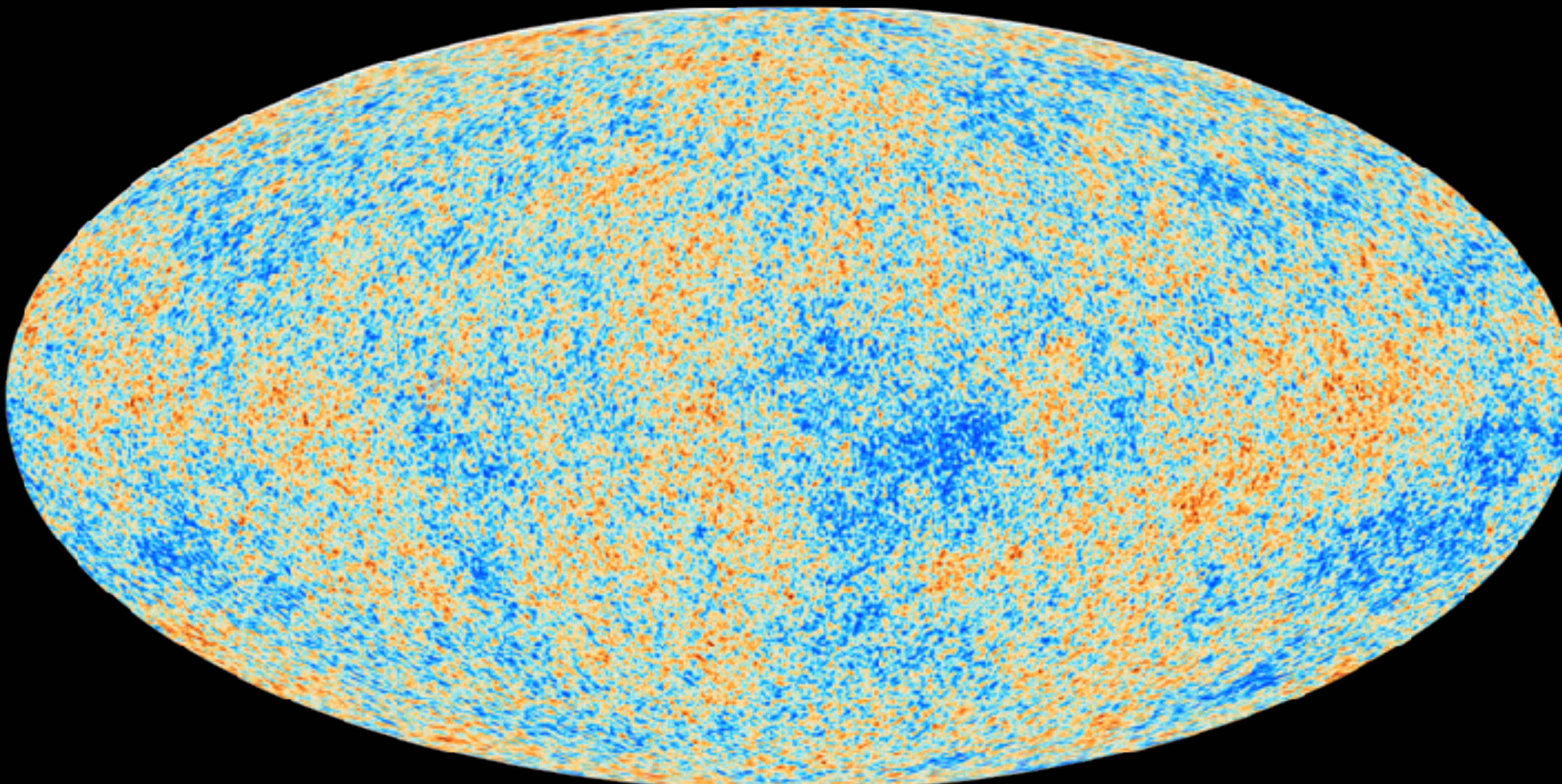
IceCube:
Building a New Window on the Universe

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?

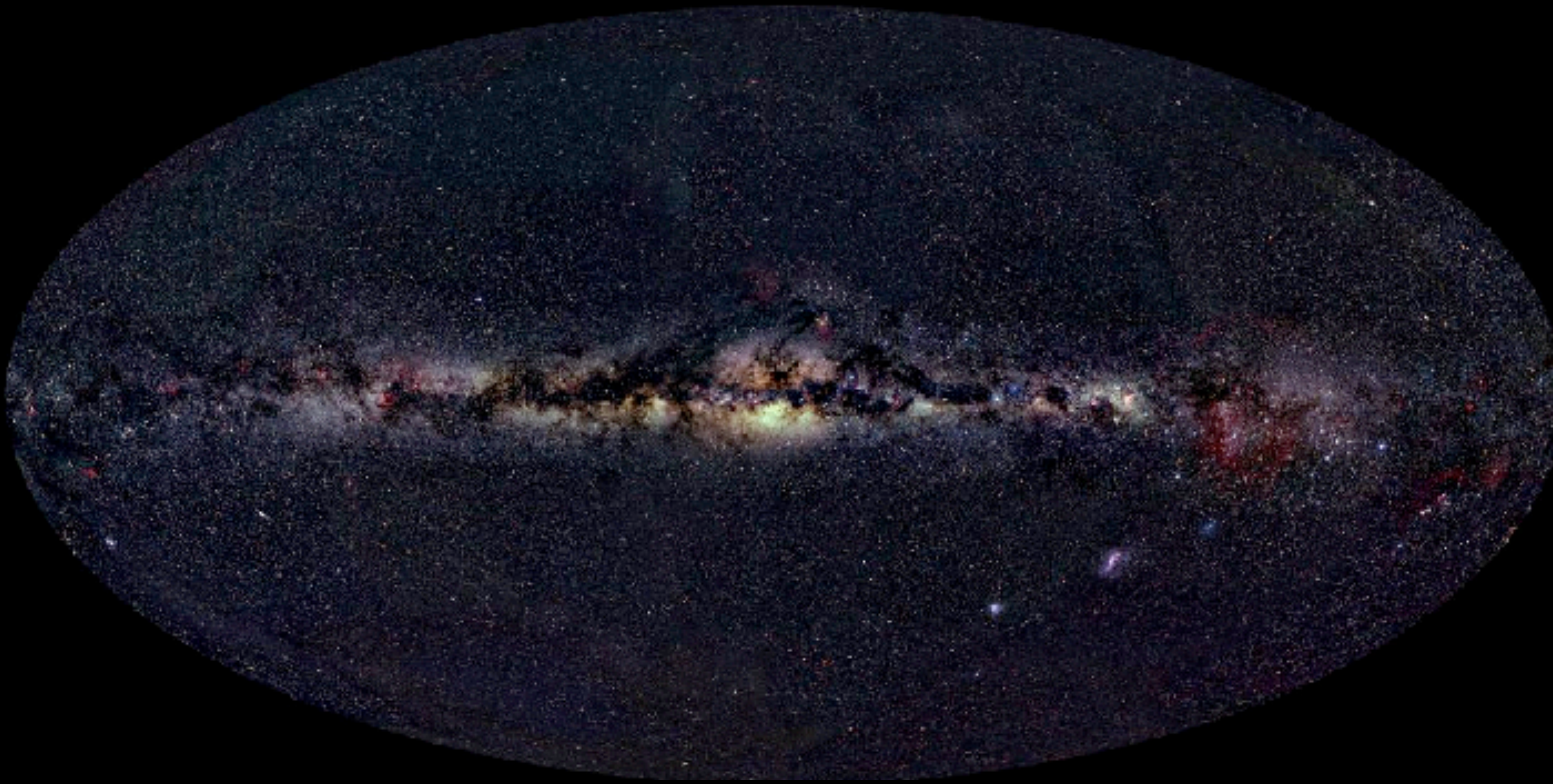
icecube.wisc.edu

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



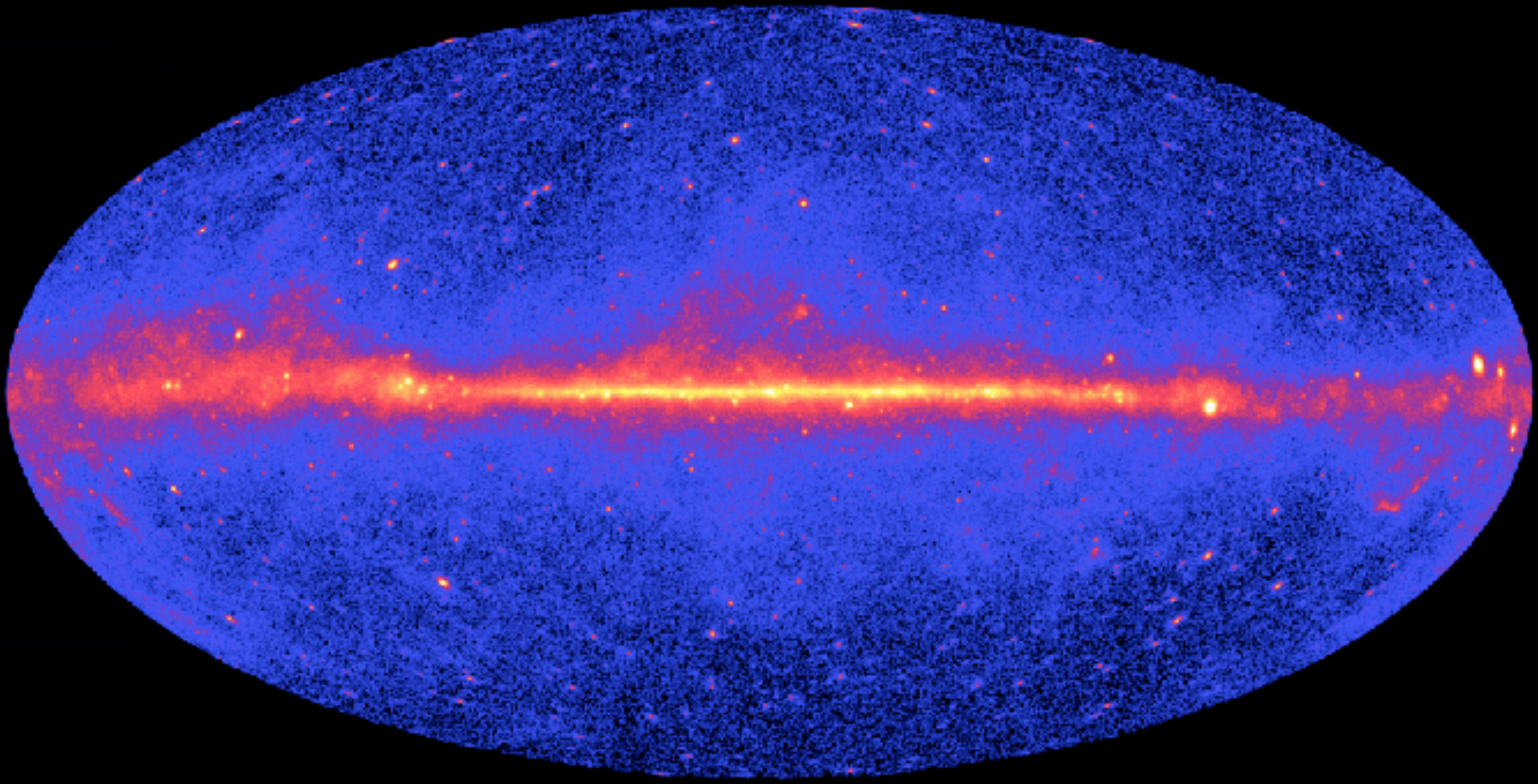
wavelength = 10^{-3} m $\Longleftrightarrow$ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



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

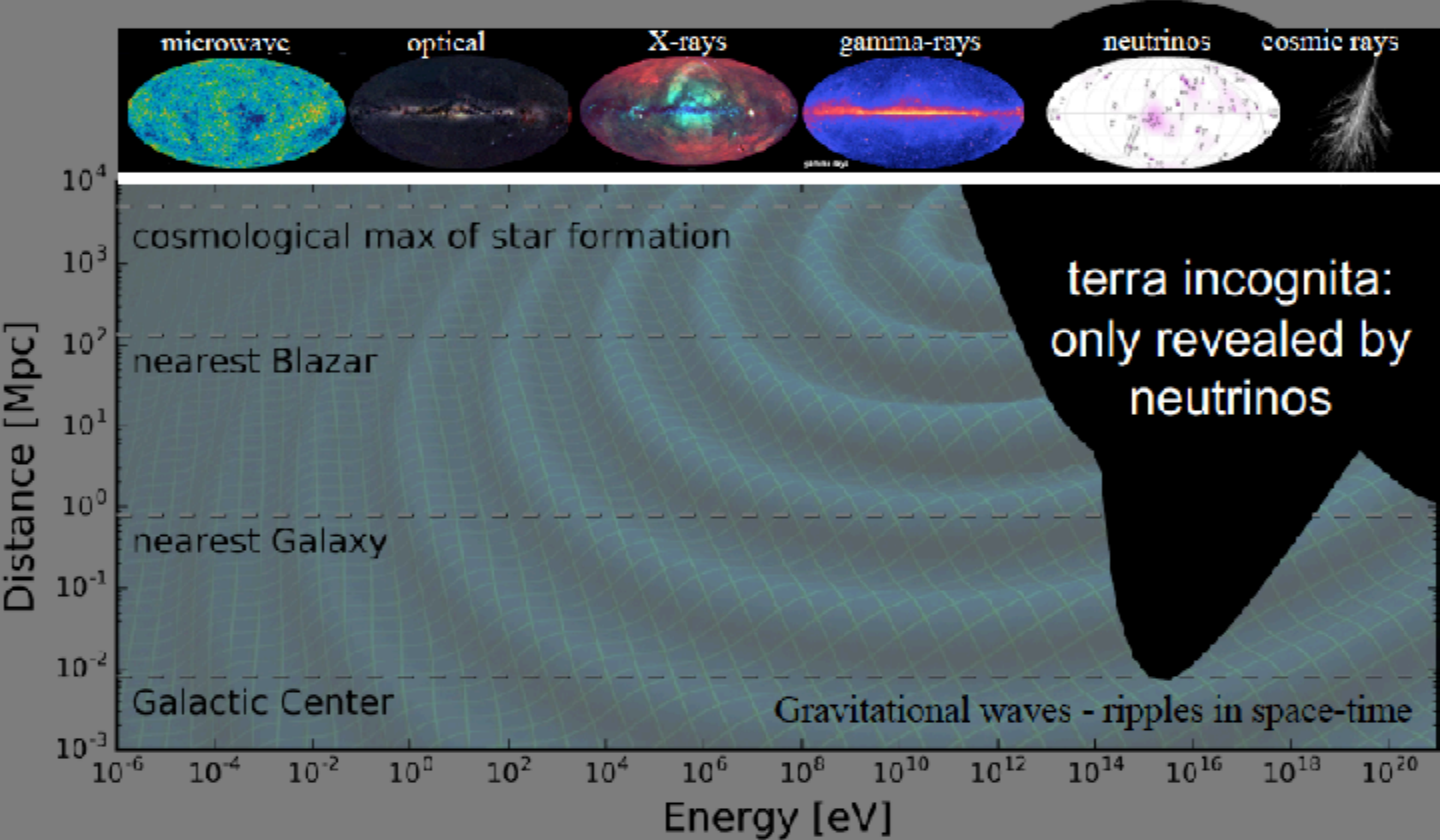
Cosmic Horizons – Gamma Radiation



wavelength = 10^{-15} m ⟺ energy = 1 GeV

Cosmic Horizons – Gamma Radiation

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



- 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

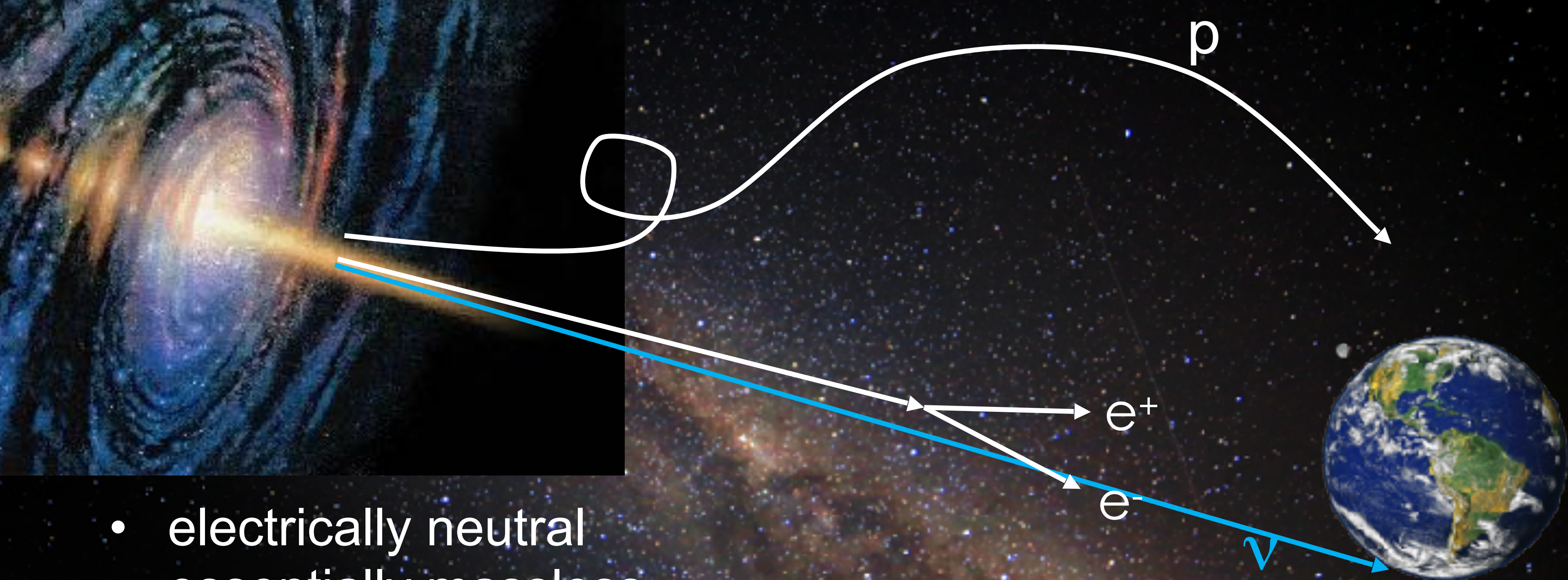
The opaque Universe

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

PeV photons interact with microwave photons (410/cm^3) before reaching our telescopes

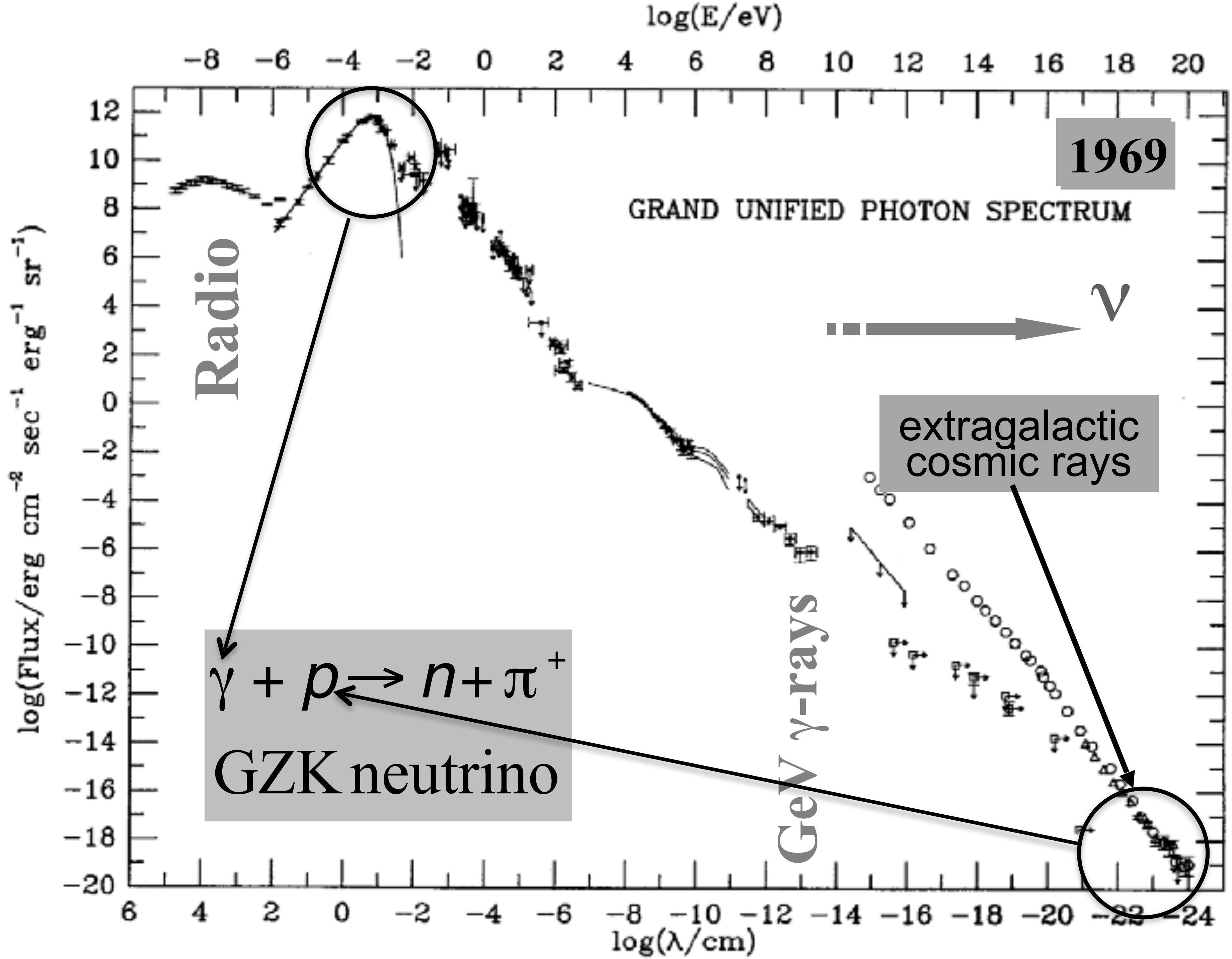
enter: neutrinos

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?



log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic
cosmic rays
GeV γ-rays
$\gamma + p \longrightarrow n + \pi^{+}$
GZK neutrino
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)

cosmic rays interact with the microwave background

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

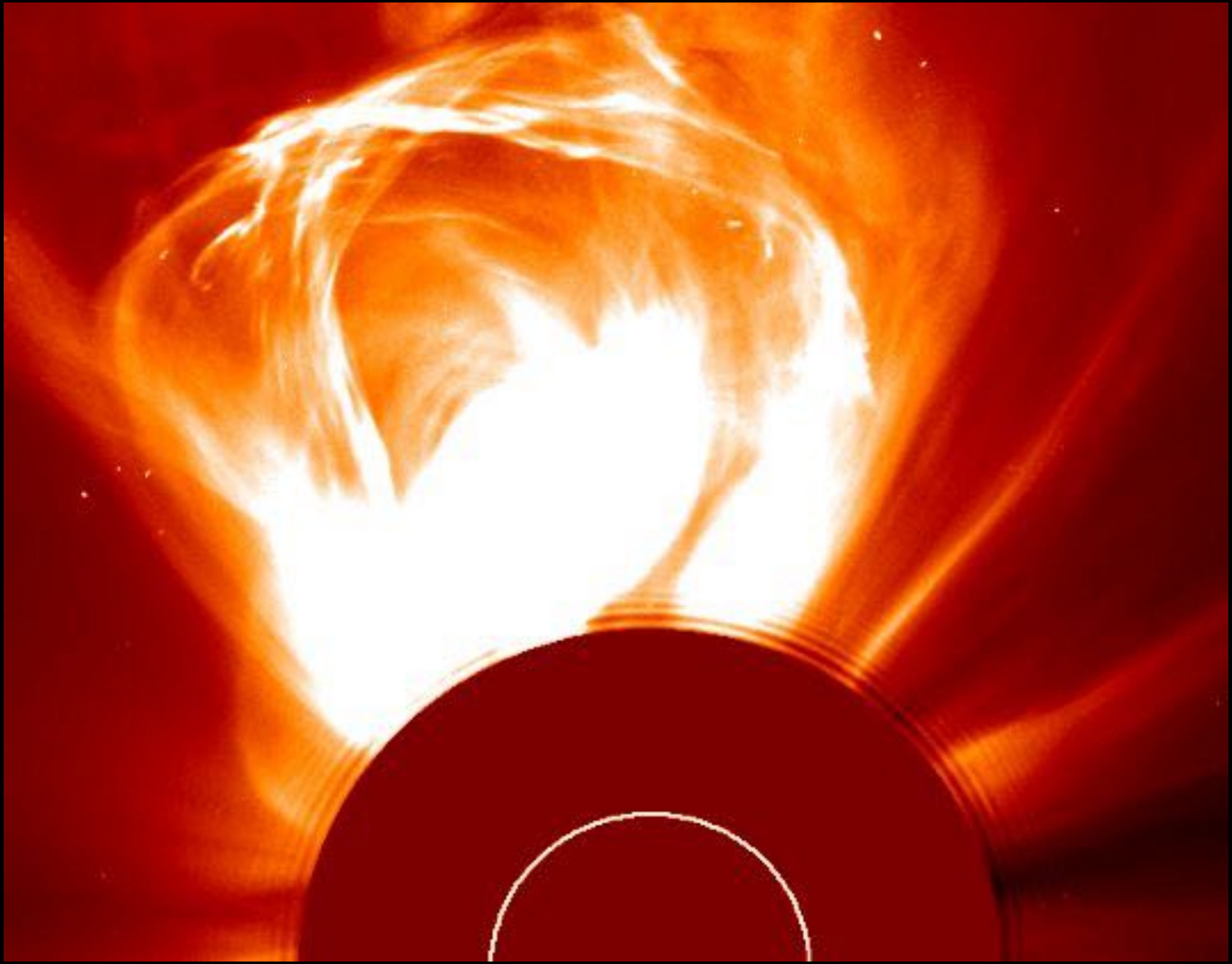
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

nonthermal universe: cosmic accelerators



- accelerator must contain the particles

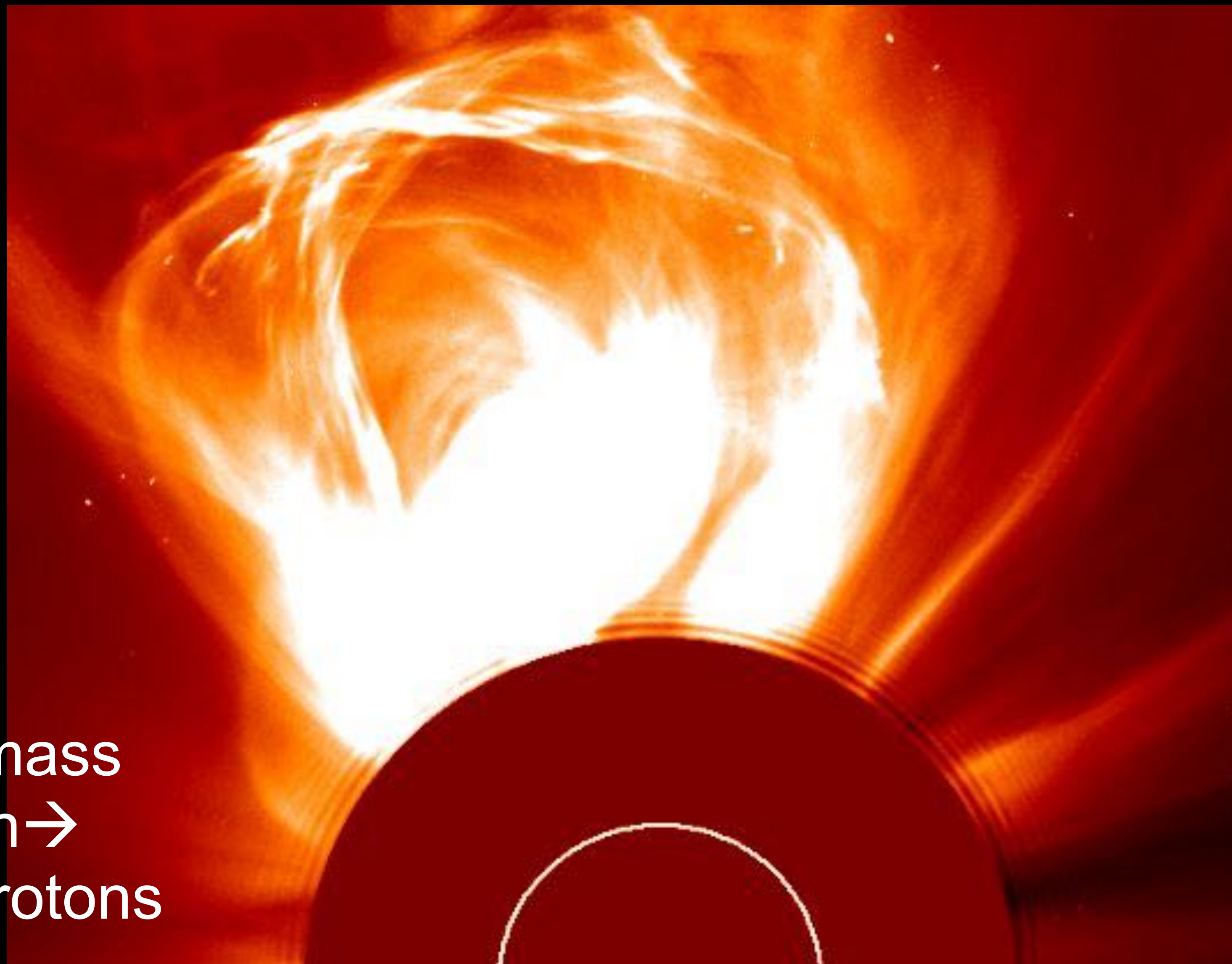
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \leq R$$

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

challenges of cosmic ray astrophysics:

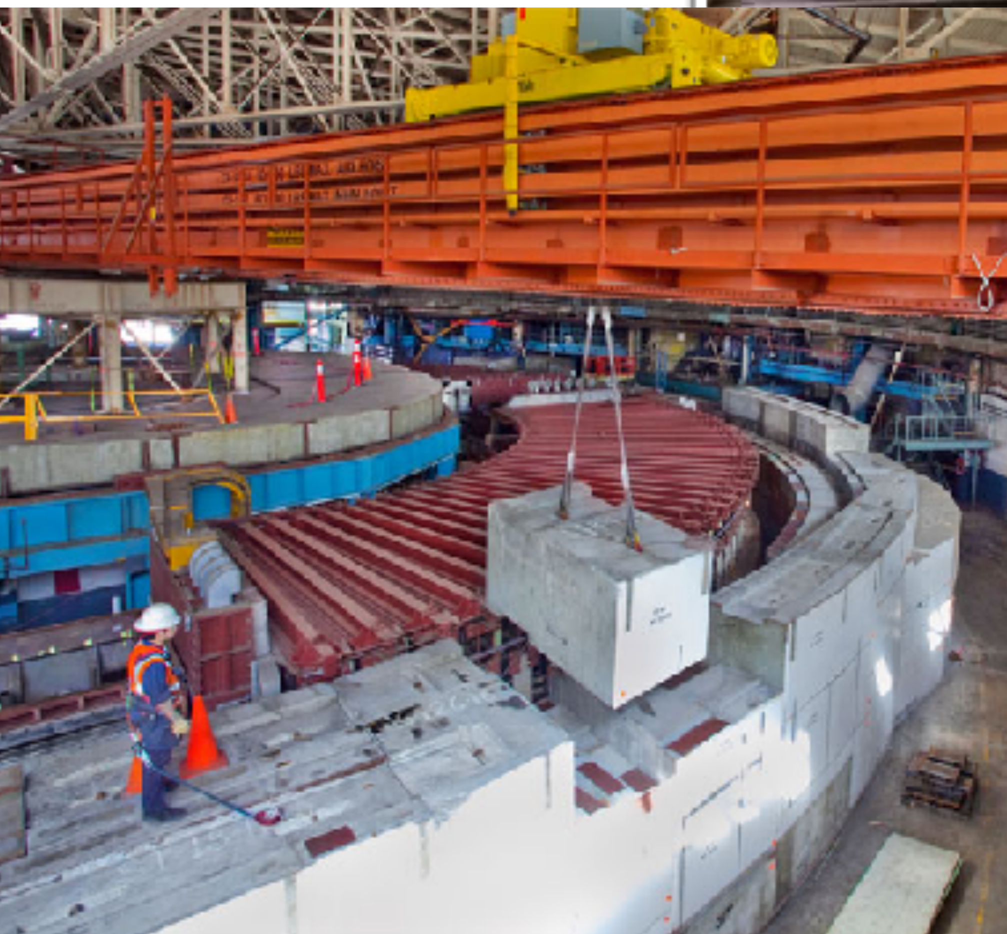
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

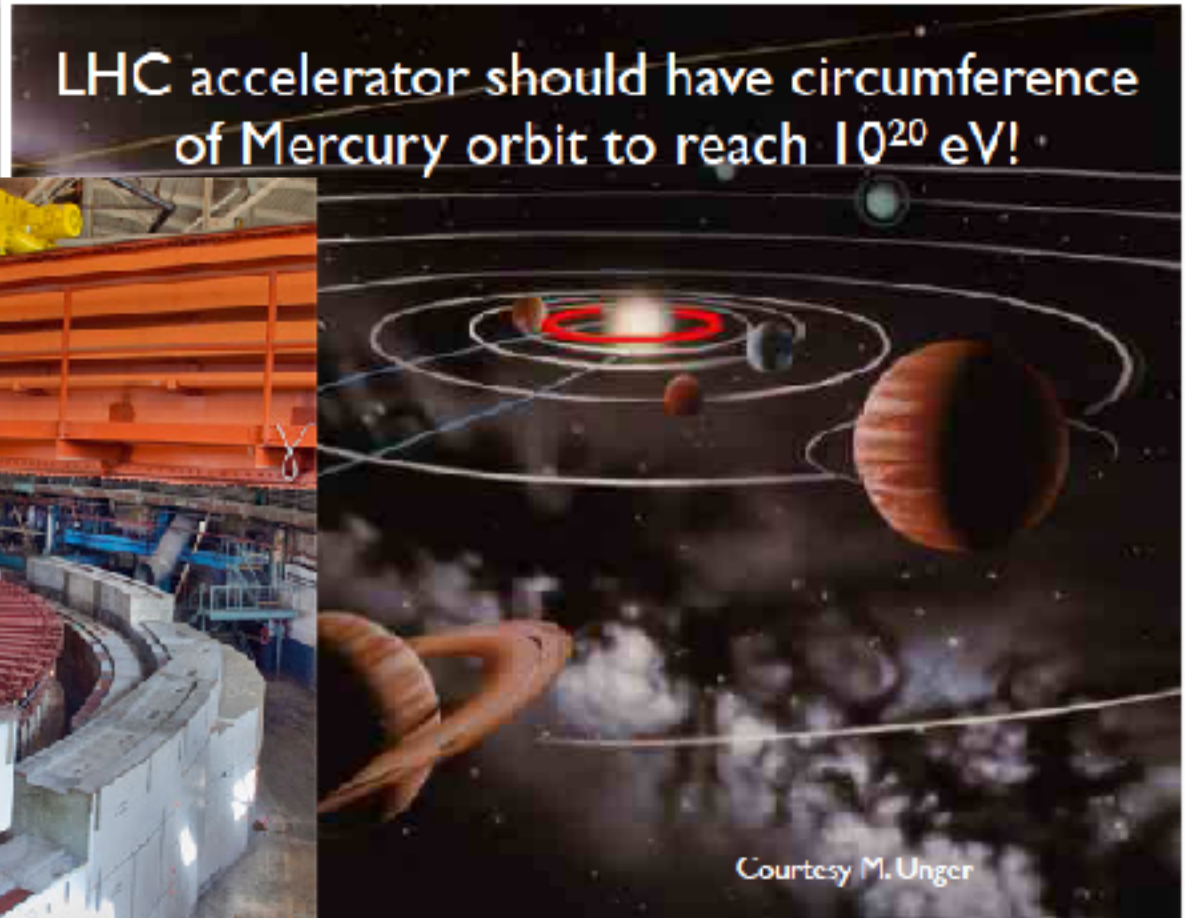
the sun constructs an accelerator

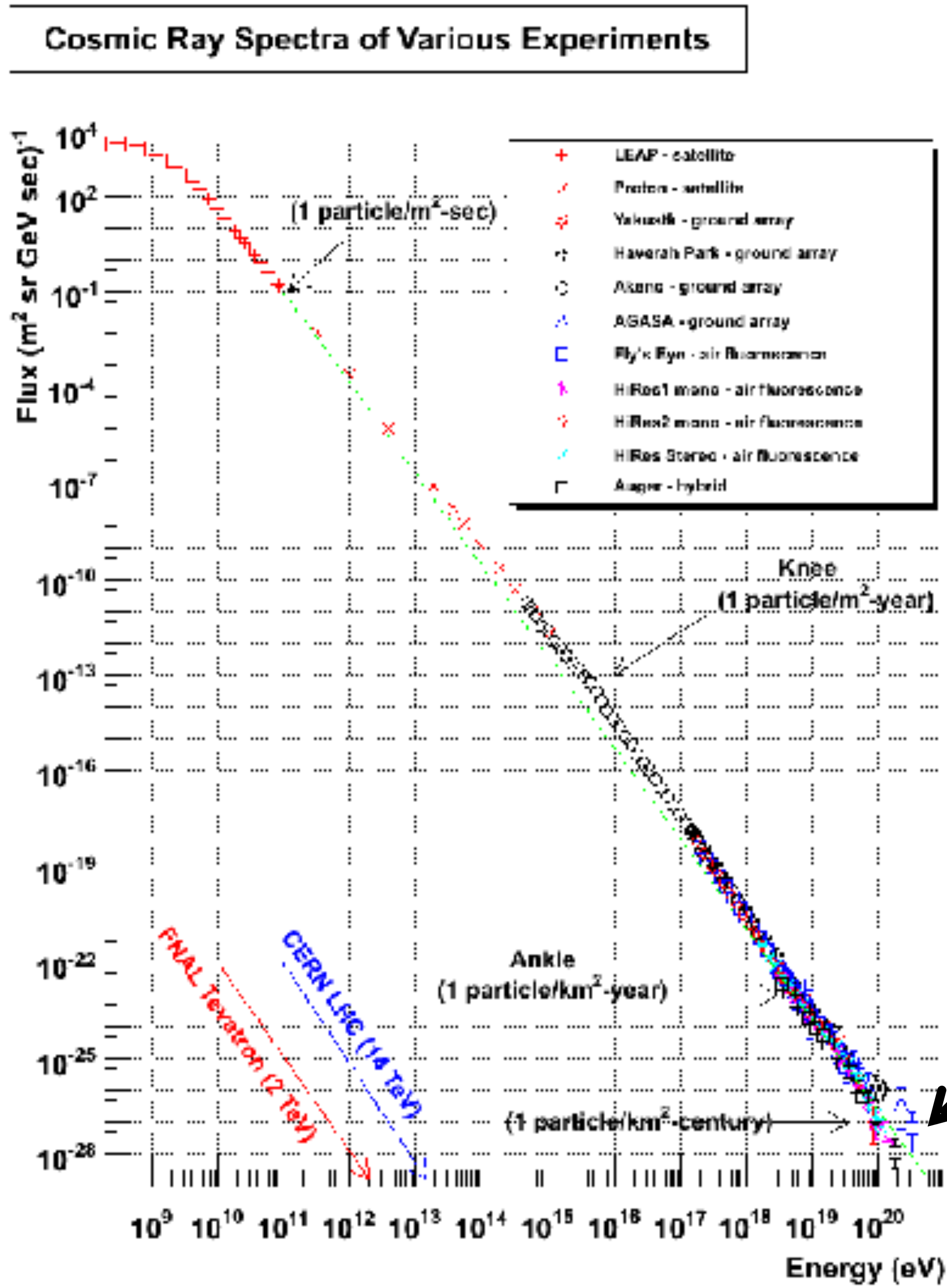


coronal mass
ejection→
10 GeV protons

accomodating energy and luminosity are challenging





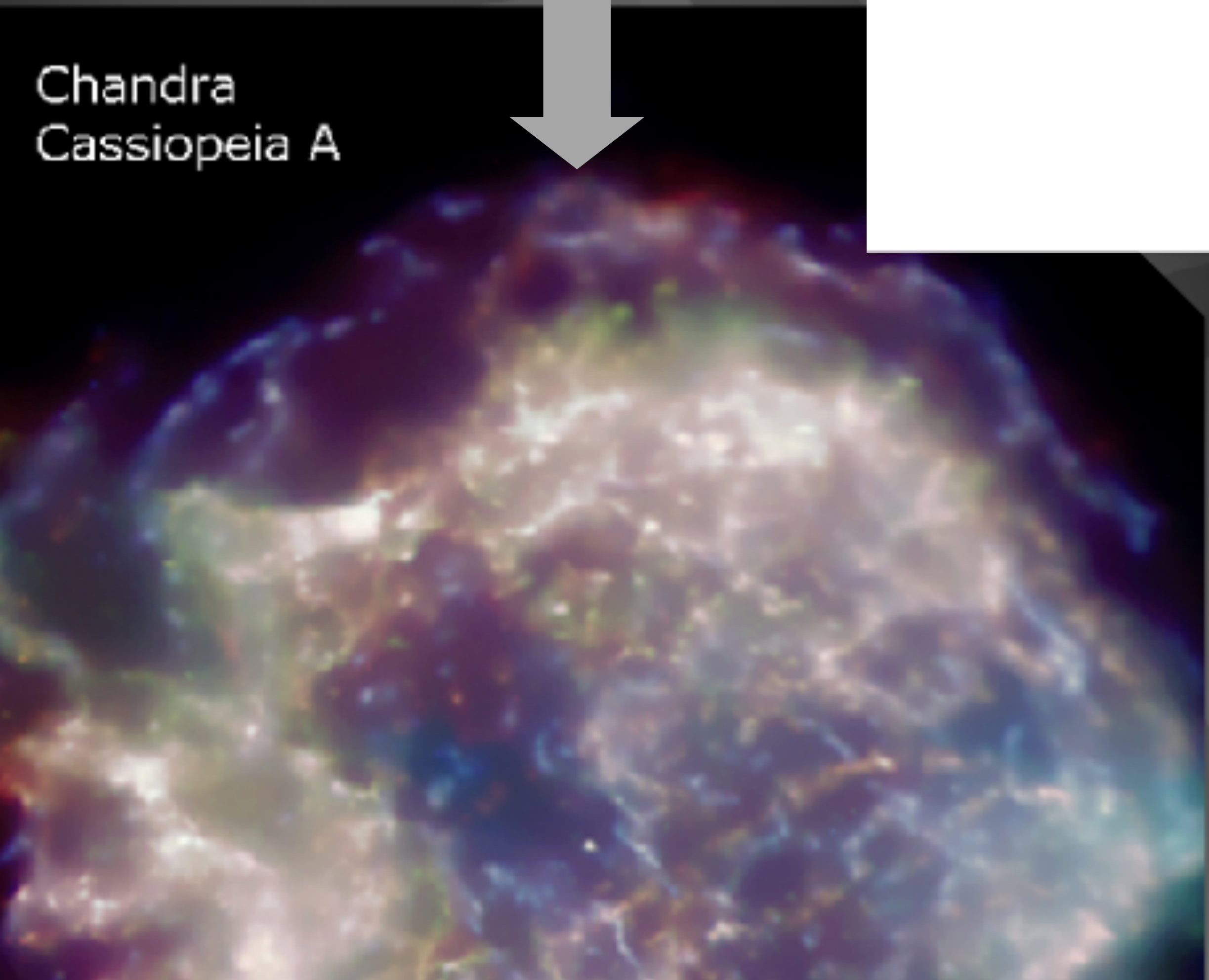


cosmic ray accelerators:
where, how?

gravitational energy from collapsing star converted into particle acceleration

LHC filling the orbit of Mercury

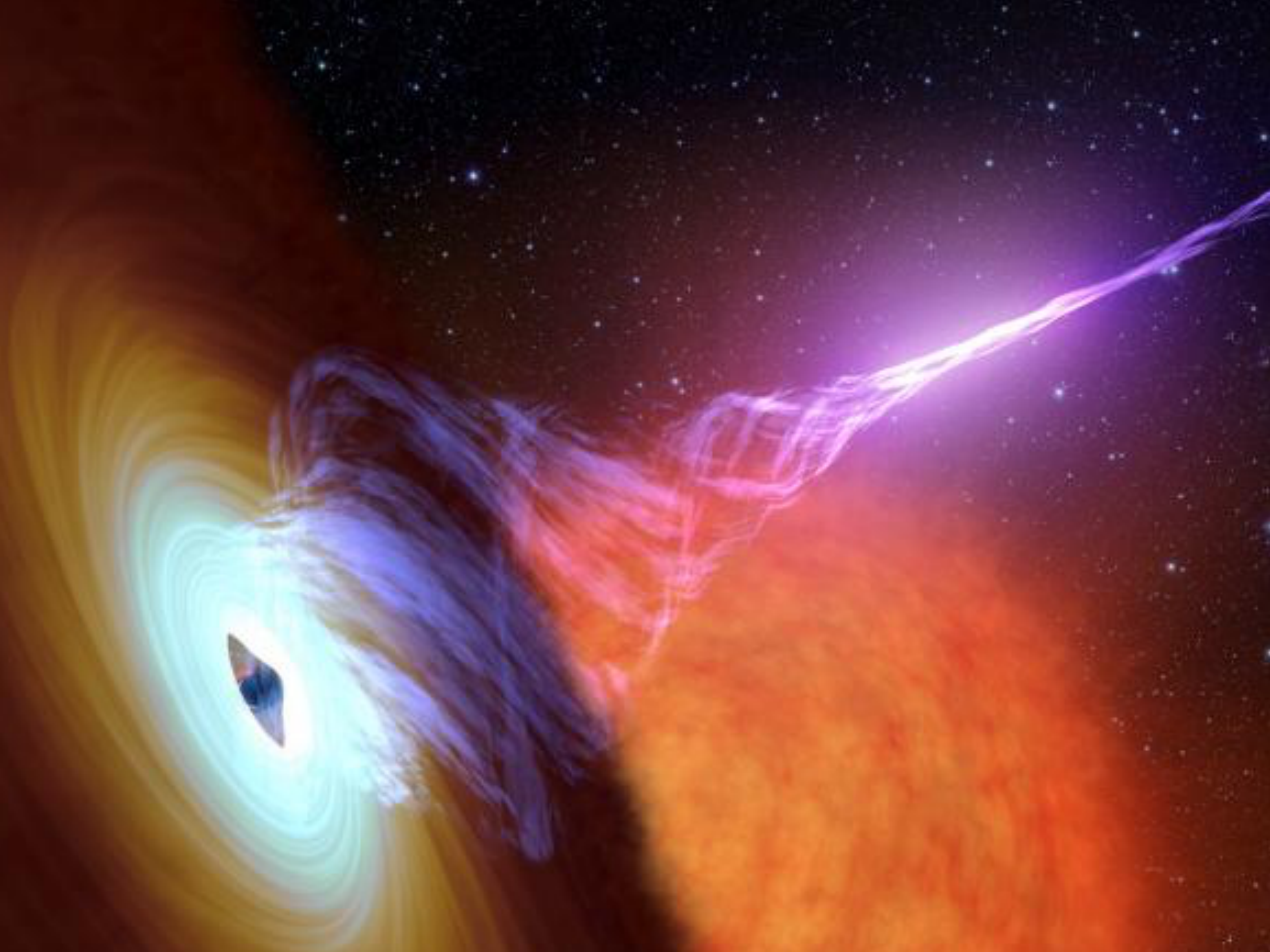
supernova remnants

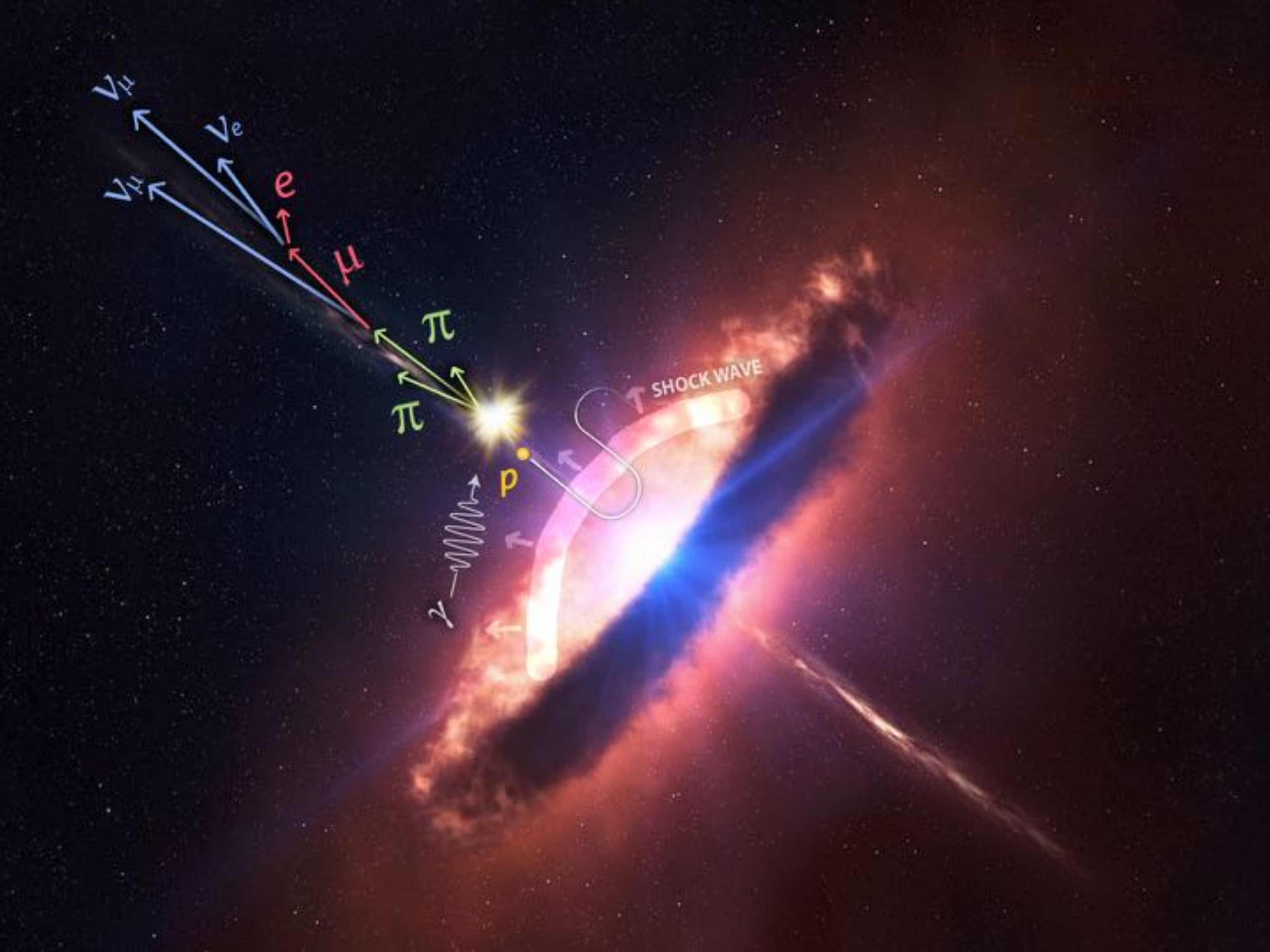


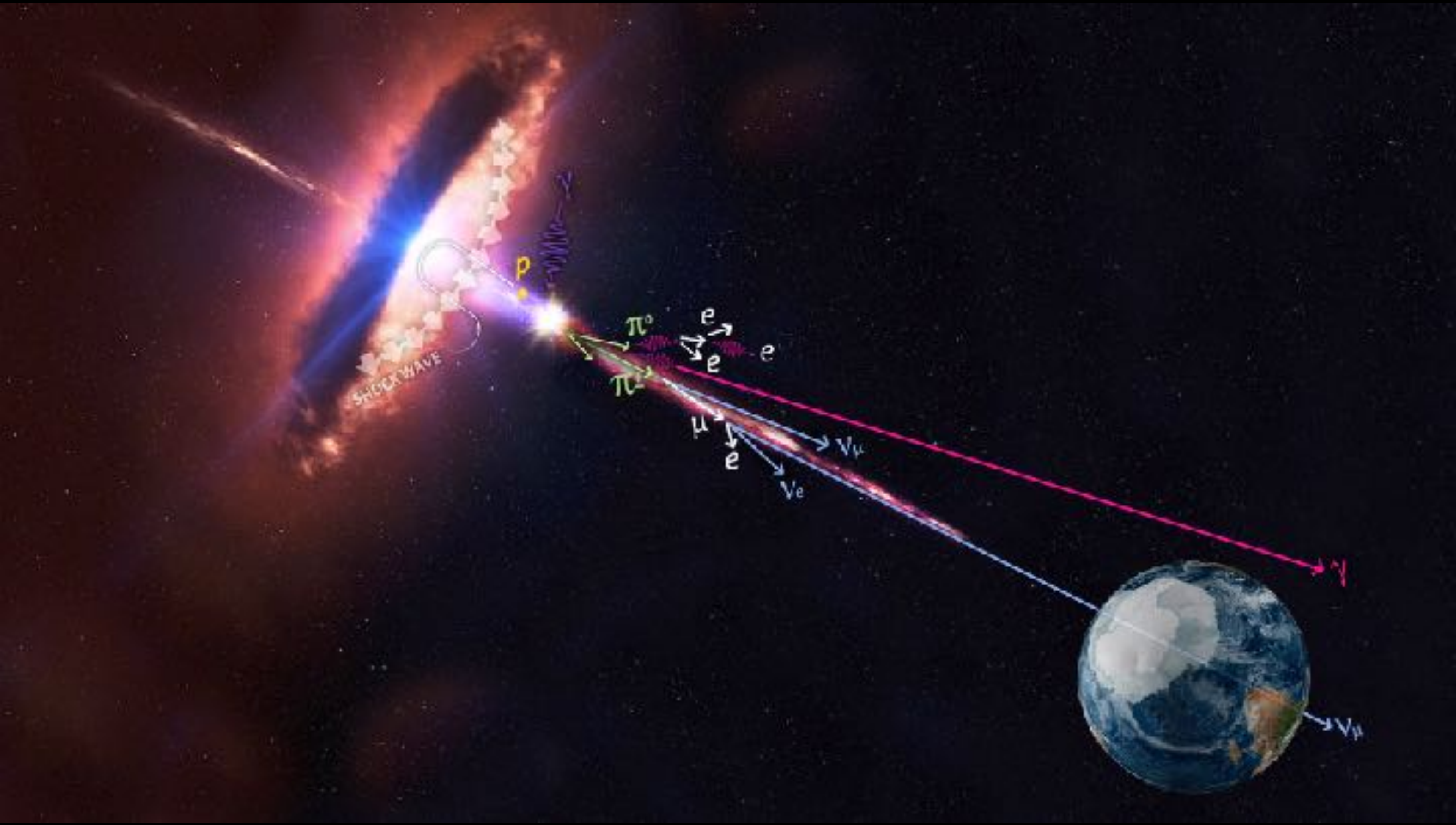
gamma ray bursts

active galaxy

particle flows near
supermassive
black hole

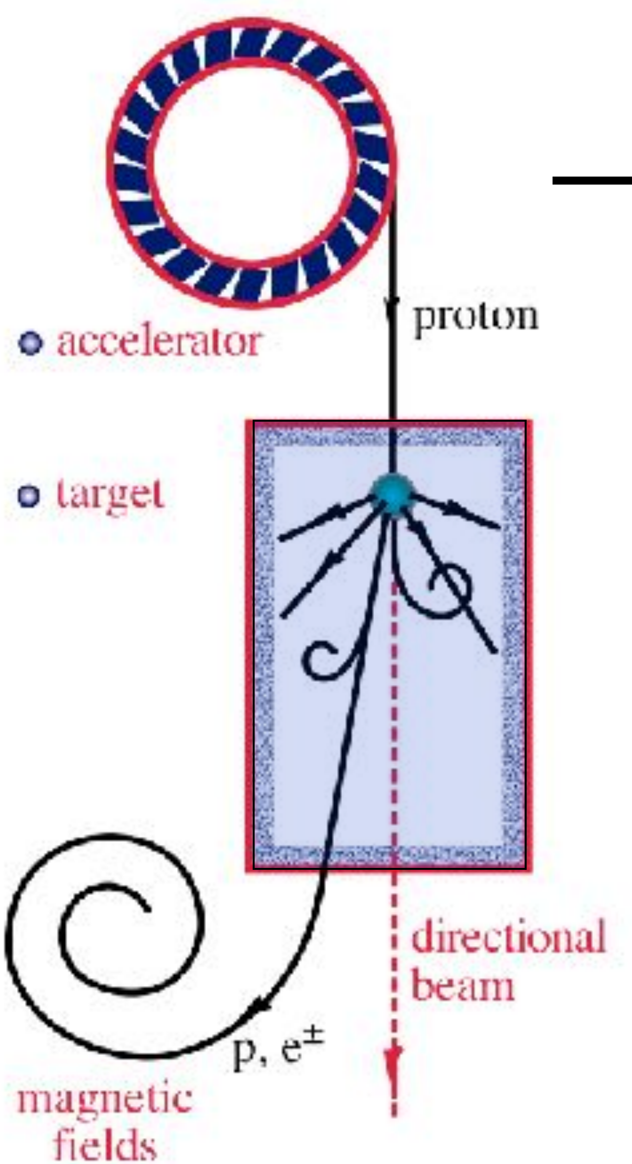



νμ
νe
e
νμ
μ
π
π
SHOCK WAVE
p
γ



blazar geometry

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

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

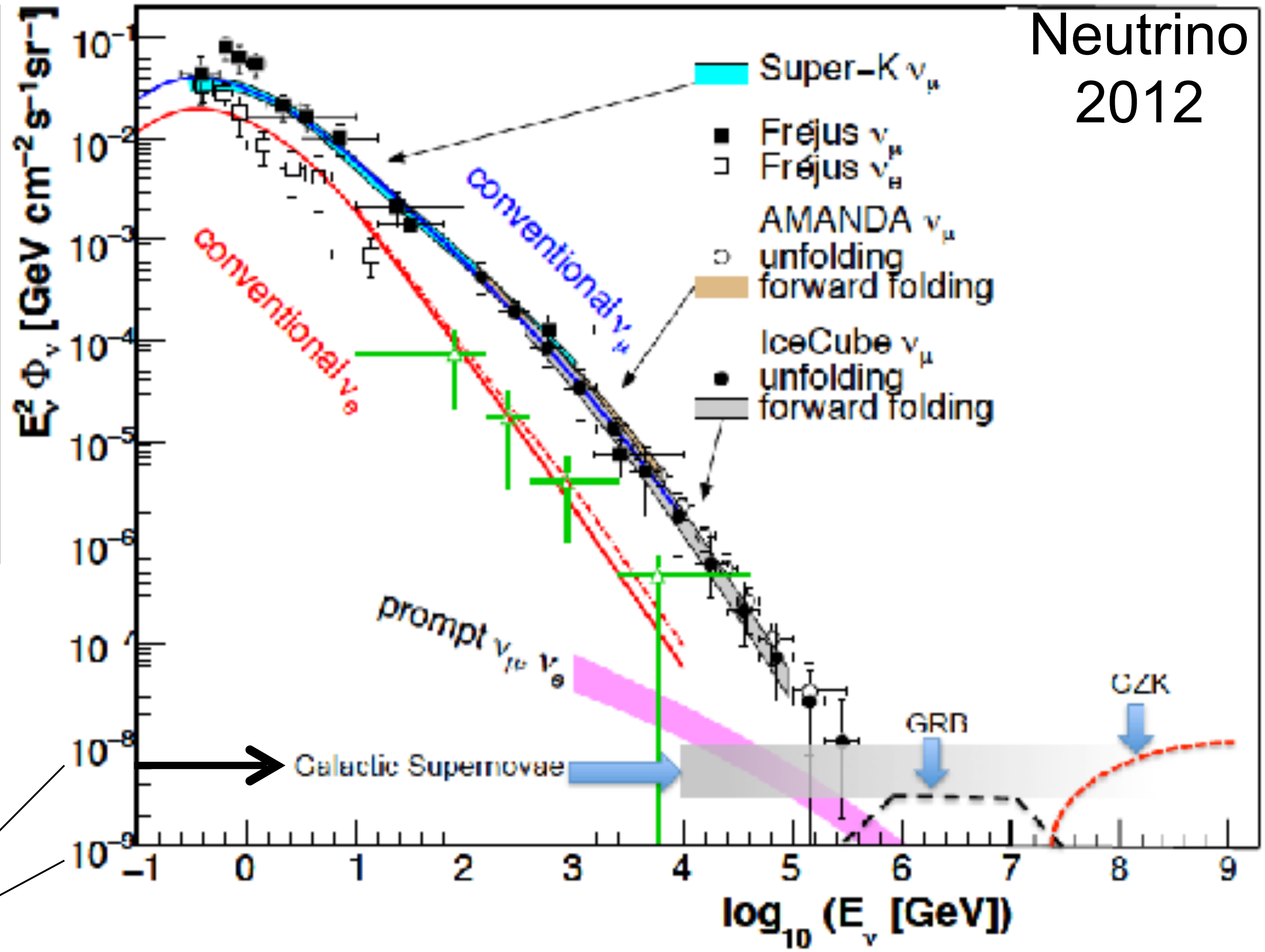
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



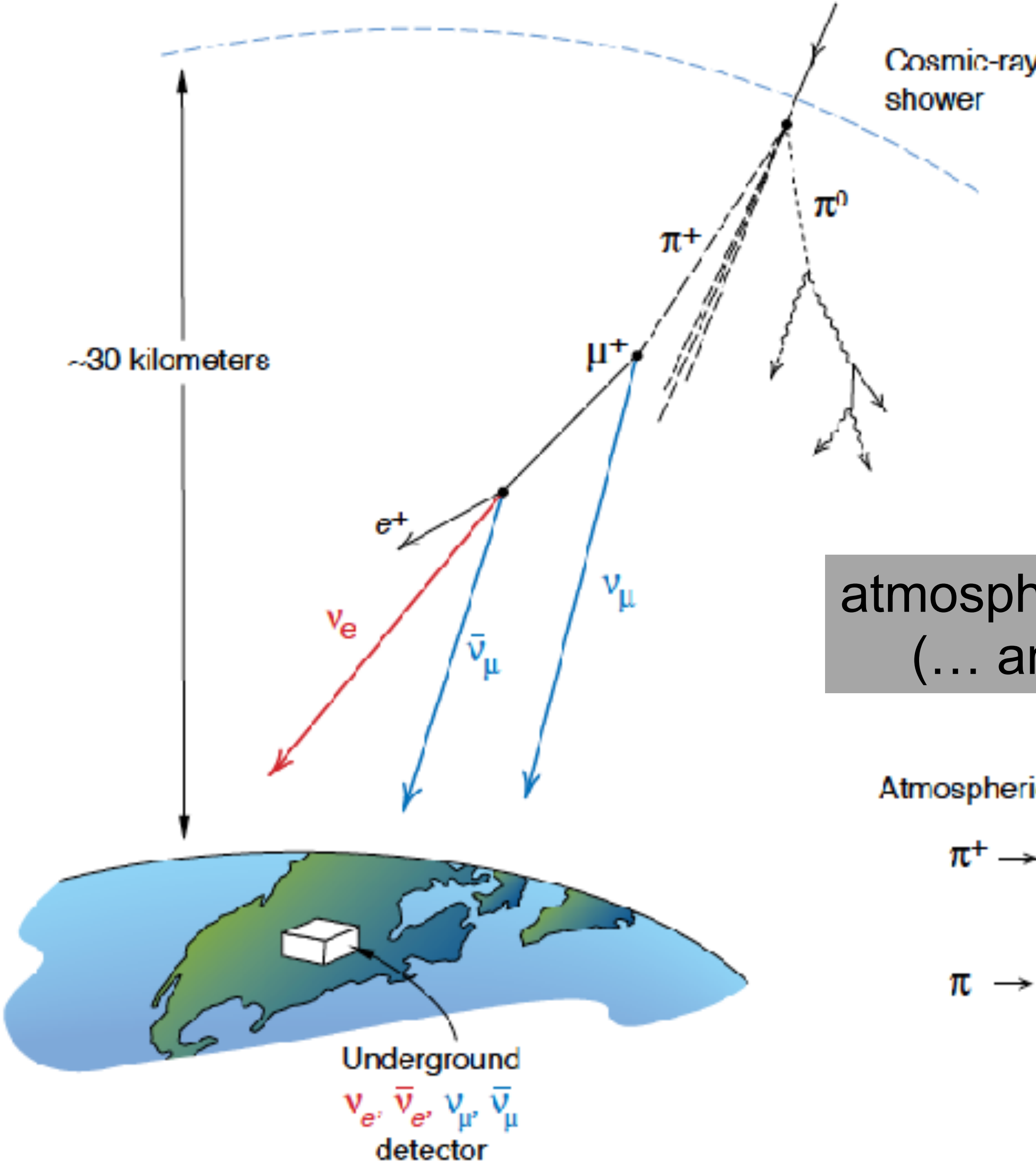
$dN/dE \sim E^{-2}$

10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV

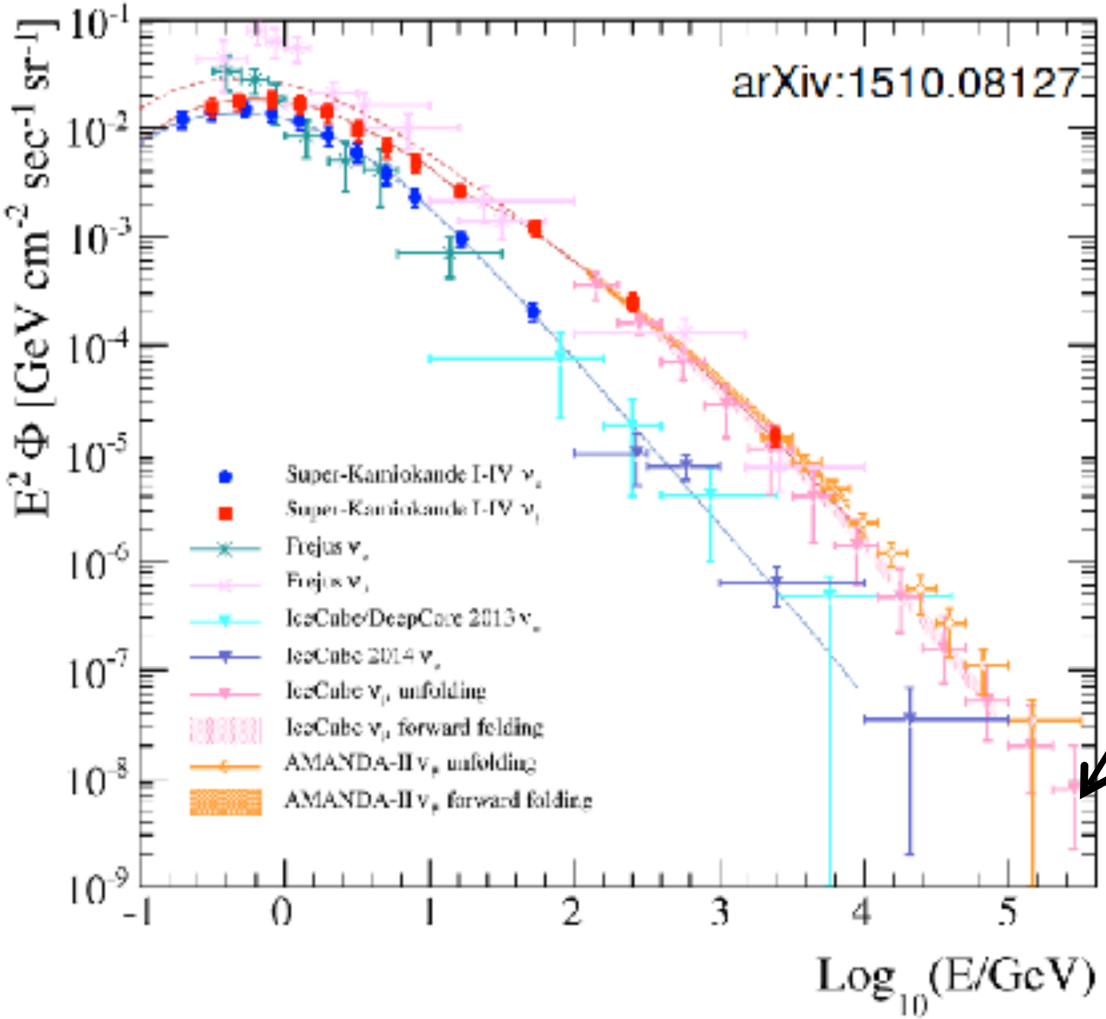


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

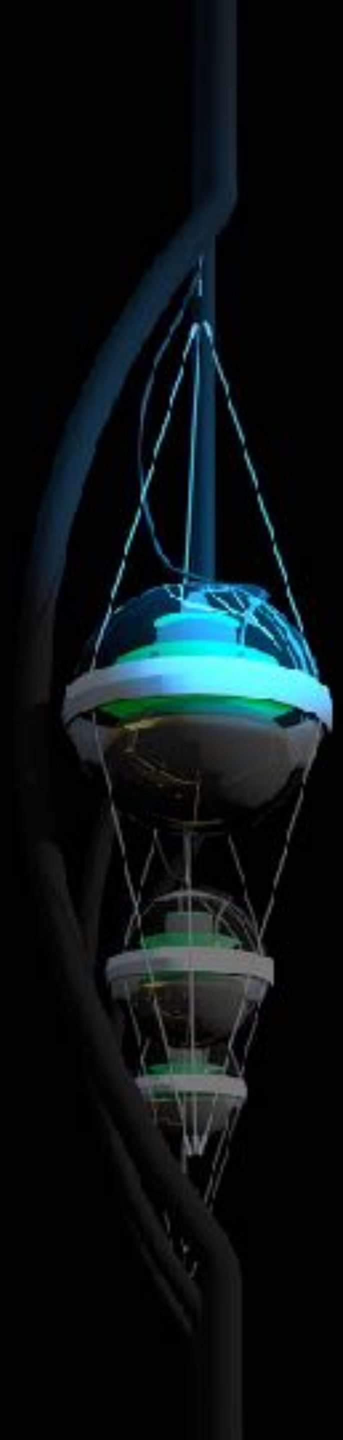
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

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



< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum (energy measurement) well understood



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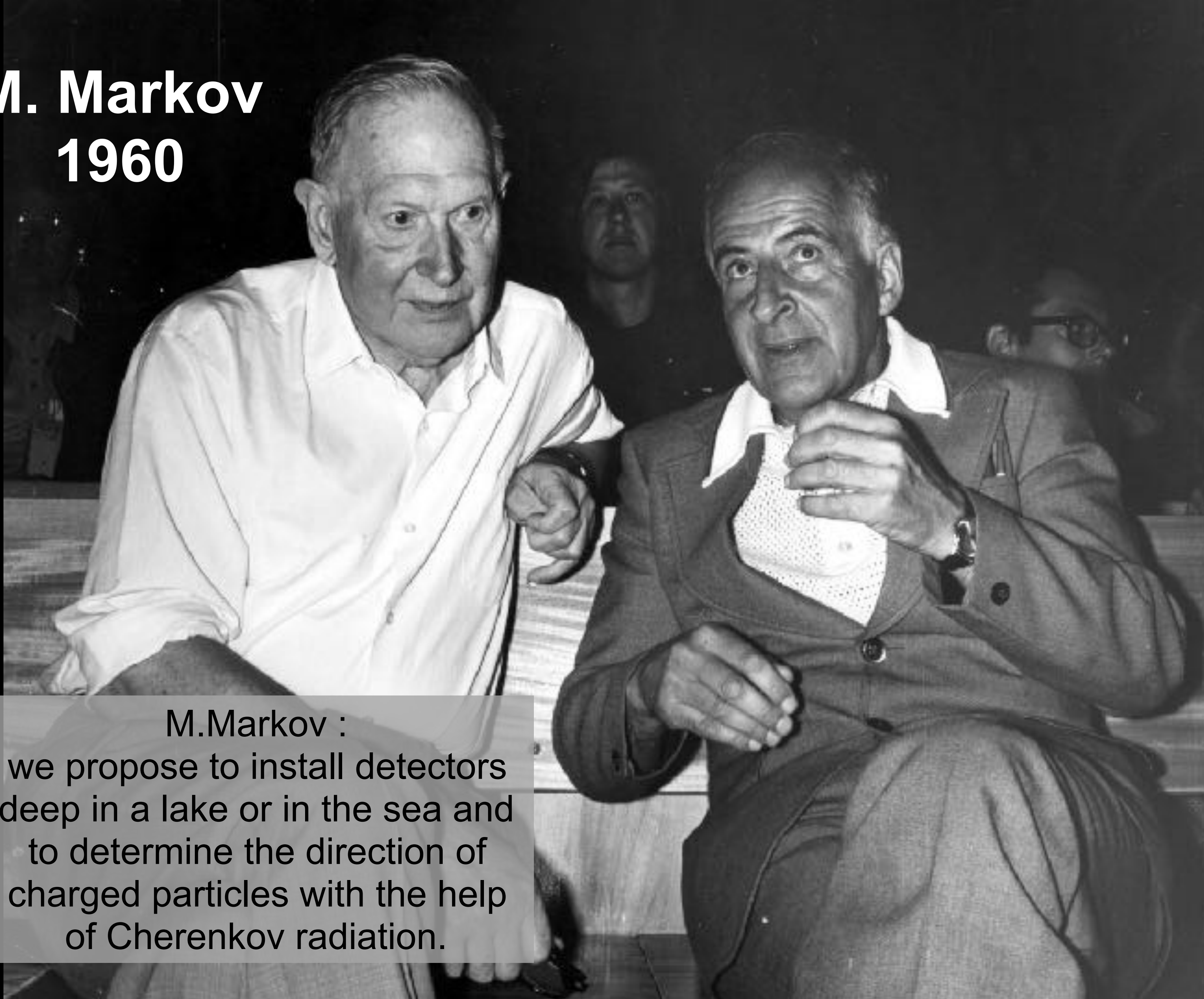
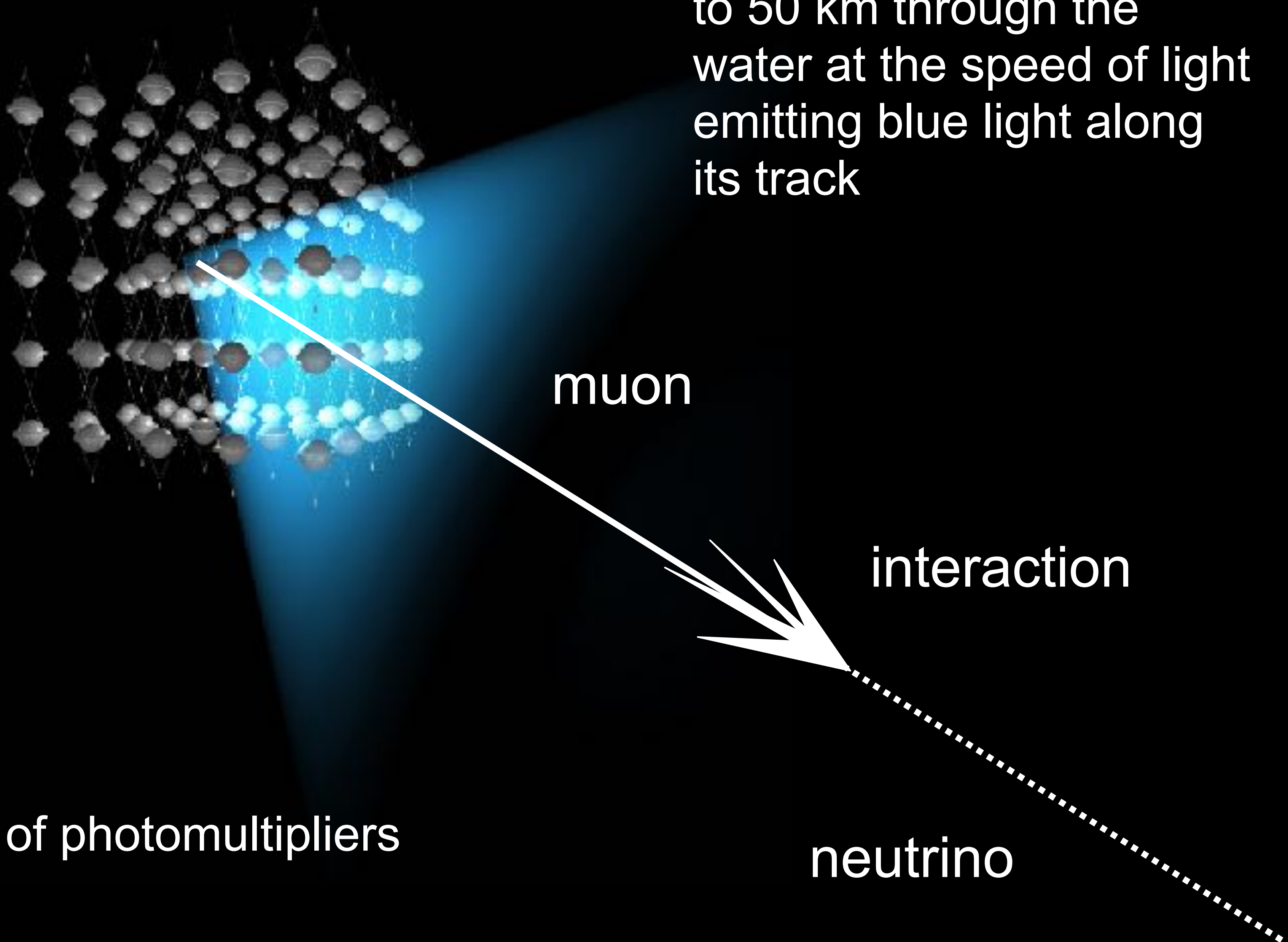
M. Markov
1960



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.

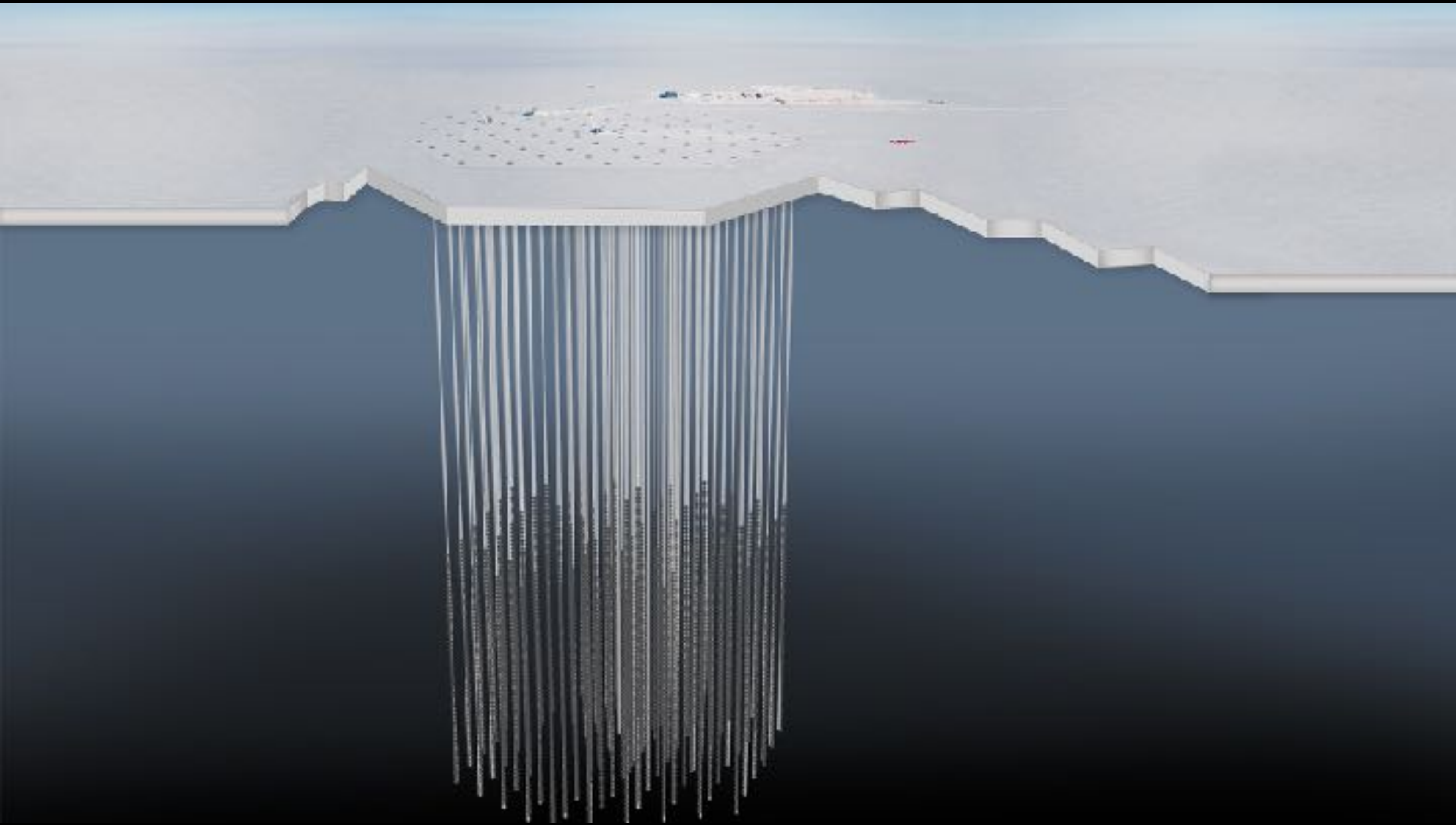
- speed of light in water < c
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



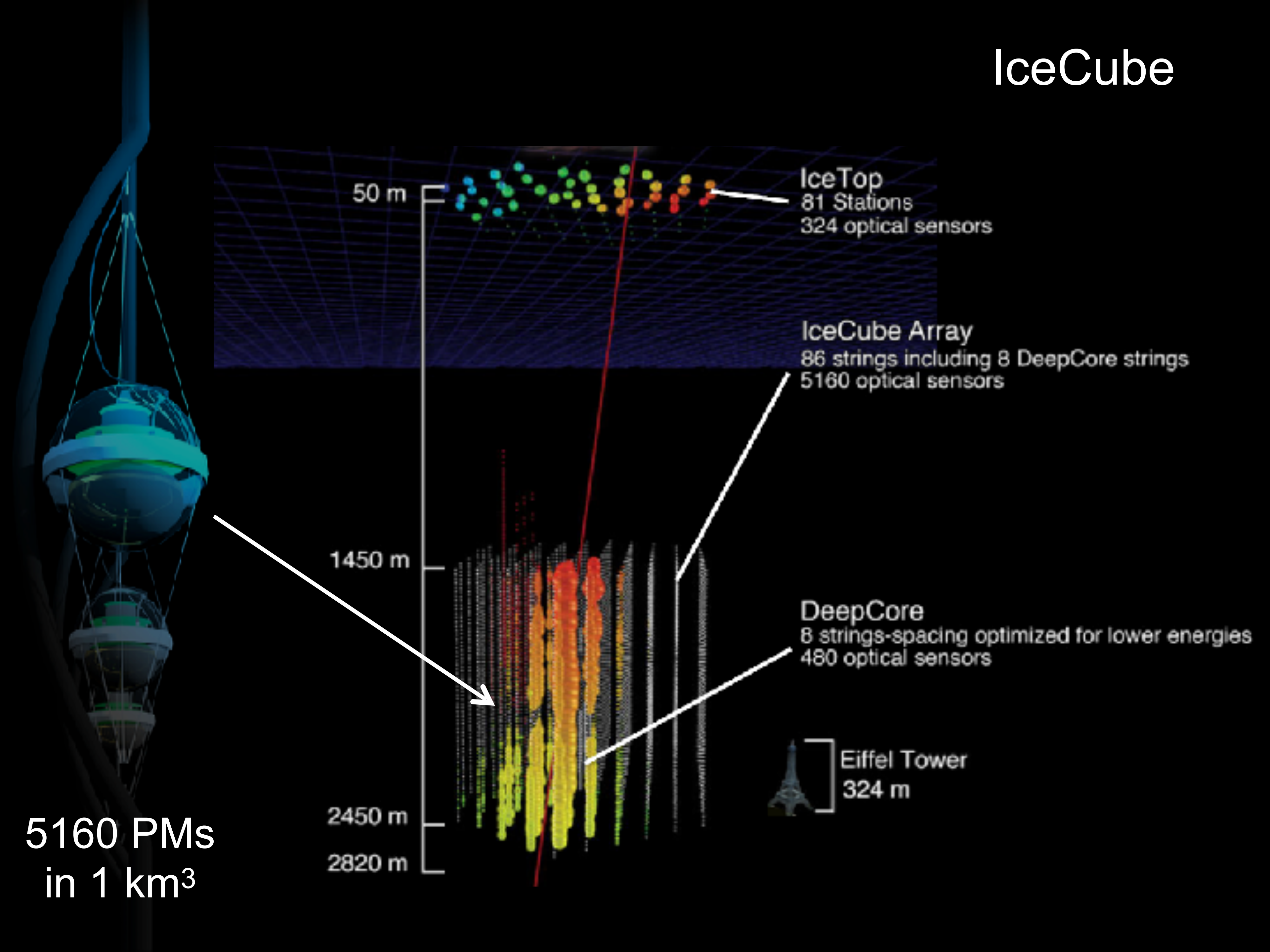
- lattice of photomultipliers


ultra-transparent ice below 1.5 km

instrument 1 cubic kilometer of natural ice below 1.45 km



IceCube

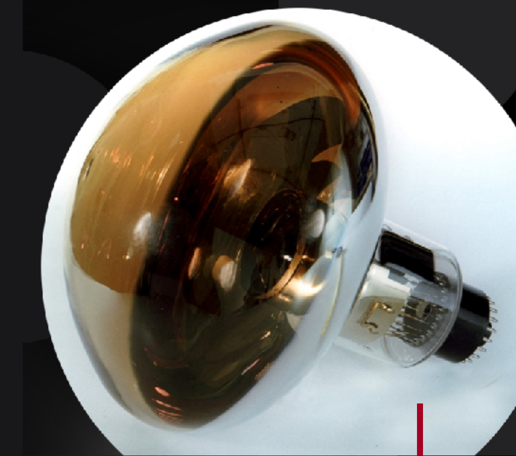


5160 PMs
in 1 km^3

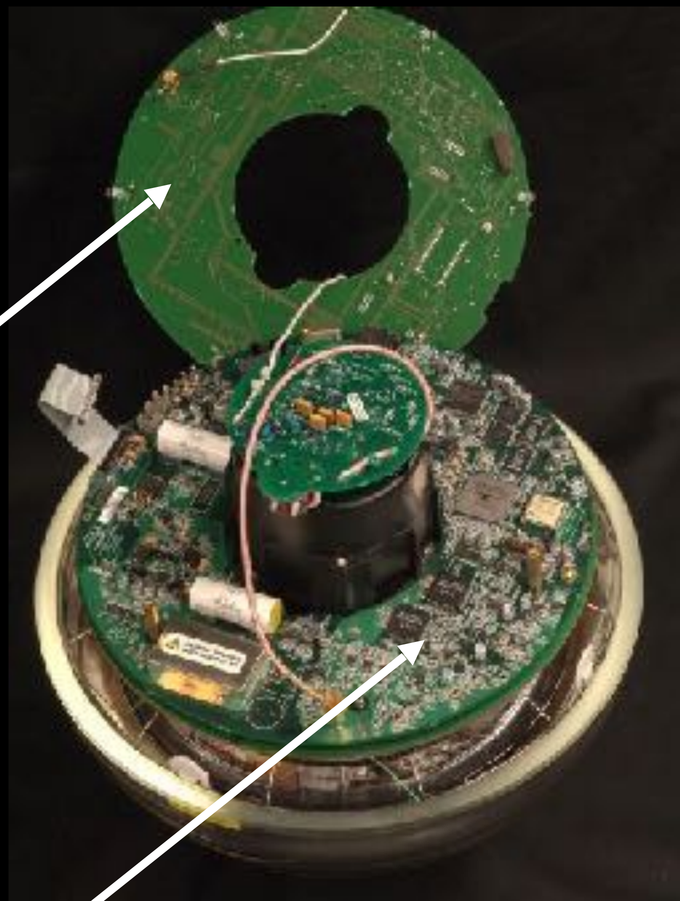
photomultiplier tube -10 inch

architecture of independent DOMs

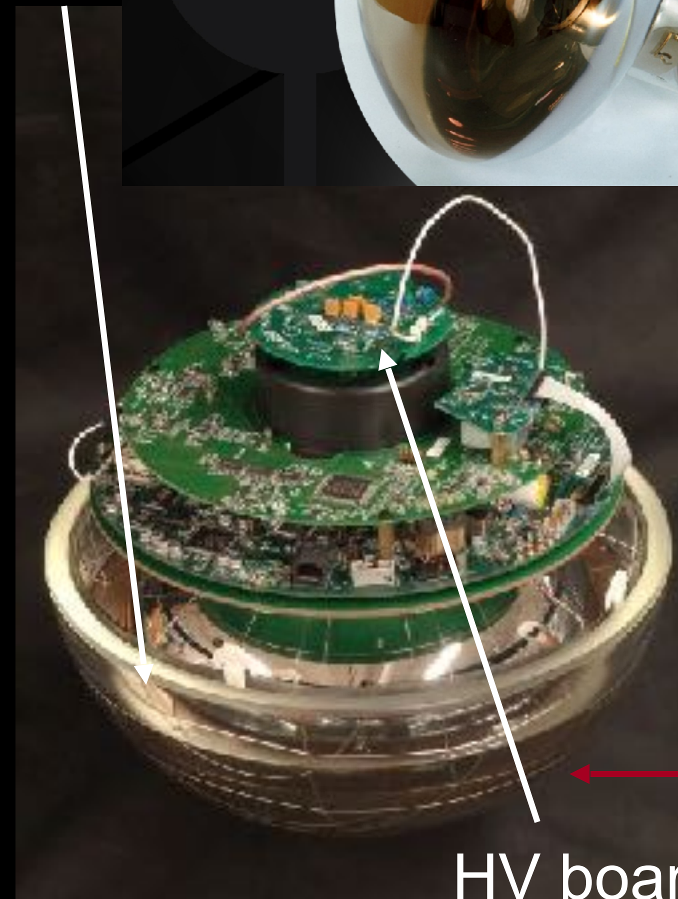
10 inch pmt



LED
flasher
board

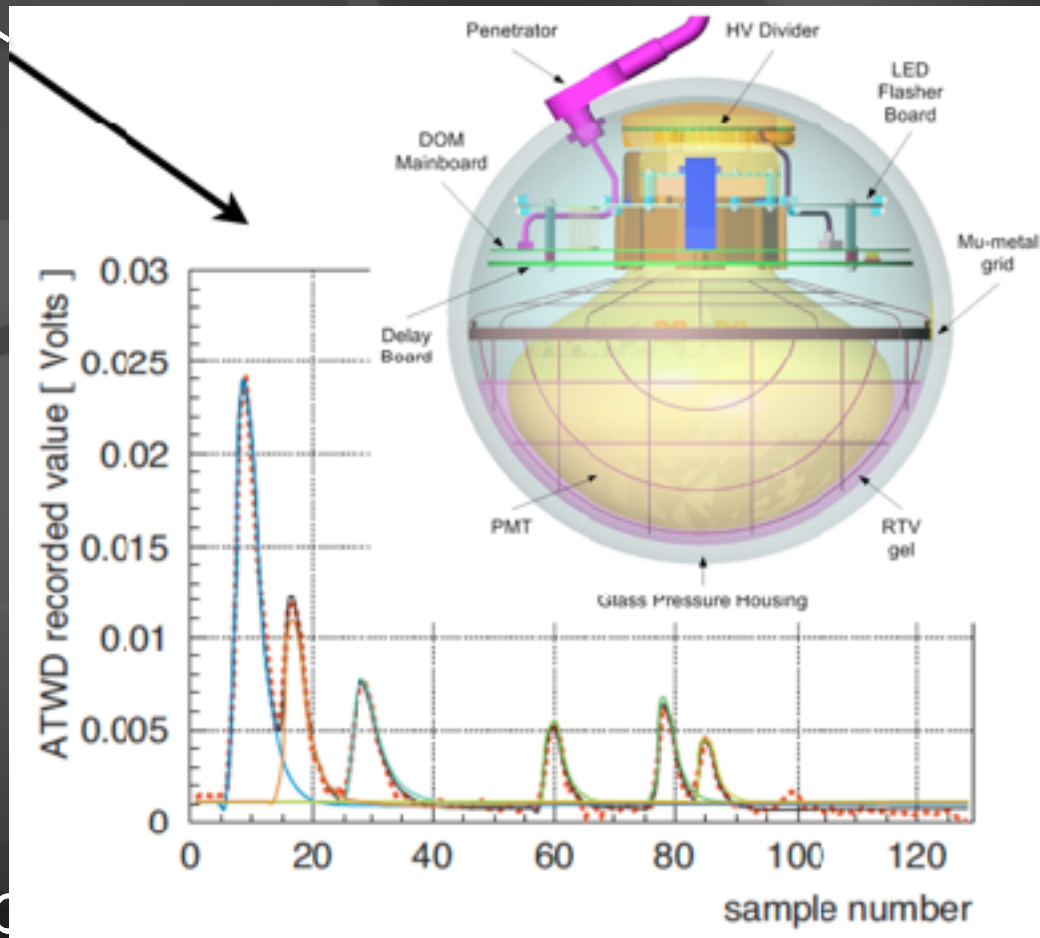


main
board

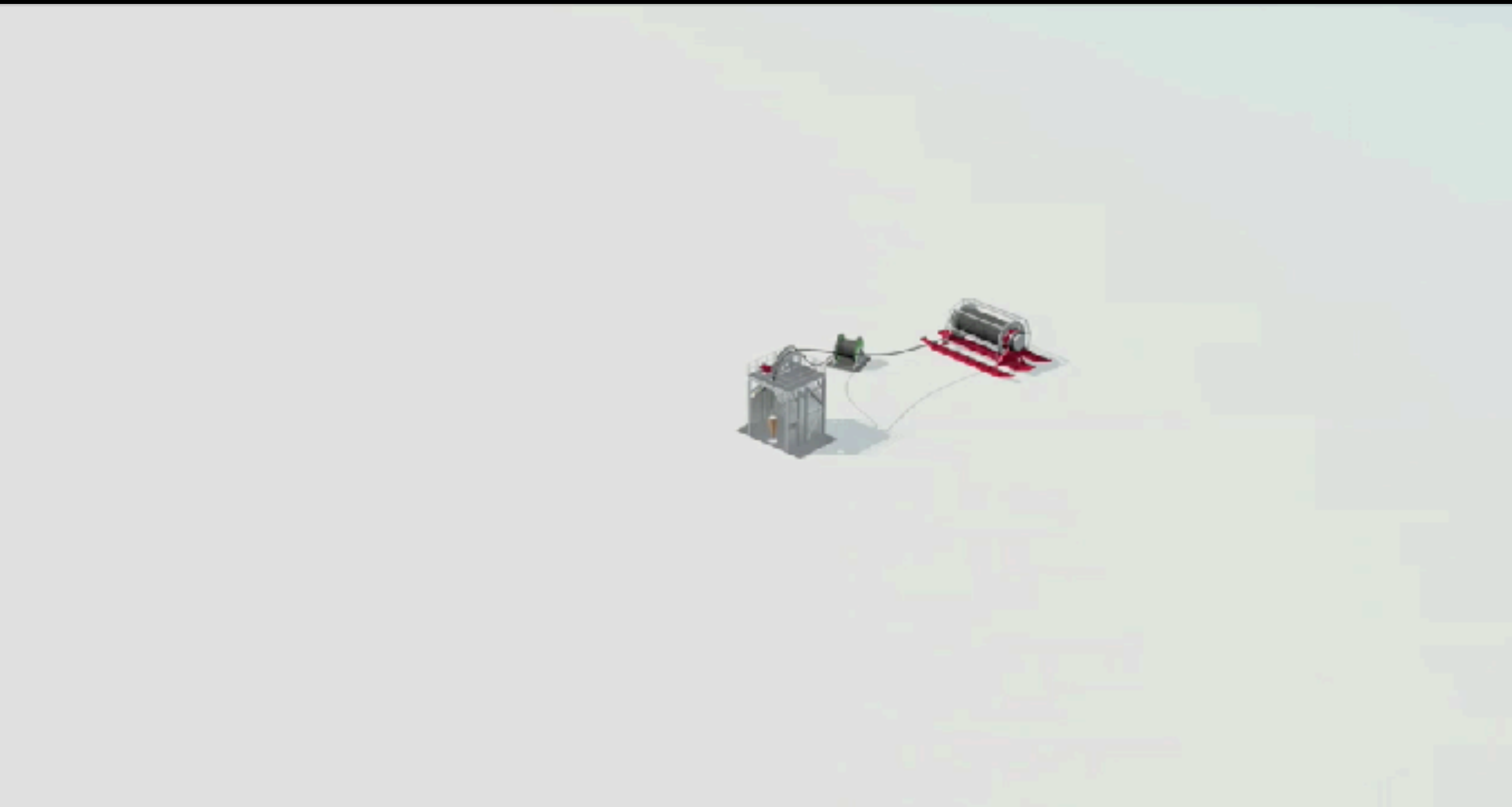


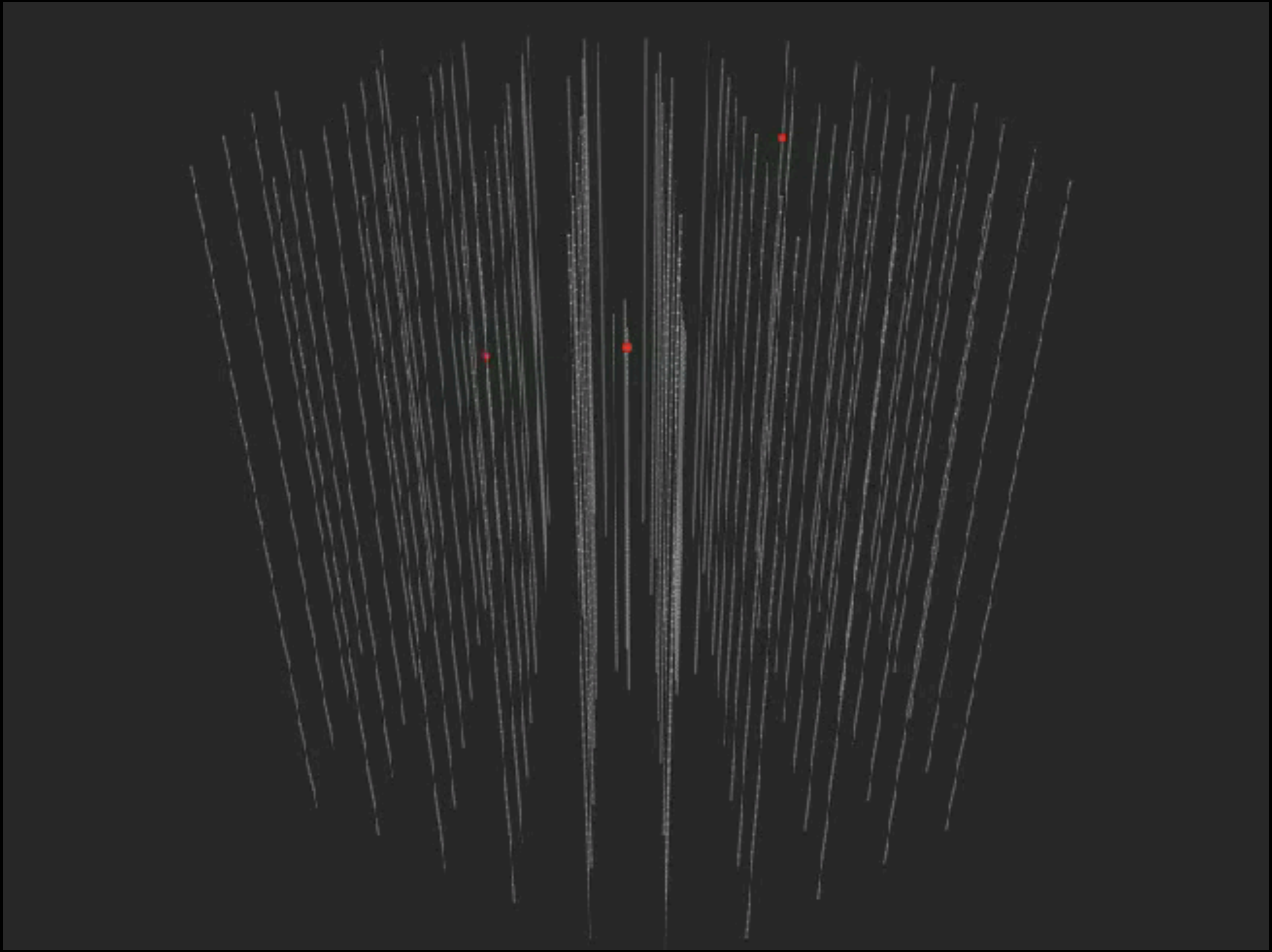
HV board

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

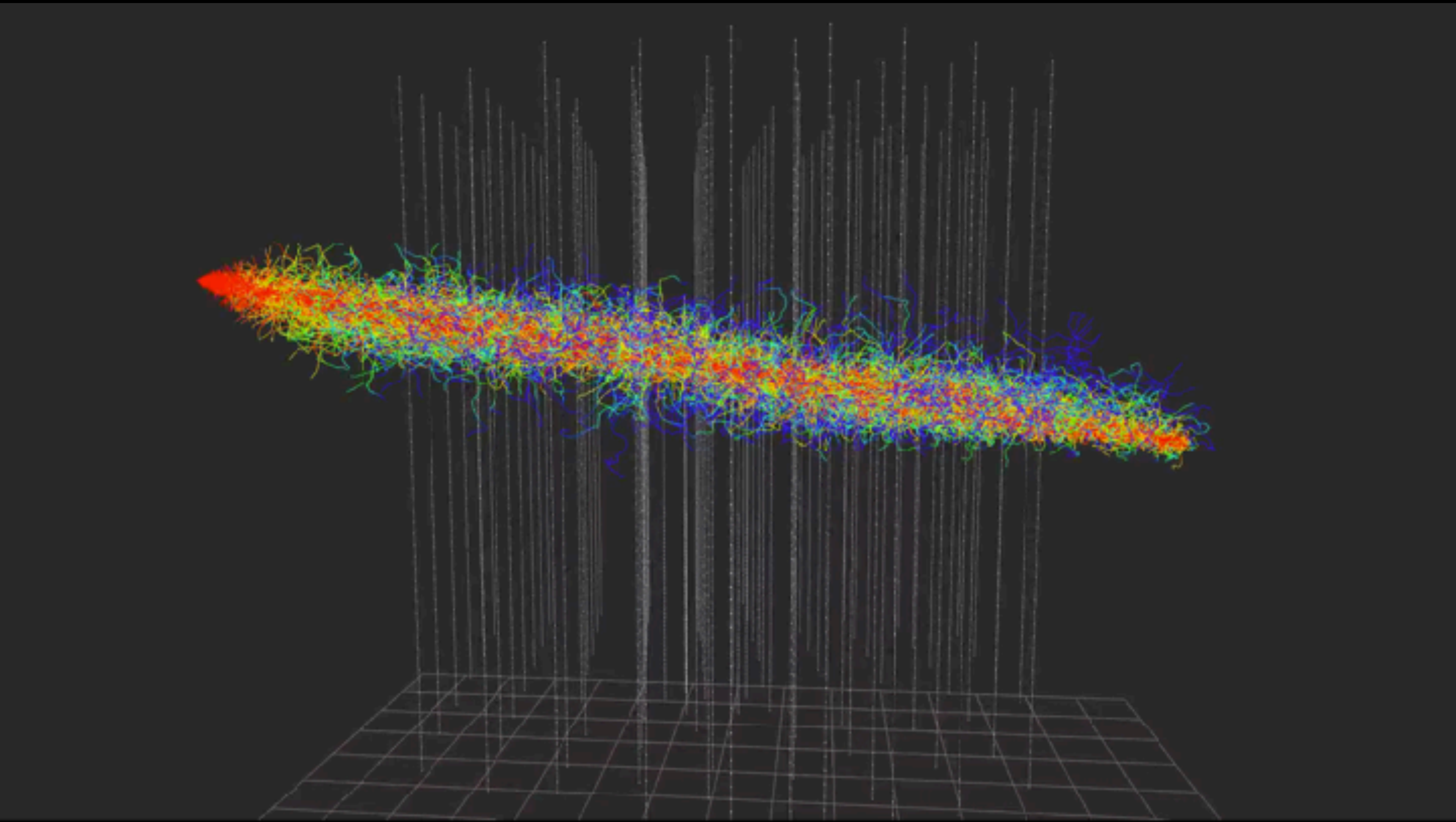


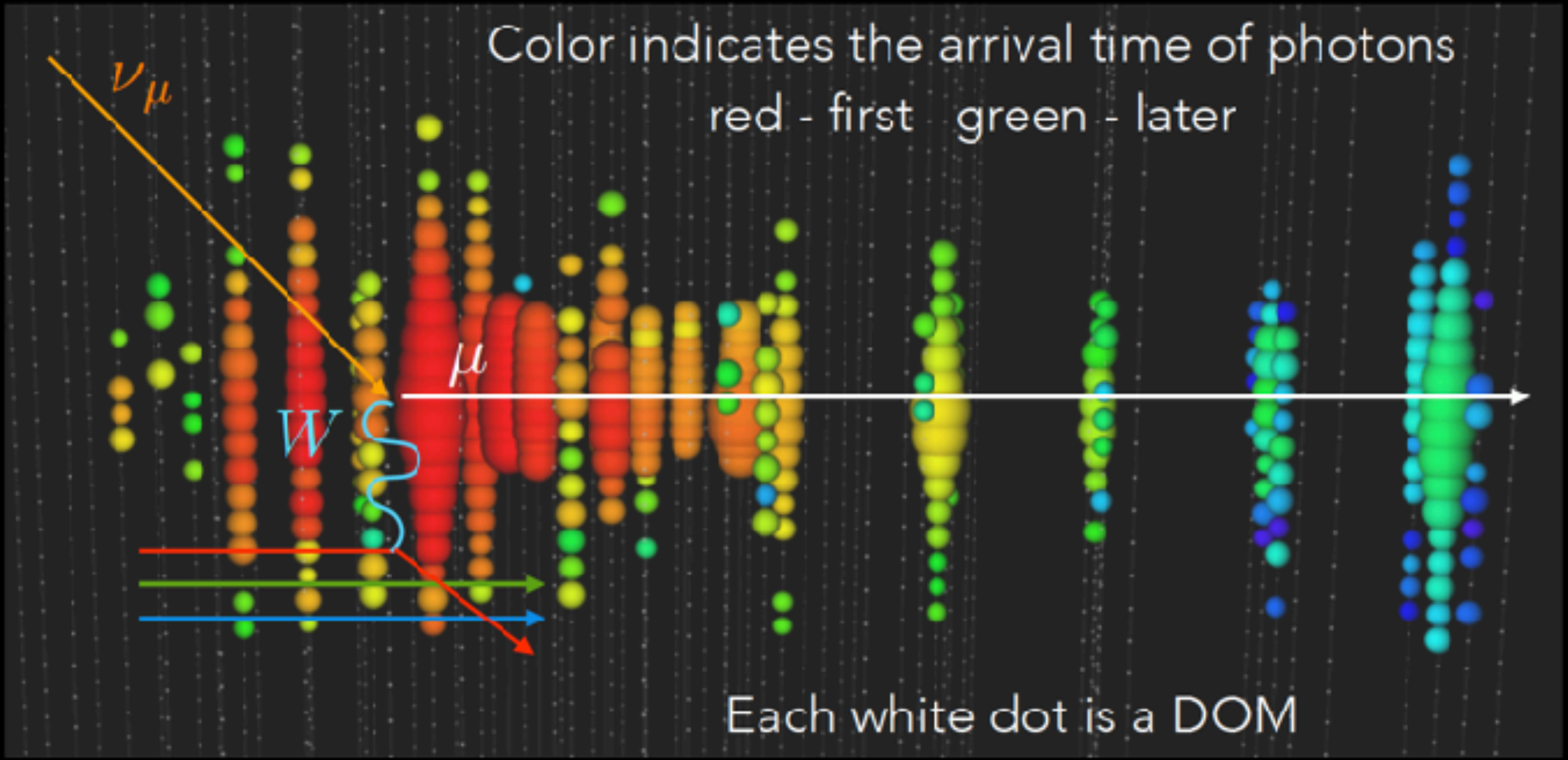
…time stamp ecision, and sends them to a computer that sorts them events…





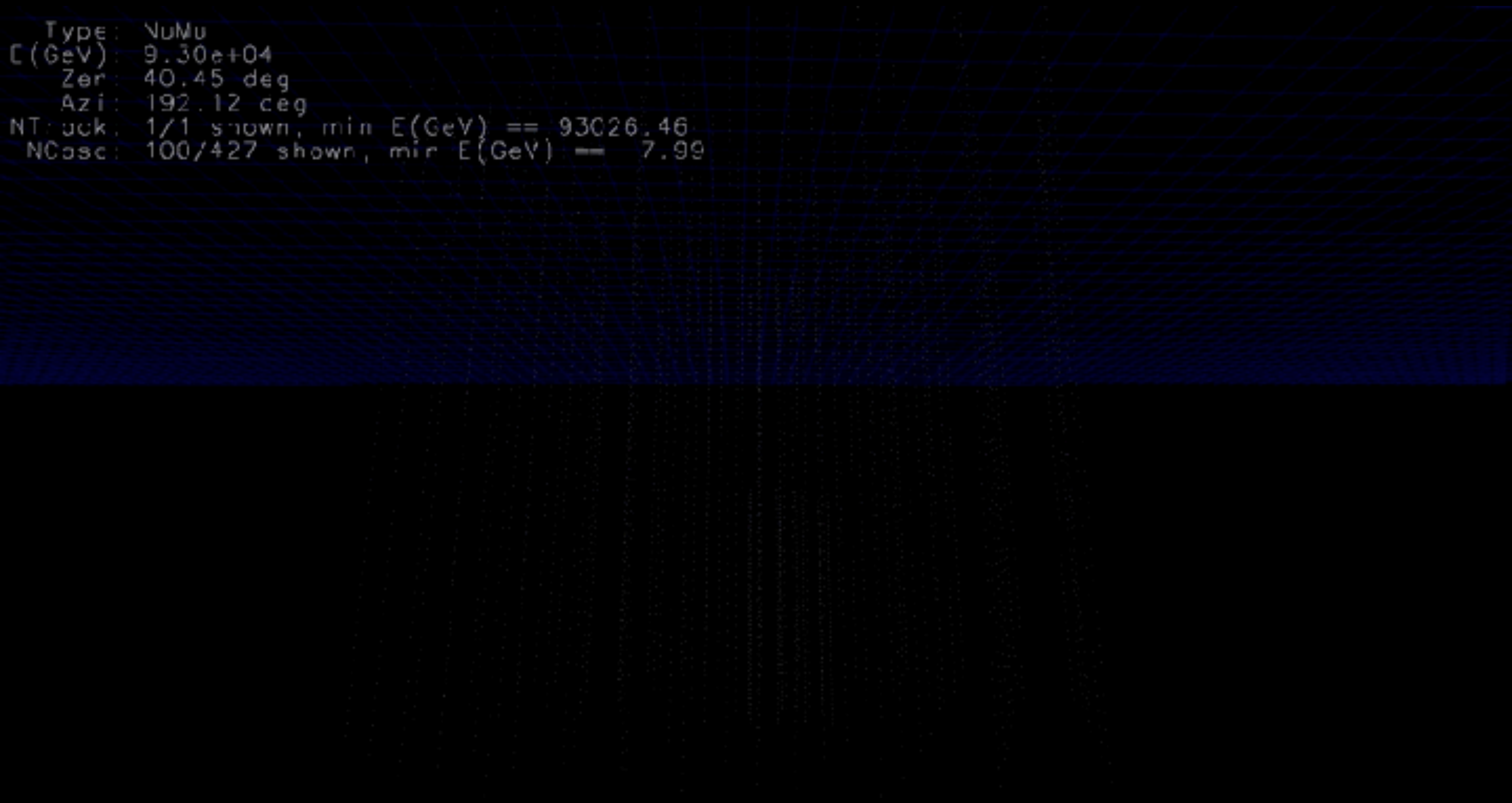
muon track: color is time; number of photons is energy neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



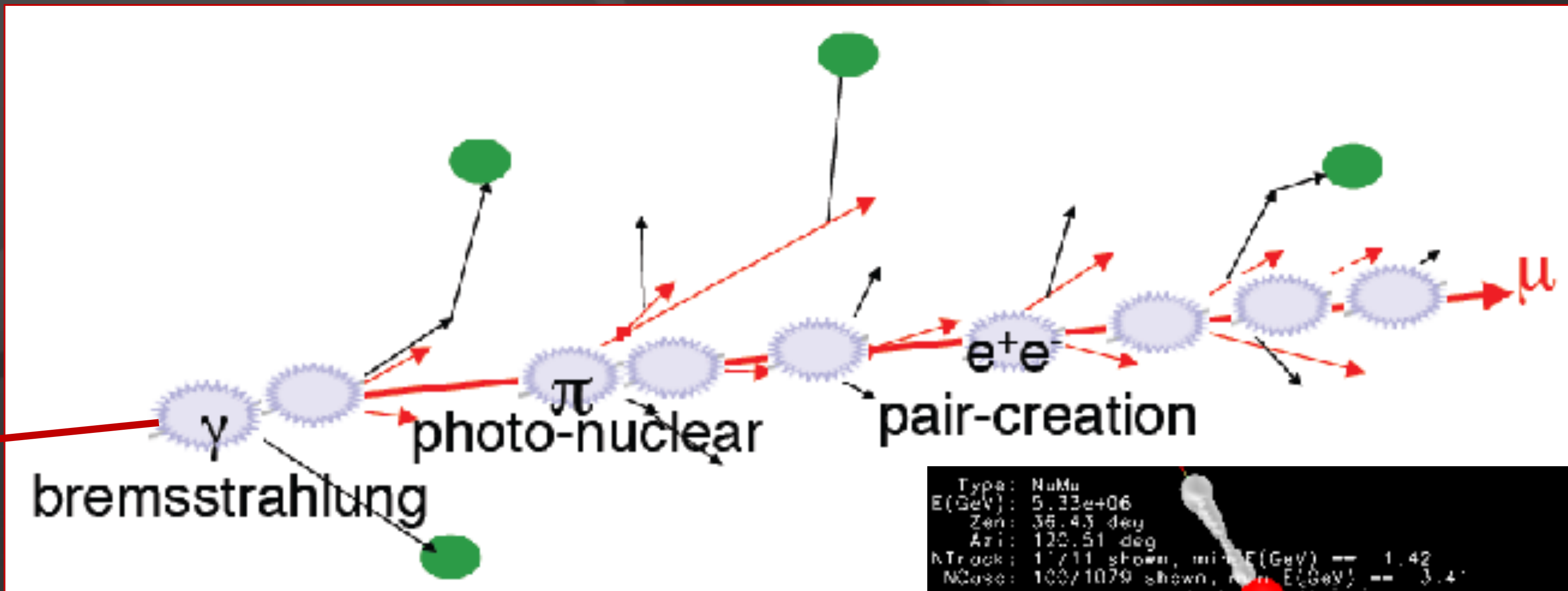


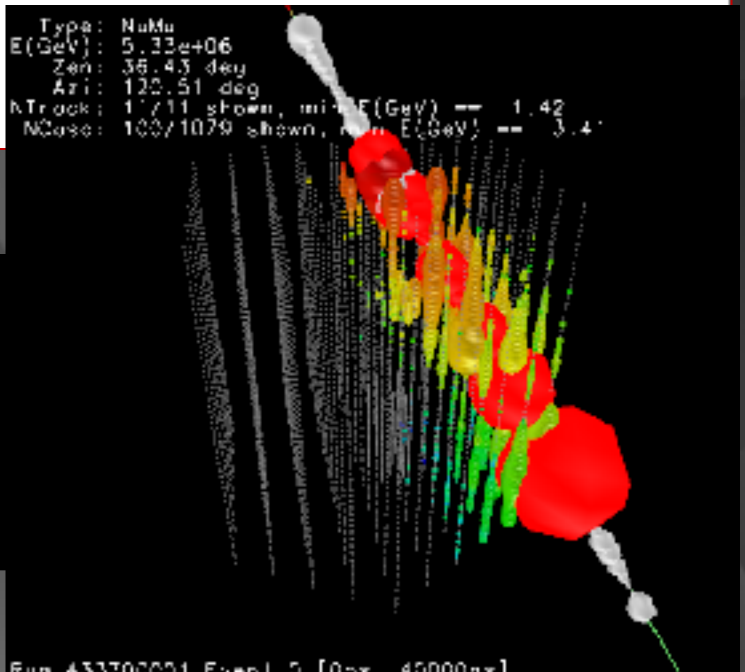
Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

93 TeV muon: light ~ energy

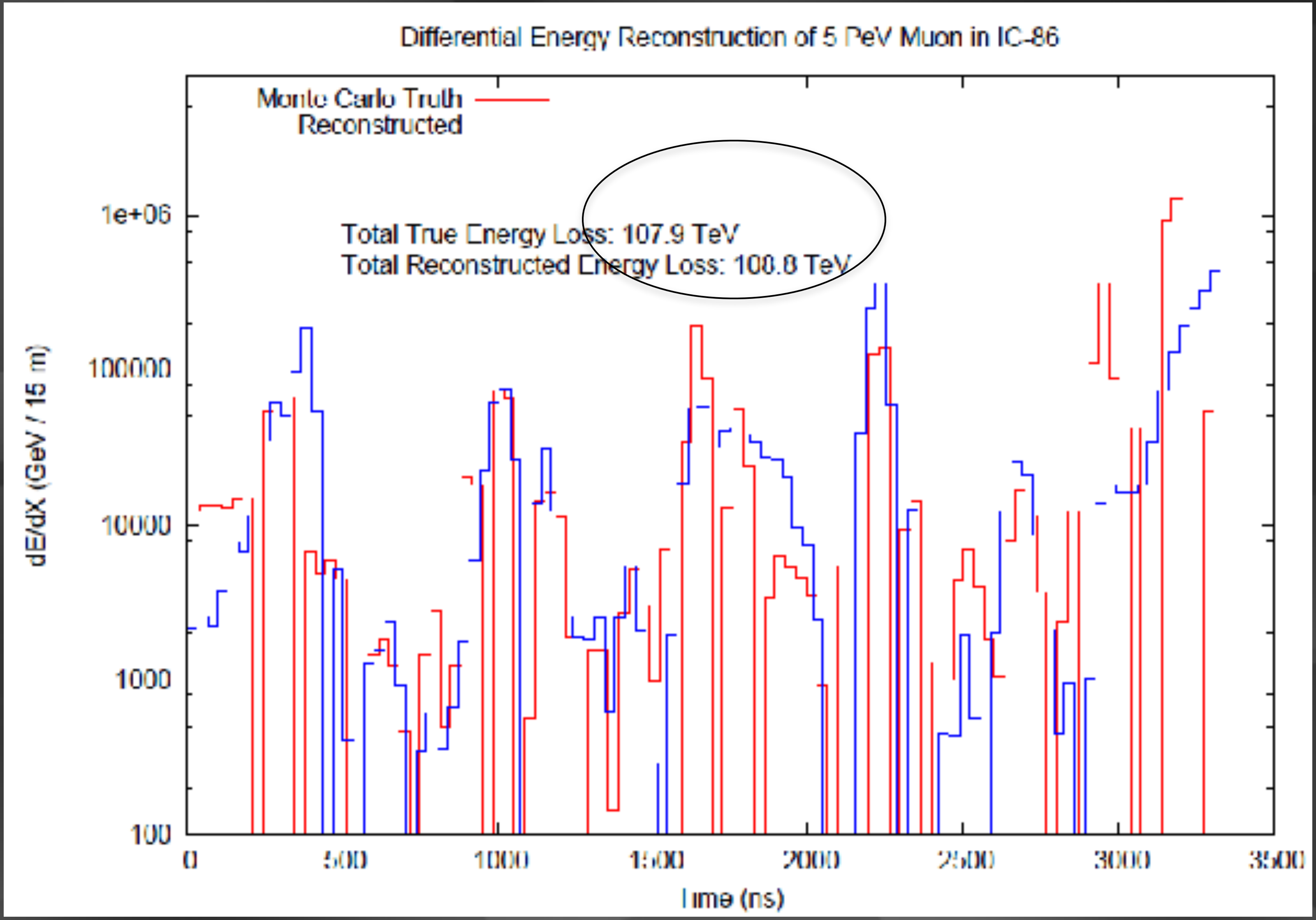


energy measurement (> 1 TeV)





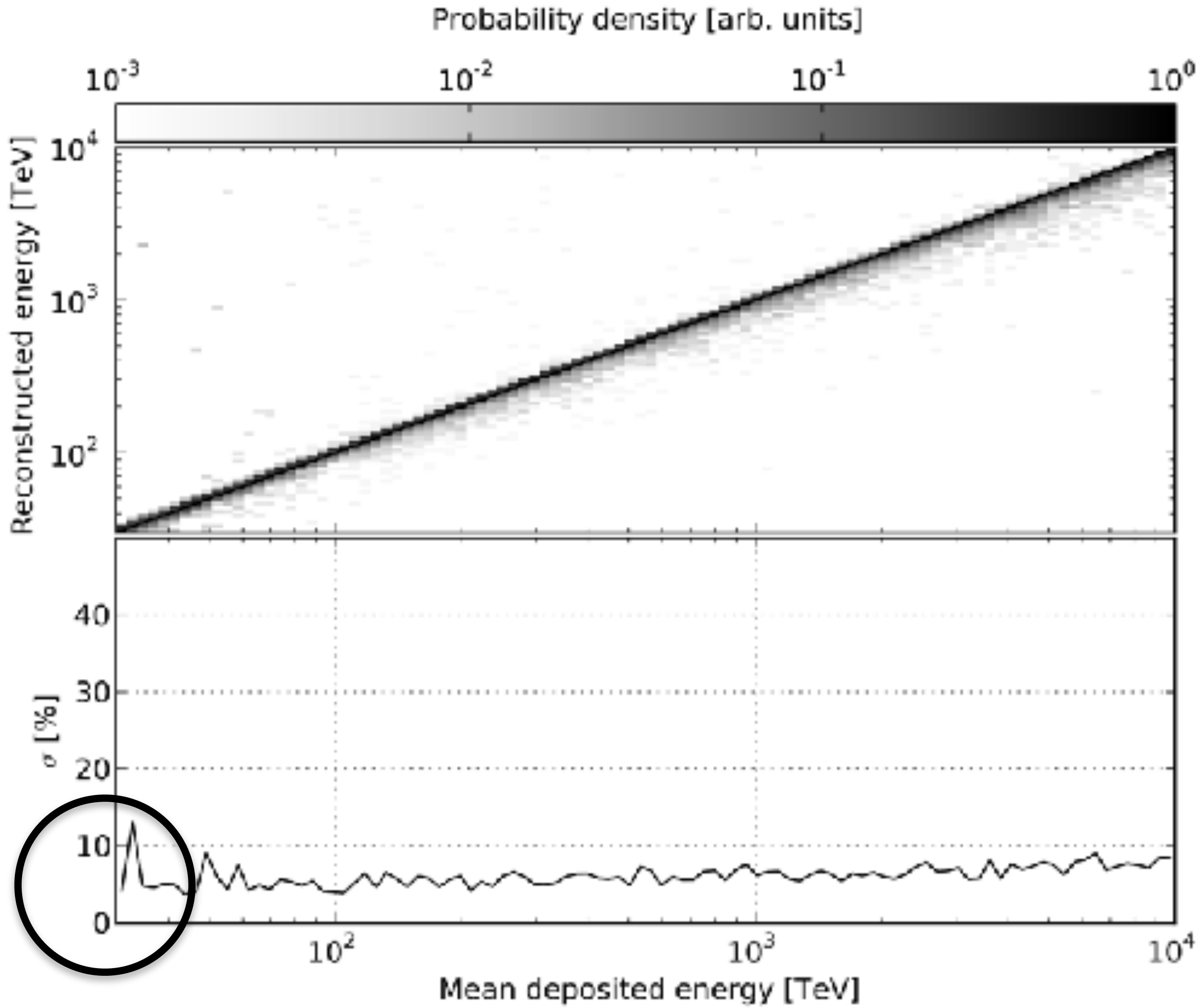
convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

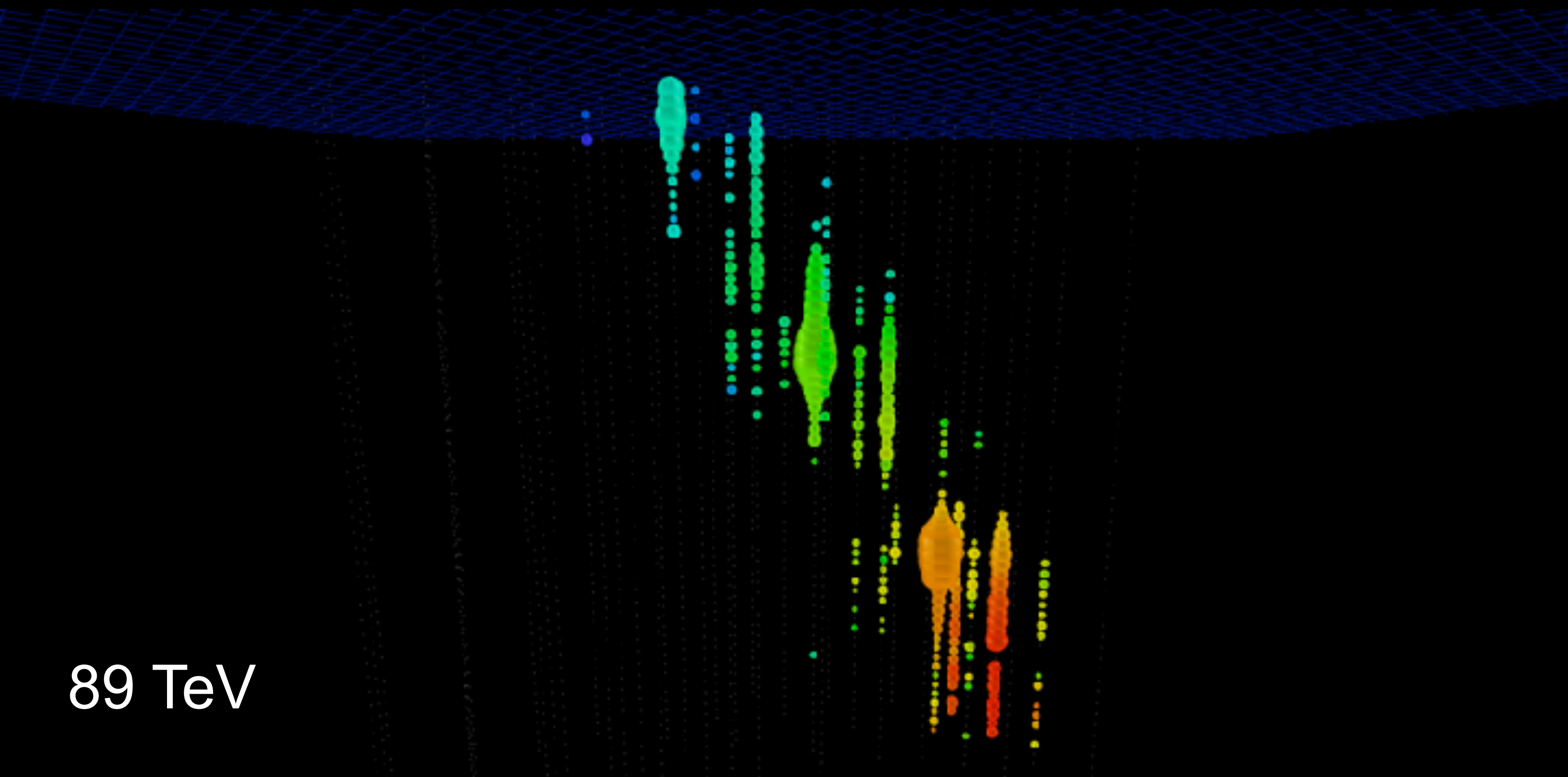


1.1 km

limited angular and energy resolution: computing → ice properties

energy reconstruction of electromagnetic showers



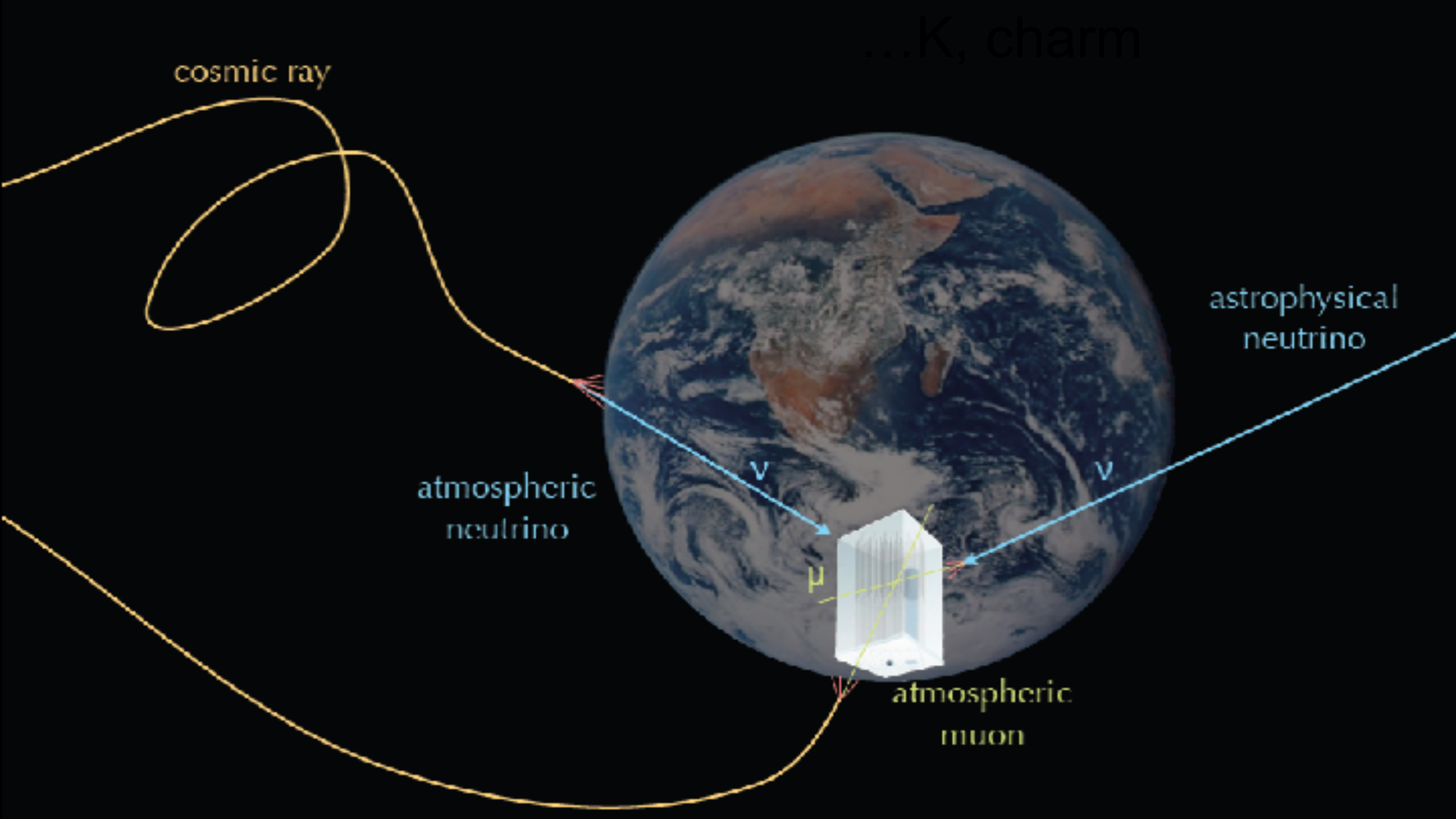


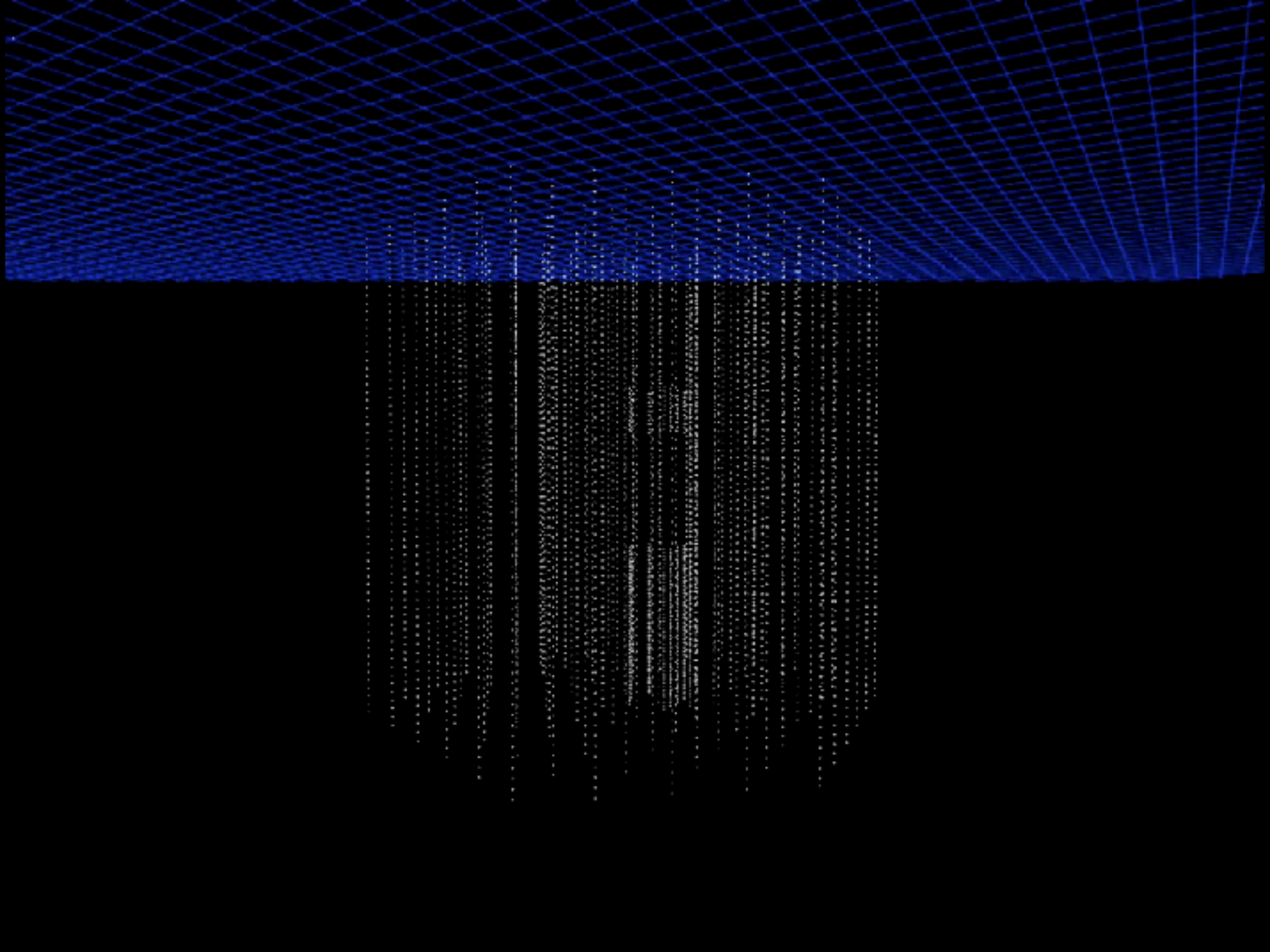
89 TeV

radius ~ number of photons
time ~ red → purple

Run 113641 Event 33553254 [0ns, 16748ns]

Signals and Backgrounds





… you looked at 10msec of data !

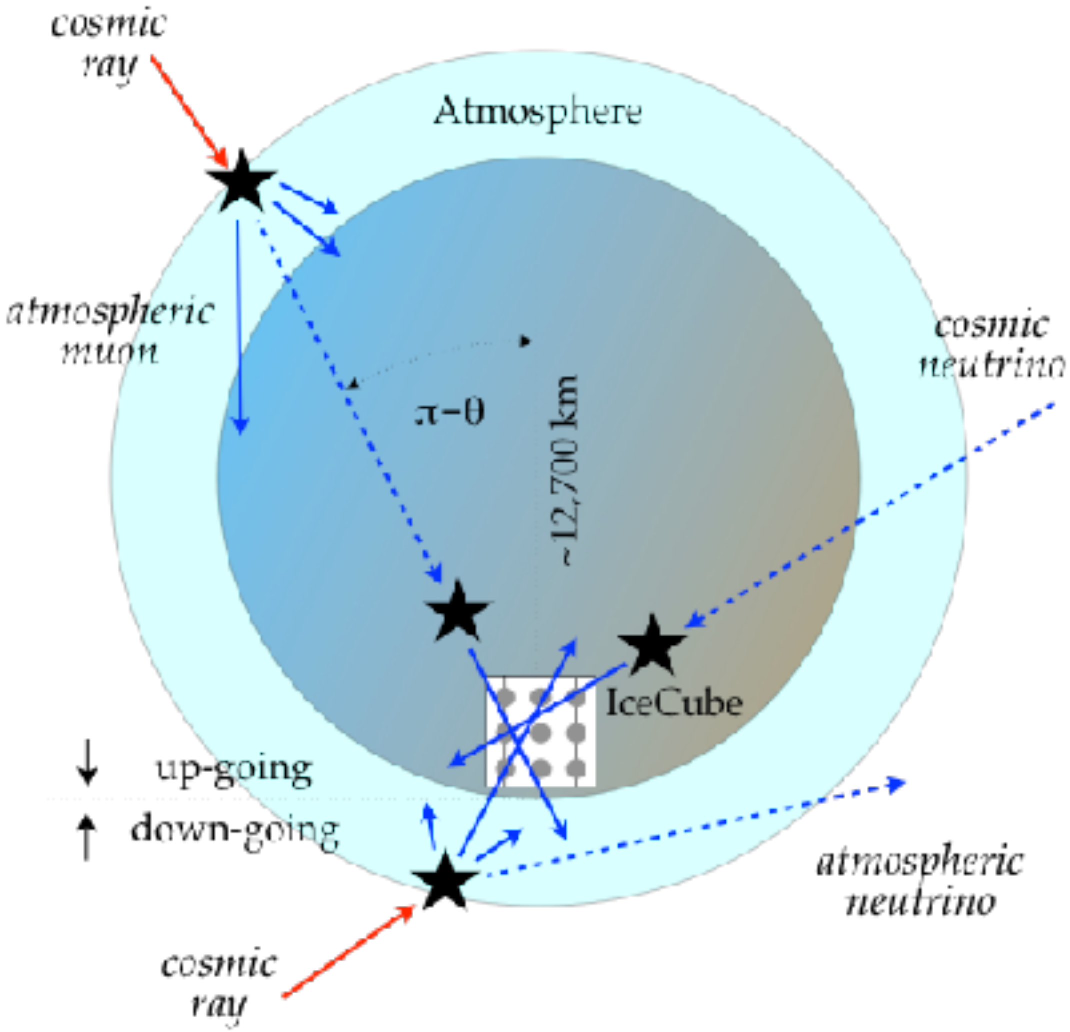
muons detected per year:

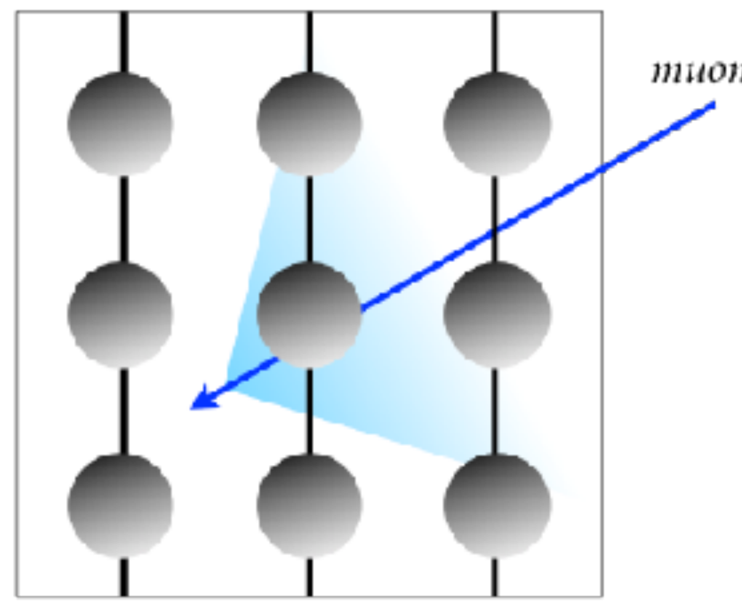
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^{5}$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

** 1 every 6 minutes

- rejecting atmospheric muons

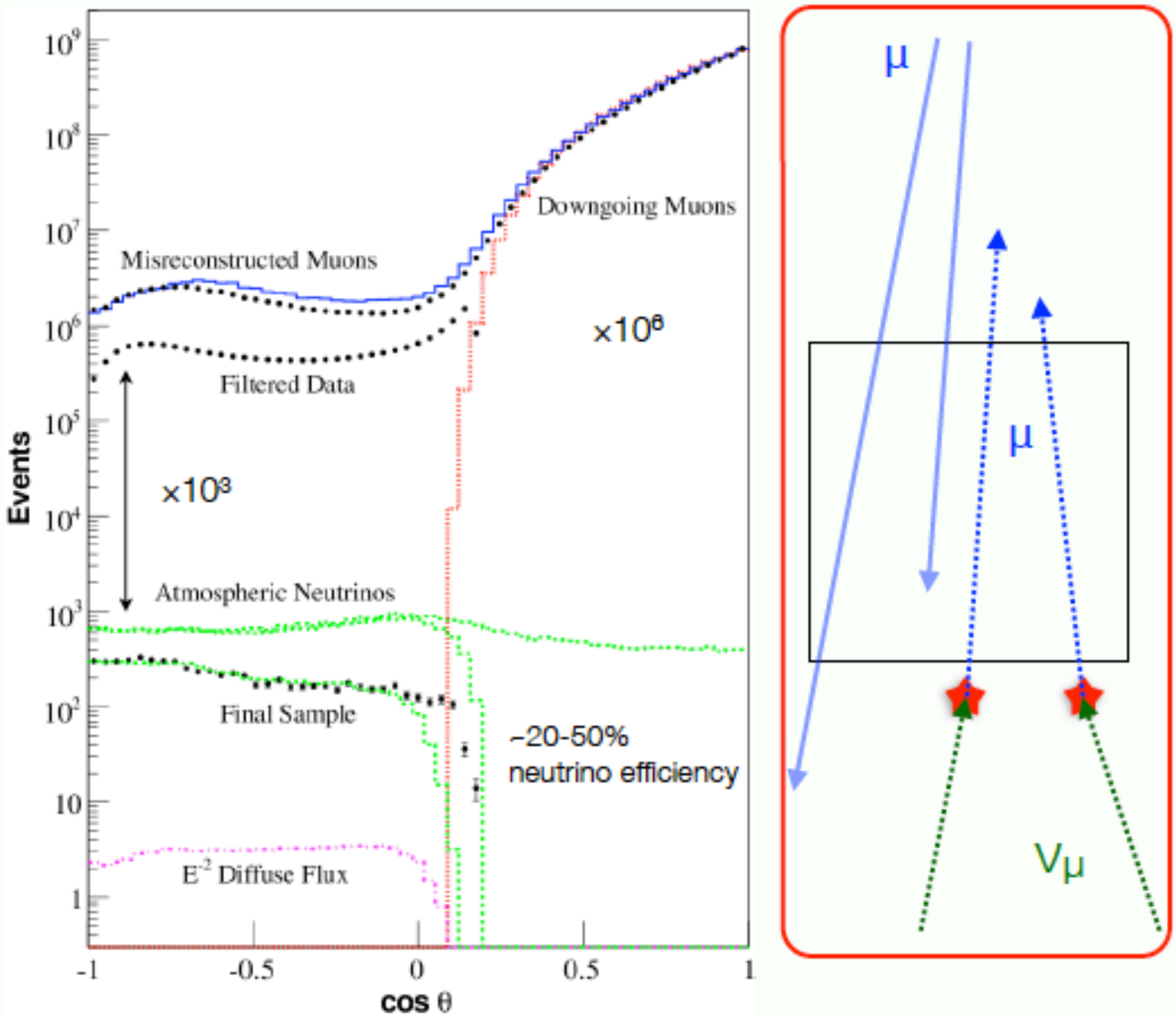




Cherenkov light detection
in optical modules

- rejecting atmospheric neutrinos

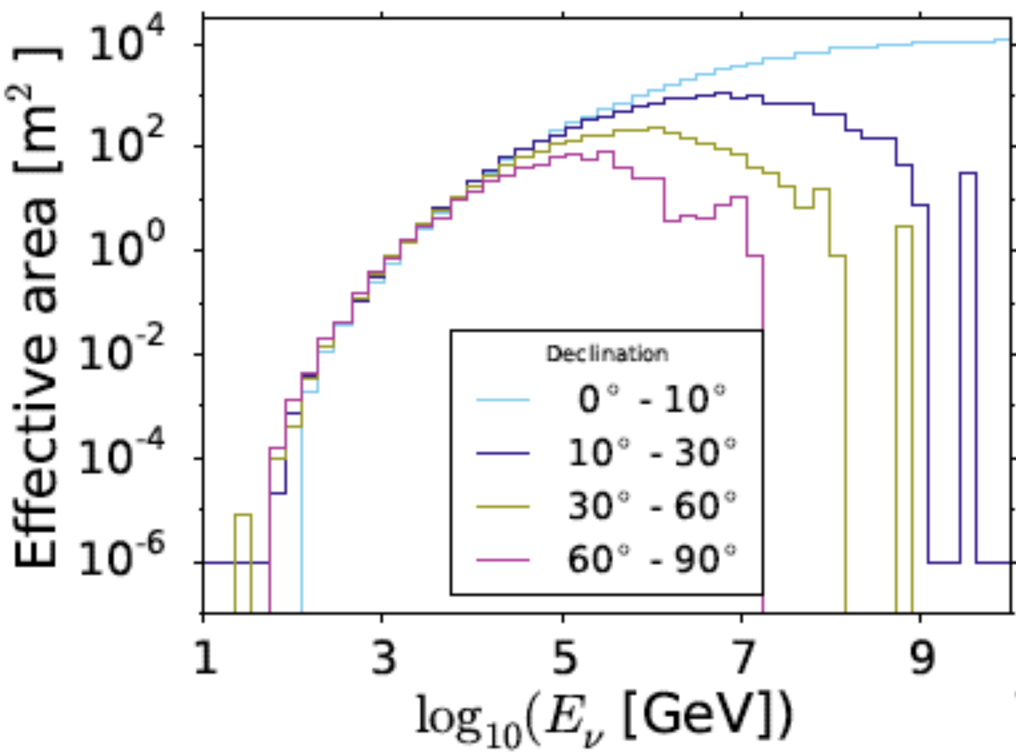
through-going (tracks)



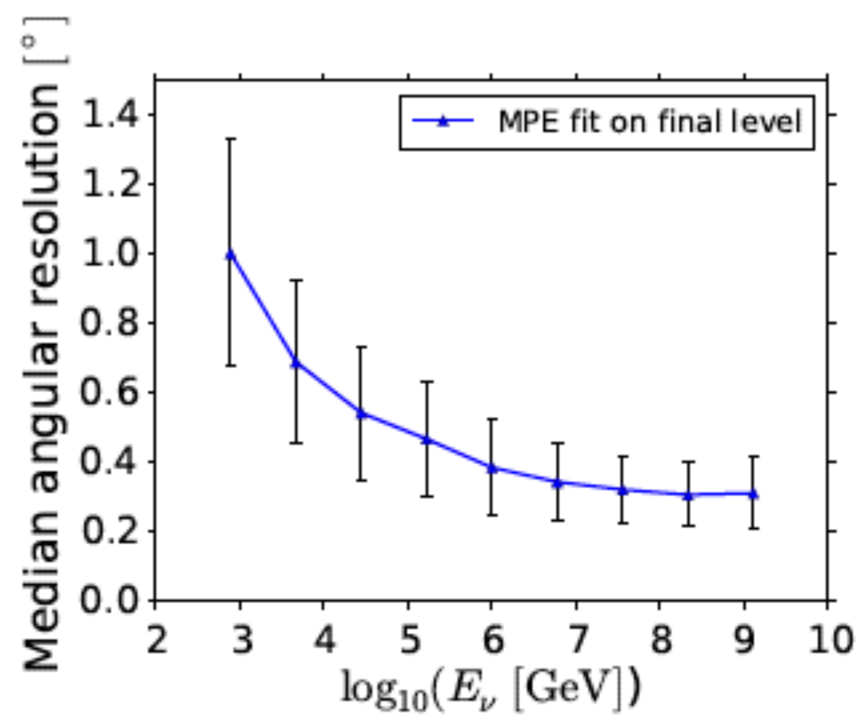
selection cuts for on-line numu extraction

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



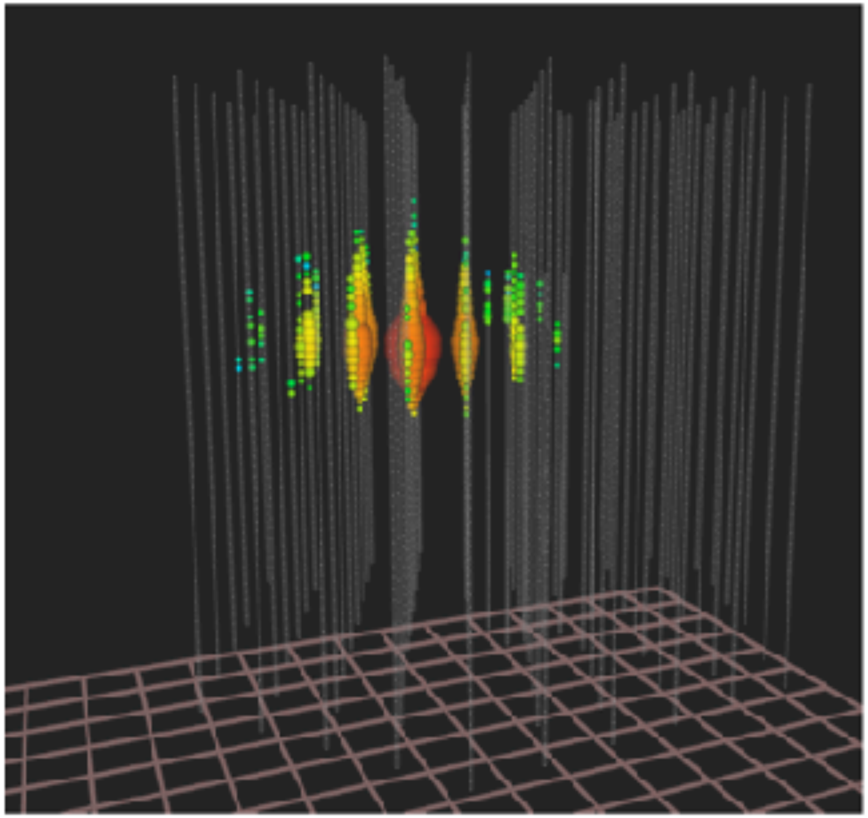
Effective area [m^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Declination
0° - 10°
10° - 30°
30° - 60°
60° - 90°
1
3
5
7
9
$\log_{10}(E_\nu$ [GeV])

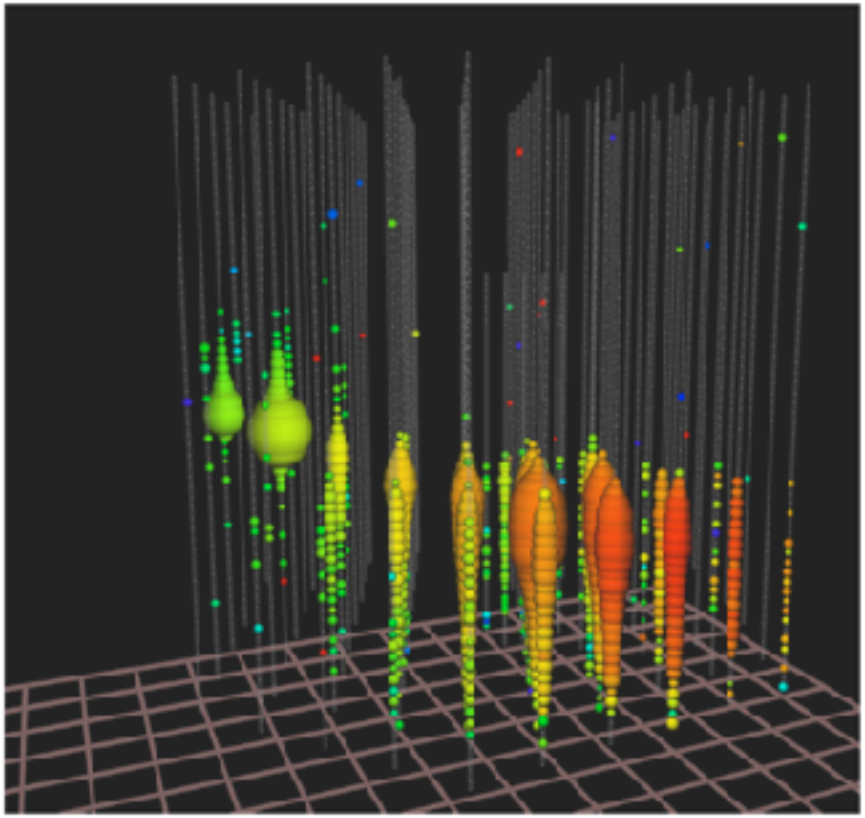


Median angular resolution [°]
MPE fit on final level
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])

isolated neutrinos interacting *inside* the detector (HESE)

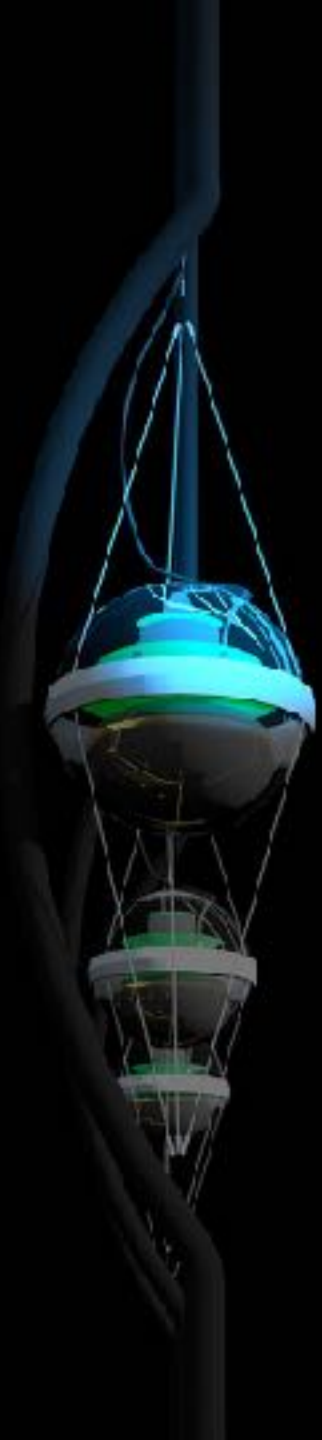
up-going muon tracks (UPMU)





total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5°)



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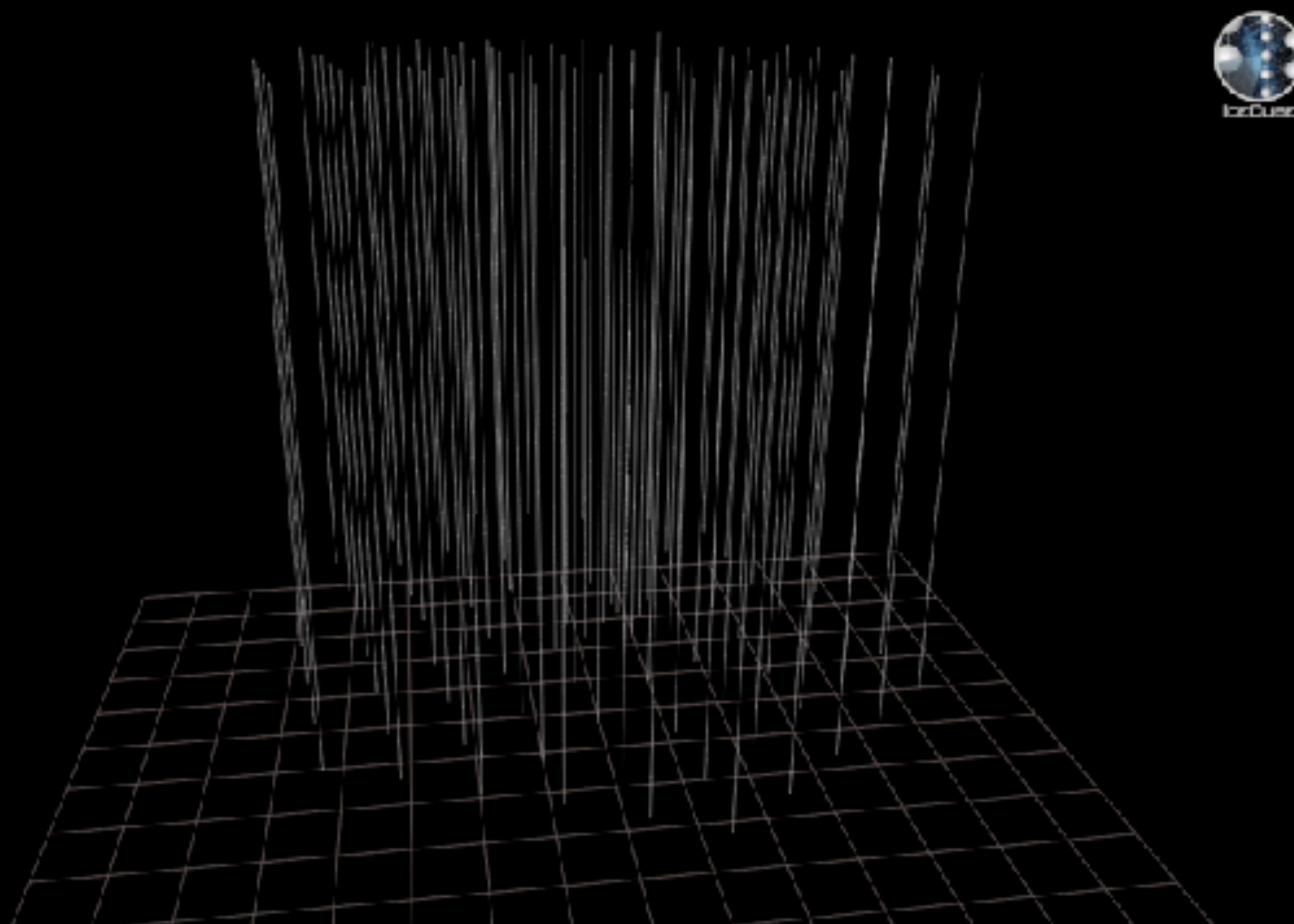
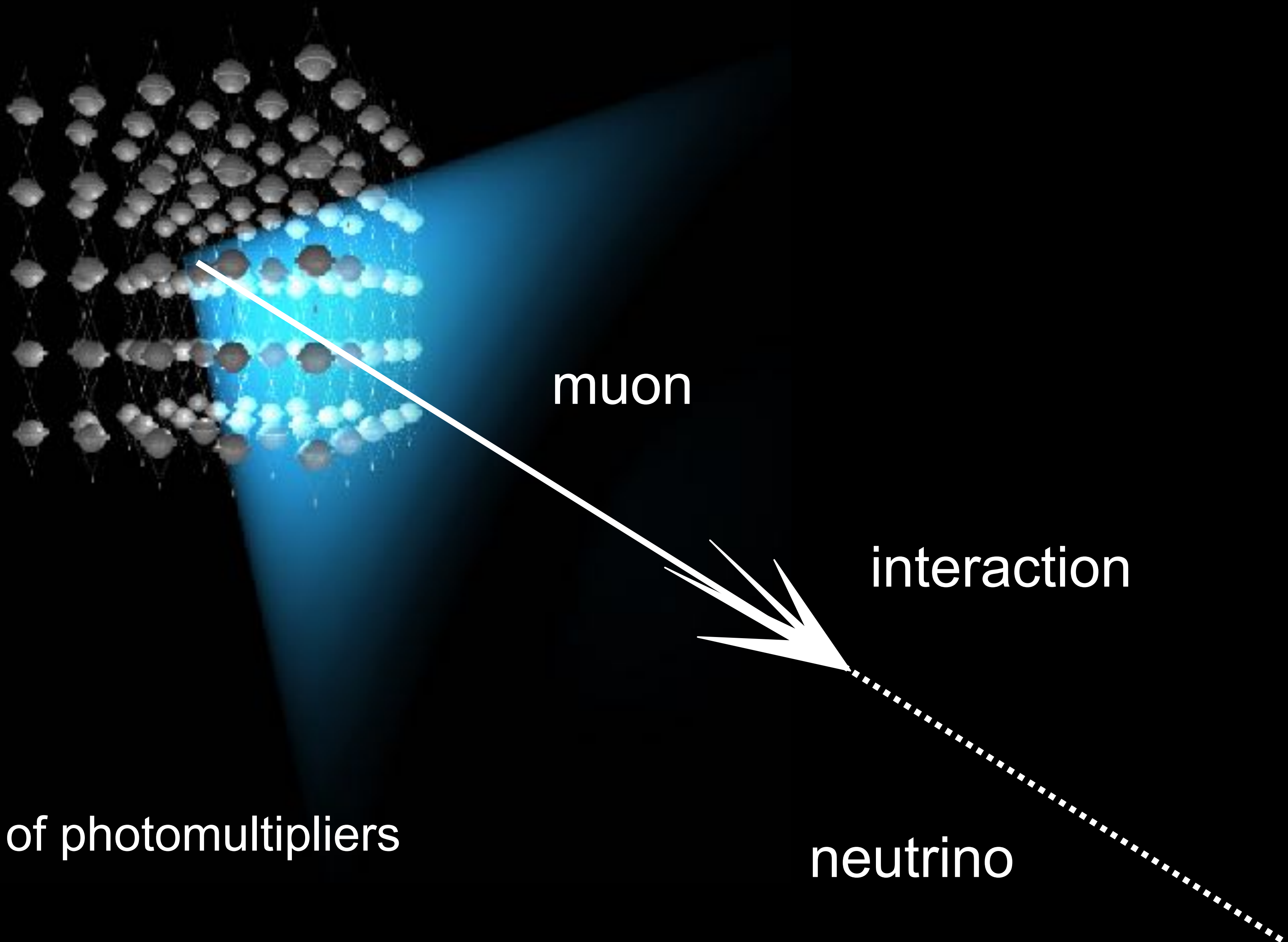
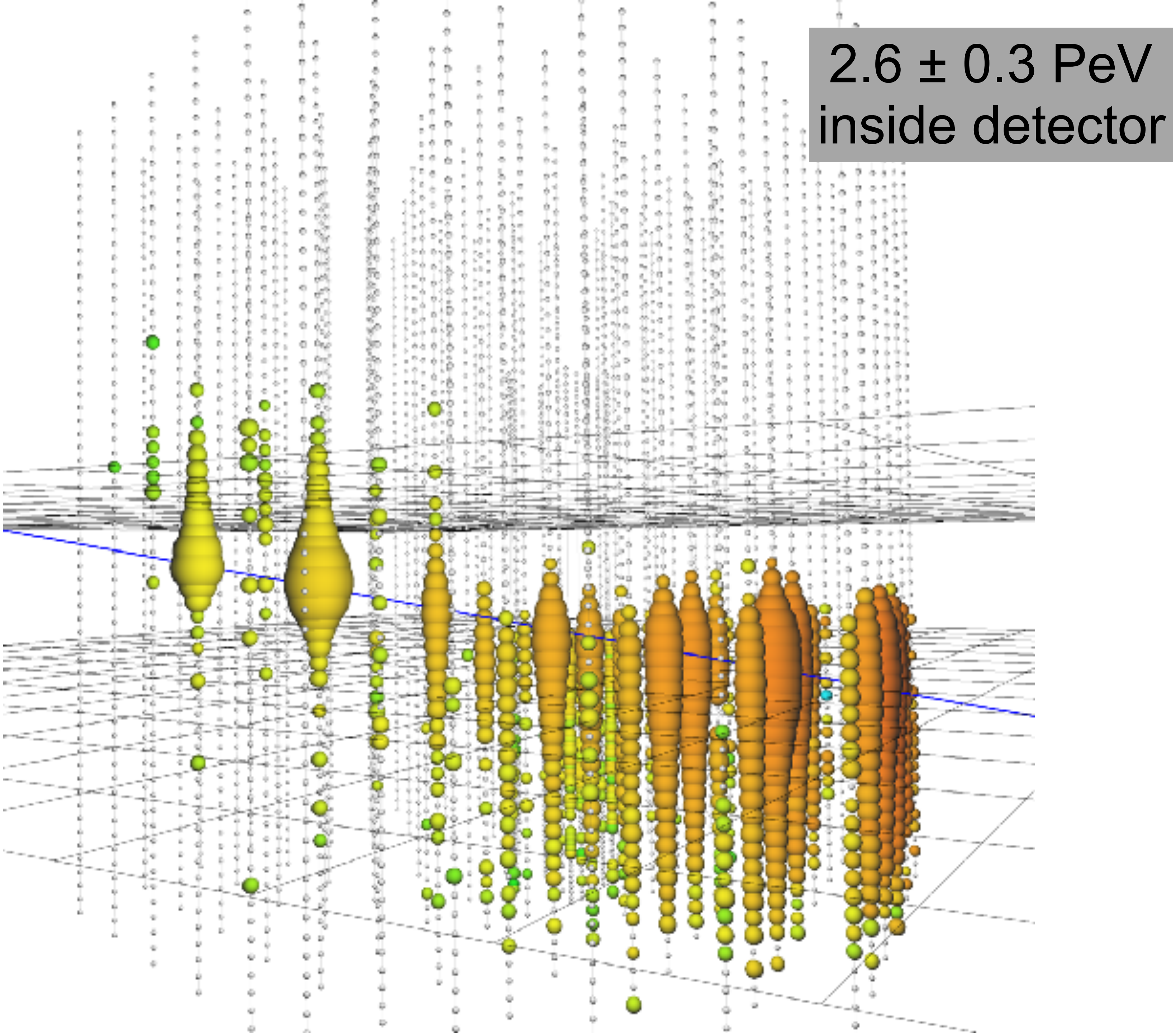
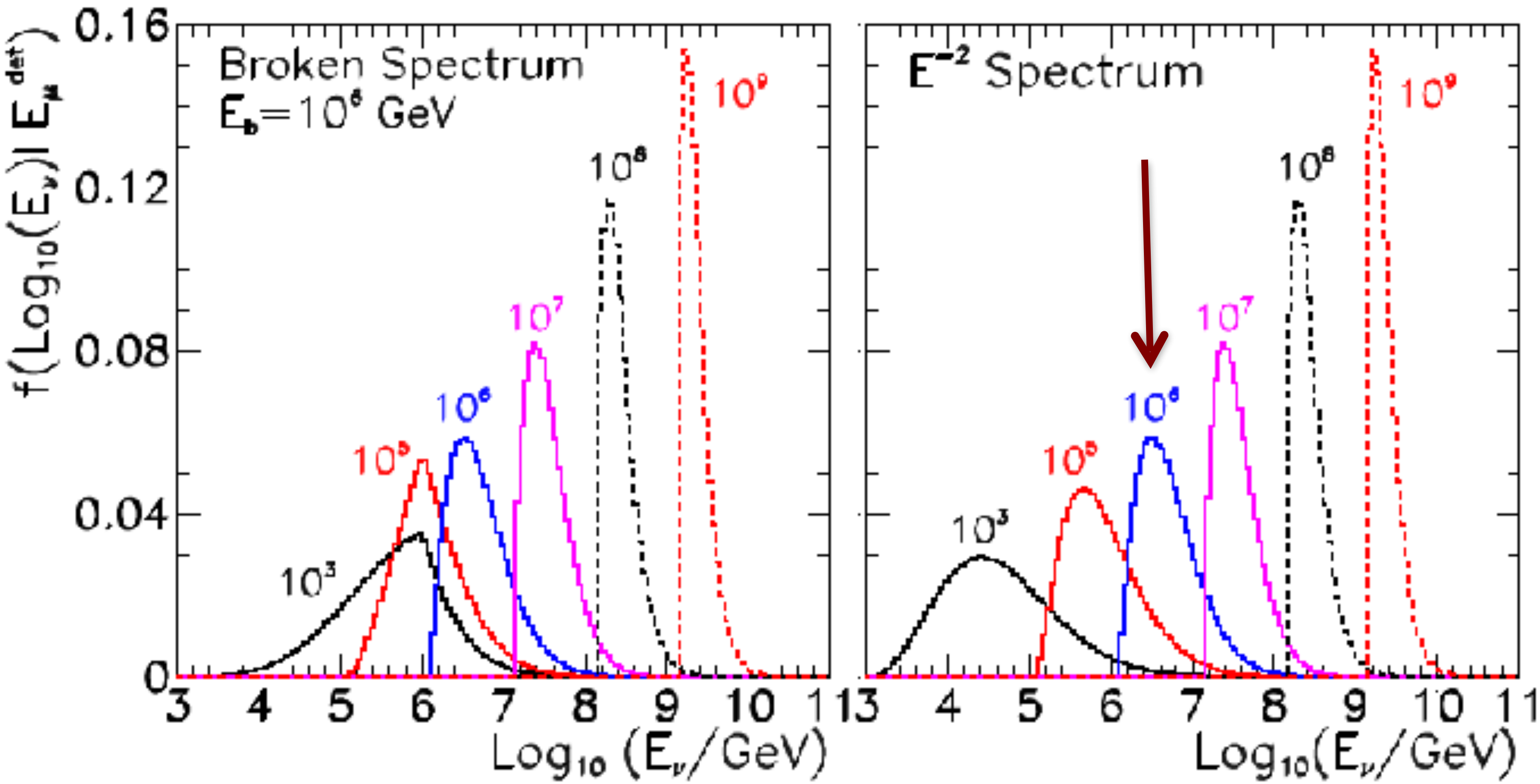

IceCube



• lattice of photomultipliers

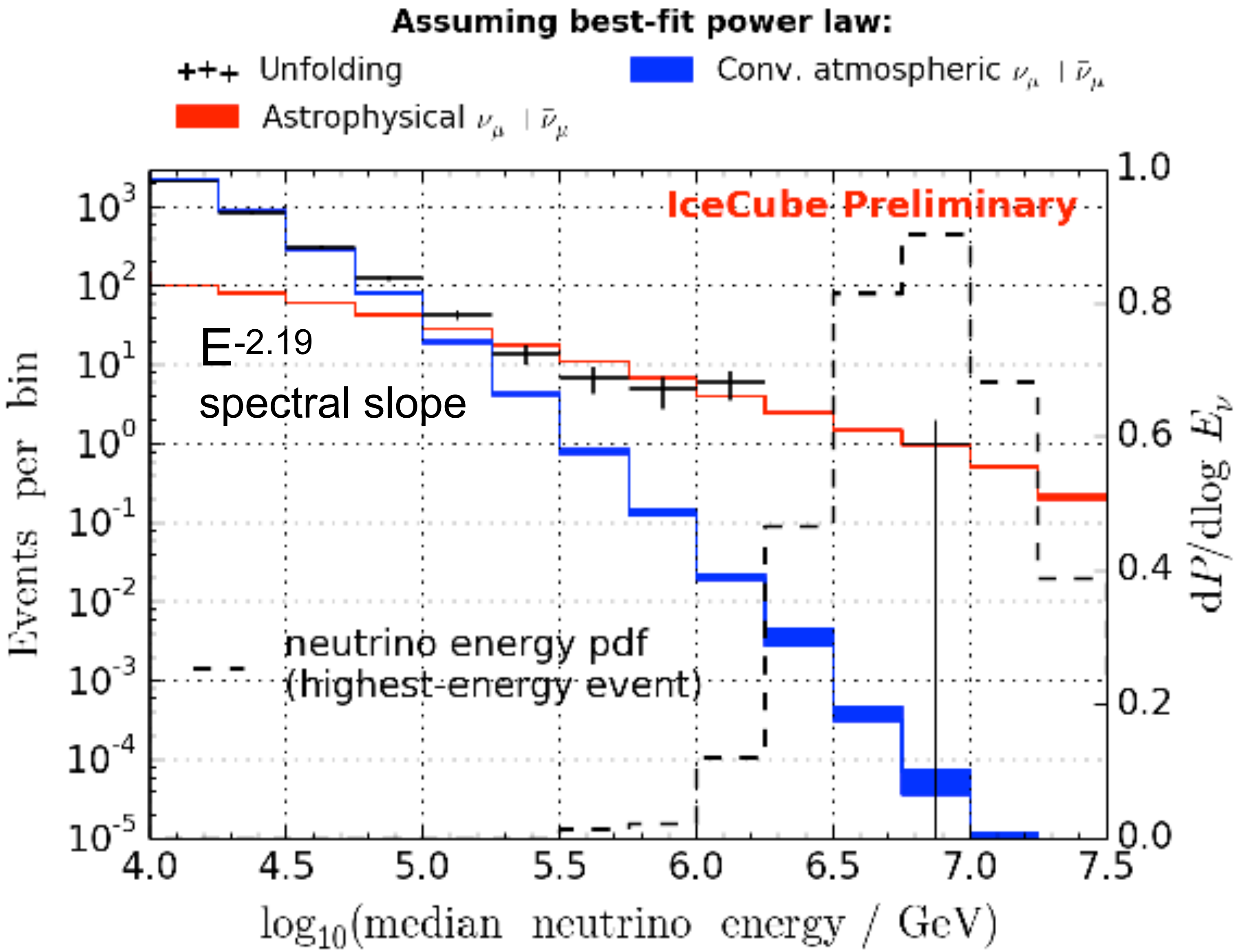

2.6 ± 0.3 PeV
inside detector

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



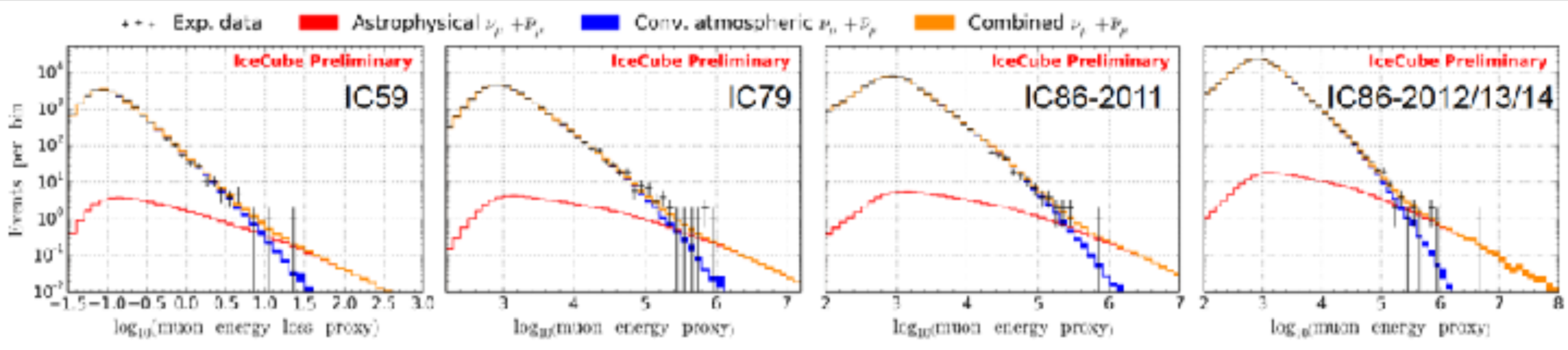
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric

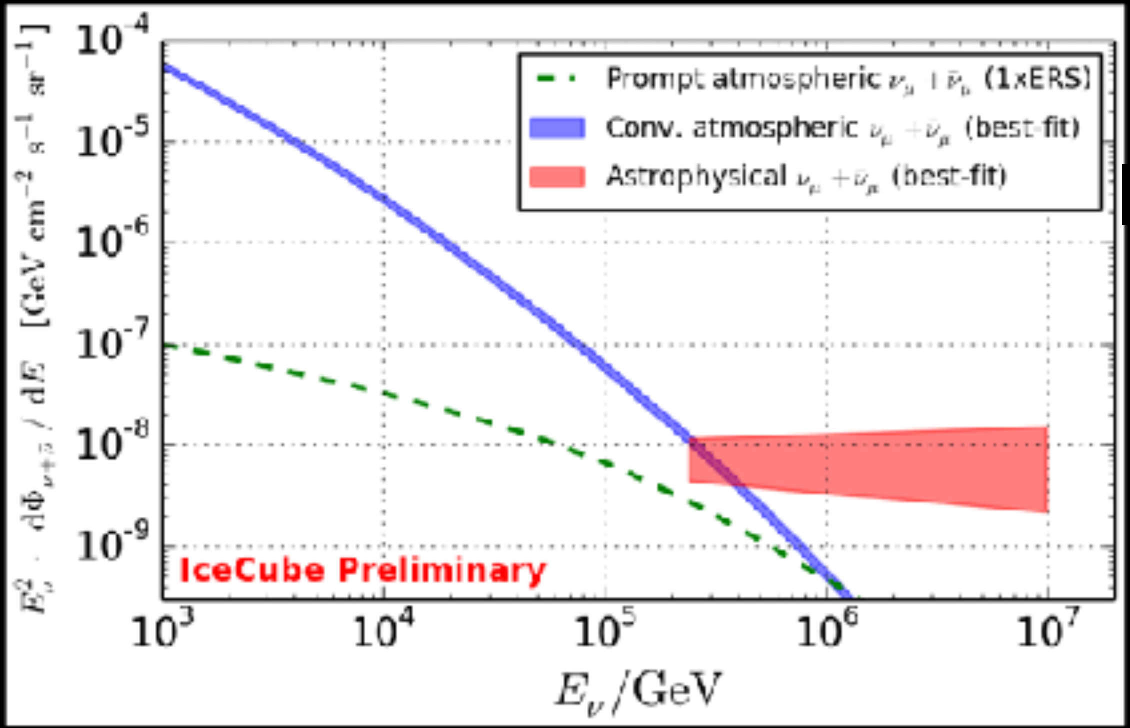
atmospheric background: less than one event/deg^2/year



after 7 years → 6.4 sigma

120 cosmic neutrinos/year/flavor





- **Best-fit astrophysical normalization:**

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

- **Best-fit spectral index:**

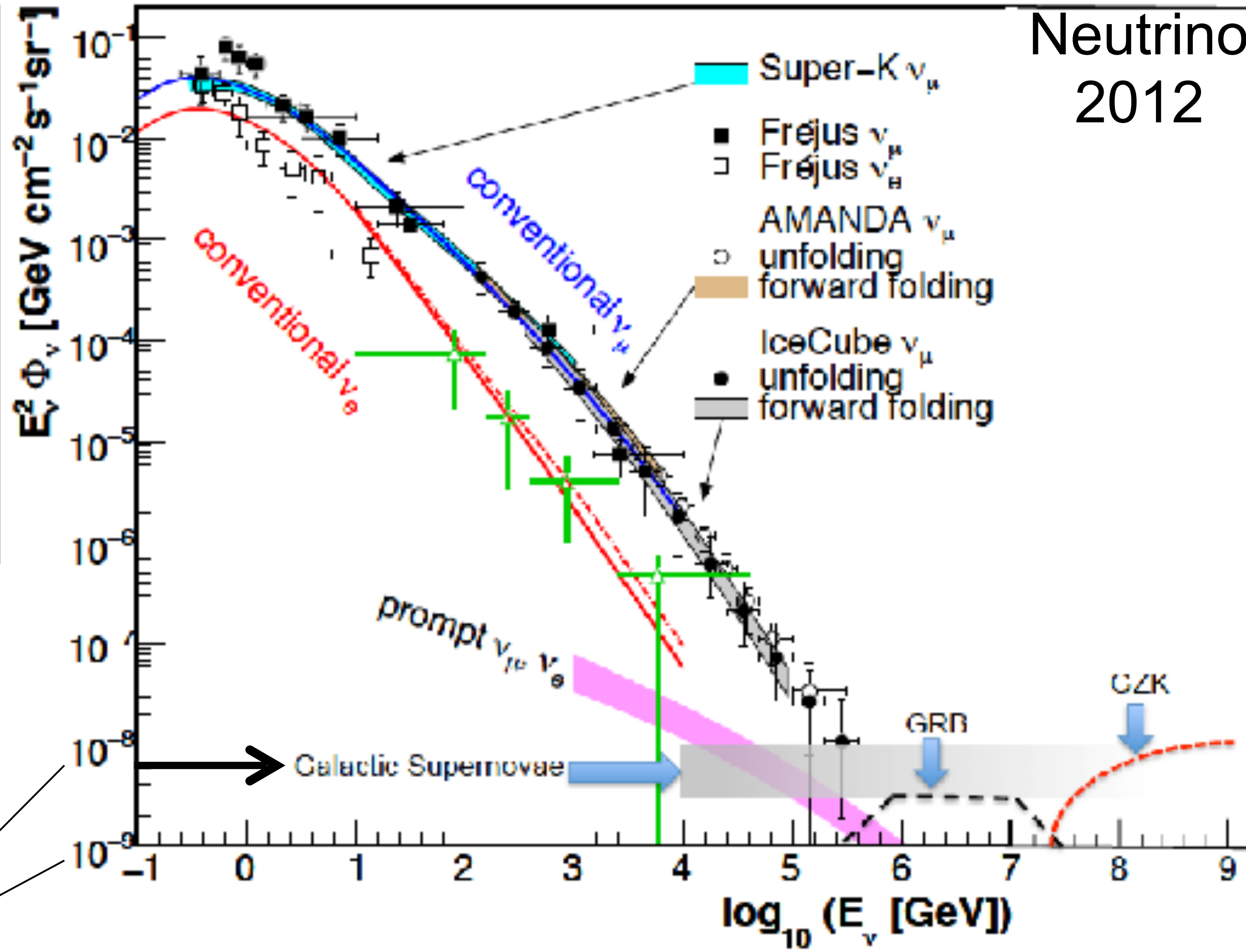
  γ_{astro} = 2.16 ± 0.11

- **Energy ranges:**

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



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

10—100 events per year for fully efficient detector

atmospheric

cosmic

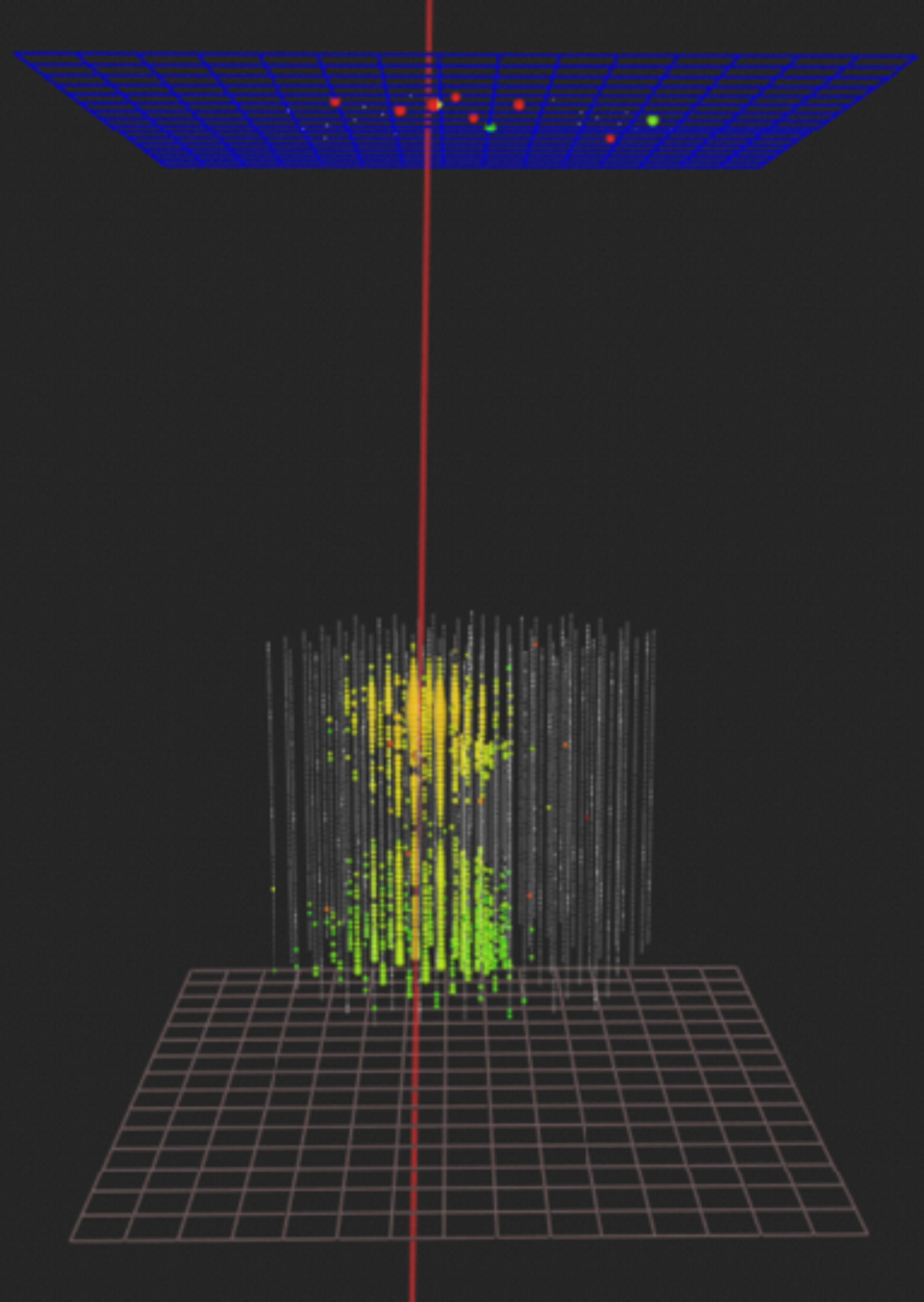
100 TeV

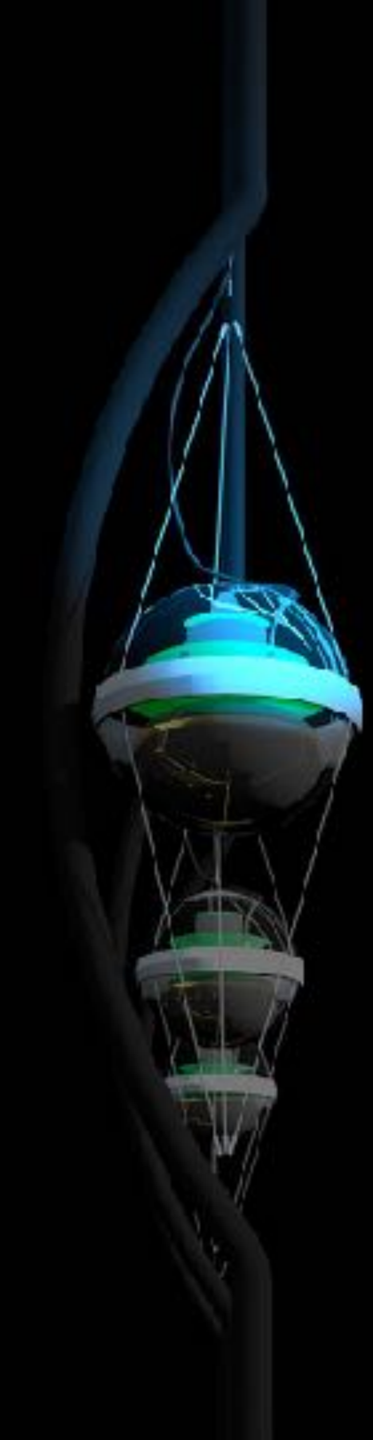
430 TeV inside detector

PeV ν_μ

no air shower

all cosmic neutrinos are isolated by self-veto





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

cosmic rays interact with the microwave background

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

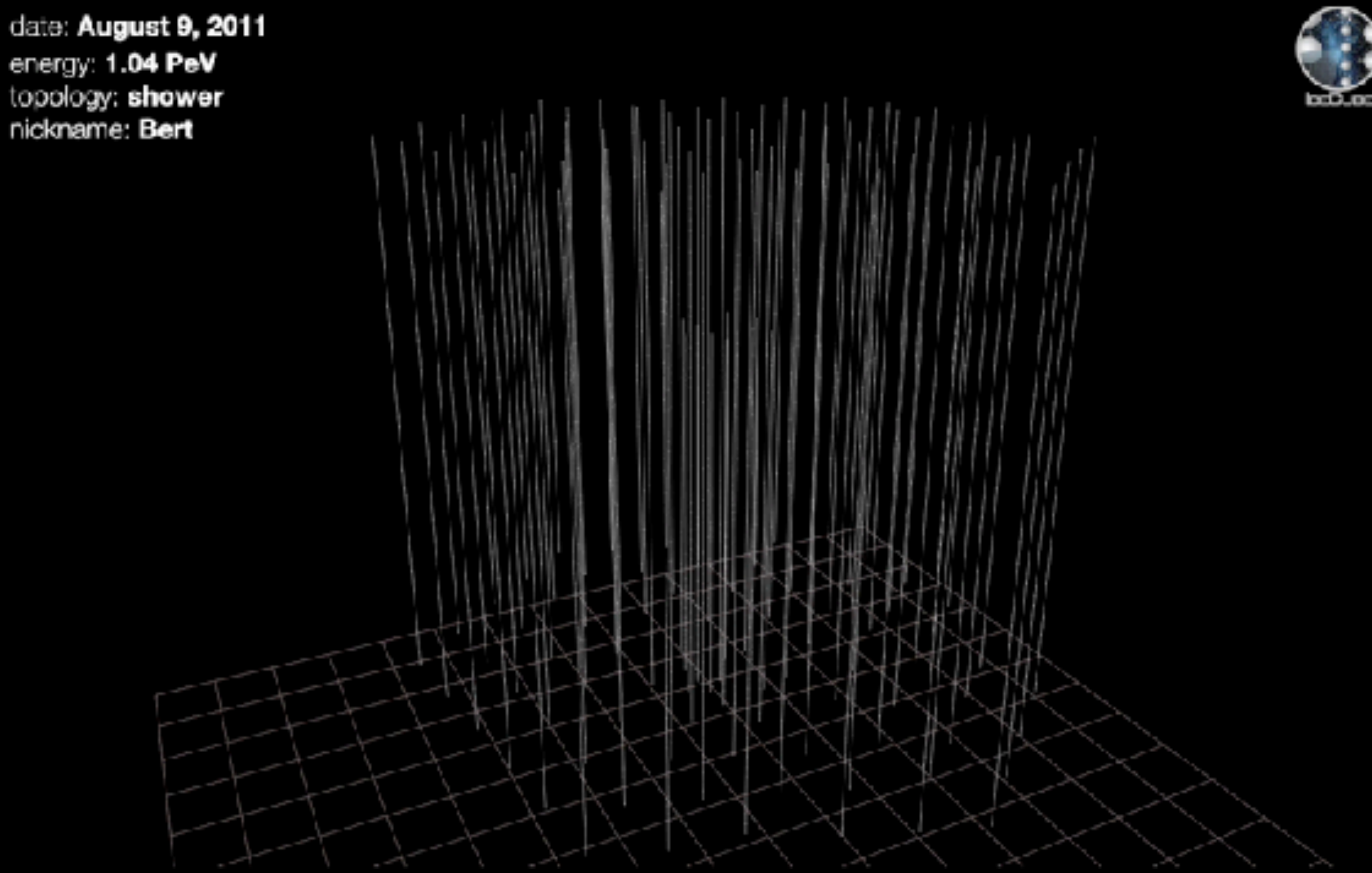
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

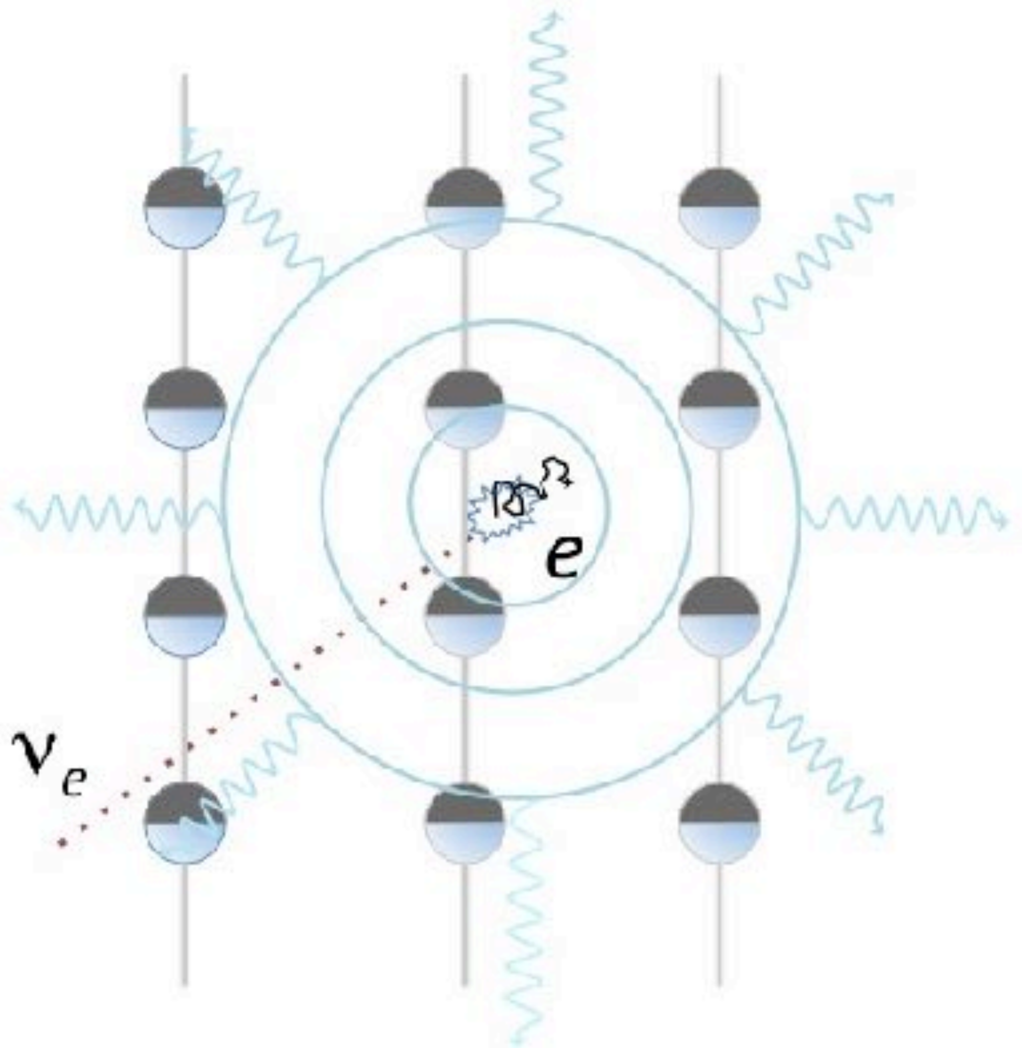
GZK neutrino search: two neutrinos with > 1,000 TeV

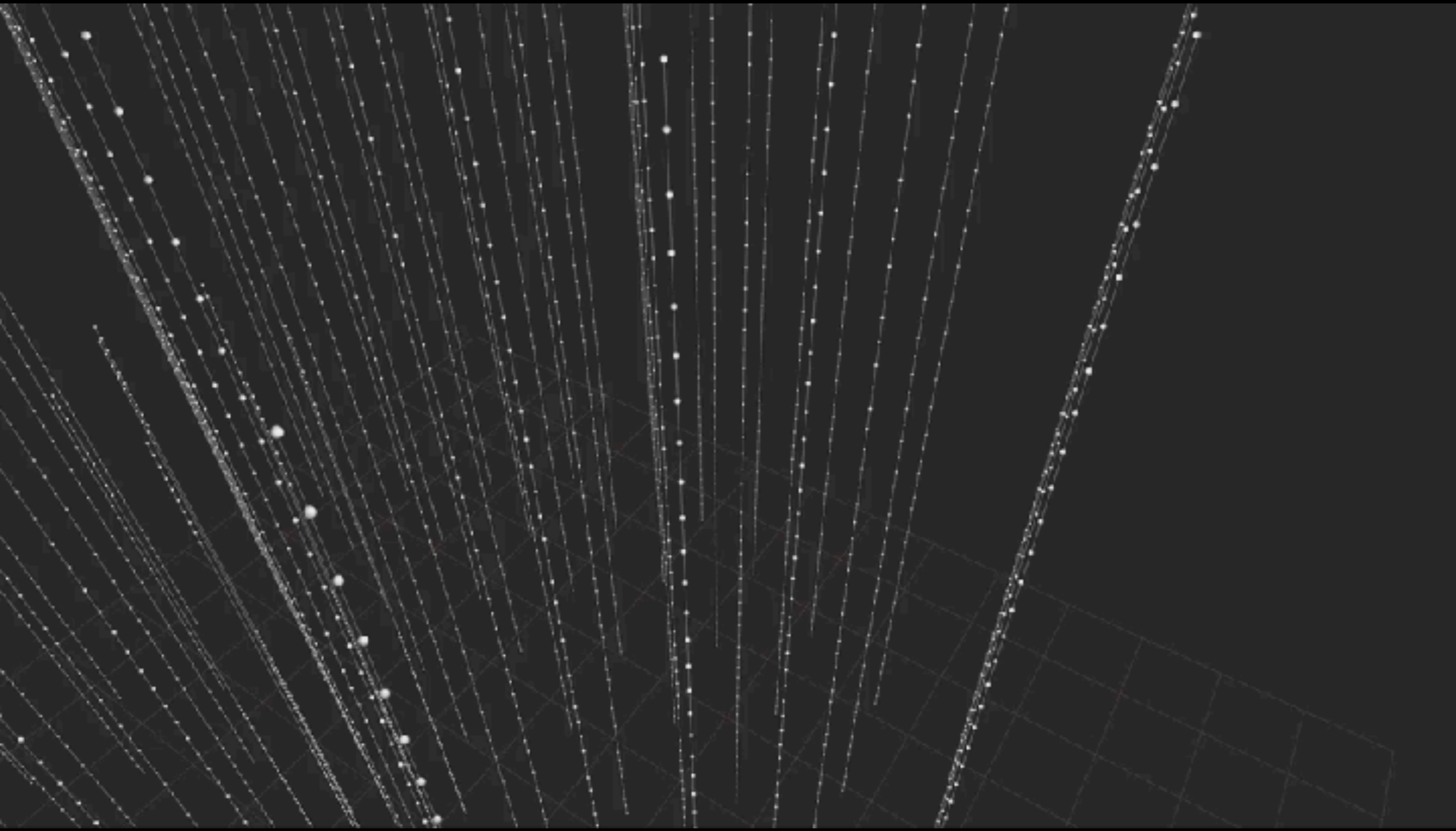


electron showers versus muon tracks

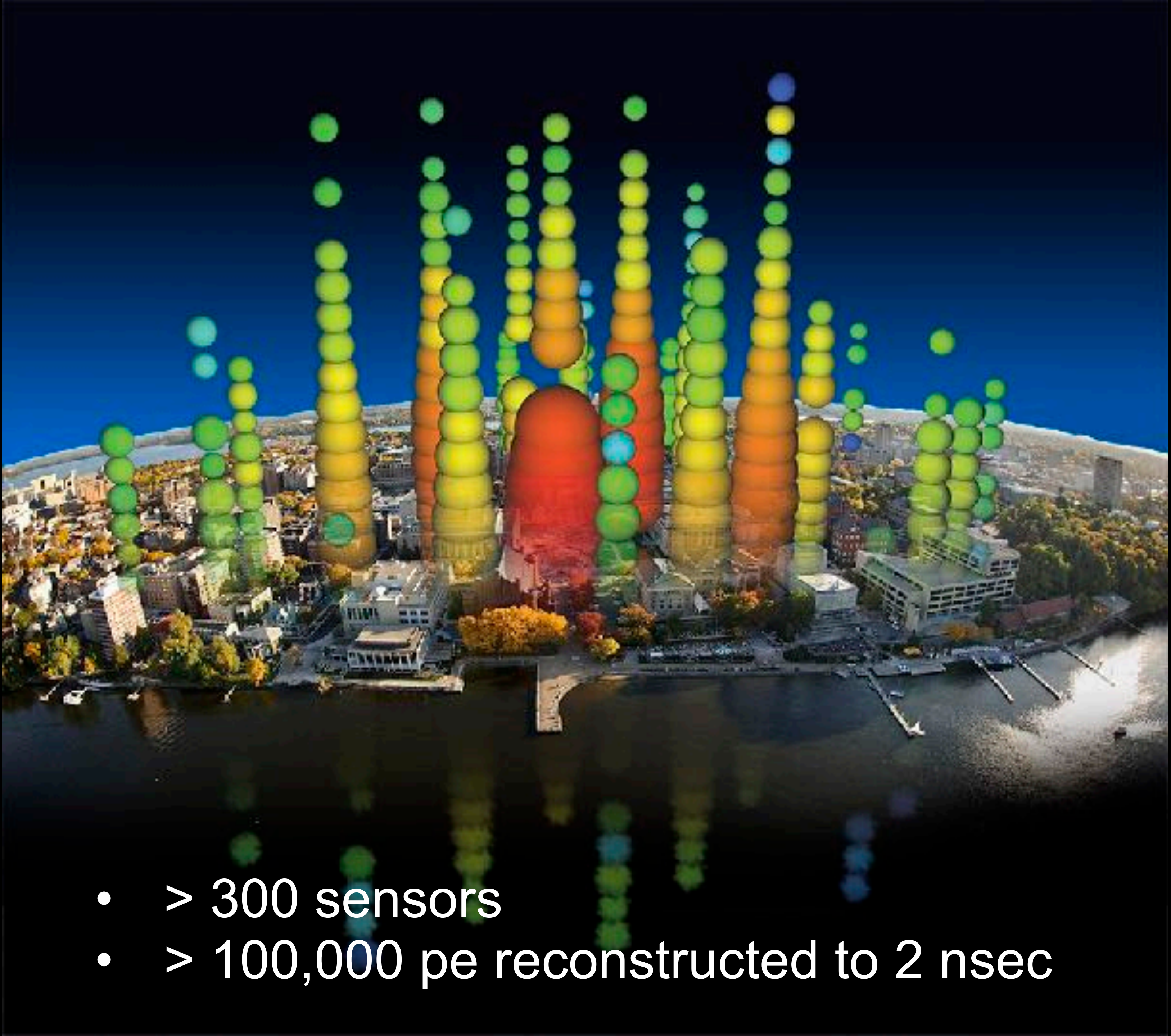
PeV ν_e and ν_τ showers:

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



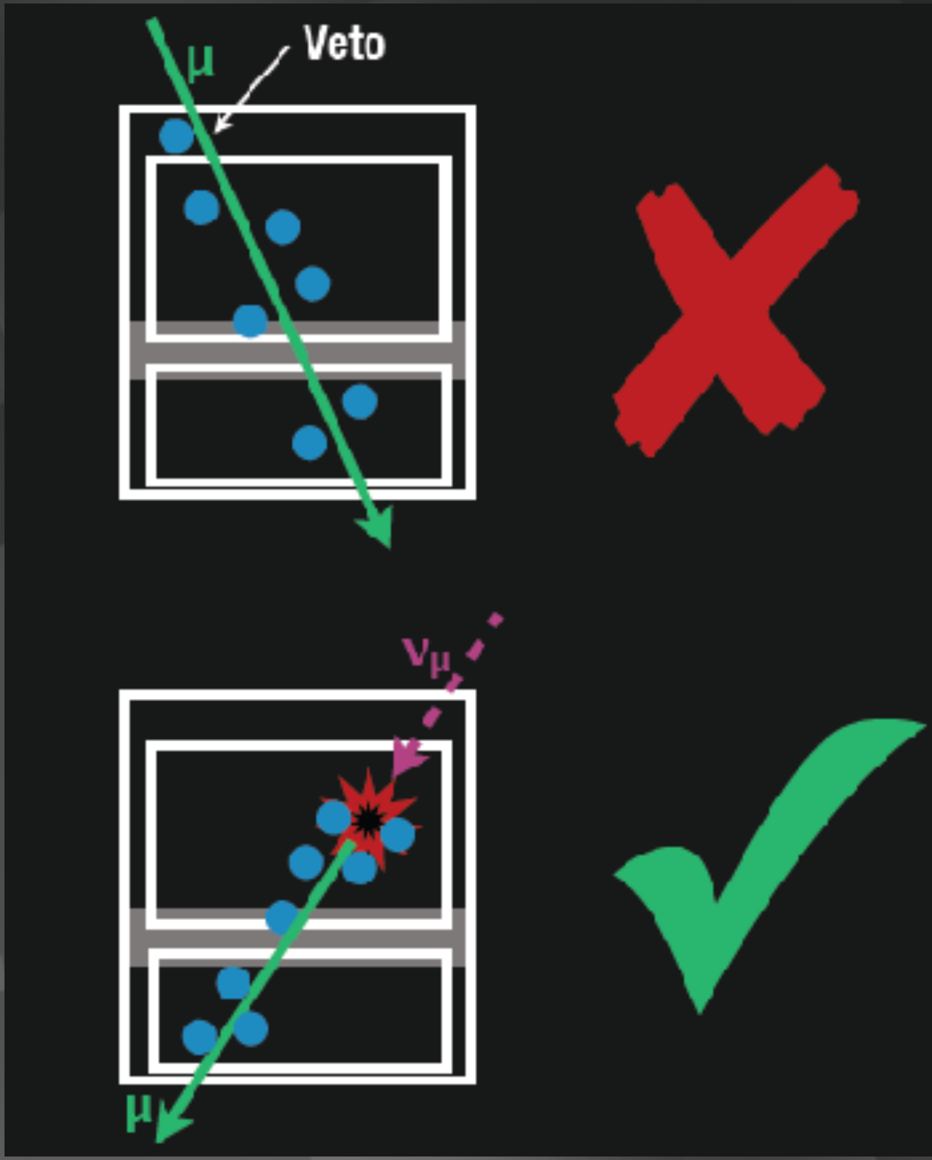


size = energy & color = time = direction

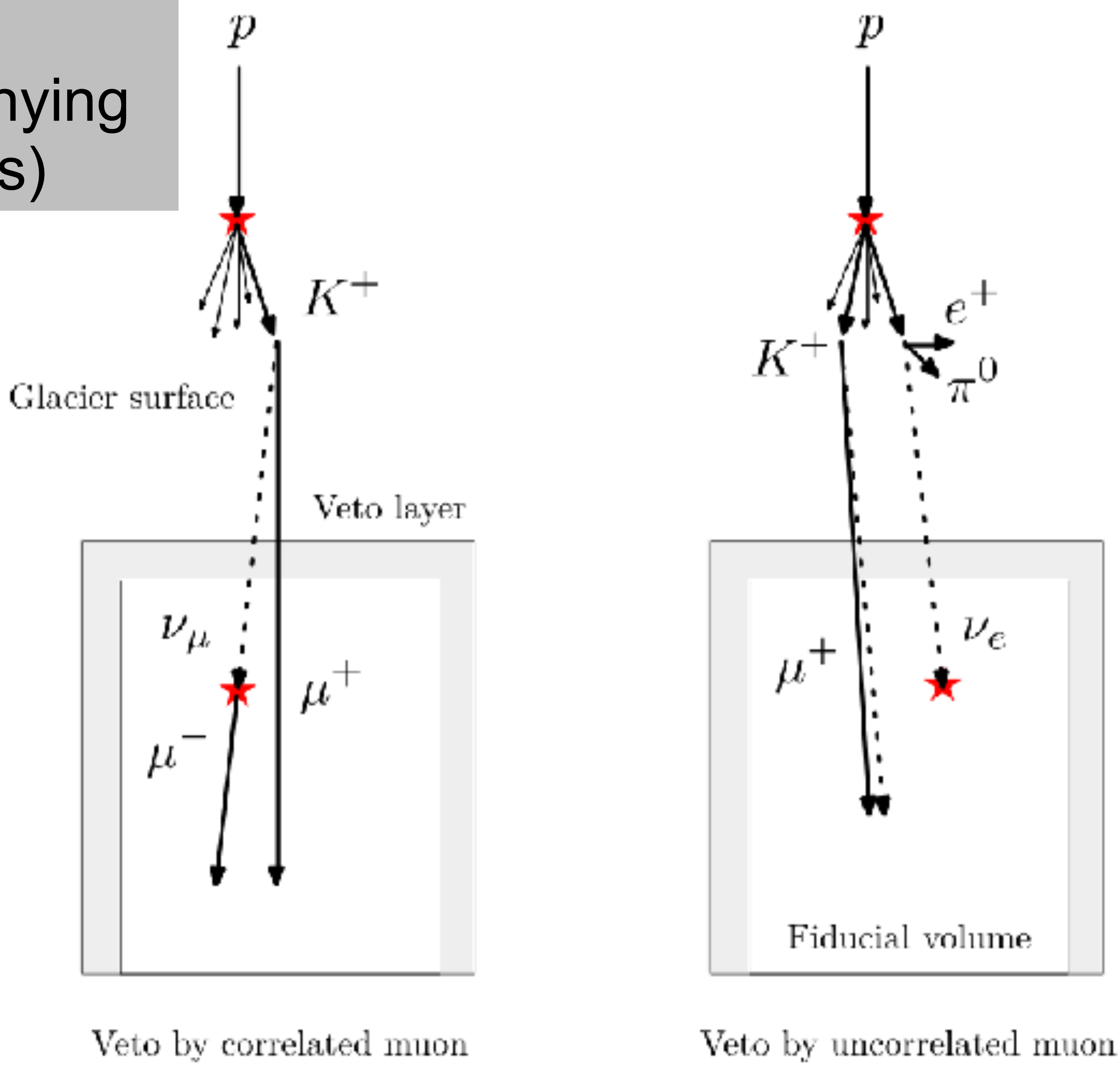


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

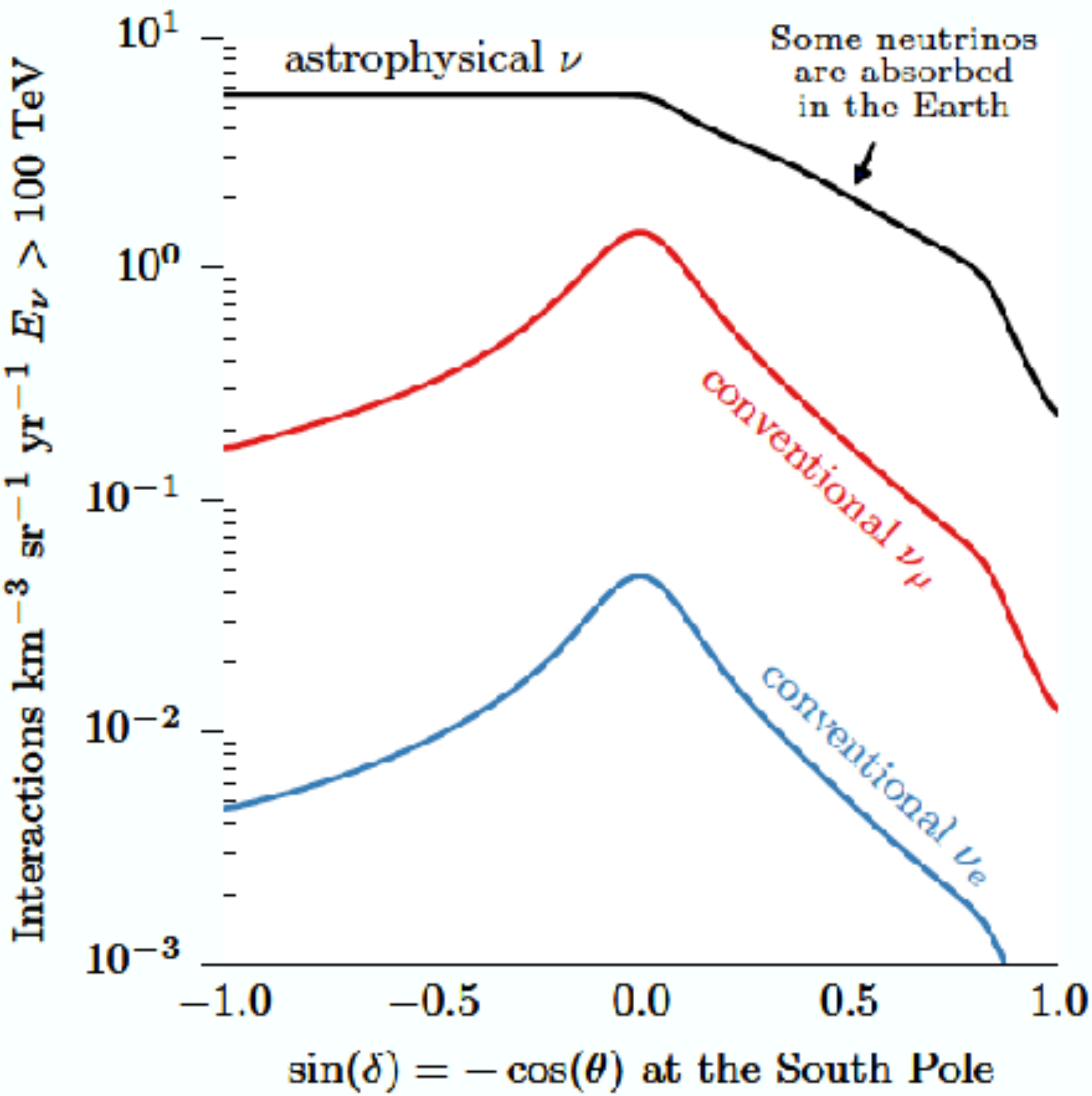
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



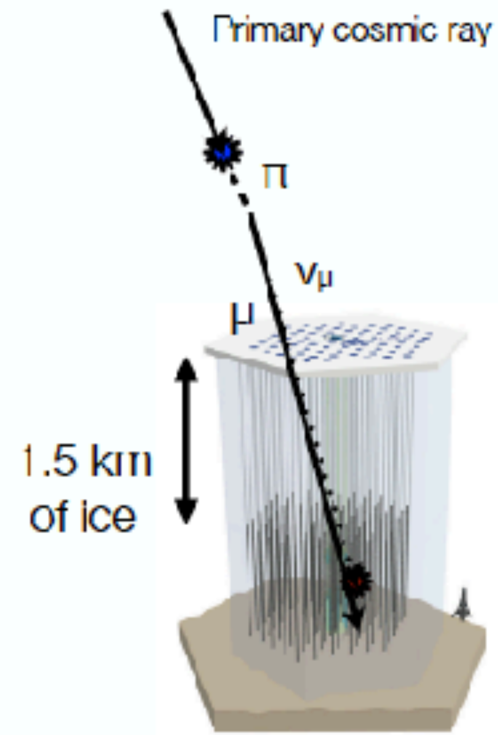
no accompanying muon(s)



Atmospheric neutrino self-veto



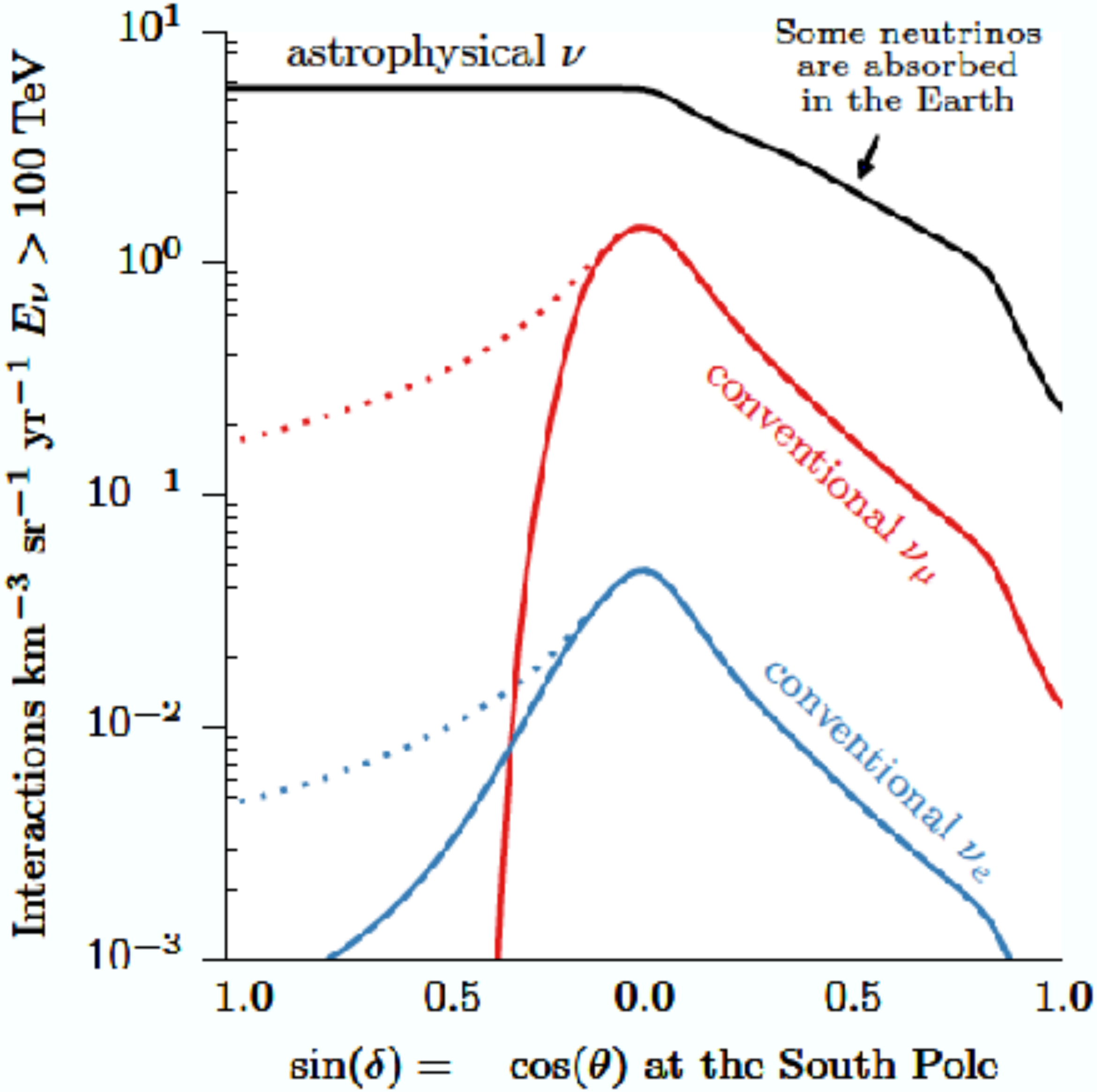
An active muon veto removes down going atmospheric neutrinos.



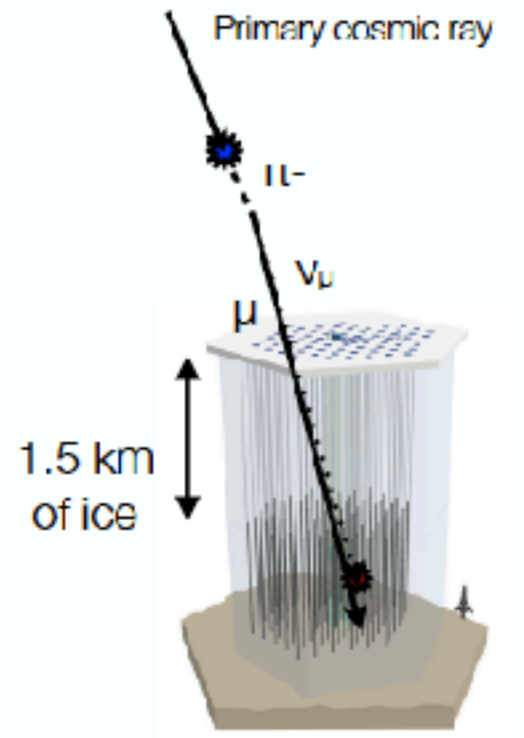
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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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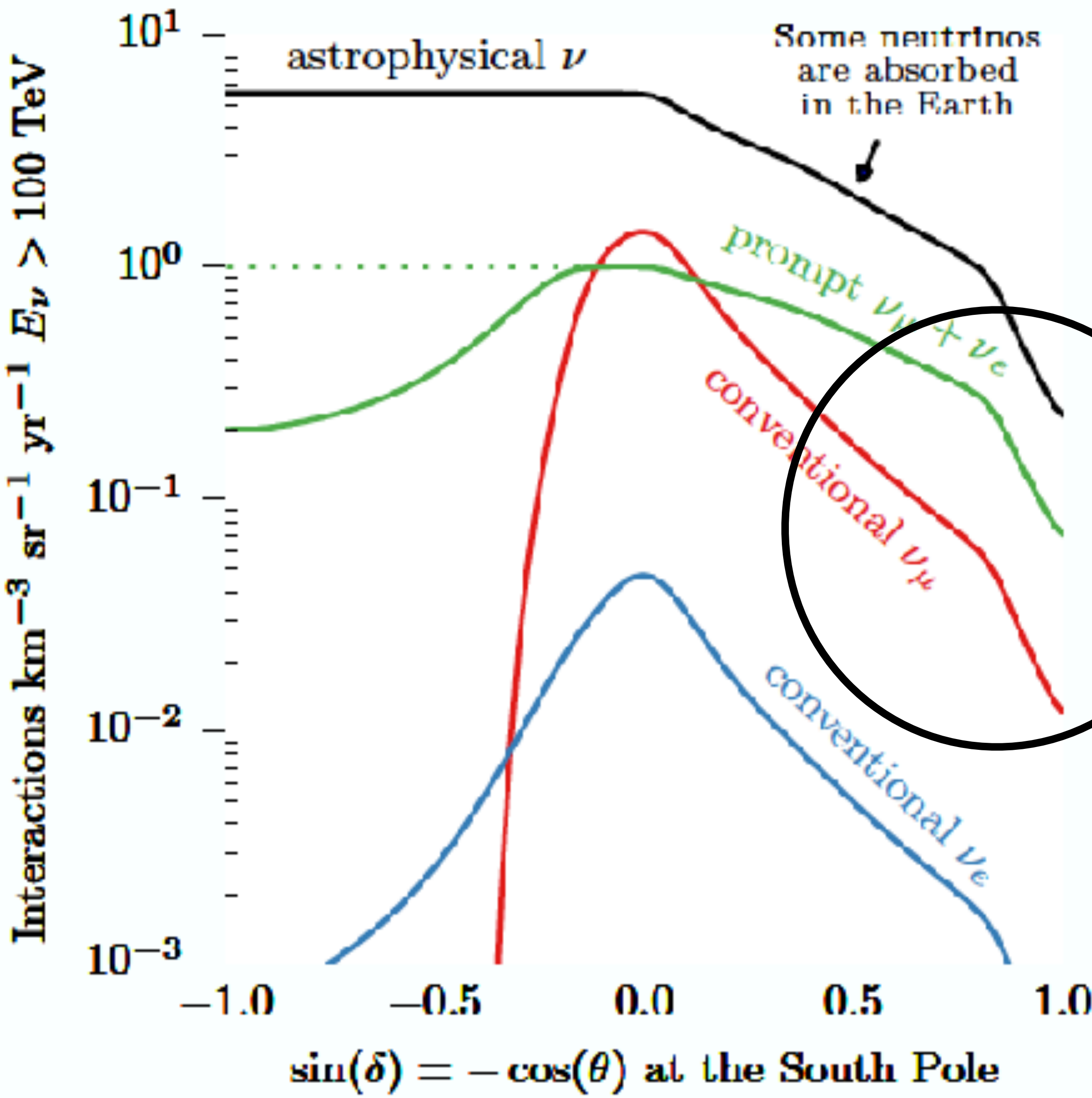
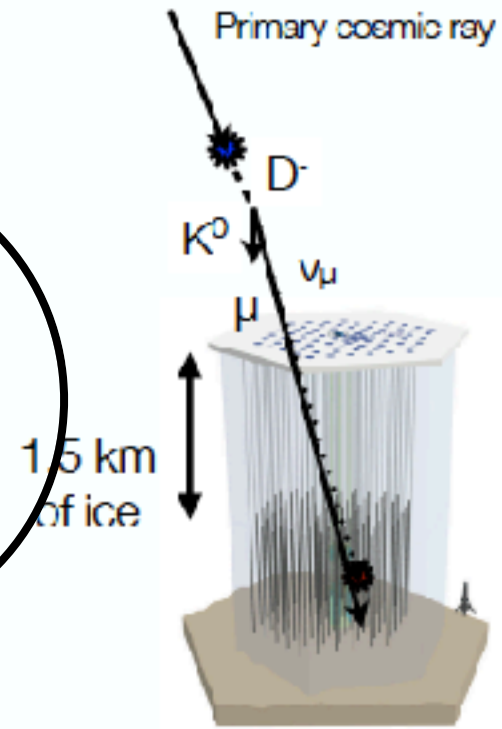
Atmospheric neutrino self-veto



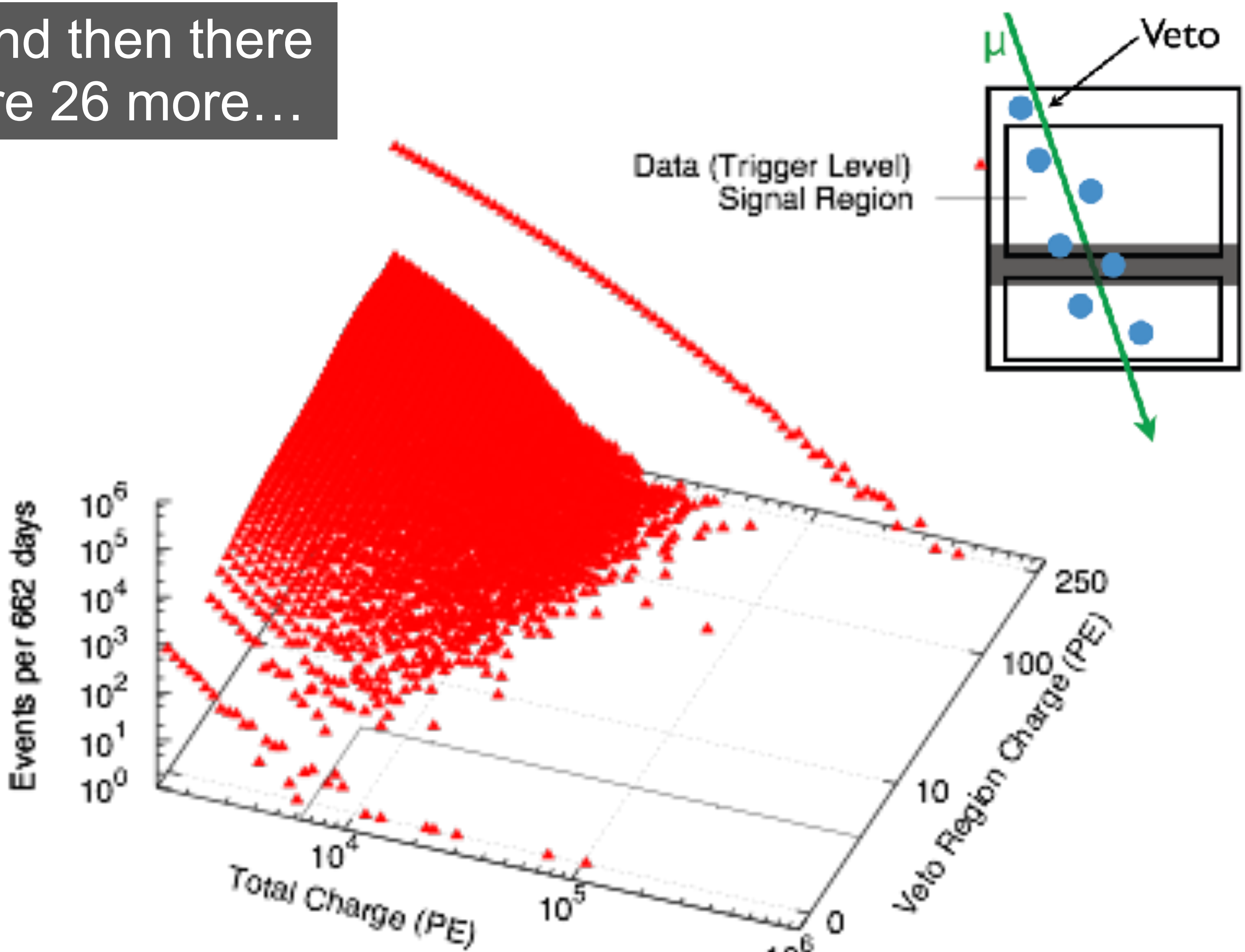
Prompt atmospheric neutrinos are vetoed, too.



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

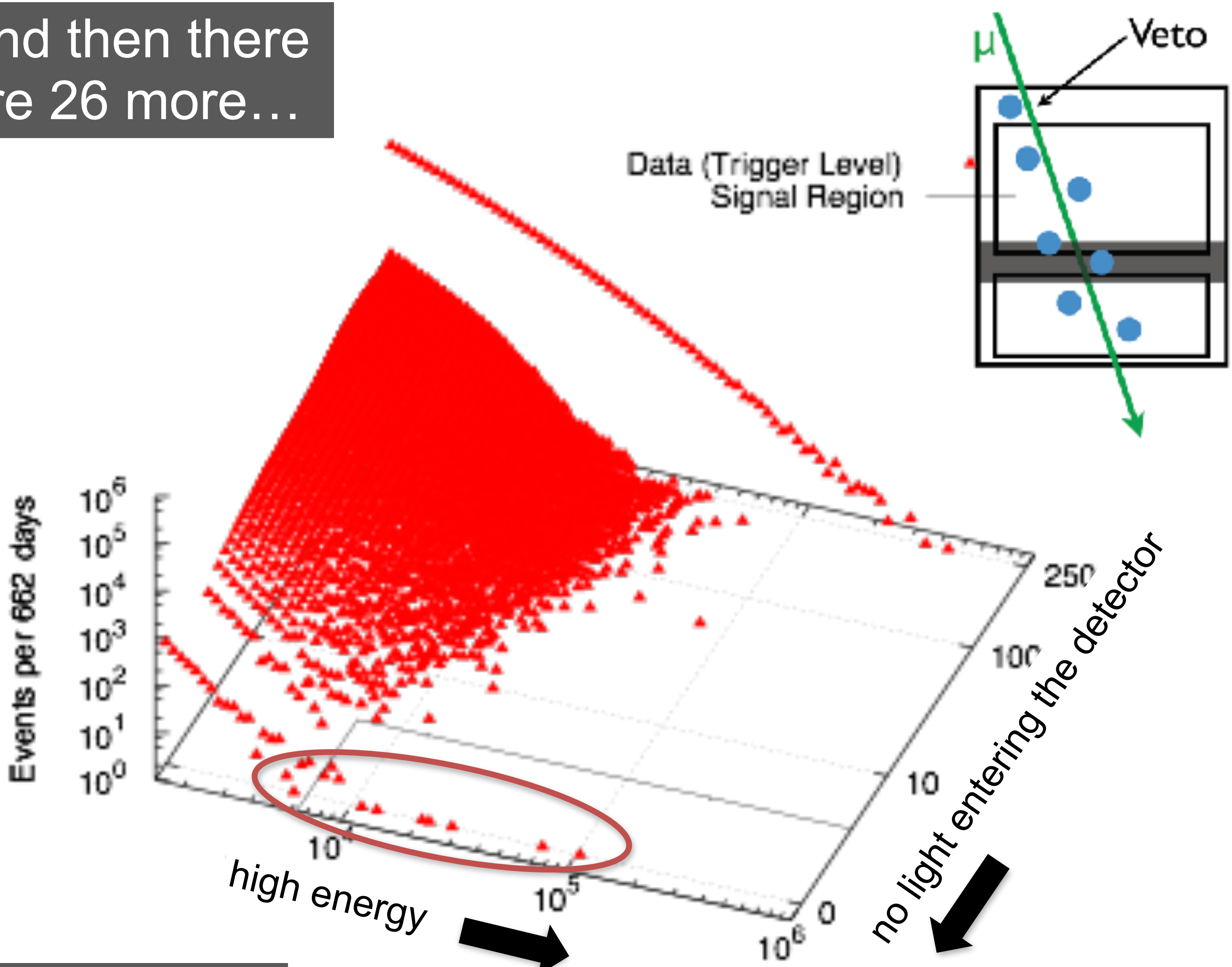
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

…and then there were 26 more…

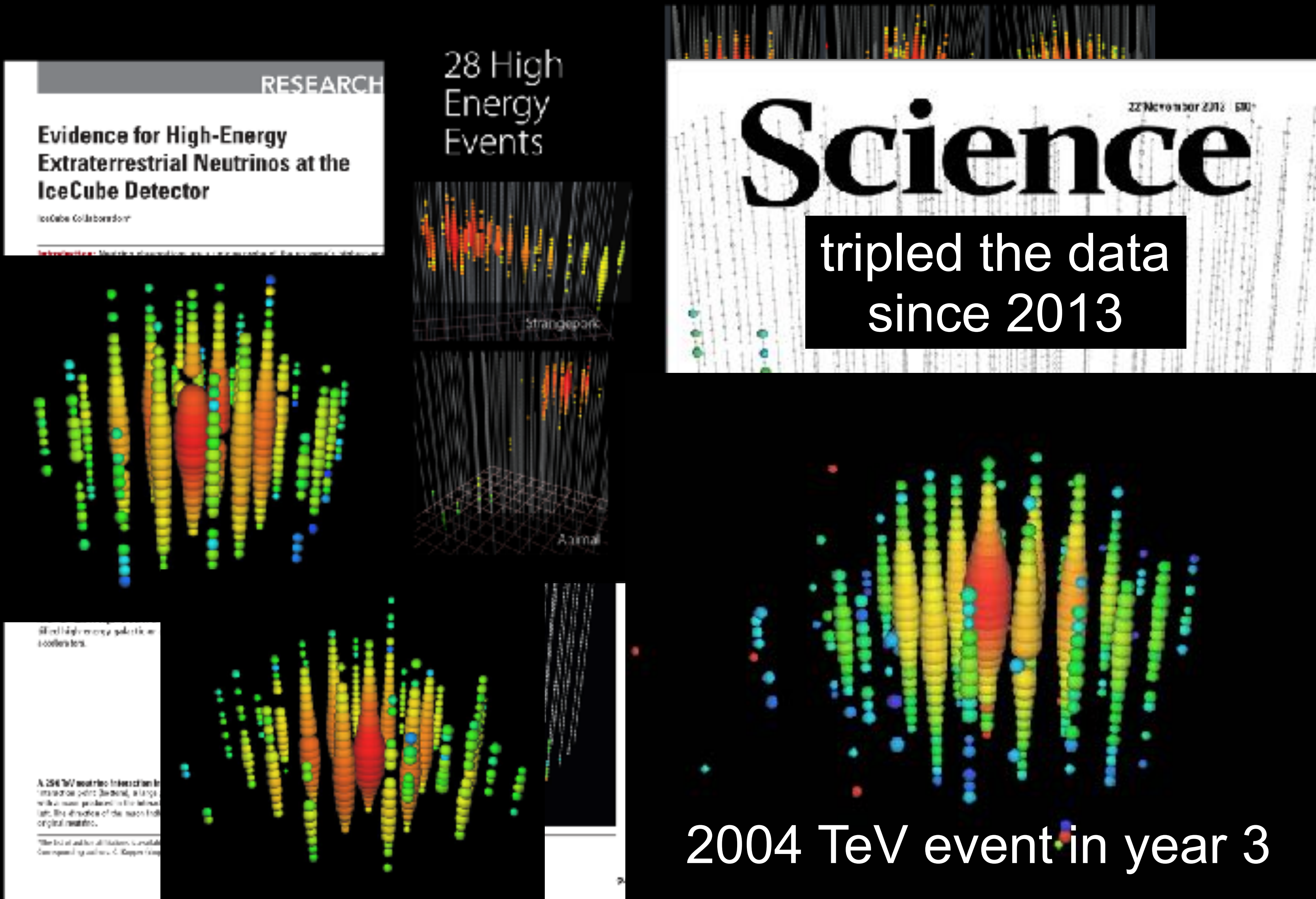


data: 86 strings one year

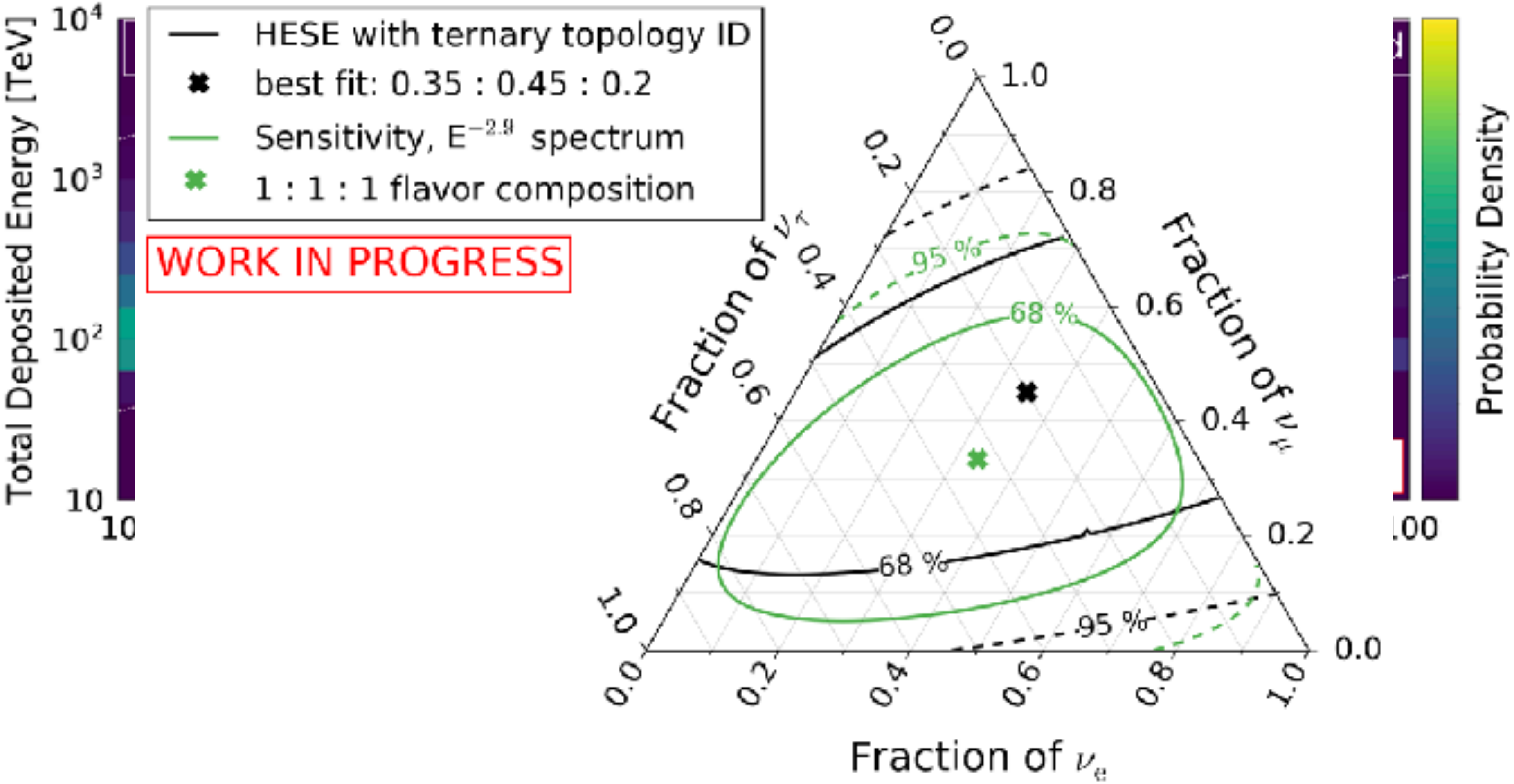
…and then there were 26 more…



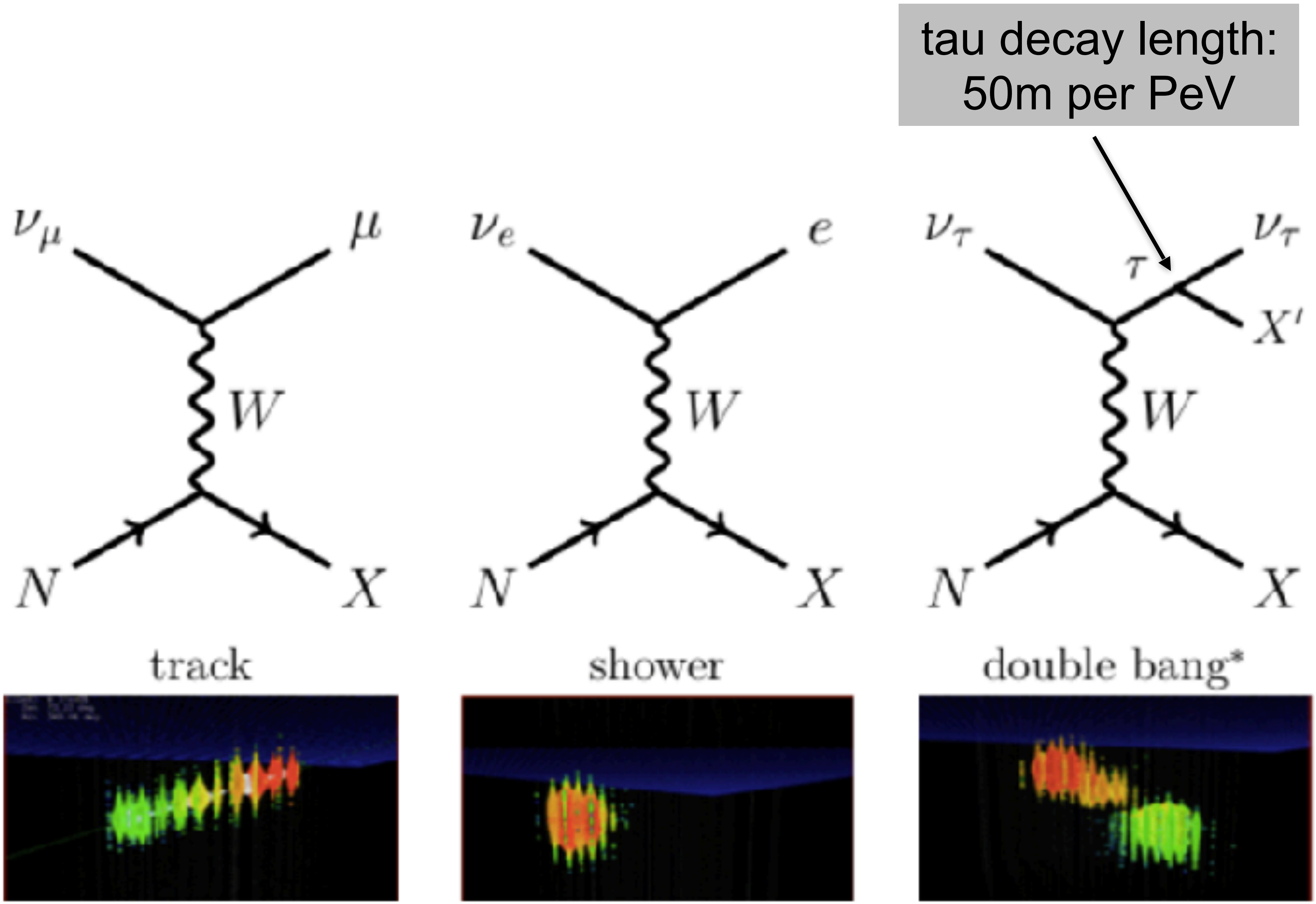
data: 86 strings one year


RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
28 High Energy Events
Science
tripled the data since 2013
2004 TeV event in year 3

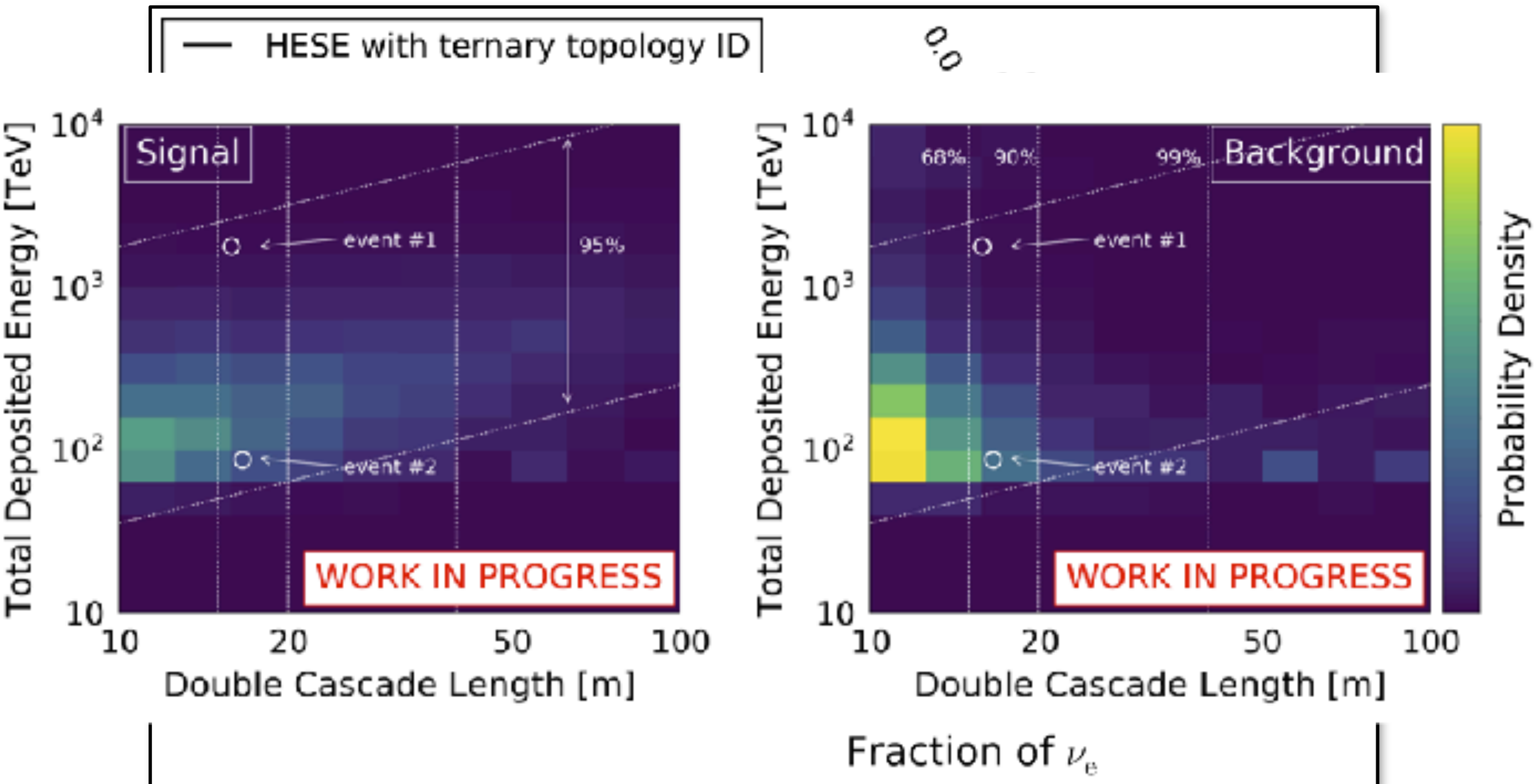
high-energy starting events – 7.5 yr



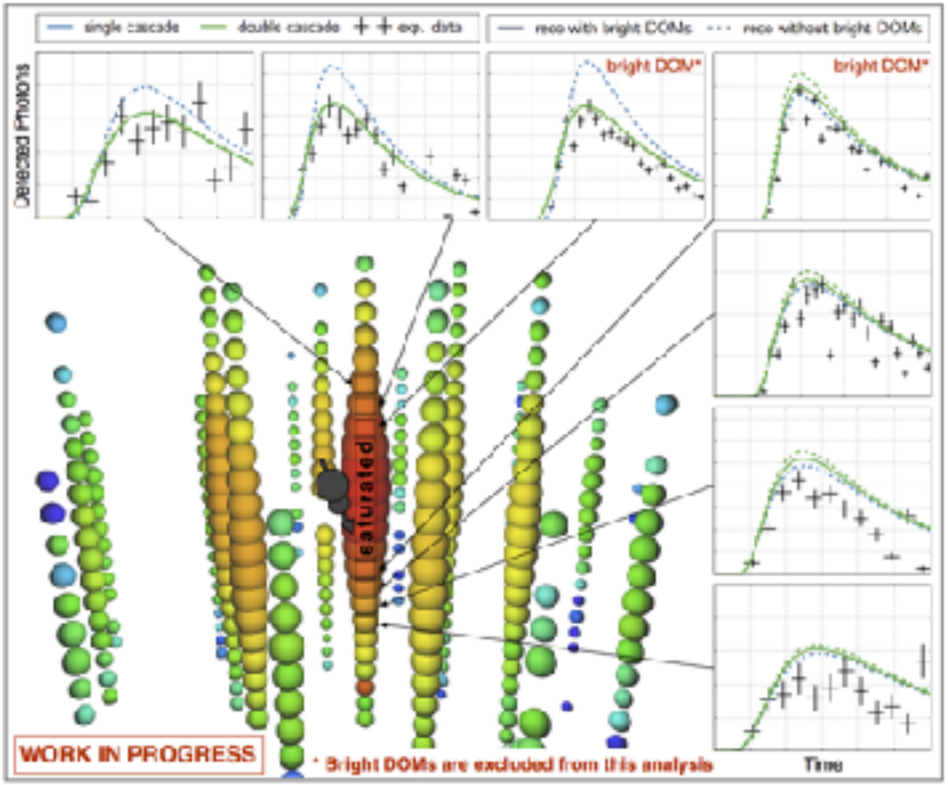
oscillations of PeV neutrinos over cosmic distances to 1:1:1

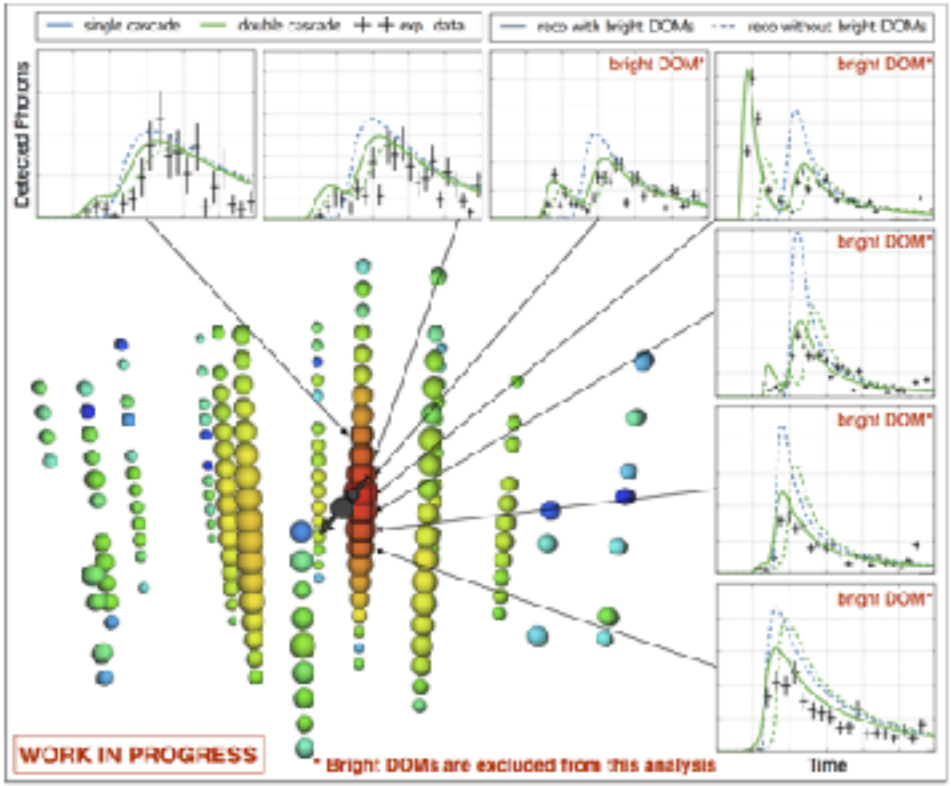

tau decay length:
50m per PeV
ν_μ
μ
W
N
X
ν_e
e
W
N
X
ν_τ
τ
ν_τ
X'
W
N
X
track
shower
double bang*

high-energy starting events – 7.5 yr



high-energy starting events (starting) – 7.5 yr





Double cascade Event #1

Double cascade Event #2

“Bright” DOMs not used in reconstruction
Direction and two reconstructed cascades shown in dark gray

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

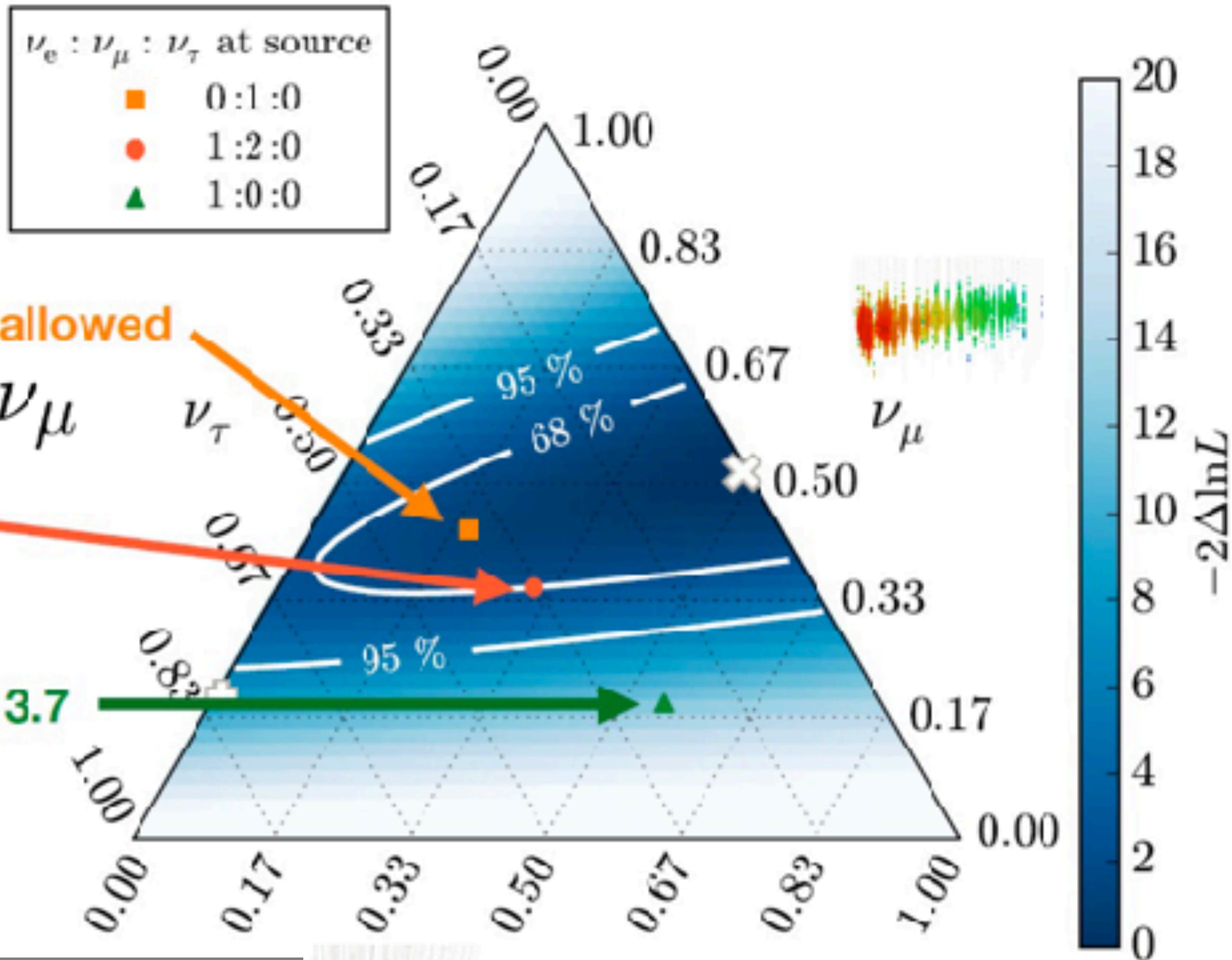
Muon-damped pion decay: allowed

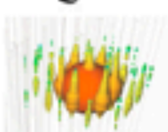
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

Pion decay: allowed

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

Neutron decay: rejected at 3.7





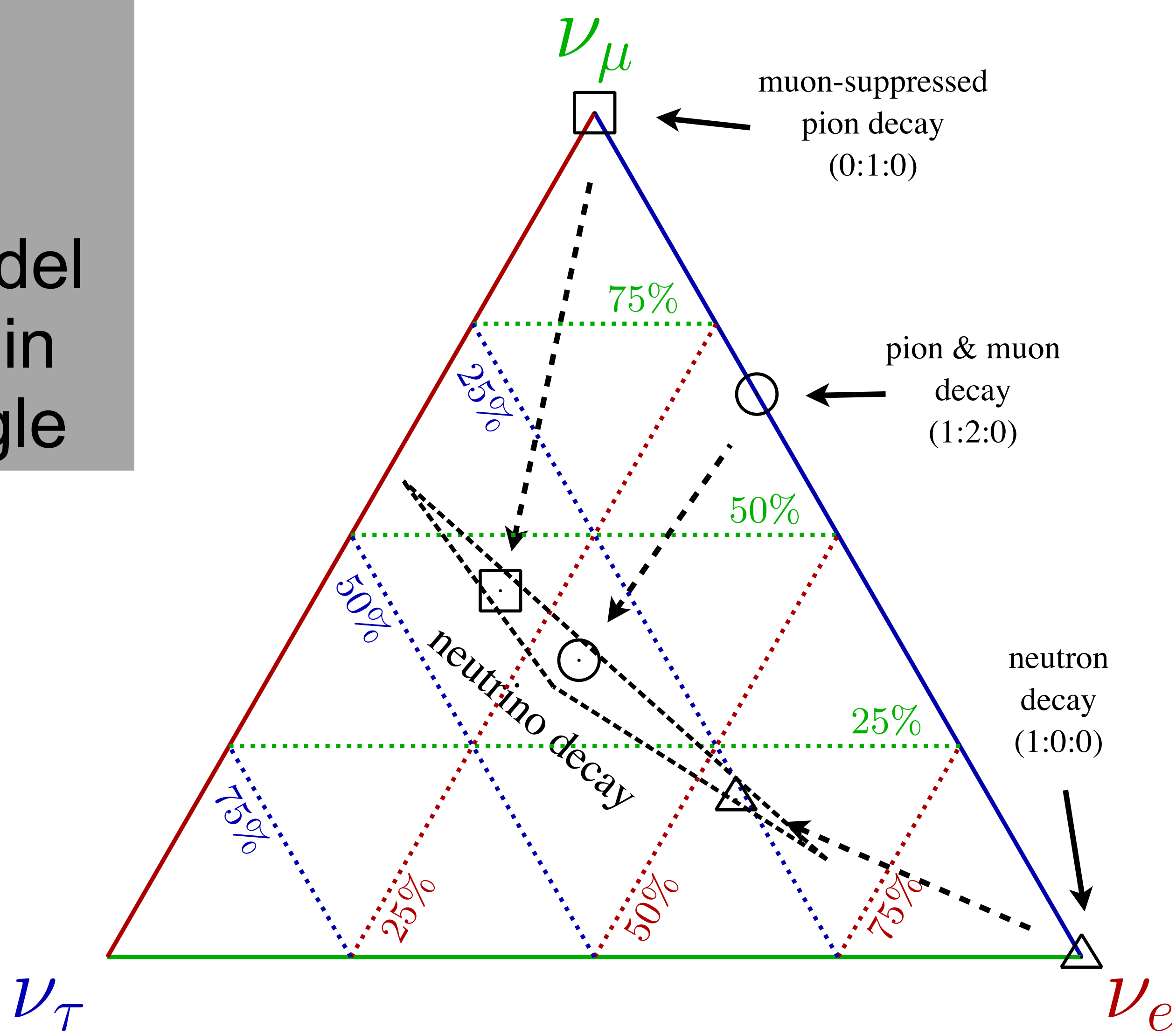
oscillate over cosmic distances to 1:1:1

ApJ 809, 98 (2015)

new physics ?

if not…

every model ends up in the triangle

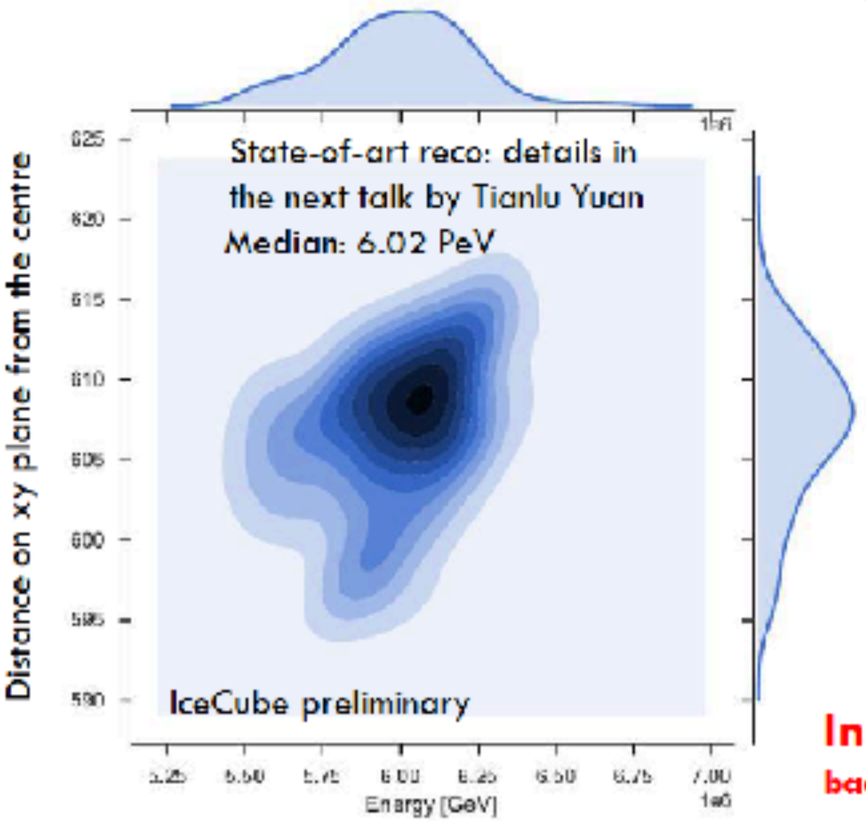


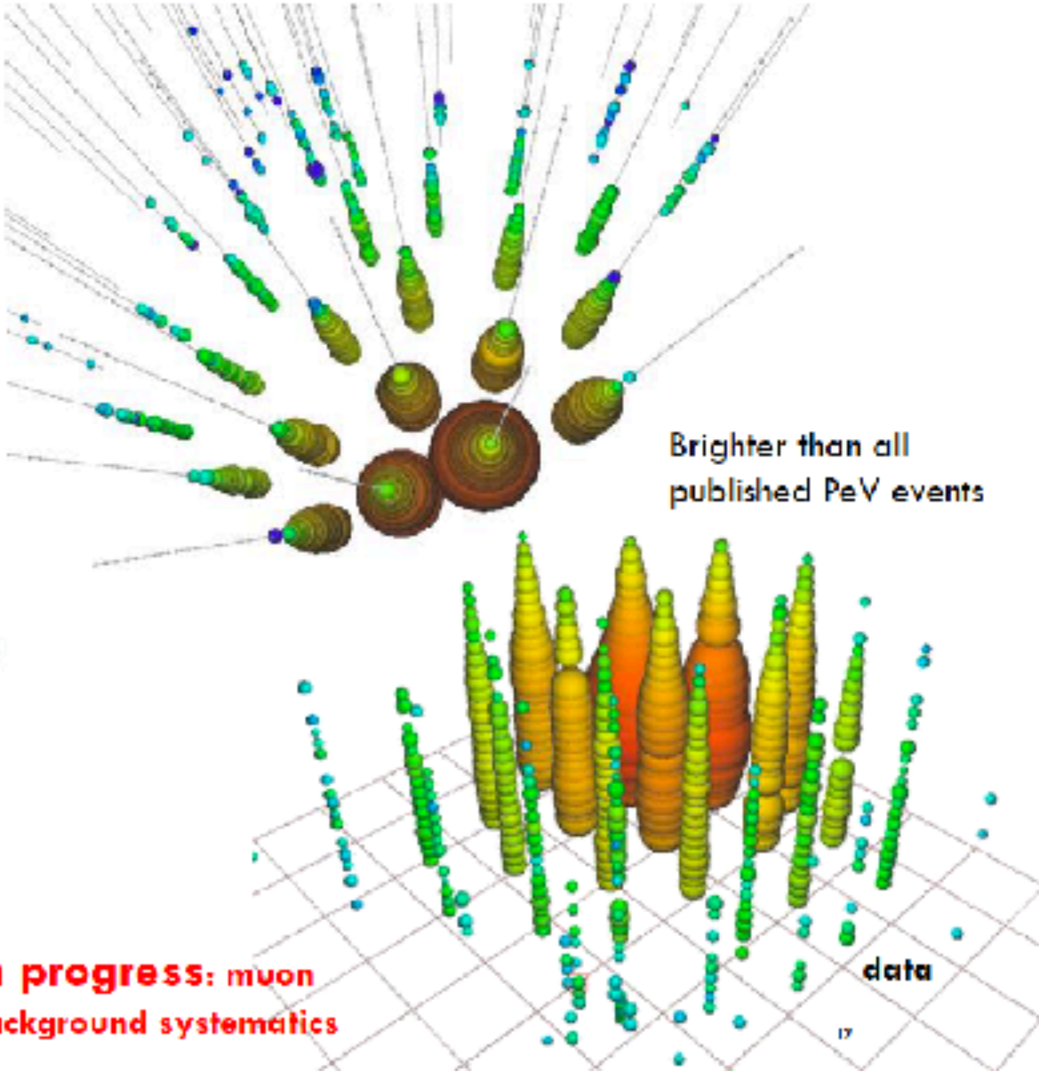
the first Glashow resonance event:

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

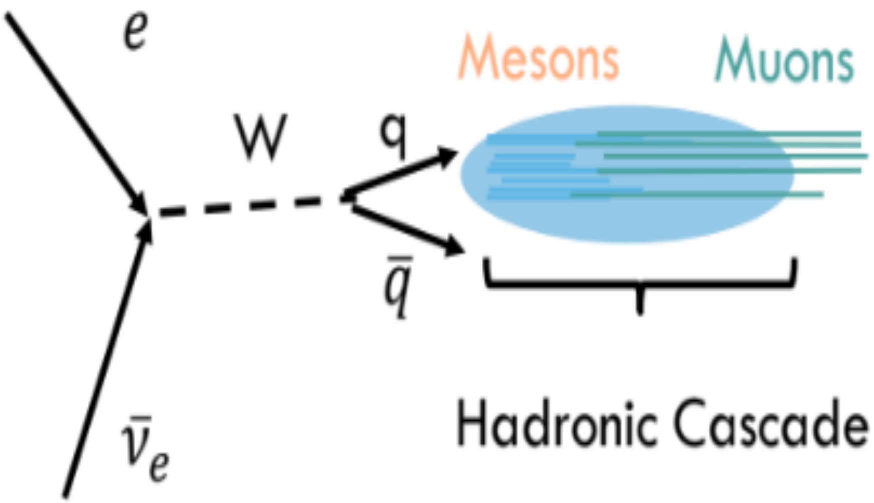
Partially contained event with energy ~ 6 PeV

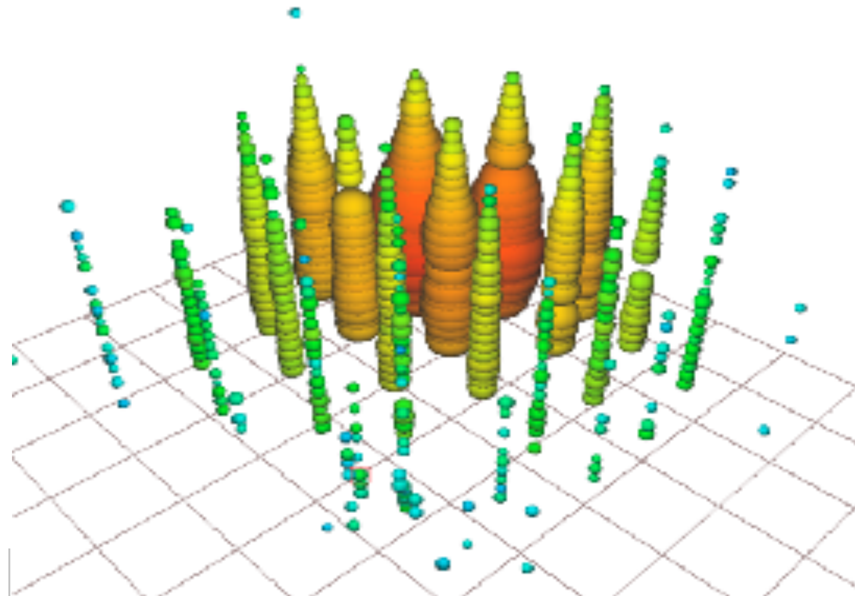
HIGHEST-ENERGY NEUTRINO CANDIDATE

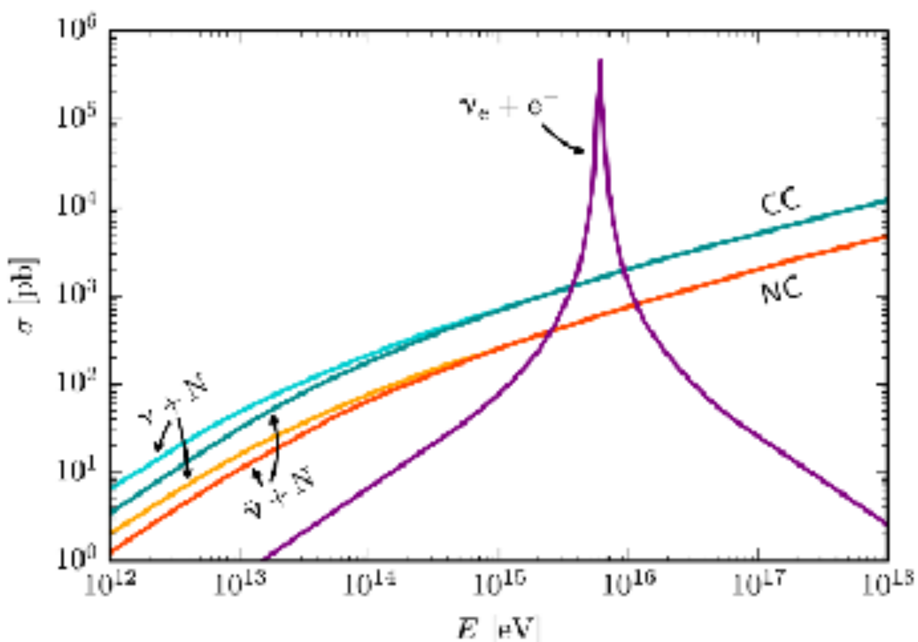




Glashow resonance: anti-ν_e + atomic electron → real W





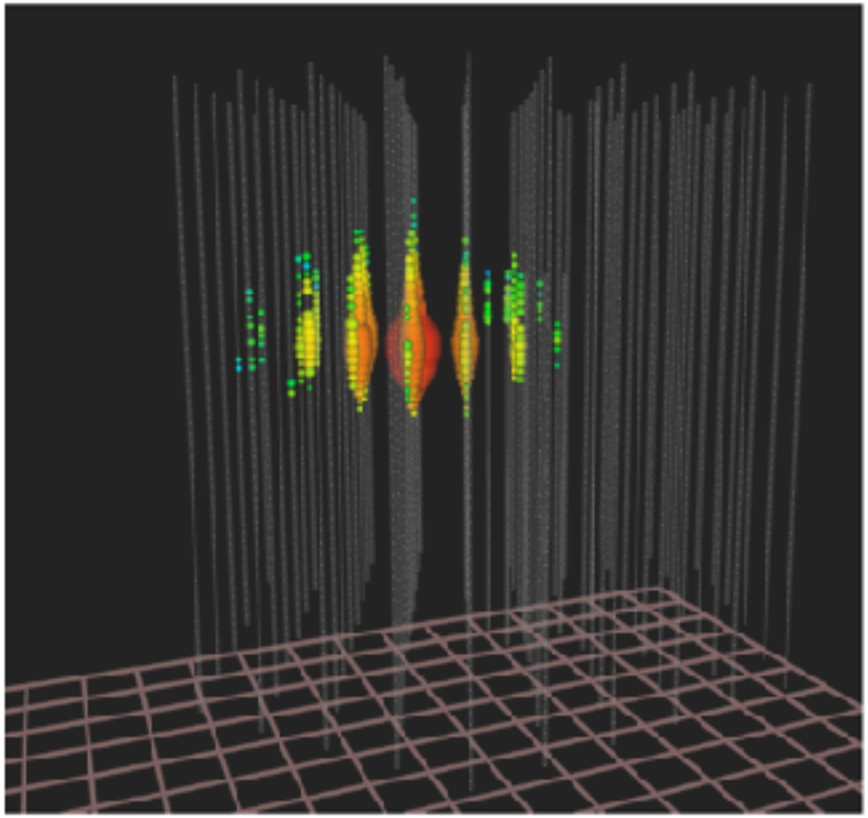


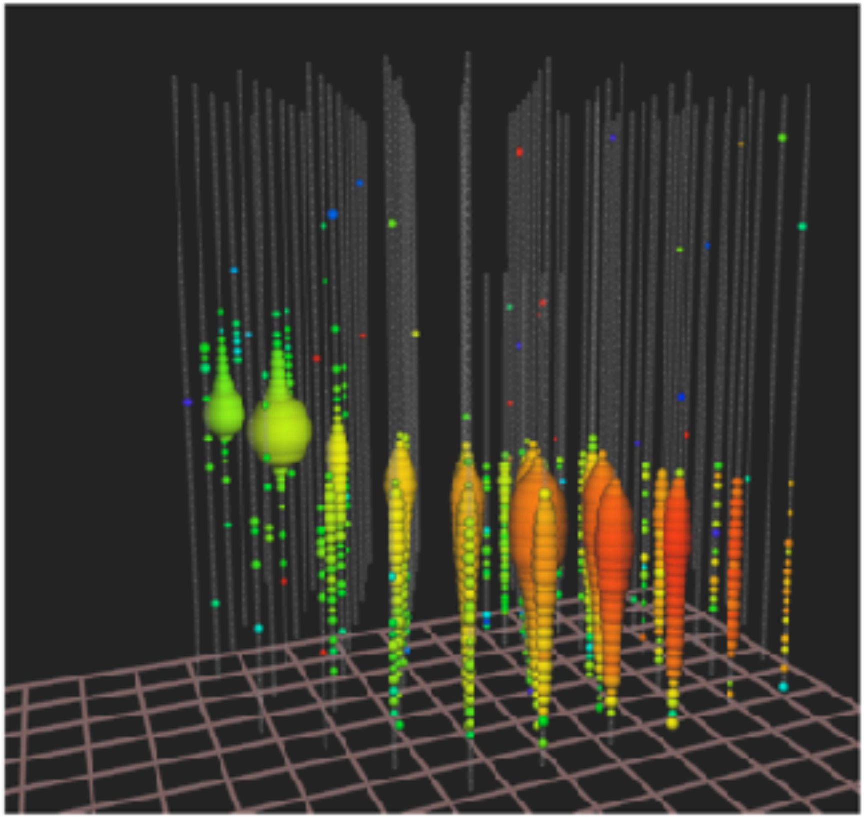
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

are the two observations consistent

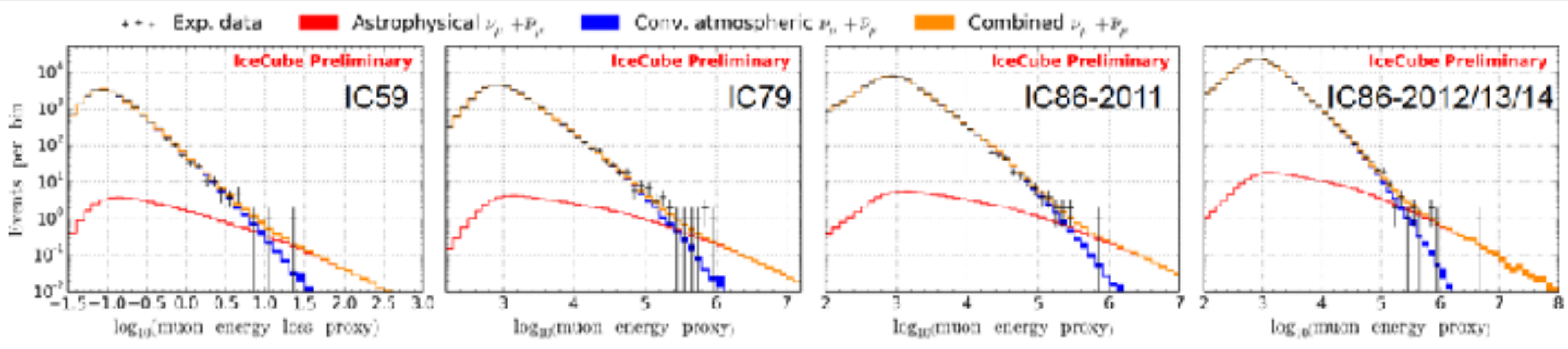




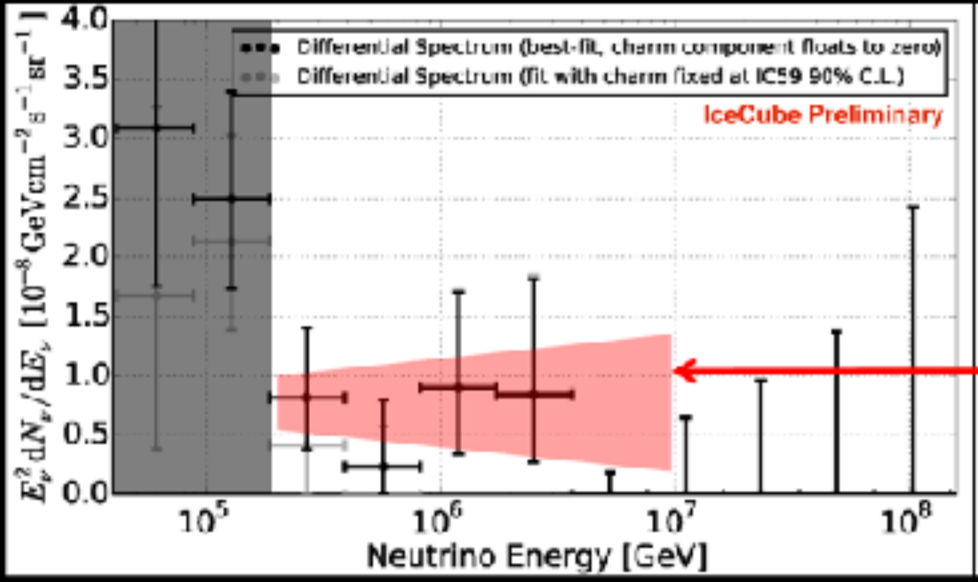
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)

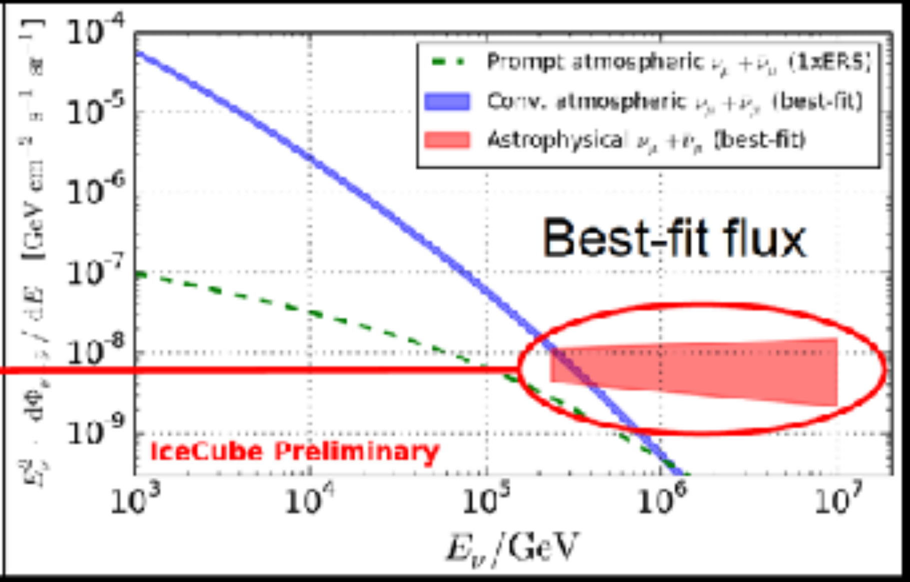
after 6 years: 3.7→ 6.0 sigma



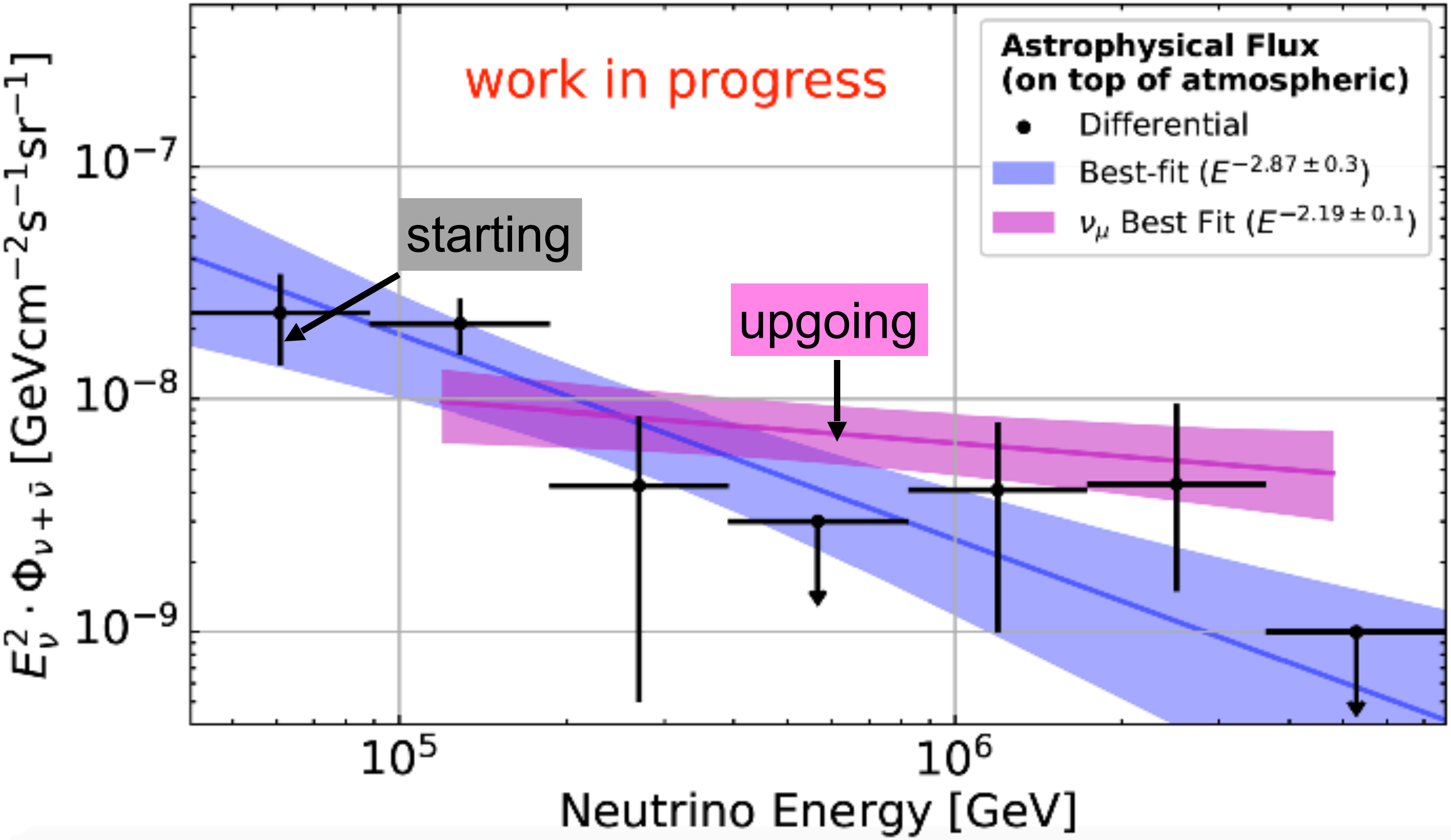
HESE 4 year unfolding
(→ dominated by shower-like events)



6 year up-going numu analysis

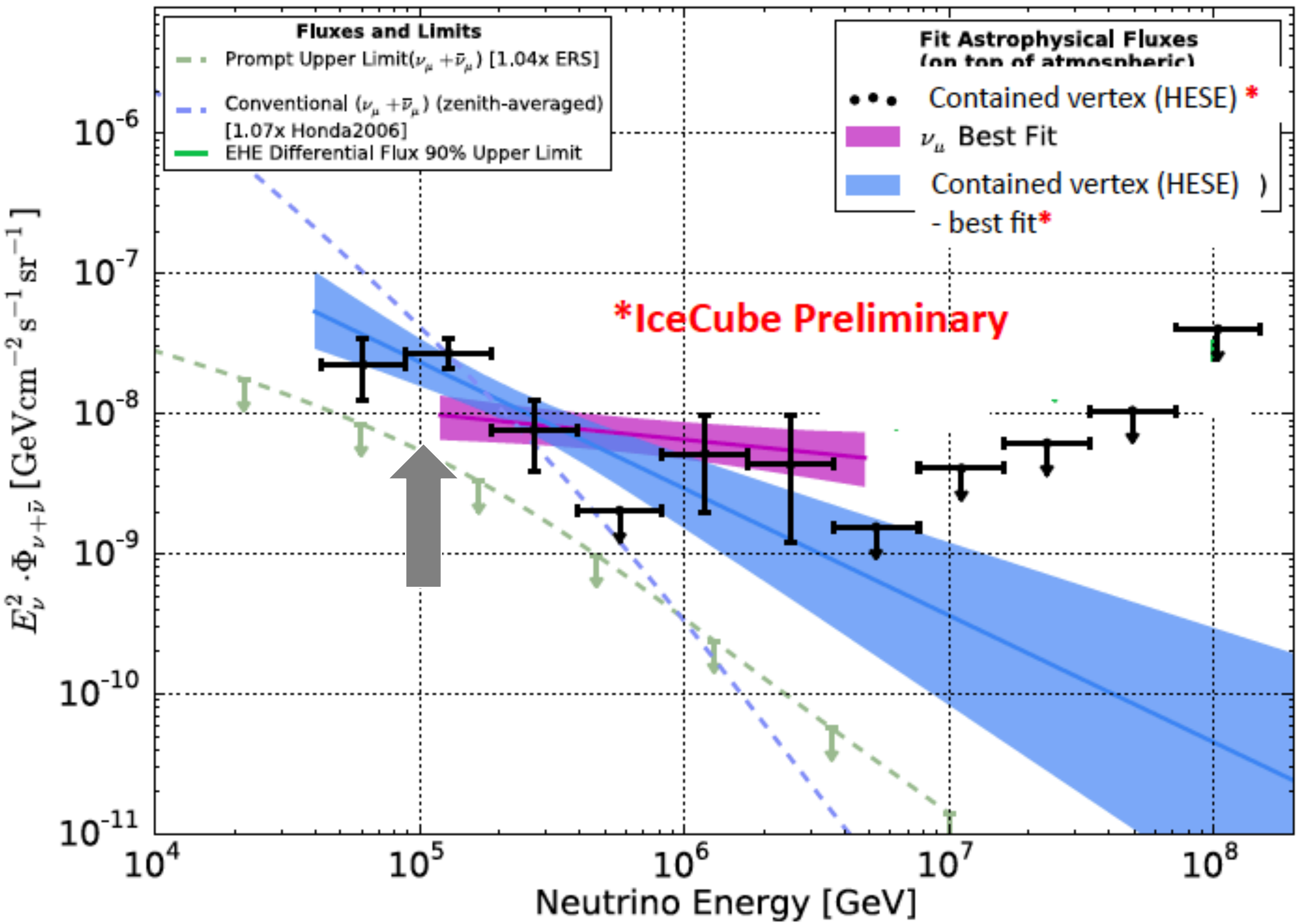


high-energy starting events – 7.5 yr

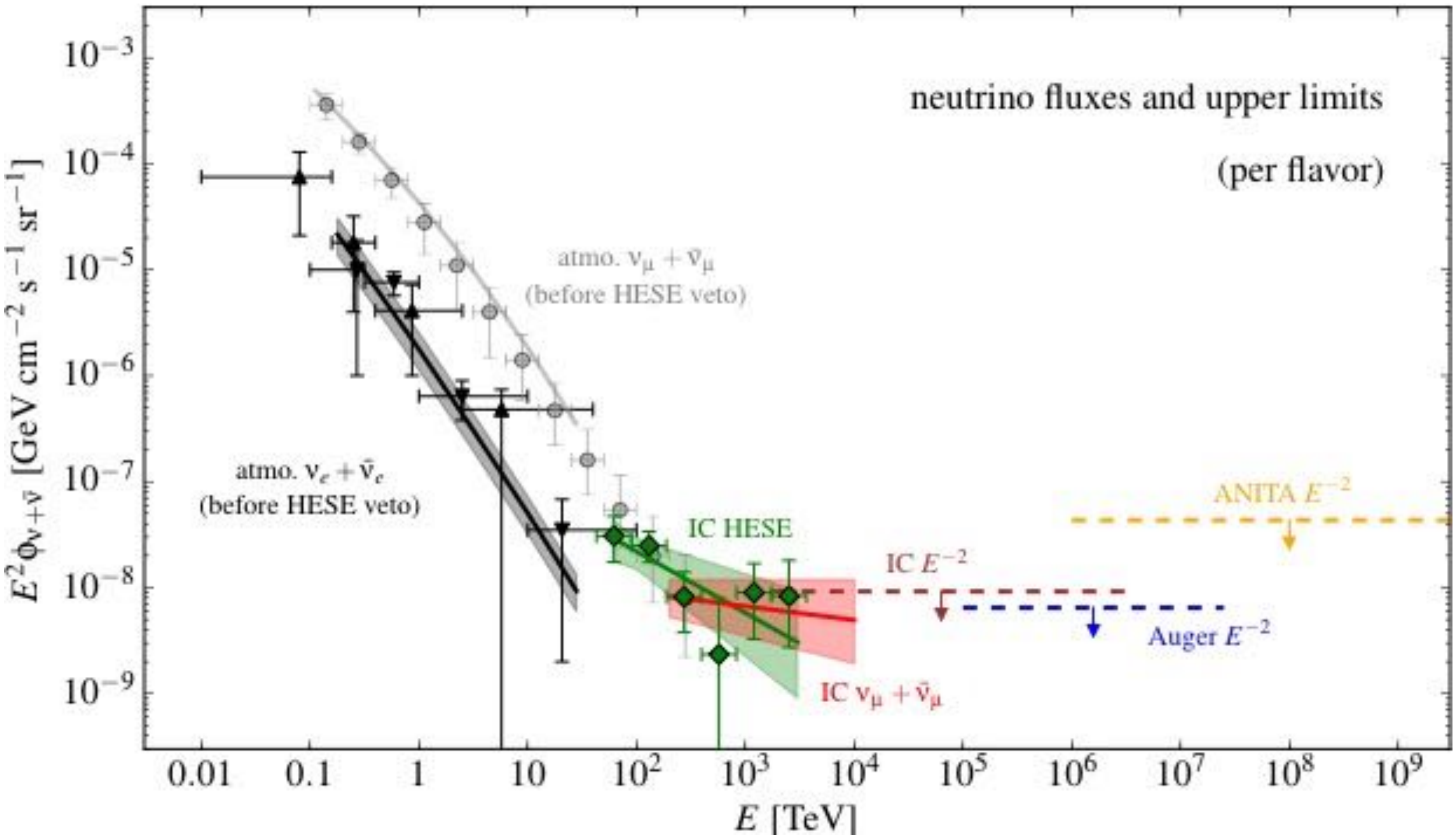


- two methods are consistent
- excess cosmic flux < 100 TeV?

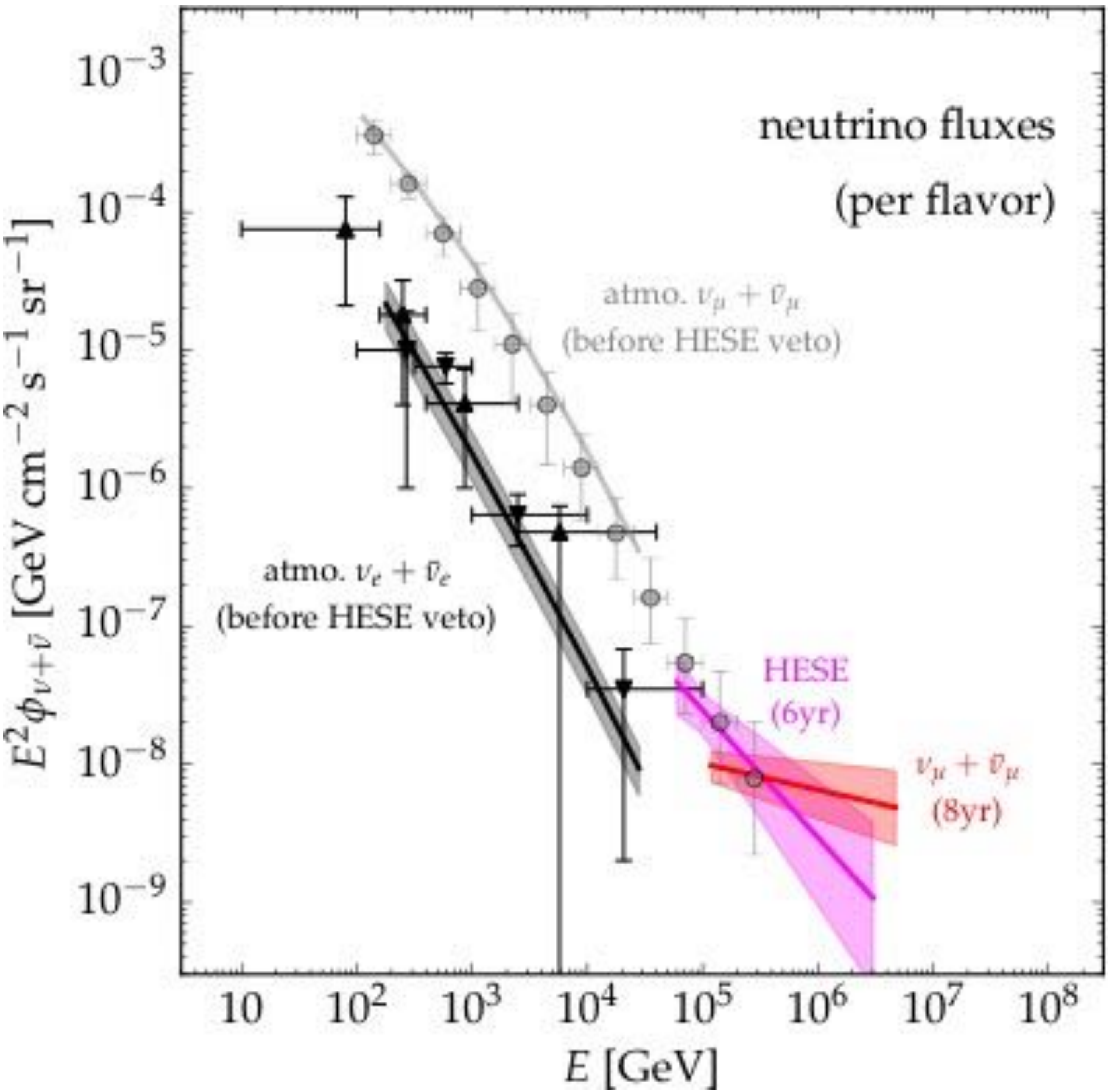
- cosmic neutrinos below 100 TeV ?


Fluxes and Limits
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
EHE Differential Flux 90% Upper Limit
Fit Astrophysical Fluxes
Contained vertex (HESE) *
ν_μ Best Fit
Contained vertex (HESE) - best fit*
*IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^4
10^5
10^6
10^7
10^8

not background: prompt decay of charm particles produced in the atmosphere

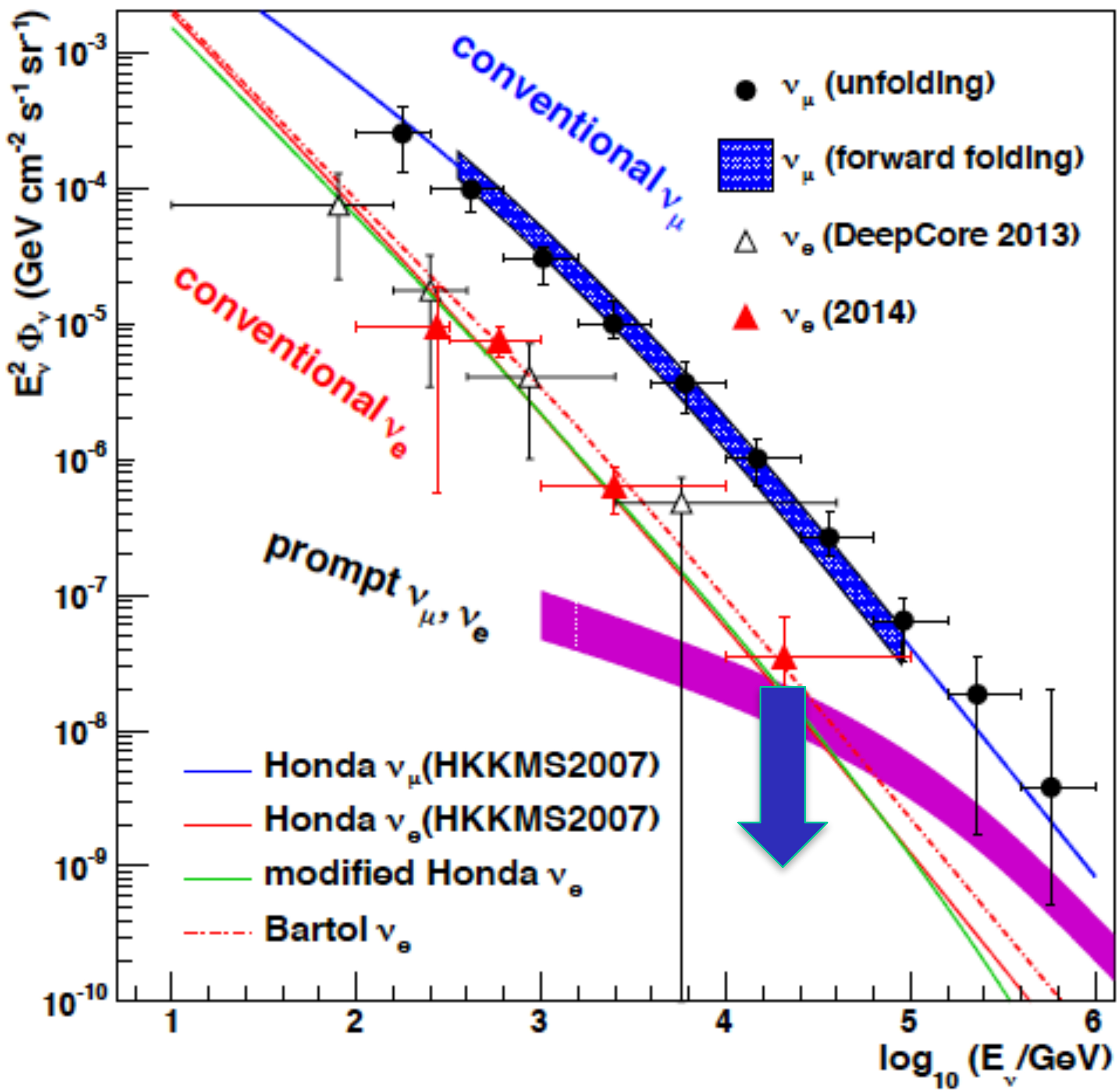


- tracks cosmic ray flux in energy, isotropic in zenith, normalization unknown: does not fit the data
- neutrino events are isolated
- incompatible with observes atmospheric *electron* neutrino spectrum

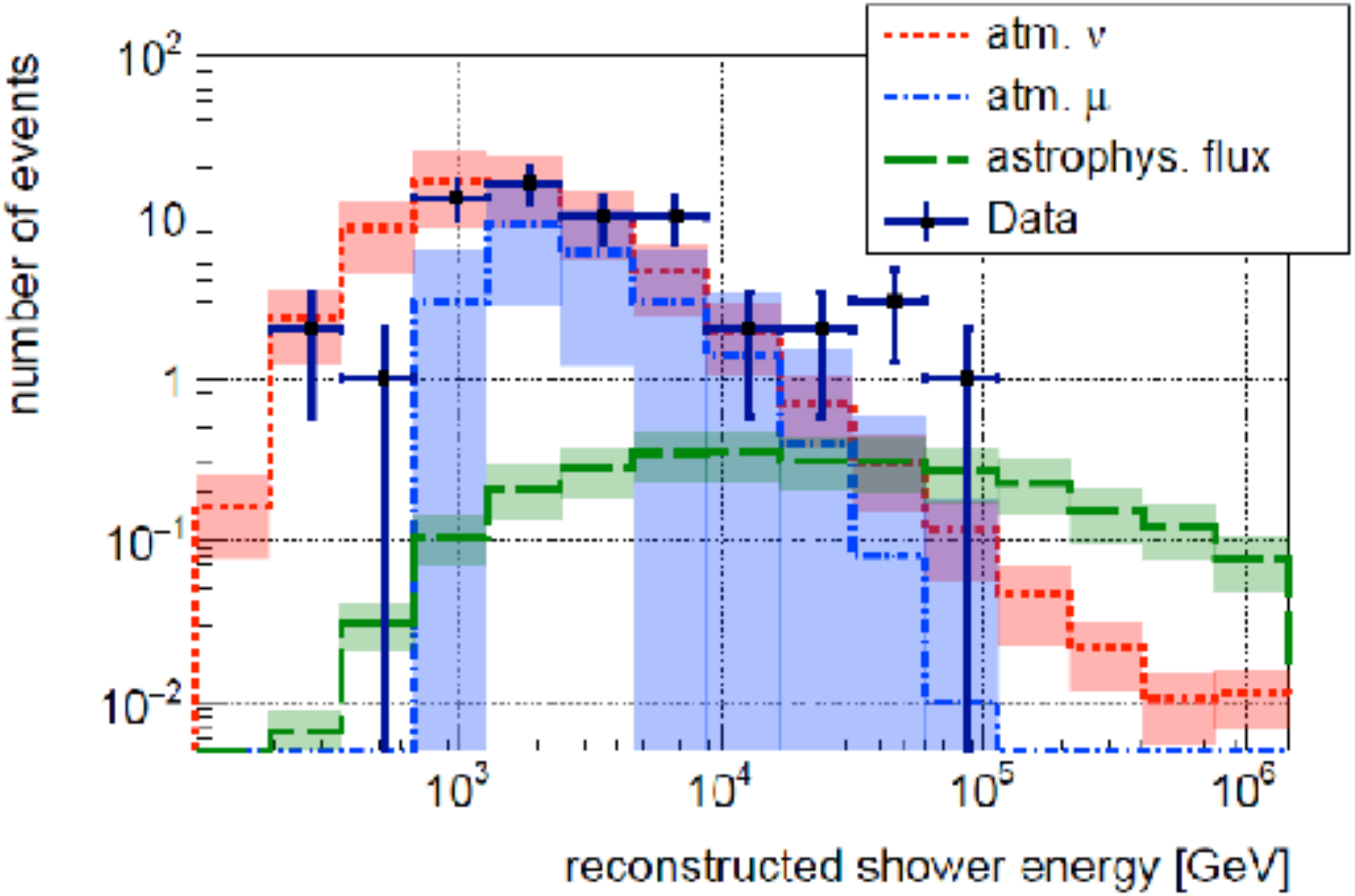


neutrino fluxes
(per flavor)
atmo. $\nu_\mu + \bar{\nu}_\mu$
(before HESE veto)
atmo. $\nu_e + \bar{\nu}_e$
(before HESE veto)
HESE
(6yr)
$\nu_\mu + \bar{\nu}_\mu$
(8yr)
$E^2 \phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8

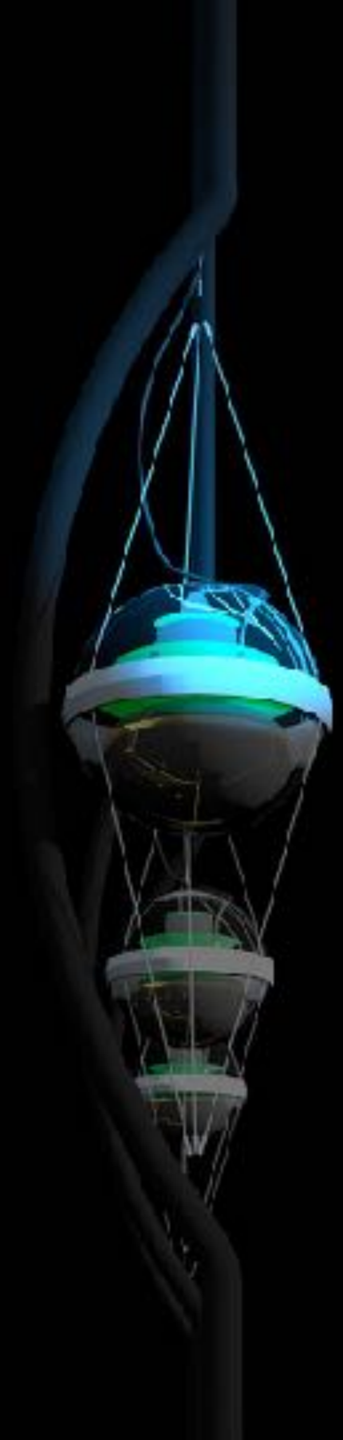
charm limited by atmospheric electrons



ANTARES



atm. ν
atm. μ
astrophys. flux
Data
number of events
10^2
10
1
10^{-1}
10^{-2}
10^3
10^4
10^5
10^6
reconstructed shower energy [GeV]

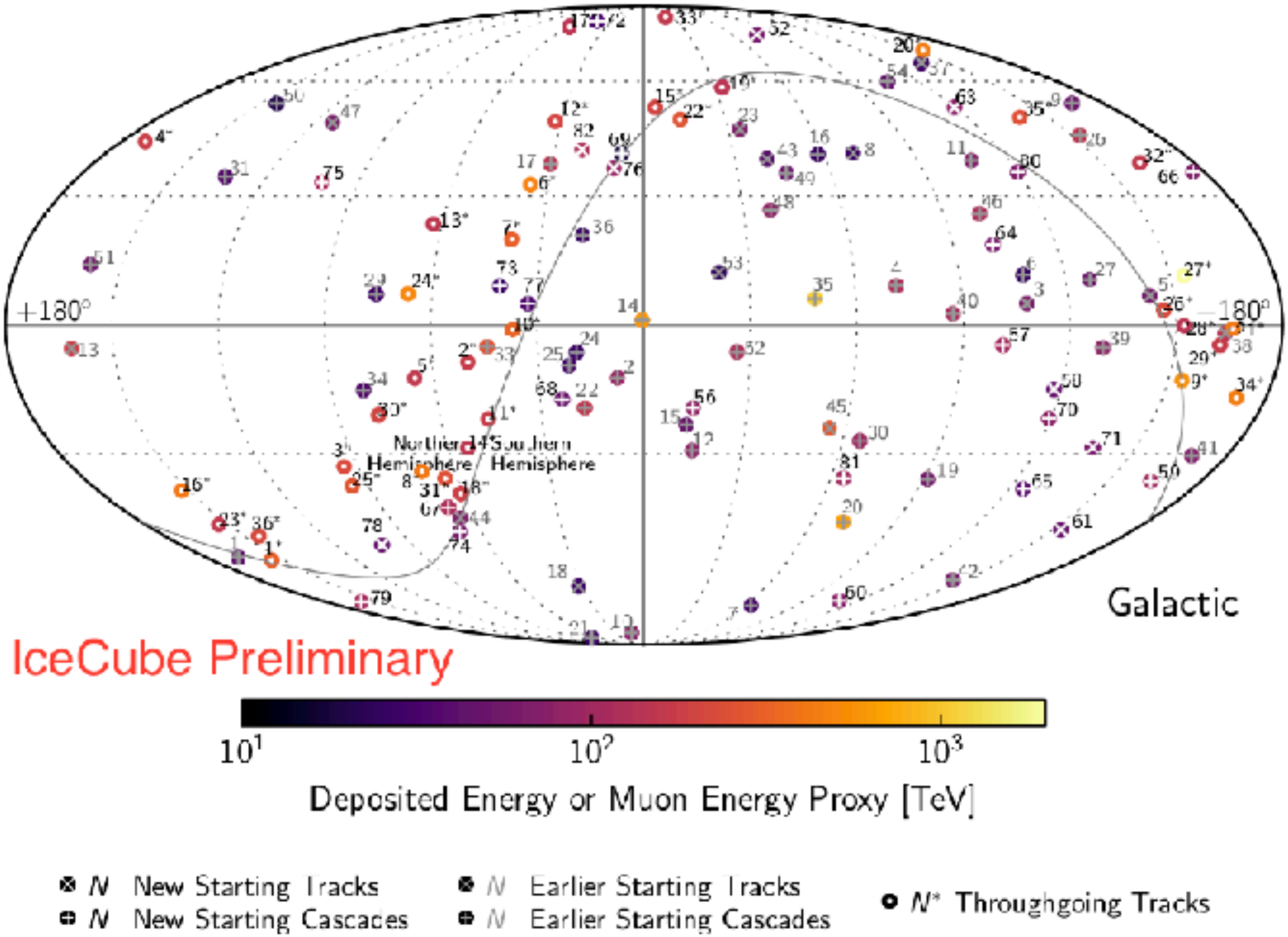


IceCube

francis halzen

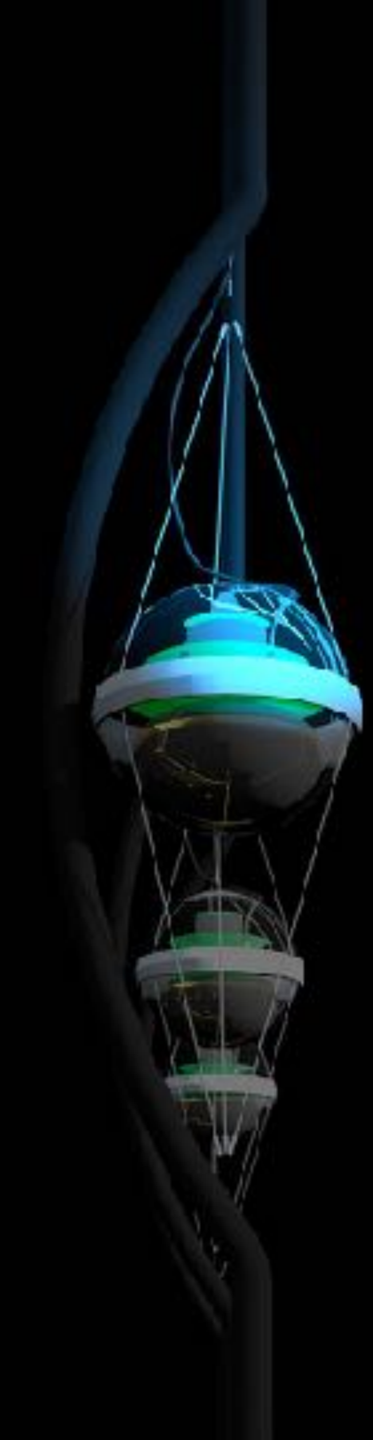
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

iceCube.wisc.edu



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

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- [decay of halo dark matter particles?]



IceCube

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
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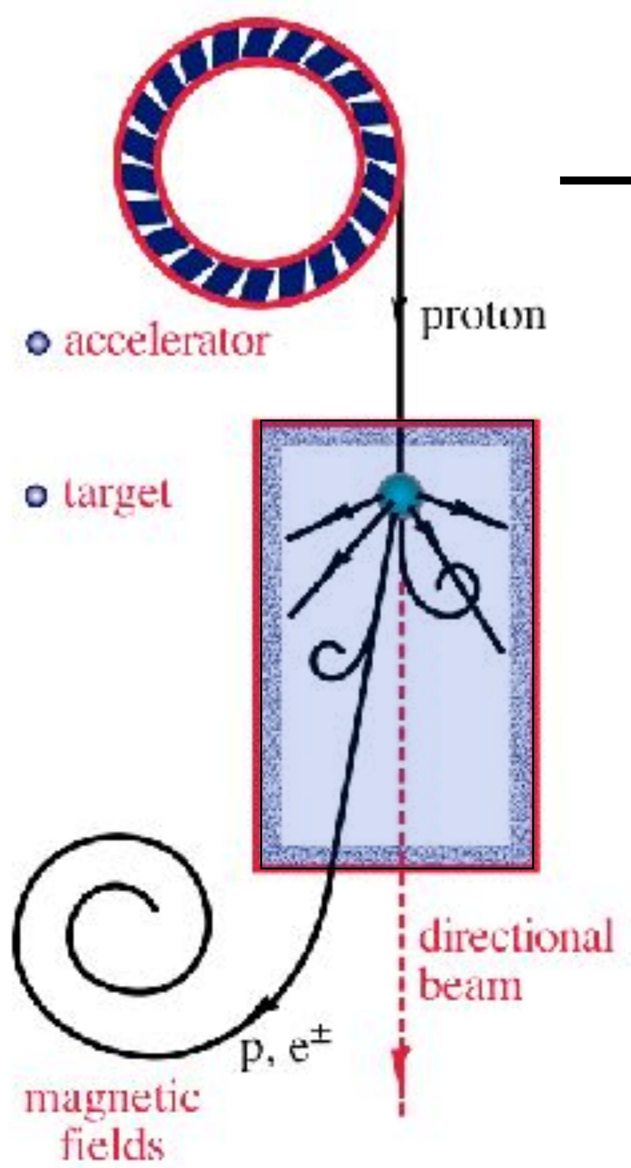
- cosmic neutrinos below 100 TeV?

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

neutral pions

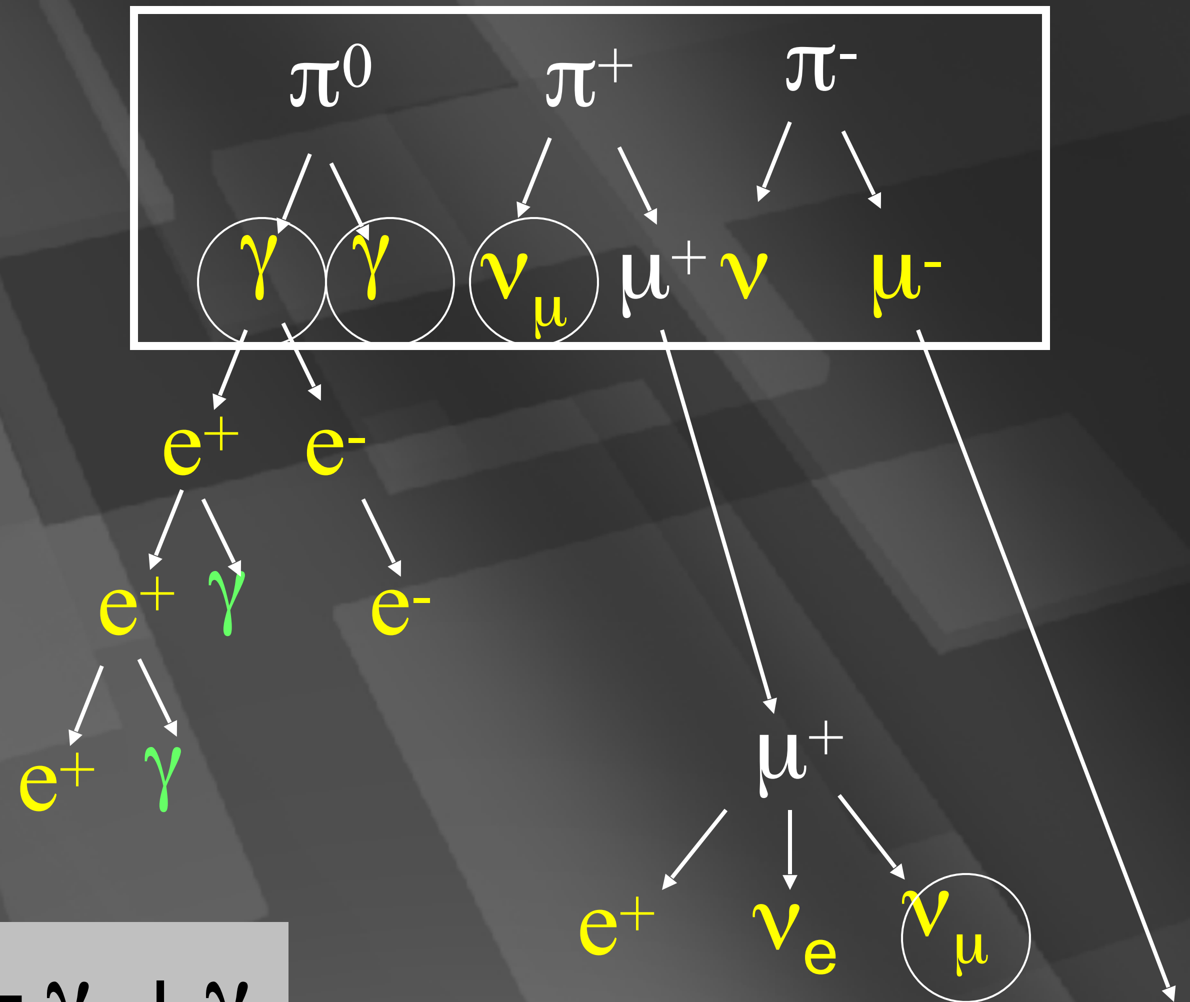
are observed as

gamma rays

charged pions

are observed as

neutrinos

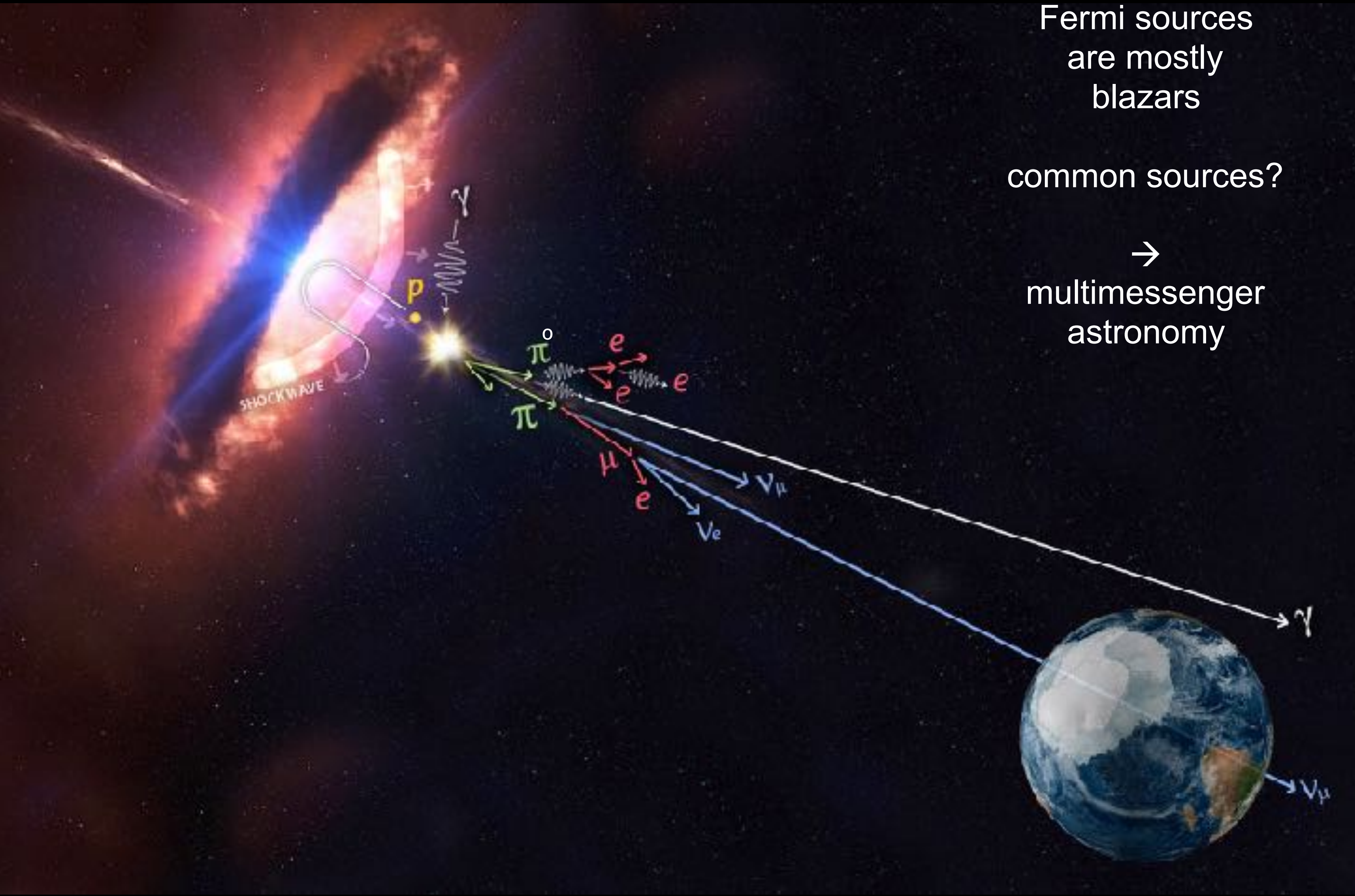


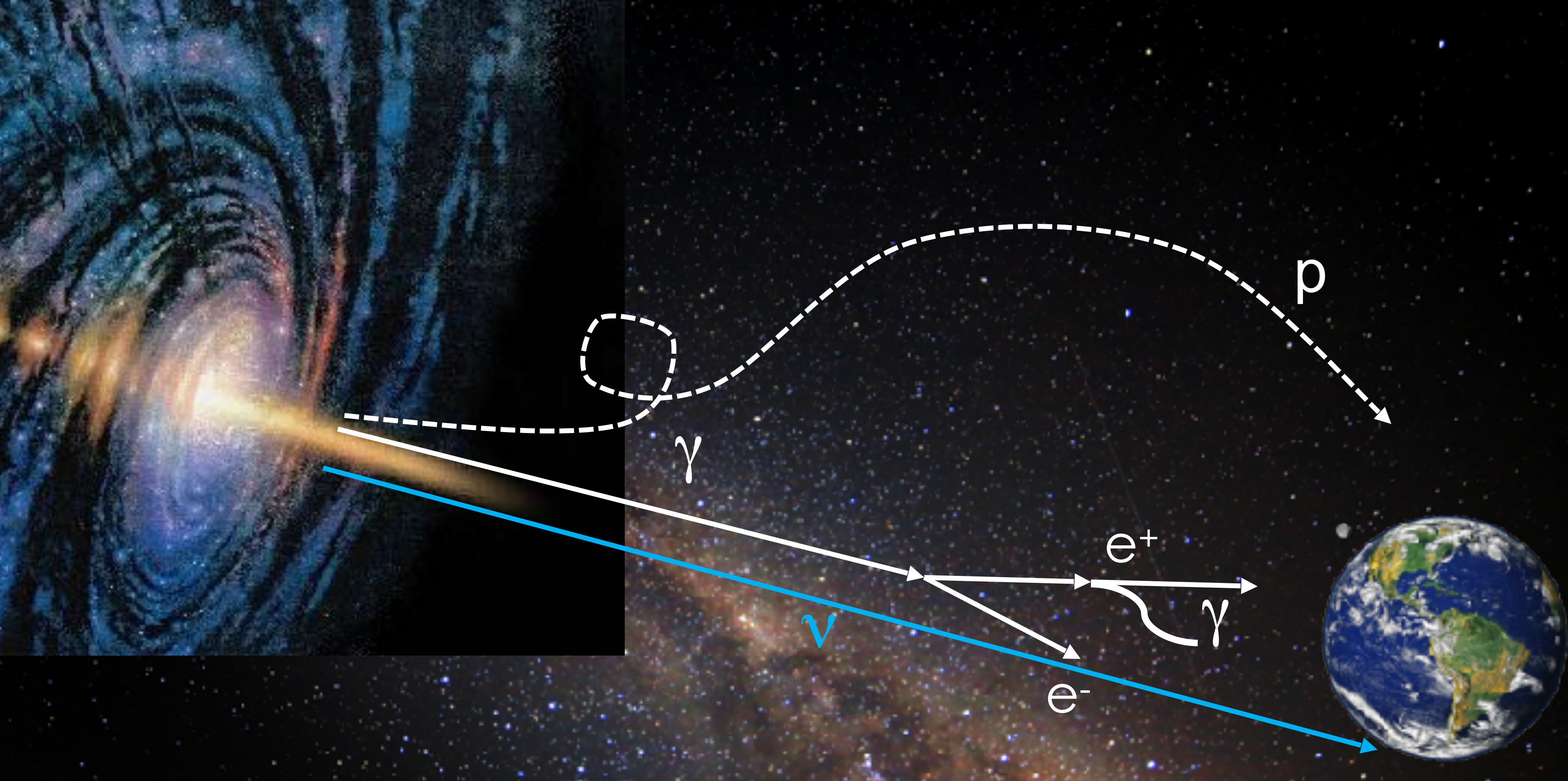
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

Fermi sources
are mostly
blazars

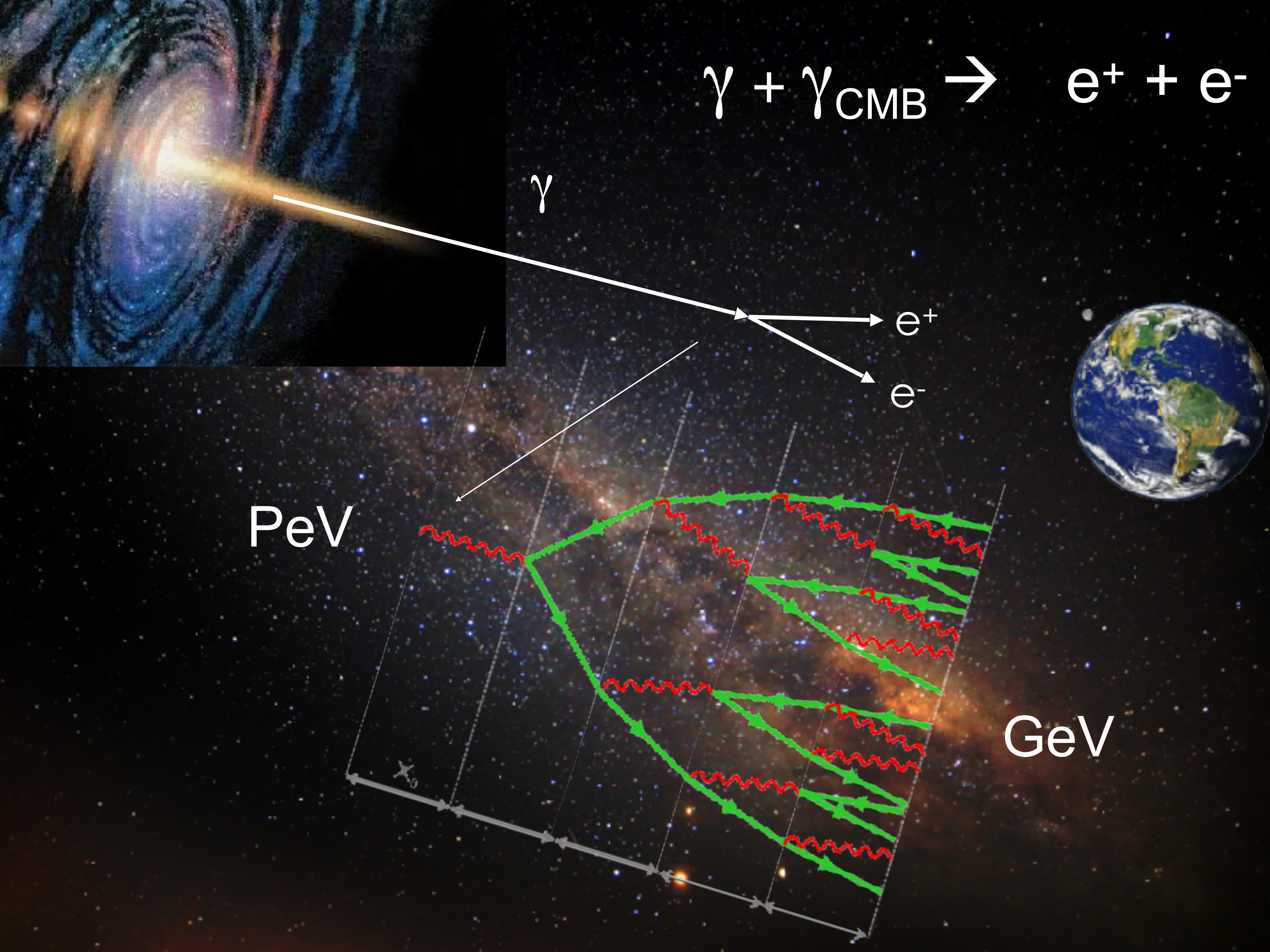
common sources?

→
multimessenger
astronomy

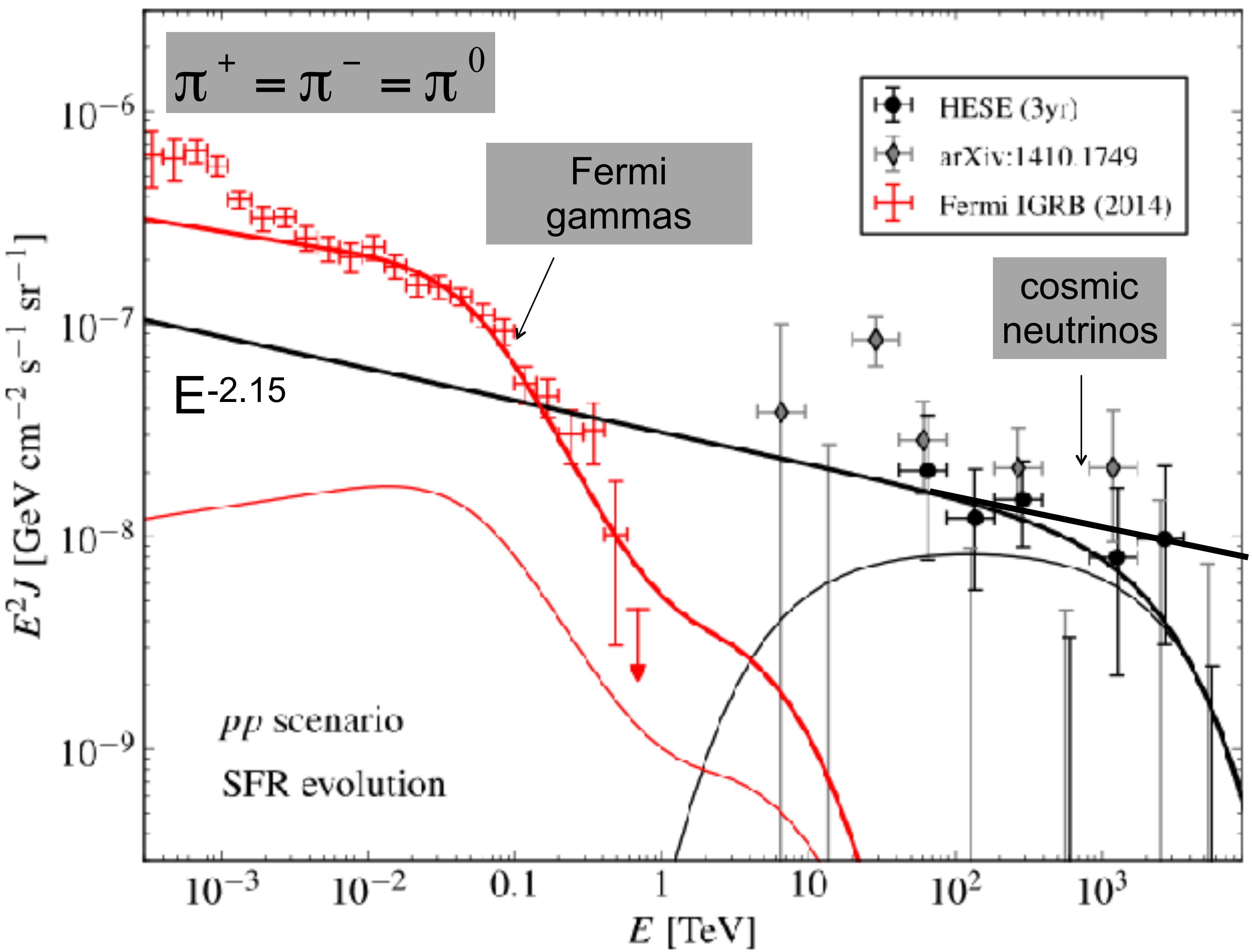




gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

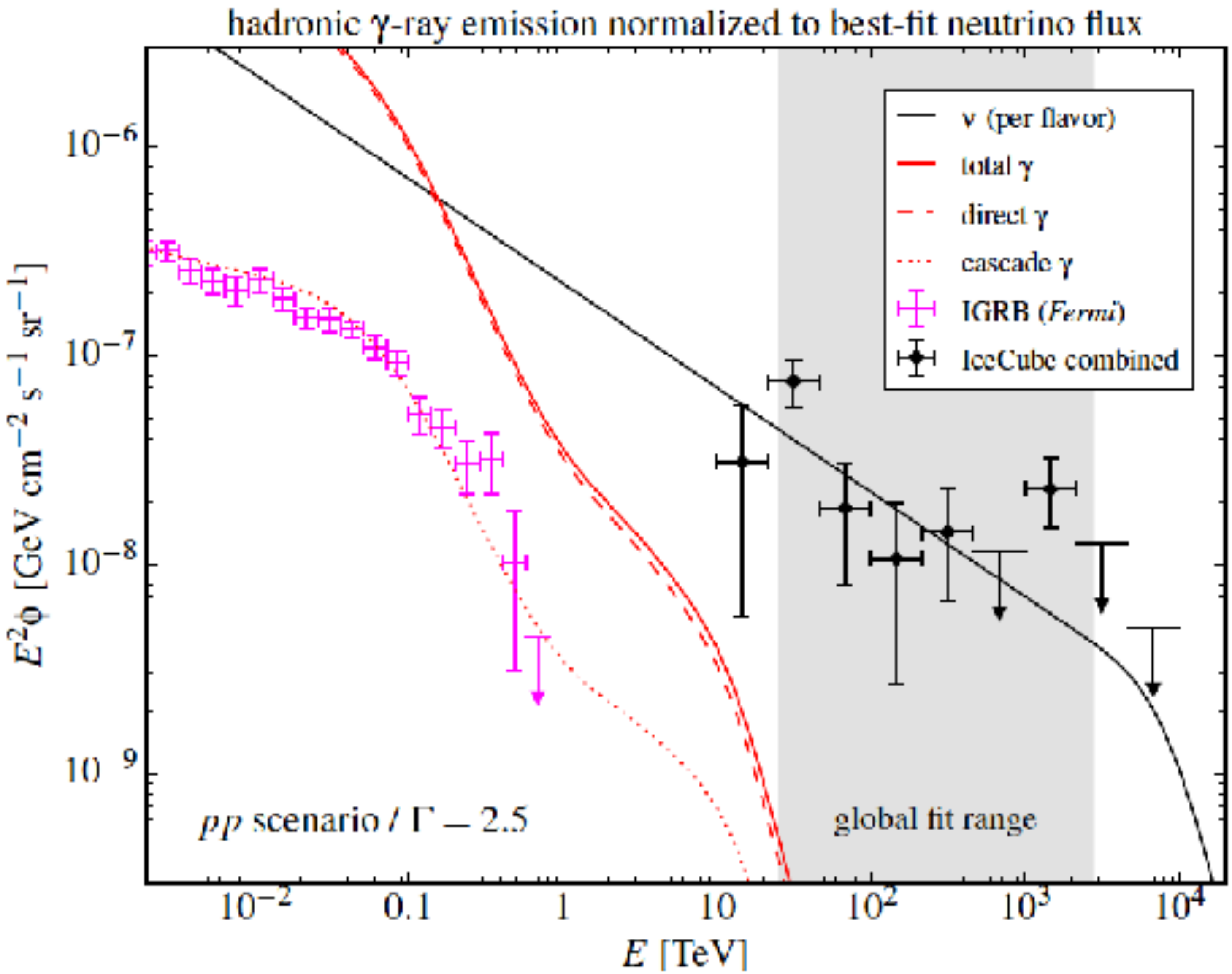


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV

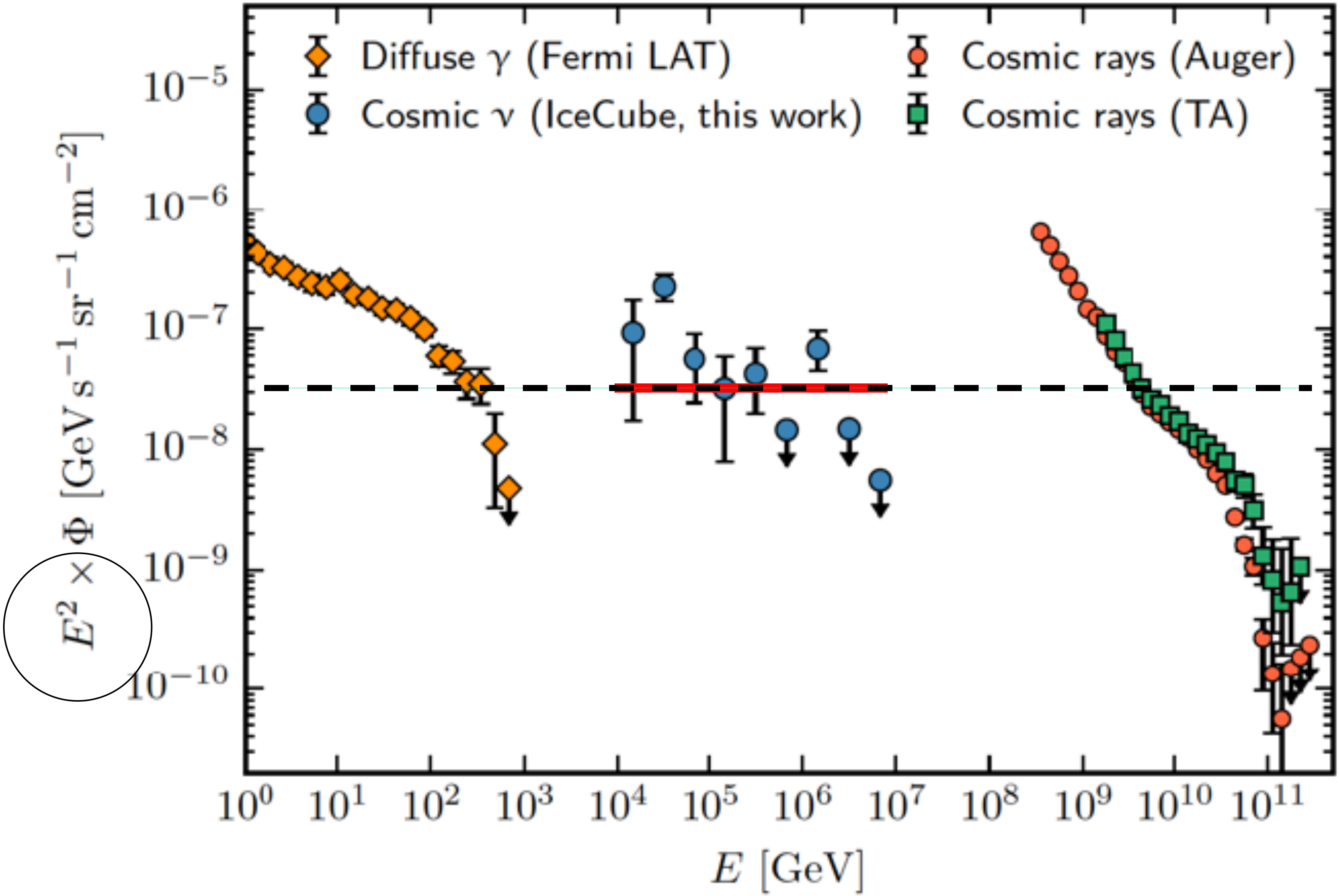


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

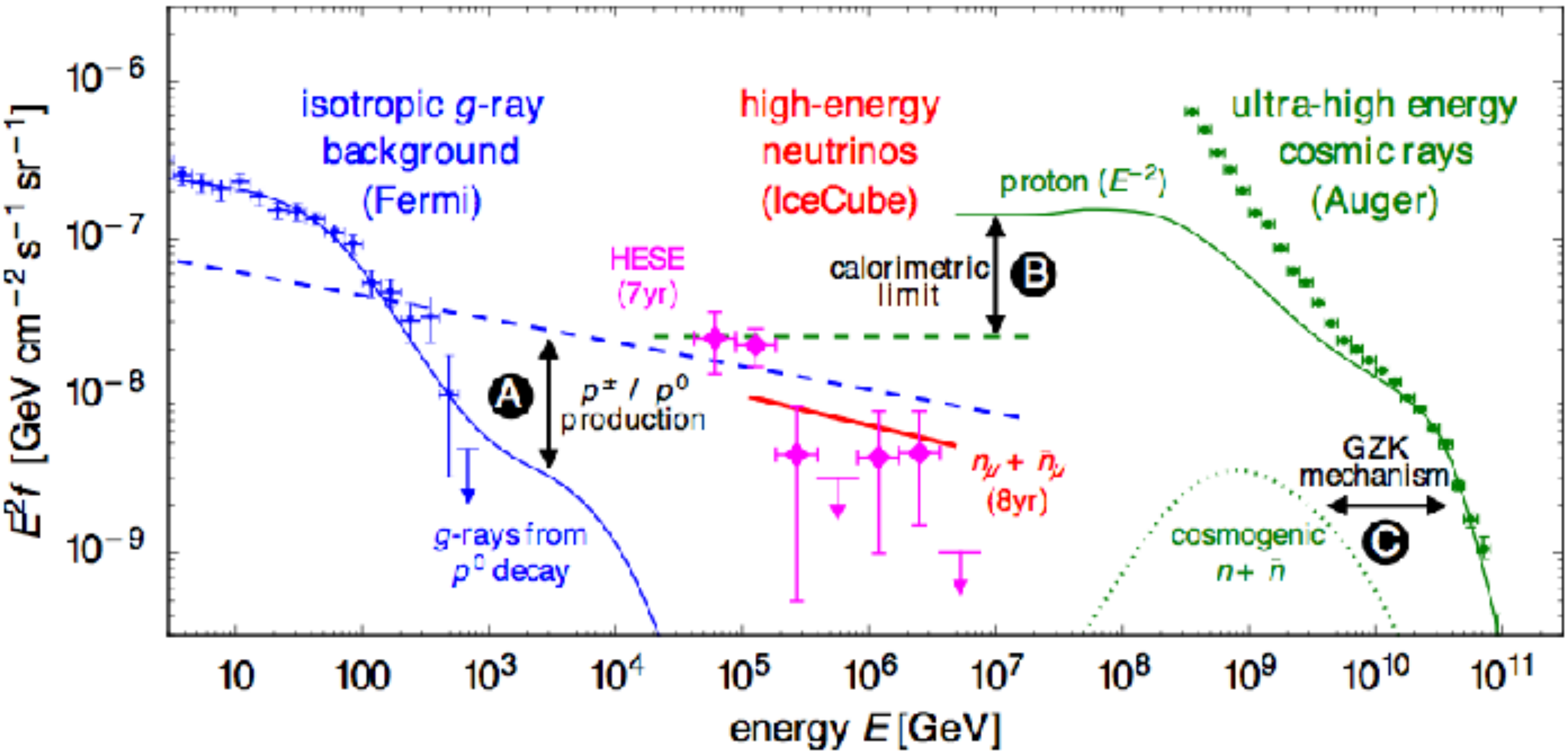
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



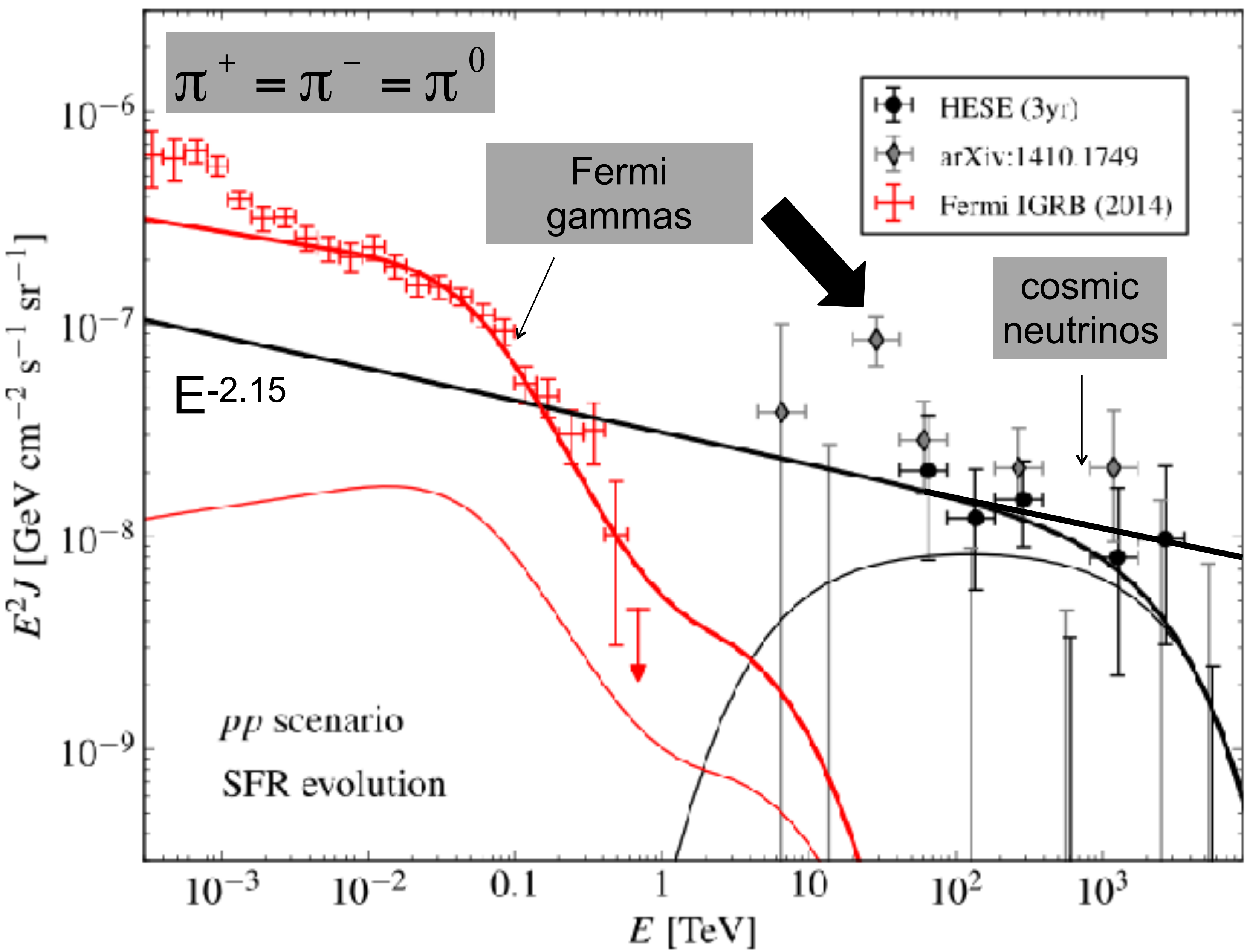
dark sources: a “problem” ?
gamma rays cascade in the source to < GeV energy



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



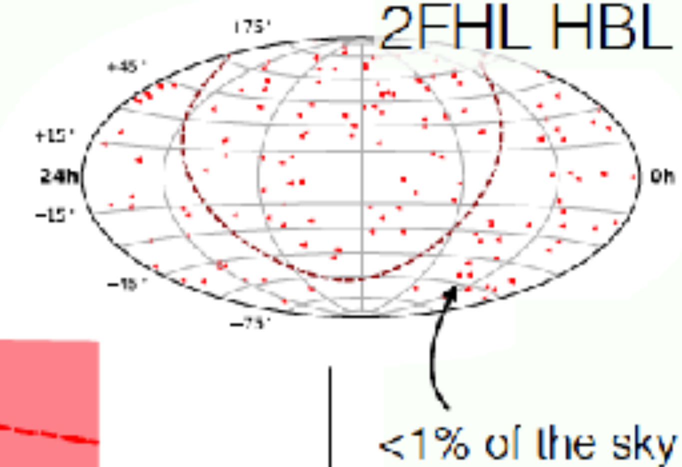
similar energy density in the Universe in extragalactic cosmic rays

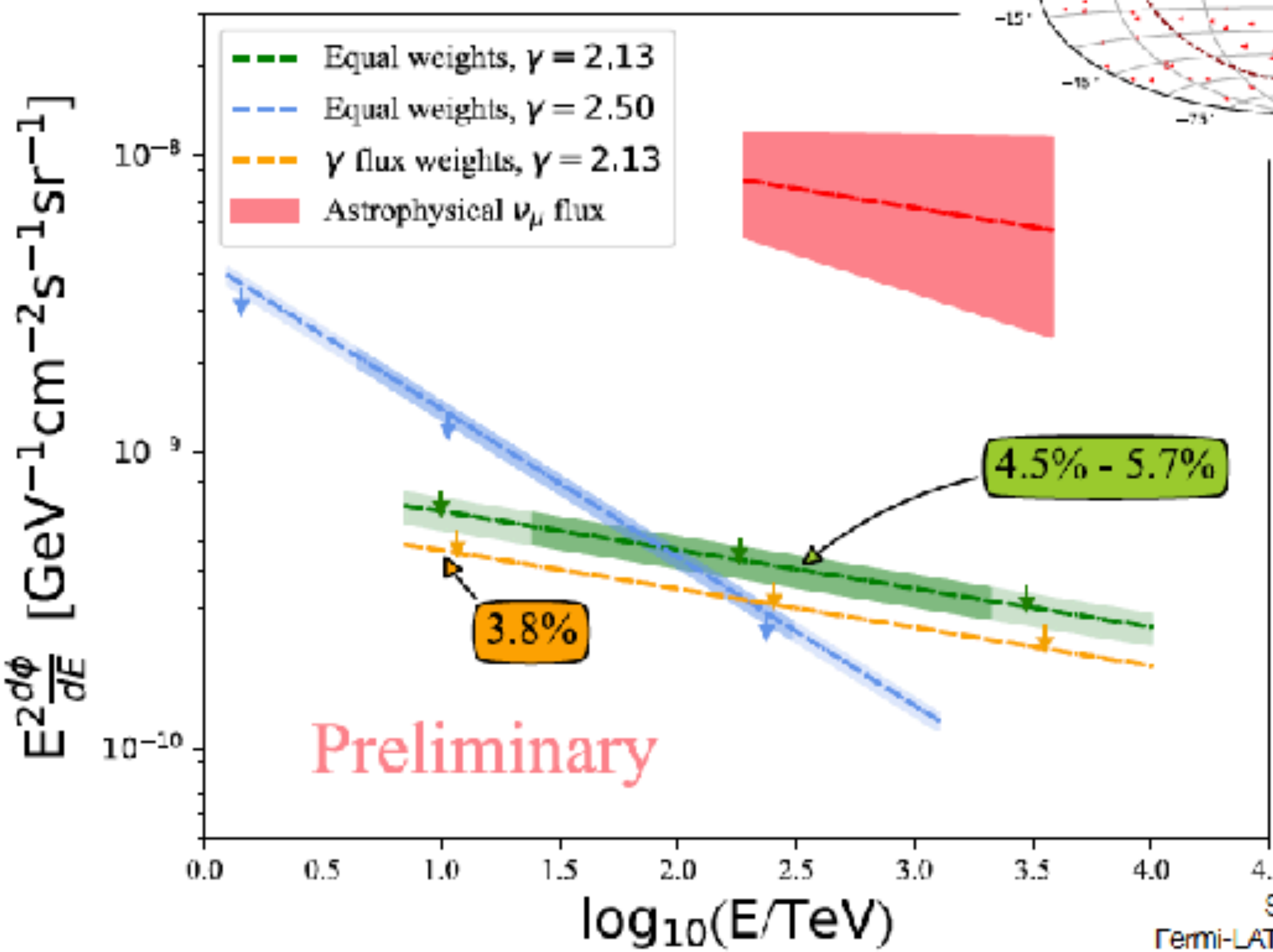


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

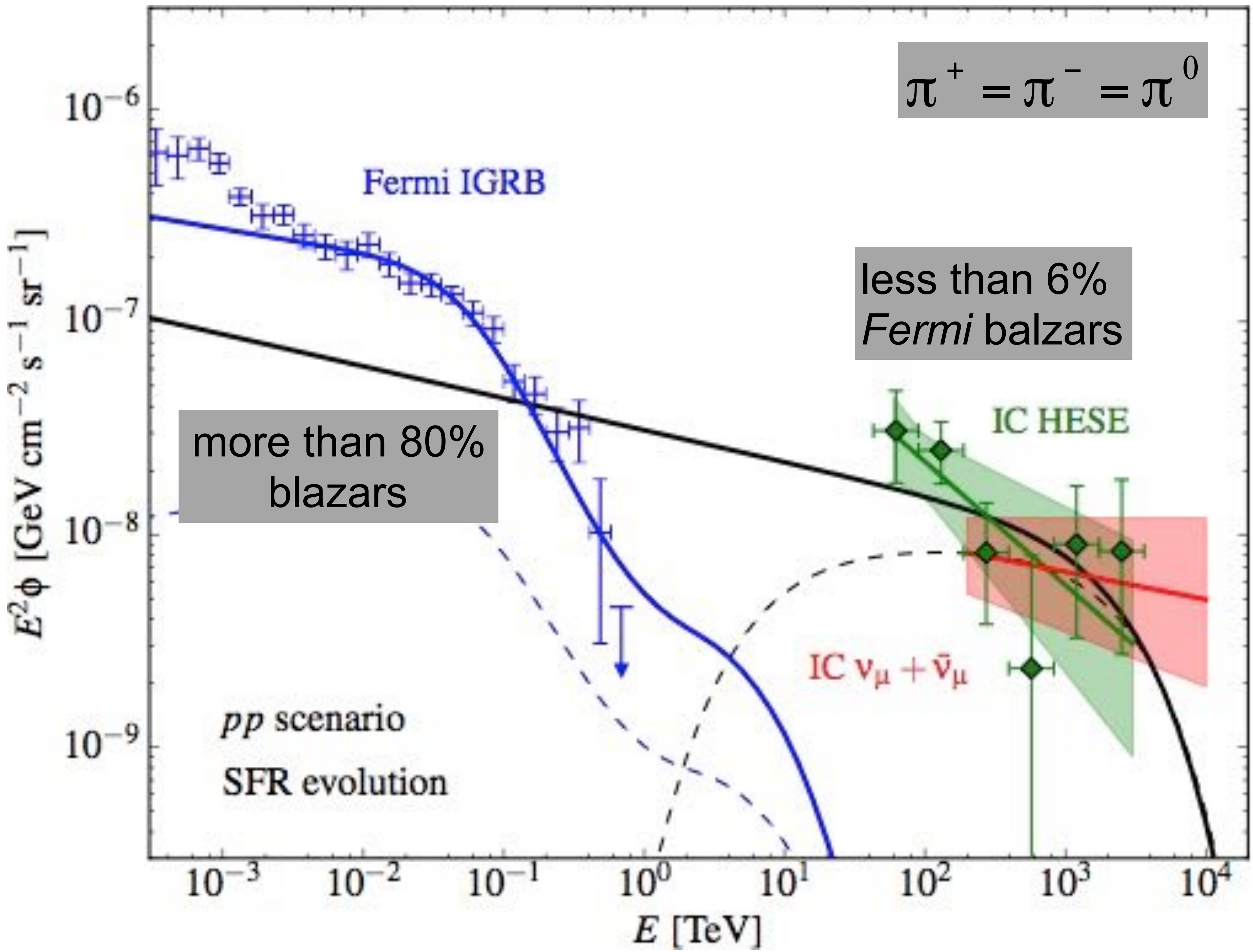
Population studies: blazar catalog search

Blazars account for:
85% of extragalactic γ background
< 6-27% of the IceCube neutrino flux



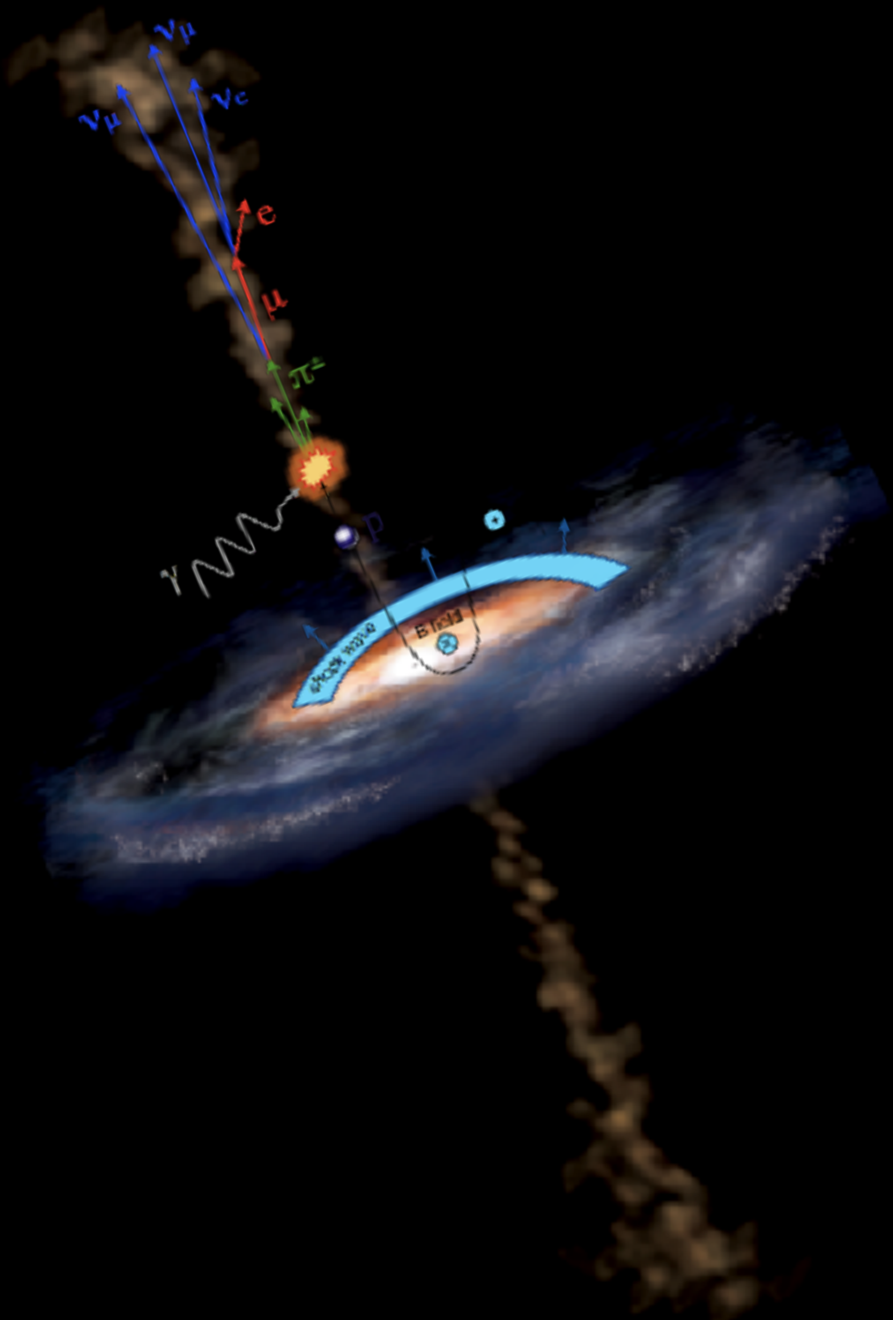


See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45



$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
less than 6%
Fermi balzars
more than 80%
blazars
IC HESE
IC $\nu_\mu + \bar{\nu}_\mu$
pp scenario
SFR evolution
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

- two component cosmic neutrino flux?
- cosmic accelerators do not follow a power-law spectrum?
- note that the gammas rays accompanying < 100 TeV neutrinos are not seen suggesting a hidden source(s)



Fermi sources
are mostly
blazars

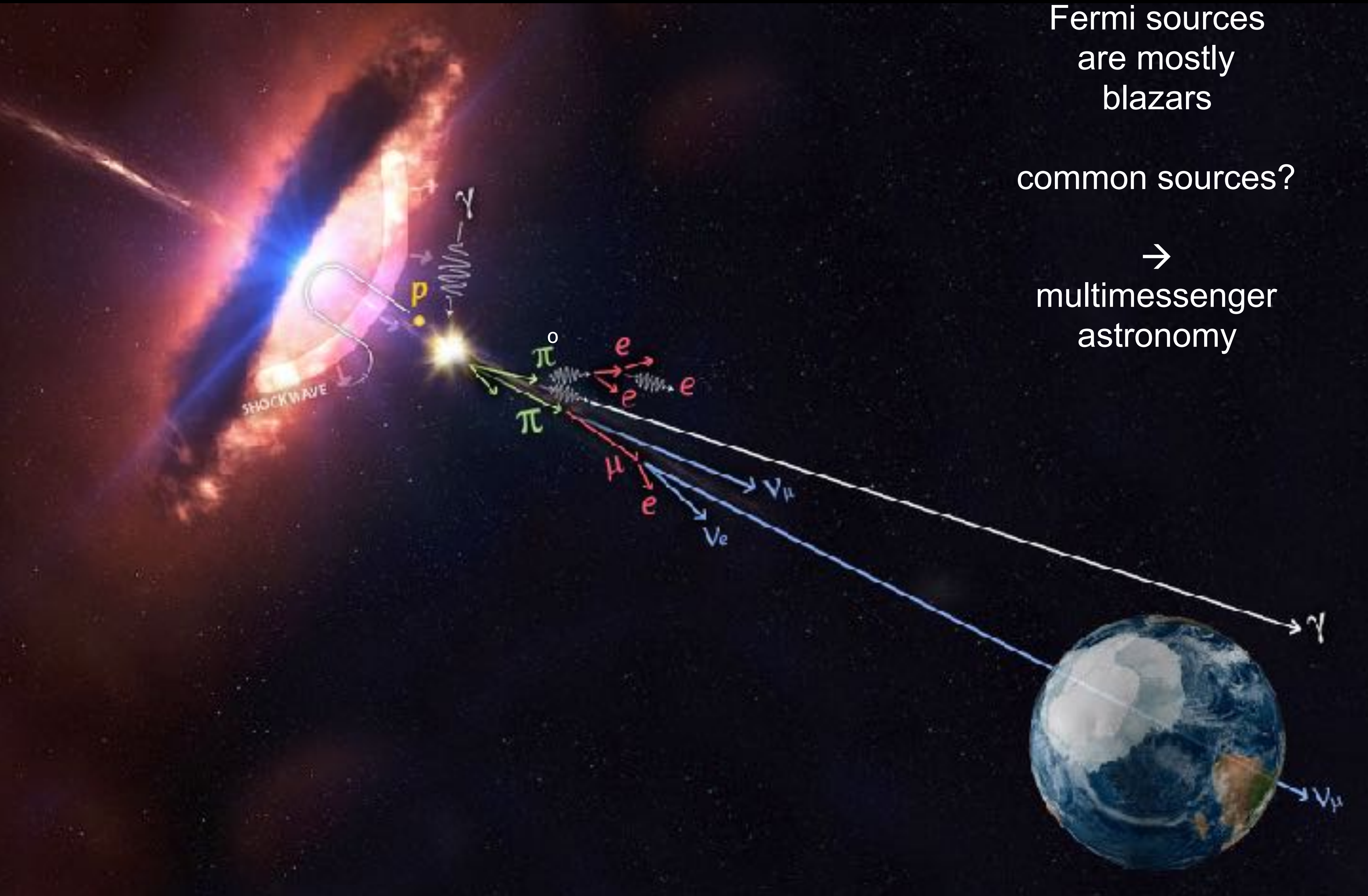
common sources?

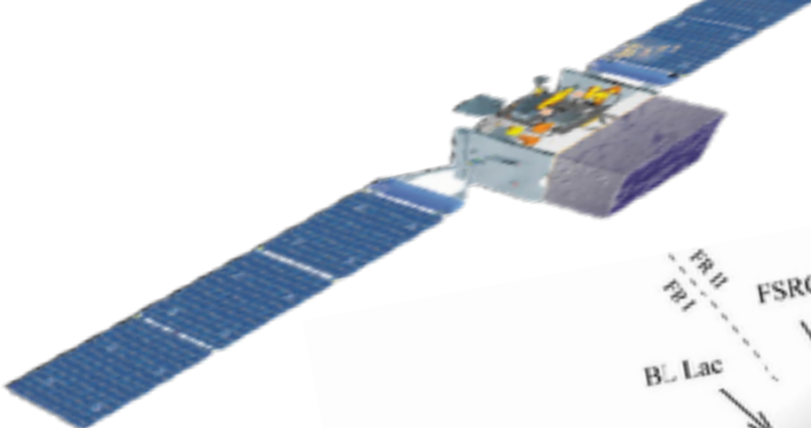
→
multimessenger
astronomy

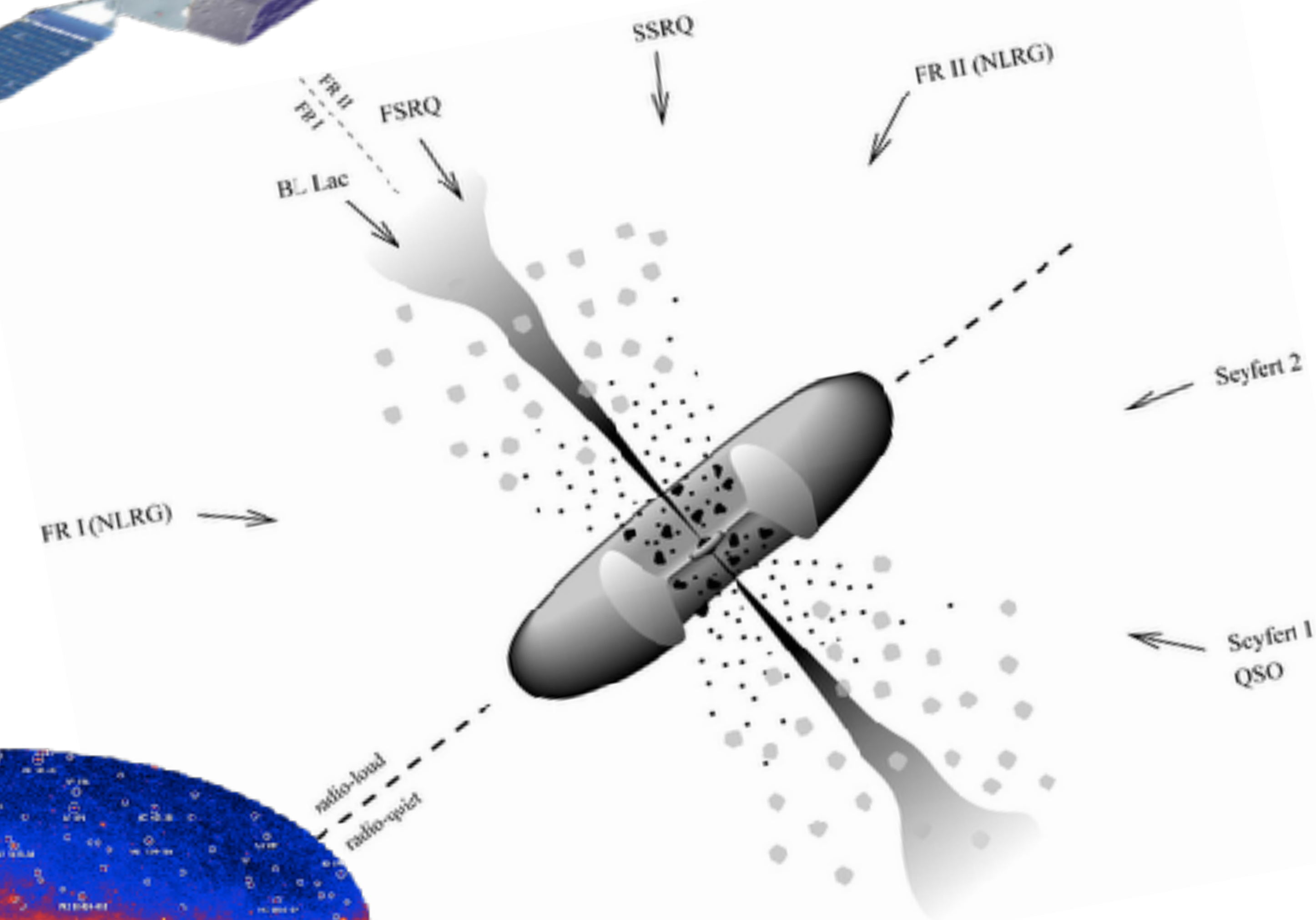
Fermi sources are mostly blazars

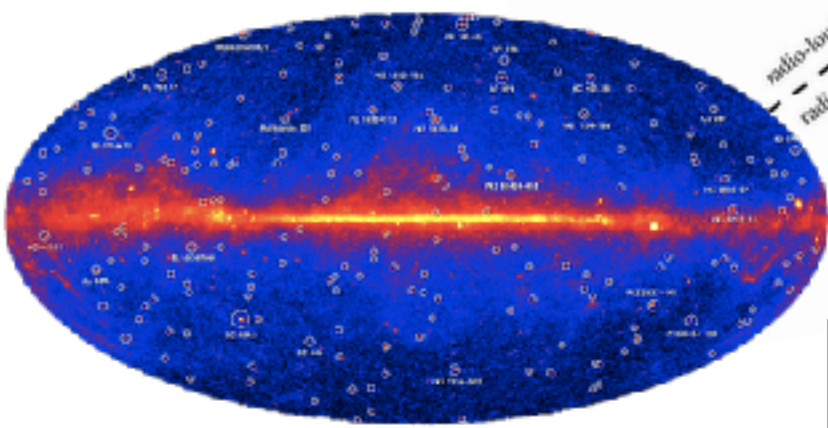
common sources?

→
multimessenger astronomy

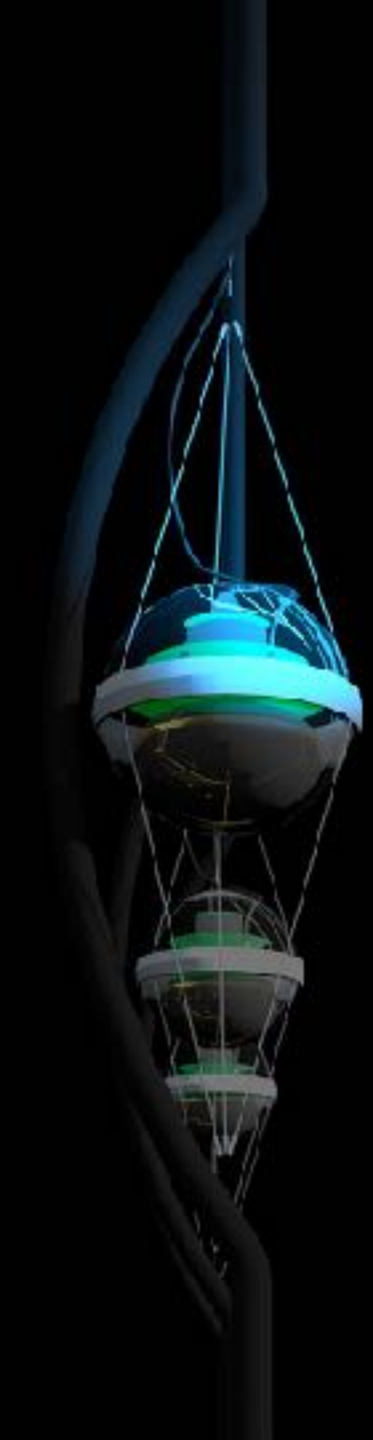








Fermi sky: mostly bazars



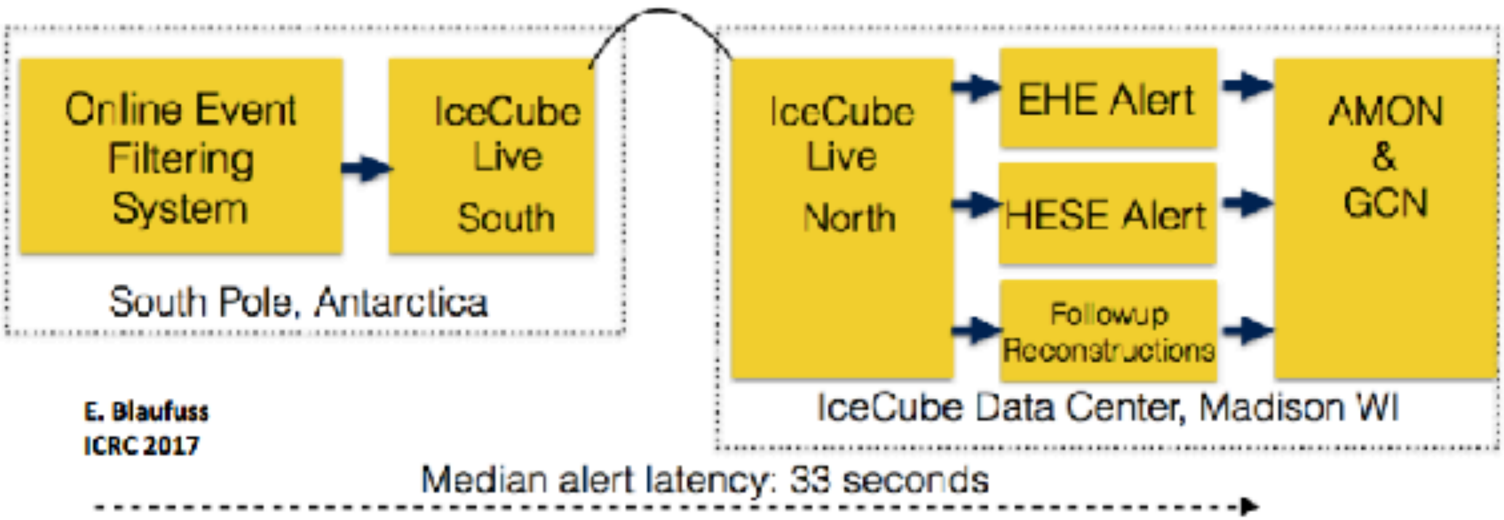
IceCube

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

Realtime alerts from IceCube

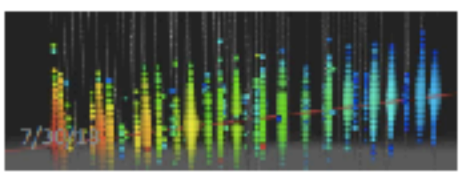


E. Blaufuss
ICRC 2017

Upcoming improvements:

- **New starting event selections**
- **Cascades**
- **Higher astrophysical purity**
- **Improved event information in alerts**

13 alerts sent since 2016
First alert sent within 1 minute
Detailed follow-ups after a few hours



	Starting Tracks	Throughgoing tracks
Energy	**> 60 TeV**	**> 500 TeV**
Alerts per year	**4.8**	**4 - 5**
Signal events per year	**1.1**	**2.5 - 4**

IceCube Coll.: Astropart. Phys., 92, 30 (2017)

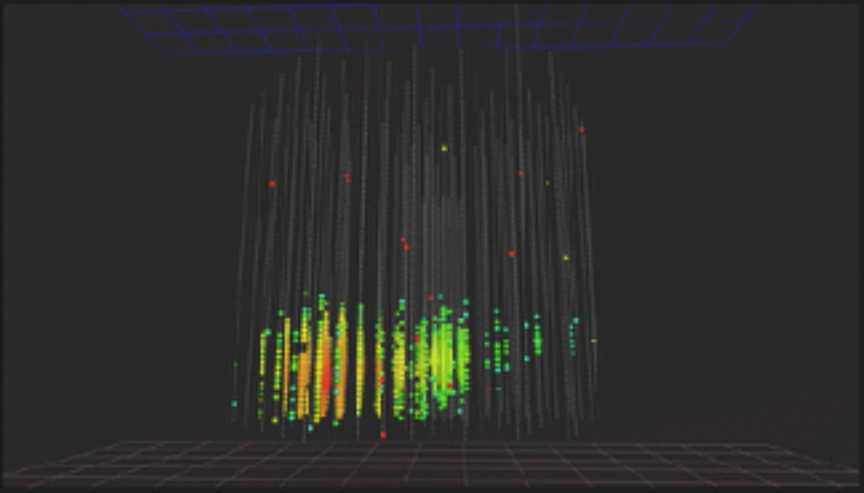
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

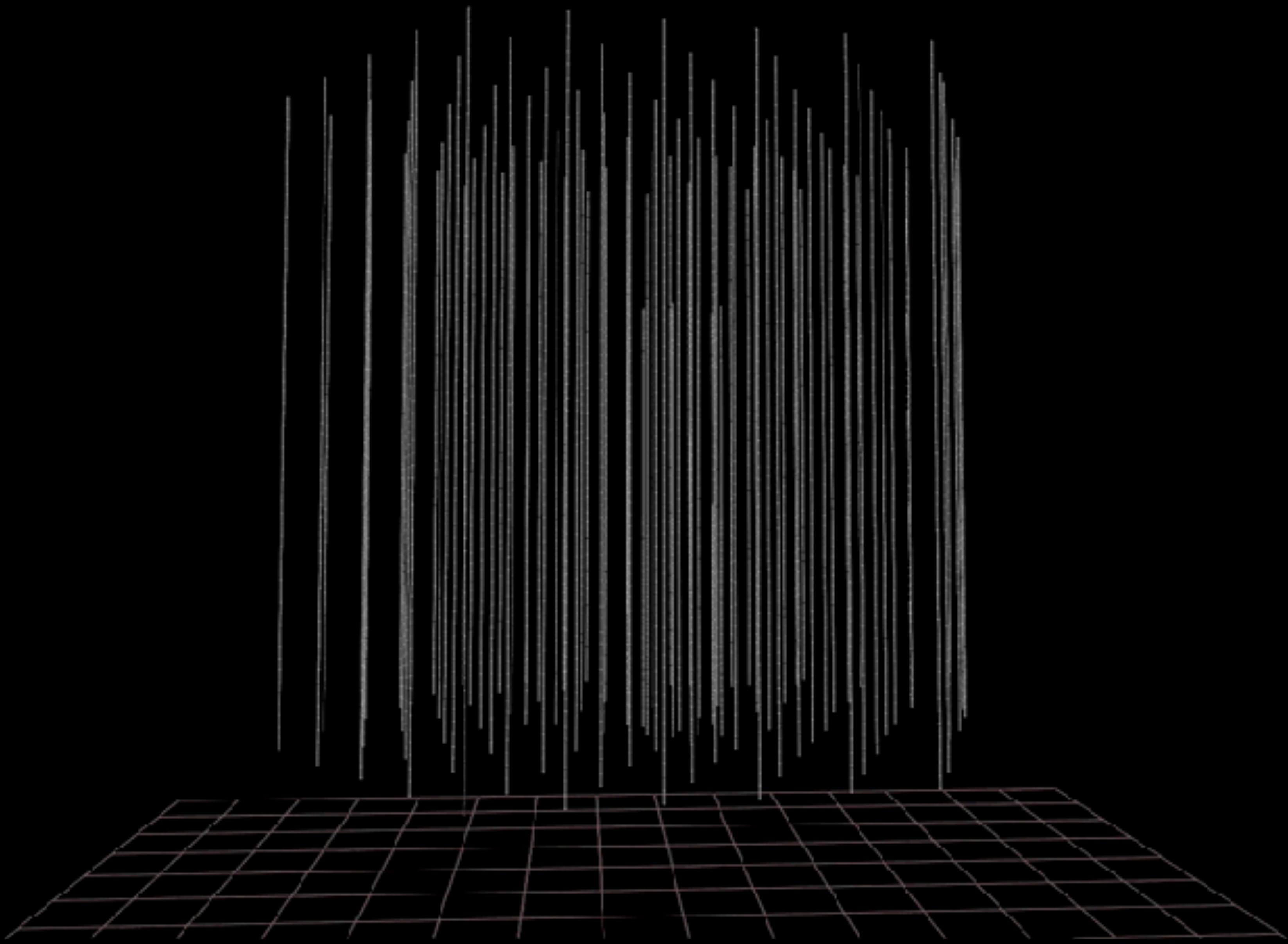
We send **rough reconstructions first** and then **update them.**



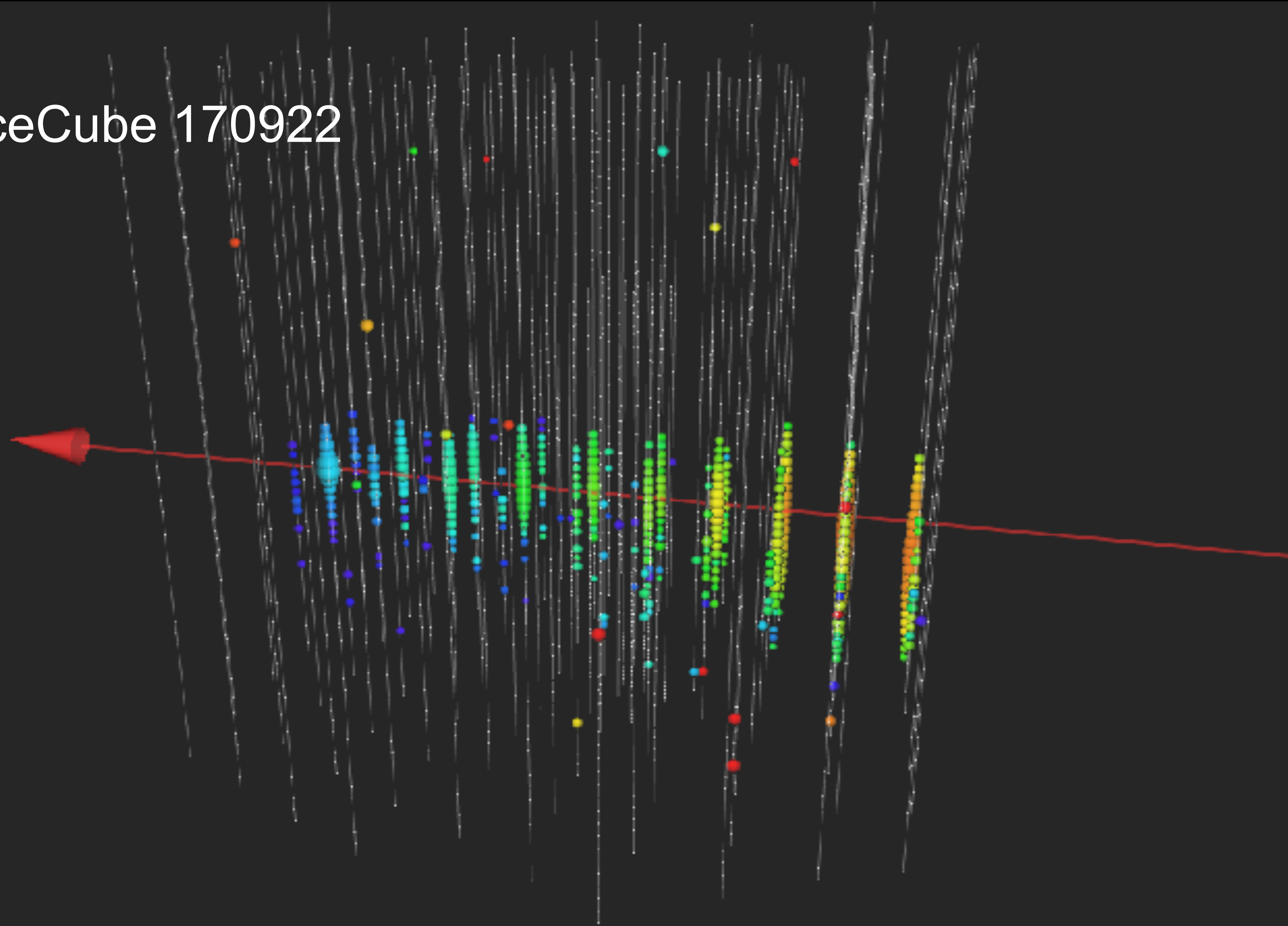
IceCube Trigger

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]
```



IceCube 170922

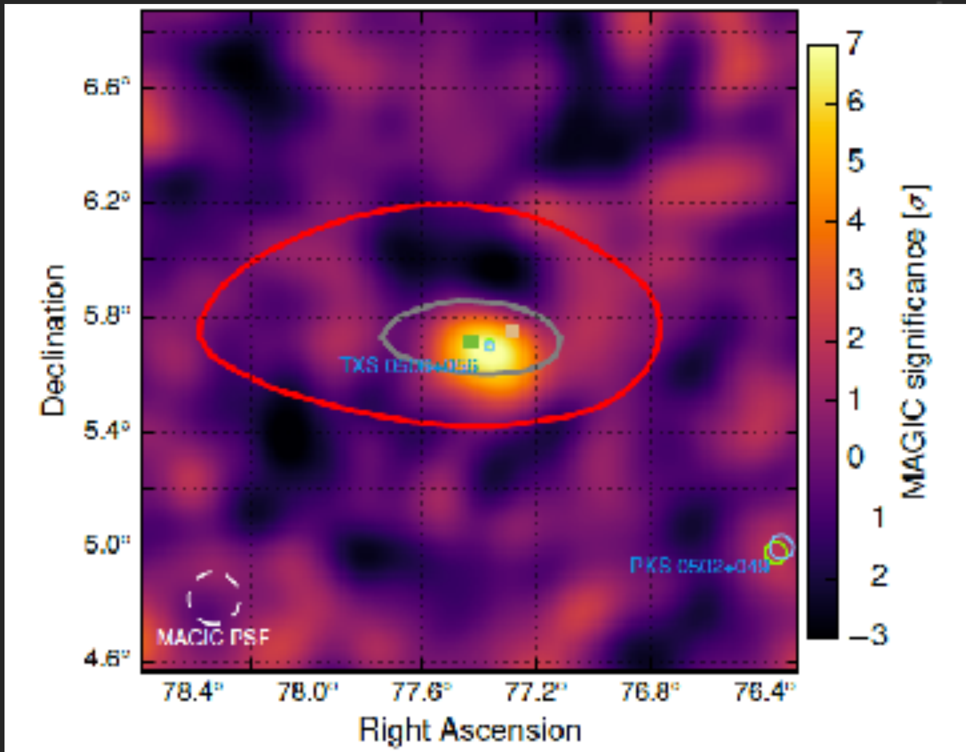


multiwavelength campaign launched by IC 170922

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

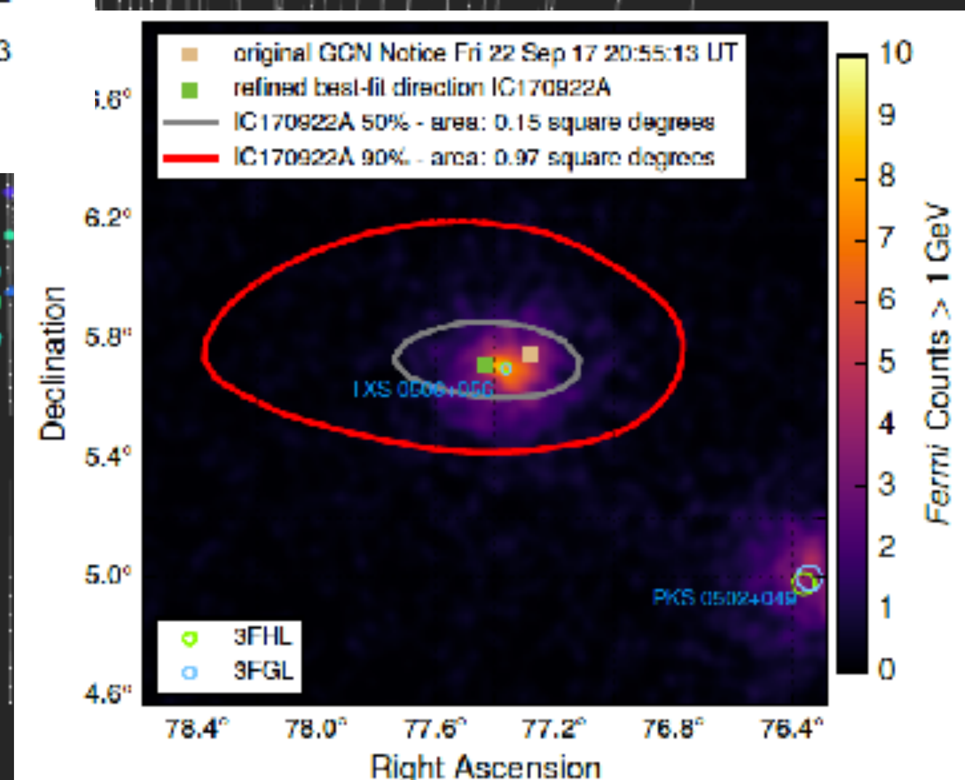
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^o Dec 5.72^o
- Fermi-LAT: flaring blazar within 0.1^o (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

IceCube 170922

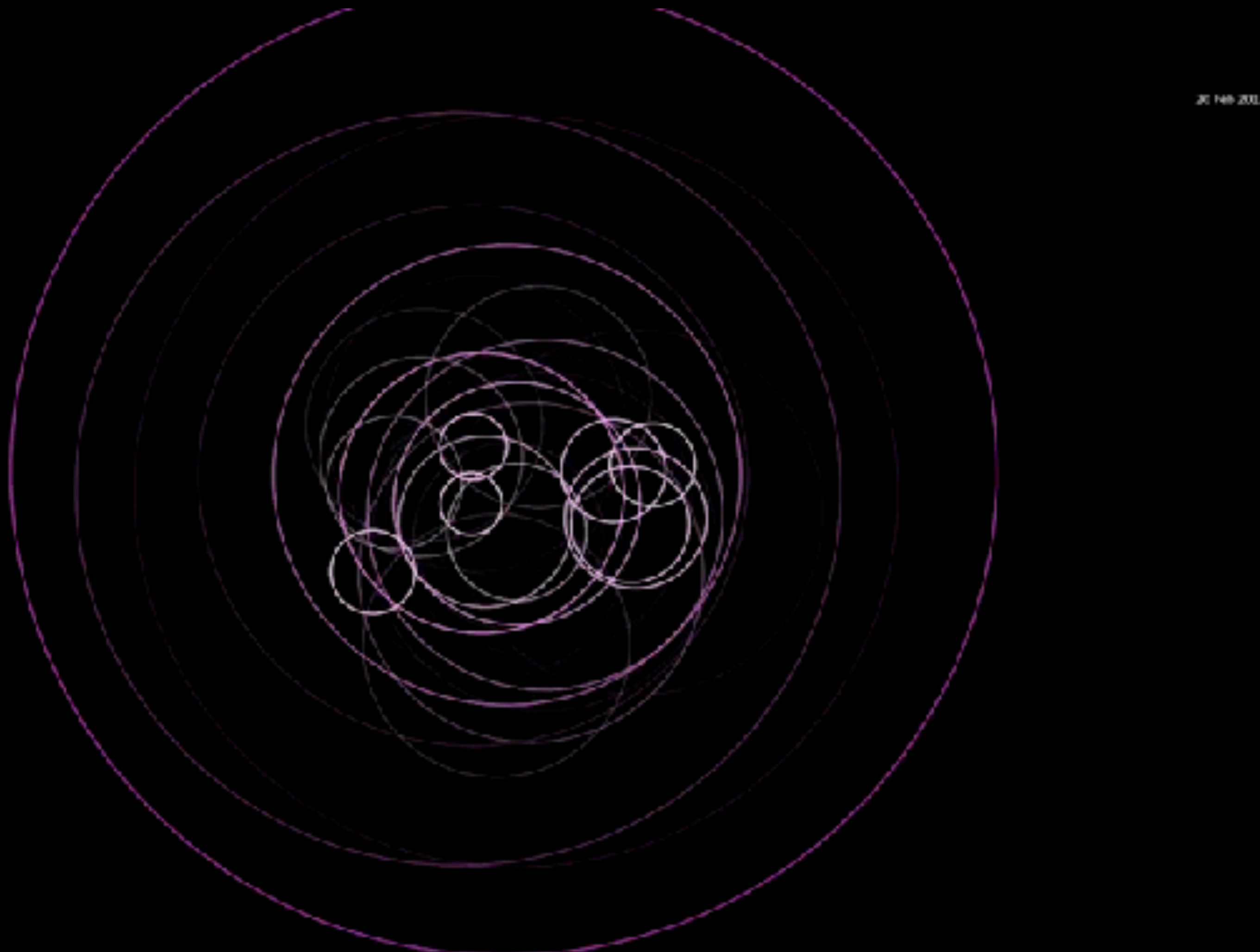


Fermi
detects a flaring blazar within 0.1°

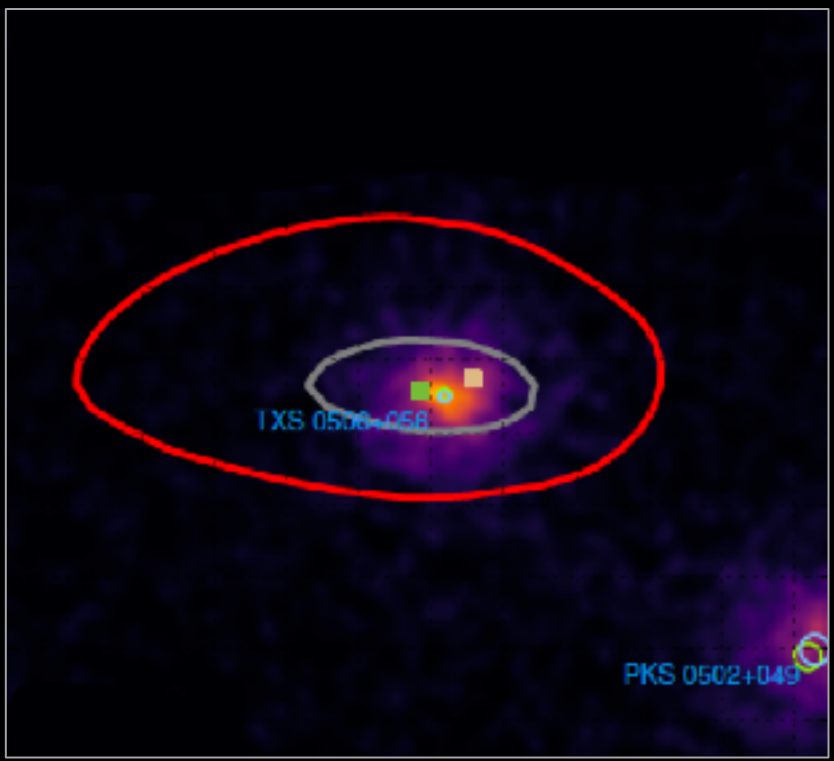
MAGIC
detects emission of
> 100 GeV gammas



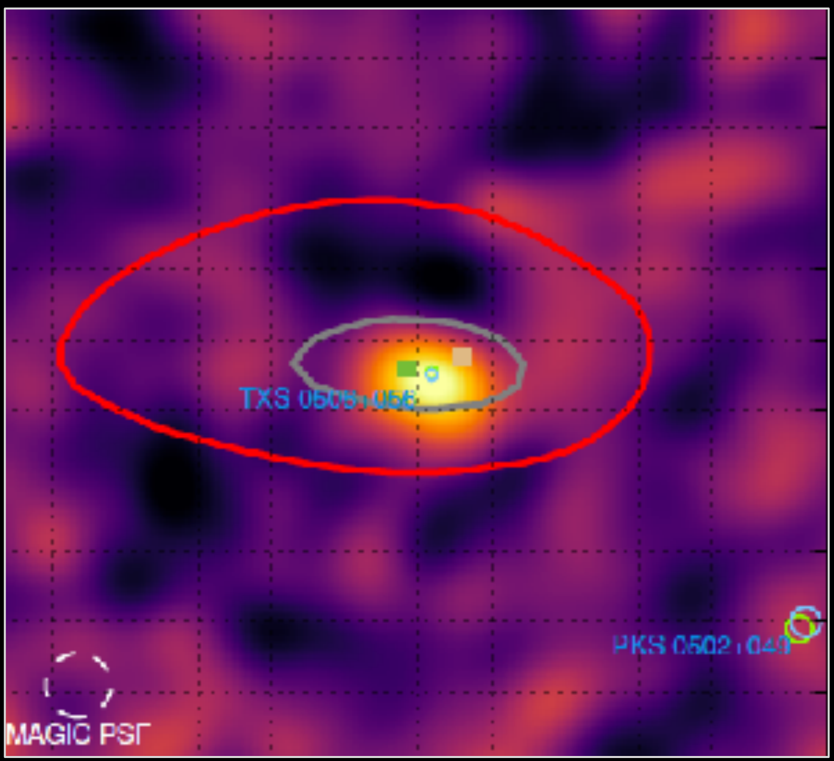
build-up over several months followed by rapid daily variability



Neutrino points within 0.06° of a known Fermi blazar



MAGIC detects emission of >100 GeV gammas



MAGIC atmposheric Cherenkov telescope

INTEGRAL
MAXI
Fermi
NuSTAR
Swift
OVRO
VERITAS
VLA
ASAS-SN
Subaru
MAGIC
GTC
Kapteyn
ANTARES
Kanata
Kiso
VLT
ASAS-SN
H.E.S.S
SALT
IceCube Neutrino Observatory

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
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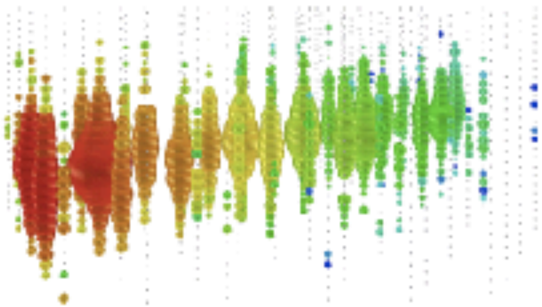
- Fermi-LAT: flaring blazar within 0.1^{o} (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

The Source: TXS 0506+056

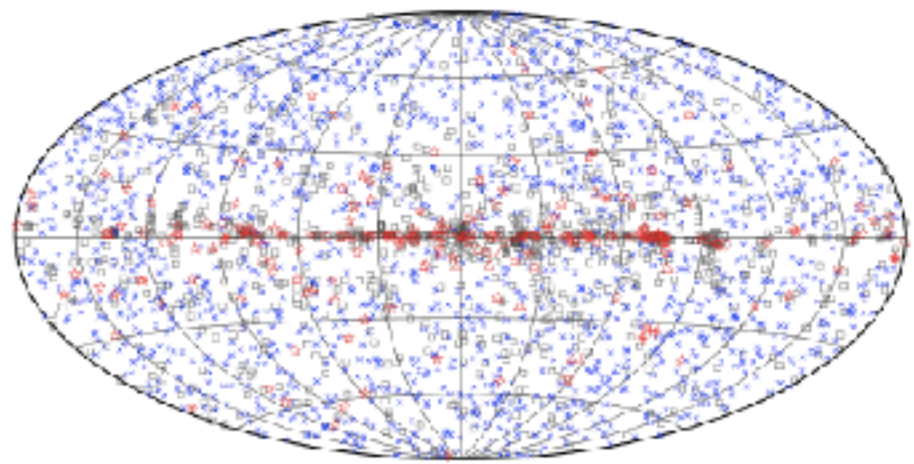
- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

- Outshines nearby blazars like Mrk421, Mrk 501, and 1ES 1959+650 by more than an order of magnitude

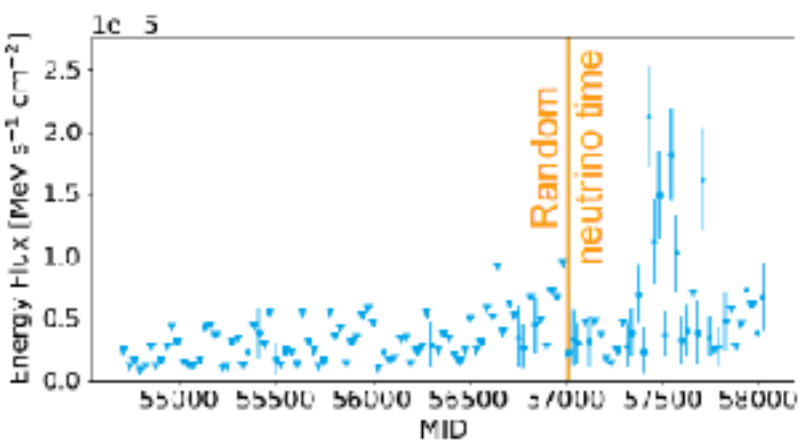
How Likely is it a Chance Probability?



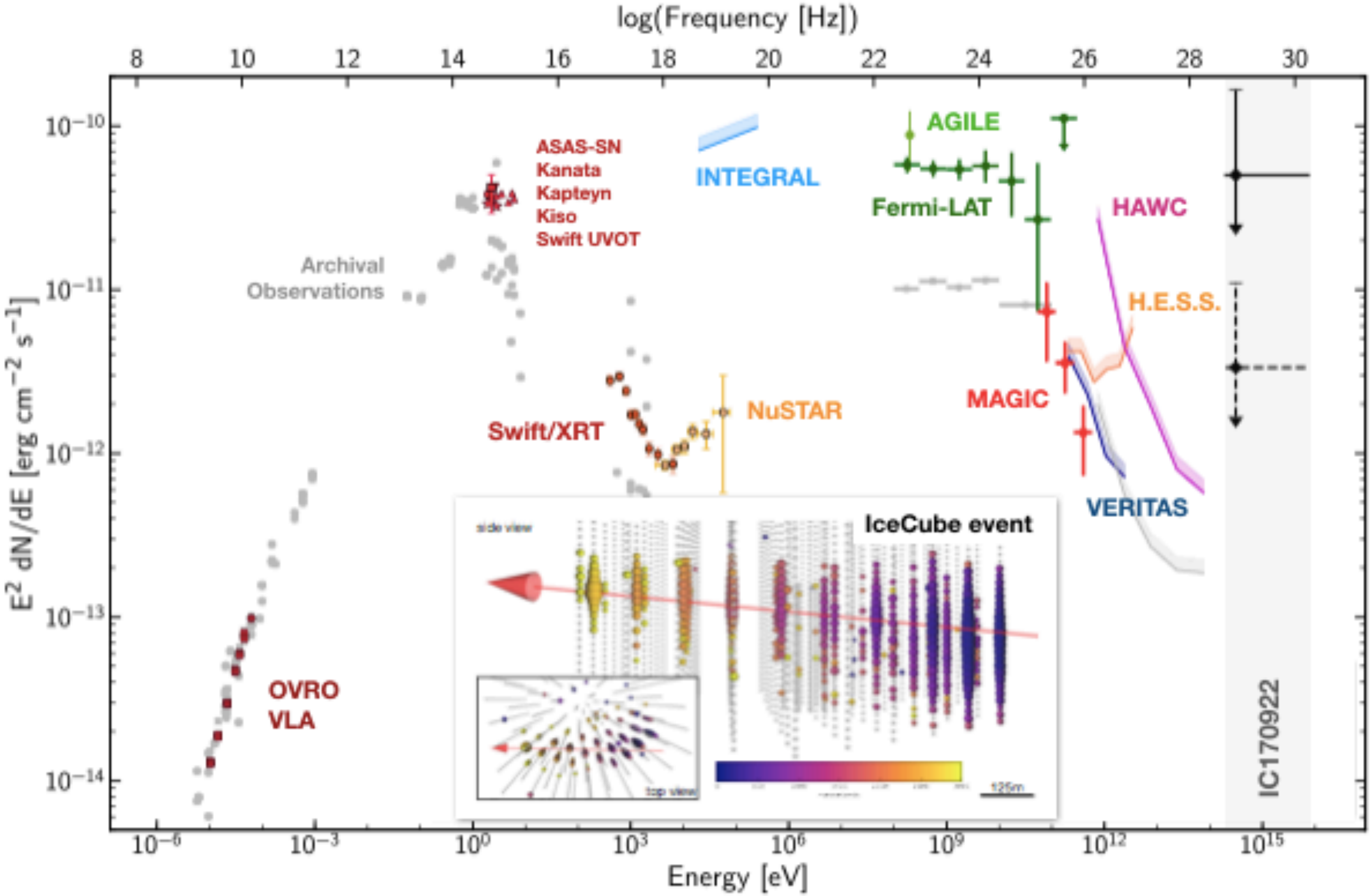
Step I: Draw a random neutrino from a representative sample of high-energy muon-track events



Step II: Are there any extra-galactic Fermi source close in space to the neutrinos?



Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

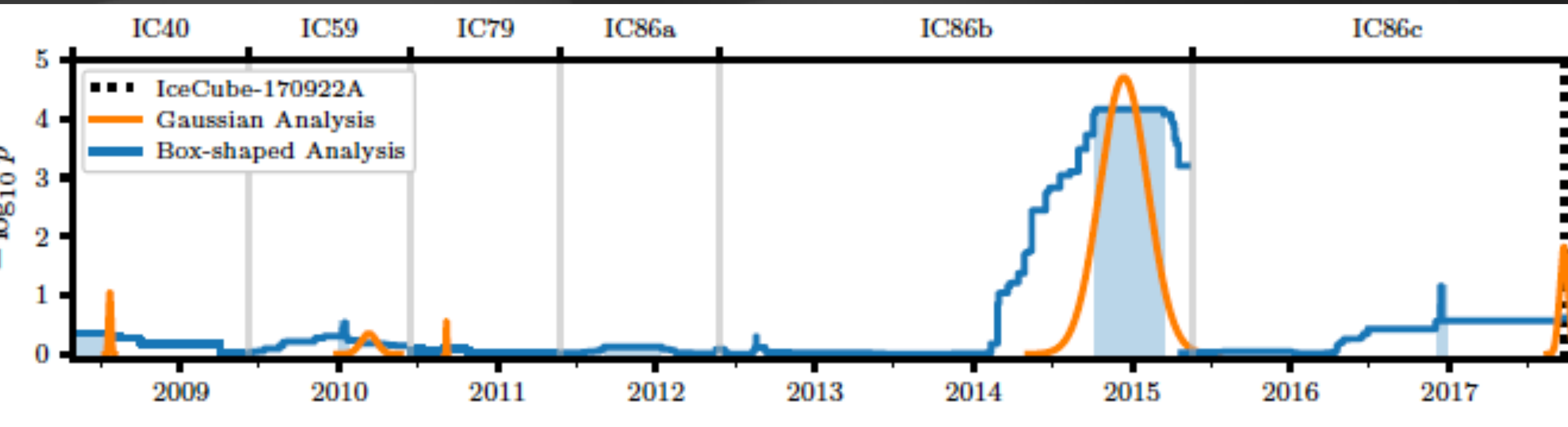


log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
ASAS-SN
Kanata
Kapteyn
Kiso
Swift UVOT
INTEGRAL
AGILE
Fermi-LAT
HAWC
Archival
Observations
H.E.S.S.
MAGIC
NuSTAR
Swift/XRT
VERITAS
IceCube event
side view
top view
125m
OVRO
VLA
IC170922
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]

multiwavelength campaign launched by IC 170922

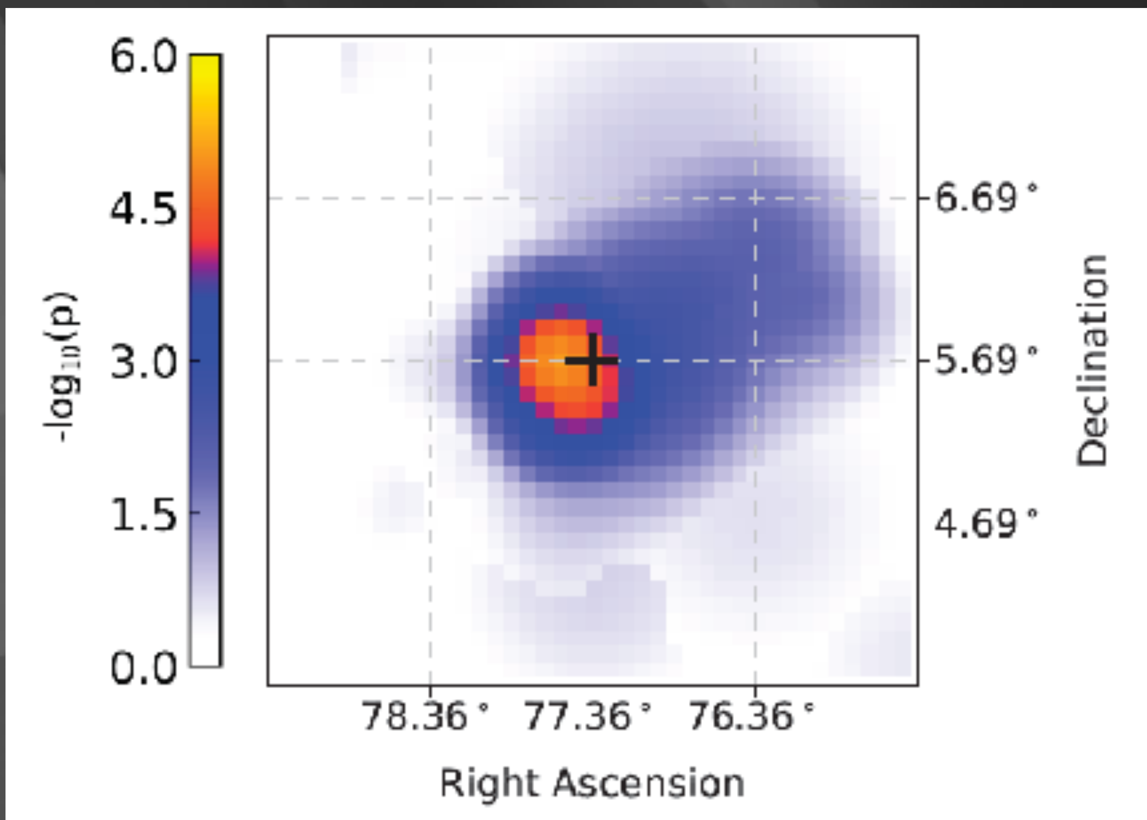
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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



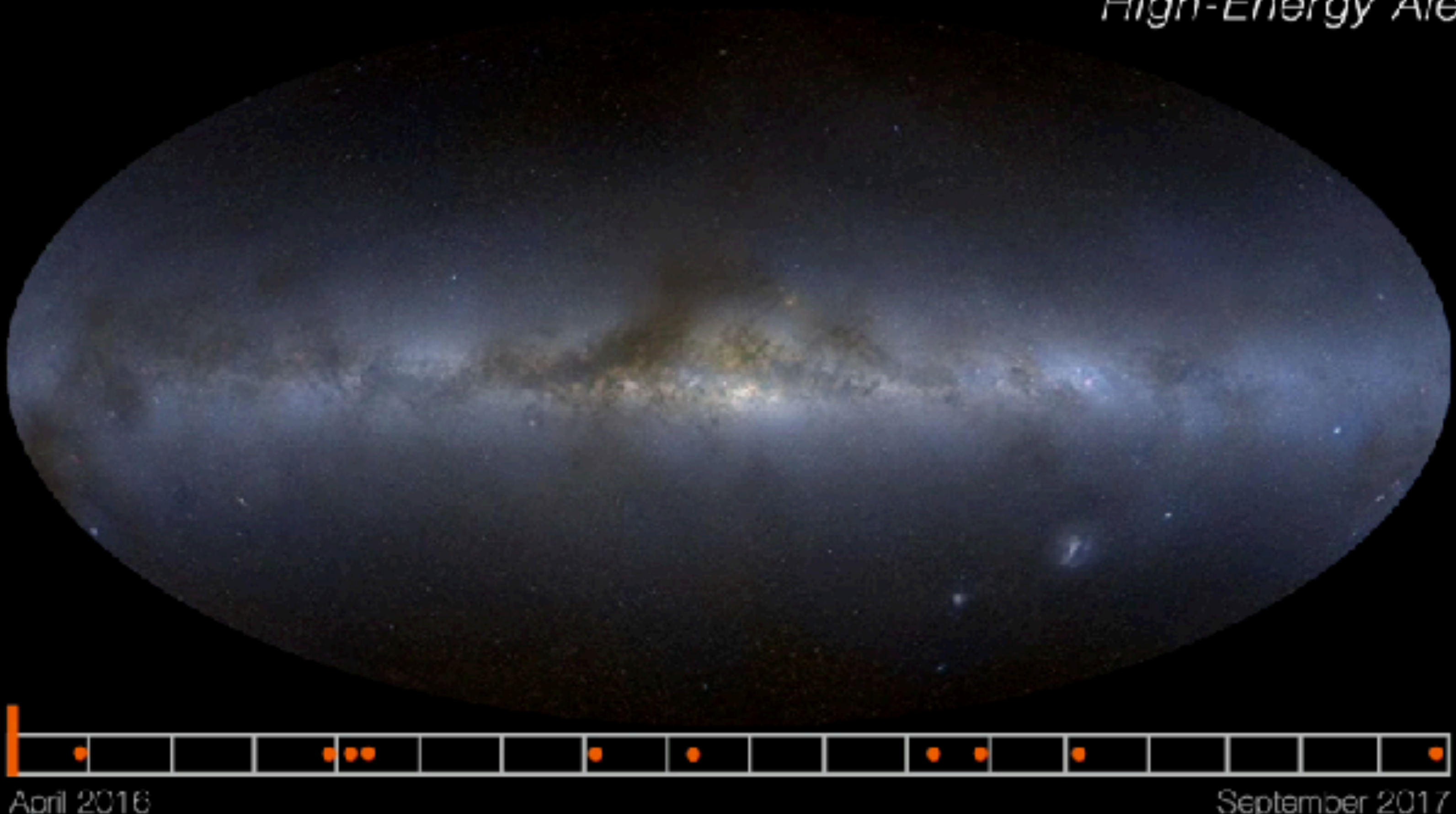
search in archival IceCube data:

- ~100 day flare in December 2014
- accompanied by hardest Fermi spectrum in 10 yrs ($E^{-1.7}$)



IceCube

High-Energy Alerts



19 events on a background < 6 in 150 days

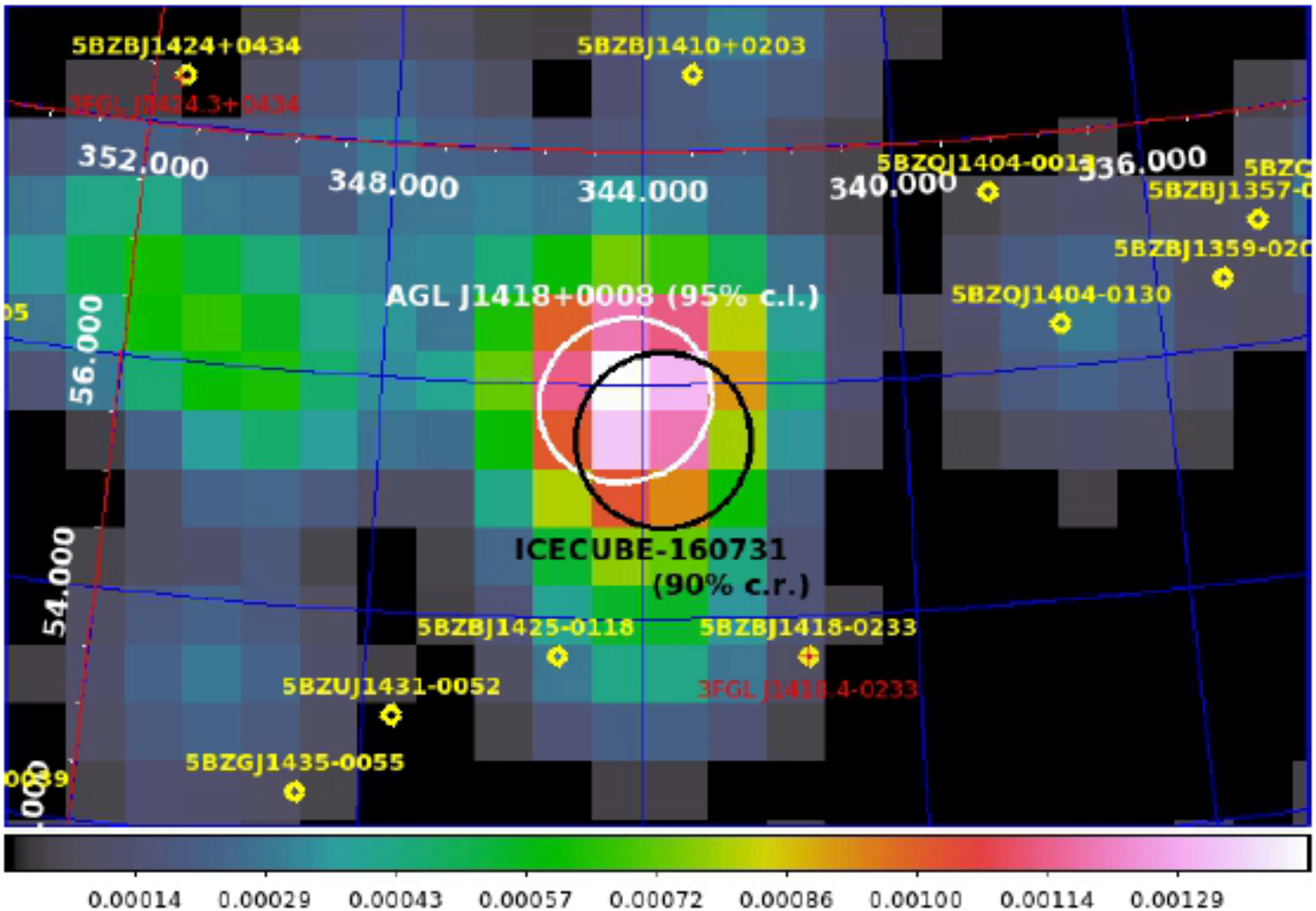
we identified a source of high energy cosmic rays:

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

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

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]



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

TANAMI blazars in the IceCube PeV neutrino fields

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P.G. Edwards[11], D. Eisenacher[2], D. Elsässer[2], K. Fehn[9], U. Fritsch[9], N. Gehrels[3], C. Gräfe[1,2], C. Großberger[12], H. Hase[13], S. Horiuchi[14], C. James[9], A. Kappes[2], U. Katz[9], A. Kreikenbohm[1,2], I. Kreykenbohm[1], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], J.E.J. Lovell[15], C. Müller[1,2], C. Phillips[11], C. Plötz[13], J. Quick[16], T. Steinbring[1,2], J. Stevens[11], D. J. Thompson[3], and A.K. Tzioumis[11]

(Affiliations can be found after the references)

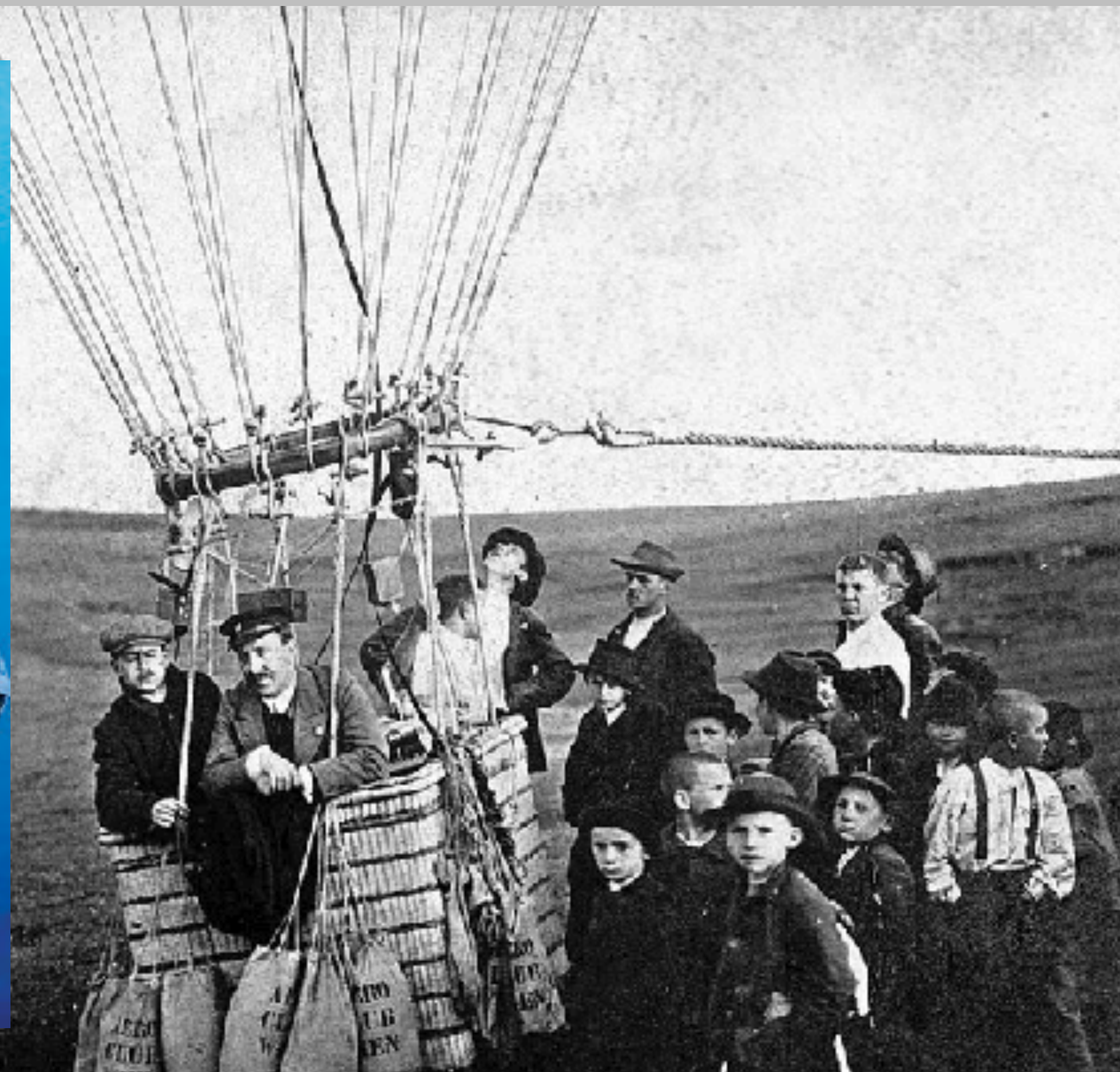
Received 15 May 2014 / Accepted 2 June 2014

ABSTRACT

The IceCube Collaboration has announced the discovery of a neutrino flux in excess of the atmospheric background. Owing to the steeply falling atmospheric background spectrum, events at PeV energies most likely have an extraterrestrial origin. We present the multiwavelength properties of the six radio-brightest blazars that are positionally coincident with these events using contemporaneous data of the TANAMI blazar sample, including high-resolution images and spectral energy distributions. Assuming the X-ray to γ-ray emission originates in the photoproduction of pions by accelerated protons, the integrated predicted neutrino luminosity of these sources is high enough to explain the two detected PeV events.

Key words. neutrinos – galaxies: active – quasars: general

Victor Hess 1912



- Galactic sources?

neutral pions

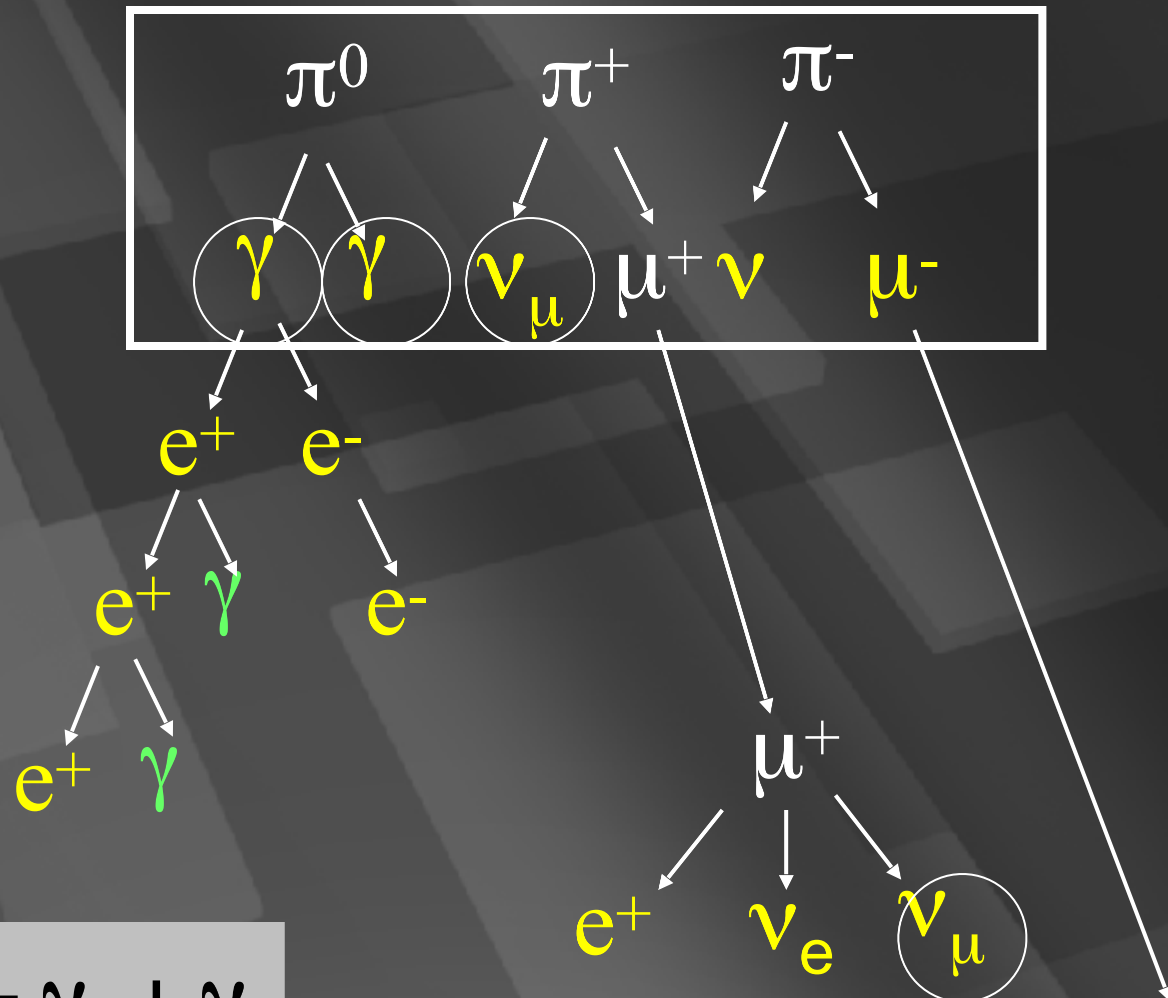
are observed as

gamma rays

charged pions

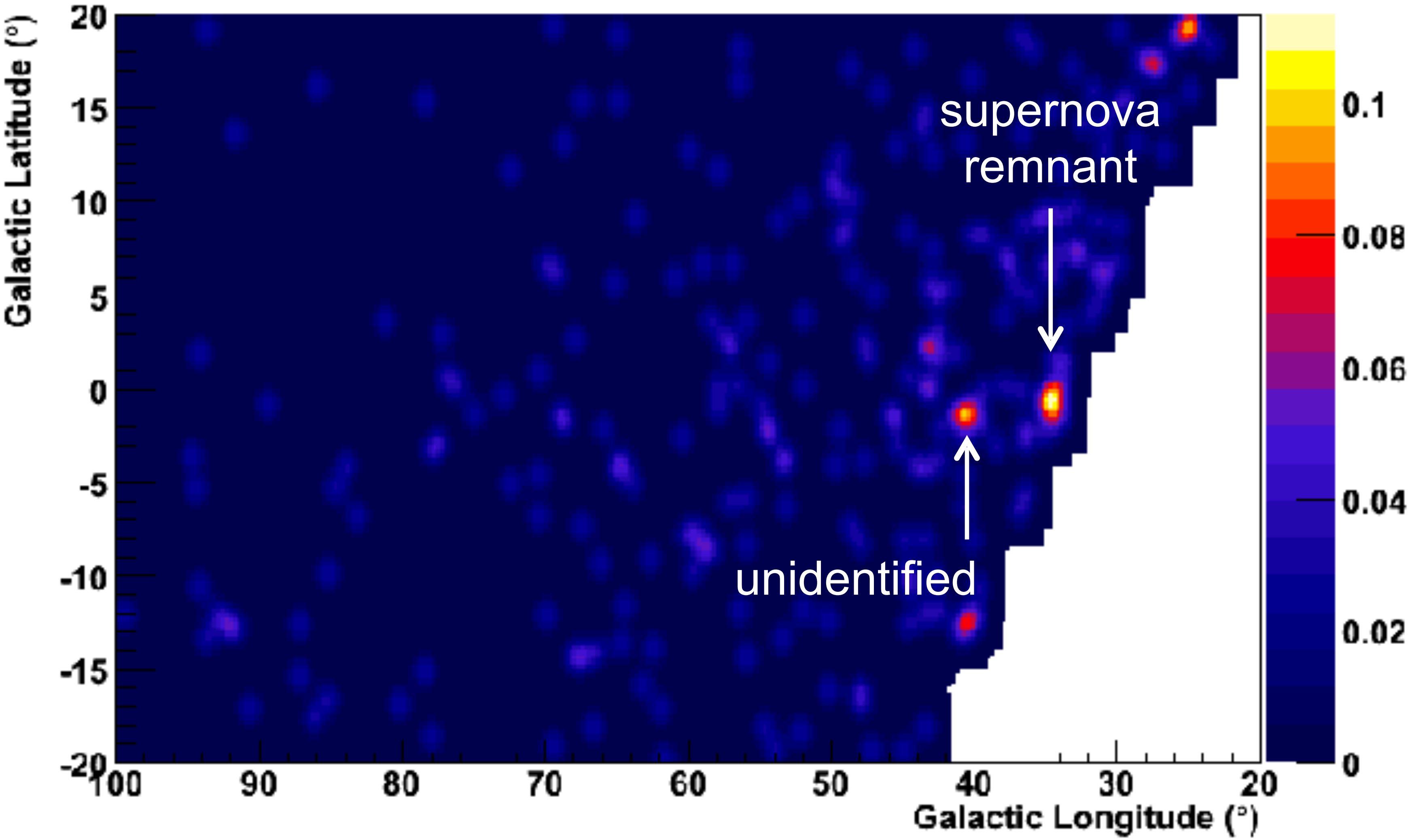
are observed as

neutrinos

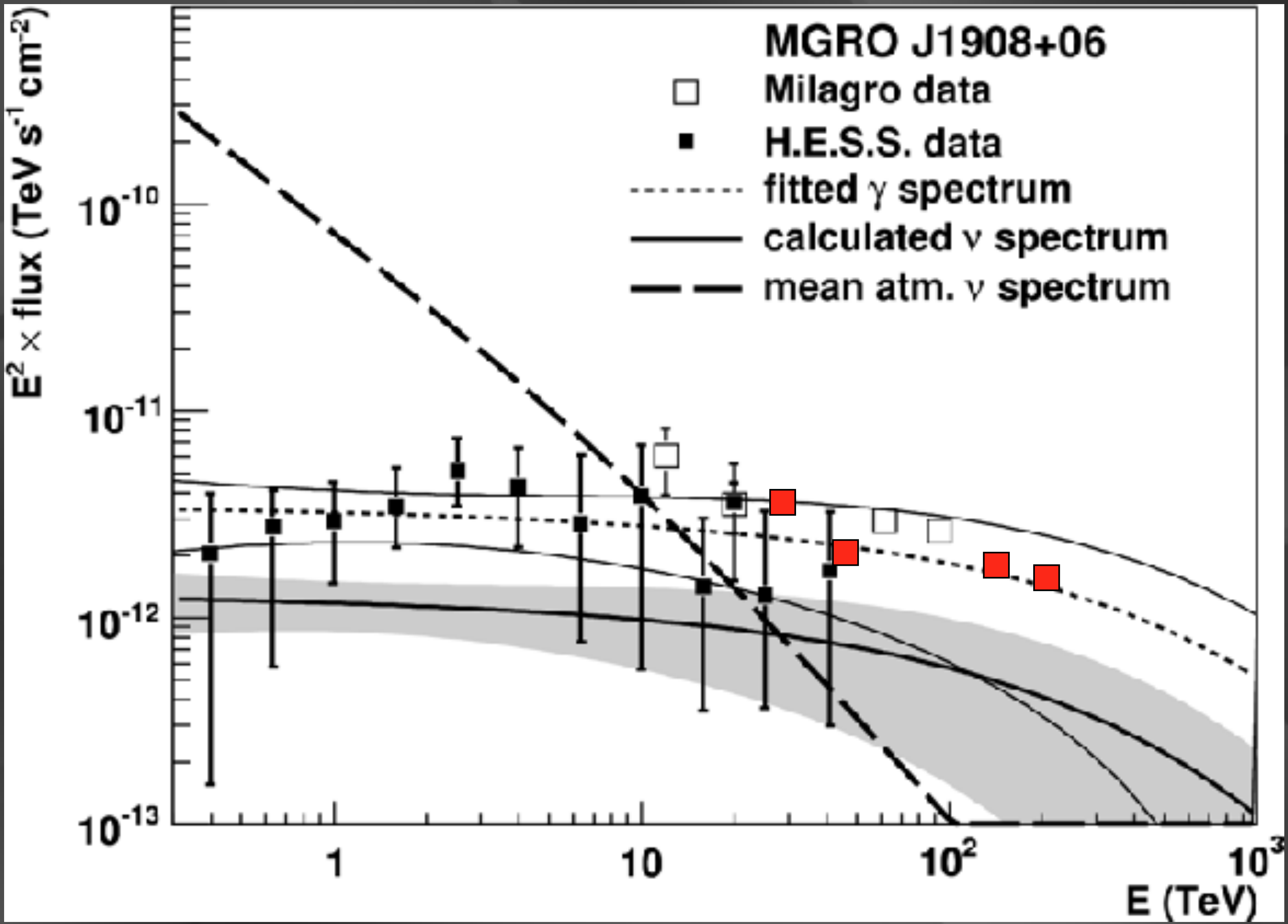


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

2007 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.



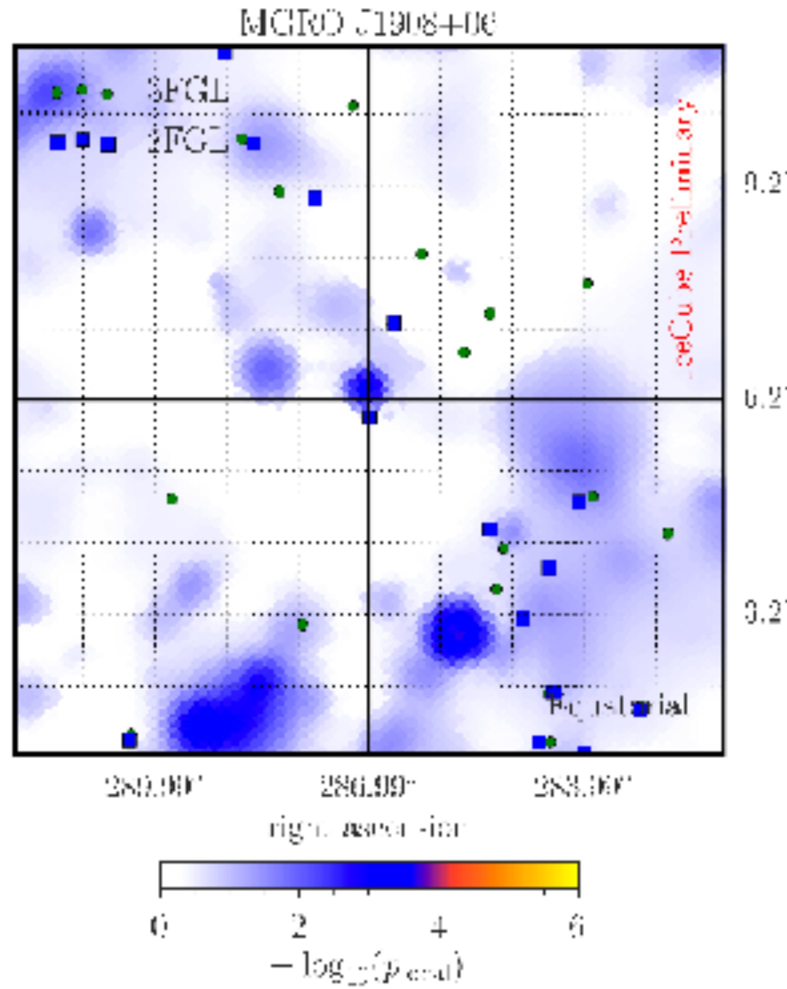
MGRO J1908+06: the first Pevatron? (2007!)



- most significant source in pre-defined list (p-value 0.003 pretrial)
- joined HAWC-IceCube analysis in progress using photon templates

Table 1: Results of the pre-defined source list.

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.060	0.00	$4.47 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.066	0.00	$6.37 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.75	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7800	-0.243	0.00	$1.06 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17 \cdot 10^{-12}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.71 \cdot 10^{-13}$
3C454.3	FSRQ	343.50	16.1[illegible]	0.0072	[illegible]	5.98	$1.26 \cdot 10^{-13}$
4C 38.41	FSRQ	248.81	[illegible]	0.0055	[illegible]	6.62	$1.72 \cdot 10^{-12}$
MGRO J1908+06	NI	286.99	[illegible]	0.0032	[illegible]	3.28	$1.15 \cdot 10^{-12}$
Geminga	PWN	98.48	17.7[illegible]	0.9754	[illegible]	0.00	$1.10 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	[illegible]	4.32	$8.65 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	[illegible]	-3.191	0.00	$1.30 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.3069	0.033	0.88	$1.06 \cdot 10^{-12}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
Cyg A	SRG	299.87	40.73	0.0049	5.335	4.30	$1.78 \cdot 10^{-12}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.5887	-0.888	0.00	$1.83 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.98	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$



Detector Complementarity

Wide-field / Continuous Operation

VHE Sensitivity

Fermi, AGILE, EGRET

HAWC, ARGO, Milagro

VERITAS, HESS, MAGIC

<u>Space-Based</u>

- All sky coverage
- GeV range (area->flux limited)

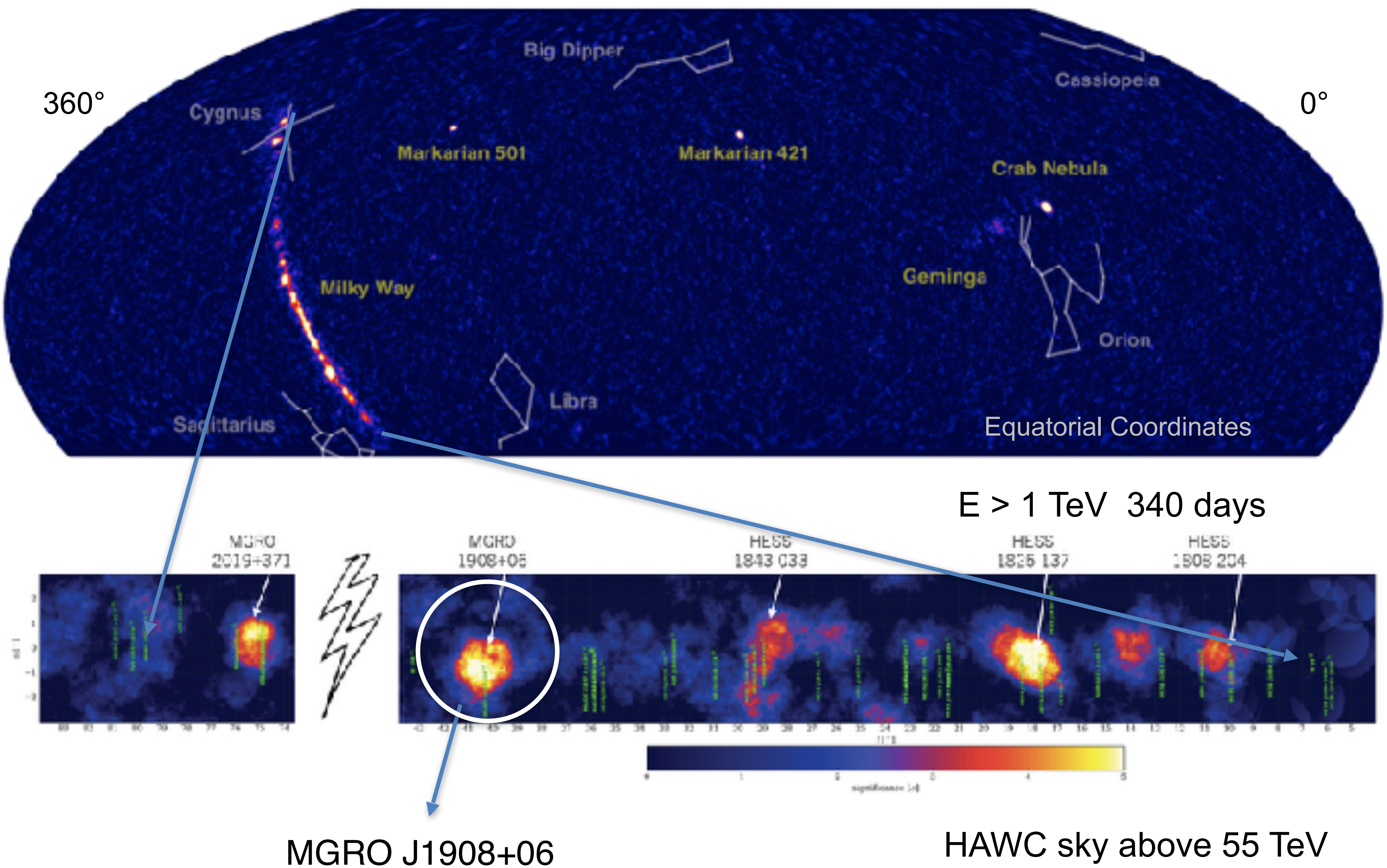
<u>Ground Arrays</u>

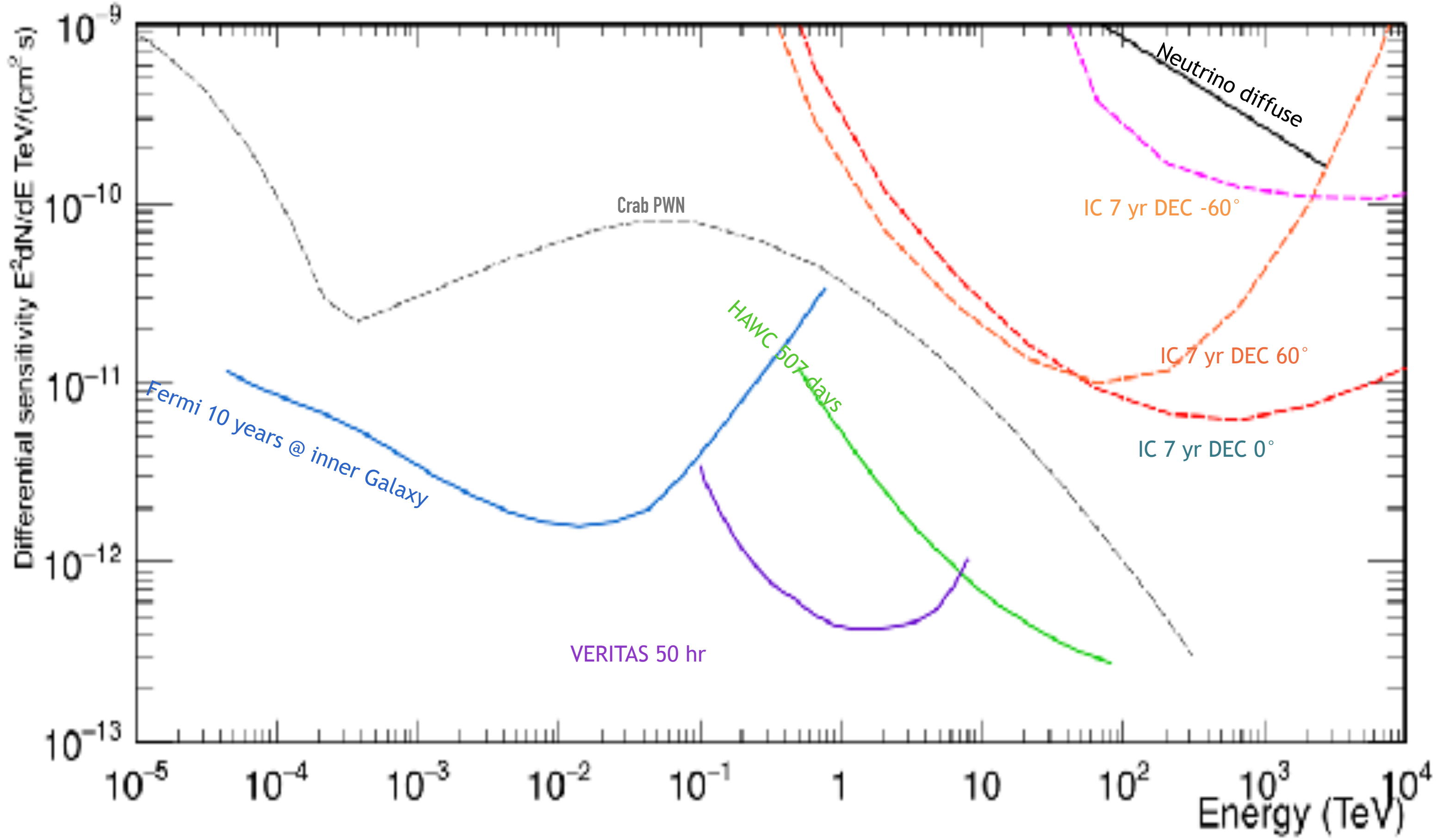
- 95% duty cycle, ~2 sr f.o.v.
- Daily coverage of $2/3$ sky
- Unbiased surveys
- Highest energies, E > 100 GeV

<u>IACTs</u>

- Excellent pointing
- Highest energies
- Surveys limited

HAWC View of Gamma Ray Sky





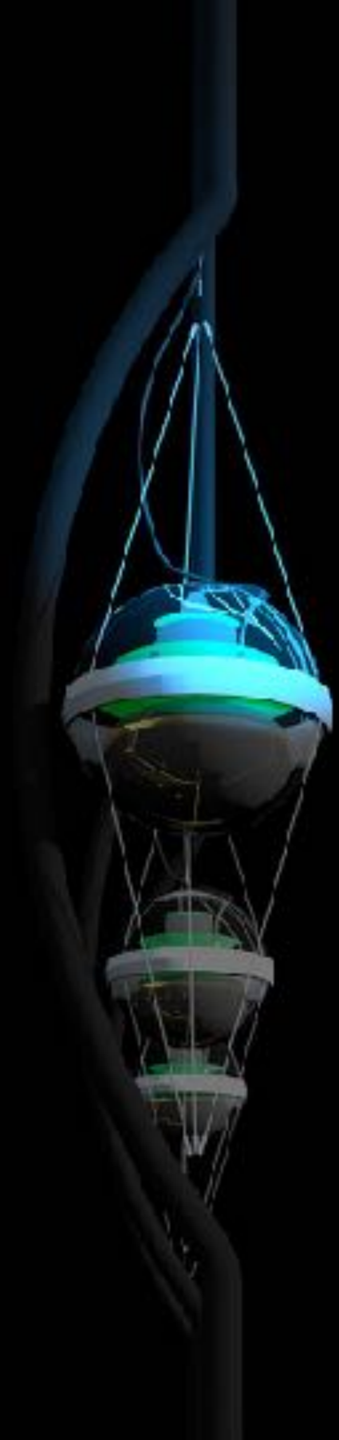
Comparisons with HAWC

- HAWC is better at detecting very large emission region (θ> 1 degree).
  HAWC is also a survey instrument, so they are accumulating exposure in ~40% of all sky they are surveying.
  This is especially important for E> a few TeV energy range.

Detected sources are largely SNR/PWNs (2 blazars)

- VERITAS is better at detecting gamma-rays with E<a few TeV with moderate exposure w/ source size < 1 degree.
  Much better instantaneous sensitivity for E< a few tens of TeV with moderate exposure.
  Better angular resolution, energy resolution.

Detected various sources (40 extragalactic sources, 33 galactic sources)



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?

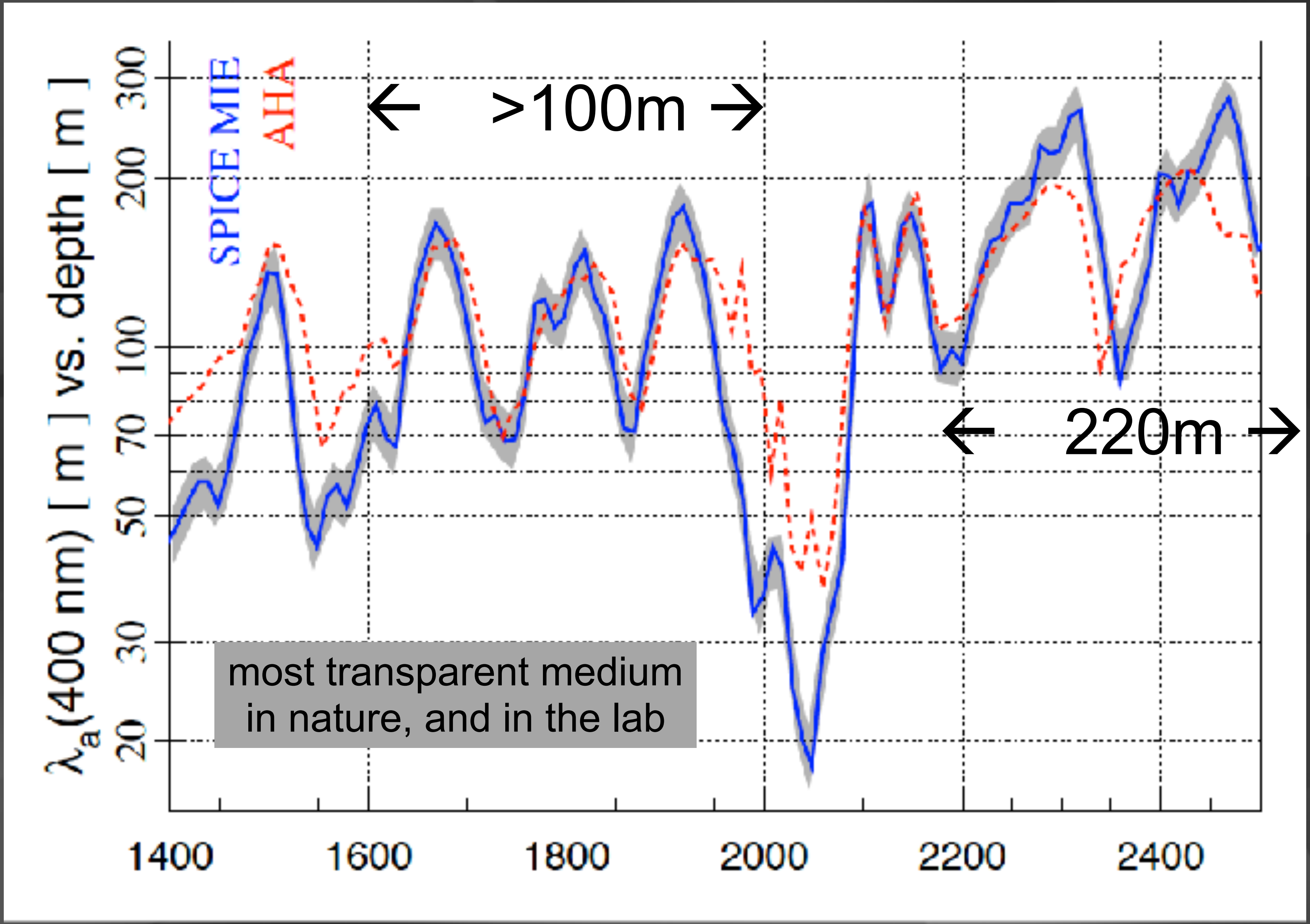
IceCube.wisc.edu

- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of ~ 0.1 degree will see multiple neutrinos from single sources and identify the sources

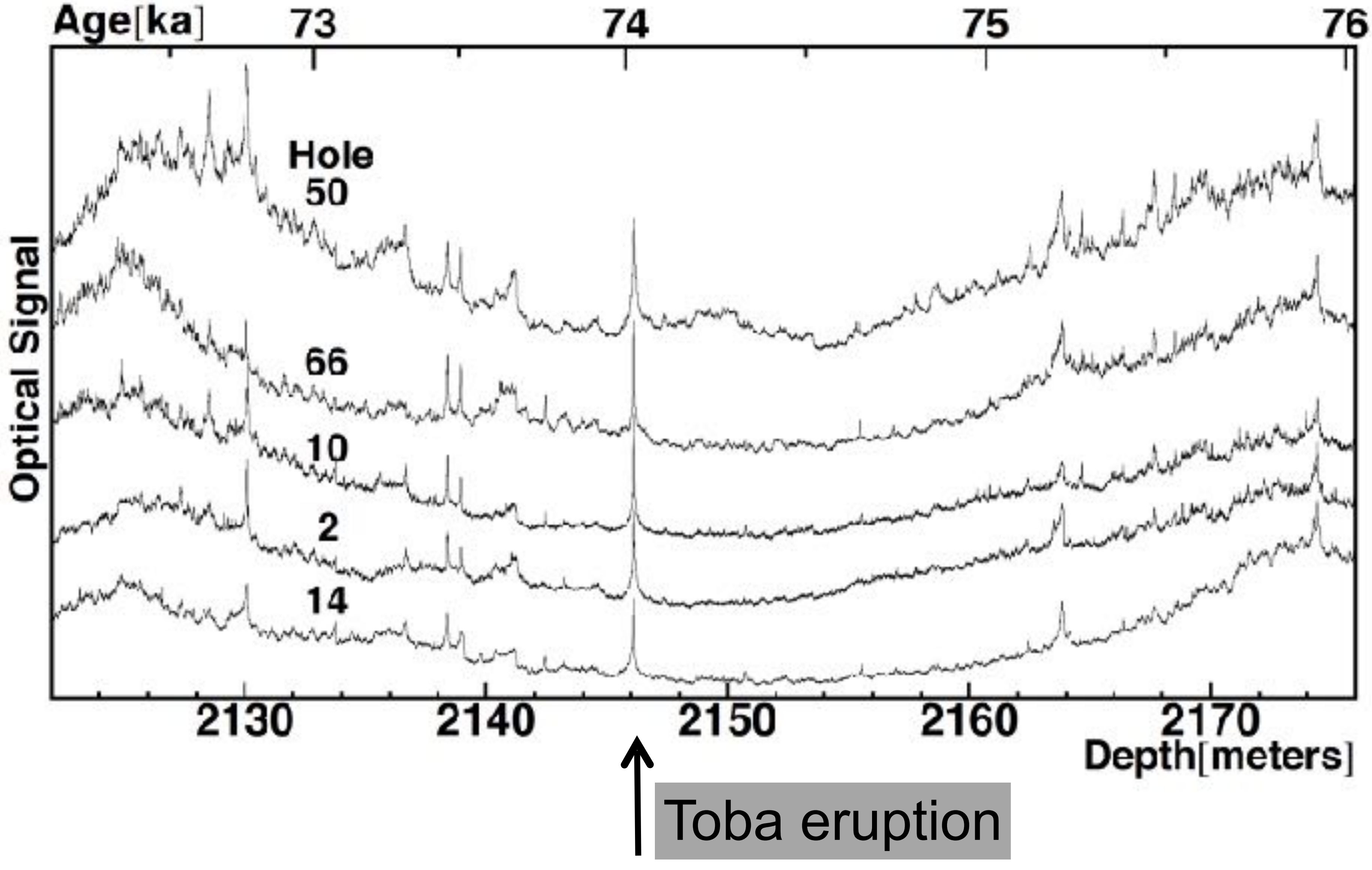
- need 1,000 events versus 100 now in a few years

- discovery instrument → astronomical telescope

absorption length of Cherenkov light



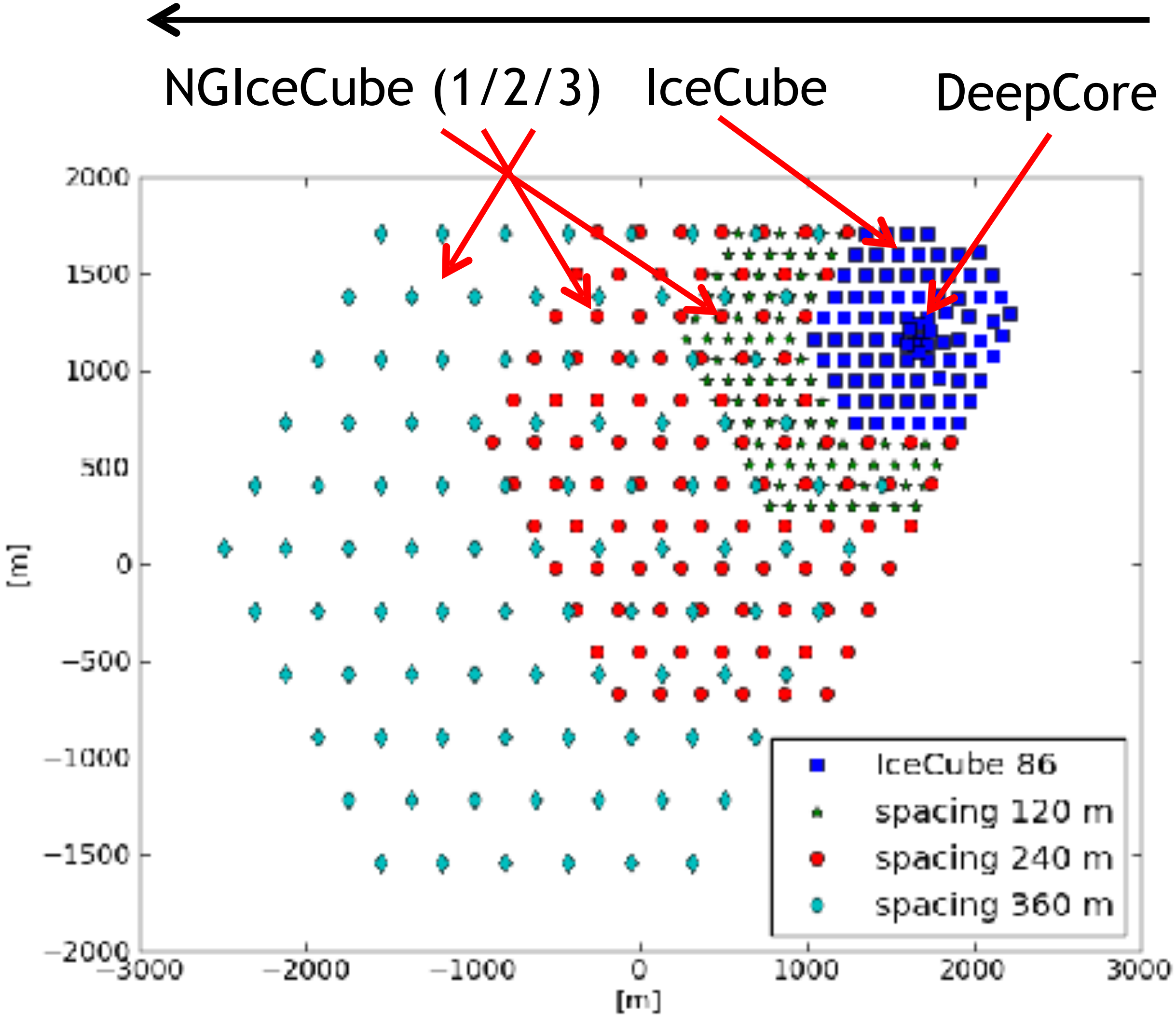
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

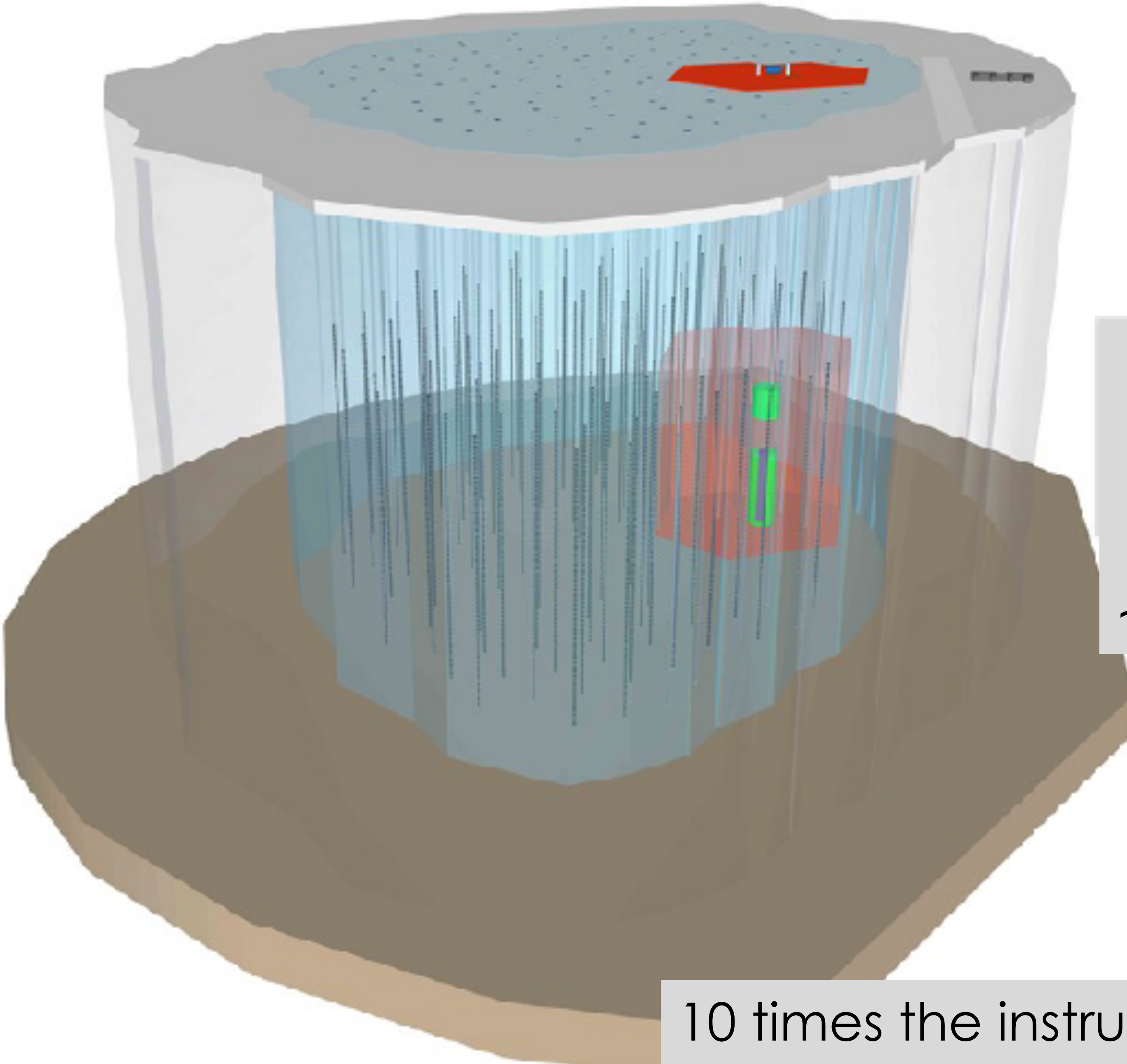
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



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

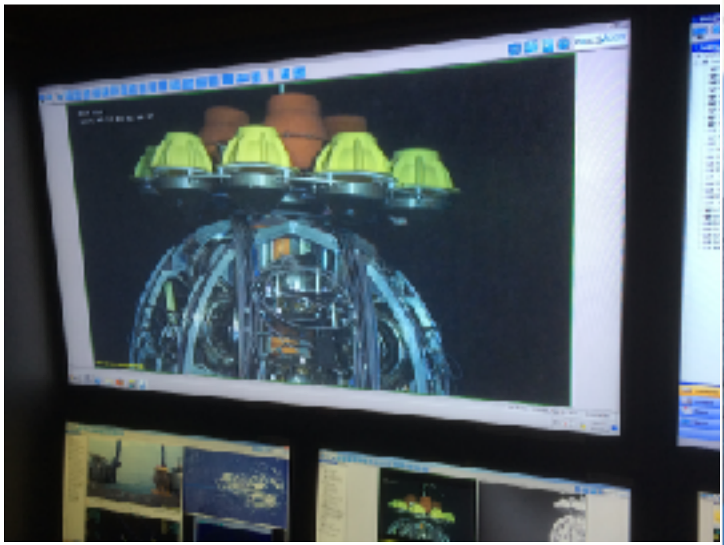
Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

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



120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume
for the same budget as IceCube



KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

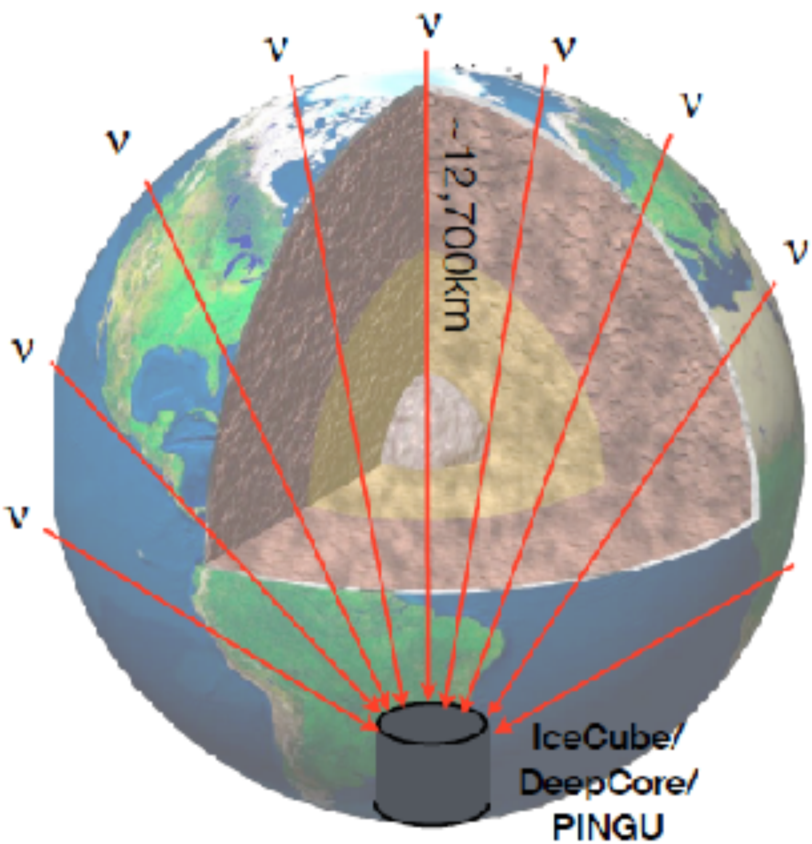
Conclusions

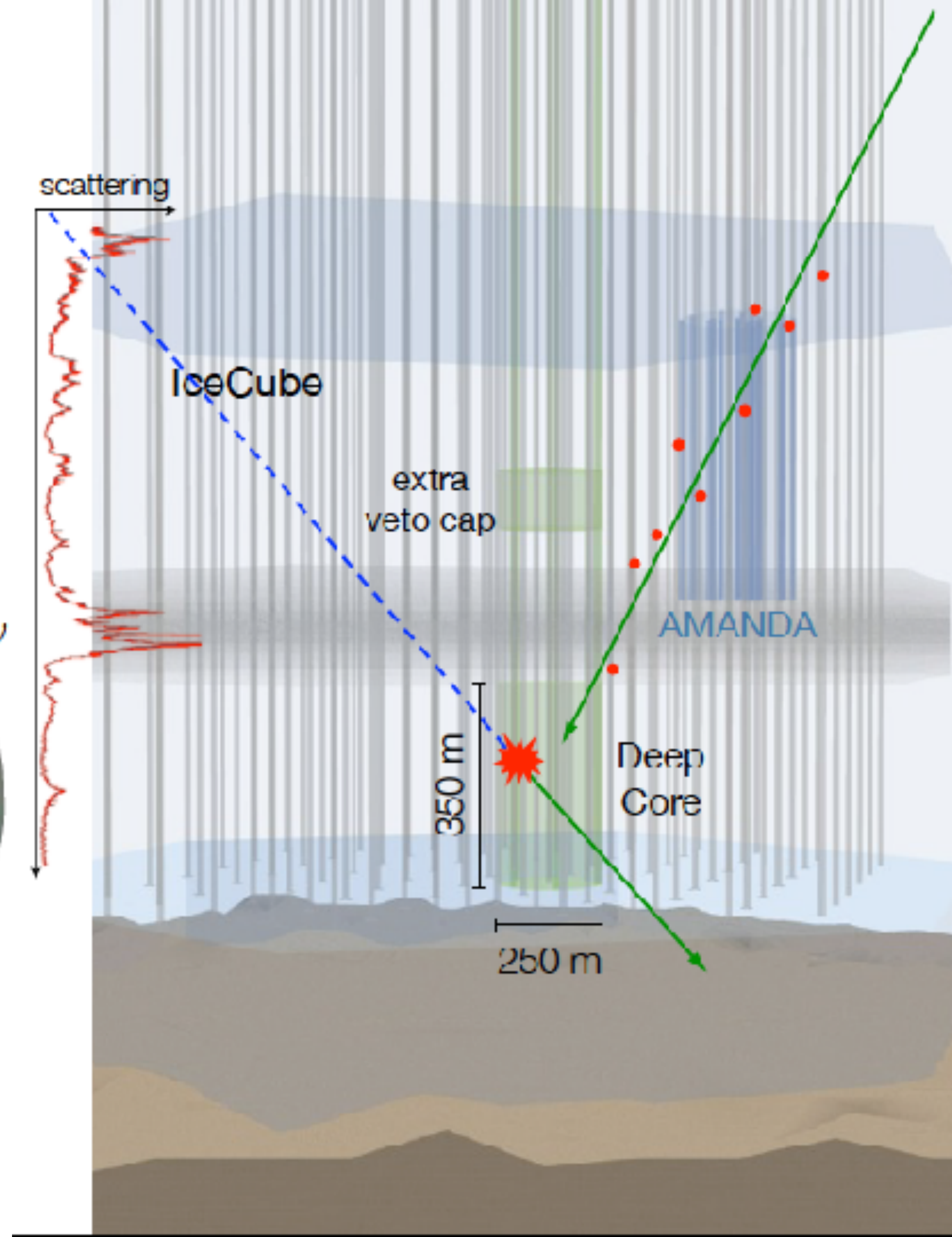
- more to come from IceCube: many analyses have not exploited more than one year of data
- analyses are not in the background-dominated regime
- next-generation detector(s):

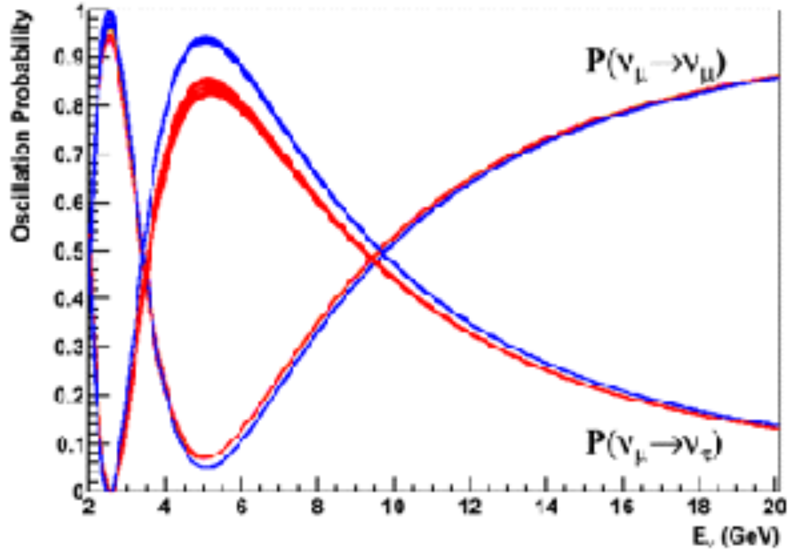
  1. discovery → astronomy (also KM3NeT, GVD)
  2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
  3. potential for discovery

- neutrinos are never boring!

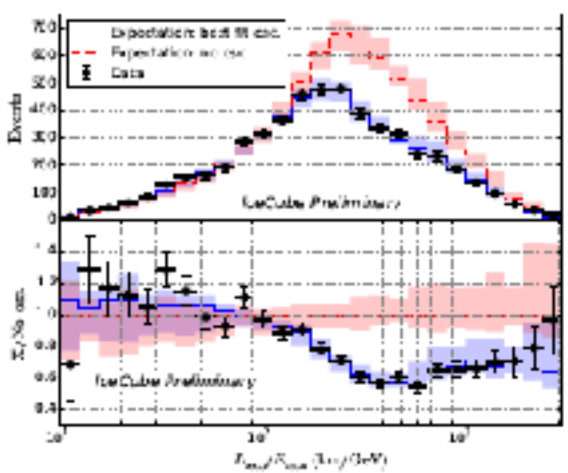
one half million atmospheric neutrinos…

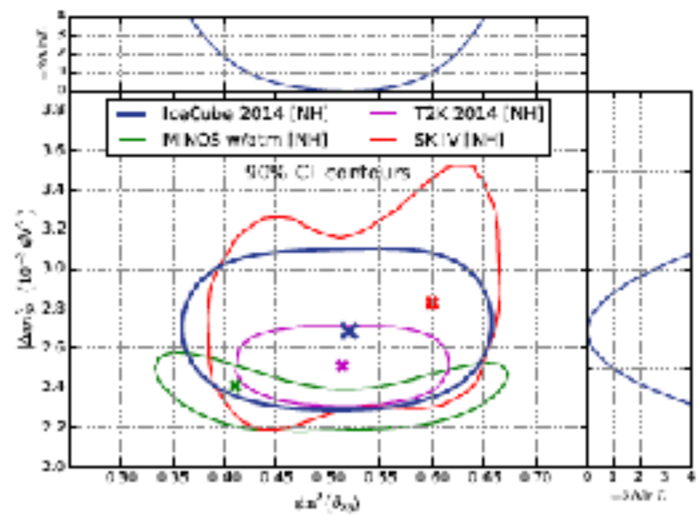






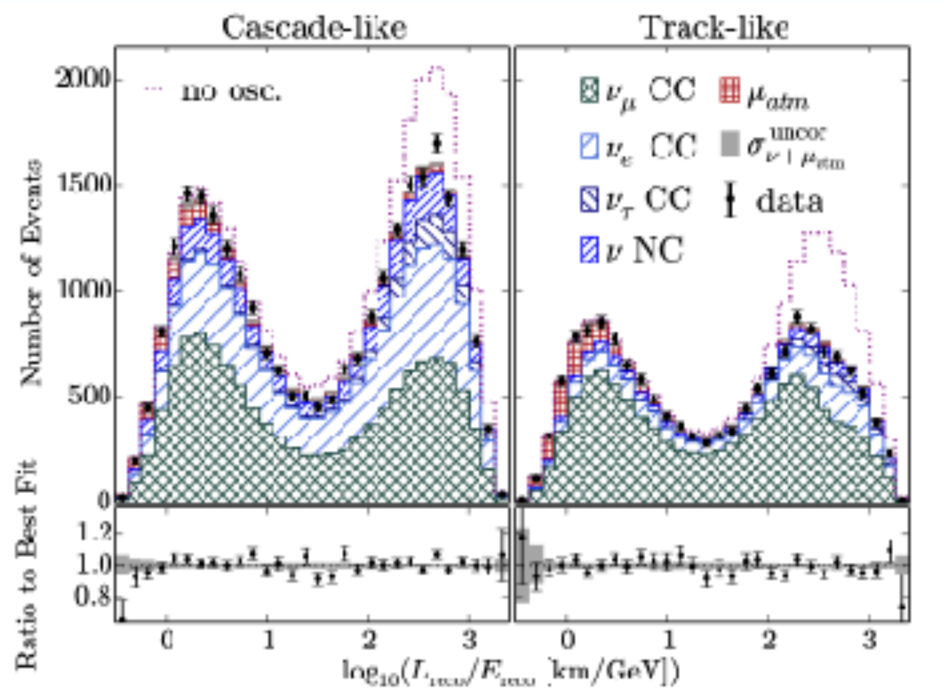
oscillations at 20 GeV



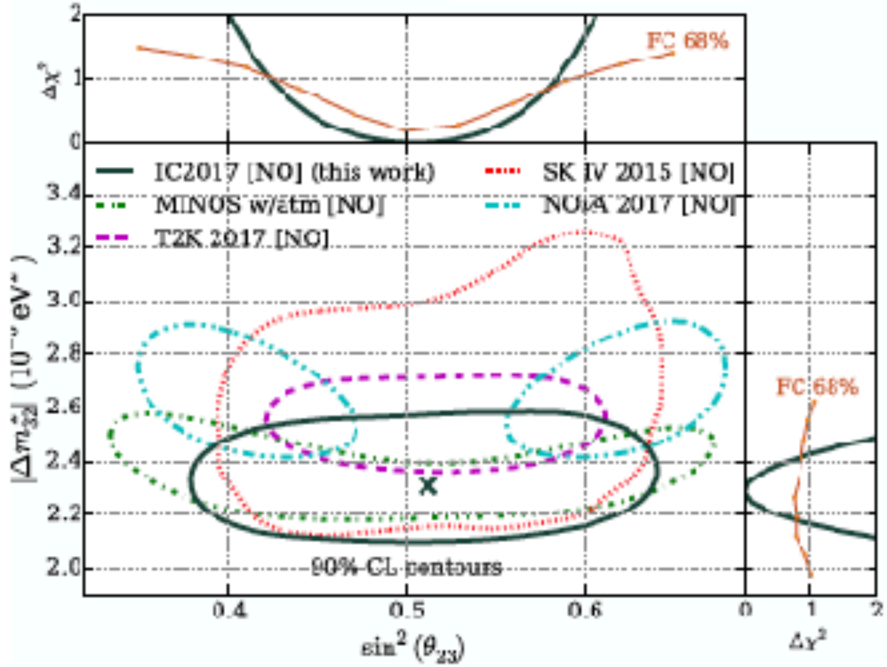


DeepCore: mapping the first oscillation dip at 10X higher energy
new physics?

Neutrino Oscillation



IceCube. PRL 2018



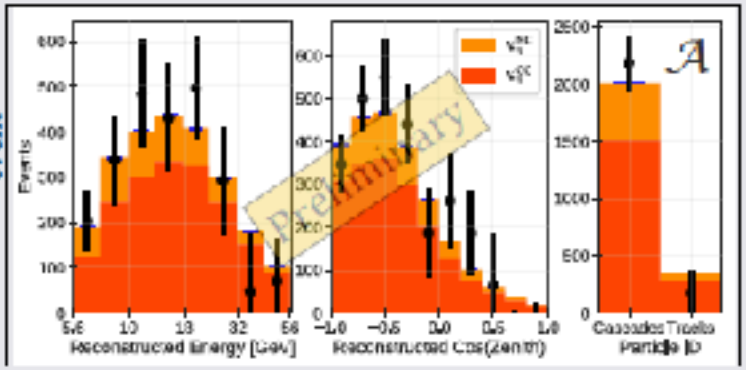
- 3 years of IceCube Deep Core data
- measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\text{eV}^2$$

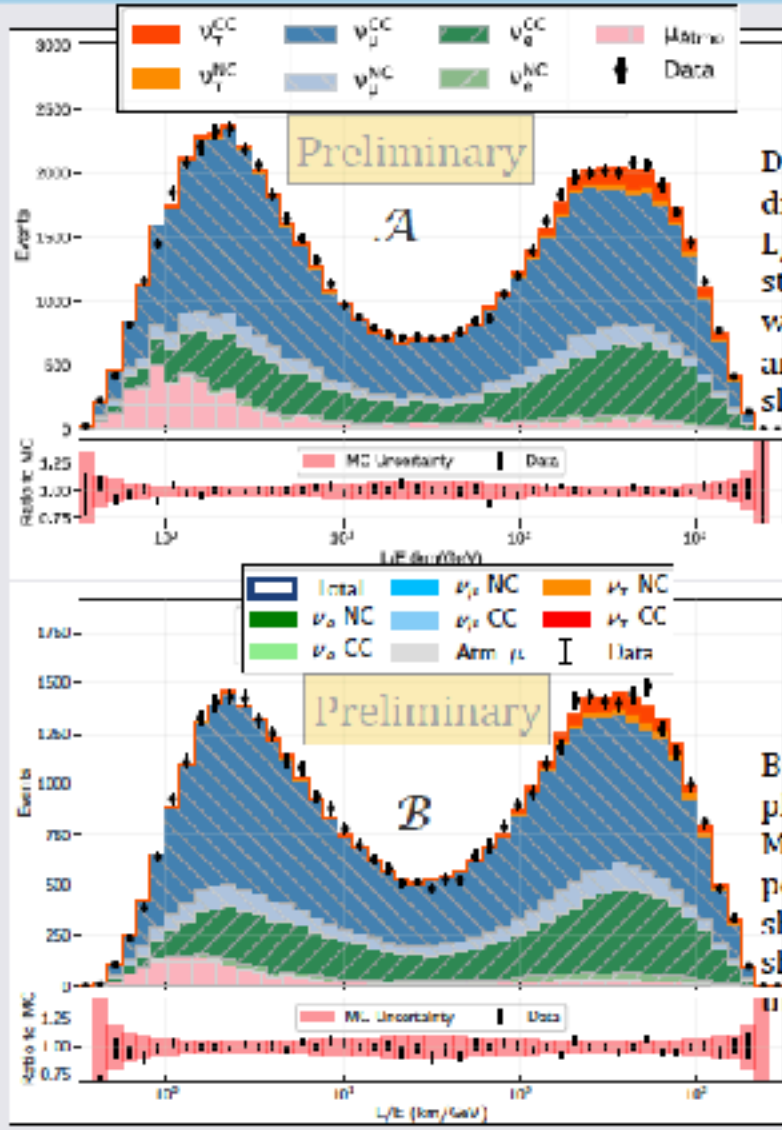
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Data distributions with best fit ν_e / ν_μ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.

N_{event}



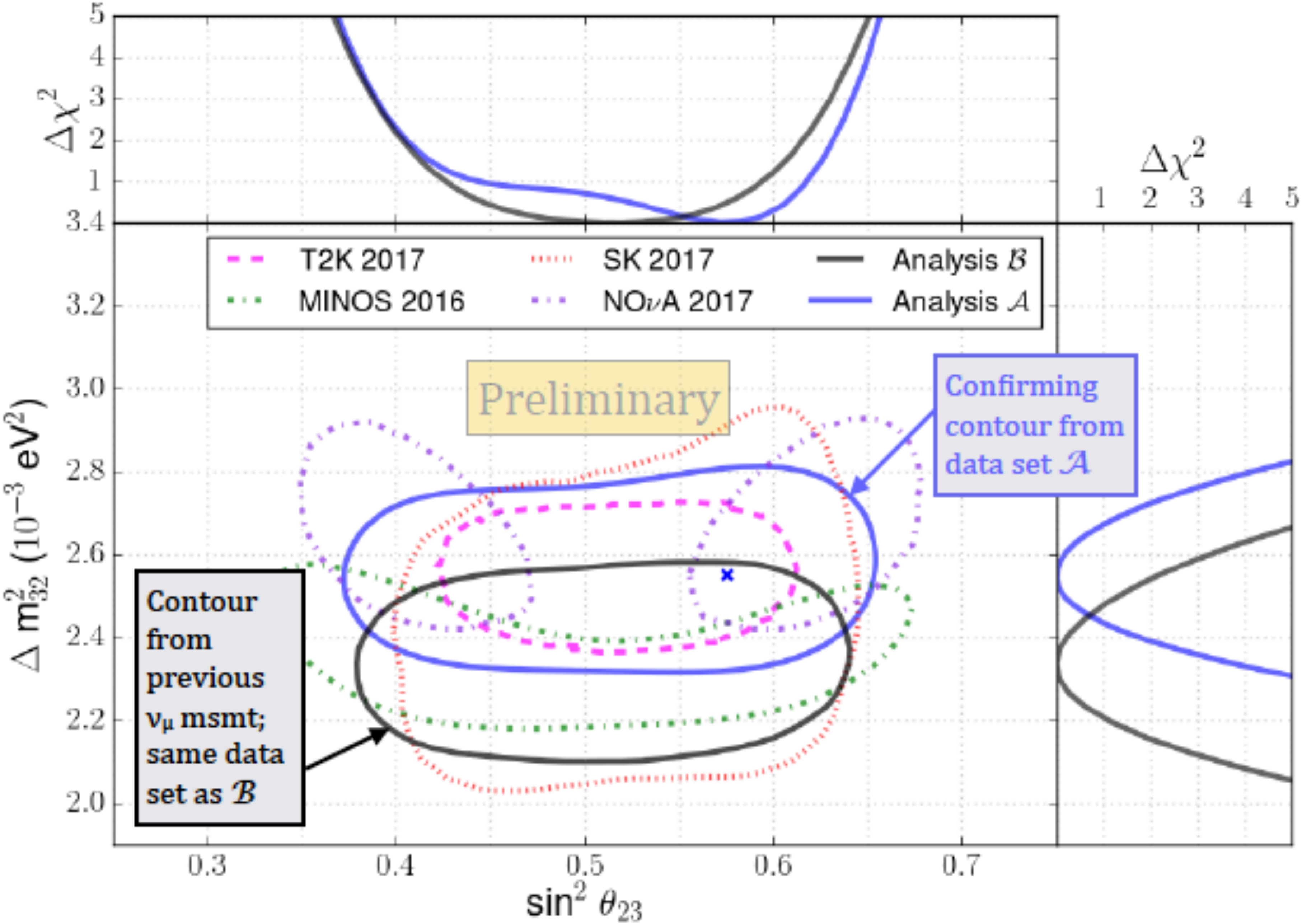
E_{reco} (GeV) $\cos(\theta_{zen})_{reco}$ PID_{reco}



$(L/E)_{reco}$ (km/GeV)

Data distributions vs. L/E (points with stat. error bars), with best-fit ν and μ bkgds. shown (hists.).

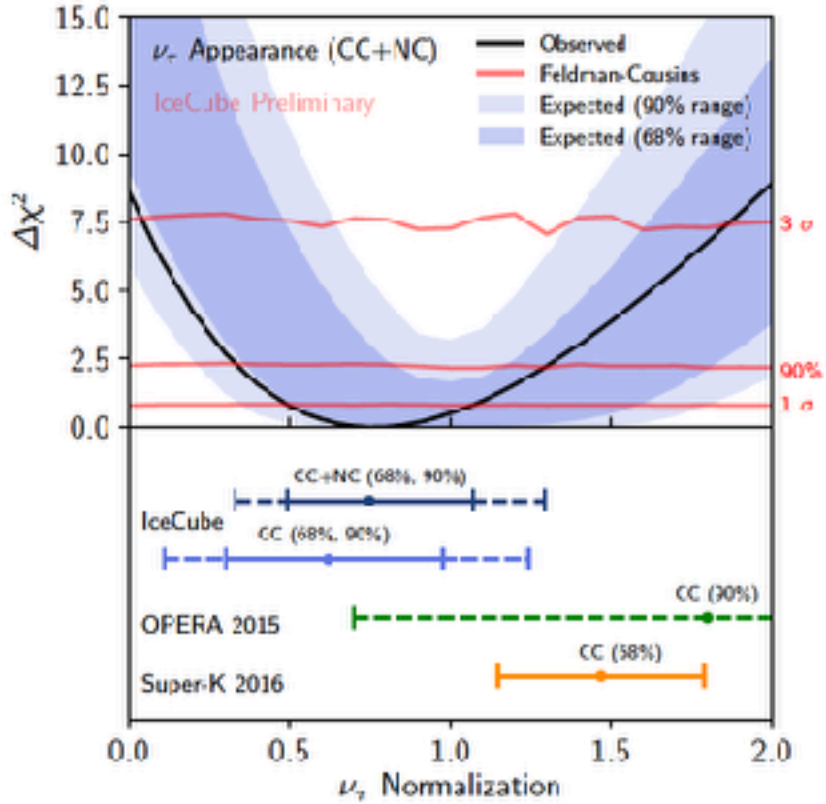
Bottom of each plot shows data/MC at best fit point, with shaded region showing stat. unc. of best fit.



Δχ²
T2K 2017
SK 2017
Analysis ℬ
MINOS 2016
NOνA 2017
Analysis 𝒜
Preliminary
Confirming contour from data set 𝒜
Contour from previous νμ msmt; same data set as ℬ
Δ m²₃₂ (10⁻³ eV²)
sin² θ₂₃

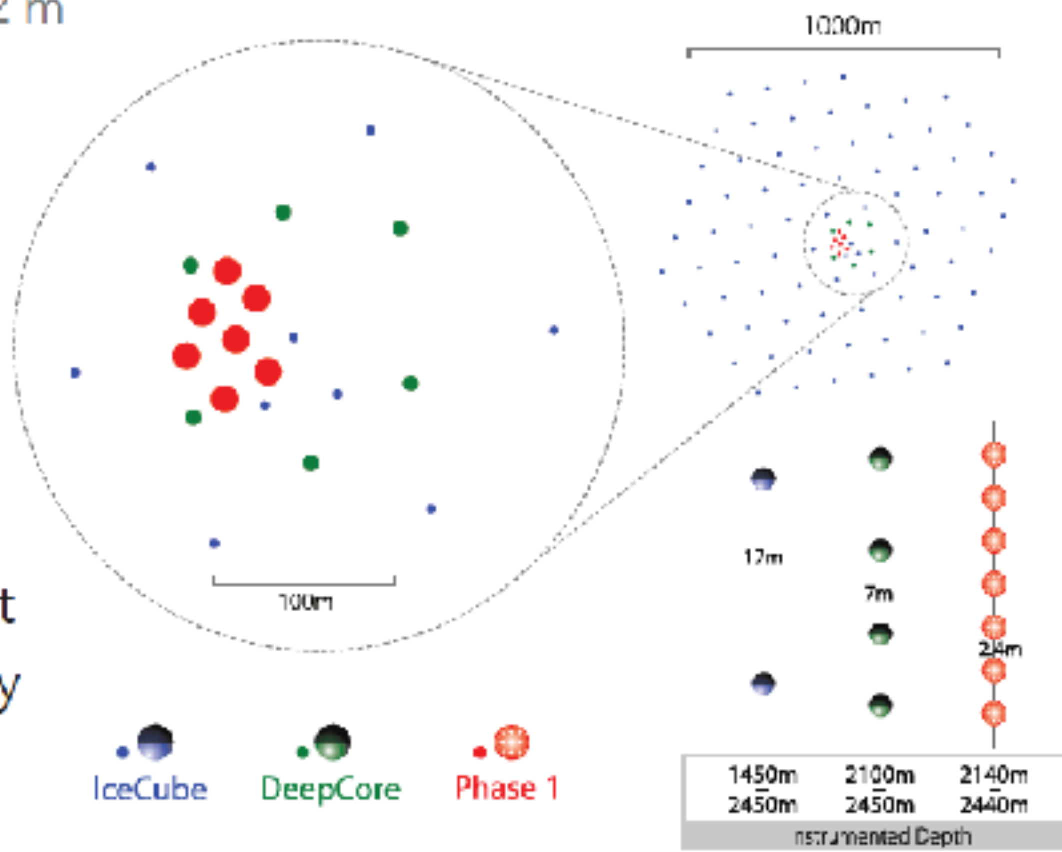
Tau Appearance and PMNS Unitarity

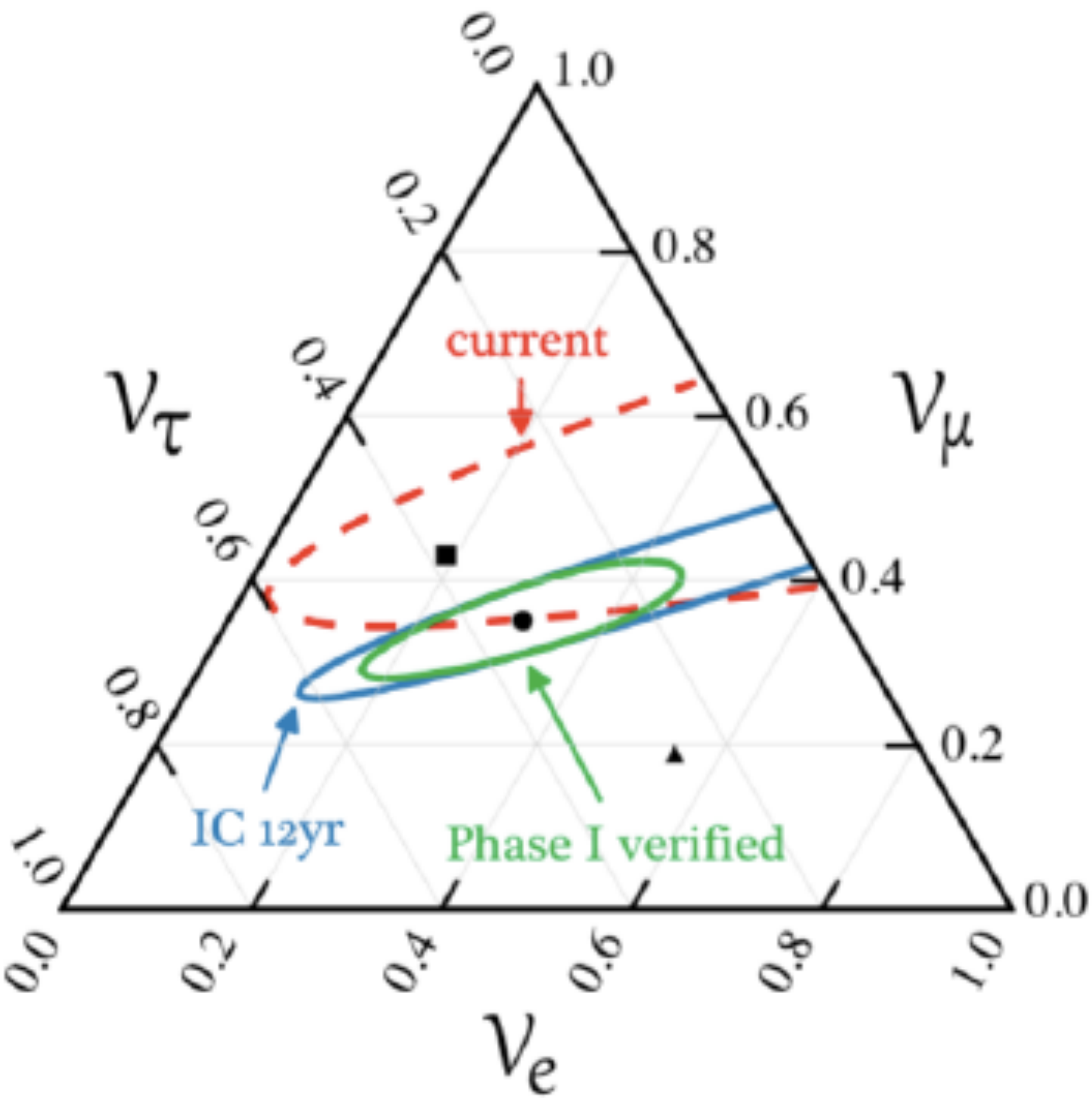
- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix



Next Step: the IceCube Upgrade

- 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



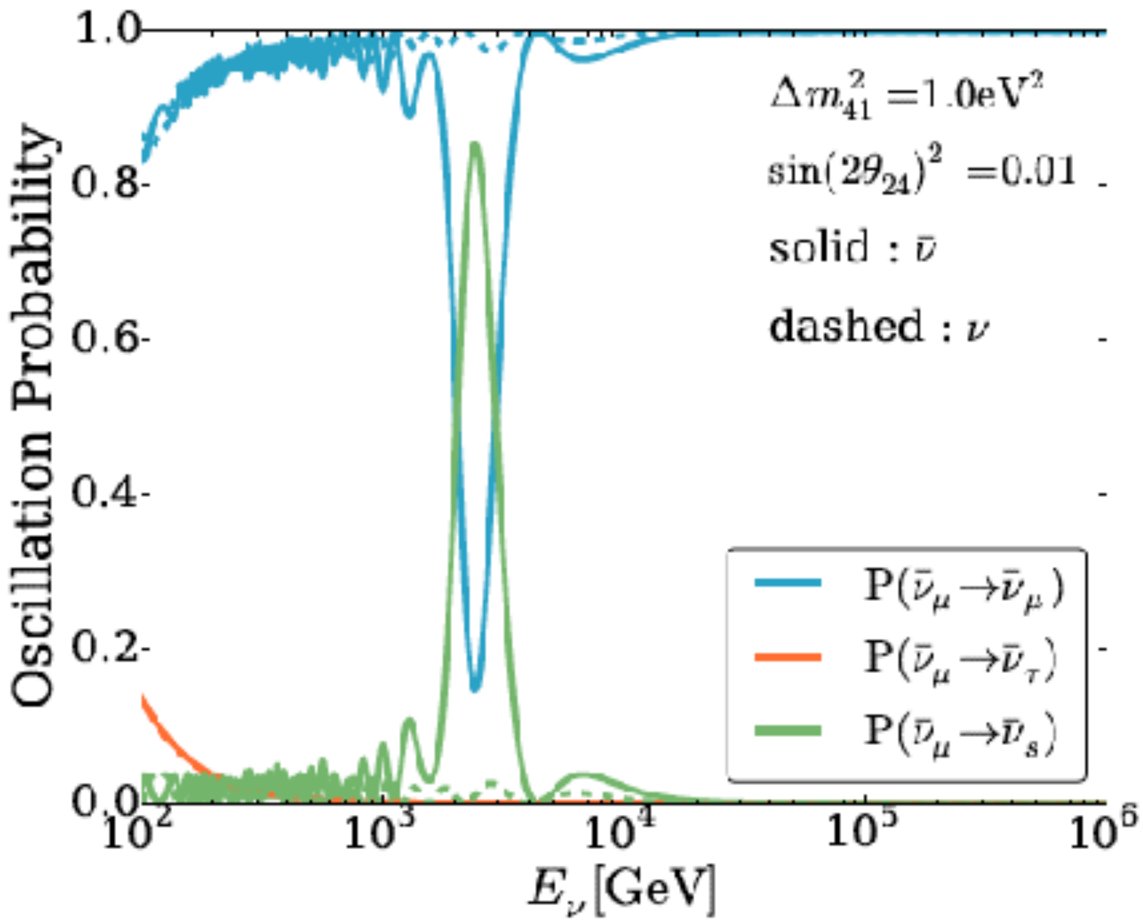


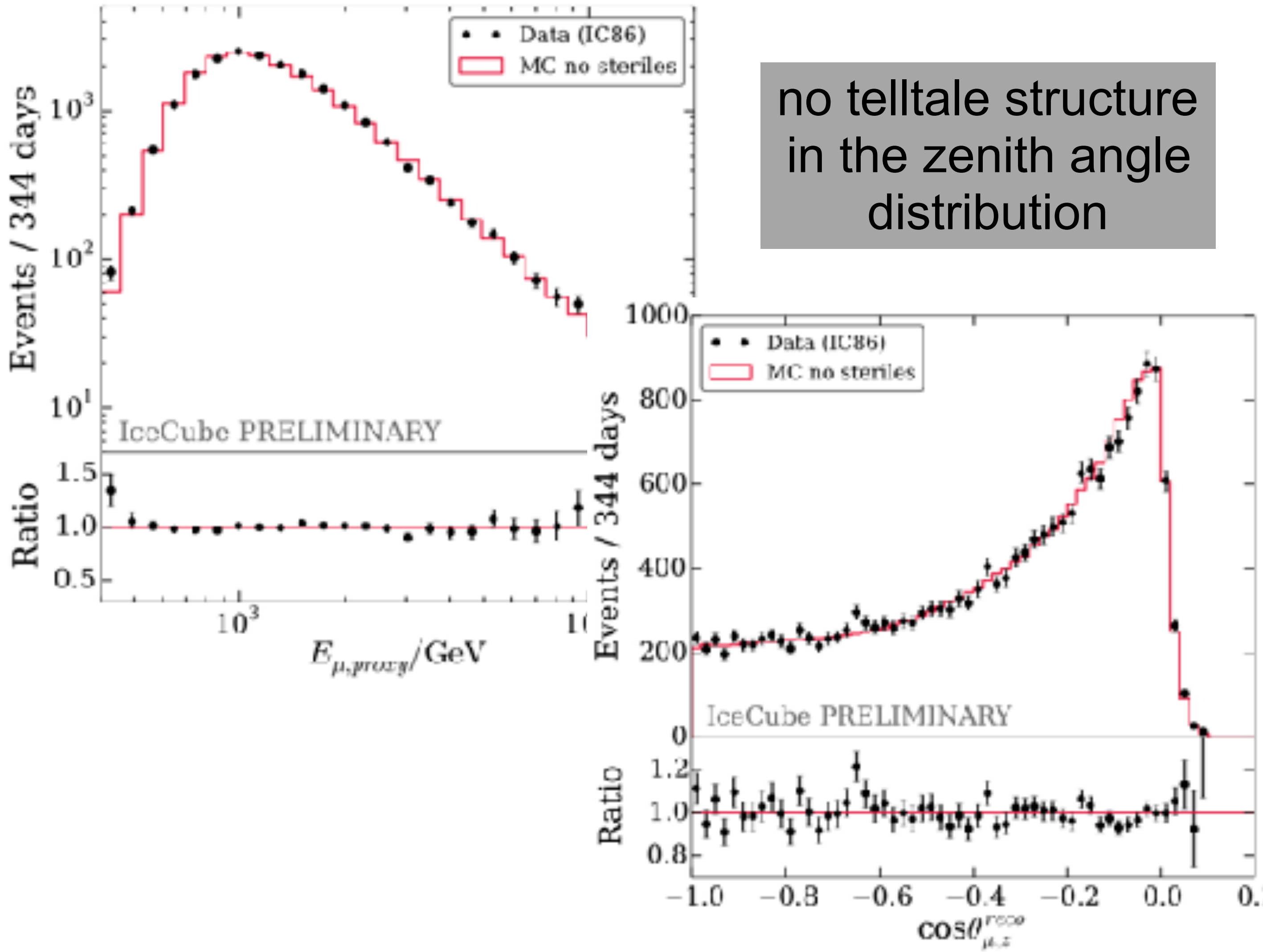
current
IC 12yr
Phase I verified
ν_τ
ν_μ
ν_e
0.0
0.2
0.4
0.6
0.8
1.0

eV sterile neutrino → Earth MSW resonance for TeV neutrinos

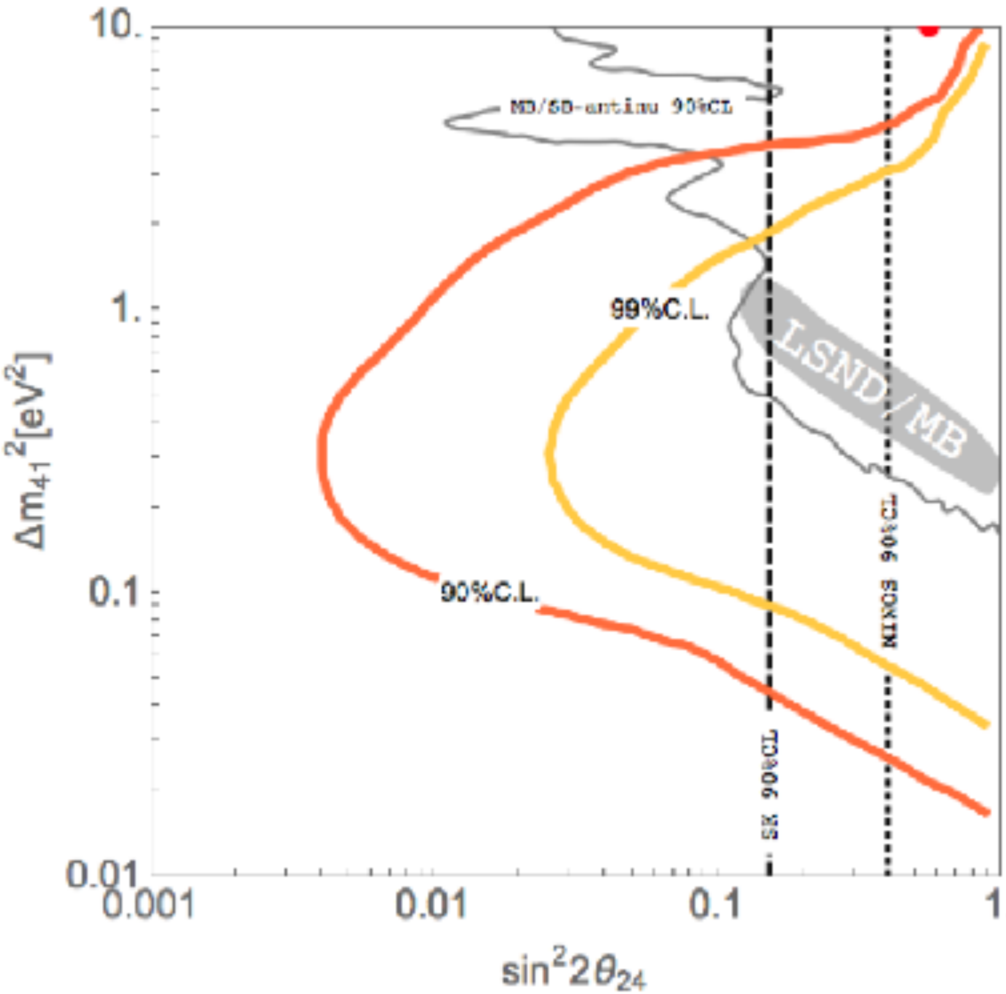
effect happens when

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





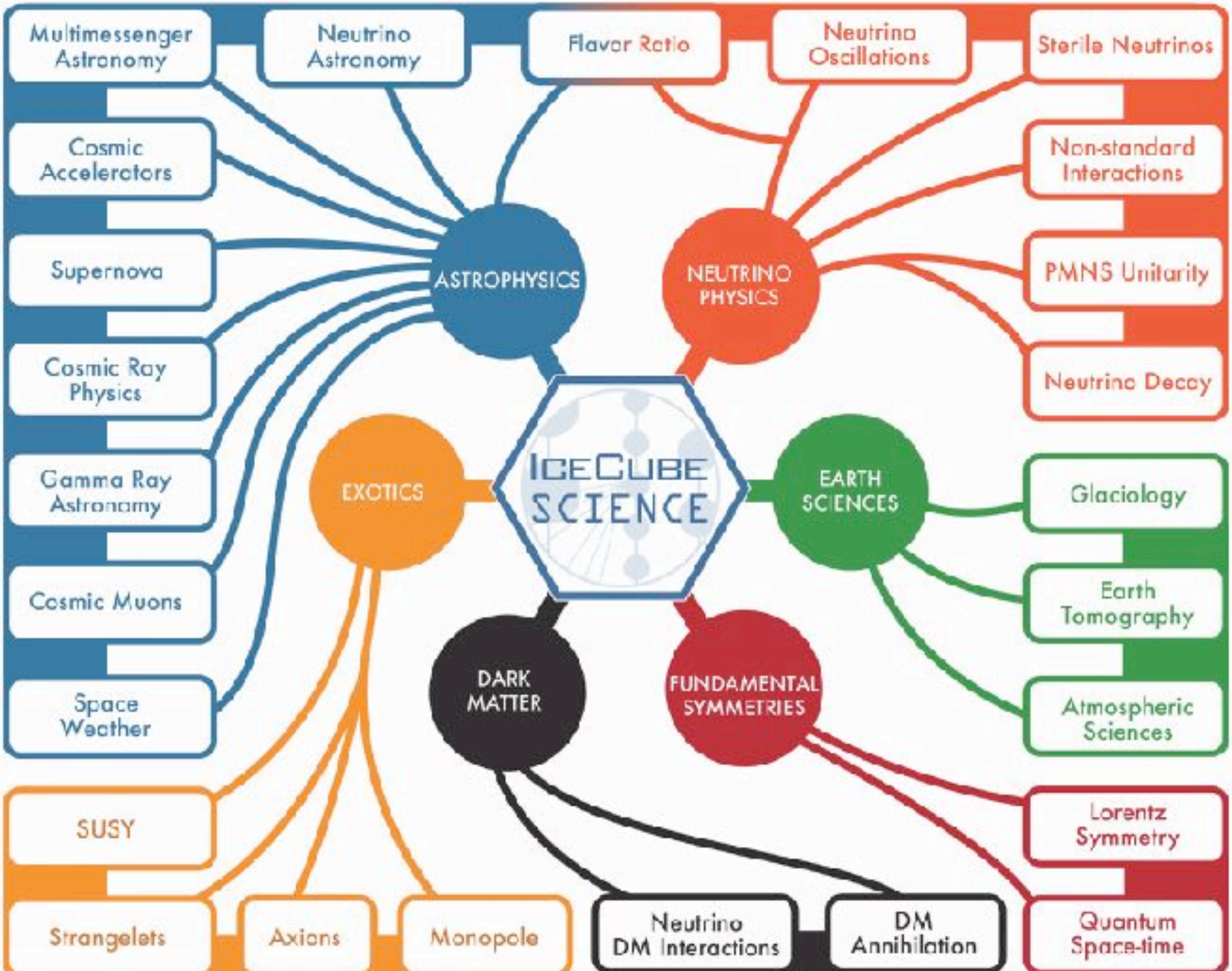
no telltale structure in the zenith angle distribution



from 1 → 7 years of data
soon

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
- ….


Multimessenger Astronomy
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Cosmic Accelerators
Non-standard Interactions
Supernova
ASTROPHYSICS
NEUTRINO PHYSICS
PMNS Unitarity
Cosmic Ray Physics
Neutrino Decay
Gamma Ray Astronomy
EXOTICS
ICECUBE SCIENCE
EARTH SCIENCES
Glaciology
Cosmic Muons
Earth Tomography
DARK MATTER
FUNDAMENTAL SYMMETRIES
Space Weather
Atmospheric Sciences
SUSY
Lorentz Symmetry
Strangelets
Axions
Monopole
Neutrino DM Interactions
DM Annihilation
Quantum Space-time

Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos are essential for understanding the non-thermal universe.
- identified the first high-energy cosmic ray accelerator
- from discovery to astronomy: more events, more telescopes
  IceCube-Gen2, KM3NeT and GVD (Baikal)
- 10 years of IceCube data -pass 2 (detector geometry with individual DOMs, more photons in reconstruction, better calibration)

THE ICECUBE COLLABORATION

STRALIA 1

GDOM 1

UNITED STATES 25

ICECUBE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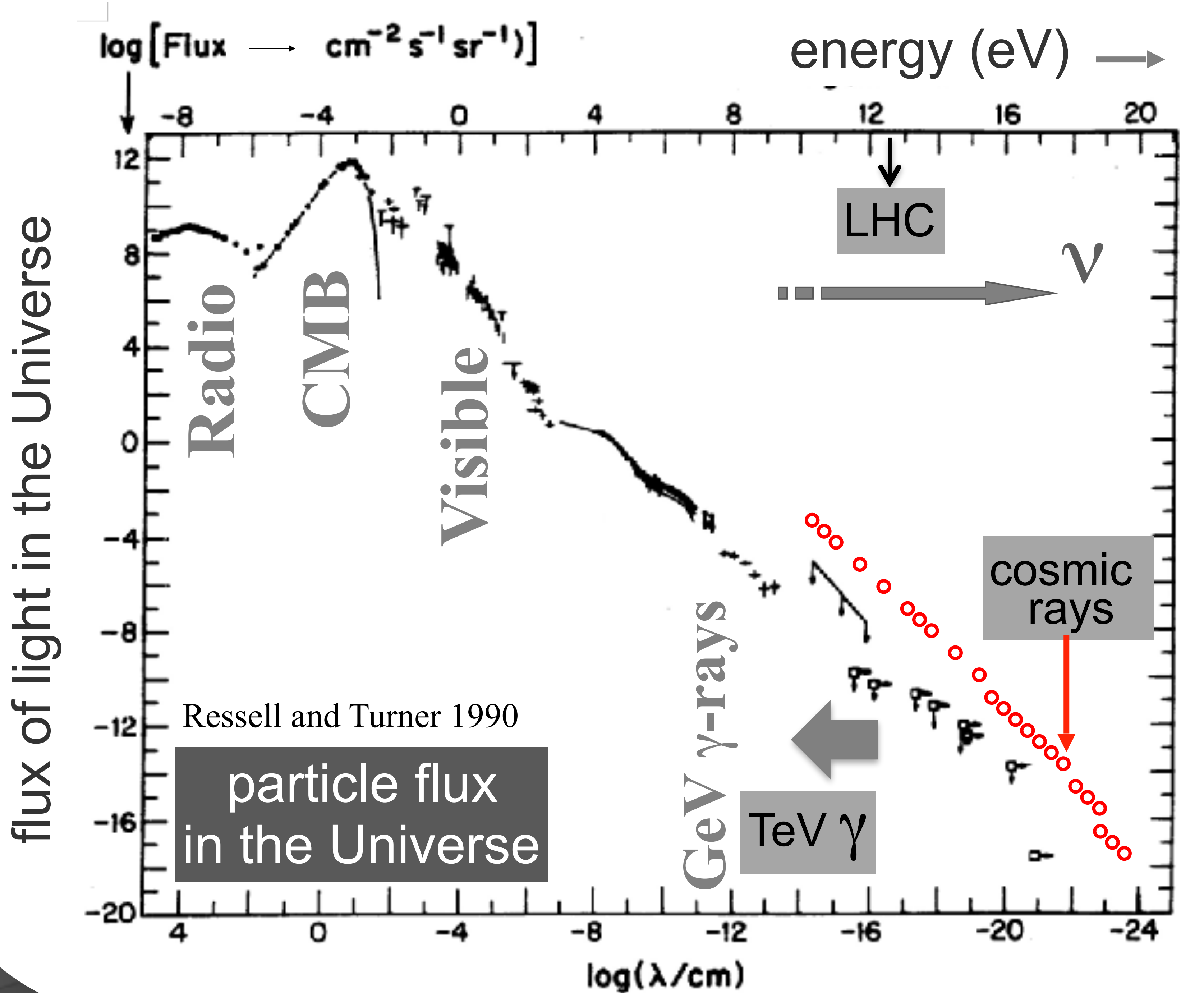
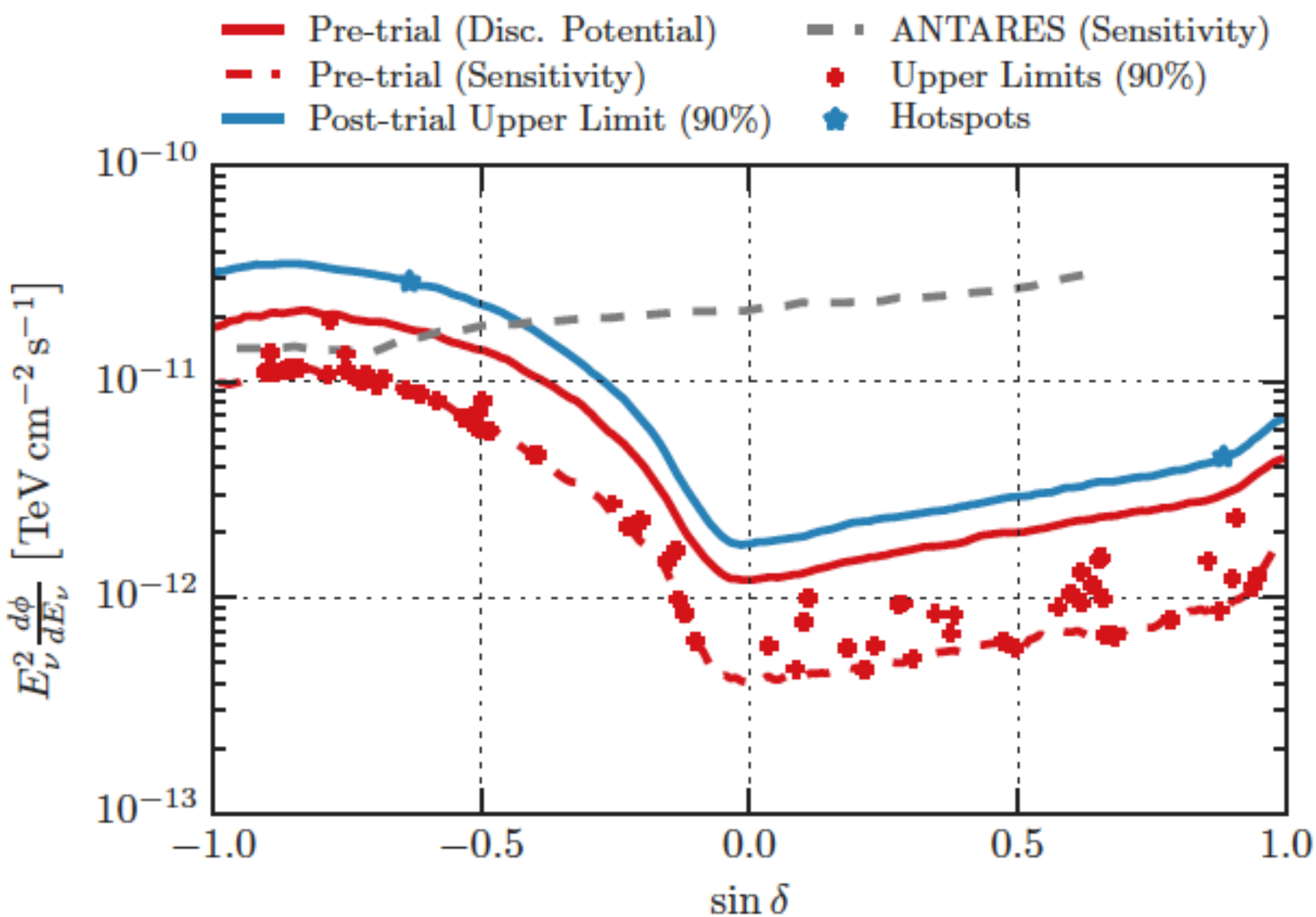
overflow slides



log[Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV)
-8 -4 0 4 8 12 16 20
12 8 4 0 -4 -8 -12 -16 -20
LHC
ν
Radio
CMB
Visible
GeV γ-rays
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe
4 0 -4 -8 -12 -16 -20 -24
log(λ/cm)
flux of light in the Universe



when resolved point sources?

Olbers paradox

$$\phi_{\text{diff}} = \int d^3r \frac{L_\nu}{4\pi r^2} \cdot \rho$$

diffuse flux is measured

nearest source

$$\frac{4}{3}\pi d_{ns}^3 \cdot \rho = 1$$

and

$$d_{\text{ns}} \sim \rho^{-1/3}$$

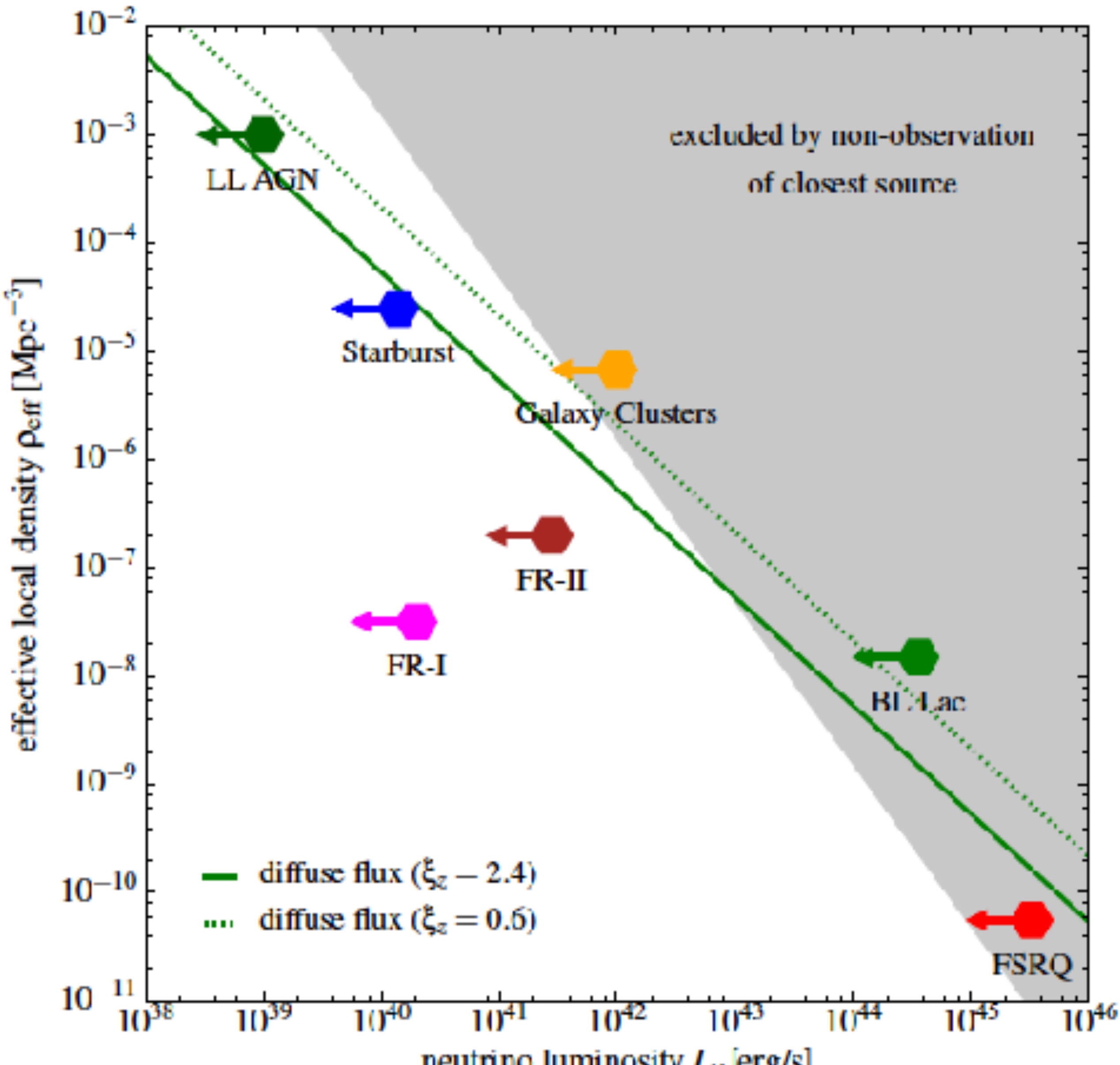
$$\phi_{\text{ns}} = \frac{L_\nu}{4\pi d_{\text{ns}}^2} \sim (L_\nu \cdot \rho)\, d_{\text{ns}} \sim \phi_{\text{diff}} \cdot \rho^{-1/3}$$

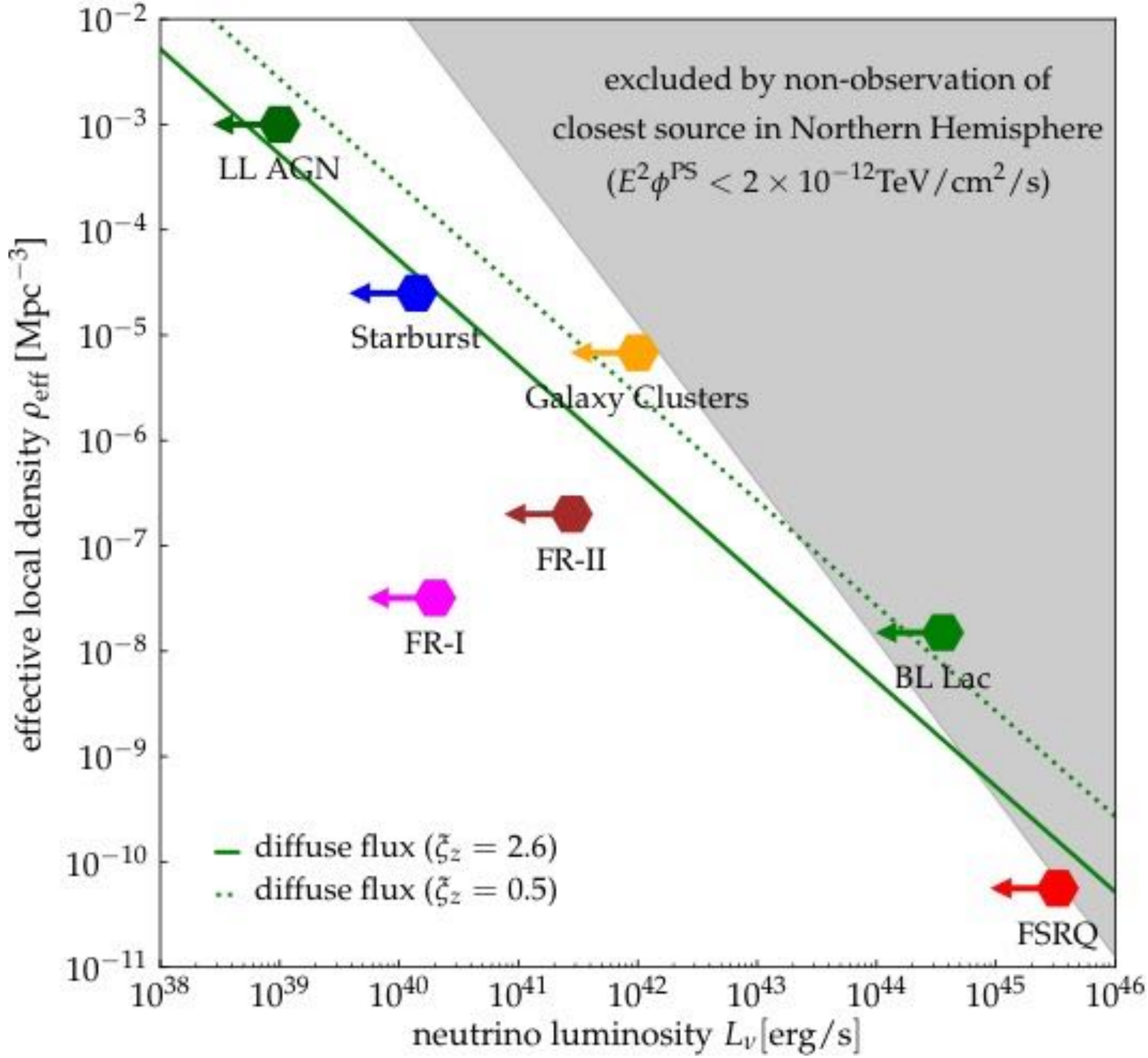
flux nearest source = (diffuse flux observed)(density of sources)$^{-1/3}$

Olbers paradox

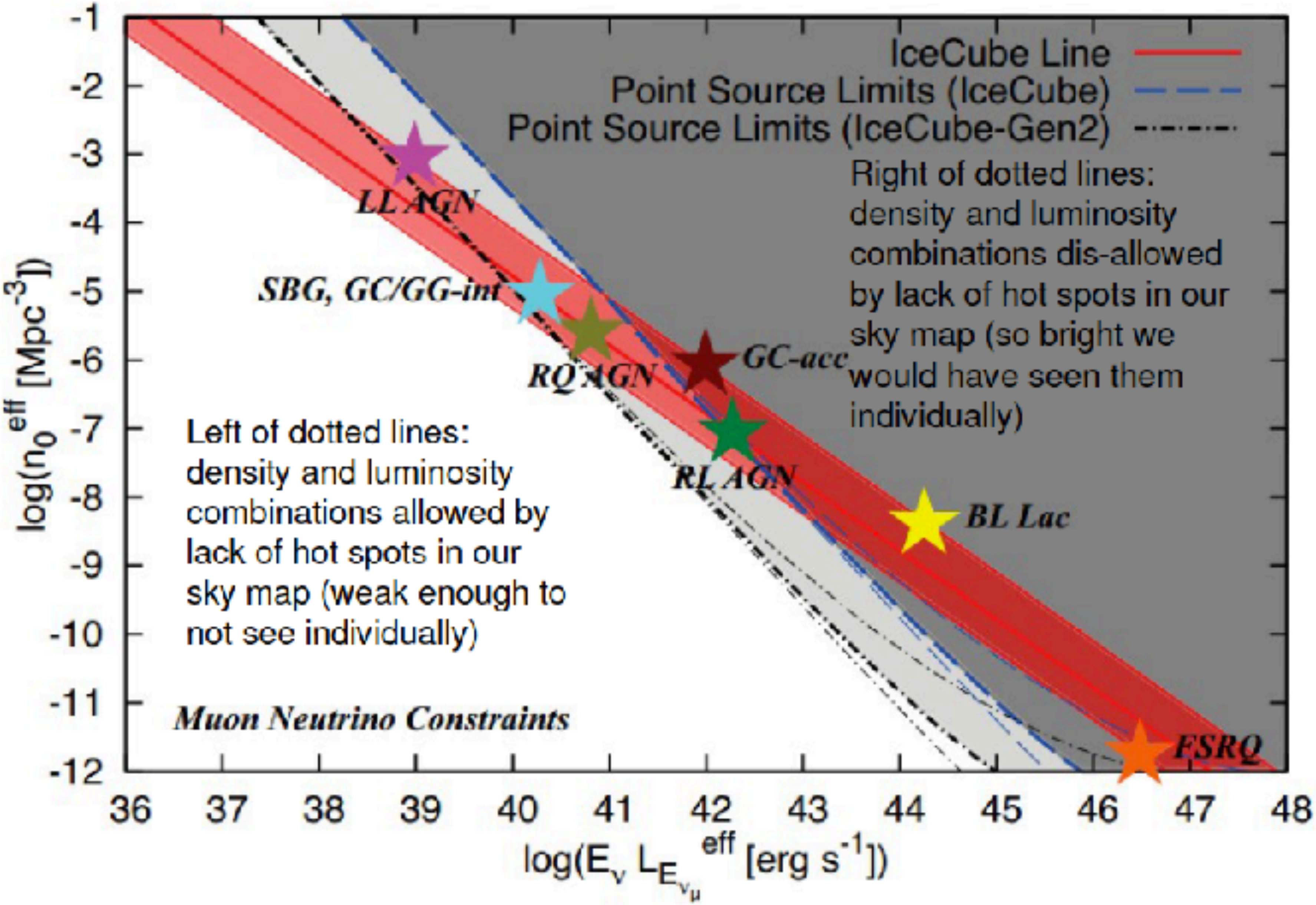
density 10^{-7} Mpc^{-3} soon !

blazars, FSRQ…

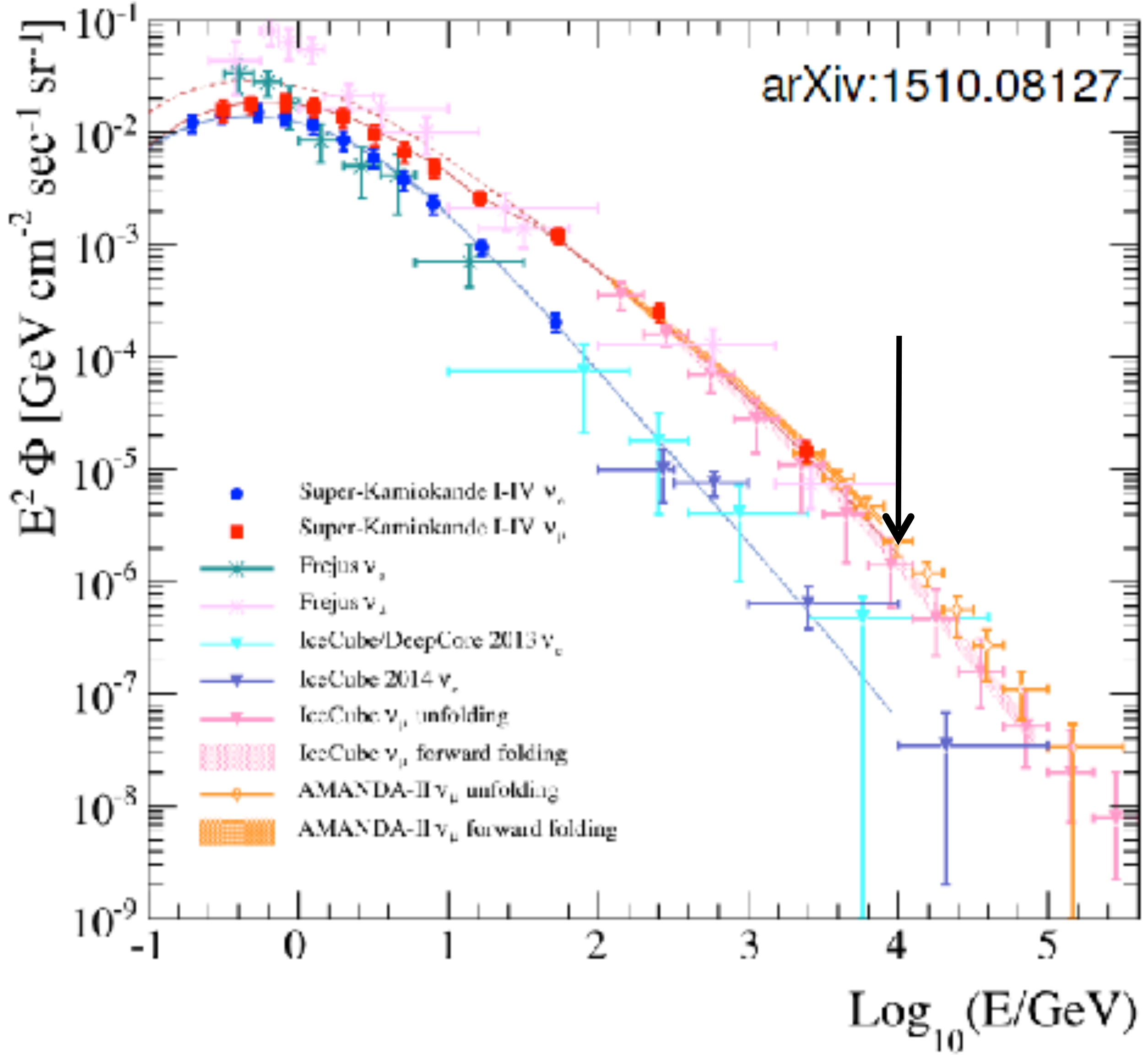




excluded by non-observation of
closest source in Northern Hemisphere
($E^2\phi^{PS} < 2 \times 10^{-12}$TeV/cm^2/s)
LL AGN
Starburst
Galaxy Clusters
FR-II
FR-I
BL Lac
FSRQ
diffuse flux ($\xi_z = 2.6$)
diffuse flux ($\xi_z = 0.5$)
effective local density ρ_{eff} [Mpc^{-3}]
neutrino luminosity L_ν[erg/s]



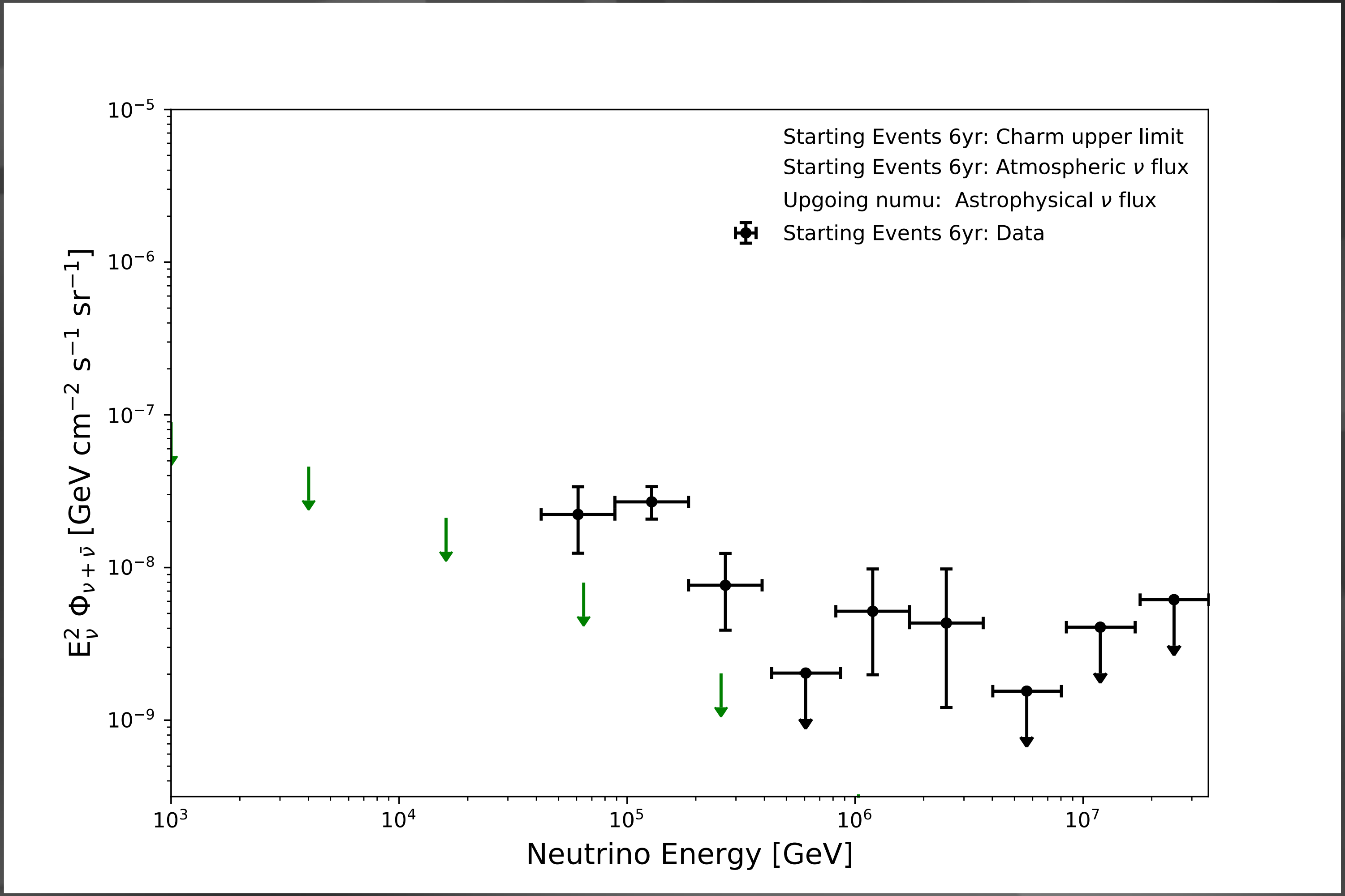
IceCube Line
Point Source Limits (IceCube)
Point Source Limits (IceCube-Gen2)
Right of dotted lines: density and luminosity combinations dis-allowed by lack of hot spots in our sky map (so bright we would have seen them individually)
Left of dotted lines: density and luminosity combinations allowed by lack of hot spots in our sky map (weak enough to not see individually)
LL AGN
SBG, GC/GG-int
RQ AGN
GC-acc
RL AGN
BL Lac
FSRQ
Muon Neutrino Constraints
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
36
37
38
39
40
41
42
43
44
45
46
47
48
log(n0eff [Mpc-3])
log(Eν LEνμeff [erg s-1])



atmospheric neutrino spectrum (energy measurement) well understood at 10 TeV in terms of conventional neutrinos; charm contribution is small

not background: prompt decay of charm particles produced in the atmosphere

- tracks cosmic ray flux in energy, isotropic in zenith (normalization unknown): does not fit the data
- neutrino events are isolated
- constrained by atmospheric *electron* neutrino spectrum



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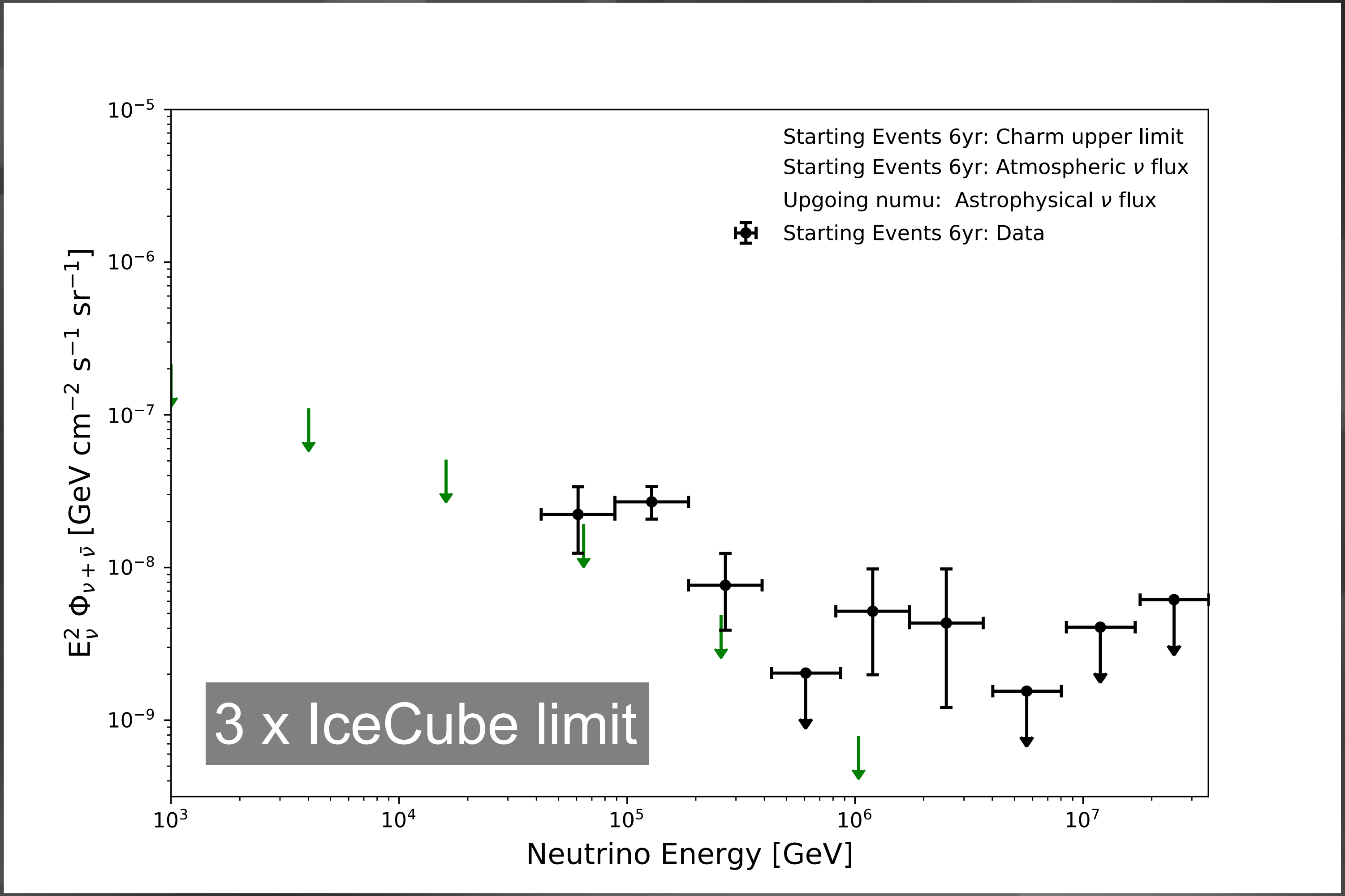
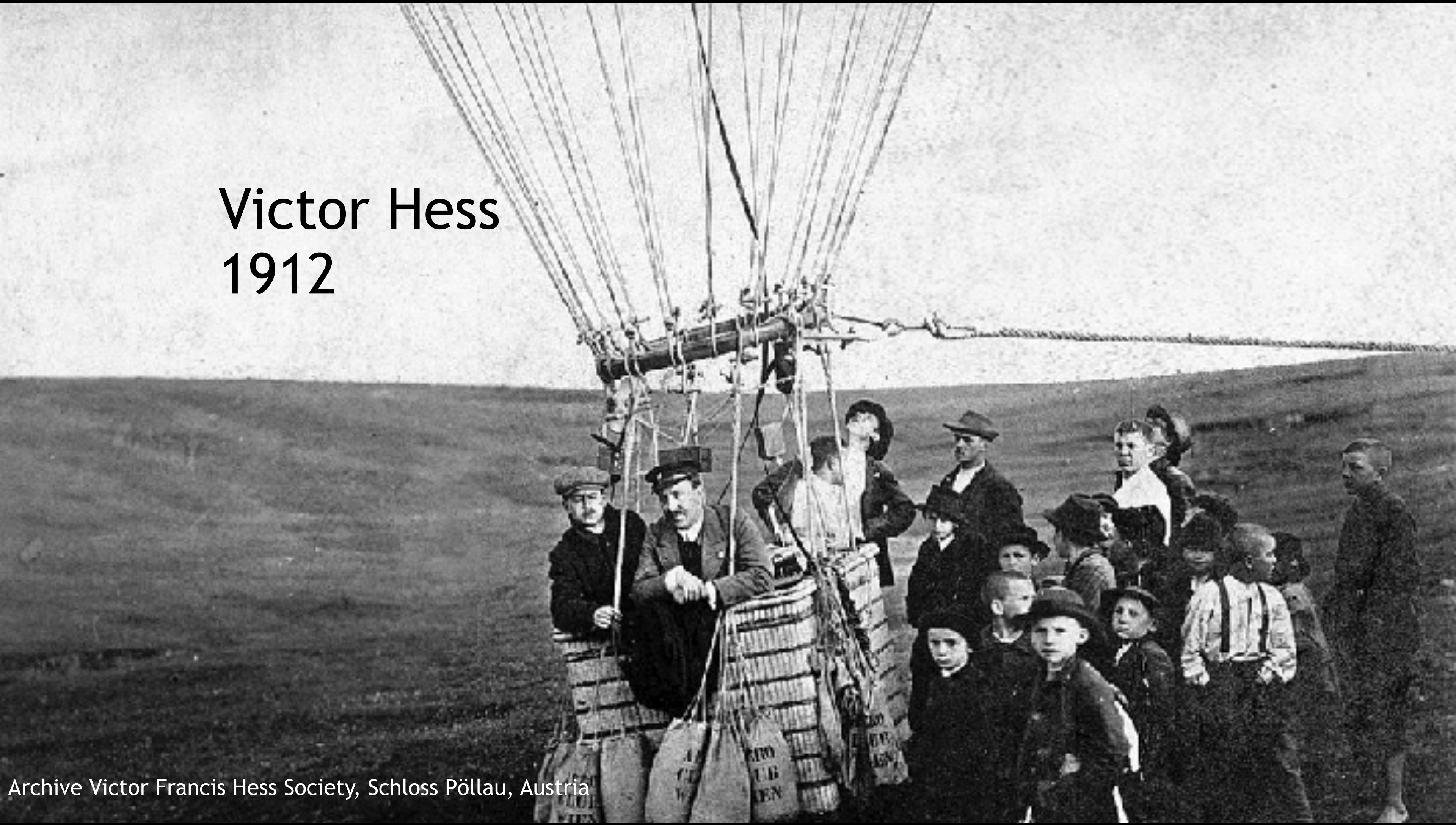
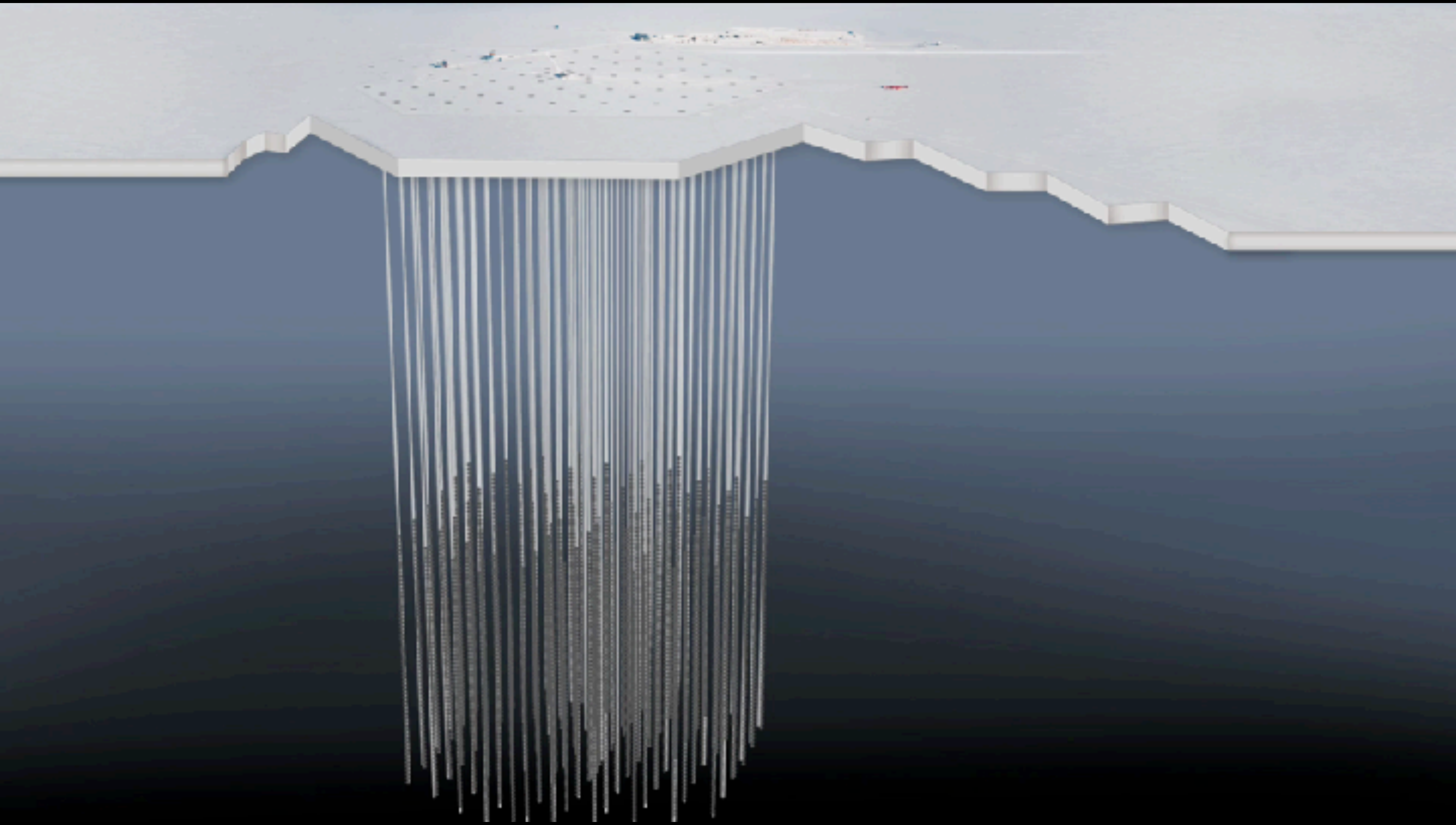
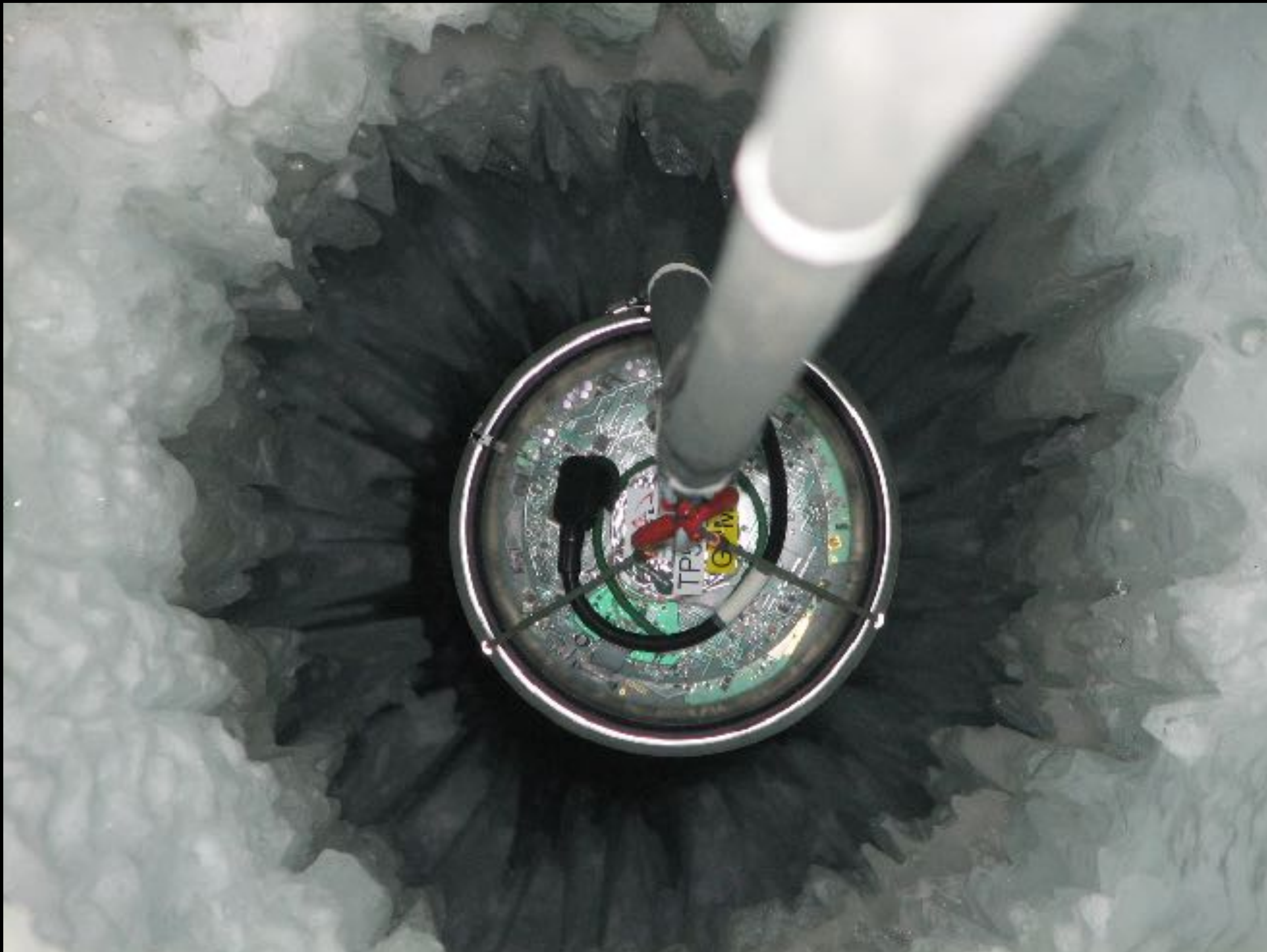


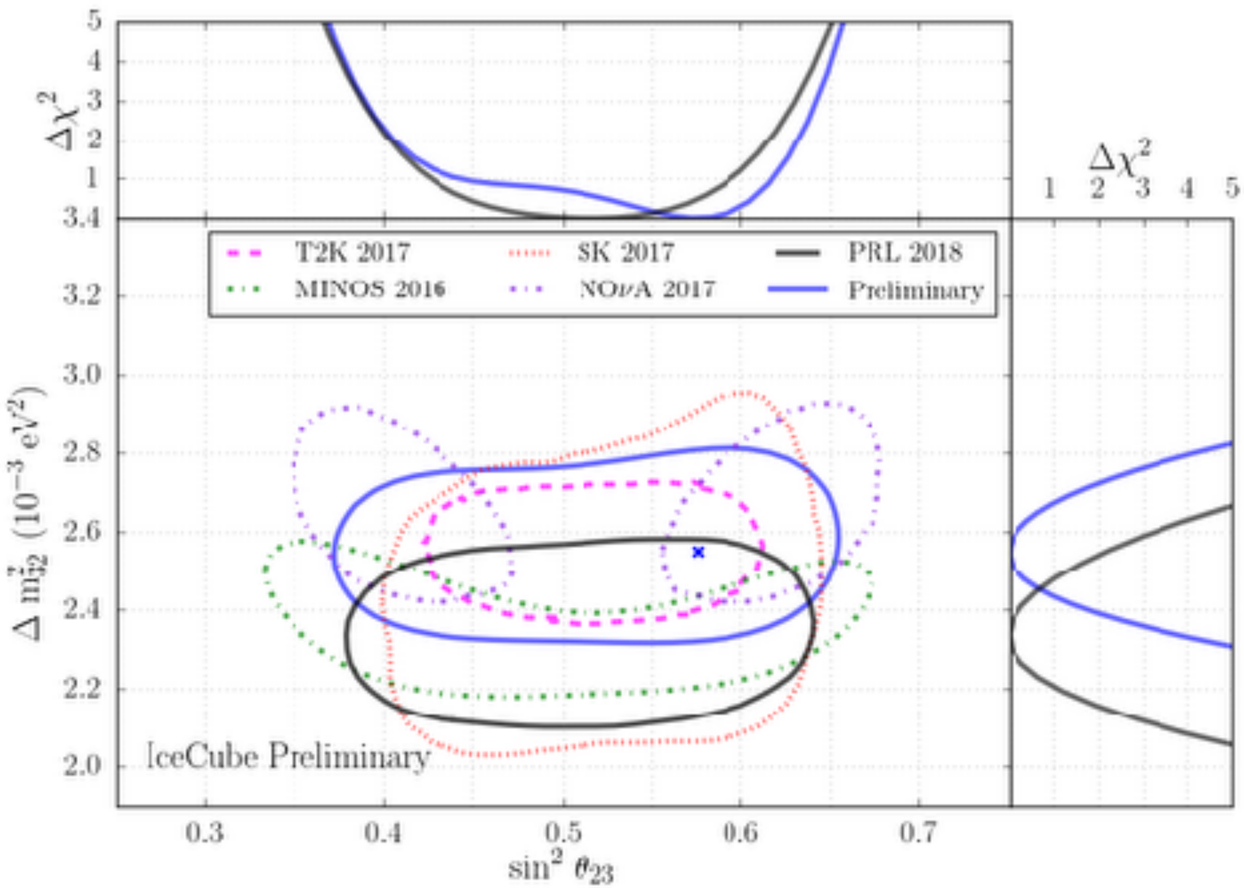


Victor Hess
1912

Archive Victor Francis Hess Society, Schloss Pöllau, Austria

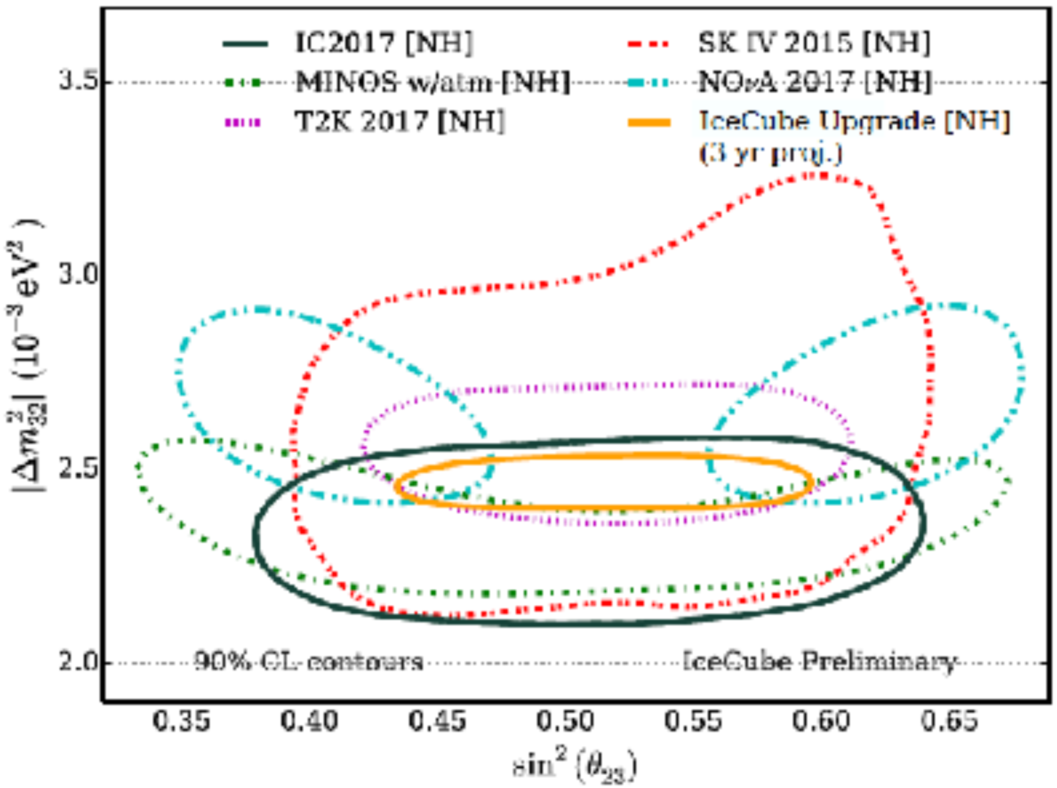





T2K 2017
SK 2017
PRL 2018
MINOS 2016
NOνA 2017
Preliminary
IceCube Preliminary
$\Delta\chi^2$
$\Delta\chi^2$
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2 \theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)