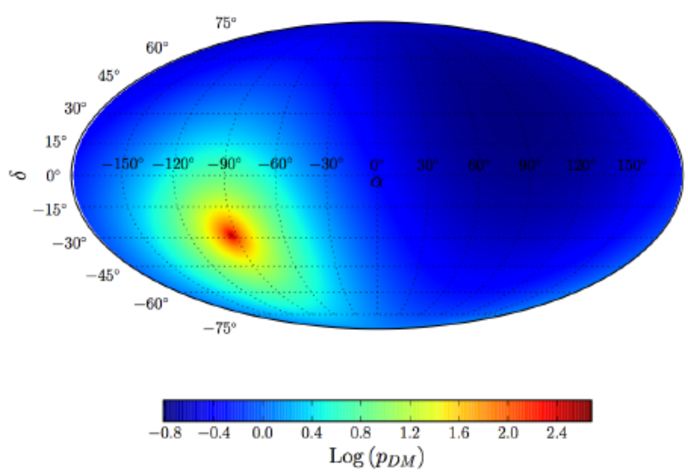
IceCube Preliminary
IceCube 7-yr Data Bkg 90% UL ($\nu_\mu \times 3$)
IceCube 6-yr Sim Bkg 90% UL ($\nu_\mu \times 3$)
KRA-γ 50 PeV cutoff
KRA-γ 5 PeV cutoff
KRA 50 PeV cutoff
KRA 5 PeV cutoff
Aartsen et al. 2015 - Power Law
Aartsen et al. 2015 - Differential
$E_\nu^2 d\Phi/dE$ [GeV cm^{-2} s^{-1}]
E_ν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

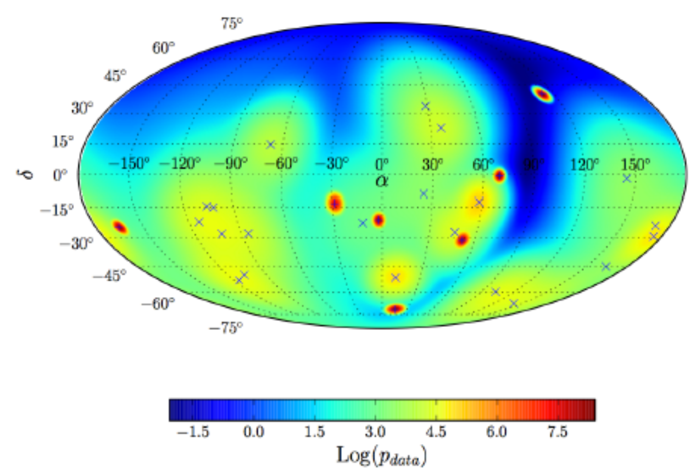
- dark matter?

expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle





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

HESE ALERT

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

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

MASTER: OT discovered during inspection of HESE 58537957 trigger

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

on 30 Aug 2016; 00:37 UT

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

bjects: Optical, Neutrinos, Request for Observations, Transient

ferred to by ATel #: 9456

Tweet | Recommend | 2

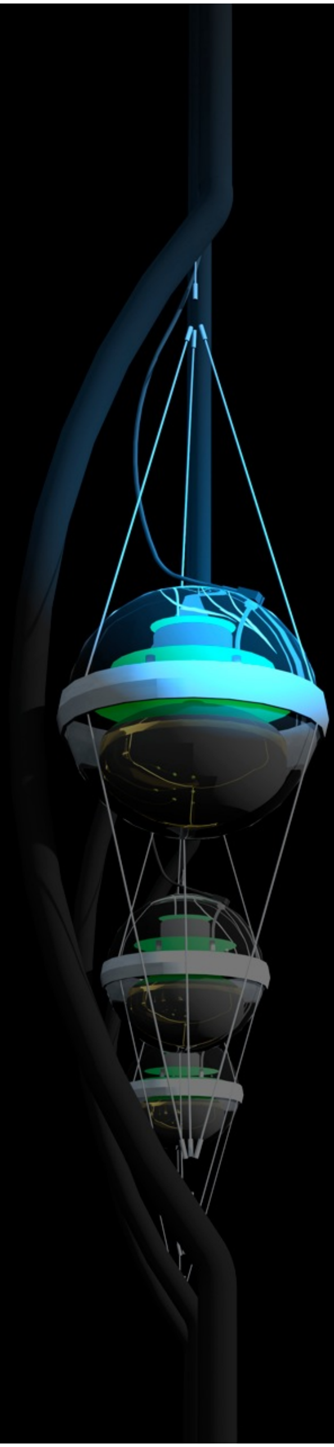
ASTER OT J130845.02-323254.9 - optical transient detection during inspection of HESE 537957_128340 alert

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

9456 MASTER OT J130 323254.9: Variable Source of the High Neutrino.
9440 Search for counte IceCube-160814A ANTARES
9425 MASTER: OT disc during inspection 58537957 trigger
9391 INTEGRAL follow- IceCube HESE 128 58537957

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

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



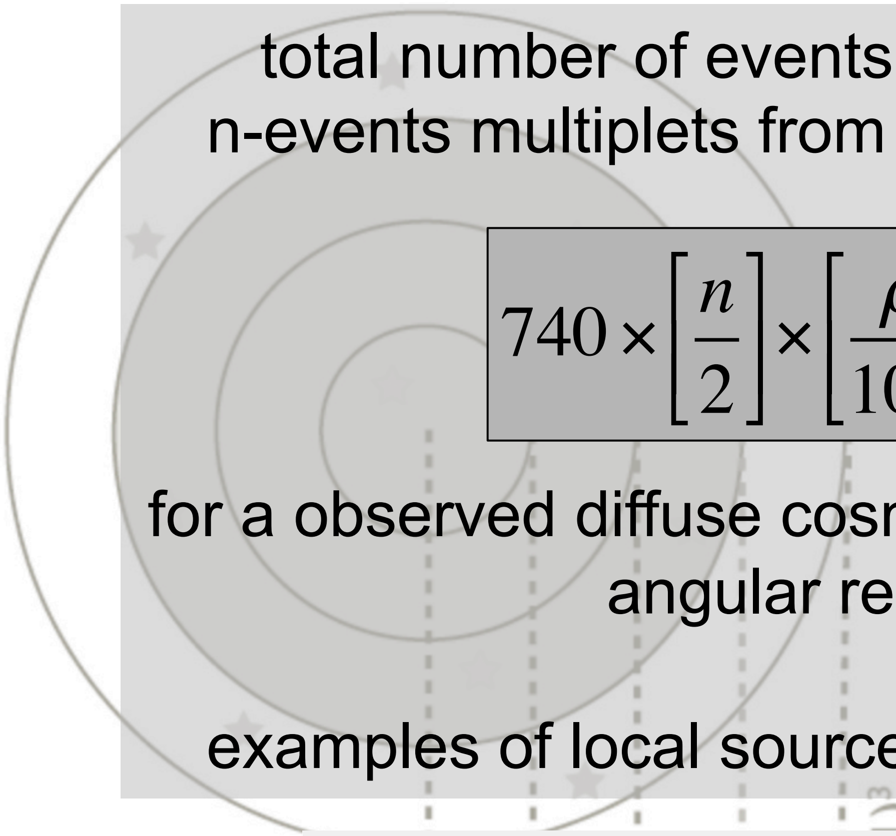
IceCube: the discovery of cosmic neutrinos
francis halzen

- 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

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):

- $10^{-3} - 10^{-2}\,\text{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\text{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\text{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\text{Mpc}^{-3}$ 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:

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

and

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

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

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

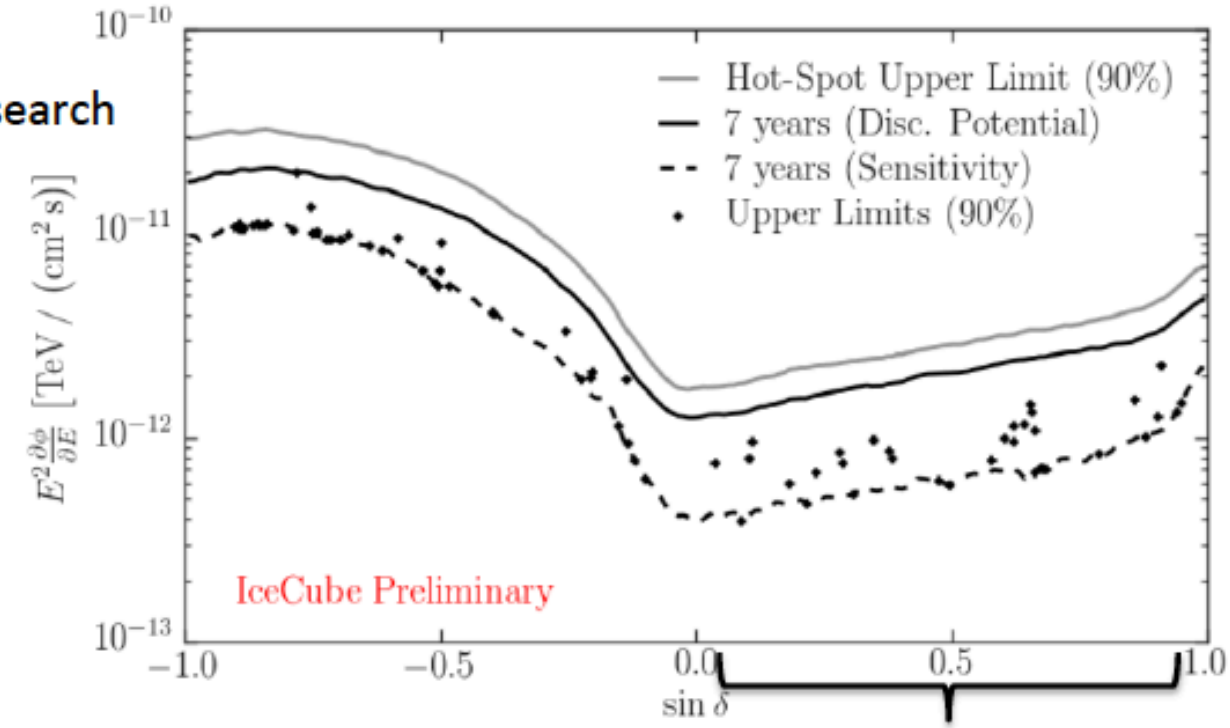
$$\#\text{ of events from the whole sky} \quad : \ \zeta L_\nu \rho R_H \otimes Area$$

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

Point source limits

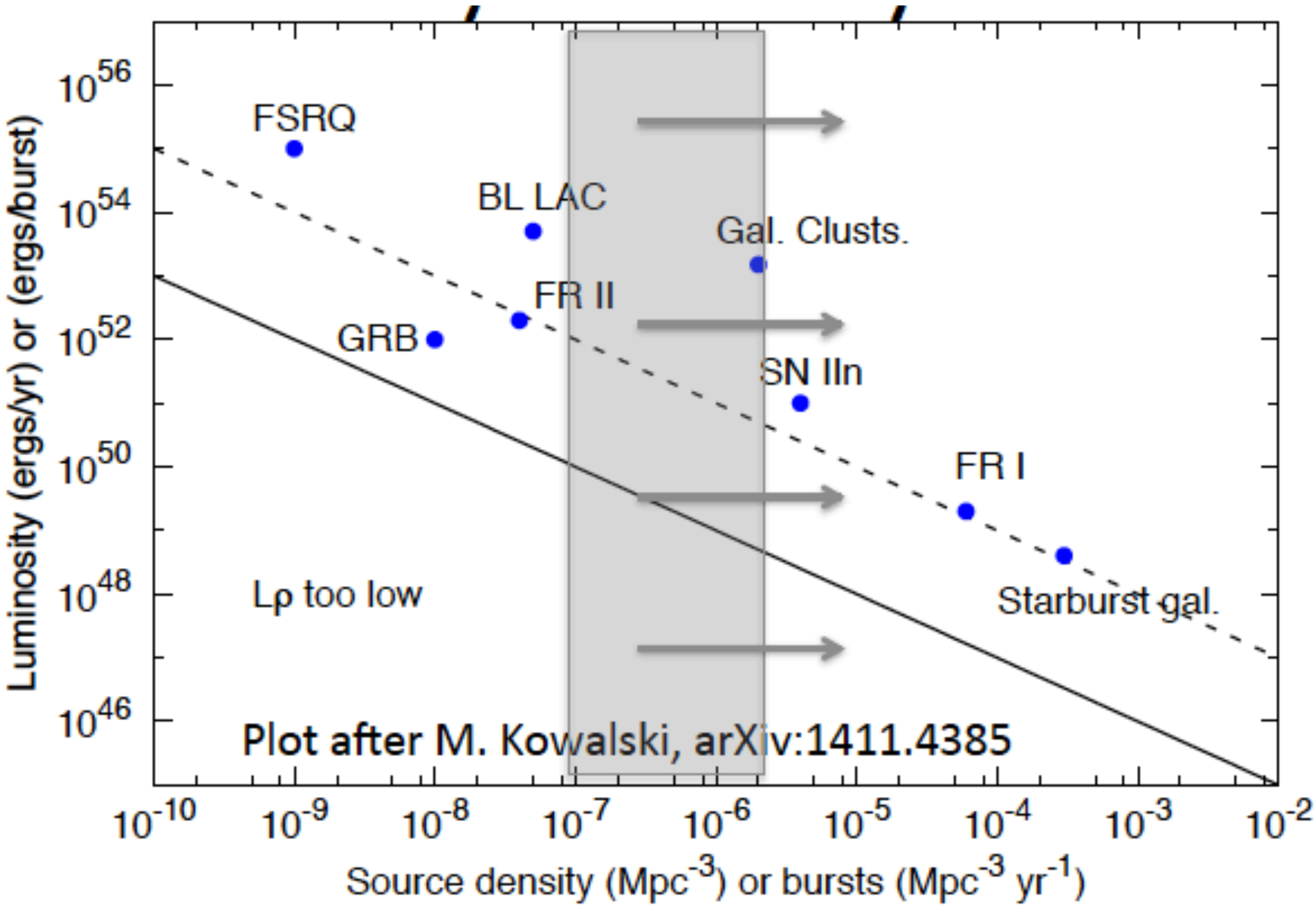
Relation between flux from whole sky and number/intensity of individual sources
P. Lipari, PR D78 (2008) 083001 … Murase & Waxman, arXiv:1607.01601

IceCube 7 yr pt src search



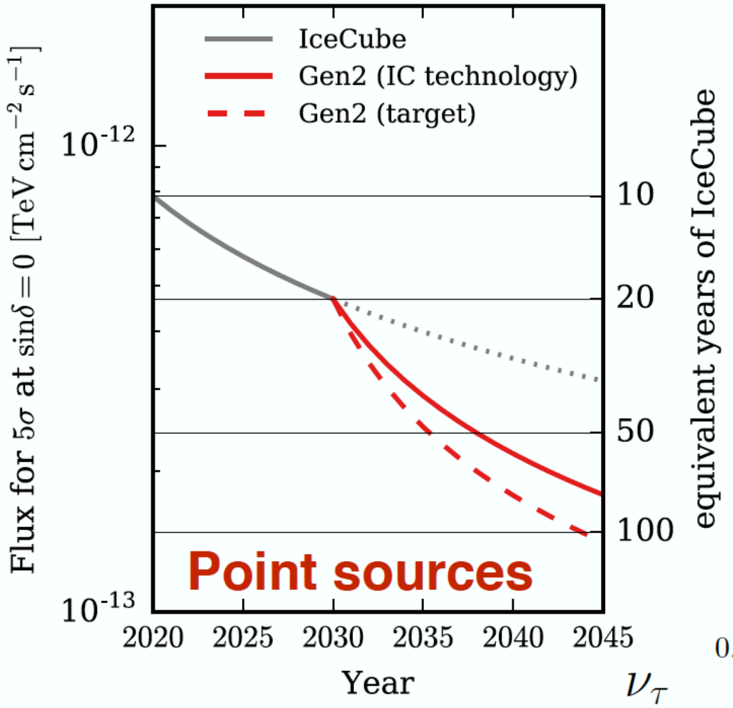
Northern hemisphere, good pointing with ν_μ-induced μ, limits

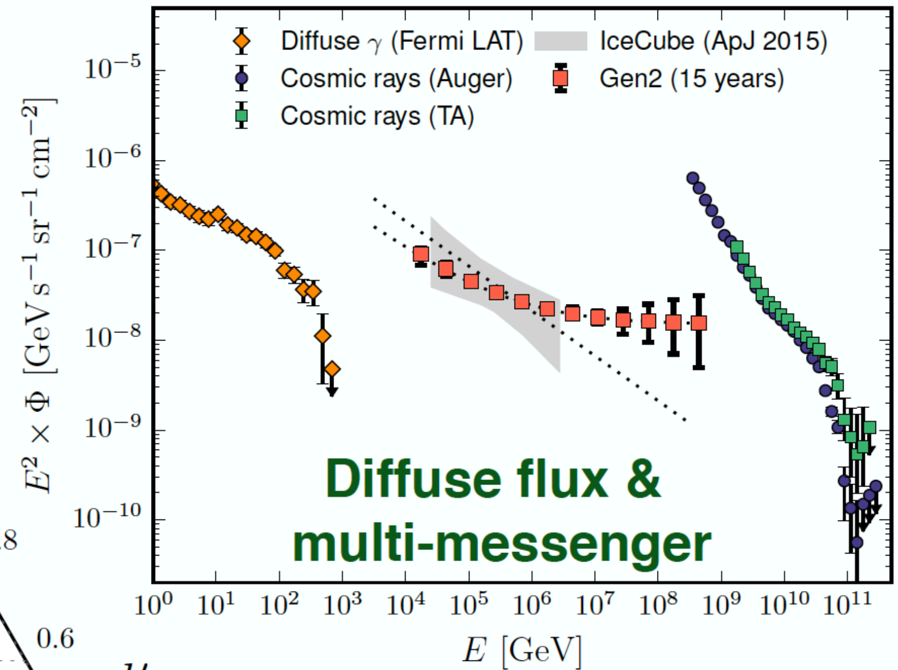
$$< 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1}}$$

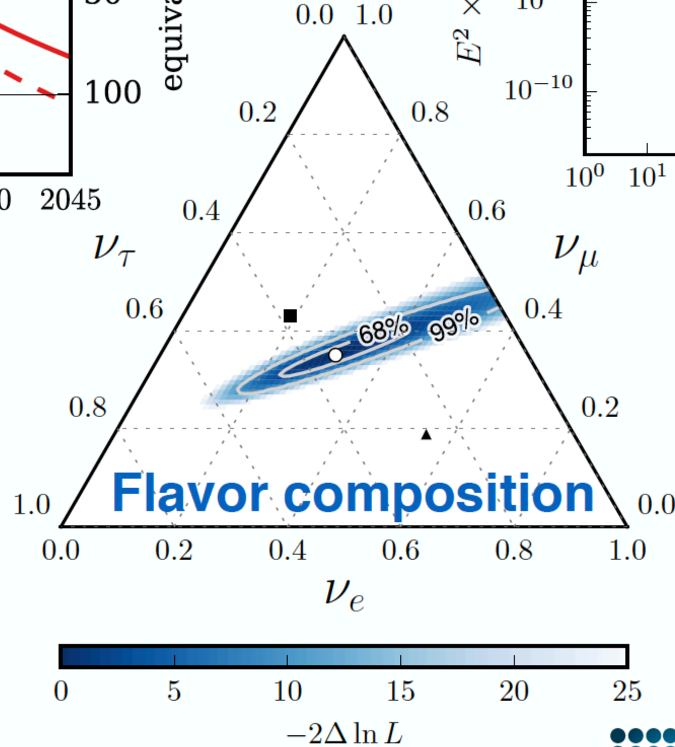


Luminosity (ergs/yr) or (ergs/burst)
10^{56}
10^{54}
10^{52}
10^{50}
10^{48}
10^{46}
FSRQ
BL LAC
Gal. Clusts.
FR II
GRB
SN IIn
FR I
Starburst gal.
Lρ too low
Plot after M. Kowalski, arXiv:1411.4385
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Source density (Mpc^{-3}) or bursts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

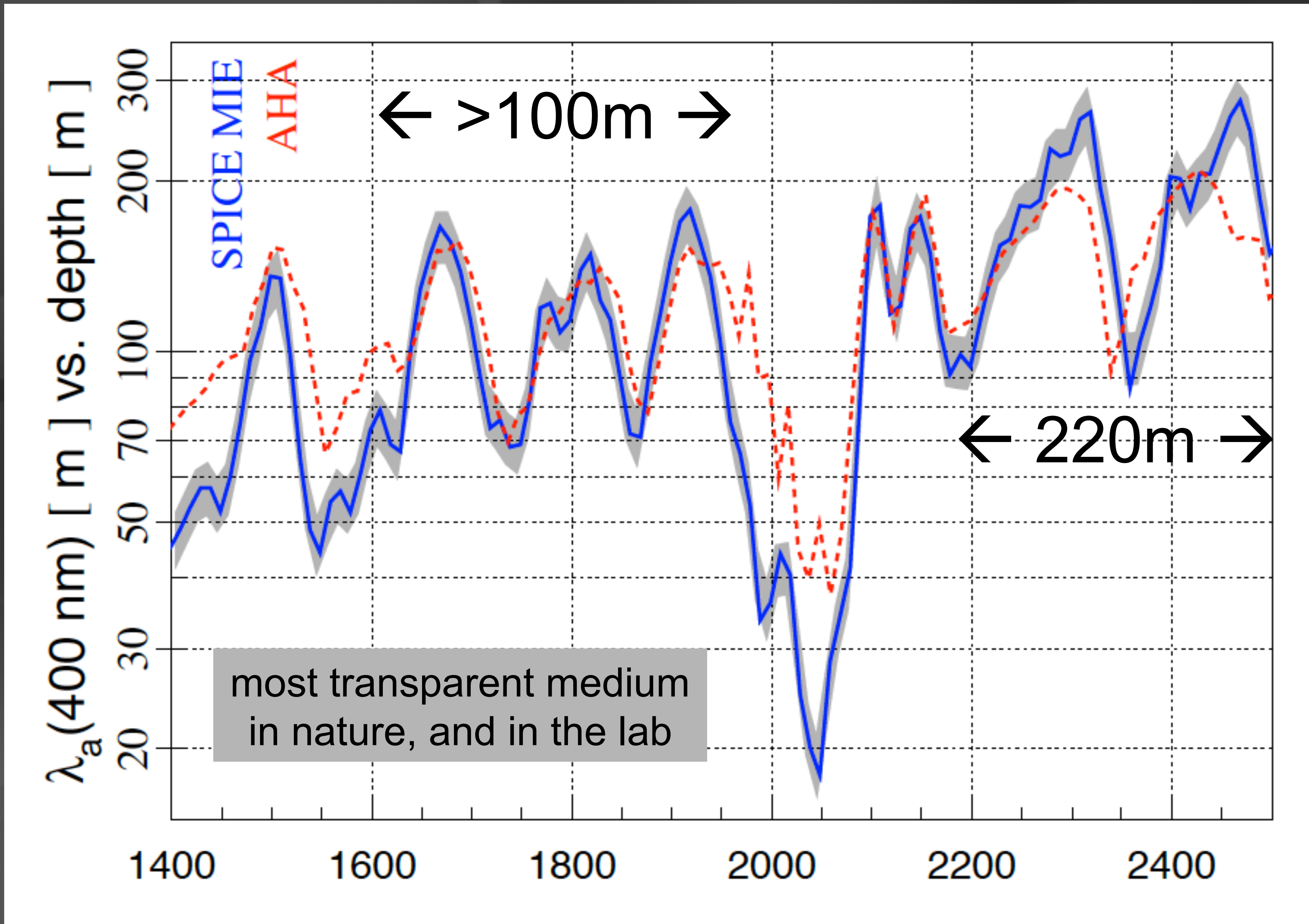
IceCube-Gen2: Science Case



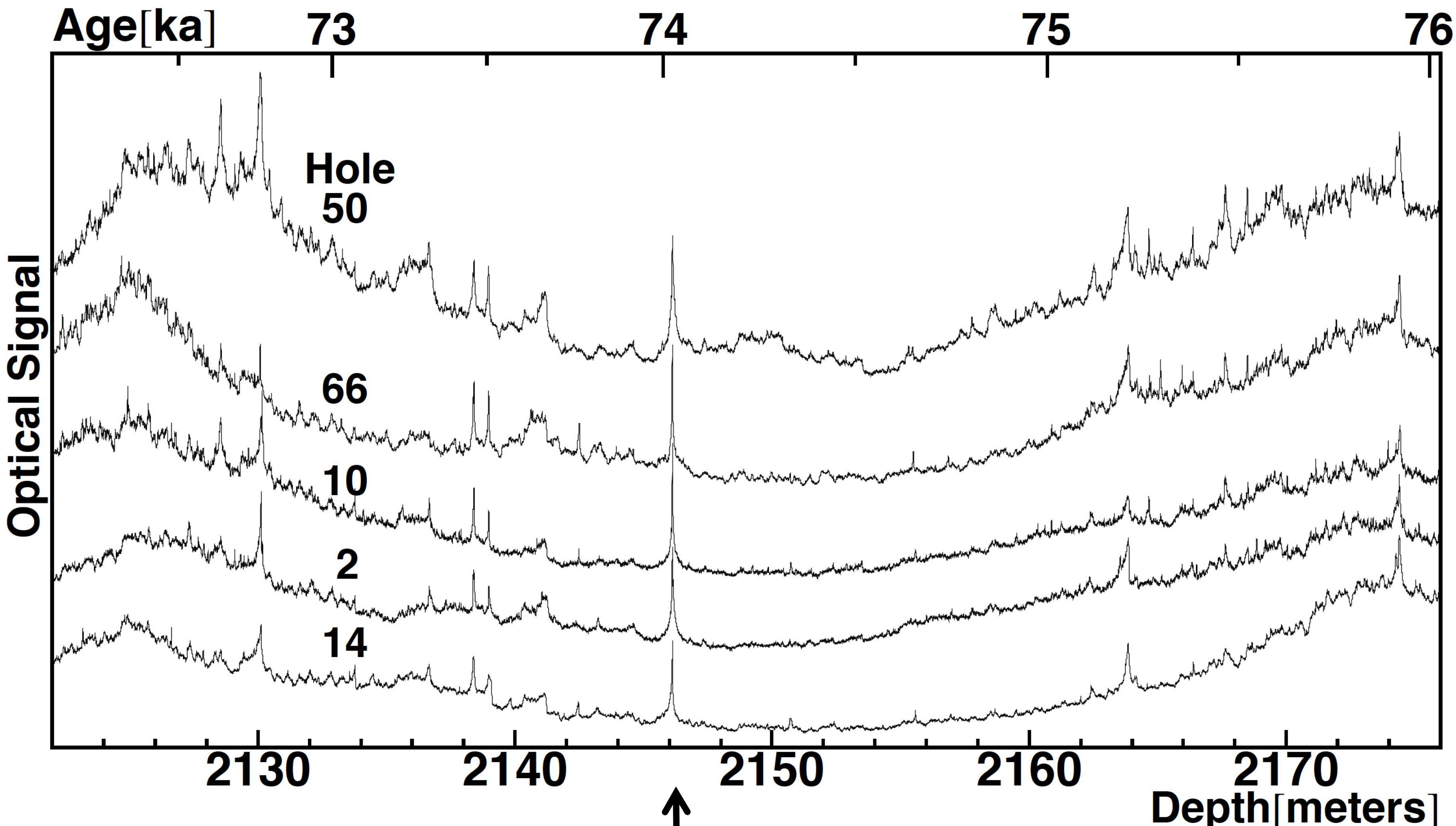




absorption length of Cherenkov light



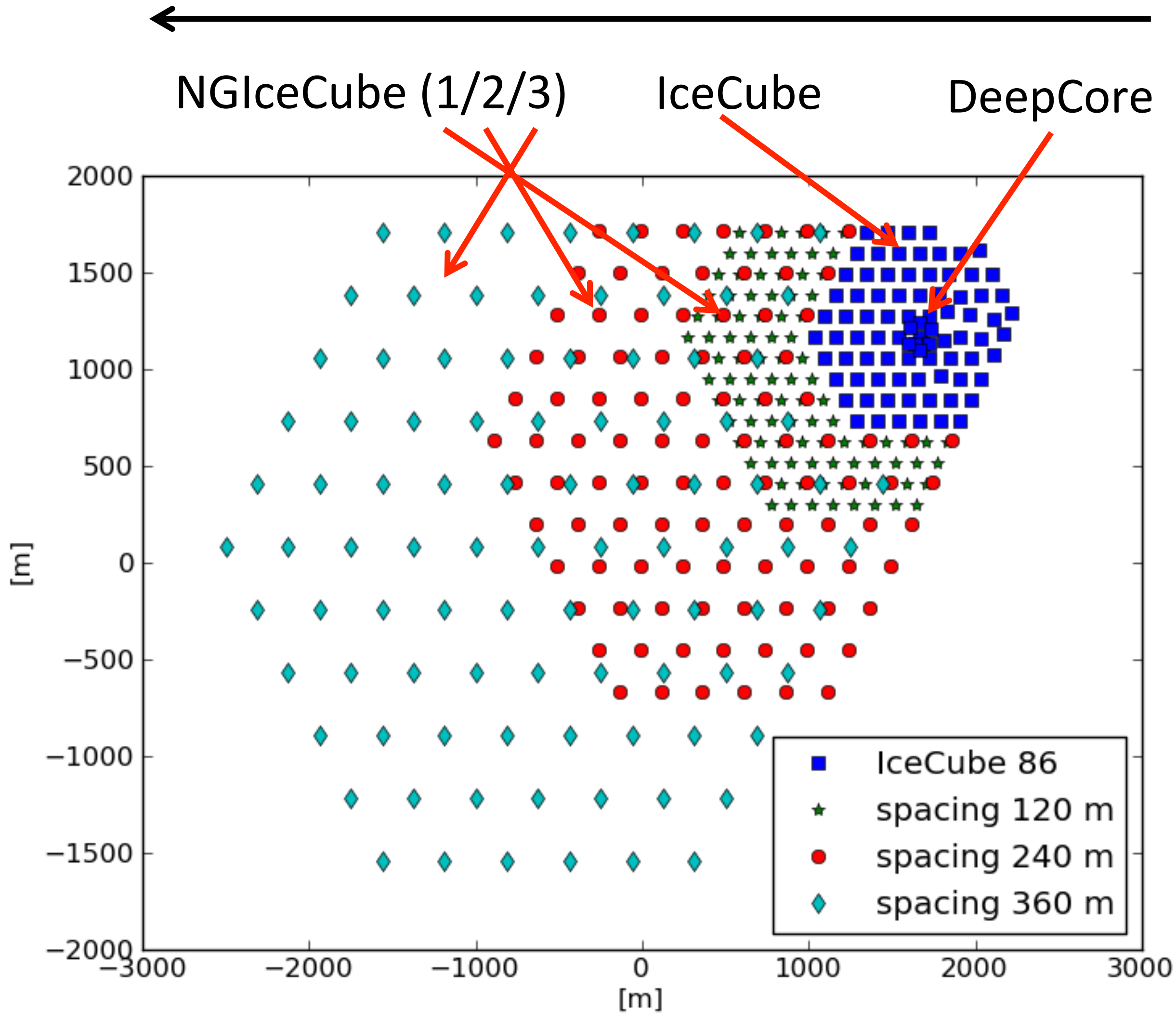
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

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



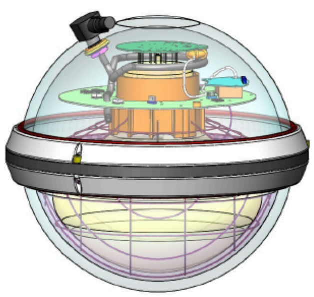
Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

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

Baseline Gen2 DOM

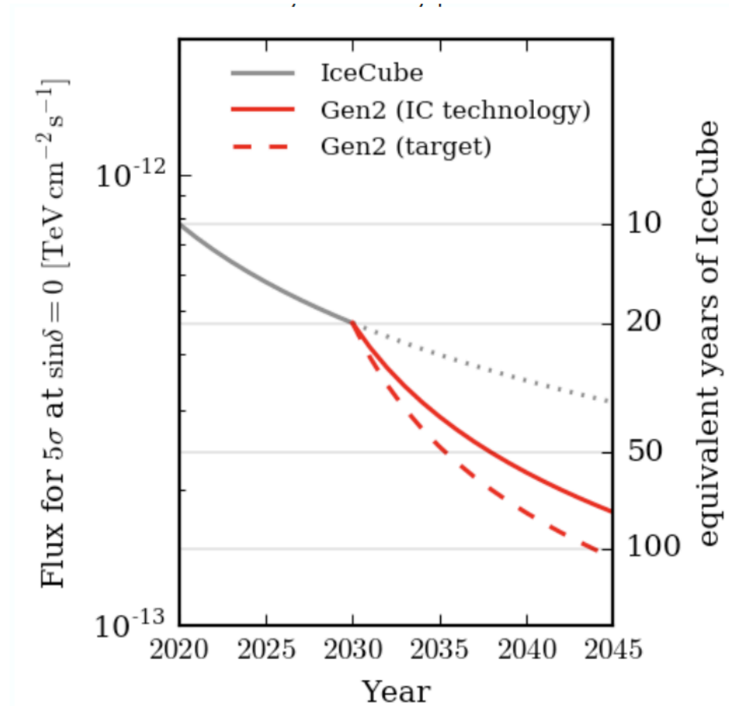
- updated electronics

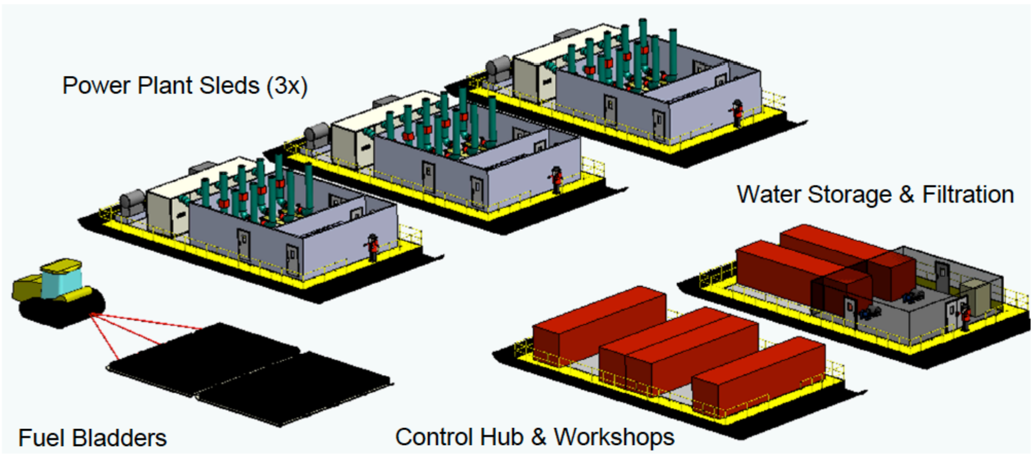


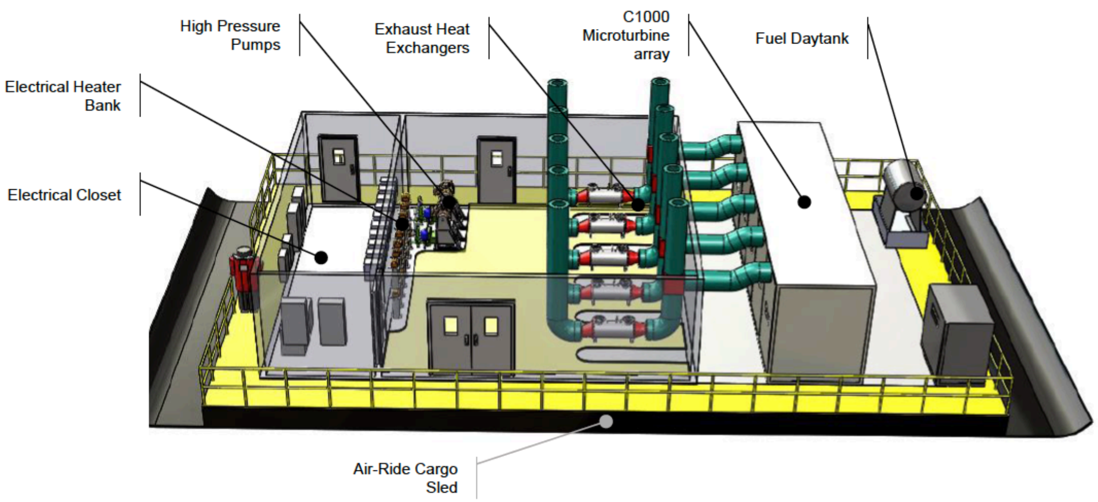
New technologies

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

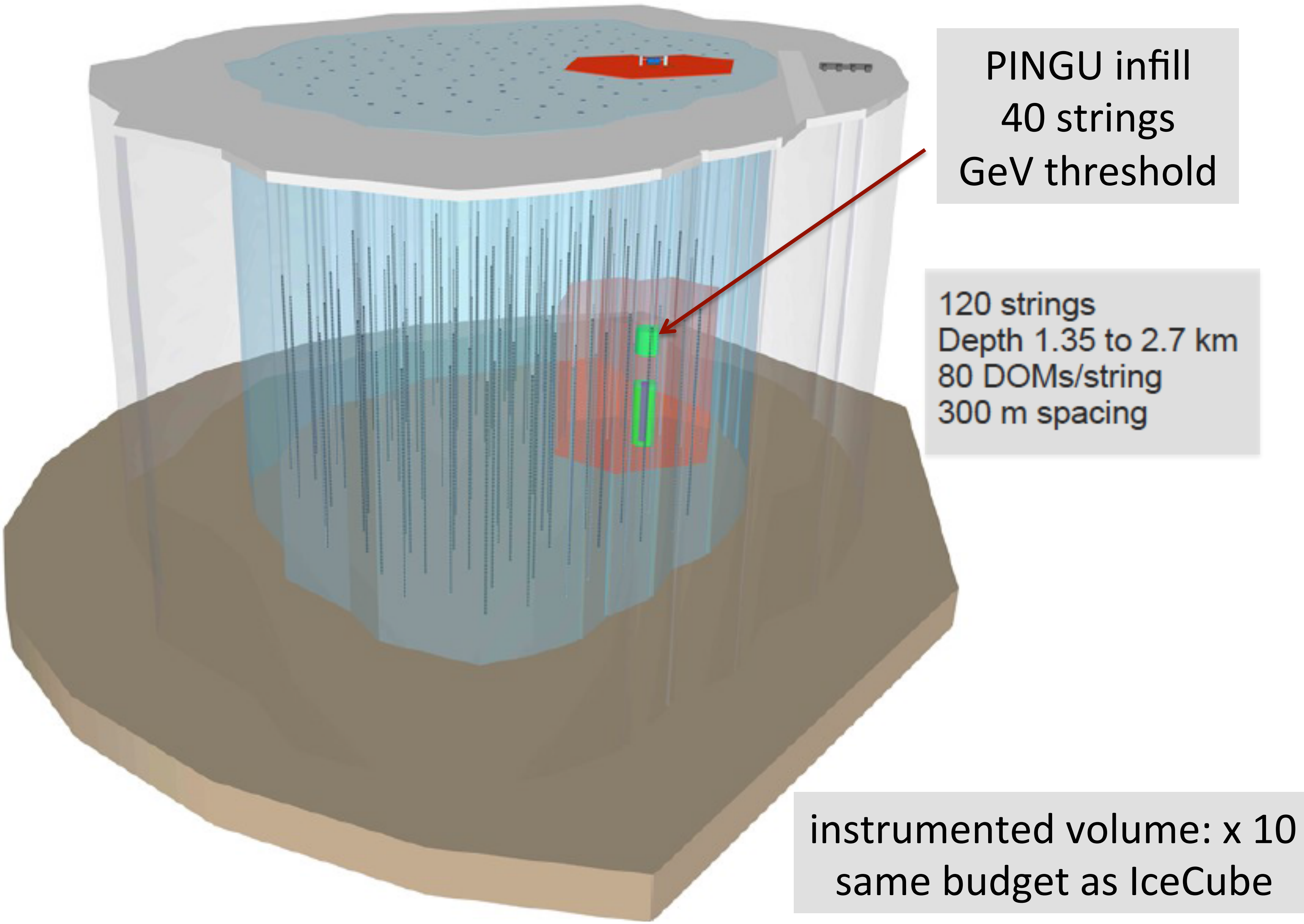
Point source sensitivity





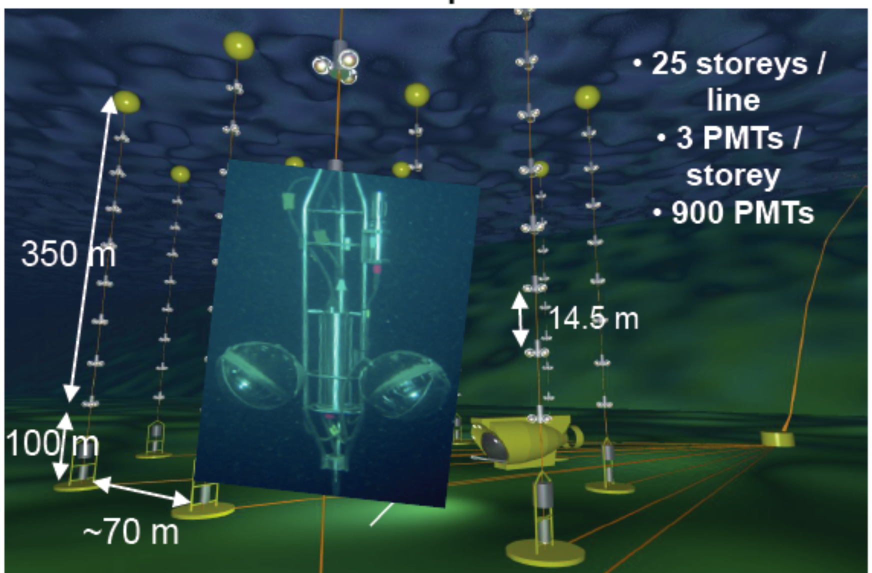


- Next-generation Enhanced Hot Water Drill
  - reduced footprint
  - smaller crew
- Transport equipment and fuel using South Pole Traverse
  - fewer flights needed
- May also reduce hole diameter
  - reduced fuel usage


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

Mediterranean Detectors

ANTARES Complete since 2008



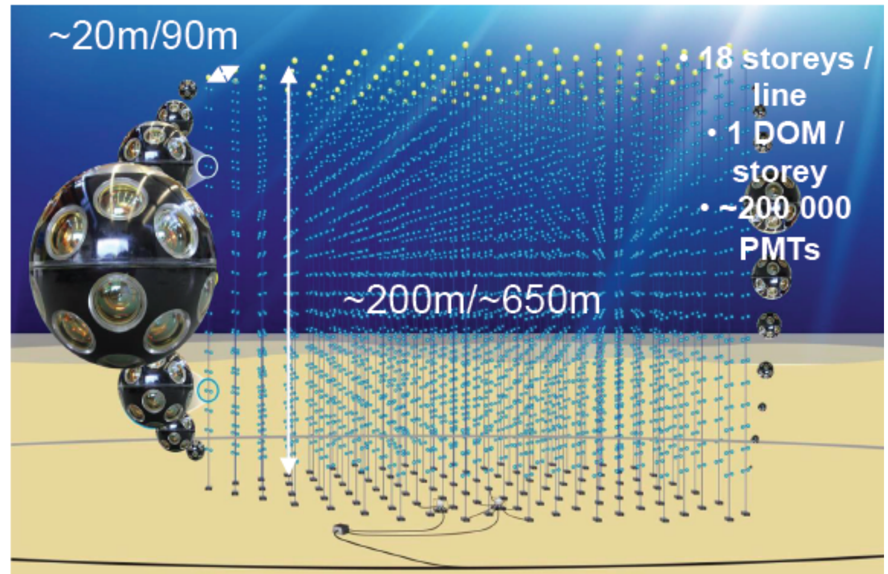
~10 Mton

12 lines

First Generation

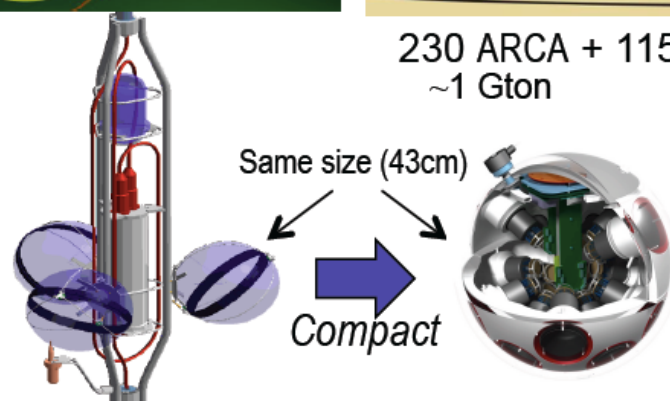
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

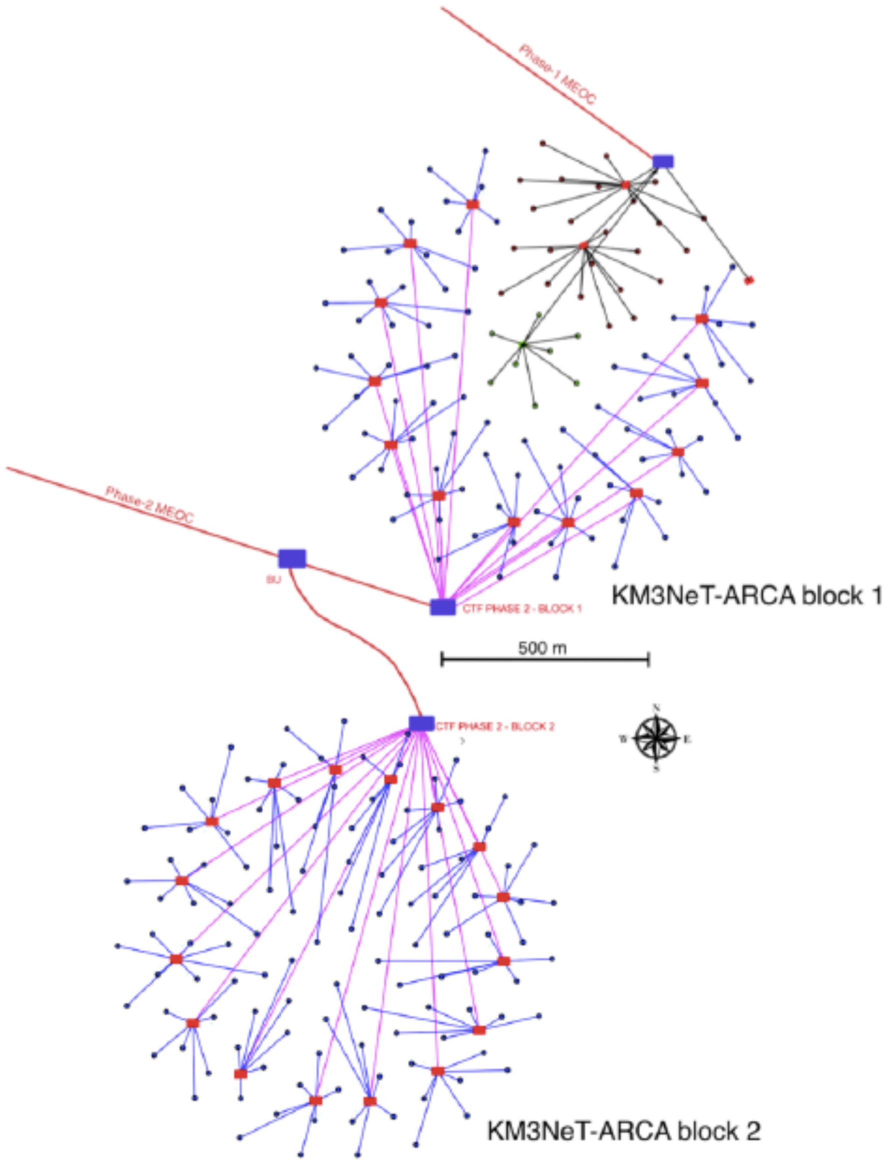
~1 Gton ~6 Mton

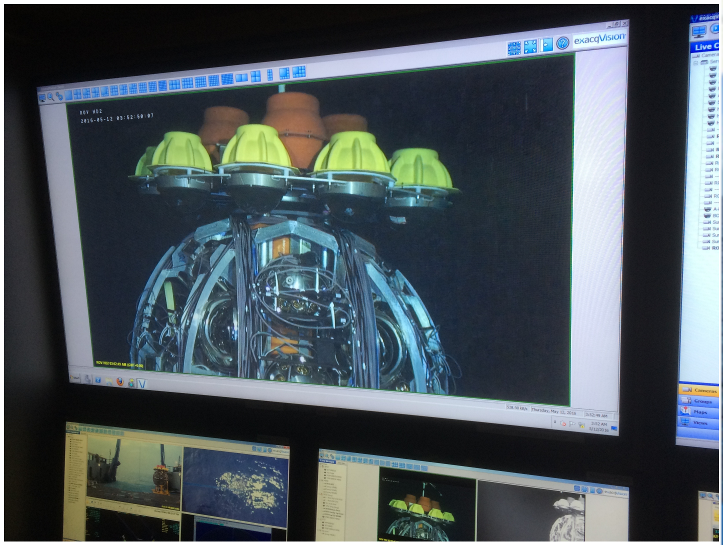


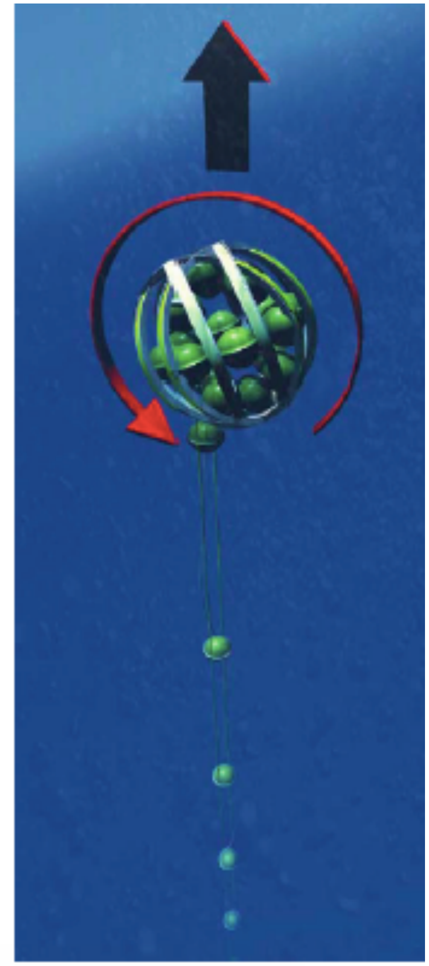
• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

High energies ARCA







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
- ….

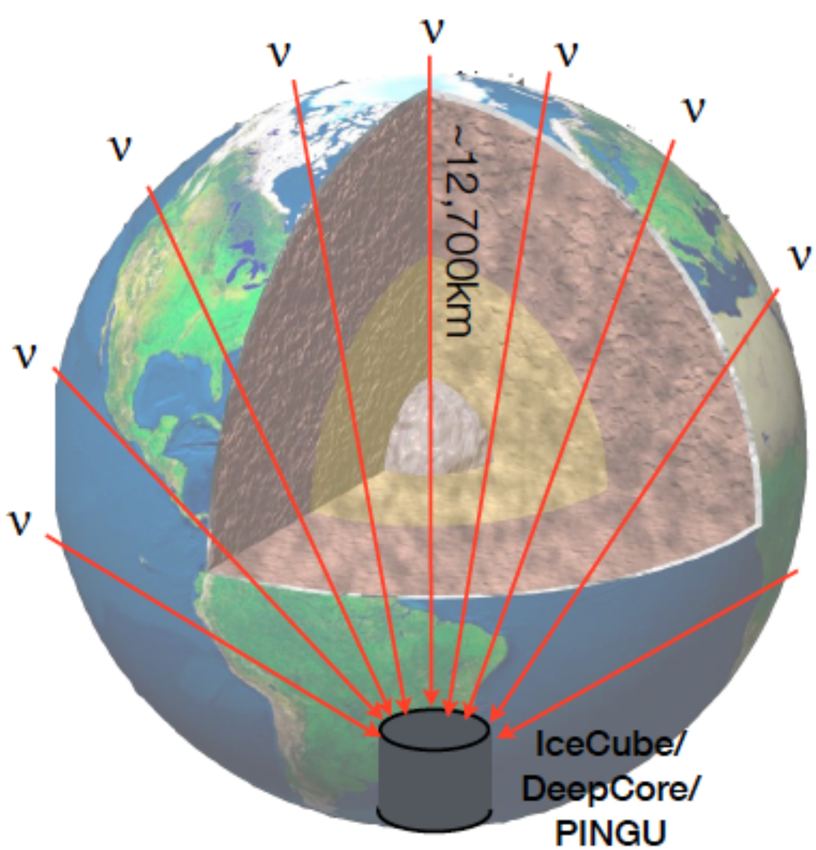
Conclusions

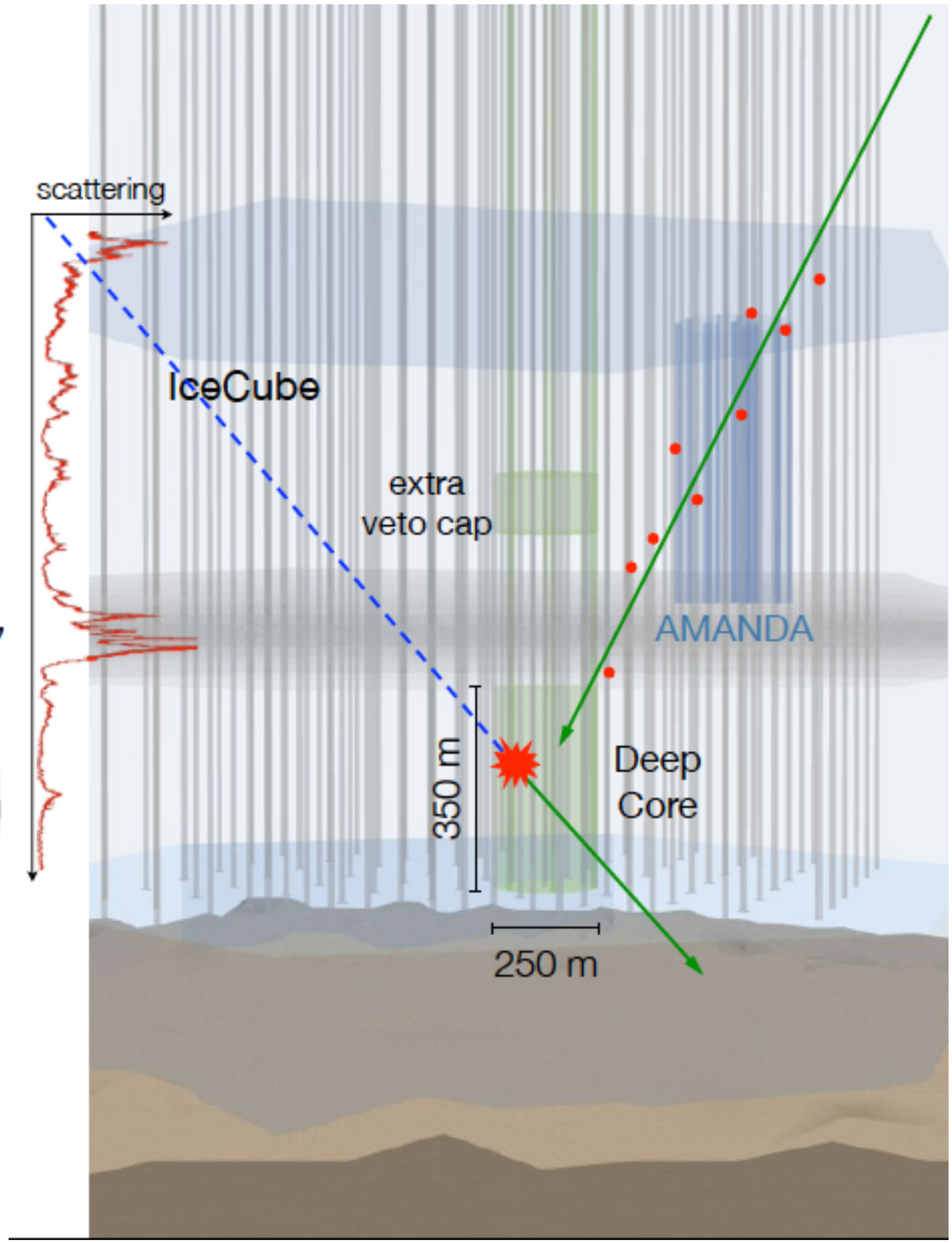
- more to come from IceCube: many analyses have not exploited more than one year of data
- analyses are not in the background-dominated regime
- next-generation detector(s):

  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!

one half million atmospheric neutrinos…

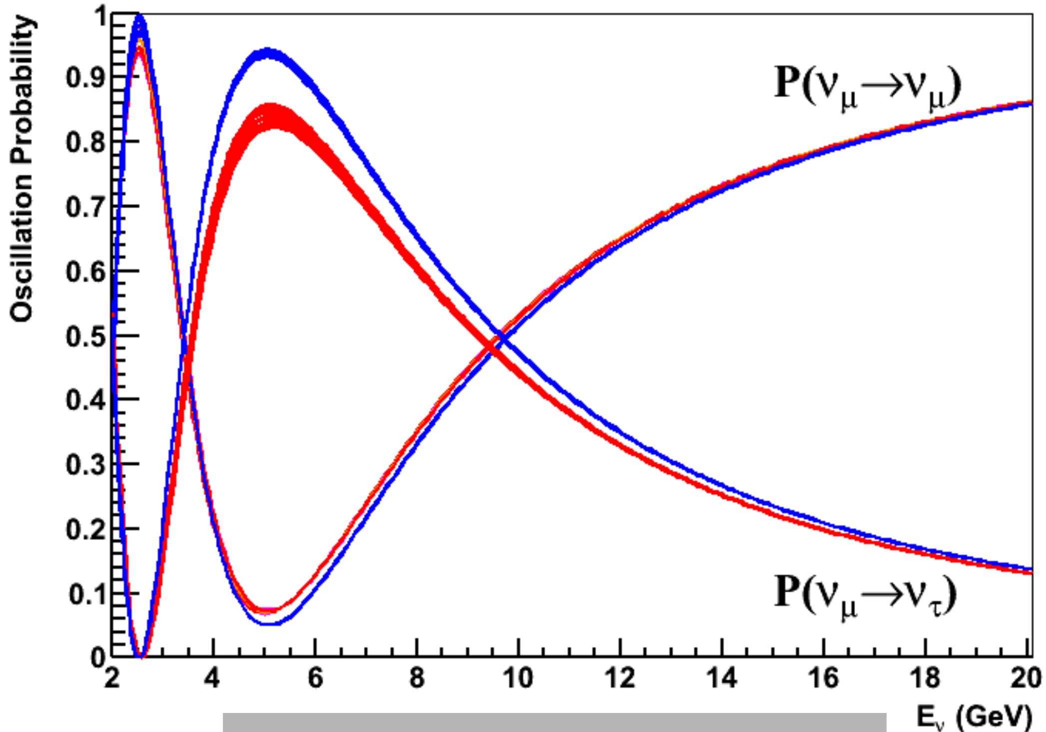




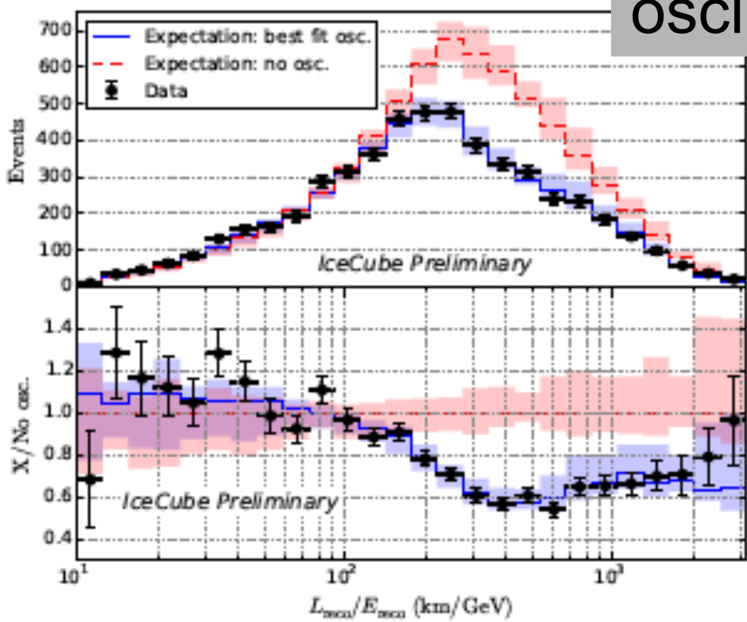
IceCube

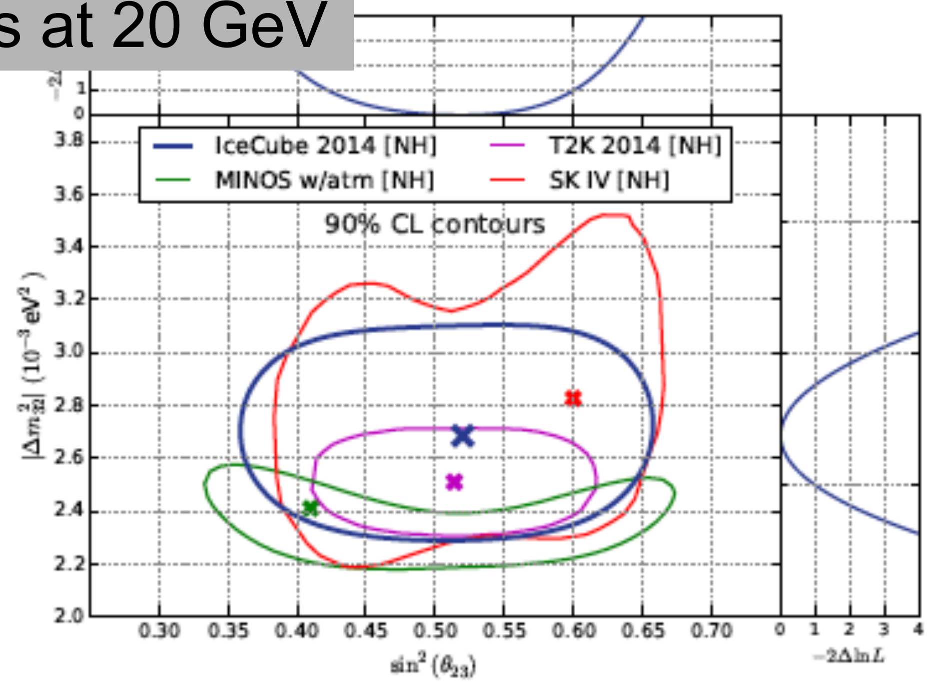
DeepCore

PINGU



oscillations at 20 GeV

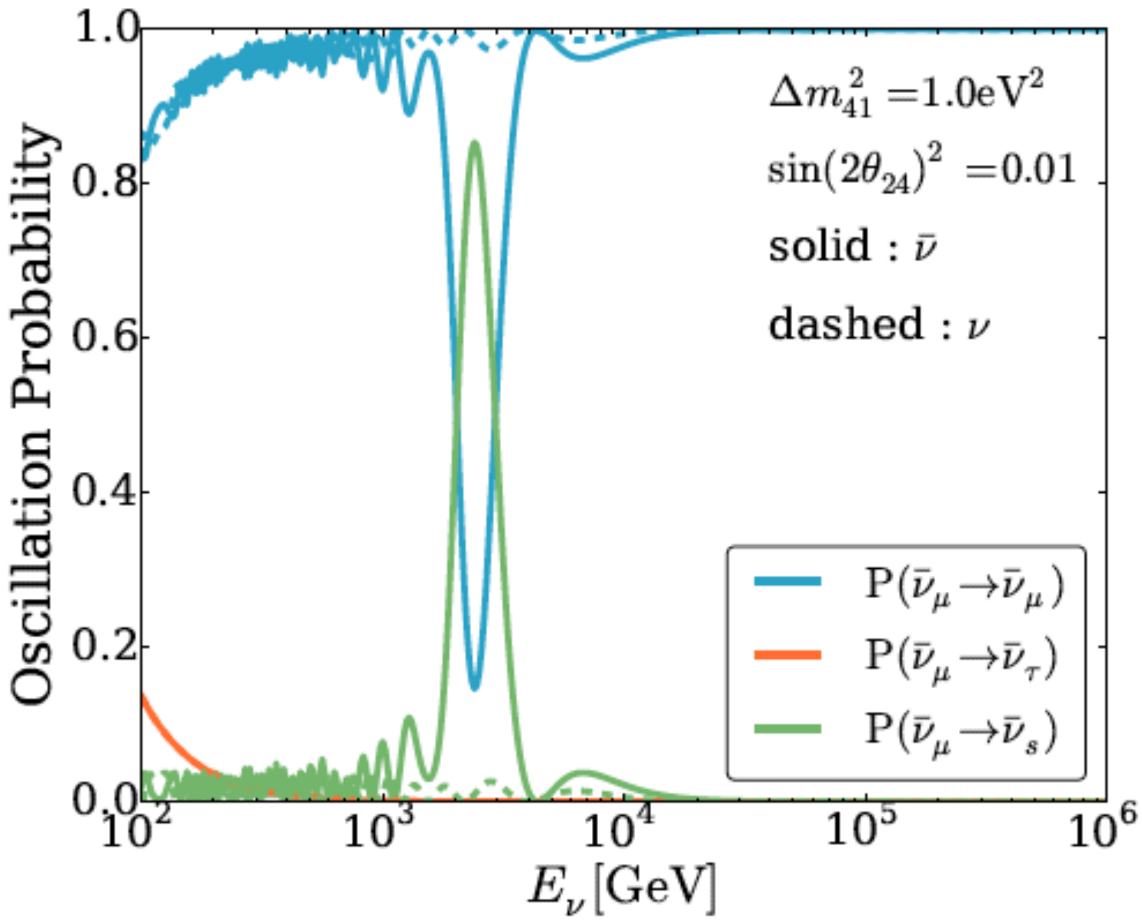


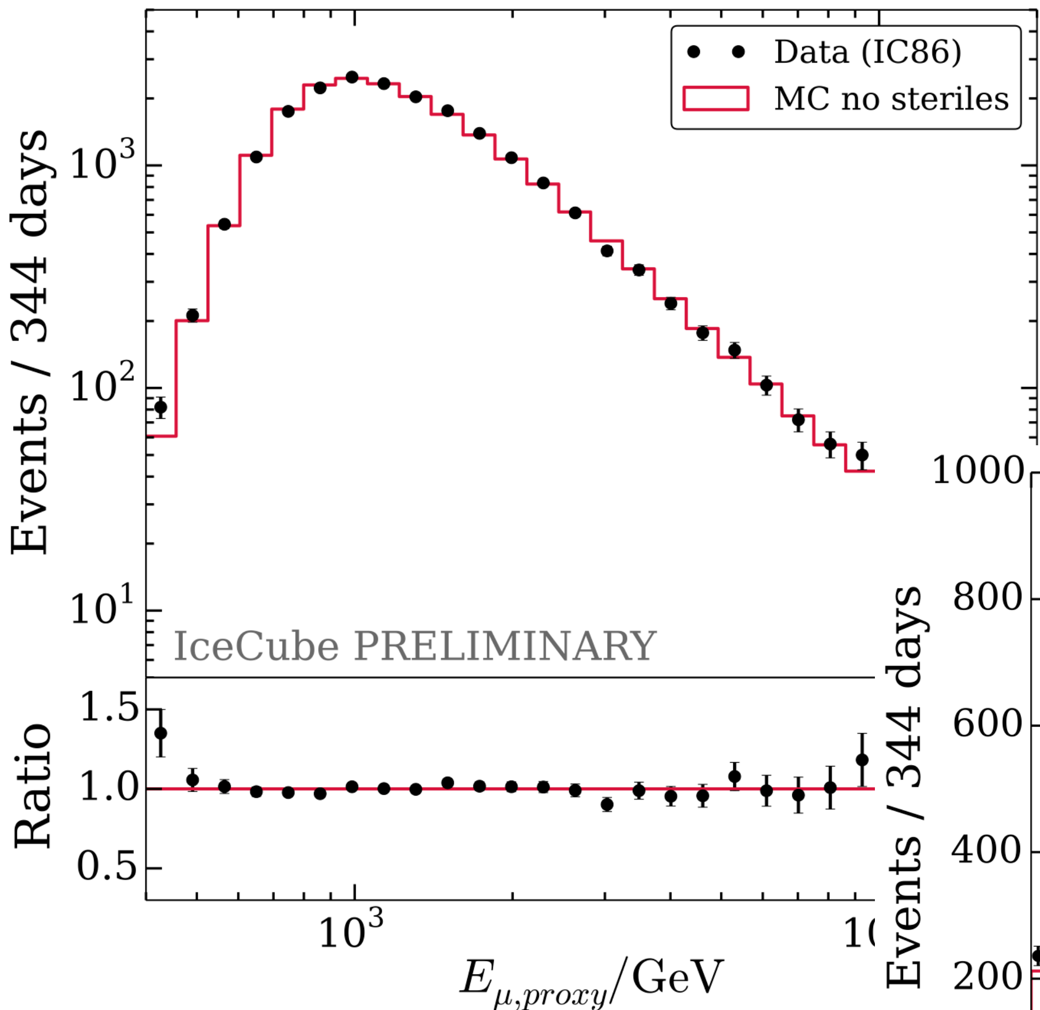


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

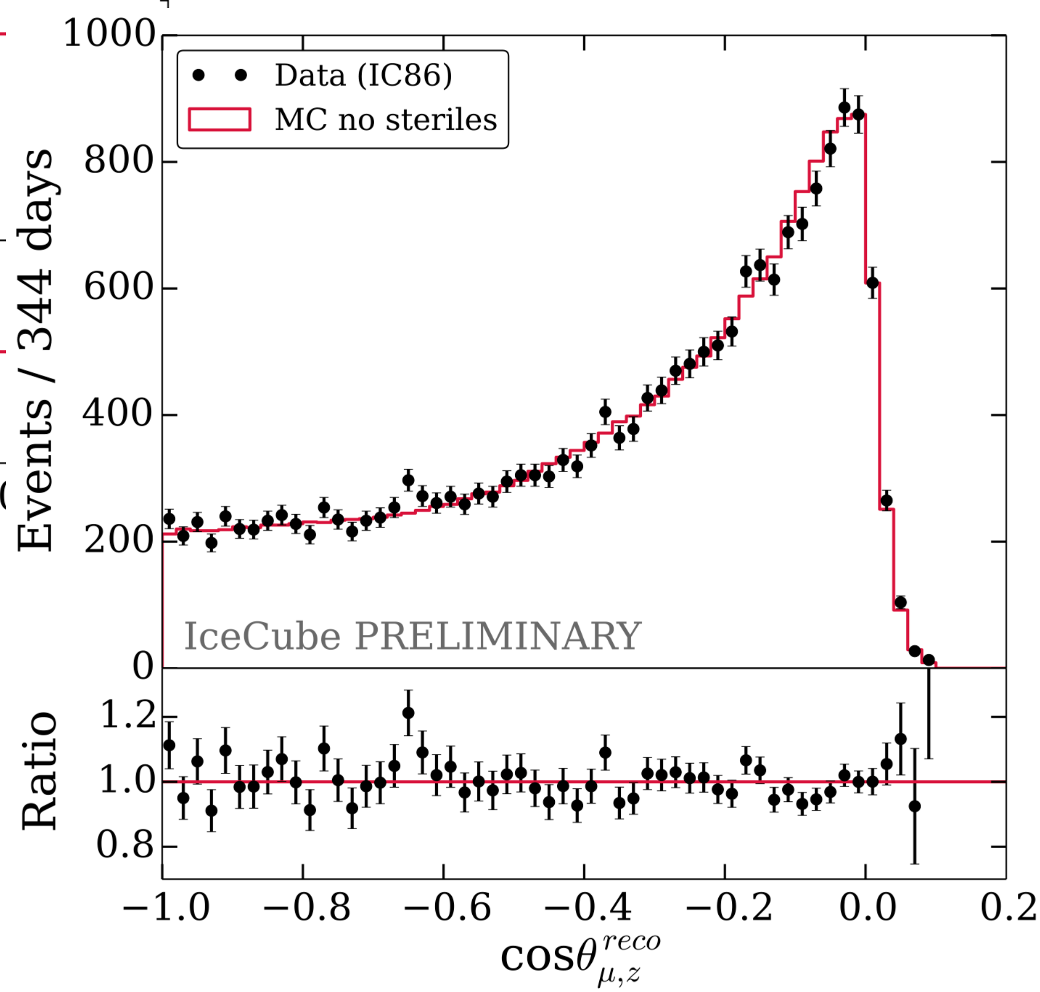
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

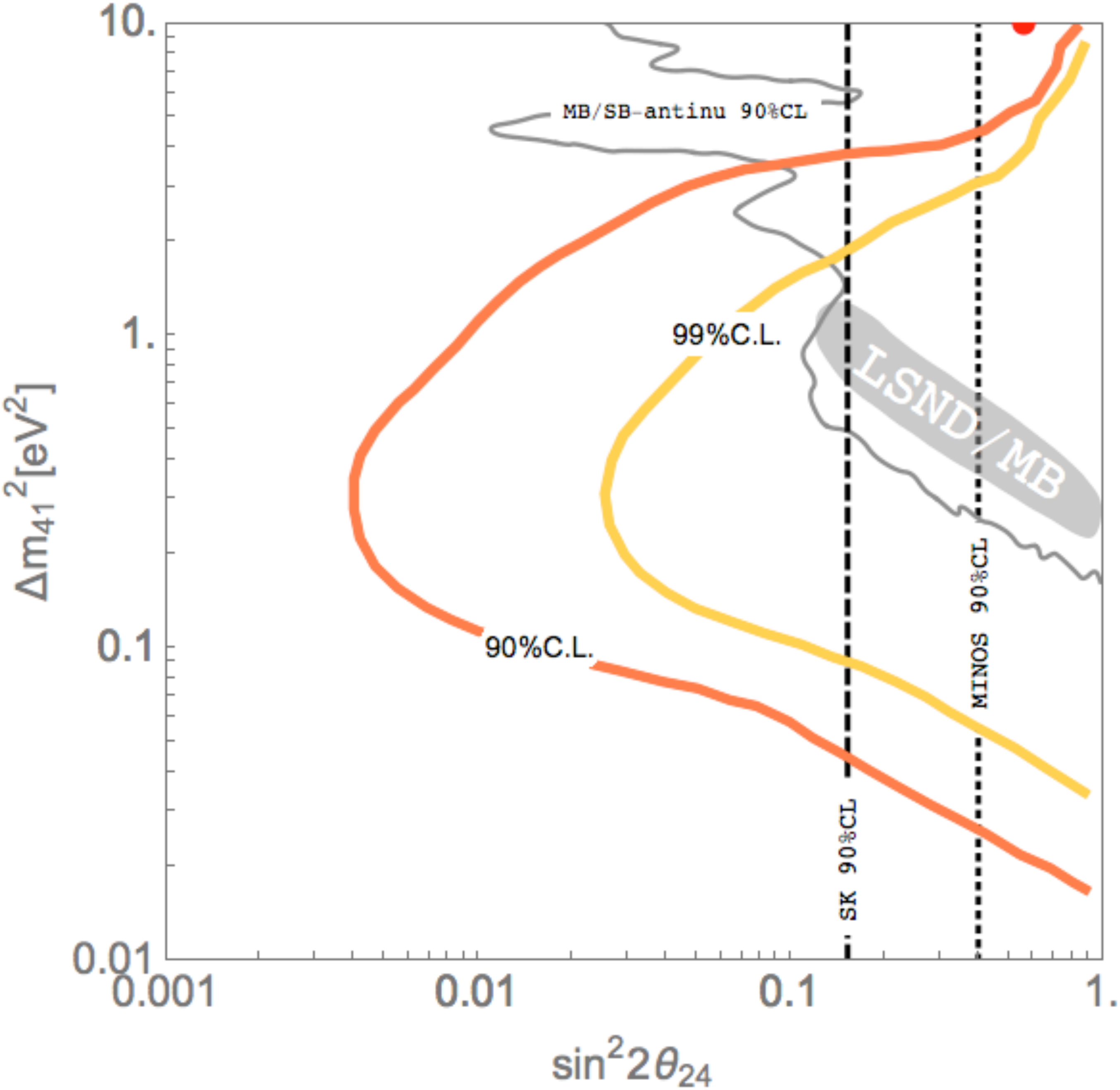
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$





no telltale structure in the zenith angle distribution





MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL
10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}^2 [eV^2]$
$\sin^2 2\theta_{24}$

Conclusions

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- analyses are not in the background-dominated regime
- next-generation detector(s):

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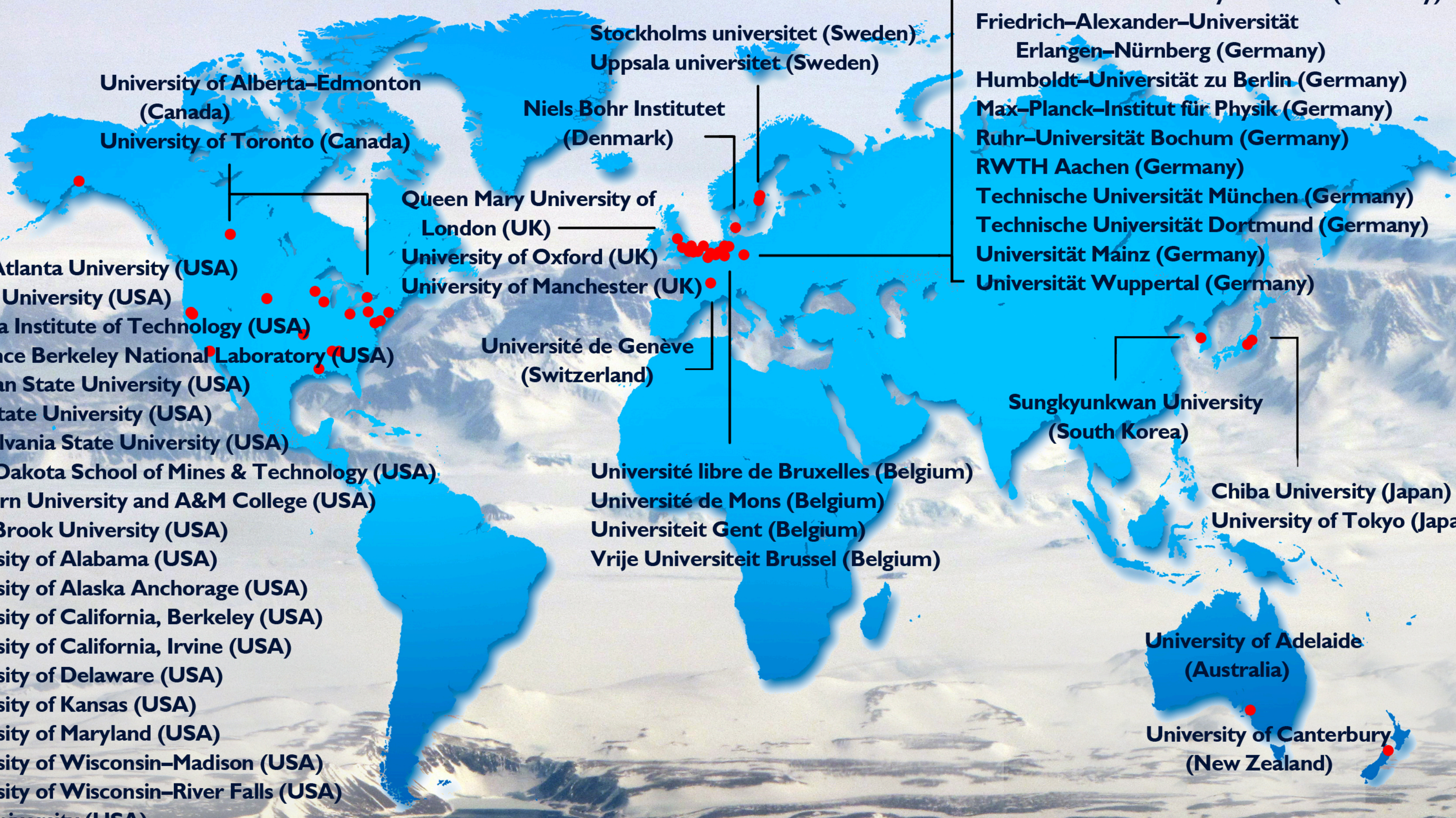
    3. potential for discovery

- neutrinos are never boring!

The IceCube–PINGU Collaboration



International Funding Agencies

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