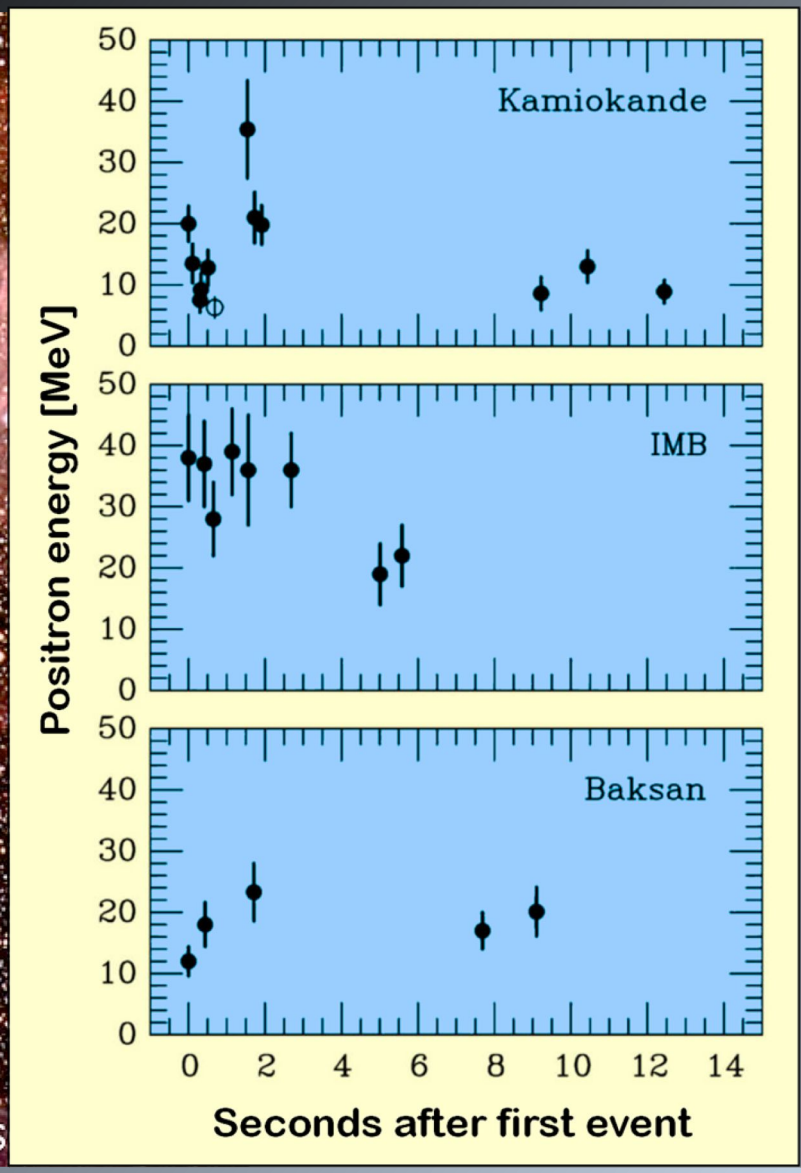
the discovery of cosmic neutrinos

francis halzen

- some history
- the challenge of best-buy theory
- a kilometer cubed detector
- the discovery of cosmic neutrinos
- where do they come from?

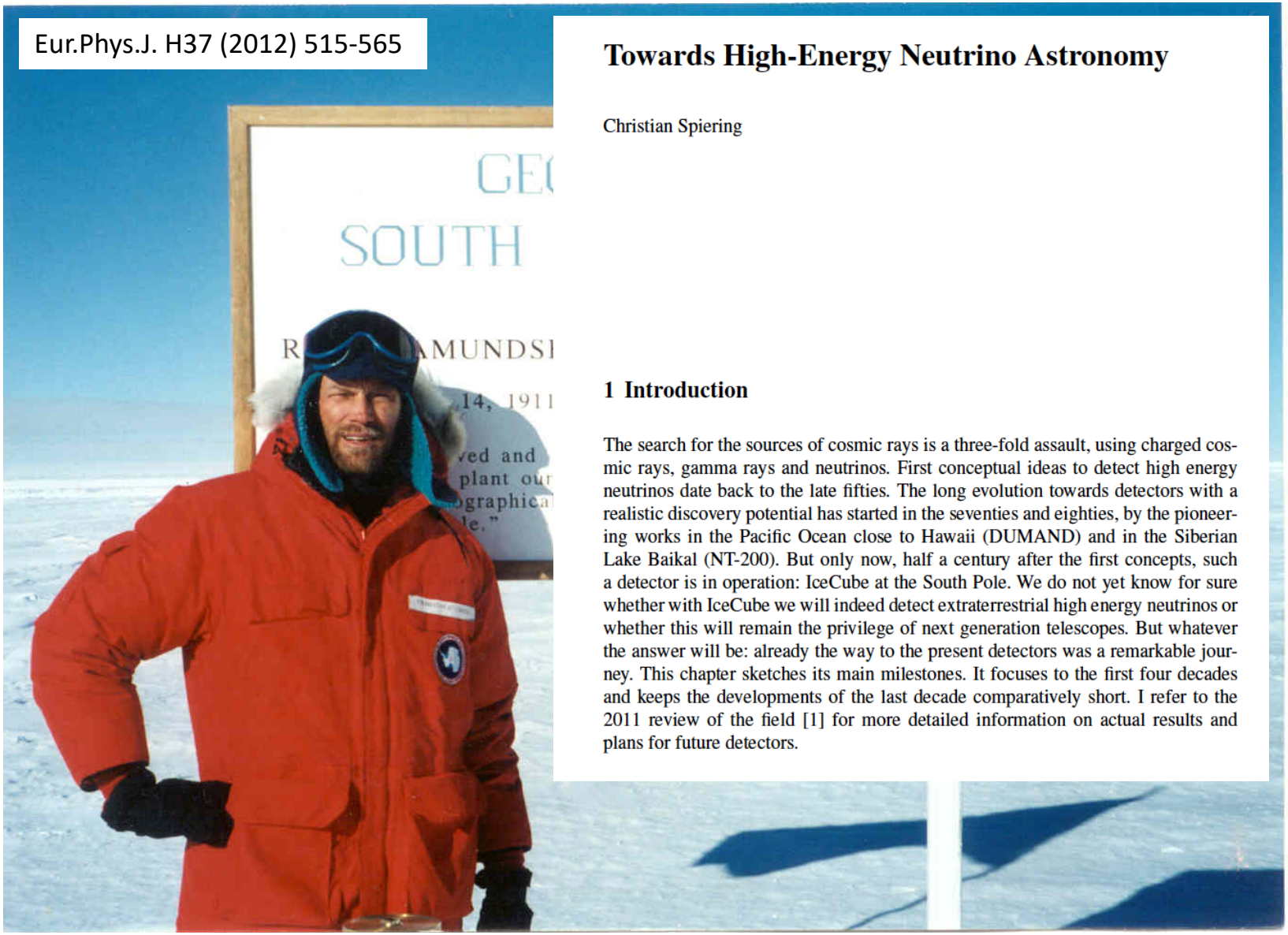
IceCube.wisc.edu

the birth of neutrino astronomy: supernova 1987A



Art Roberts, Rev.Mod.Phys. 64 (1992) 259-312
Christian Spiering and Uli Katz, Prog.Part.Nucl.Phys. 67 (2012) 651-704

Eur.Phys.J. H37 (2012) 515-565

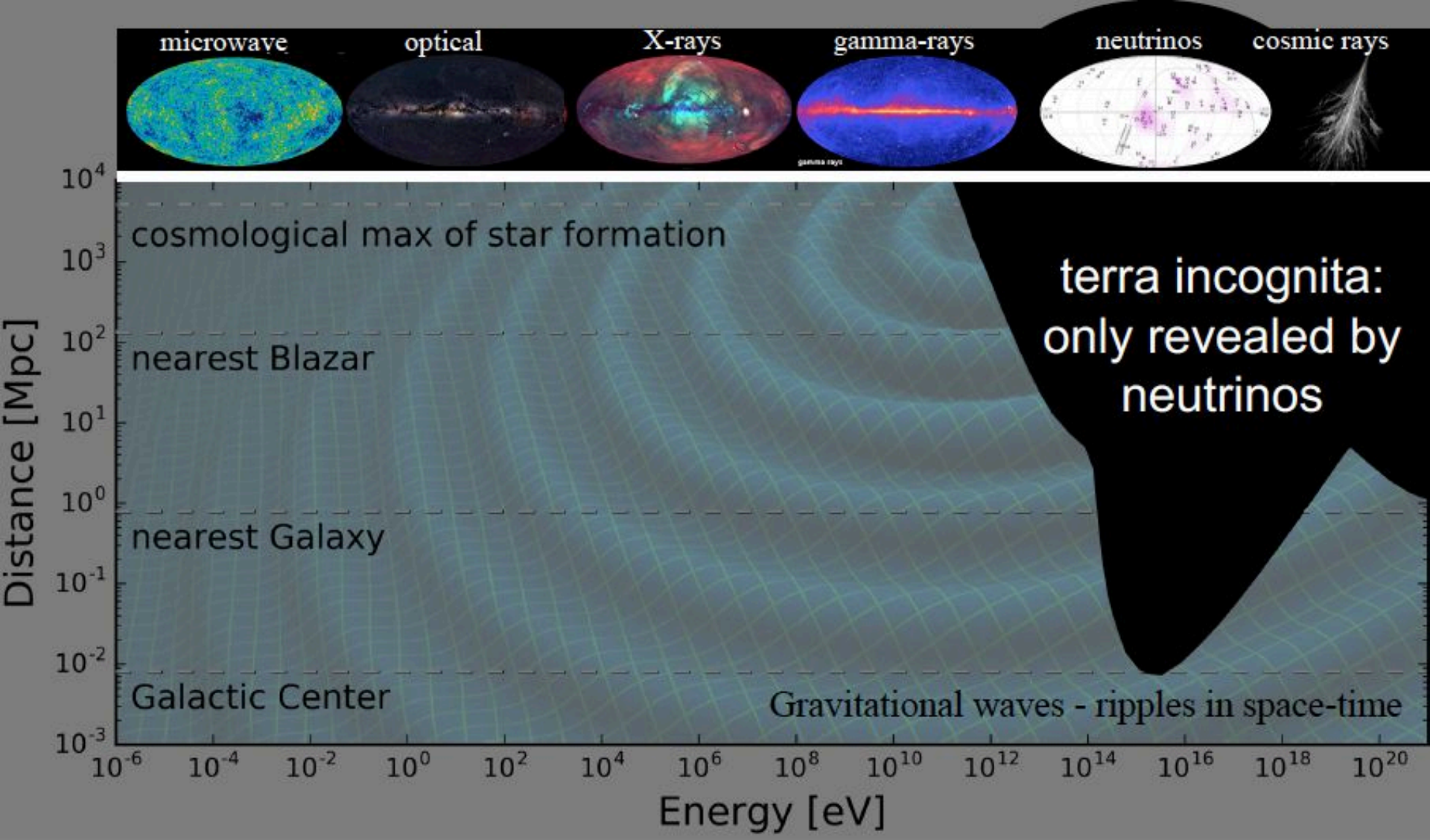


Towards High-Energy Neutrino Astronomy

Christian Spiering

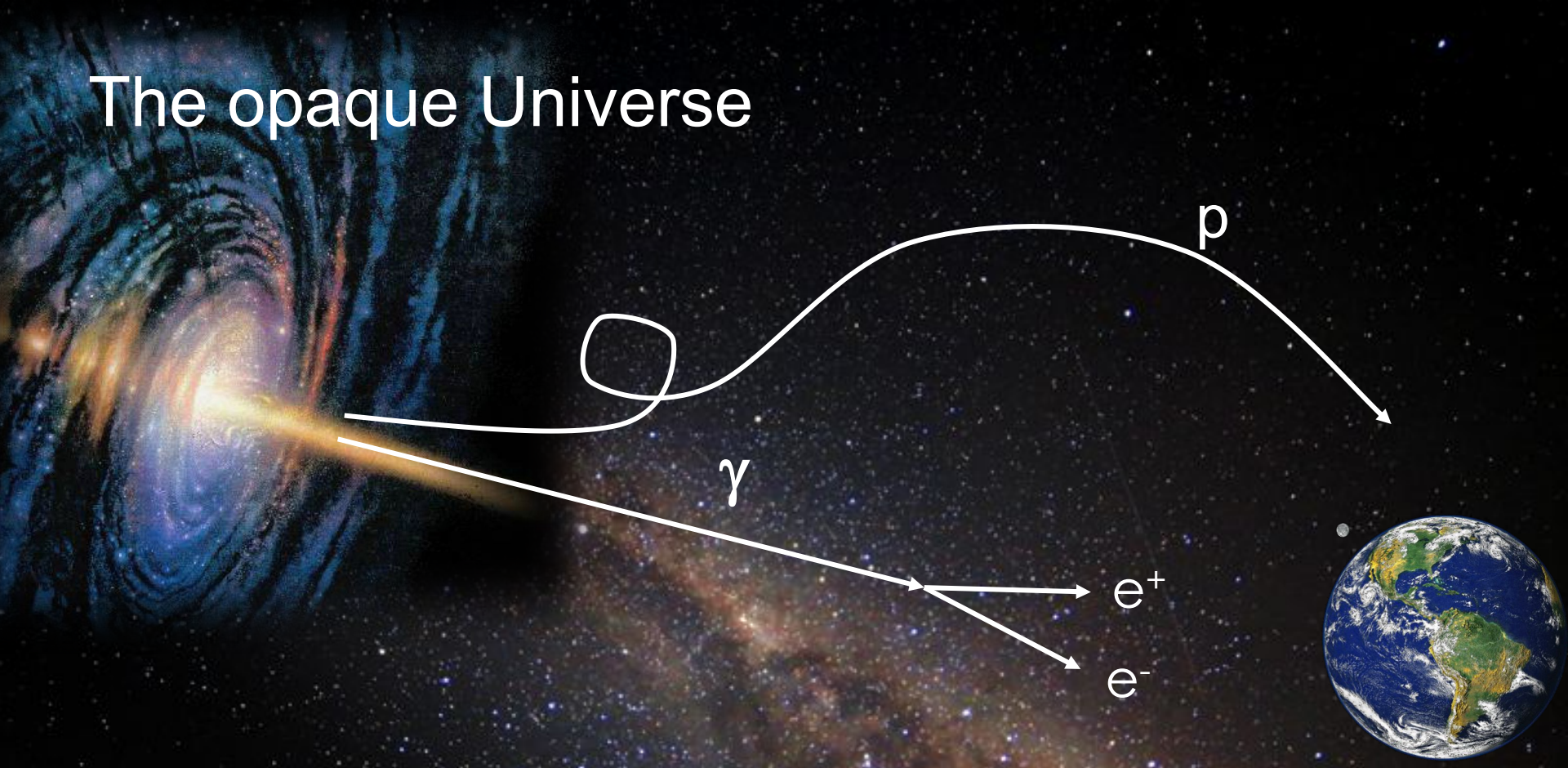
1 Introduction

The search for the sources of cosmic rays is a three-fold assault, using charged cosmic rays, gamma rays and neutrinos. First conceptual ideas to detect high energy neutrinos date back to the late fifties. The long evolution towards detectors with a realistic discovery potential has started in the seventies and eighties, by the pioneering works in the Pacific Ocean close to Hawaii (DUMAND) and in the Siberian Lake Baikal (NT-200). But only now, half a century after the first concepts, such a detector is in operation: IceCube at the South Pole. We do not yet know for sure whether with IceCube we will indeed detect extraterrestrial high energy neutrinos or whether this will remain the privilege of next generation telescopes. But whatever the answer will be: already the way to the present detectors was a remarkable journey. This chapter sketches its main milestones. It focuses to the first four decades and keeps the developments of the last decade comparatively short. I refer to the 2011 review of the field [1] for more detailed information on actual results and plans for future detectors.



- 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

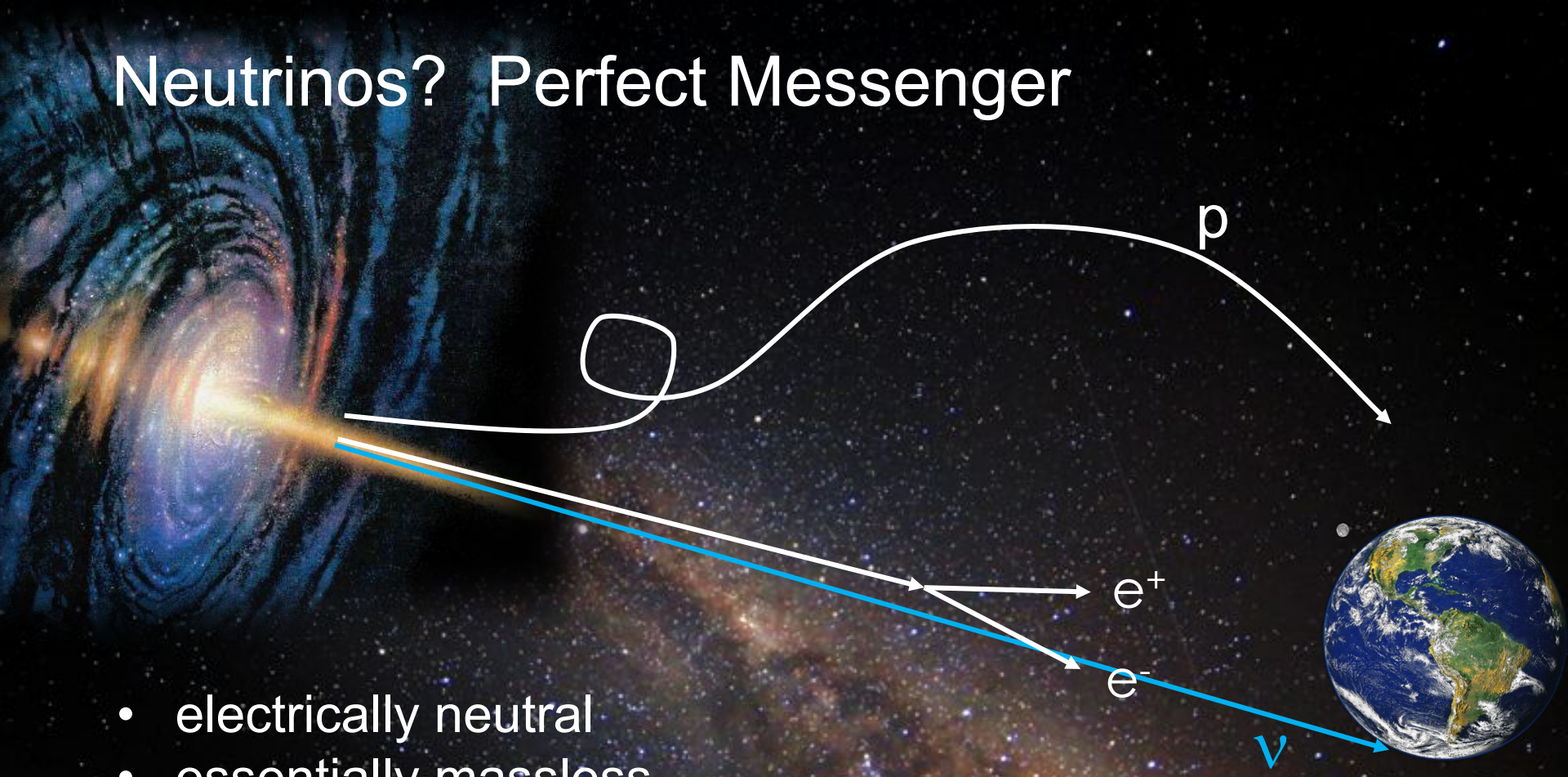


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

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

enter: neutrinos

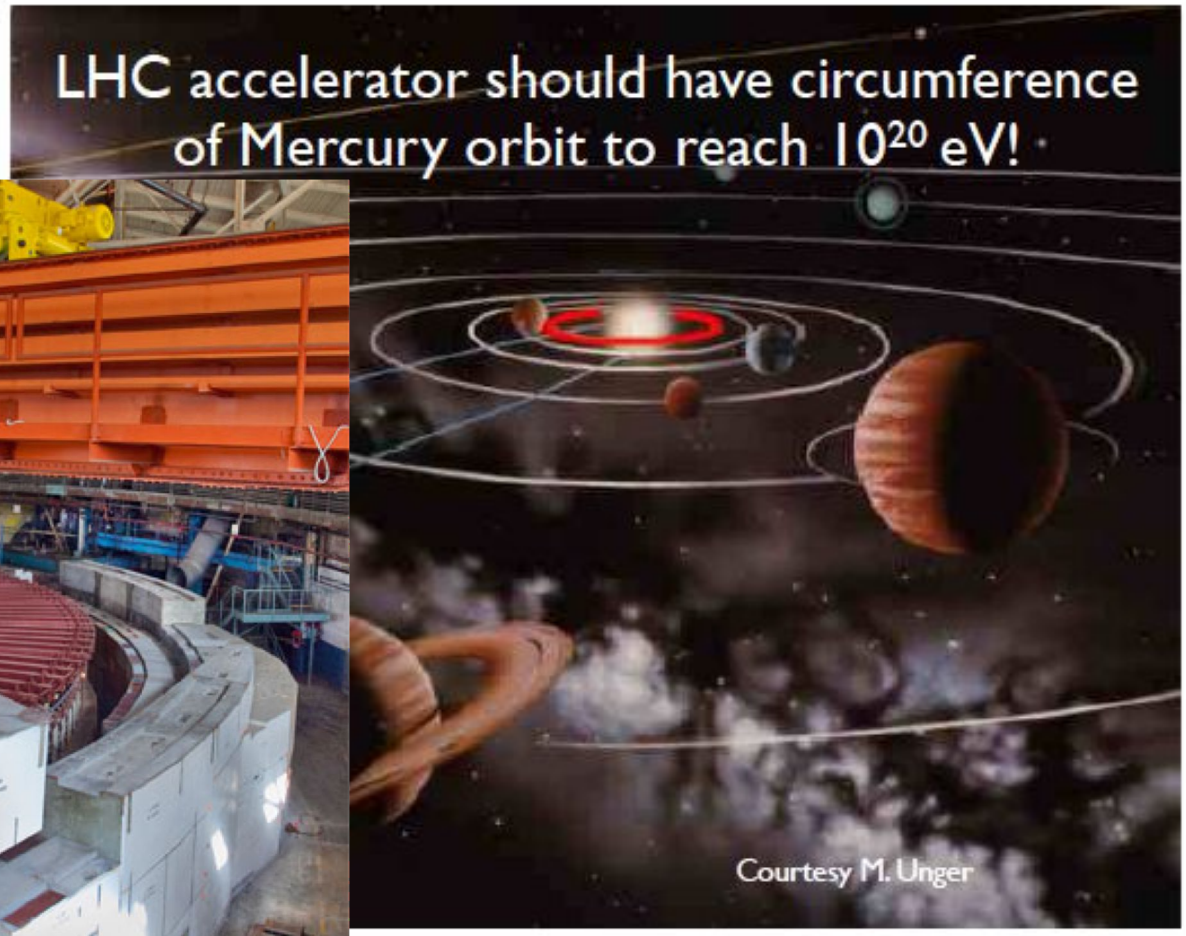
Neutrinos? Perfect Messenger



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

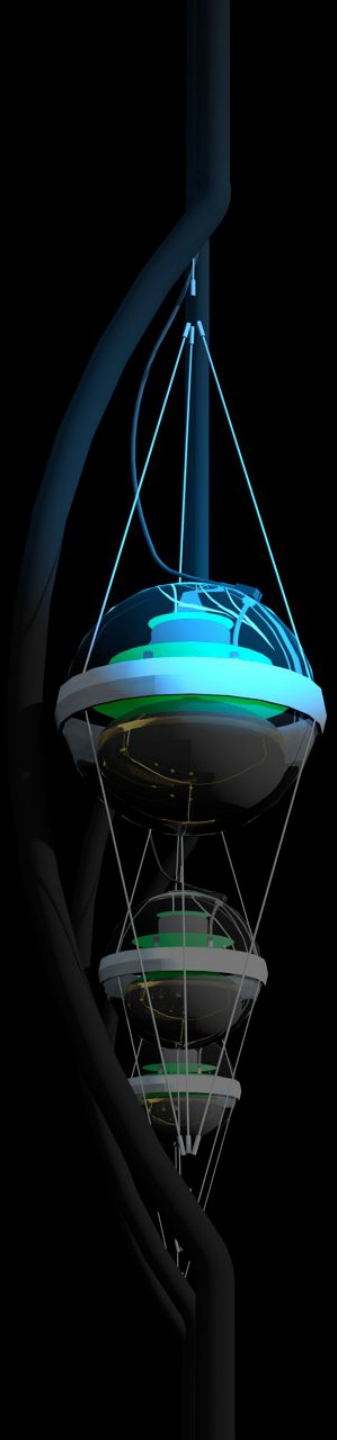
- … but difficult to detect: how large a detector?

cosmic ray accelerators



Fly's Eye 1991
3,000,000,000 TeV

accommodating energy and luminosity are challenging



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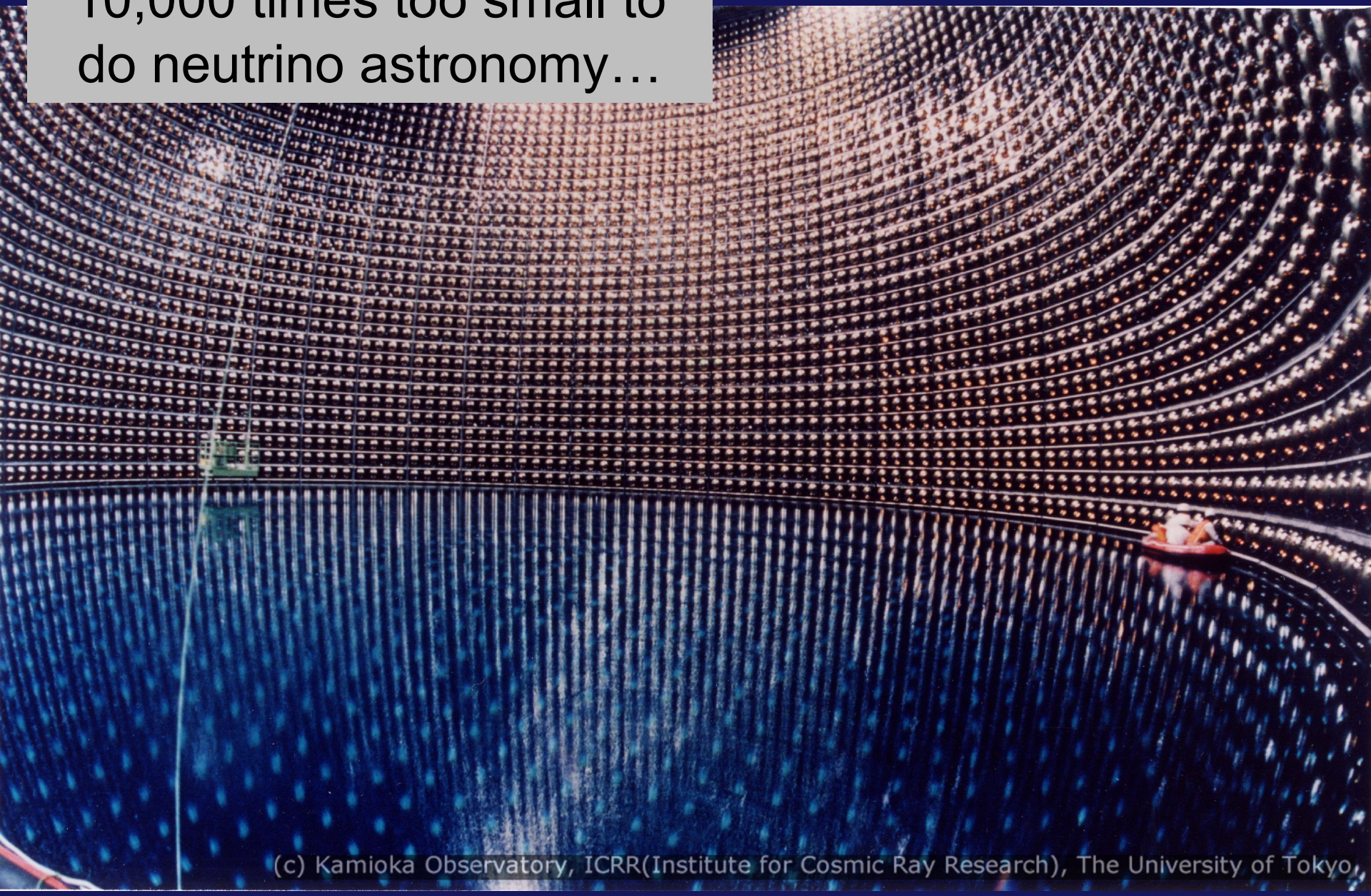
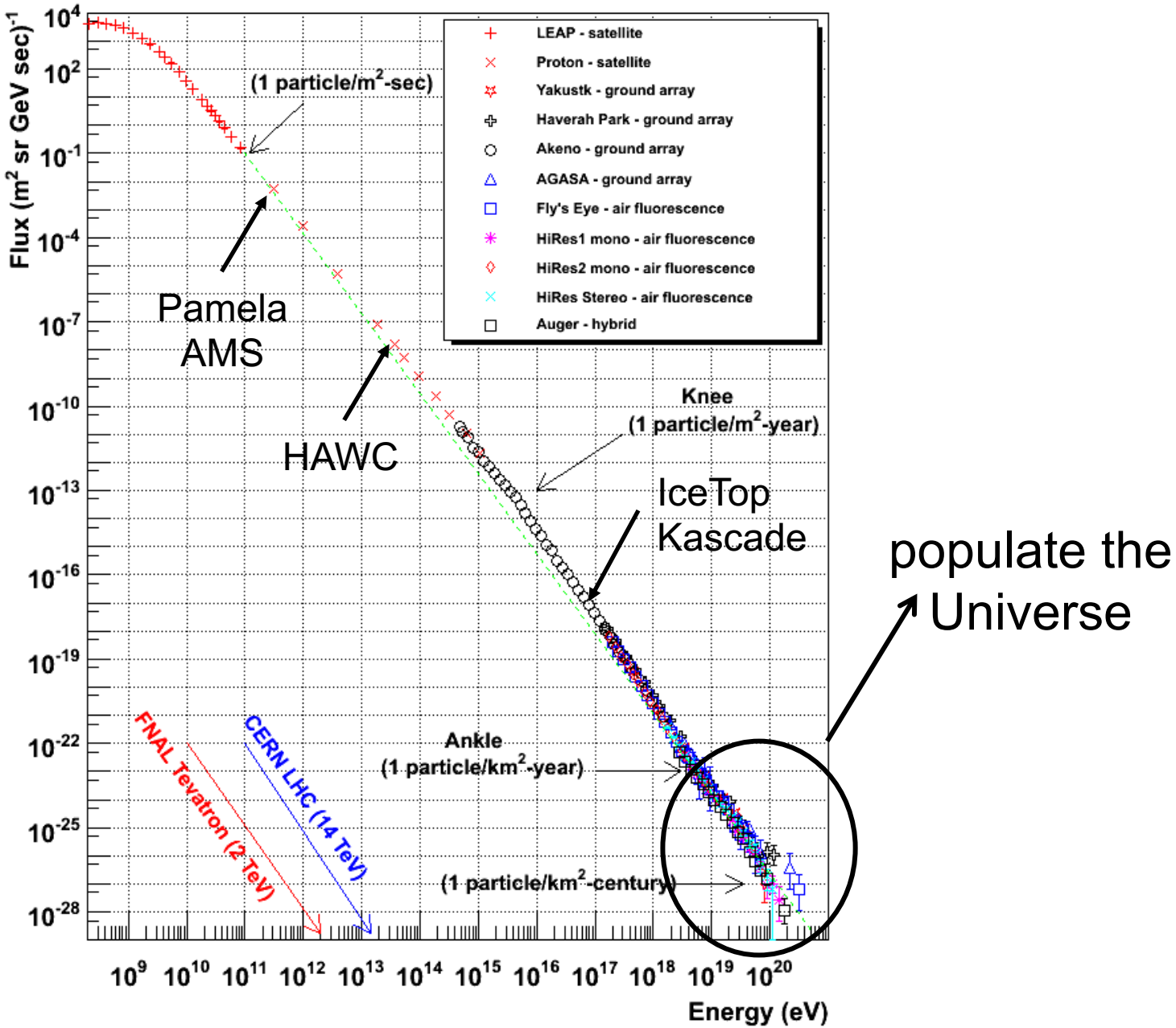
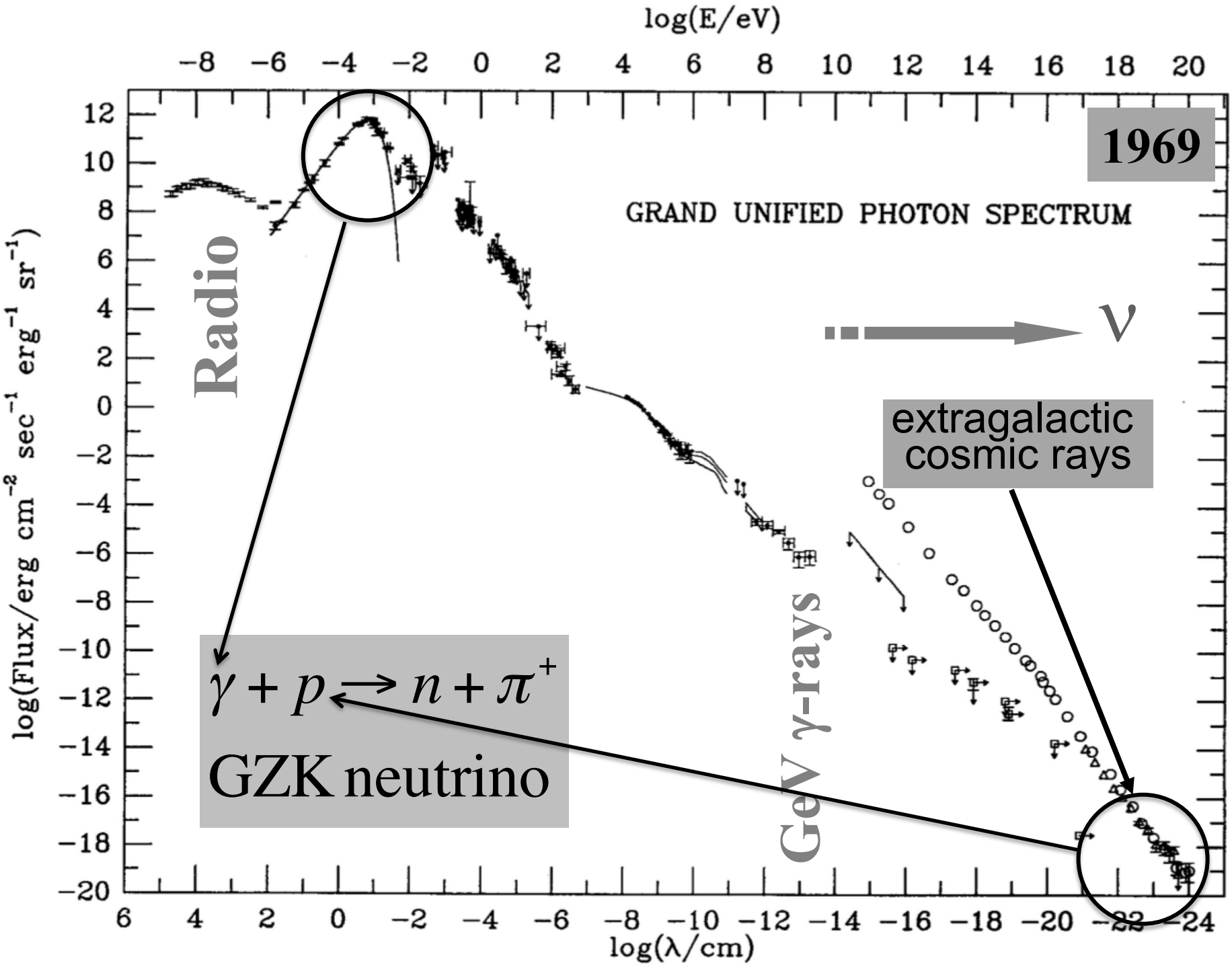
10,000 times too small to do neutrino astronomy…

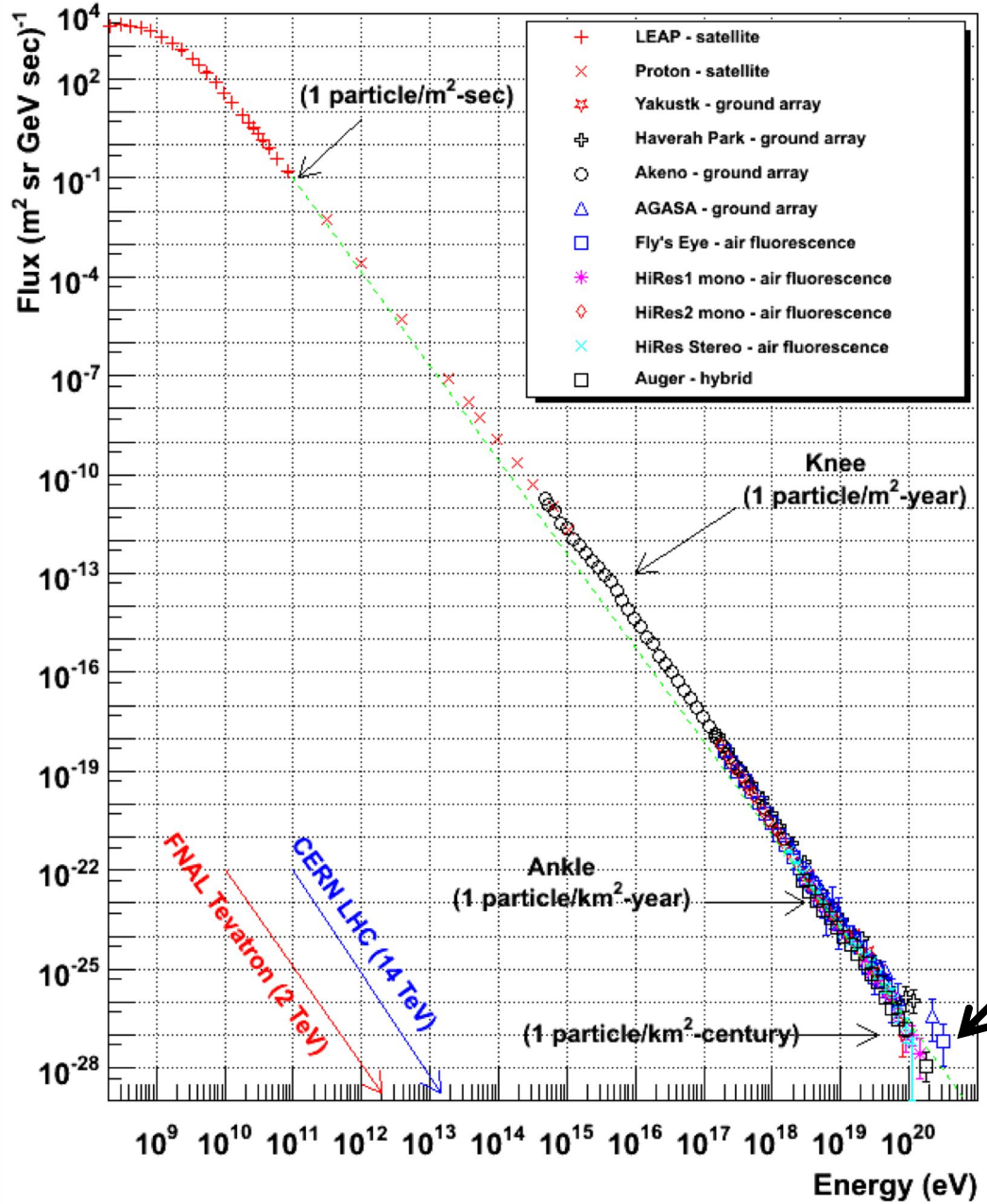


Cosmic Ray Spectra of Various Experiments




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

origin of cosmic rays: oldest problem in astronomy

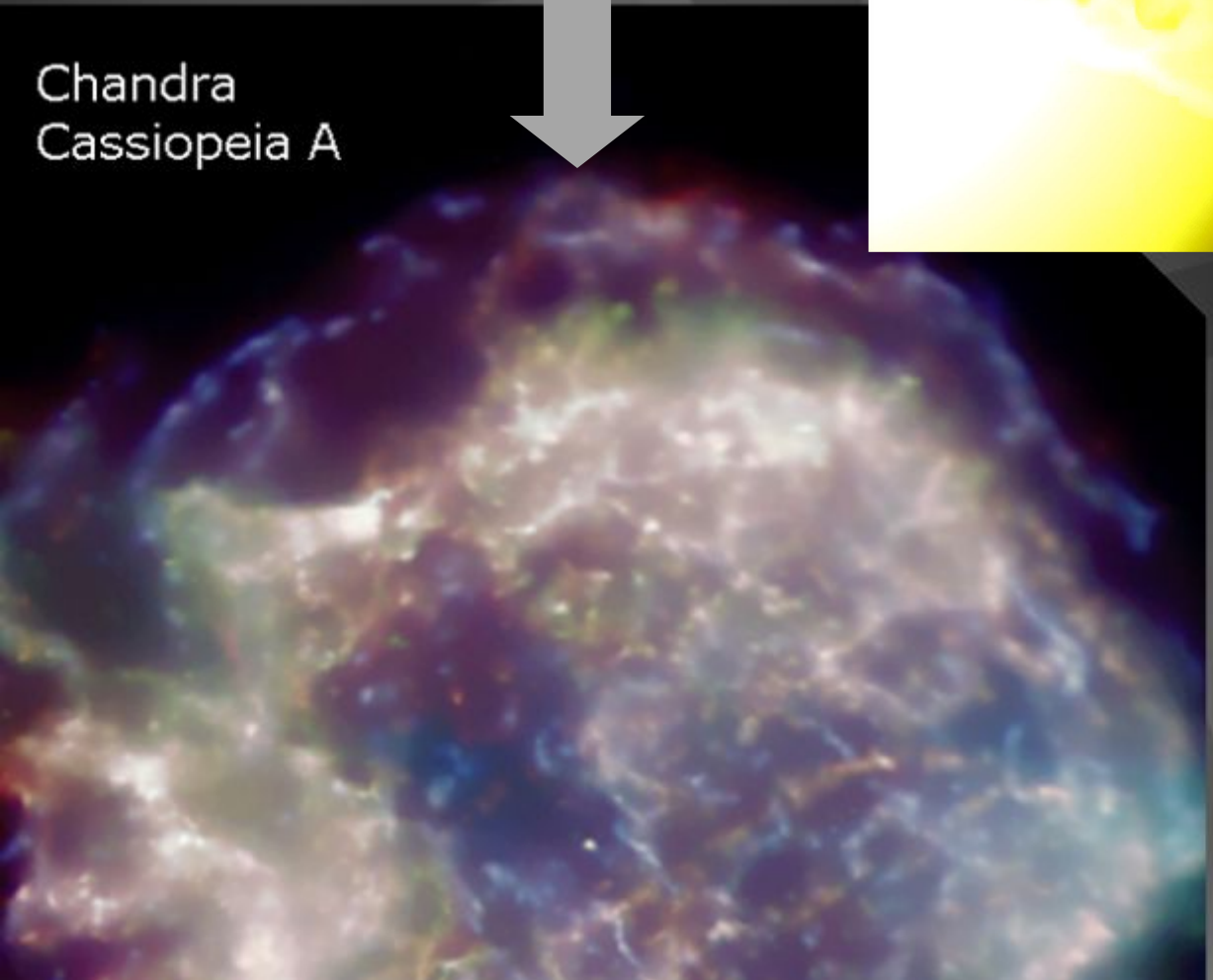


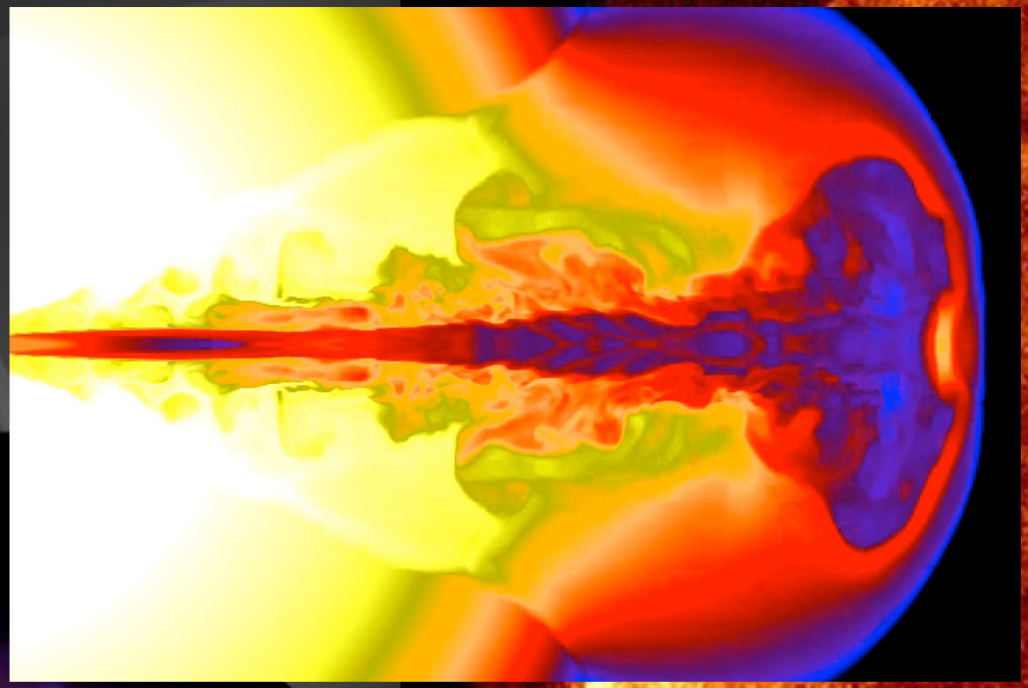
cosmic ray challenge

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

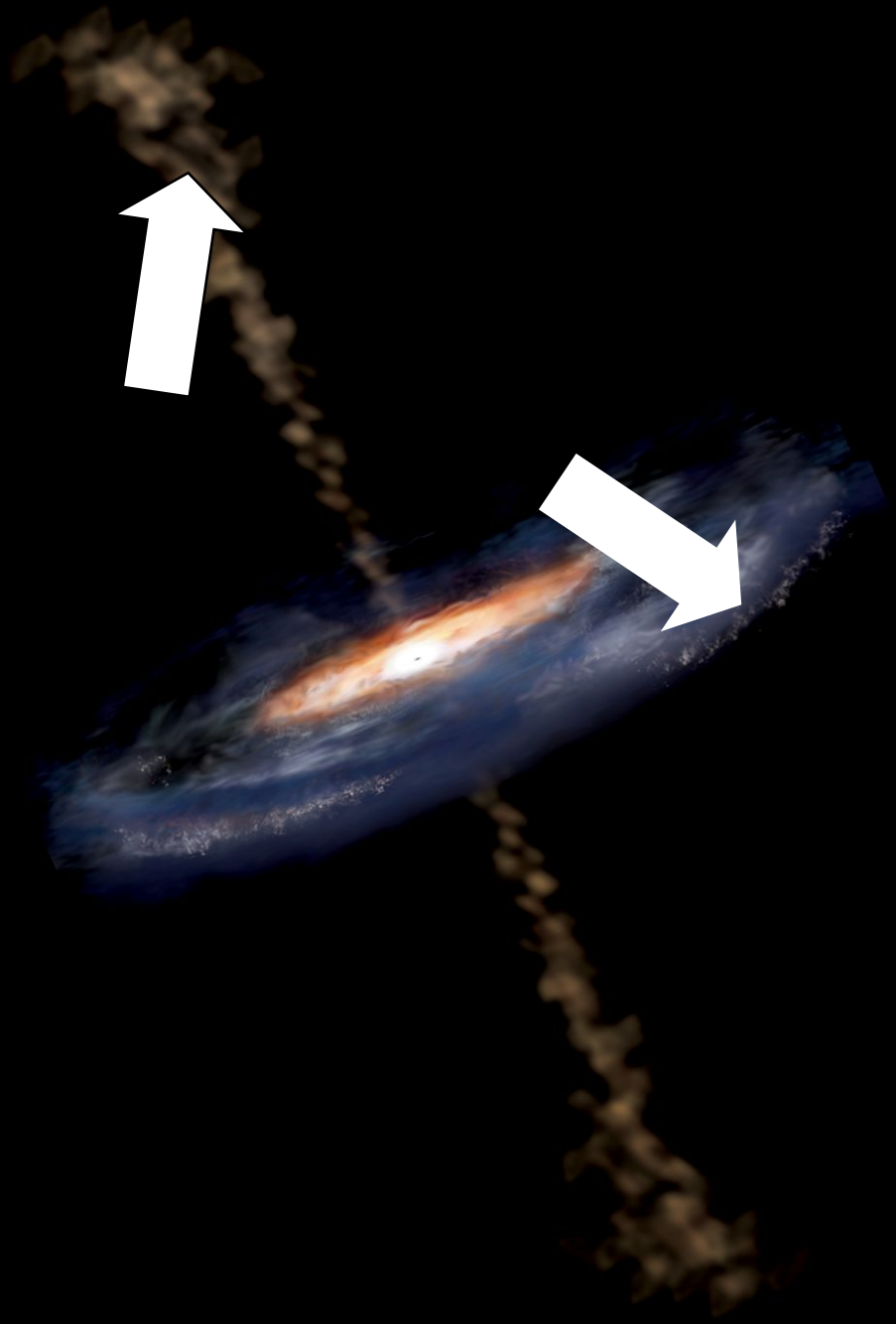
gravitational energy from collapsing stars is converted into particle acceleration?

supernova remnants





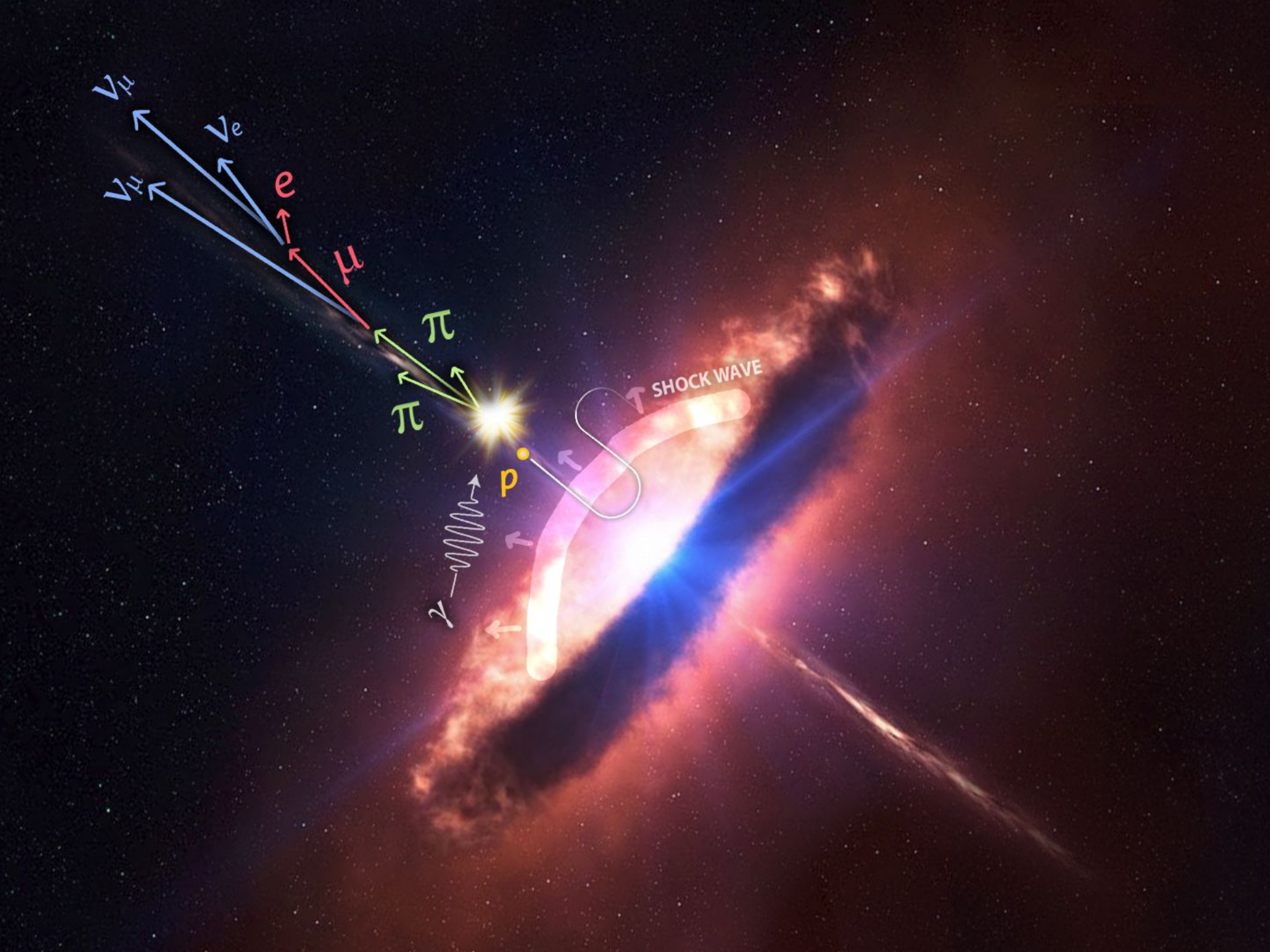
gamma ray bursts



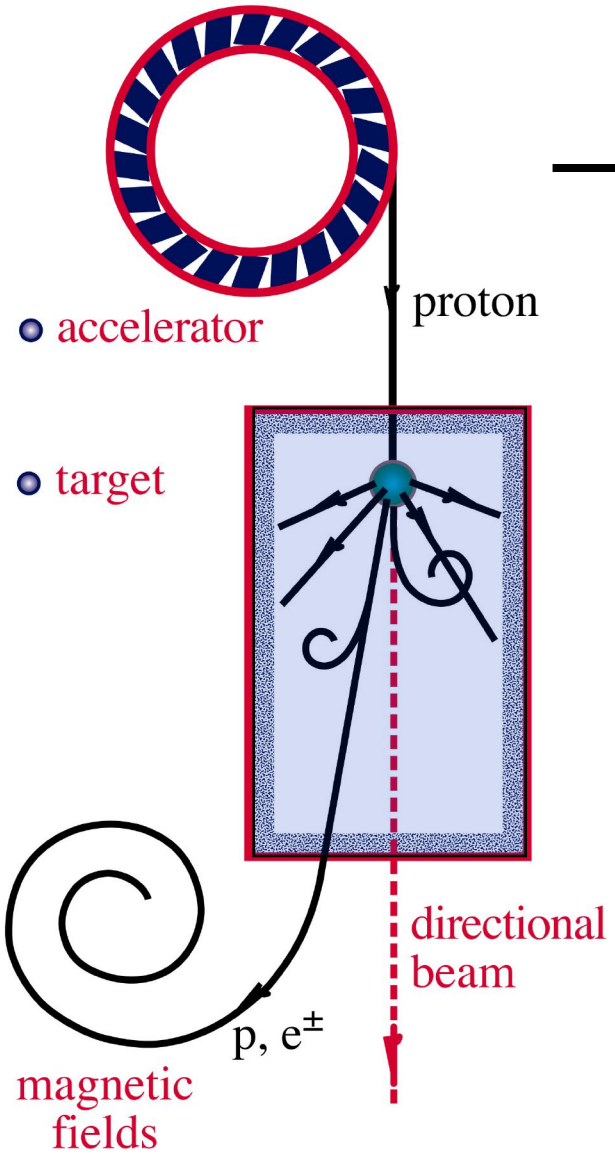
active galaxy

particle flows near supermassive black hole


active galaxy
particle flows near
supermassive
black hole


νμ
νe
νμ
e
μ
π
π
p
γ
SHOCK WAVE

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation,dust
molecular
clouds...

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

~ cosmic ray + neutrino

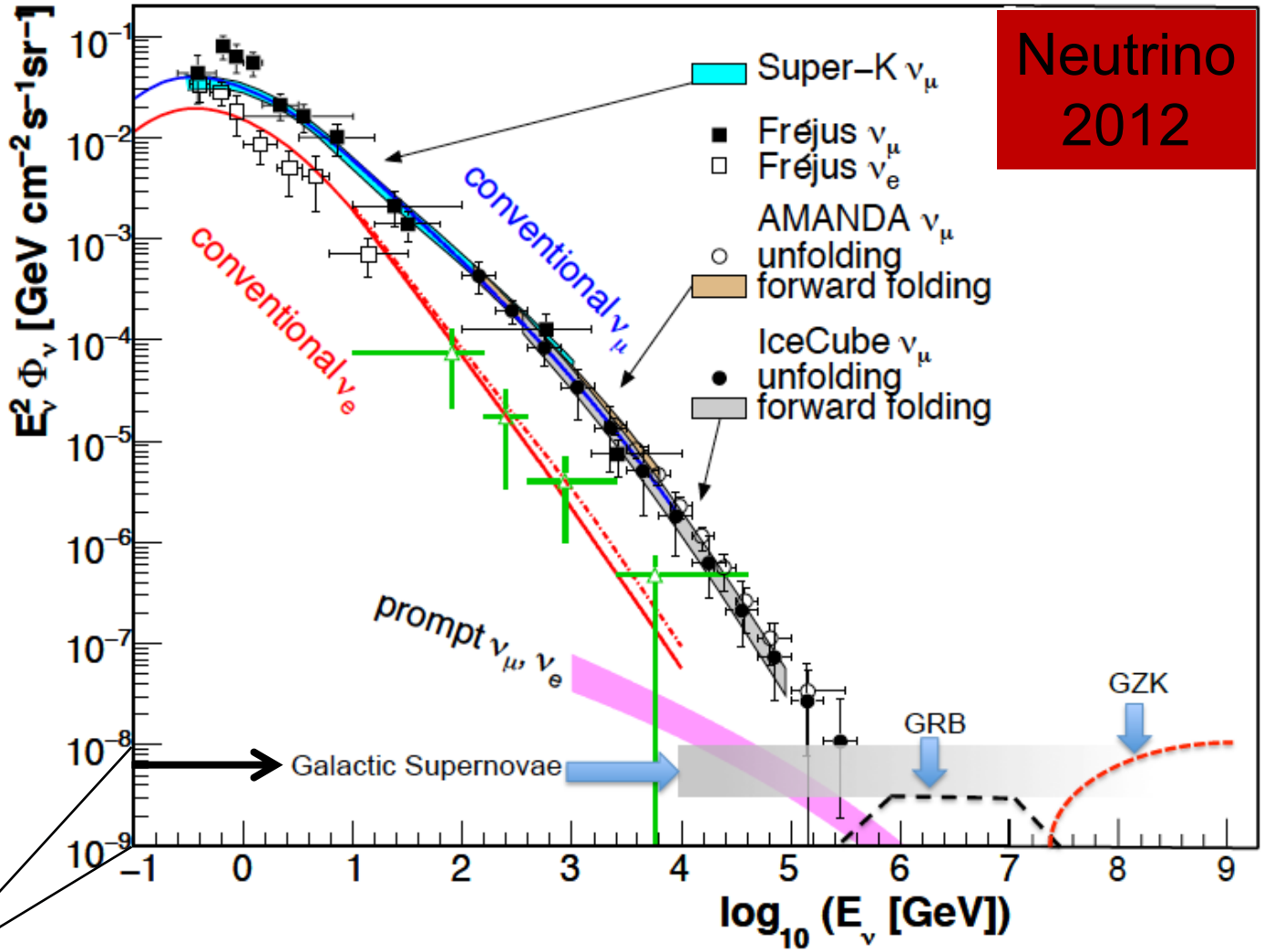
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

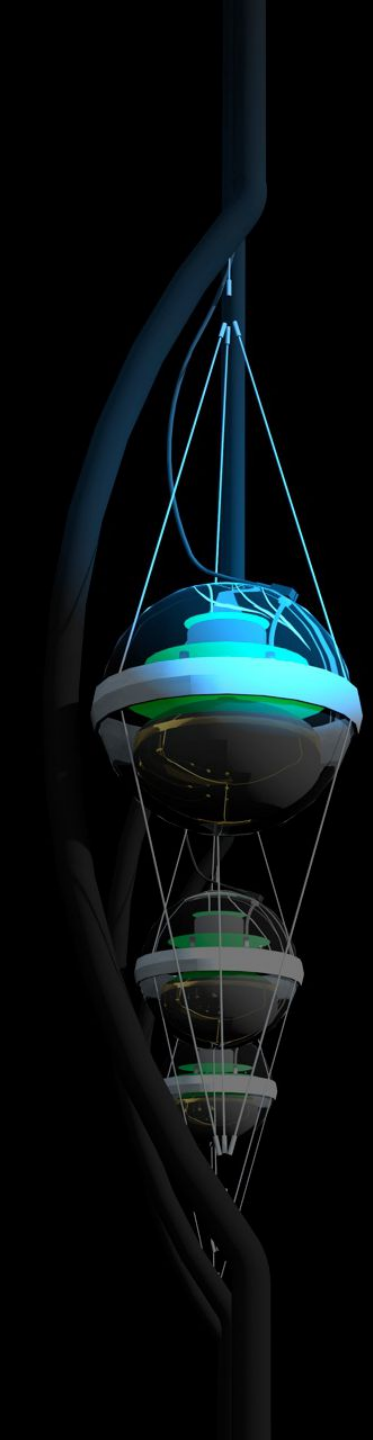
$$dN/dE \sim E^{-2}$$



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

atmospheric ⬆ cosmic

100 TeV



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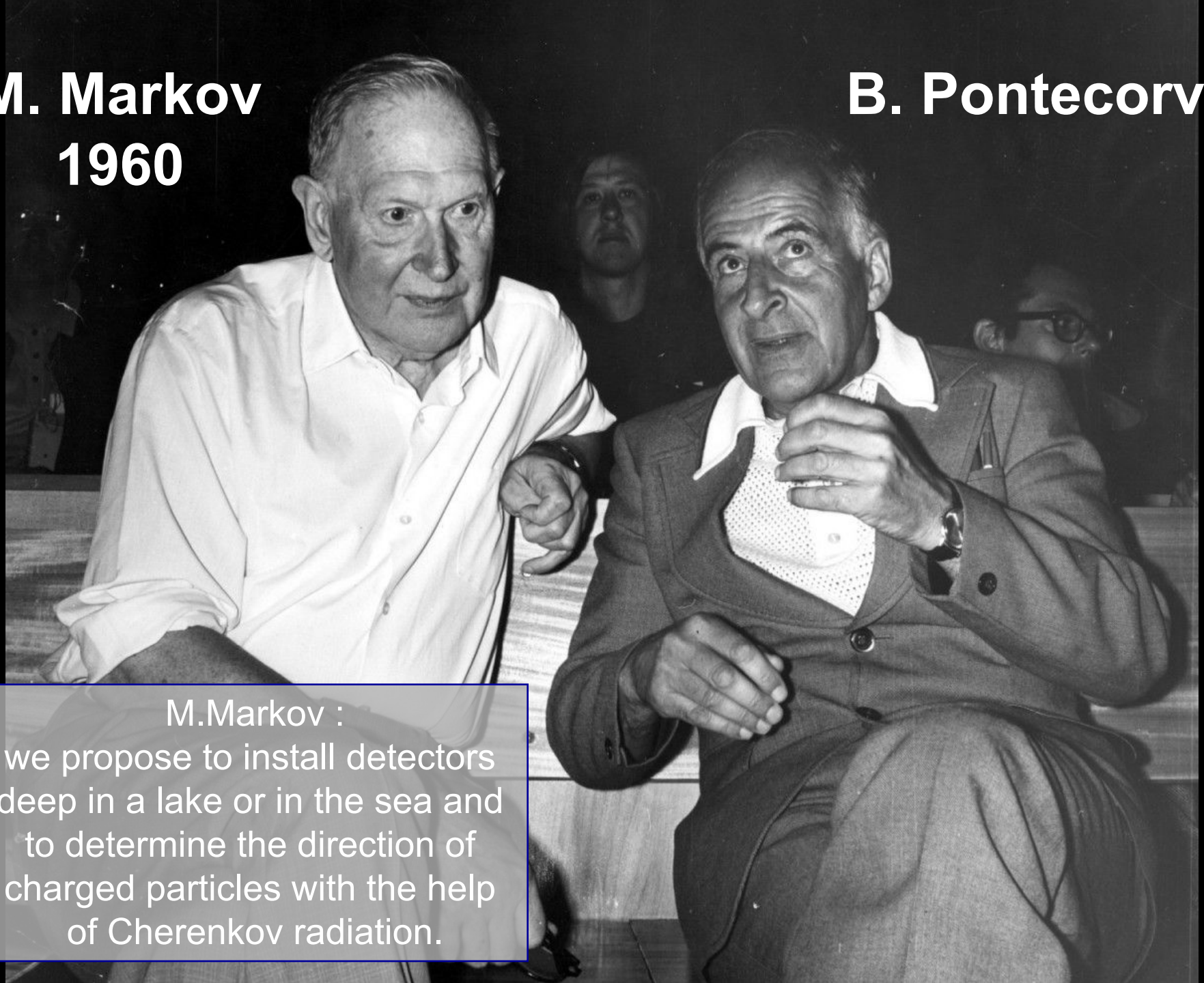
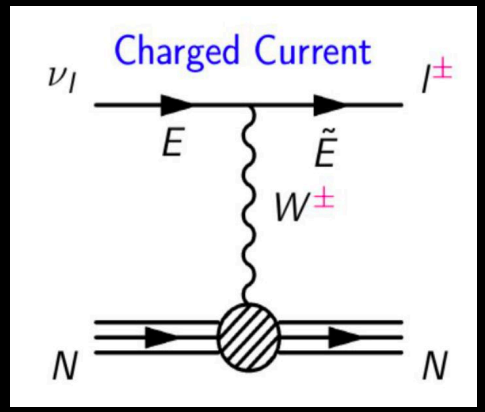


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.



a muon neutrino produces a muon with a range of kilometers

• lattice of photomultipliers

neutrino

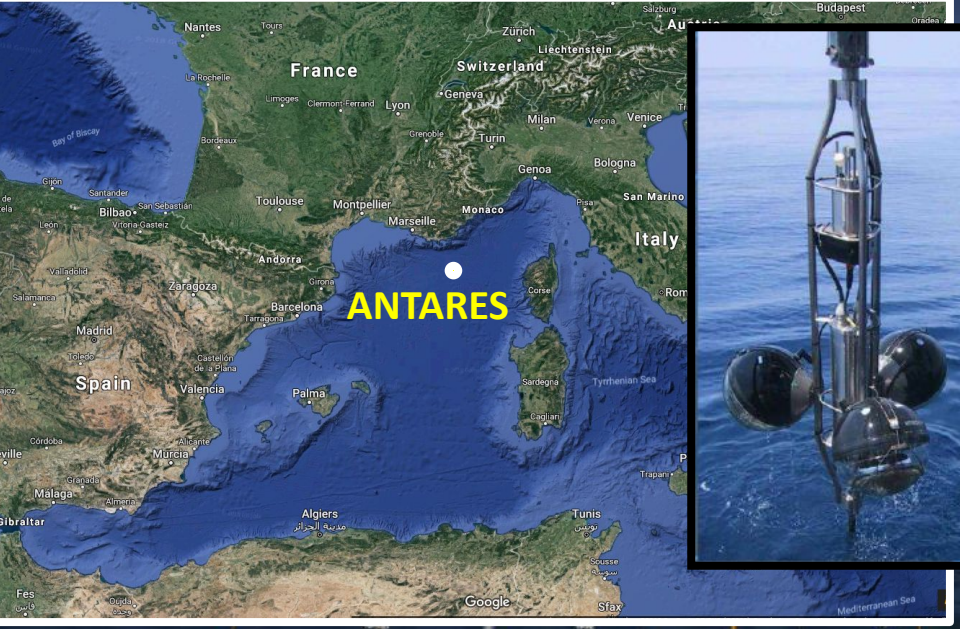
standing on the shoulder of giants

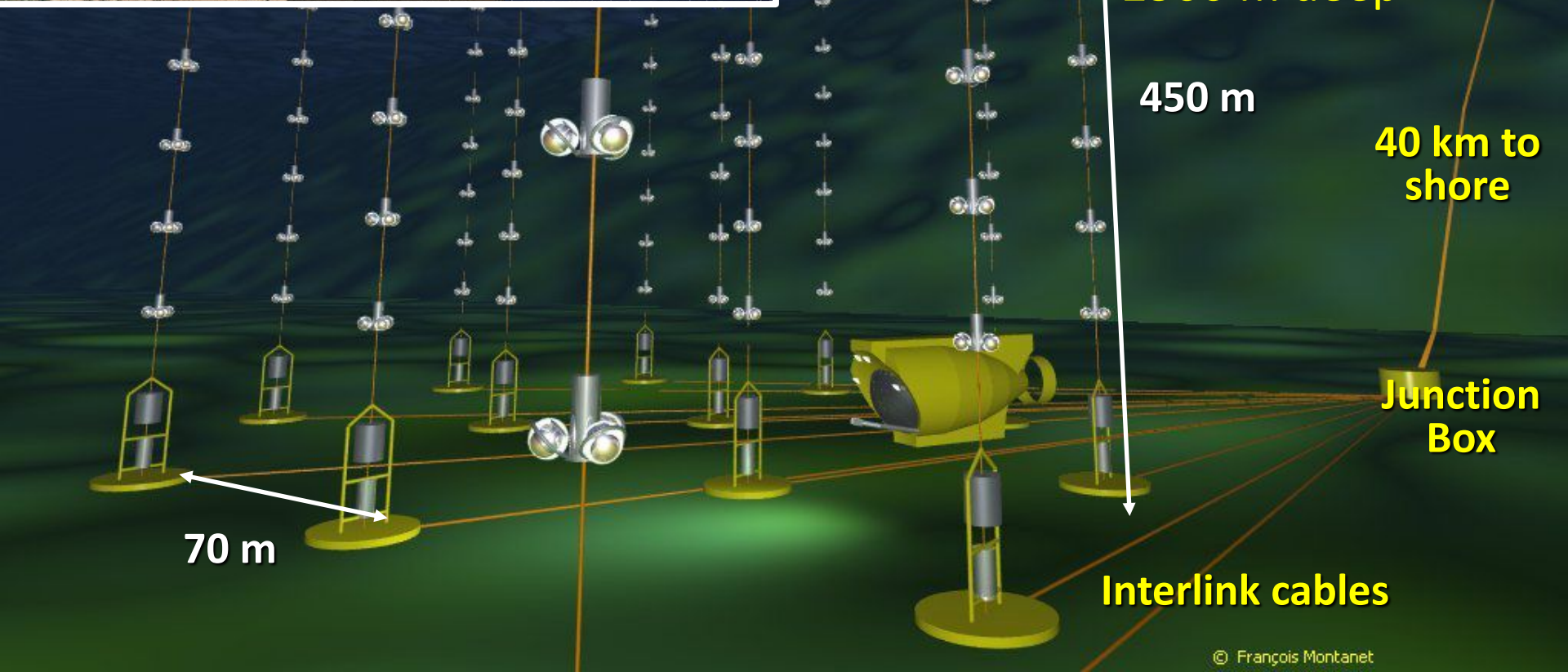
1987: DUMAND test string

Lake Baikal experiment observes atmospheric neutrinos

ANTARES

Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep





ANTARES – Diffuse flux

Sample:
- 2007 – 2015, 2450 days of livetime
- All-flavour analysis (track+showers)

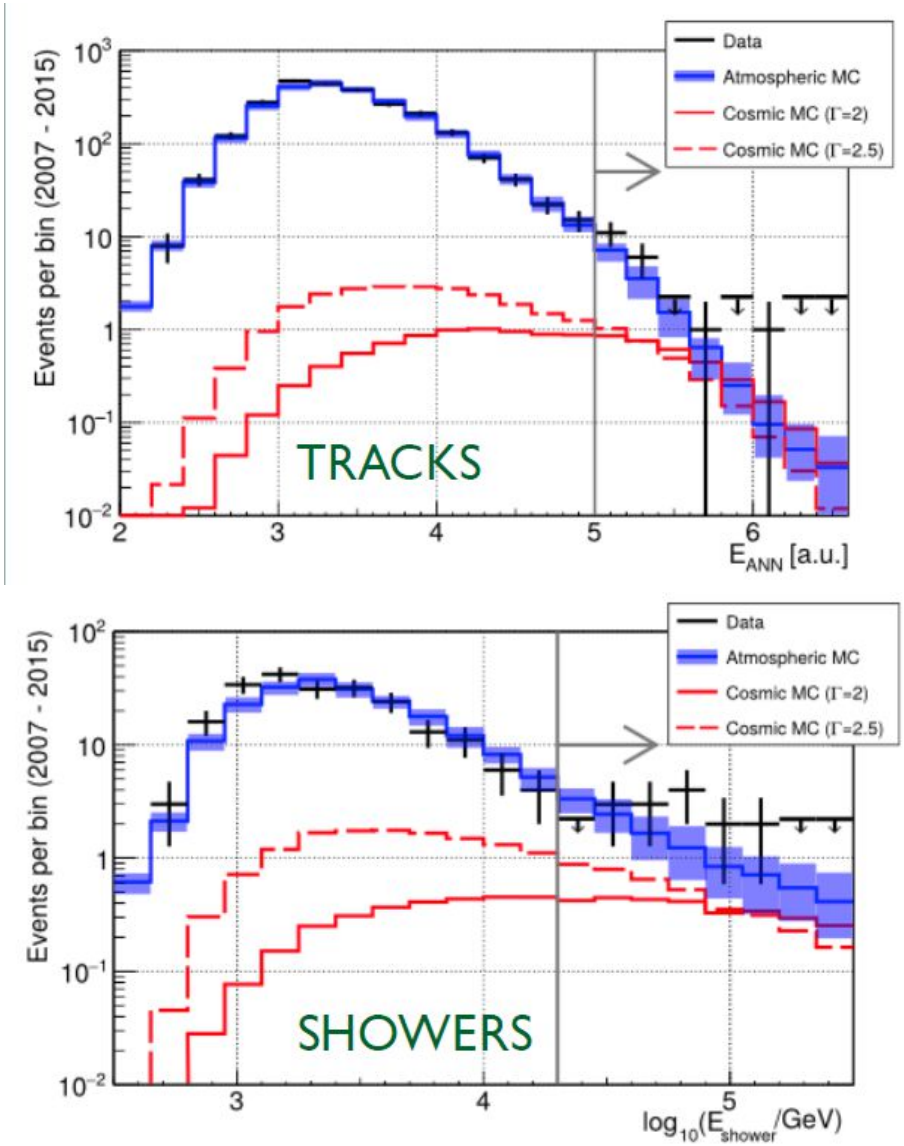
Event selection chain + energy-related cut applied to
- obtain a high-purity neutrino sample
- maximize sensitivity

Signal modeled according to the IceCube flux

Result:
33 events (19 tracks + 14 showers) in data
24 ±7 (stat.+syst.) events background in MC

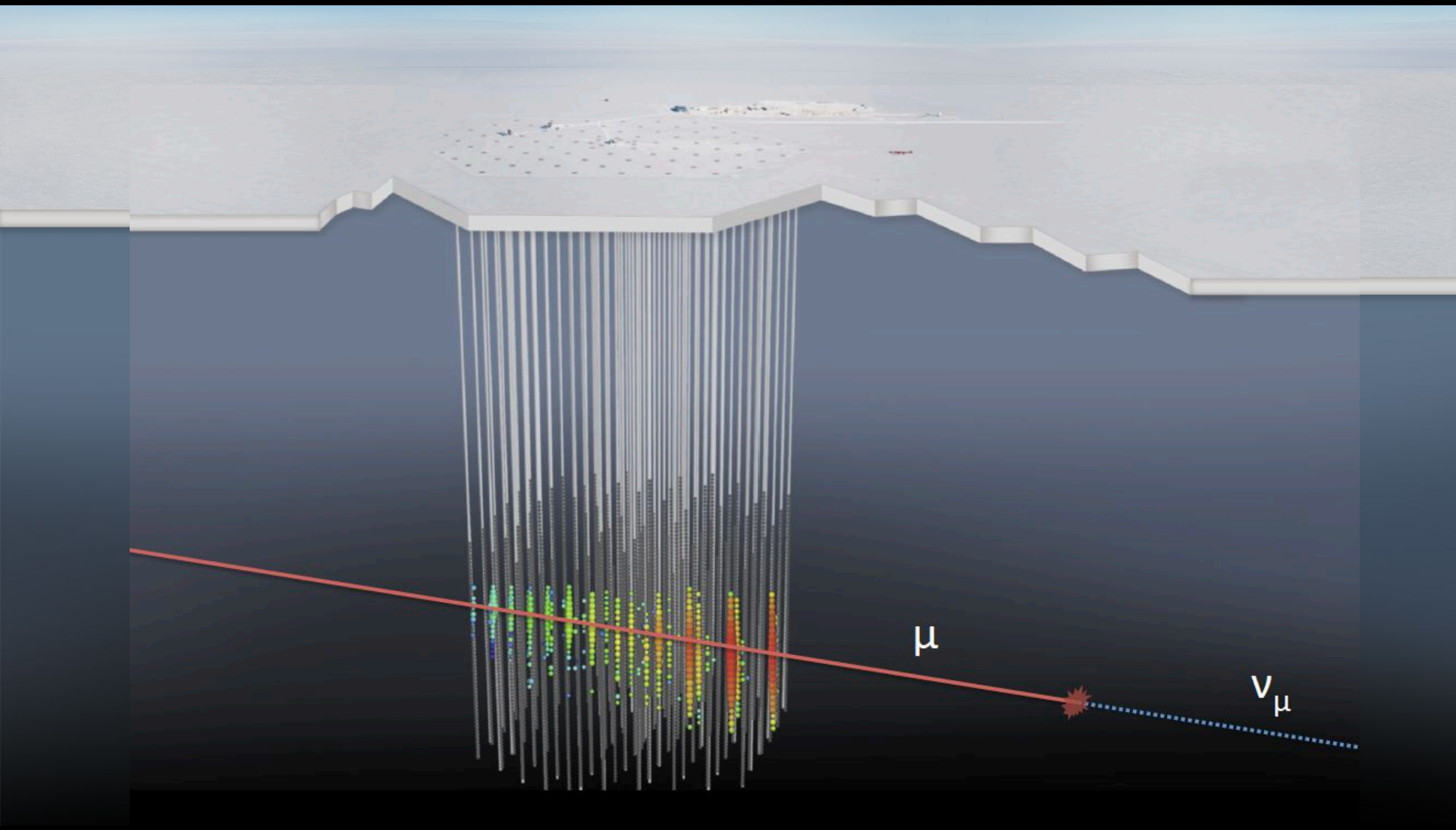
1.6σ excess, null cosmic rejected at 85% CL

ApJ 853, (2018) L7

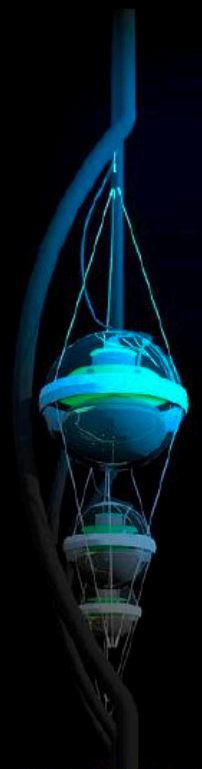



ultra-transparent ice below 1.35 km

instrument 1 cubic kilometer of natural ice below 1.45 km

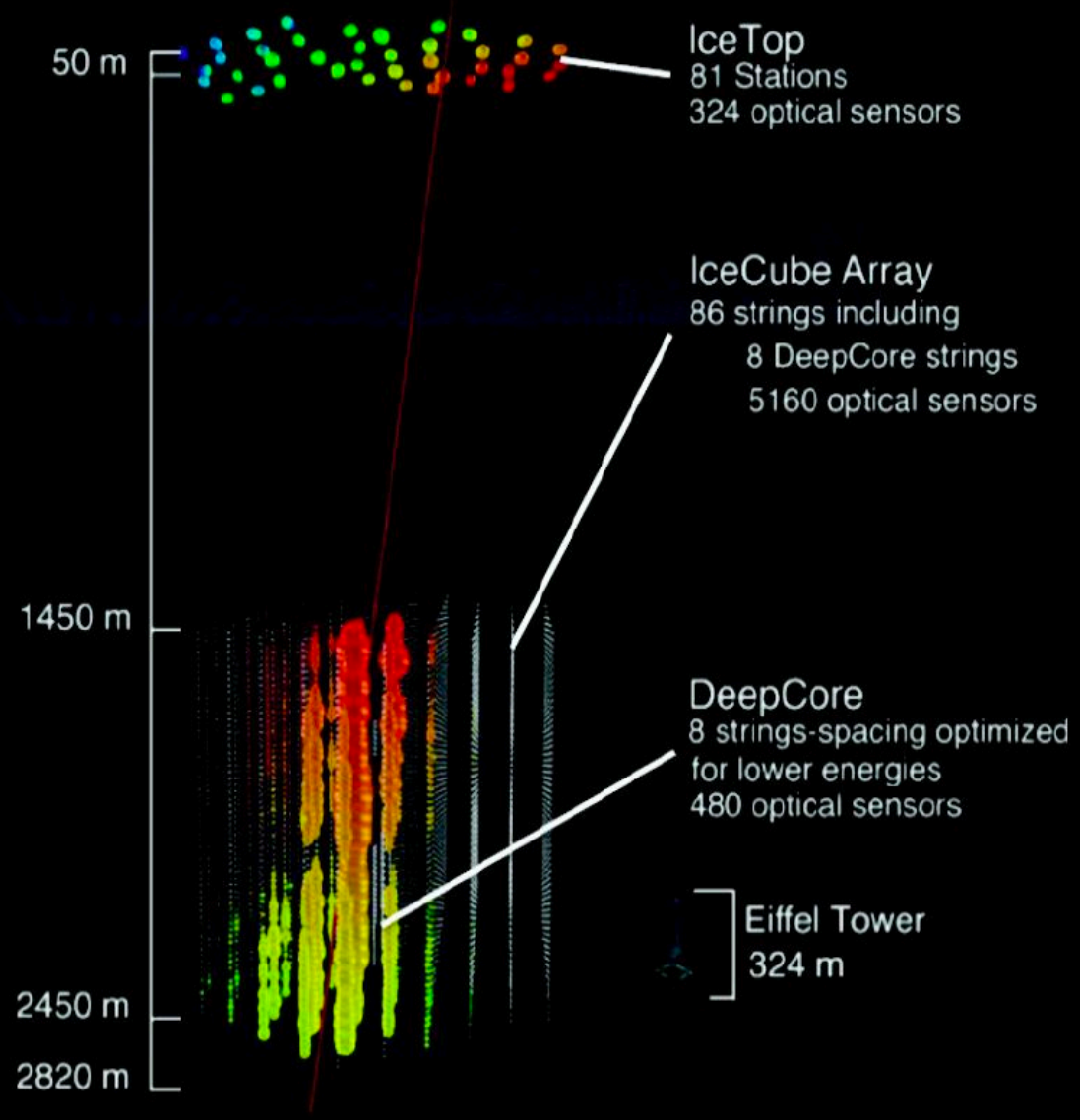


the IceCube Neutrino Observatory



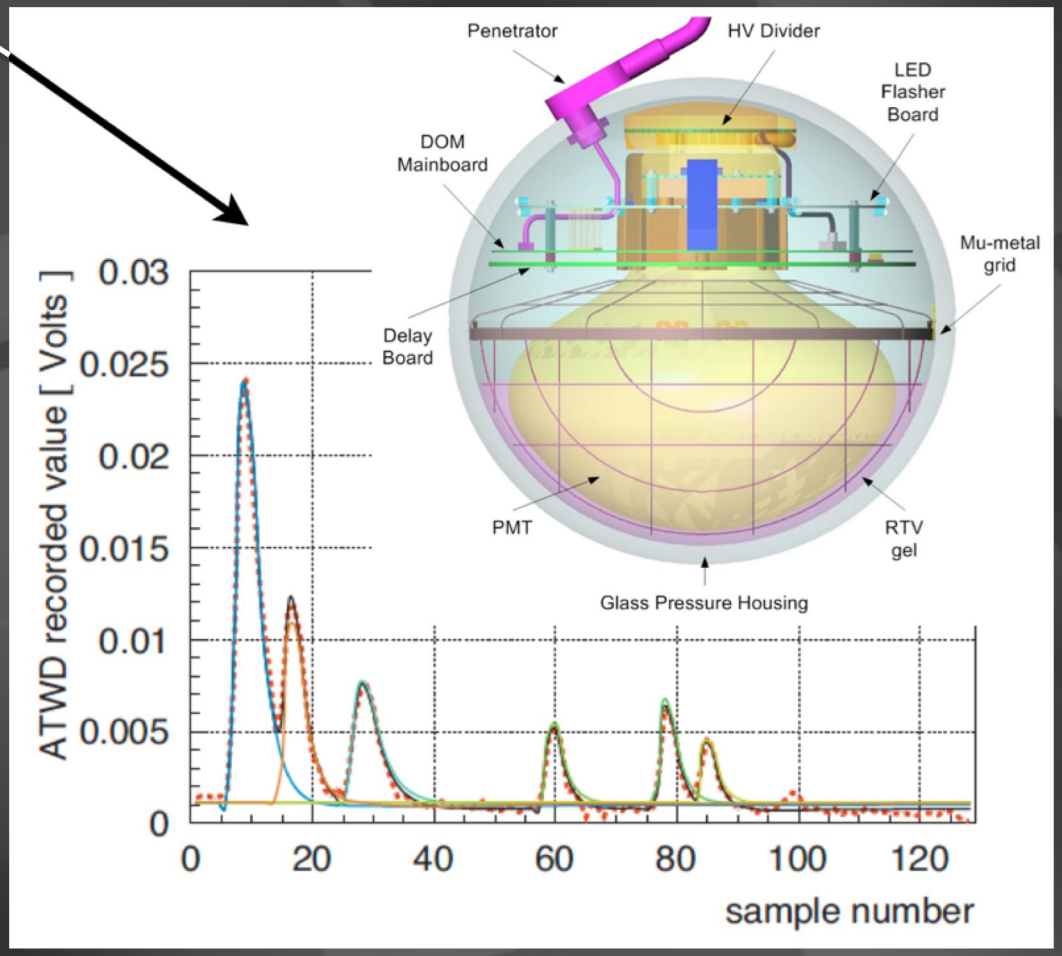
5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution



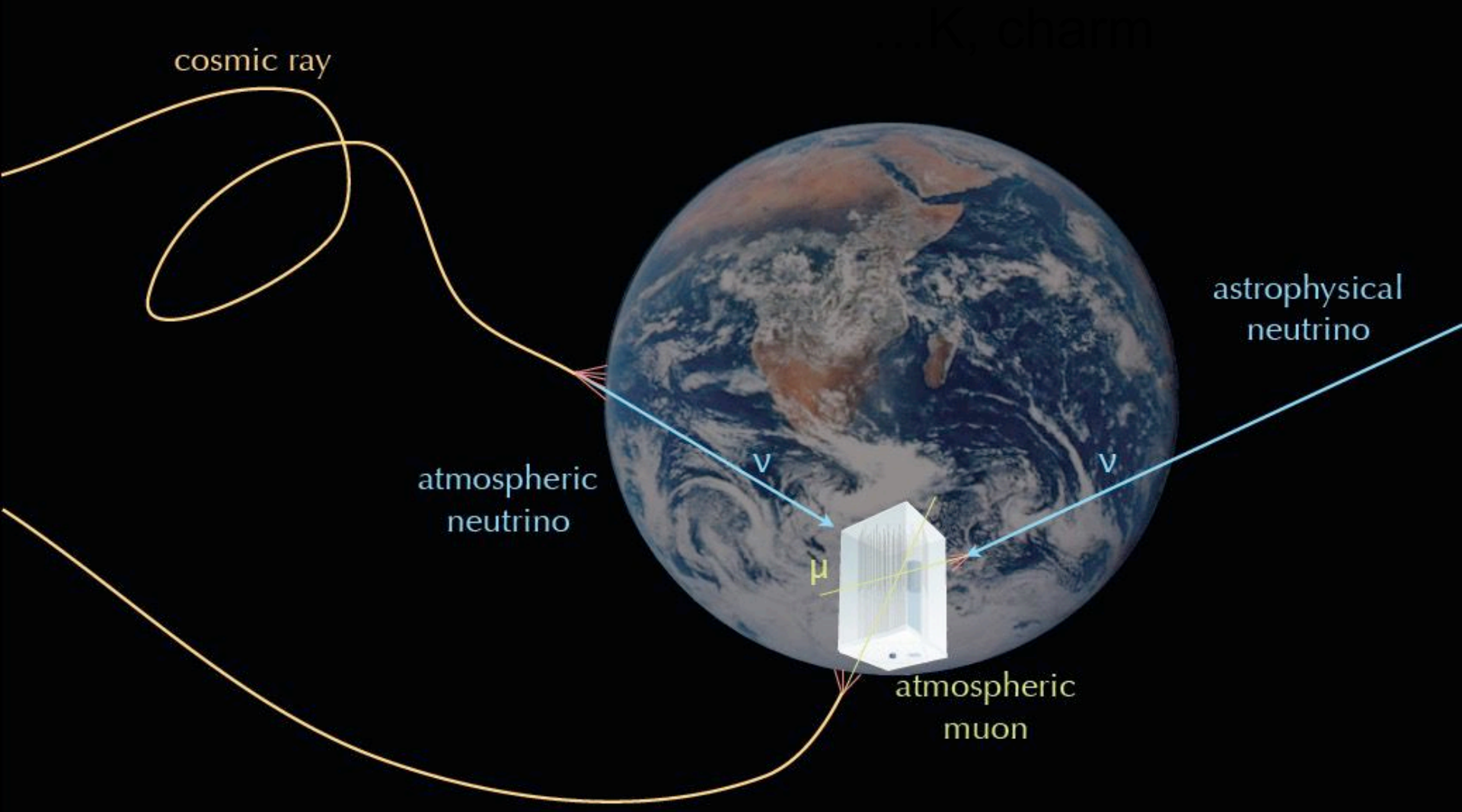
photomultiplier tube -10 inch

… 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…

Signals and Backgrounds

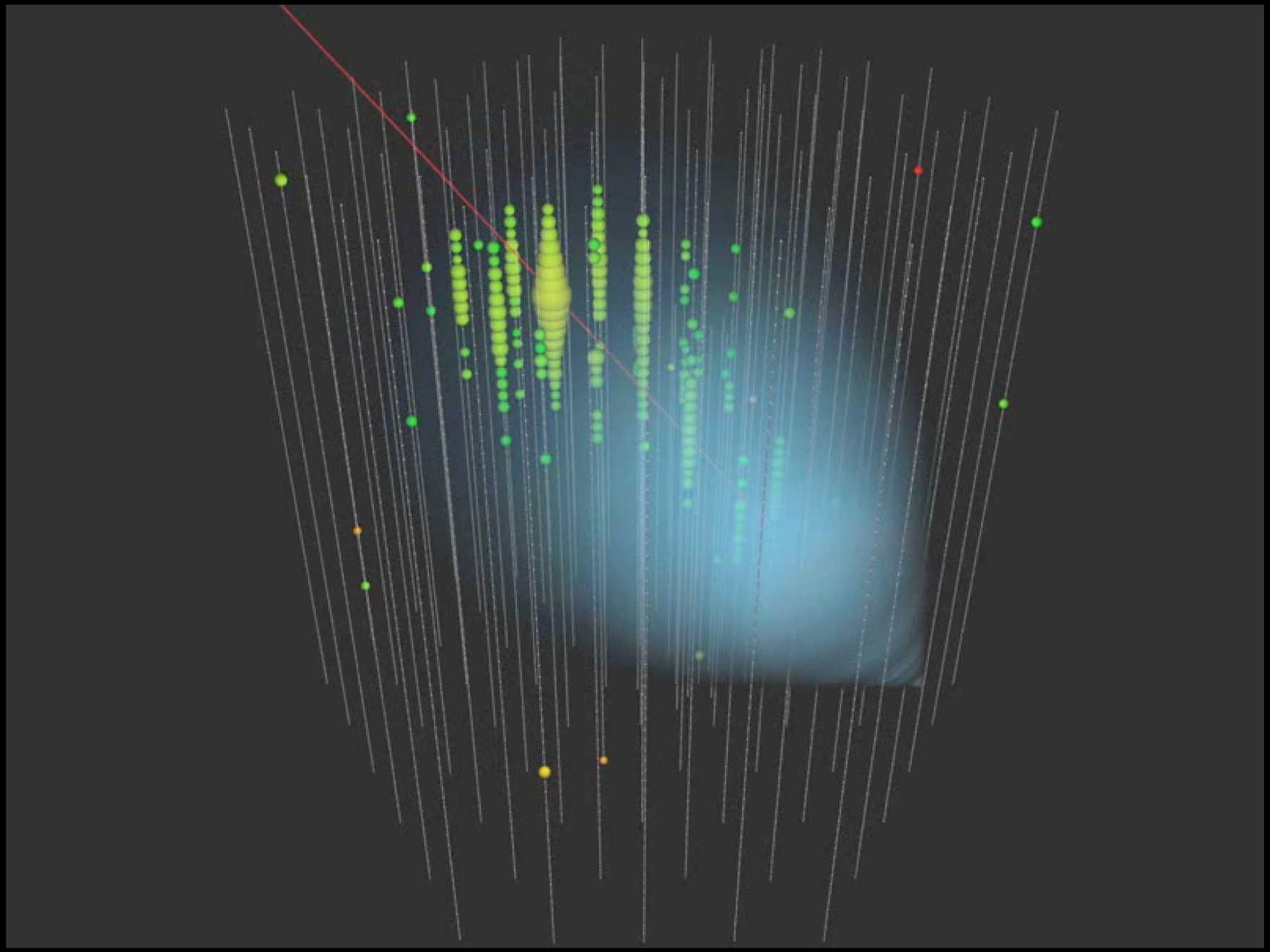


… you looked at 10msec of data !

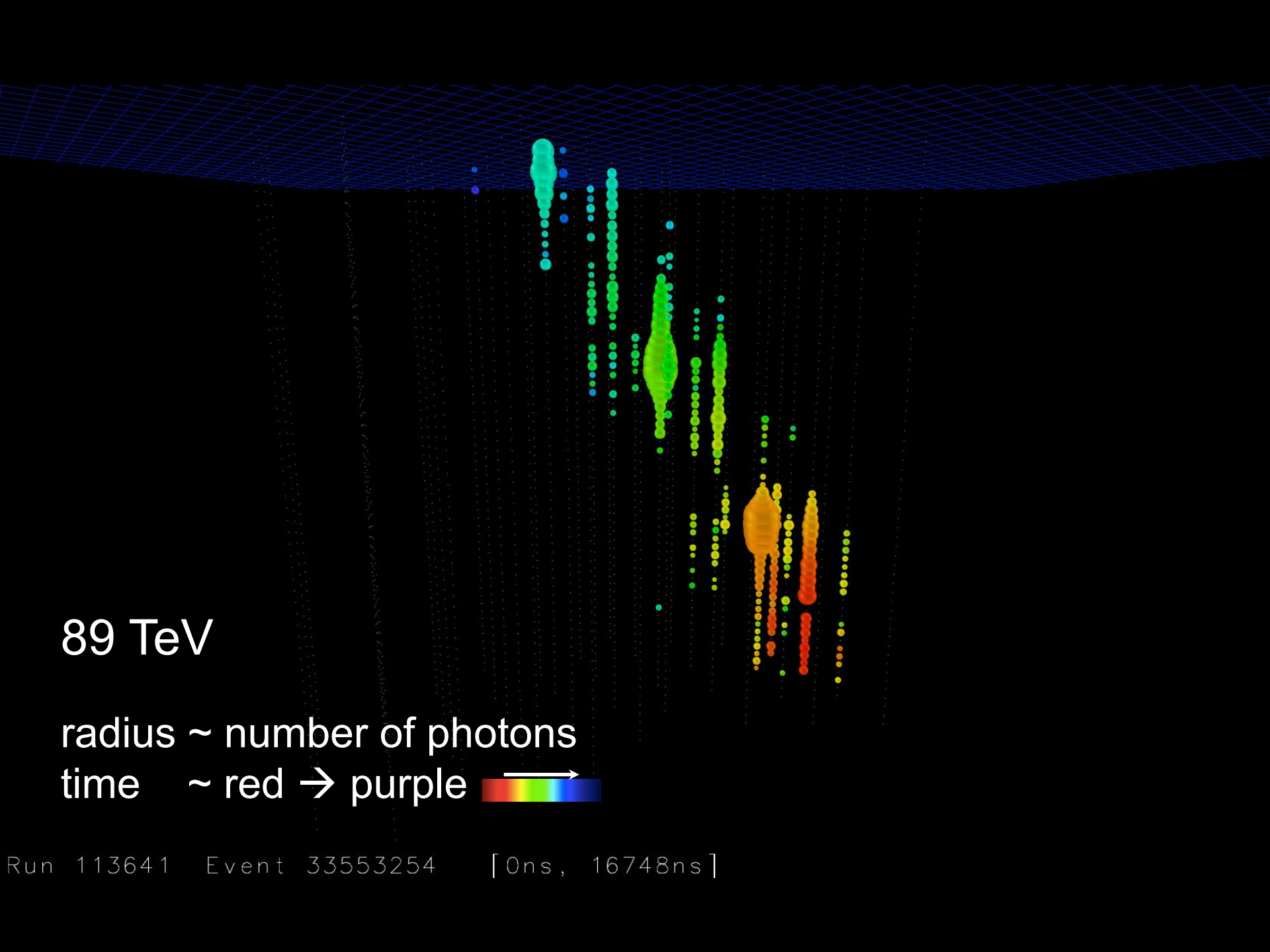
muons detected per year:

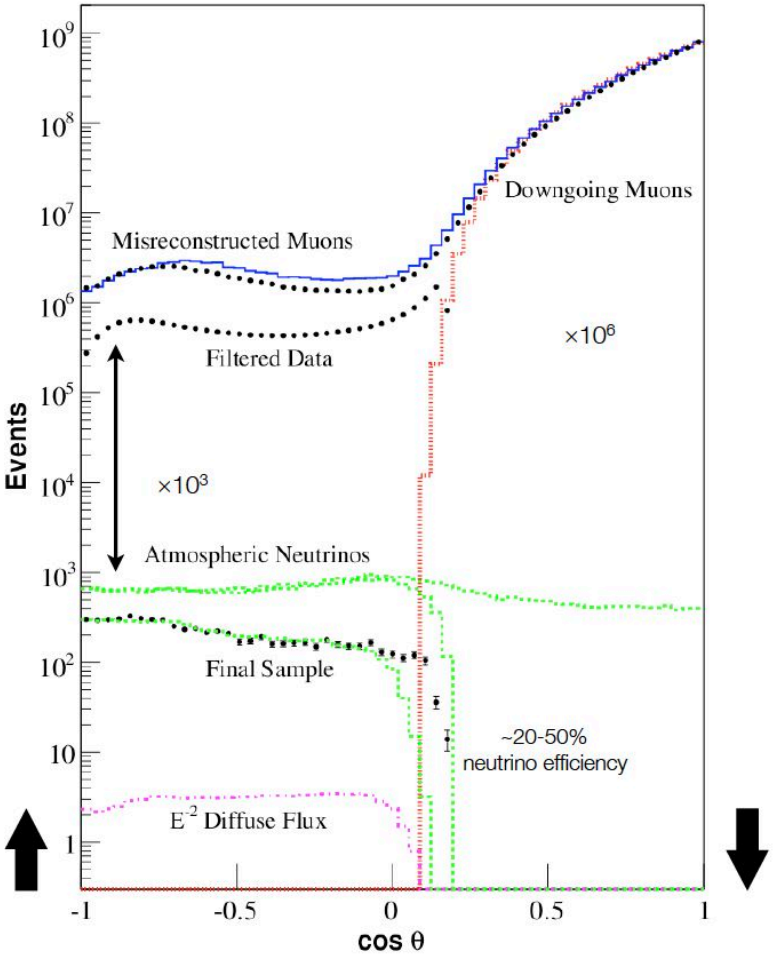
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 120

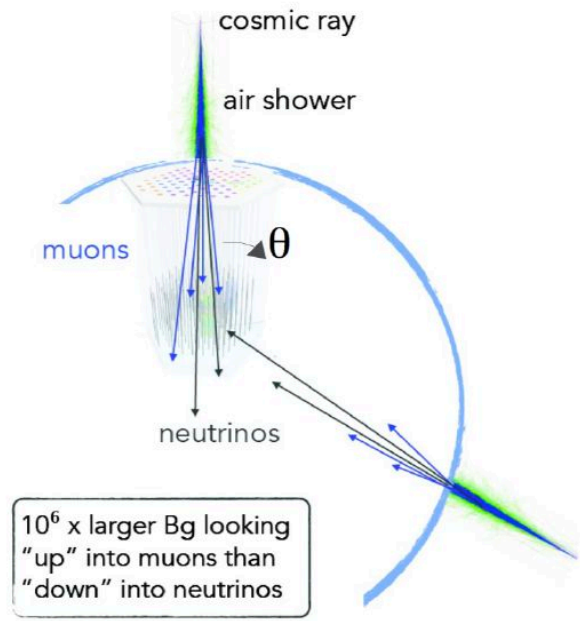
* 3000 per second ** 1 every 6 minutes



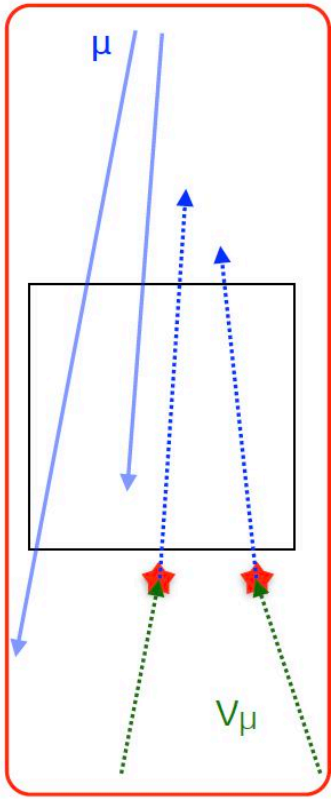
muon track: color is time; number of photons is energy


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





up-going through-going (tracks)

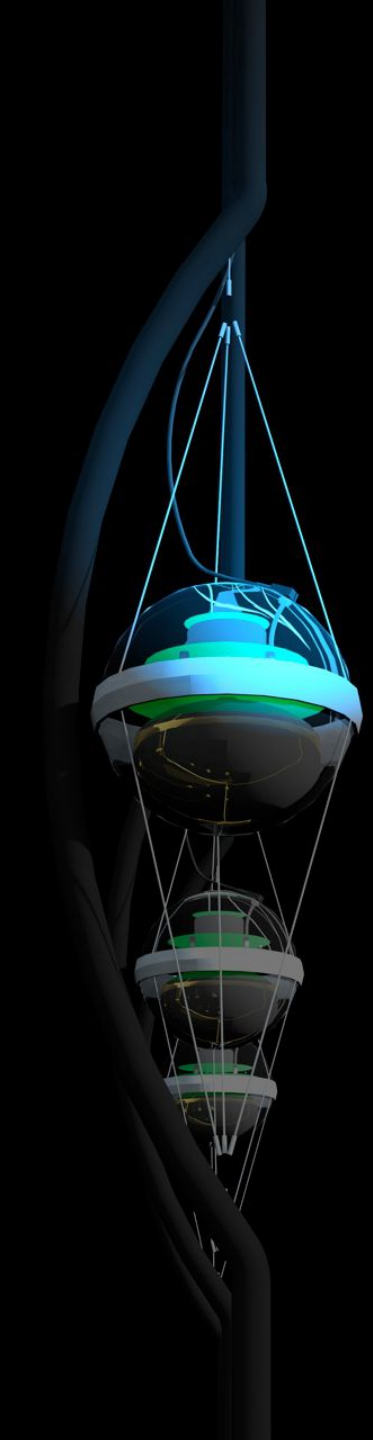


selection cuts for on-line numu extraction

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

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

…as opposed to 35 in original AMANDA publication



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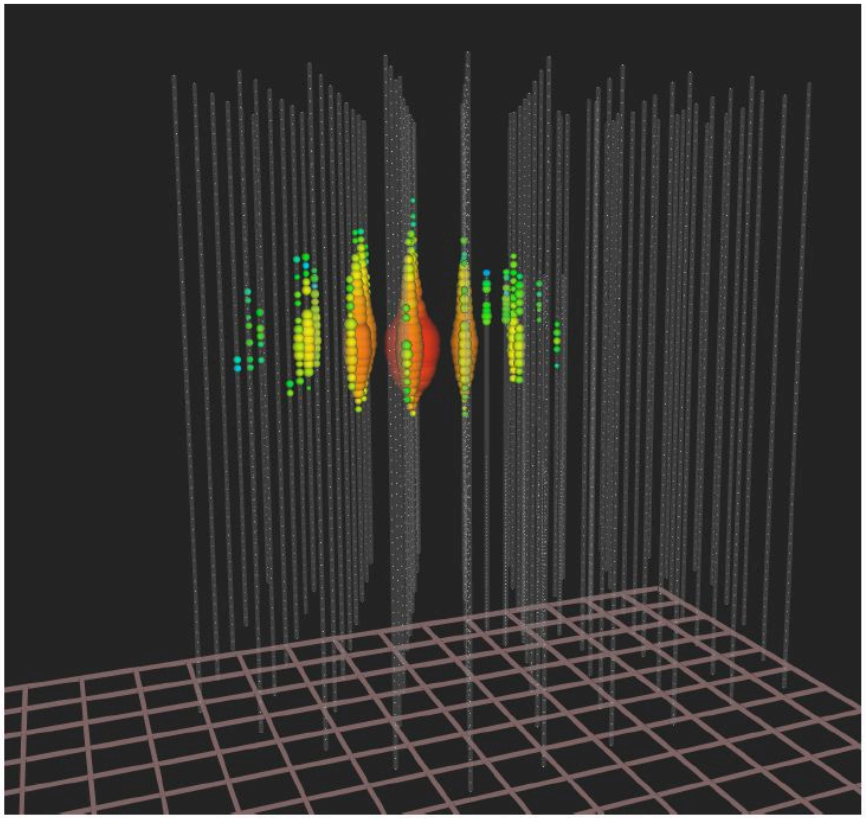
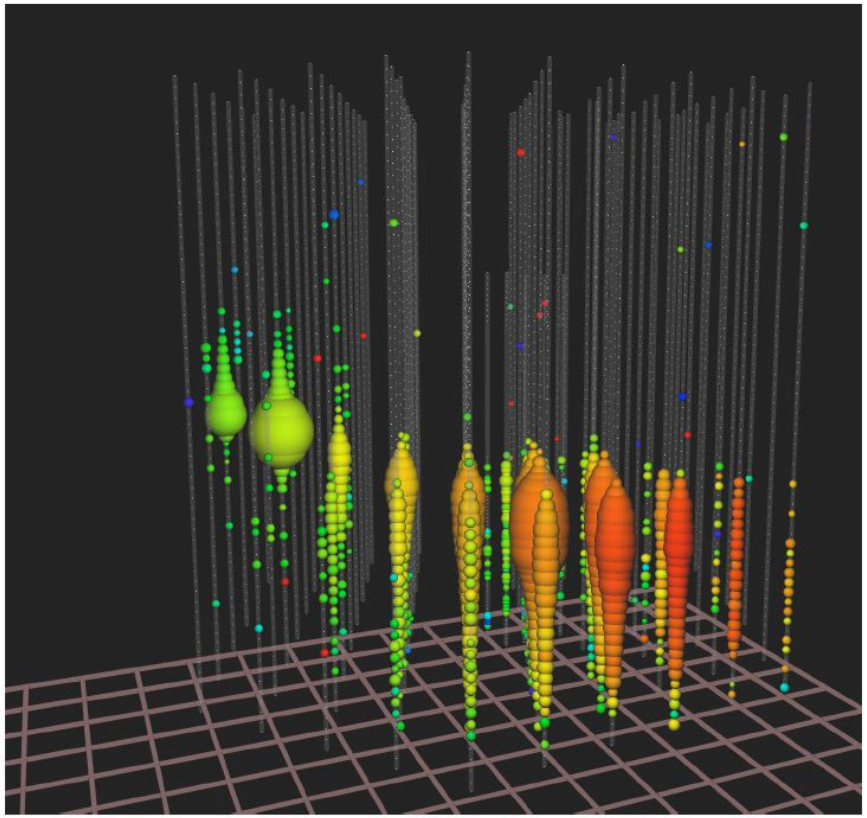
neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth

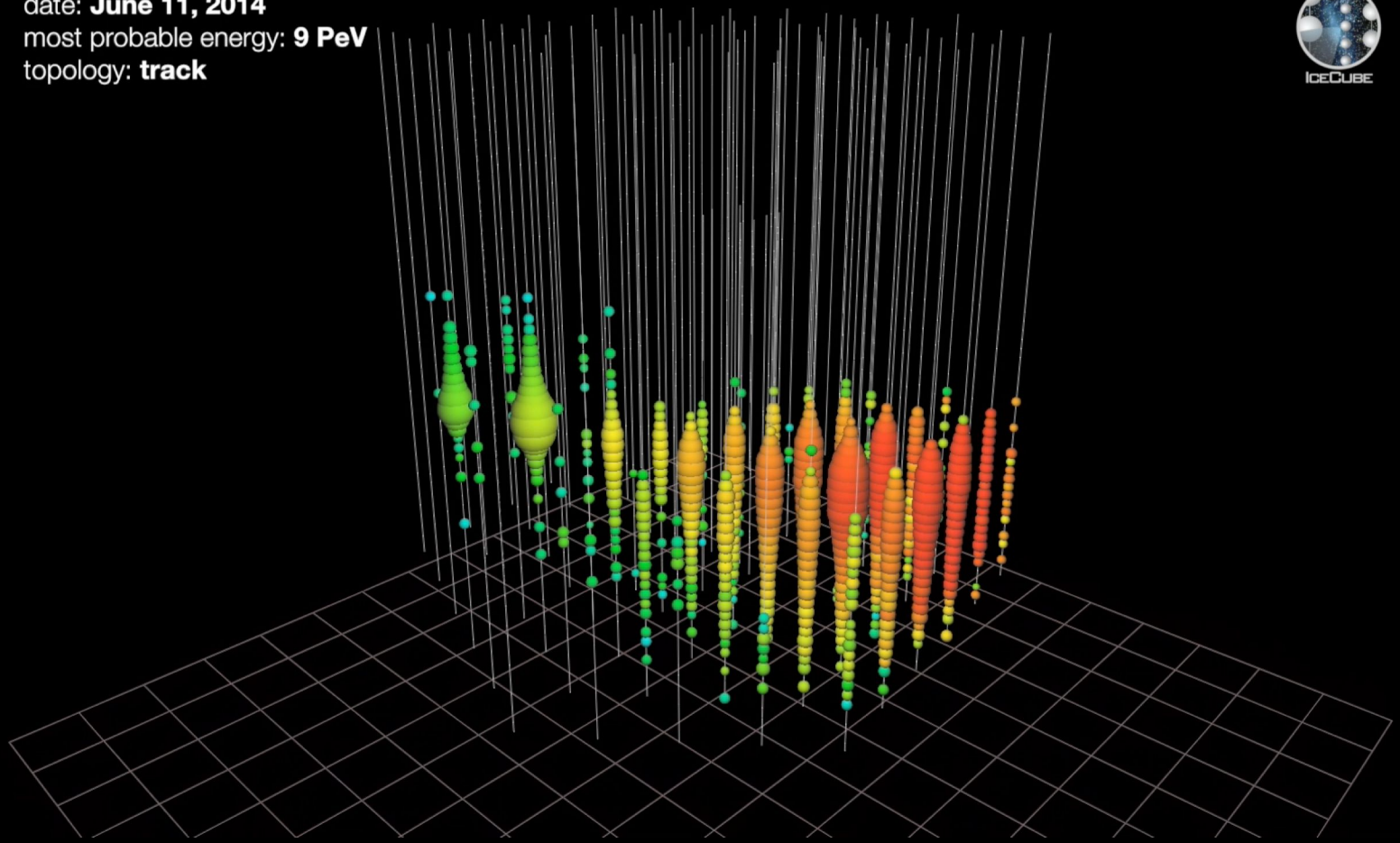


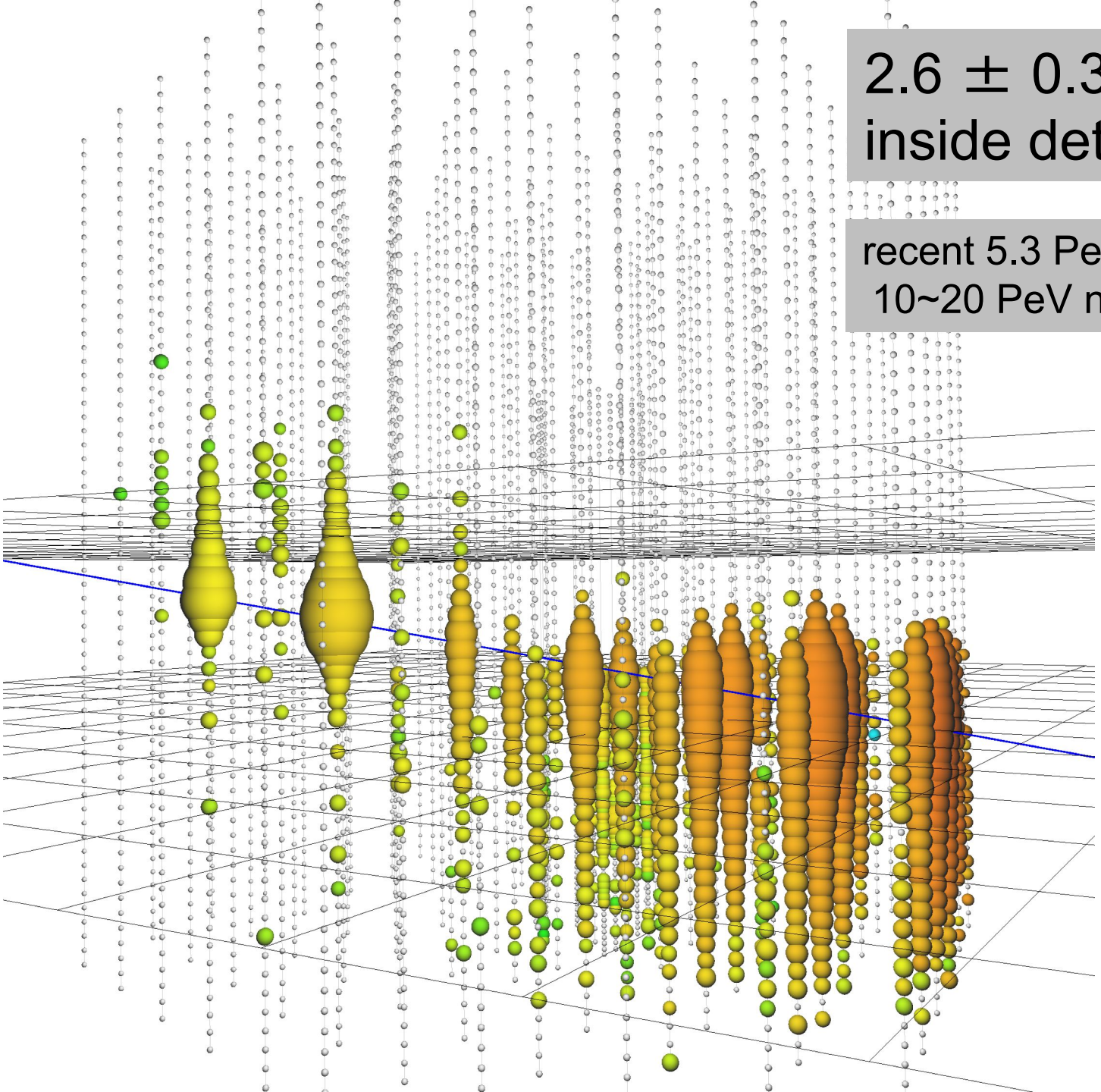


total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)

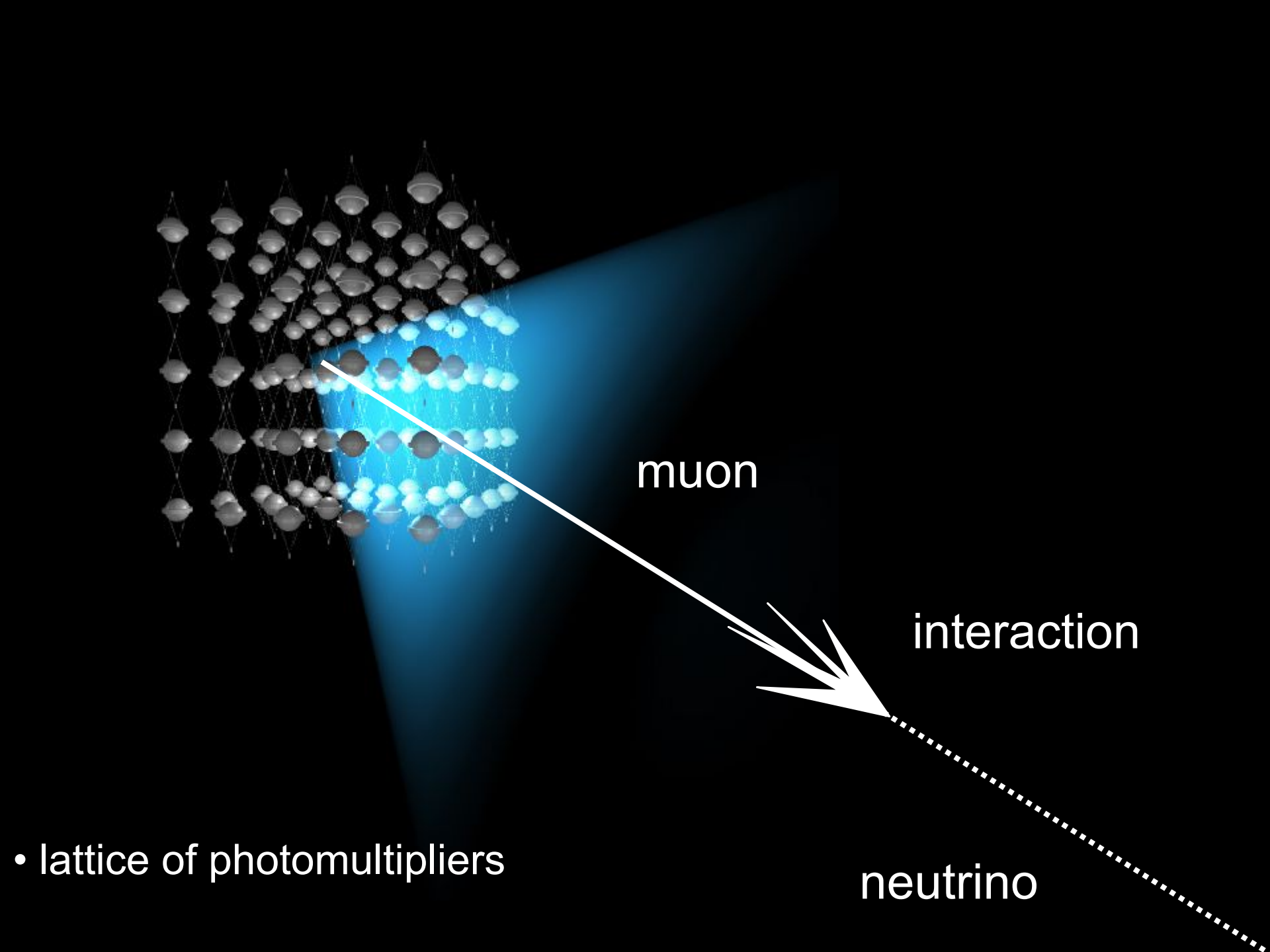
date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**





2.6 ± 0.3 PeV
inside detector

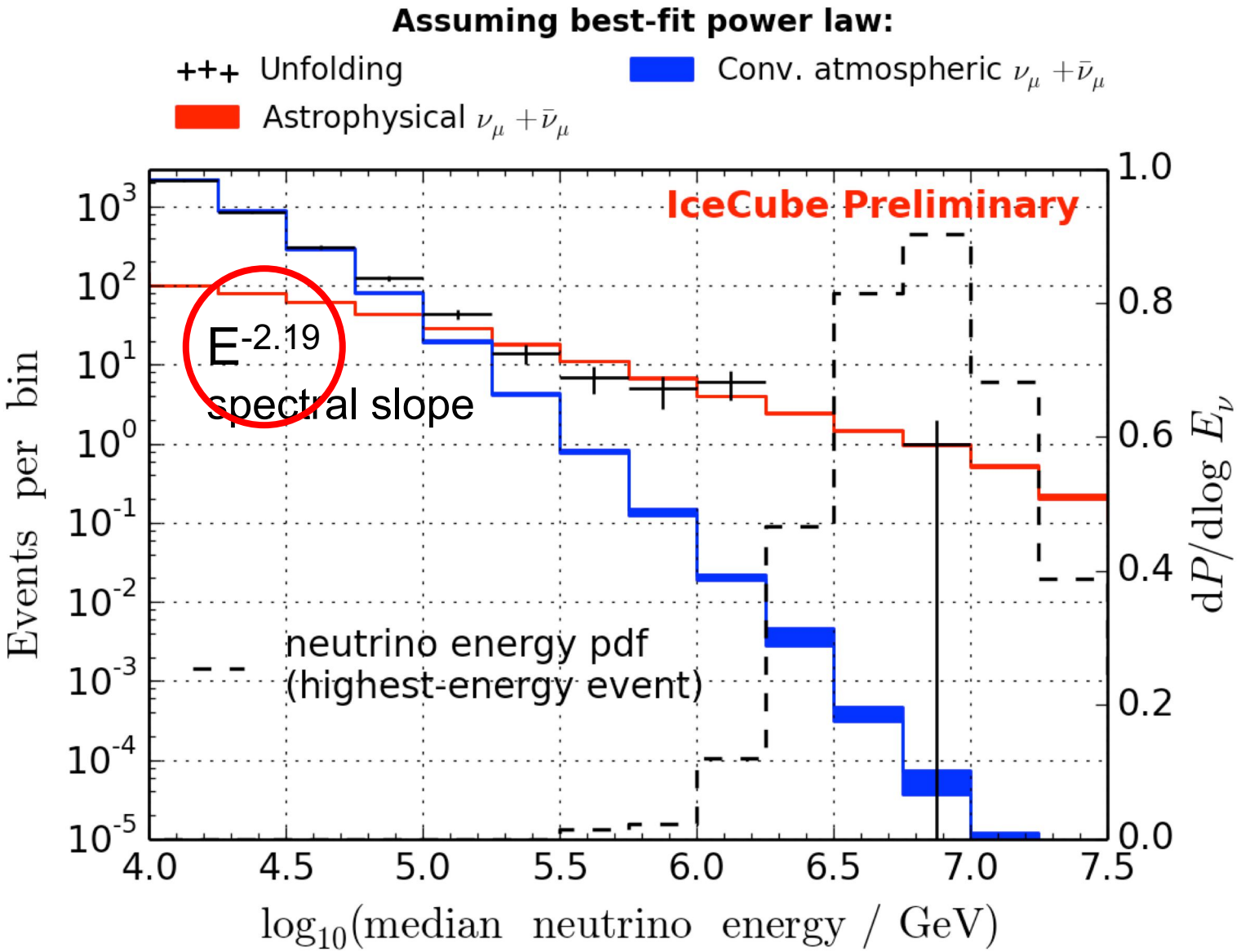
recent 5.3 PeV event
10~20 PeV neutrino



• lattice of photomultipliers

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

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

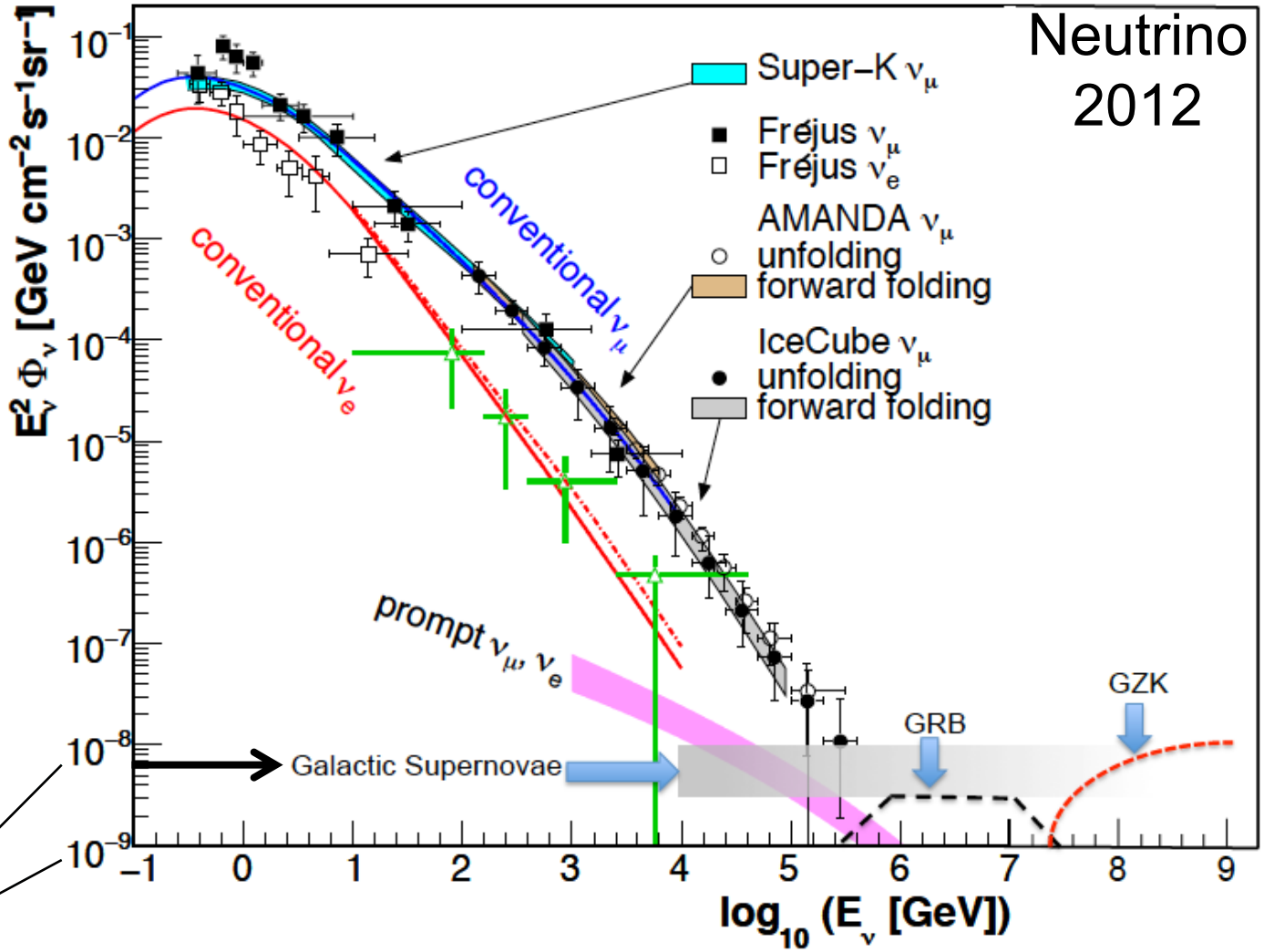


above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



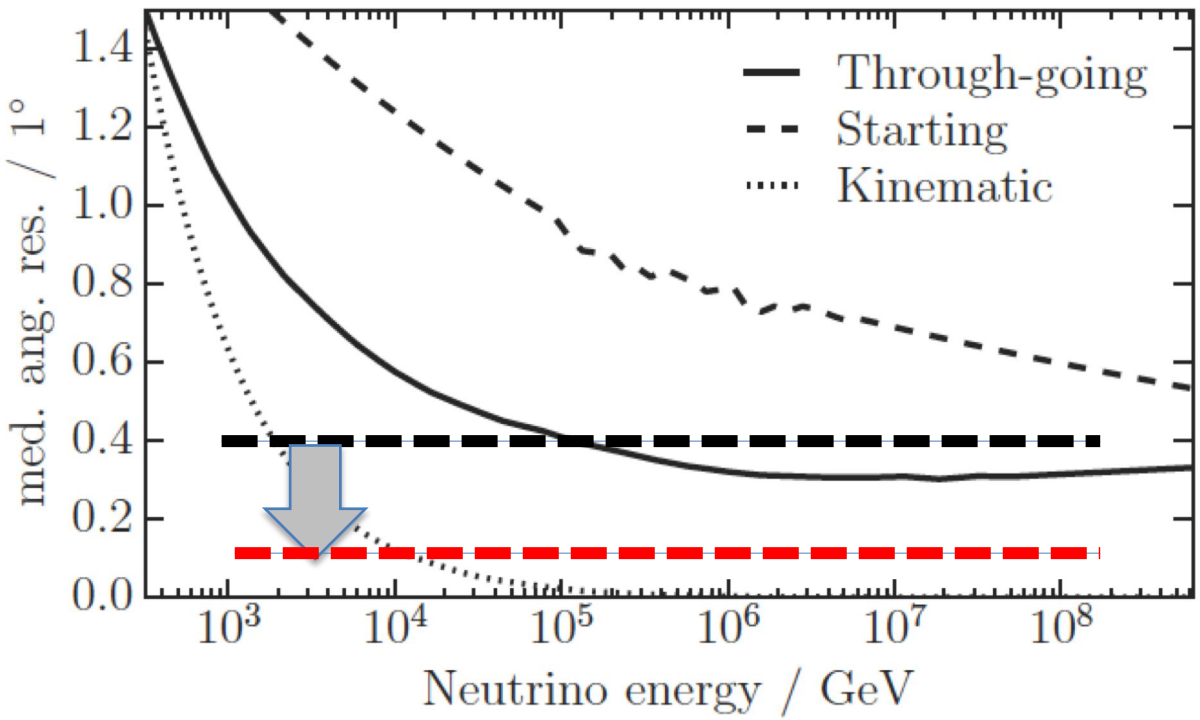
atmospheric

cosmic

100 TeV

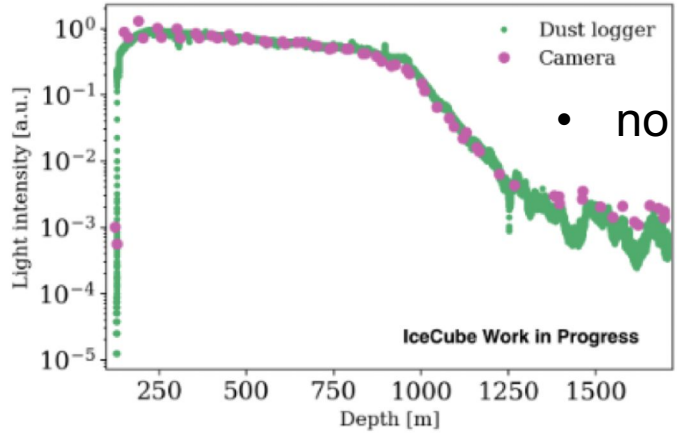
astronomy happens here:

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



ice: step by step

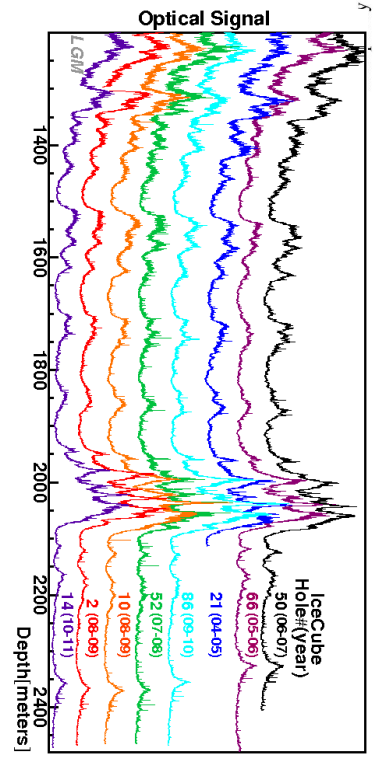
- hole ice ?

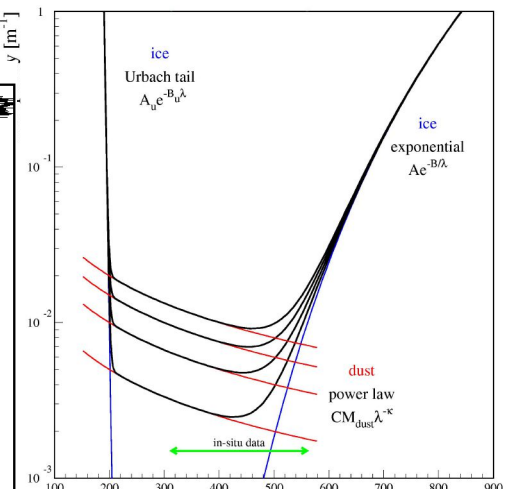


- no air bubbles/hydrates below 1350 m

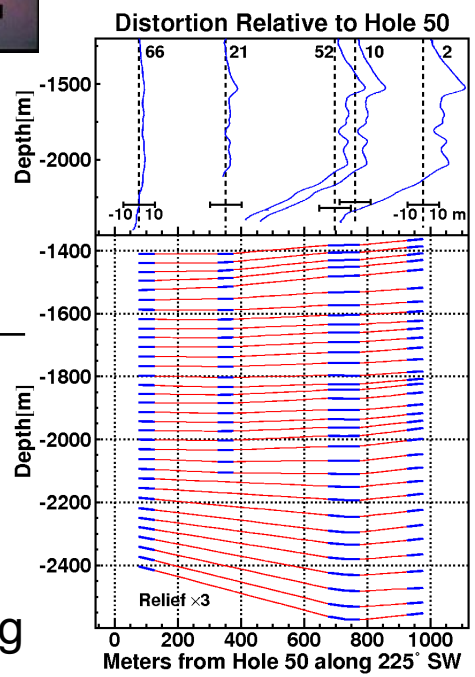
- > 100 m absorption length limited by dust

- ice layers

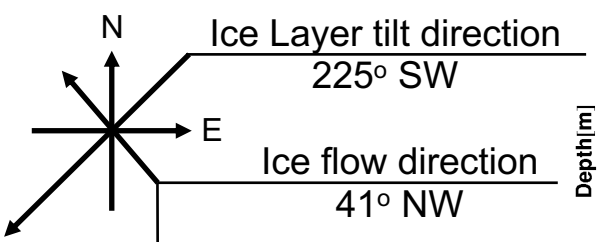




- tilted ice layers



- some birefringence ?



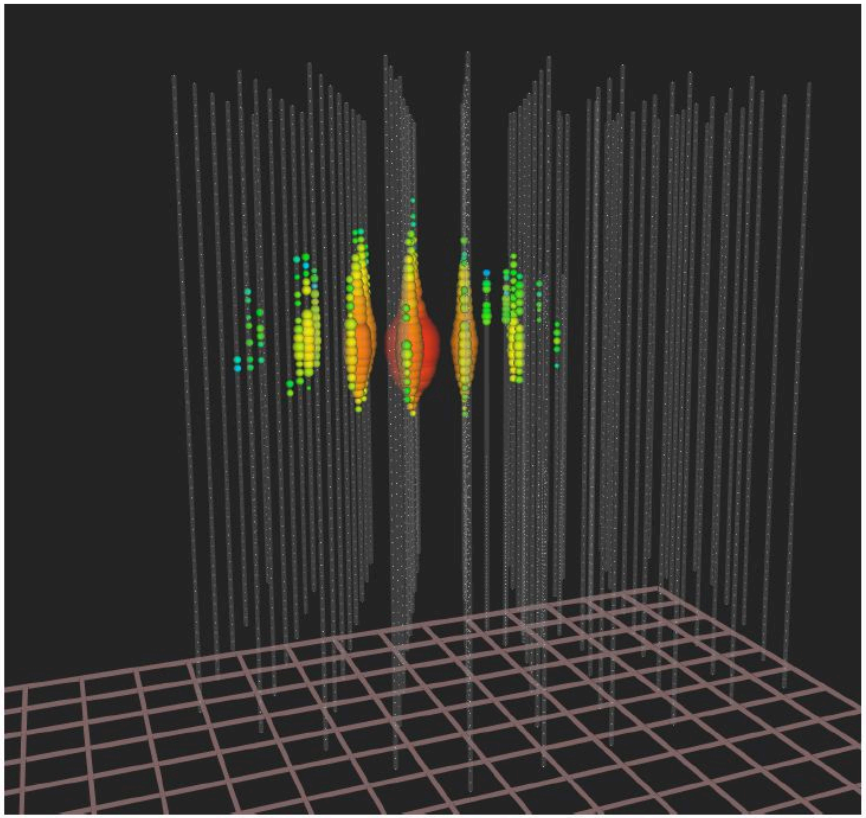
Ice Layer tilt direction
225° SW

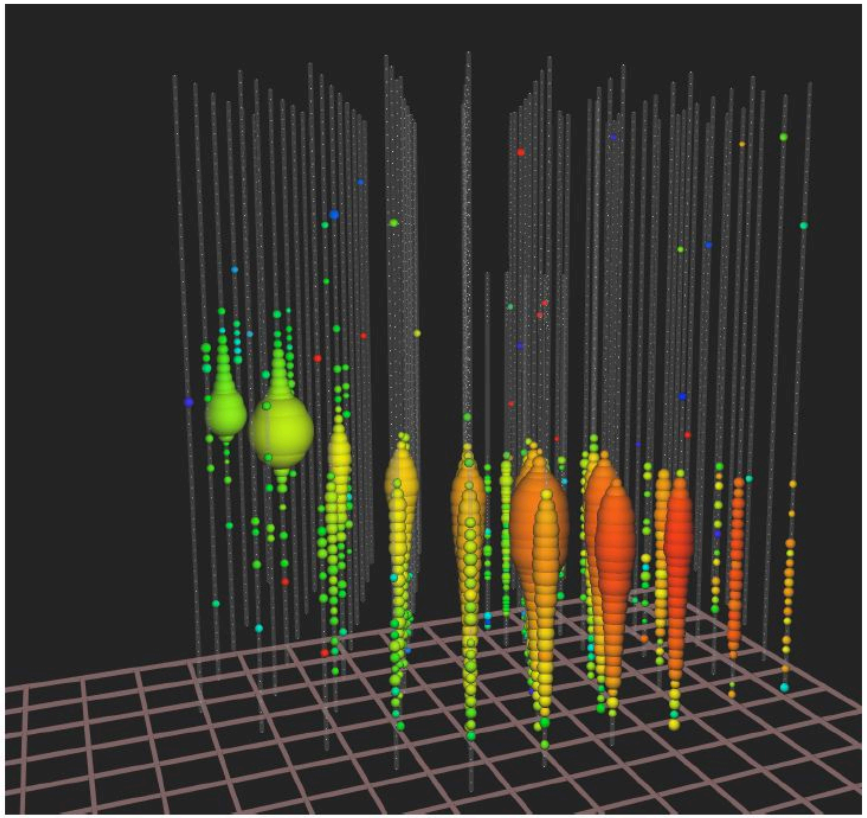
Ice flow direction
41° NW

- anisotropy
~8% less scattering
41° NW

neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth

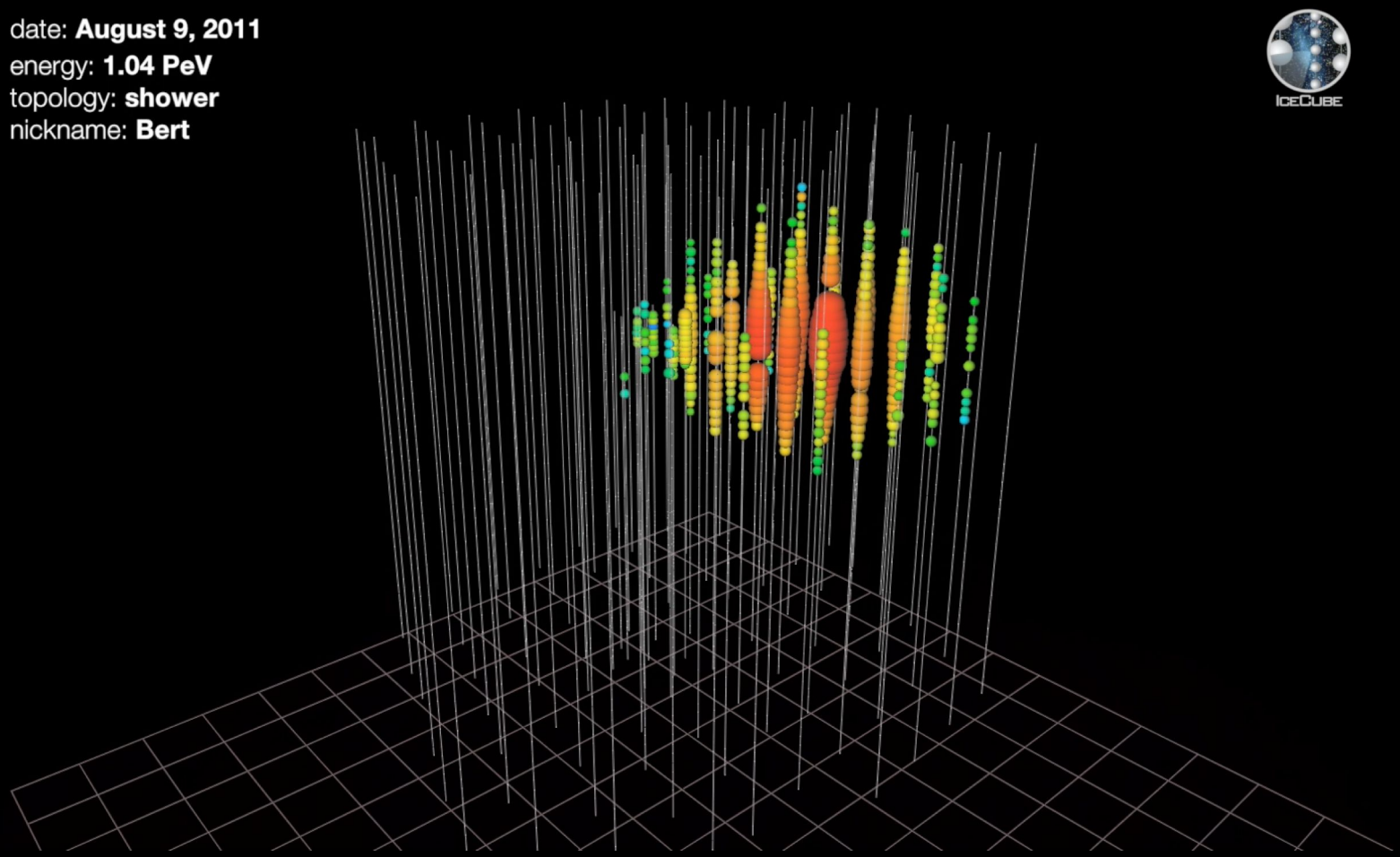




total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)

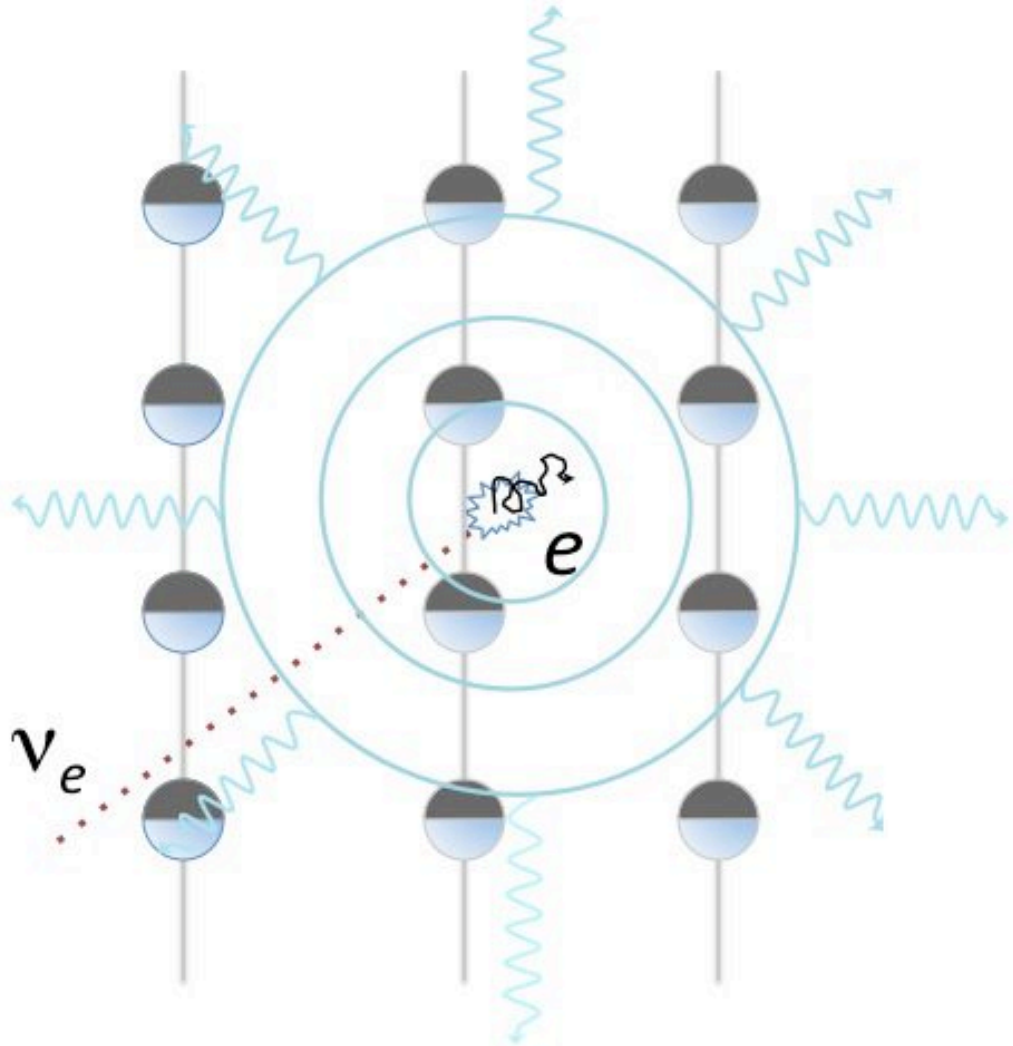
GZK neutrino search: two neutrinos with > 1,000 TeV

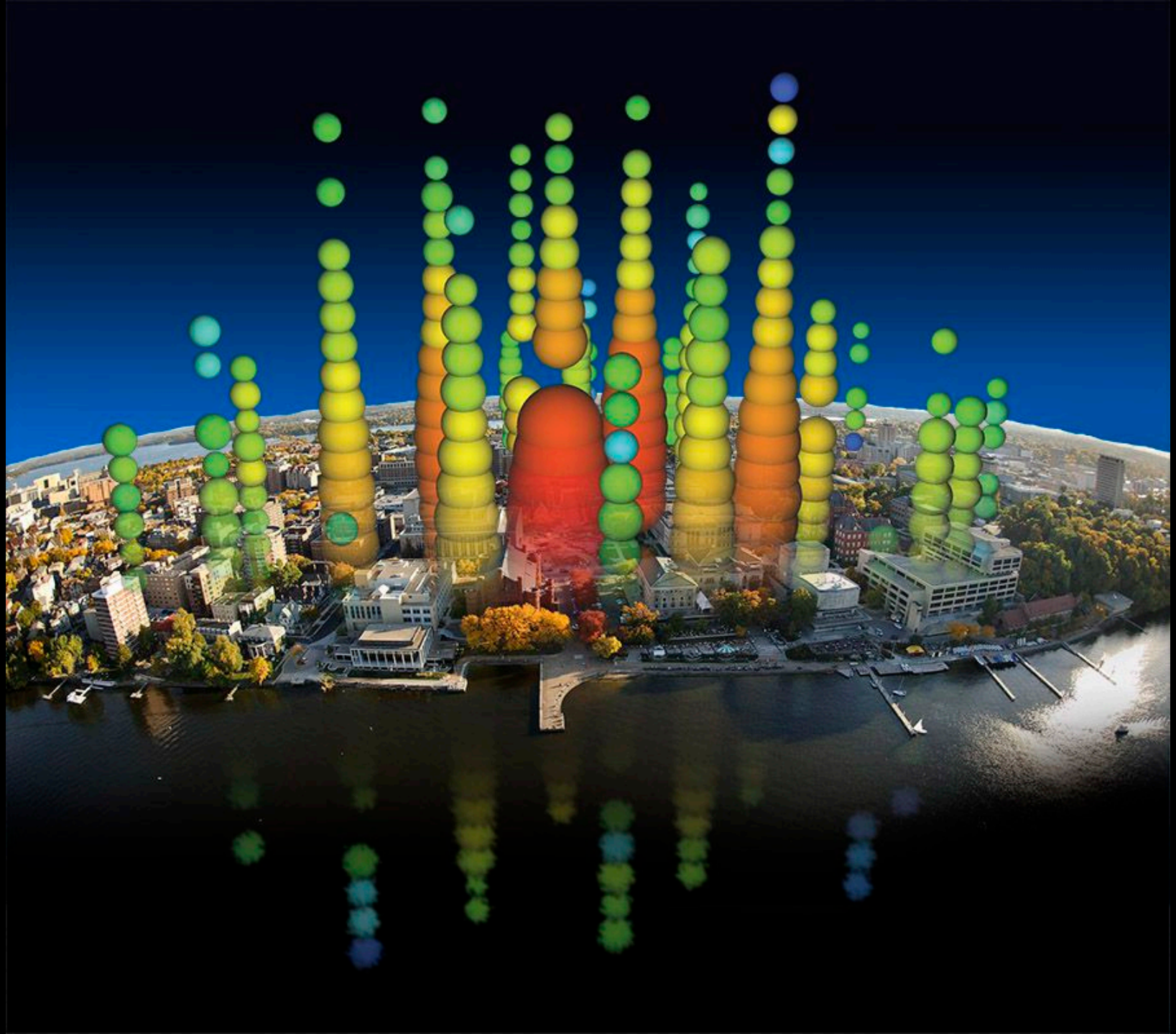


electron showers versus muon tracks

PeV ν_e and ν_τ showers:

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

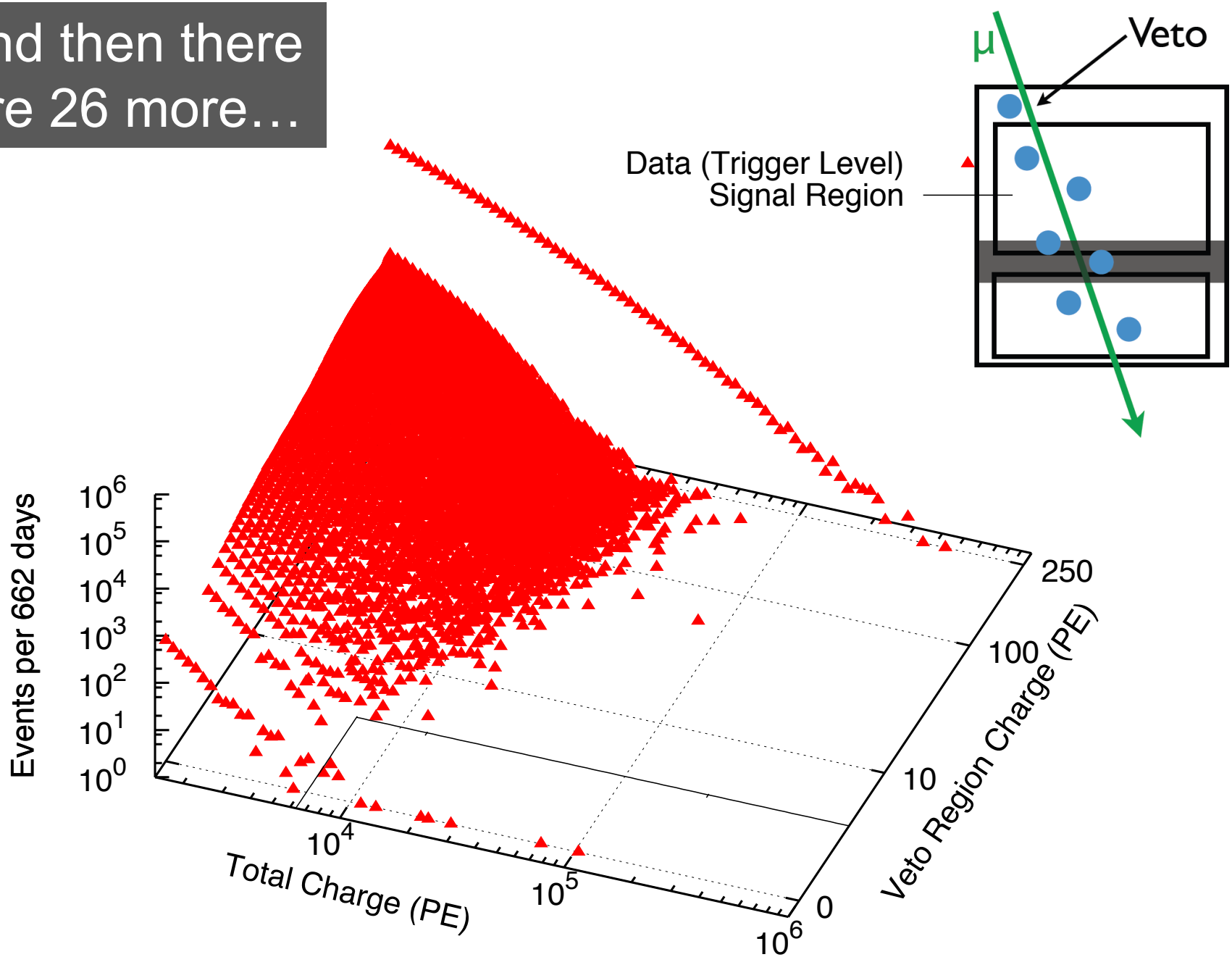




events starting inside the detector

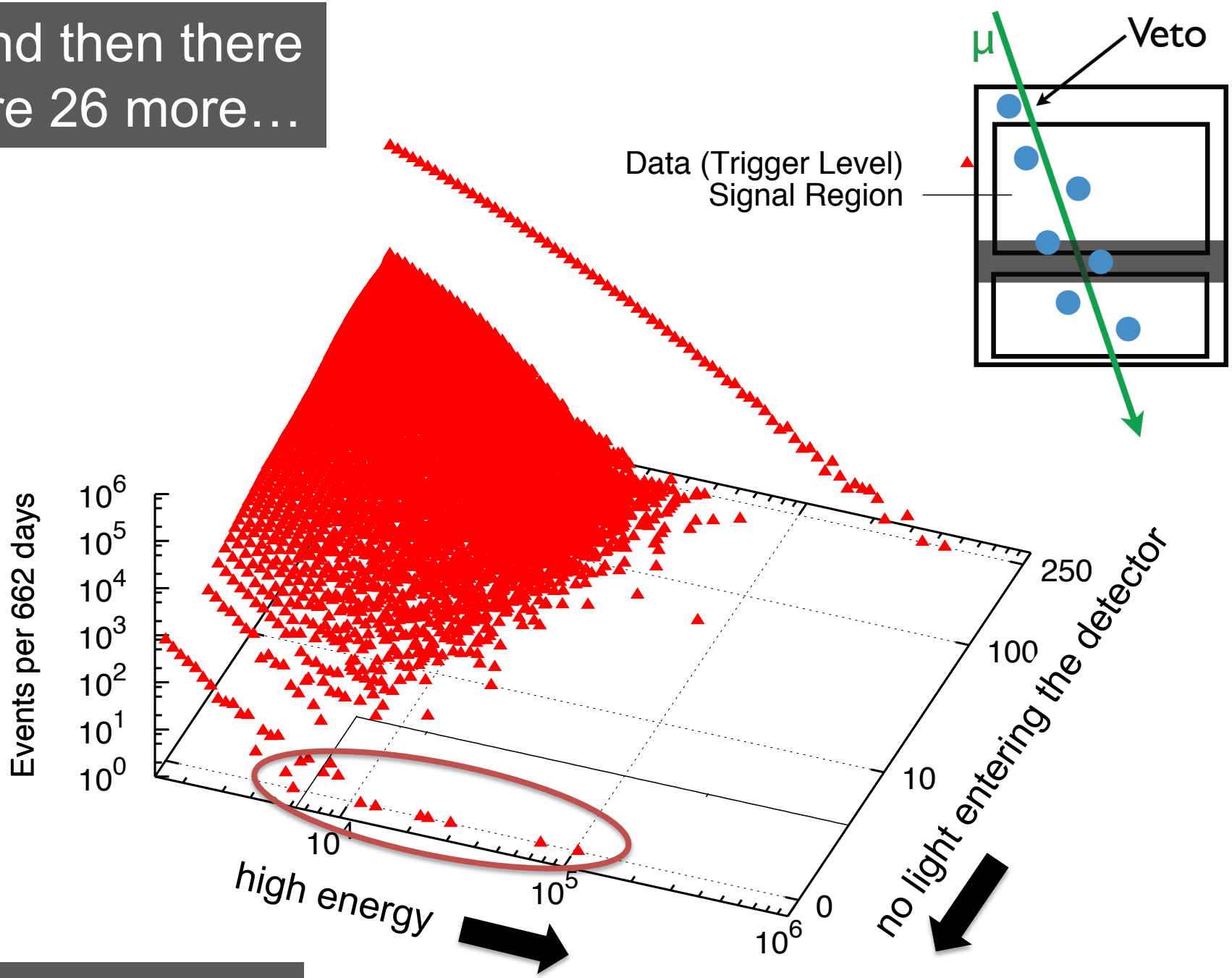
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for *atmospheric* neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry

…and then there were 26 more…



data: 86 strings one year

…and then there were 26 more…



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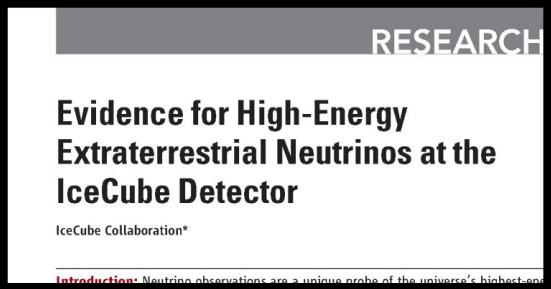
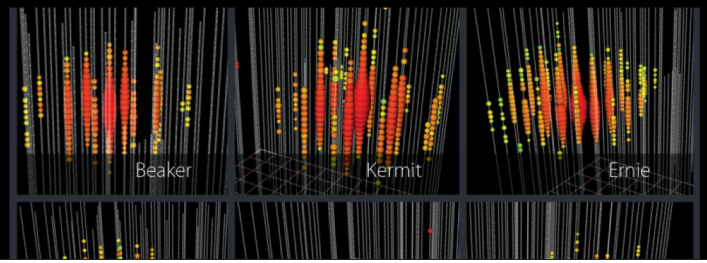
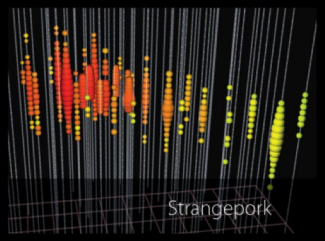

RESEARCH

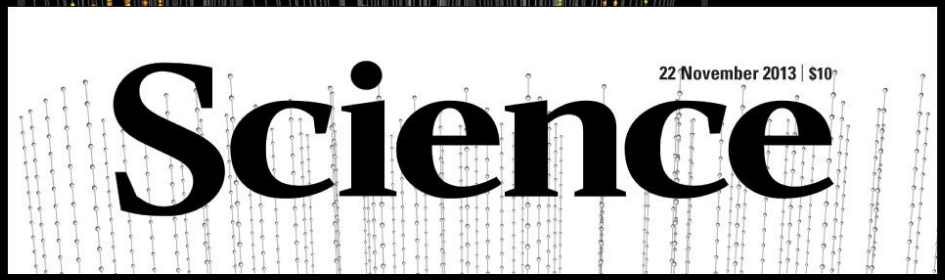
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

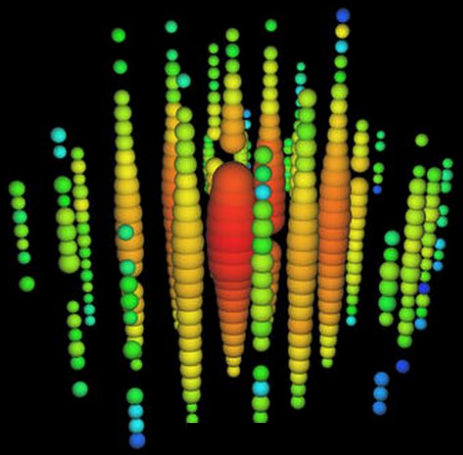
IceCube Collaboration*

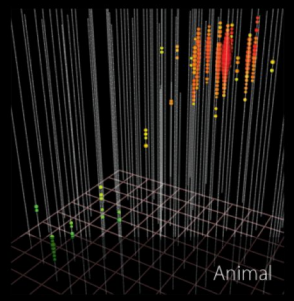
28 High Energy Events

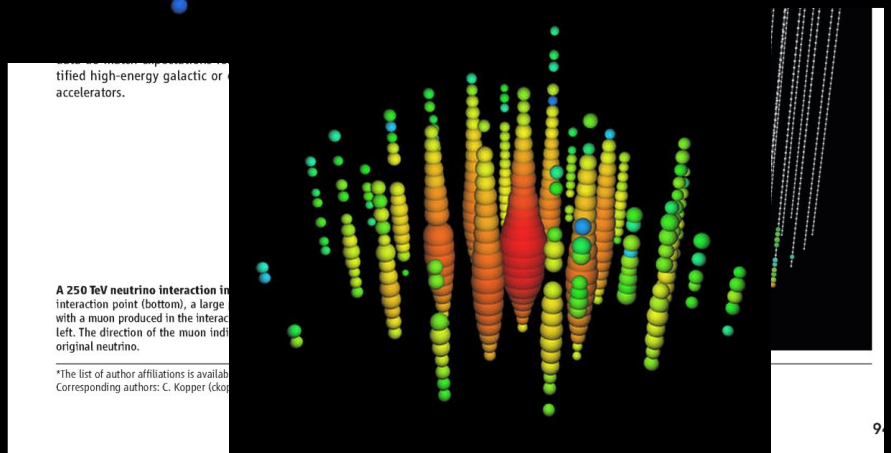






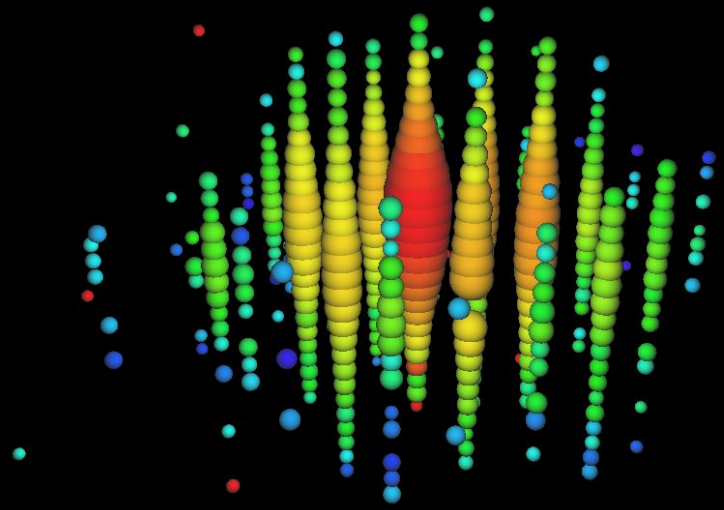





tified high-energy galactic or
accelerators.

A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon indi
original neutrino.

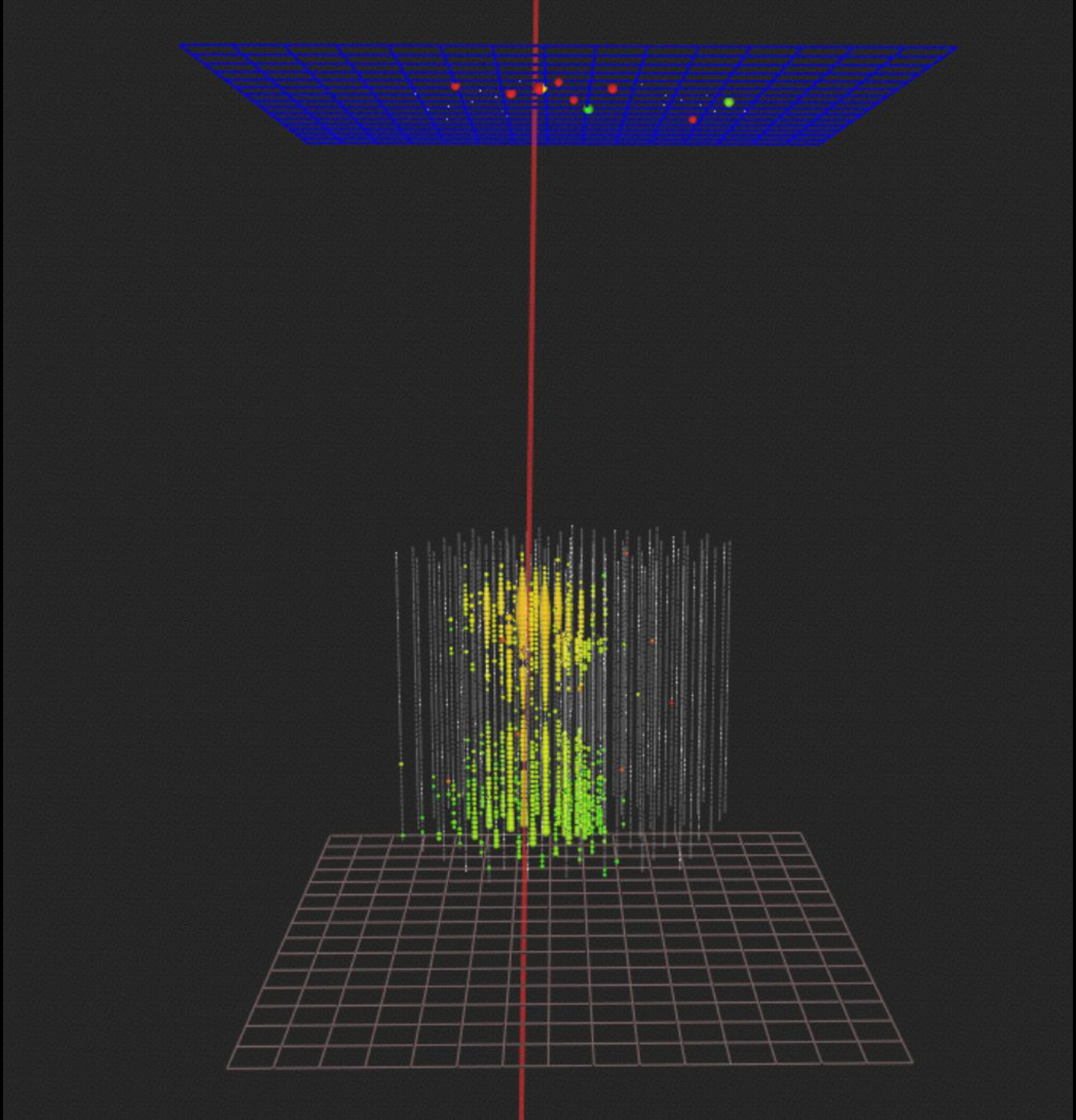
*The list of author affiliations is availab
Corresponding authors: C. Kopper (ckop



2000 TeV event in year 3

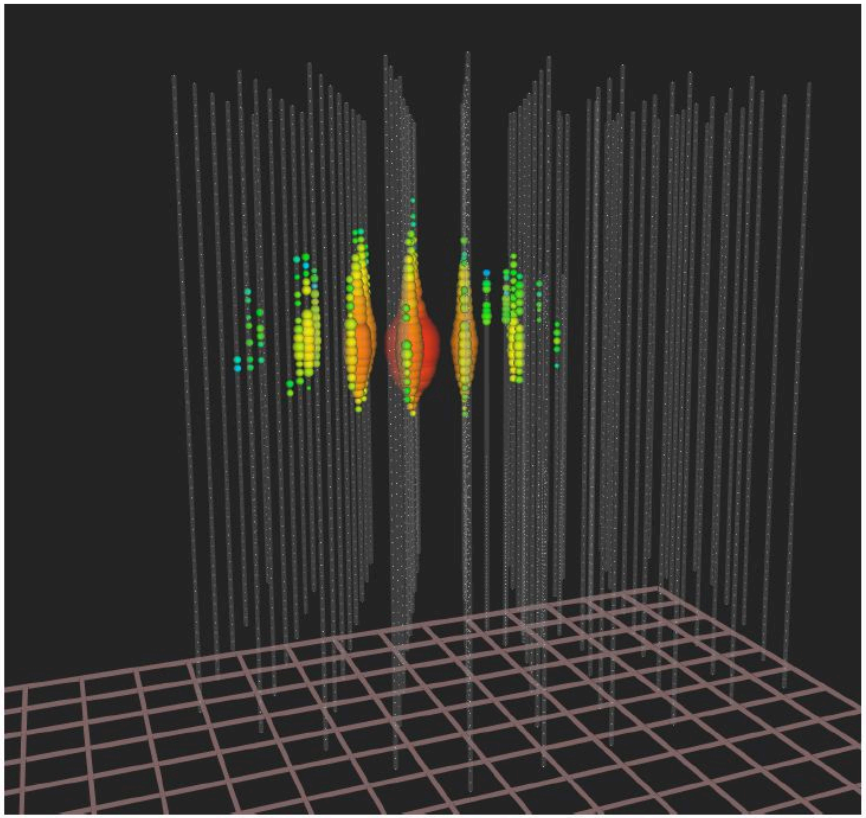
430 TeV inside detector
PeV ν_μ
no air shower

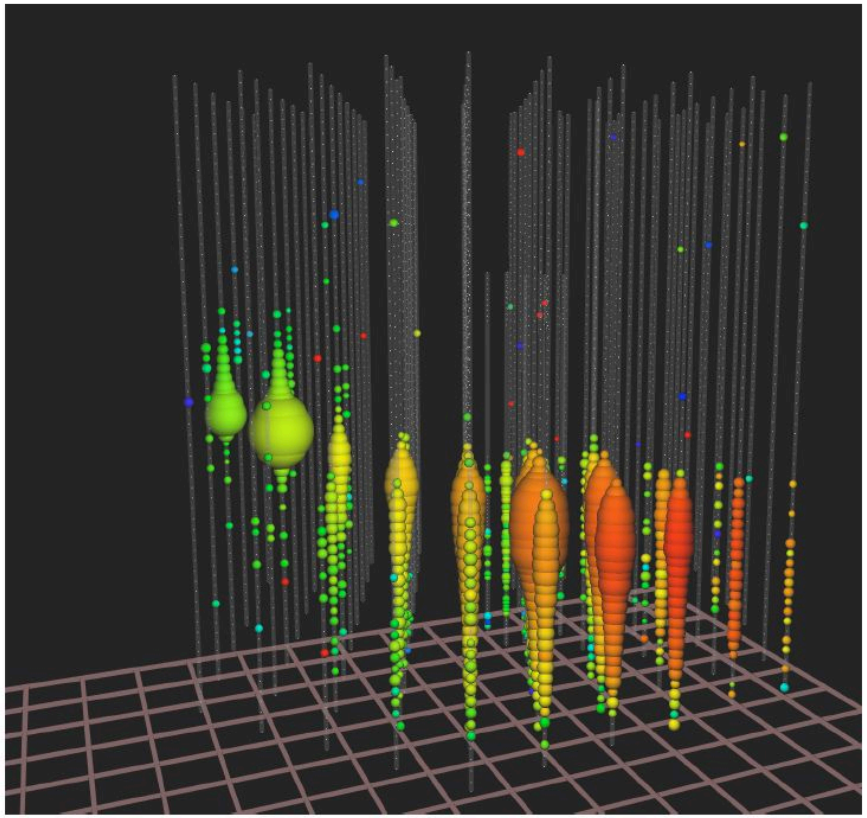
all cosmic neutrinos are isolated by self-veto



neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth





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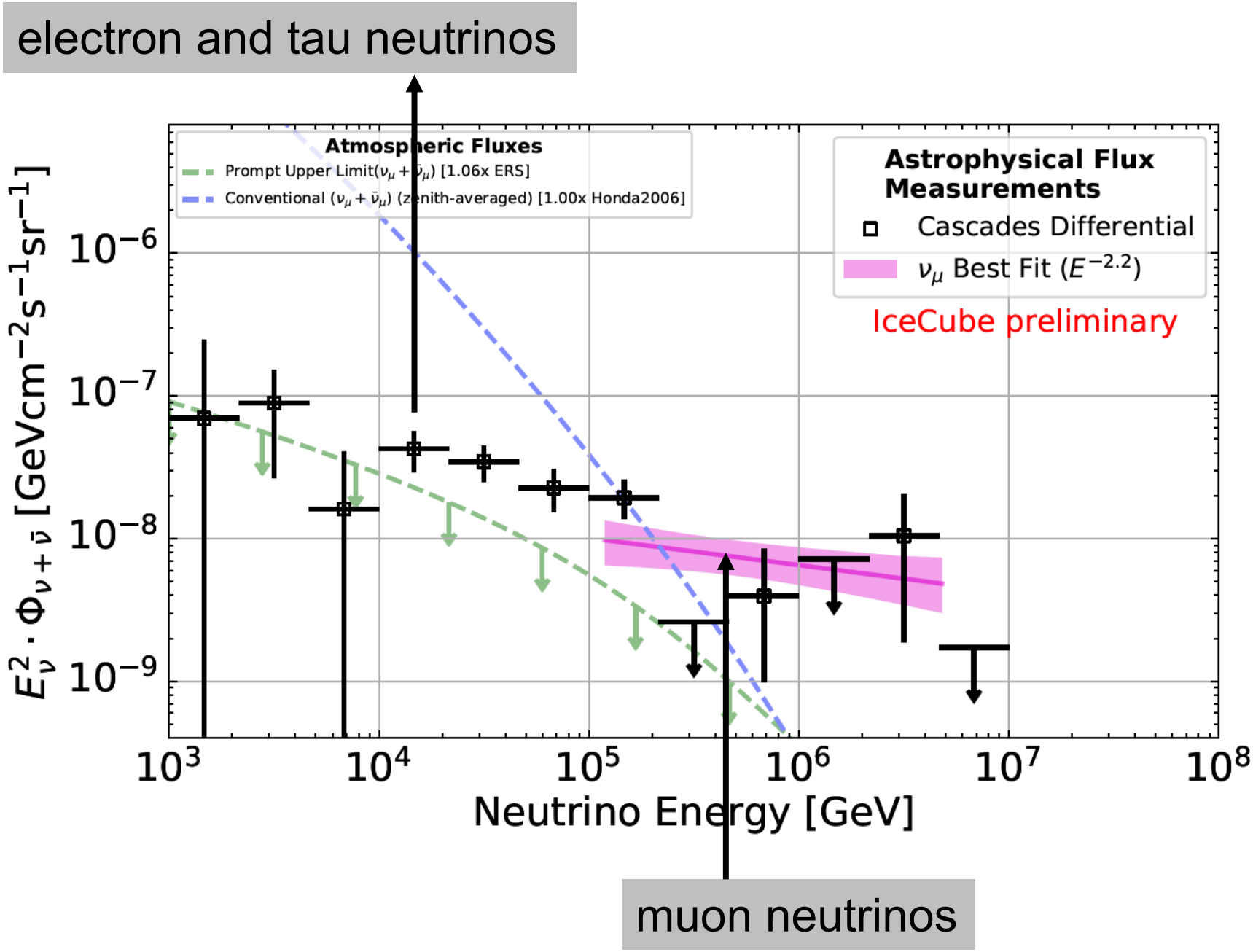
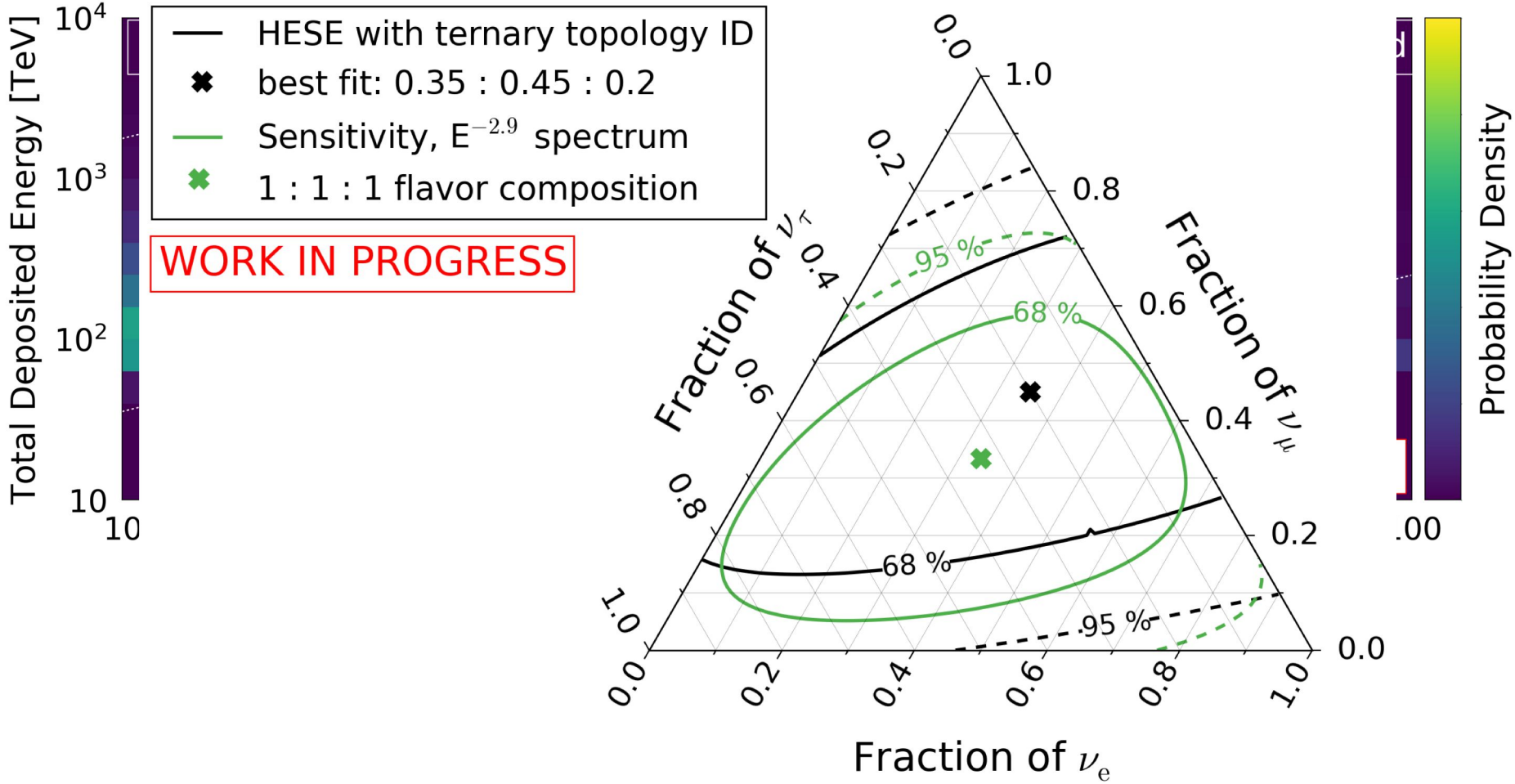
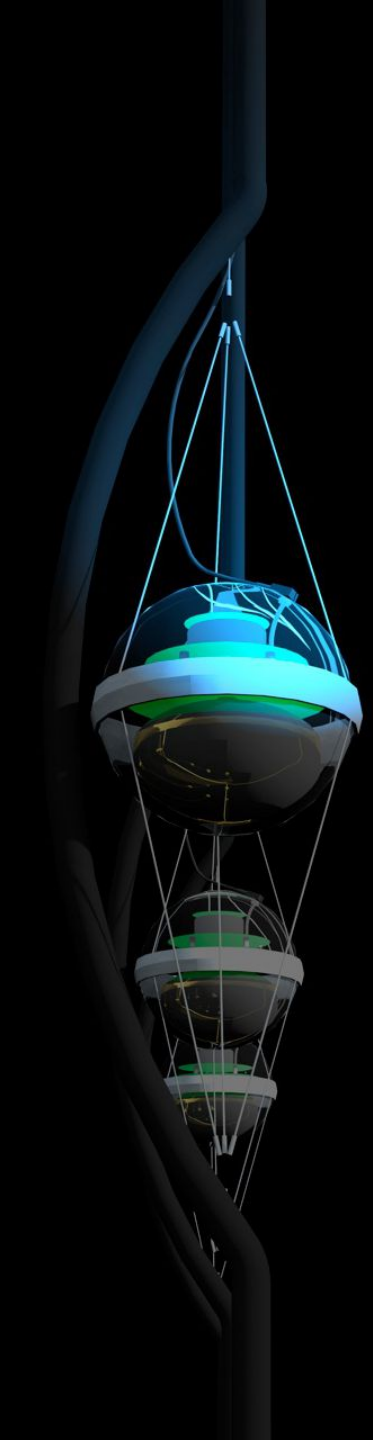

electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$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

high-energy starting events – 7.5 yr



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

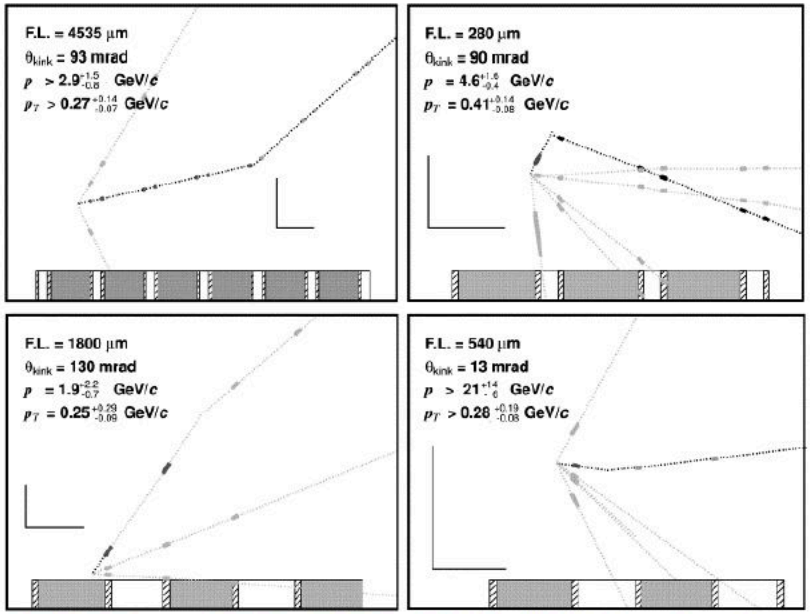


- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

icecube.wisc.edu

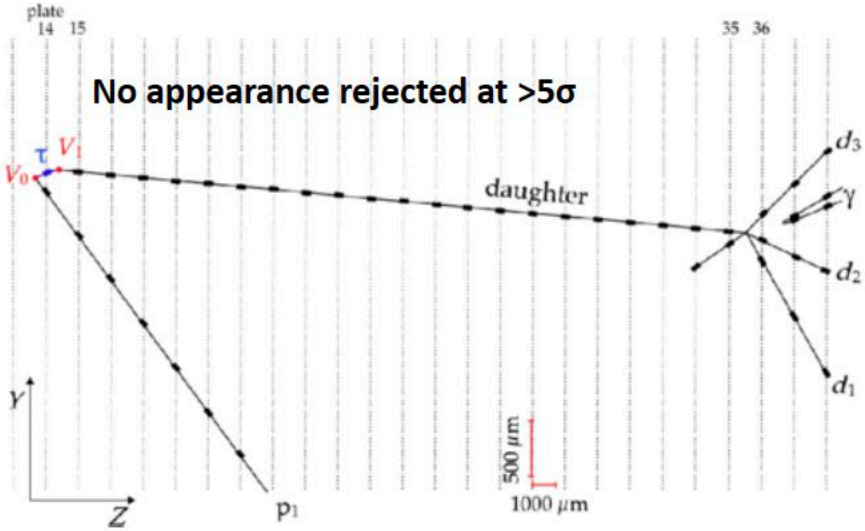
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



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

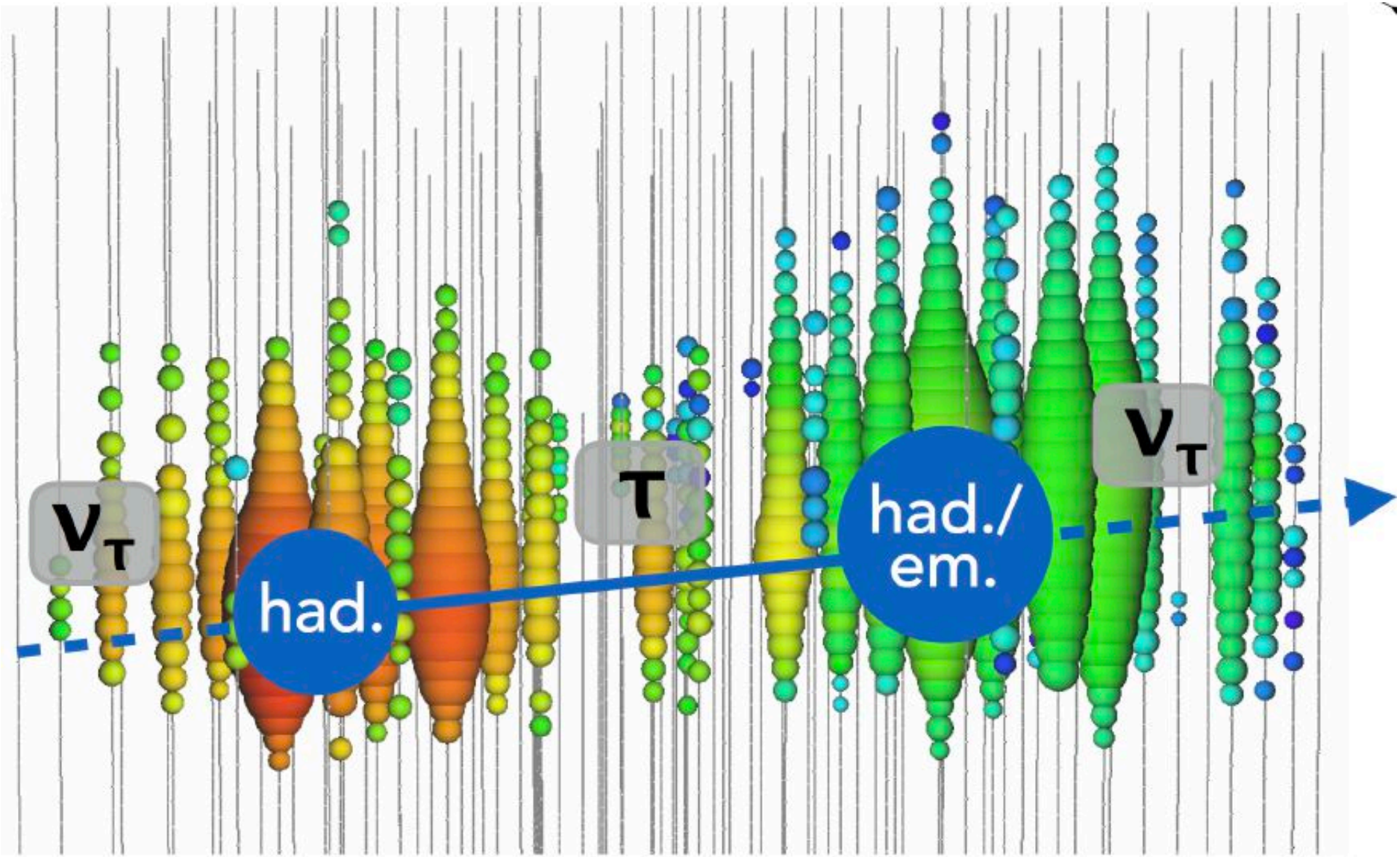
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



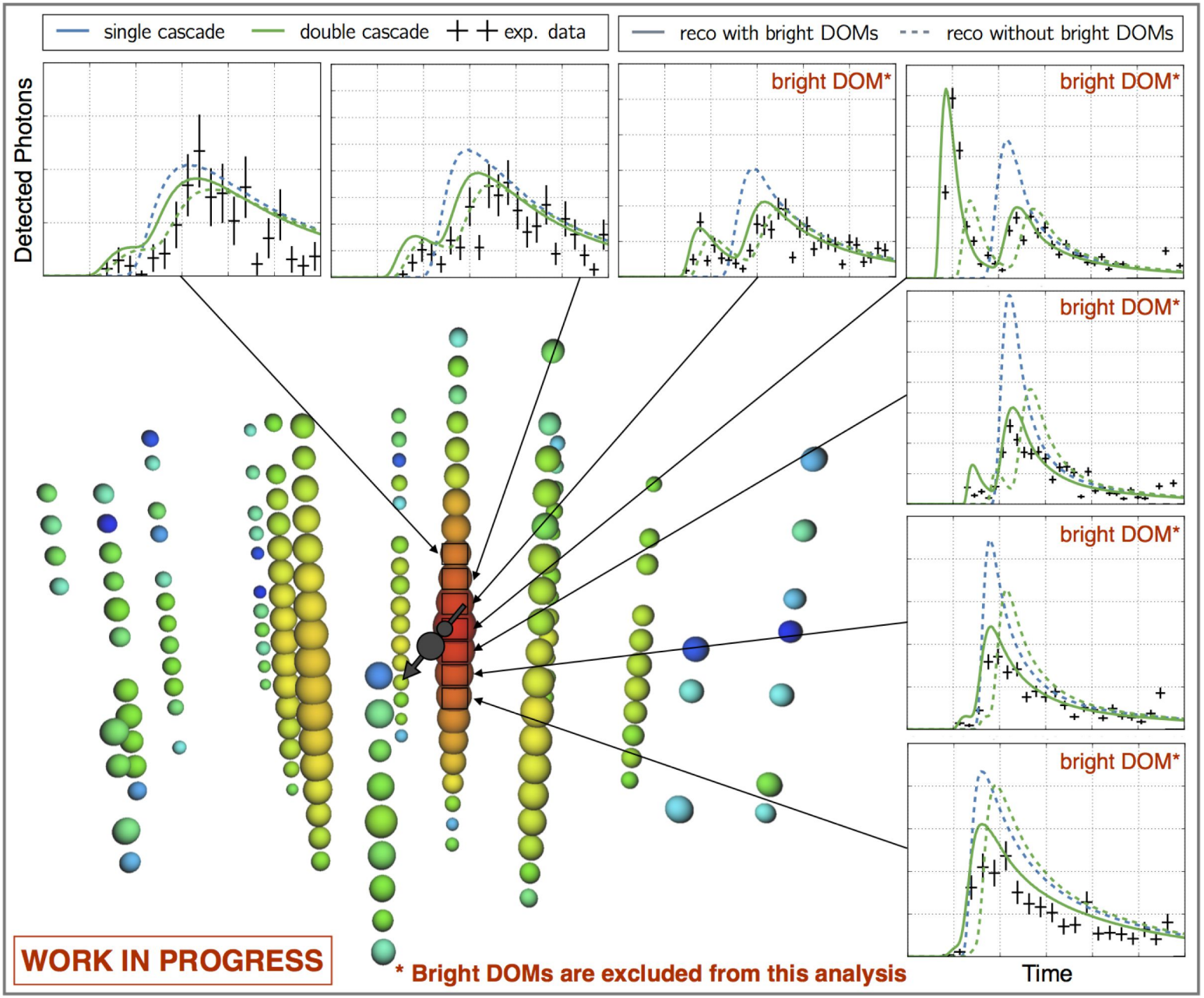
OPERA Phys. Rev. Lett. 115, 121802 (2015)

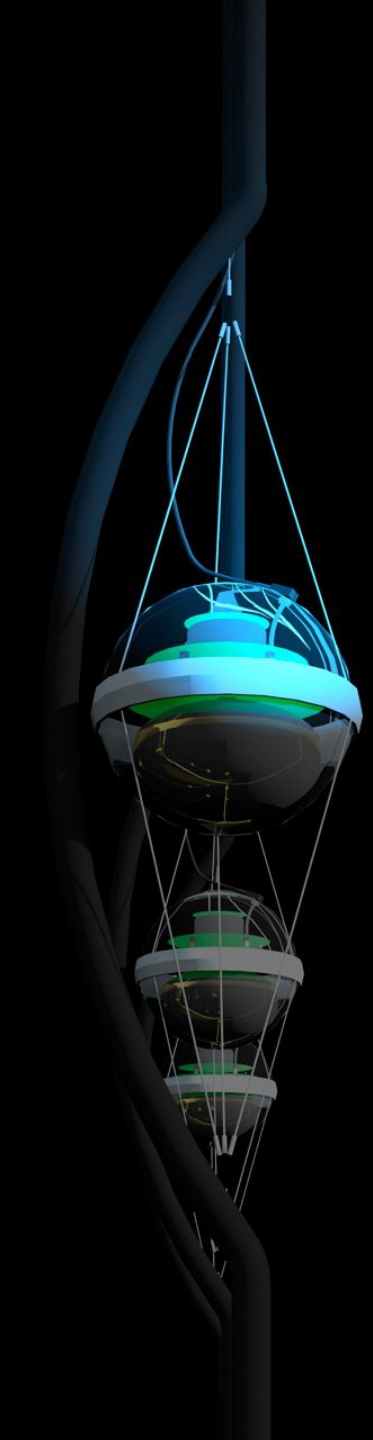
tau production and decay

tau decay length:
50m per PeV



a cosmic tau neutrino: livetime 17m





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

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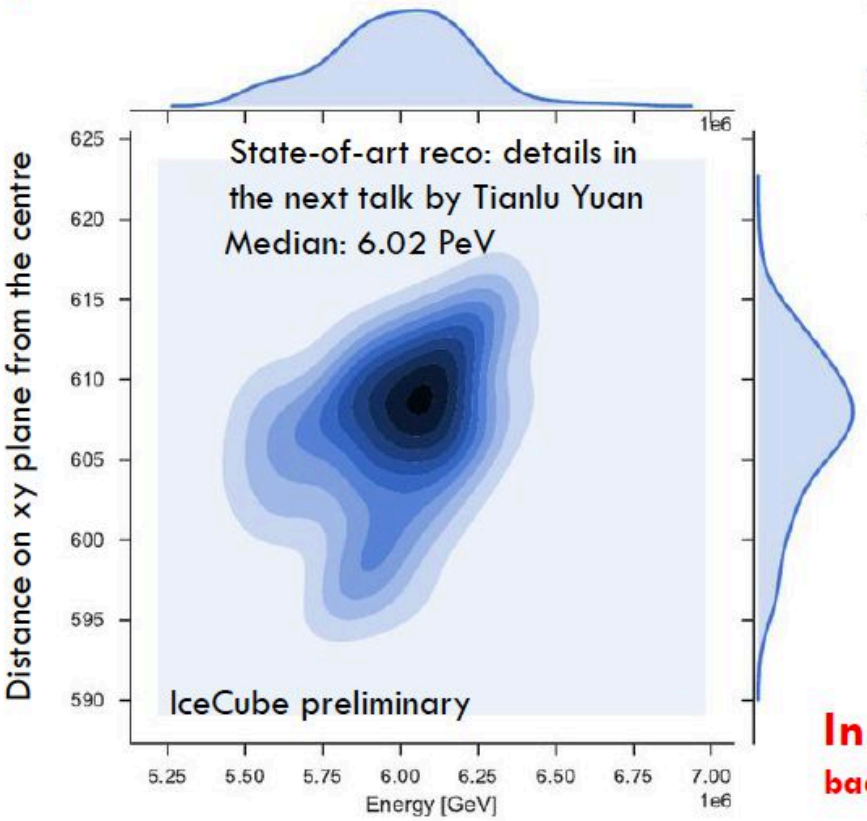
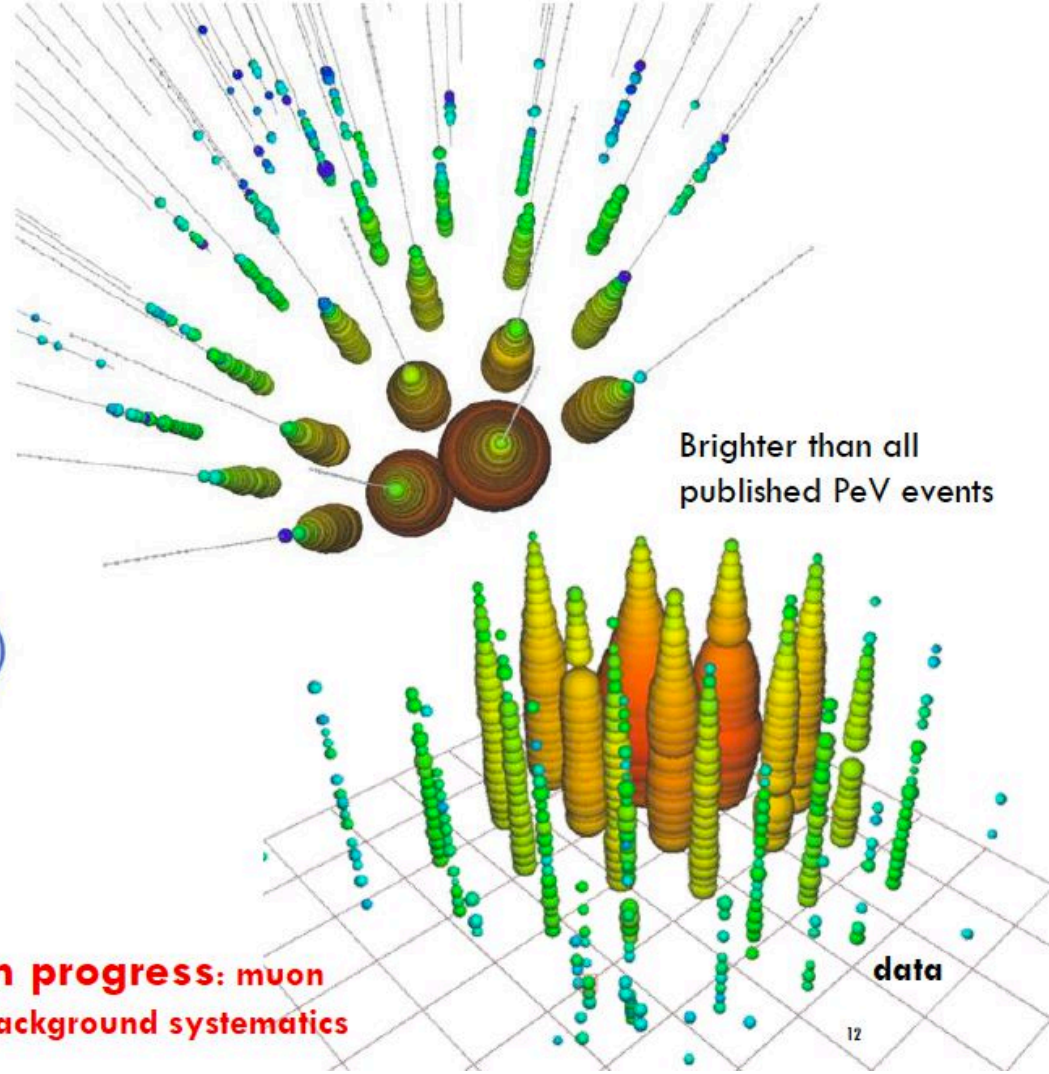
partially contained event with energy of 6.3 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE

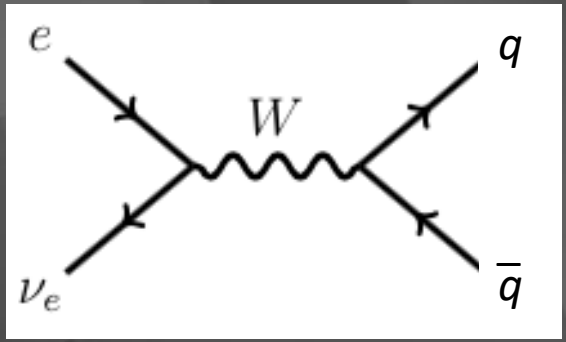




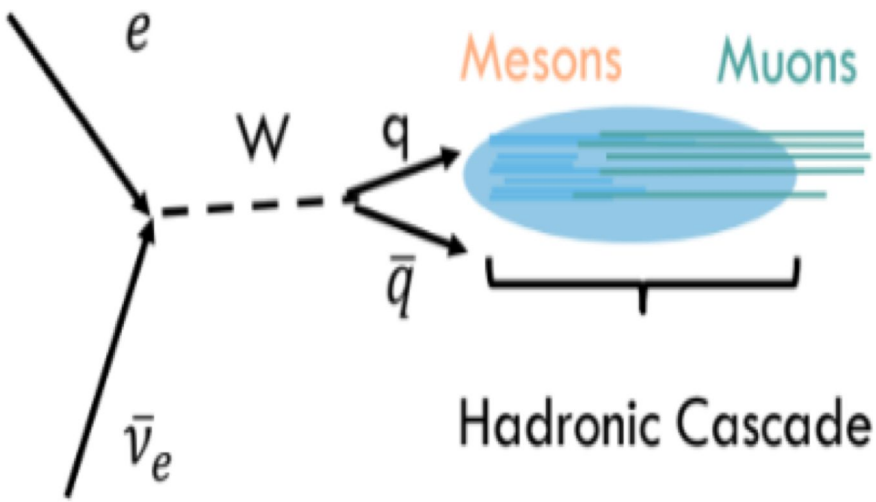
In progress: muon background systematics

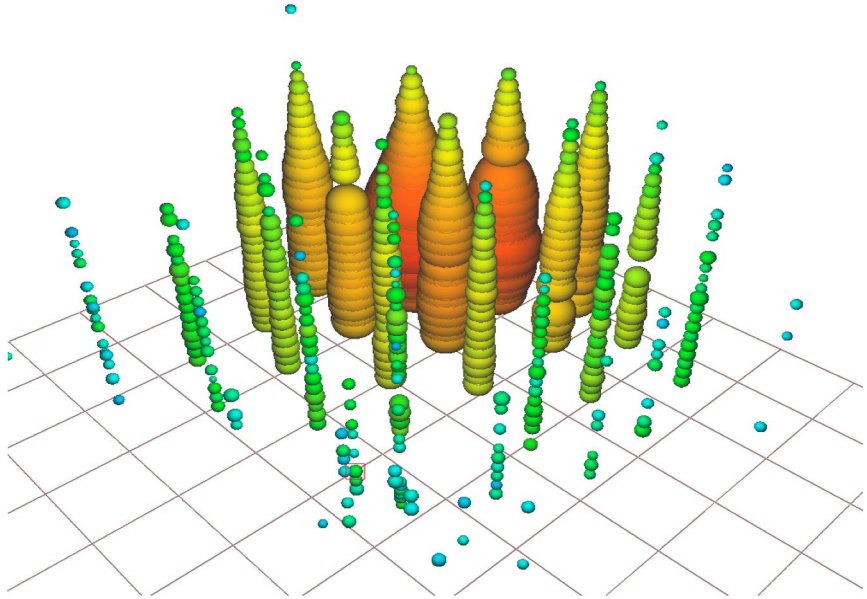
the first Glashow resonance event:

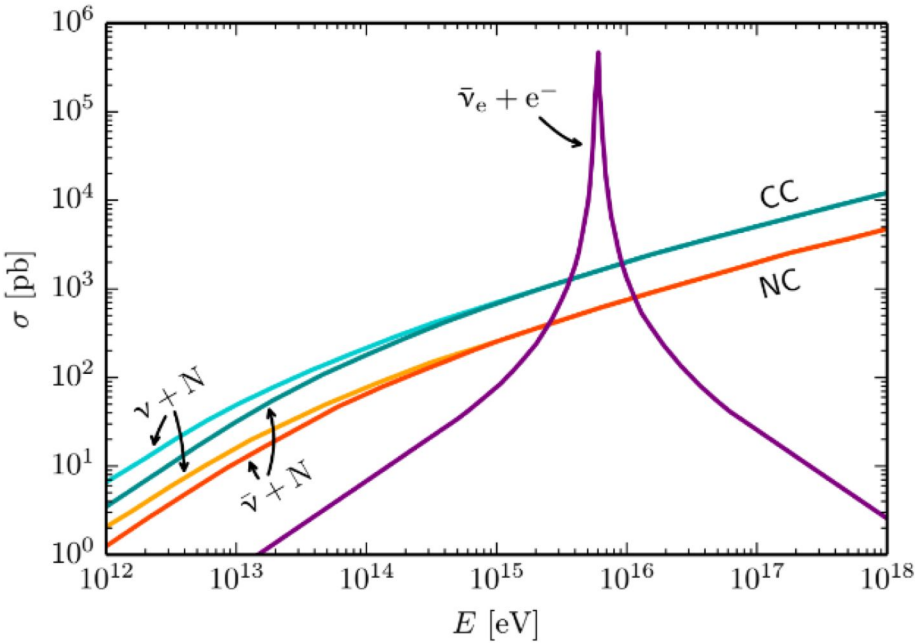
anti-ν_e + atomic electron → real W at 6.3 PeV



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





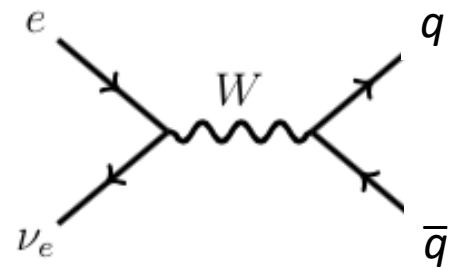


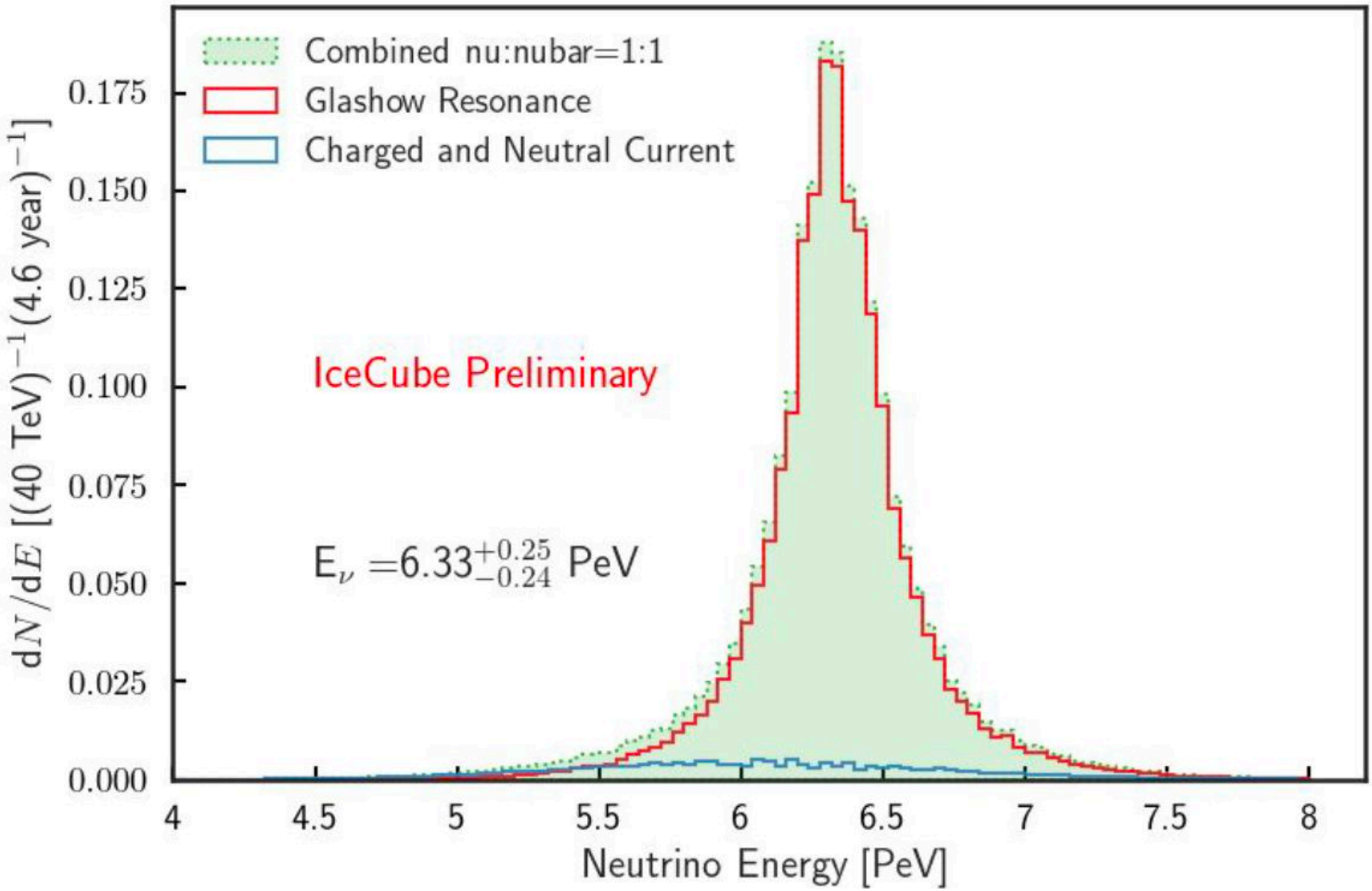
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

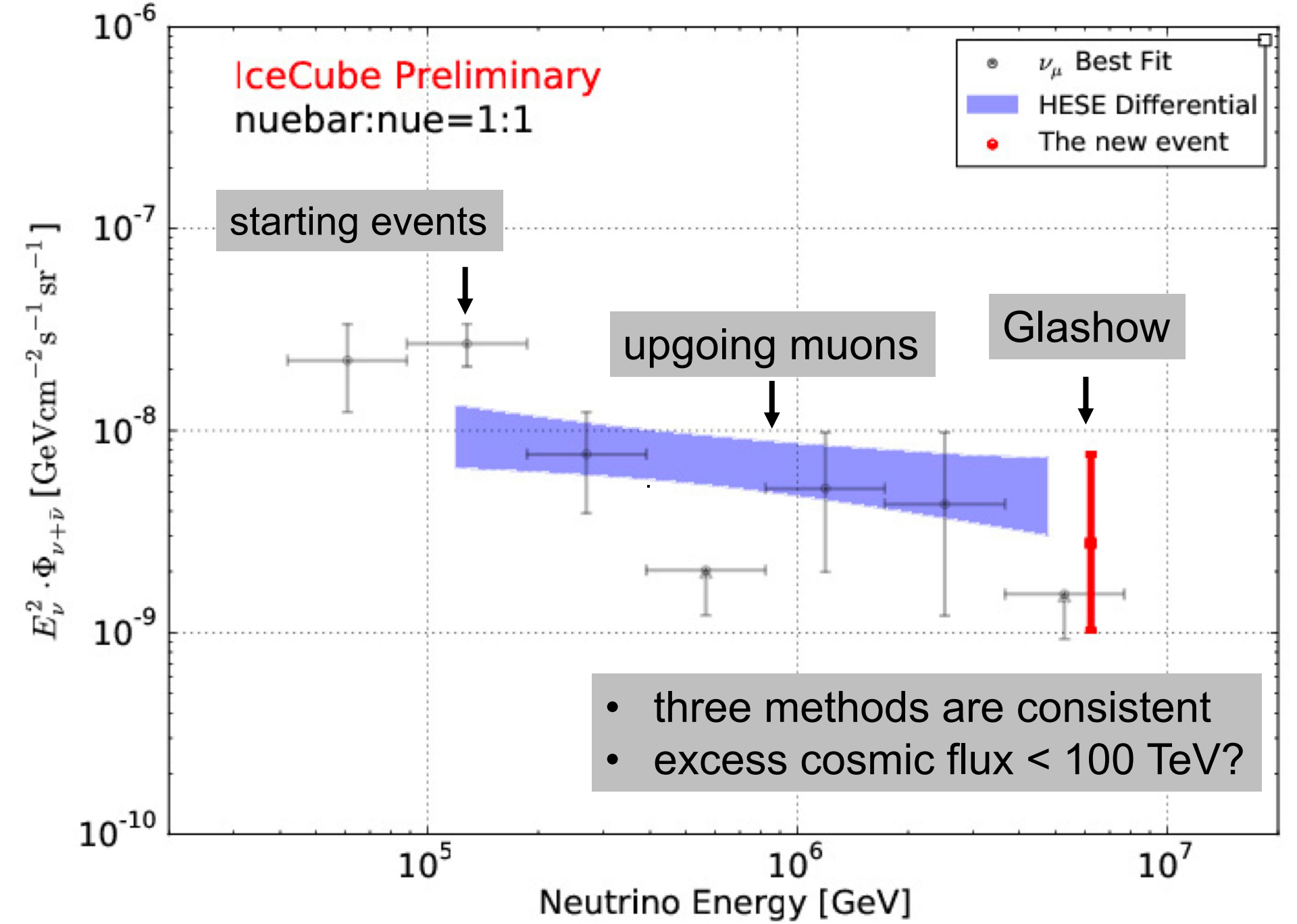
- → resonance: E_ν = 6.3 PeV

work on-going

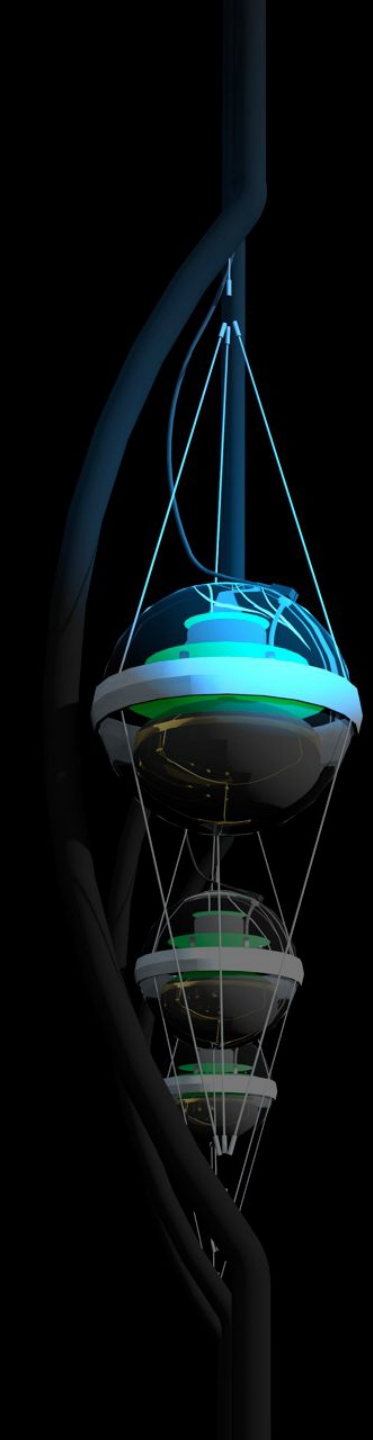
- energy measurement understood
- identification of anti-electron neutrinos







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

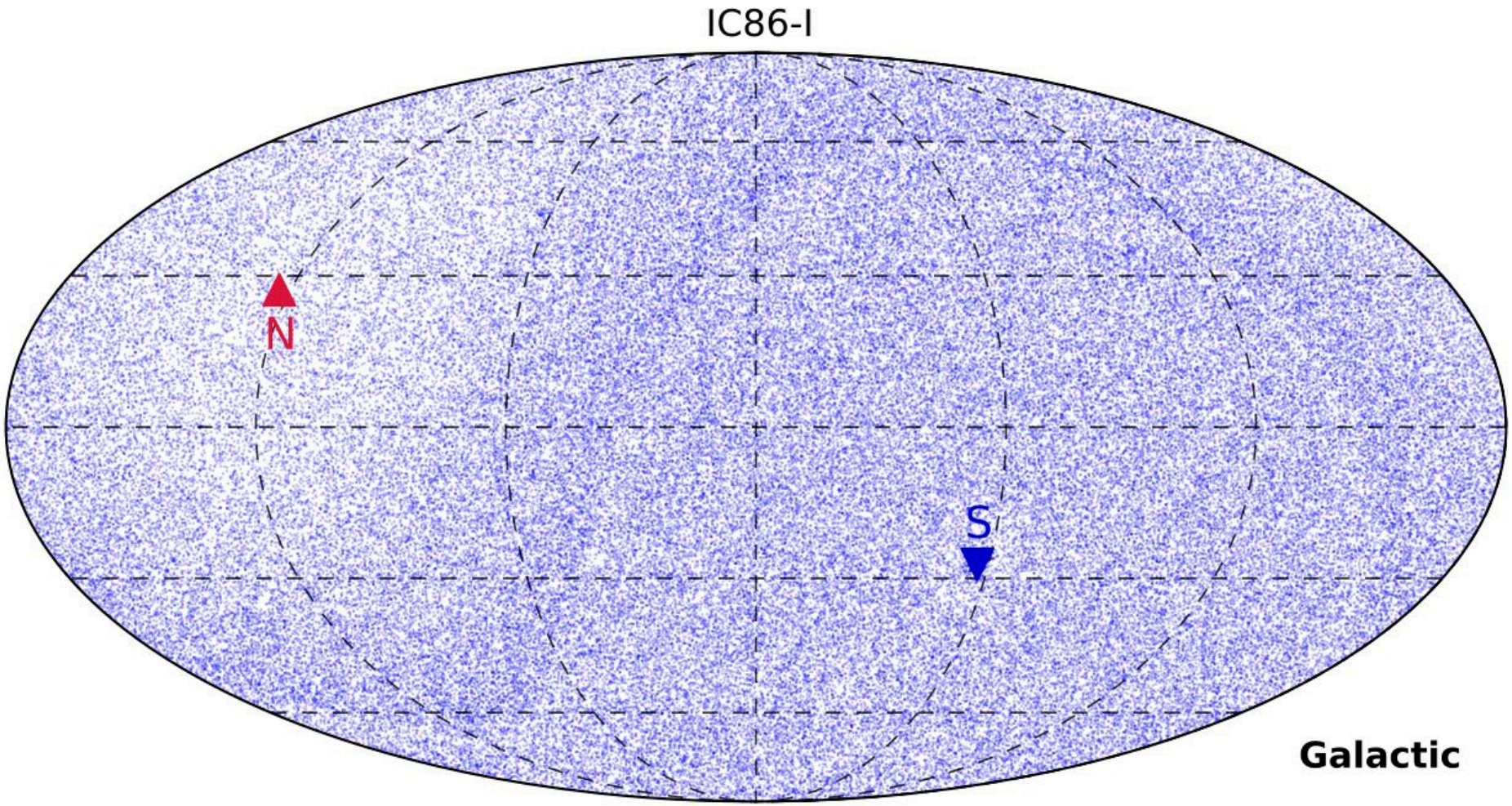


the discovery of cosmic neutrinos

francis halzen

- some history
- the challenge of best-buy theory
- a kilometer cubed detector
- the discovery of cosmic neutrinos
- where do they come from?

IceCube.wisc.edu



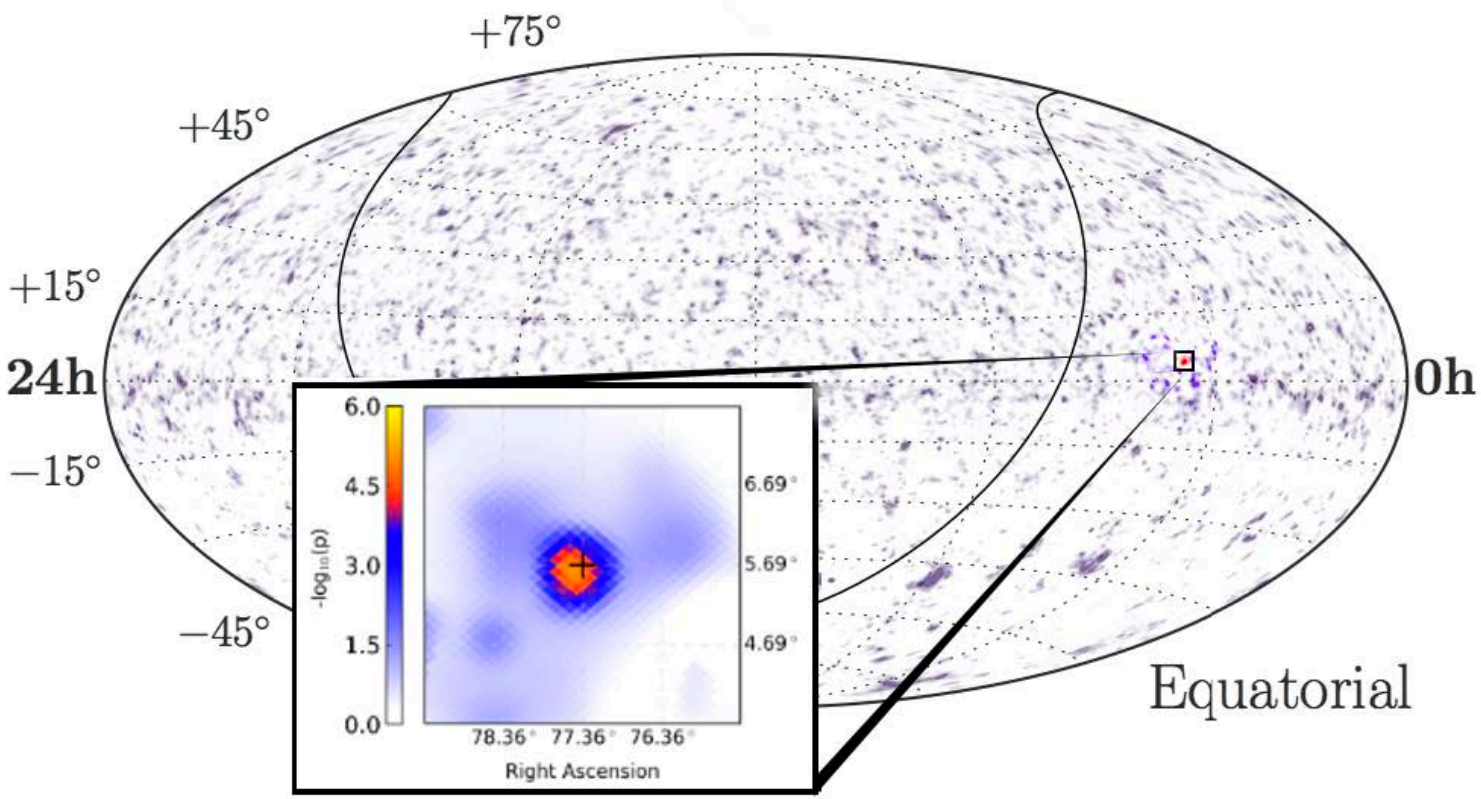
138322 neutrino candidates in one year

120 cosmic neutrinos

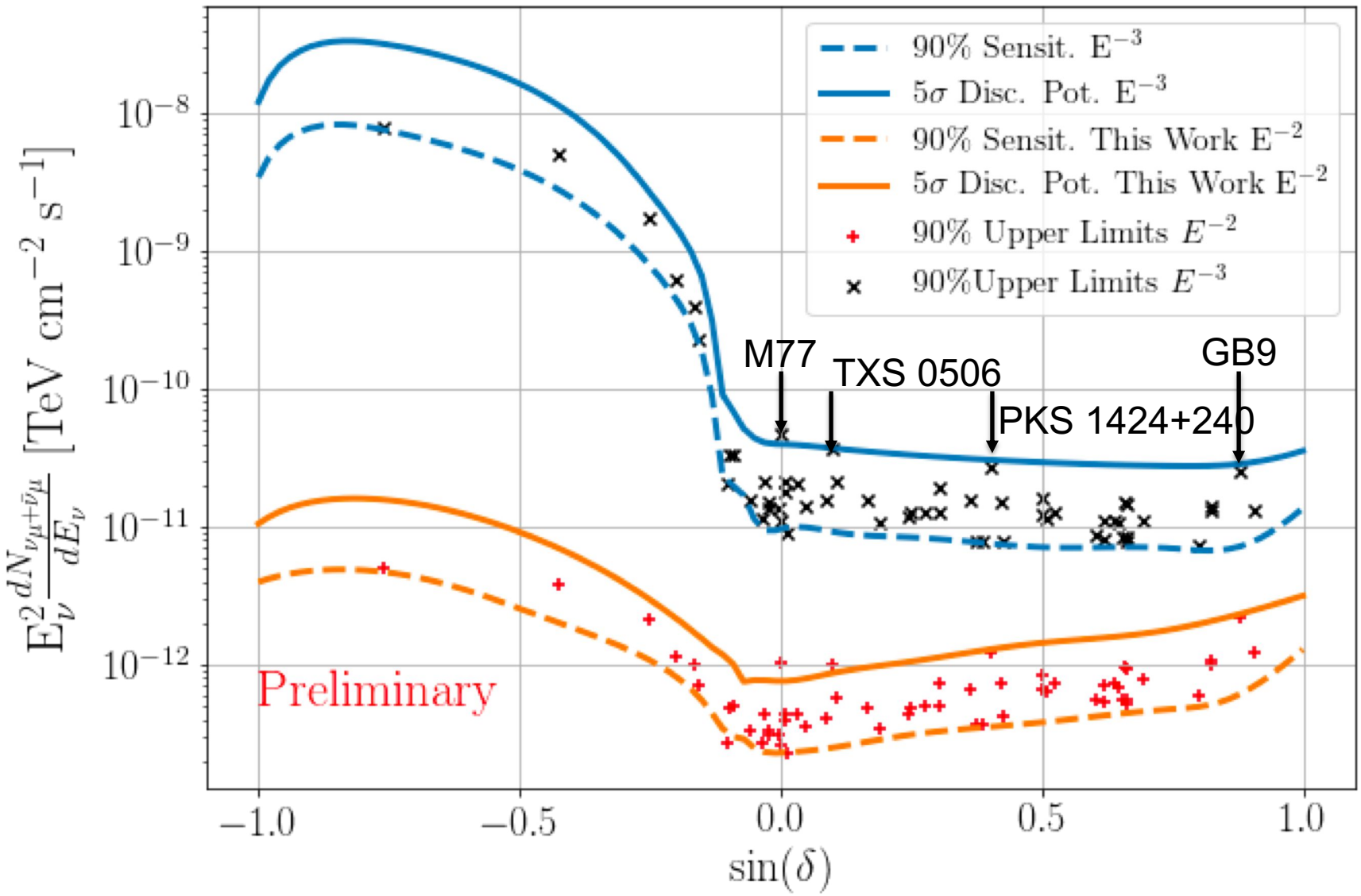
~12 separated from atmospheric background with E>60 TeV

structure in the map results from neutrino absorption by the Earth

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

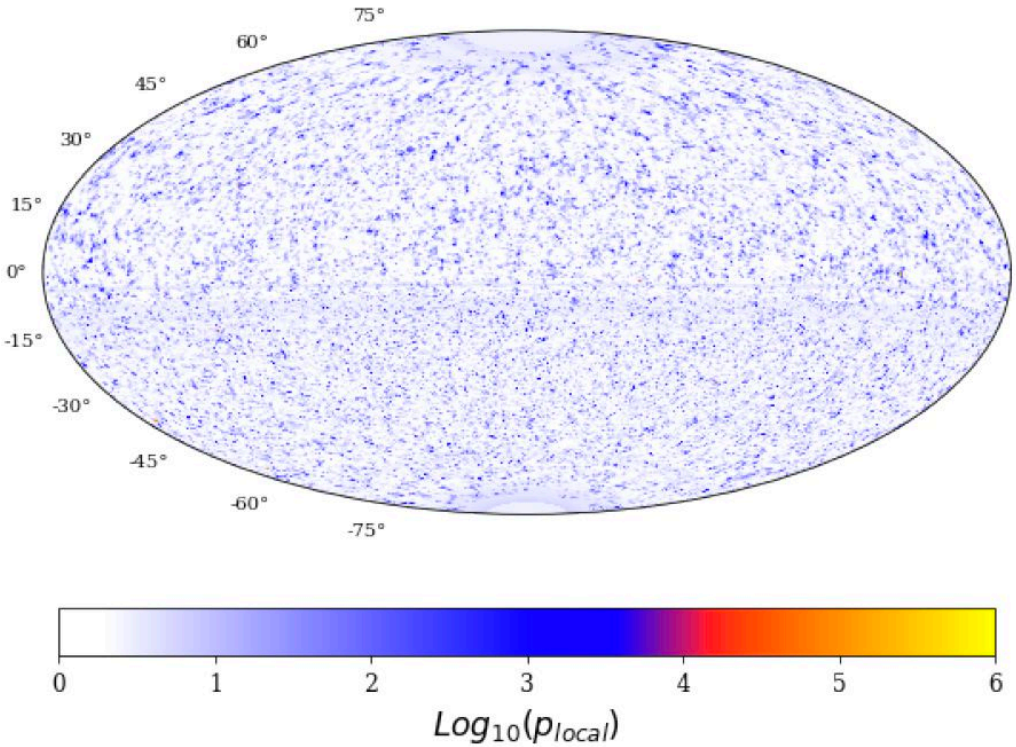


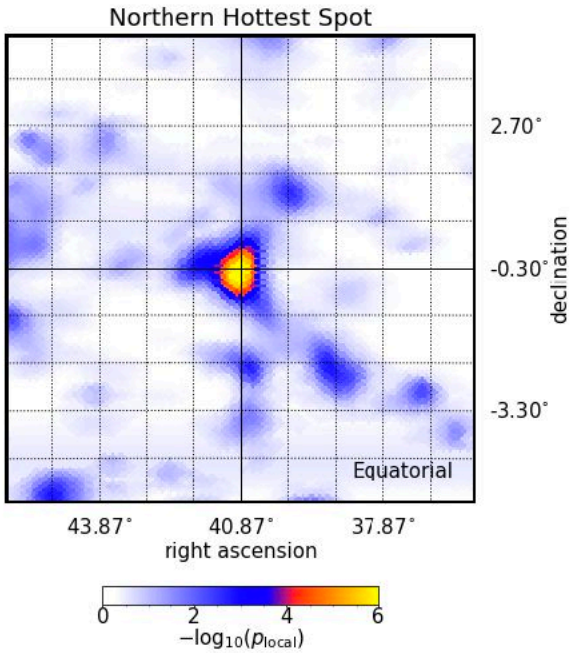
limits and fluctuations(?)

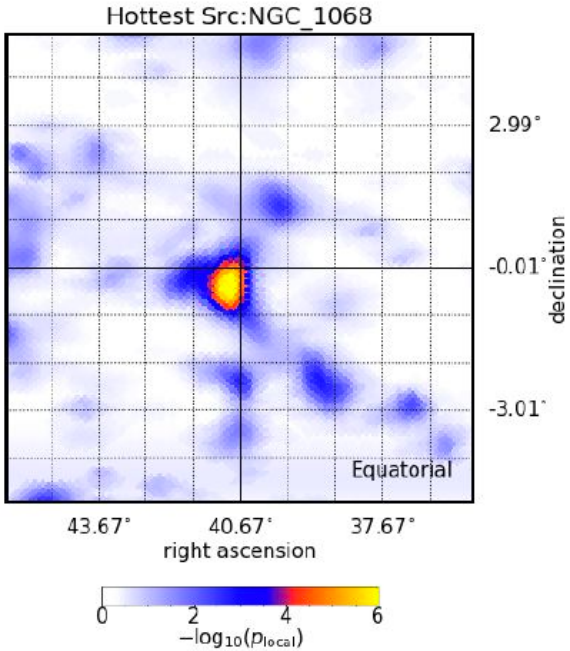


this is the case for larger detectors with better angular resolution!

10 years of muon neutrinos

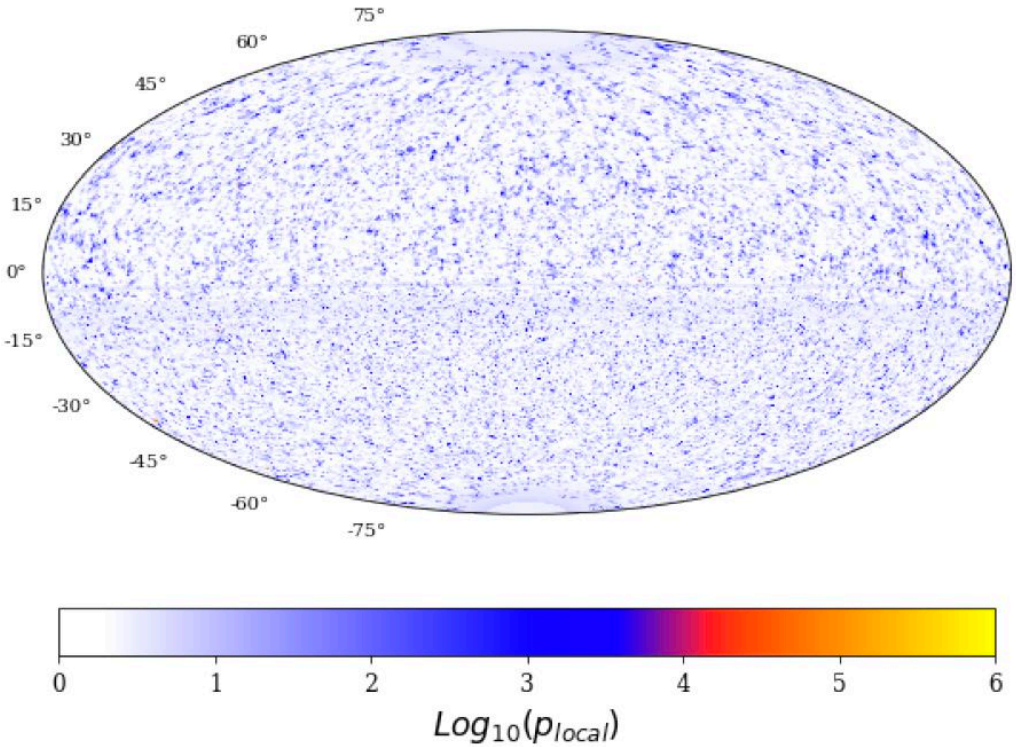


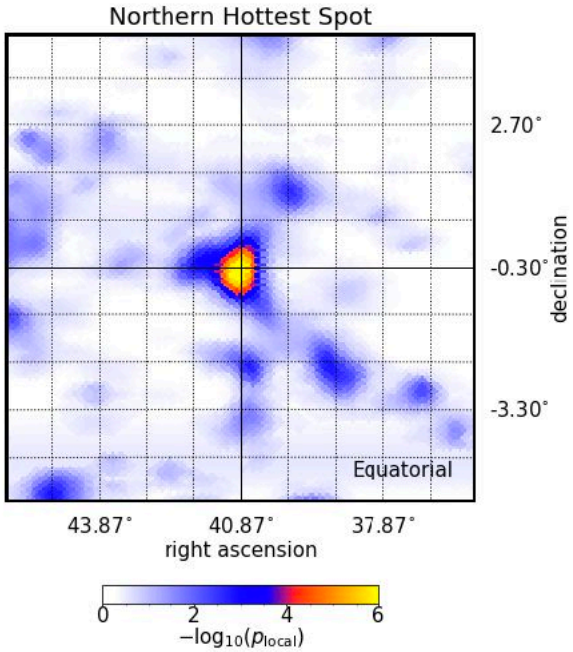


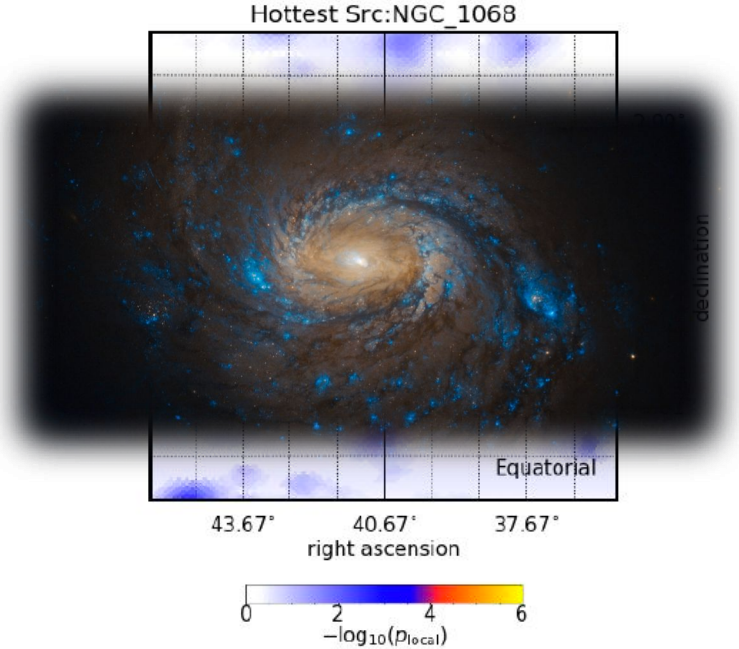


Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496

10 years of muon neutrinos







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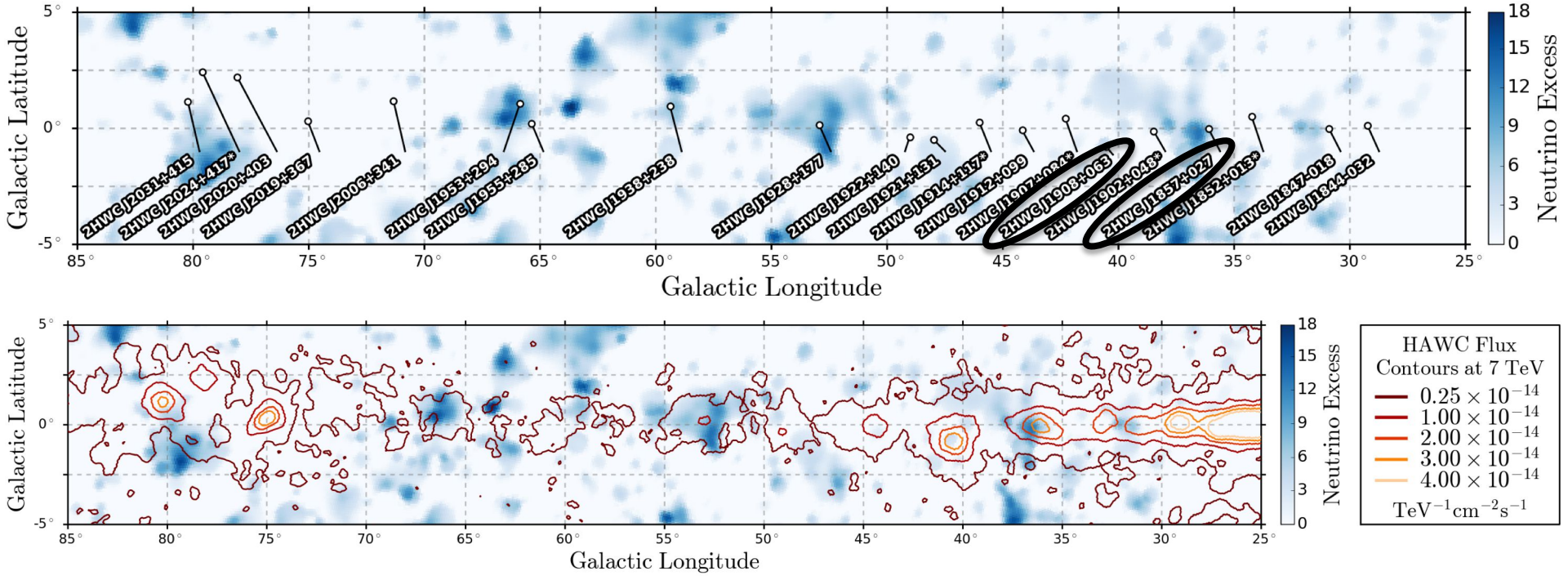
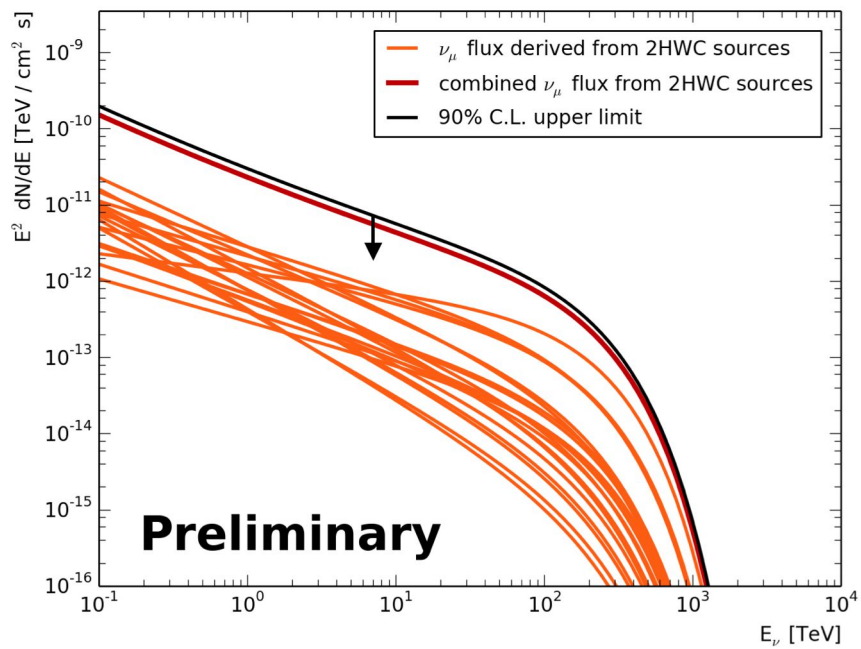
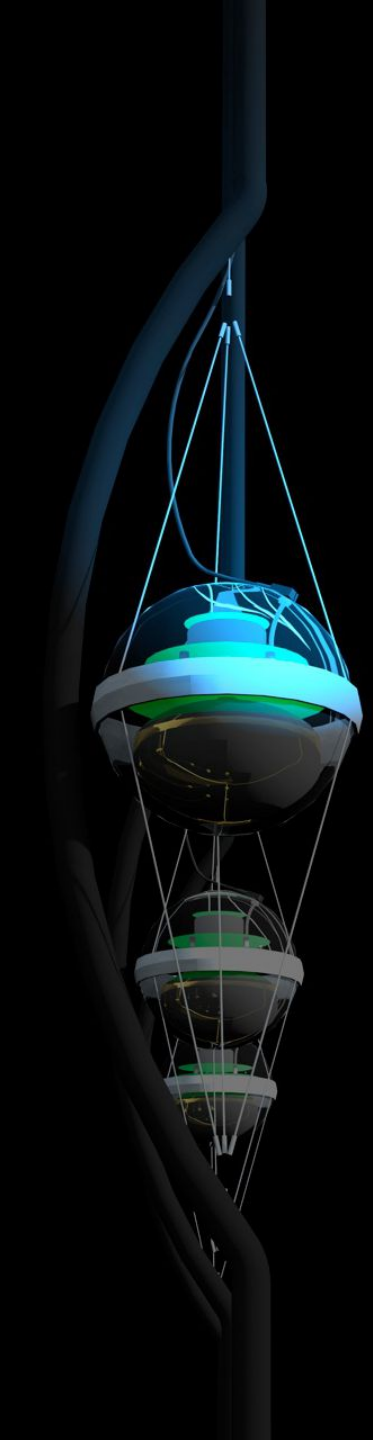
- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?



HAWC photons and IceCube neutrinos

neutrino flux at the level predicted, but not significant yet

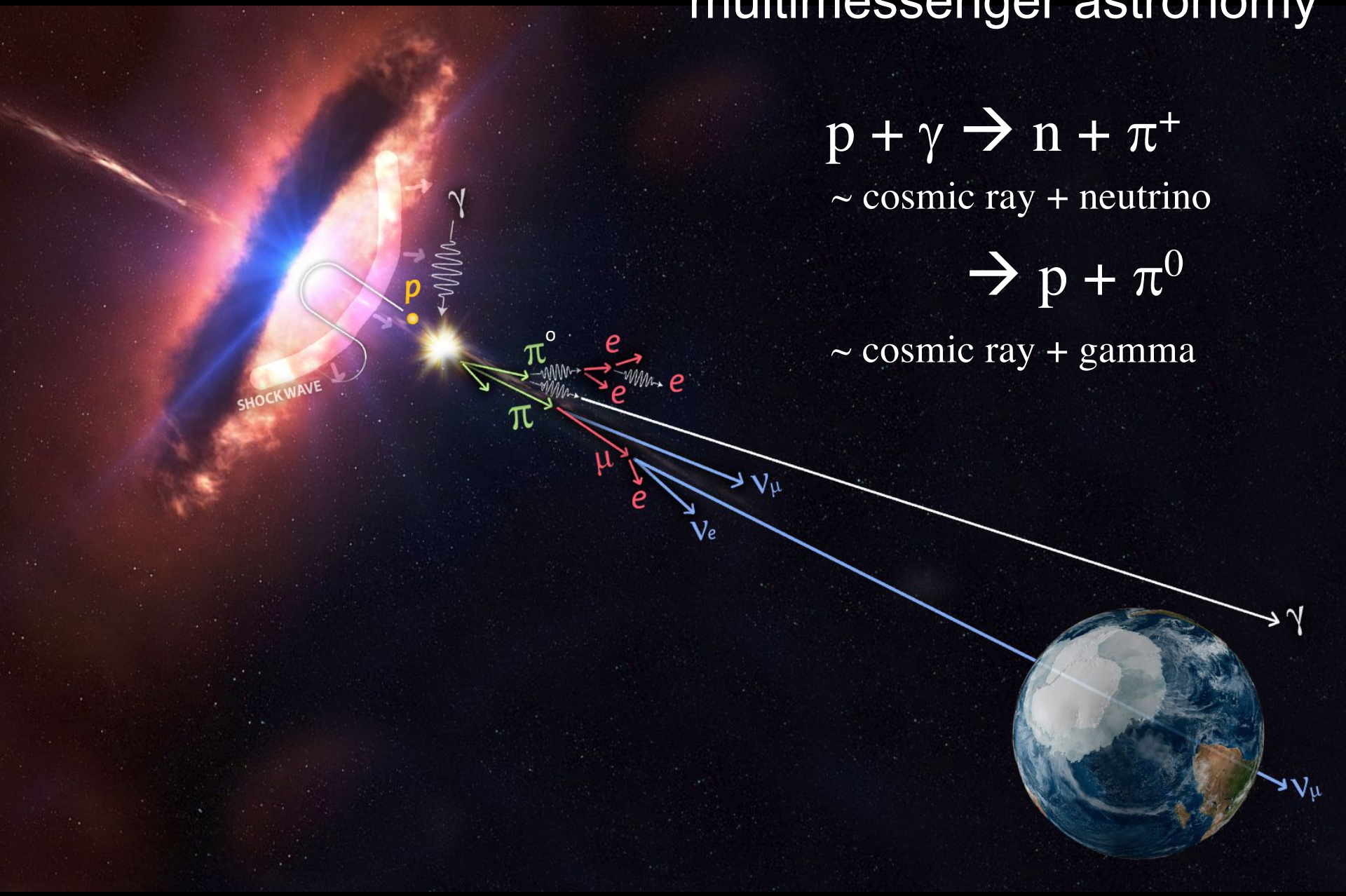




- Fermi photons and IceCube neutrinos

iceCube.wisc.edu

multimessenger astronomy

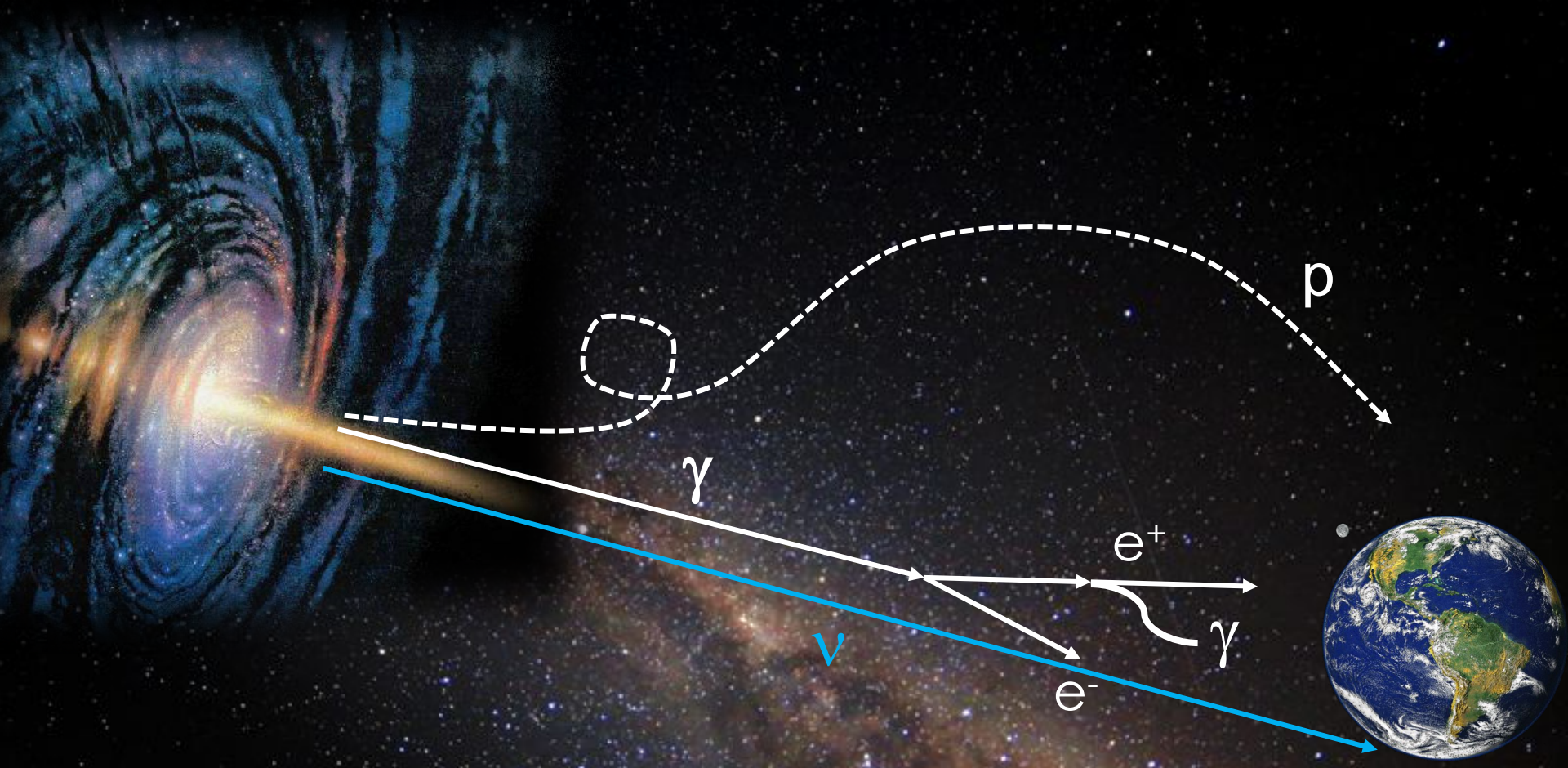


$$p + \gamma \rightarrow n + \pi^{+}$$

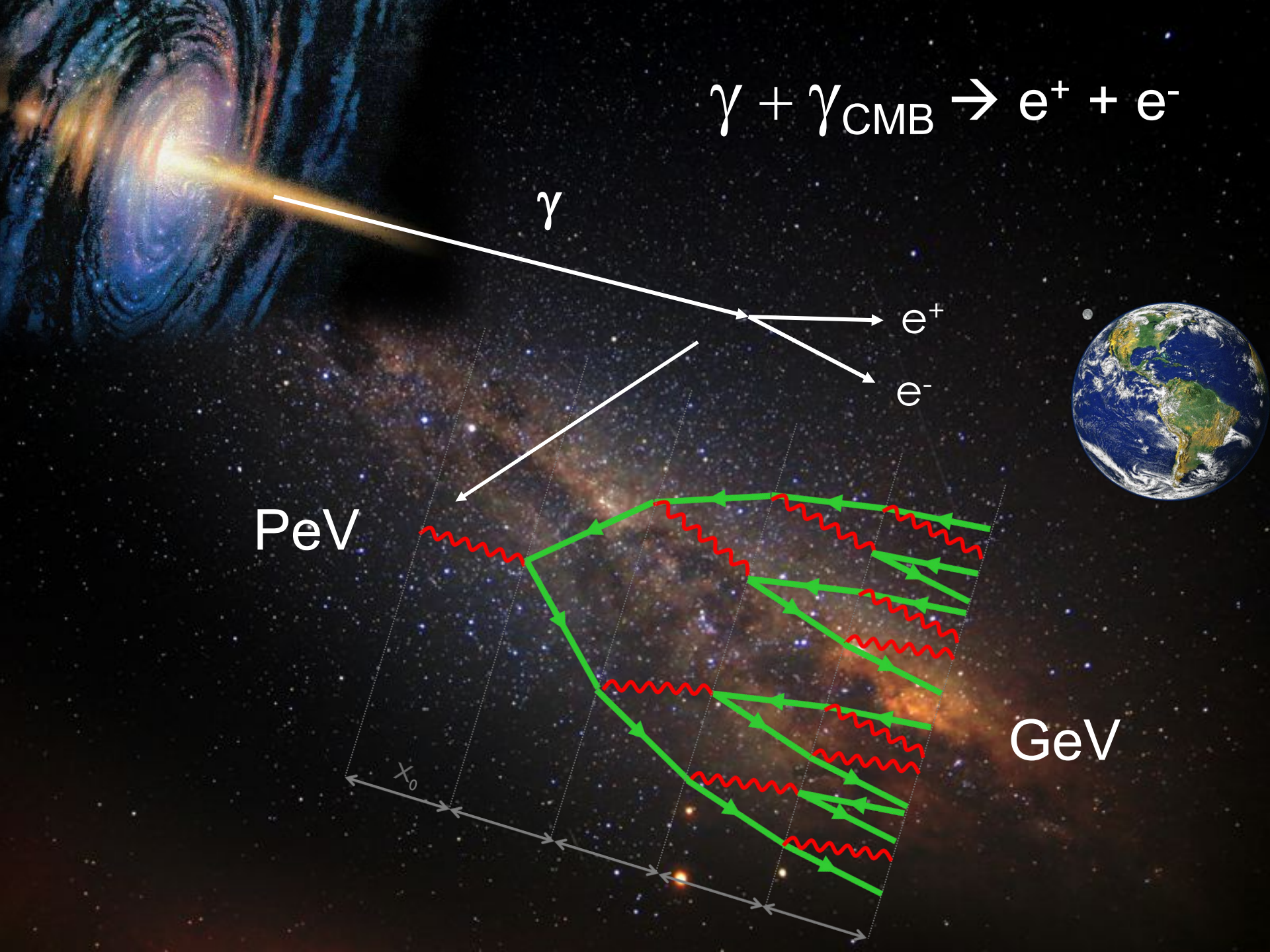
~ cosmic ray + neutrino

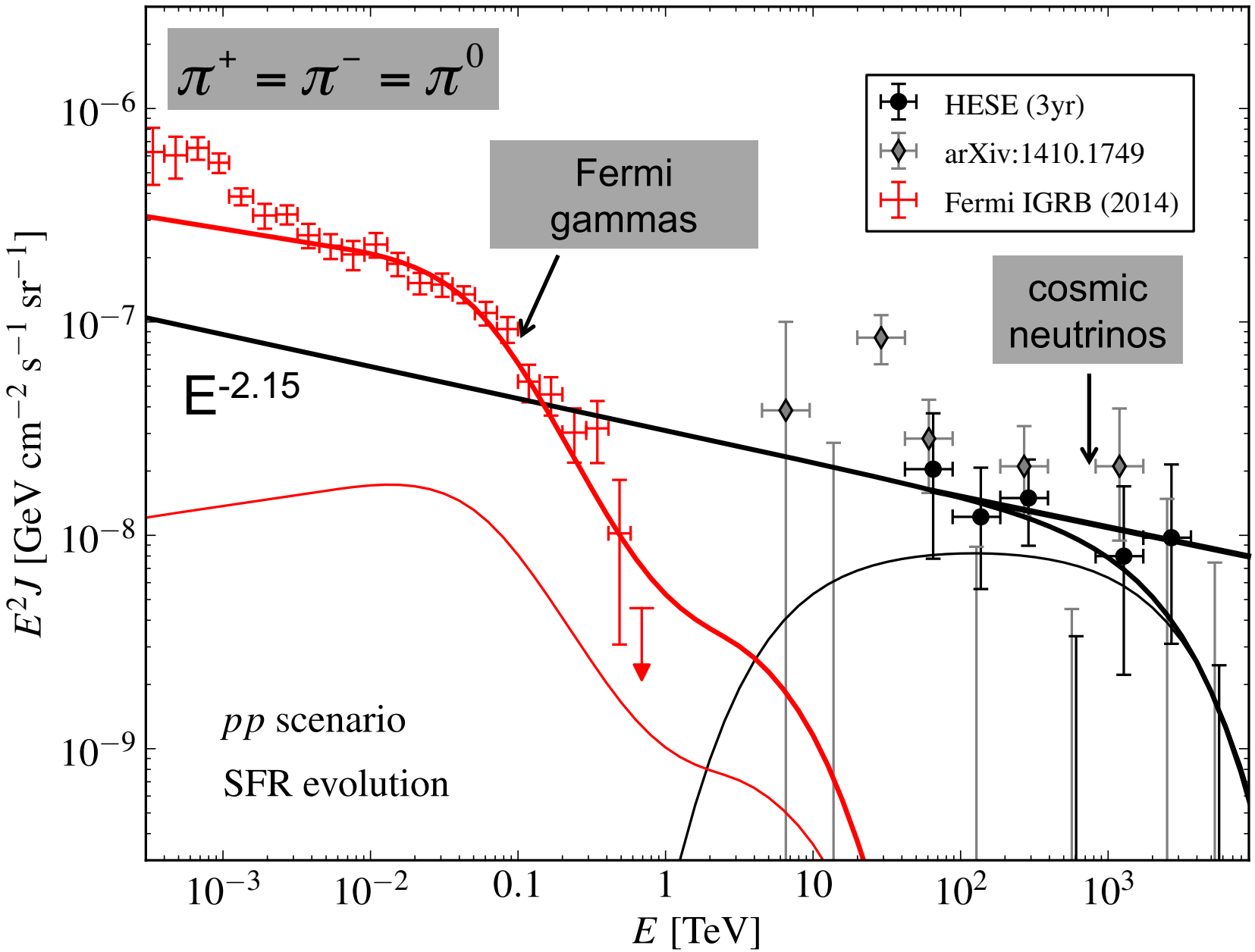
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

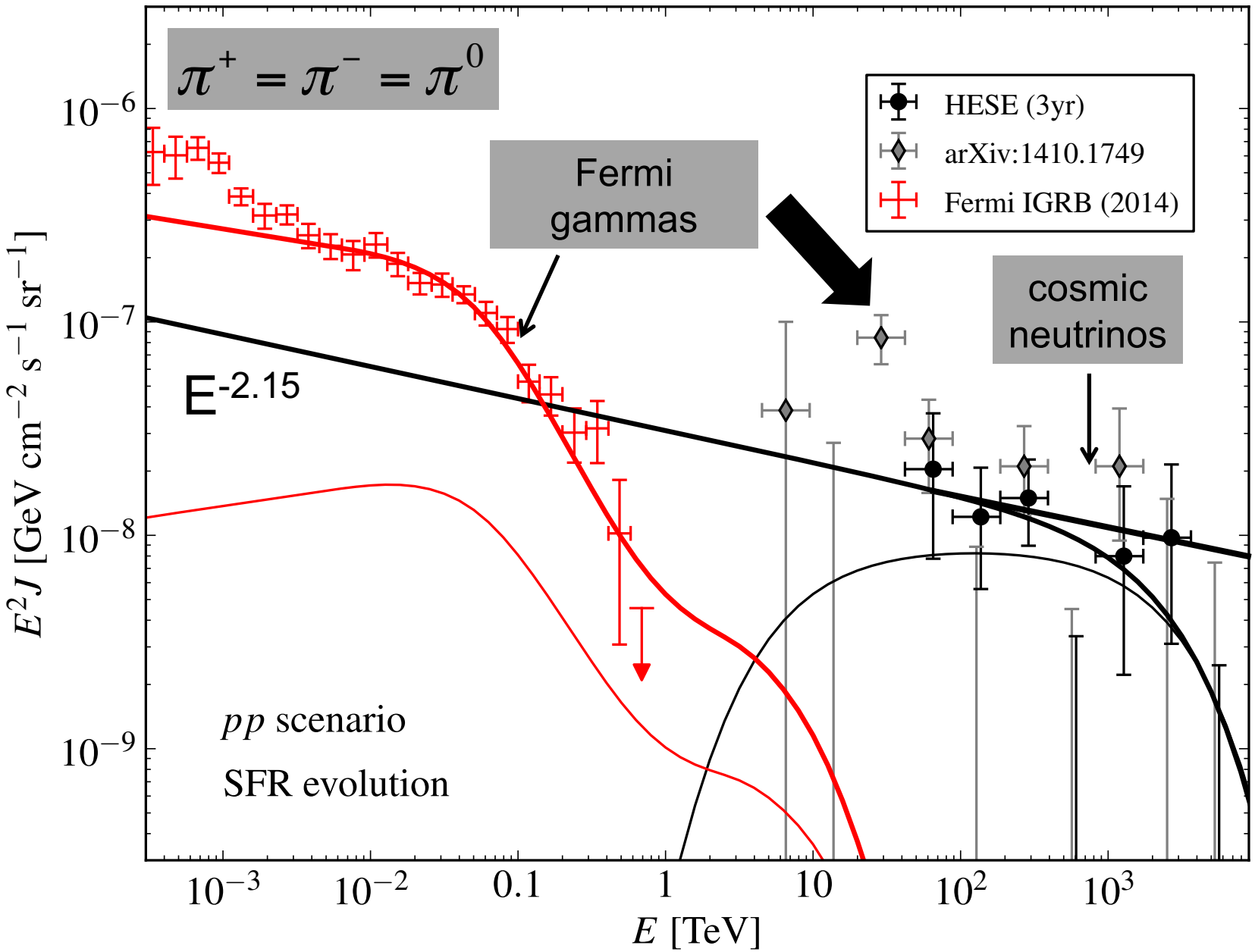


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


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


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

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays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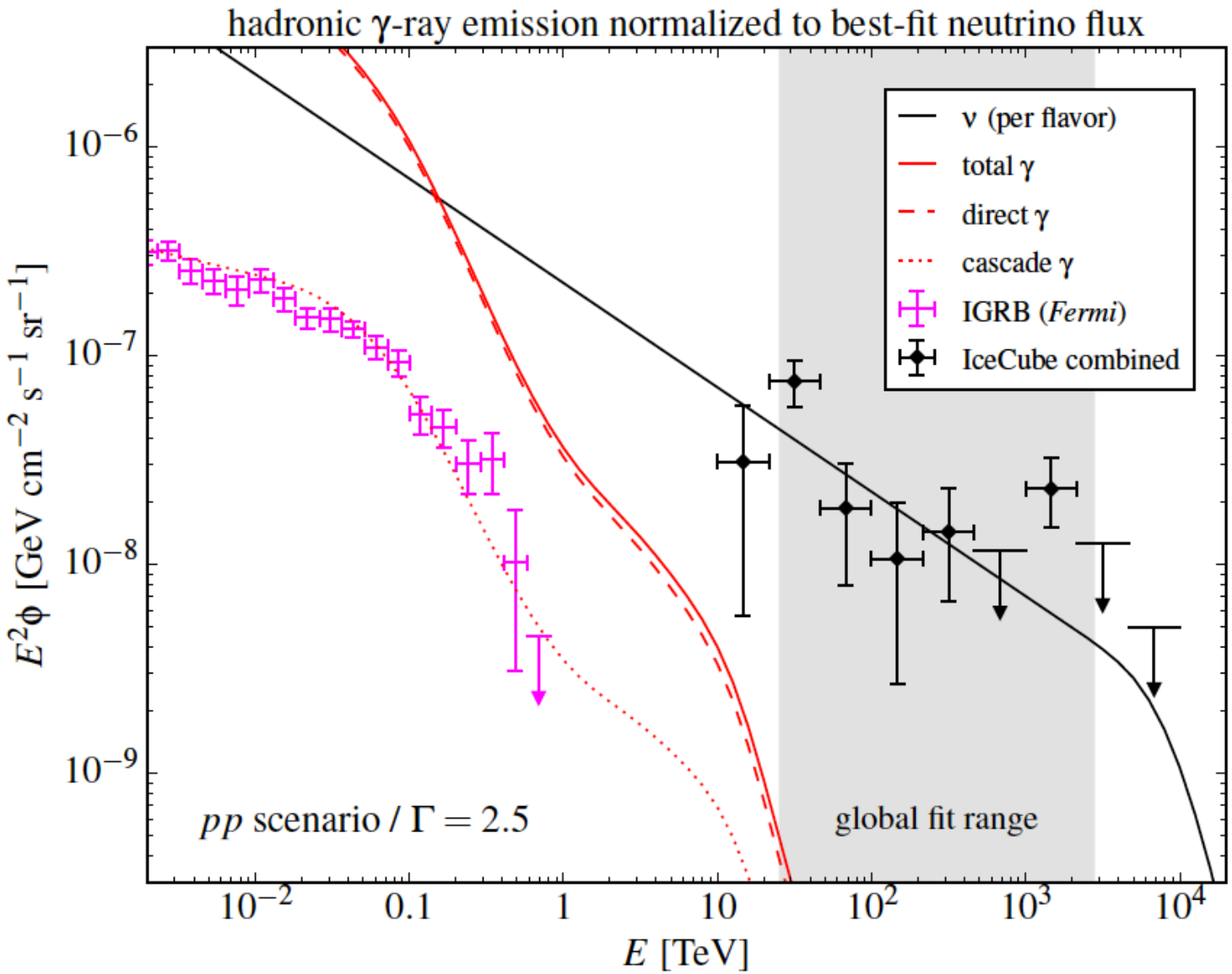
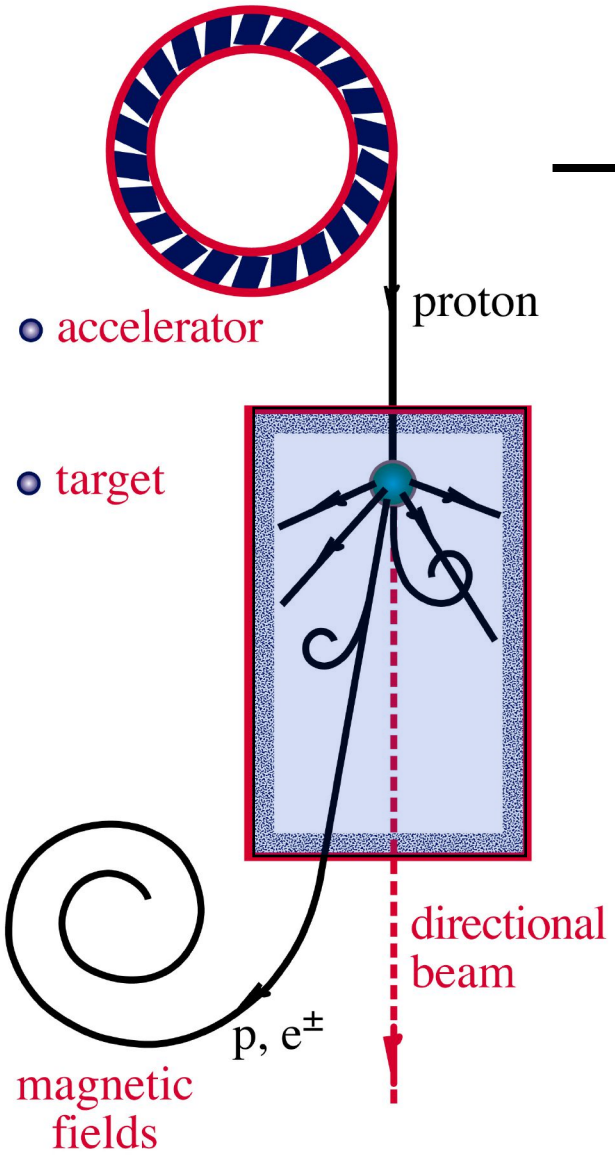
10^3



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

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

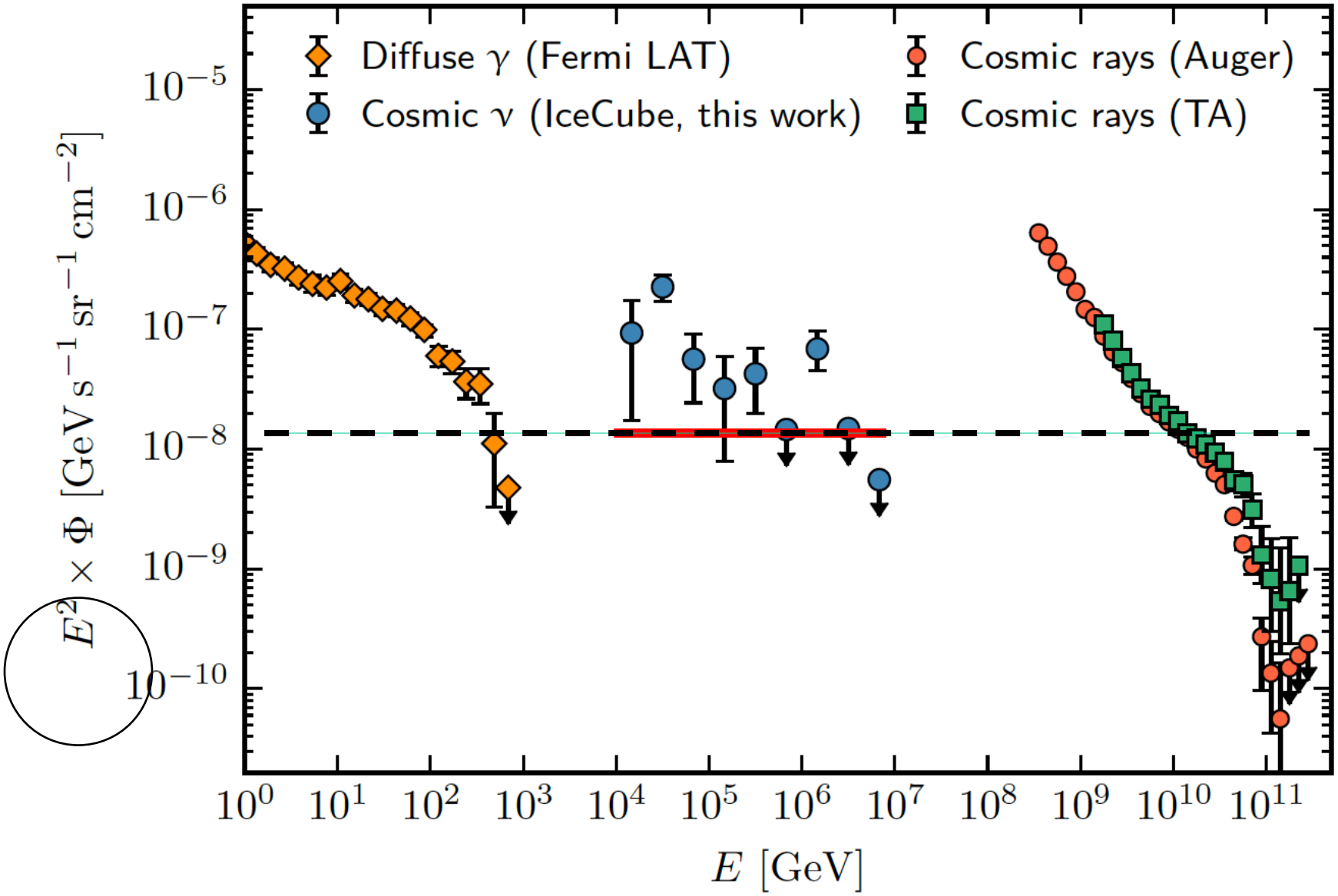
sources may be opaque to photons!

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

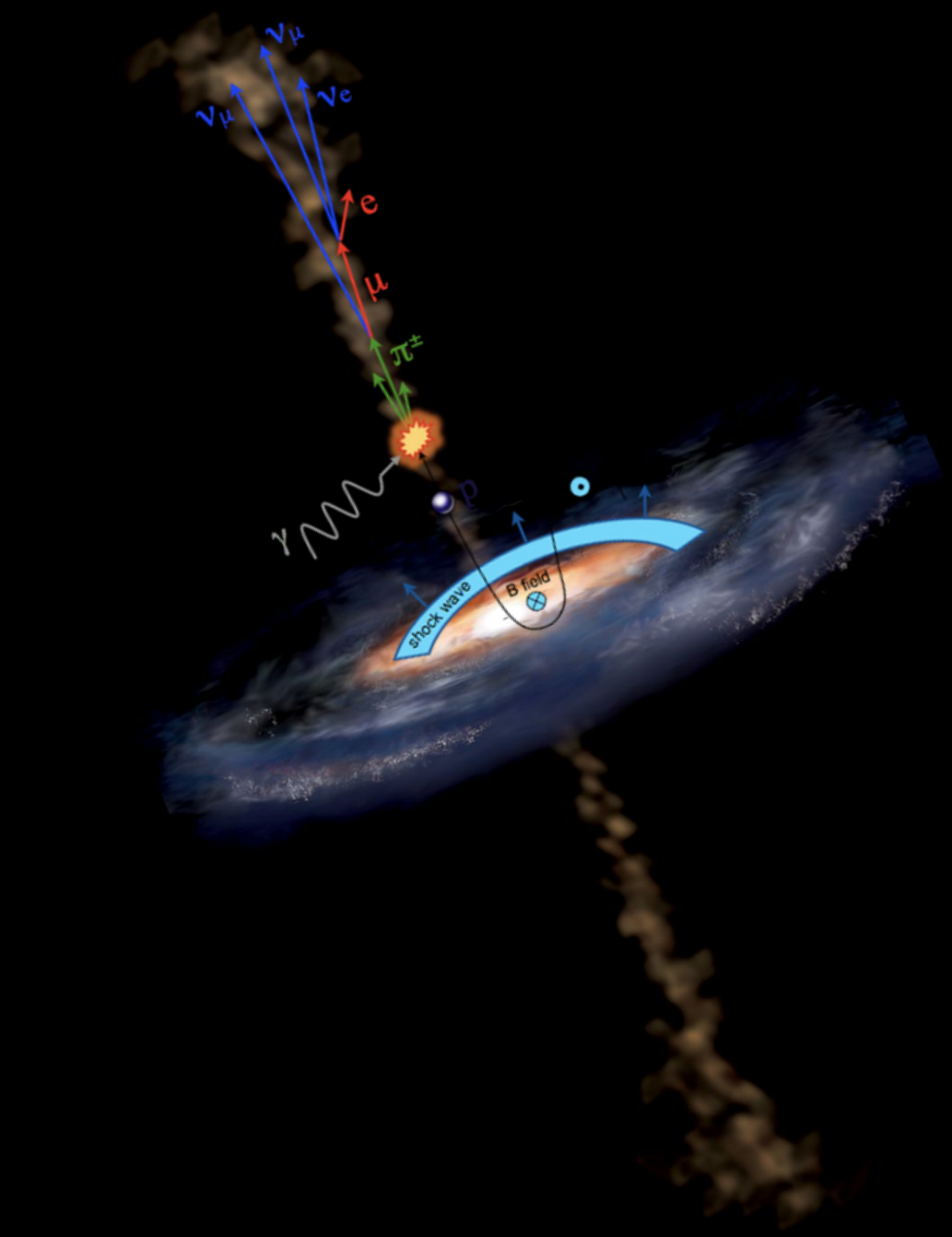
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma



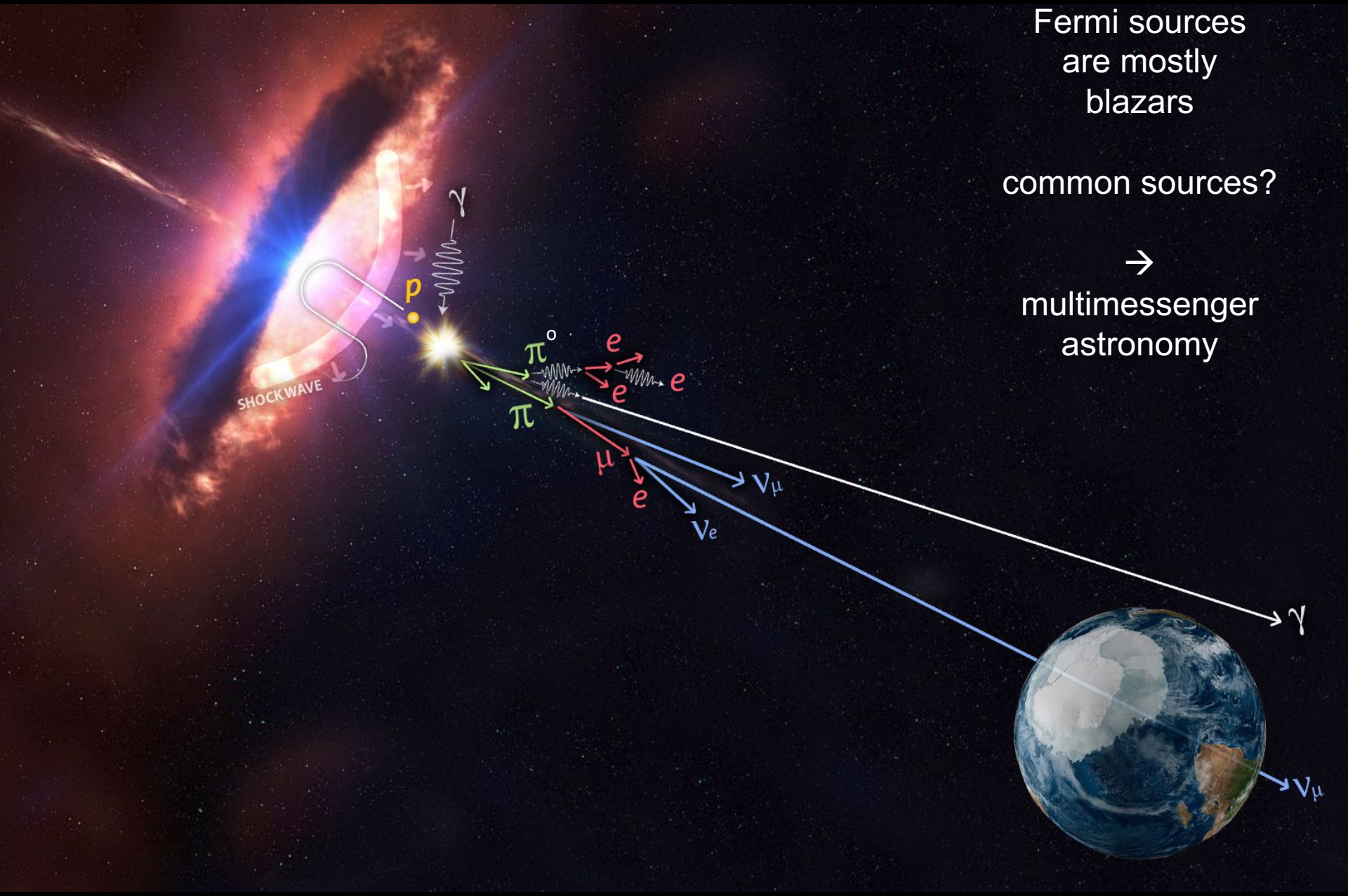
energy in the Universe in gamma rays, neutrinos and cosmic rays



Fermi sources are mostly blazars

common sources?

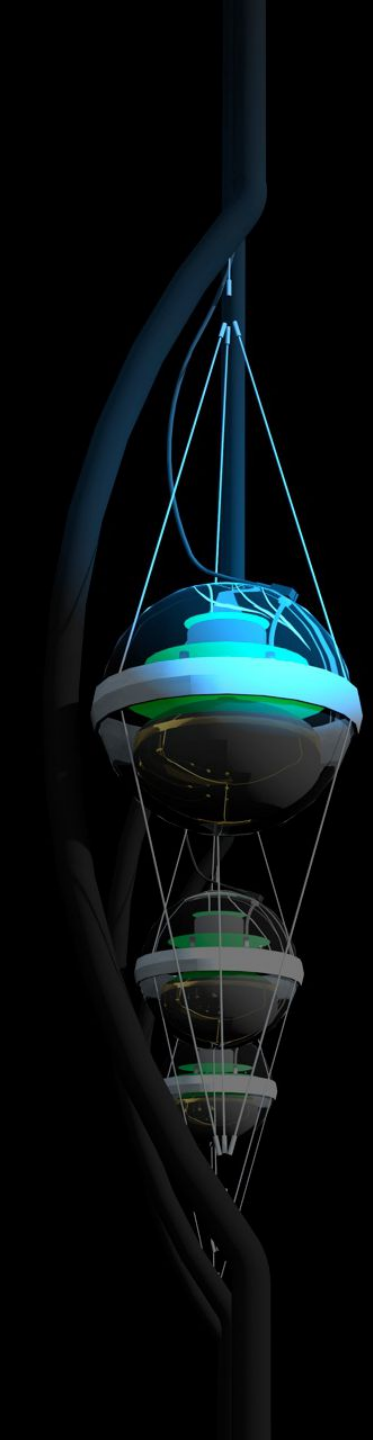
→ multimessenger astronomy



Fermi sources are mostly blazars

common sources?

→ multimessenger astronomy



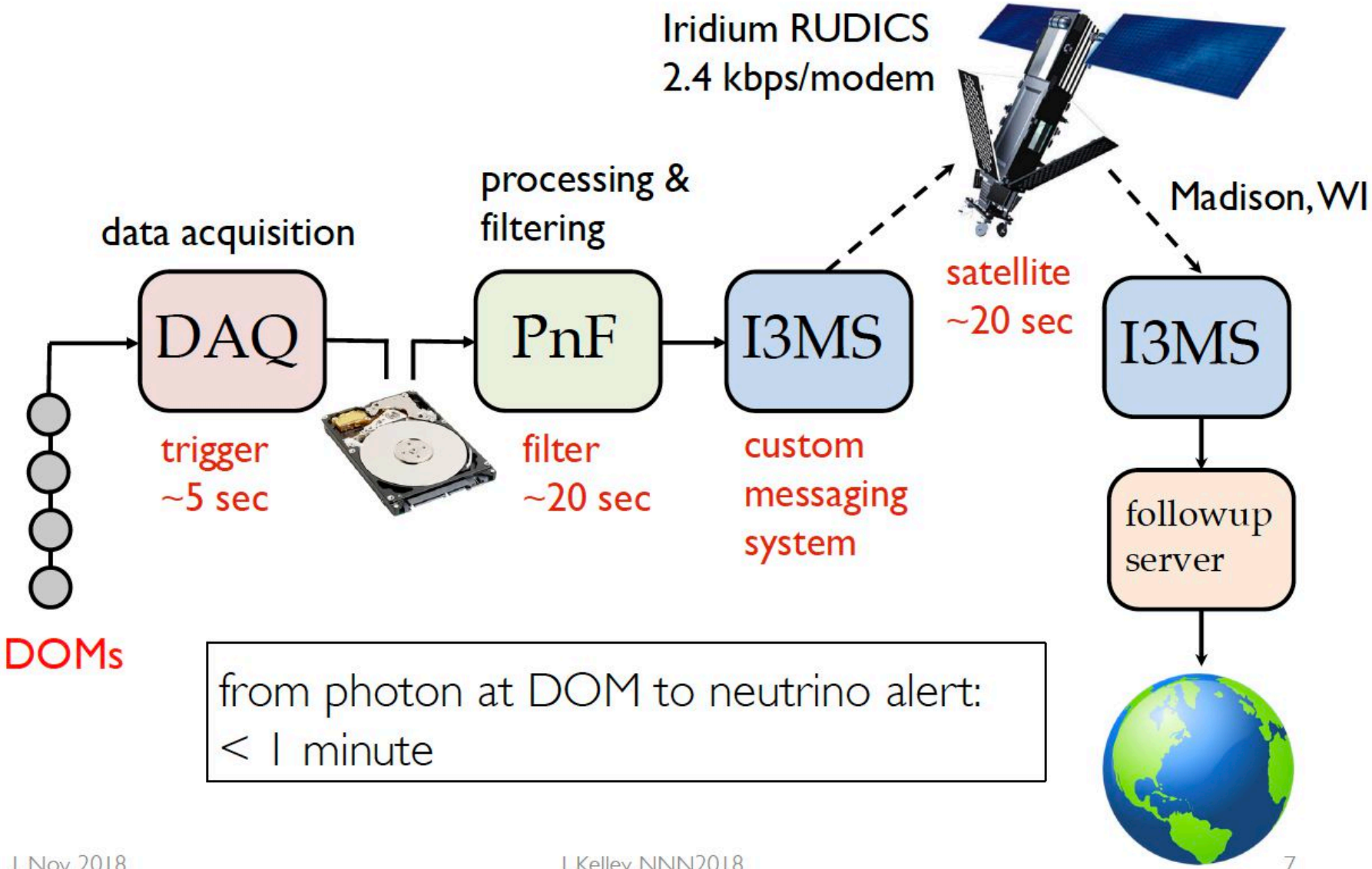
multimessenger astronomy:
the first high-energy cosmic ray accelerator

iceCube.wisc.edu

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

M. Richman

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

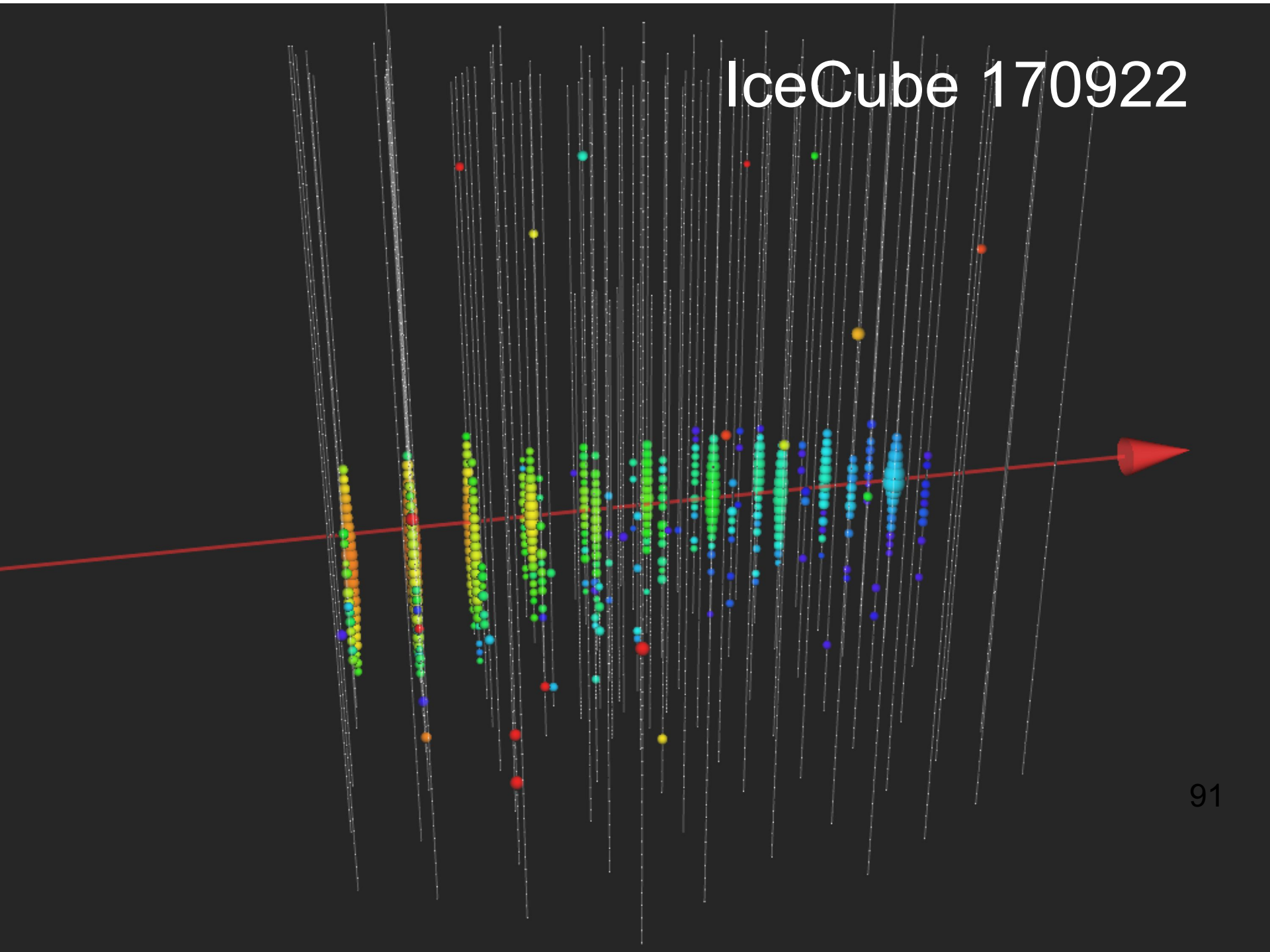


from photon at DOM to neutrino alert:
< 1 minute

IceCube Trigger

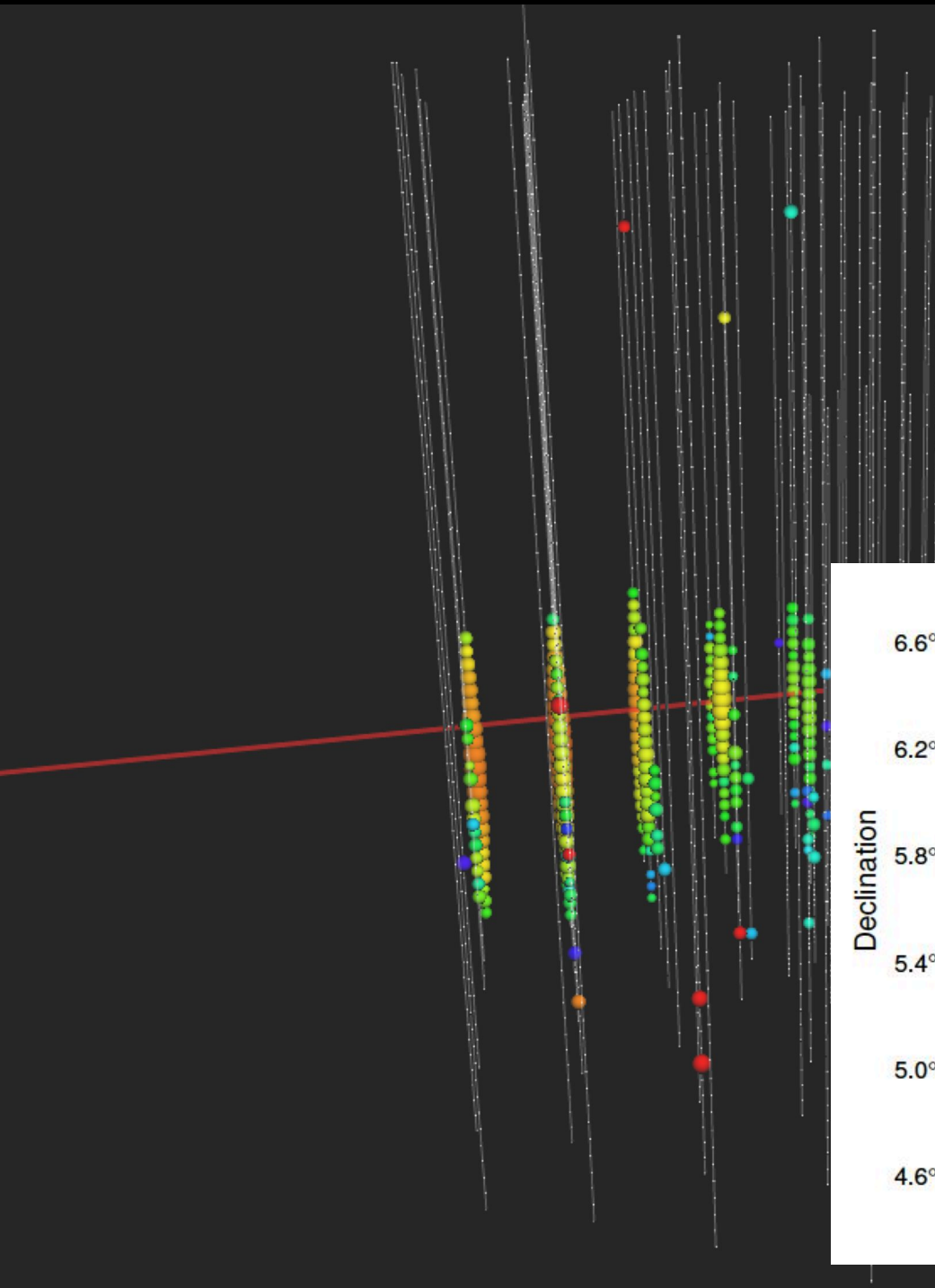
43 seconds after trigger, GCN notice was sent

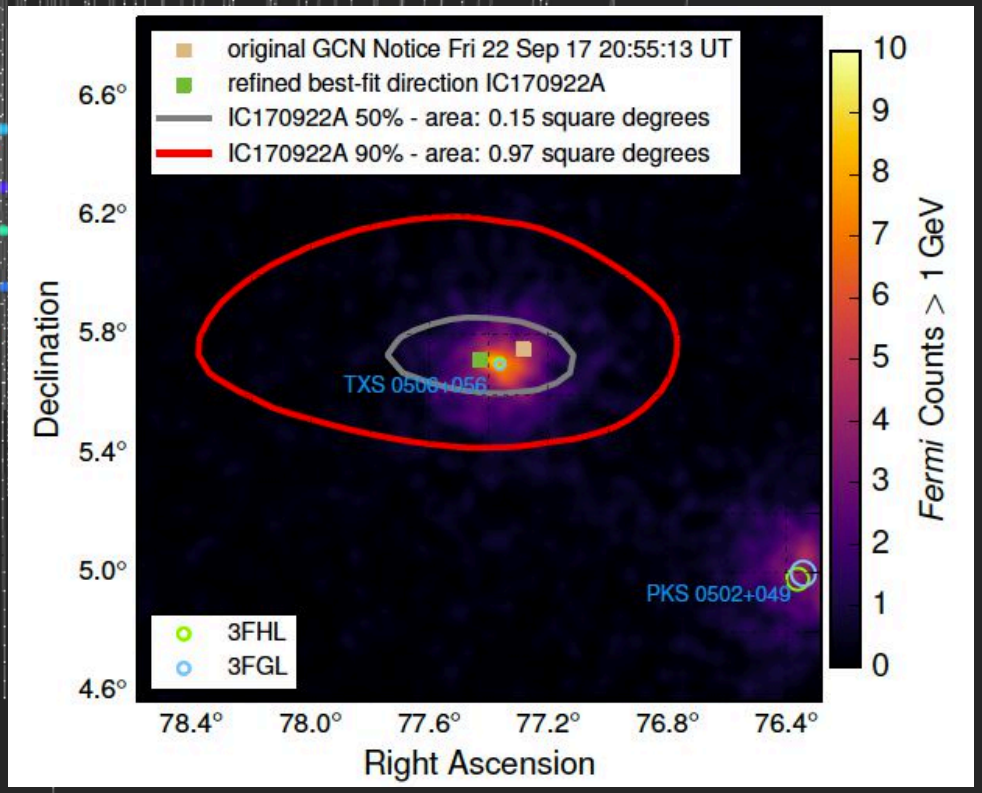
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   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]
```

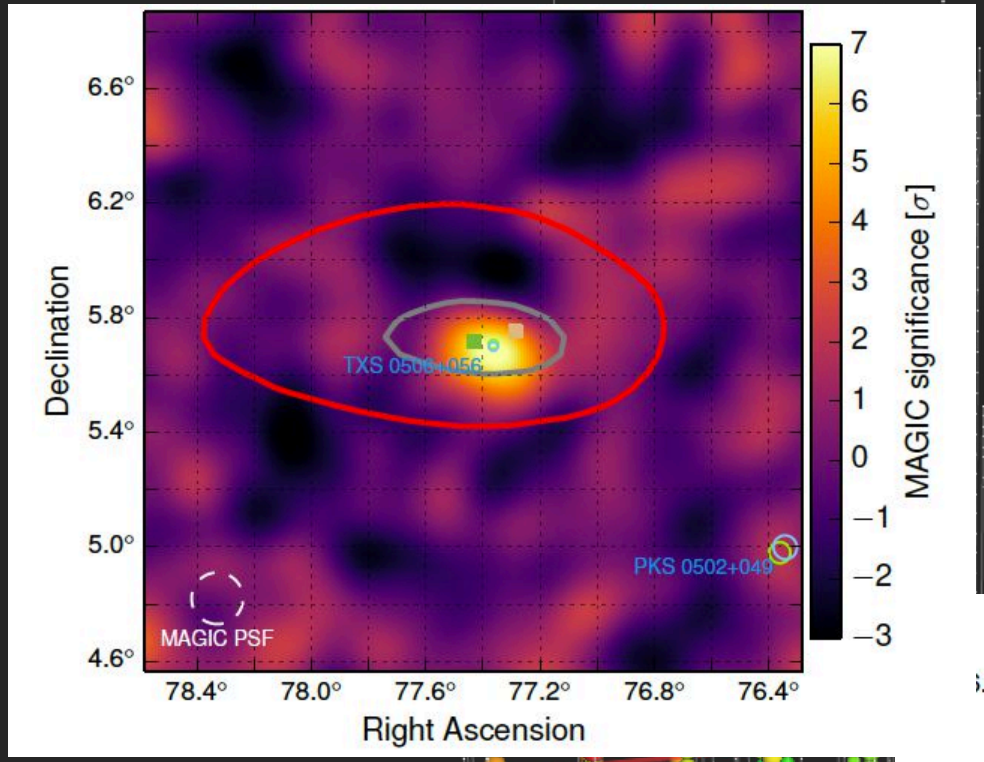

IceCube 170922

IceCube 170922

Fermi
detects a flaring
blazar within 0.1°



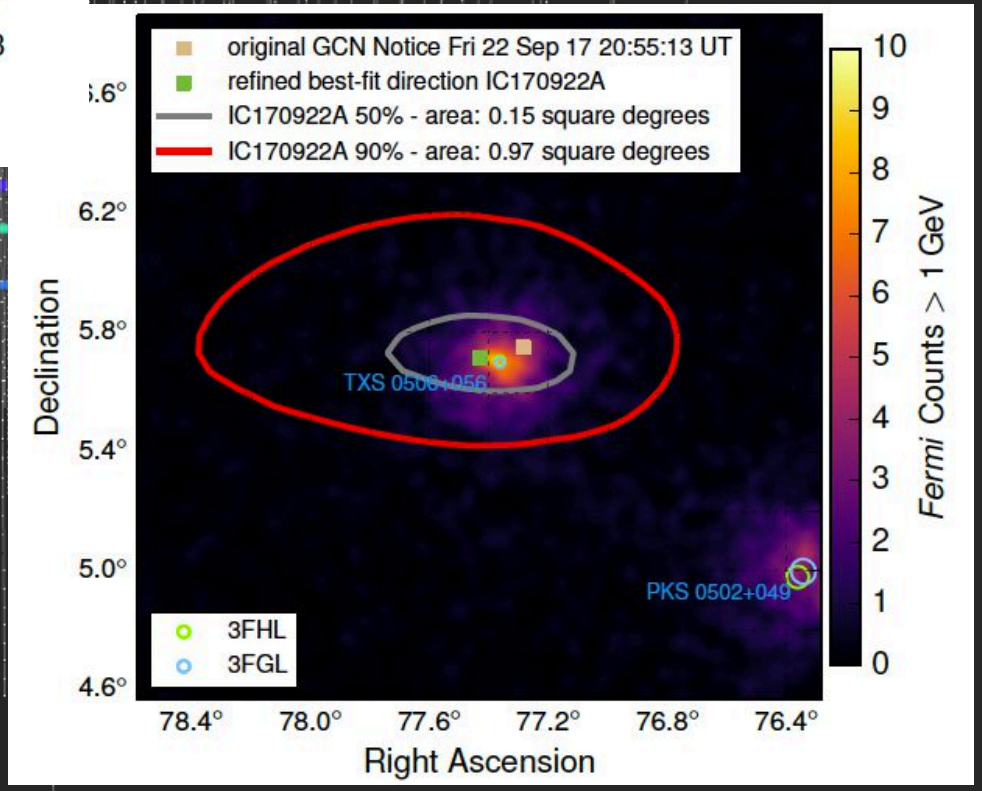




IceCube 170922

Fermi
detects a flaring
blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas



Follow-up detections of IC170922 based on public telegrams

arXiv:1802.01939v1 [astro-ph.GA] 6 Feb 2018

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

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

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[2] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*
[3] *Università degli Studi dell'Insubria, Via Valleggio 11 I-22100 Como - ITALY*
[4] *INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY*
[5] *Instituto de Astrofisica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*
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(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

ABSTRACT

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

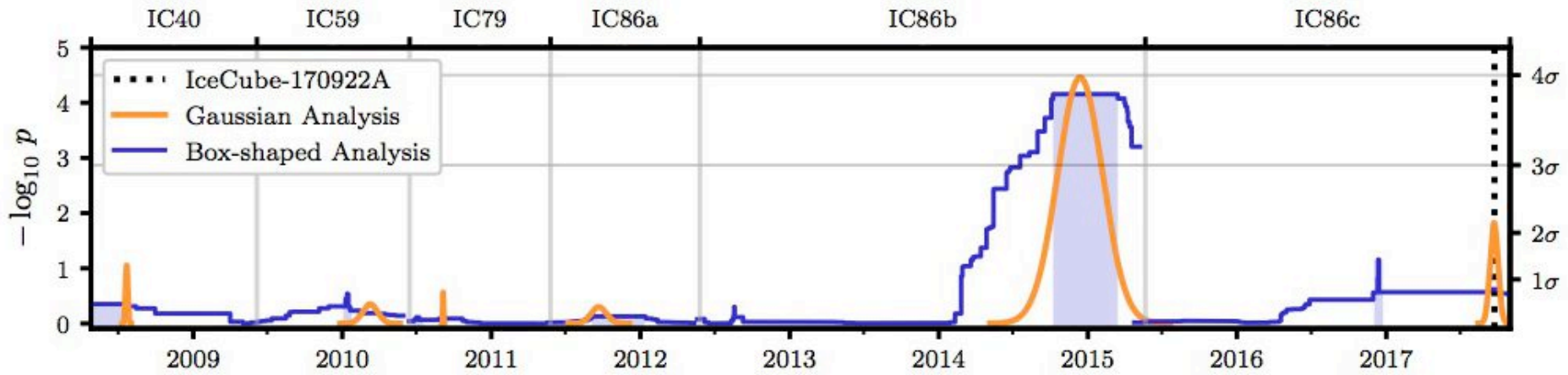
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

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

multiwavelength campaign launched by IC 170922

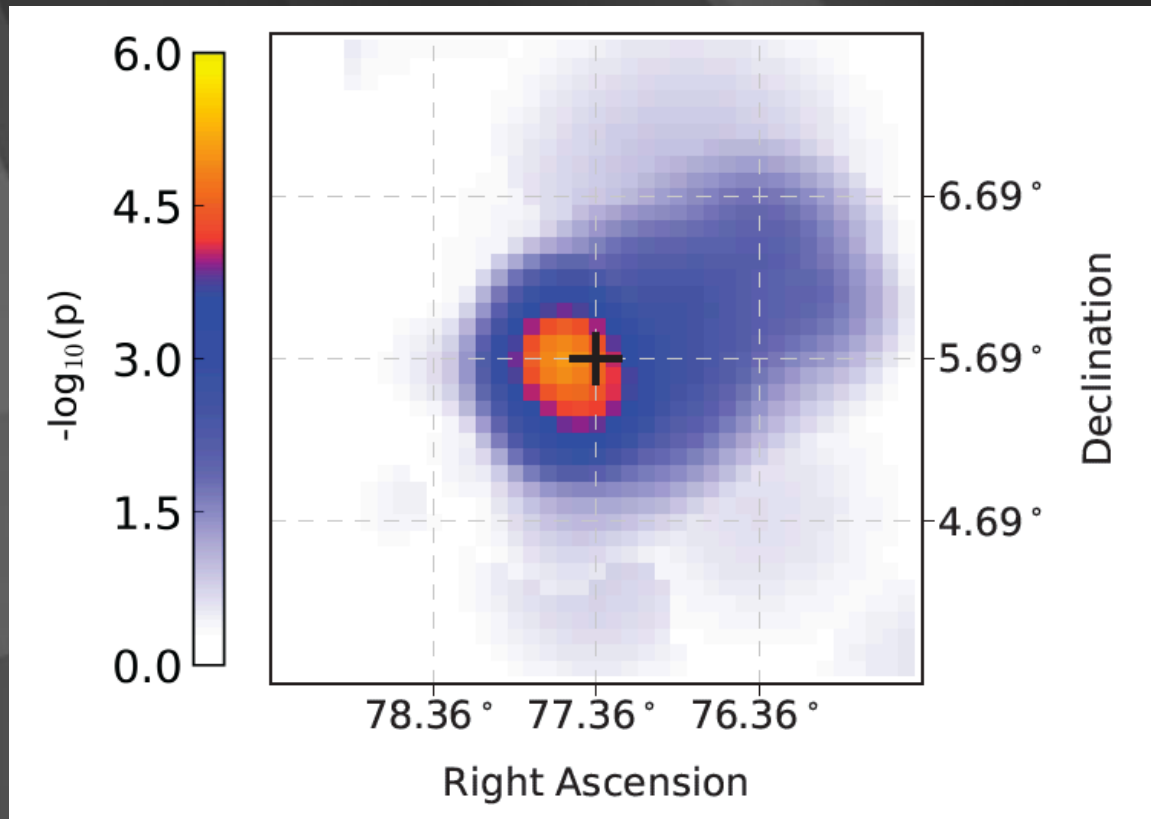
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

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

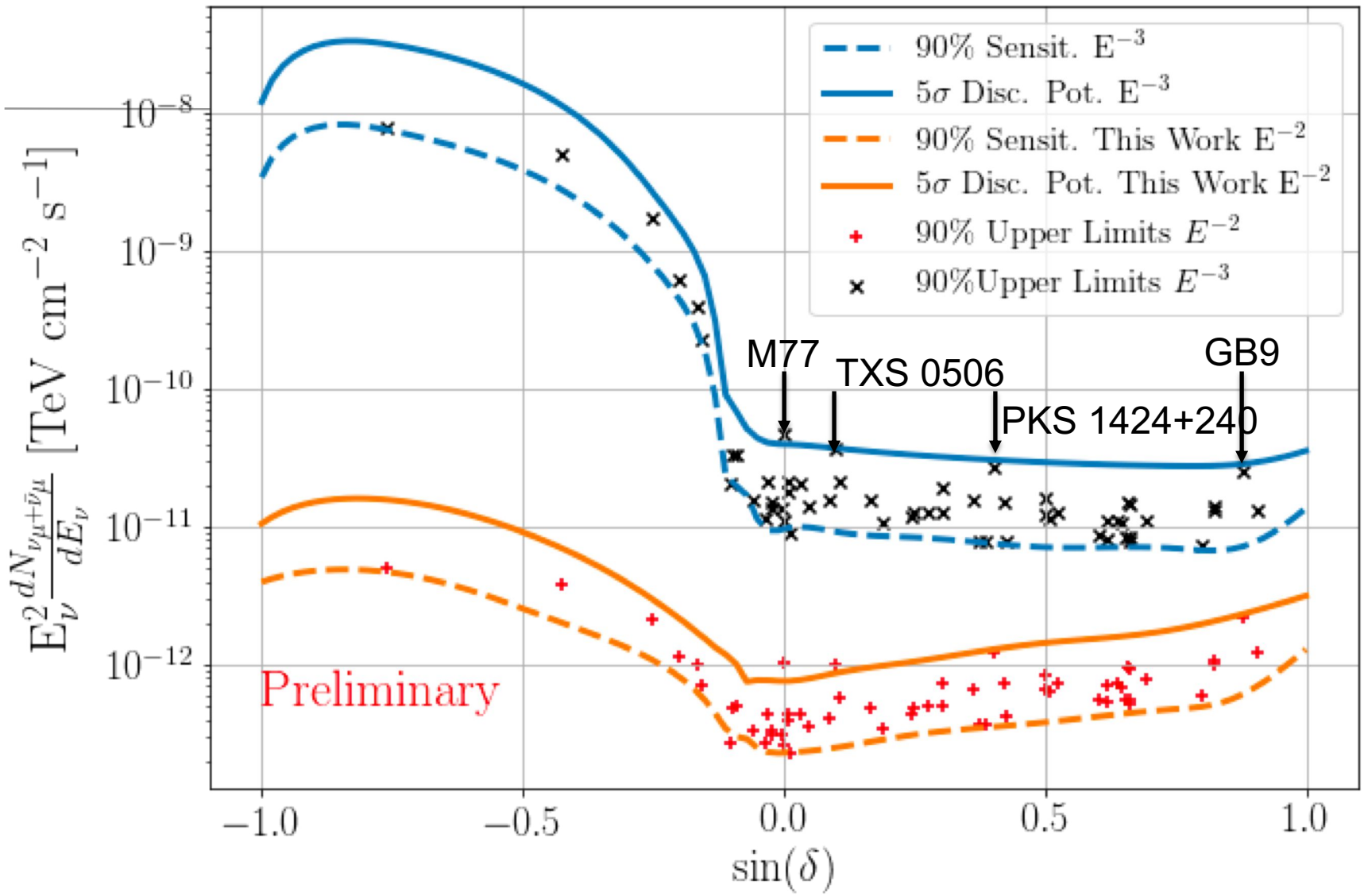


search in archival IceCube data:

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



Why not seen before?



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

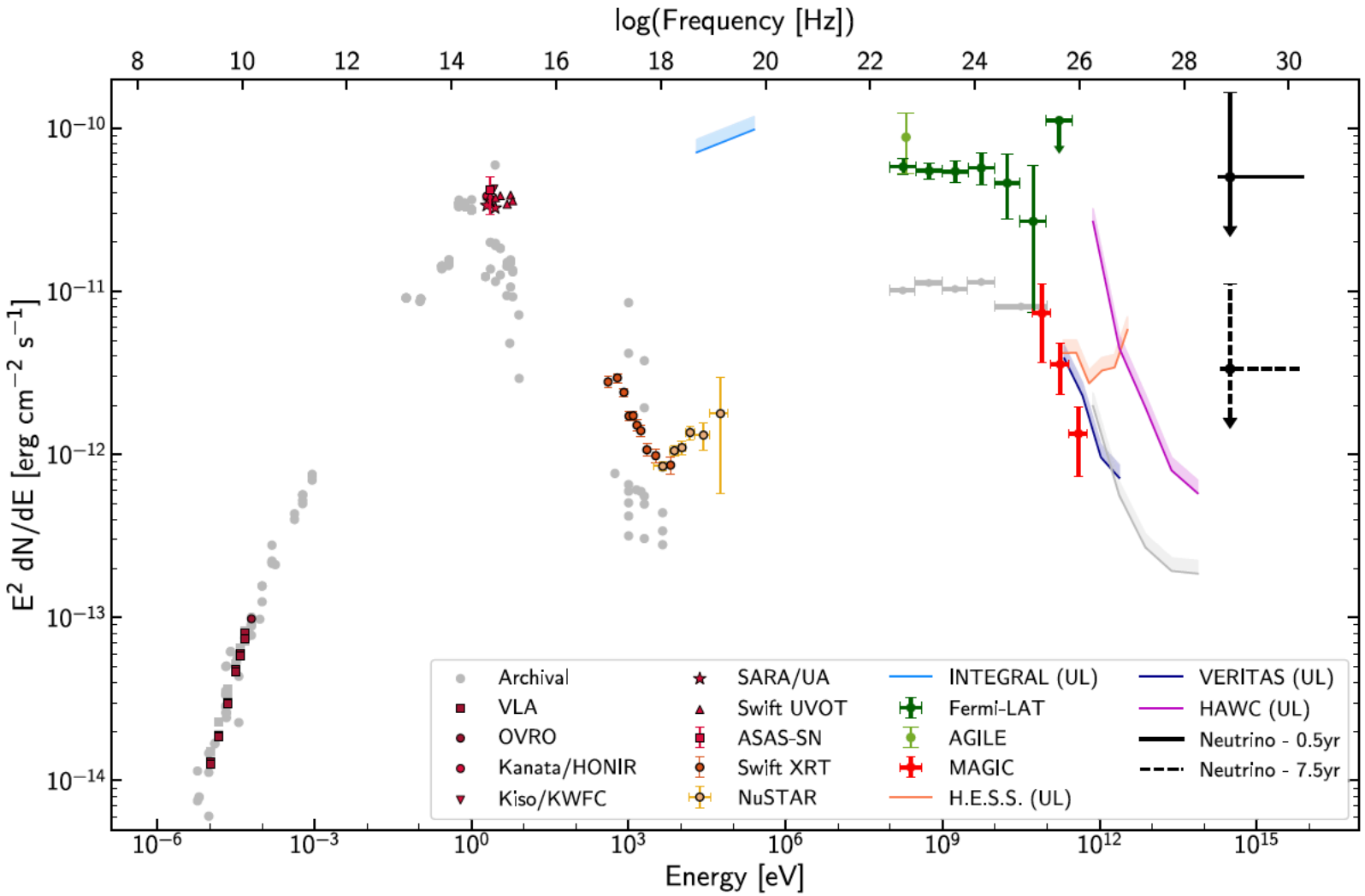
we identified a source of high energy cosmic rays:

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

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

its 10-year flux is dominated by a 150-day burst

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



we know that this one is a cosmic ray source

are blazars the sources

of the cosmic neutrinos?

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

of the highest energy cosmic rays?

measured flux satisfies the energy requirement

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

relation between flaring sources and the diffuse flux ?

diffuse ν_μ flux

TXS luminosity

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

density of blazars

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

vanilla blazars cannot accommodate the 2014 burst

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

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

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

proton beam normalized to the energy density in cosmic rays

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

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

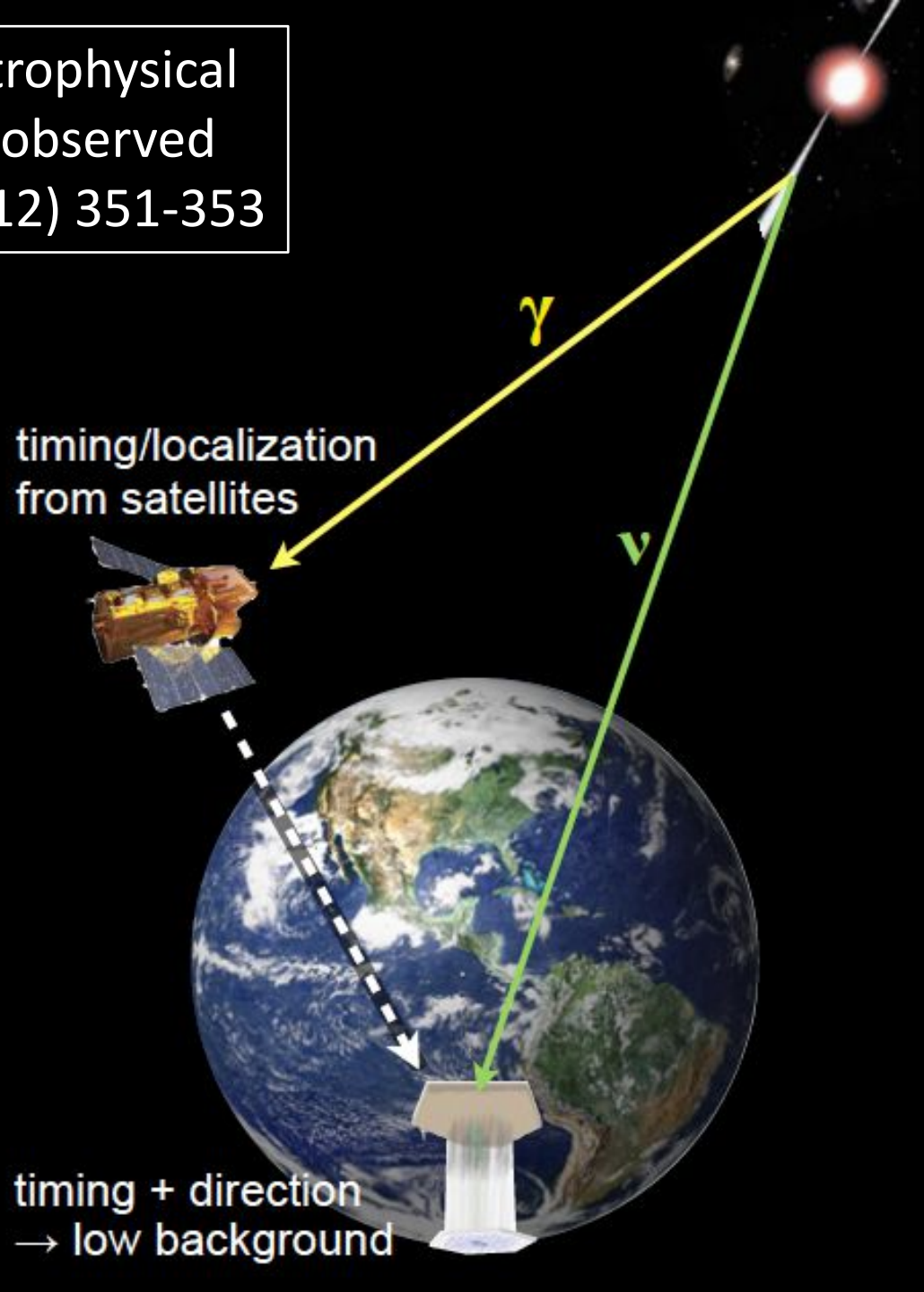
opacity of the gamma ray target

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

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

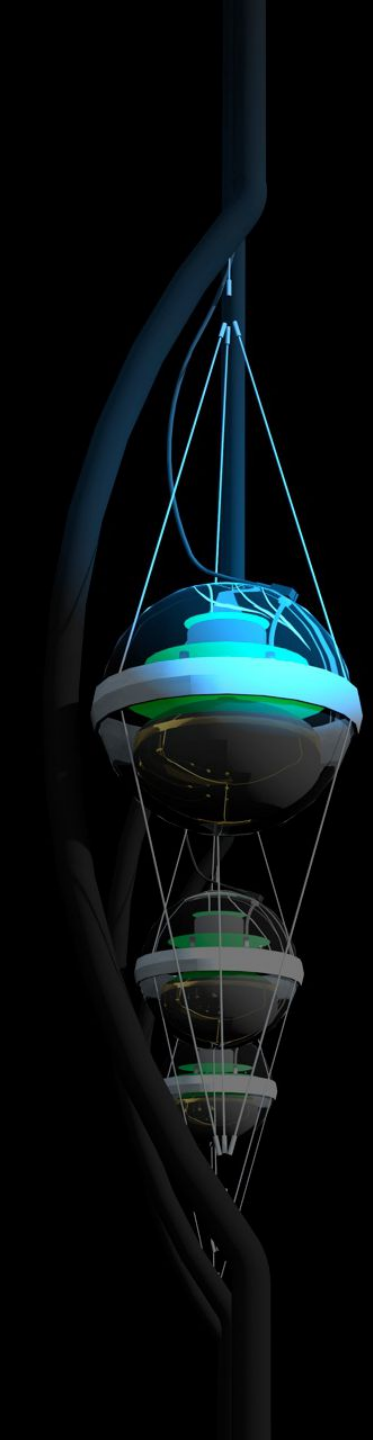
accompanying photons below Fermi threshold

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



neutron star-neutron star merger

LIGO-VIRGO



neutrino astronomy 2019

- it exists
- more neutrinos
- more telescopes

icecube.wisc.edu

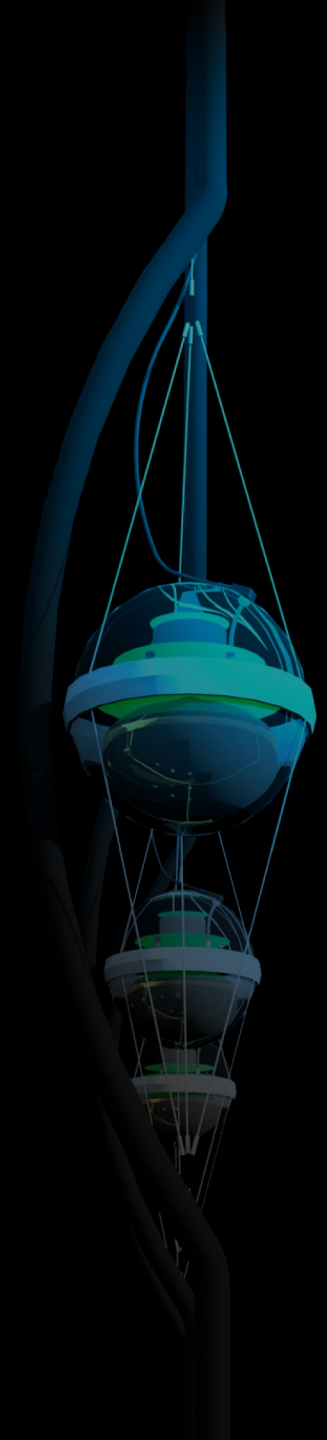
THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

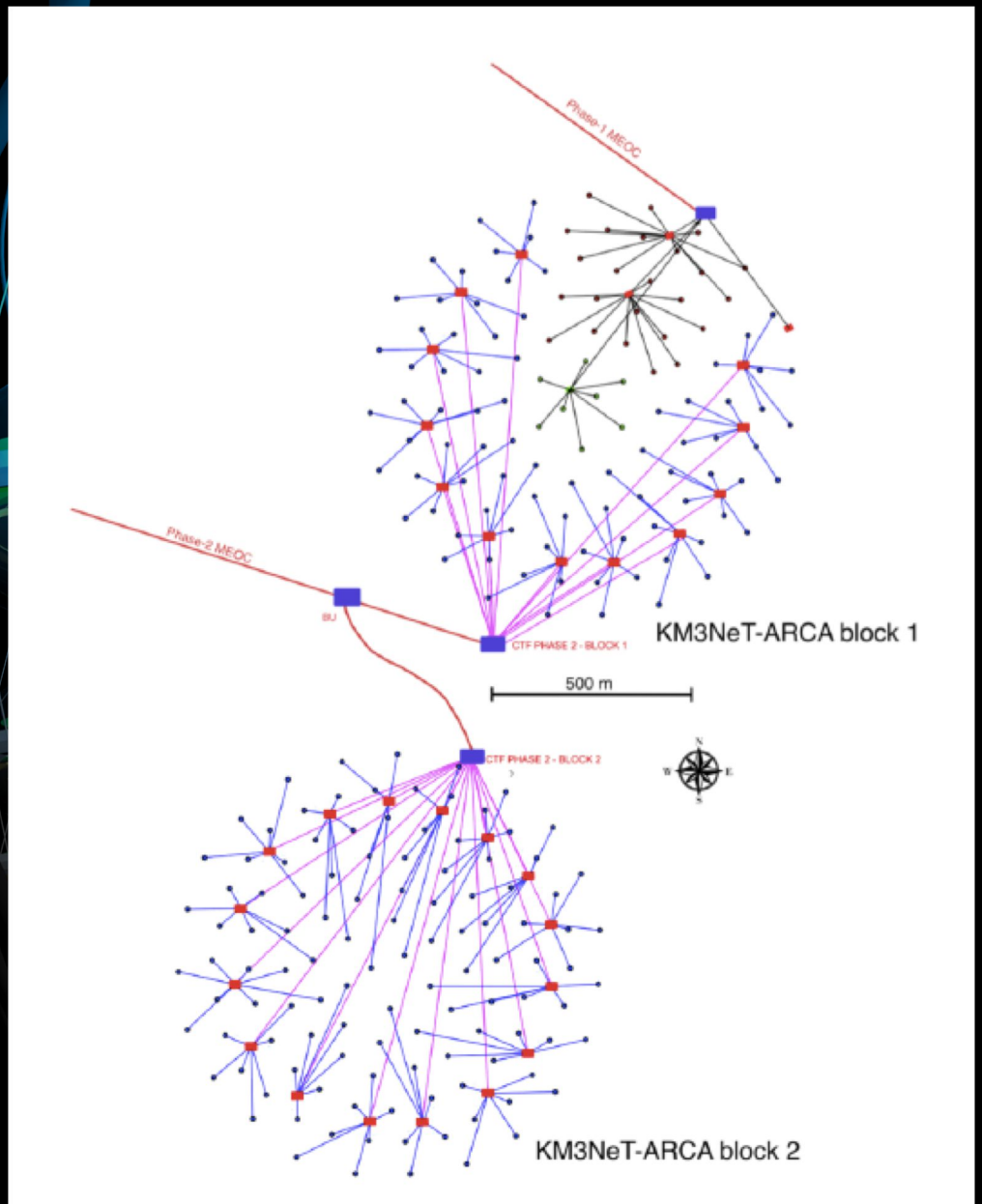
UNITED STATES 25

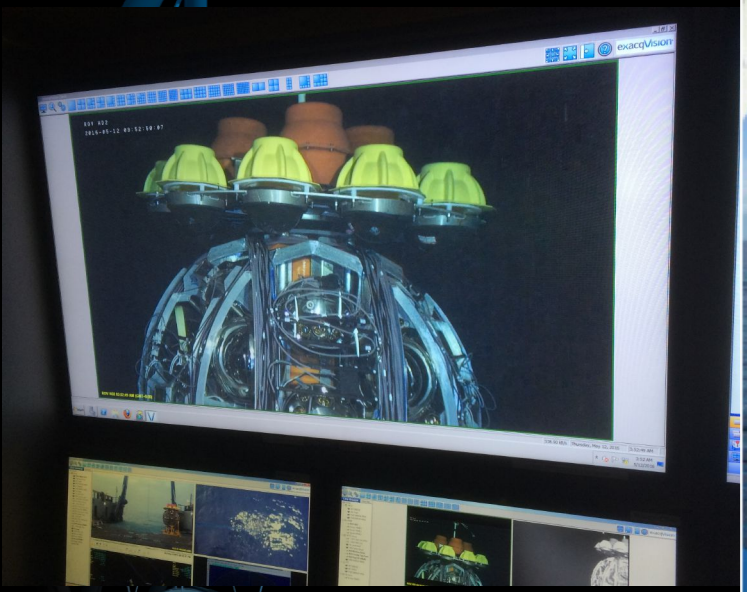
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

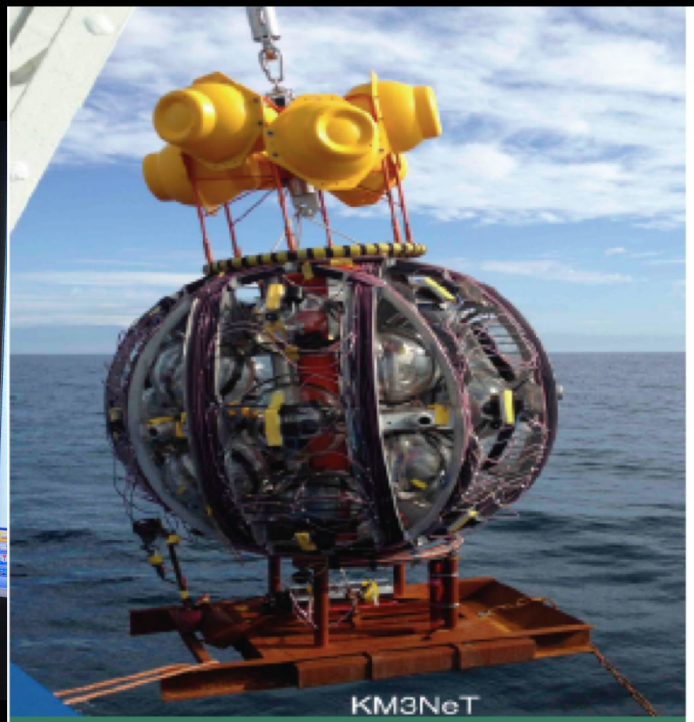


overflow slides

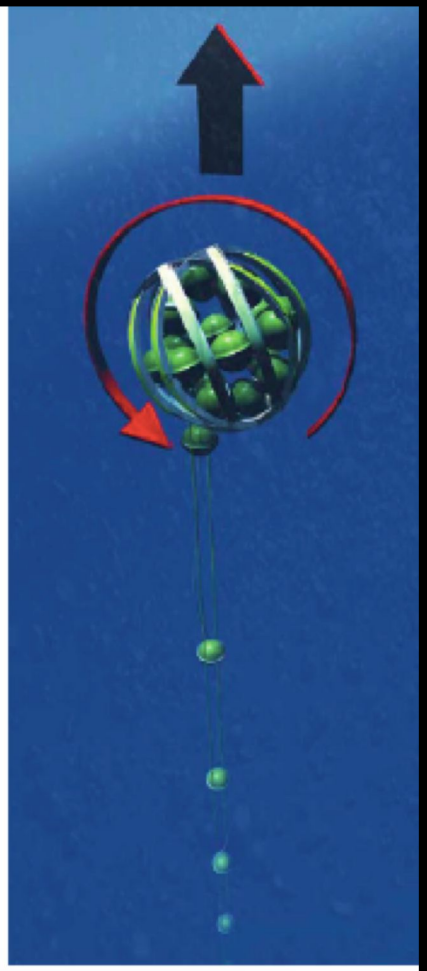
High energies ARCA



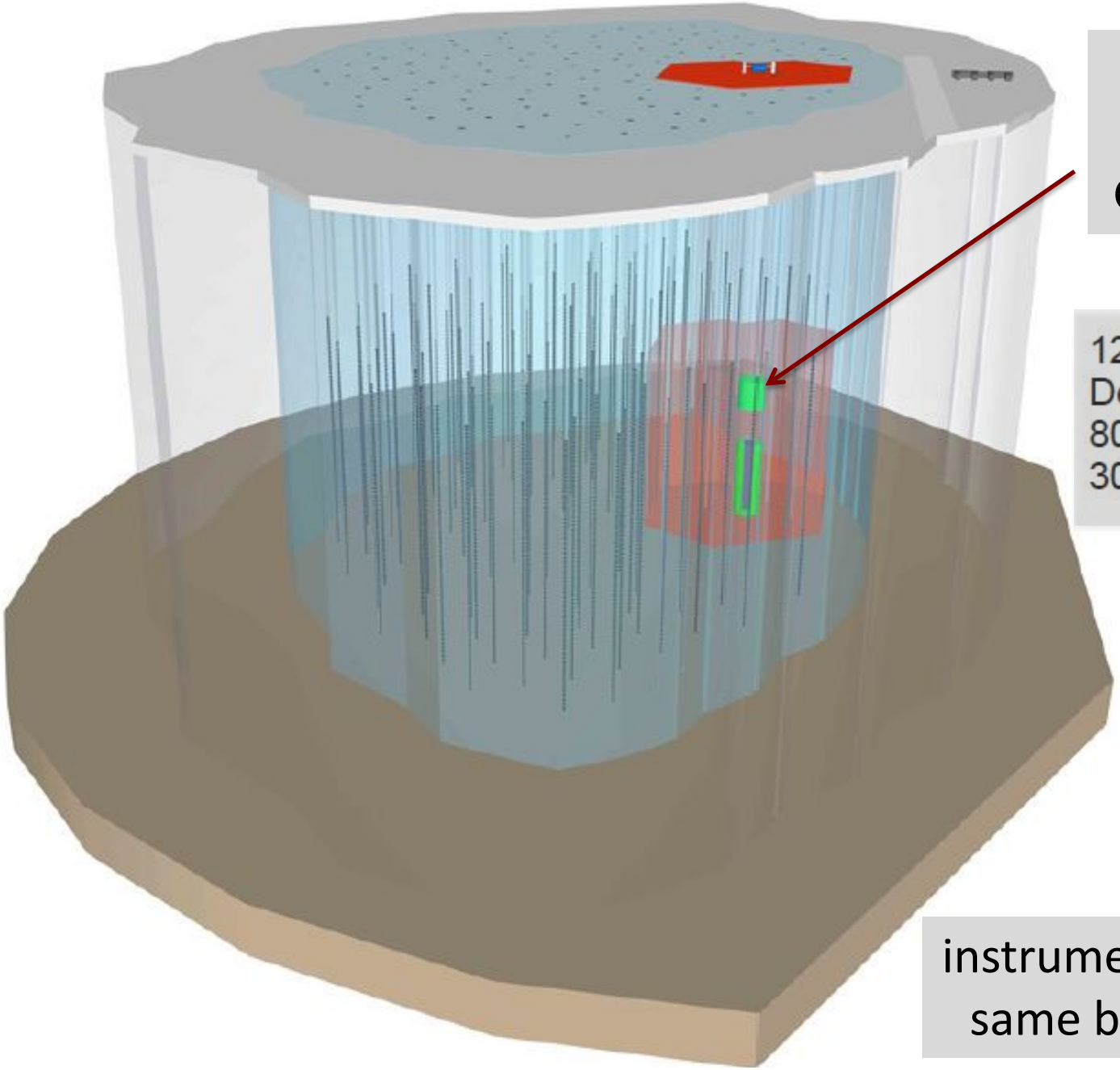




rapid deployment
autonomous unfurling
recoverable



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

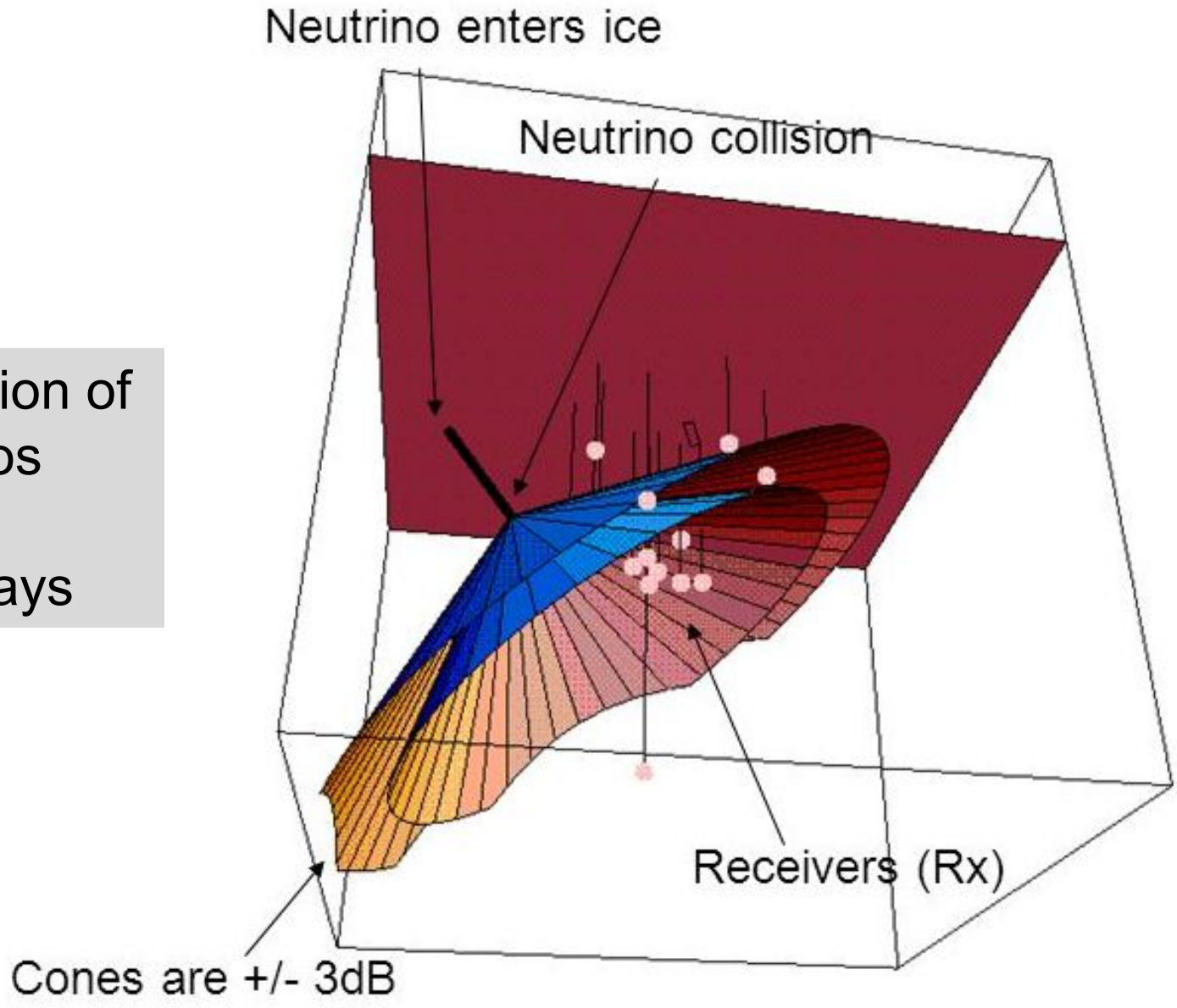


PINGU infill
40 strings
GeV threshold

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

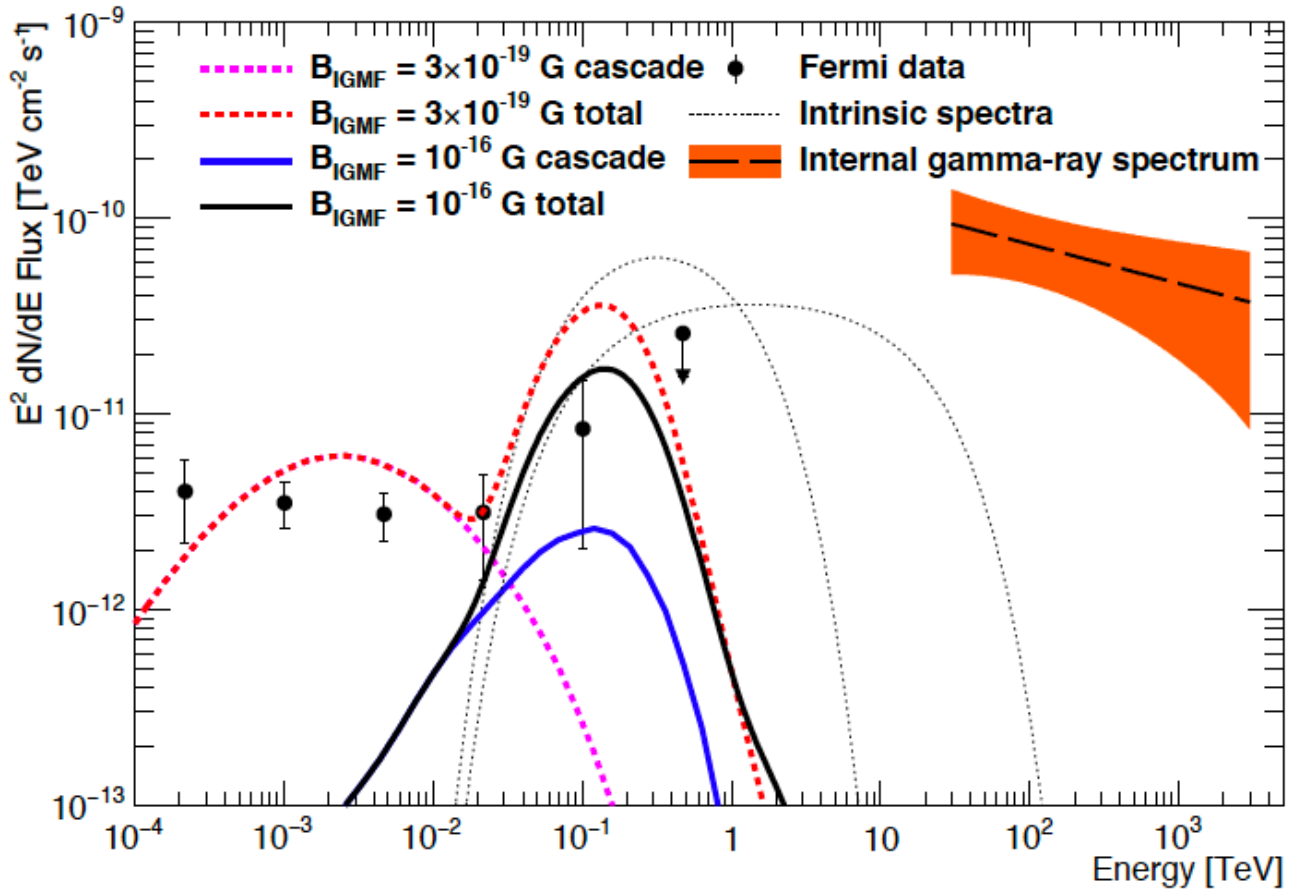
instrumented volume: x 10
same budget as IceCube

radio detection of
neutrinos
and
cosmic rays



the multimessenger picture

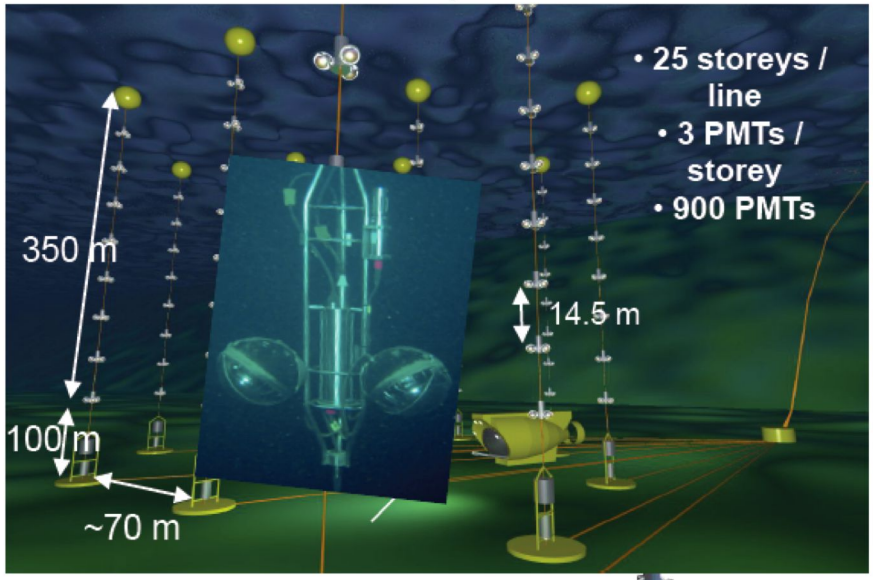
neutrino flux $\xrightarrow{\text{multimessenger relation}}$ gamma ray flux cascades to lower energy in the source $\xrightarrow{\text{EBL absorption}}$ observed flux @ Fermi



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

Mediterranean Detectors

ANTARES Complete since 2008



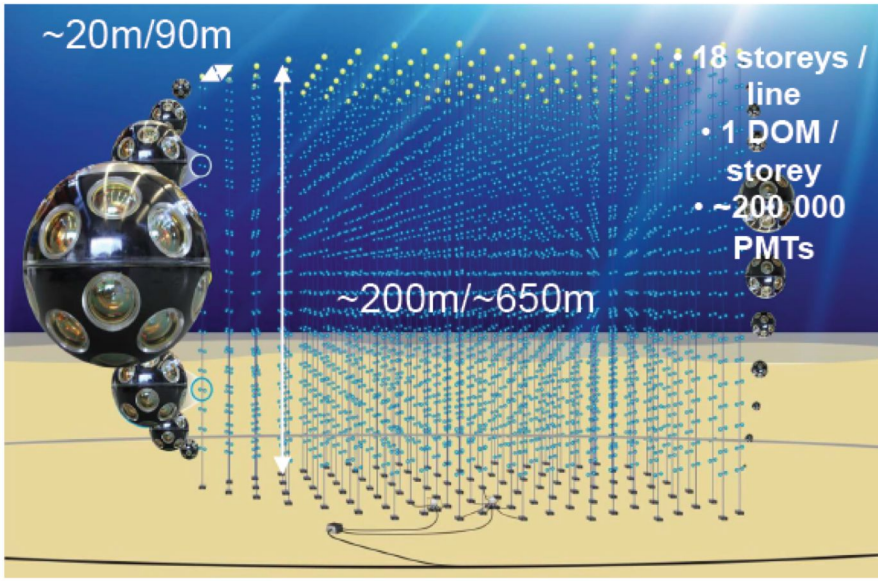
~10 Mton

12 lines

First Generation

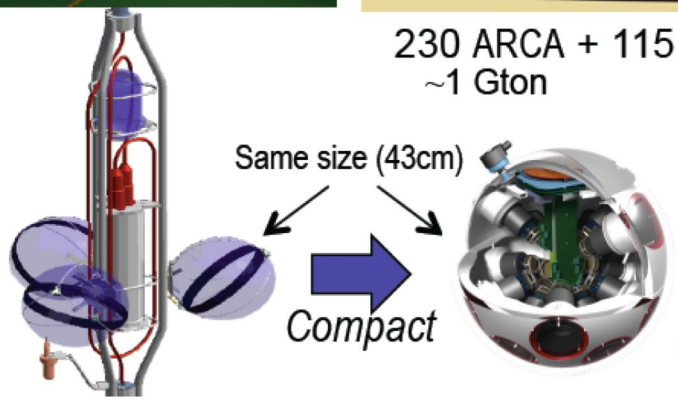
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton

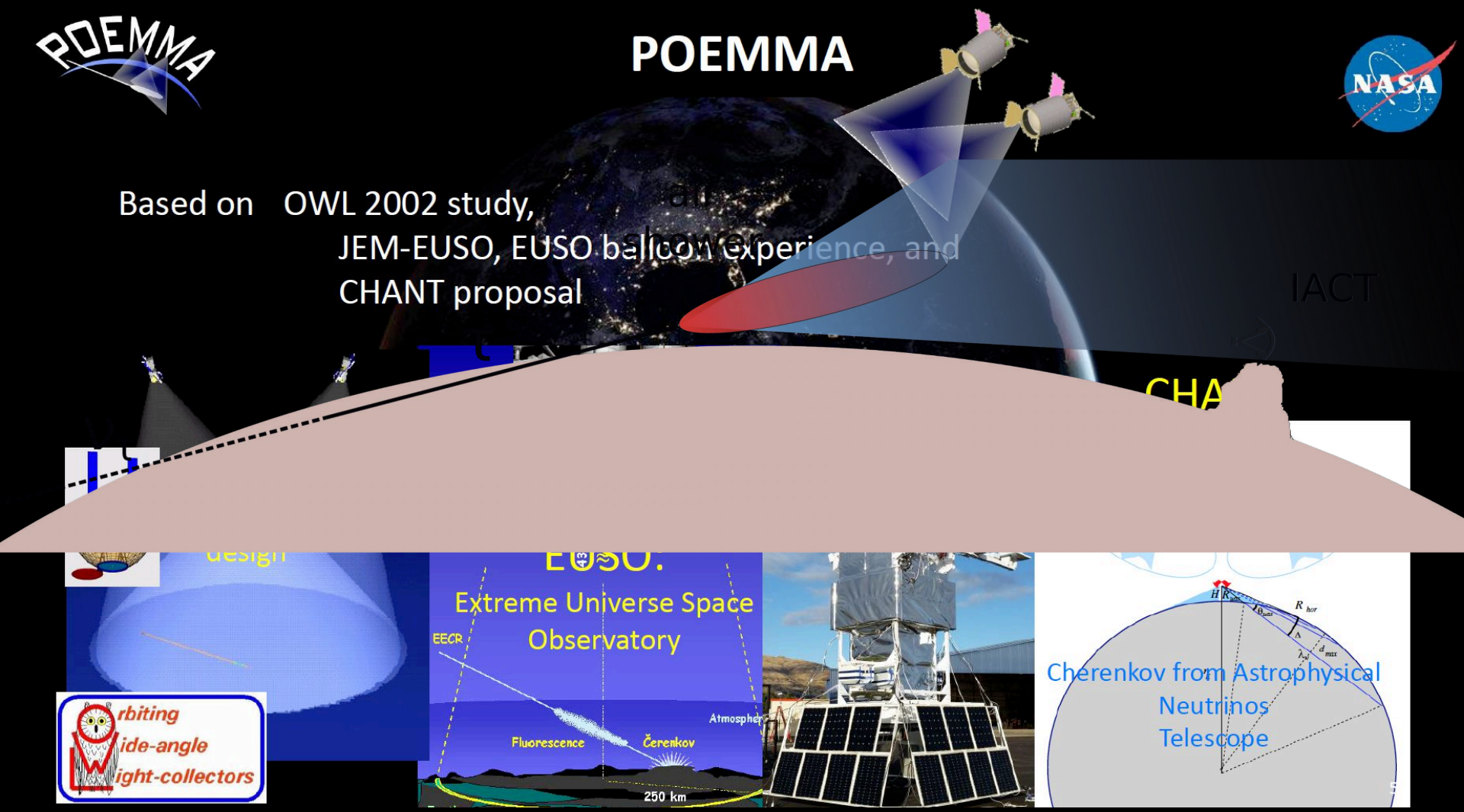


- DOM: 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

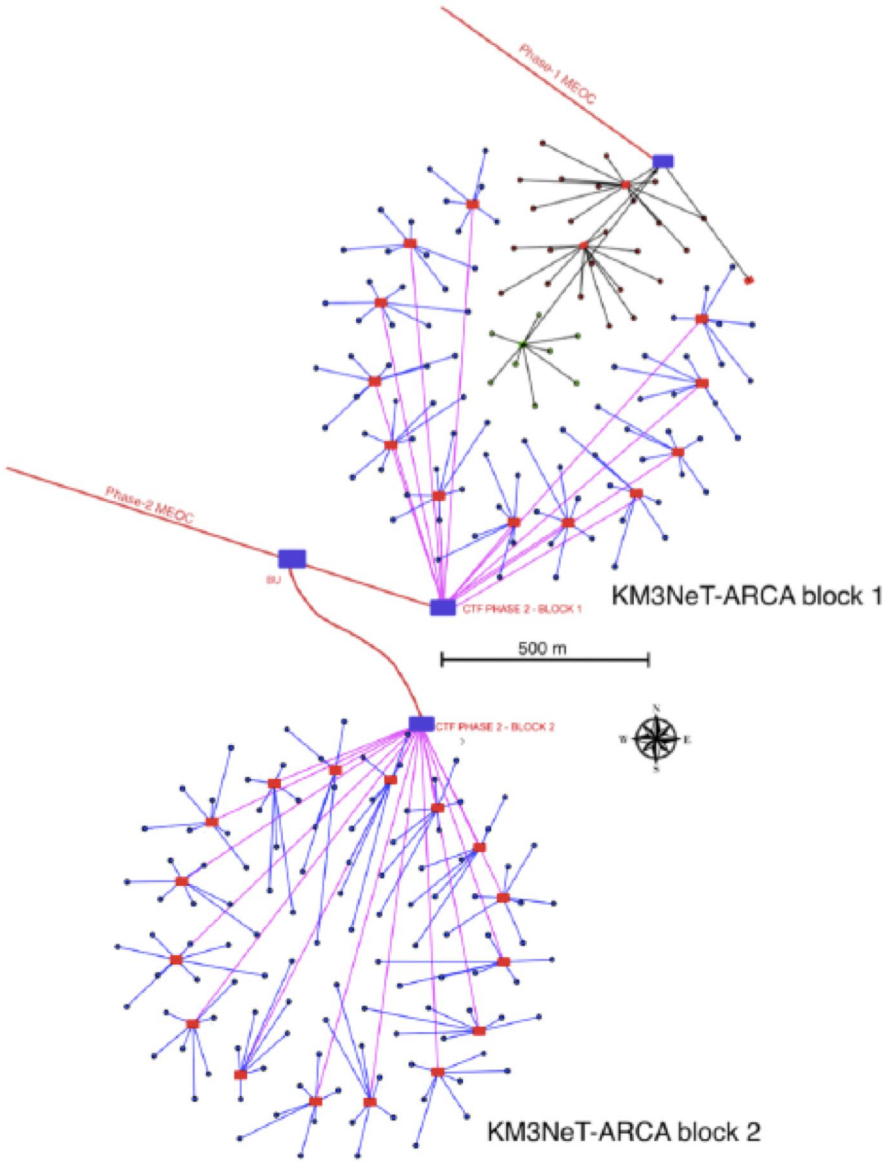
A. Kouchner, Neutrino 2016

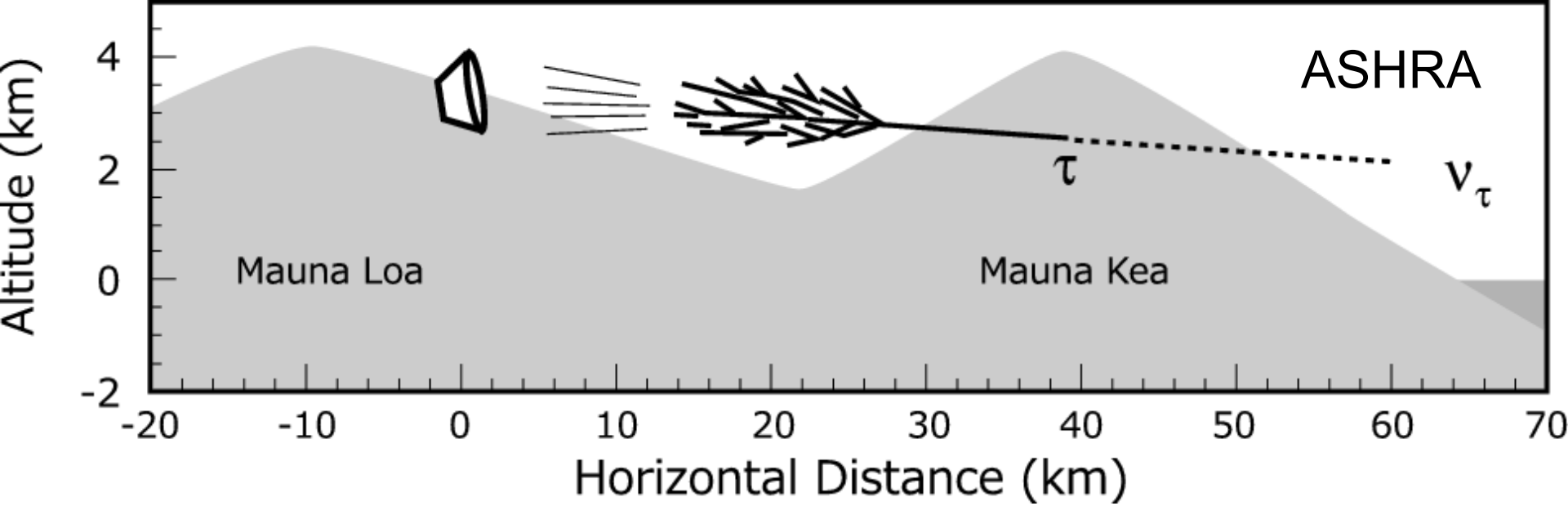
POEMMA

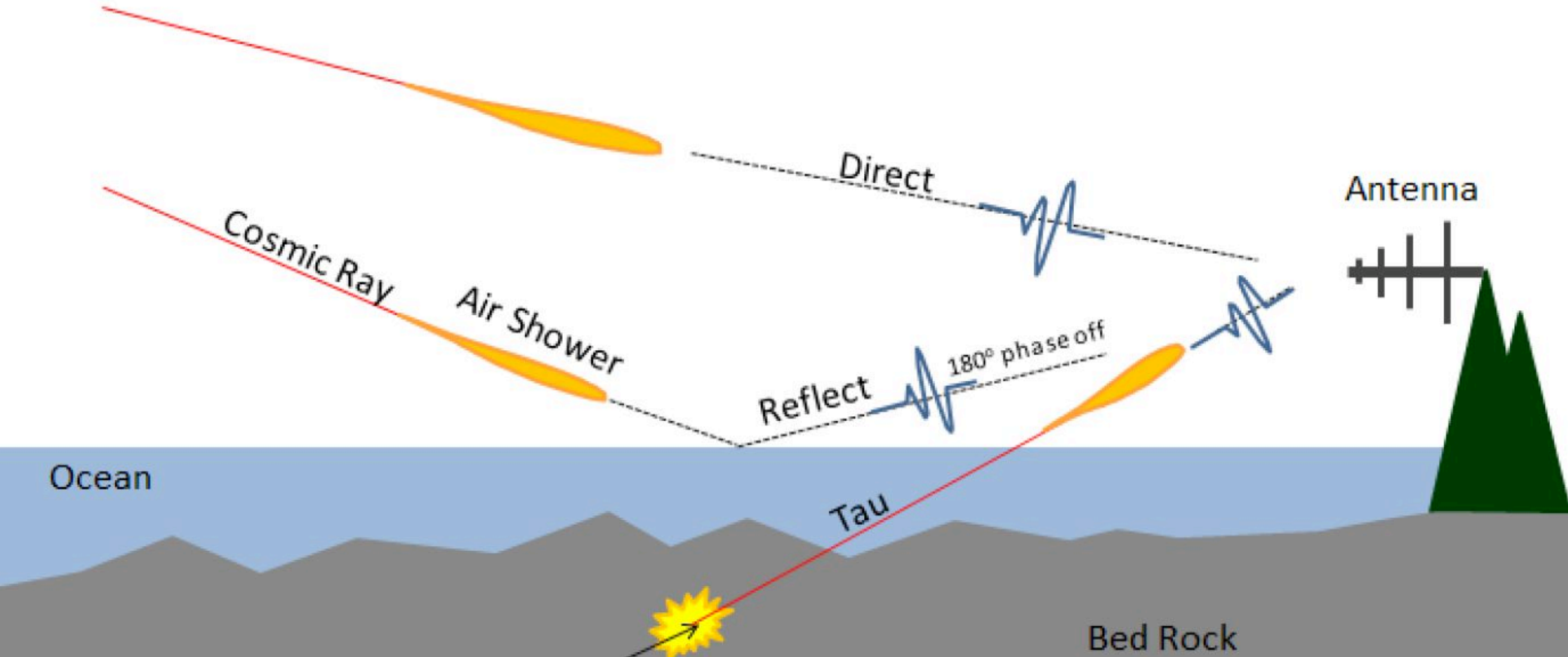
Based on OWL 2002 study,
JEM-EUSO, EUSO balloon experience, and
CHANT proposal



High energies ARCA

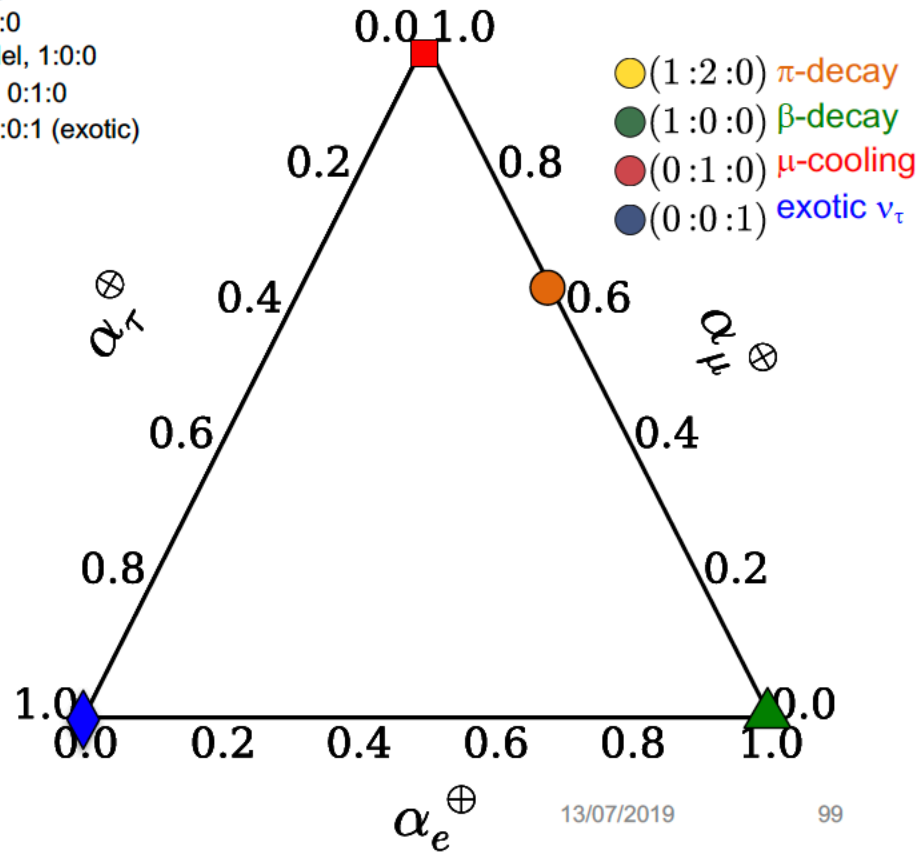



ASHRA
Altitude (km)
4
2
0
-2
-20
-10
0
10
20
30
40
50
60
70
Horizontal Distance (km)
Mauna Loa
Mauna Kea
τ
ν_τ


Direct
Antenna
Cosmic Ray
Air Shower
Reflect
180° phase off
Ocean
Tau
Bed Rock

There are 3 astrophysical neutrino production models

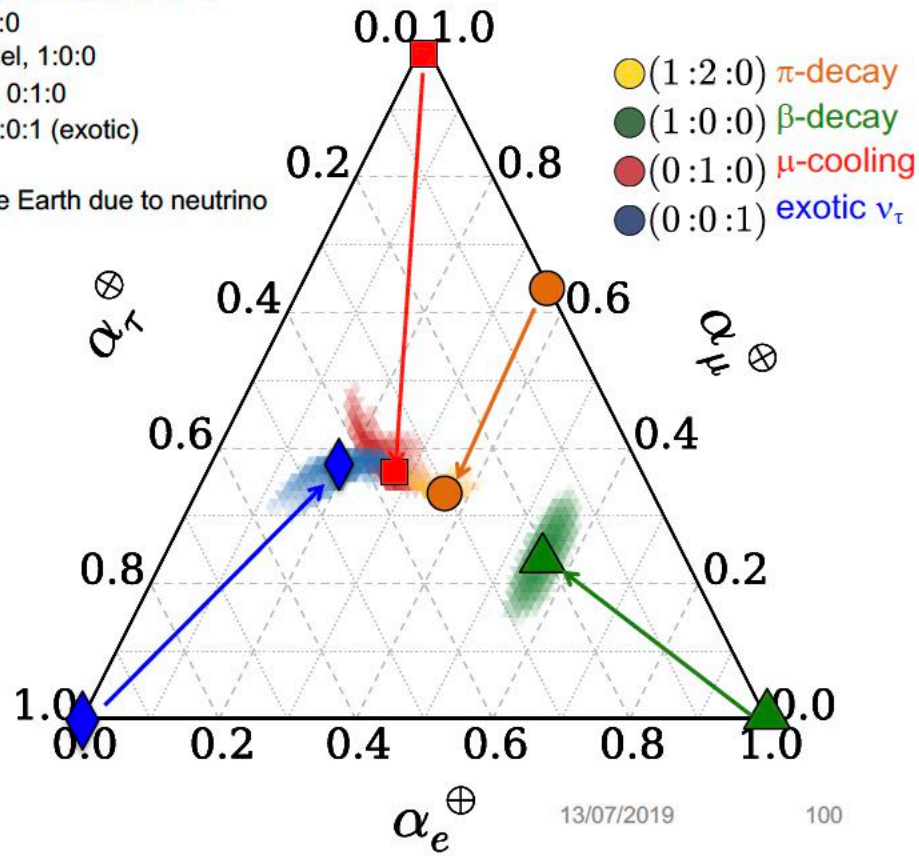
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1 (exotic)



There are 3 astrophysical neutrino production models

i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1 (exotic)

Initial flavour ratio is modified on the Earth due to neutrino mixing



4. Neutrino flavour ratio

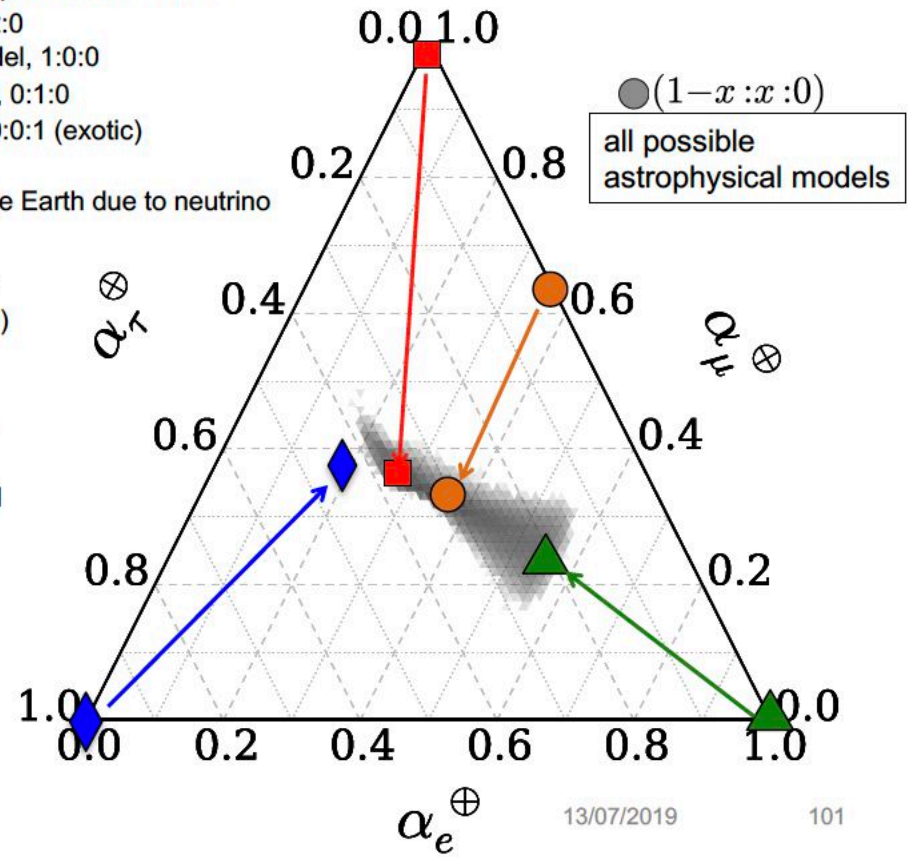
There are 3 astrophysical neutrino production models

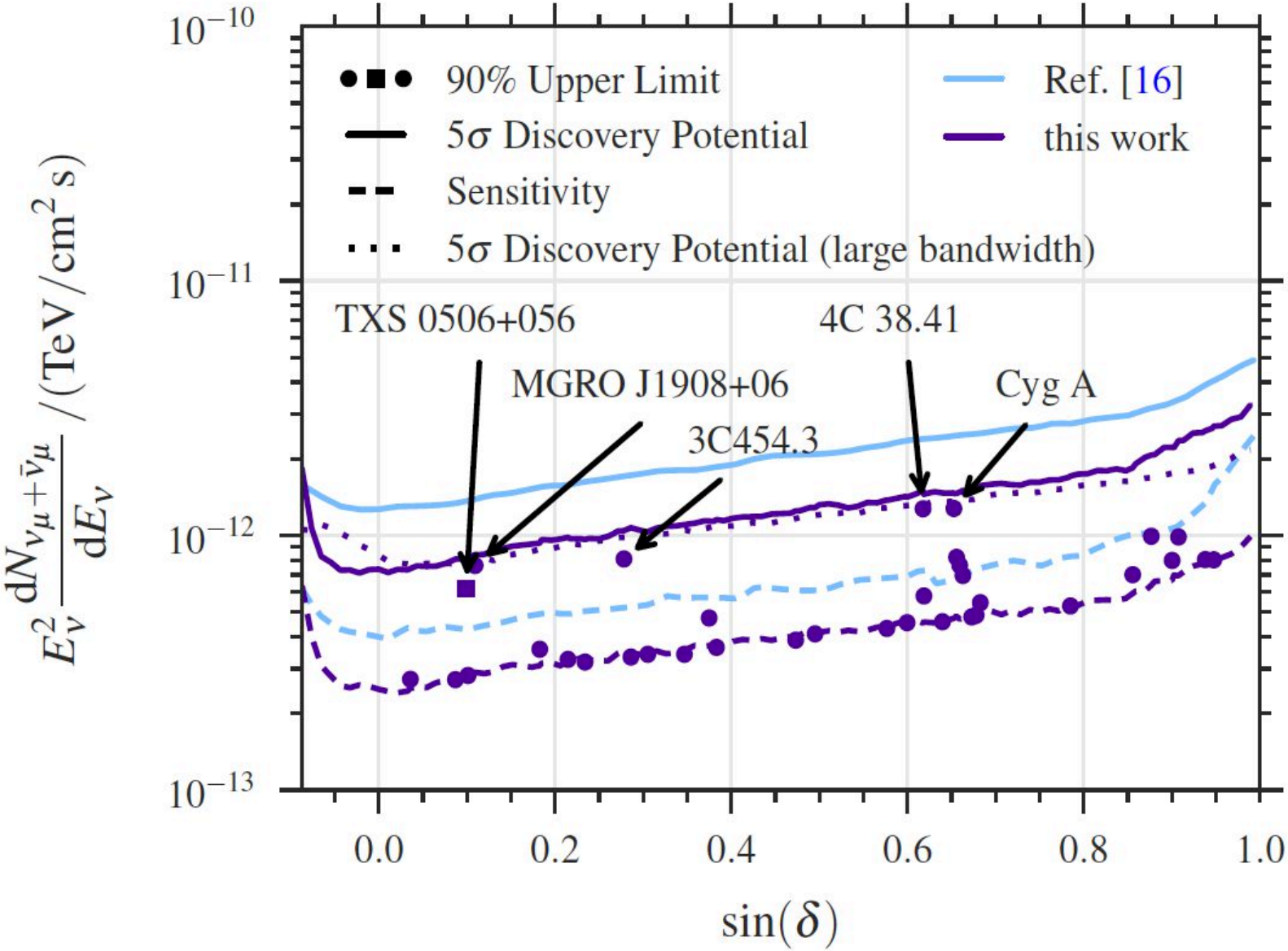
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1 (exotic)

Initial flavour ratio is modified on the Earth due to neutrino mixing

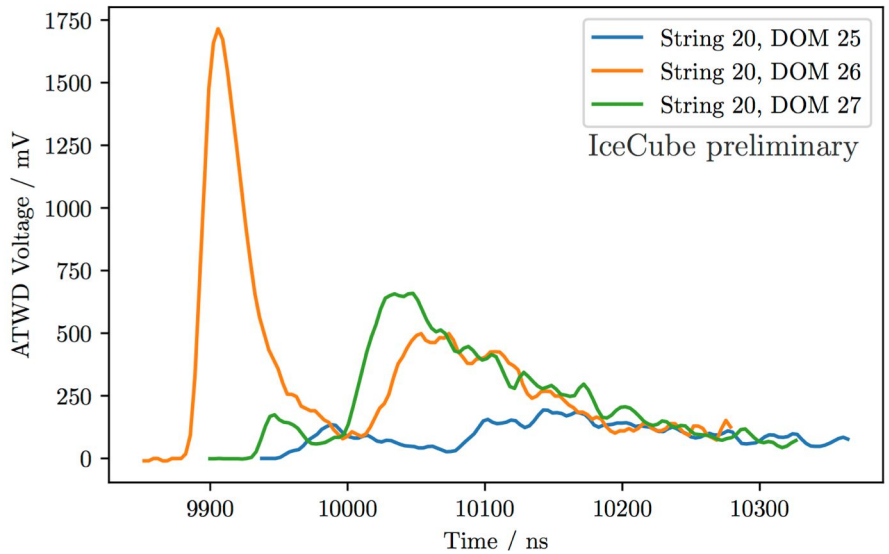
Astrophysical neutrinos = hadronic (pion) process → (1:0:0) and (0:1:0) are too extreme astrophysical neutrino flavour models and all realistic models are between them

All possible flavour ratio is confined in a small space.

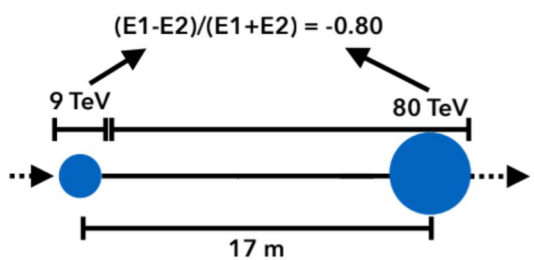




search assuming E-2.19 (diffuse) spectrum



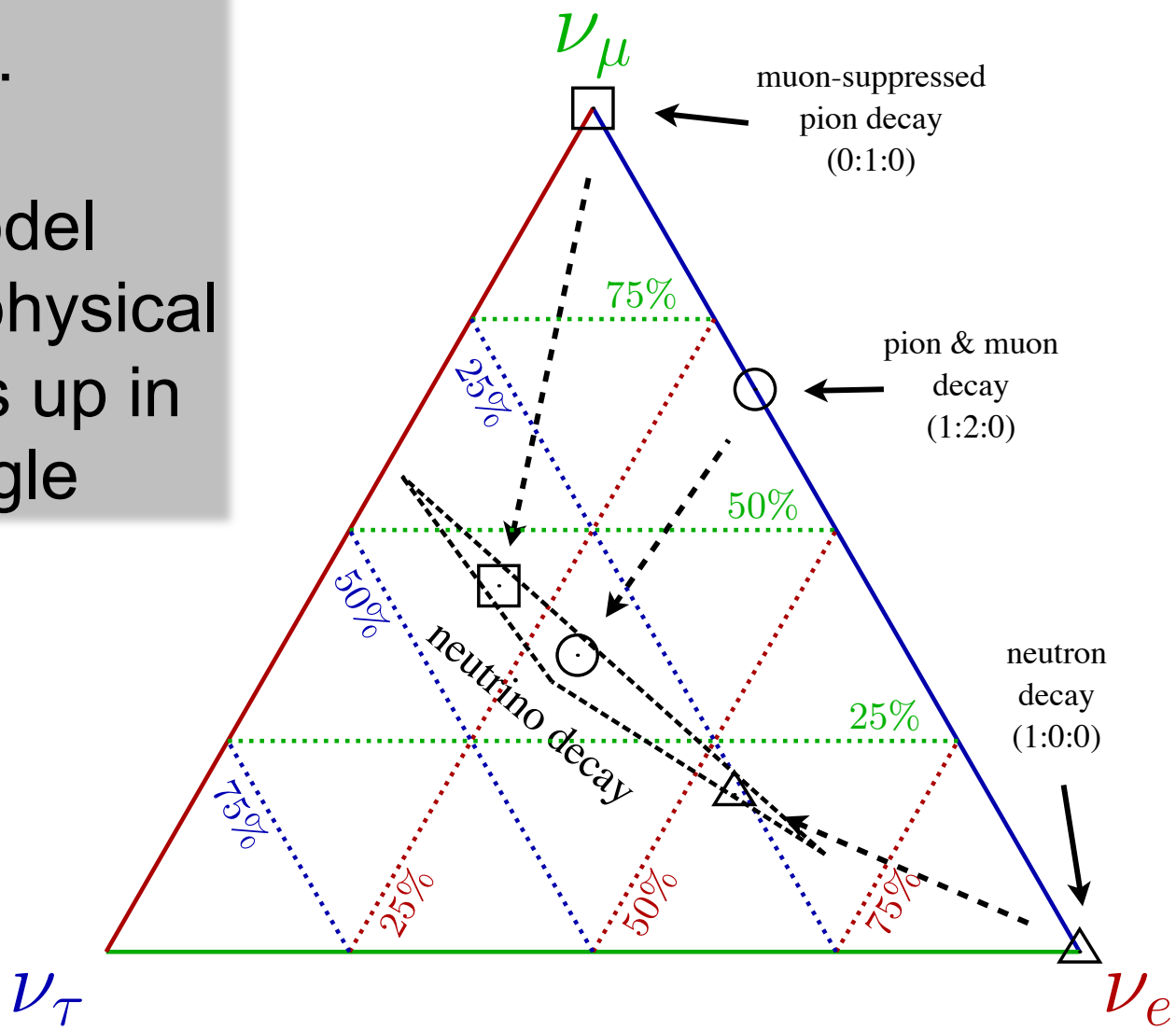
tau event identified in
3 different analyses



new physics ?

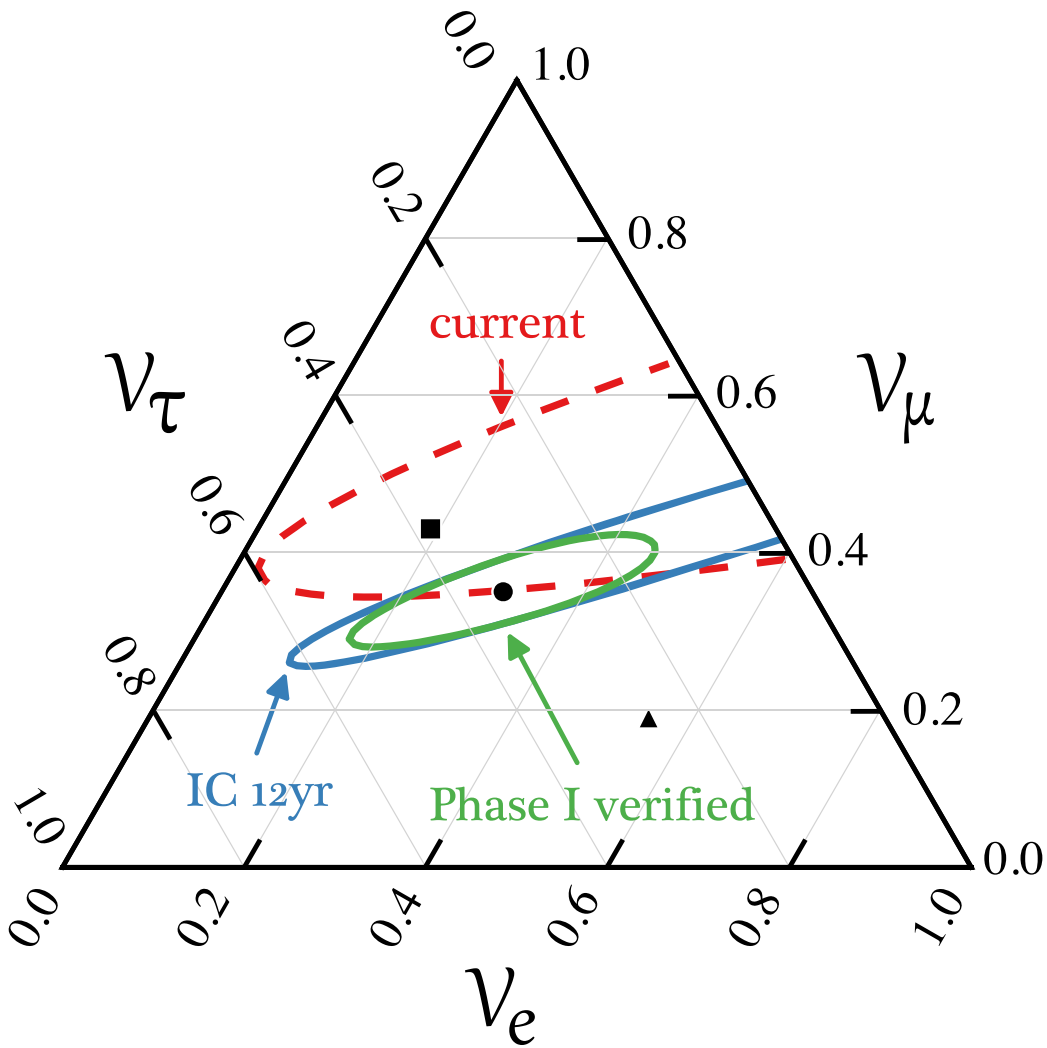
if not…

every model
for the astrophysical
source ends up in
the triangle

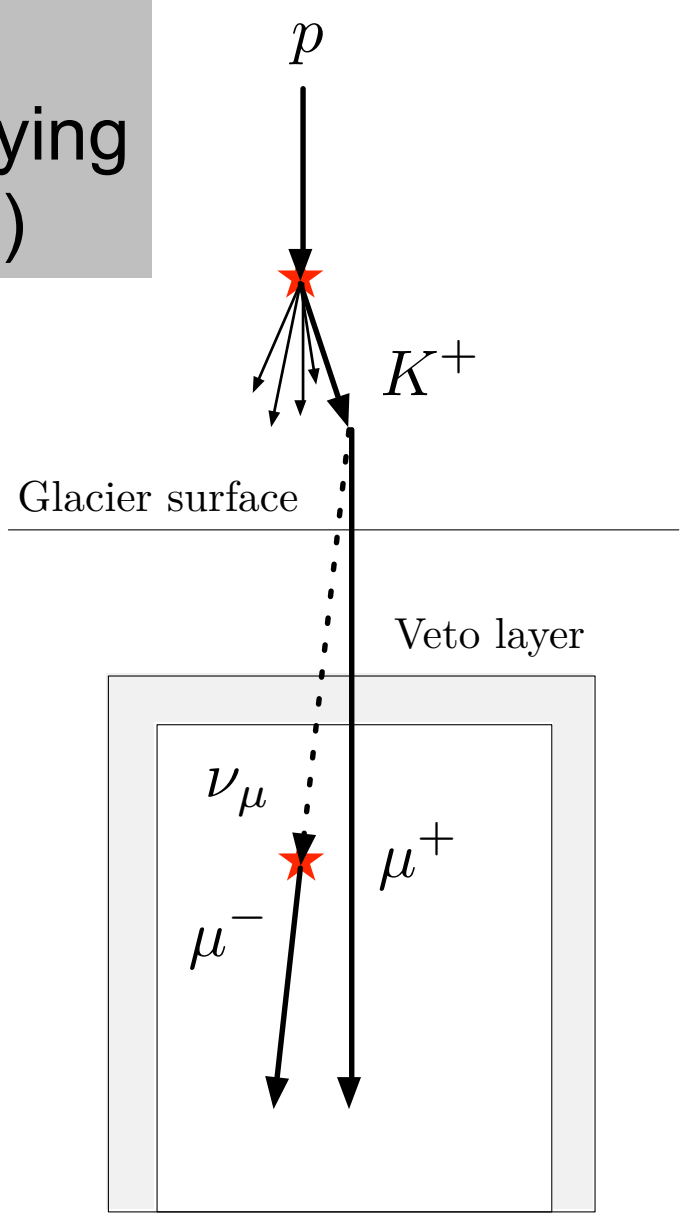


ongoing upgrade: 2022 deployment

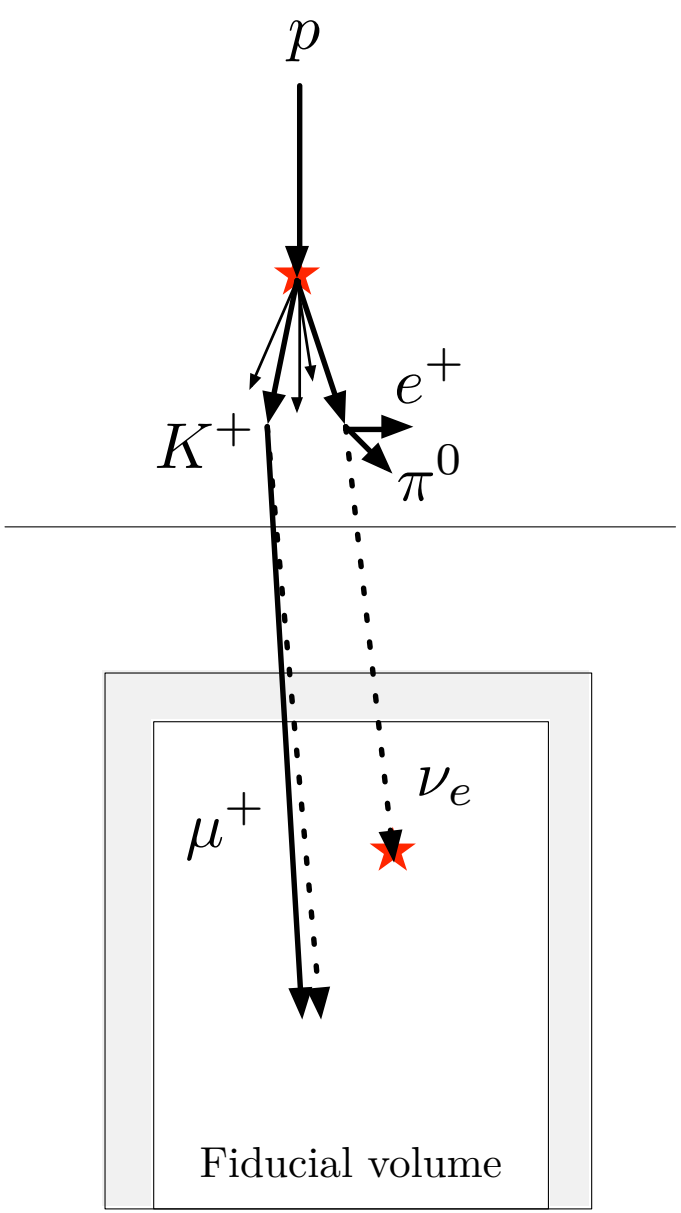
- neutrino oscillation at PeV energy
- nutau: test of the 3-neutrino scenario
- neutrino physics BSM
- IceCube Gen2 pathfinder



no accompanying muon(s)



Veto by correlated muon



Veto by uncorrelated muon