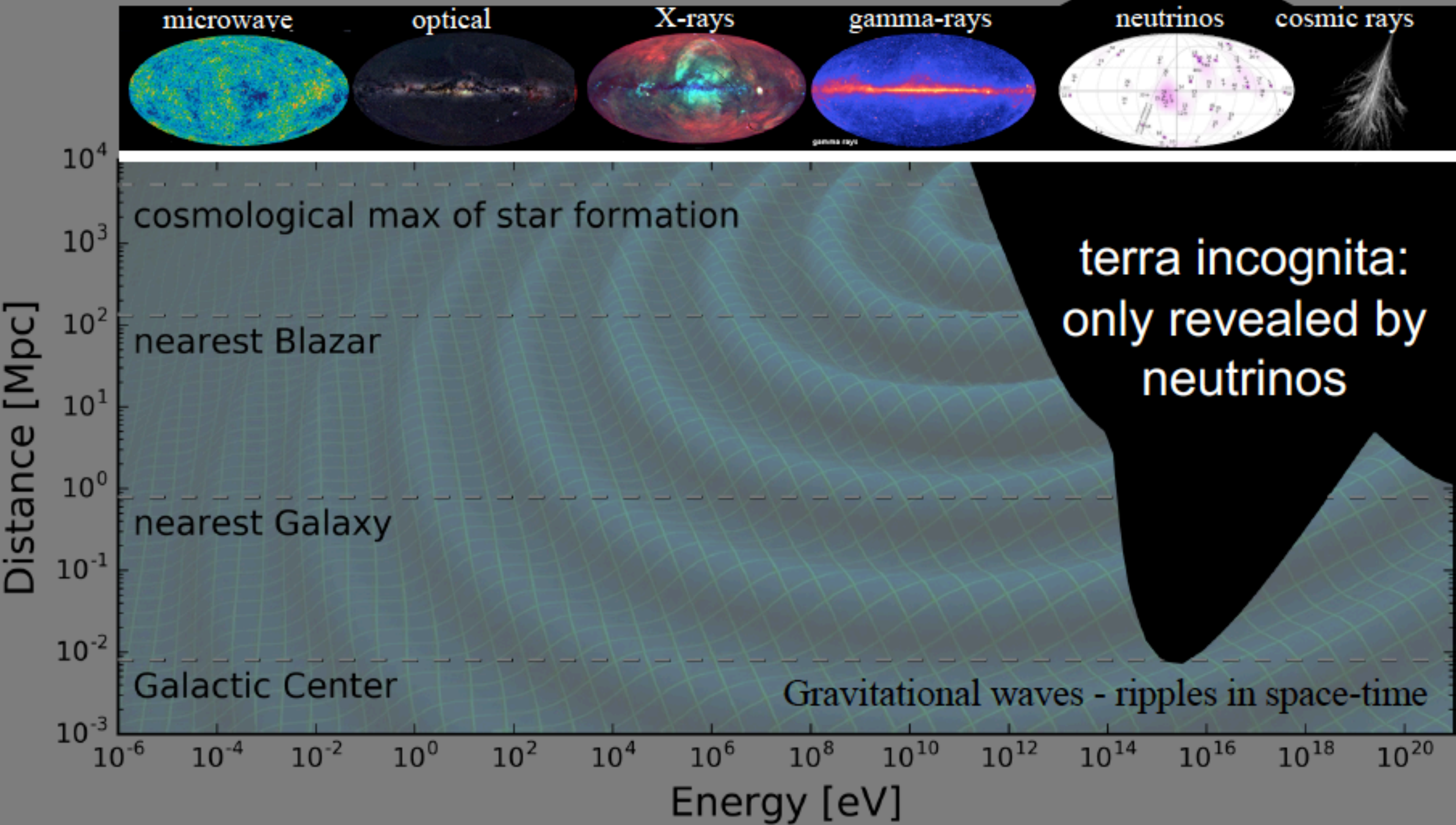
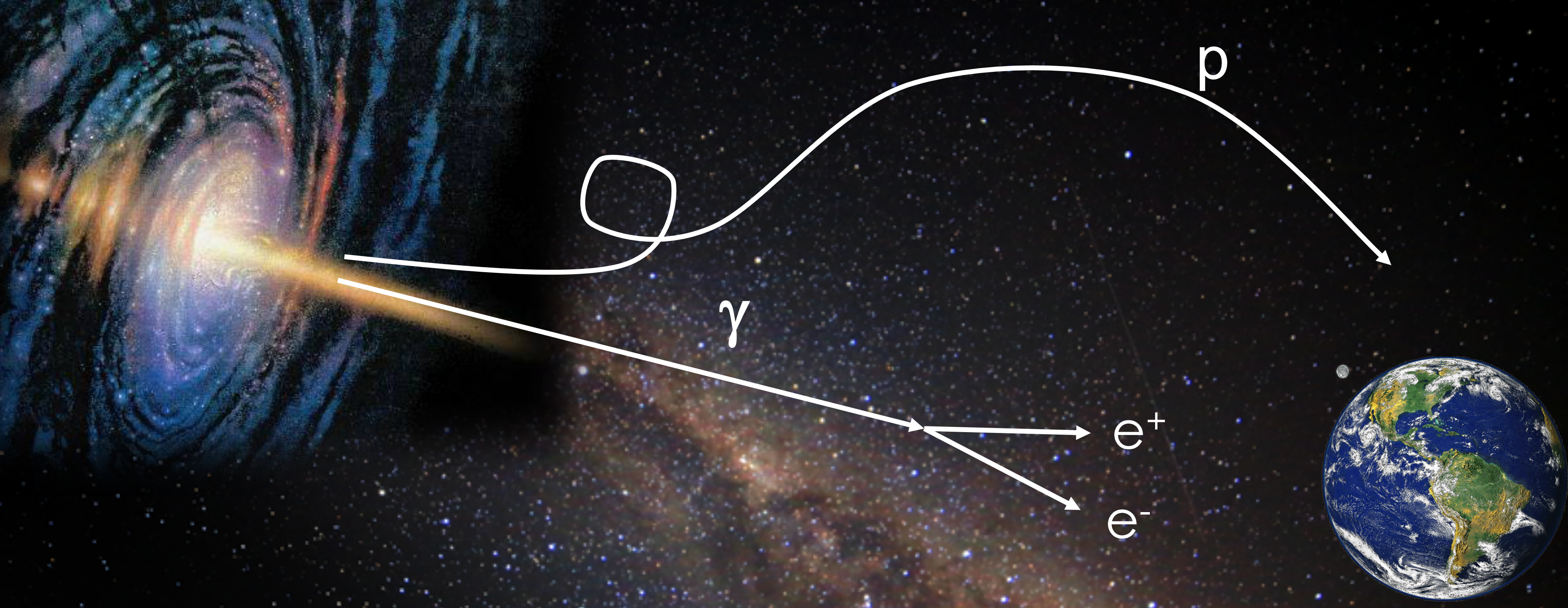
IceCube: the discovery of cosmic neutrinos
francis halzen

- neutrino astronomy and the origin of cosmic rays
- IceCube
- the discovery of cosmic neutrinos
- IceCube neutrinos and Fermi photons
- where do they come from?
- the first cosmic ray accelerator(s)



- 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

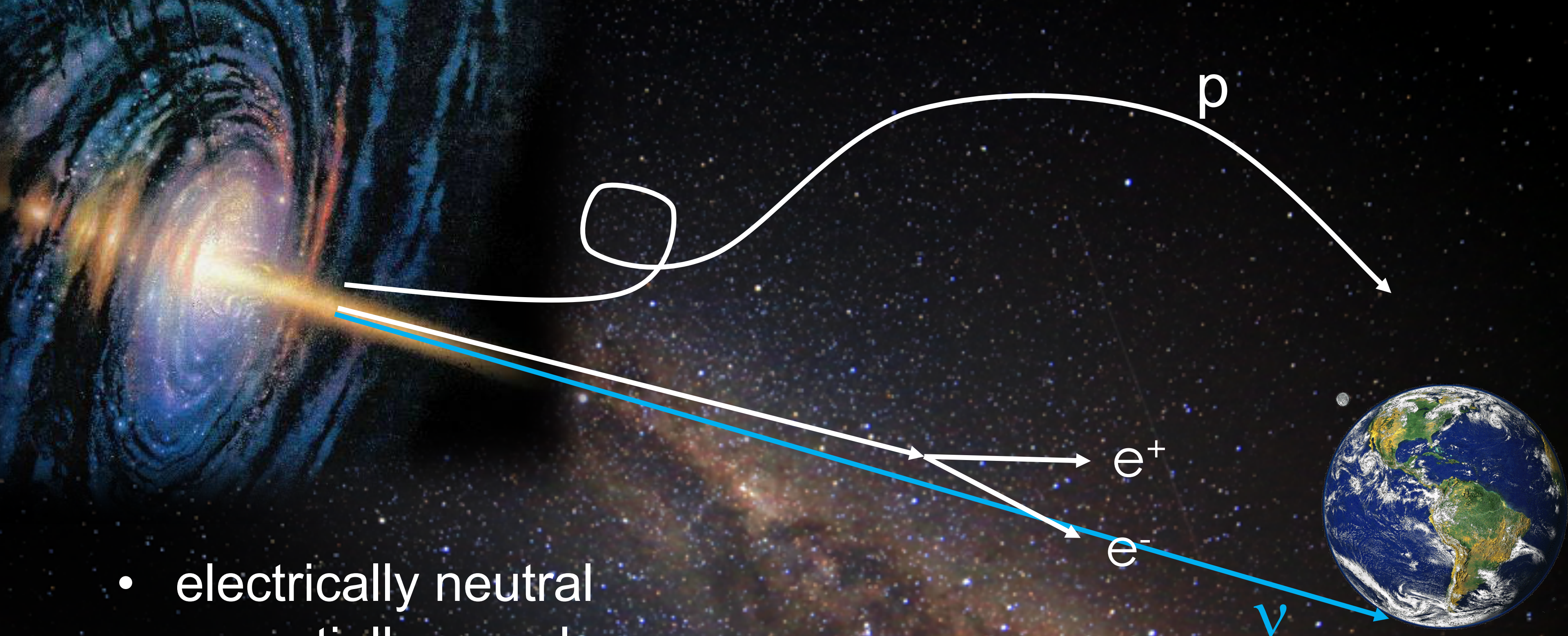


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

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

enter: neutrinos

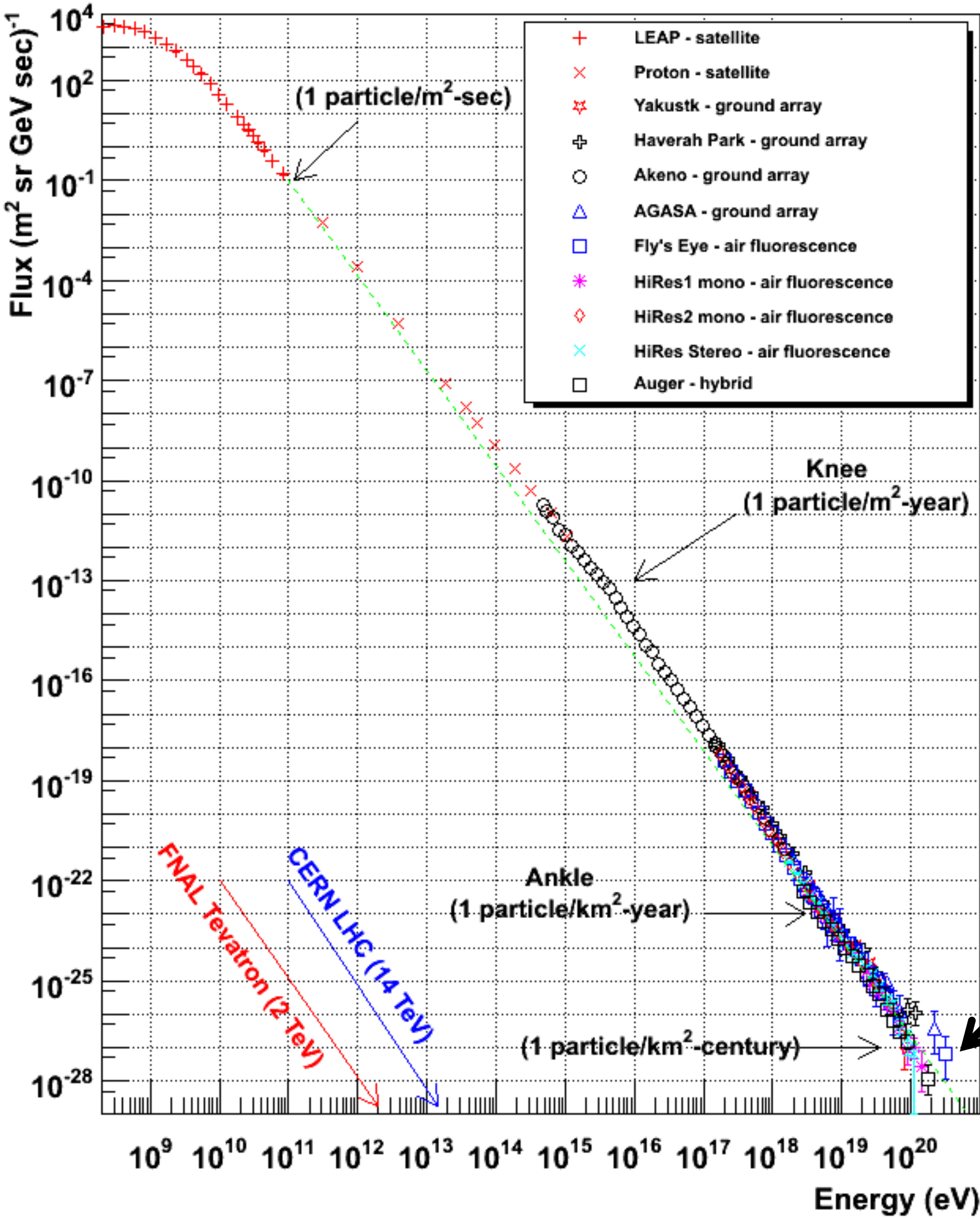
Neutrinos? Perfect Messenger



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

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

origin of cosmic rays: oldest problem in astronomy

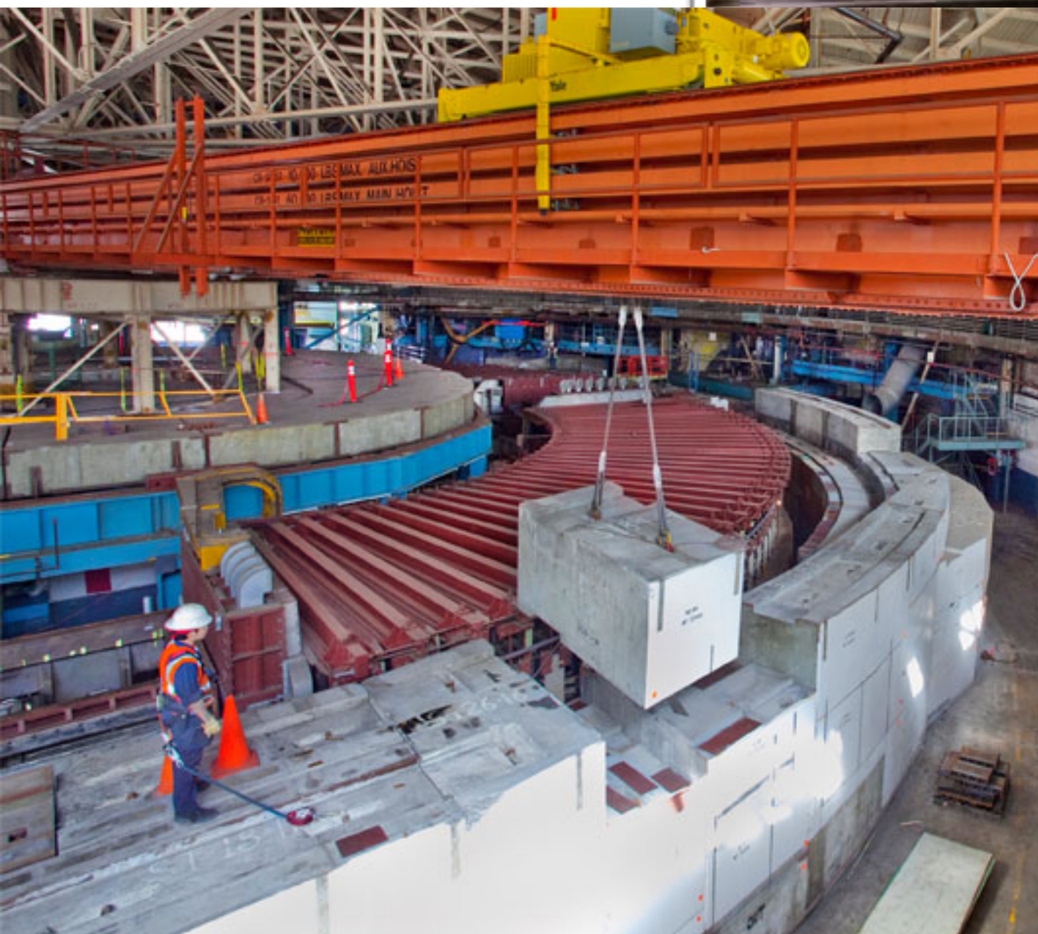


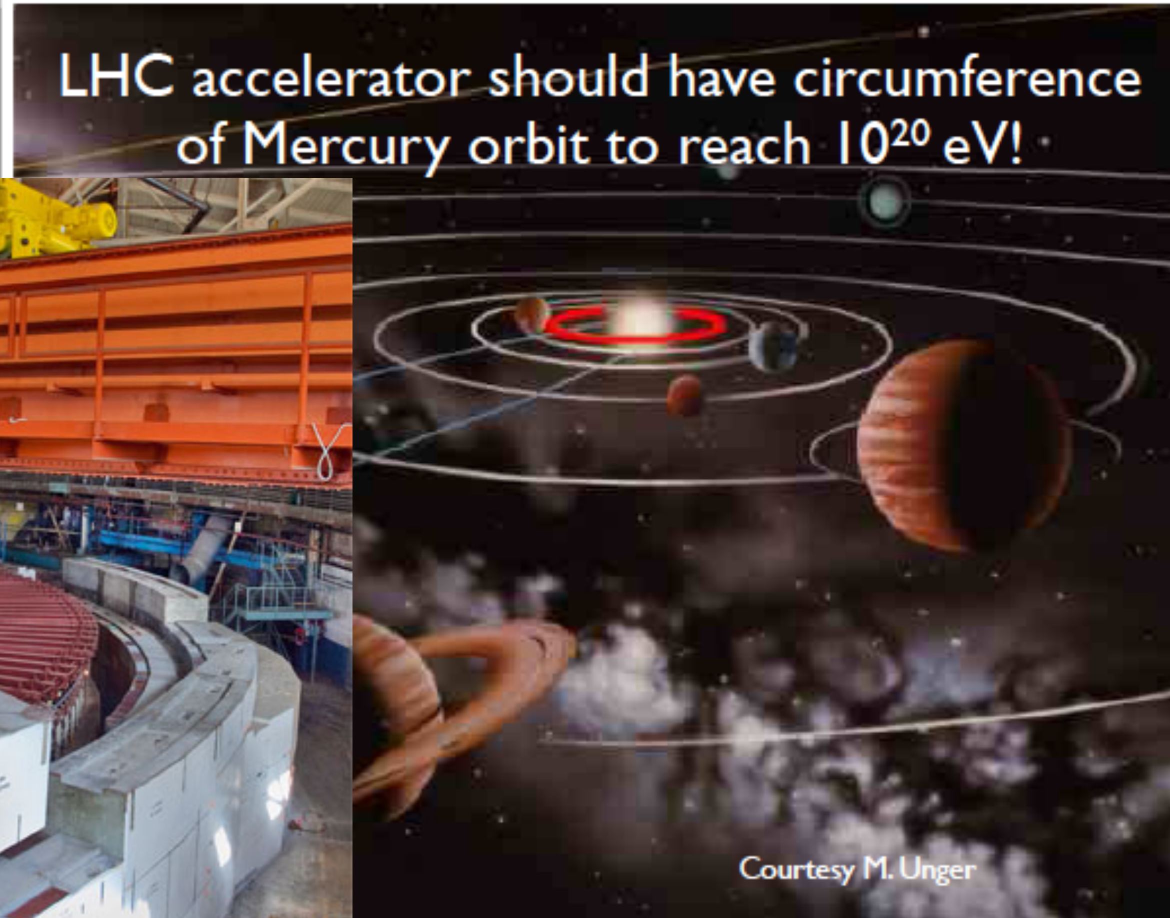
cosmic ray challenge

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

gravitational energy from collapsing stars is converted into particle acceleration?

cosmic ray accelerators

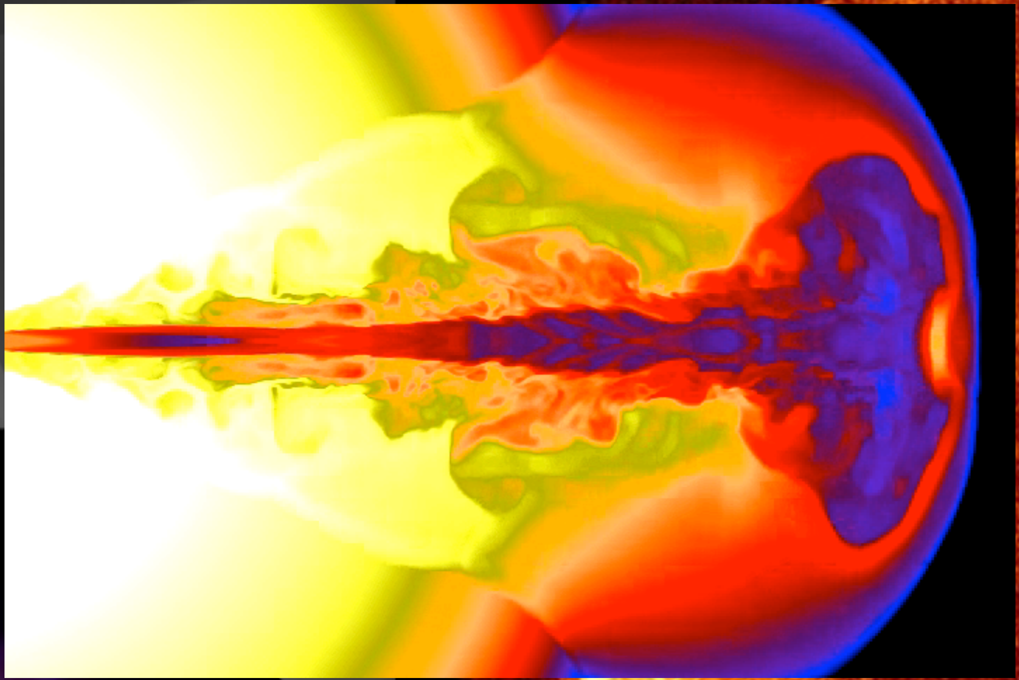




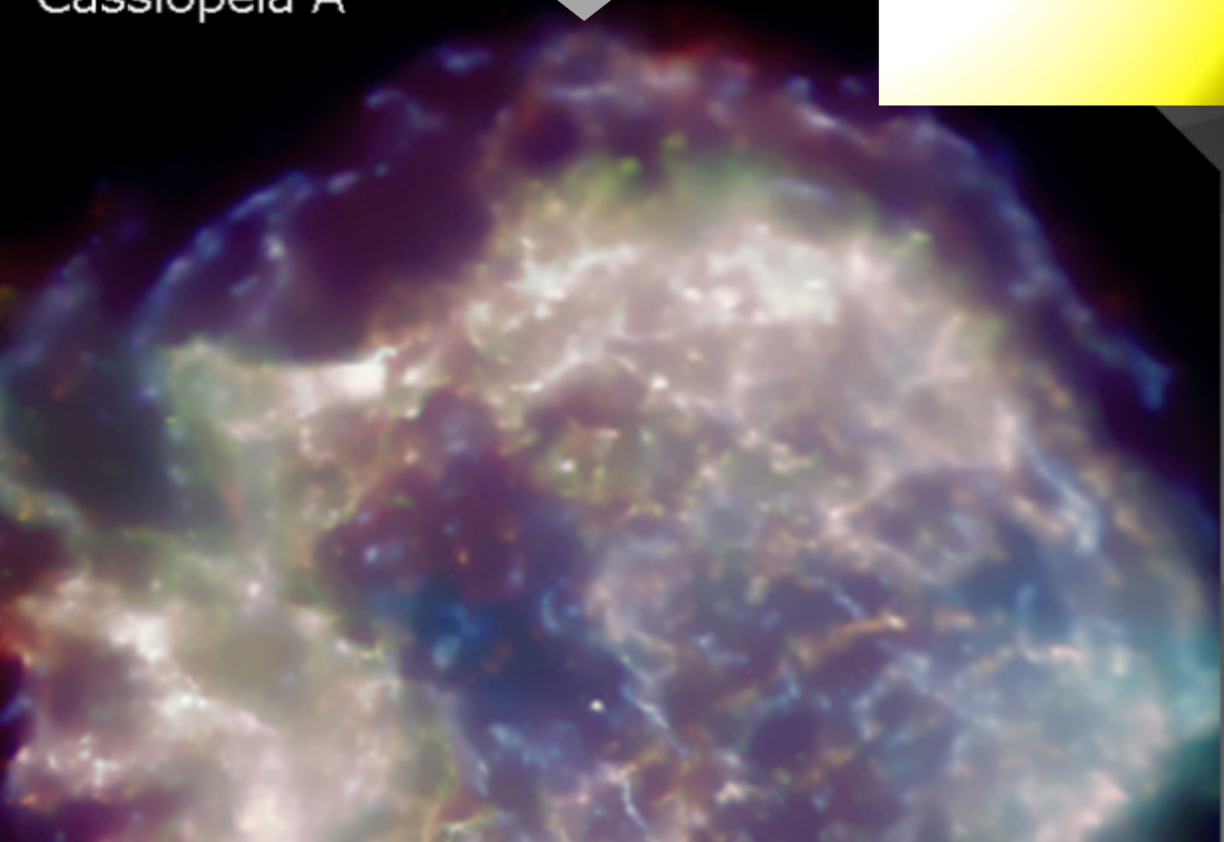
Fly's Eye 1991
300,000,000 TeV

accommodating energy and luminosity are challenging

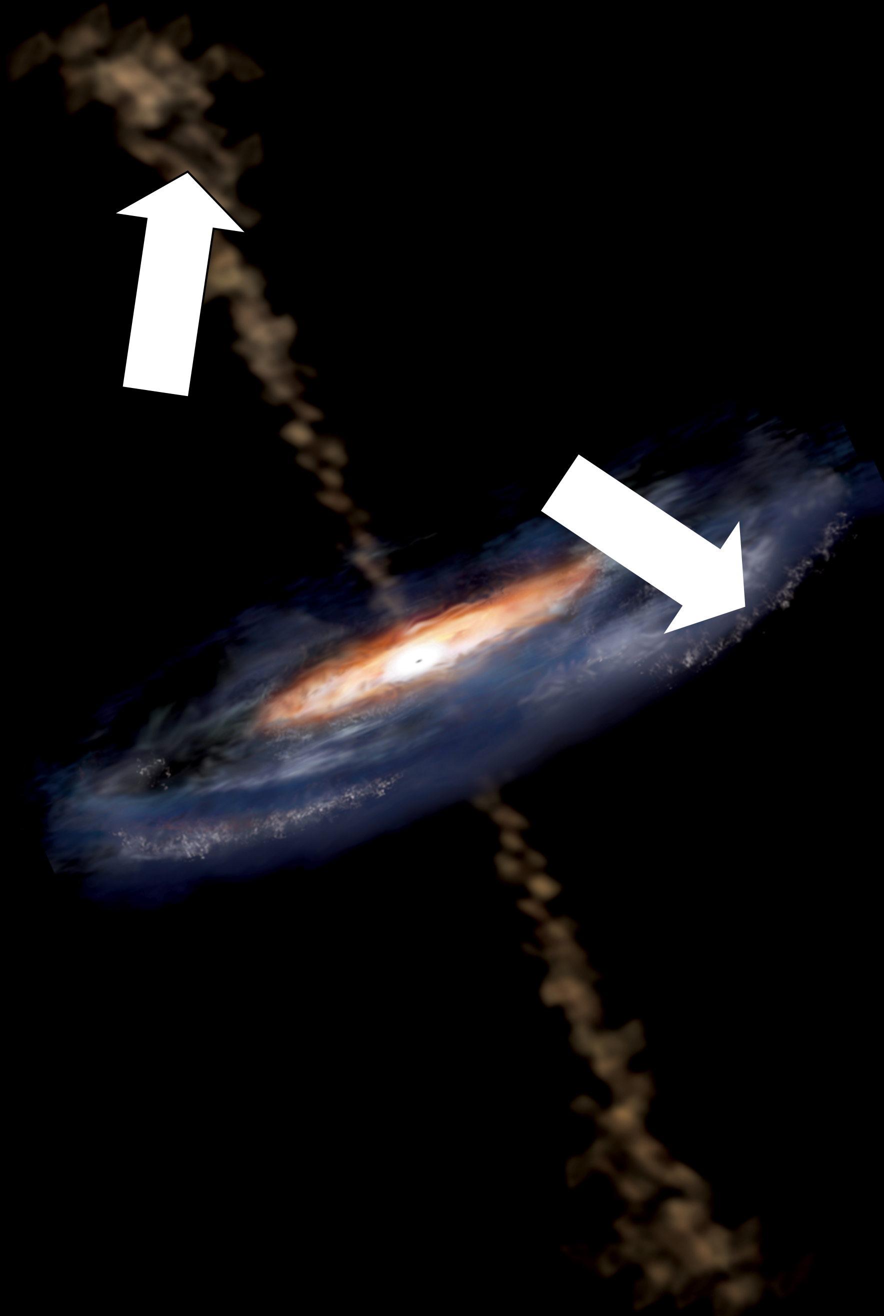
supernova remnants



Chandra
Cassiopeia A

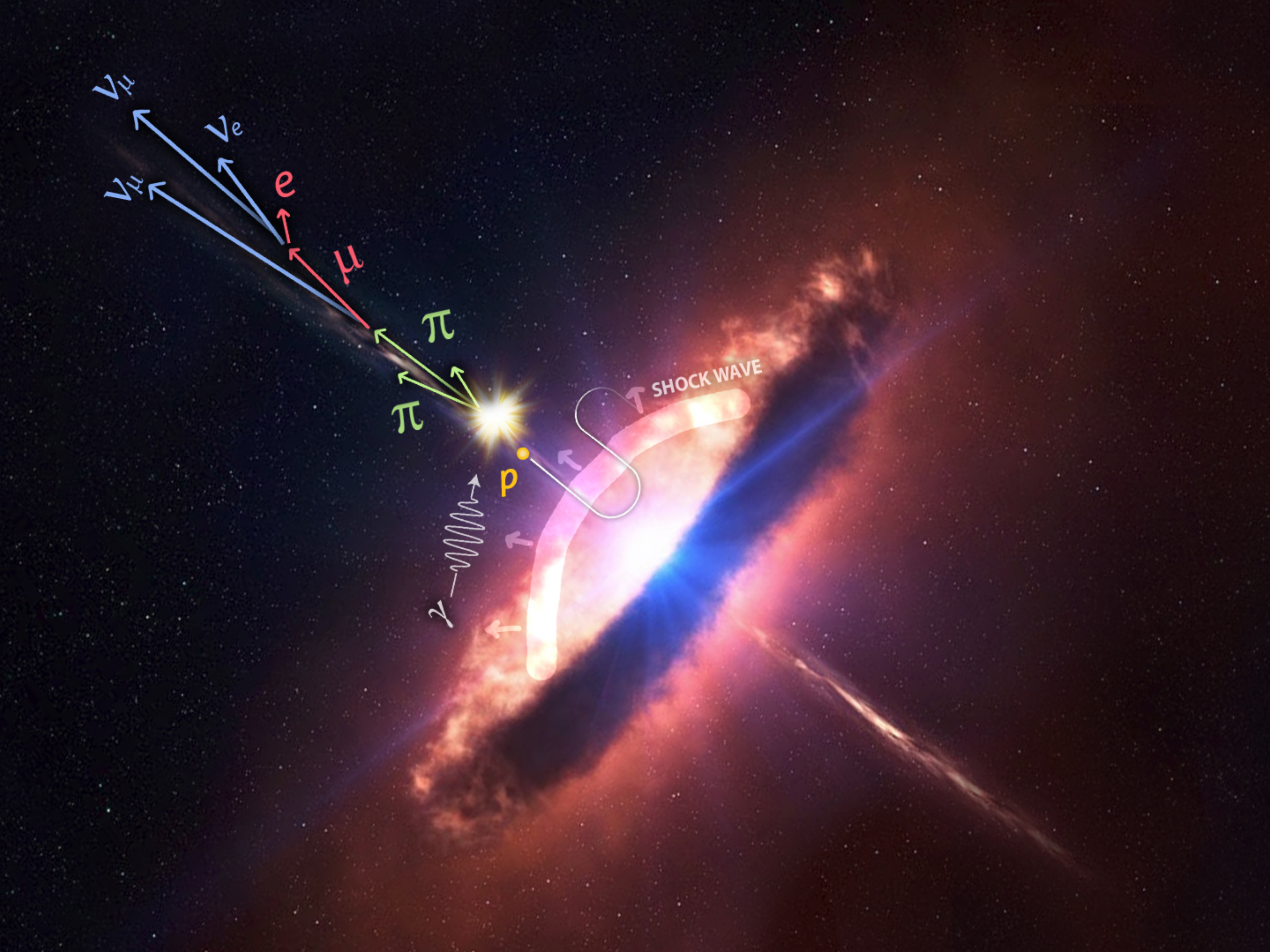


gamma ray bursts



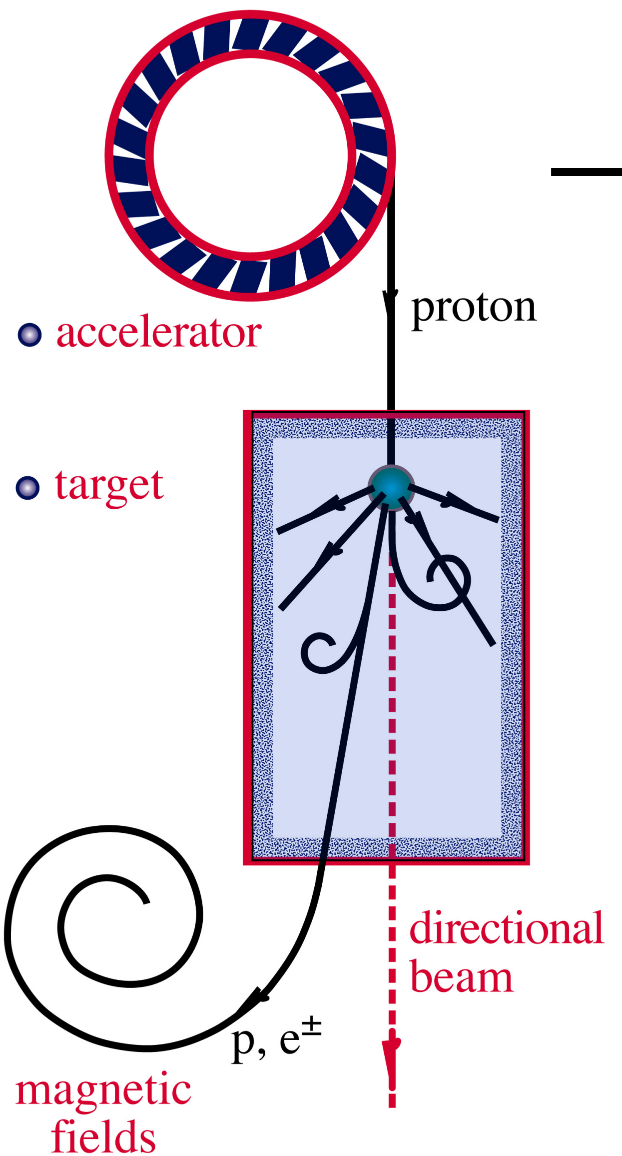
active galaxy

particle flows near
supermassive
black hole



νμ
νe
e
νμ
μ
π
π
p
SHOCK WAVE
γ

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

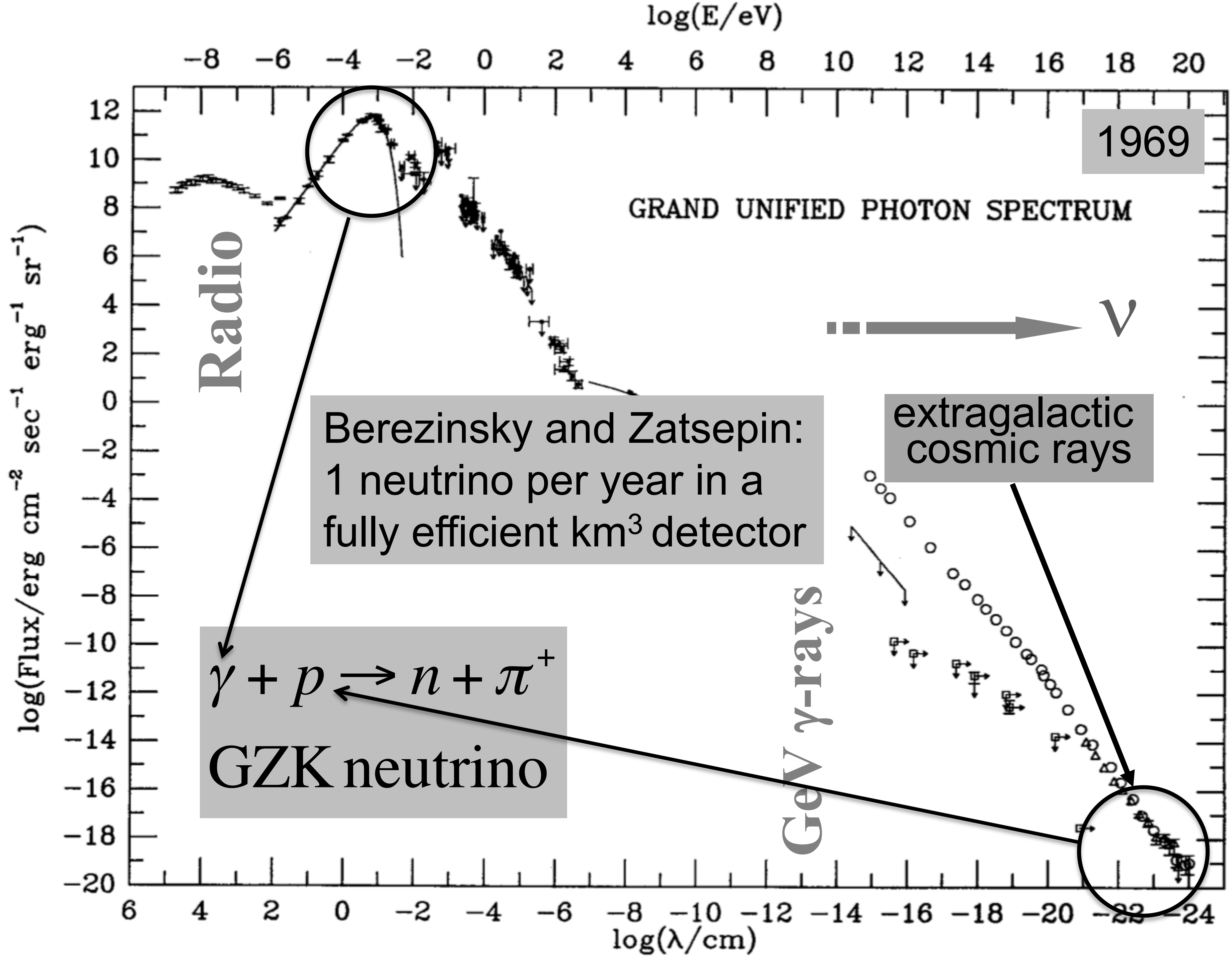
radiation and dust

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

~ cosmic ray + neutrino

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

~ cosmic ray + gamma



log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
Berezinsky and Zatsepin:
1 neutrino per year in a
fully efficient km^3 detector
extragalactic
cosmic rays
GeV γ-rays
$\gamma + p \rightleftarrows n + \pi^+$
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 $\boxed{\text{(}10^{6}\text{ TeV) energy}}$ appear

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

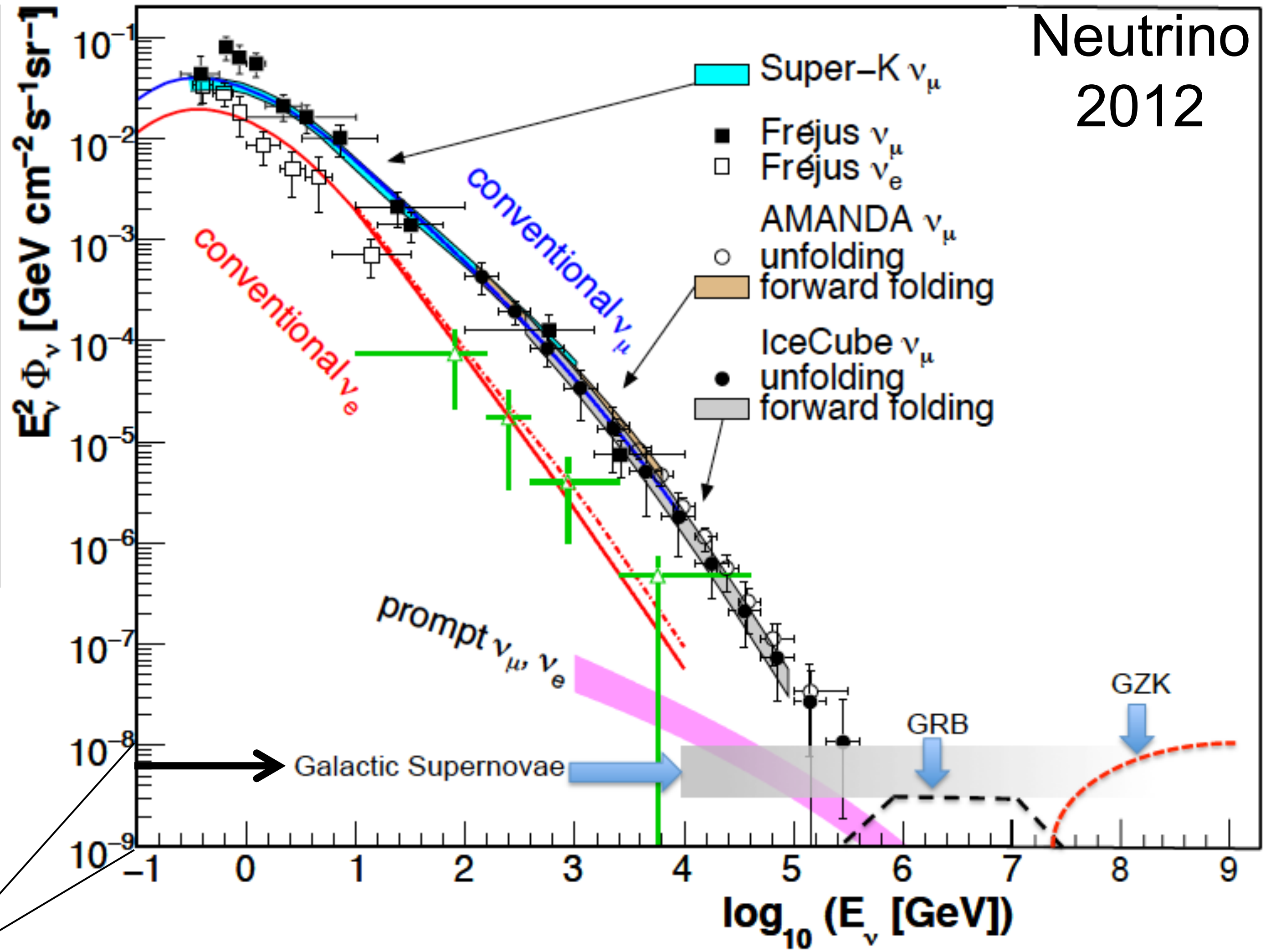
1 event per $\boxed{\text{cubic kilometer}}$ per year

...but it points at its source!

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

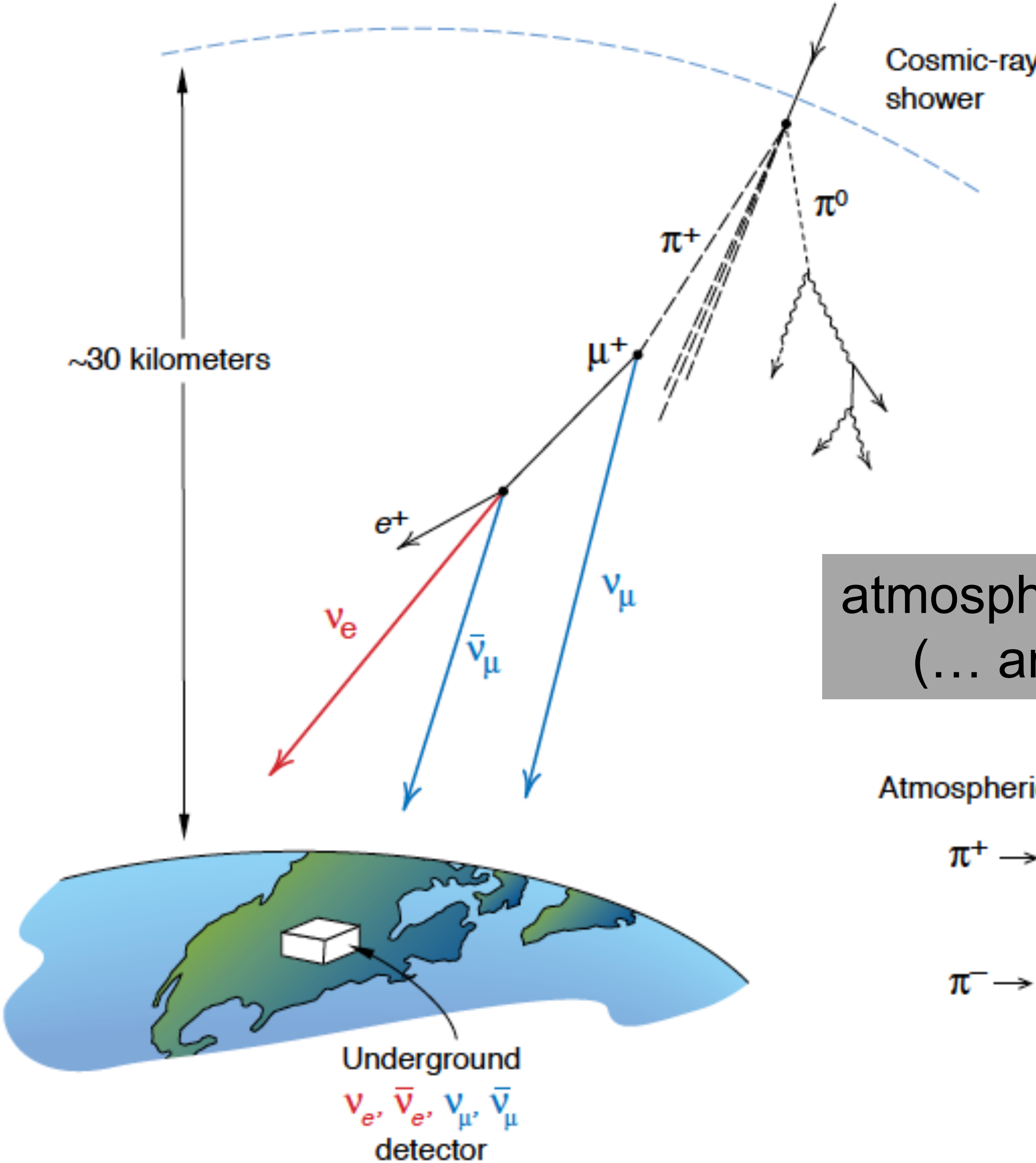


10-10^2 events per year for a fully efficient km^3 detector

atmospheric cosmic

100 TeV

atmospheric neutrinos
(… and muons!)

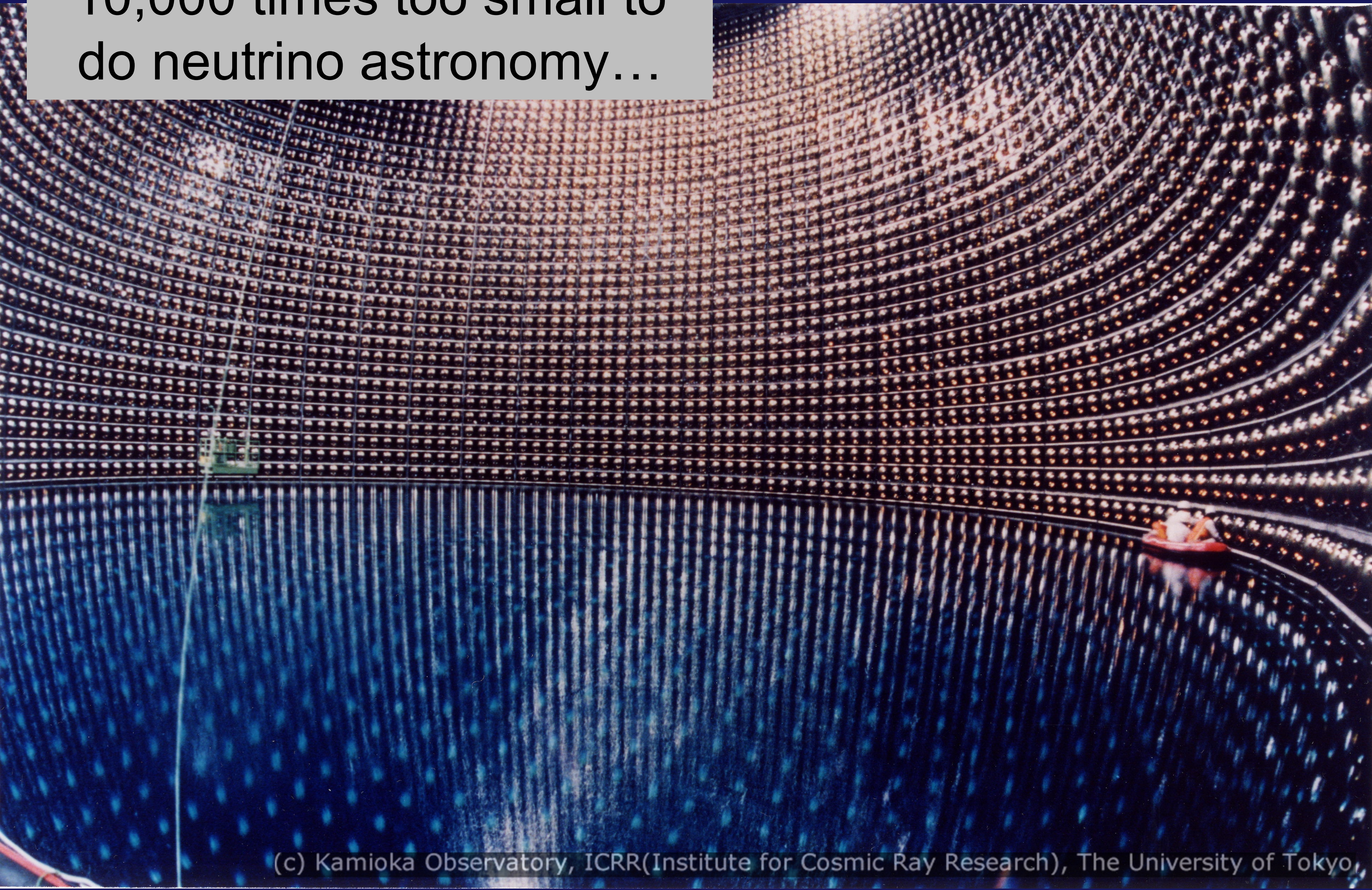


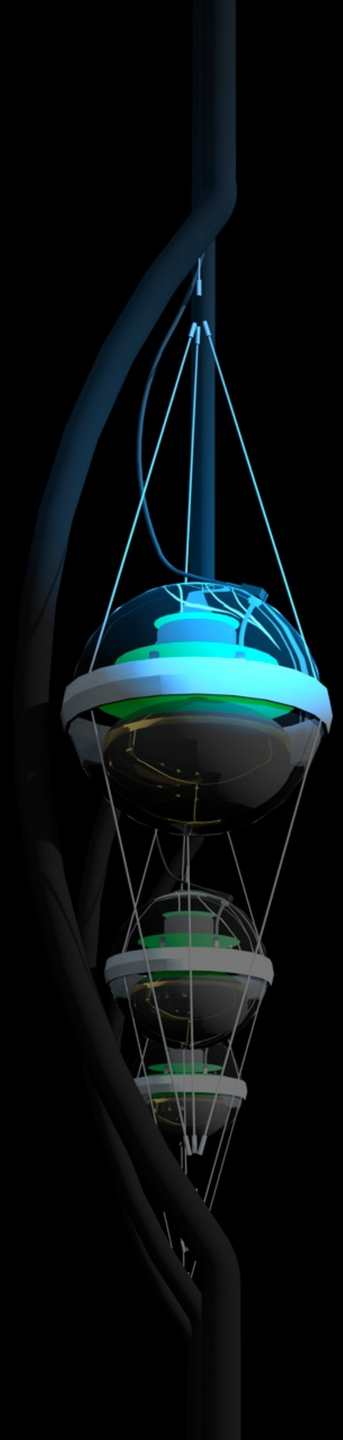
Atmospheric neutrino source

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

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

10,000 times too small to do neutrino astronomy…





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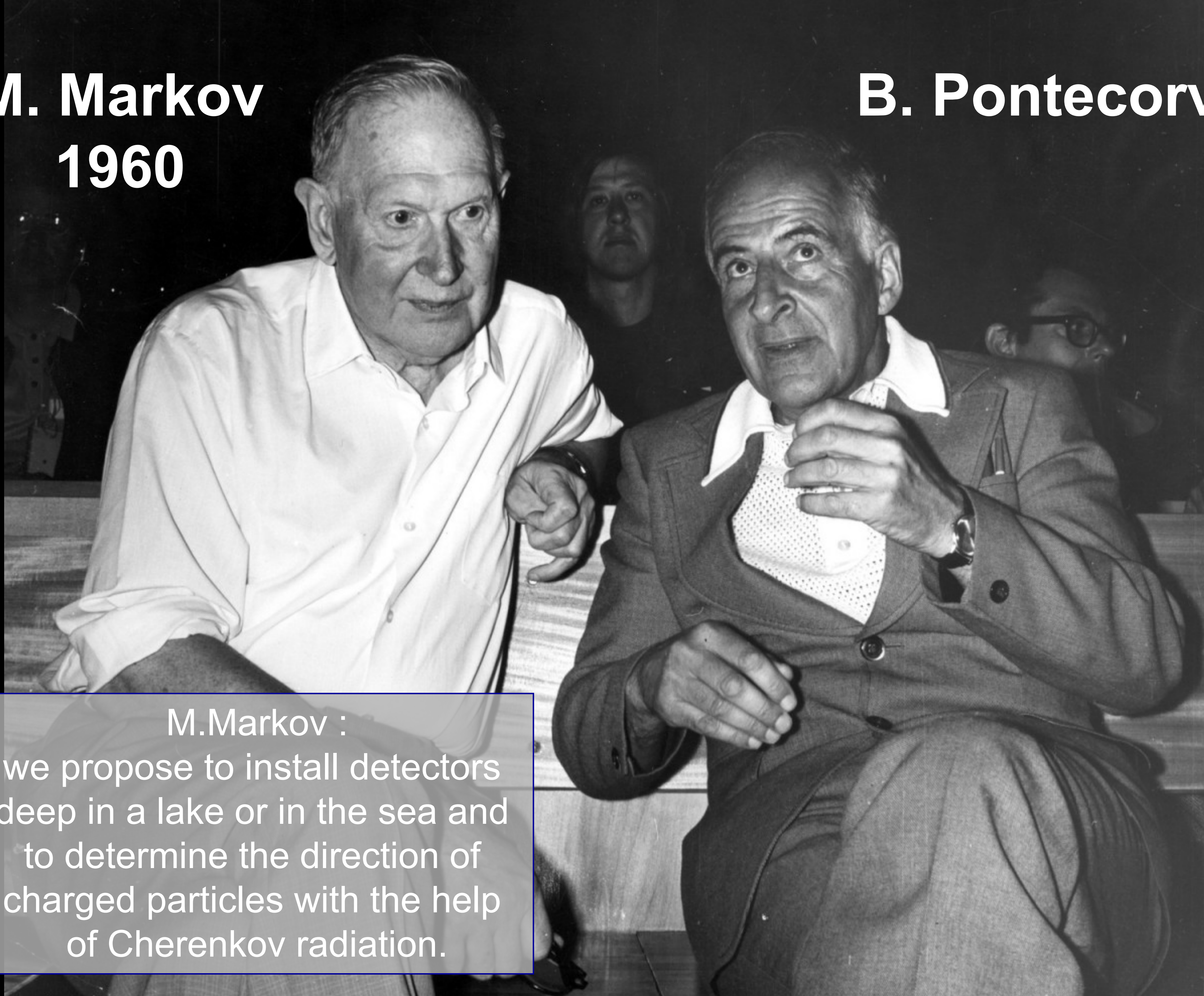
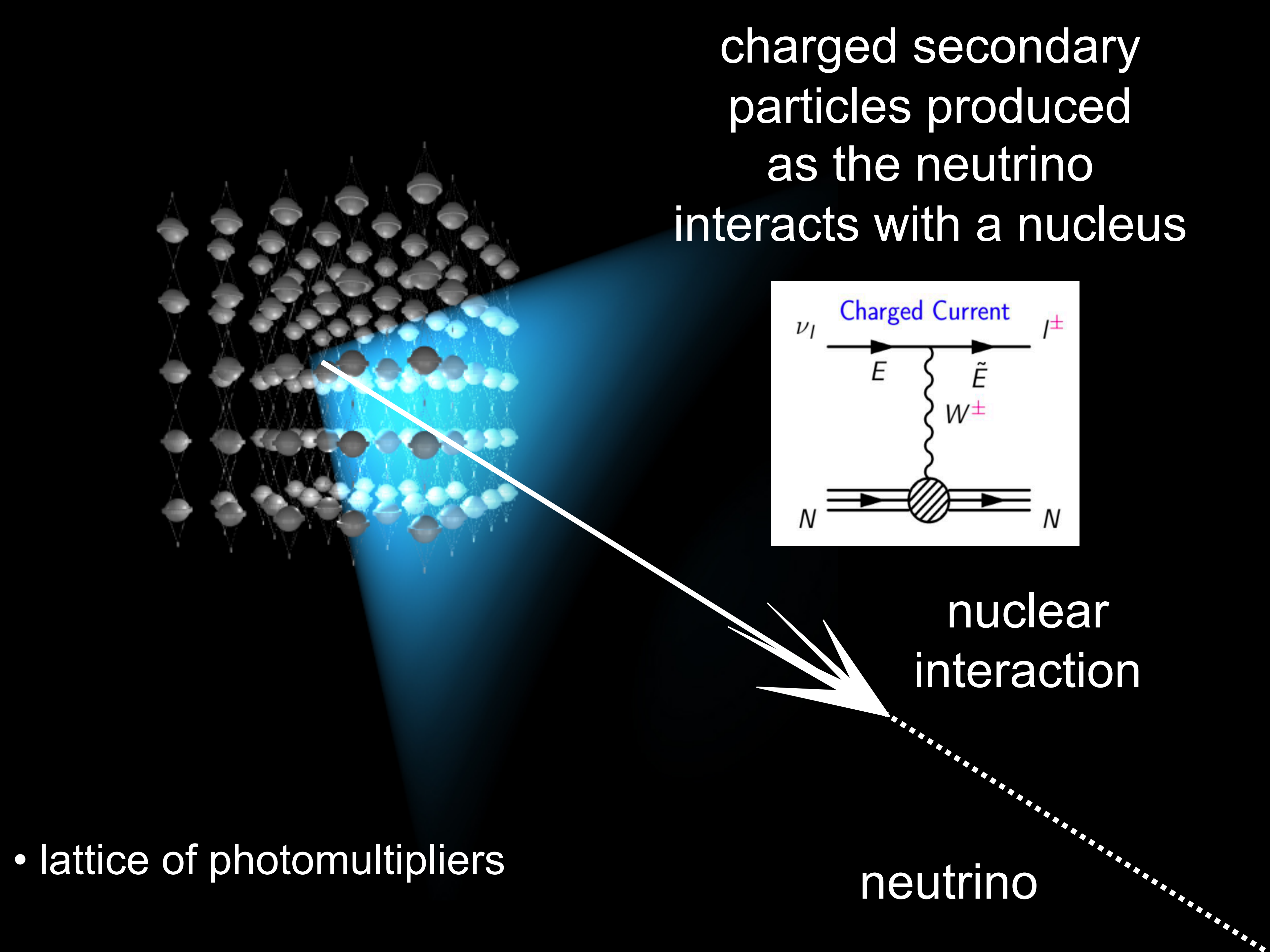
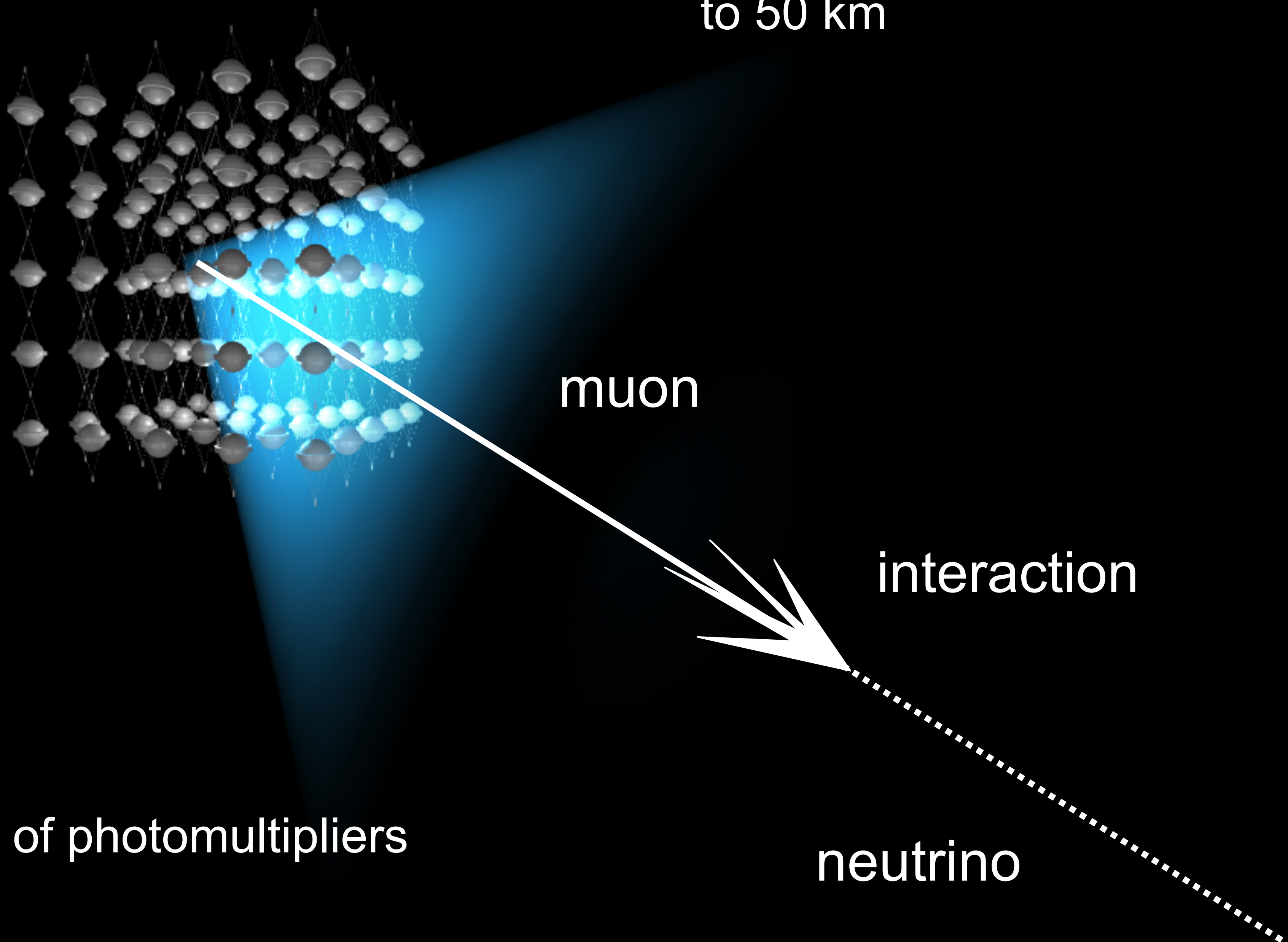
IceCube.wisc.edu


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



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

- speed of light in water < c
- muon range from 50 m to 50 km



- lattice of photomultipliers

standing on the shoulder of giants

1987: DUMAND test string

Lake Baikal experiment observes atmospheric neutrinos


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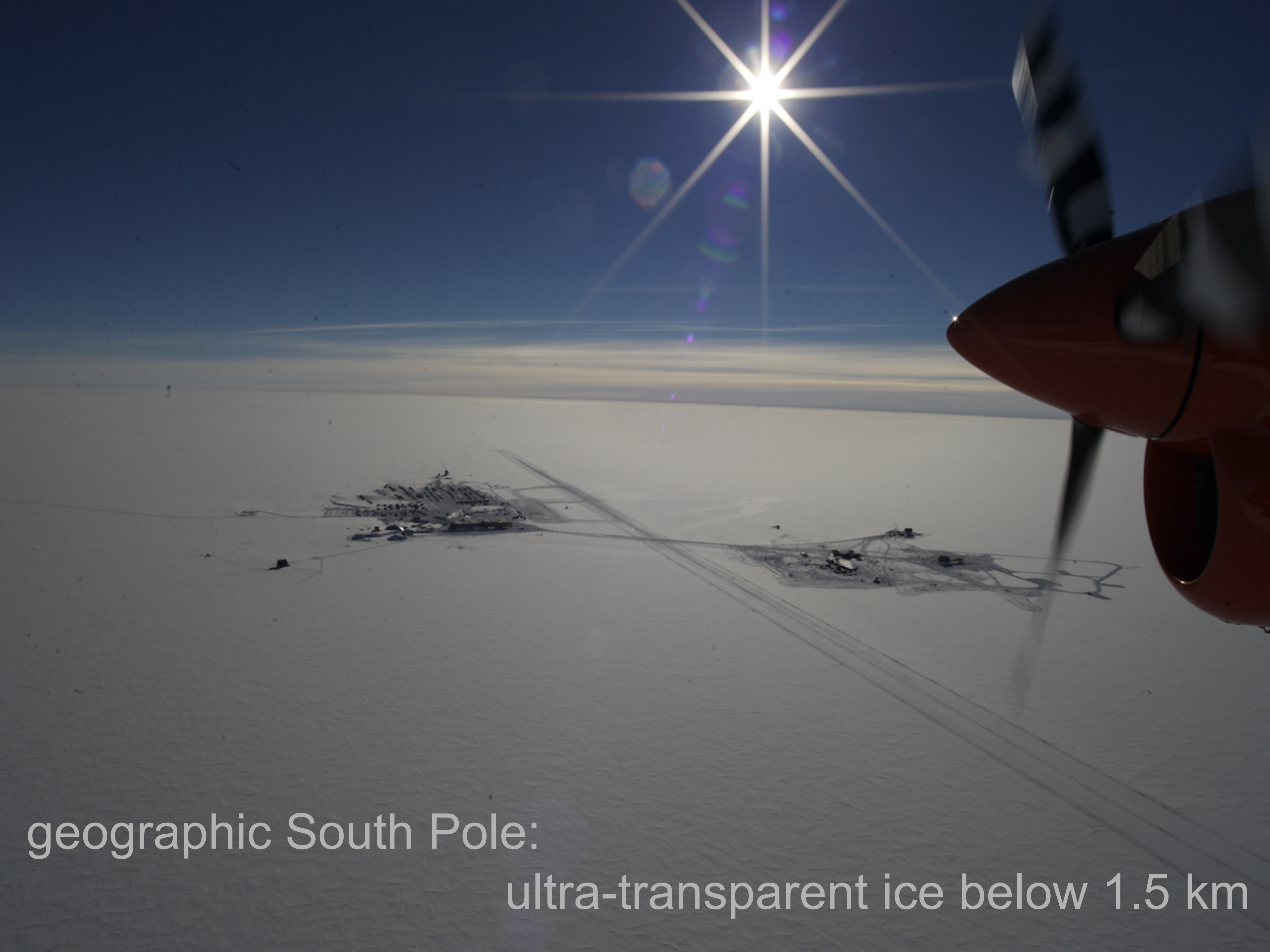
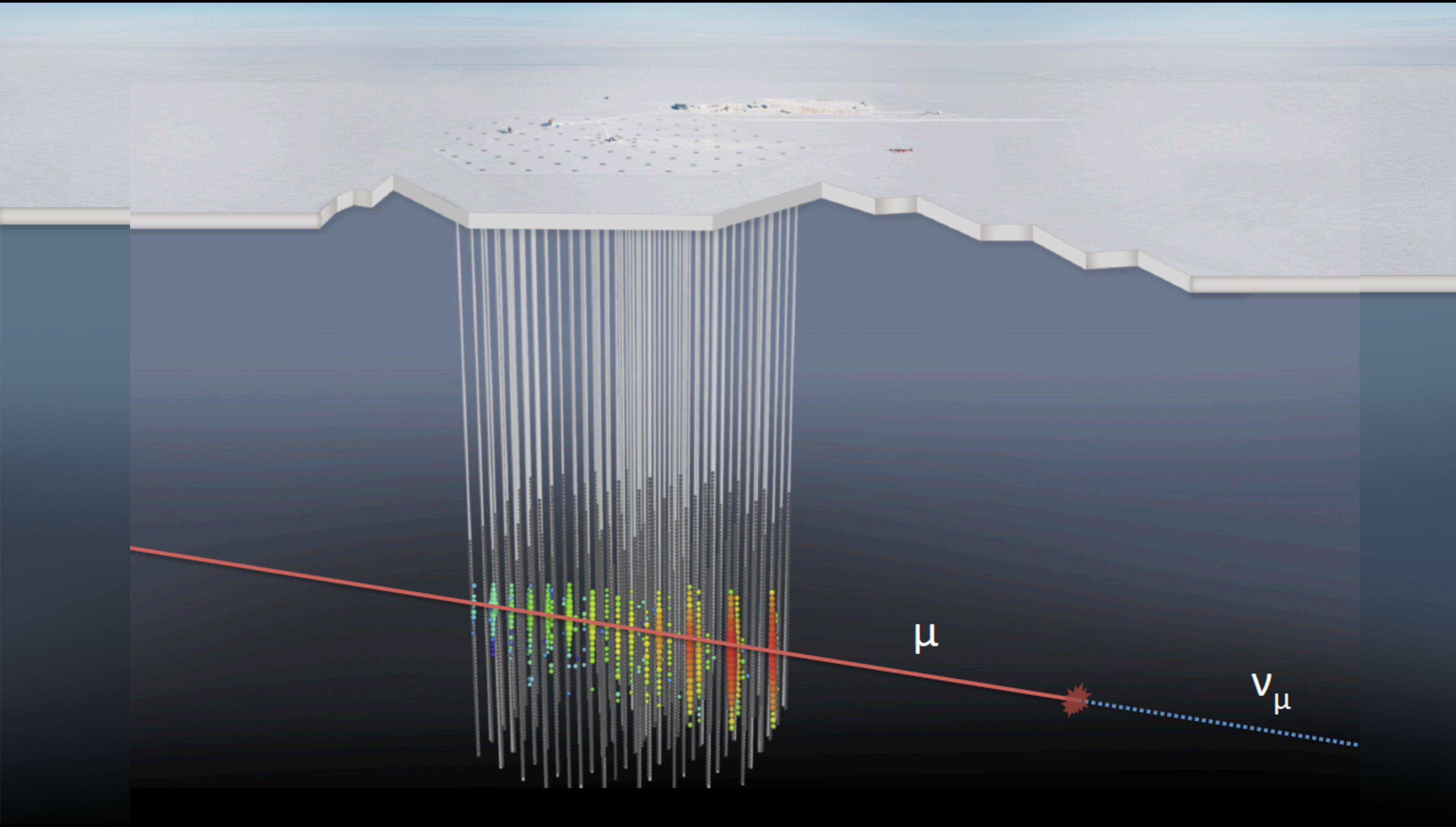

geographic South Pole:
ultra-transparent ice below 1.5 km

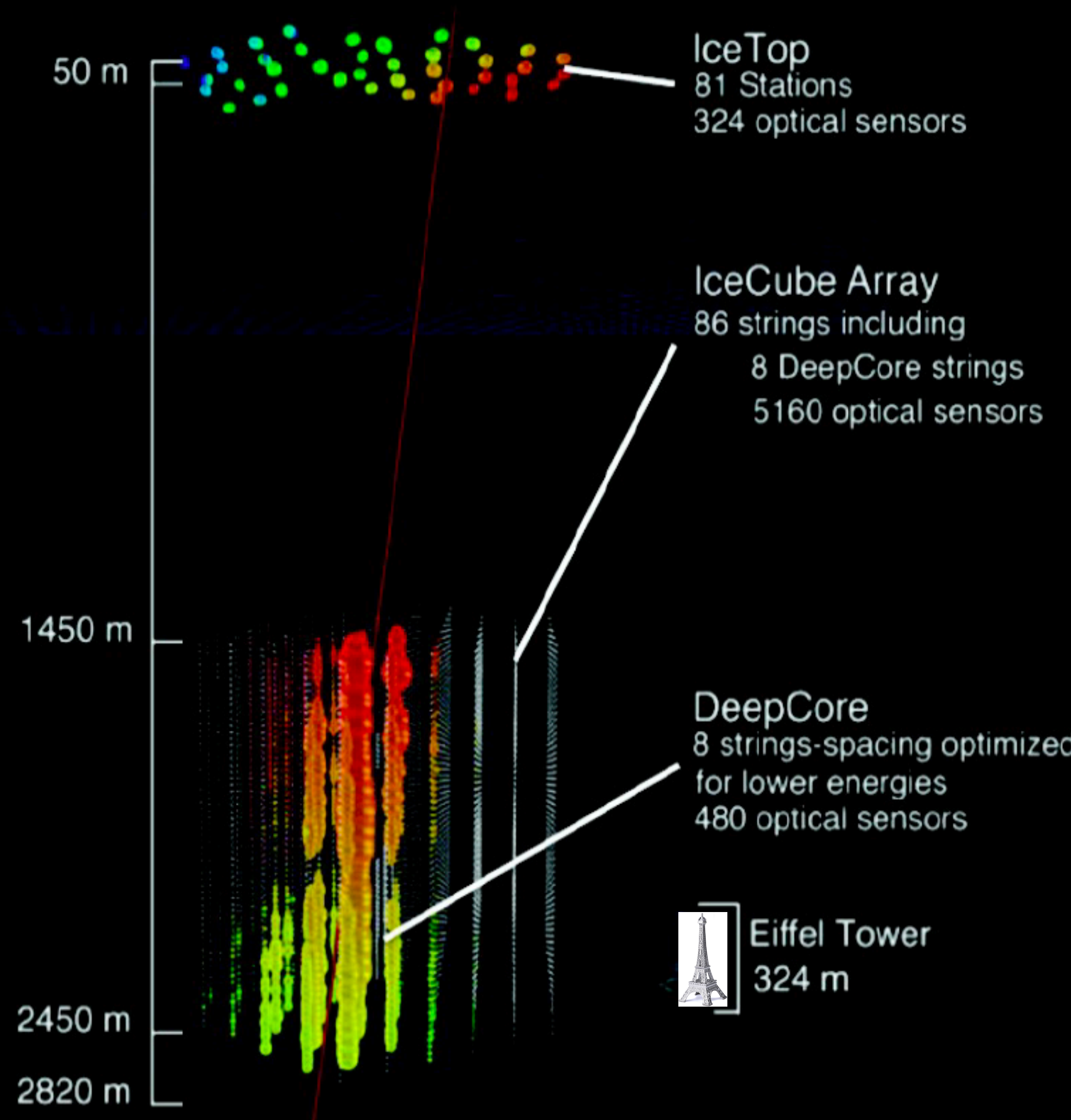
instrument 1 cubic kilometer of natural ice below 1.45 km



the IceCube Neutrino Observatory

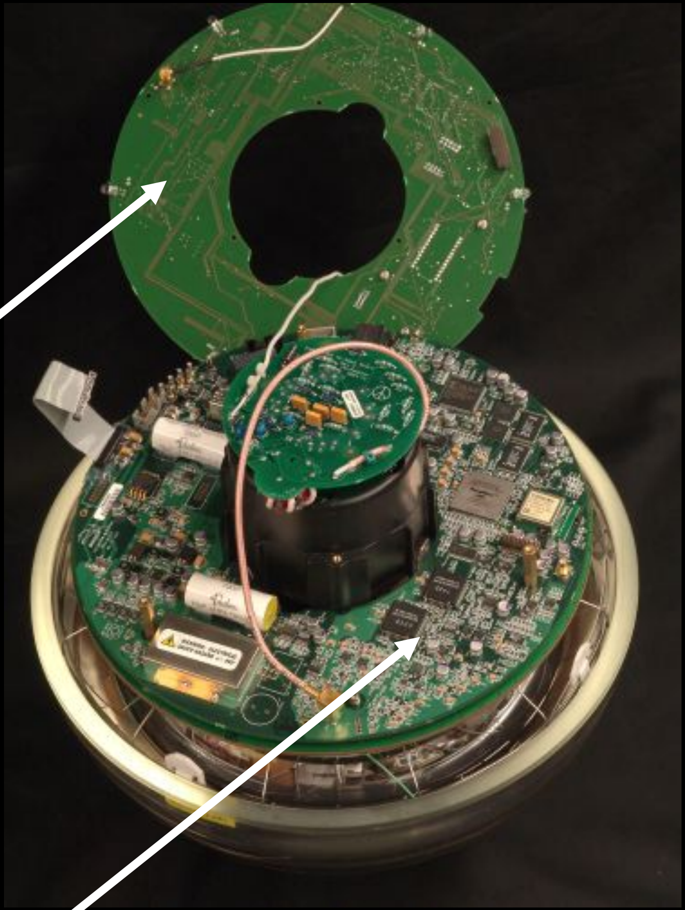
5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

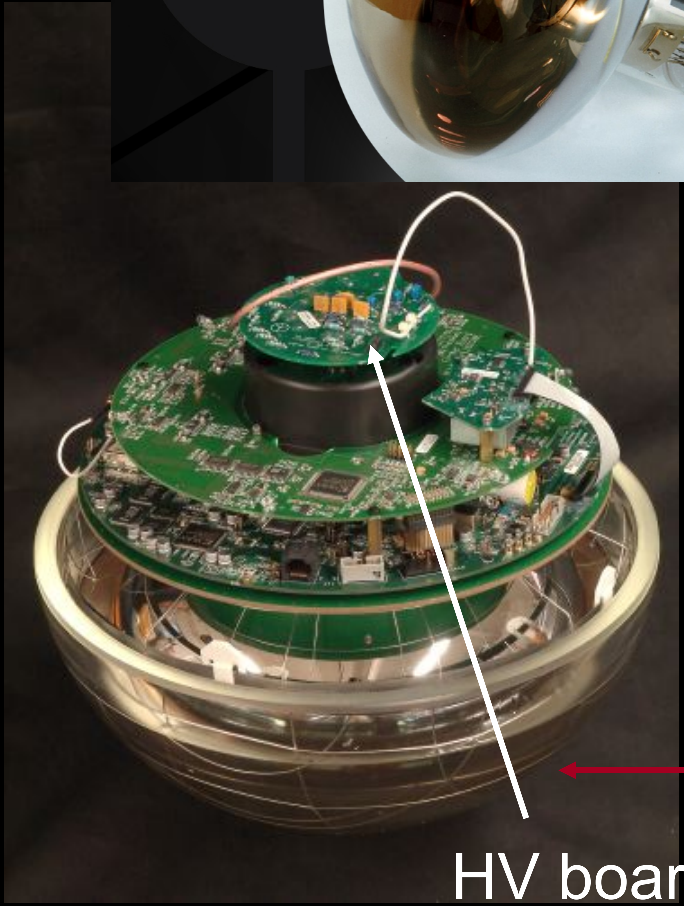
2 ns time resolution



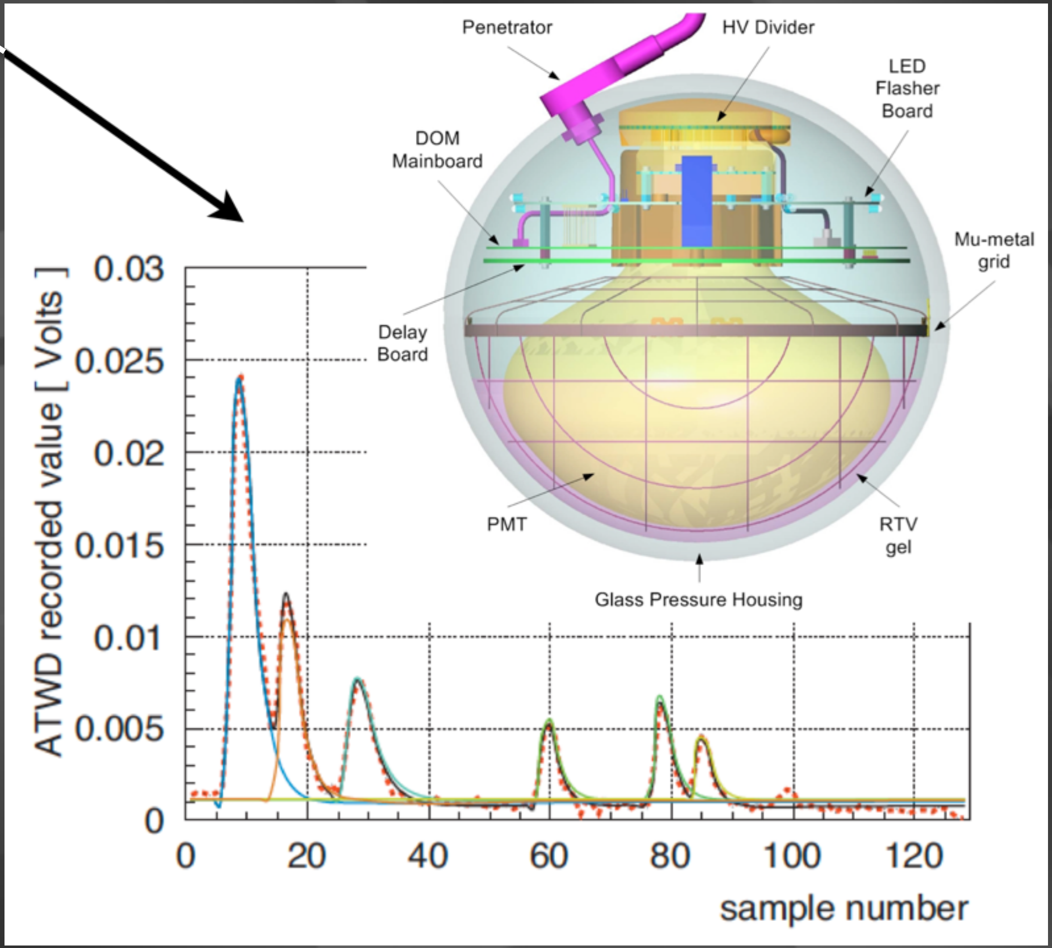
photomultiplier tube -10 inch

architecture of independent DOMs

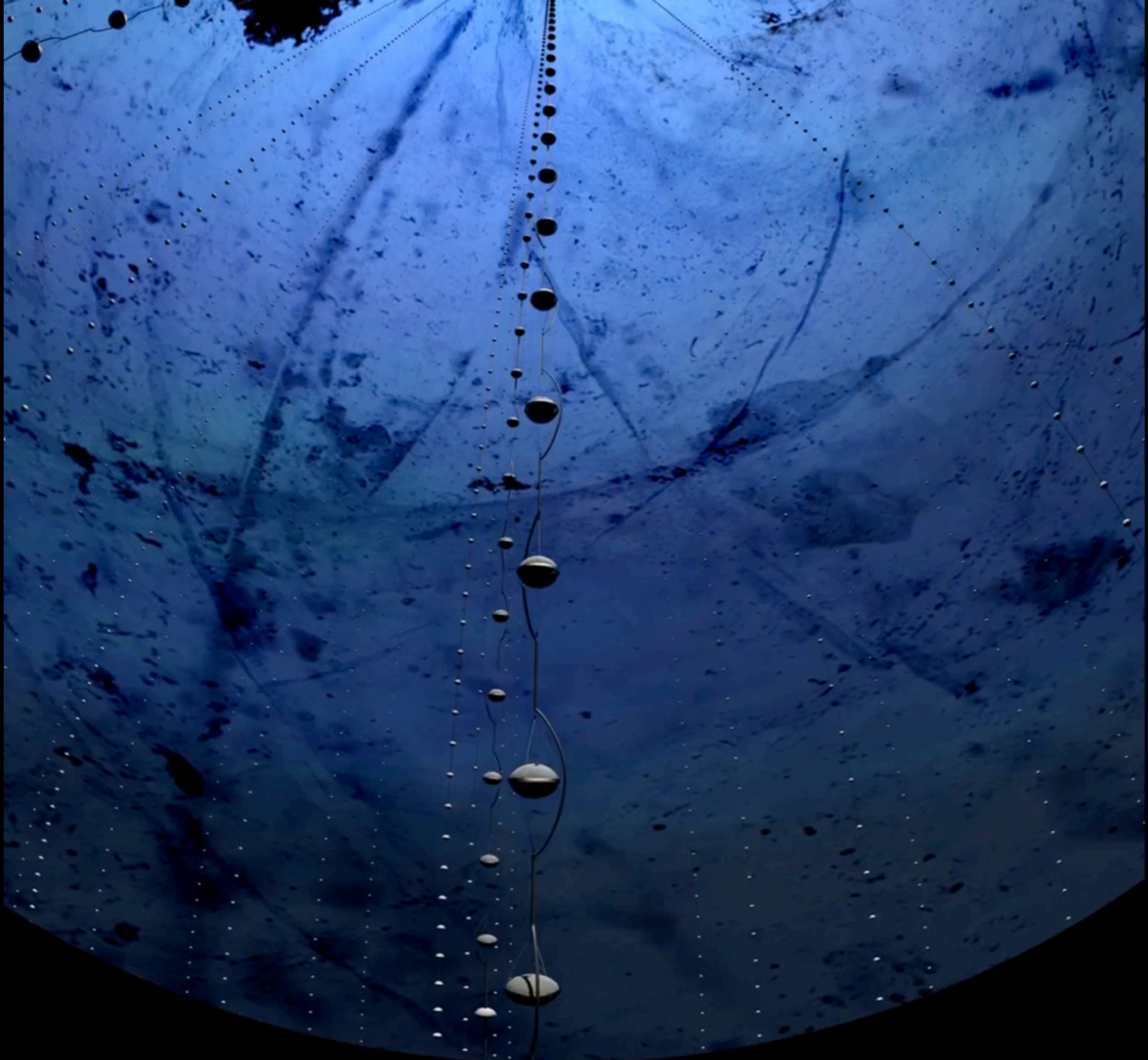


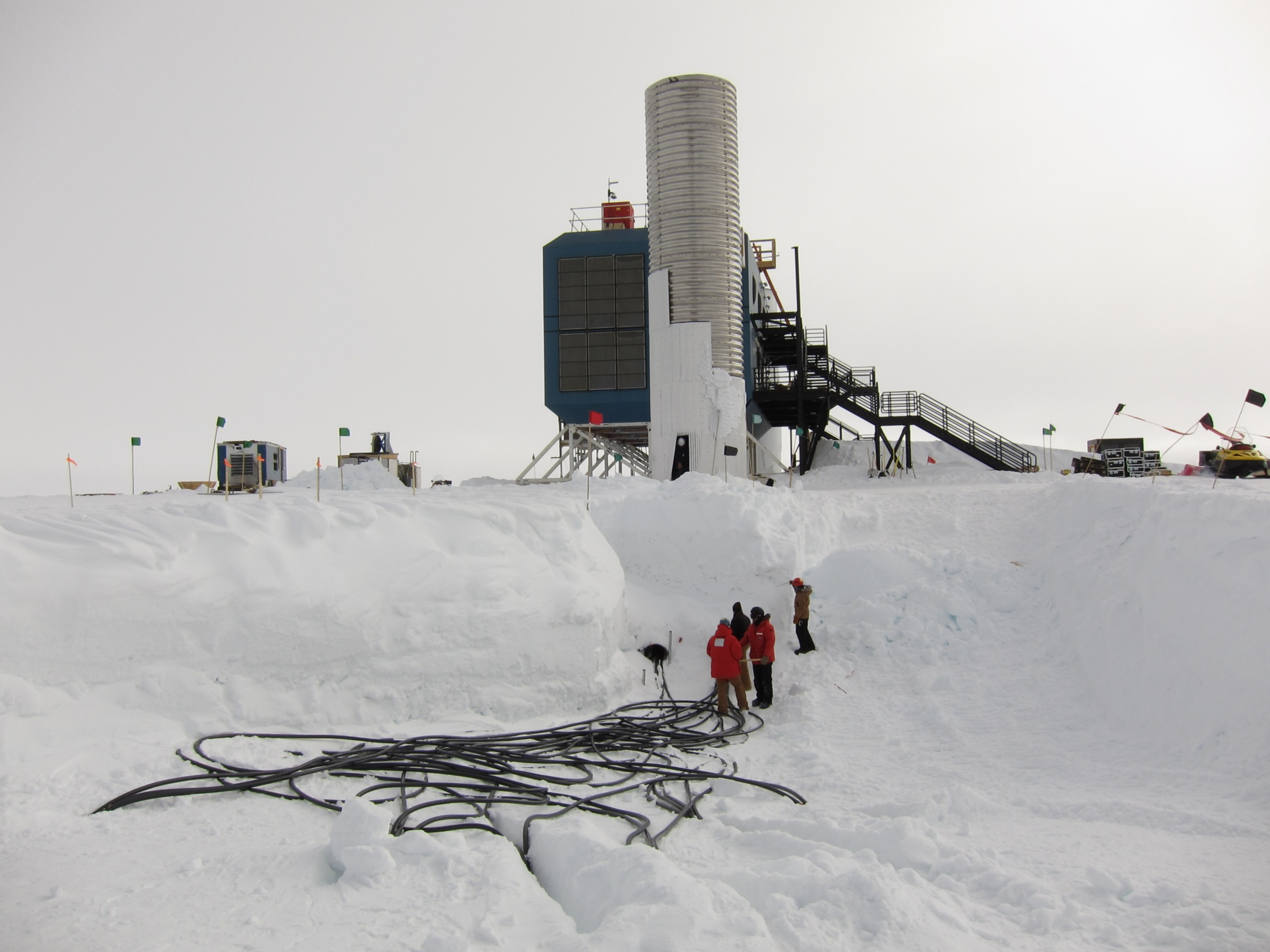


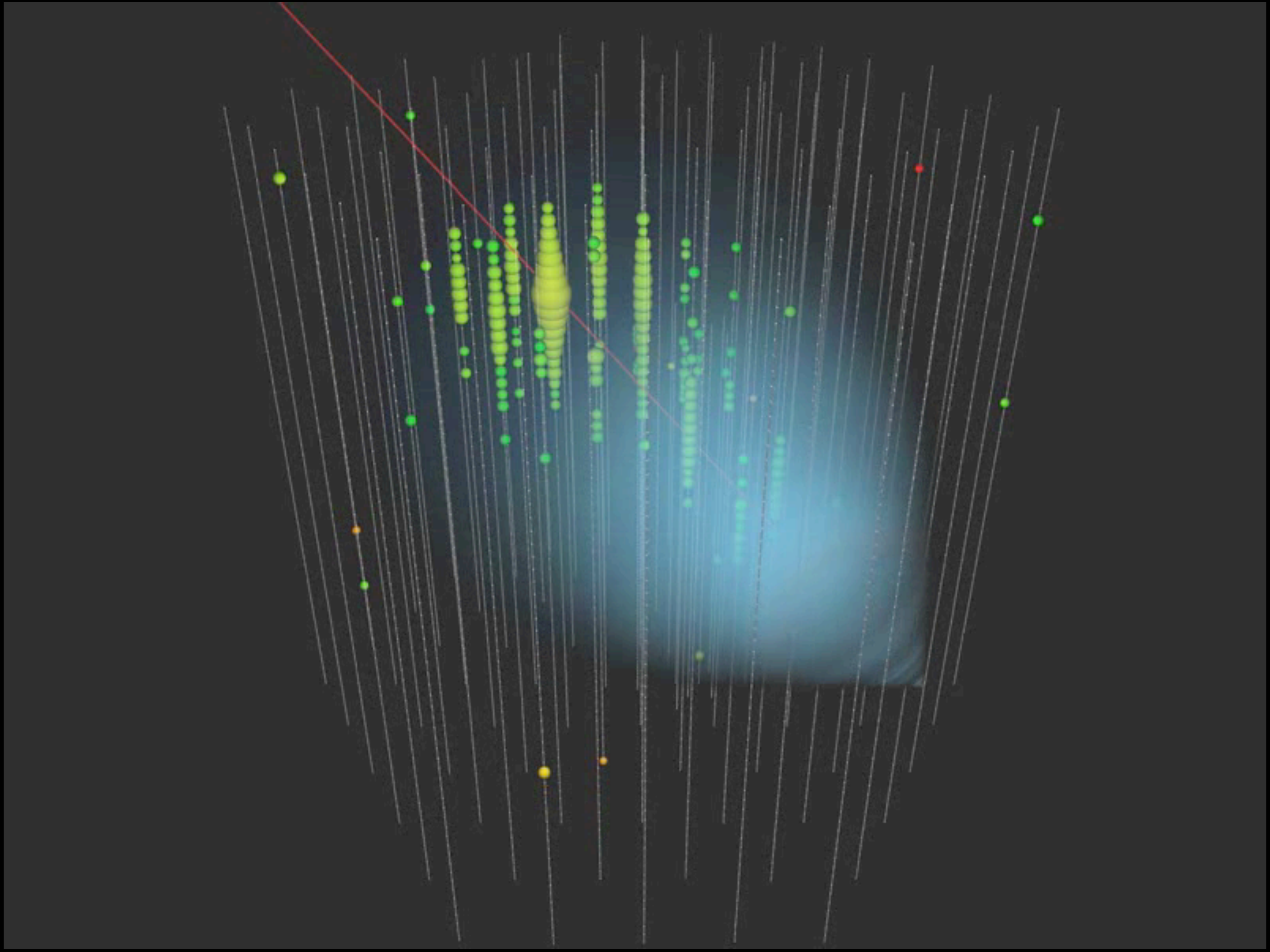
… each Digital Optical Module independently collects light signals like this, digitizes them,



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

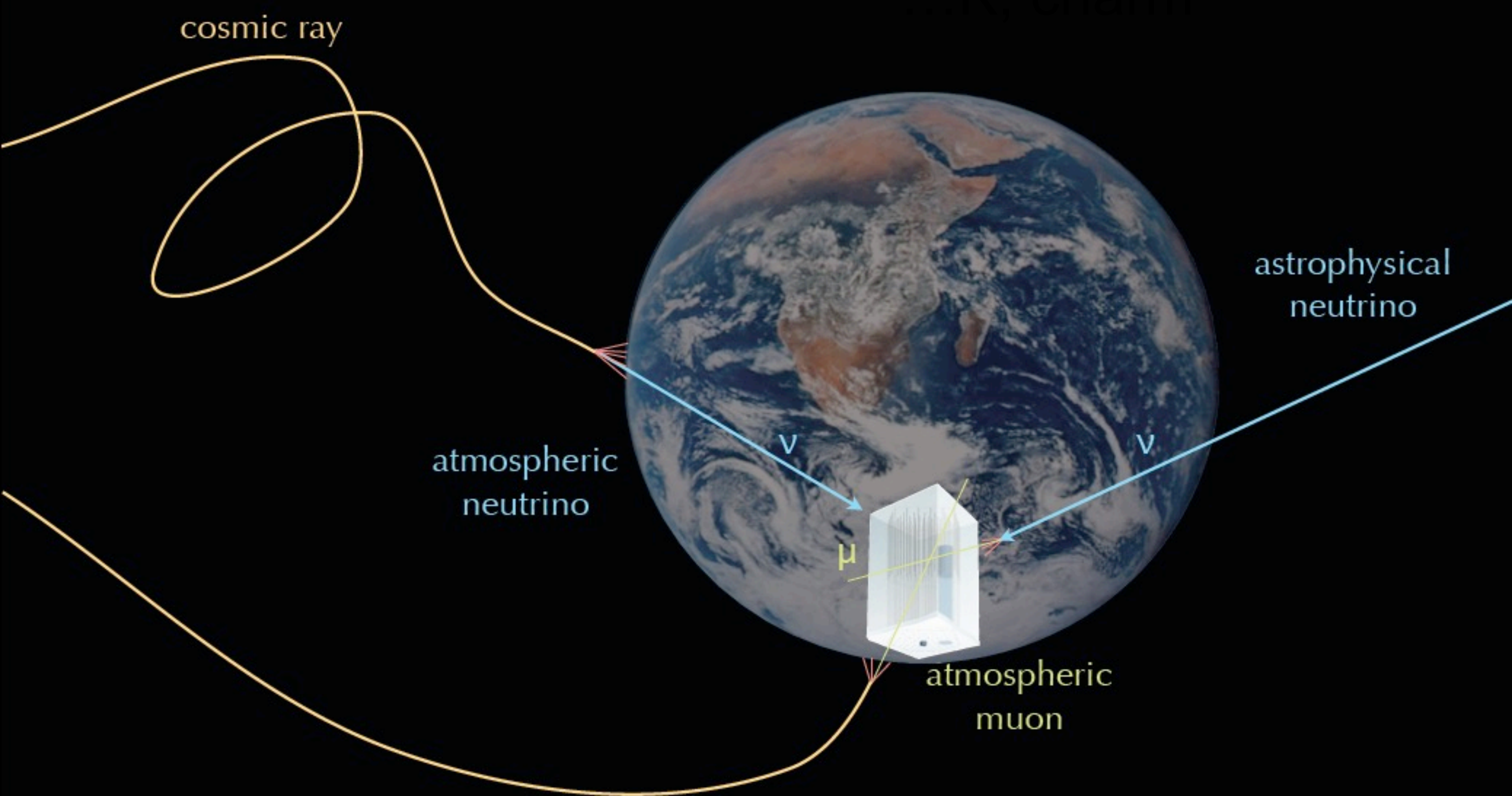


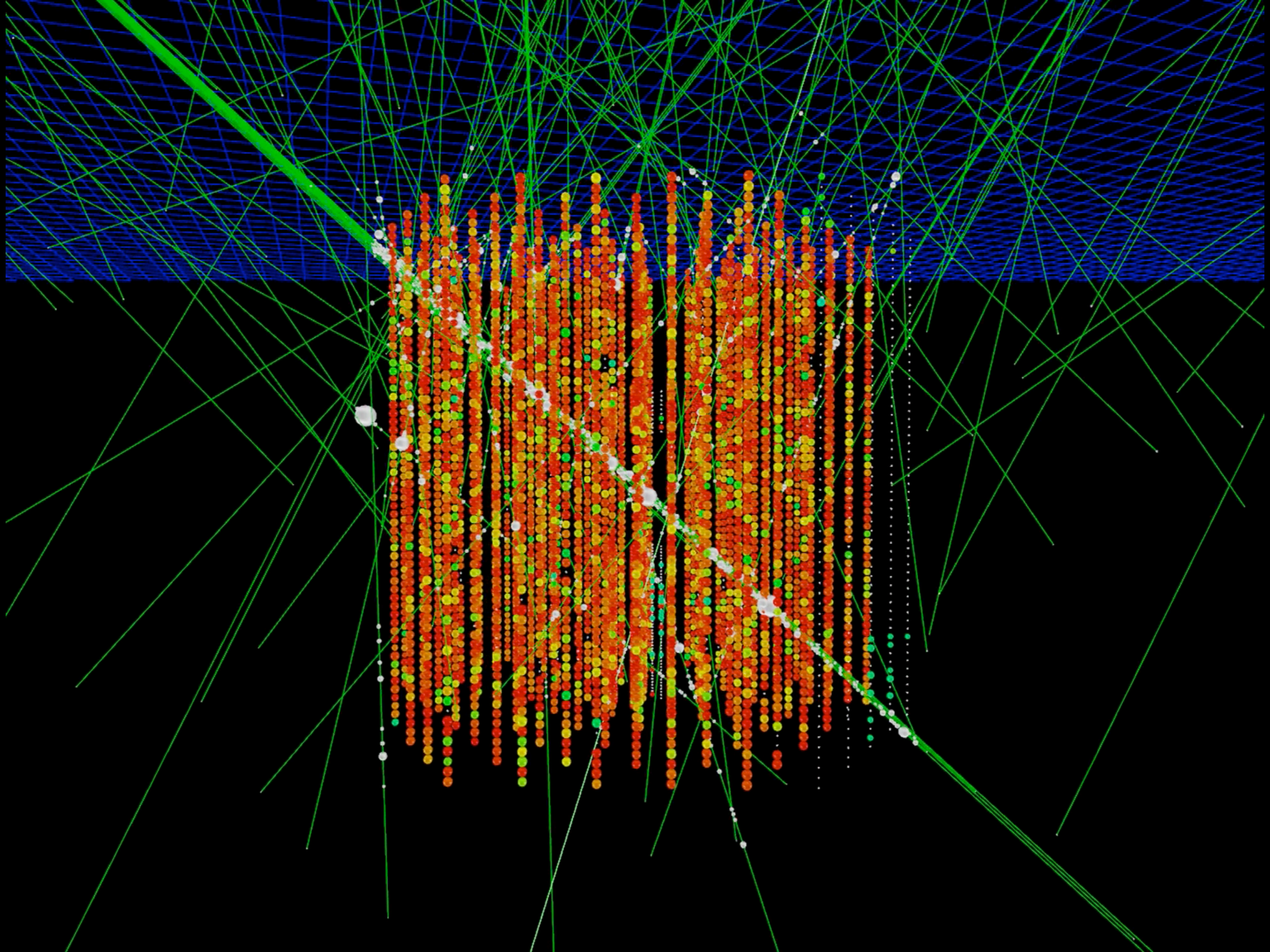




muon track: color is time; number of photons is energy

Signals and Backgrounds





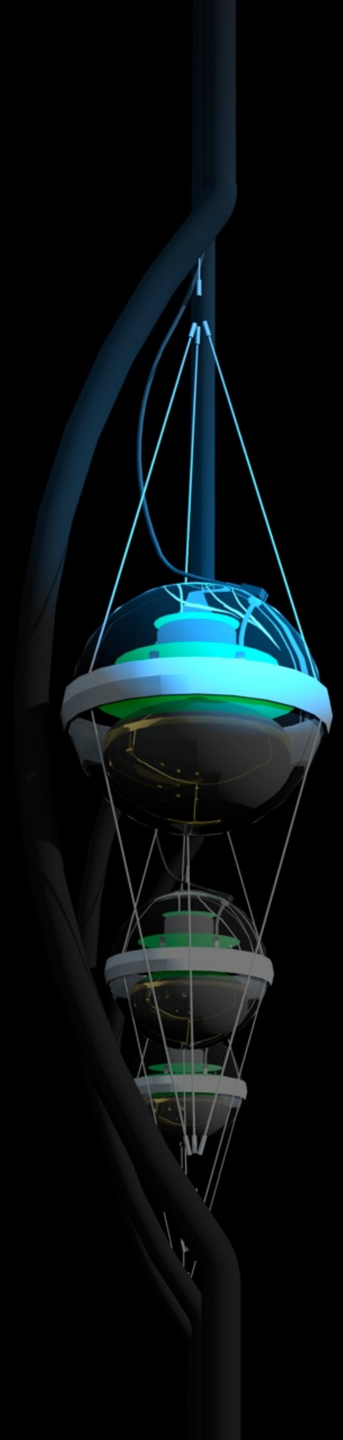
… you looked at 10msec of data !

muons detected per year:

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

* 3000 per second

** 1 every 6 minutes



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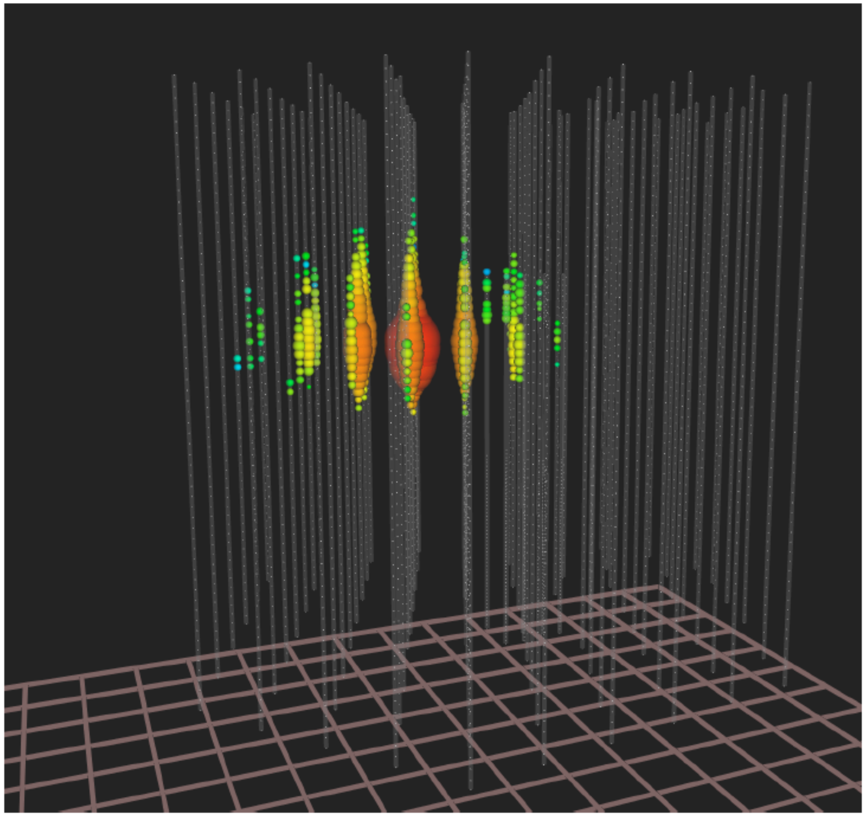
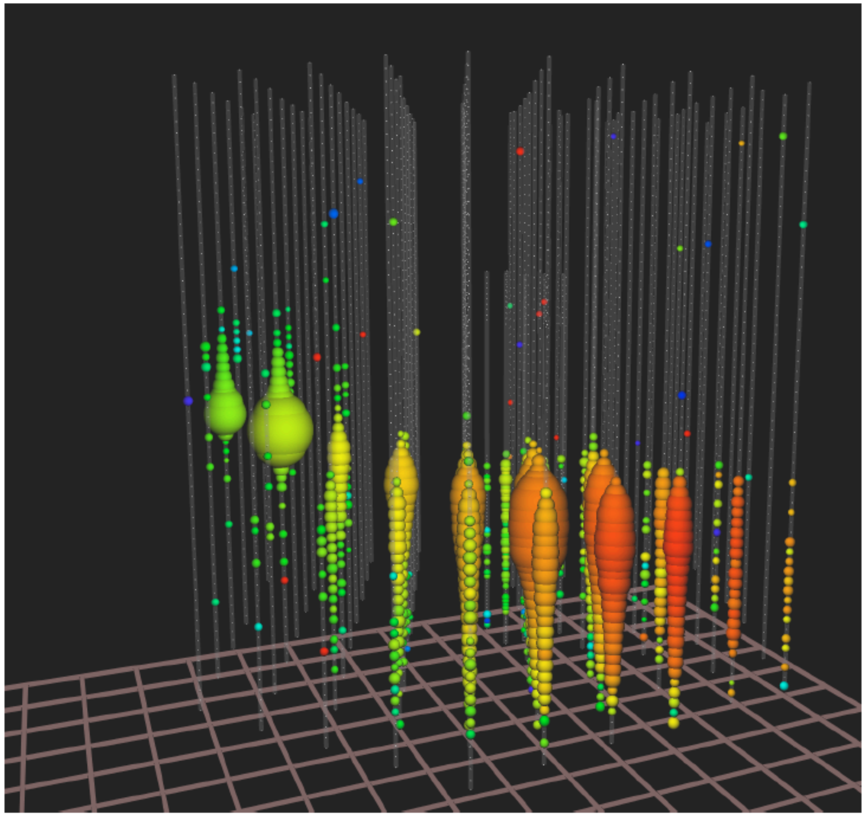
neutrinos interacting
inside the detector

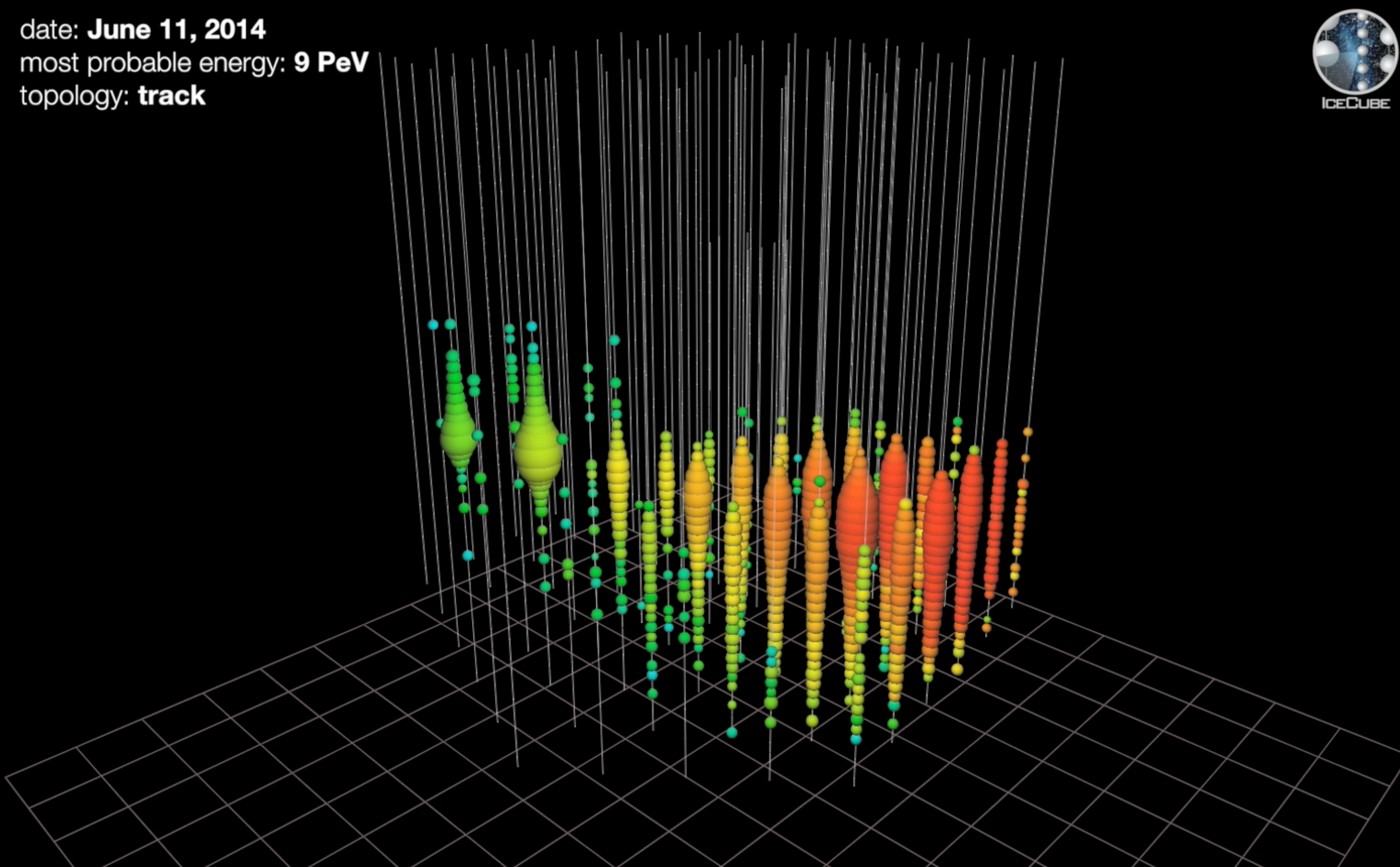
muon neutrinos
filtered by the Earth

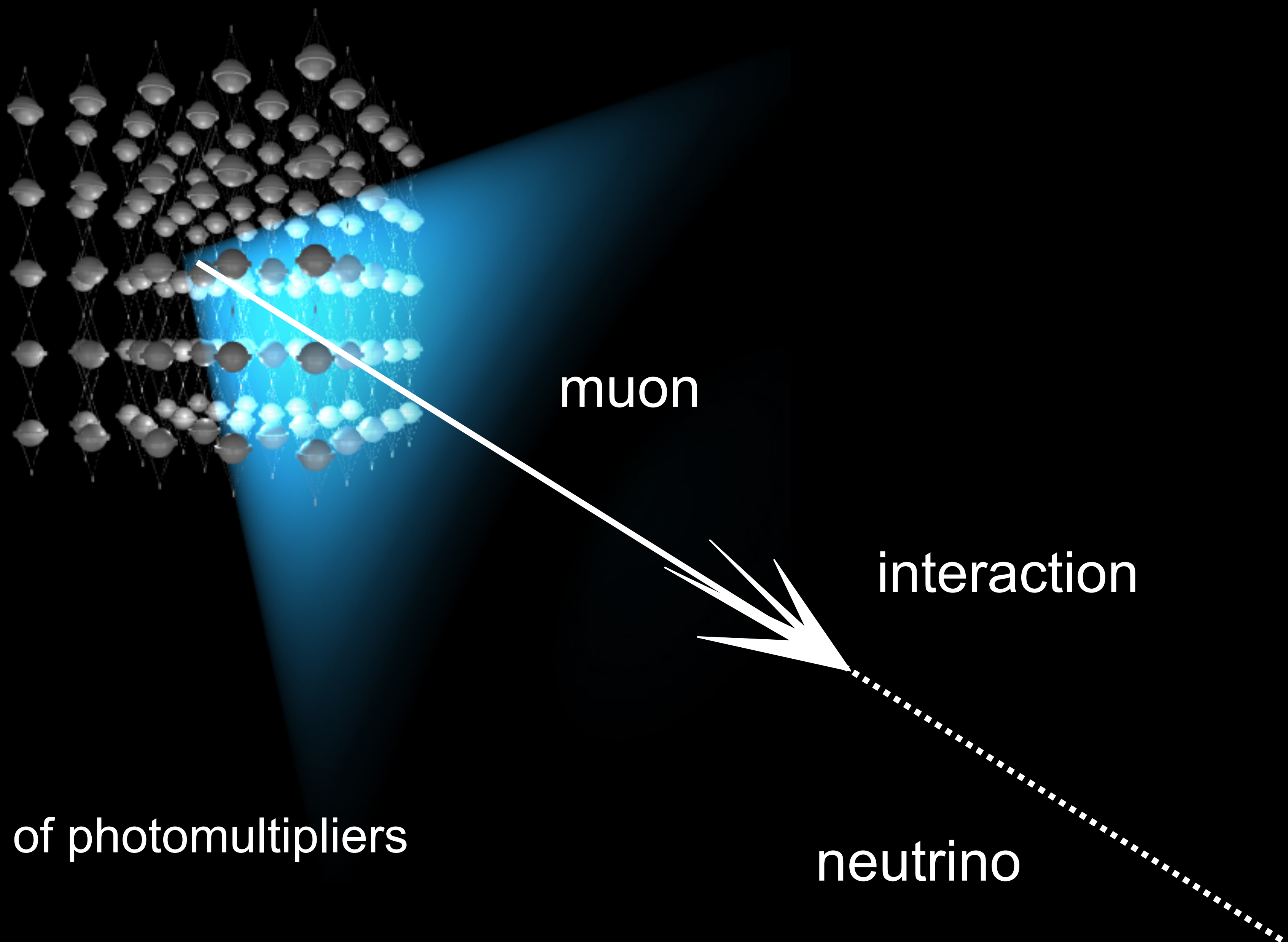




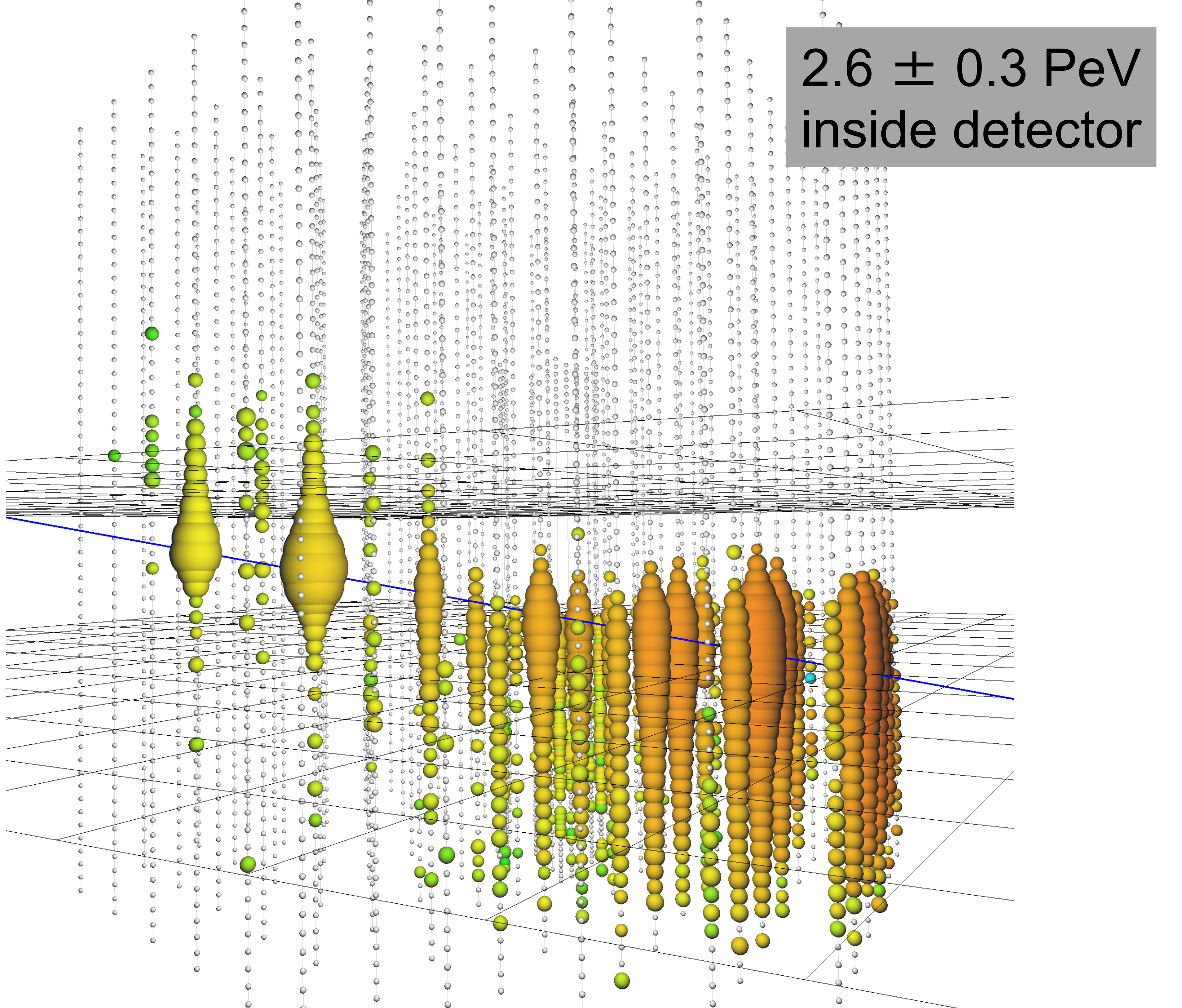
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)

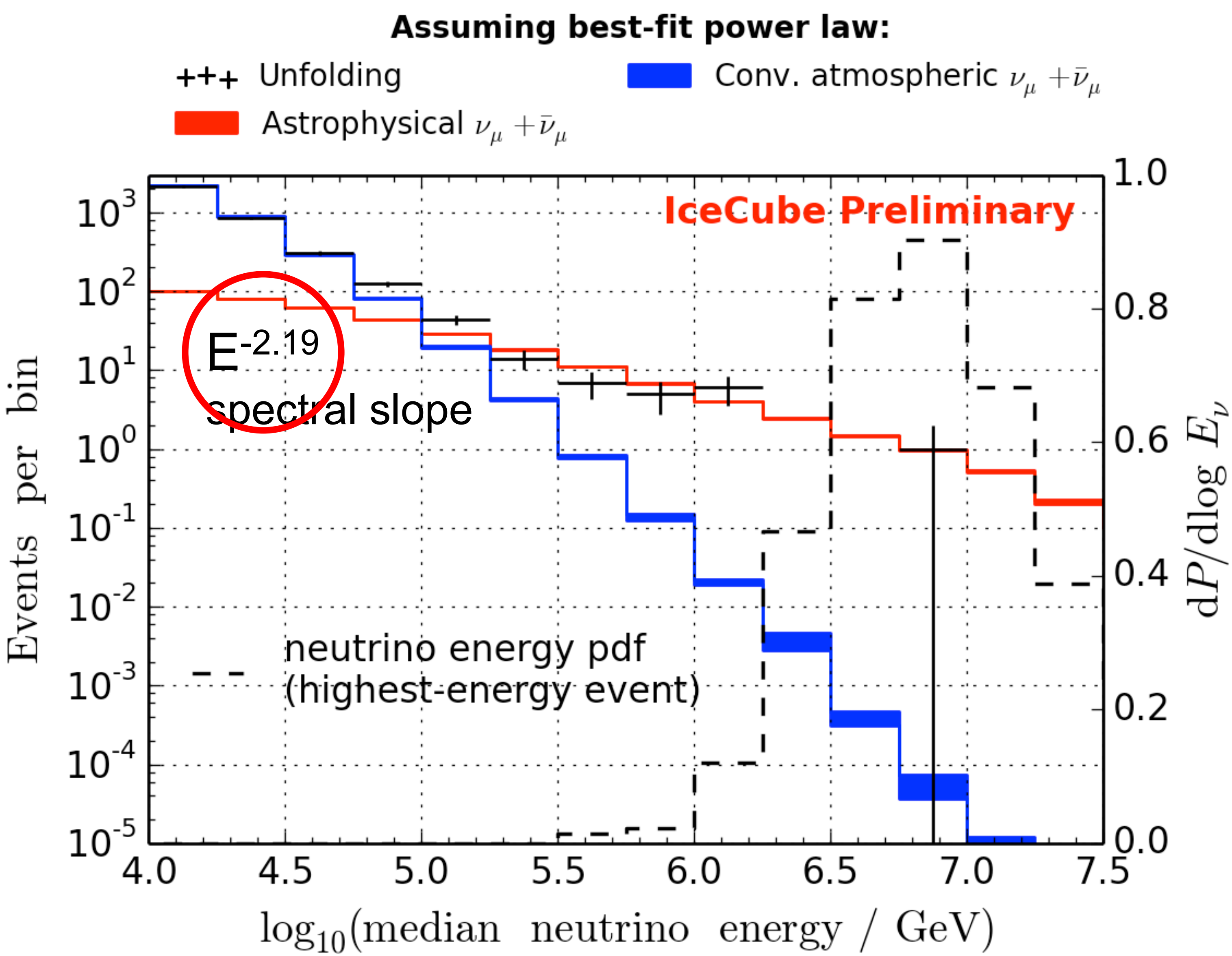

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
ICECUBE



- lattice of photomultipliers


2.6 ± 0.3 PeV
inside detector

~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg^2/year

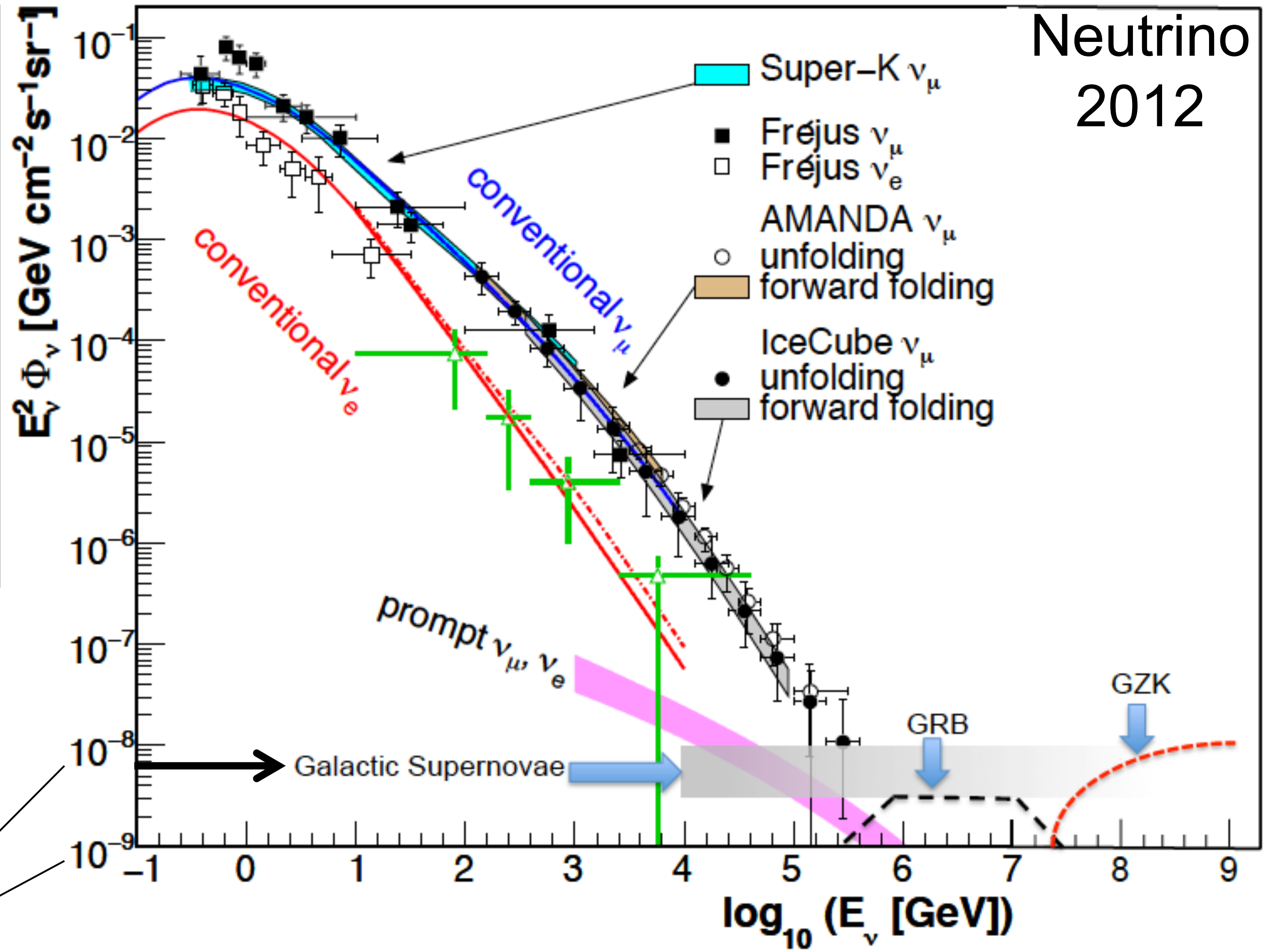


above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



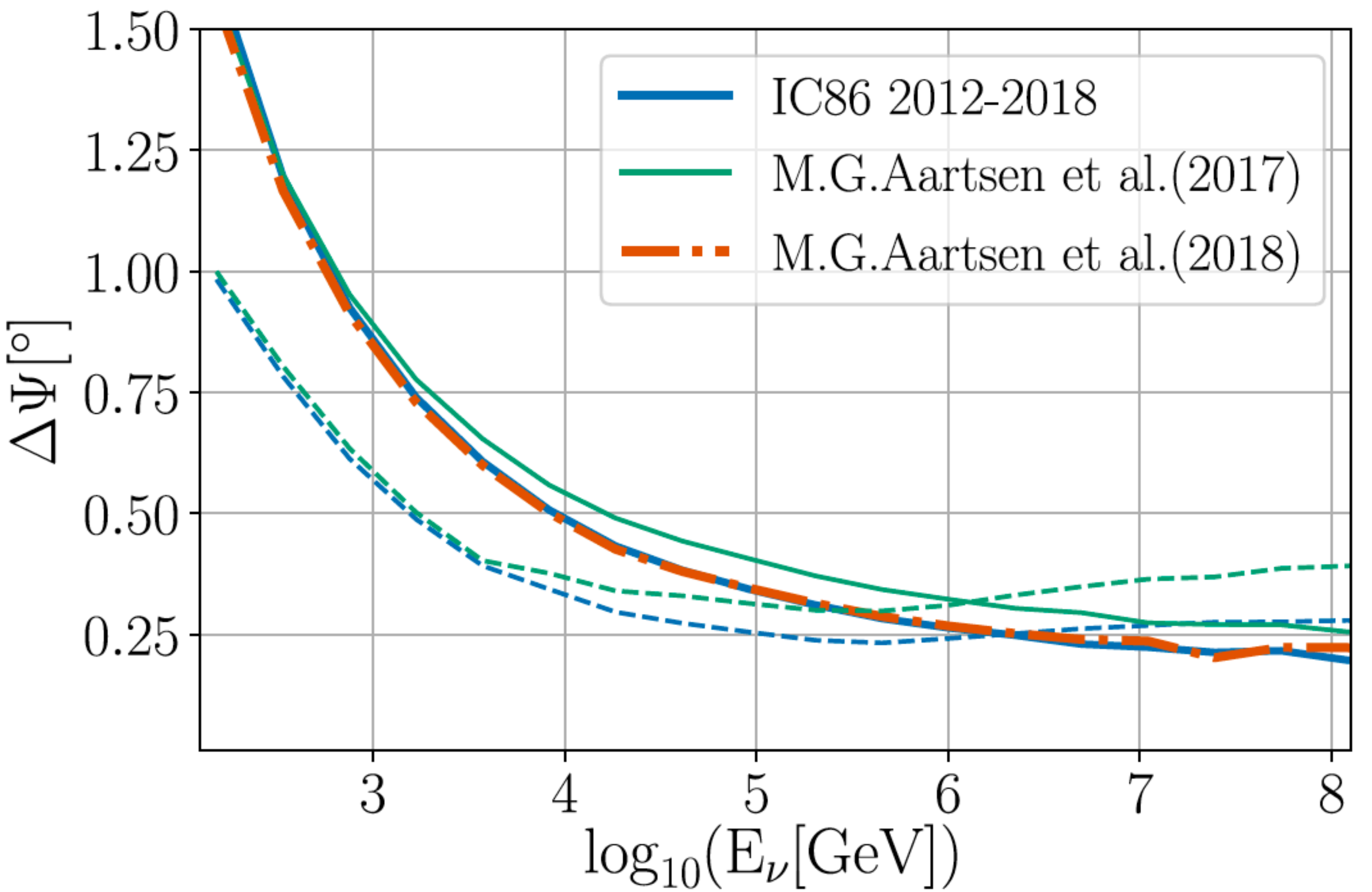
atmospheric

cosmic

100 TeV

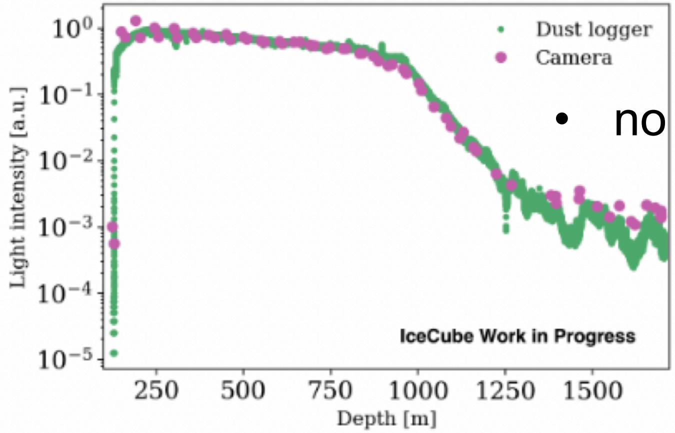
astronomy

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



ice: step by step

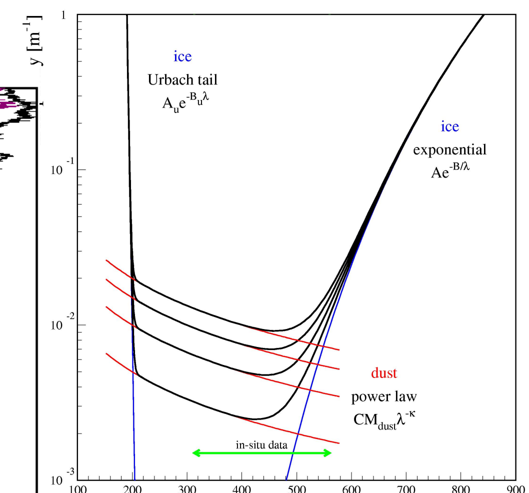
- hole ice ?



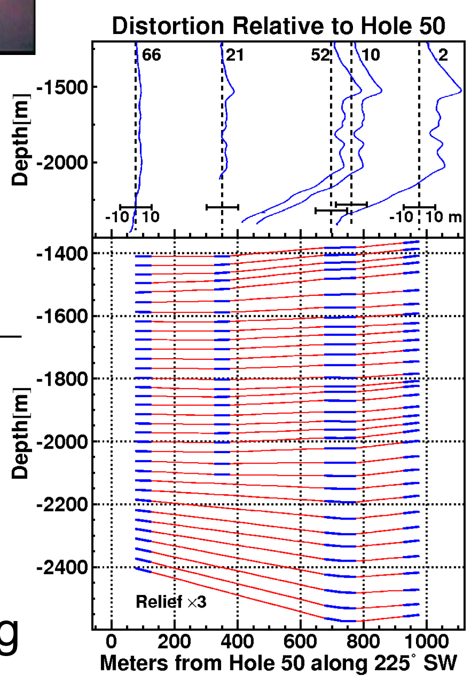
- no air bubbles/hydrates below 1350 m

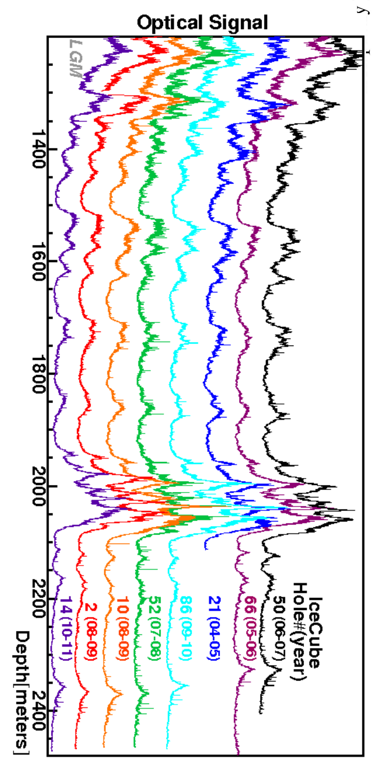
- > 100 m absorption length limited by dust

- ice layers

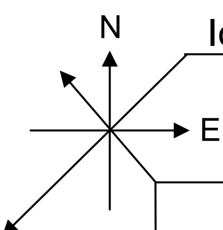


- tilted ice layers





- birefringence ice chrystals ?



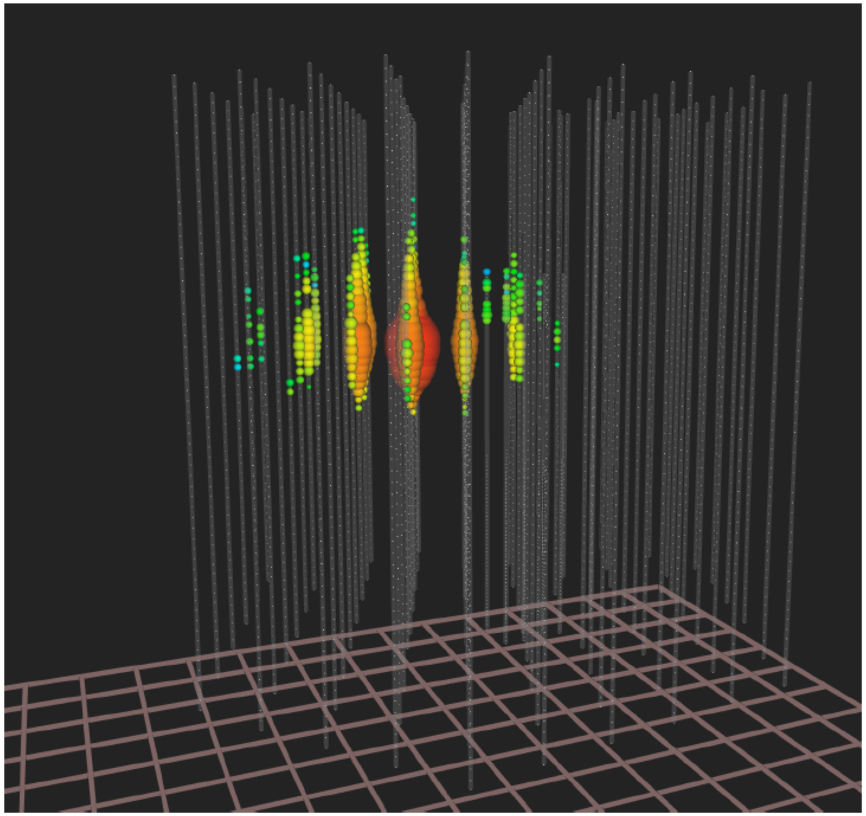
Ice Layer tilt direction
225° SW

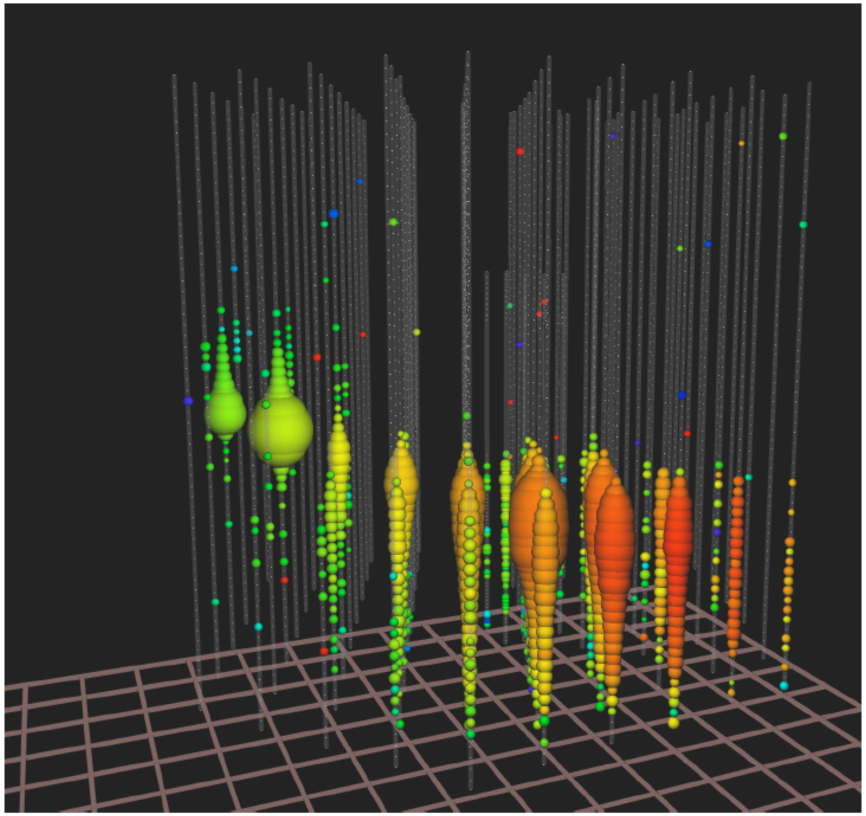
Ice flow direction
41° NW

- anisotropy ~8% less scattering
41° NW

neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth





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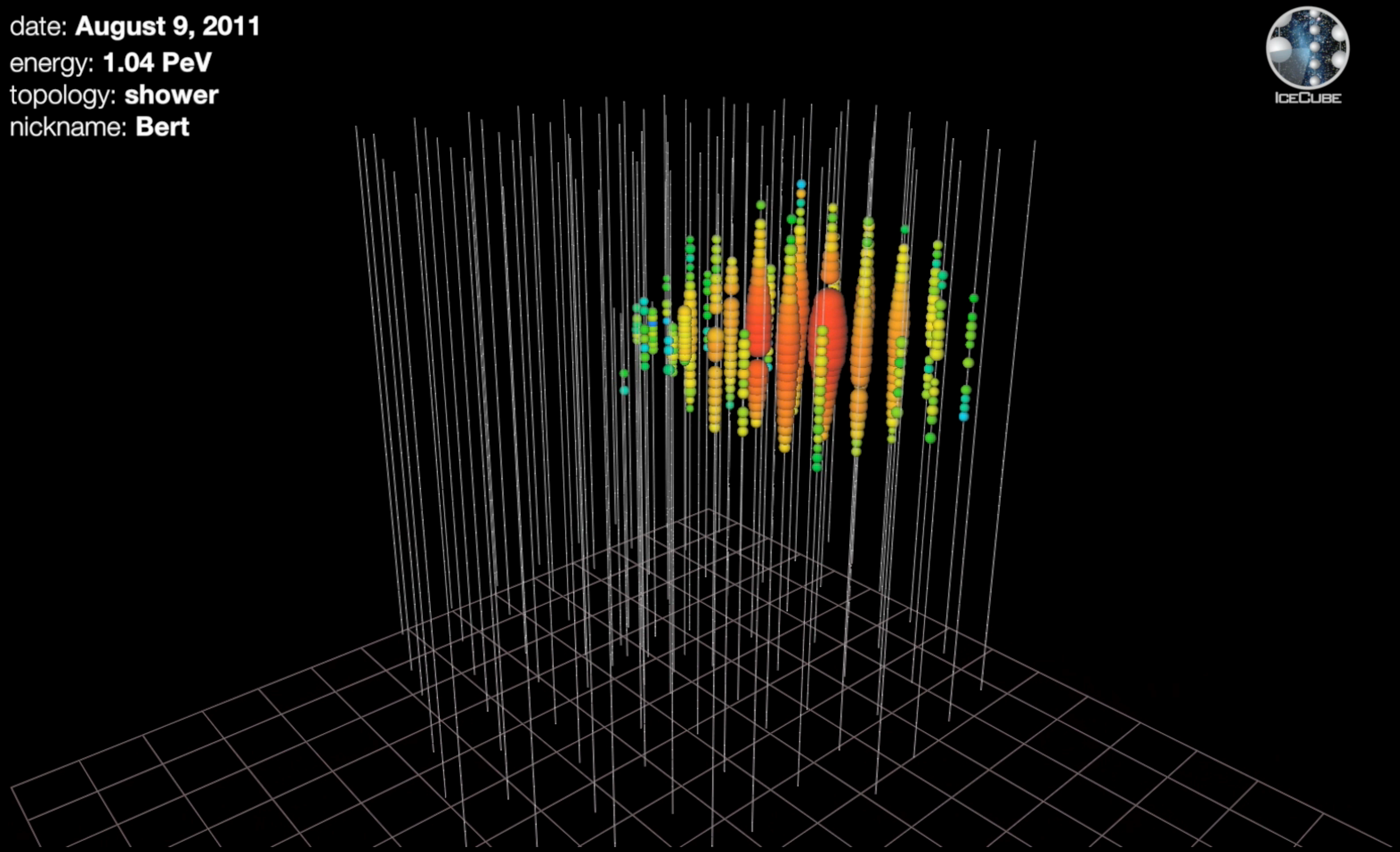
superior (<0.4°)

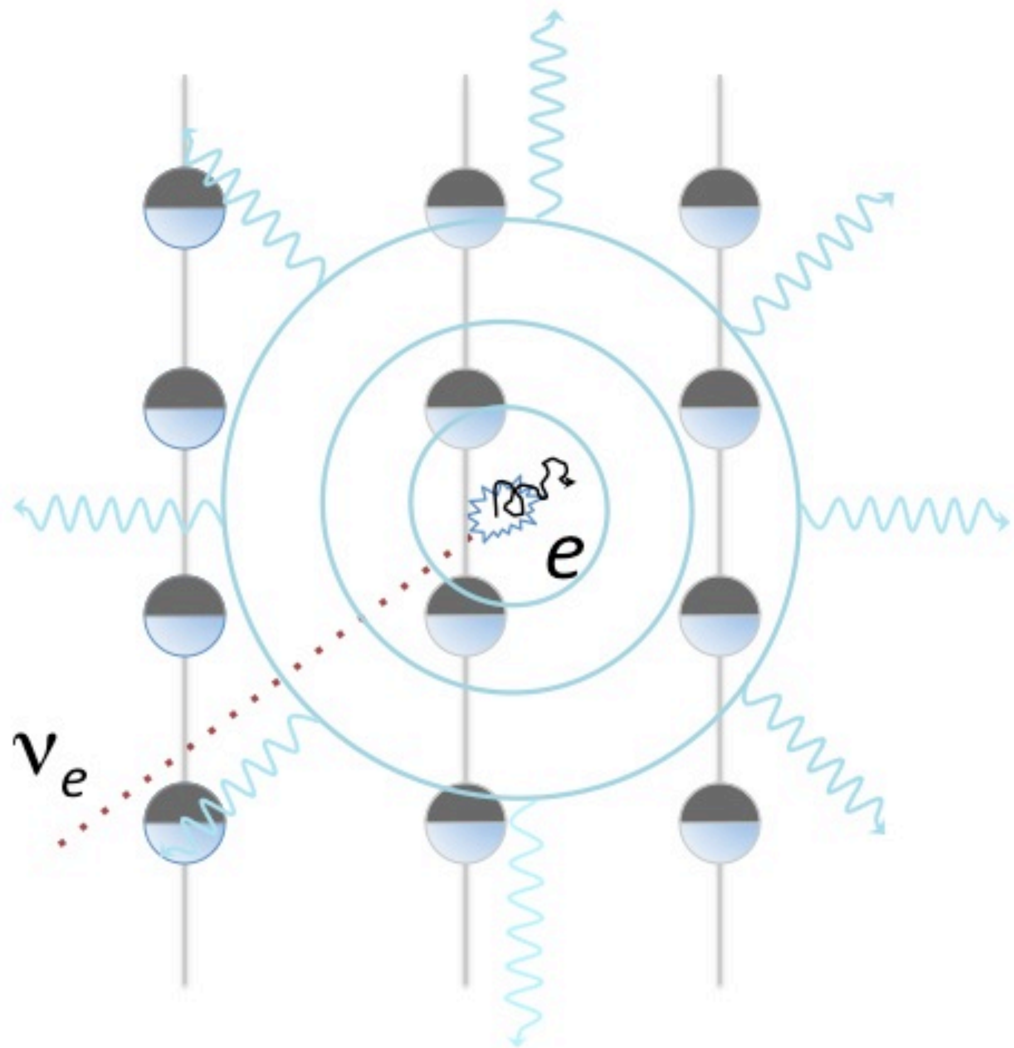
GZK neutrino search: two neutrinos with > 1,000 TeV

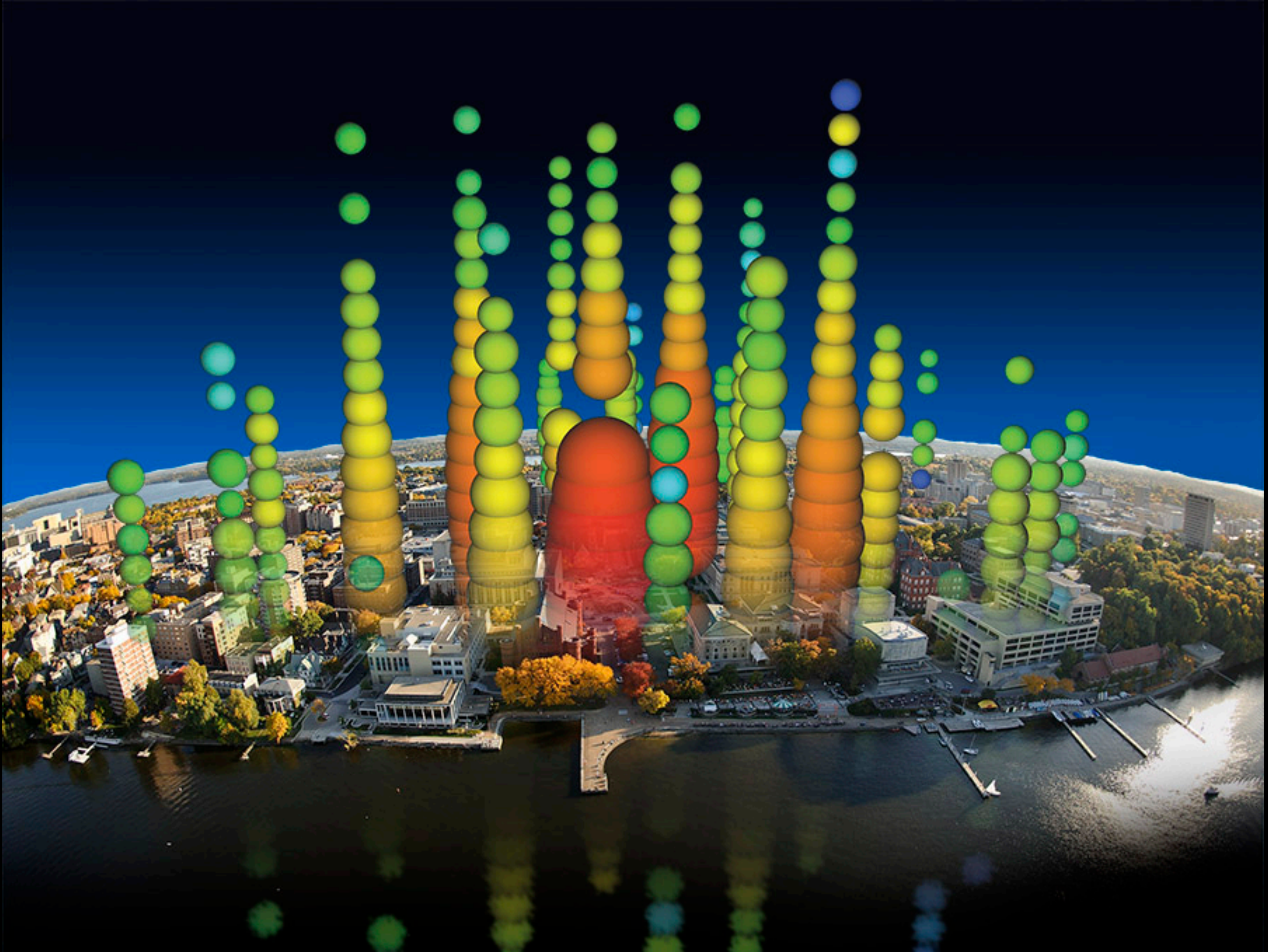


electron showers versus muon tracks

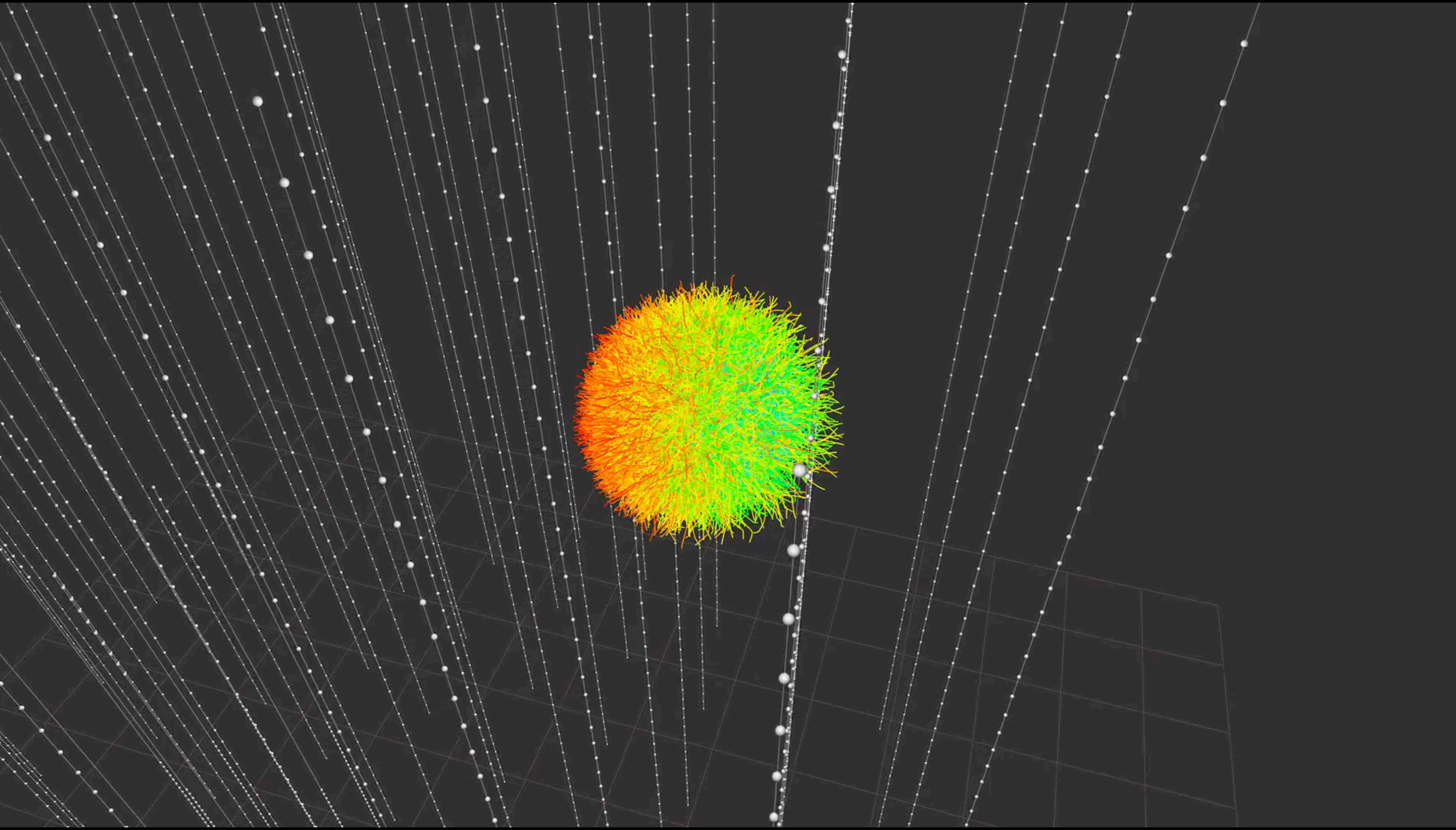
PeV ν_e and ν_τ showers:

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





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

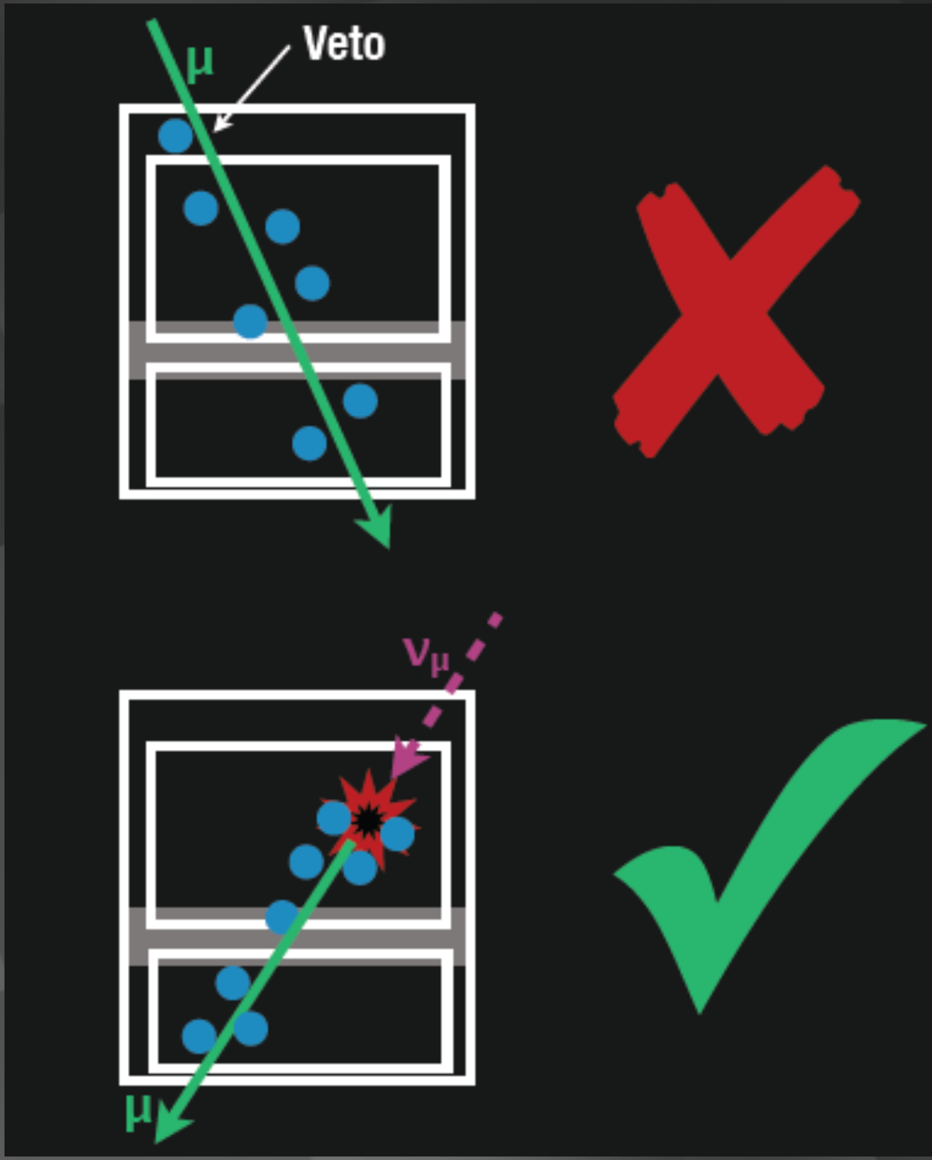


size = energy

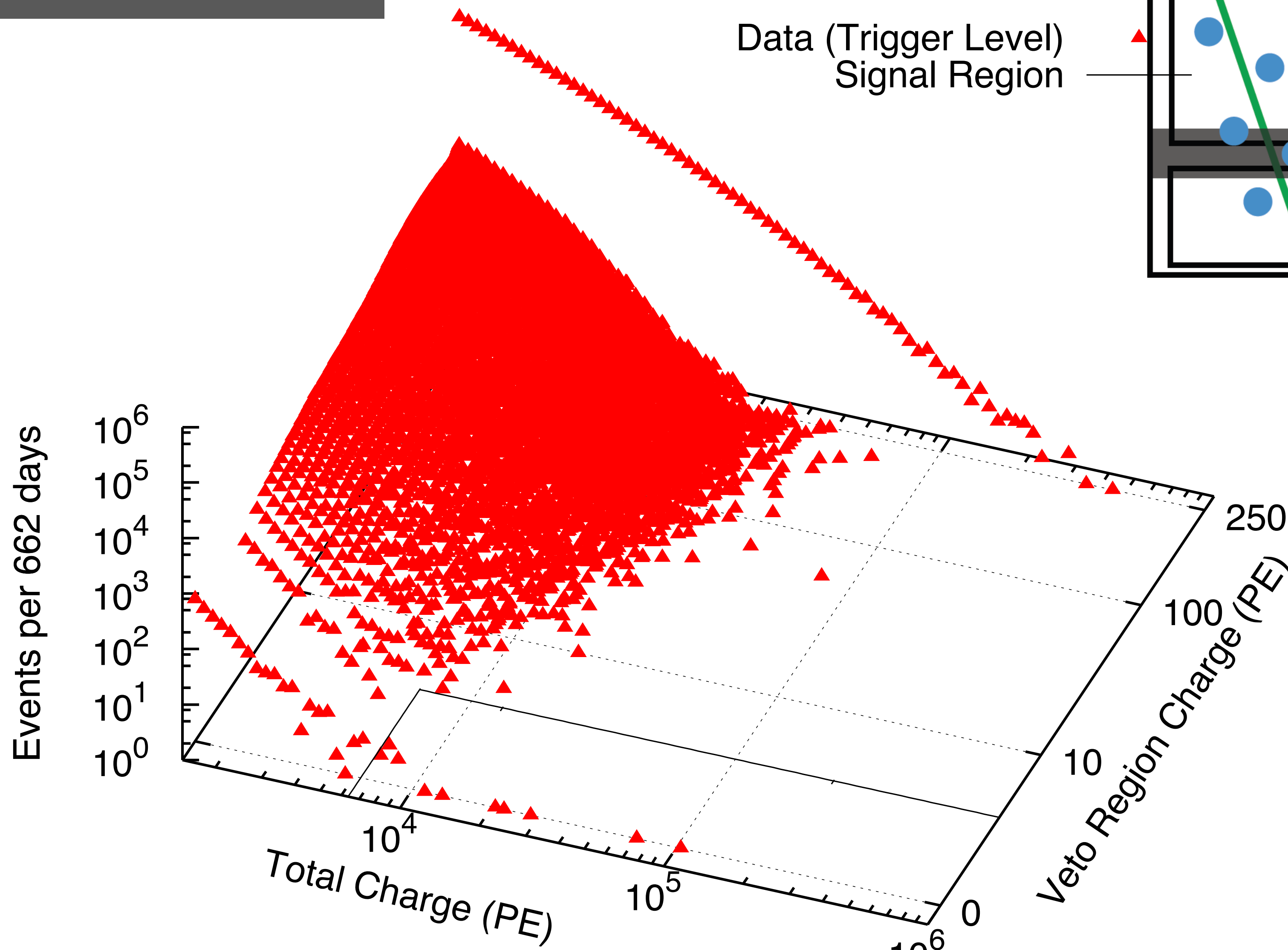
color = time = direction

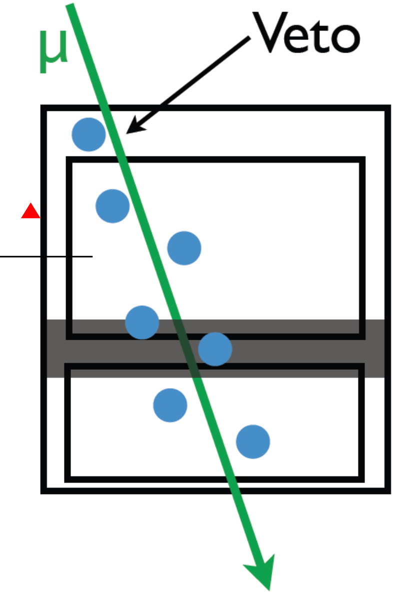
events starting inside the detector

- ✓ 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



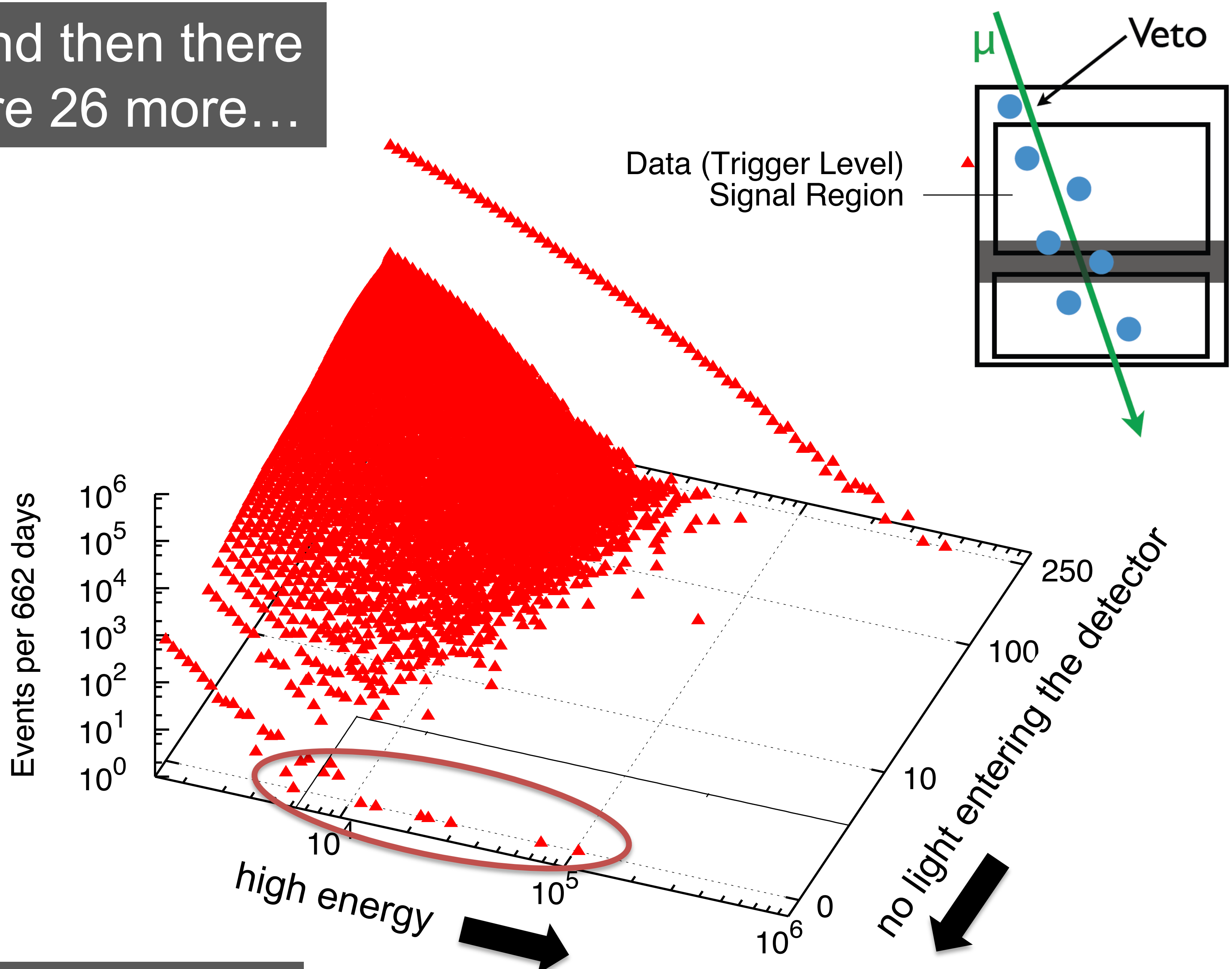
…and then there were 26 more…





data: 86 strings one year

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



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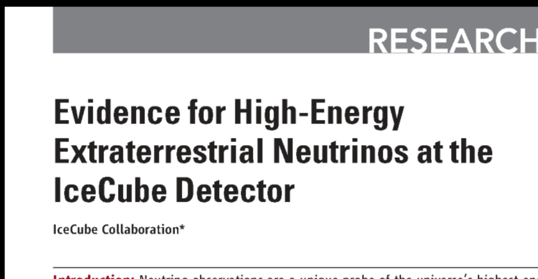
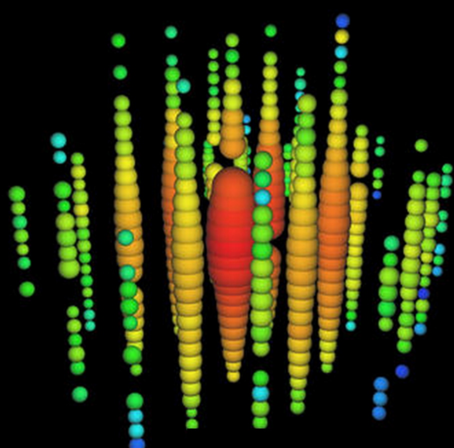
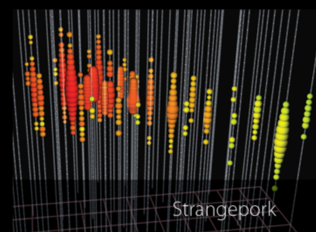
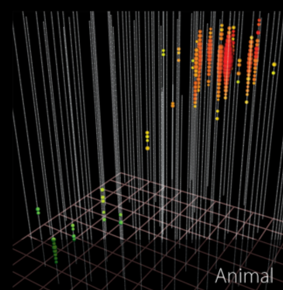
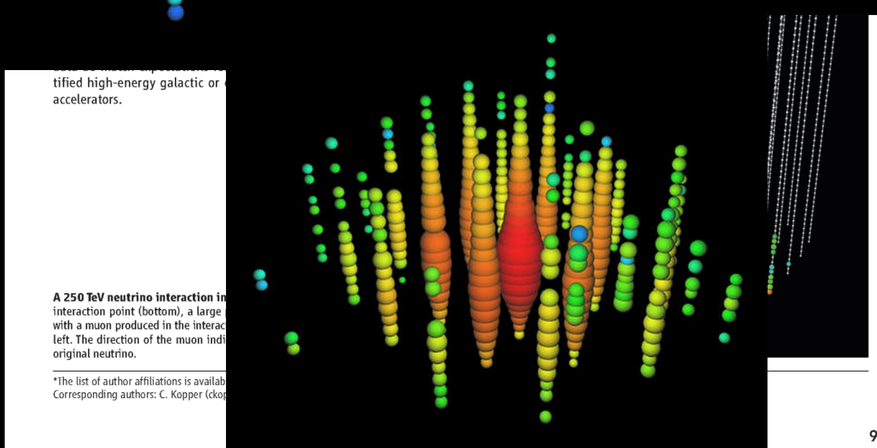


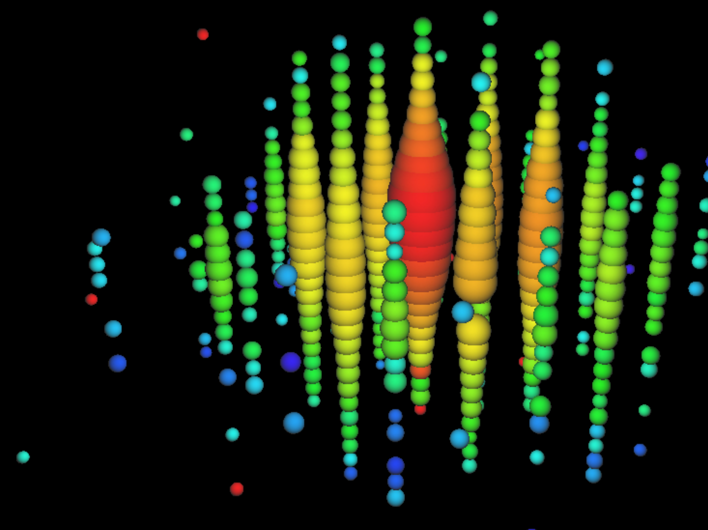


28 High Energy Events





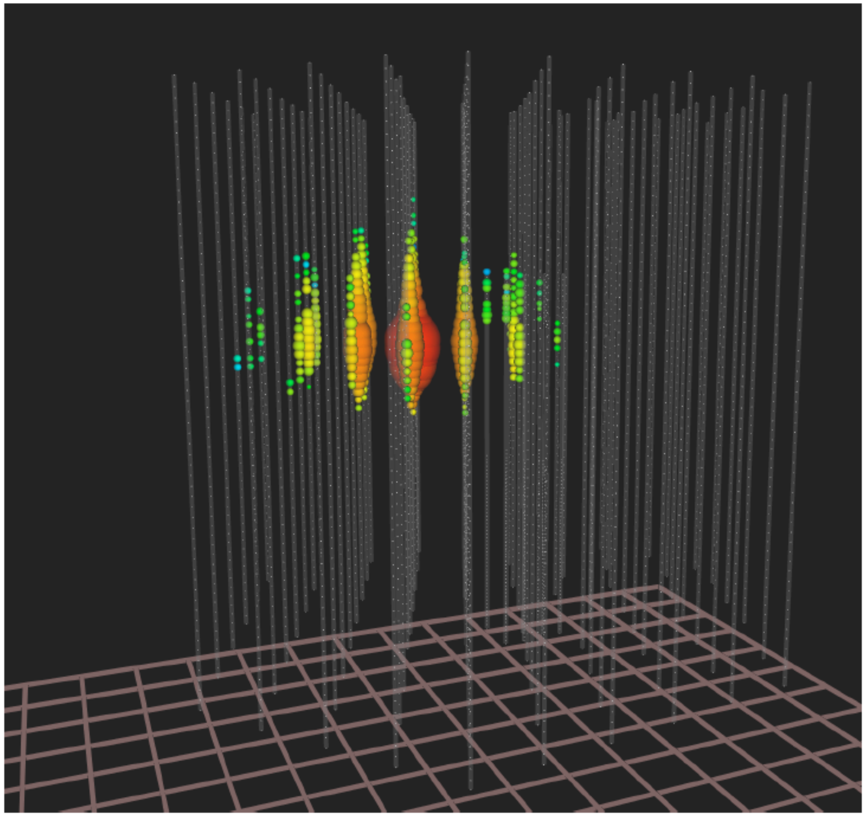


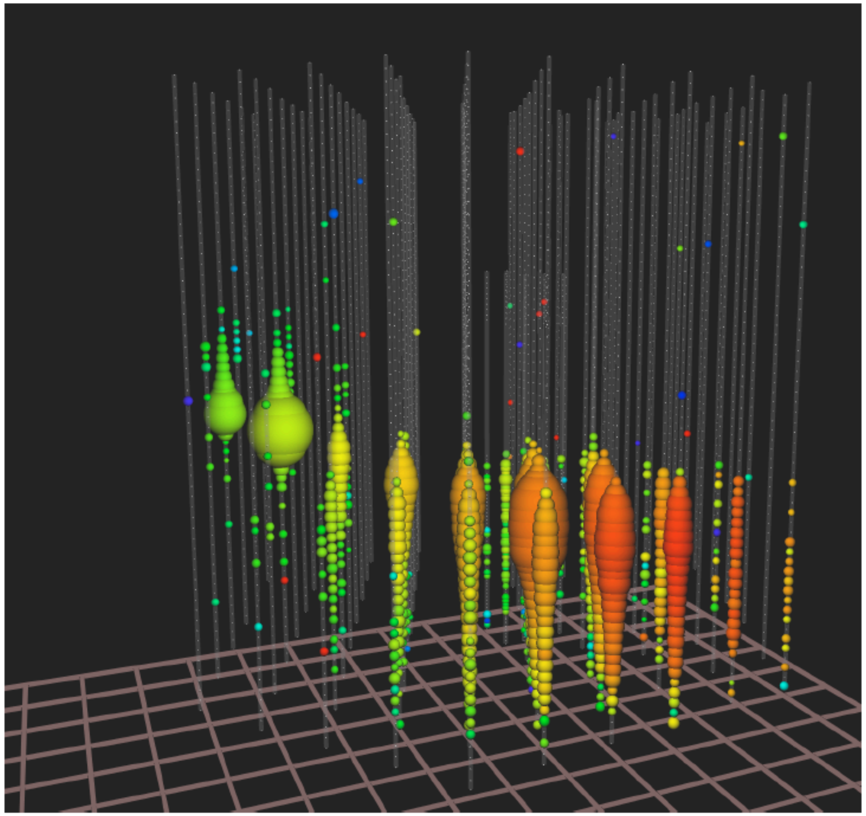


2004 TeV event in year 3

neutrinos interacting
inside the detector

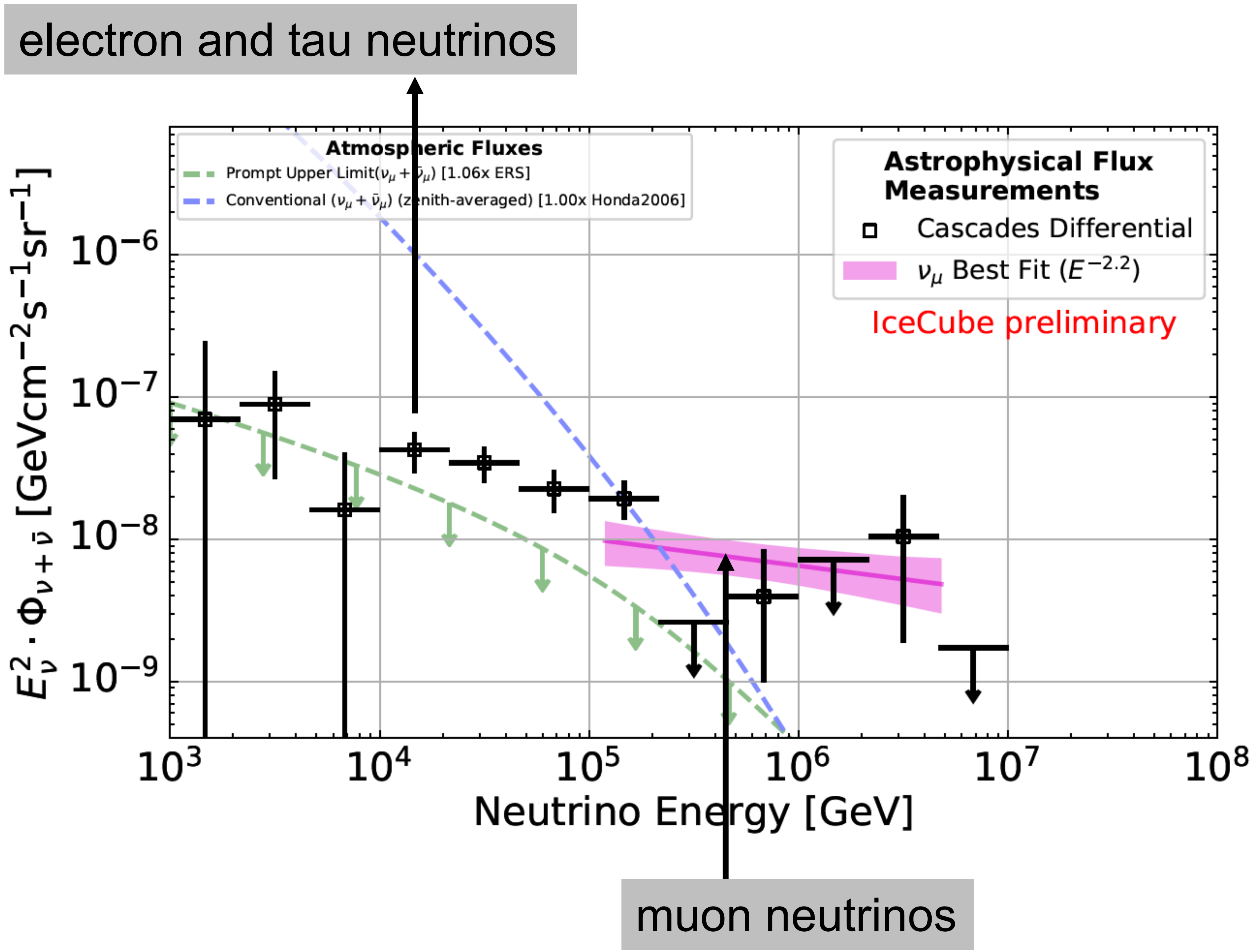
muon neutrinos
filtered by the Earth





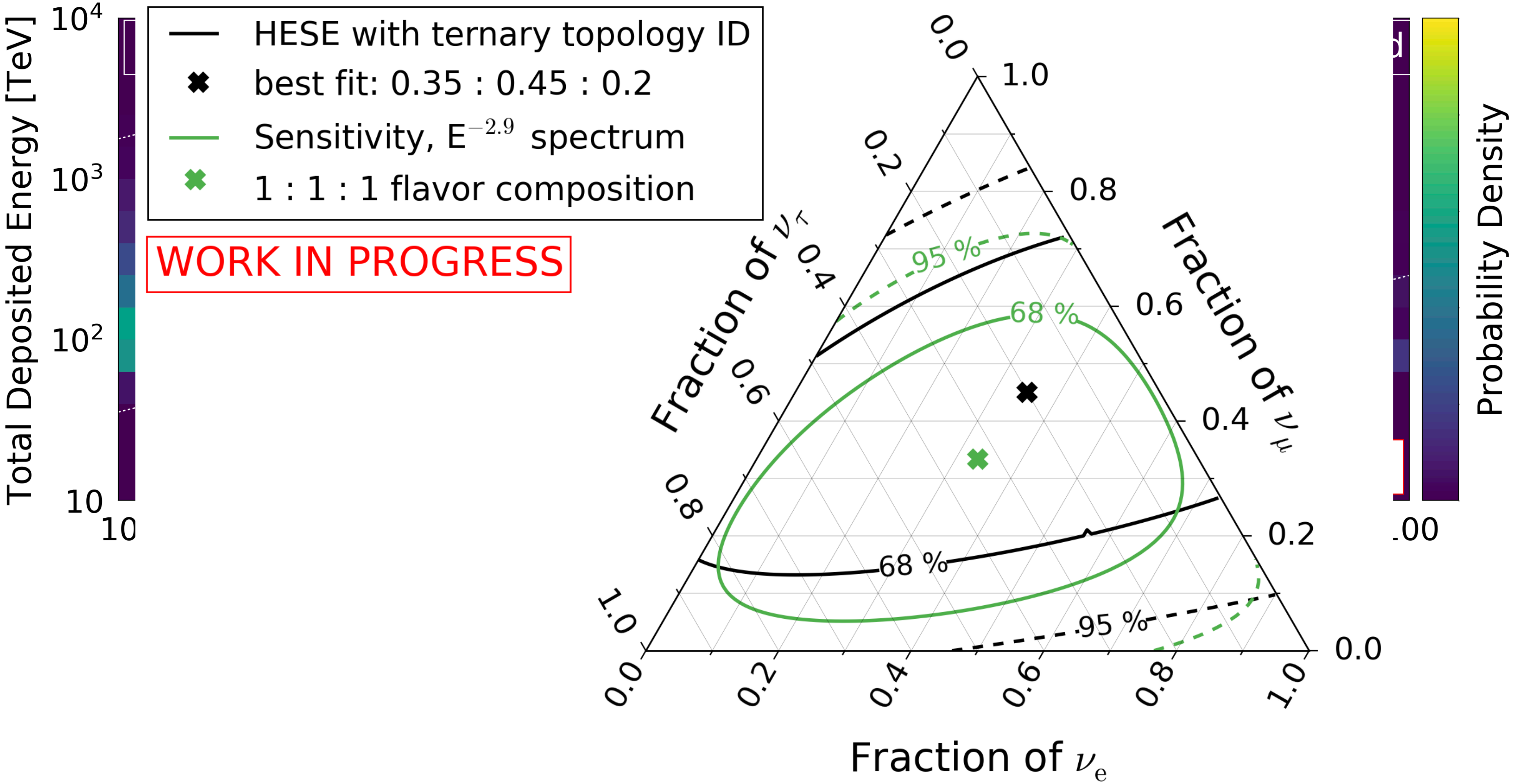
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)



electron and tau neutrinos
muon 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]

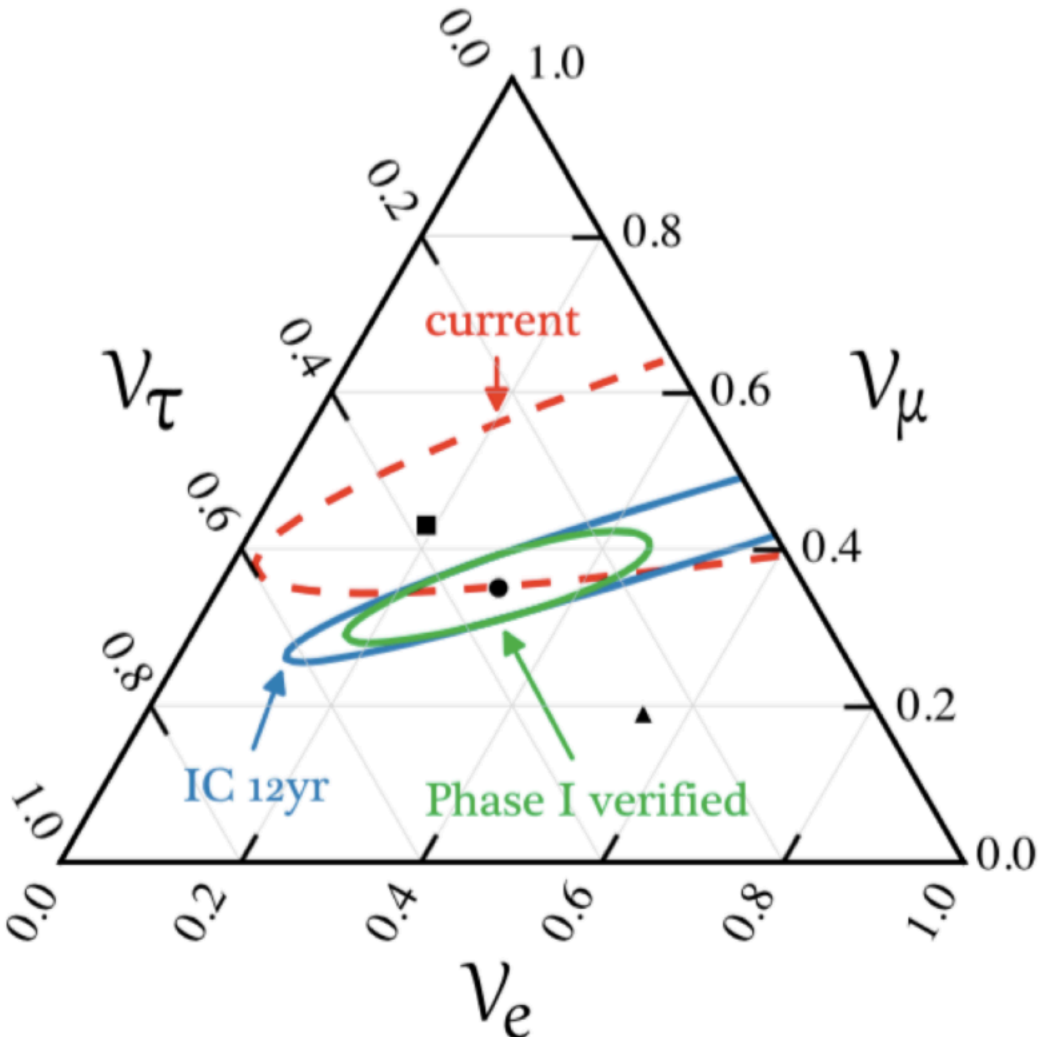
high-energy starting events – 7.5 yr

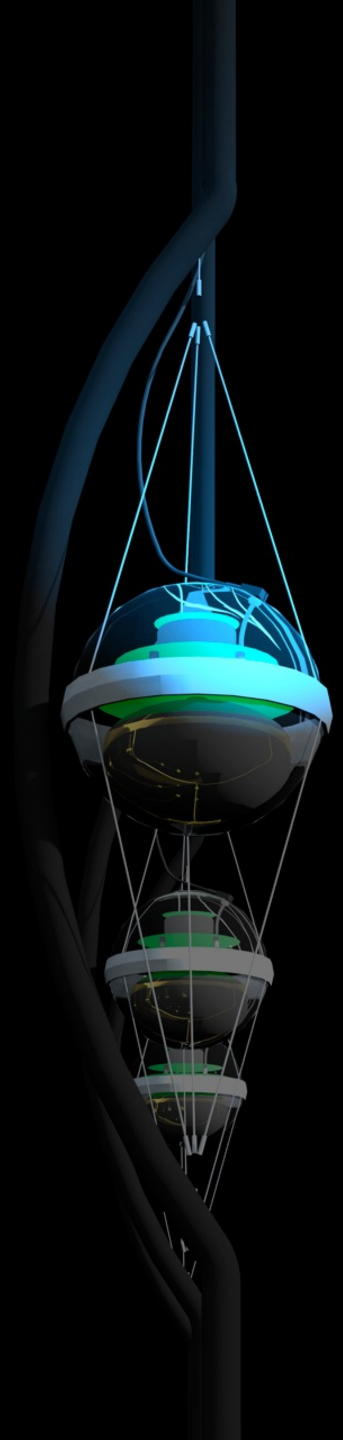


oscillations of PeV neutrinos over cosmic distances to 1:1:1

ongoing upgrade:
2022 deployment

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





cosmic neutrinos: four independent observations

→ muon neutrinos through the Earth
→ starting neutrinos: all flavors
→ tau neutrinos
→ Glashow resonance event

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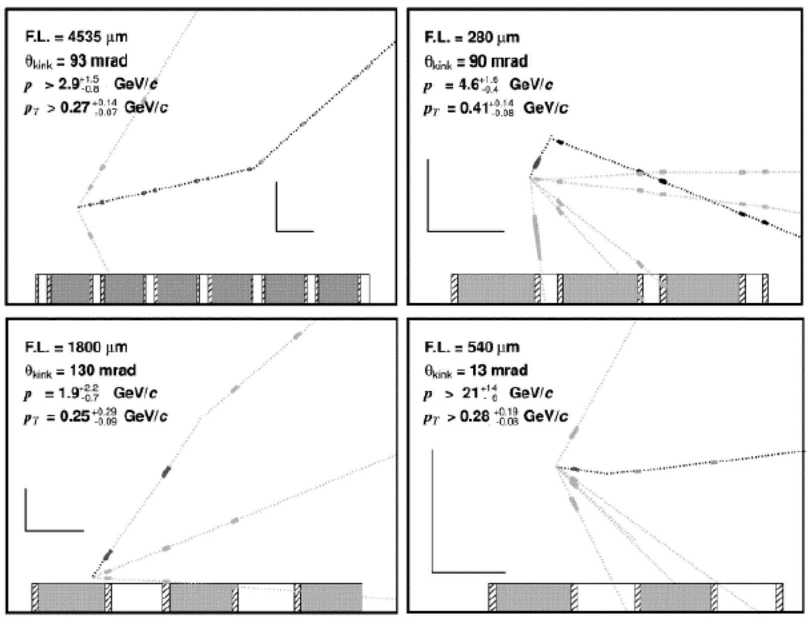
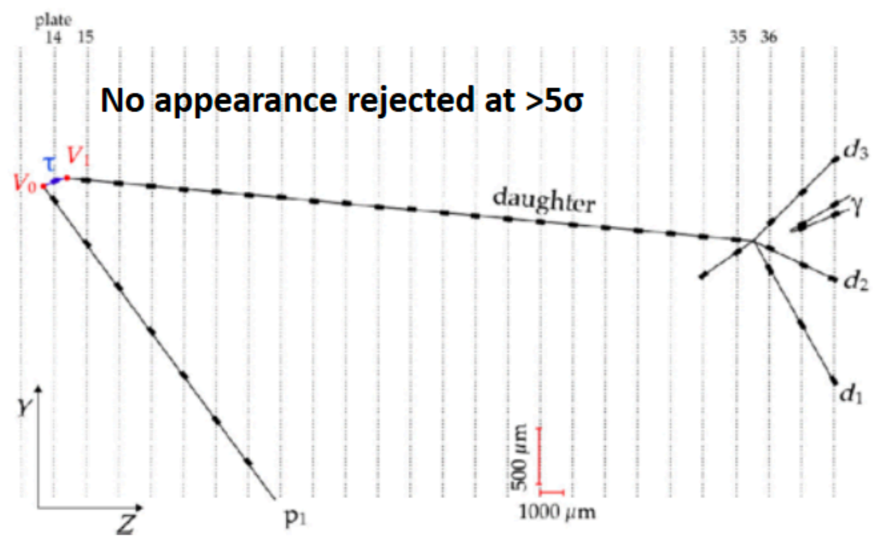
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



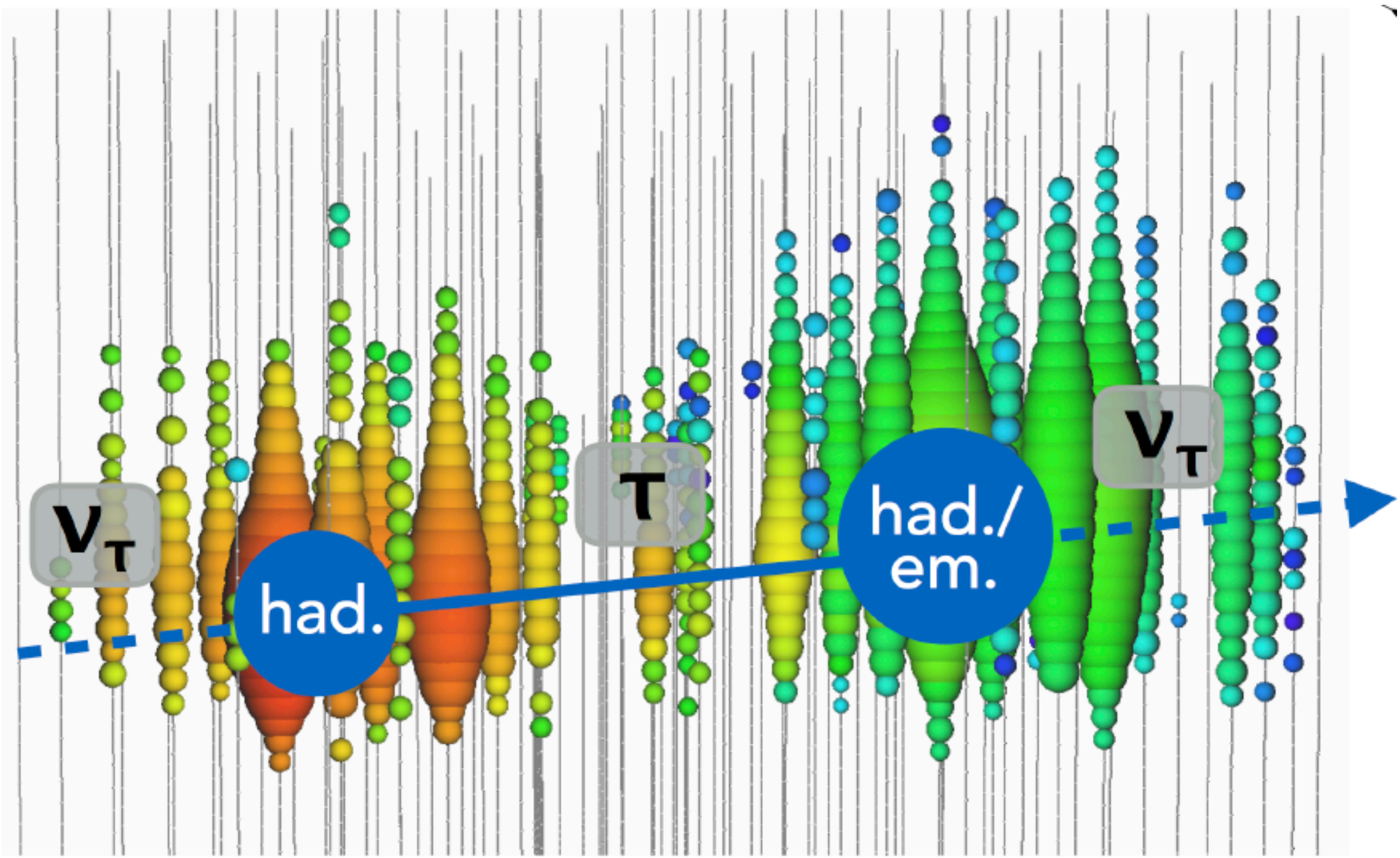
DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

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

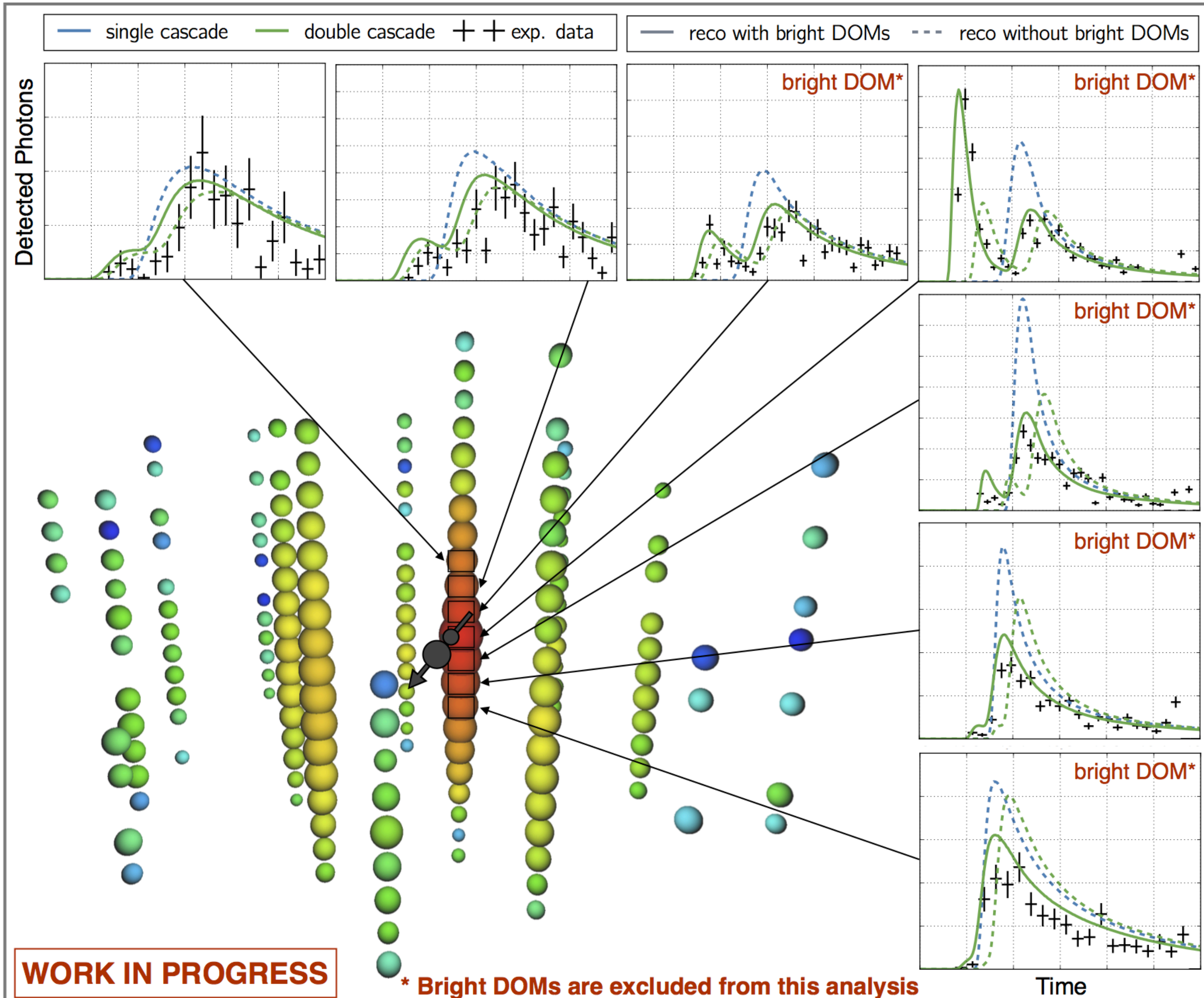


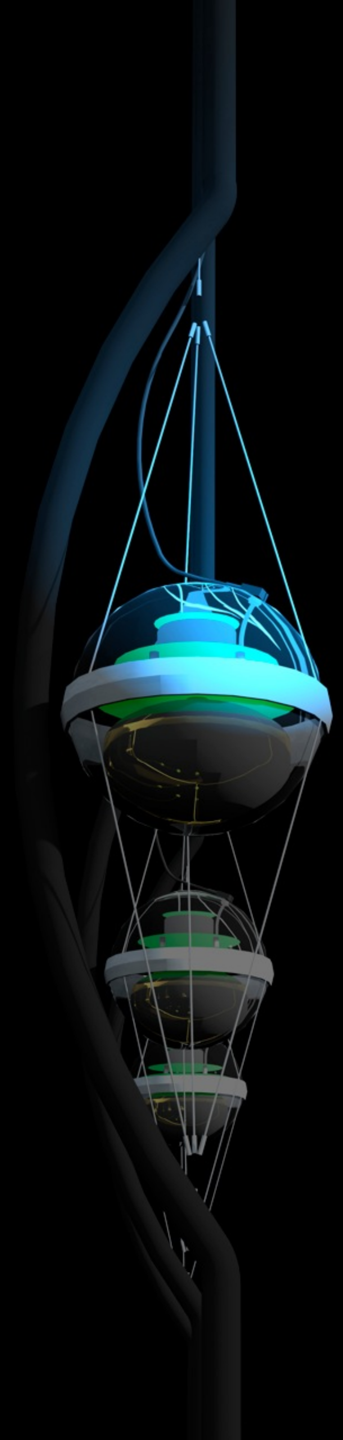
OPERA Phys. Rev. Lett. 115, 121802 (2015) tau production and decay

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

→ tau neutrinos

→ Glashow resonance event

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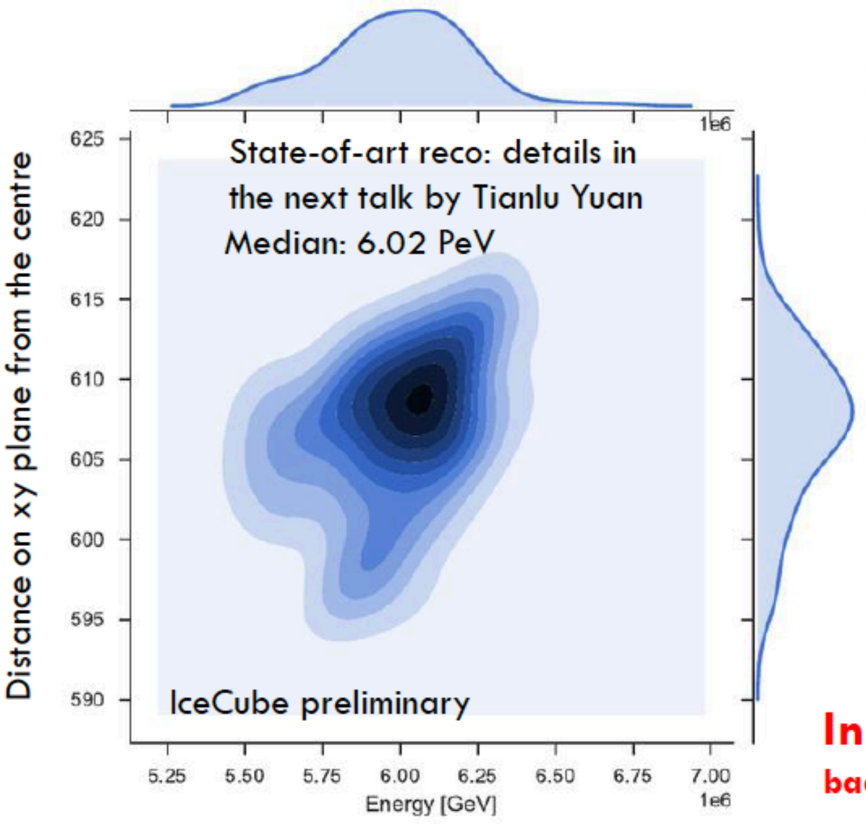
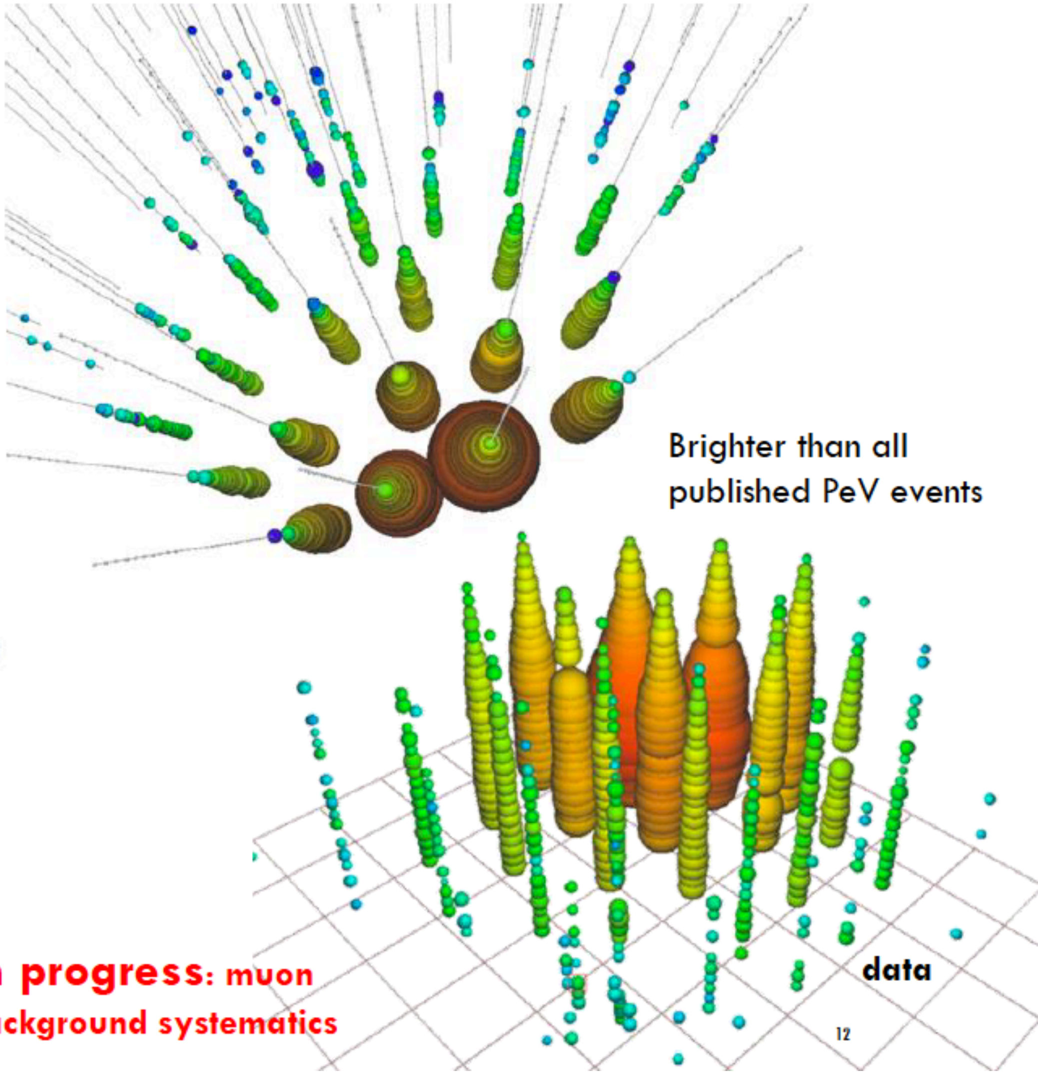
partially contained event with energy of 6.3 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE

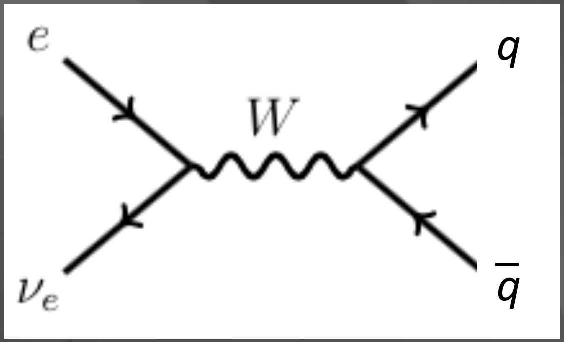




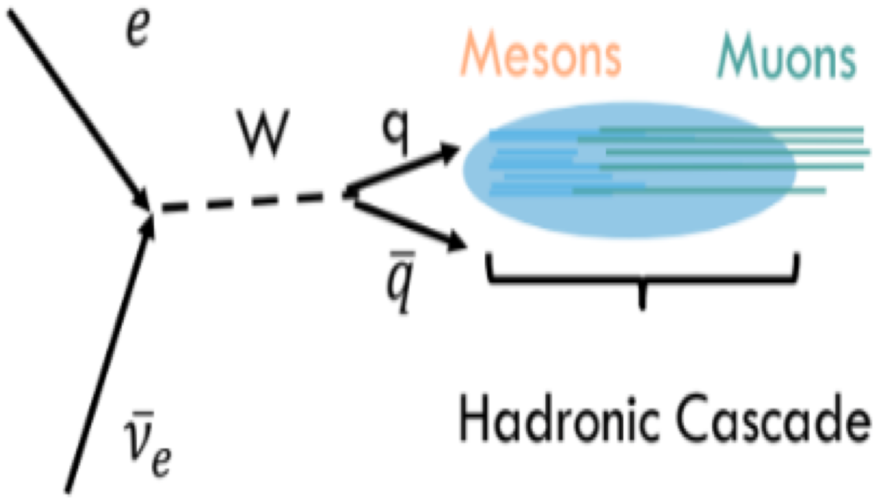
In progress: muon background systematics

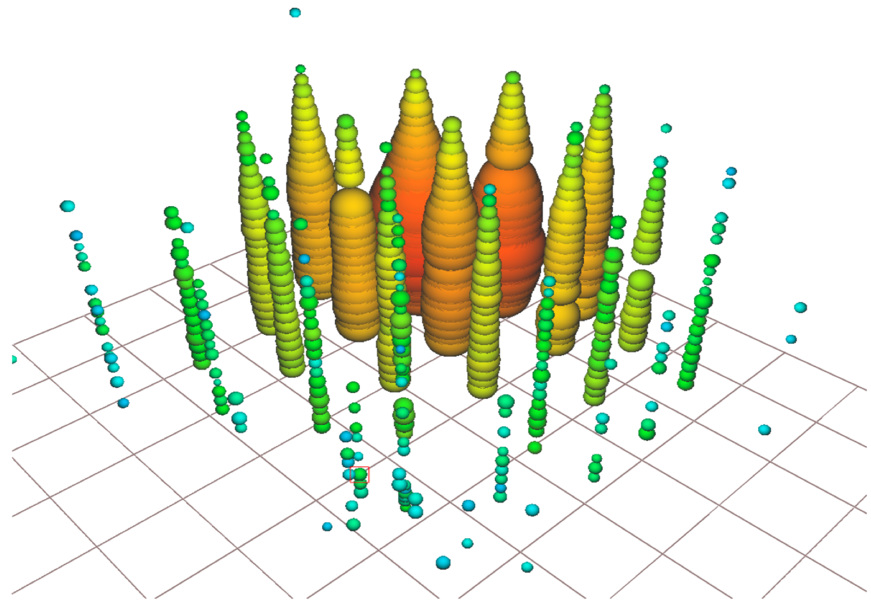
the first Glashow resonance event:

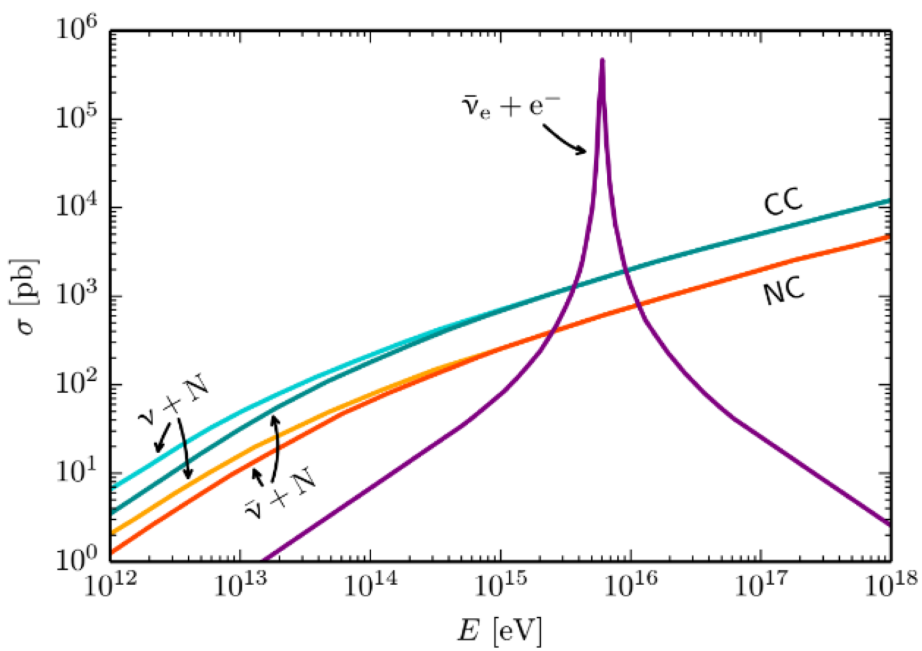
anti-ν_e + atomic electron → real W at 6.3 PeV



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





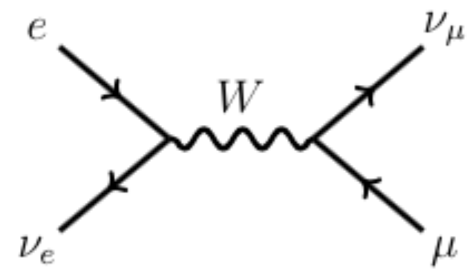


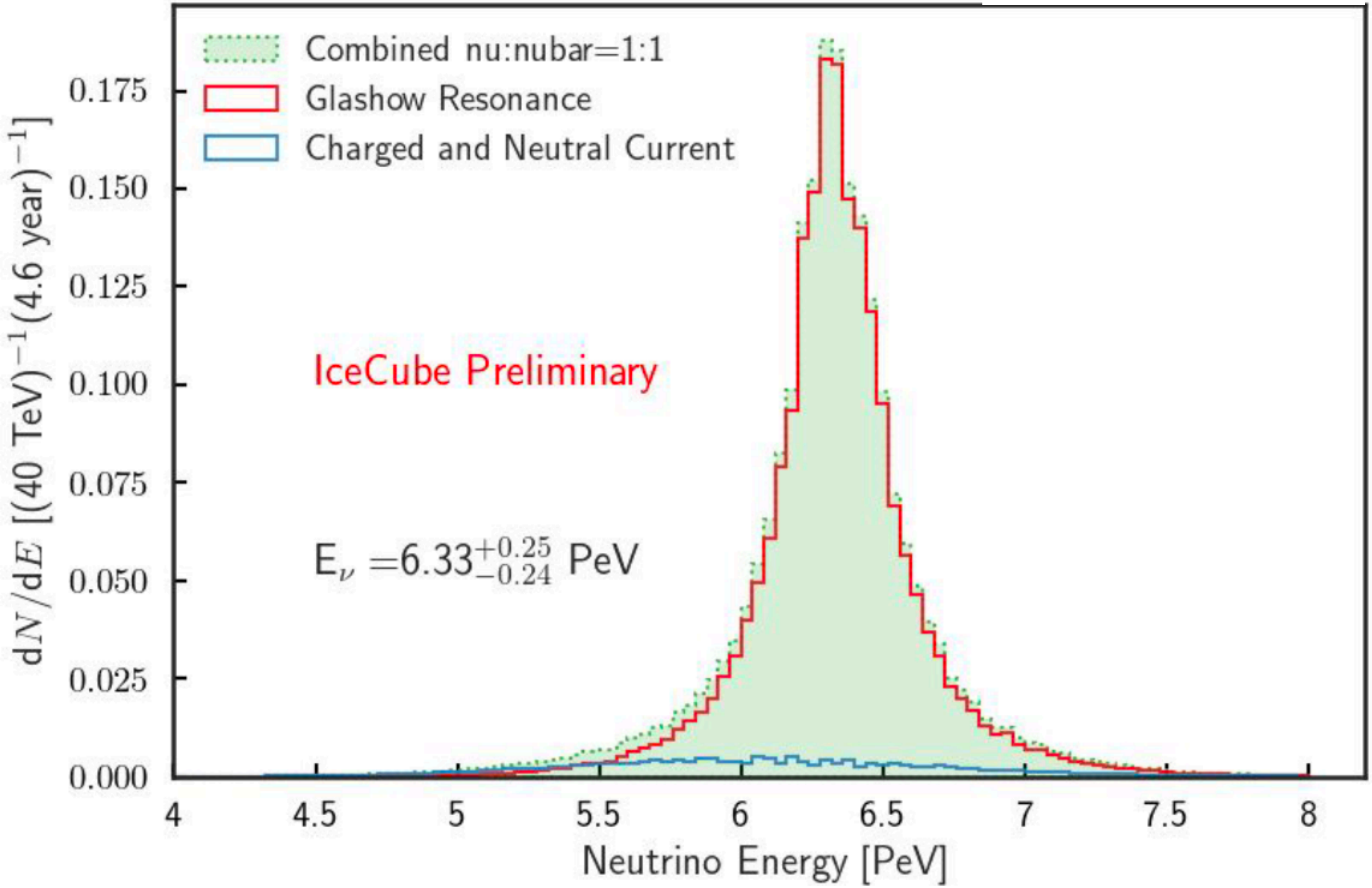
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

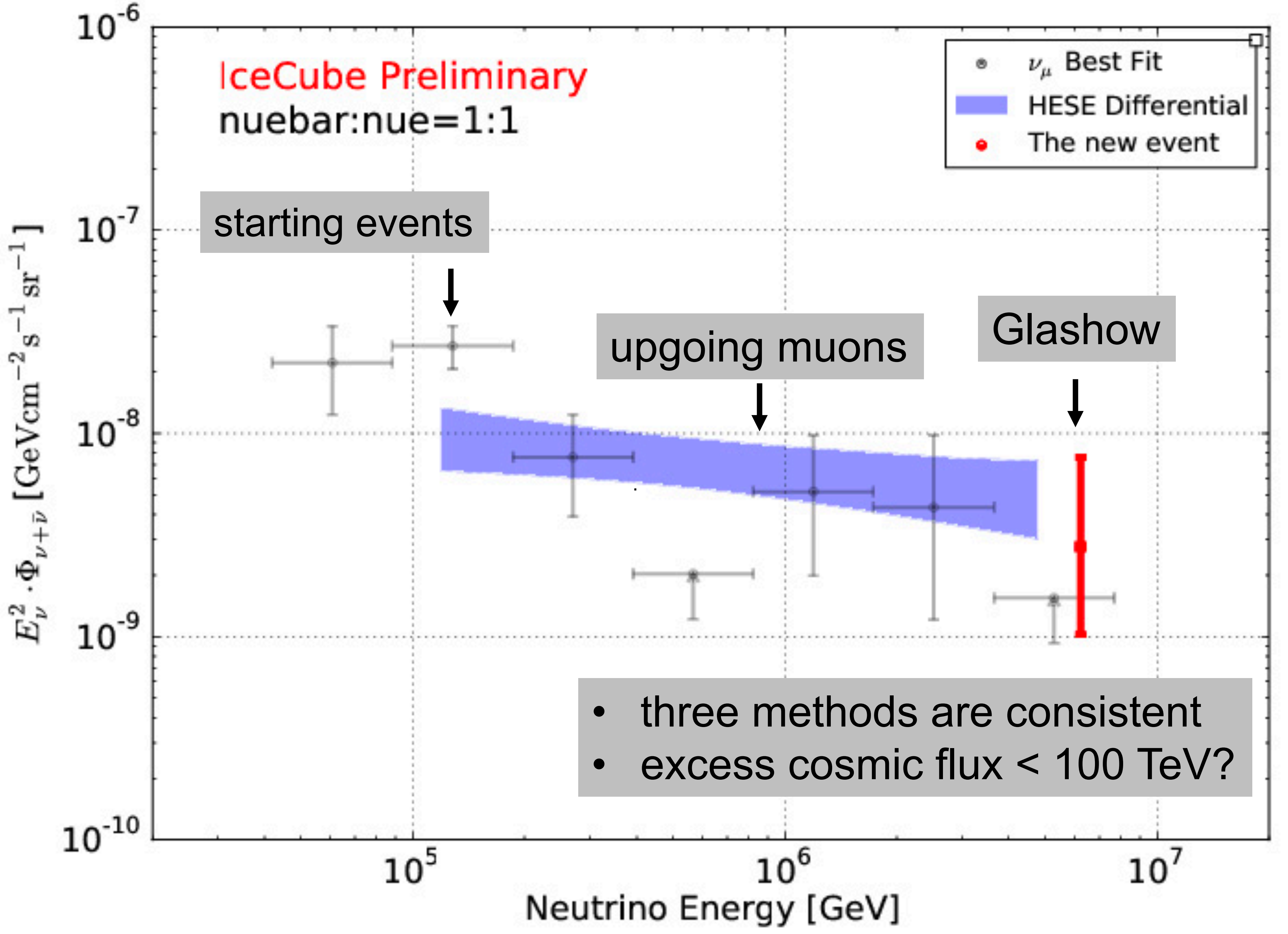
- → resonance: E_ν = 6.3 PeV

work on-going

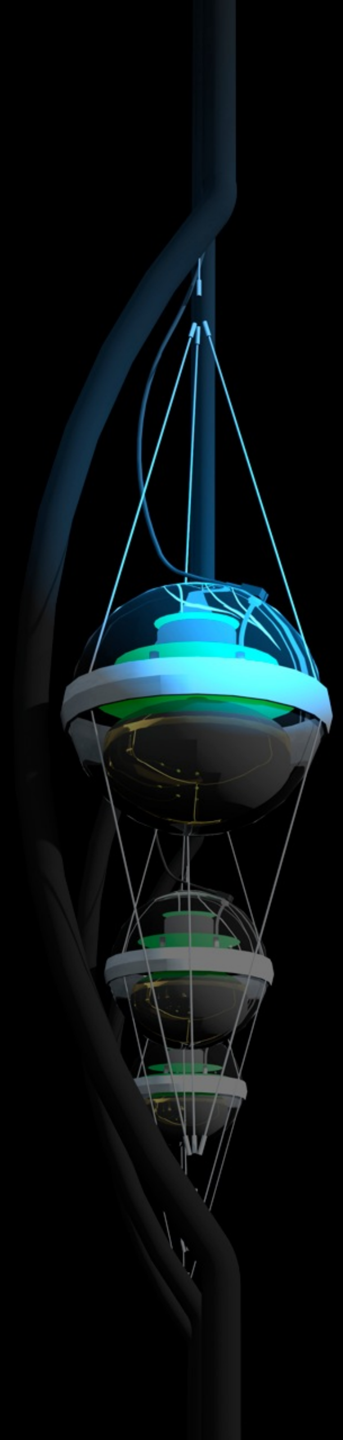
- energy measurement understood
- identification of anti-electron neutrinos







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



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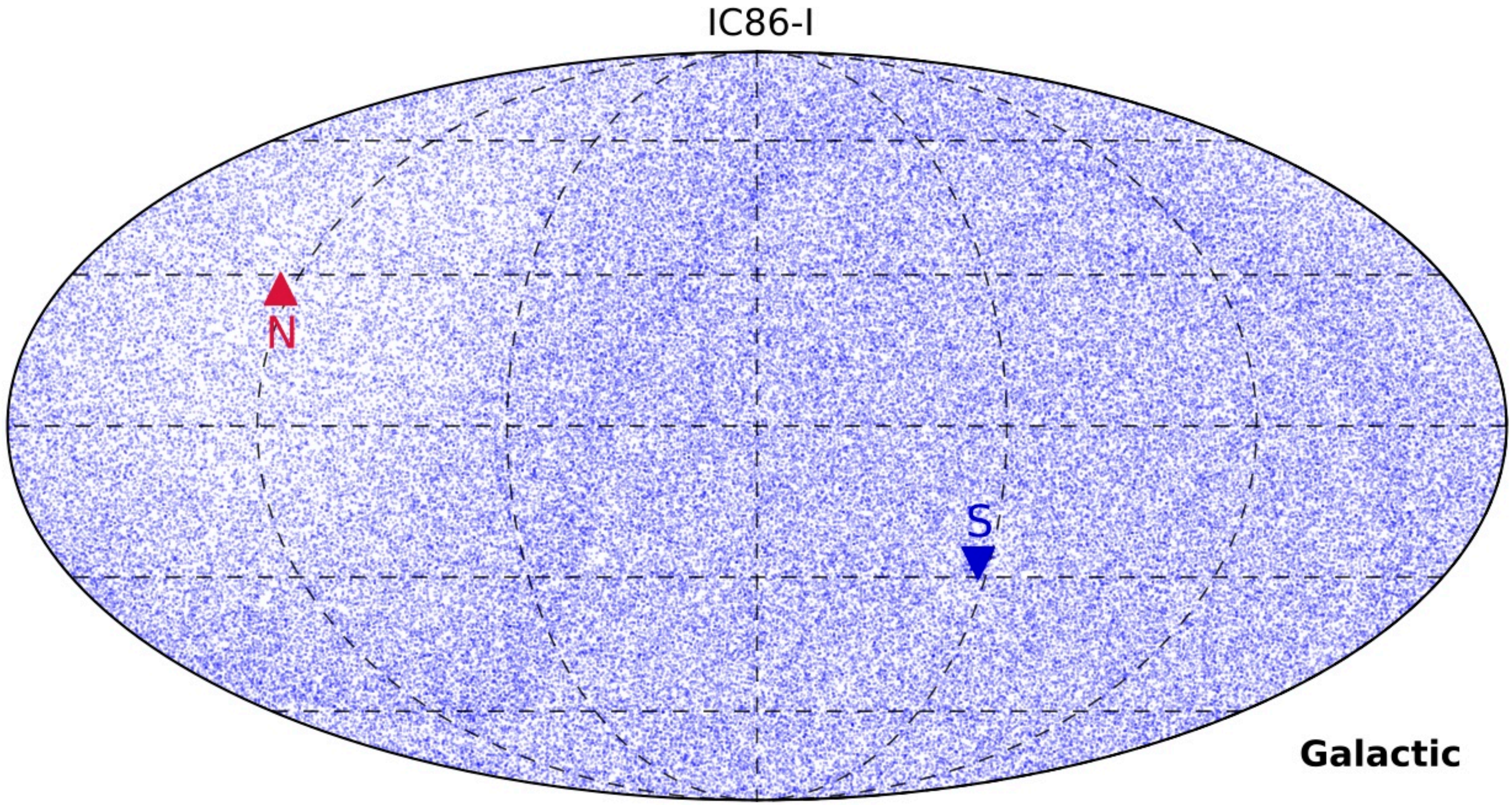
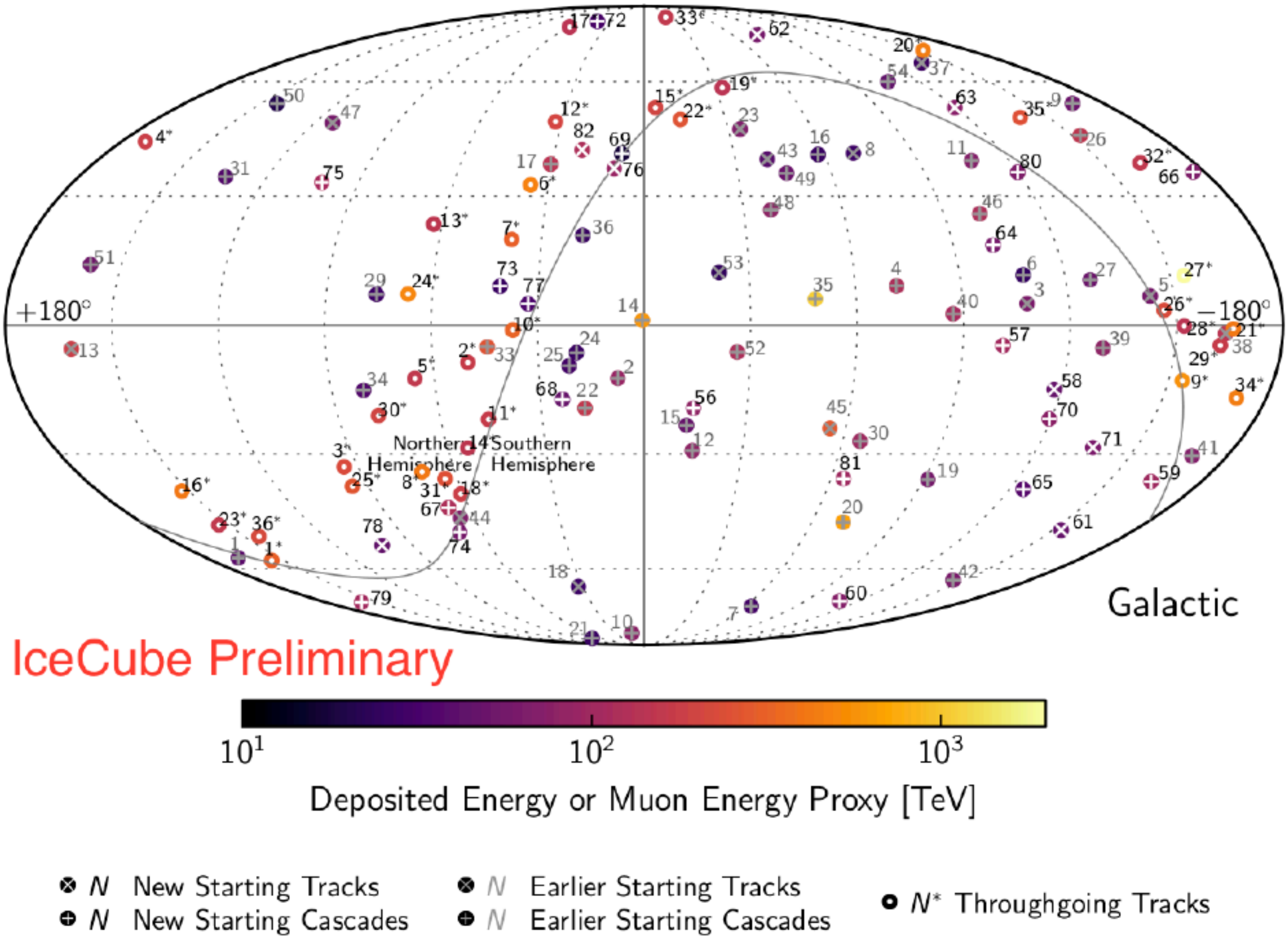


138322 neutrino candidates in one year

120 cosmic neutrinos

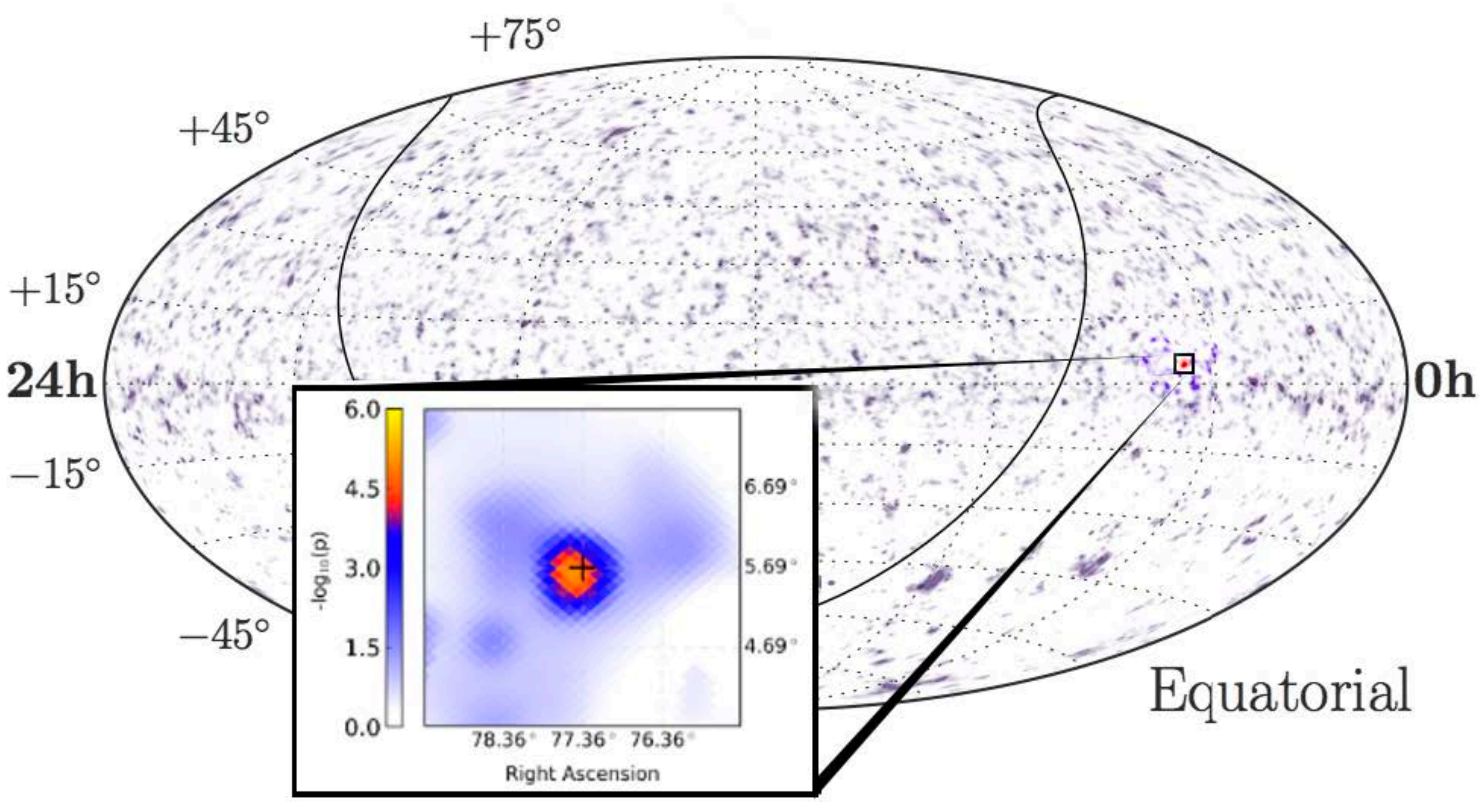
~12 separated from atmospheric background with E>60 TeV

structure in the map results from neutrino absorption by the Earth

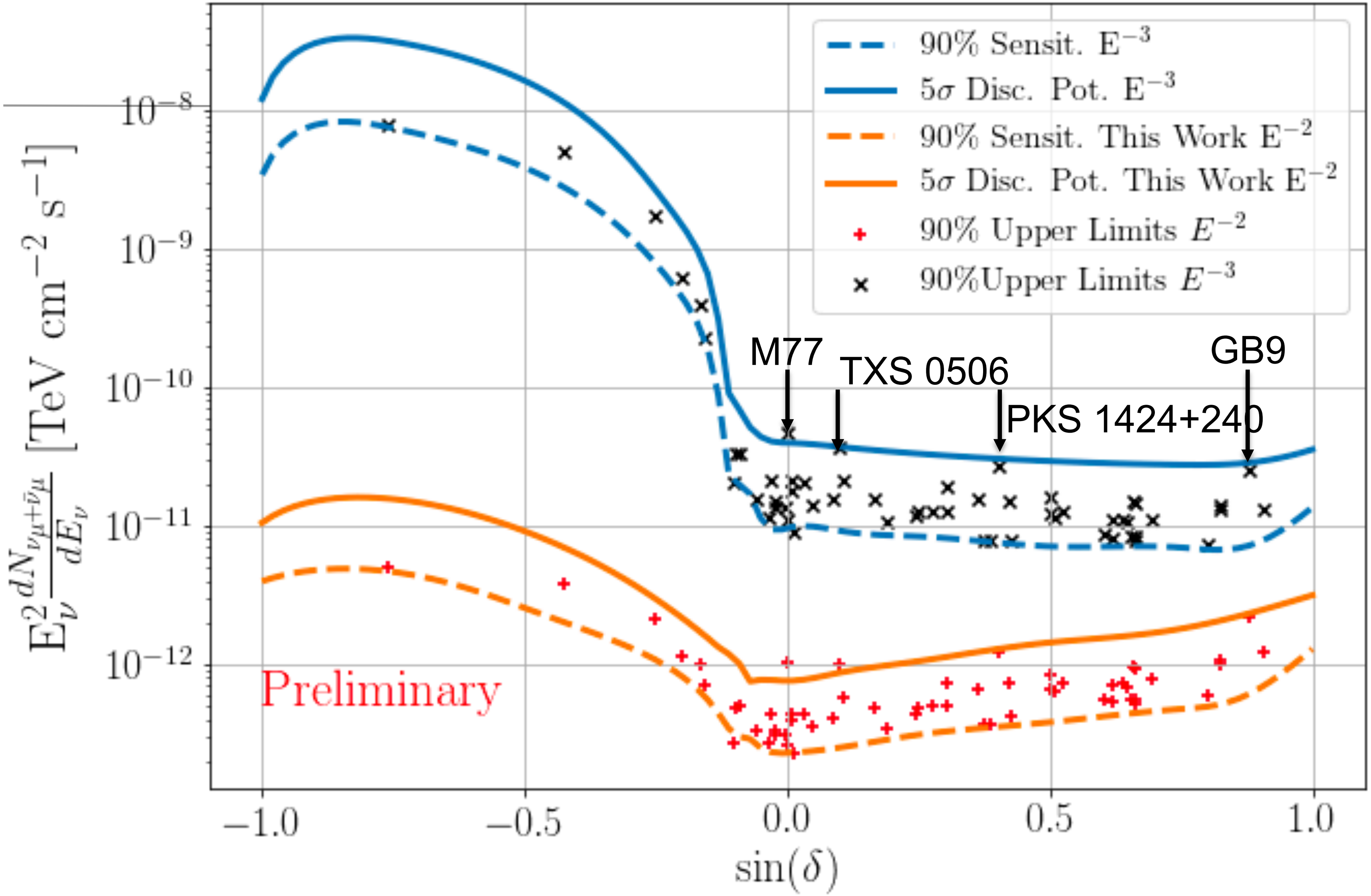


+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

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

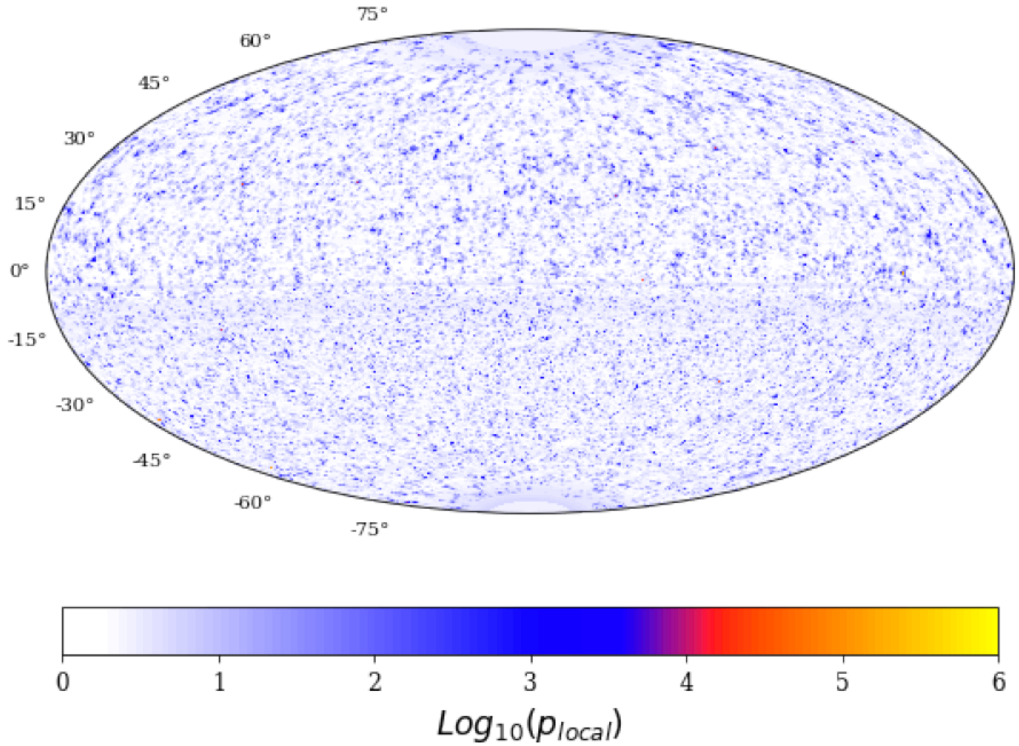


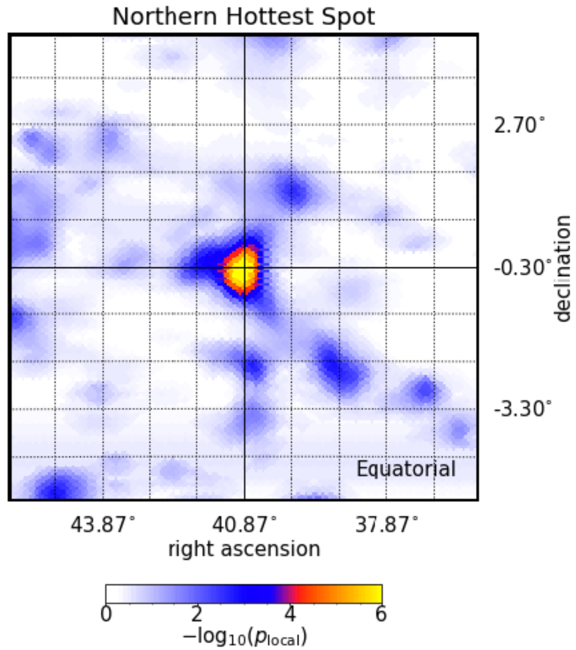
limits and fluctuations(?)

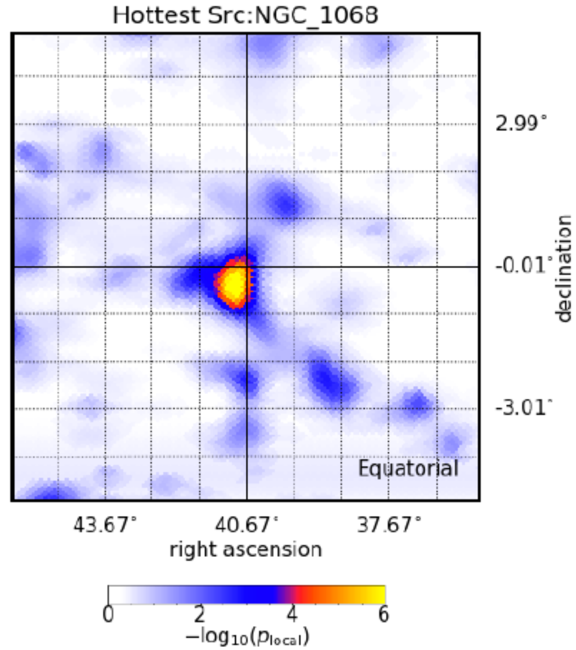


this is the case for larger detectors with better angular resolution!

10 years of muon neutrinos

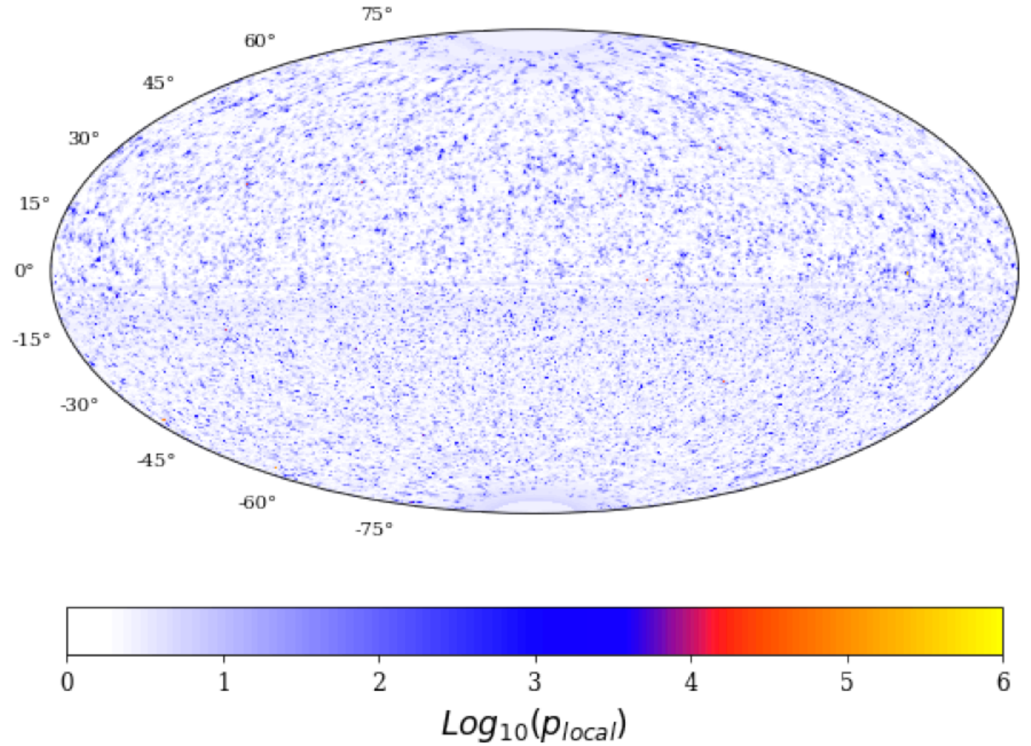


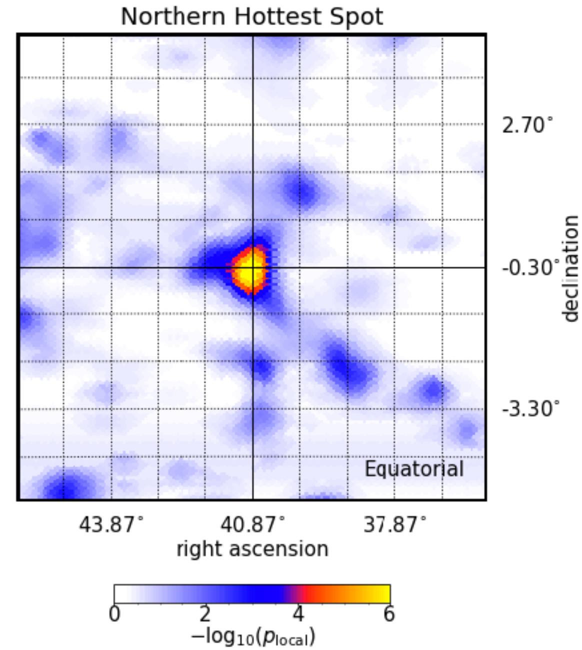


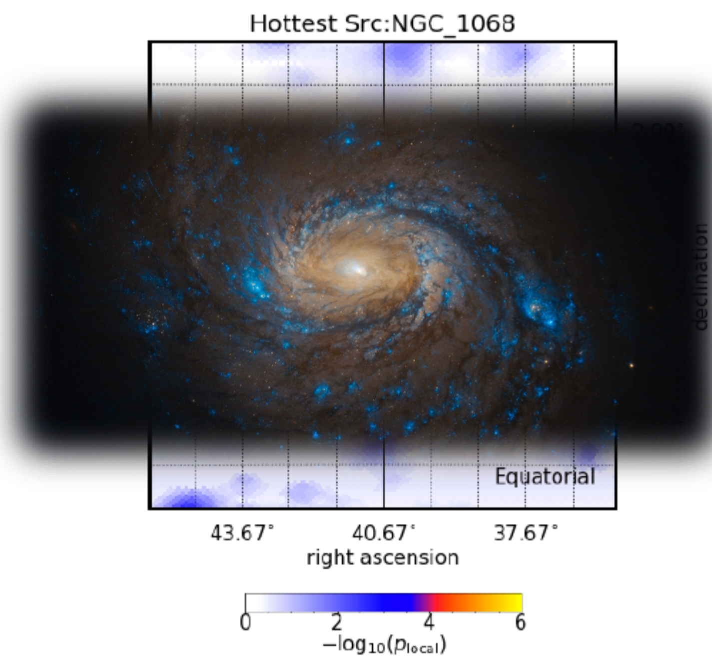


Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496

10 years of muon neutrinos







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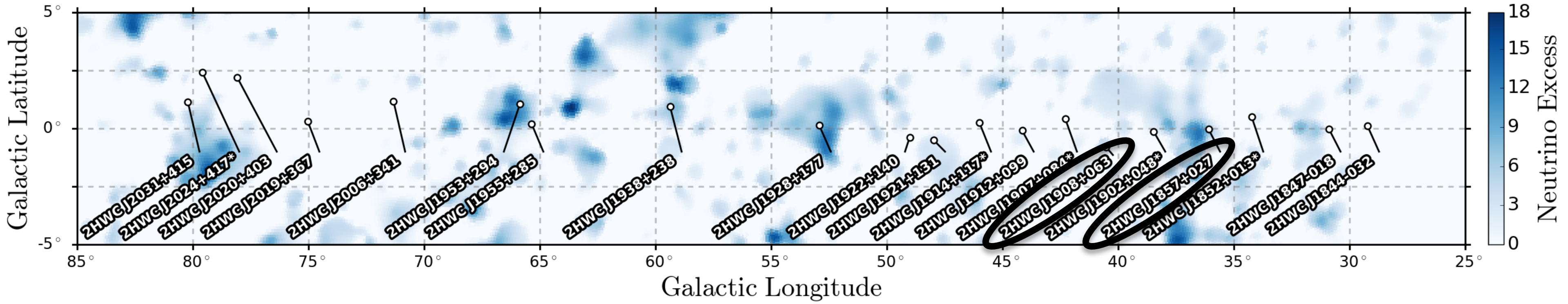
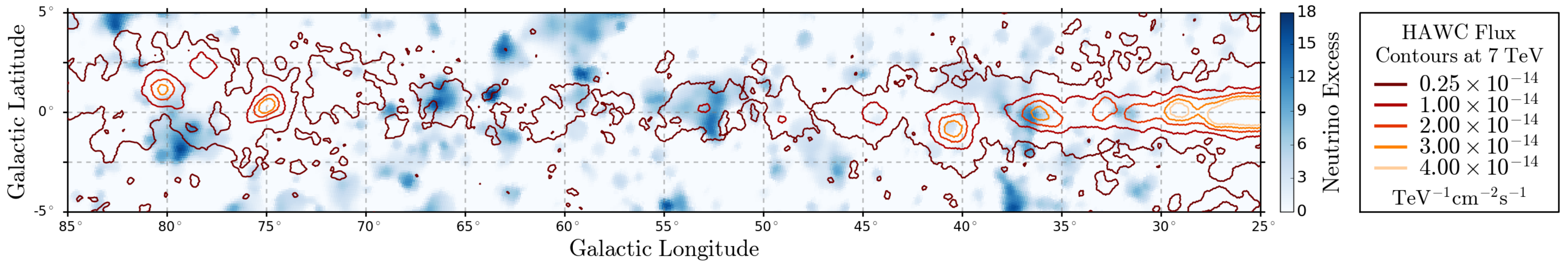
	UNID	0.496	0.496

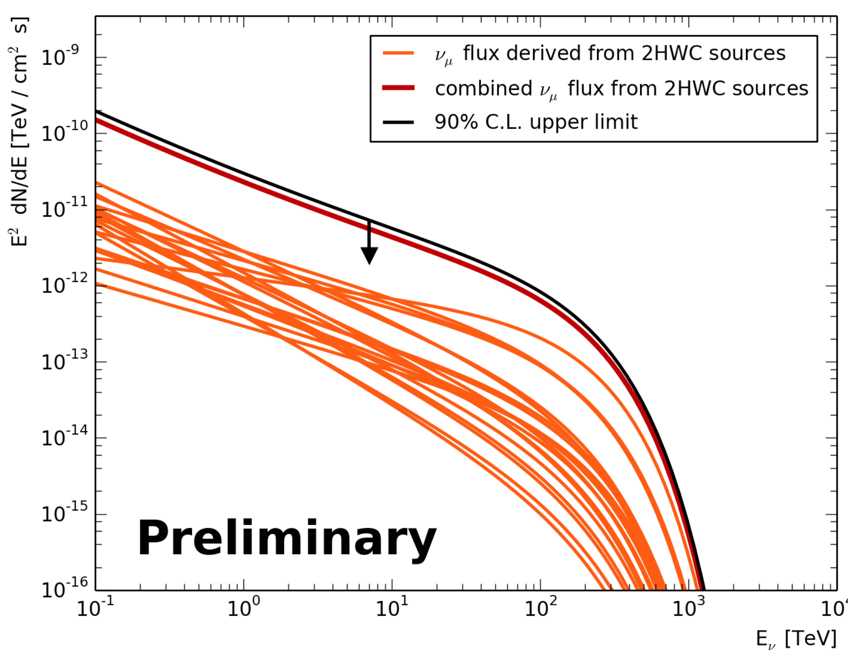
- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

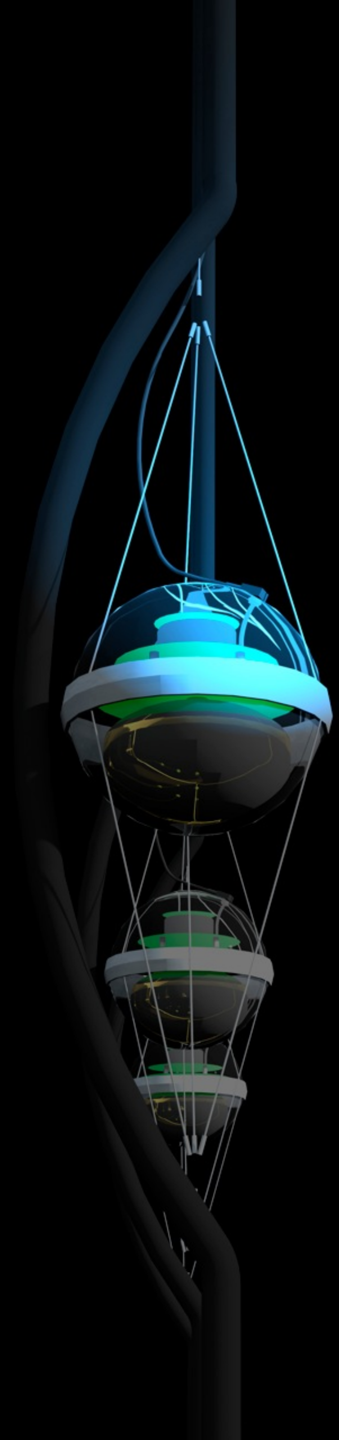




HAWC photons and IceCube neutrinos

neutrino flux at the level predicted, but not significant yet





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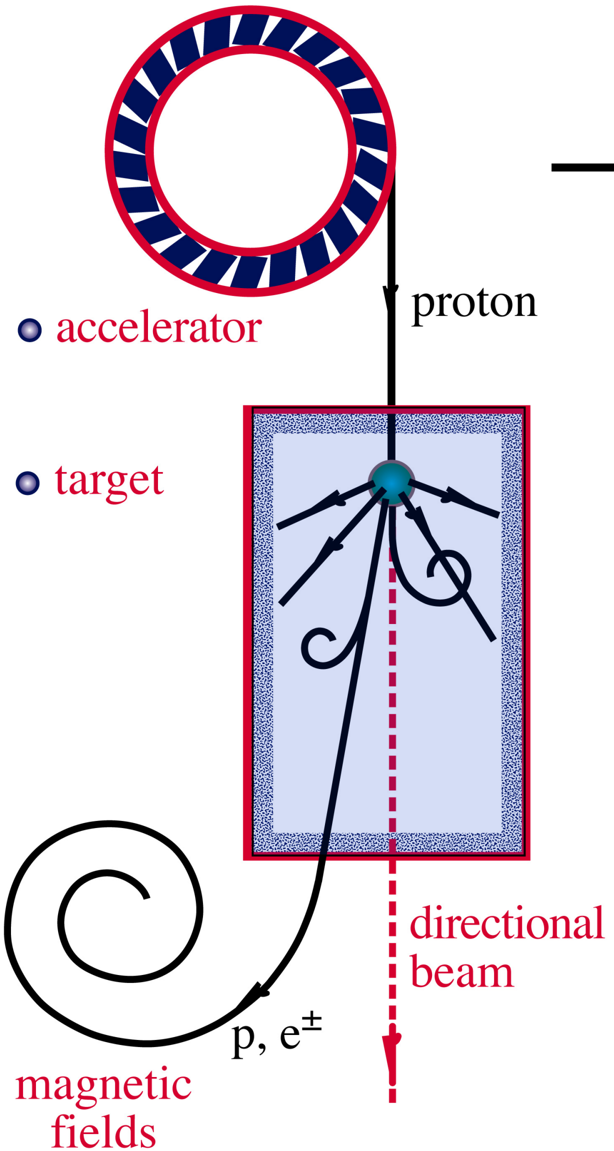
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

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

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

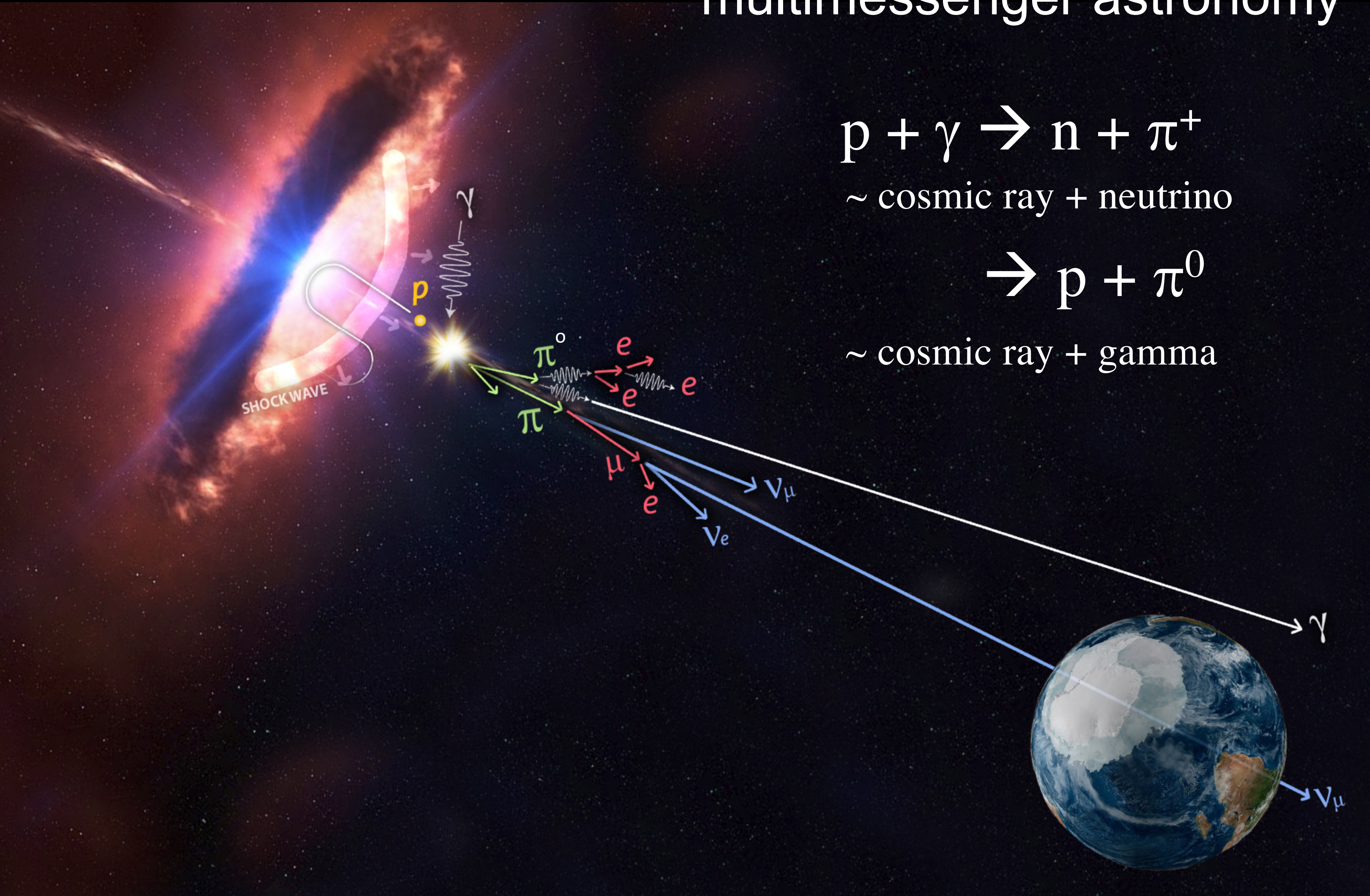
multimessenger astronomy

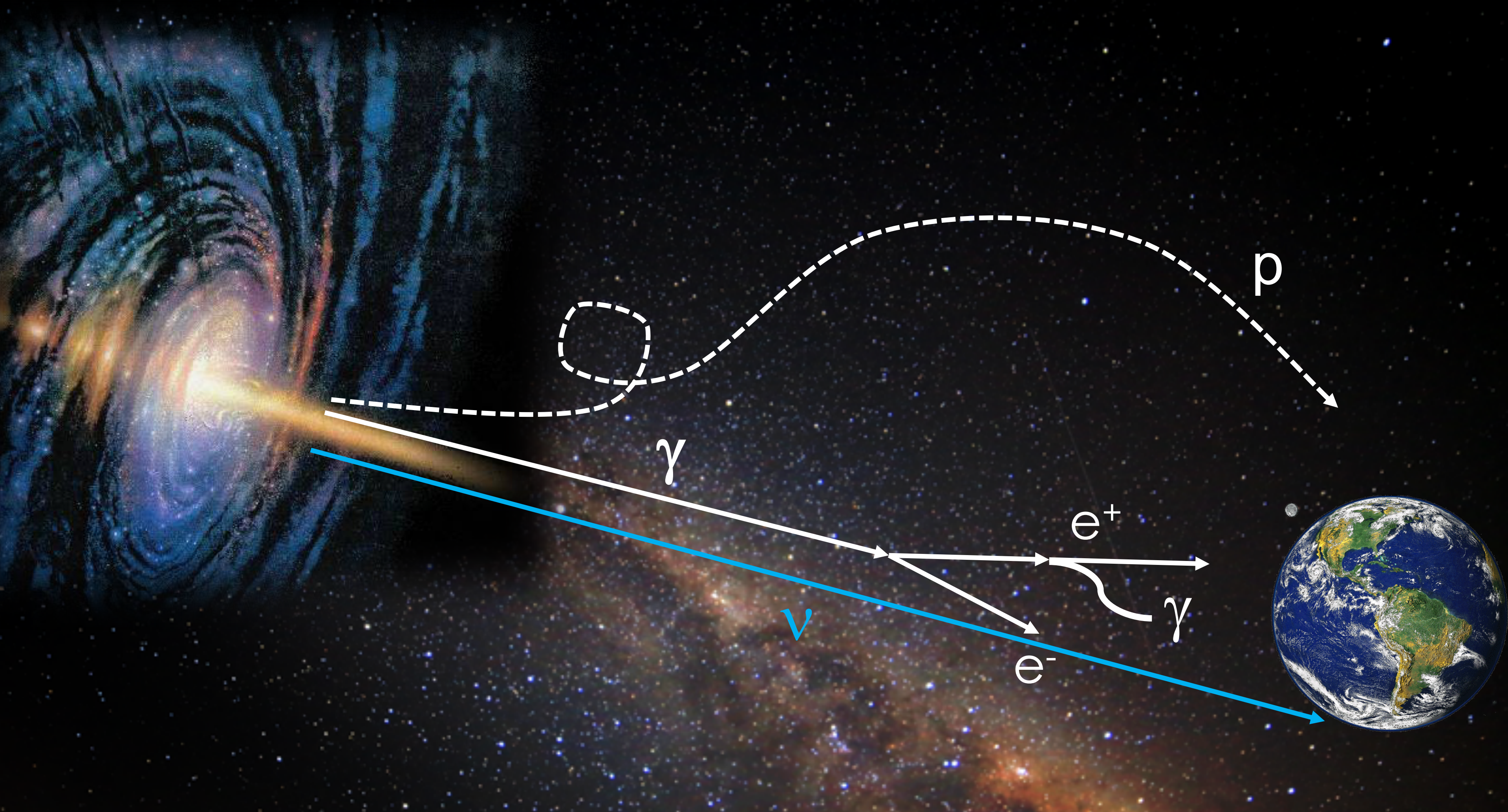
$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

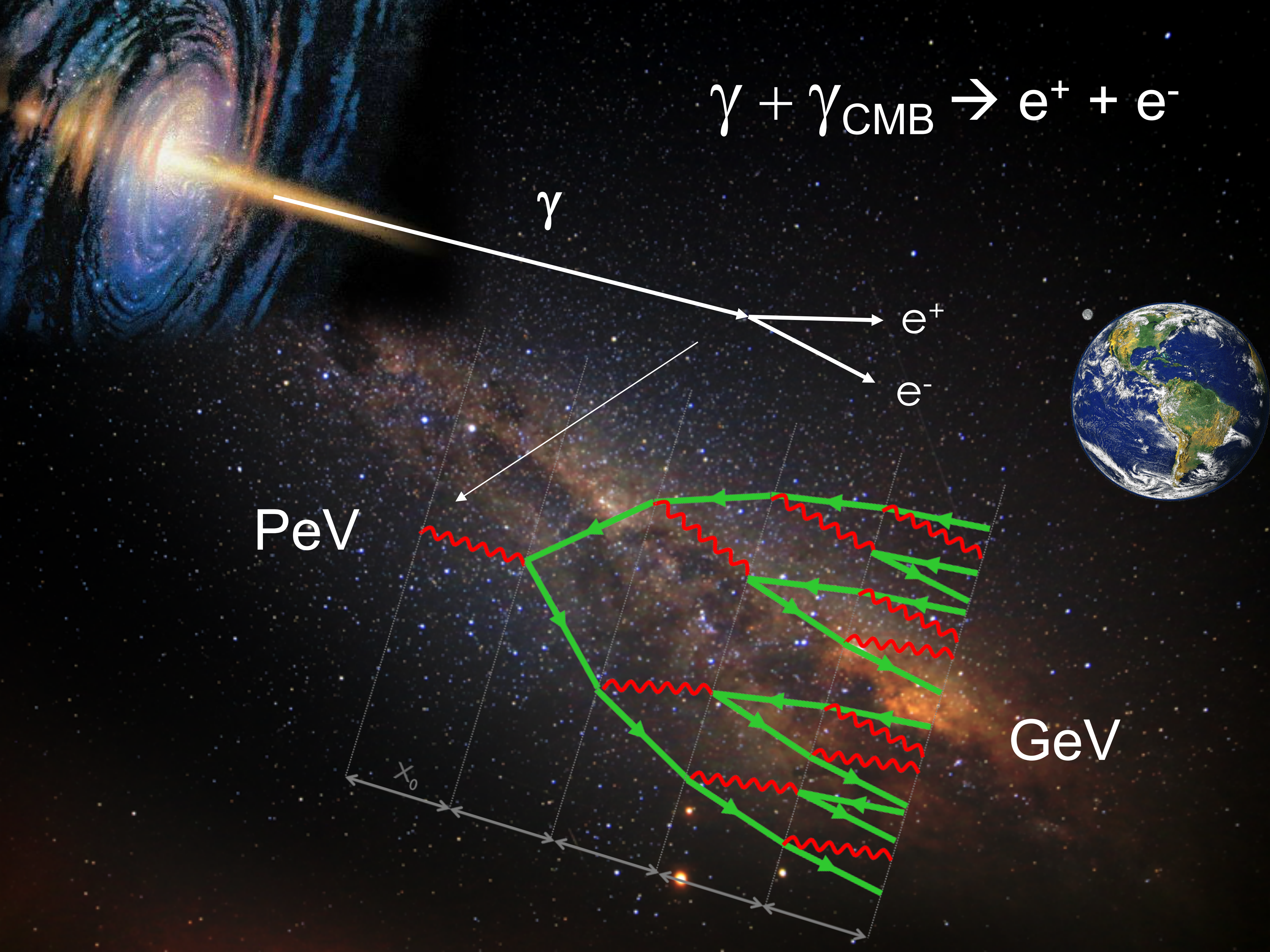
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

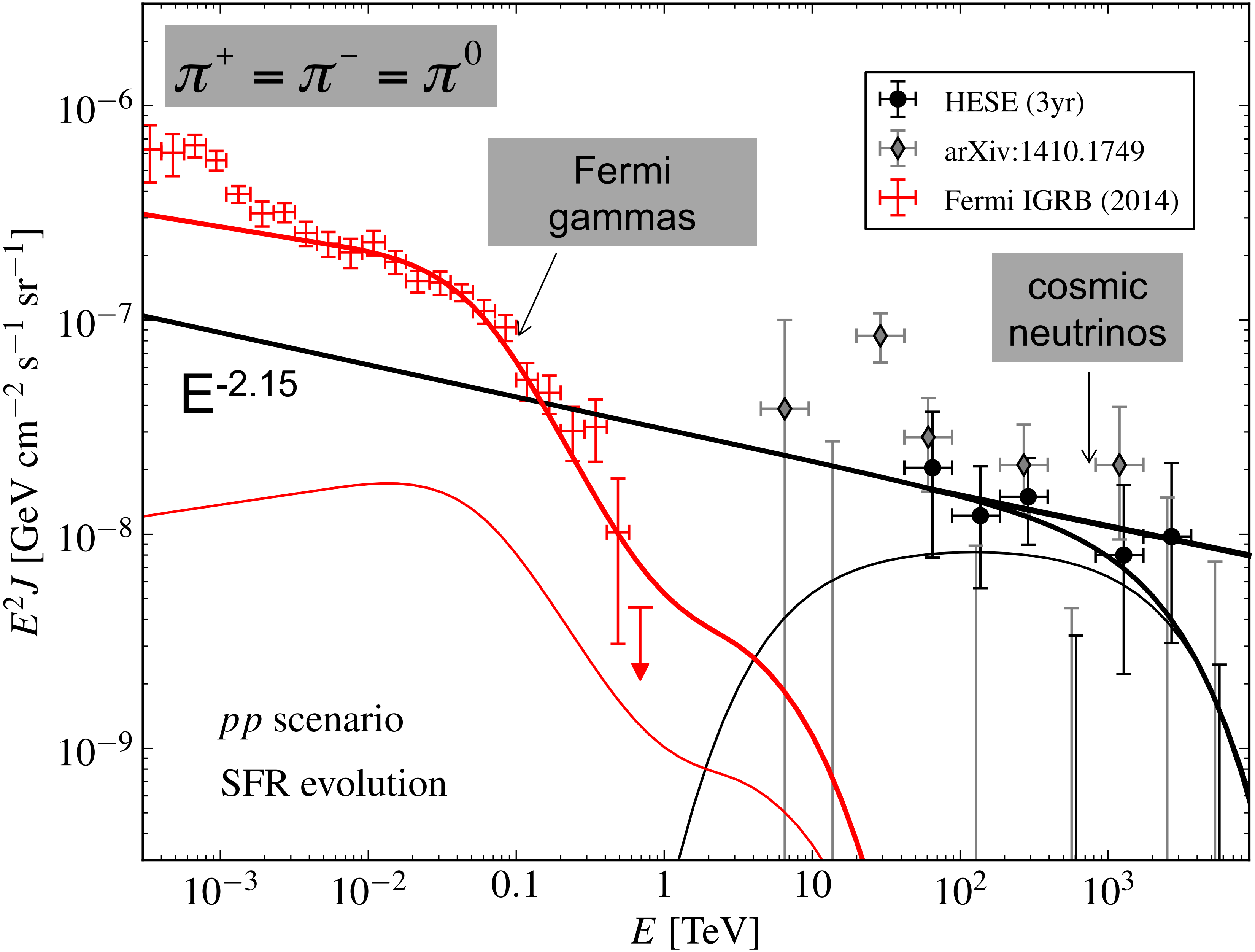




gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

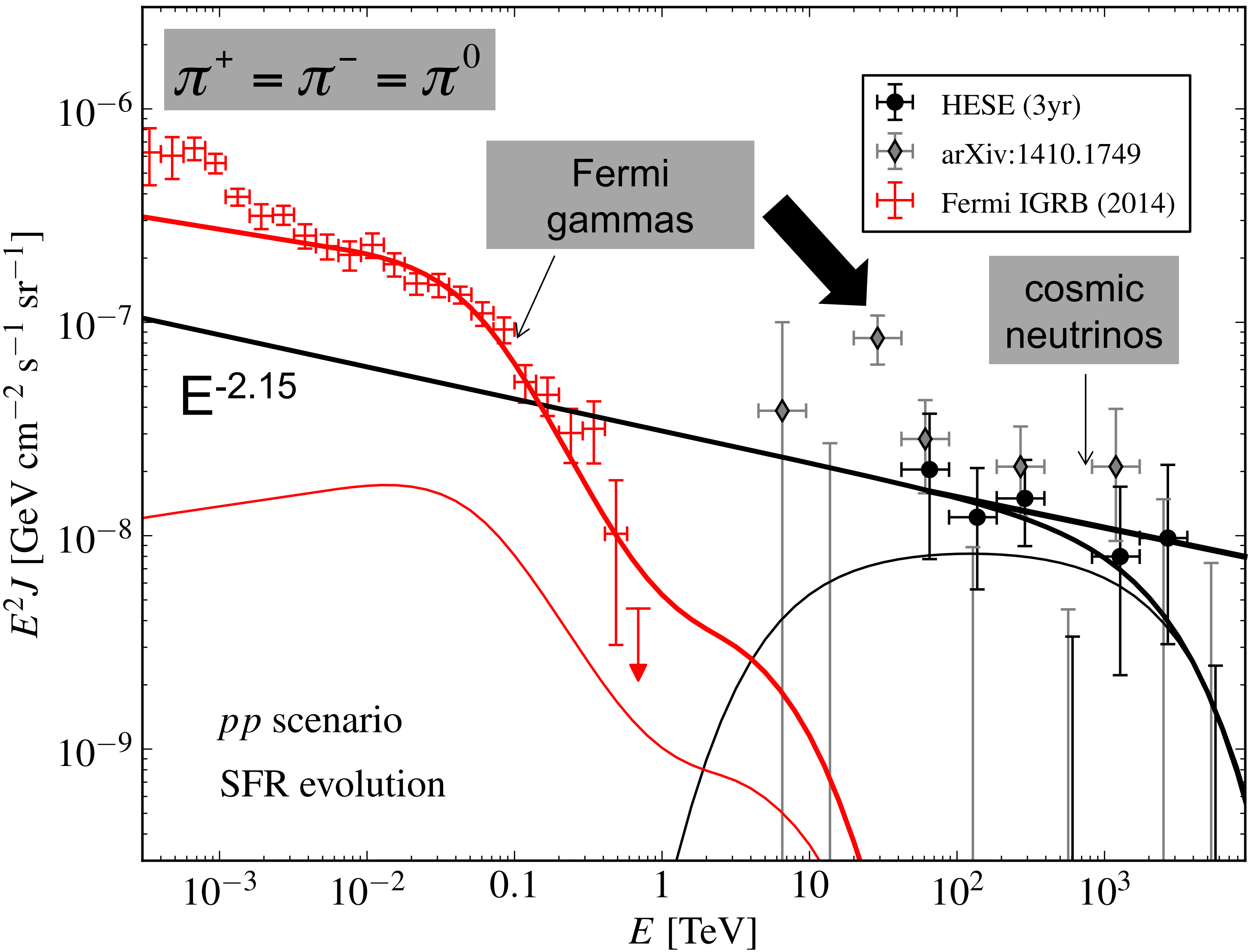


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

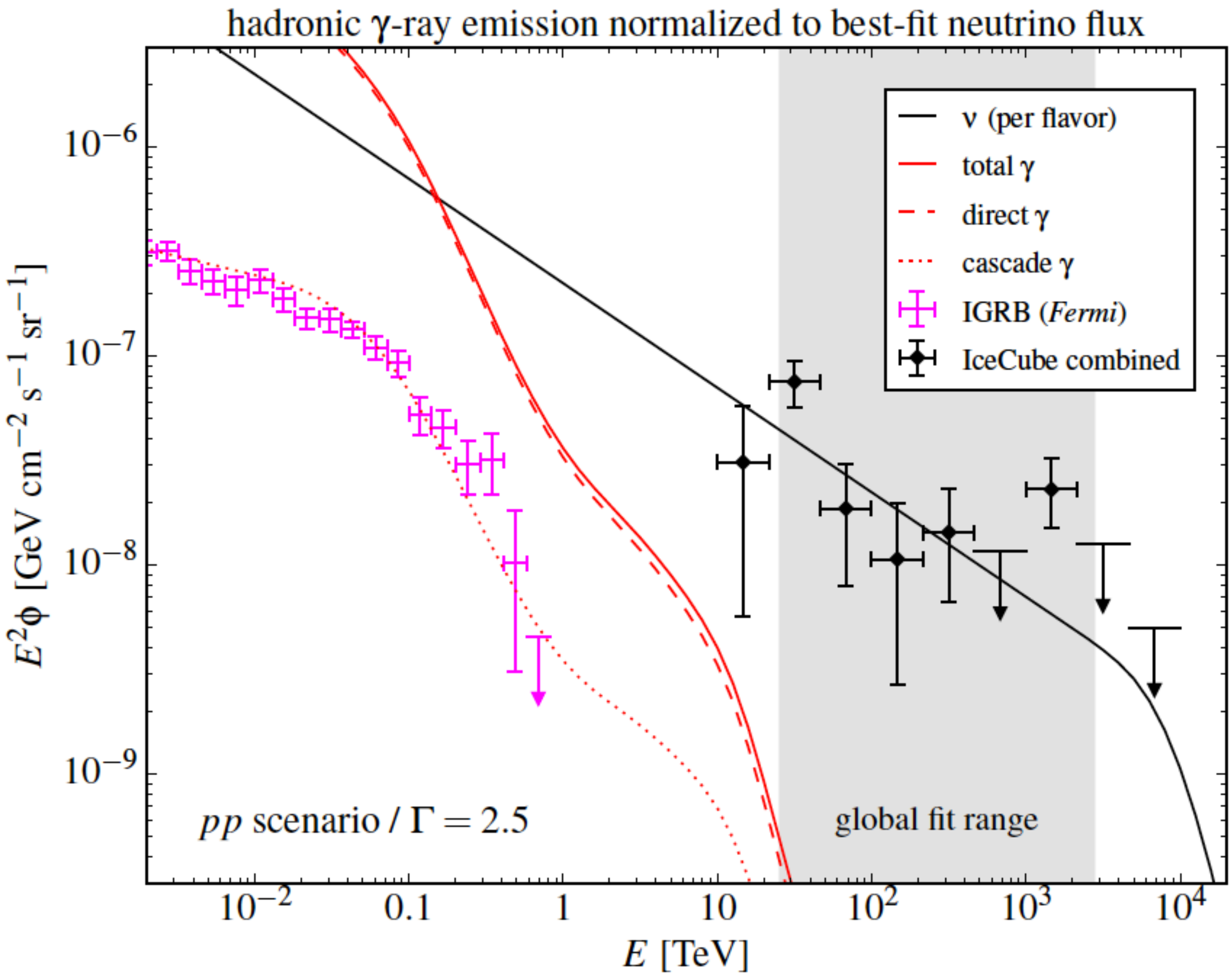


$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

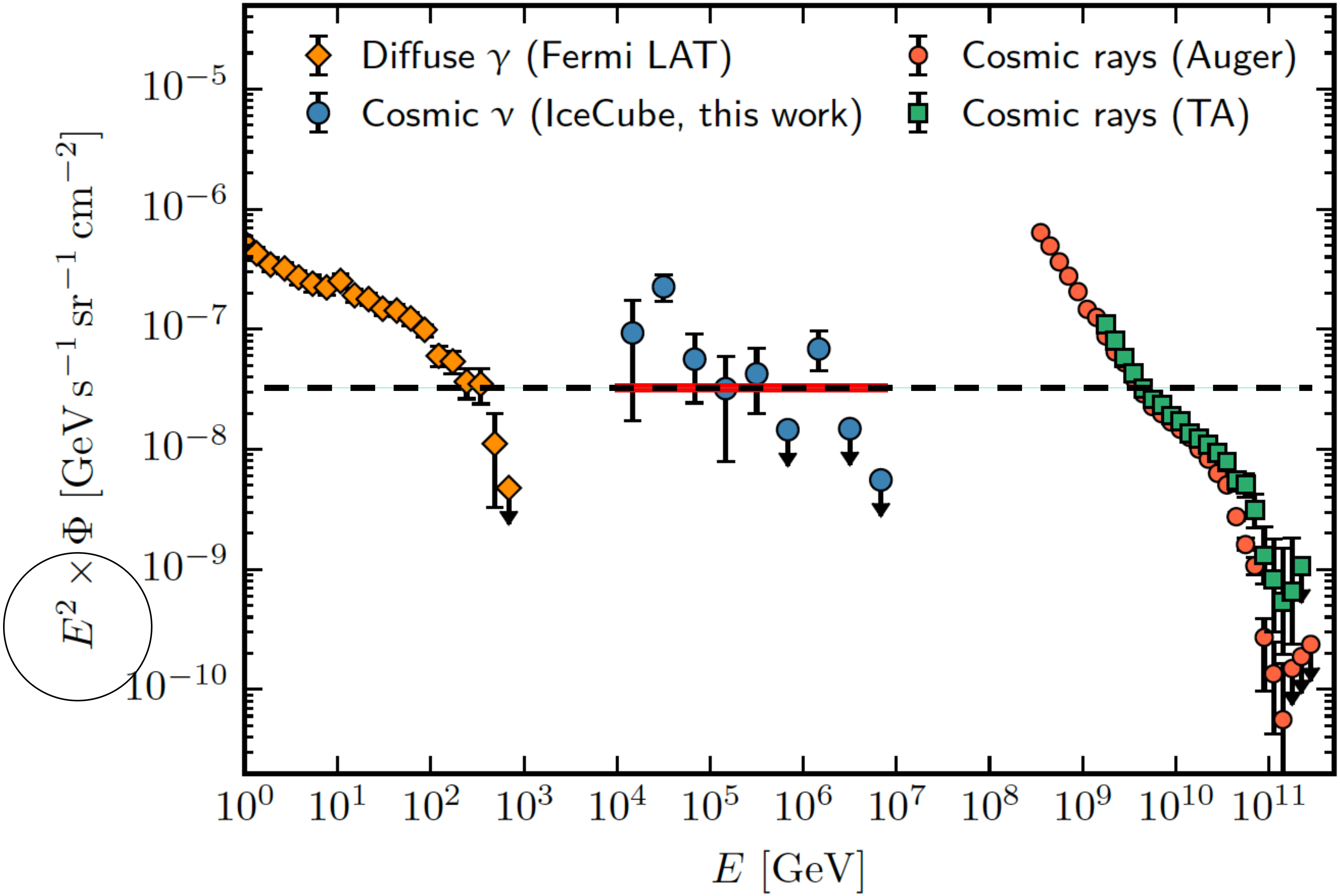
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



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



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

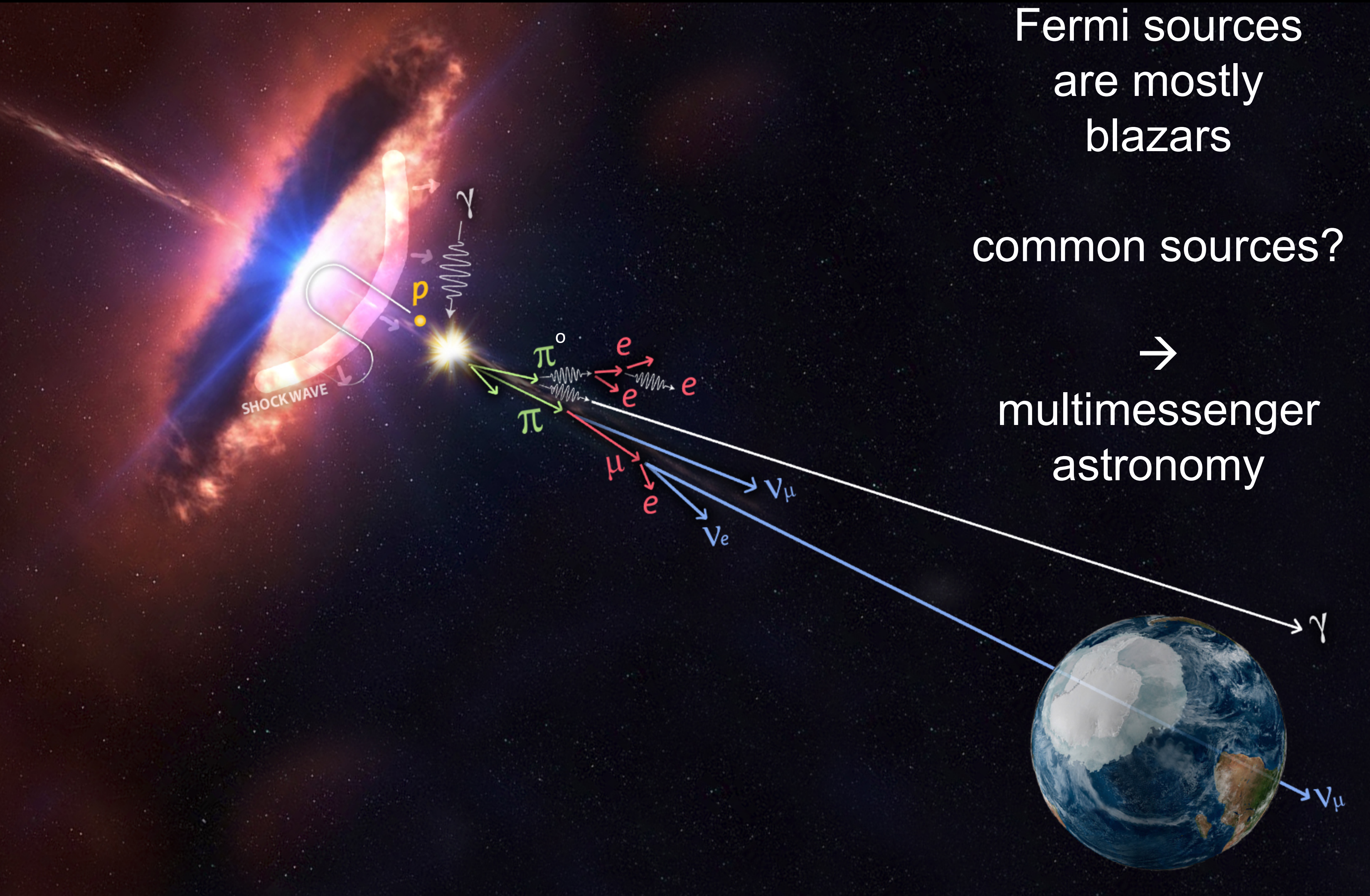


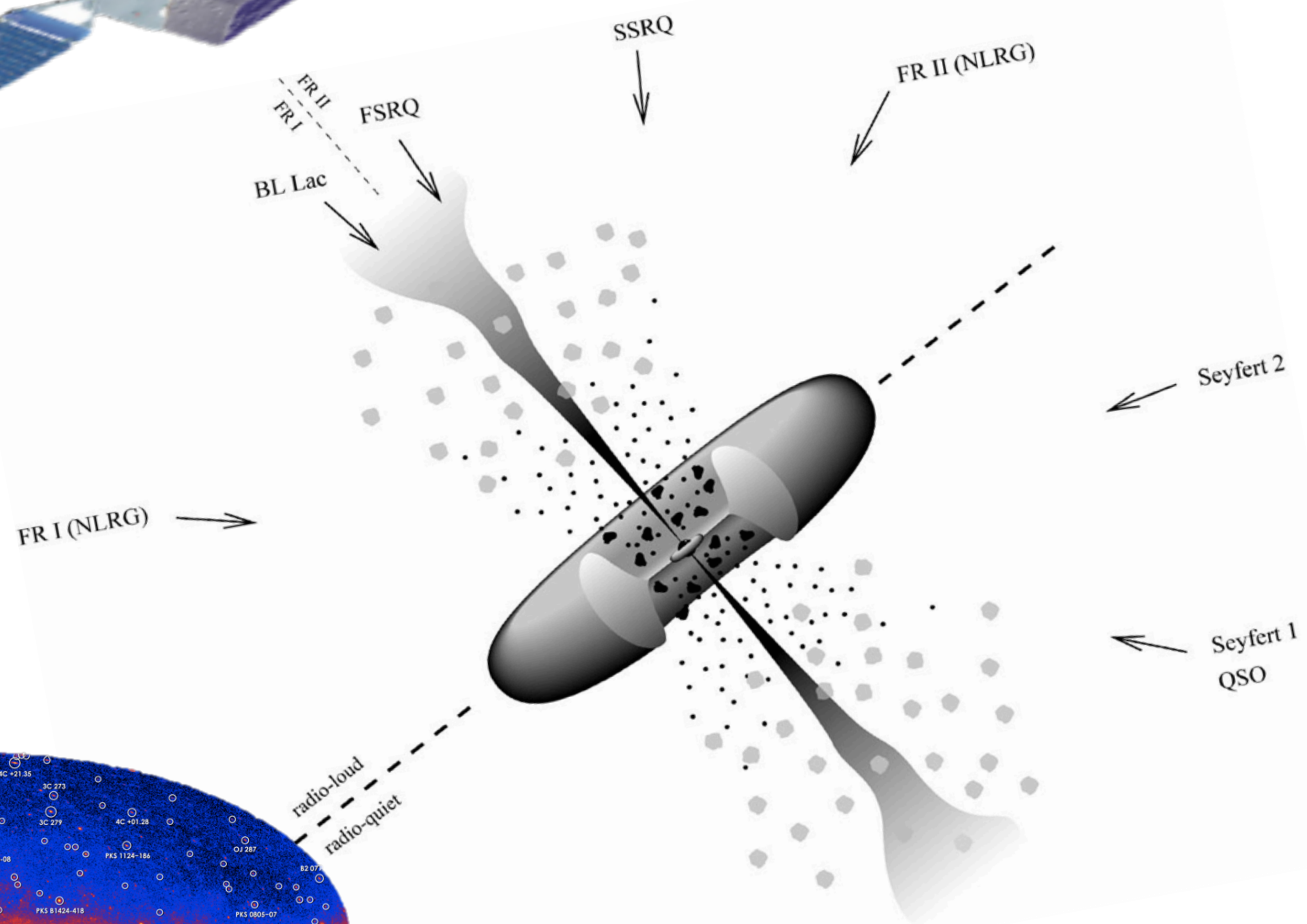
energy in the Universe in gamma rays, neutrinos and cosmic rays

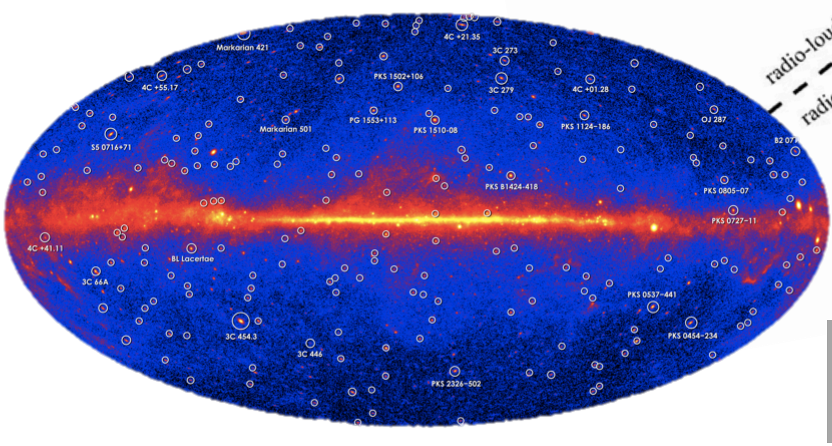
Fermi sources
are mostly
blazars

common sources?

→
multimessenger
astronomy



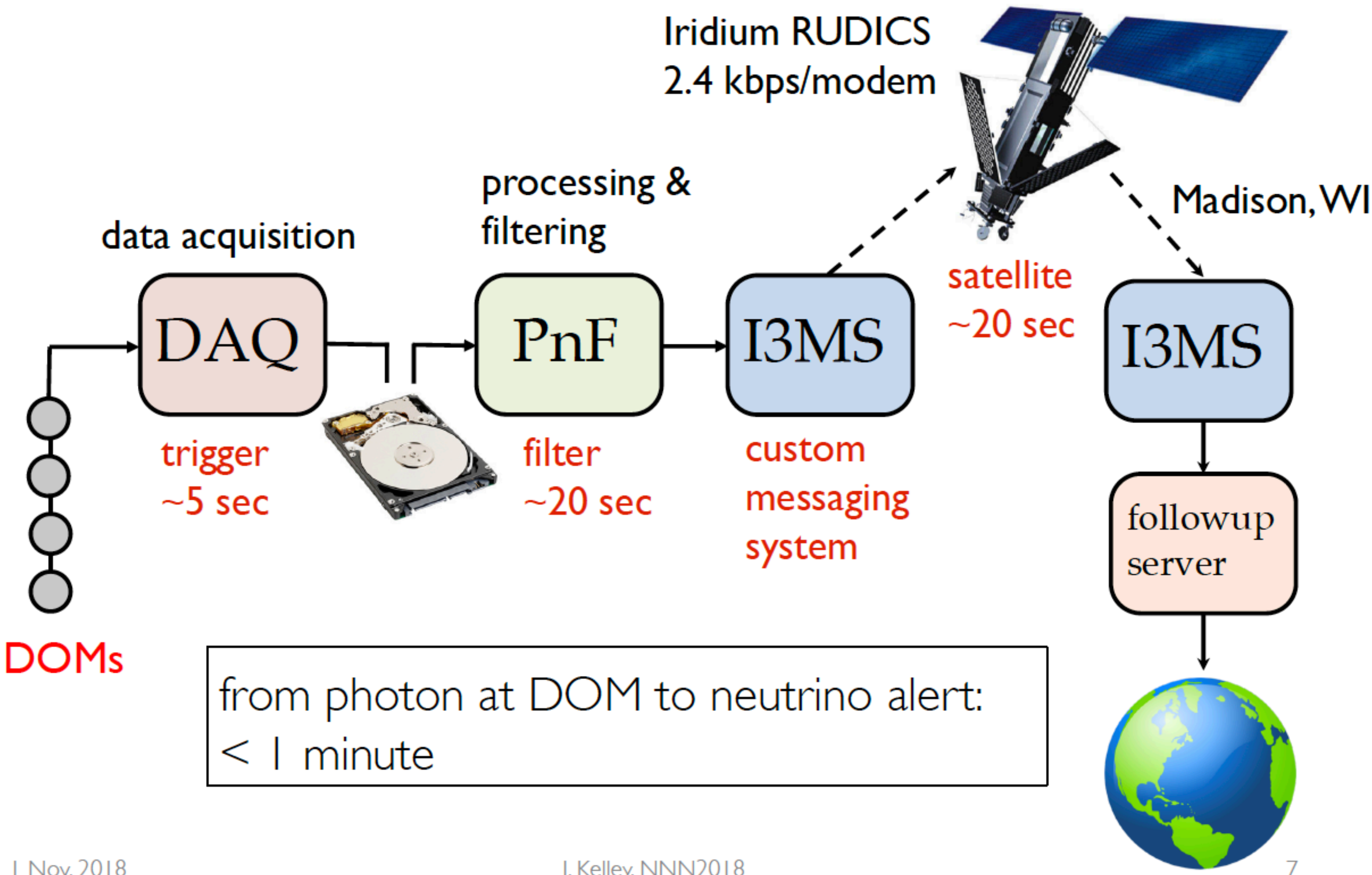




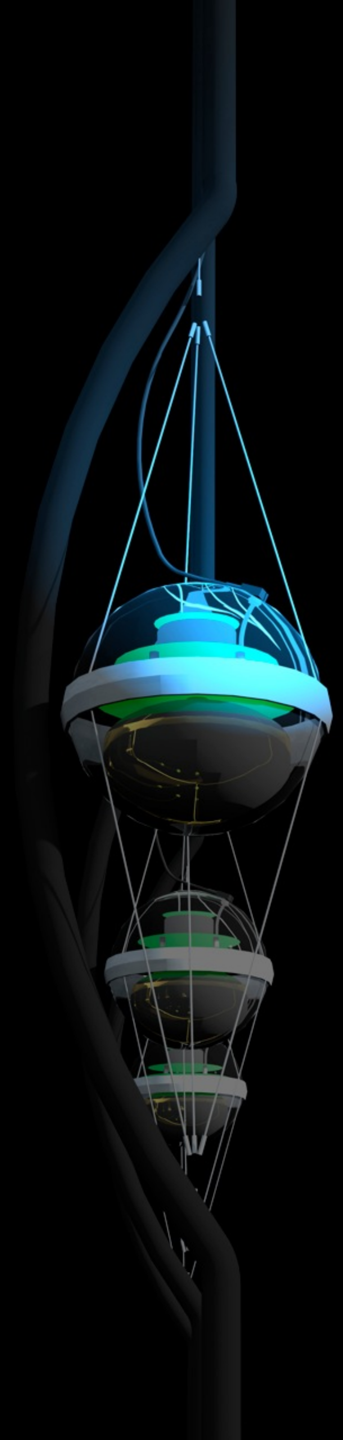
Fermi sky: mostly bazars

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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



from photon at DOM to neutrino alert:
< 1 minute



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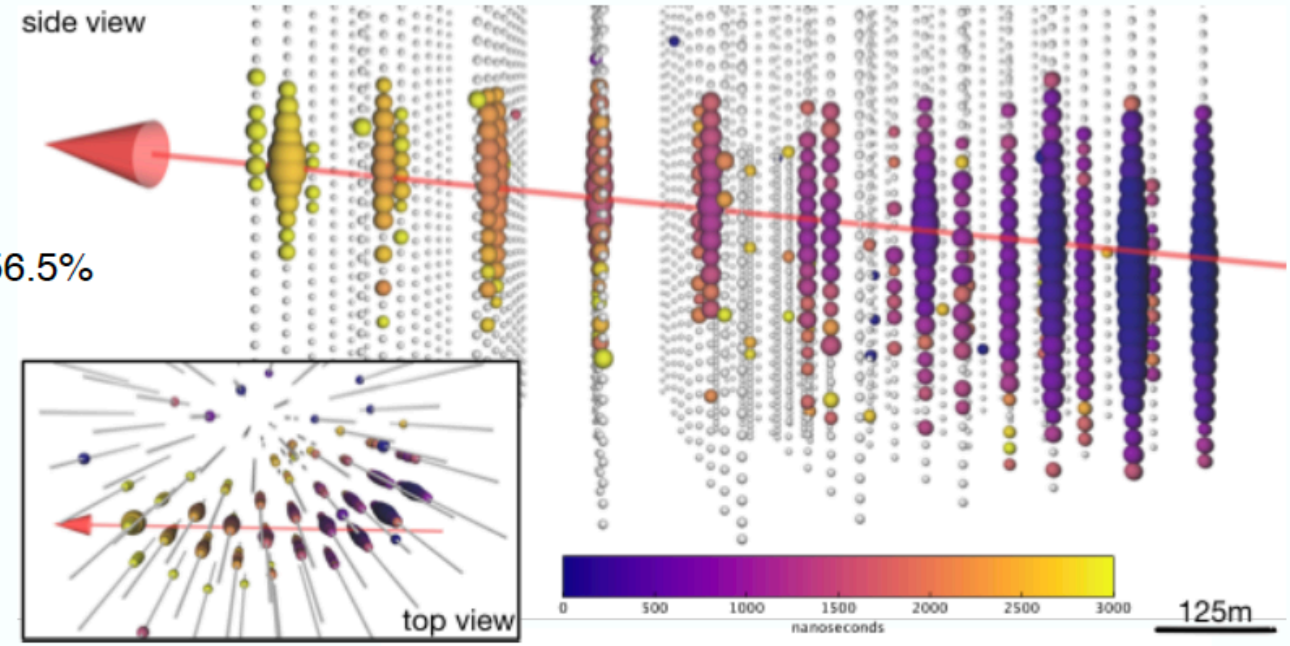
IceCube Trigger

43 seconds after trigger, GCN notice was sent

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

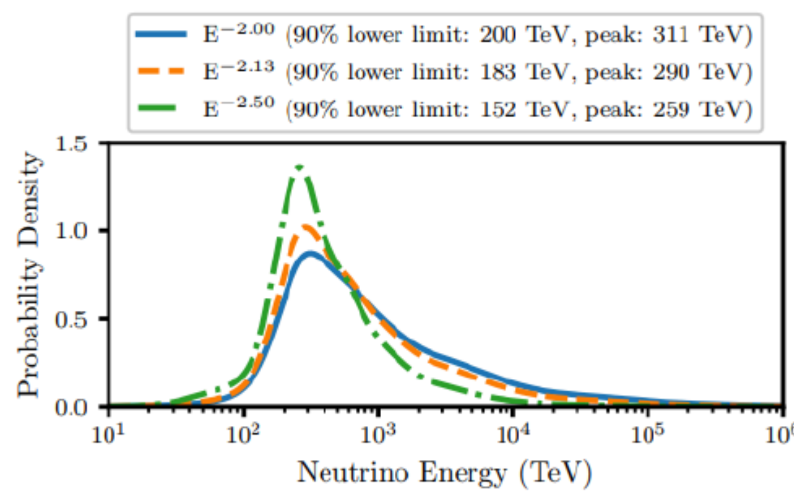
IC-170922A

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



Signalness: 56.5%

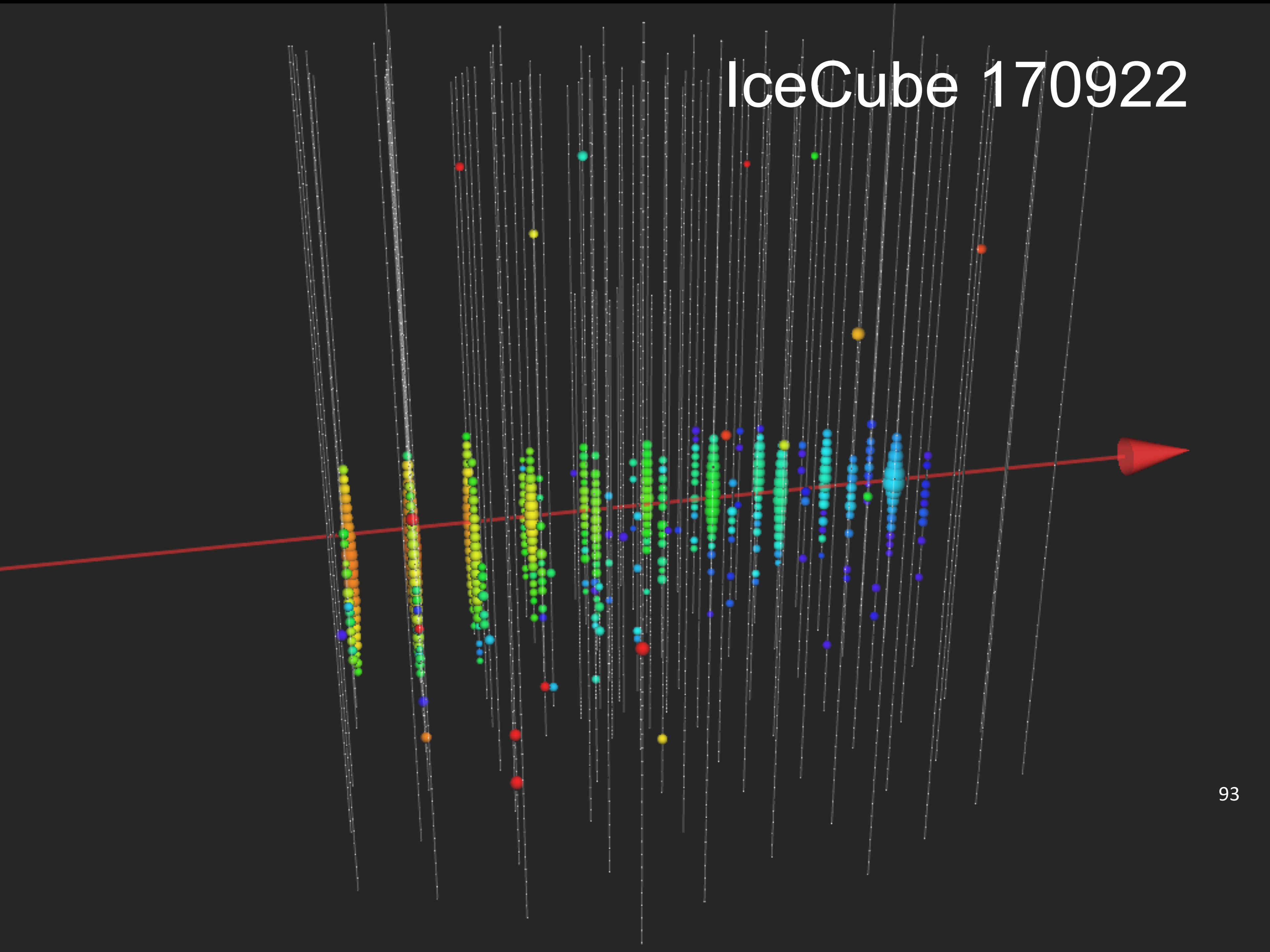
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



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

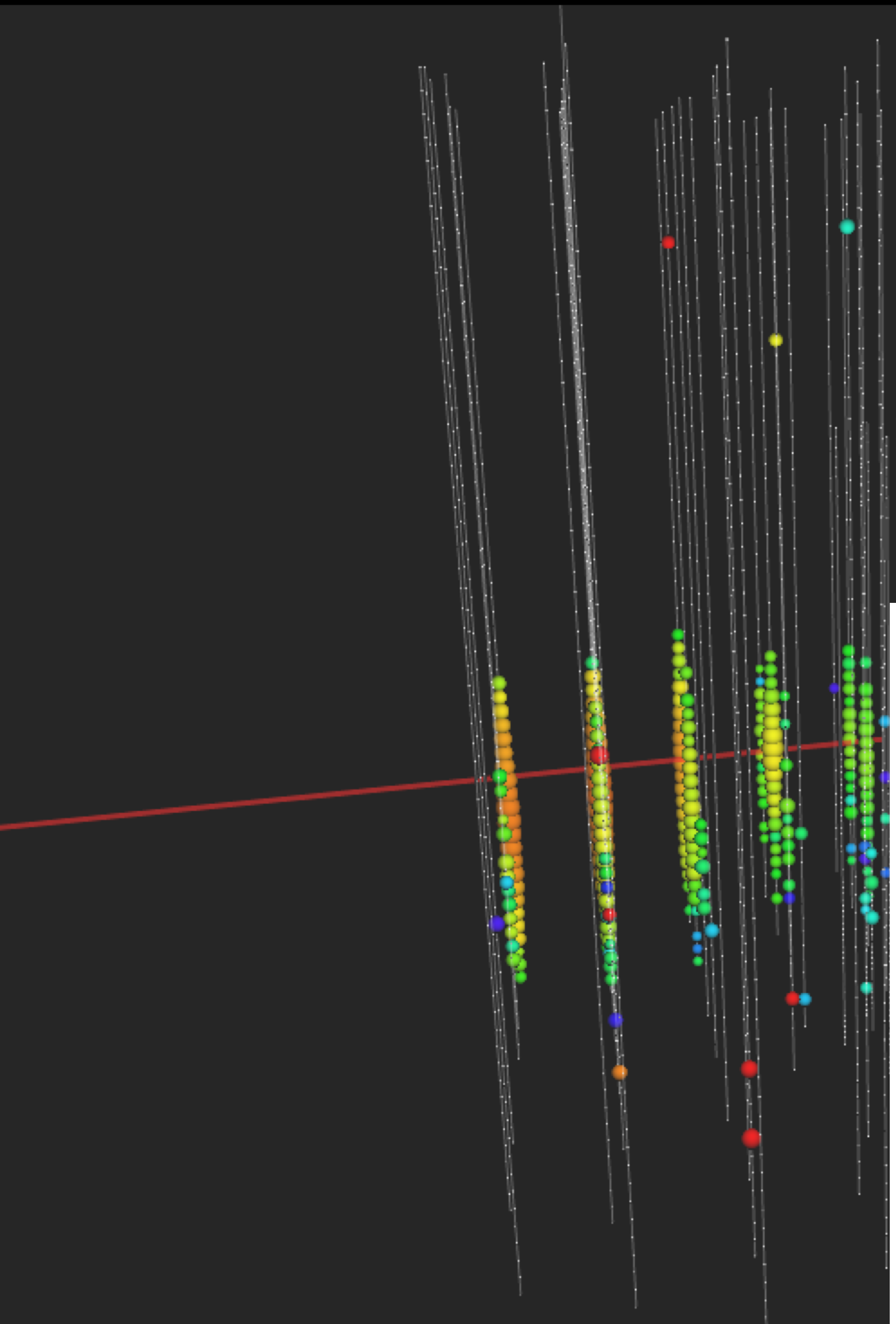
https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

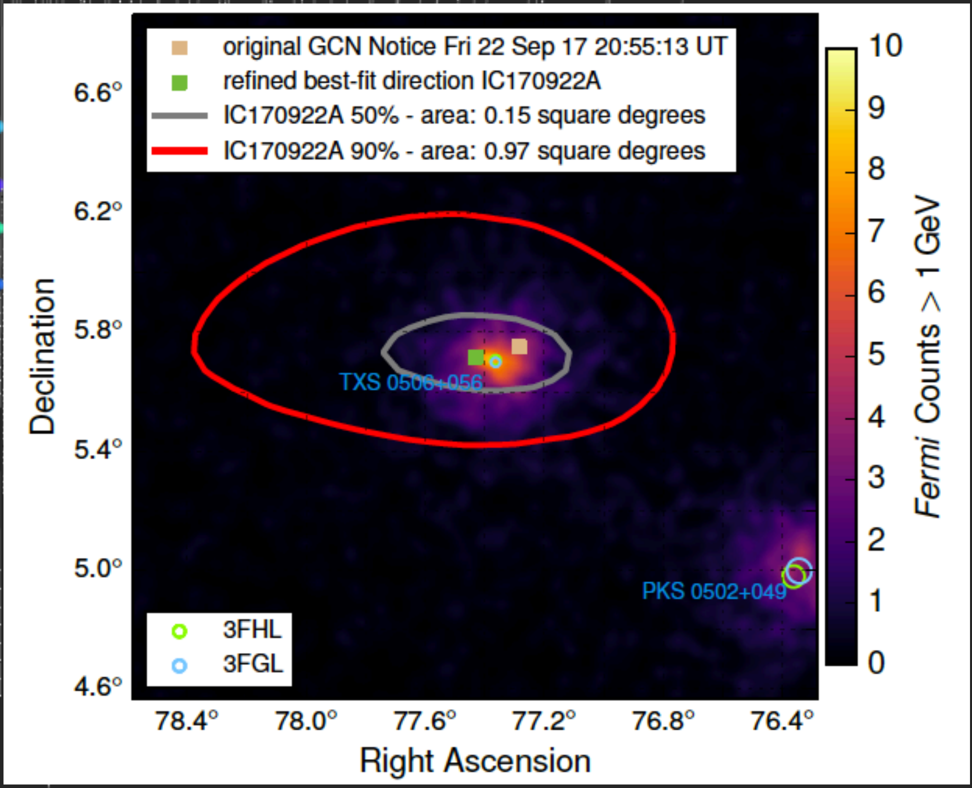
IceCube 170922



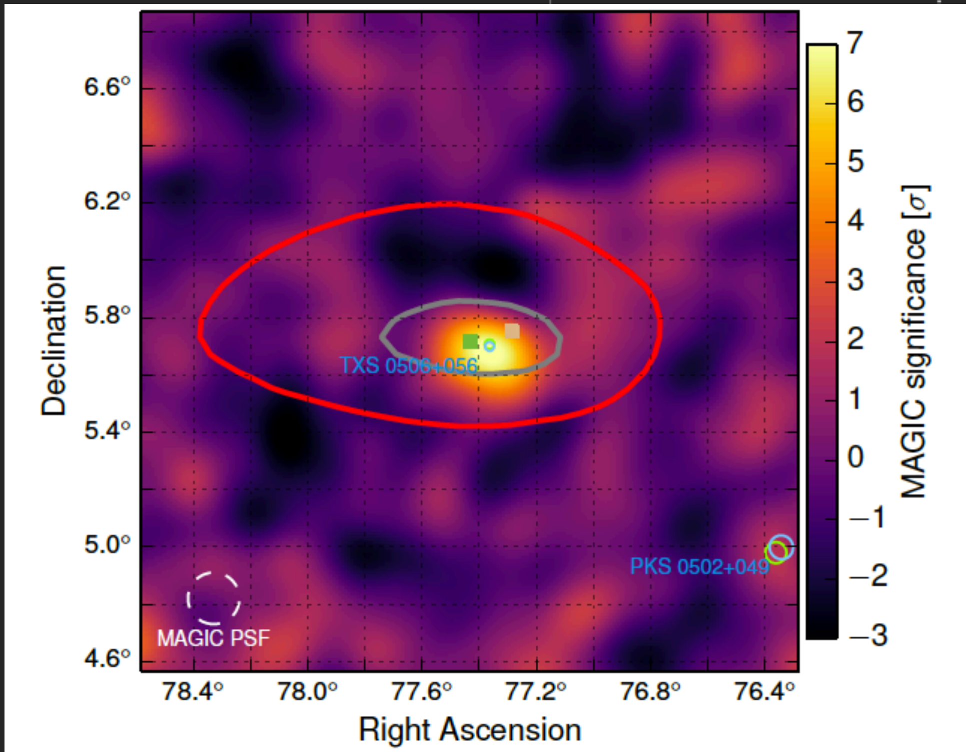
IceCube 170922

Fermi detects a flaring blazar within 0.06°



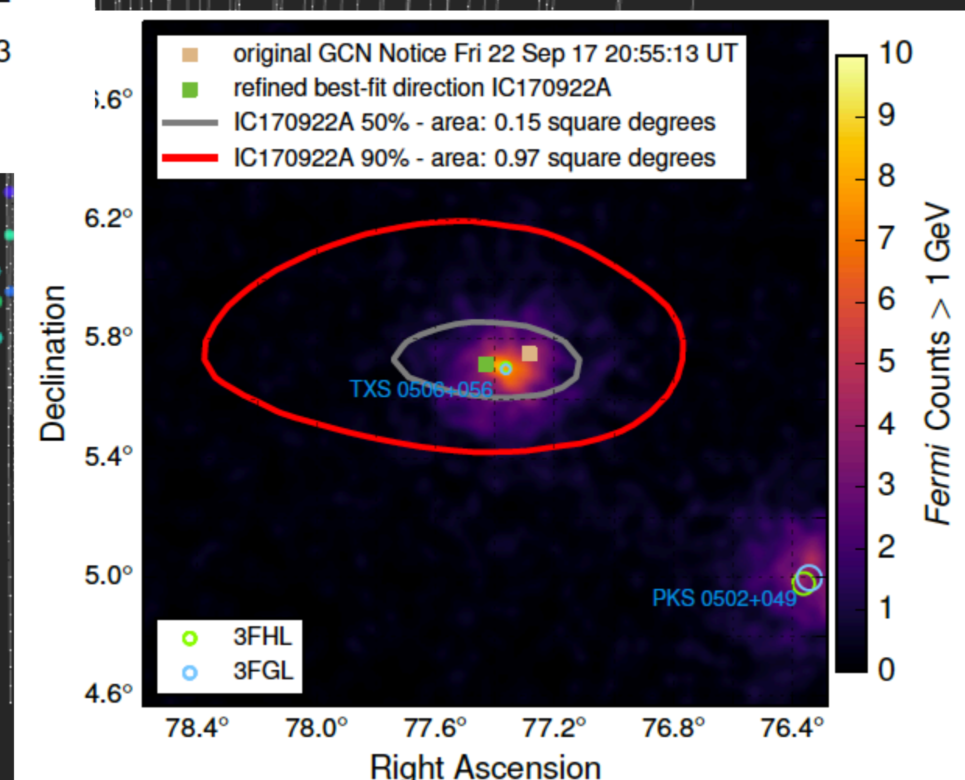


IceCube 170922



Fermi
detects a flaring
blazar within 0.1°

MAGIC
detects emission of
> 100 GeV gammas



MAGIC atmposheric Cherenkov telescope

Follow-up detections of IC170922 based on public telegrams

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

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

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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.

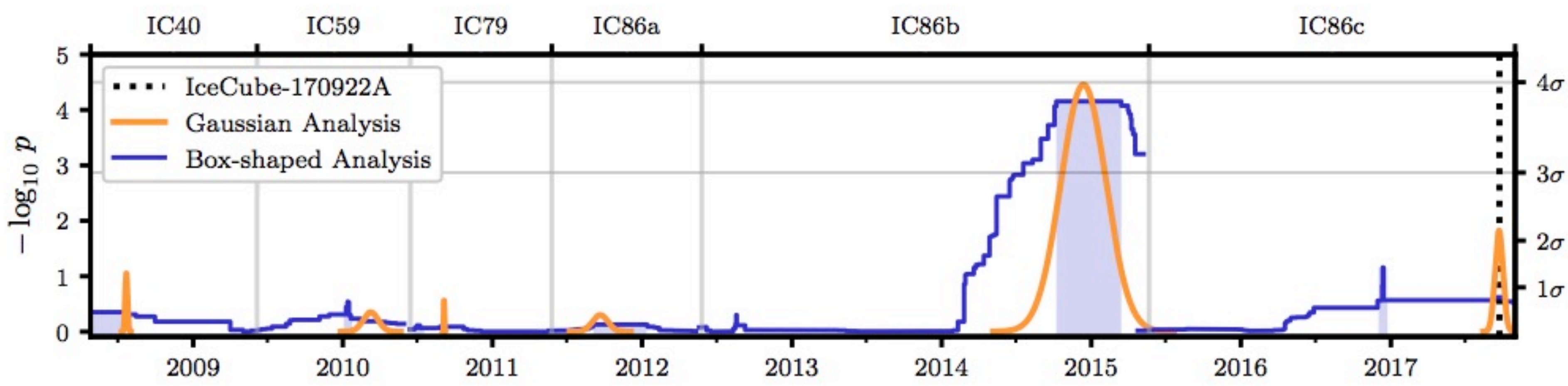
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

- 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

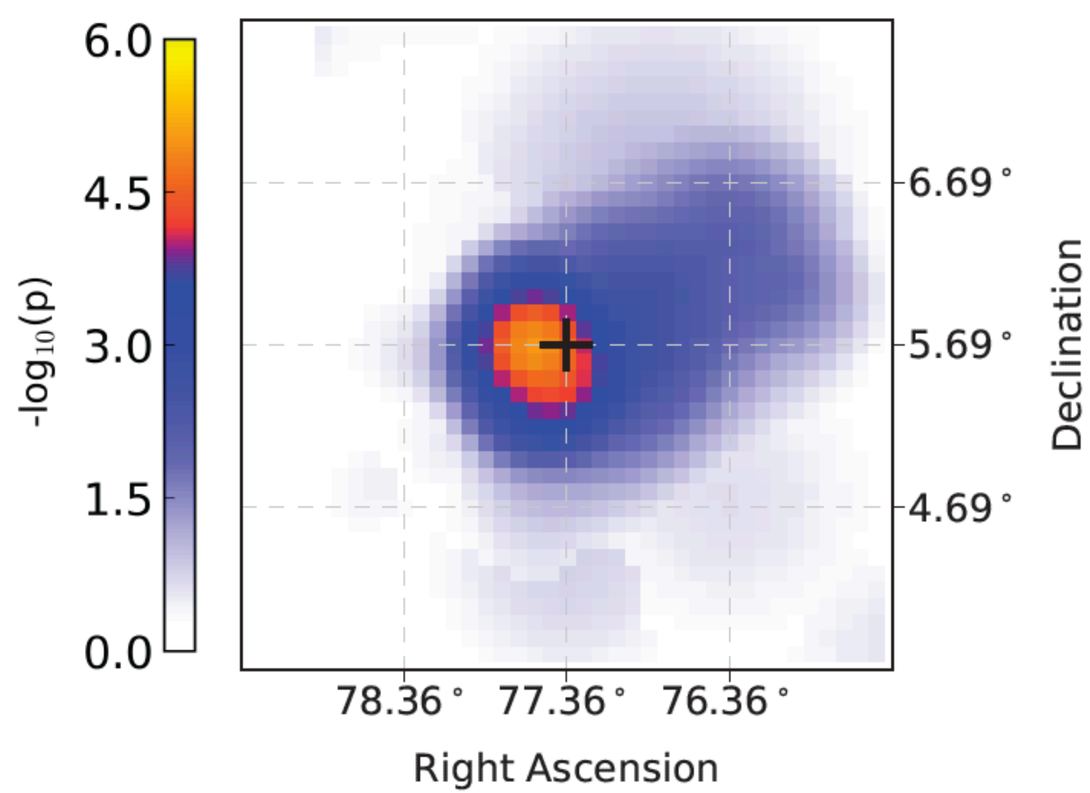
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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

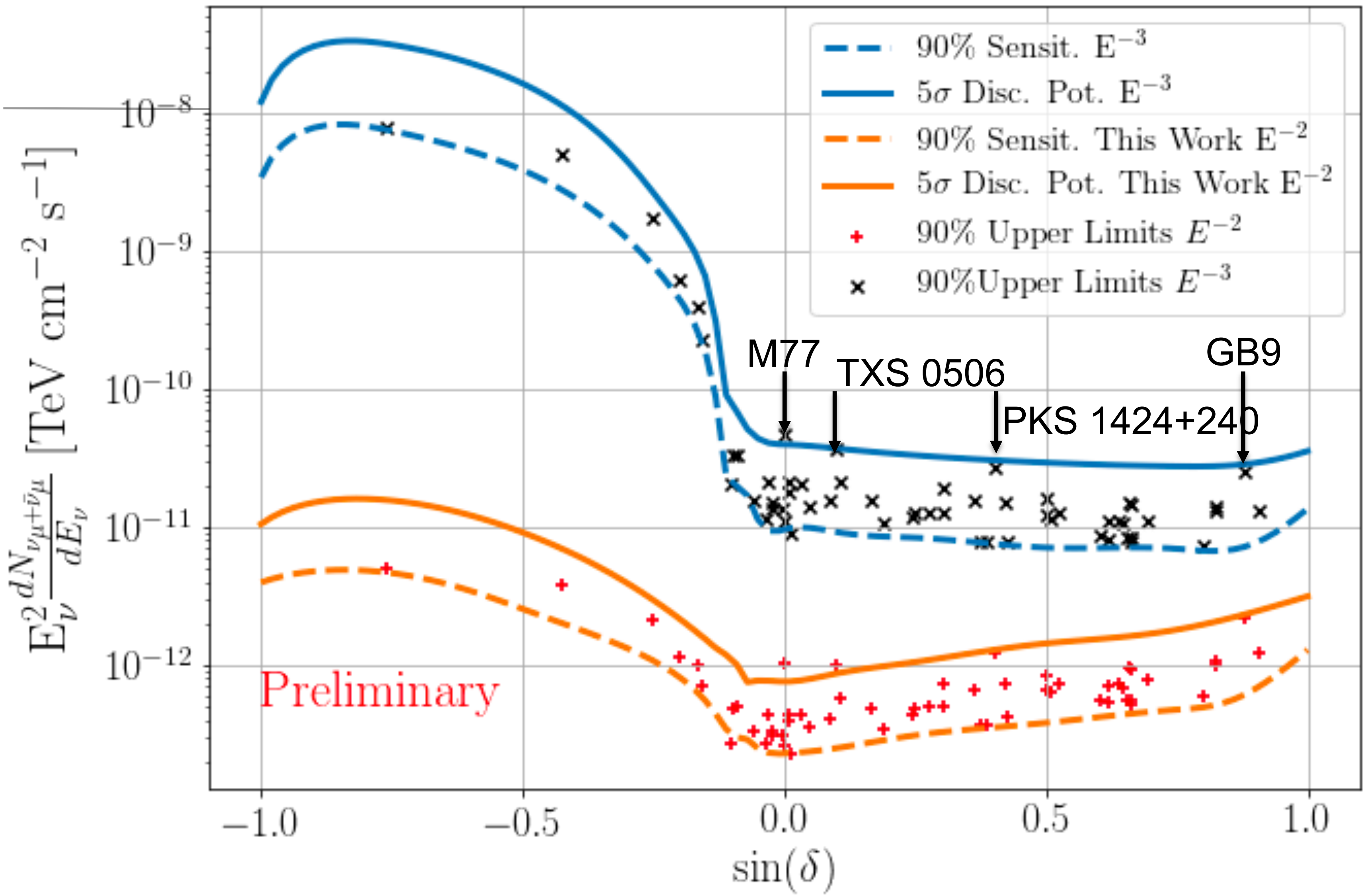


search in archival IceCube data:

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

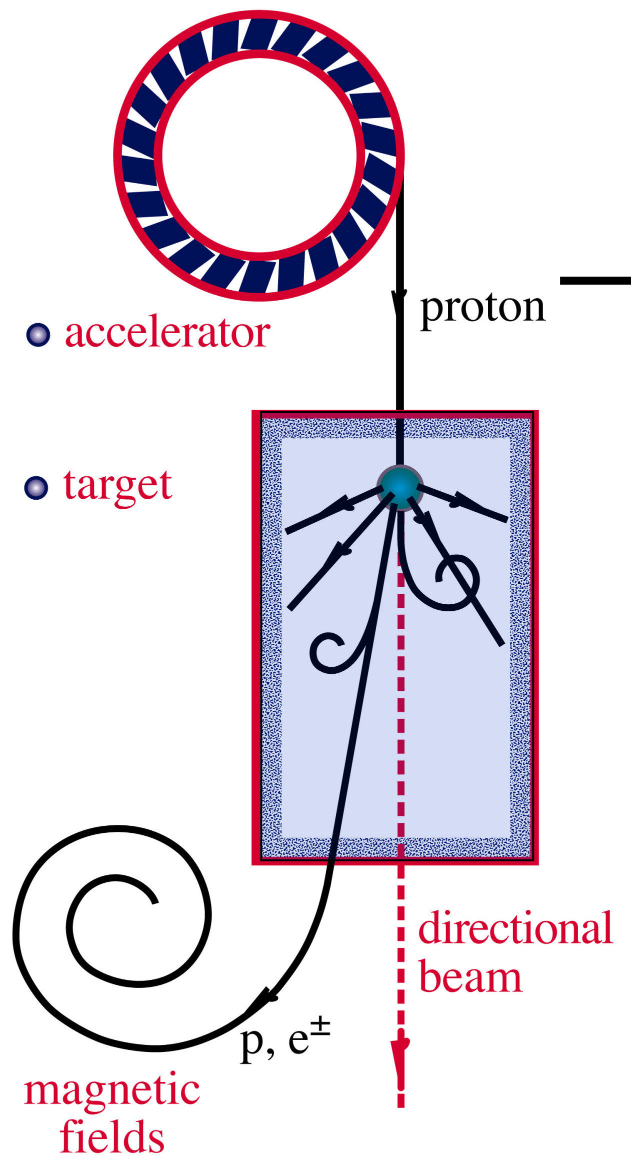


Why not seen before?



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

ν and γ beams : heaven and earth



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

$\rightarrow$ cosmic ray + neutrino

black hole
neutron star

radiation
and dust

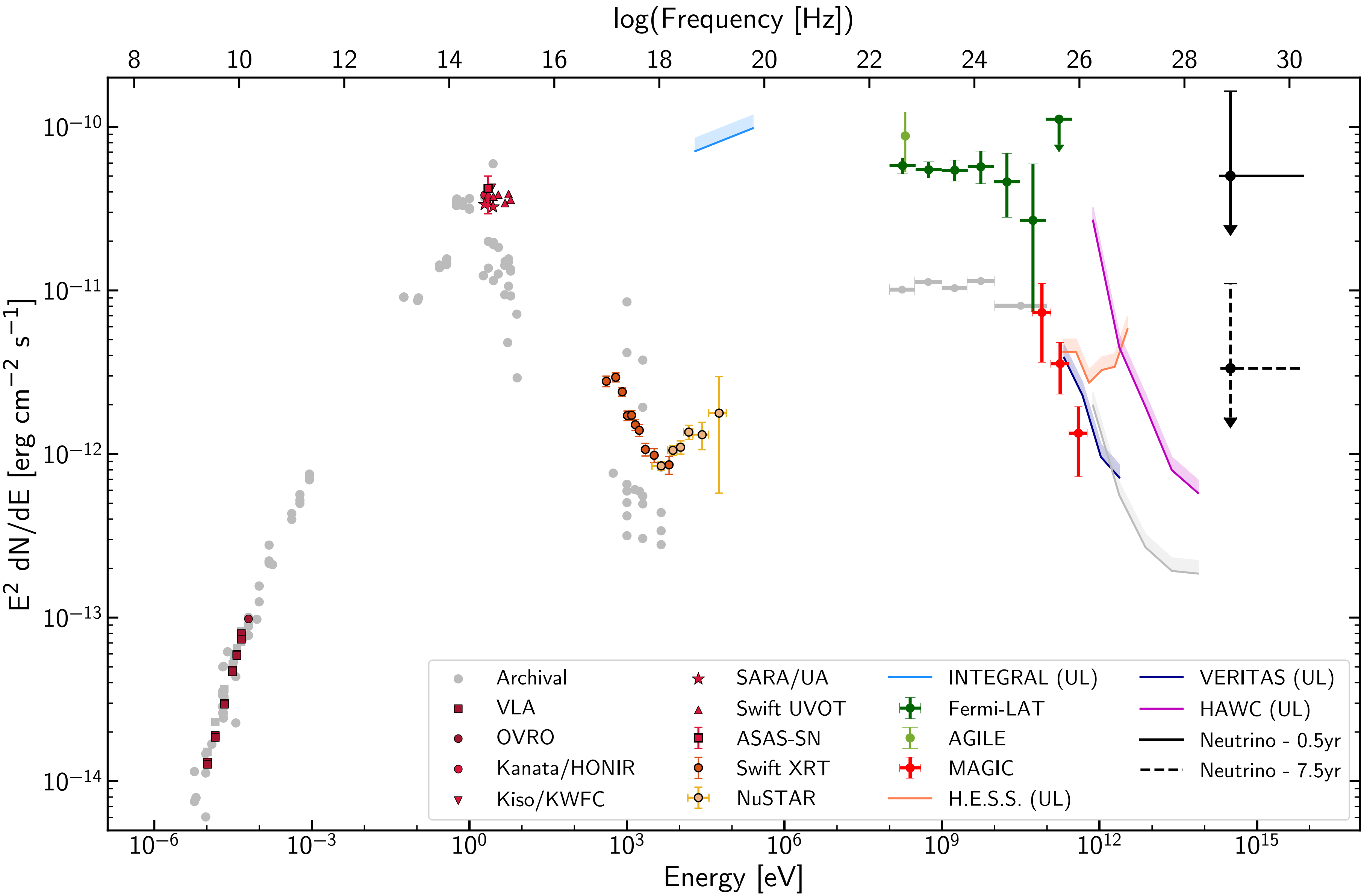
neutrino source
needs an accelerator
and
a target
source opacity?

we identified a source of high energy cosmic rays:

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

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

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



we know that this one is a cosmic ray source


We finally
IC170922
weak
2014-15 neutrino burst

three points regarding the TXS 0506+056 neutrino source:

- If every blazar produced neutrinos at the level of TXS 0506+056, the sources would overproduce the total flux observed by IceCube by a factor of 20.
- TXS 0506+056 must indeed belong to a special subclass of sources, as already suggested by the large redshift.
- A source that produces 13 neutrinos in 110 days has a target density for producing neutrinos that is large and therefore opaque to high-energy gamma rays. It takes a massive accretion event onto the black hole to accommodate the 2014-15 observation. The 2014-15 burst cannot be, and is not, accompanied by a Fermi flare.

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

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

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

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

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

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

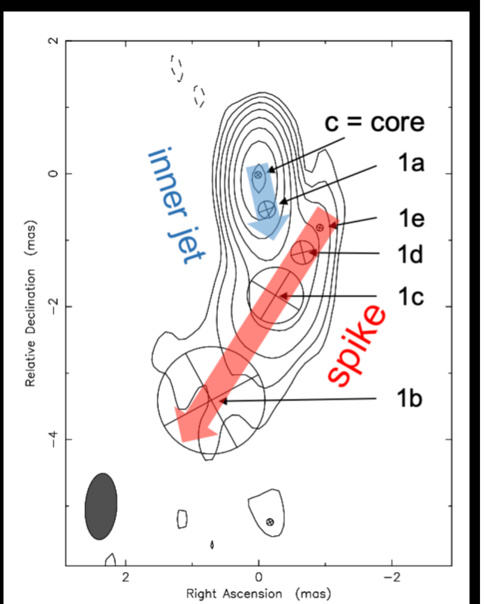
vanilla blazars cannot accommodate the 2014 burst

- need a major accretion on the black hole to create a target that can produce the 2014-15 neutrino burst
- a target that produces 13 neutrinos in 110 days is opaque gamma rays that lose energy in the source even before reaching the EBL
- there can be no gamma ray flare
- coincident gamma ray flux can be accommodated for $\tau_{p\gamma} \sim 0.4$

TXS 0506+056 is a galaxy merger

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

theory confirms observation



Astronomy & Astrophysics manuscript no. output
July 31, 2019

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

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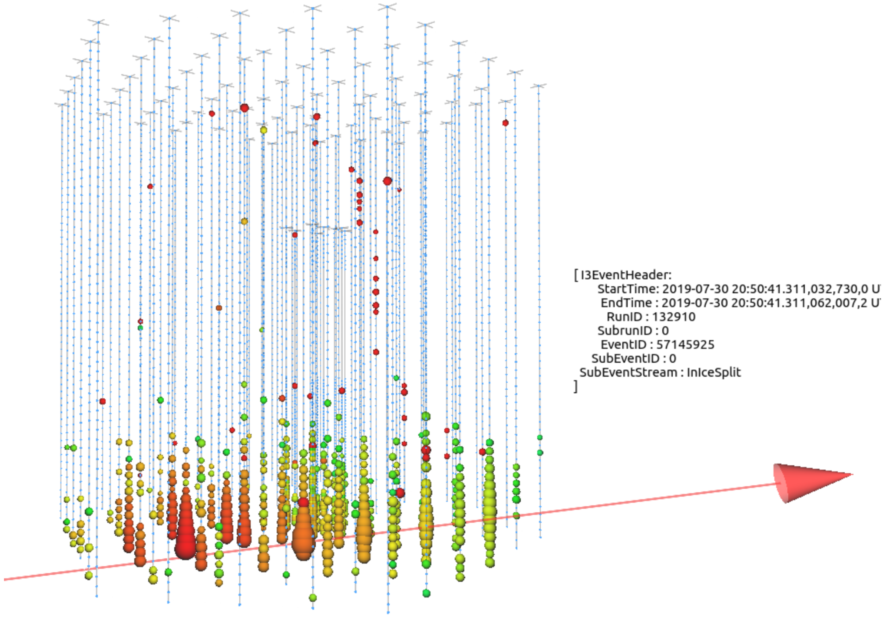
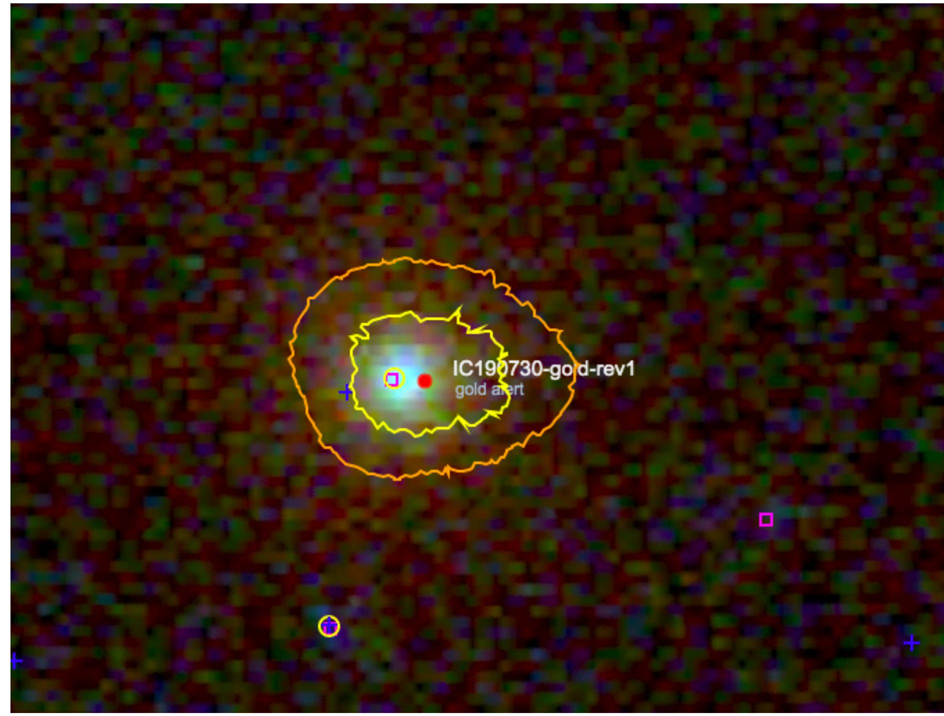
ABSTRACT

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





IC 190730

300 TeV

- coincident with PKS 1502+106
- galaxy merger

[Previous | Next]

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

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

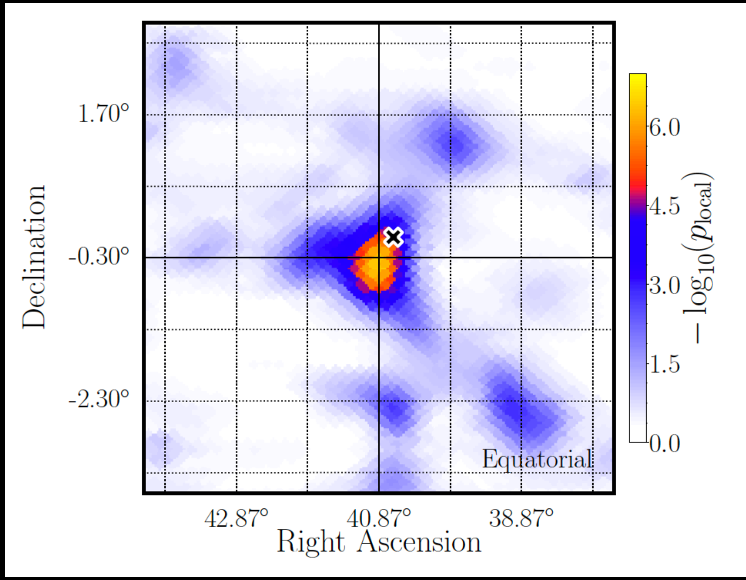
Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

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

Related

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



evidence for M77 (NGC1086)

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

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

Astronomy & Astrophysics

Molecular line emission in NGC 1068 imaged with ALMA★

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

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Received 19 March 2014 / Accepted 4 June 2014

ABSTRACT

Aims. We investigate the fueling and the feedback of star formation and nuclear activity in NGC 1068, a nearby (D = 14 Mpc) Seyfert 2 barred galaxy, by analyzing the distribution and kinematics of the molecular gas in the disk. We aim to understand if and how gas accretion can self-regulate.

Methods. We have used the Atacama Large Millimeter Array (ALMA) to map the emission of a set of dense molecular gas ($n(H_2) \simeq 10^{5-6}$ cm^{-3}) tracers (CO(3–2), CO(6–5), HCN(4–3), HCO$^+$(4–3), and CS(7–6)) and their underlying continuum emission in the central $r \sim 2$ kpc of NGC 1068 with spatial resolutions ~0.3″–0.5″ (~20–35 pc for the assumed distance of D = 14 Mpc).

Results. The sensitivity and spatial resolution of ALMA give an unprecedented detailed view of the distribution and kinematics of the dense molecular gas ($n(H_2) \geq 10^{5-6}$cm^{-3}) in NGC 1068. Molecular line and dust continuum emissions are detected from a $r \sim 200$ pc off-centered circumnuclear disk (CND), from the 2.6 kpc-diameter bar region, and from the $r \sim 1.3$ kpc starburst (SB) ring. Most of the emission in HCO$^+$, HCN, and CS stems from the CND. Molecular line ratios show dramatic order-of-magnitude changes inside the CND that are correlated with the UV/X-ray illumination by the active galactic nucleus (AGN), betraying ongoing feedback. We used the dust continuum fluxes measured by ALMA together with NIR/MIR data to constrain the properties of the putative torus using CLUMPY models and found a torus radius of 20^{+6}_{-10} pc. The Fourier decomposition of the gas velocity field indicates that rotation is perturbed by an inward radial flow in the SB ring and the bar region. However, the gas kinematics from $r \sim 50$ pc out to $r \sim 400$ pc reveal a massive ($M_{\rm mol} \sim 2.7^{+0.9}_{-1.2} \times 10^7\ M_\odot$) outflow in all molecular tracers. The tight correlation between the ionized gas outflow, the radio jet, and the occurrence of outward motions in the disk suggests that the outflow is AGN driven.

Conclusions. The molecular outflow is likely launched when the ionization cone of the narrow line region sweeps the nuclear disk. The outflow rate estimated in the CND, $dM/dt \sim 63^{+21}_{-37}\ M_\odot$ yr^{-1}, is an order of magnitude higher than the star formation rate at these radii, confirming that the outflow is AGN driven. The power of the AGN is able to account for the estimated momentum and kinetic luminosity of the outflow. The CND mass load rate of the CND outflow implies a very short gas depletion timescale of ≤1 Myr. The CND gas reservoir is likely replenished on longer timescales by efficient gas inflow from the outer disk.

a neutrino source requires a proton accelerator
and
a target of photons/protons (hydrogen)

source class	accelerator	target	evidence
TXS 0506+056 blazar IC170922	active galaxy	ongoing merger of galaxies	- VLBA image - neutrino at peak of 5-year radio outburst
PKS 1502+106 blazar IC190730	active galaxy	ongoing merger of galaxies?	- neutrino at peak of 5-year radio outburst
NGC 1068 starburst	active galaxy	merger with - starforming region or satellite gal.	ALMA

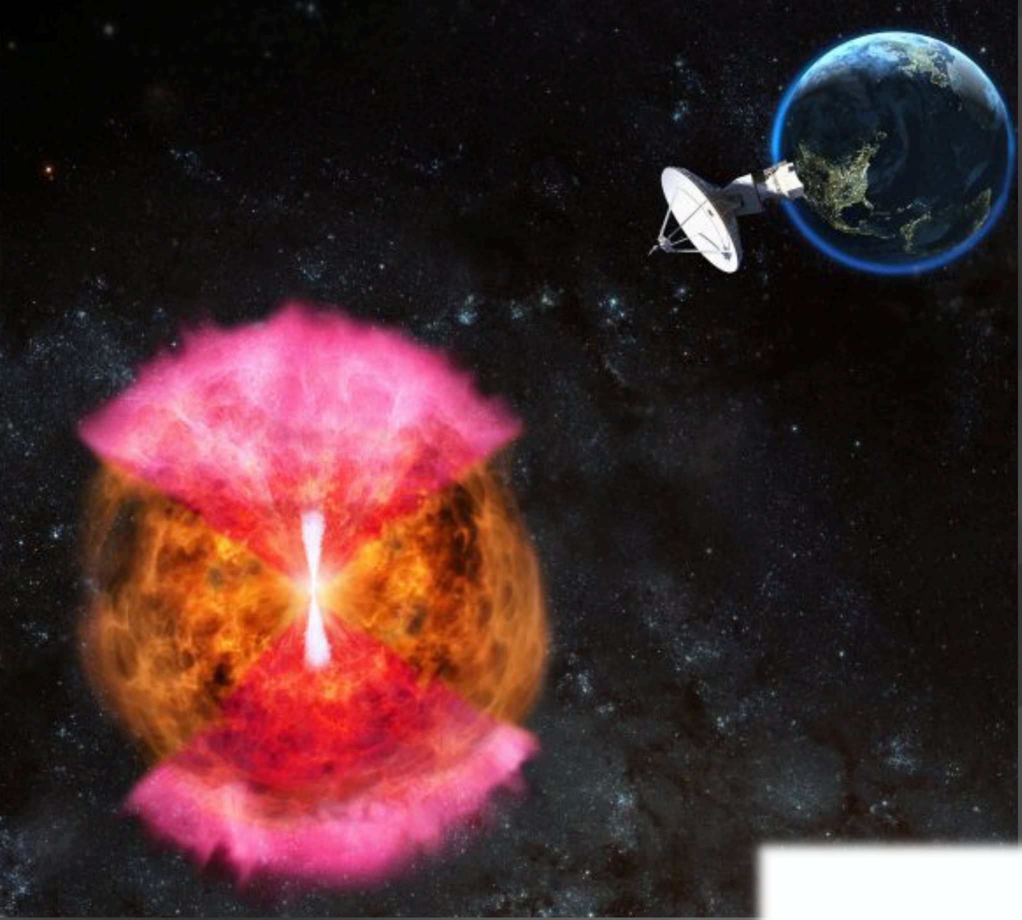
neutron star-neutron star merger

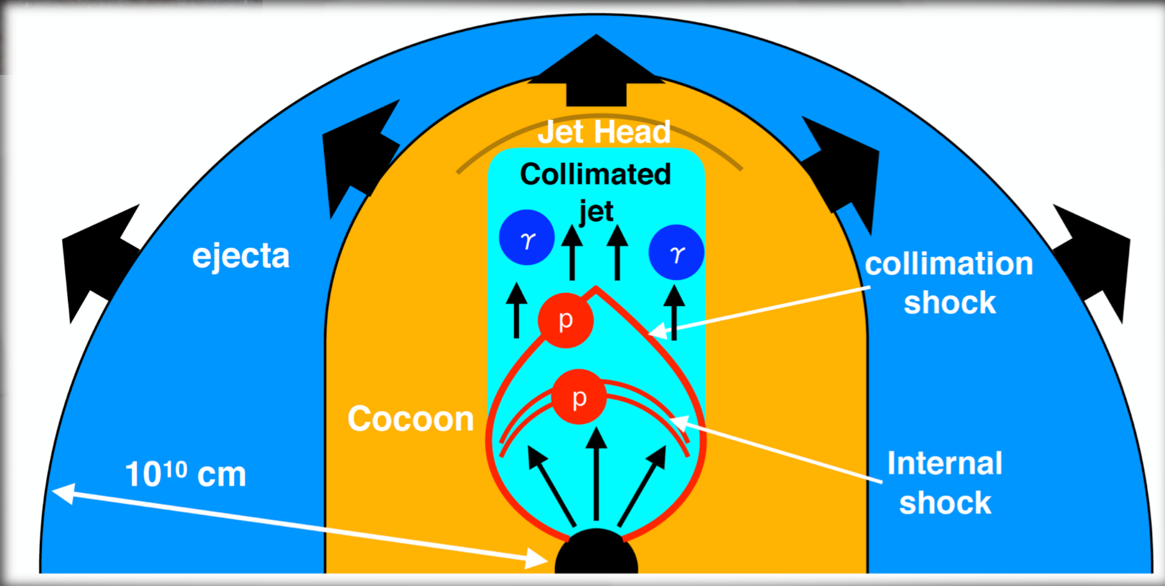
LIGO-VIRGO

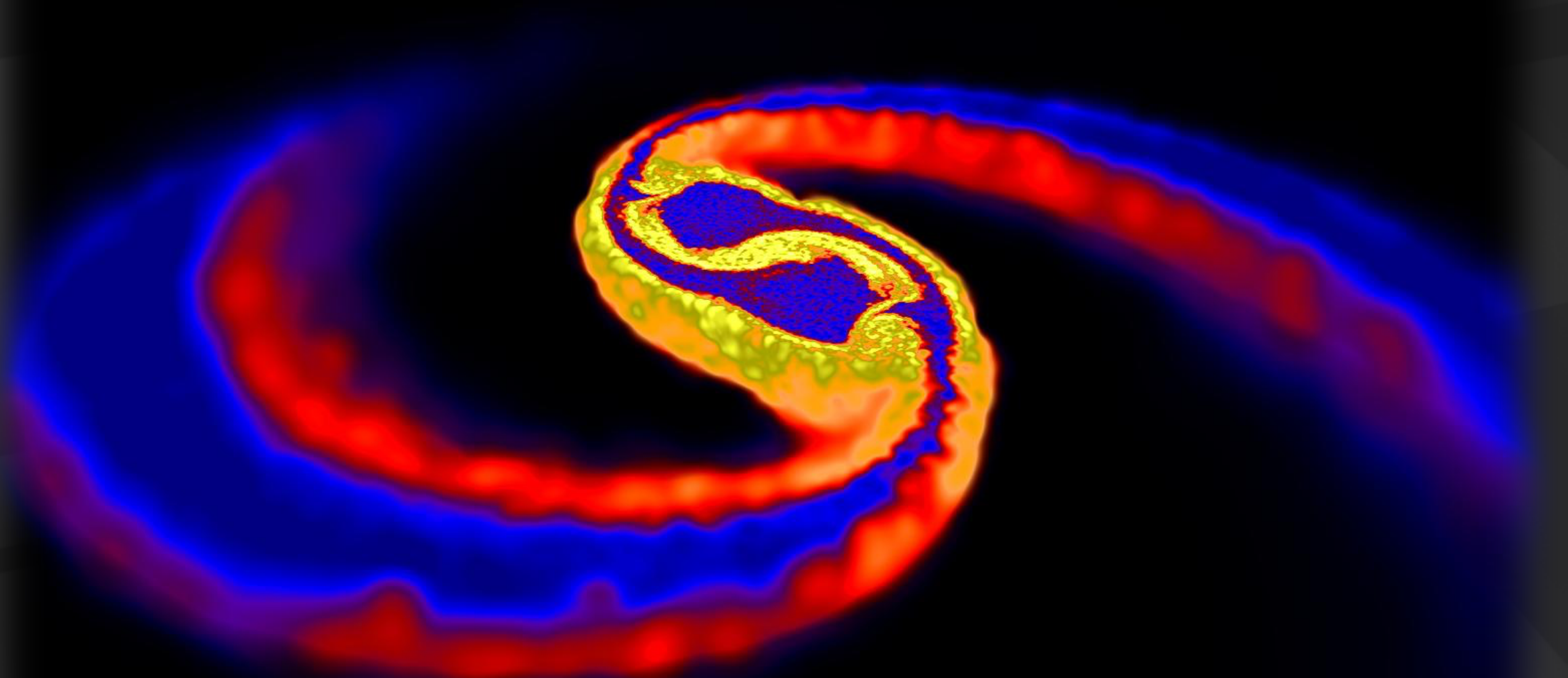
merger of neutron stars about to launch a jet high-energy neutrinos: from collimation (TeV) and internal shocks (PeV):

protons photoproduce neutrinos

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

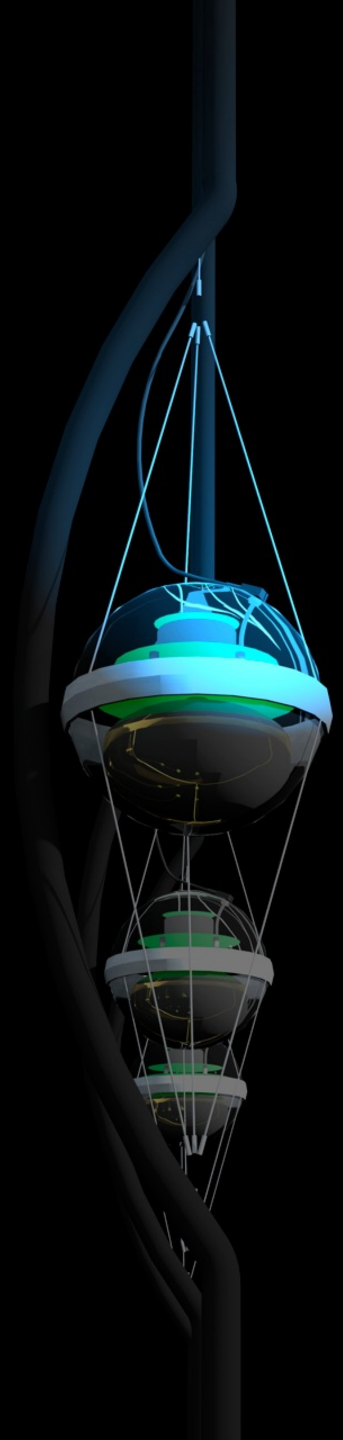






high energy neutrino coincidences with gravity waves

- optimistic calculations: with IceCube, unfortunately we still had only one event; the jet did not point in our direction (sub-threshold short GRB)
- pessimistic calculations: it will take next-generation detectors: IceCube Gen2, KM3NeT, GVD-Baikal,…

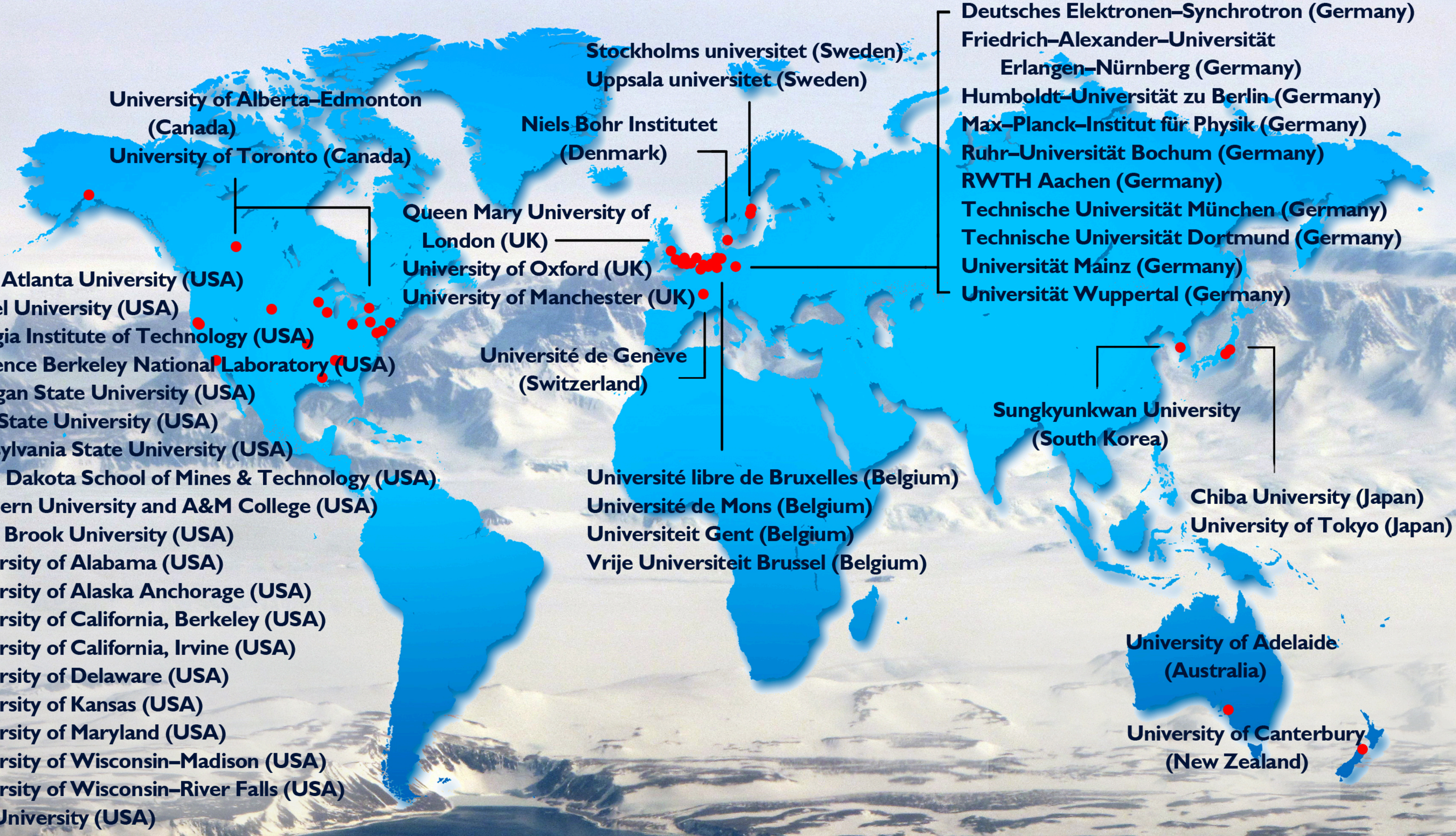


neutrino astronomy 2019

- it exists
- more neutrinos
- more telescopes

icecube.wisc.edu

The IceCube–PINGU Collaboration



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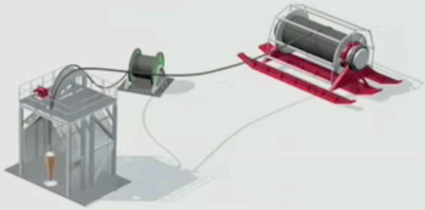
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



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 redshift evolution ?
- galaxy mergers (VLA observations during 2014 burst) ?

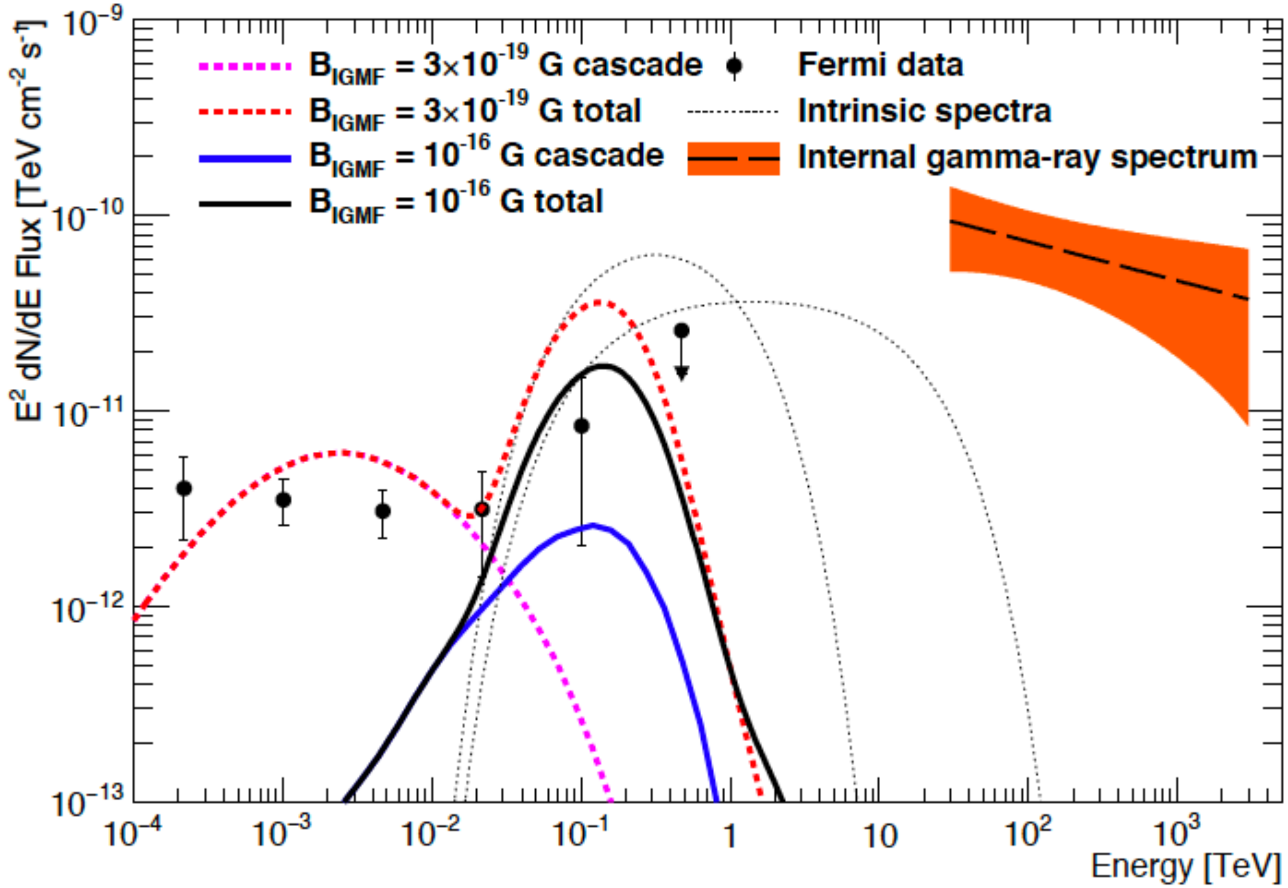
of the highest energy cosmic rays?

measured flux satisfies the energy requirement

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

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*

Kimura et al.

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

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

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

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