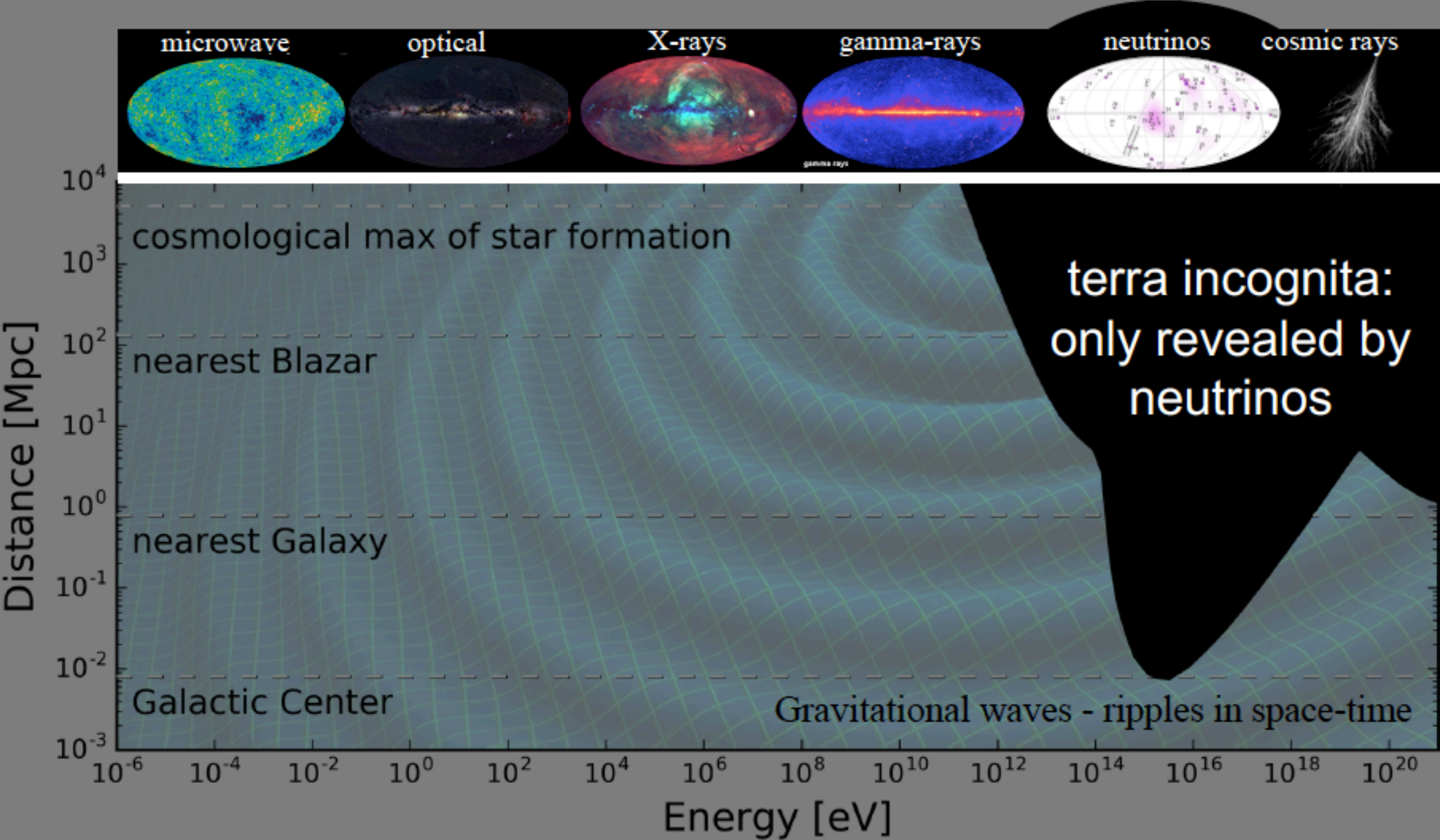
IceCube:
Building a New Window on the Universe

francis halzen

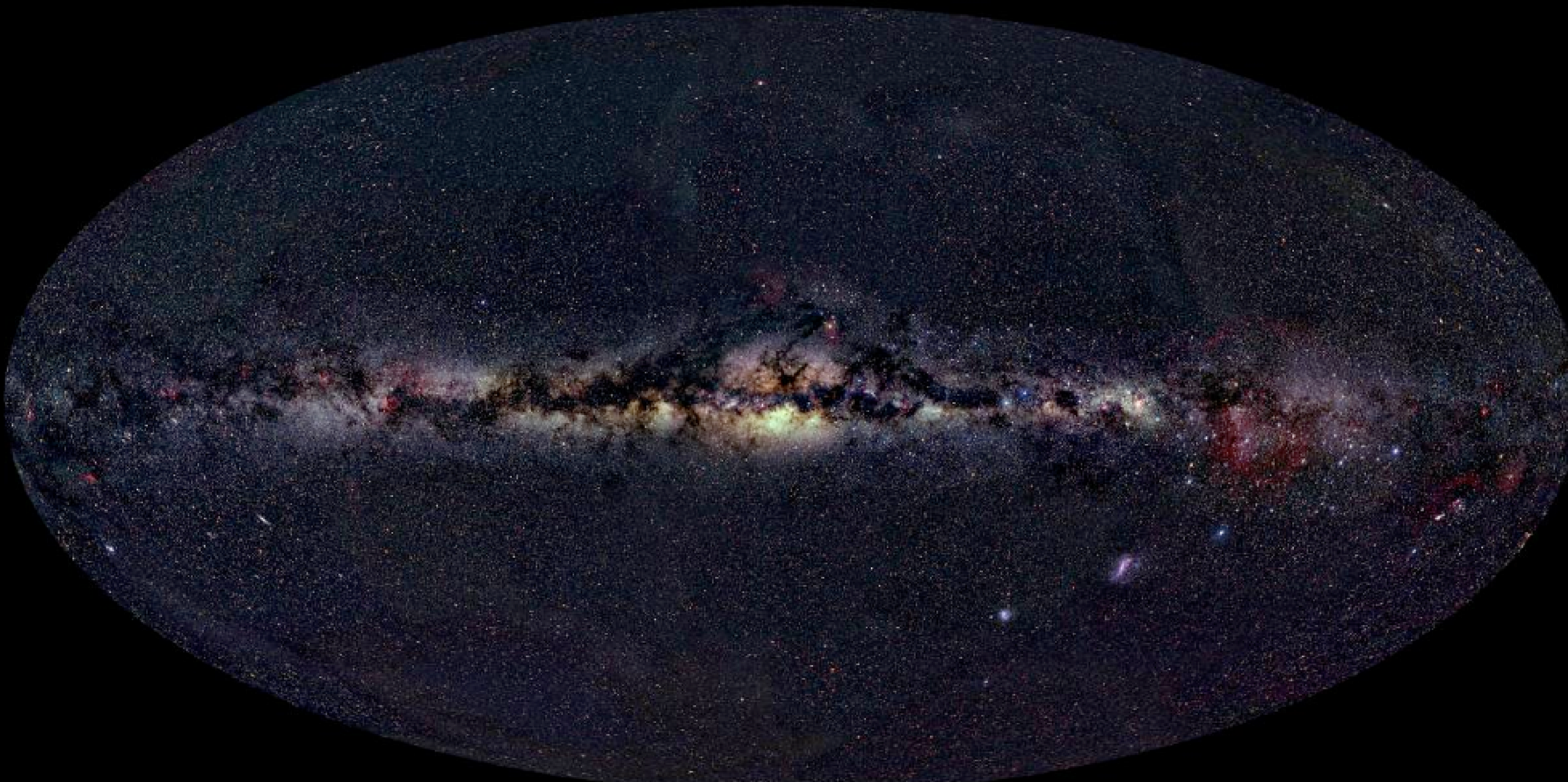
- IceCube
- cosmic neutrinos: three independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → high energy tau neutrinos
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator

icecube.wisc.edu



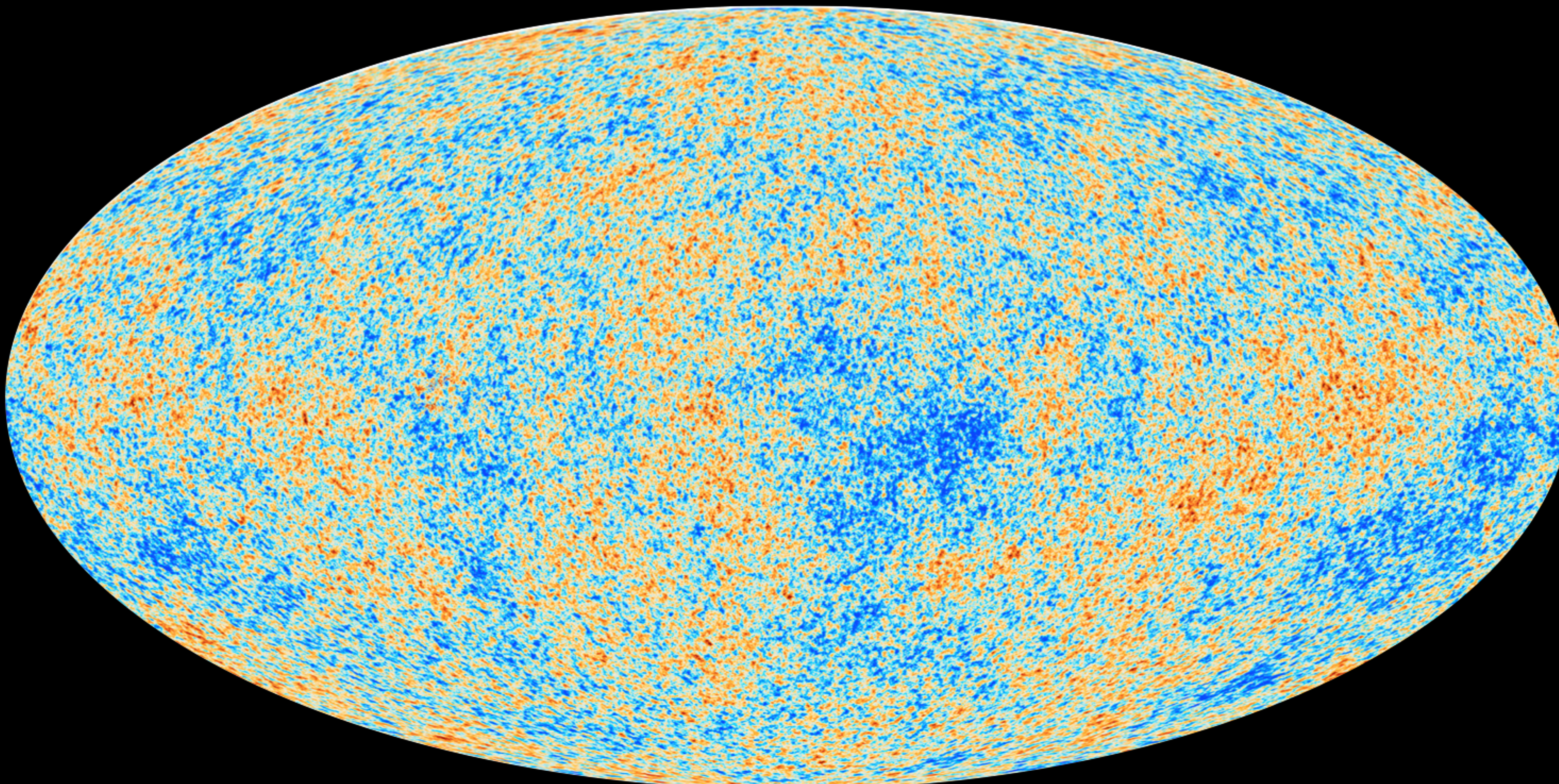
- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

Cosmic Horizons – Optical Sky



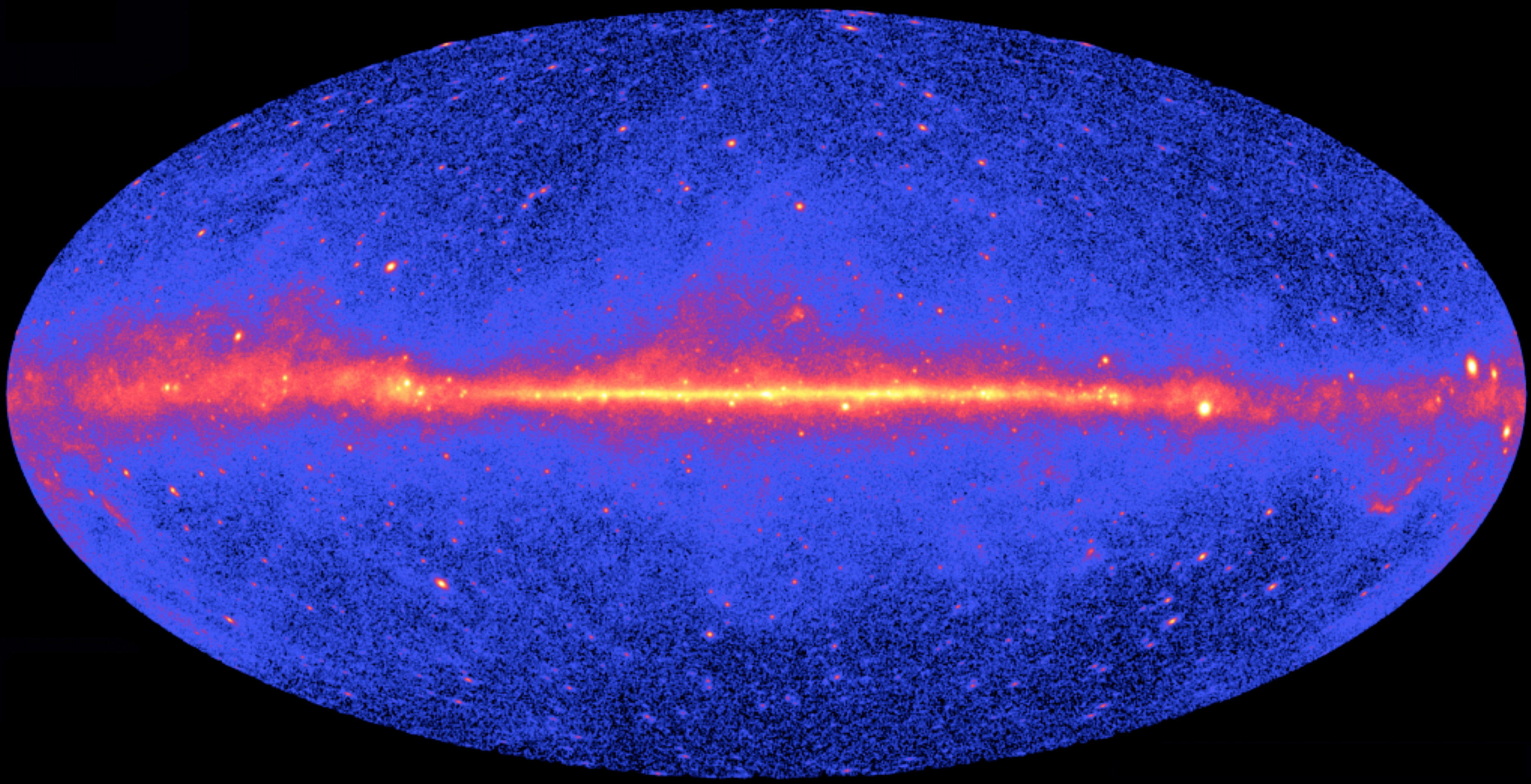
wavelength = 10^{-6} m $\Leftrightarrow$ energy = 1 eV

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



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

Cosmic Horizons – Gamma Radiation

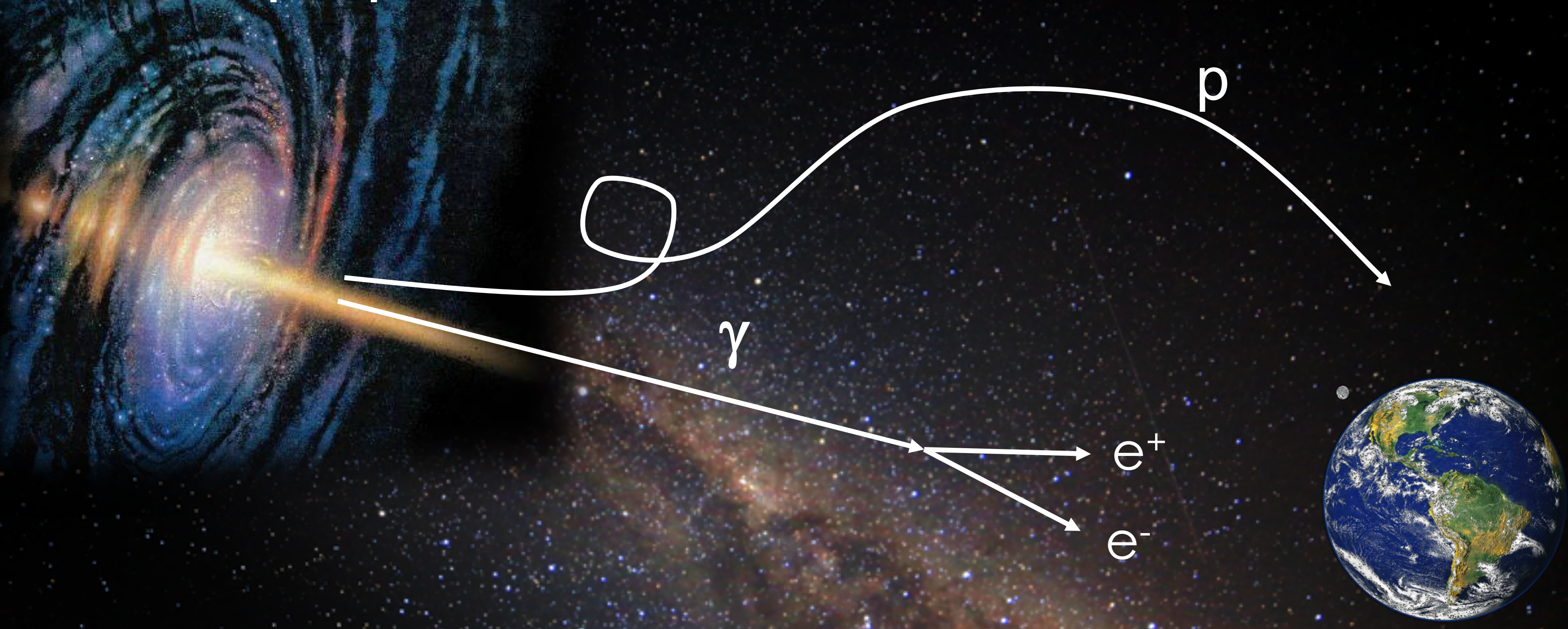


wavelength = 10^{-15} m ⇔ energy = 1 GeV

Cosmic Horizons – Gamma Radiation

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

The opaque Universe

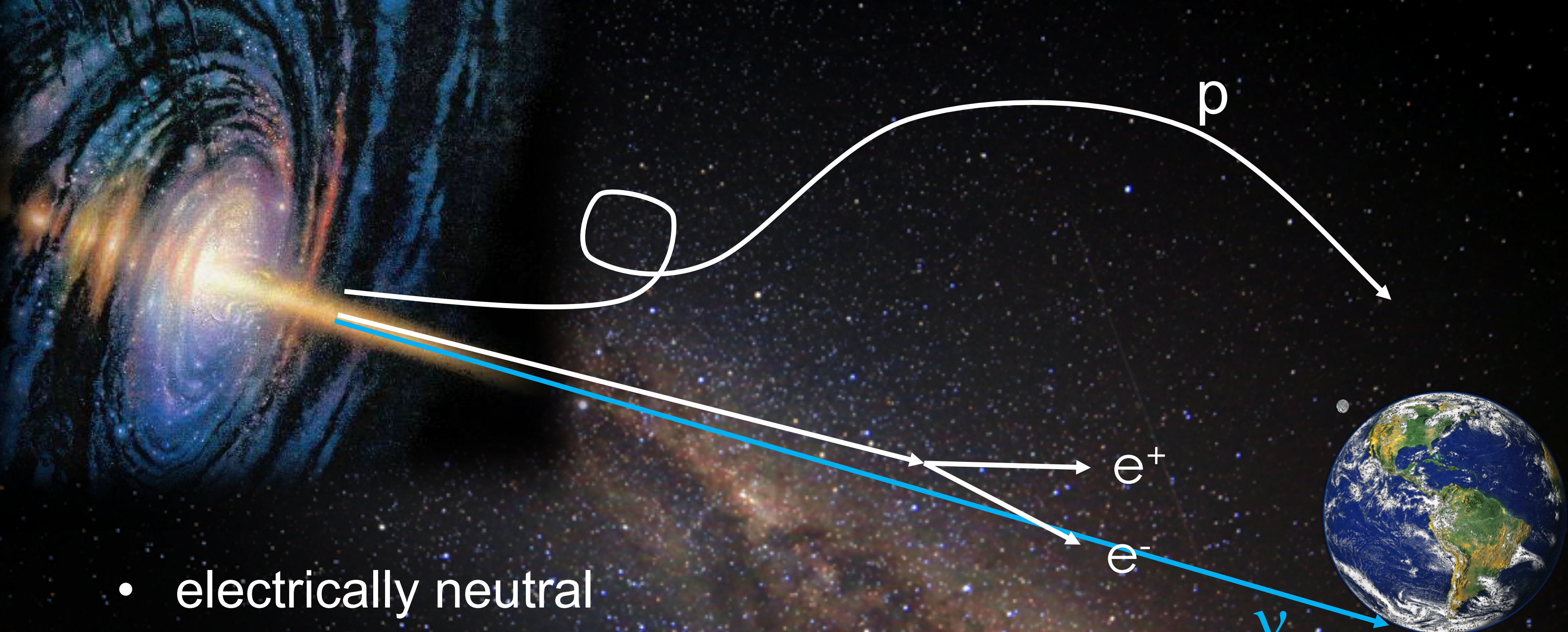


$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

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

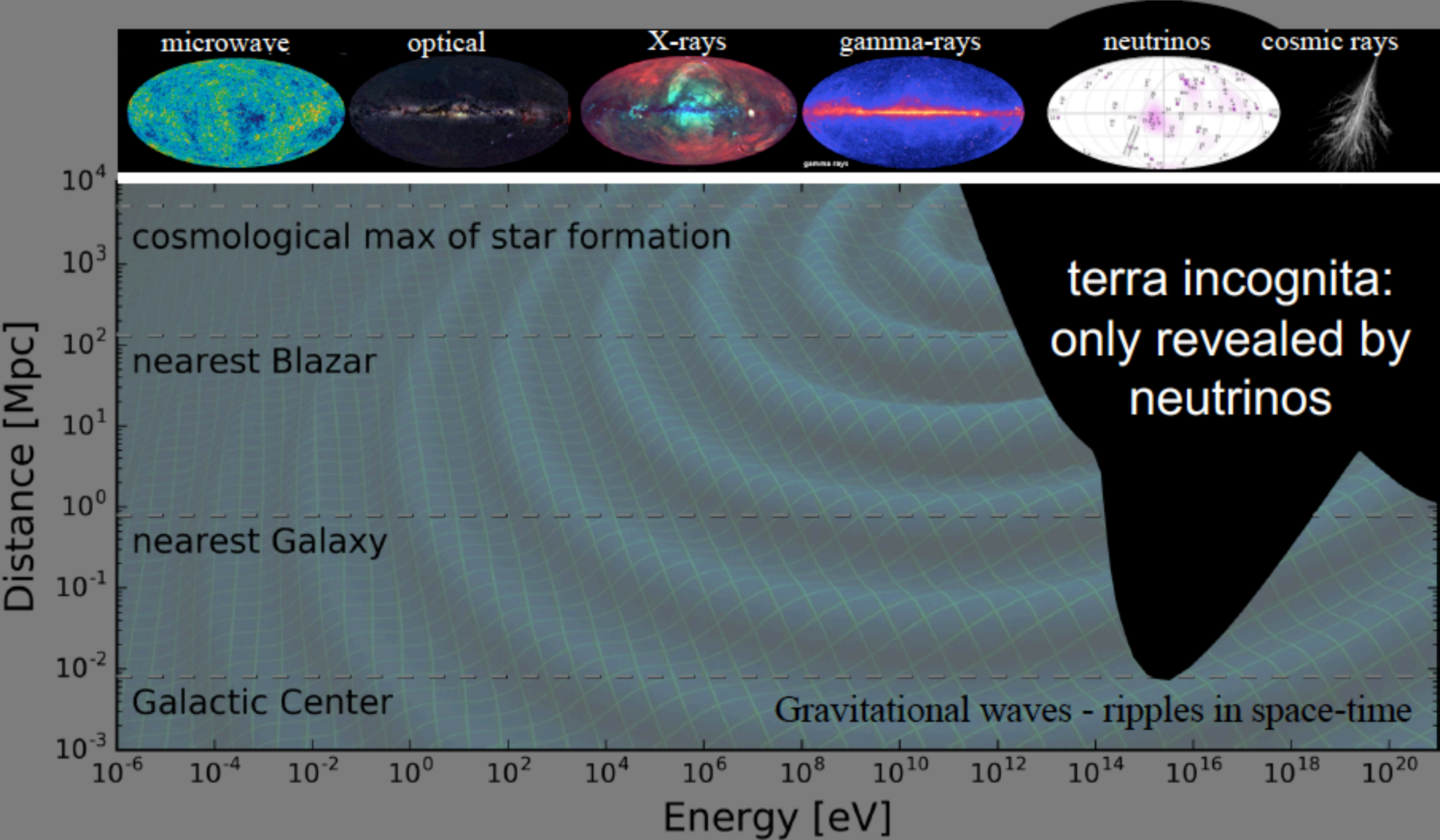
enter: neutrinos

Neutrinos? Perfect Messenger



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

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



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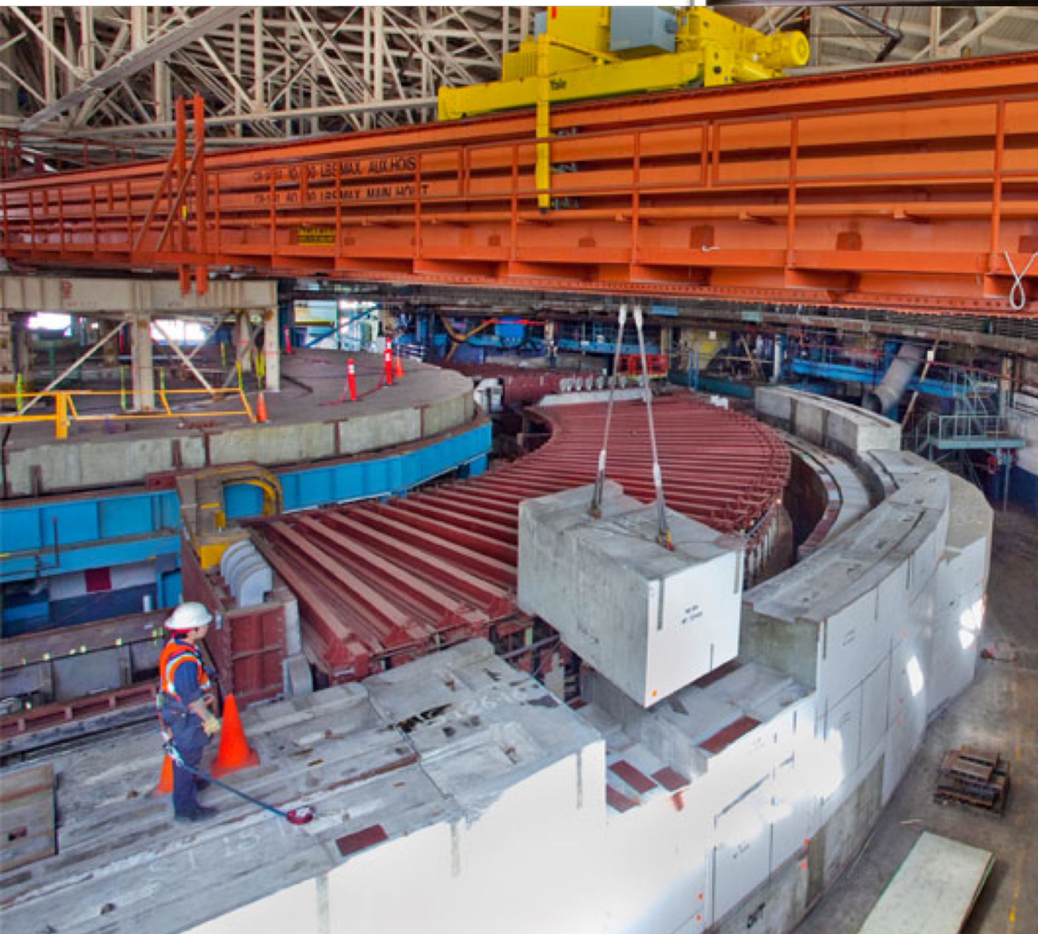
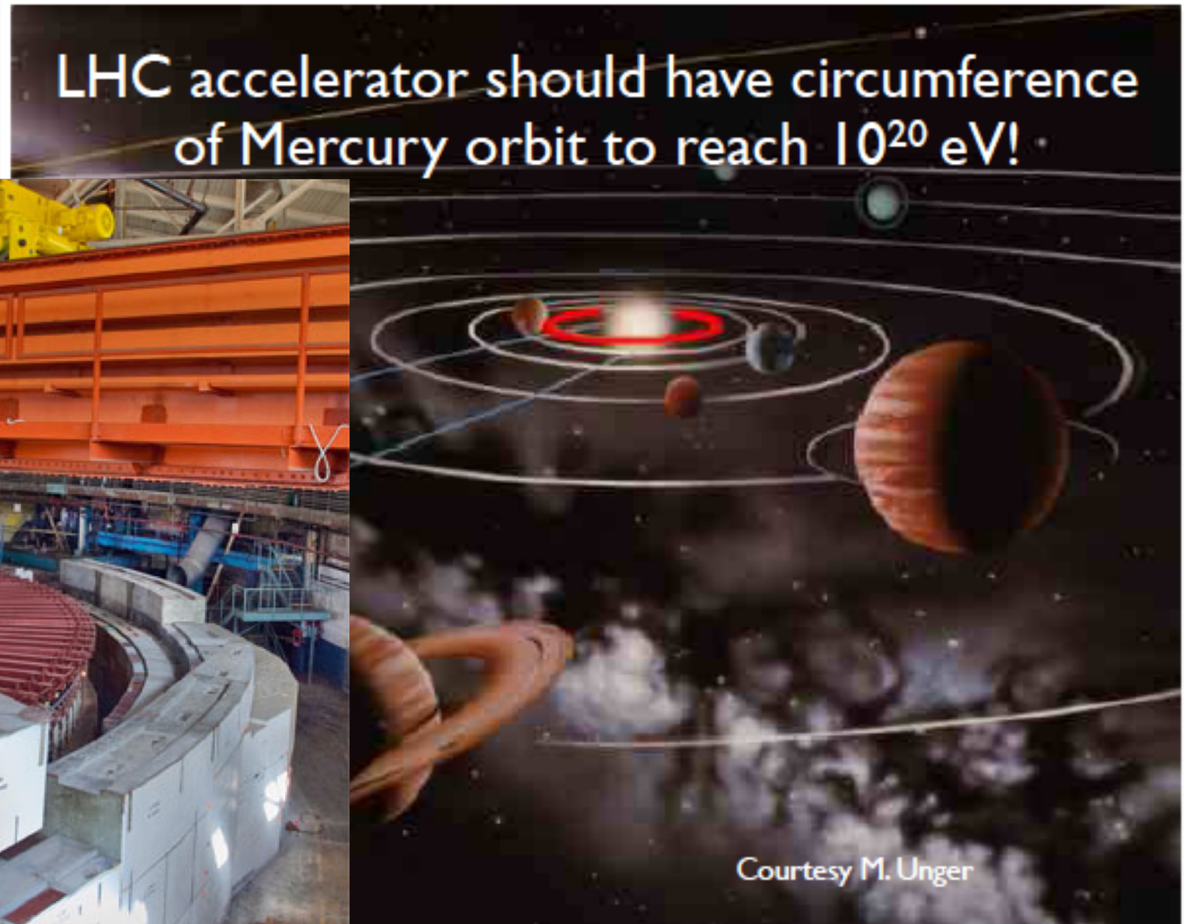
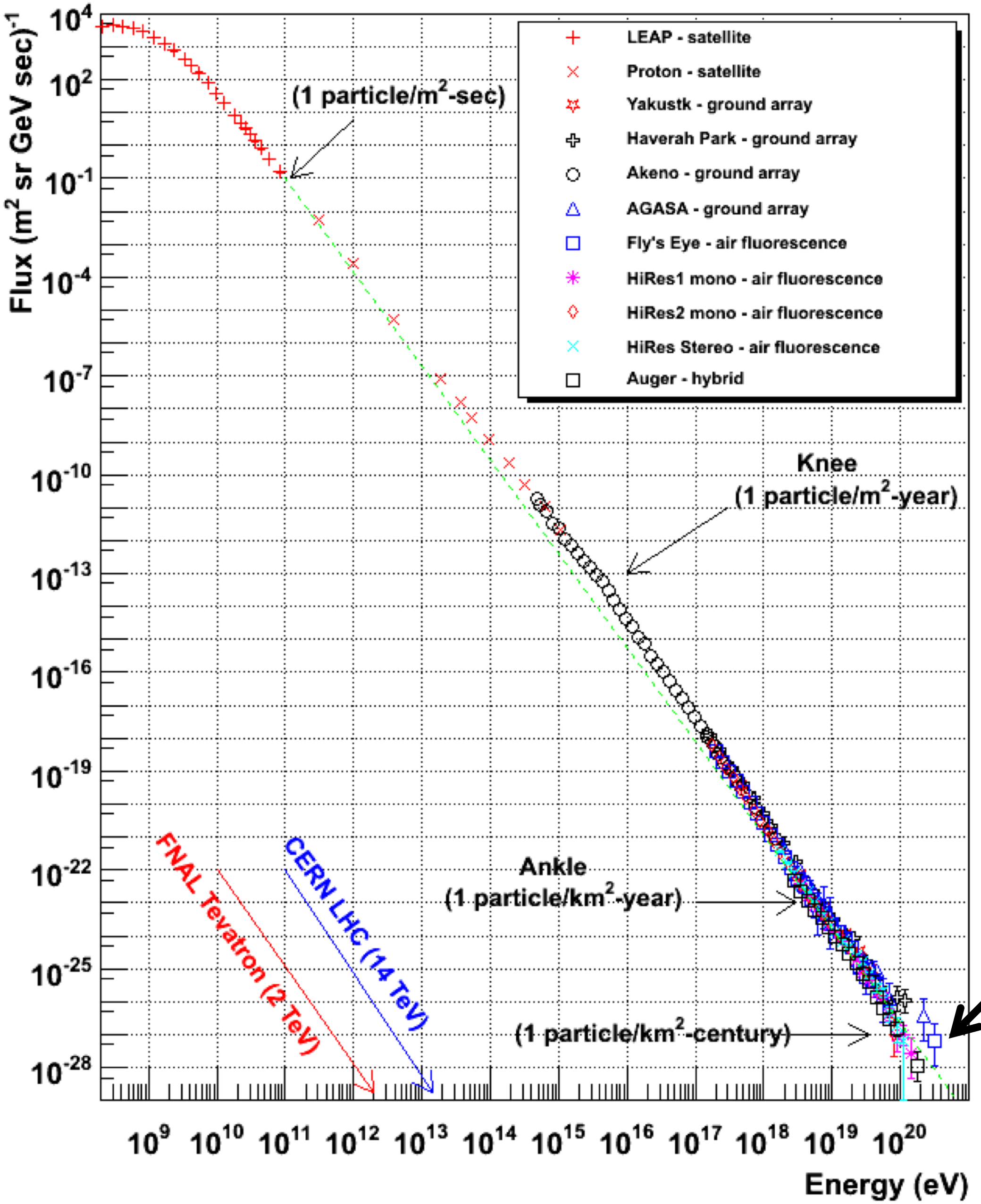
cosmic ray accelerators





accomodating energy and luminosity are challenging origin of cosmic rays: oldest problem in astronomy



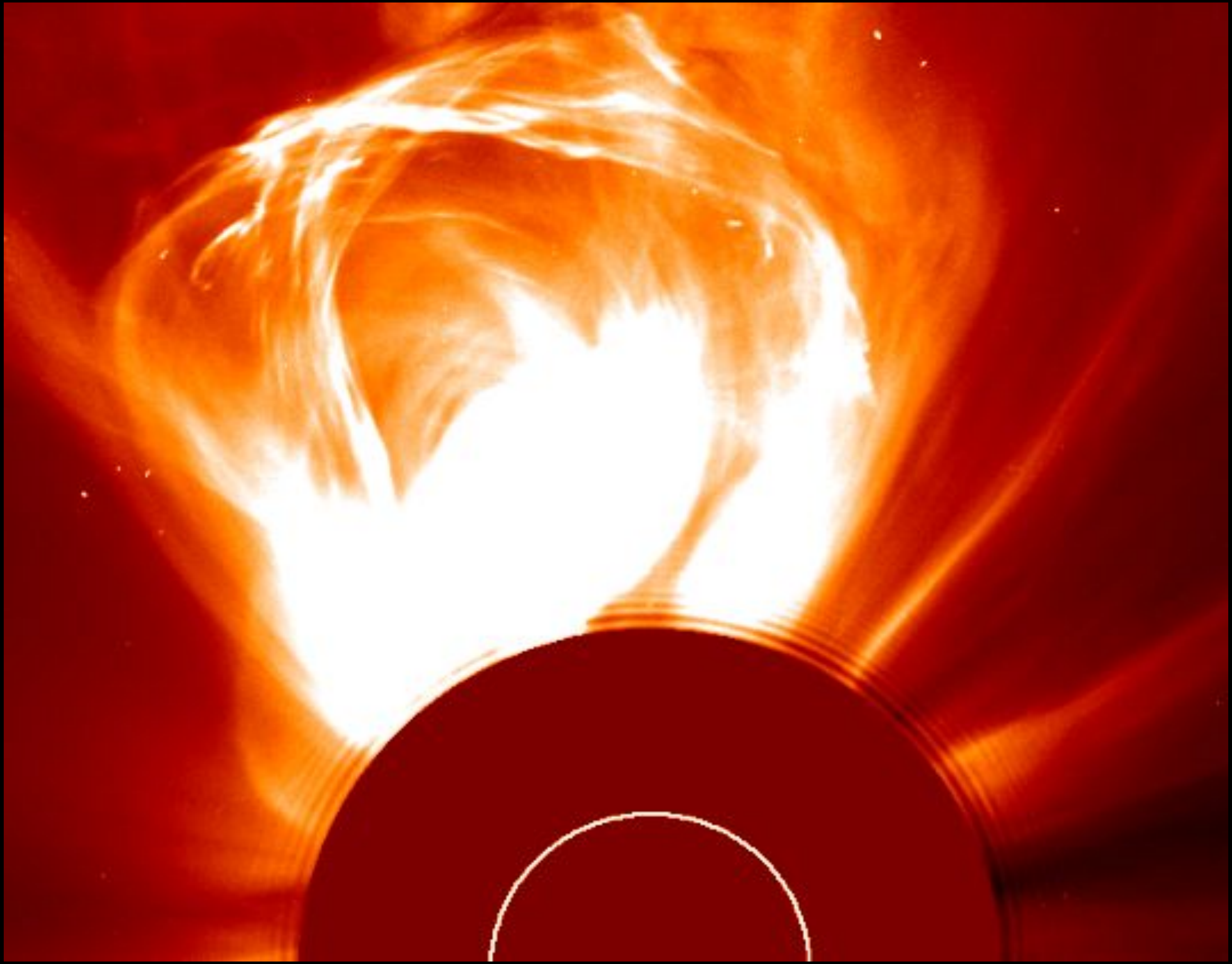
cosmic ray challenge

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

gravitational energy from collapsing stars is converted into particle acceleration?

LHC filling the orbit of Mercury

the sun constructs an accelerator



- accelerator must contain the particles

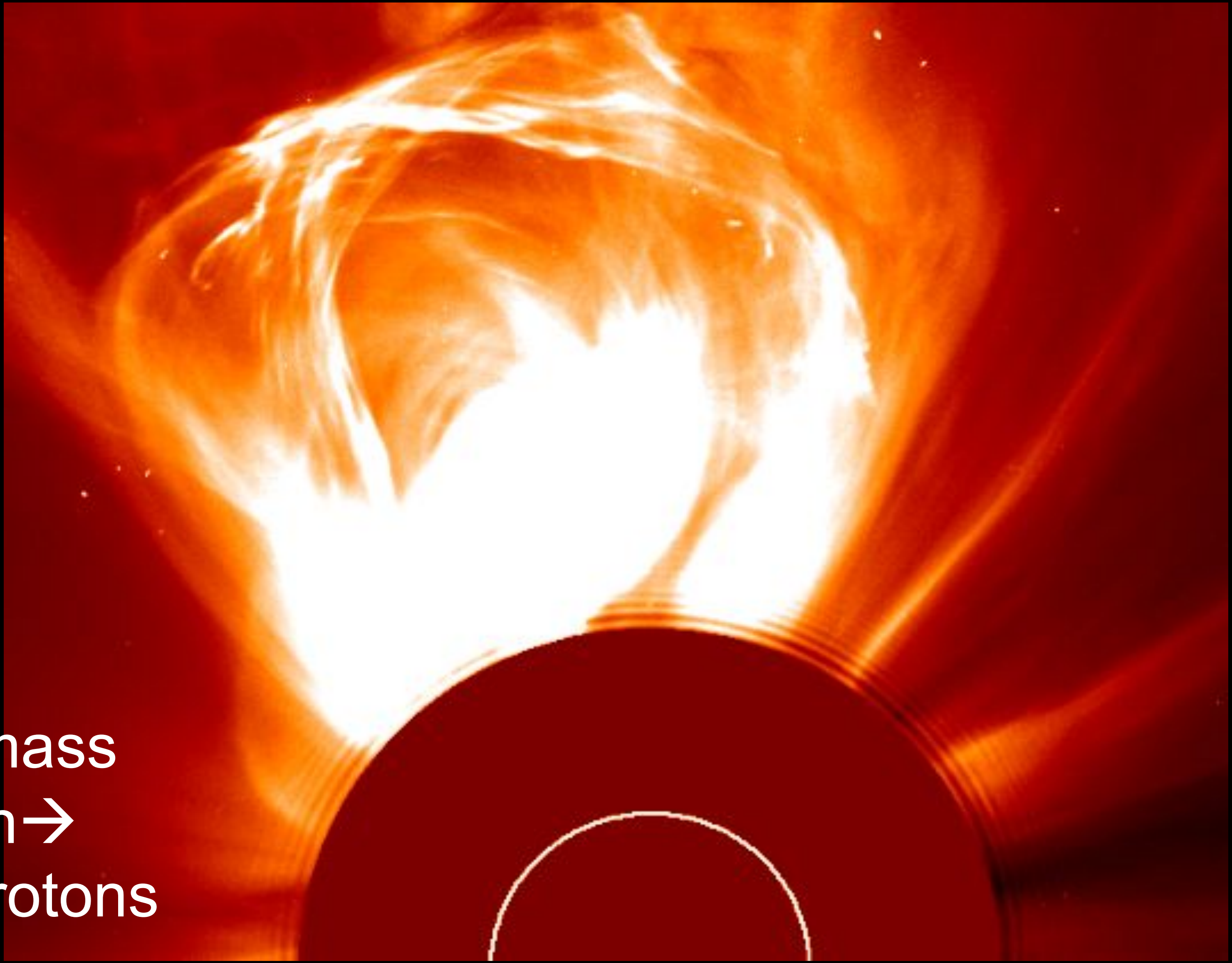
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \leq R$$

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

challenges of cosmic ray astrophysics:

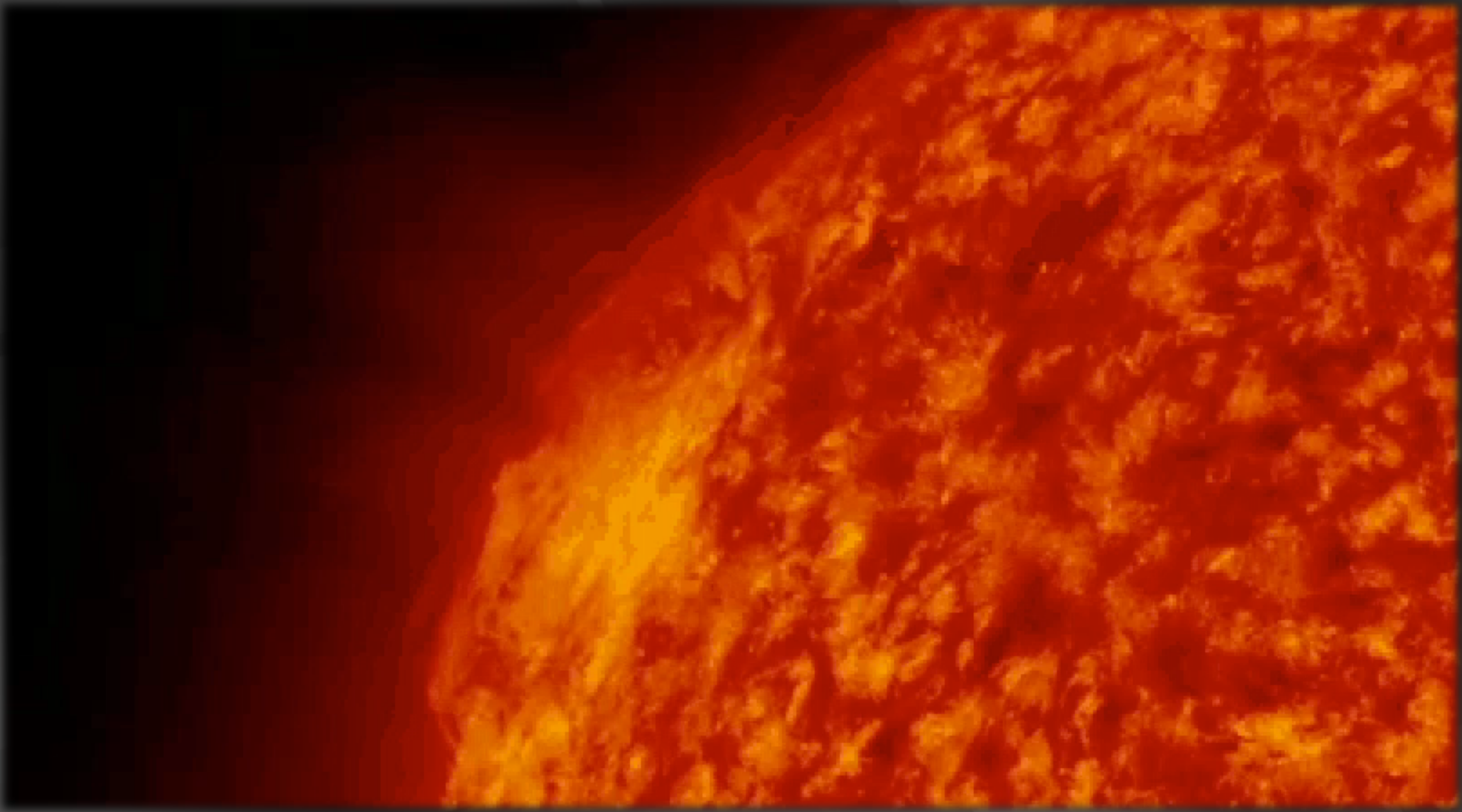
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

the sun constructs an accelerator

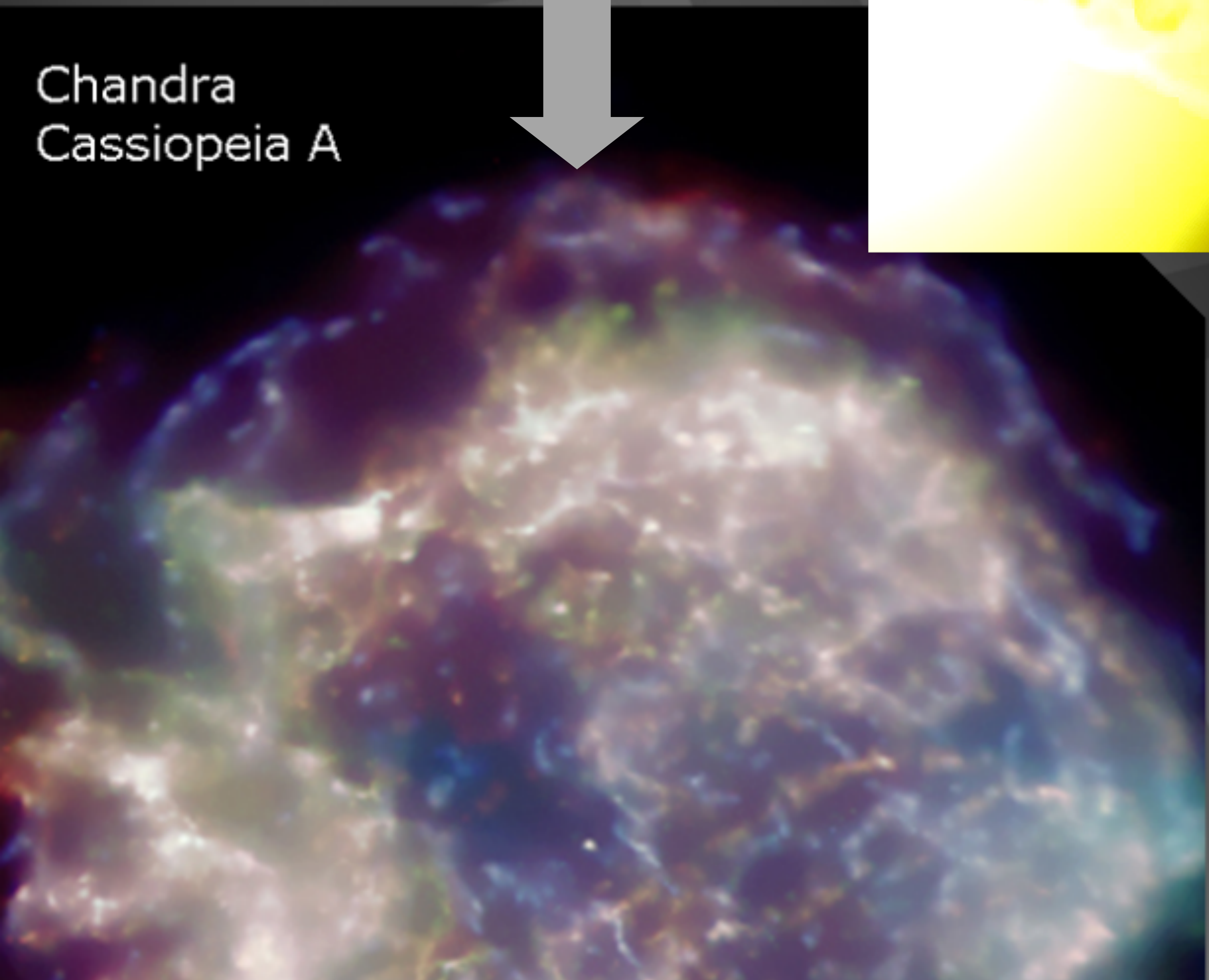


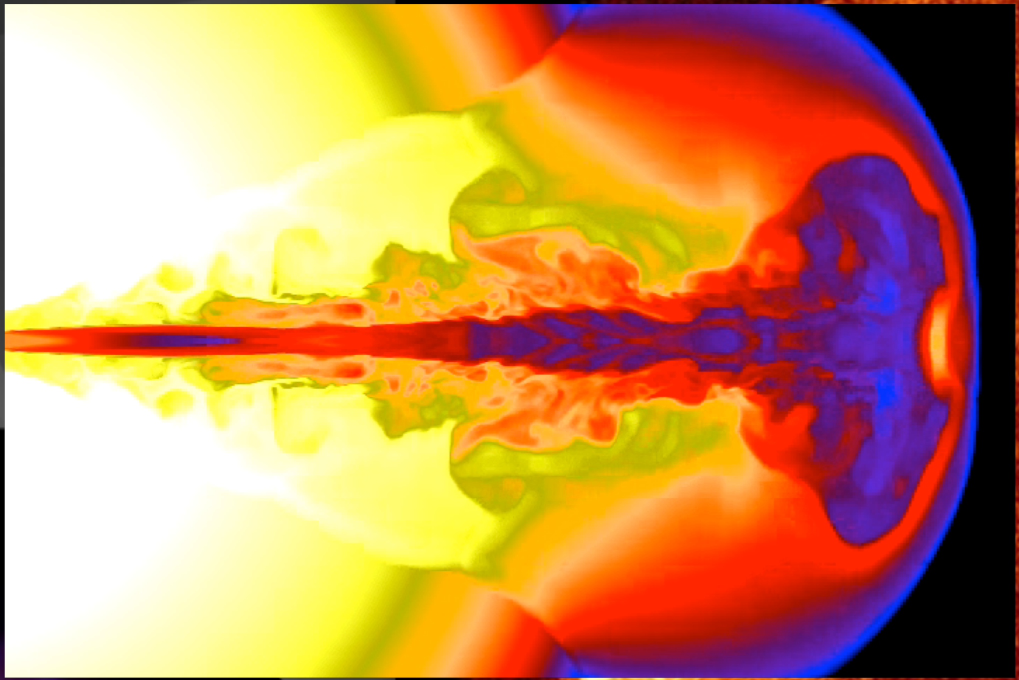
coronal mass ejection→ 10 GeV protons

the sun constructs an accelerator

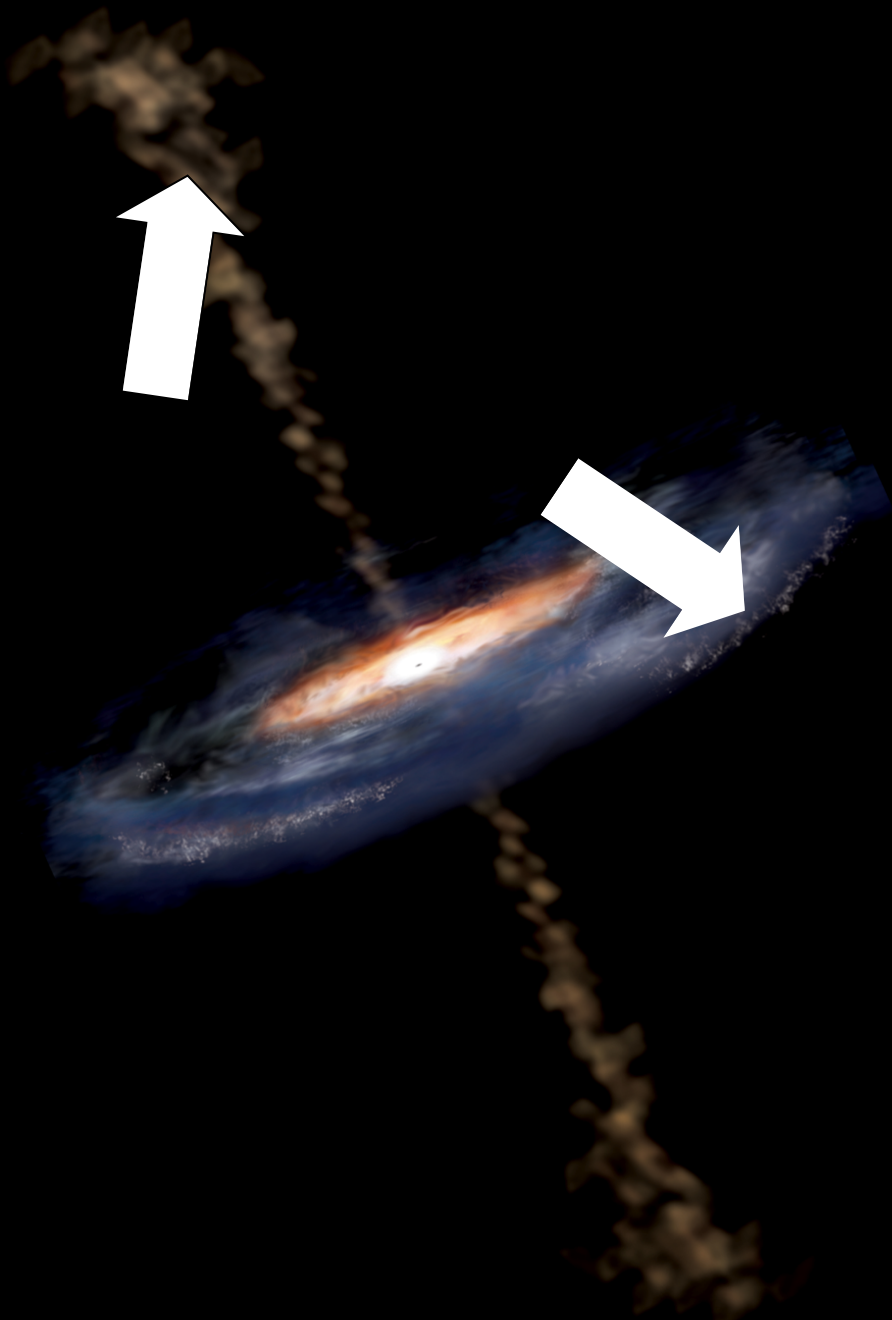


supernova
remnants



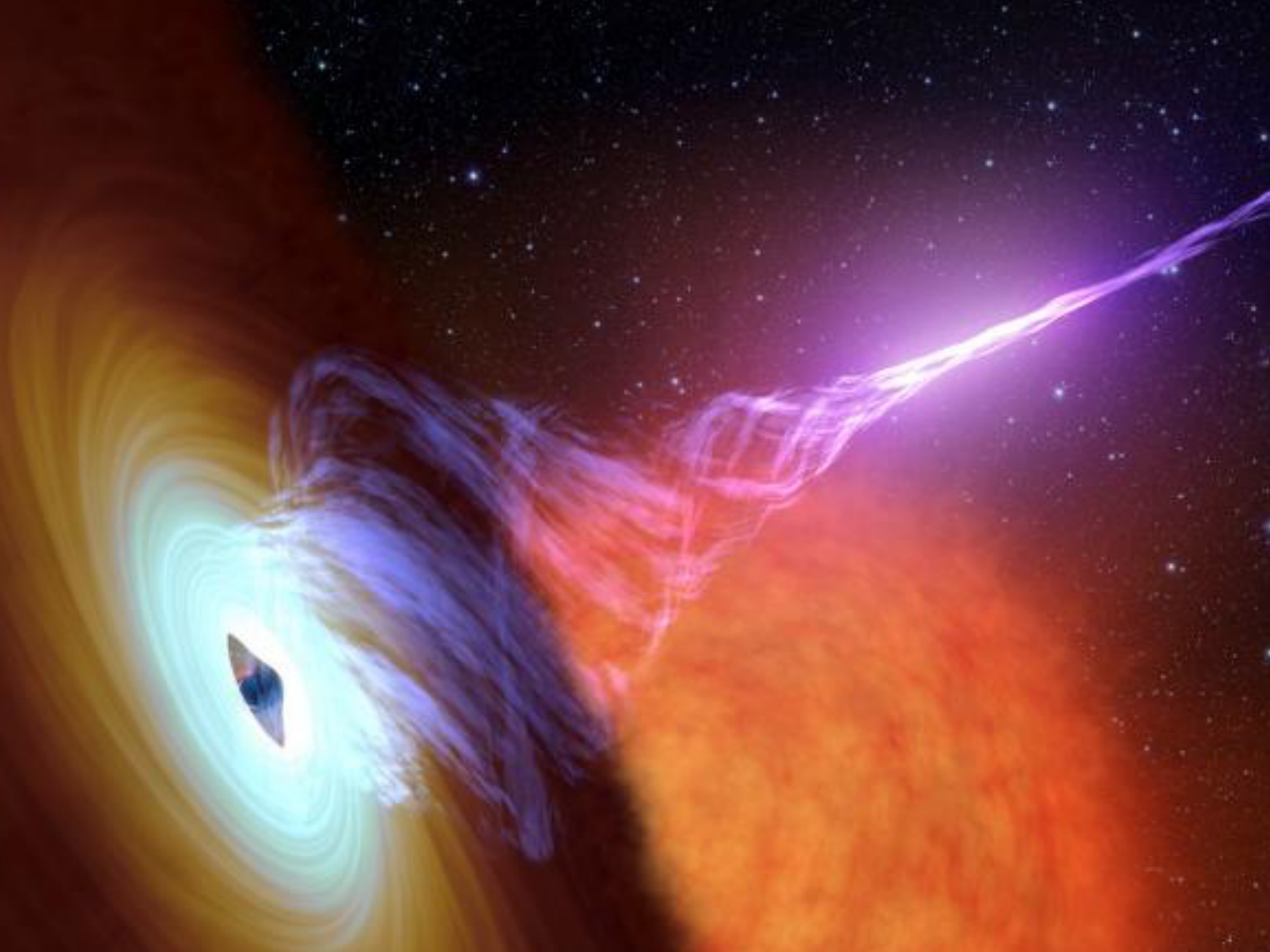


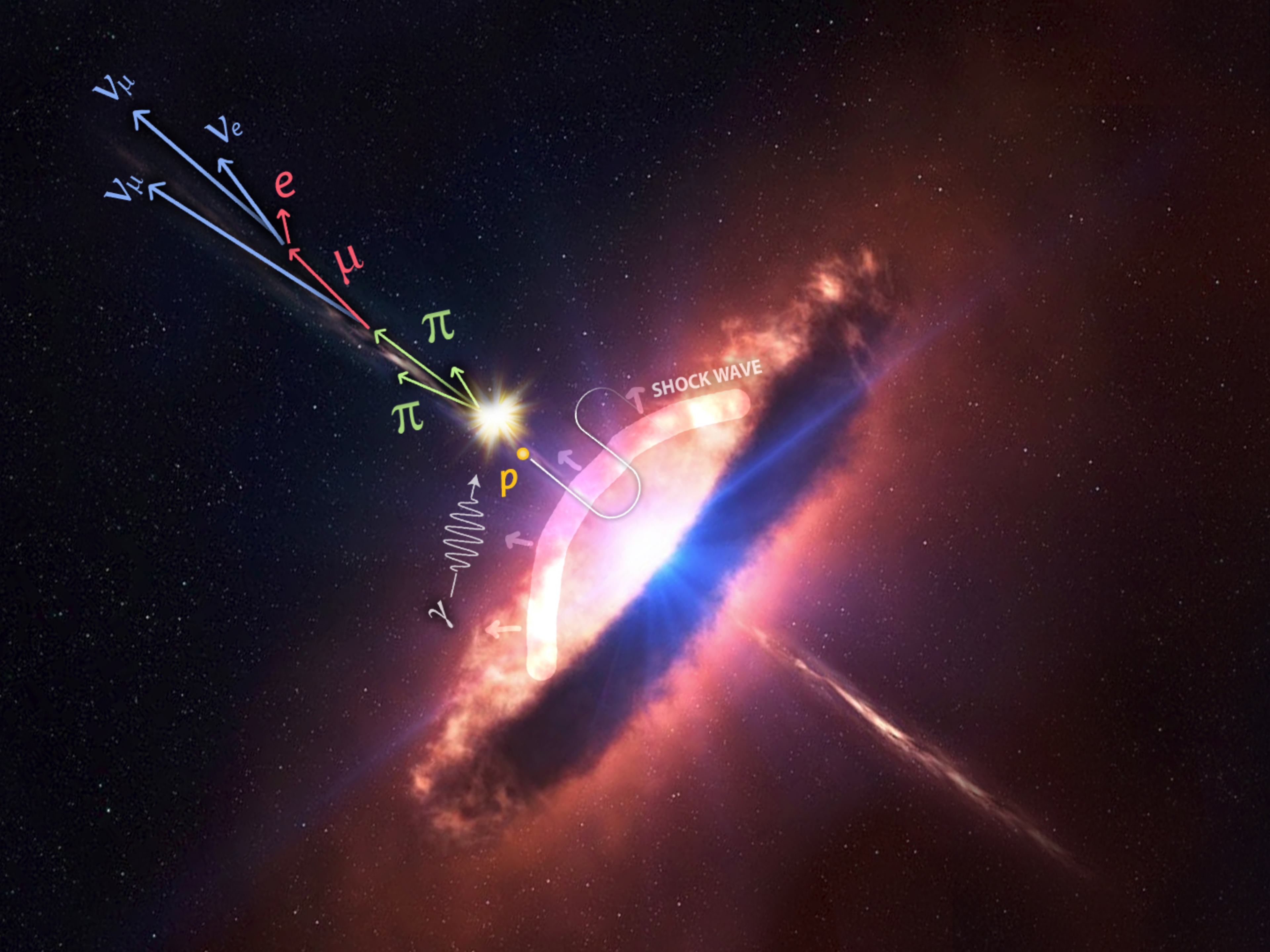
gamma
ray
bursts



active galaxy

particle flows near
supermassive
black hole



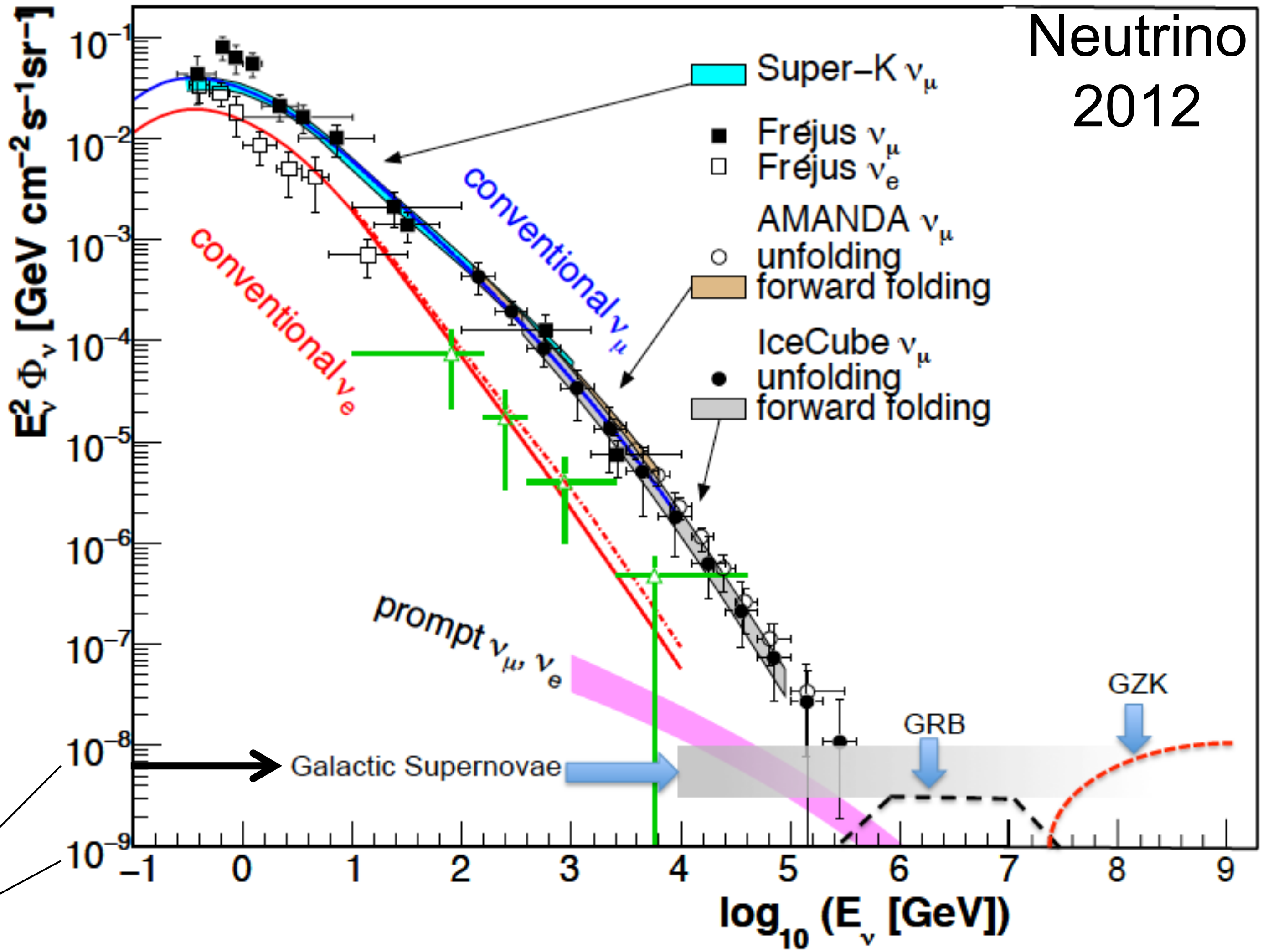


νμ
νe
e
νμ
μ
π
SHOCK WAVE
π
p
γ

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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



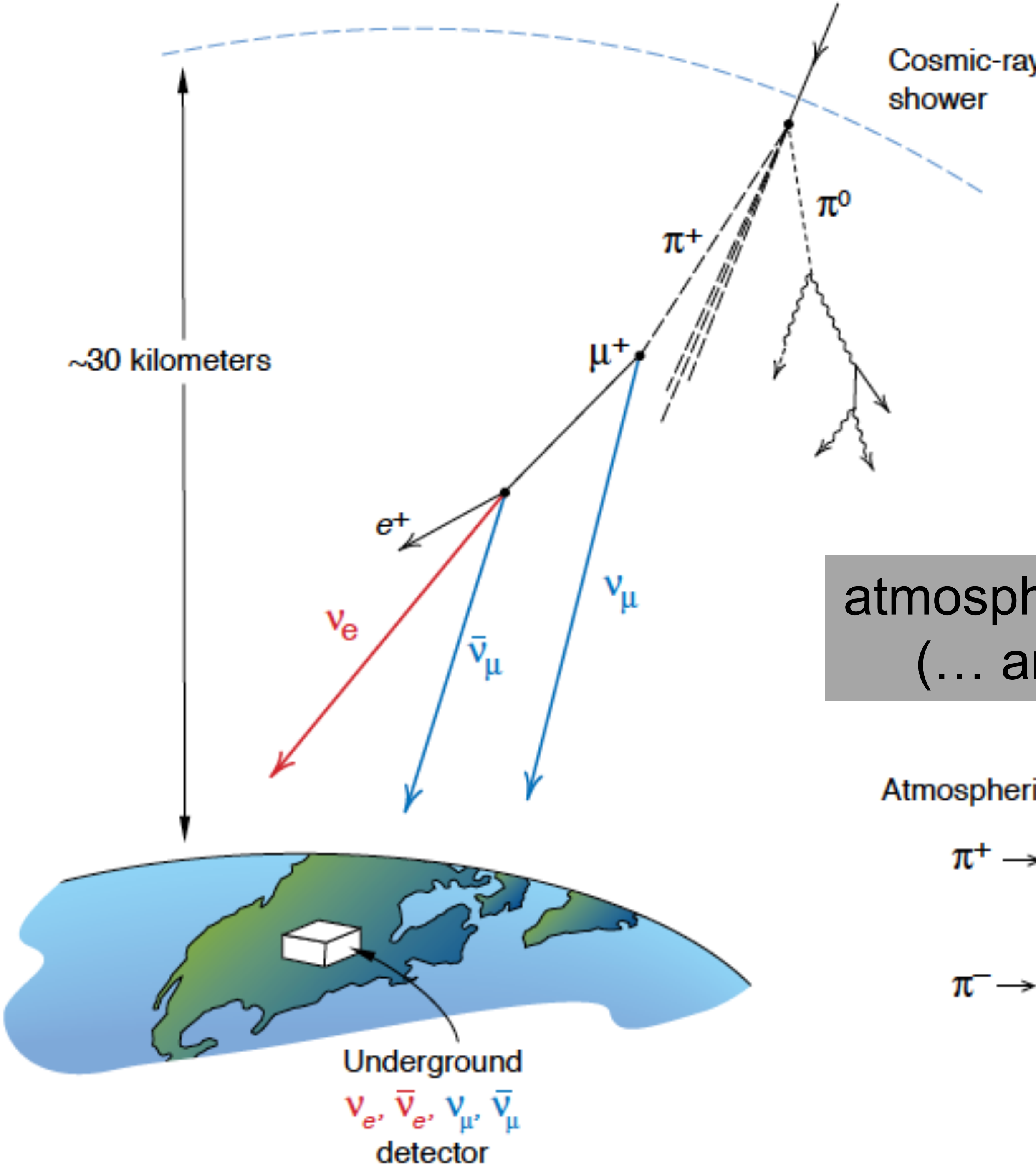
10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV

atmospheric neutrinos (… and muons!)

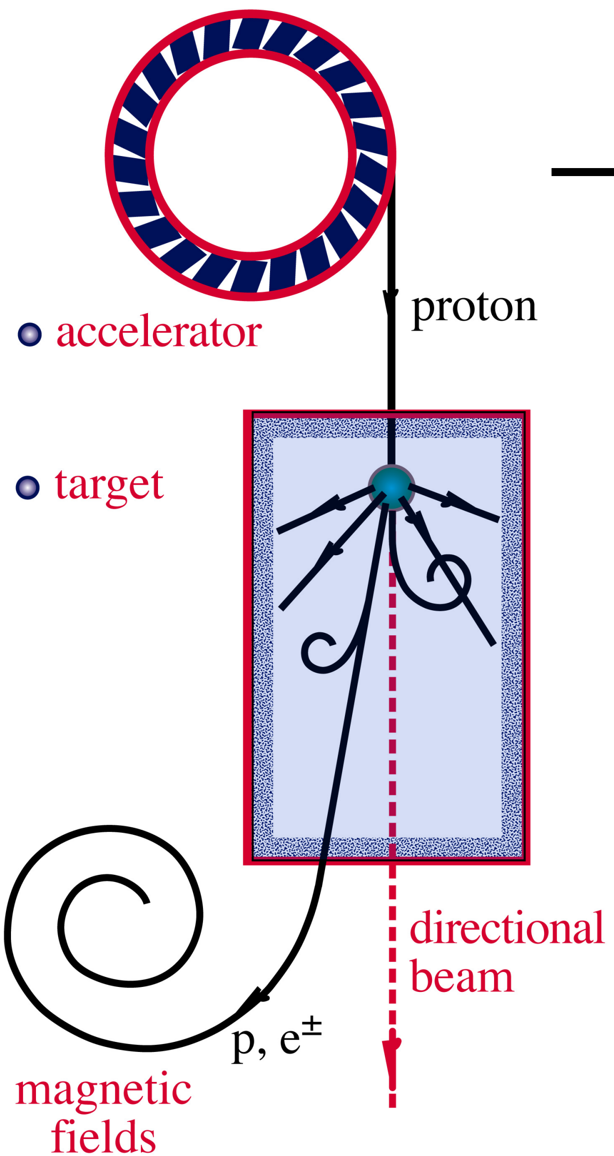


Atmospheric neutrino source

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

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

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

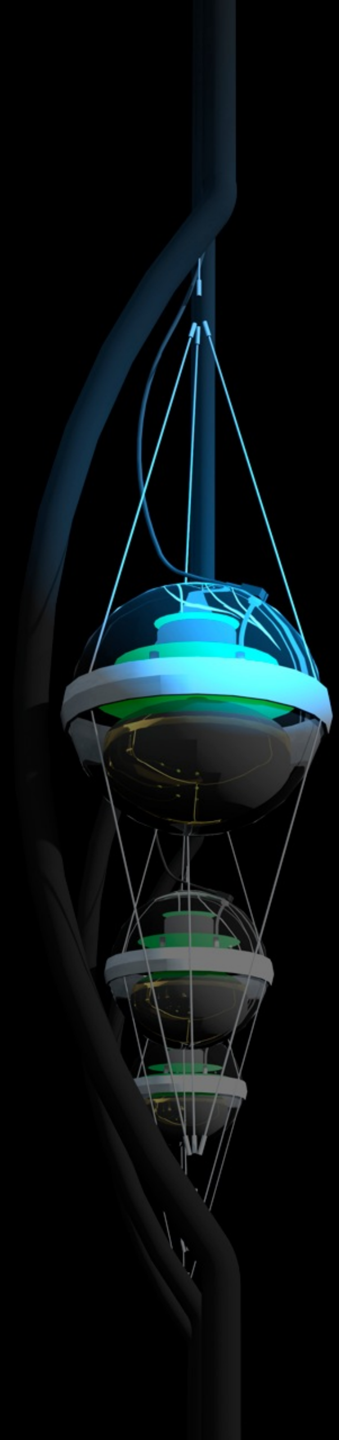
radiation and dust

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

~ cosmic ray + neutrino

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

~ cosmic ray + gamma



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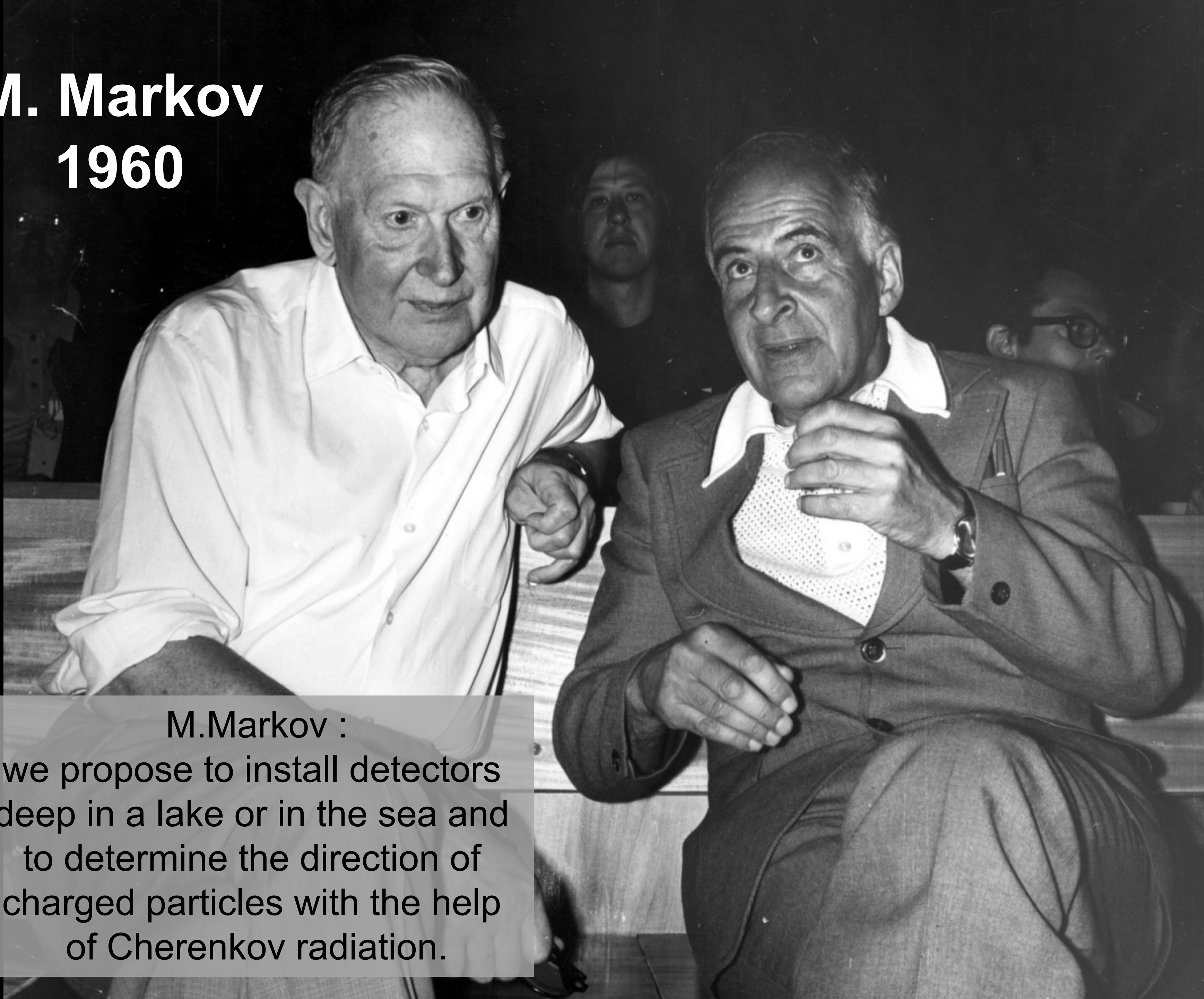
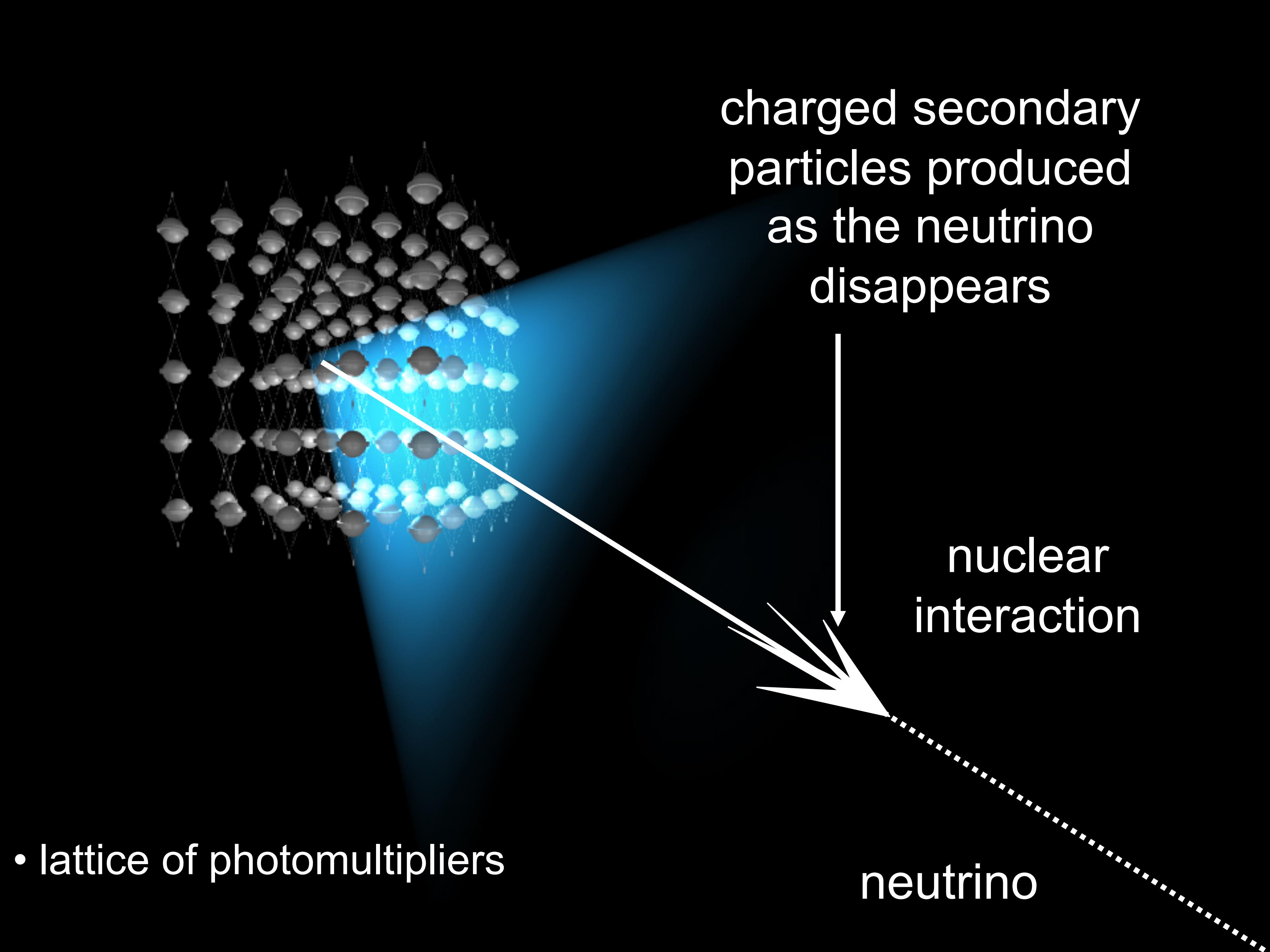
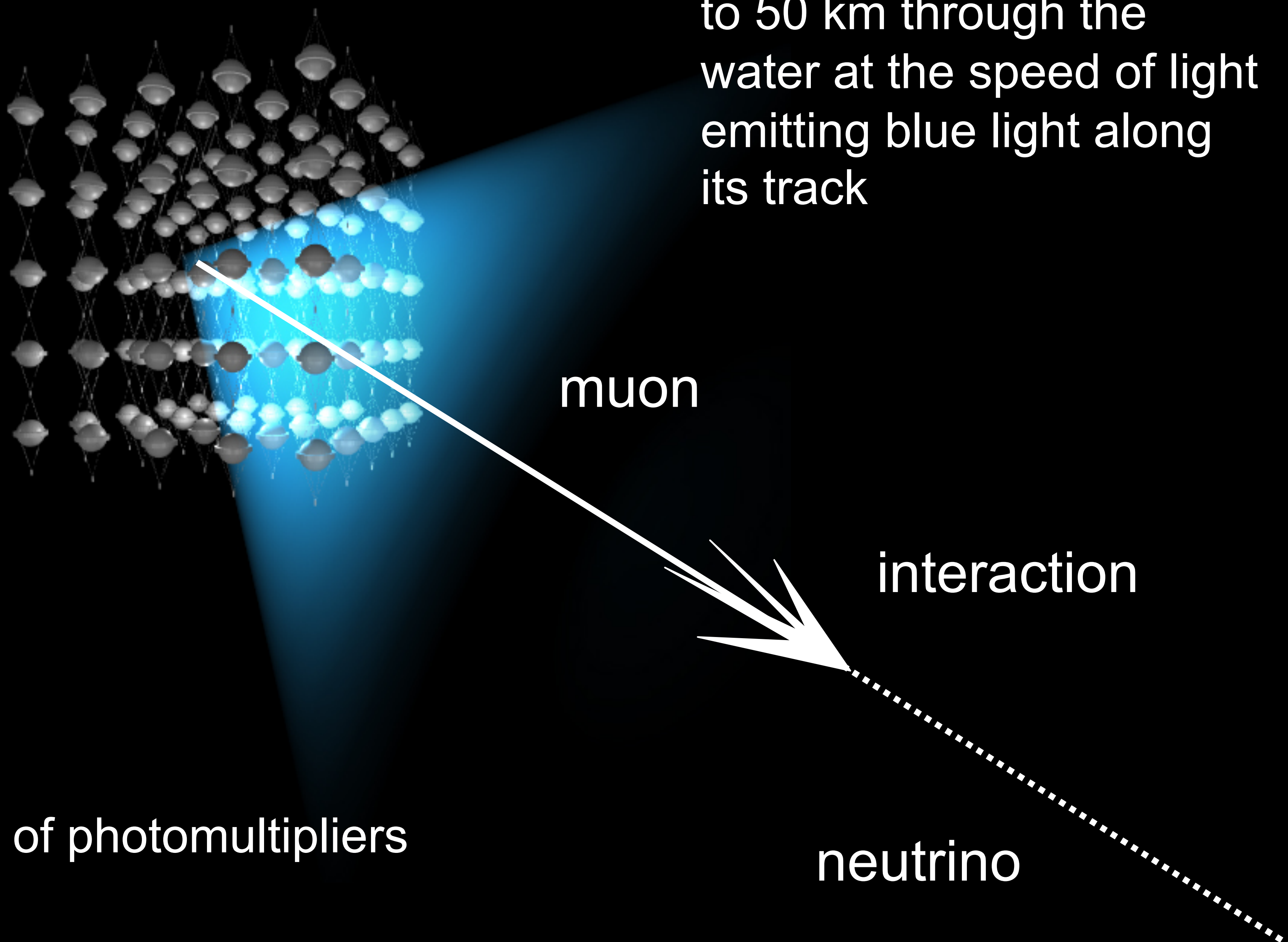
M. Markov
1960



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

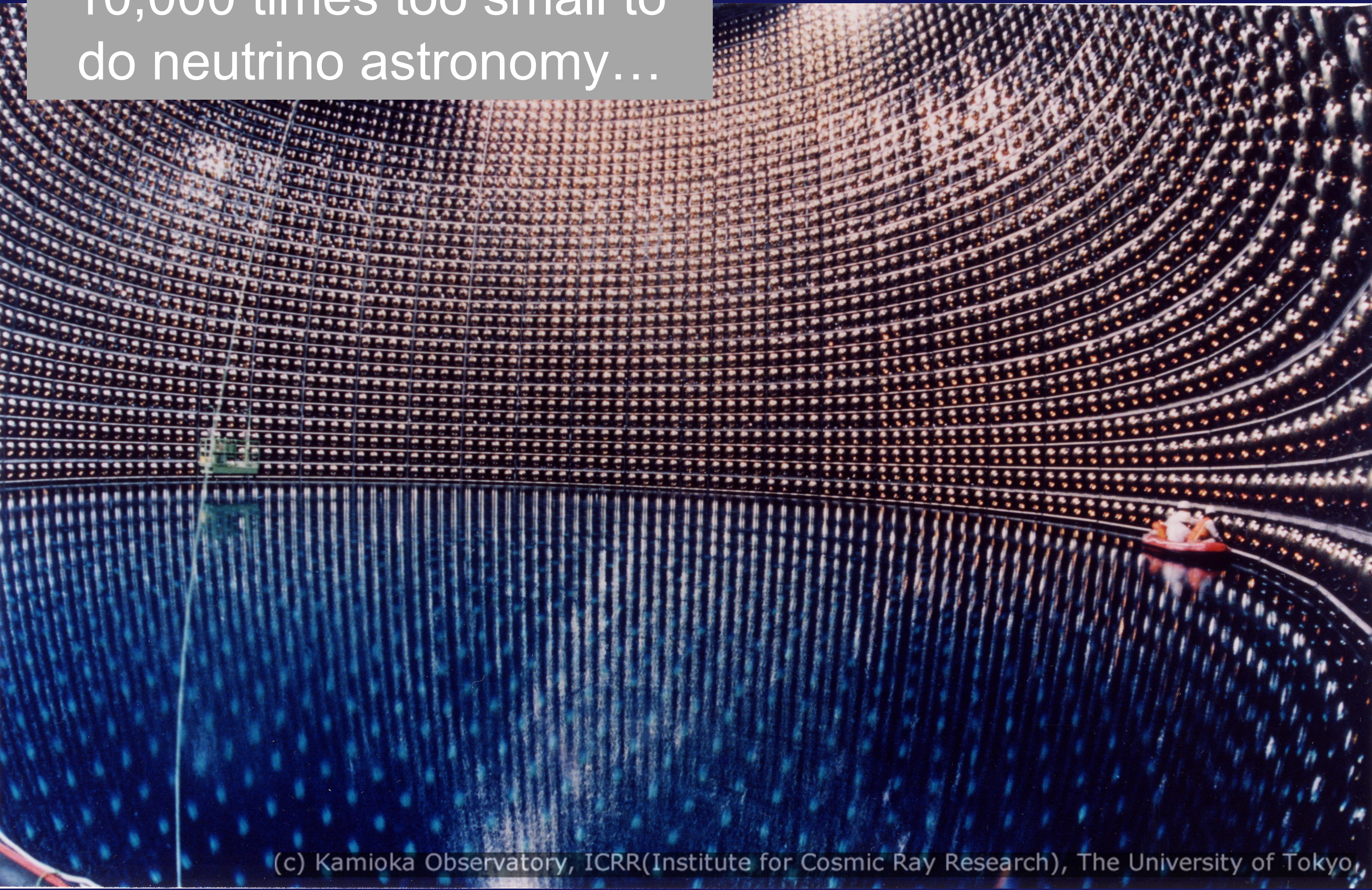

charged secondary particles produced as the neutrino disappears
nuclear interaction
• lattice of photomultipliers
neutrino

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



- lattice of photomultipliers

10,000 times too small to do neutrino astronomy…

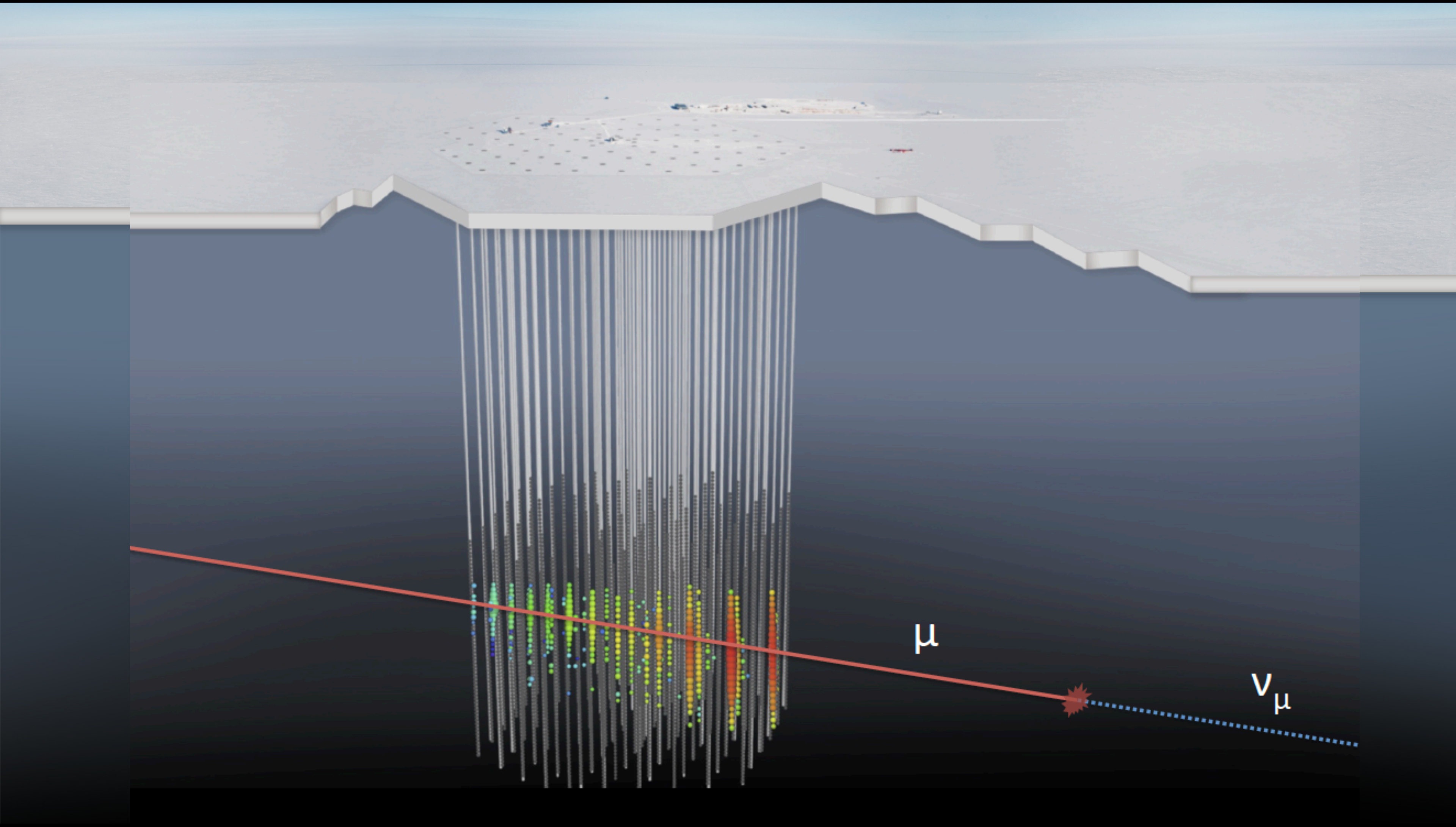


ice 1.4 kilometers below geographic South Pole

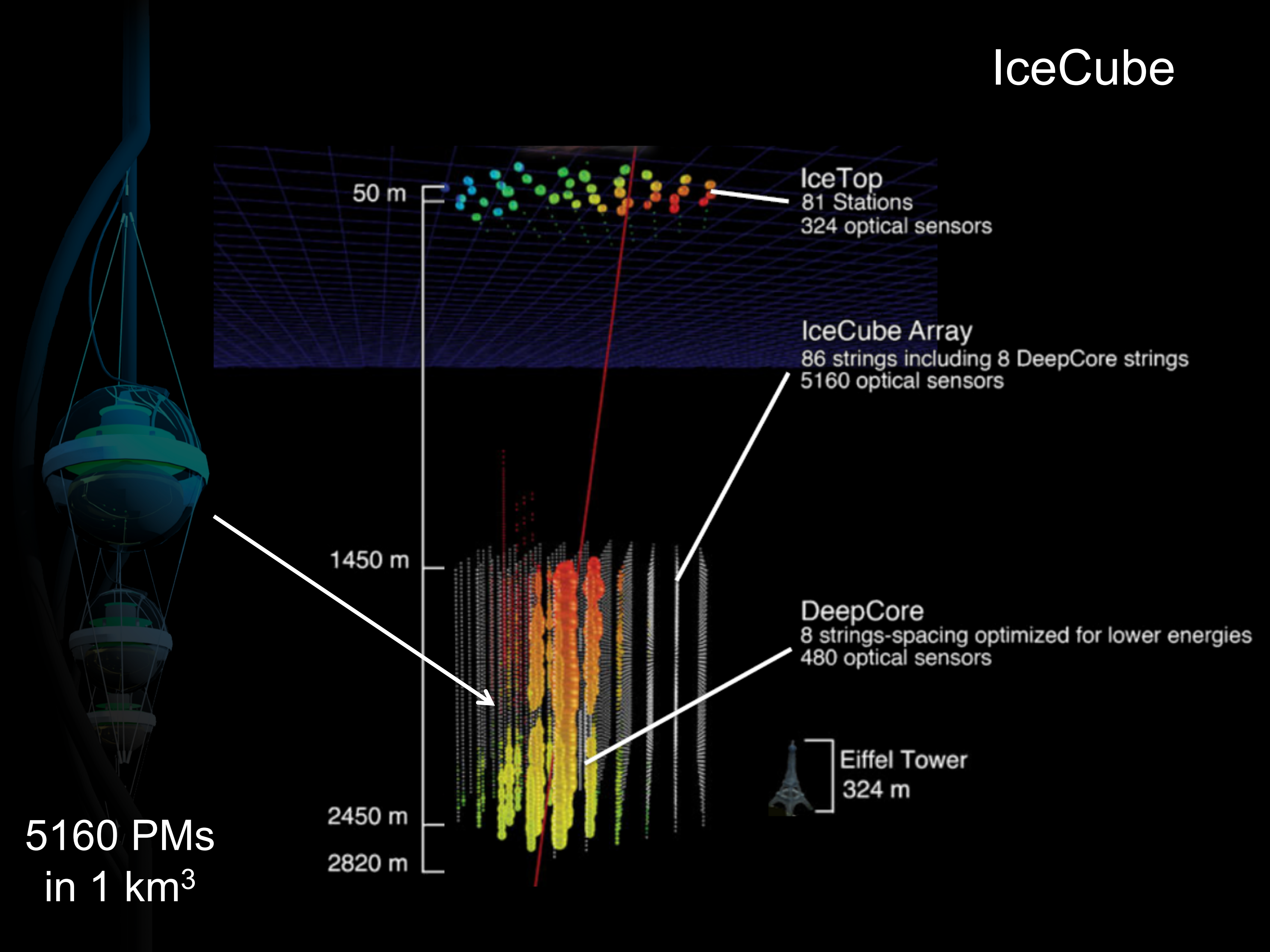
- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers


ultra-transparent ice below 1.5 km

instrument 1 cubic kilometer of natural ice below 1.45 km

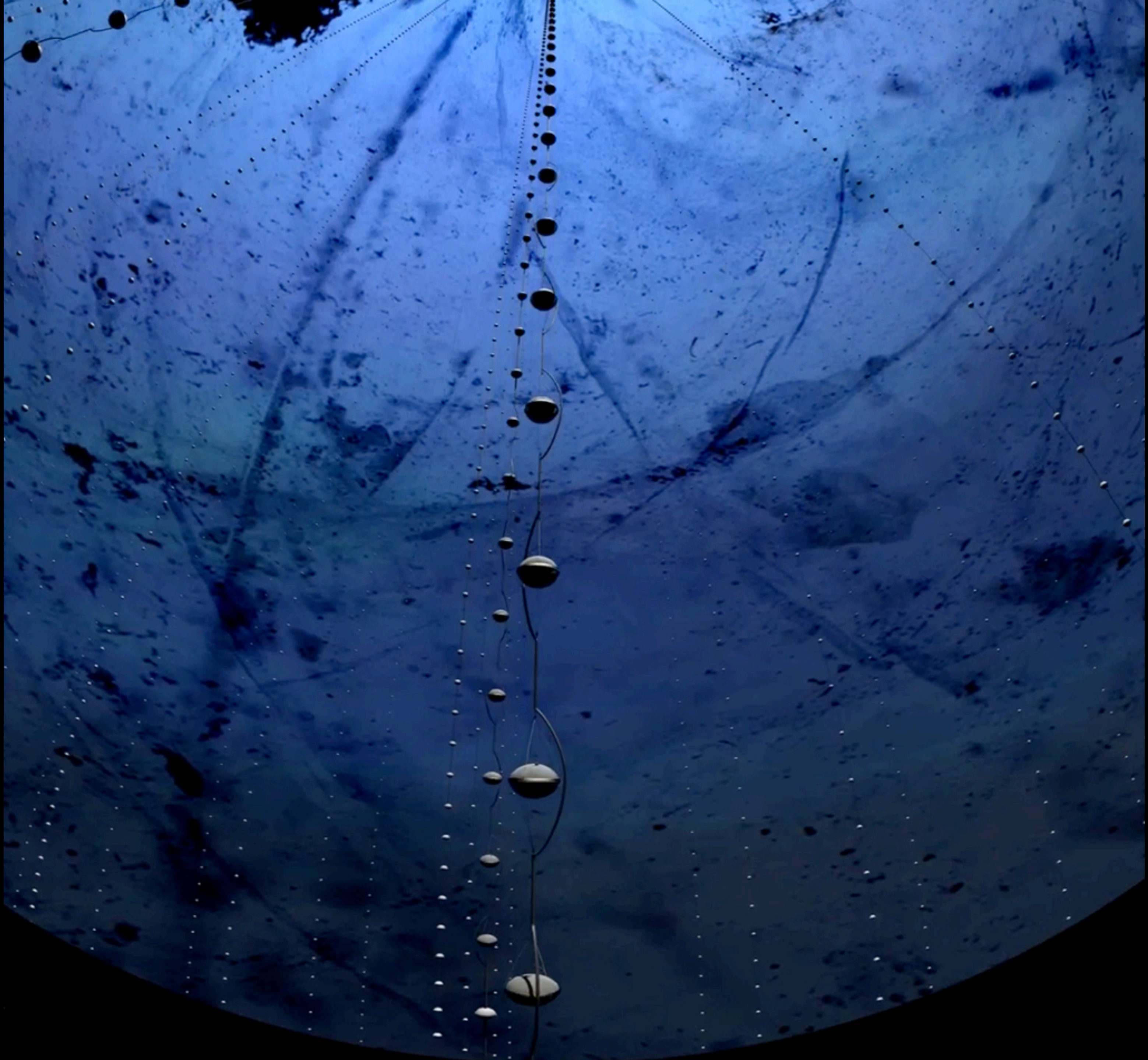


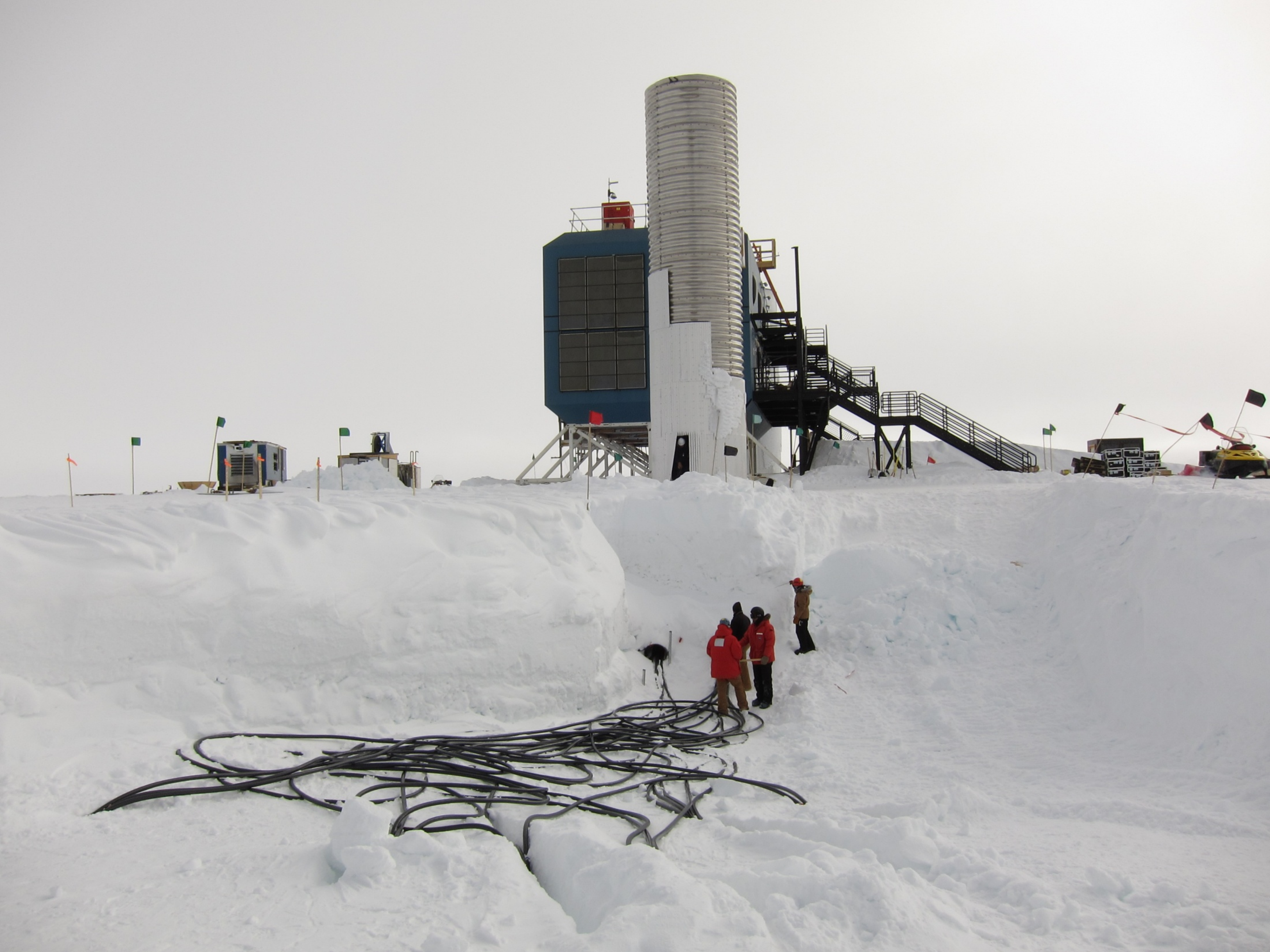
IceCube

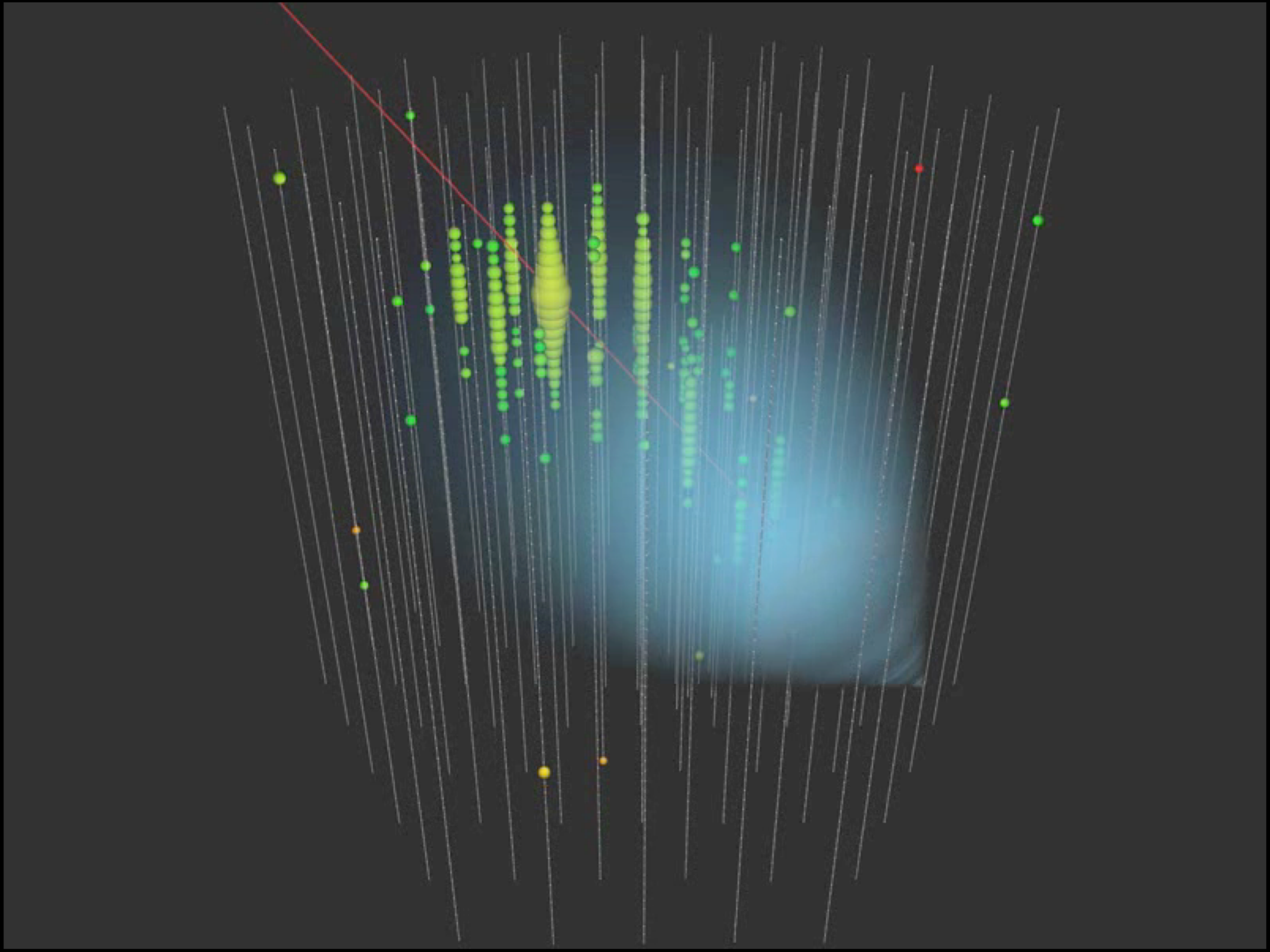


5160 PMs
in 1 km^3

photomultiplier tube -10 inch



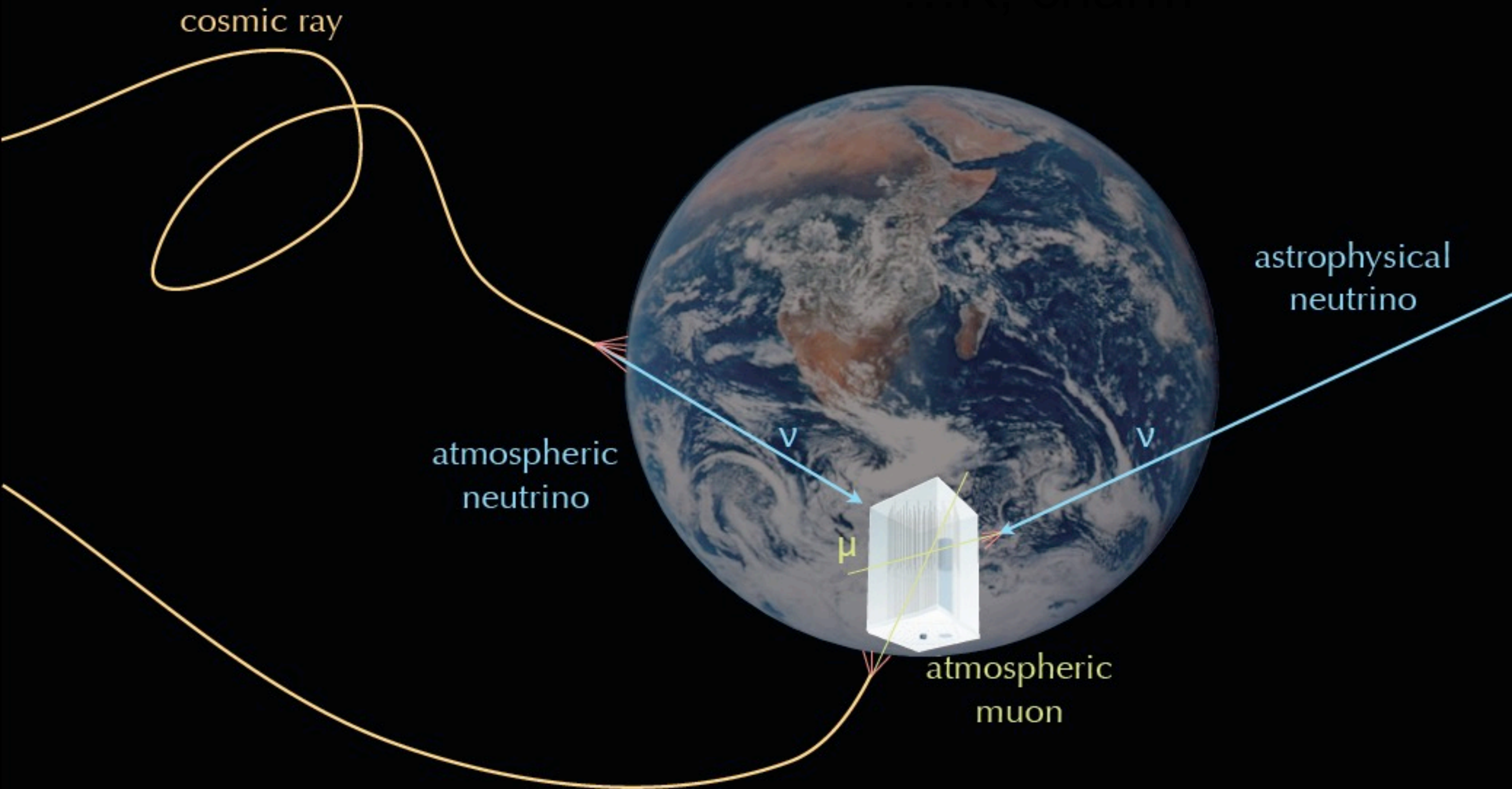




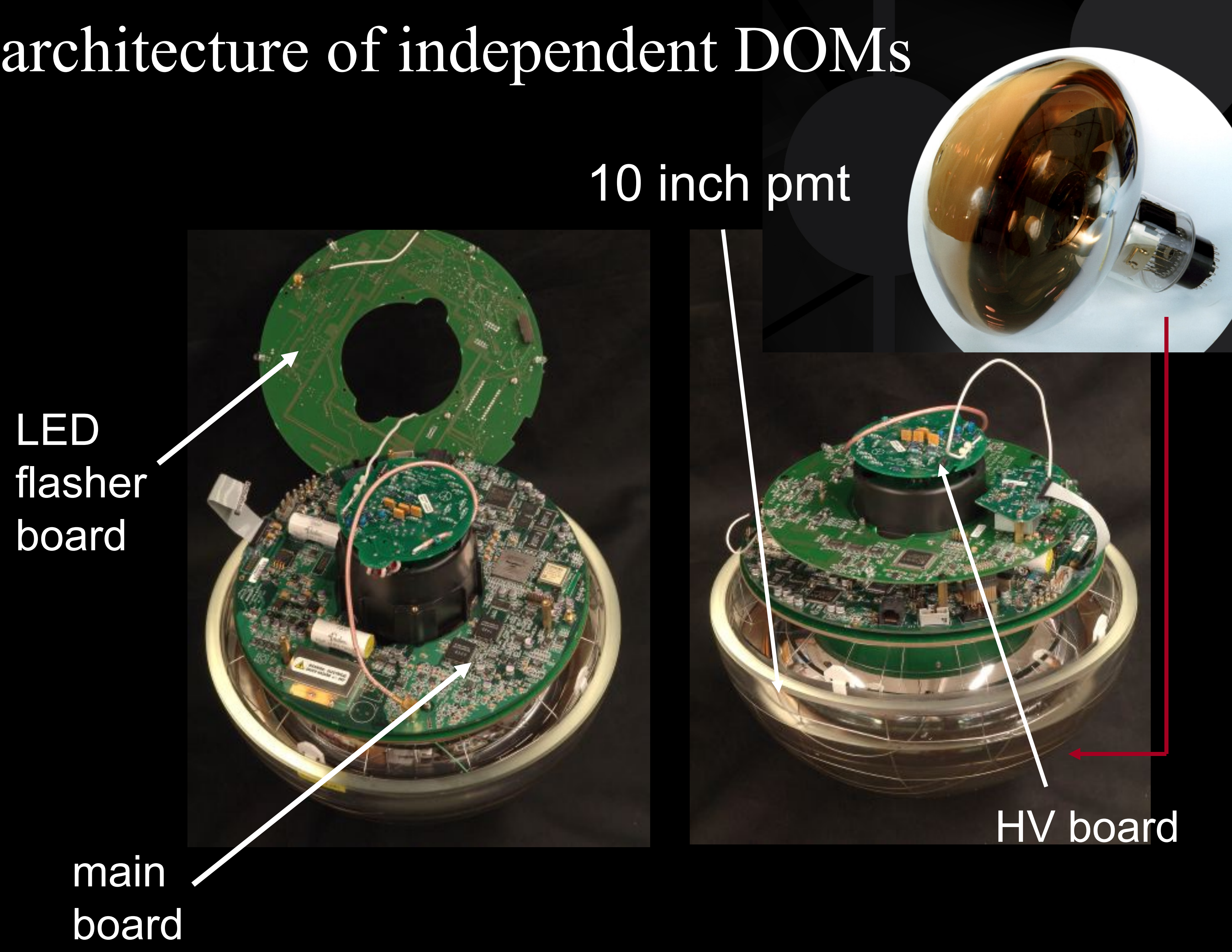
muon track: color is time; number of photons is energy

Signals and Backgrounds

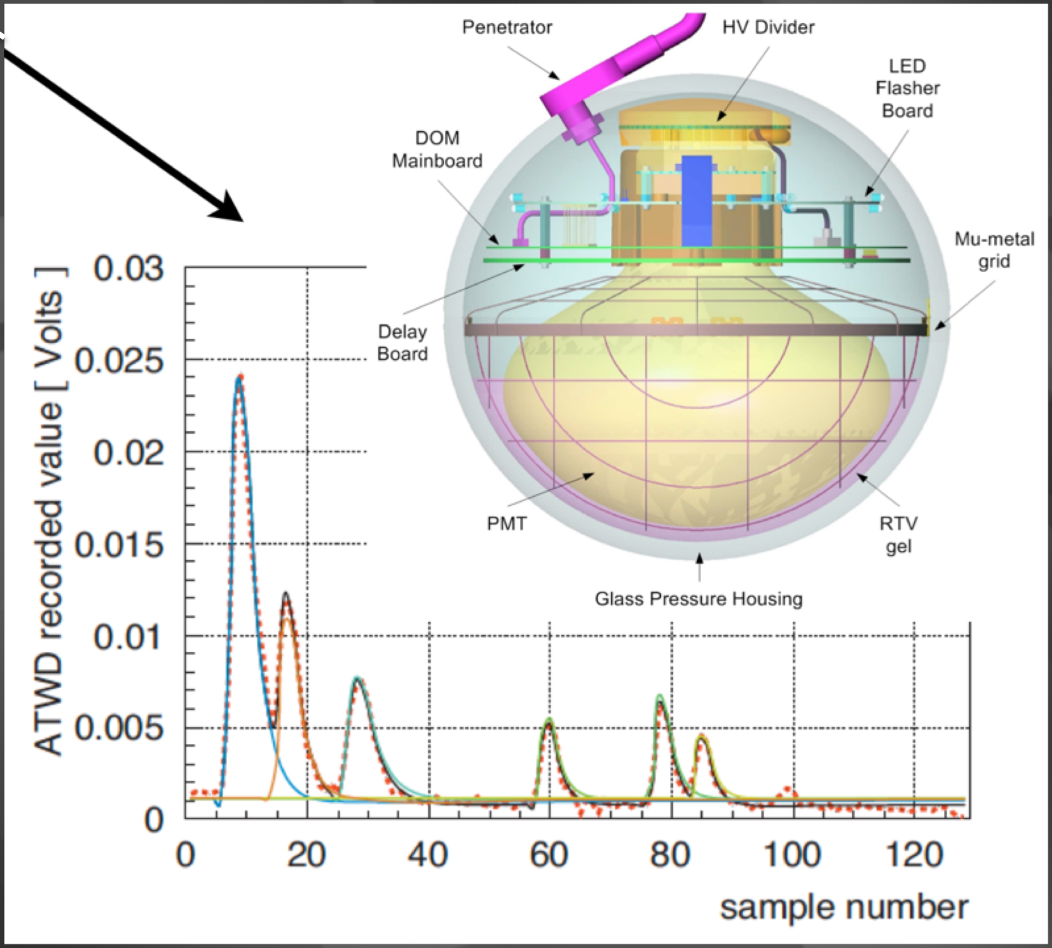
...K, charm



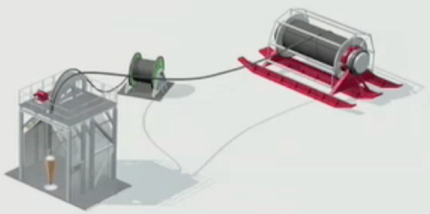
architecture of independent DOMs

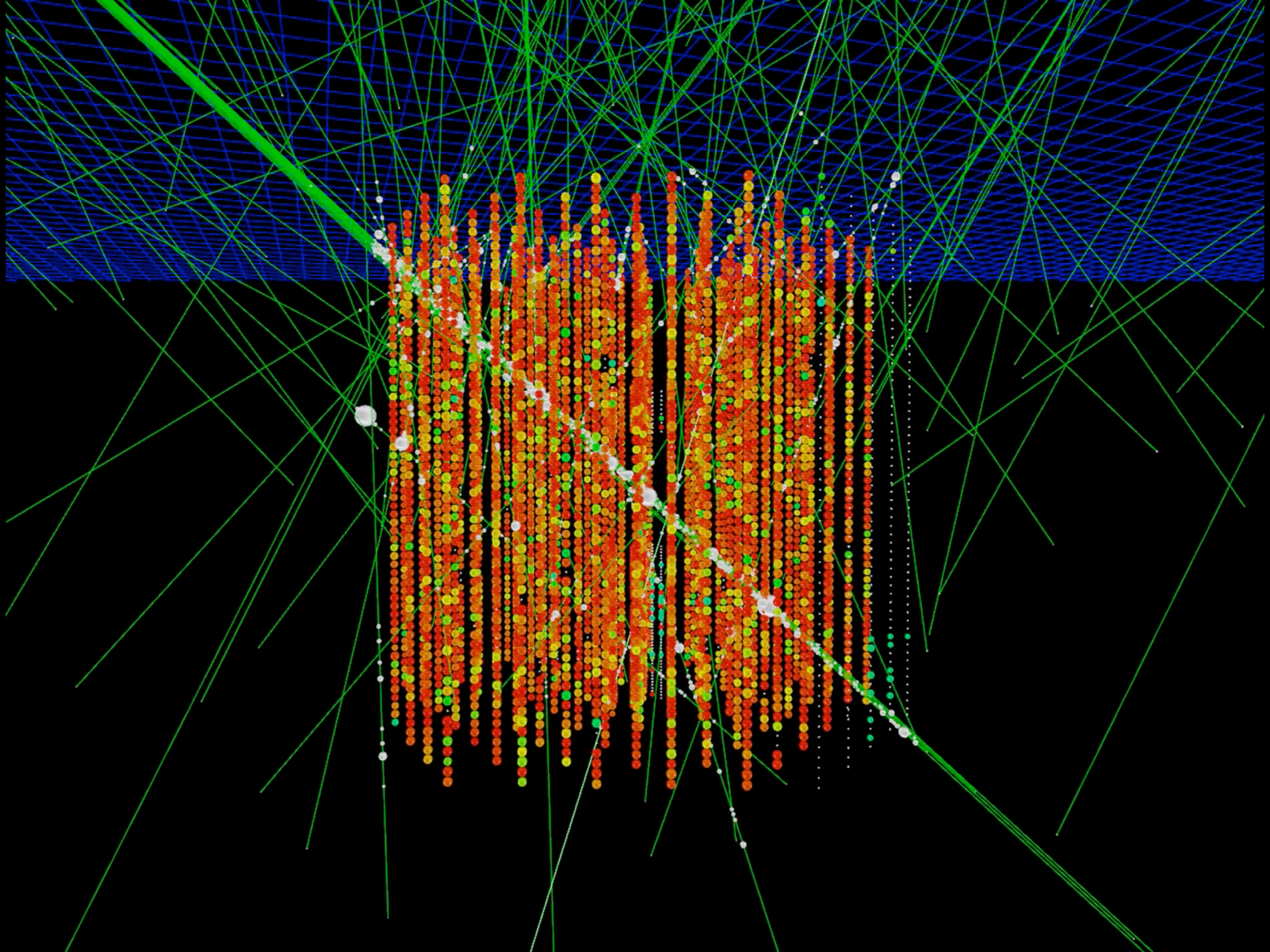


… each Digital Optical Module independently collects light signals like this, digitizes them,



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





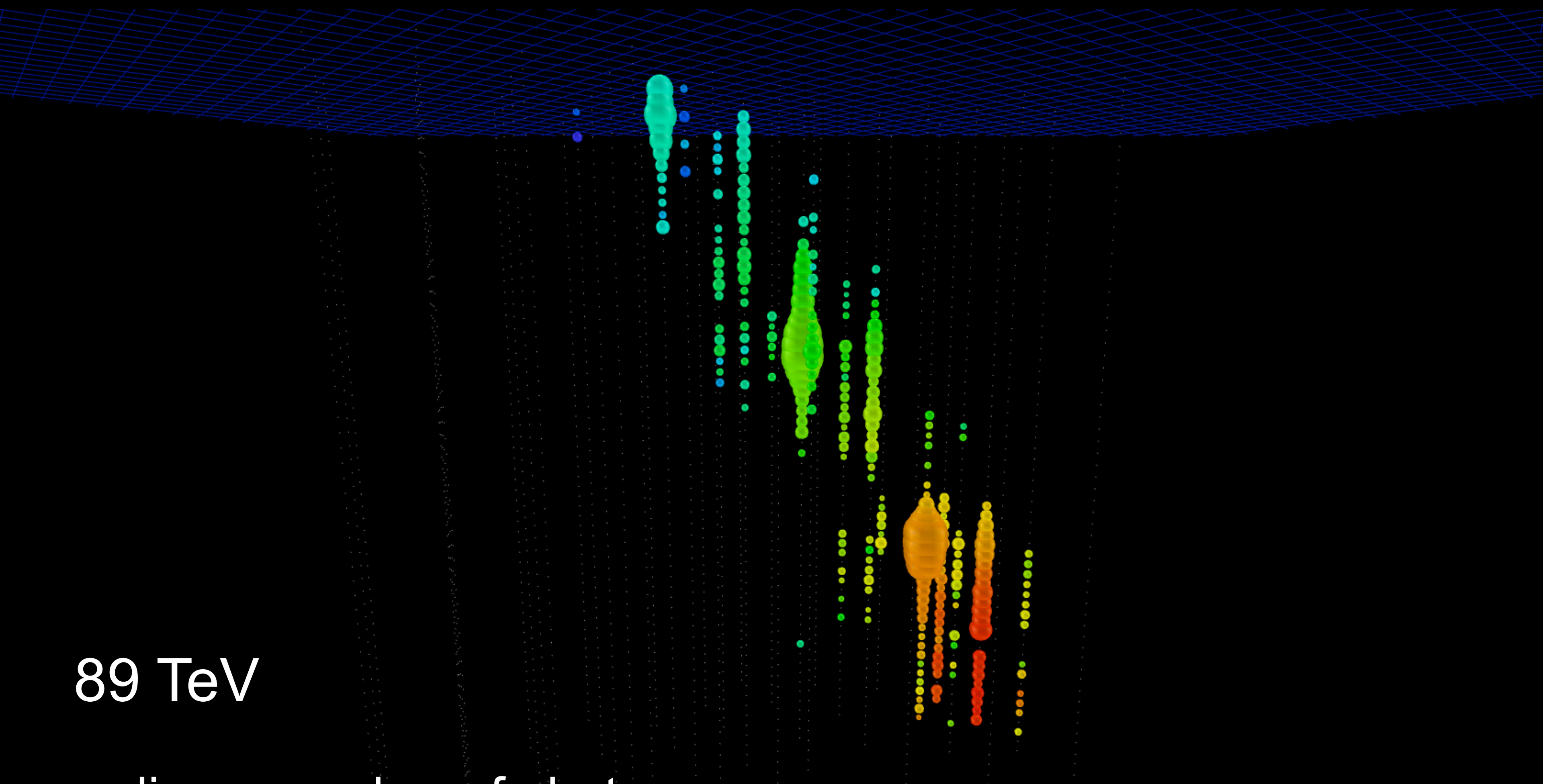
… you looked at 10msec of data !

muons detected per year:

• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	$\sim 10\text{–}10^{2}$

* 3000 per second

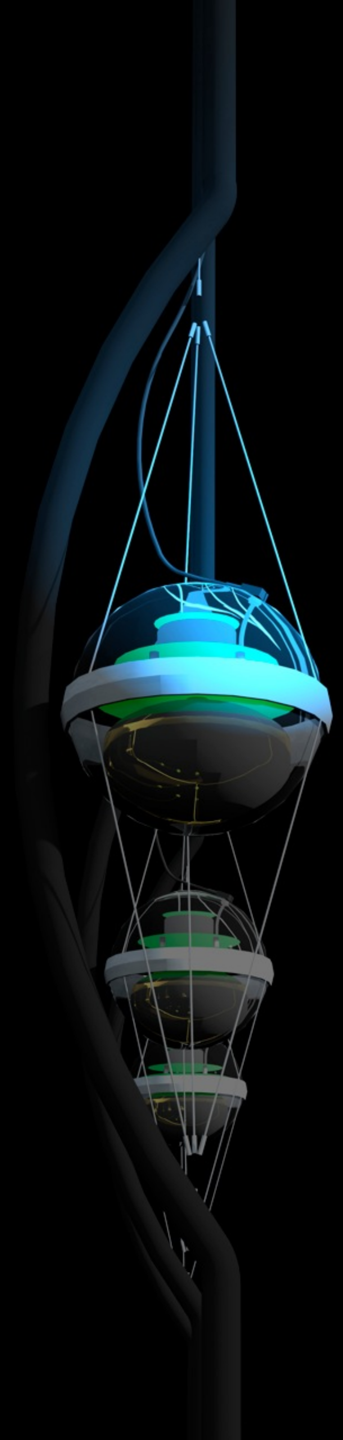
** 1 every 6 minutes



89 TeV

radius ~ number of photons
time ~ red → purple

Run 113641 Event 33553254 [0ns, 16748ns]



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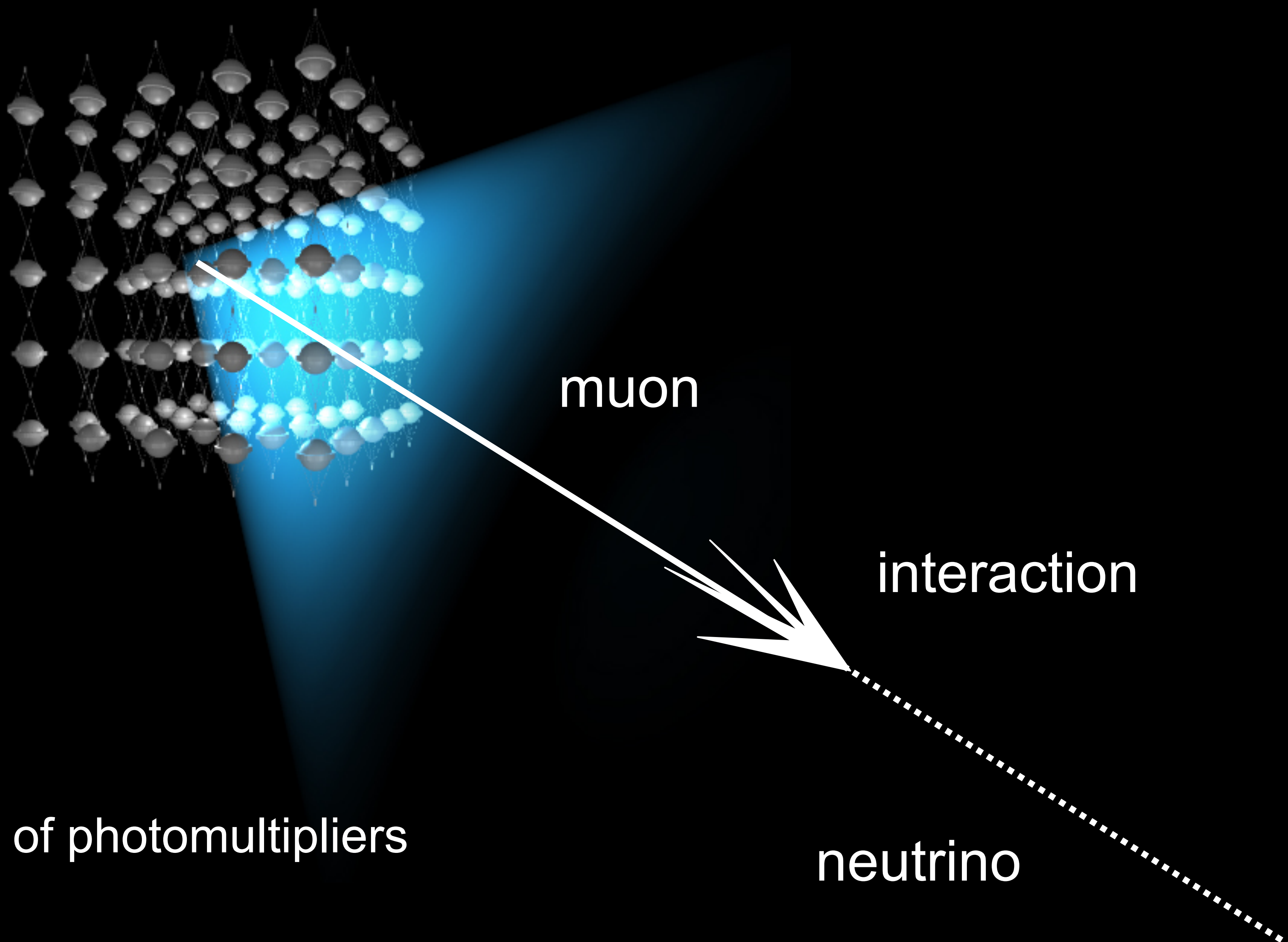
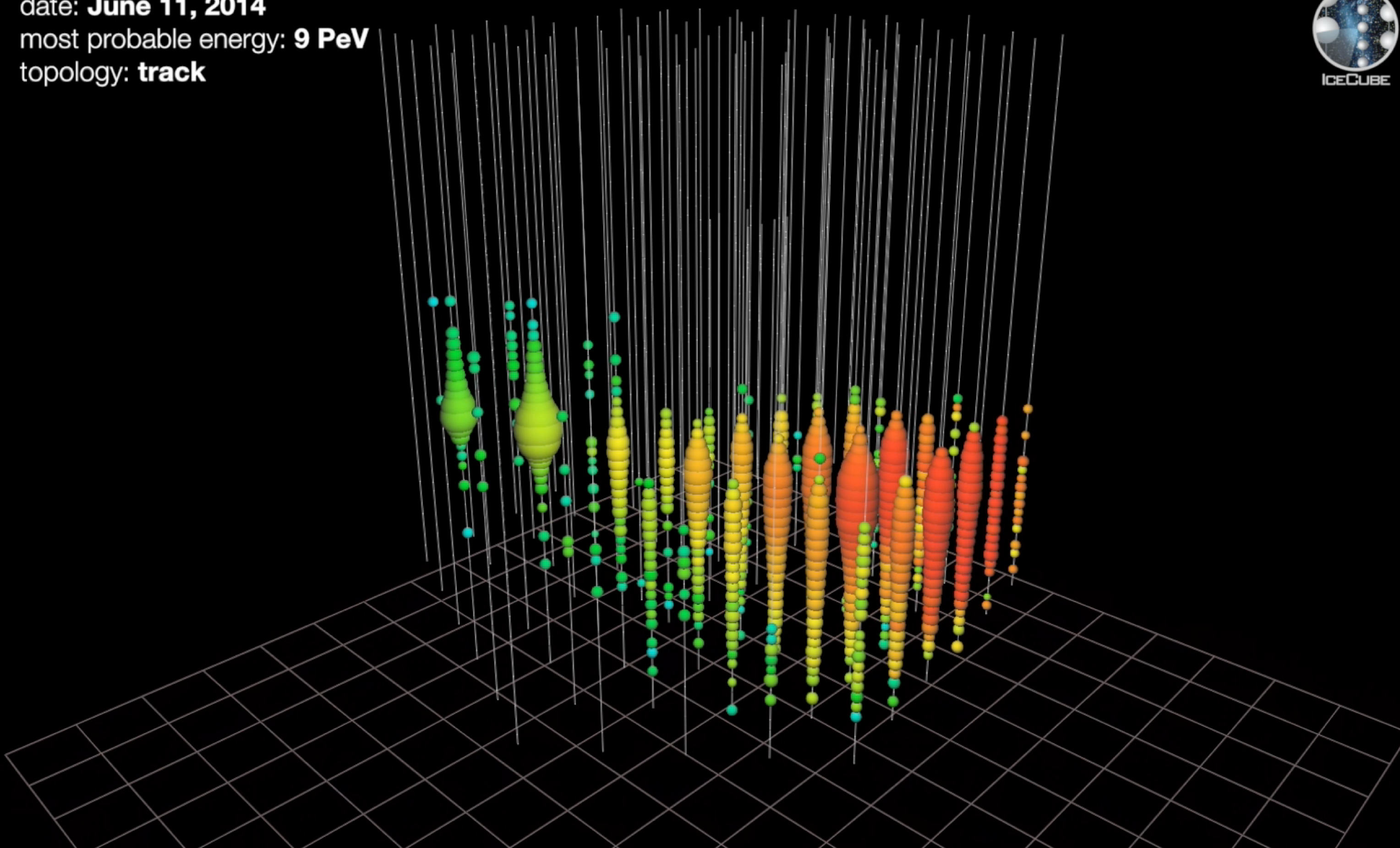
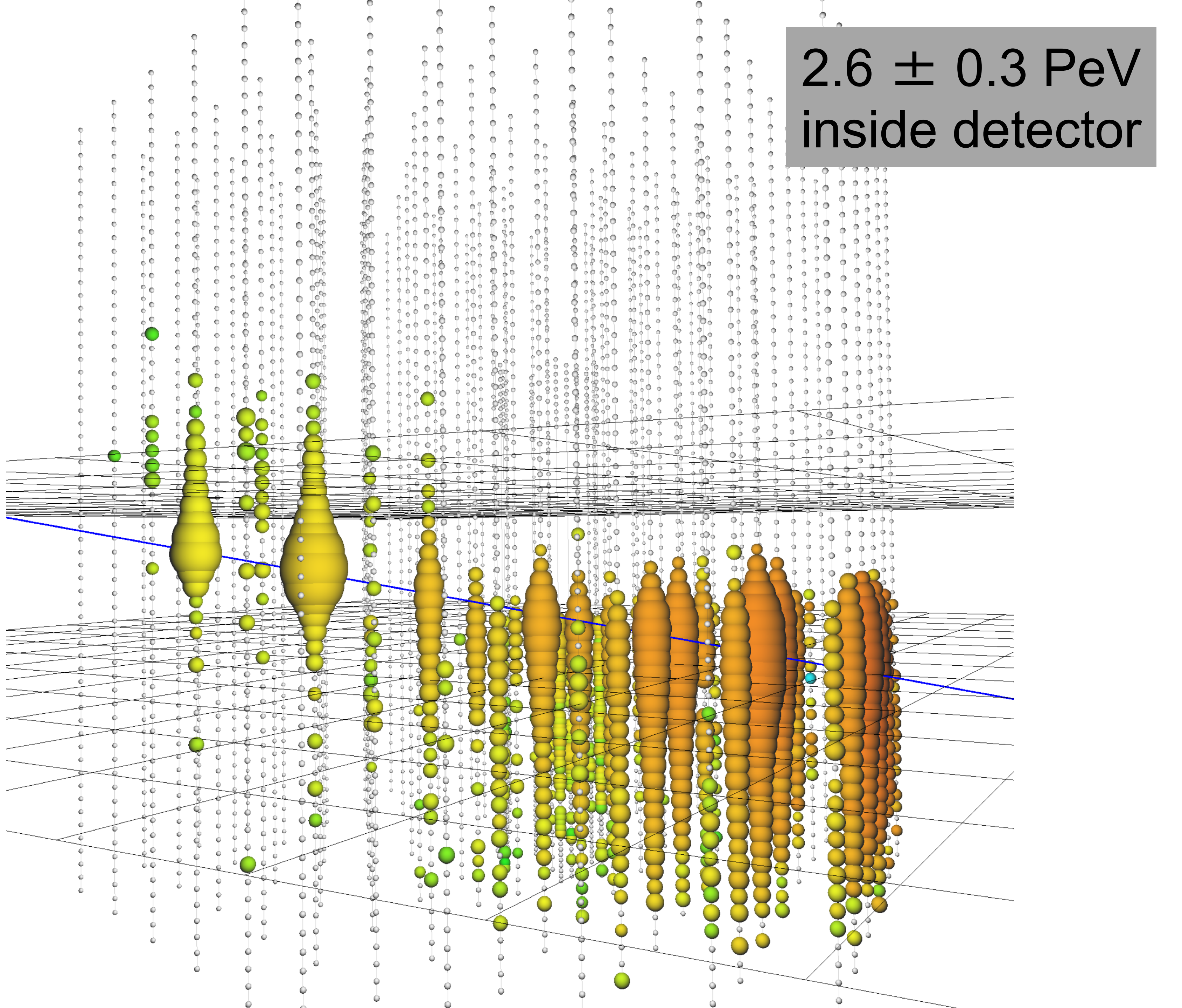


• lattice of photomultipliers

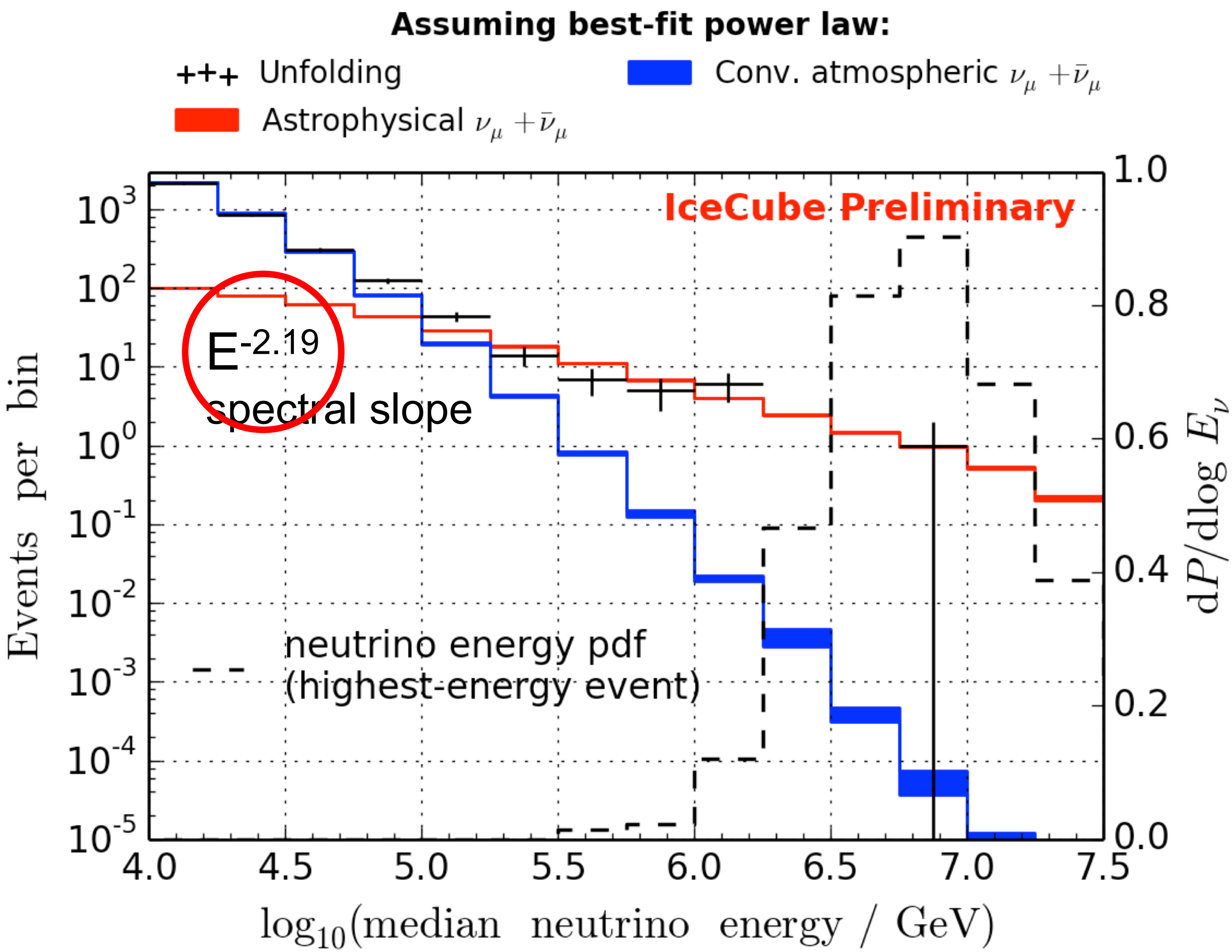
date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**




2.6 ± 0.3 PeV
inside detector

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

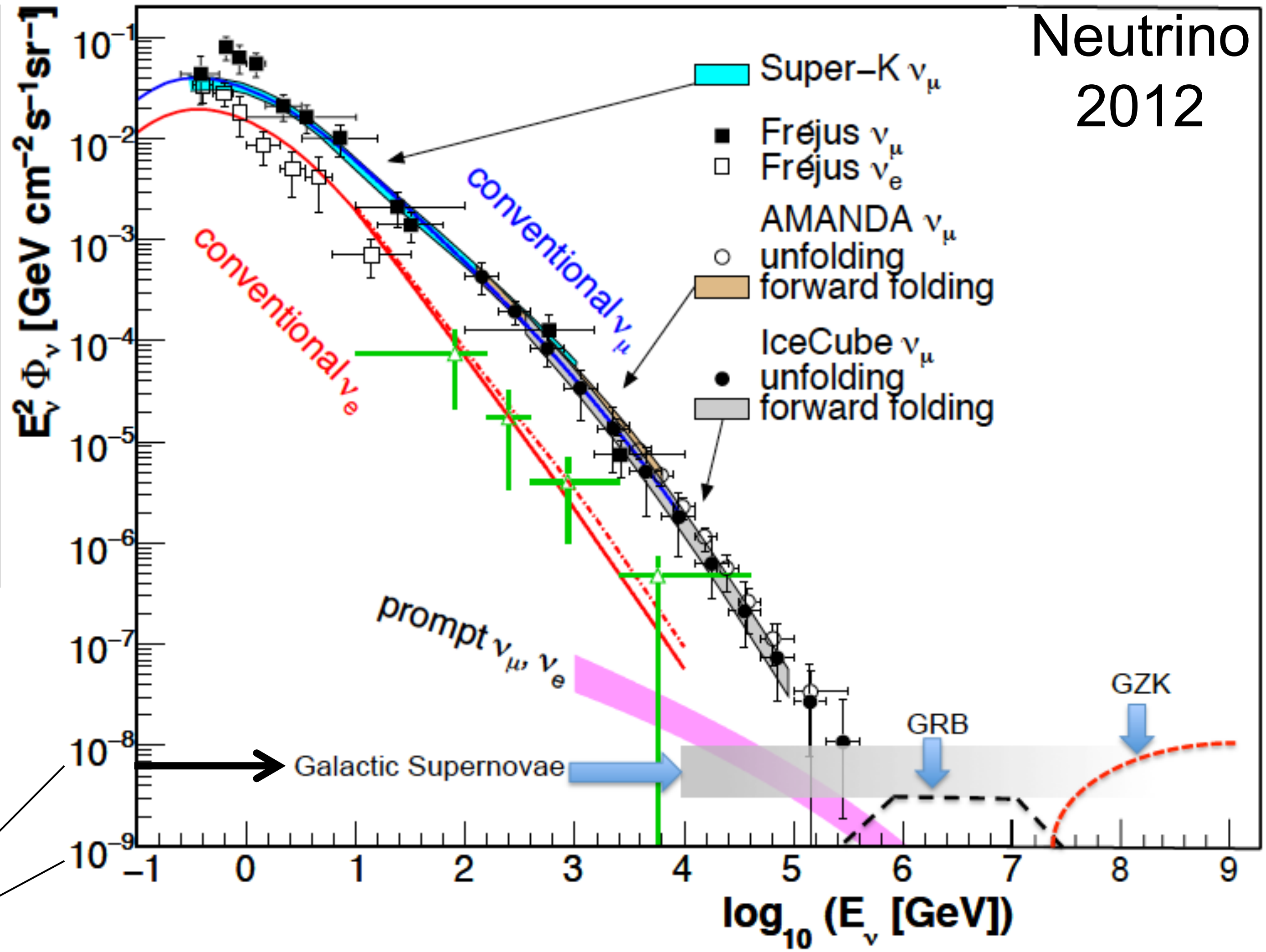
atmospheric background: less than one event/deg^2/year



above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

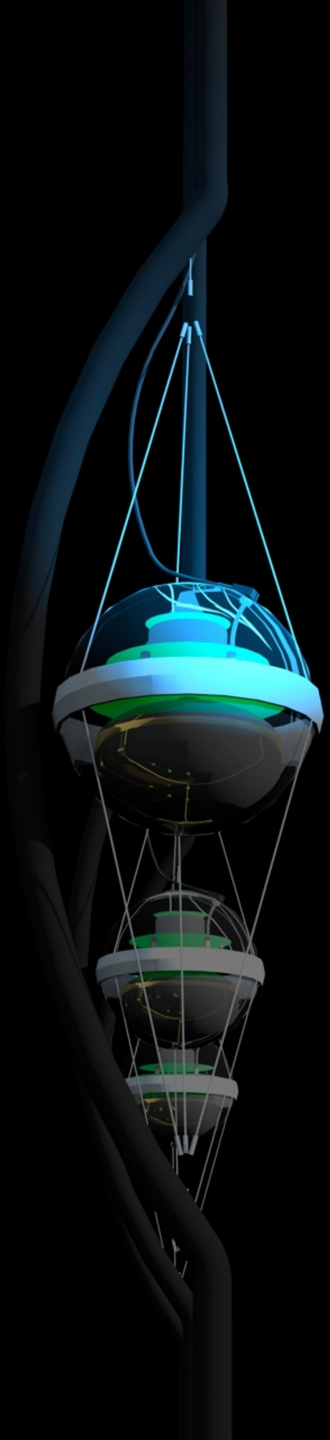


10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV



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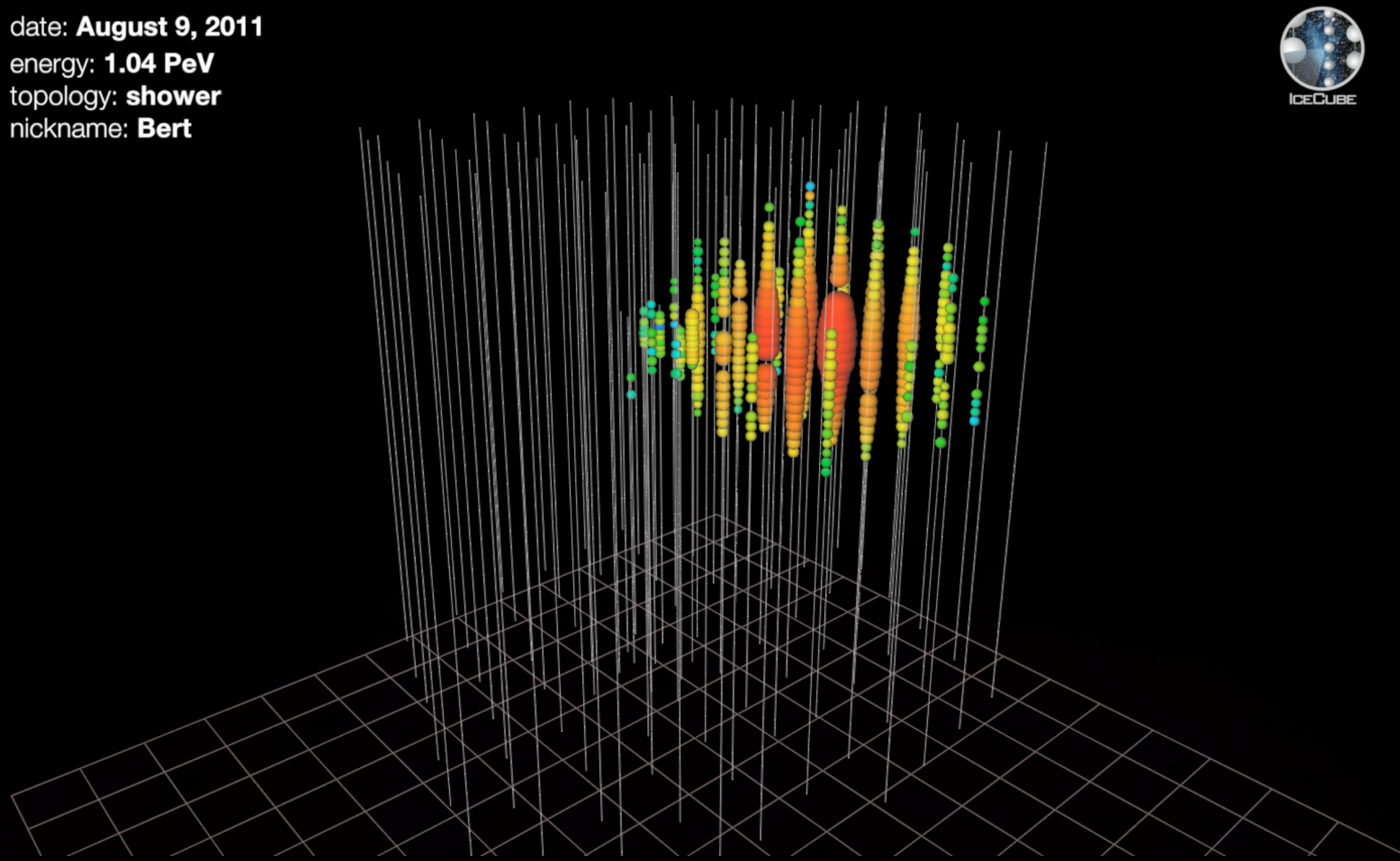
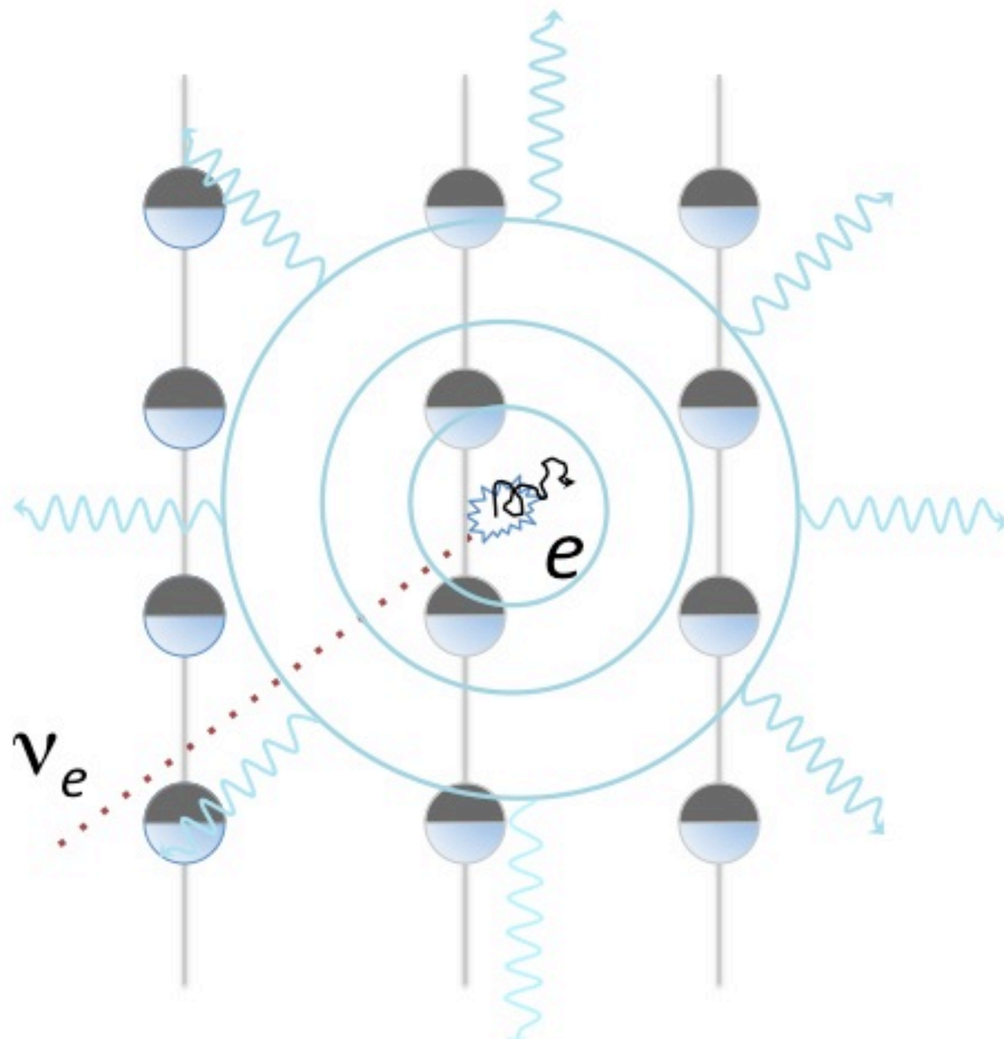
GZK neutrino search: two neutrinos with > 1,000 TeV

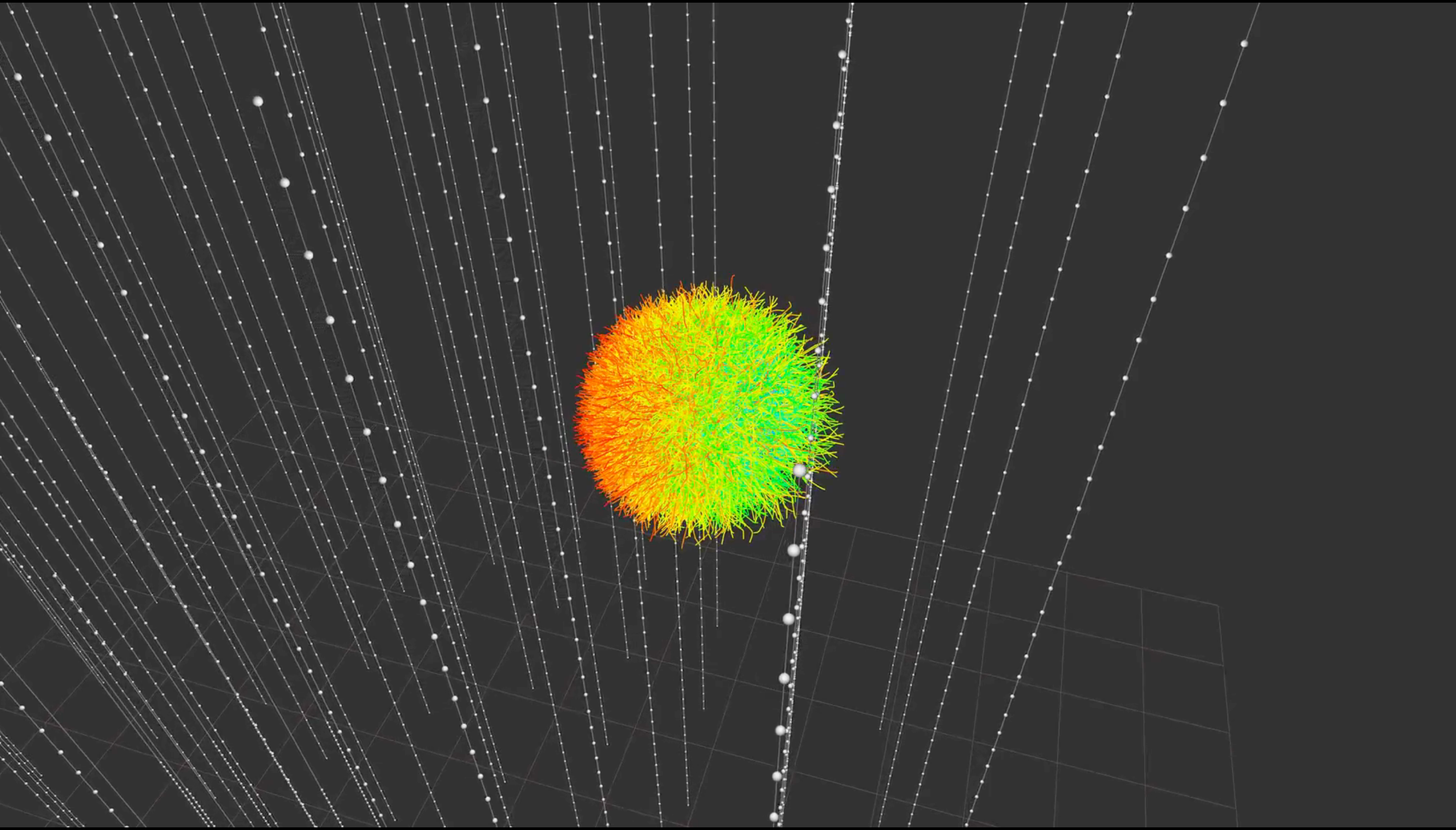


electron showers versus muon tracks

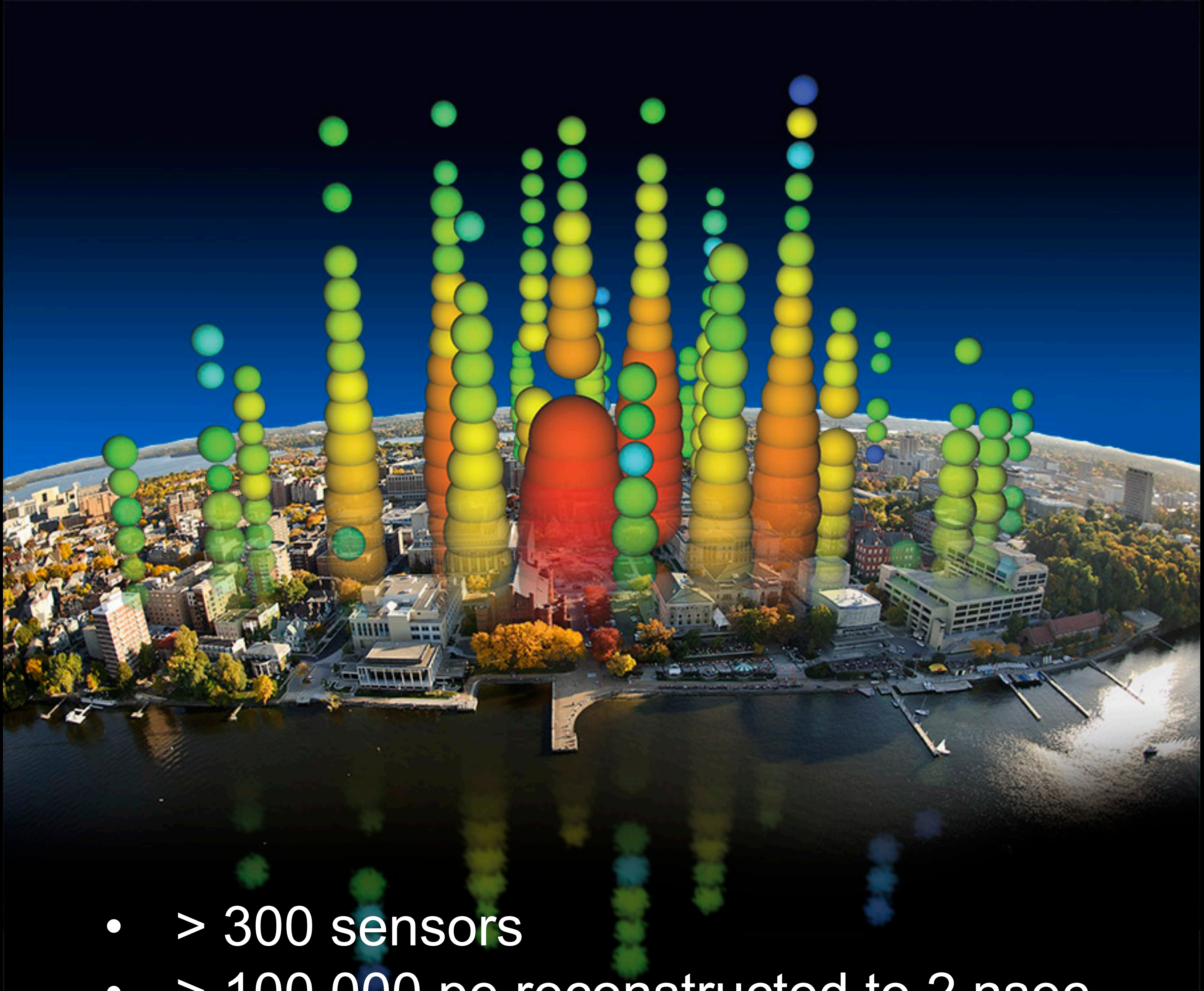
PeV ν_e and ν_τ showers:

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





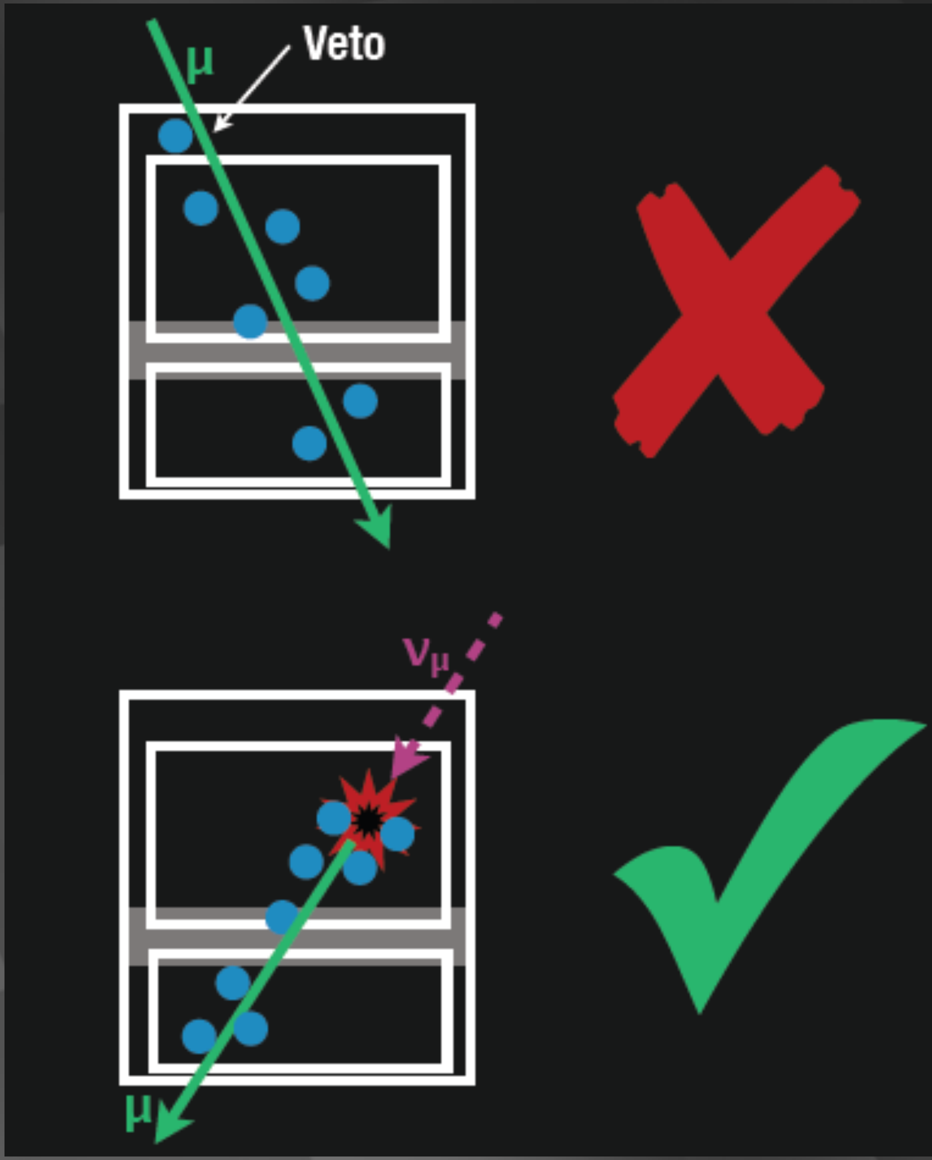
size = energy & color = time = direction



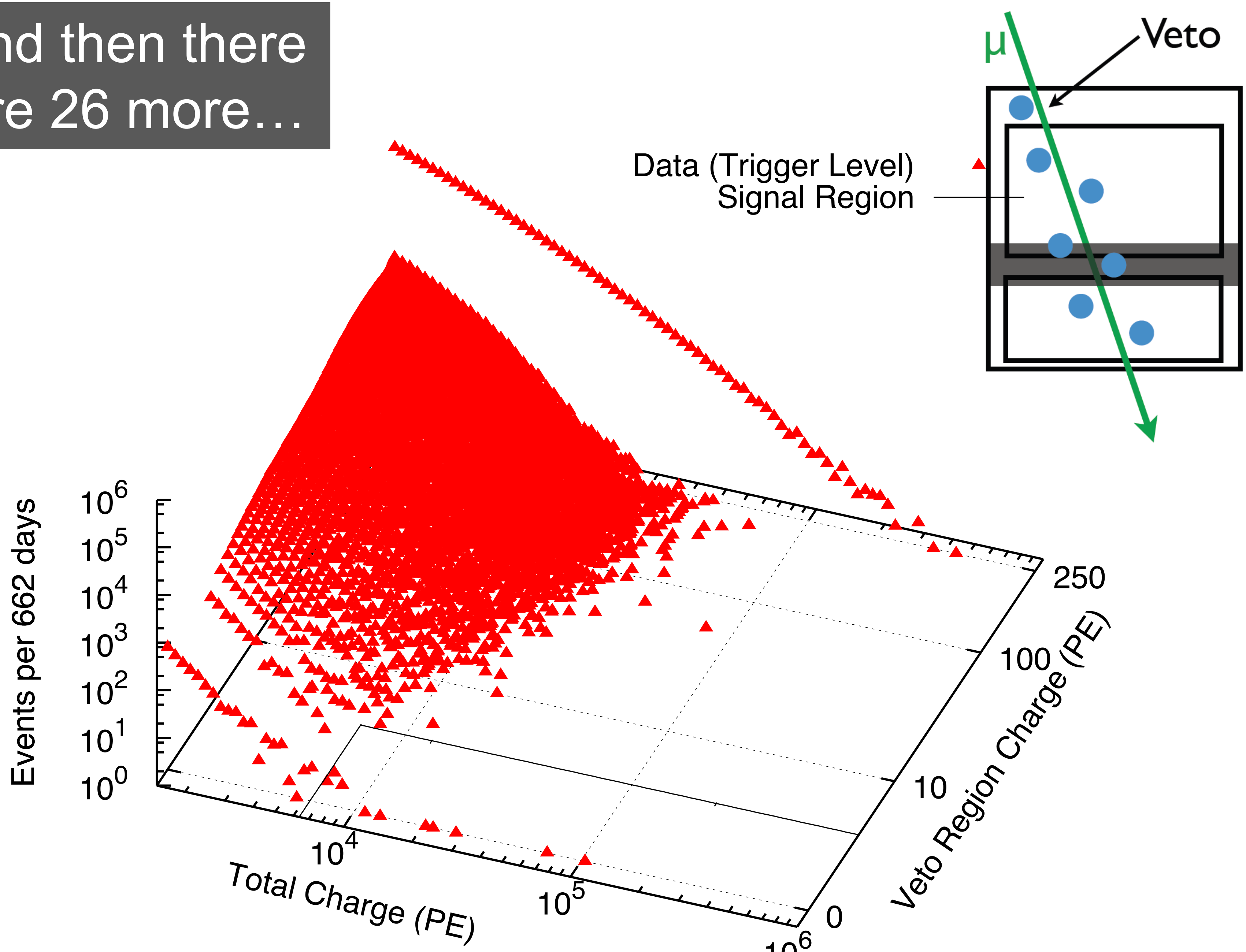
- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

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

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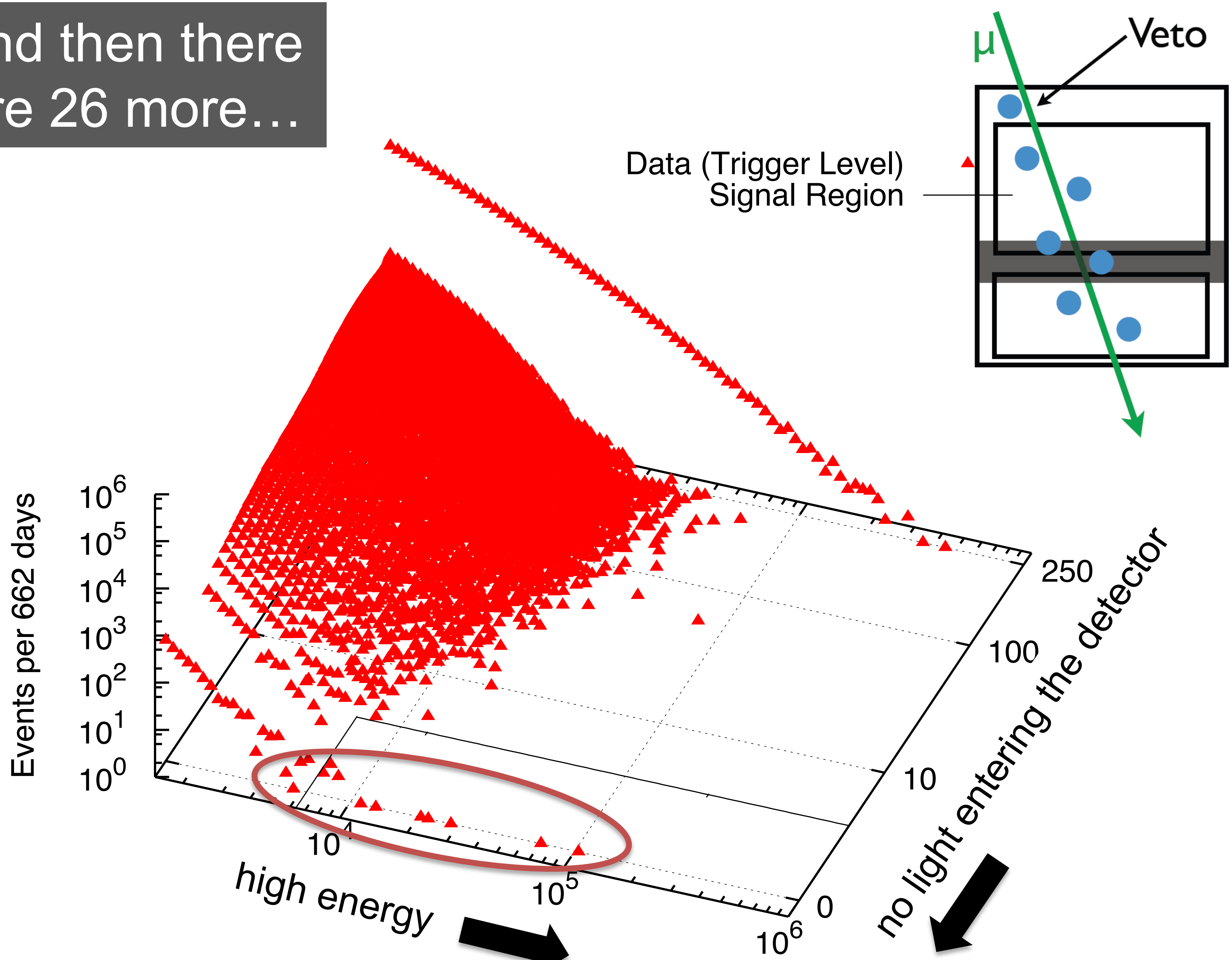
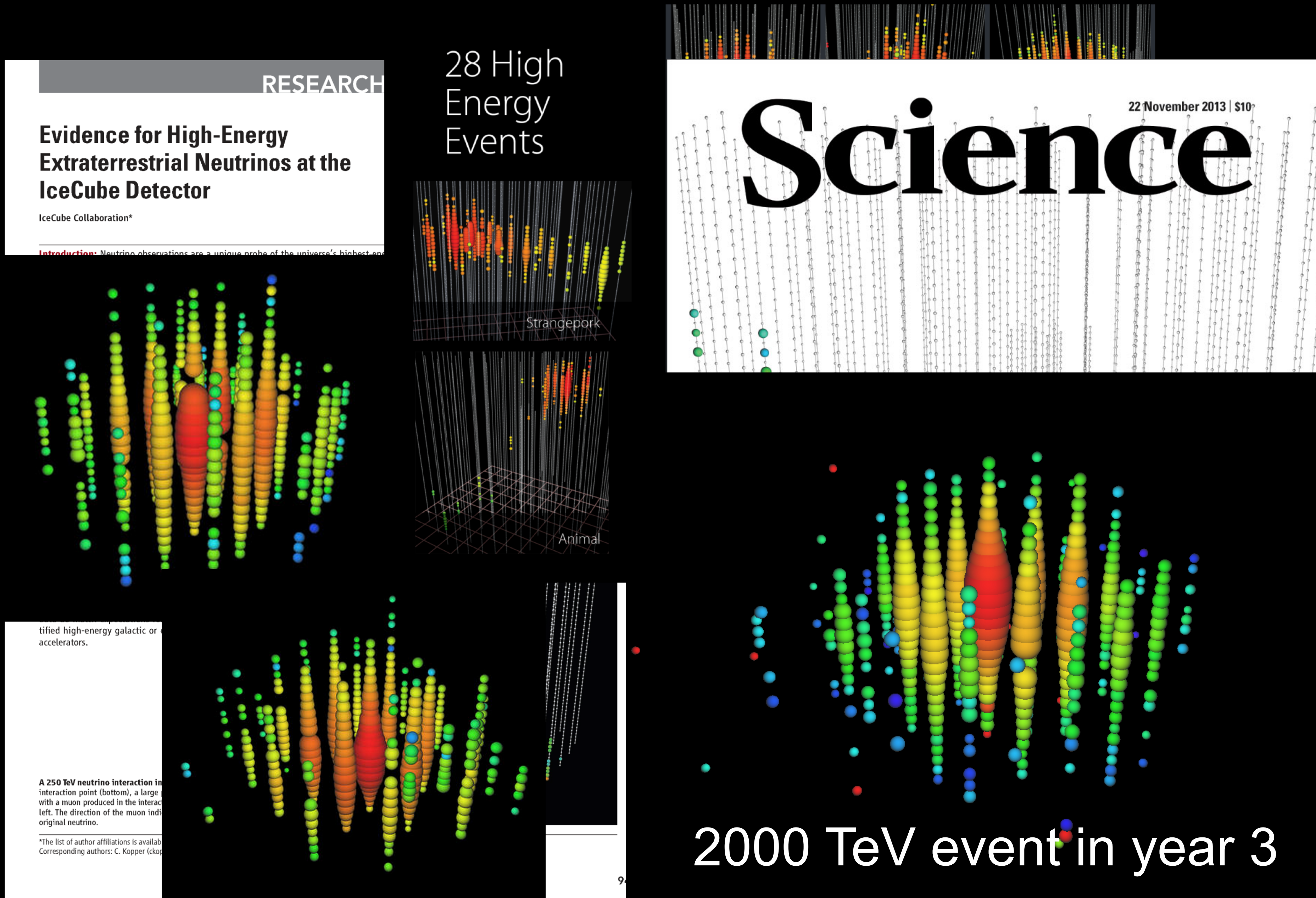
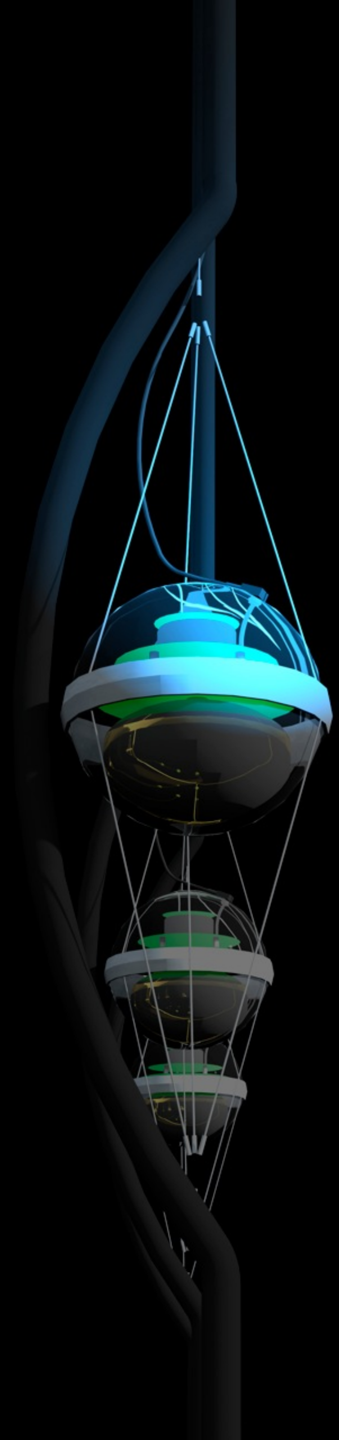


data: 86 strings one year

2 old + 26 new events



2000 TeV event in year 3



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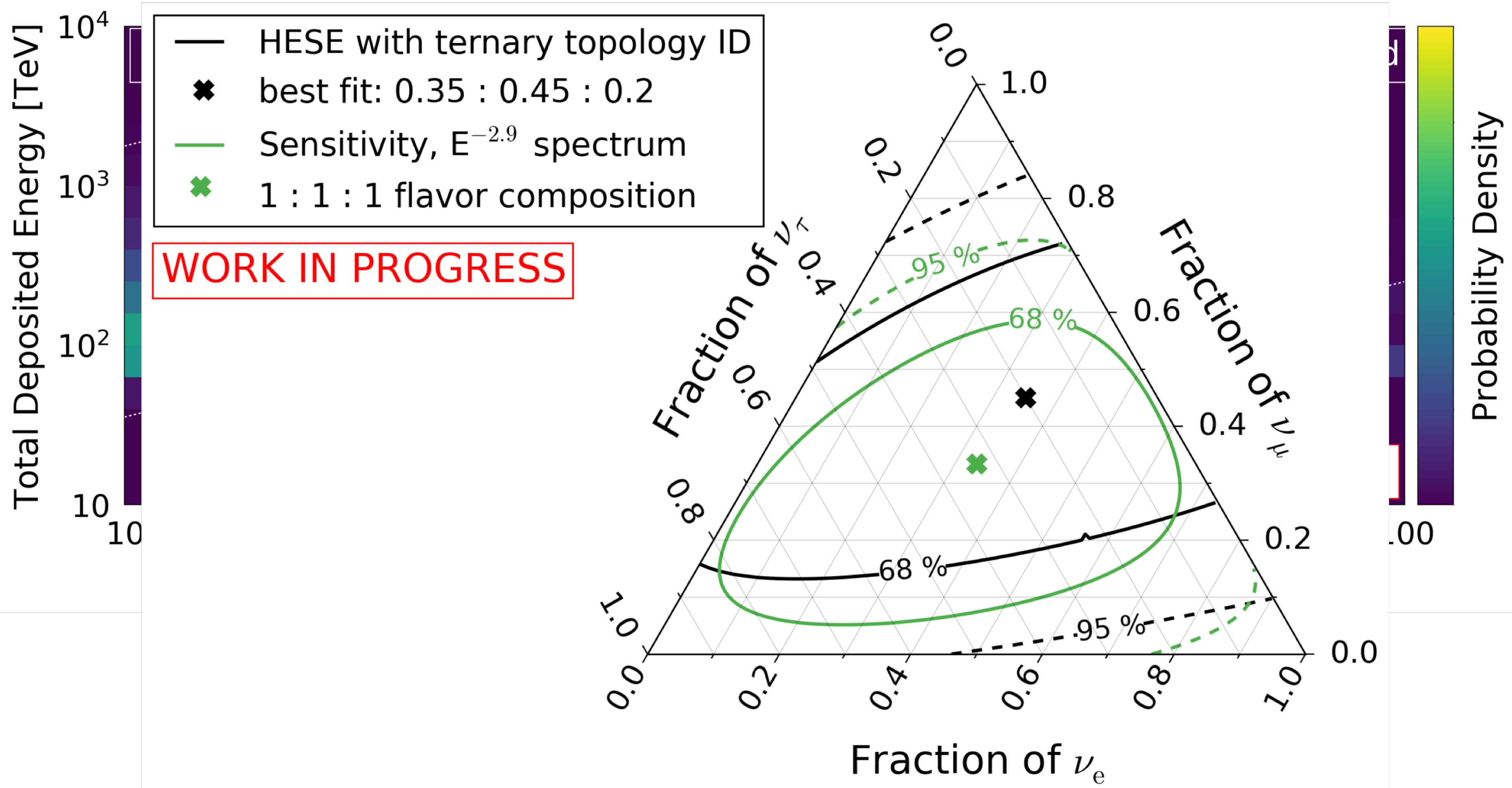
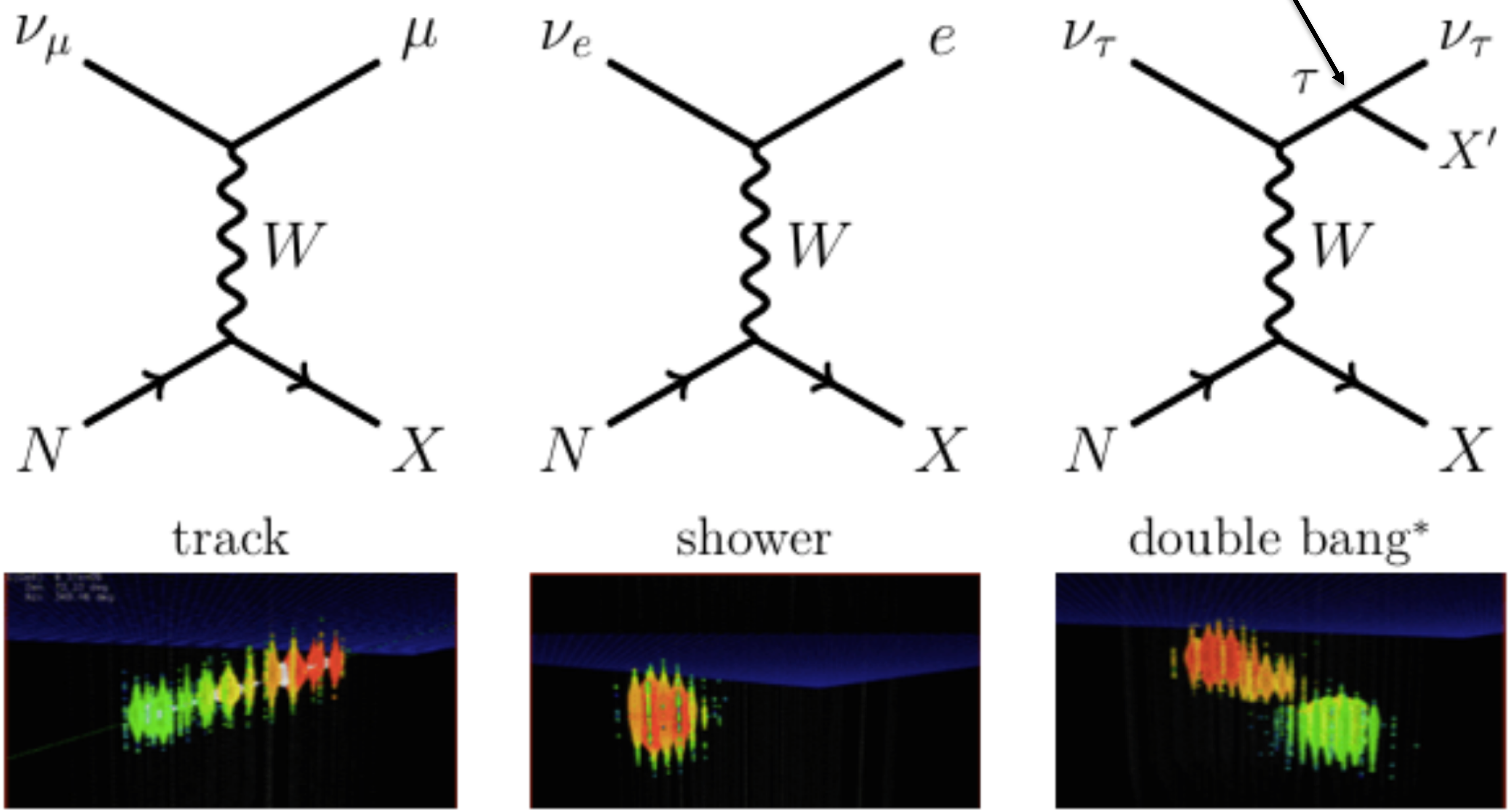
high-energy starting events – 7.5 yr

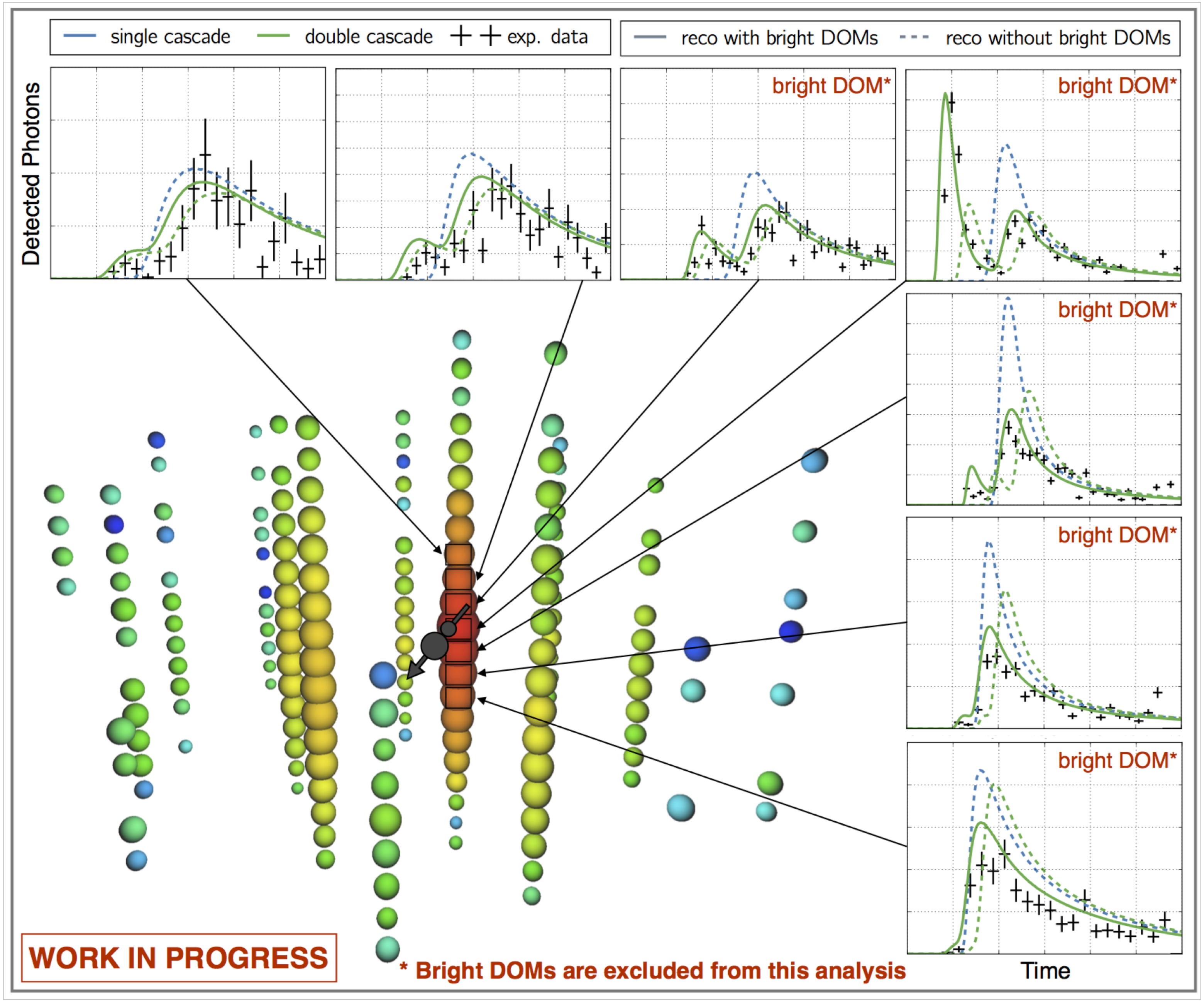


oscillations of PeV neutrinos over cosmic distances to 1:1:1

tau decay length:
50m per PeV

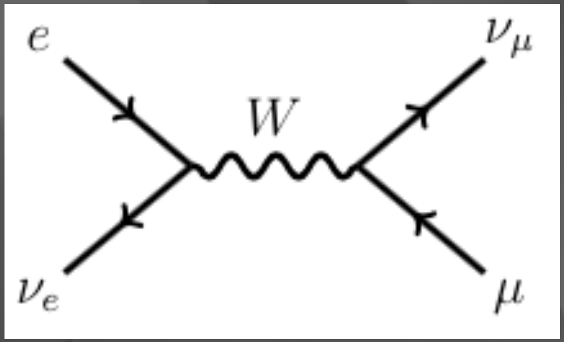


a cosmic tau neutrino: livetime 17m



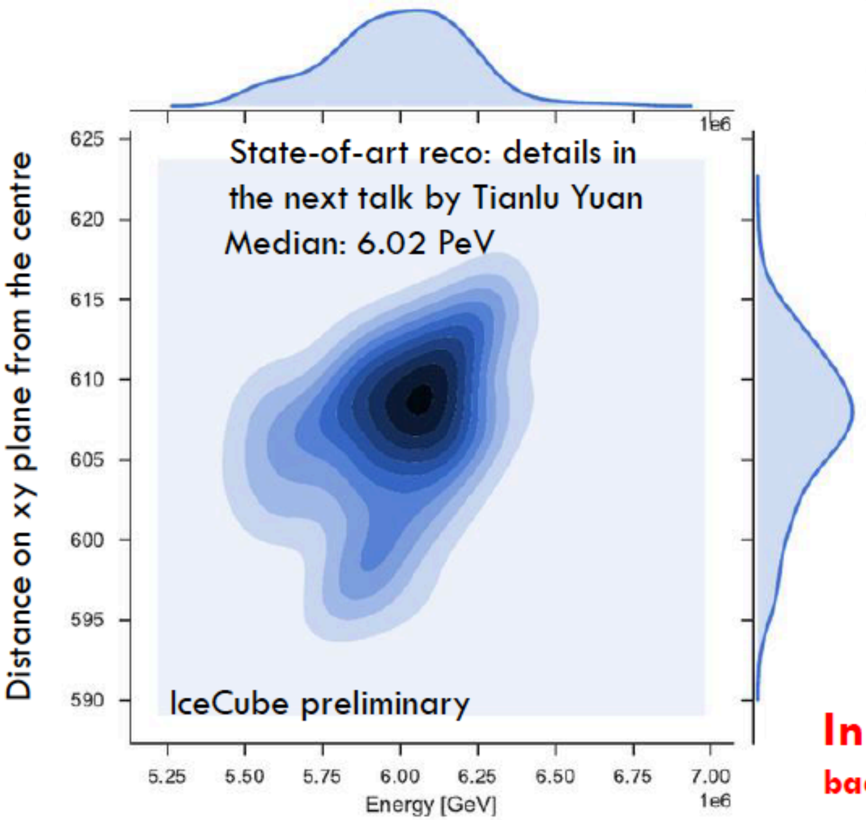
the first Glashow resonance event:

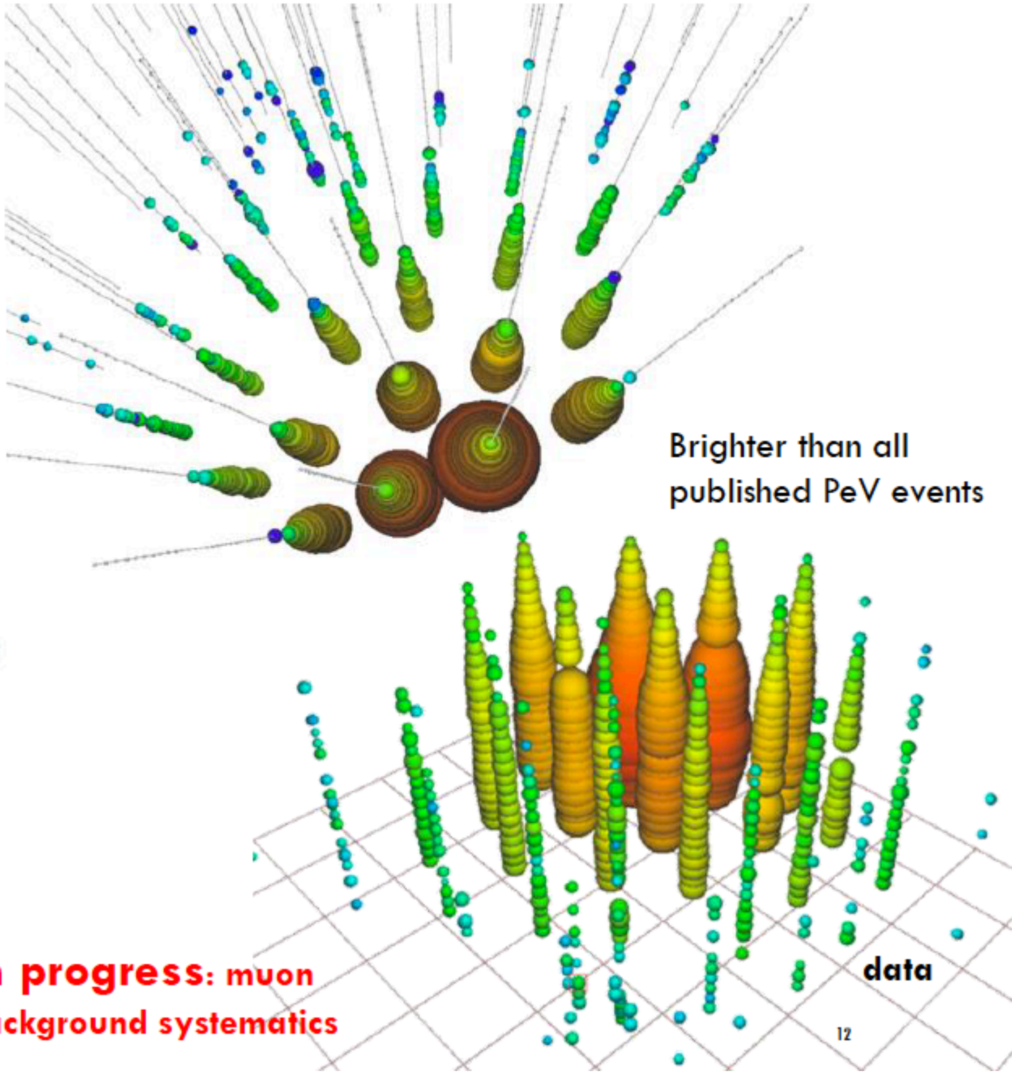
anti-ν_e + atomic electron → real W at 6.3 PeV



Partially contained event with energy ~ 6 PeV

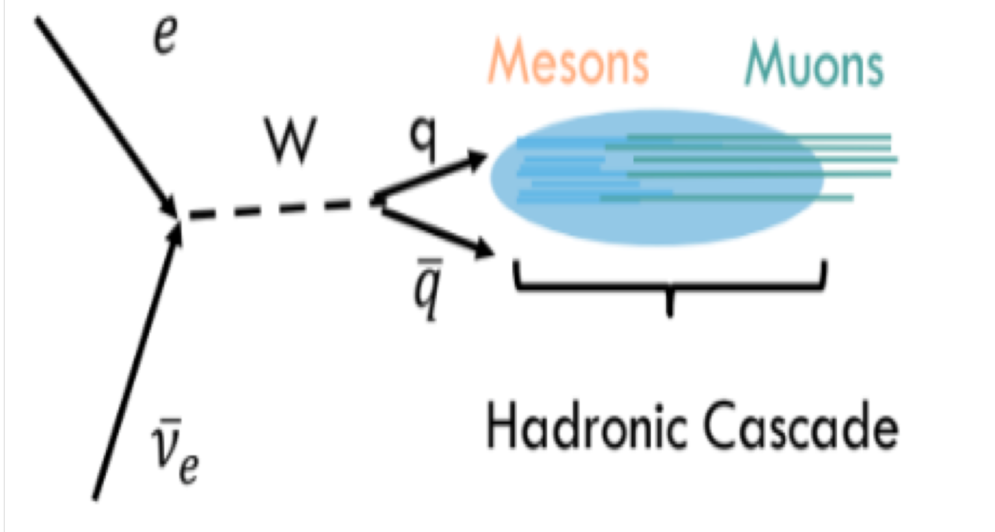
HIGHEST-ENERGY NEUTRINO CANDIDATE

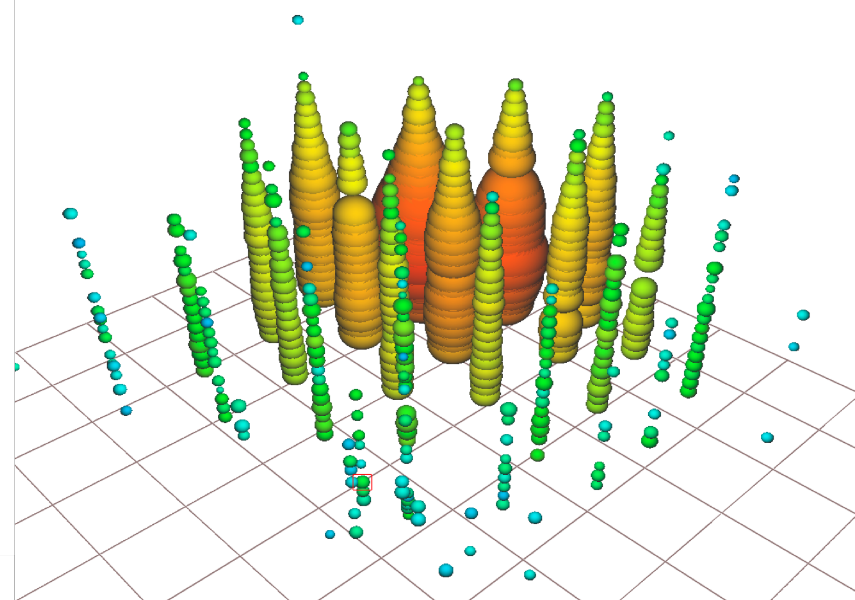


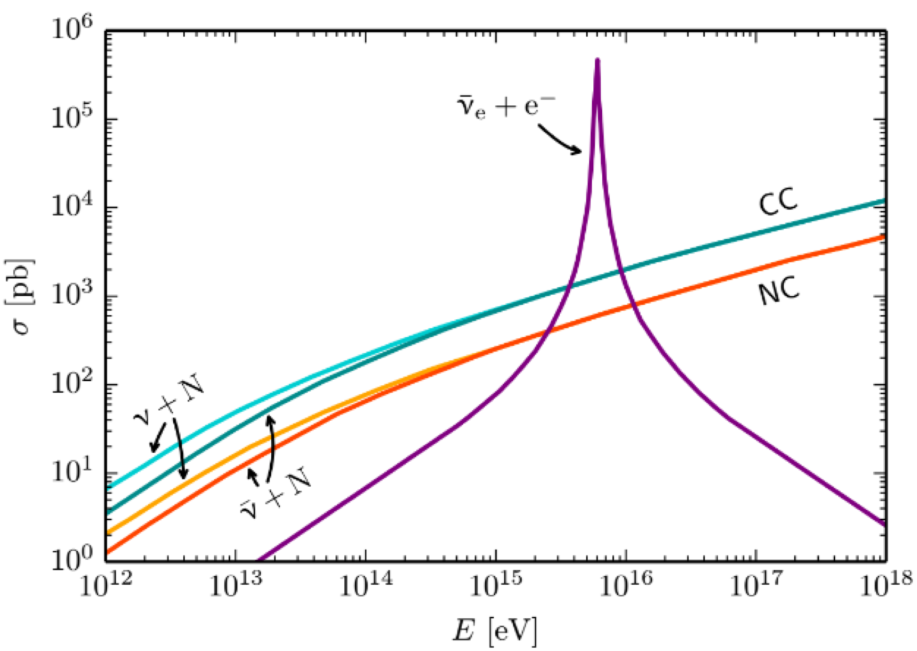


In progress: muon background systematics

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





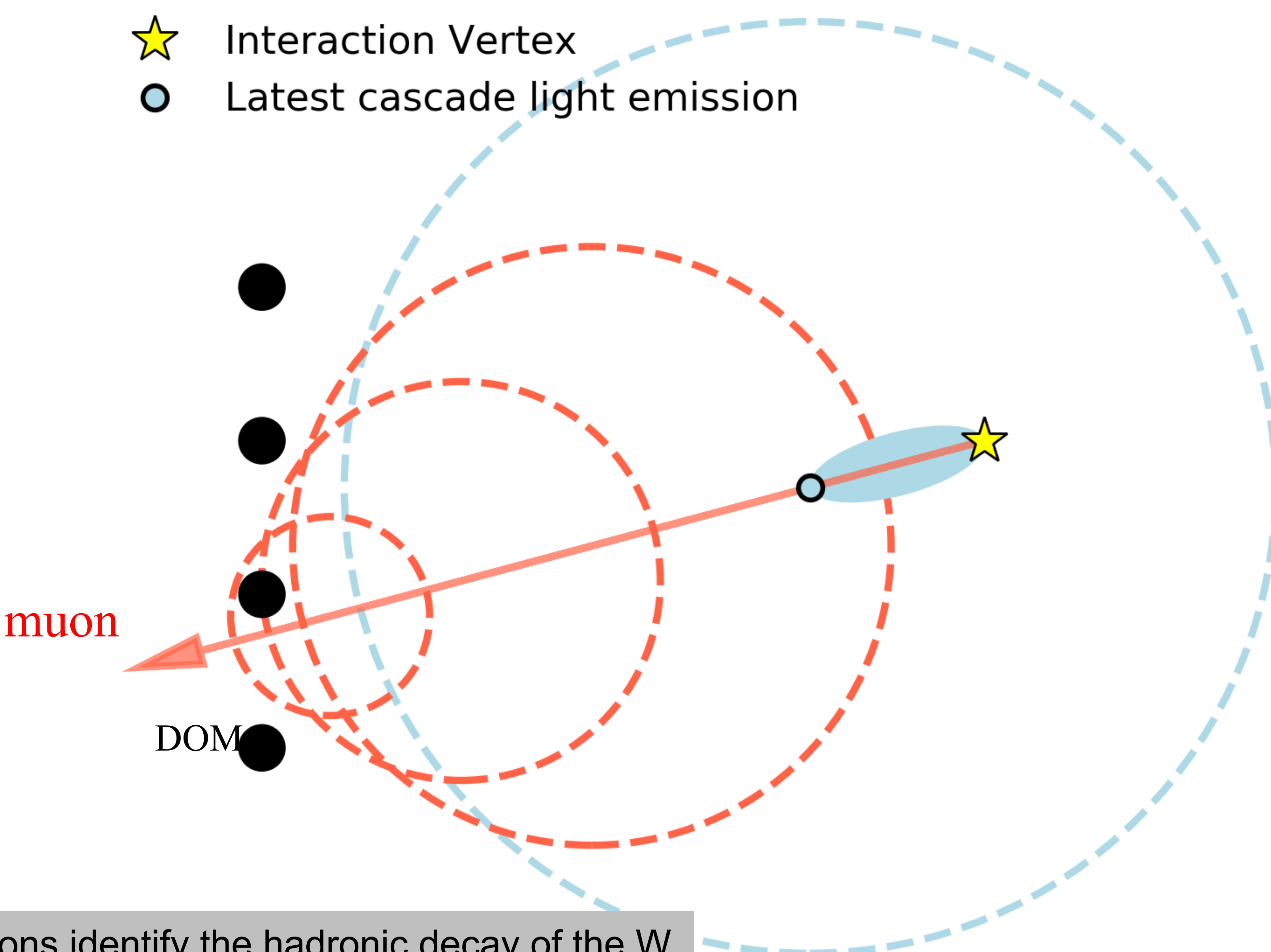


- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

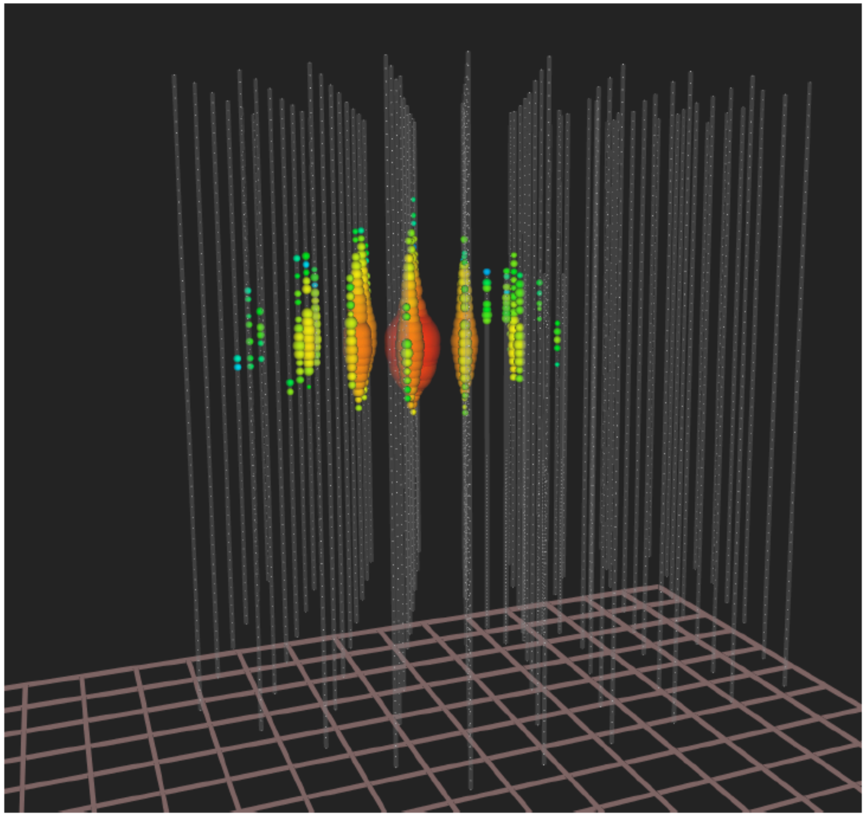
work on-going

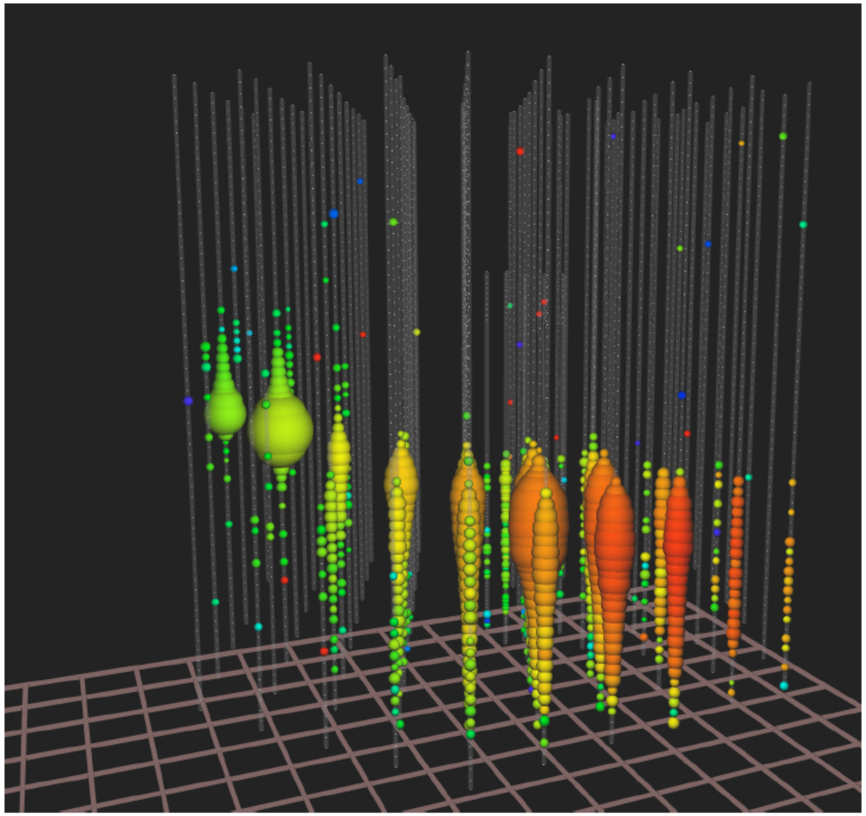
muon (v=c) outraces the light propagating from the electromagnetic component (v<c)



muons identify the hadronic decay of the W

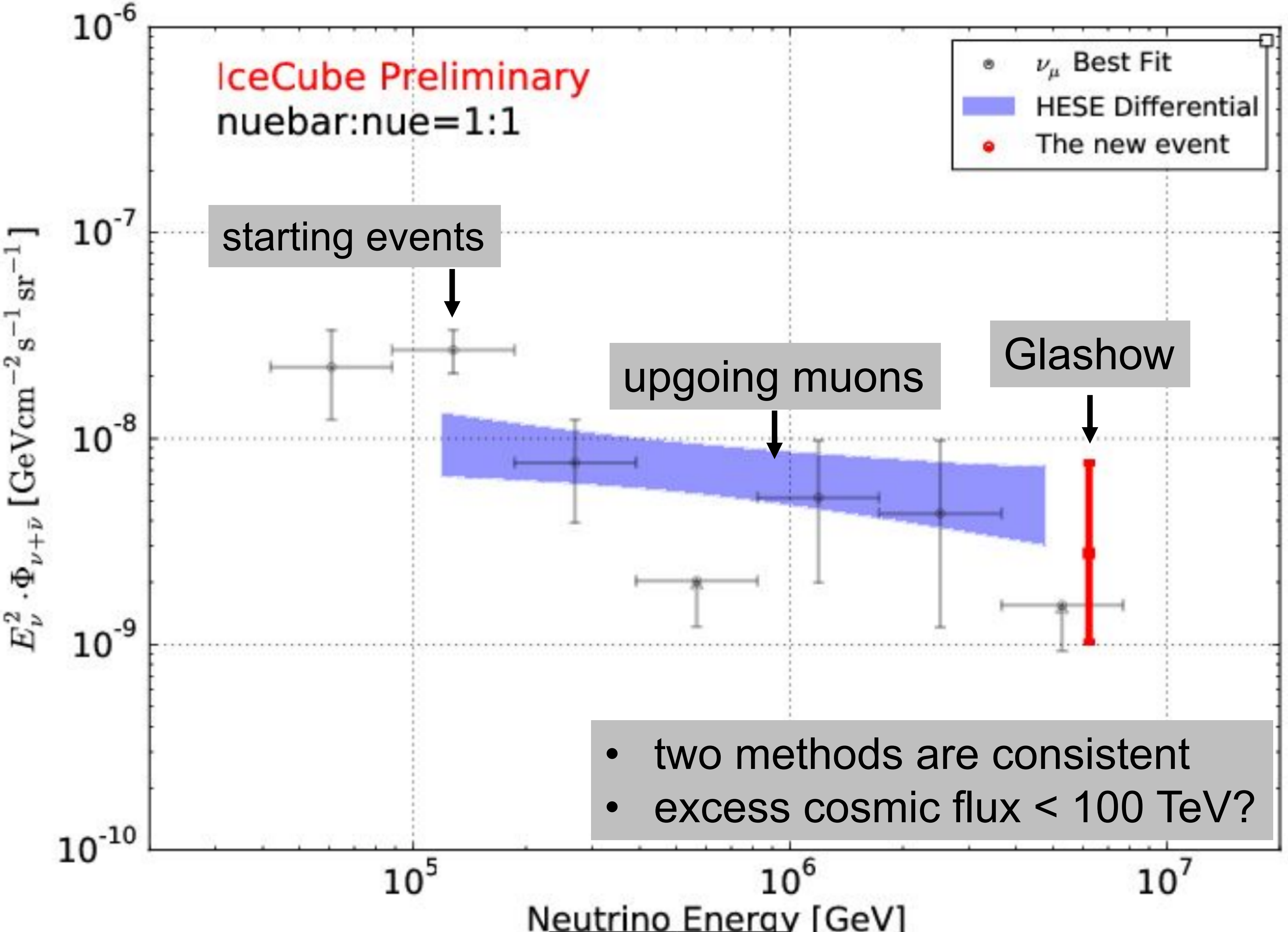
are the observations consistent?



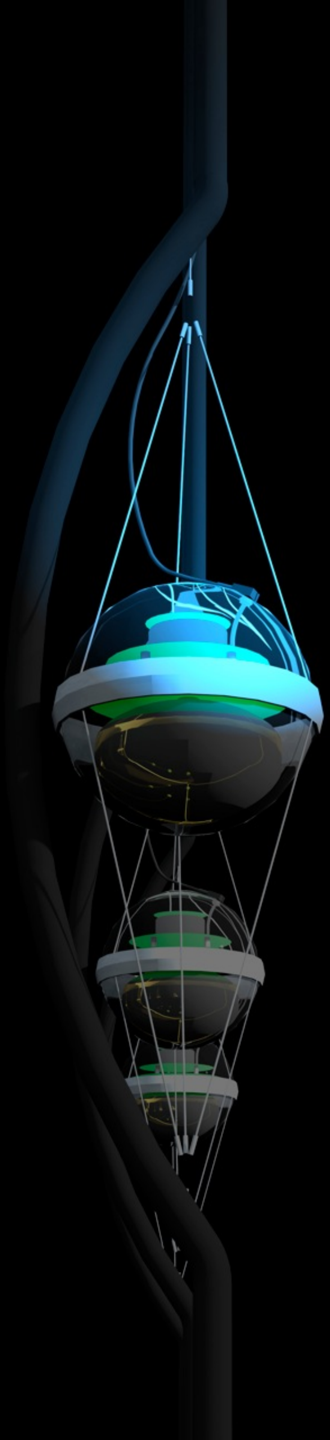


total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)



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



IceCube

francis halzen

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

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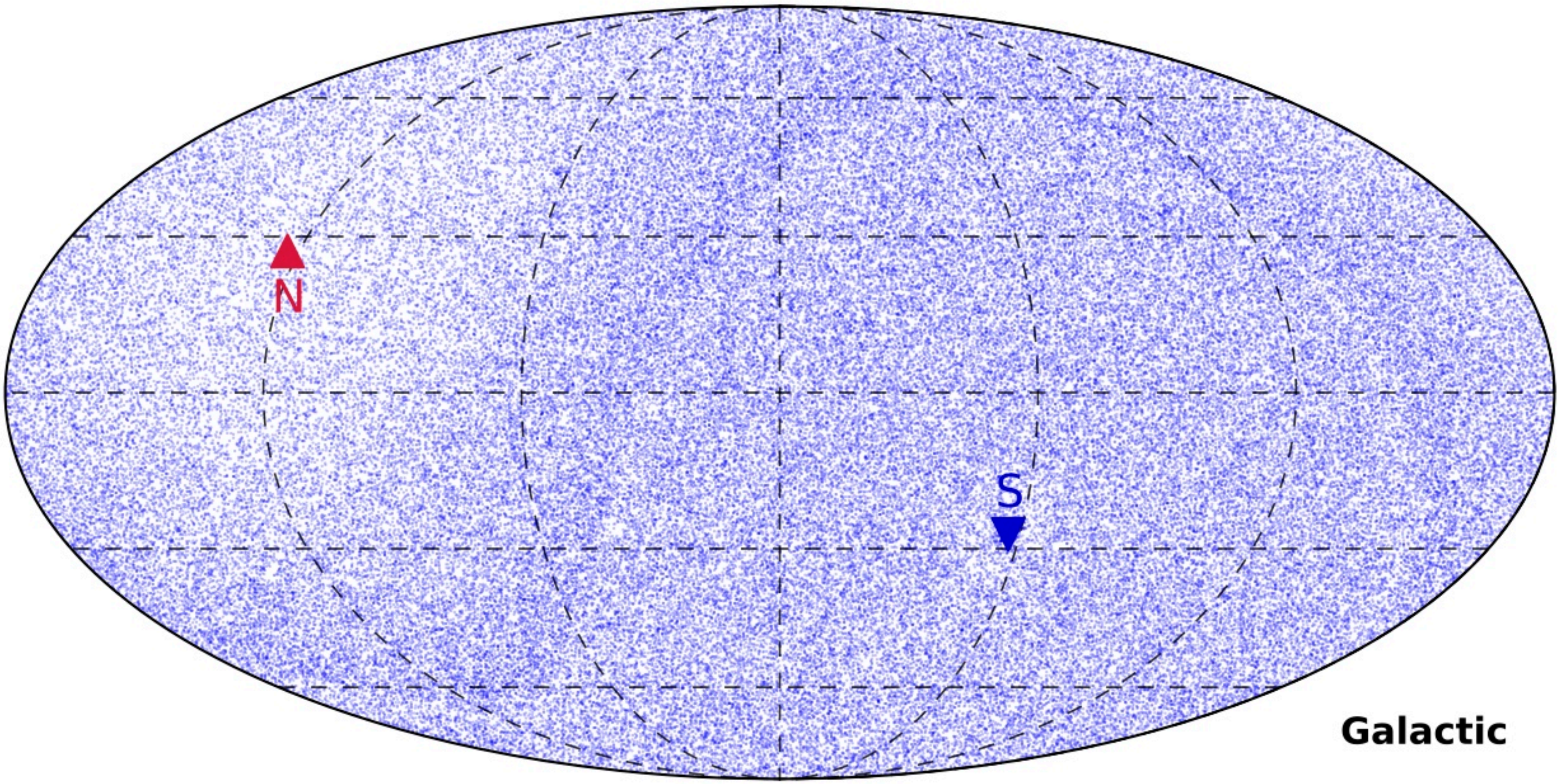
IC86-I

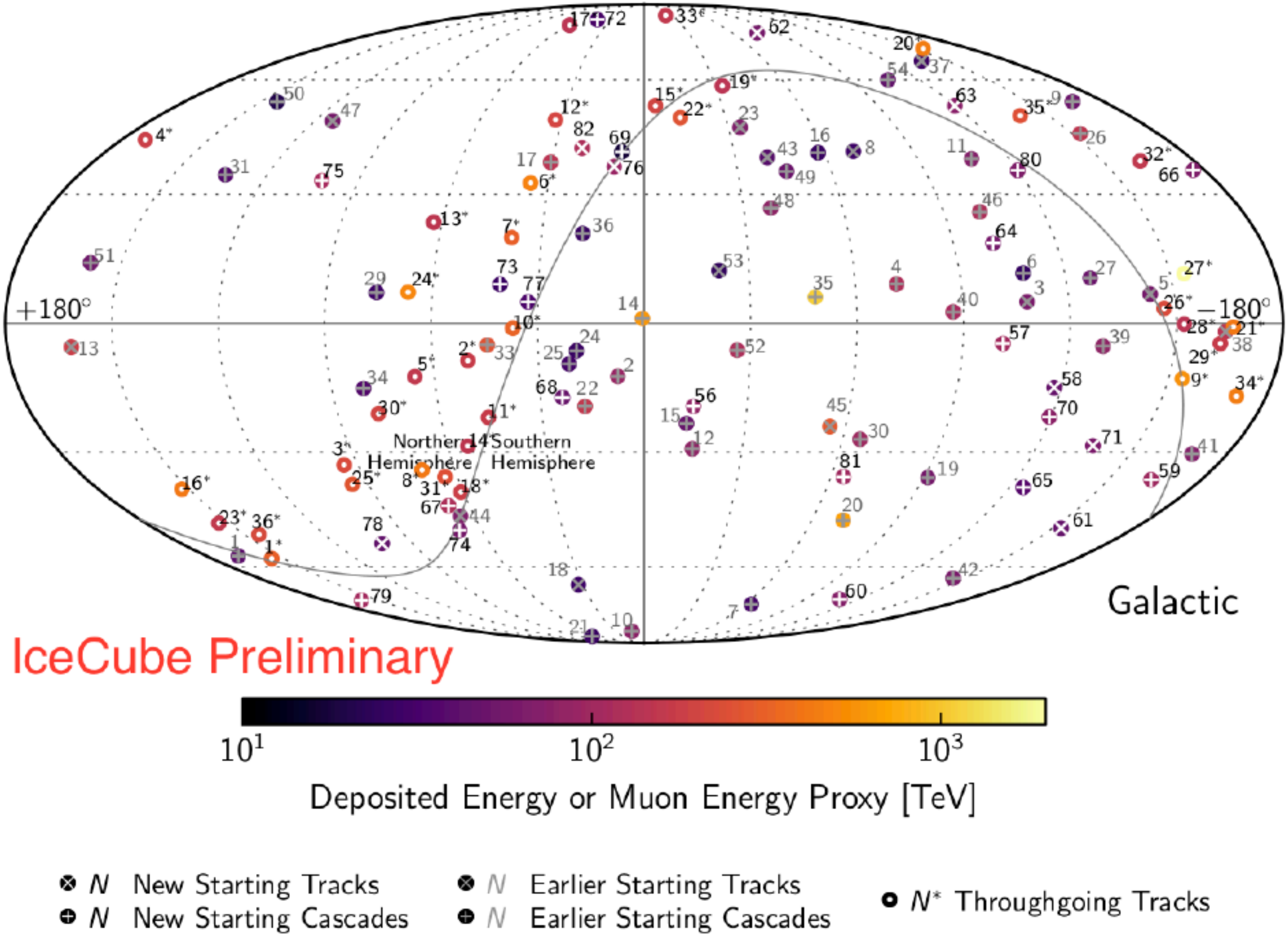


138322 neutrino candidates in one year

120 cosmic neutrinos

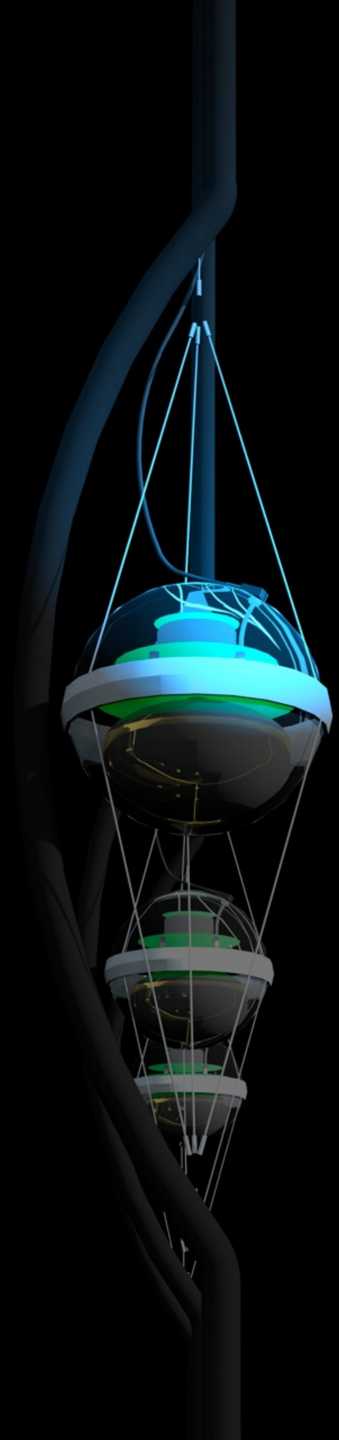
~12 separated from atmospheric background with E>60 TeV

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

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)



IceCube

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- IceCube
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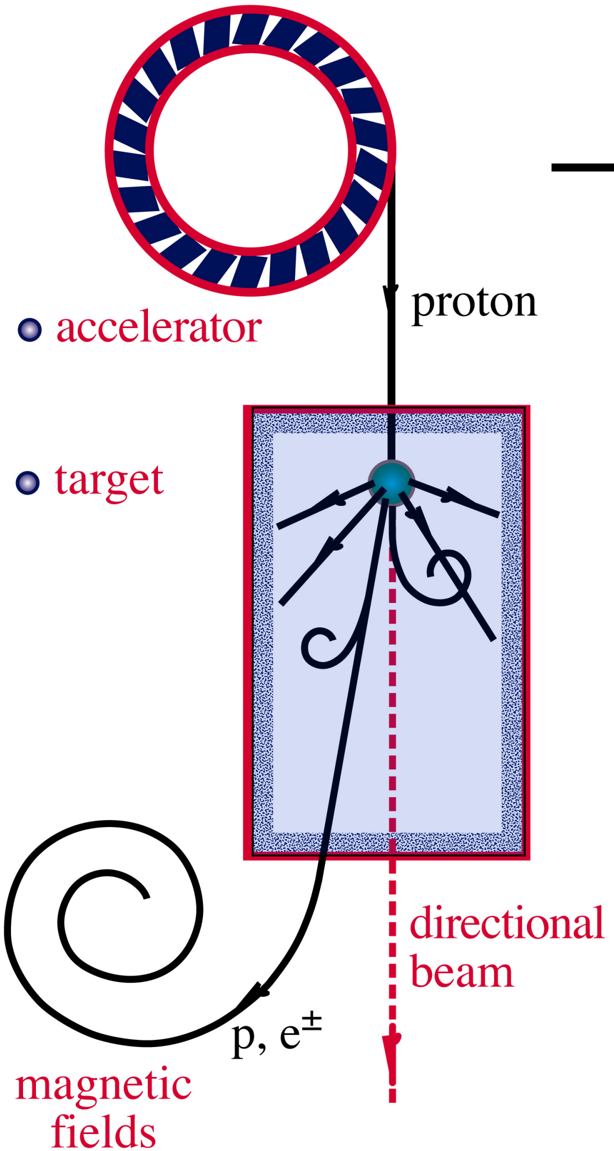
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

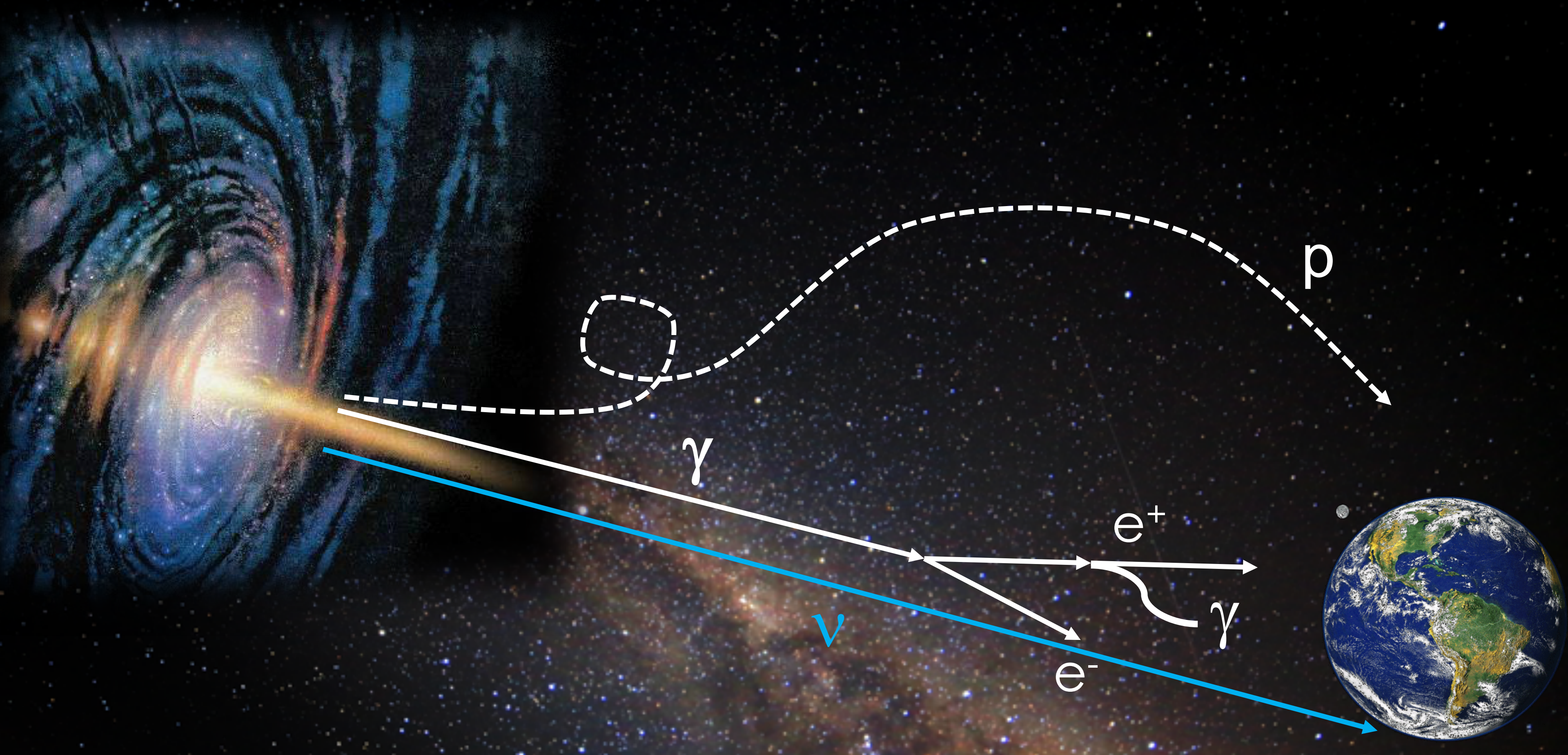
radiation and dust

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

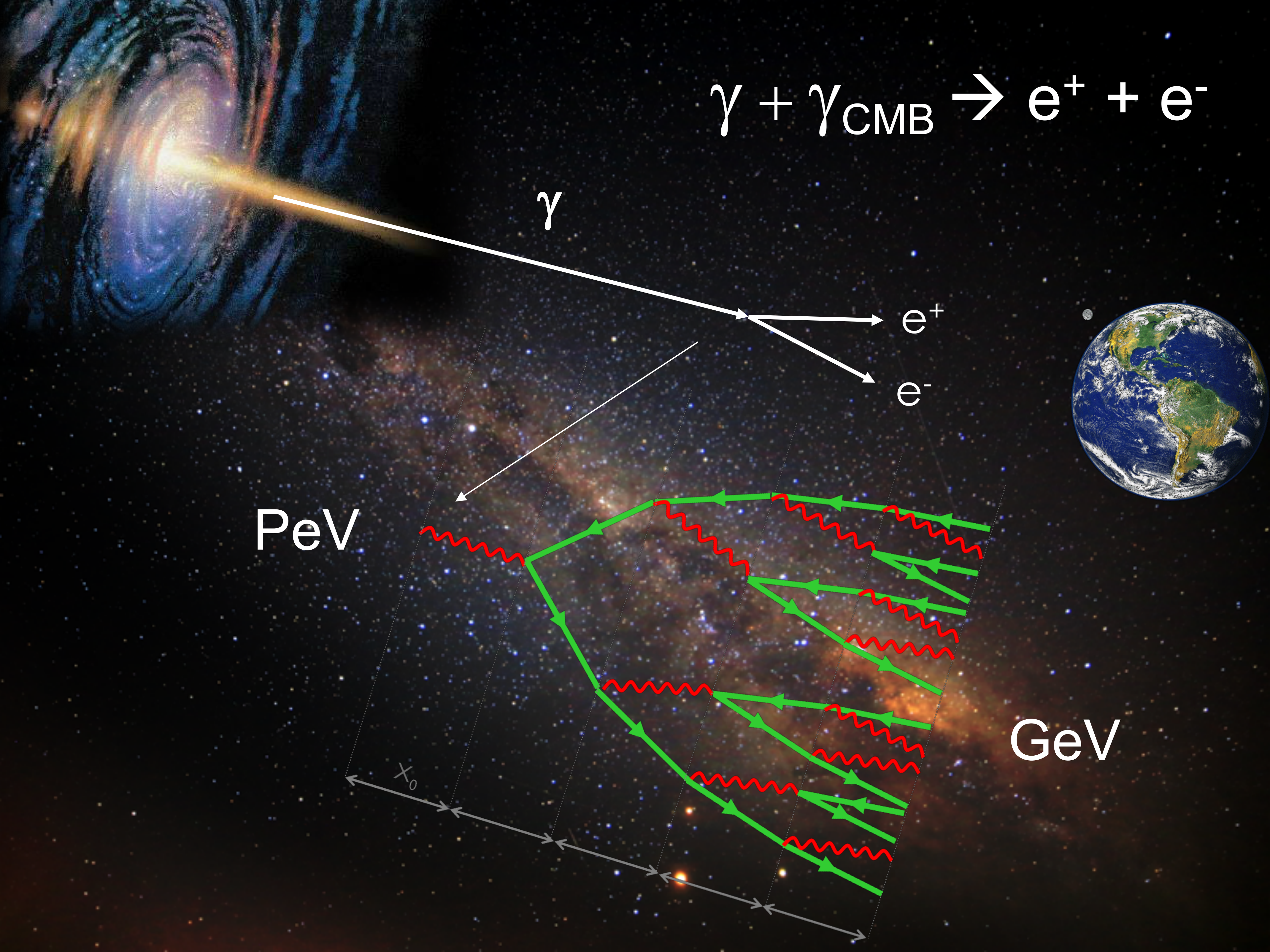
~ cosmic ray + neutrino

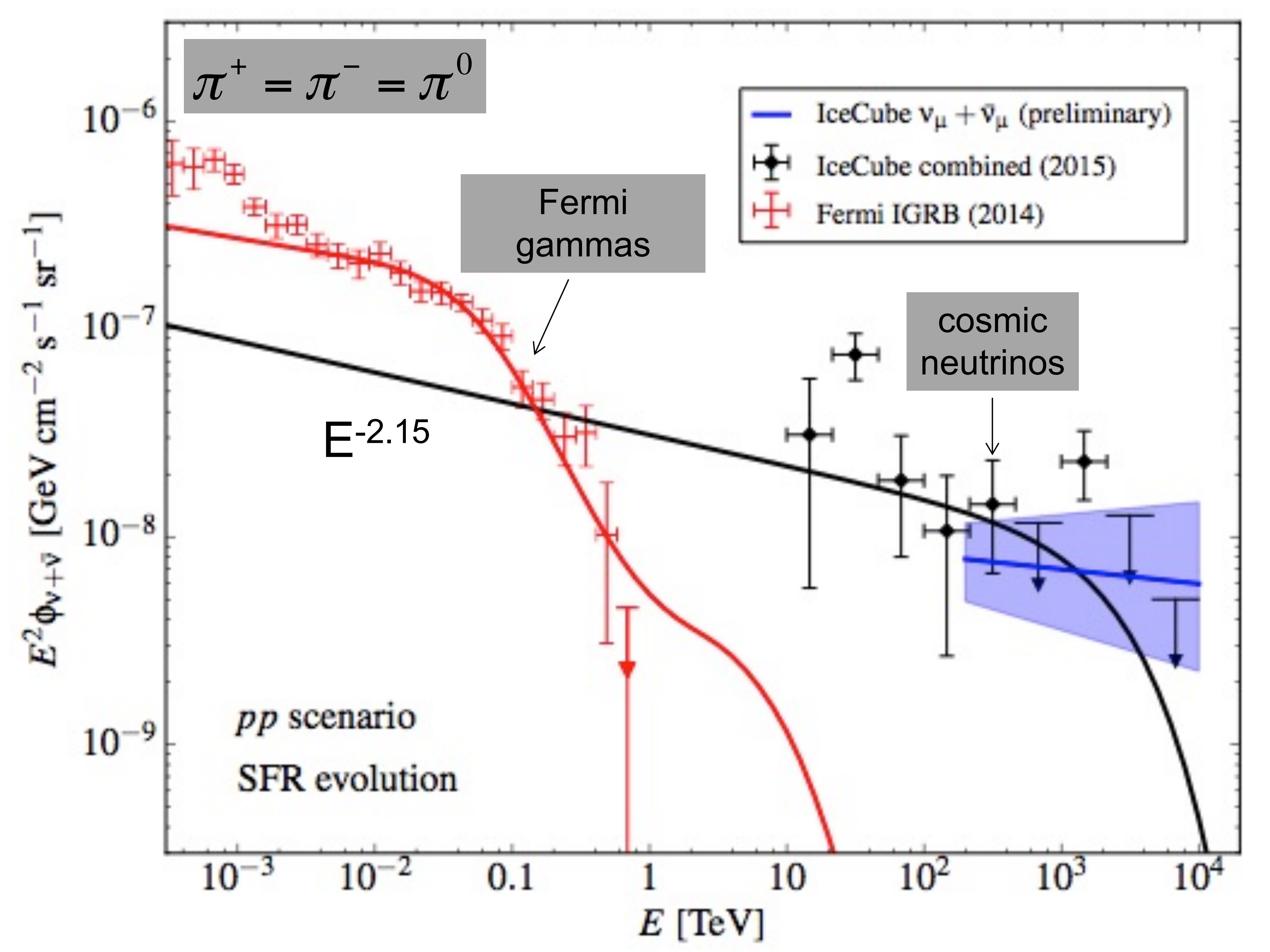
$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma



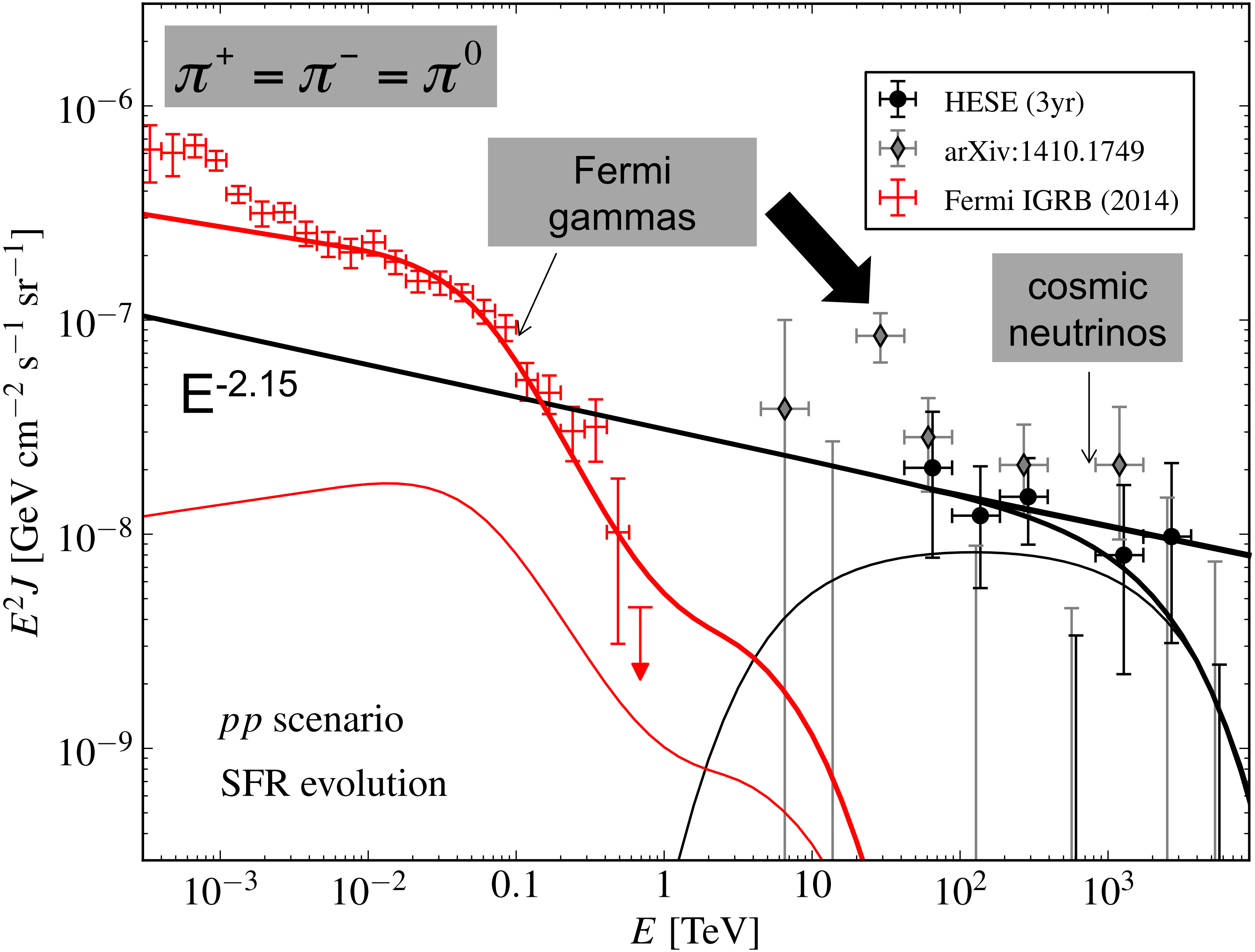
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


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



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

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

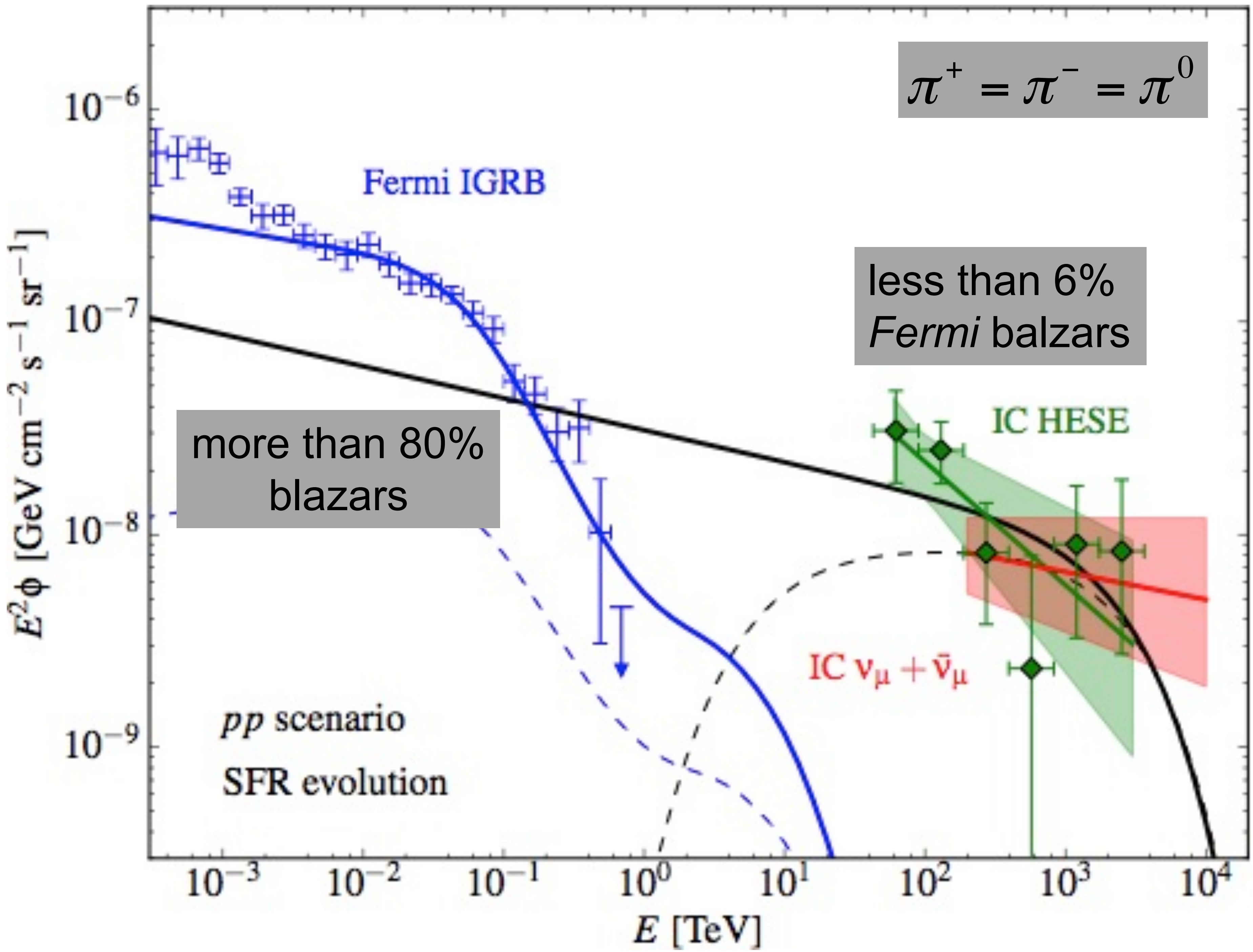


$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]

note that the gammas rays accompanying < 100 TeV neutrinos are not seen suggesting a hidden source(s)

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

- origin of events from opaque sources < 100 TeV ?

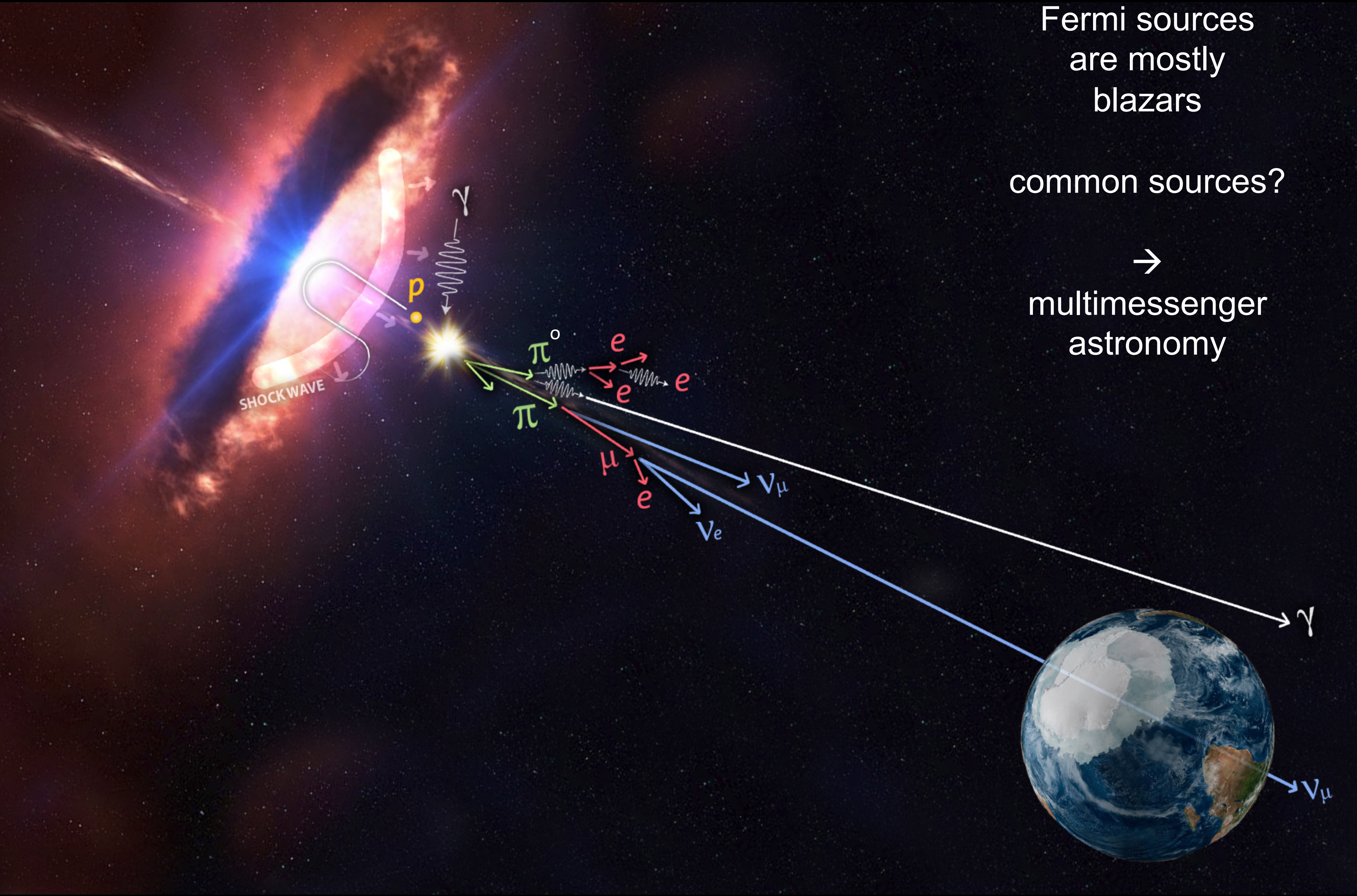


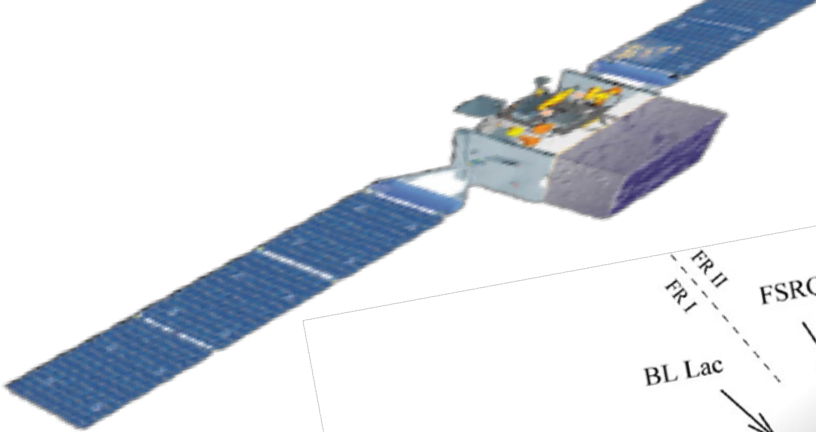
$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
less than 6%
Fermi balzars
IC HESE
more than 80%
blazars
IC $\nu_\mu + \bar{\nu}_\mu$
pp scenario
SFR evolution
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

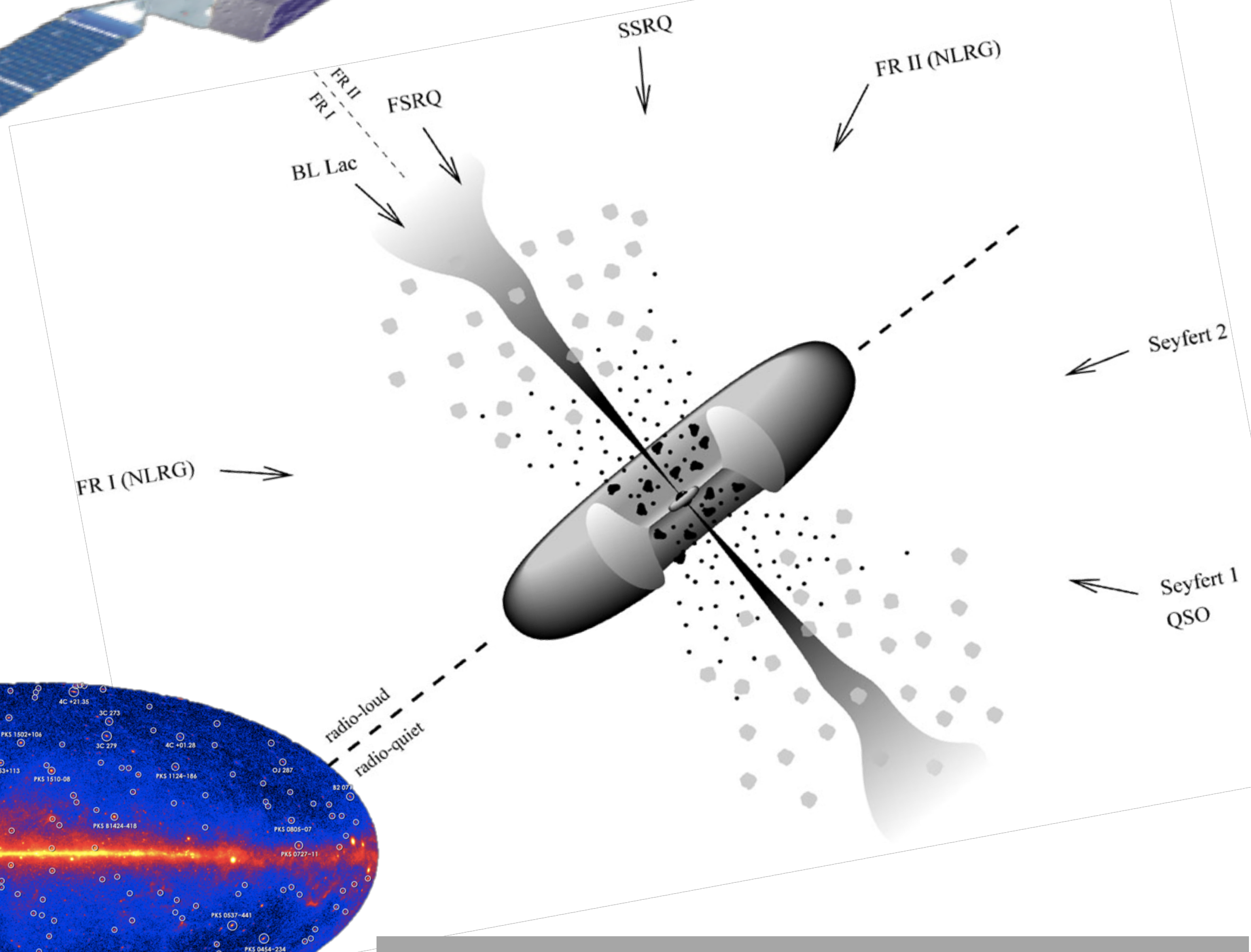
Fermi sources
are mostly
blazars

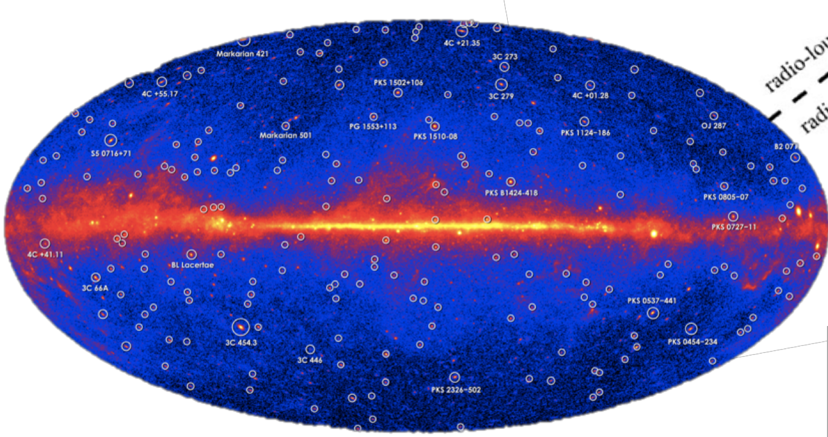
common sources?

→
multimessenger
astronomy

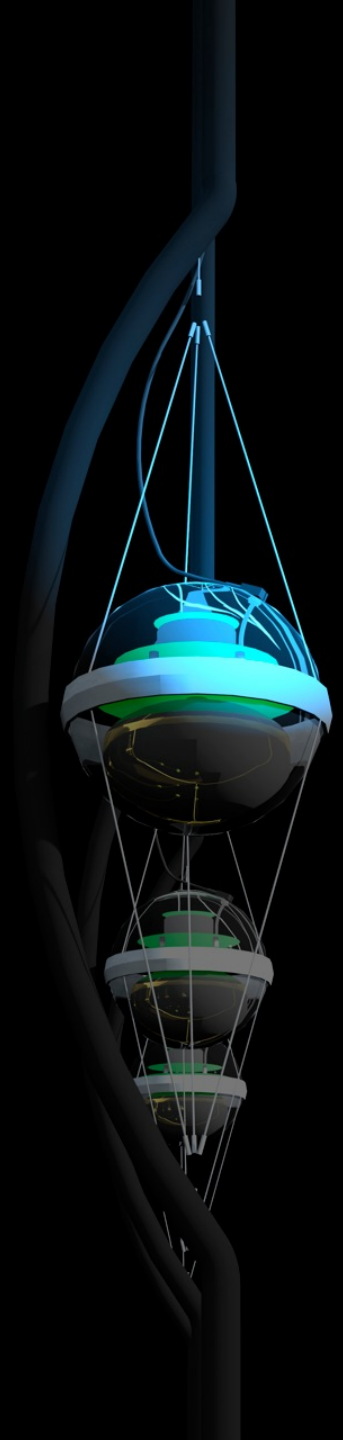








Fermi sky: mostly bazars



IceCube

francis halzen

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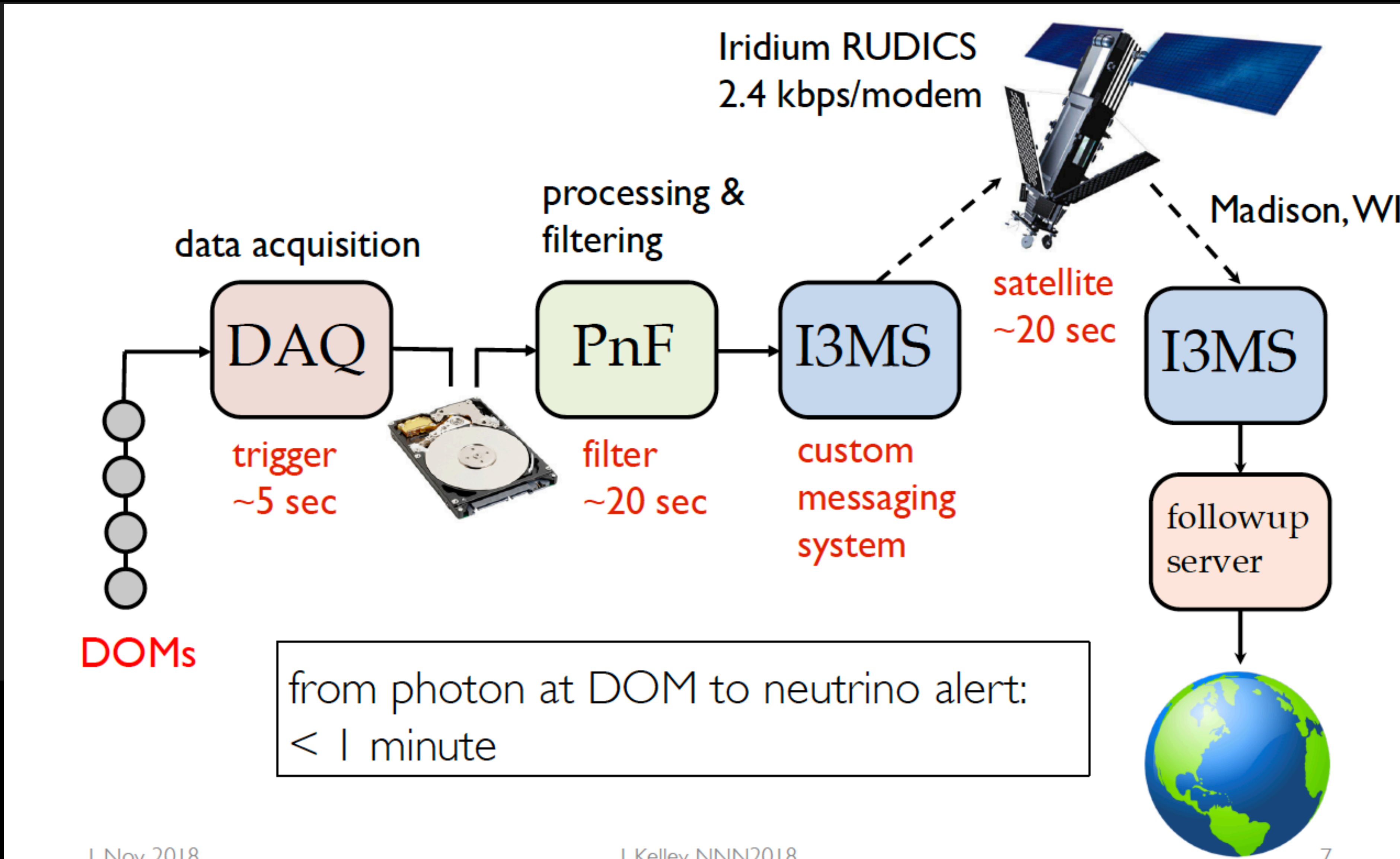
- the first high-energy cosmic ray accelerator

iceCube.wisc.edu

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

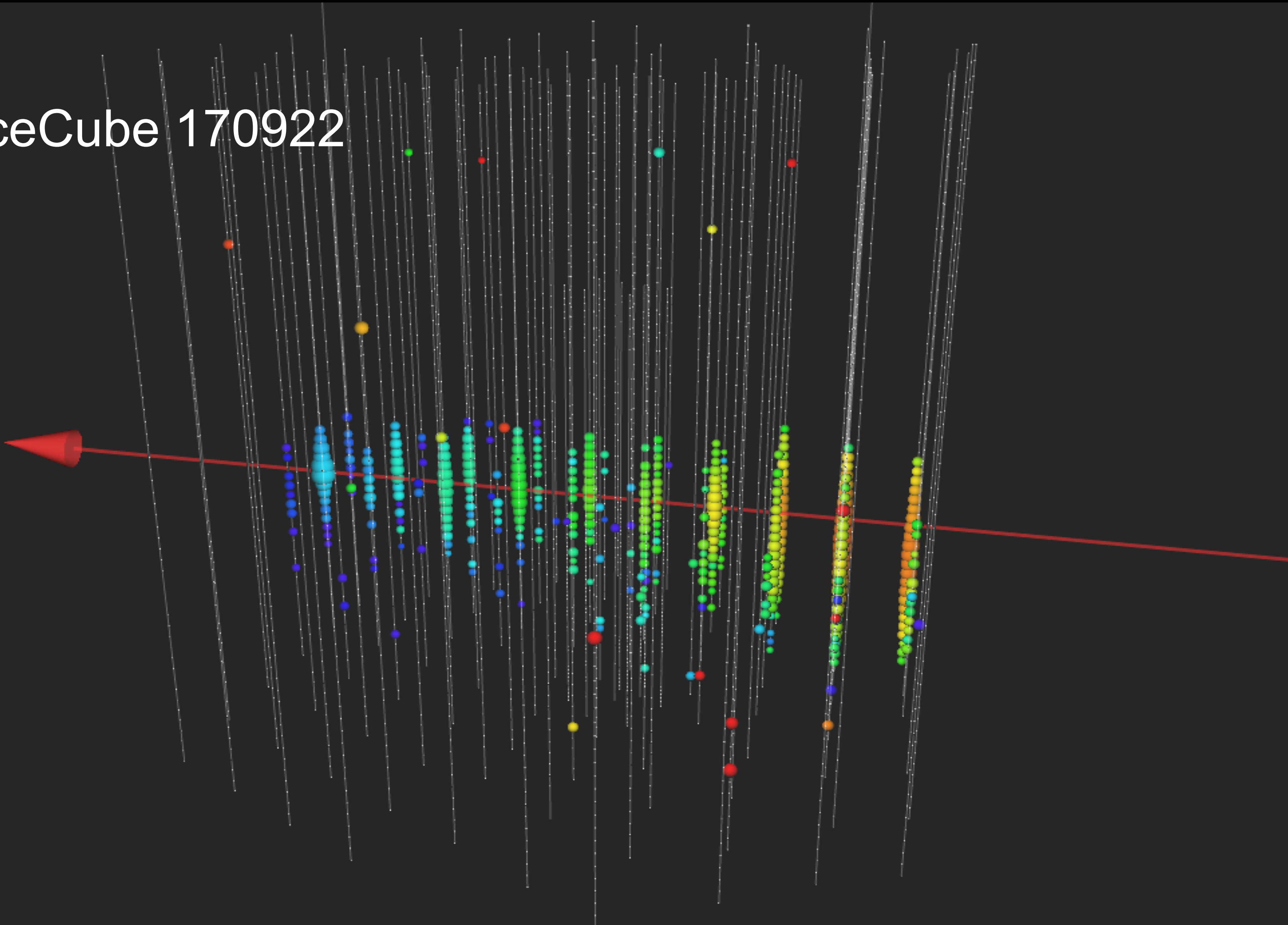


IceCube Trigger

43 seconds after trigger, GCN notice was sent

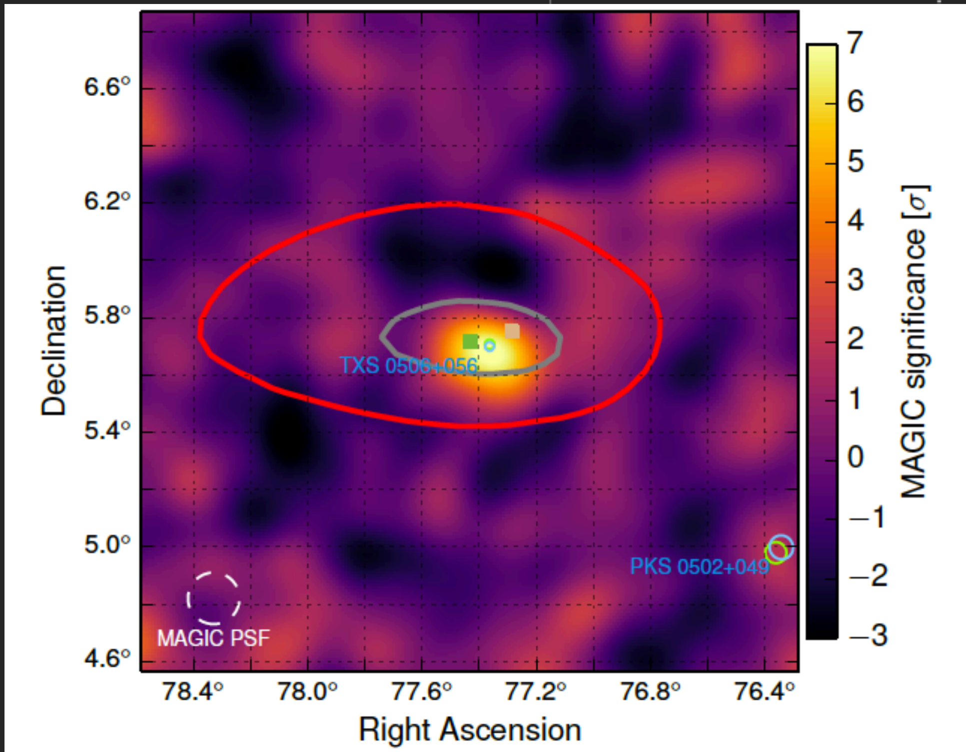
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
        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

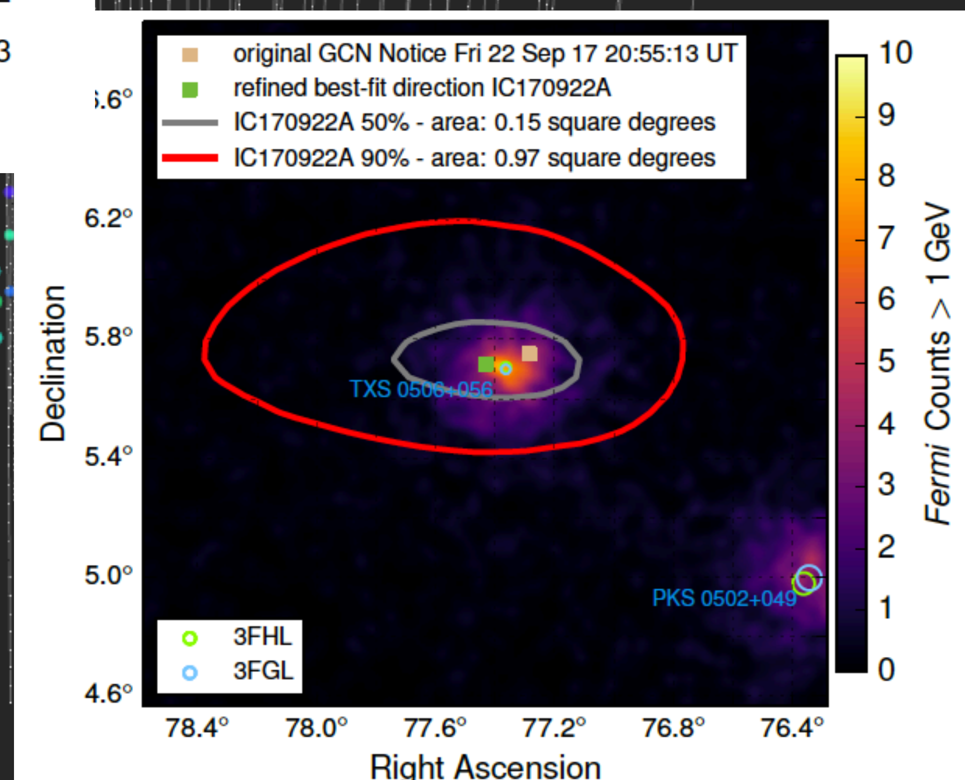


IceCube 170922

Fermi
detects a flaring
blazar within 0.06°



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.

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[1] *INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5 I-35122 Padova - ITALY*
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[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*
[6] *Universidad de La Laguna, Dpto. Astrofisica, s/n E-38206 La Laguna (Tenerife) - SPAIN*

(Received February, 2018; Revised February 7, 2018; Accepted 2018)

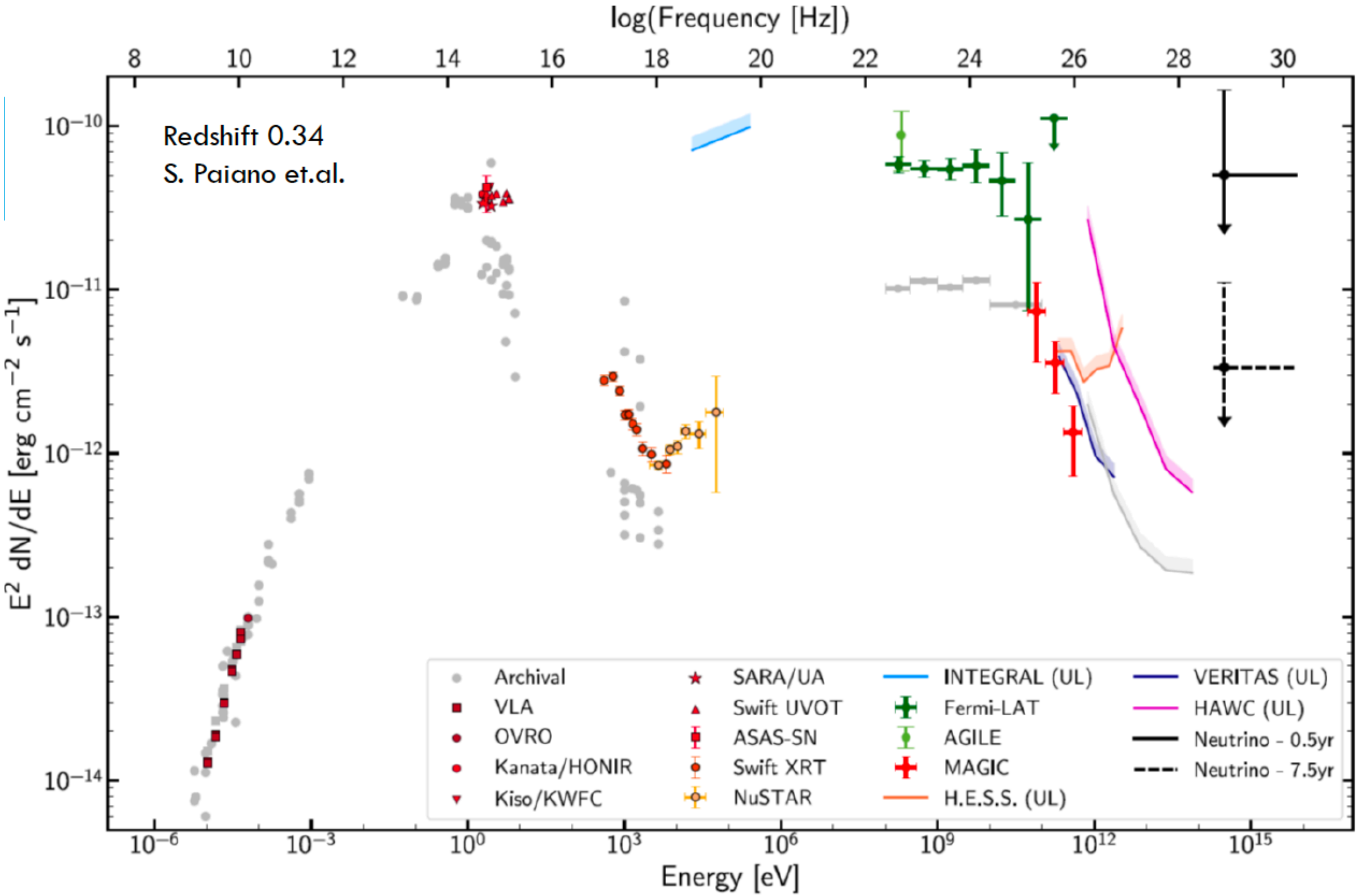
Submitted to ApJL

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!

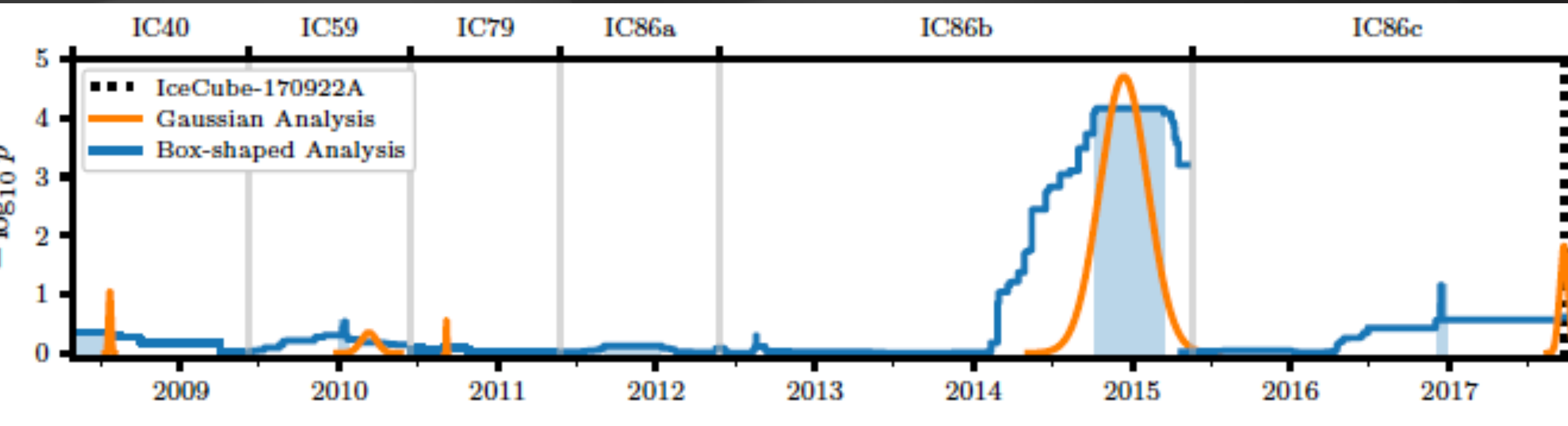


log(Frequency [Hz])
Redshift 0.34
S. Paiano et.al.
E² dN/dE [erg cm⁻² s⁻¹]
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

multiwavelength campaign launched by IC 170922

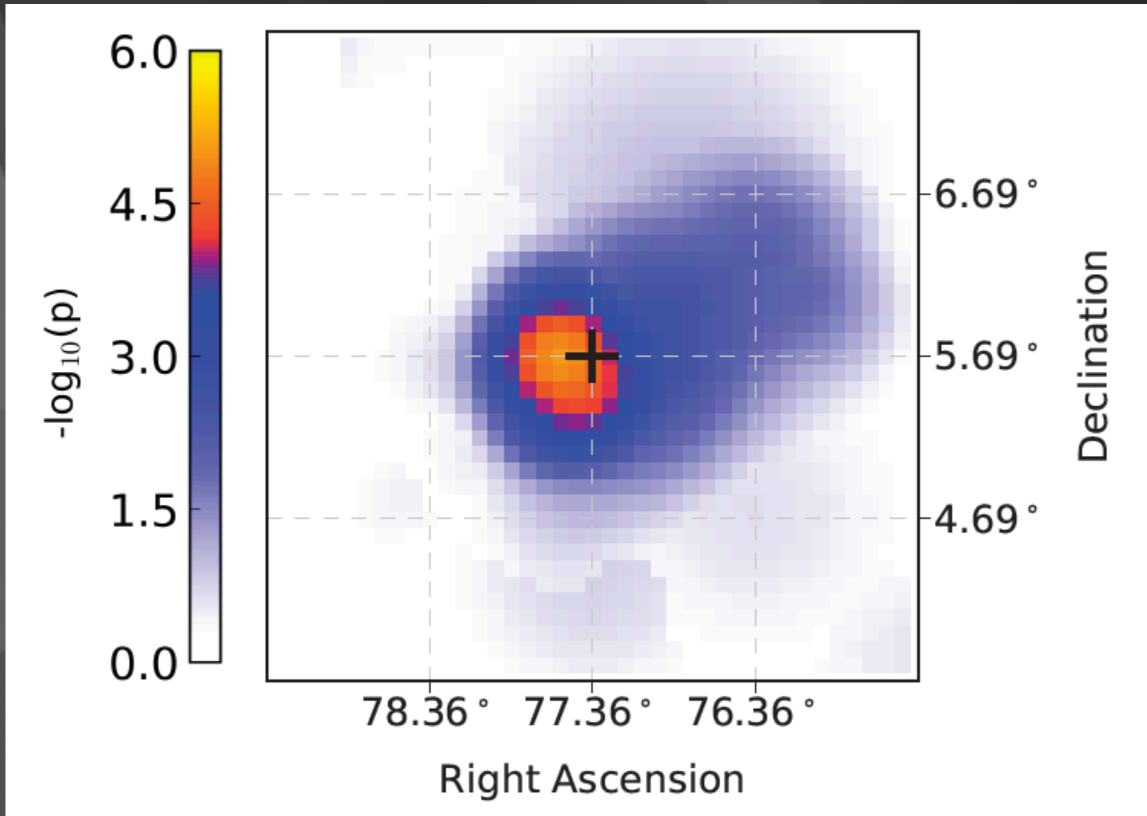
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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 0.06^o (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

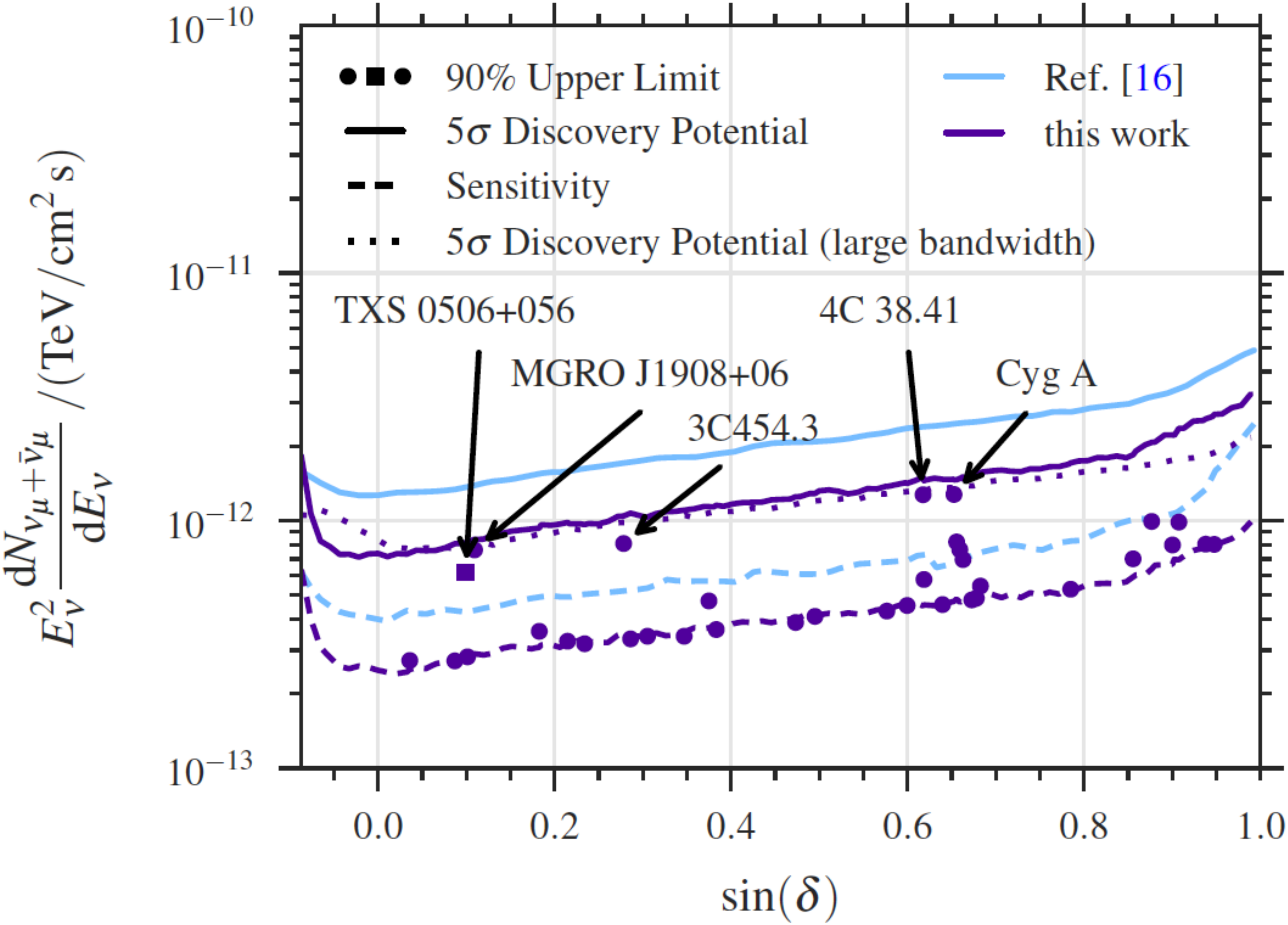


search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 10^{-5} bkg. probability
- spectrum $E^{-2.1}$



Why not seen before?

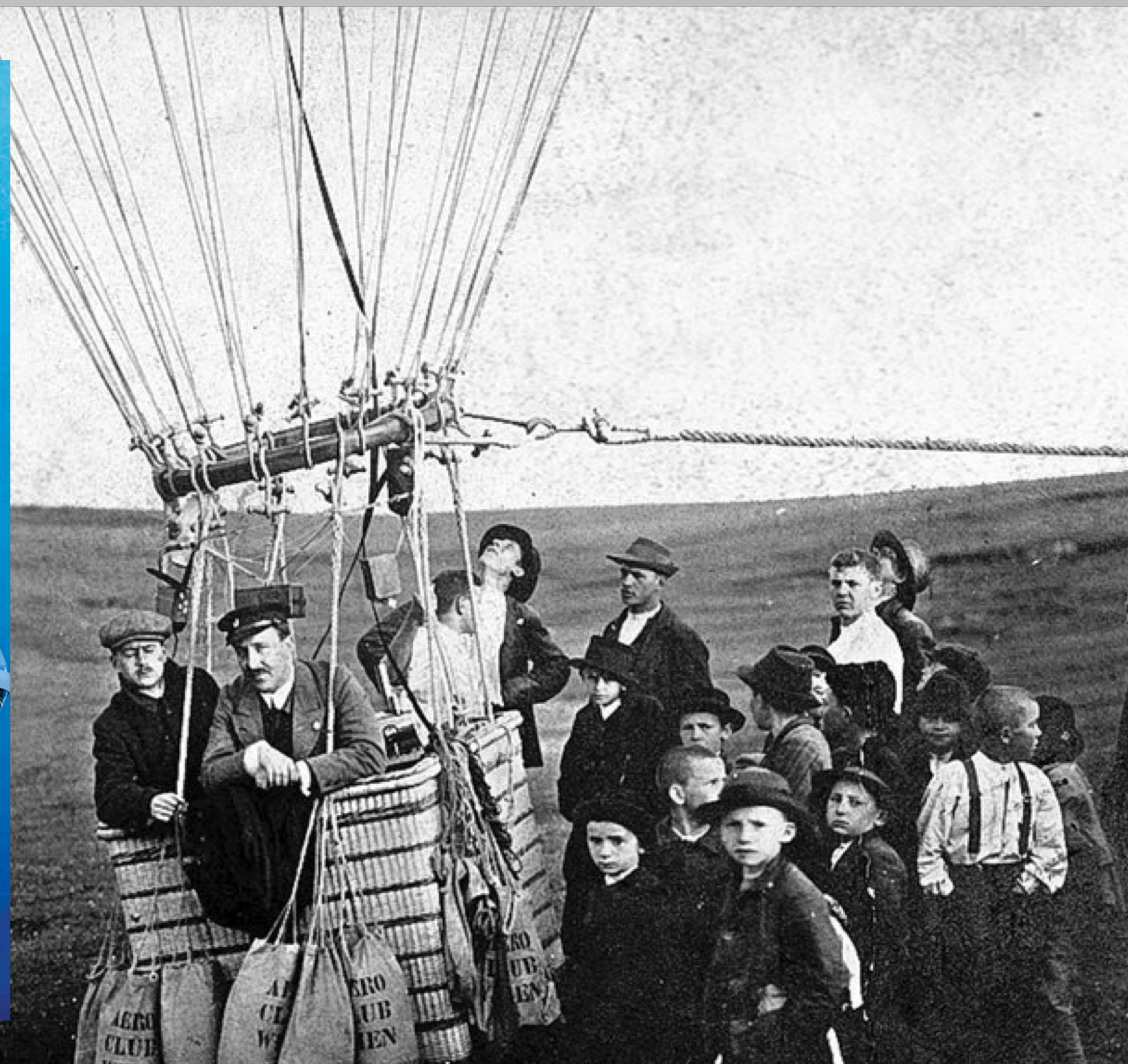


we identified a source of high energy cosmic rays:

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

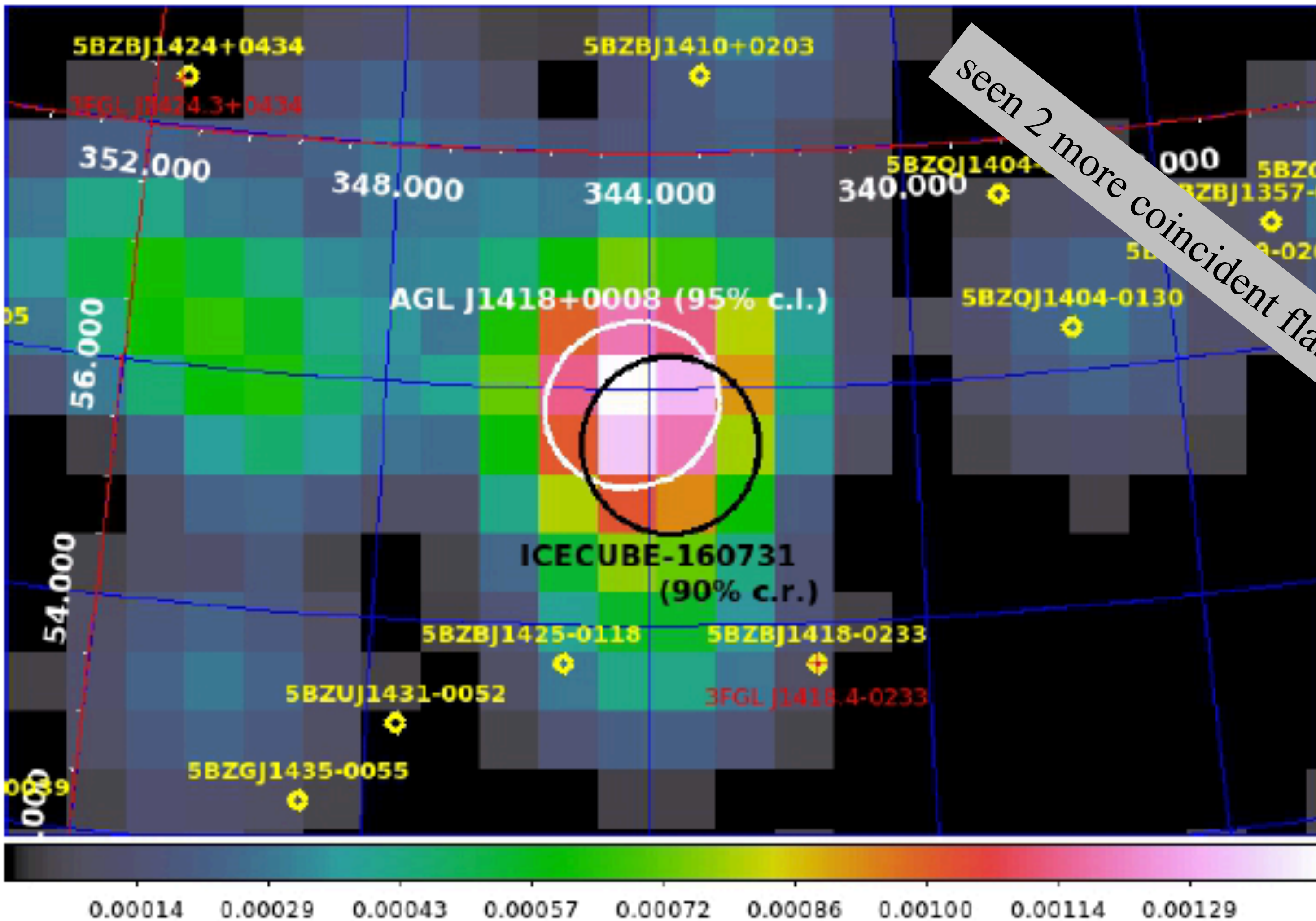
extensive multiwavelength campaign will allow us to study the first cosmic accelerator

Victor Hess 1912



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

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



seen 2 more coincident flashes

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

Did we solve the cosmic ray problem?

- The extraordinary brightness of the blazar despite its distance suggests that it may belong to a special class of sources that produce the extragalactic cosmic rays.
- IceCube flux discovered in 2013 can be accommodated by a subclass of blazars, of order 5%, that episodically produce neutrinos with the luminosity of the 2014 neutrino flare.
- 2104 flare can only be accommodated by highly efficient neutrino sources with large target photon densities that are not transparent to high-energy gamma rays. Photons lose energy in the source. (Vanilla blazar jet models do not apply.)

Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos are essential for understanding the non-thermal universe.
- identified the first high-energy cosmic ray accelerator
- from discovery to astronomy: more events, more telescopes IceCube-upgrade (→ IceCube-Gen2), KM3NeT and GVD (Baikal)

THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

UNITED STATES 25

ICECUBE
South Pole Neutrino Observatory

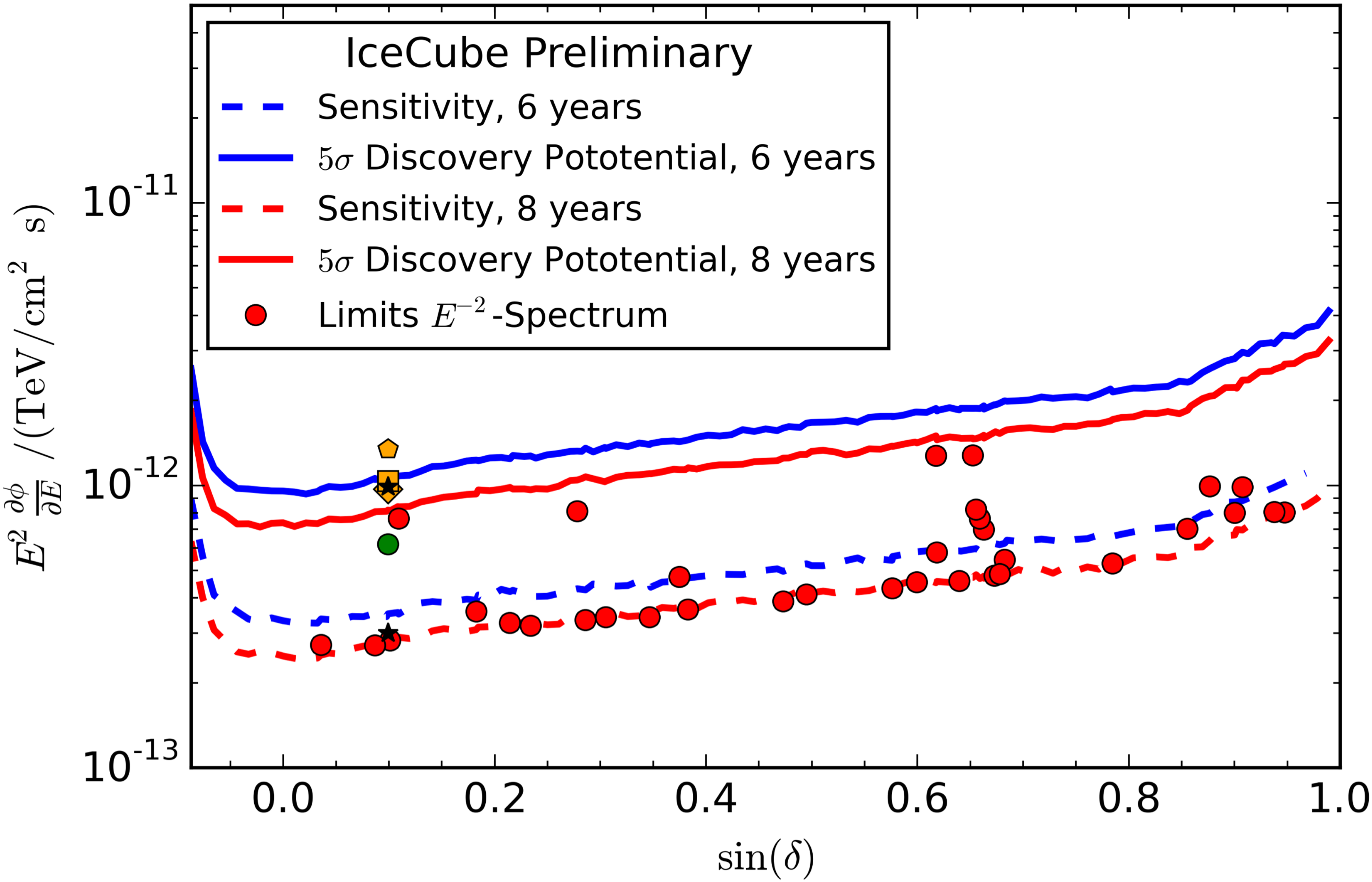
The Highest Energy Emission Detected by EGRET from Blazars

Brenda L. Dingus[1] & David L. Bertsch[2]

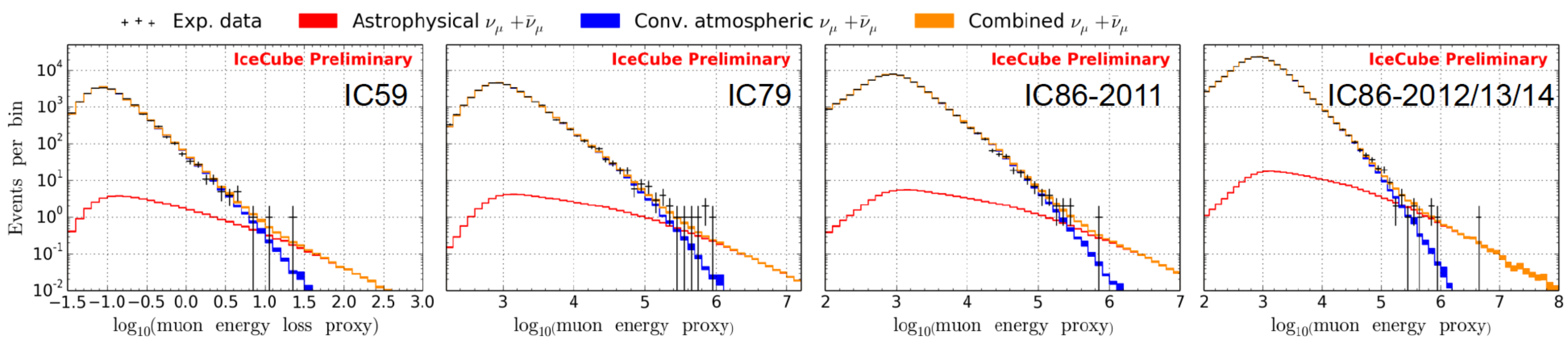
(1) Physics Department, University of Wisconsin, Madison, WI 53711
dingus@physics.wisc.edu
(2)NASA Goddard Space Flight Center, Greeenbelt, MD 20771

Abstract. Published EGRET spectra from blazers extend only to 10 GeV, yet EGRET has detected approximately 2000 γ-rays above 10 GeV of which about half are at high Galactic latitude. We report a search of these high-energy γ-rays for associations with the EGRET and TeV detected blazers. Because the point spread function of EGRET improves with energy, only ~2 γ-rays are expected to be positionally coincident with the 80 blazars searched, yet 23 γ-rays were observed. This collection of > 10 GeV sources should be of particular interest due to the improved sensitivity and lower energy thresholds of ground-based TeV observatories. One of the blazers, RGB0509+056, has the highest energy γ-rays detected by EGRET from any blazar with 2 > 40 GeV, and is a BL Lac type blazar with unknown redshift.

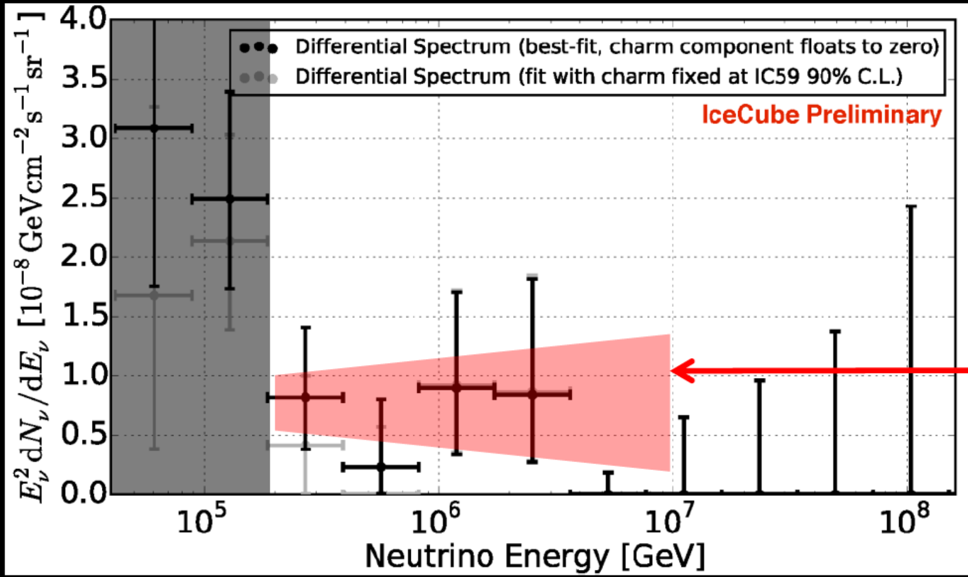
Why not seen before?



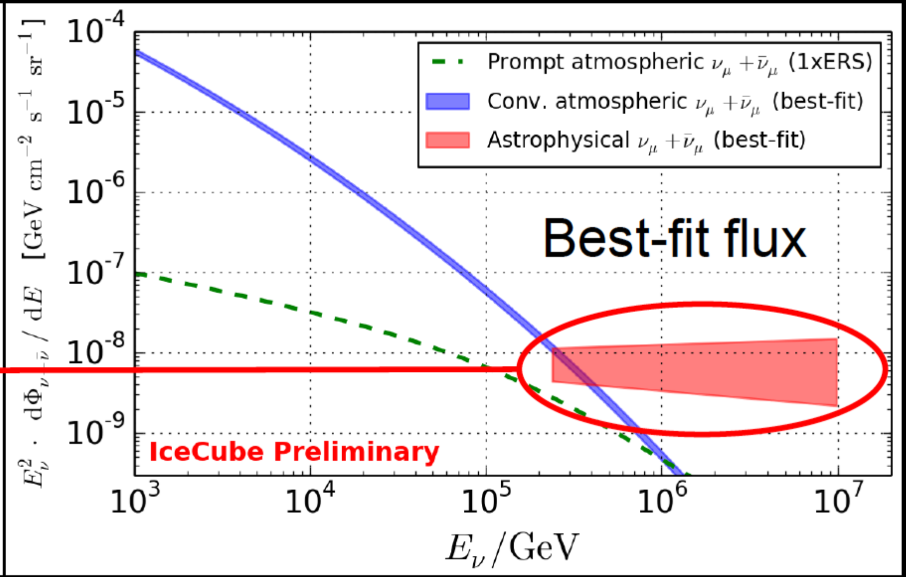
after 6 years: 3.7→ 6.0 sigma

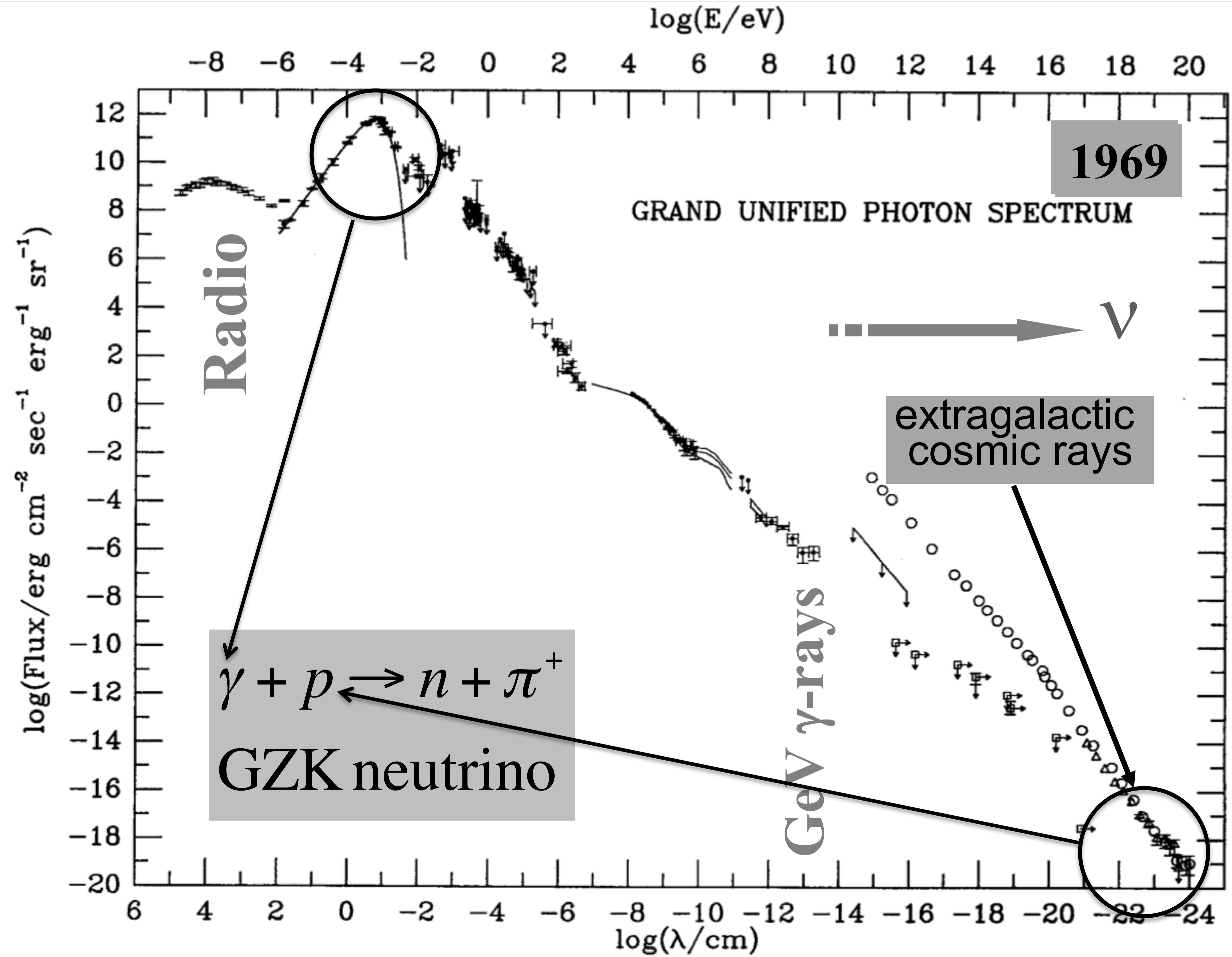


HESE 4 year unfolding
(→ dominated by shower-like events)



6 year up-going numu analysis





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

cosmic rays interact with the microwave background

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

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

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

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

...but it points at its source!

new physics ?

if not…

every model ends up in the triangle