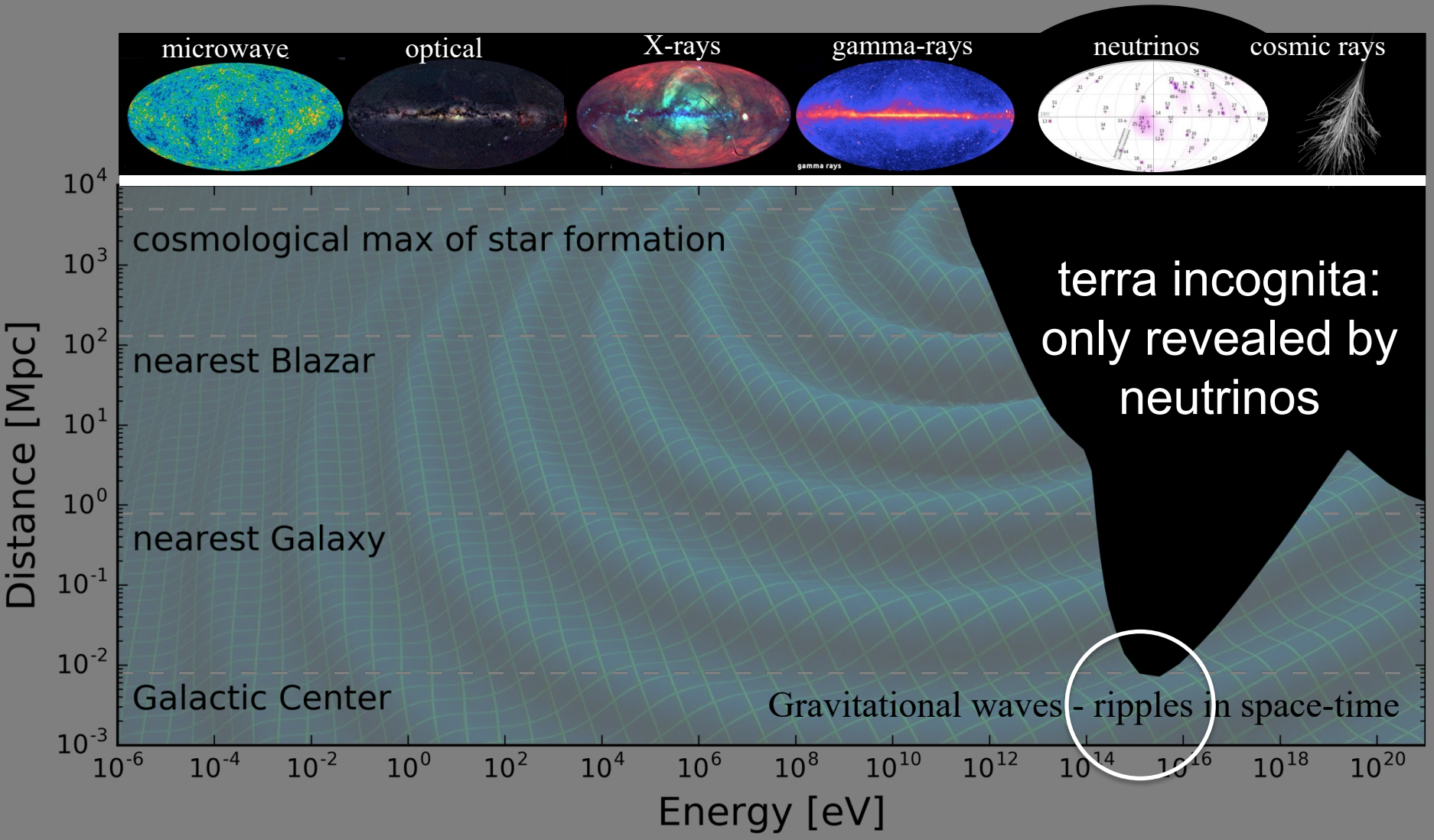
Cosmic Neutrinos and Multimessenger Astronomy

francis halzen

- neutrino astronomy and the origin of cosmic rays
- IceCube
- extragalactic cosmic neutrinos
- the large diffuse neutrino flux
- the first cosmic ray accelerator(s)

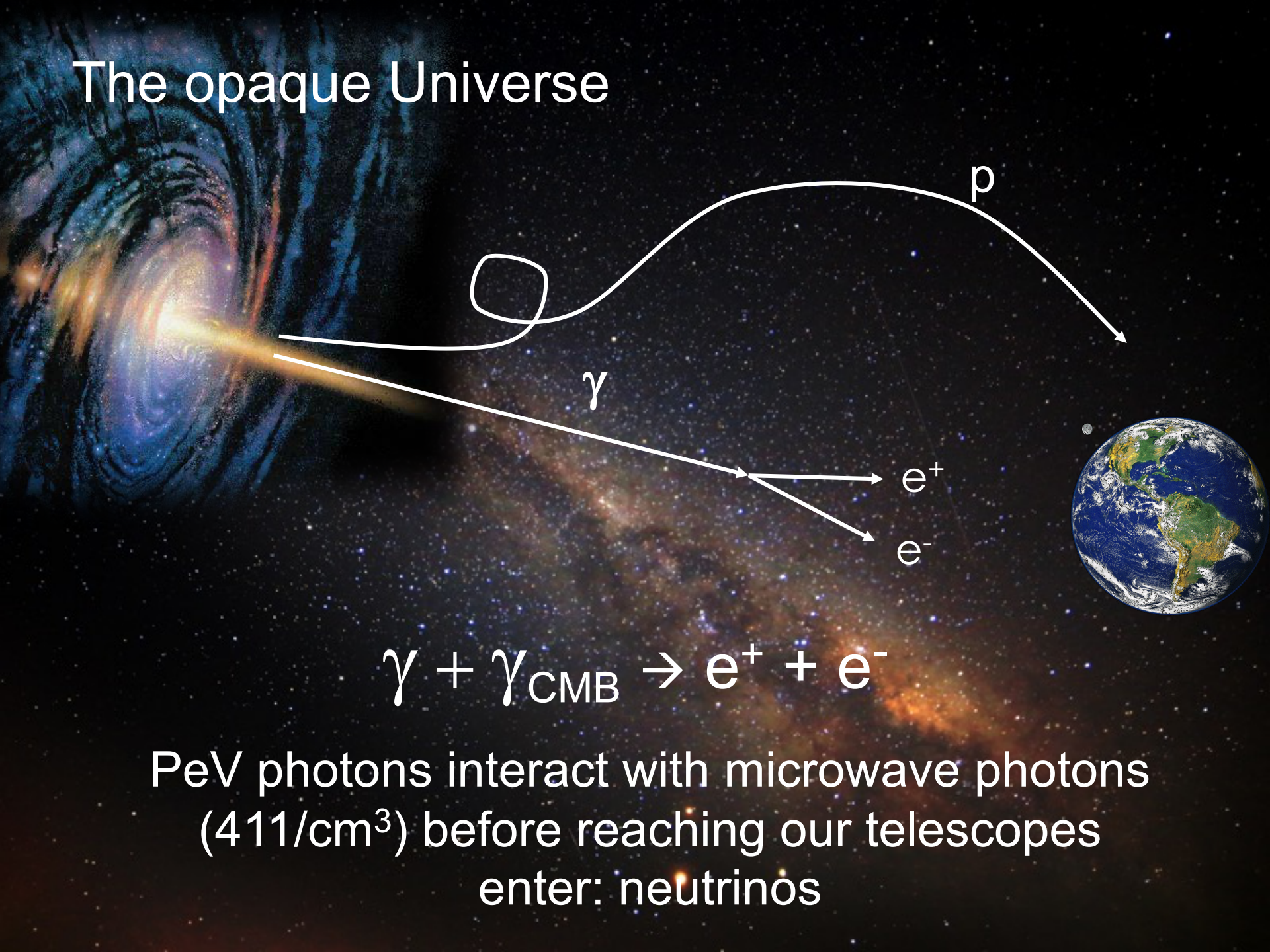
IceCube.wisc.edu

highest energy “radiation” from the Universe: neutrinos and cosmic rays (not photons)



Universe is opaque to electromagnetic radiation above ~100 TeV

The opaque Universe

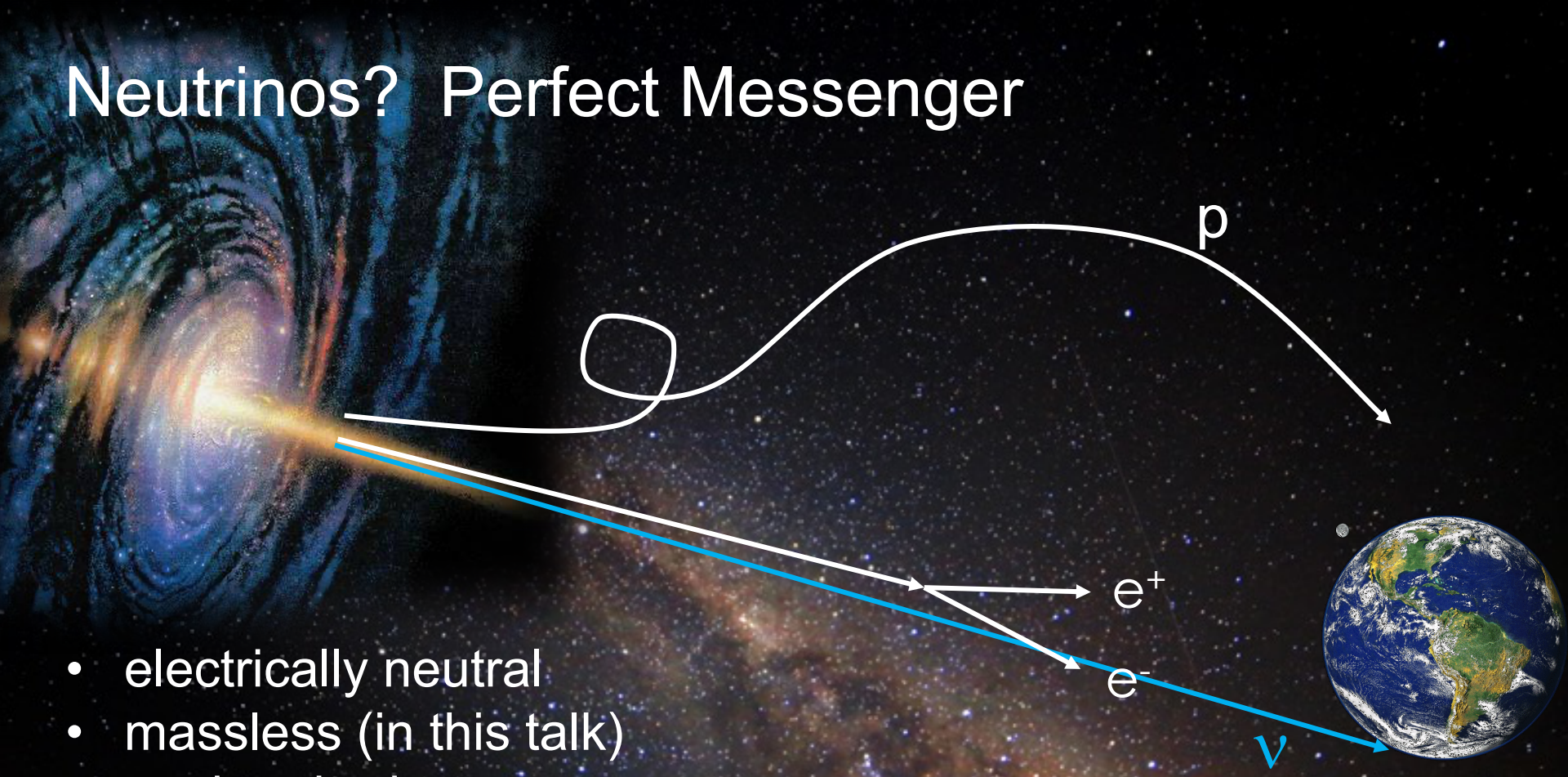


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

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

enter: neutrinos

Neutrinos? Perfect Messenger

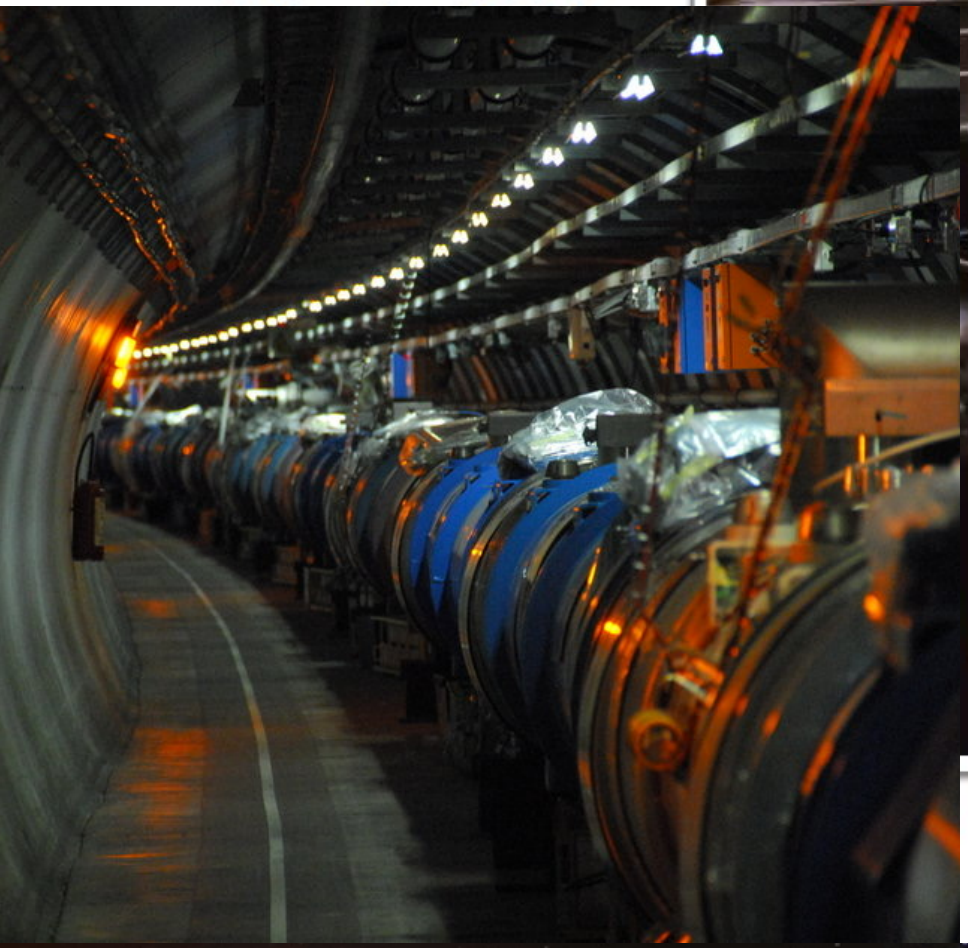


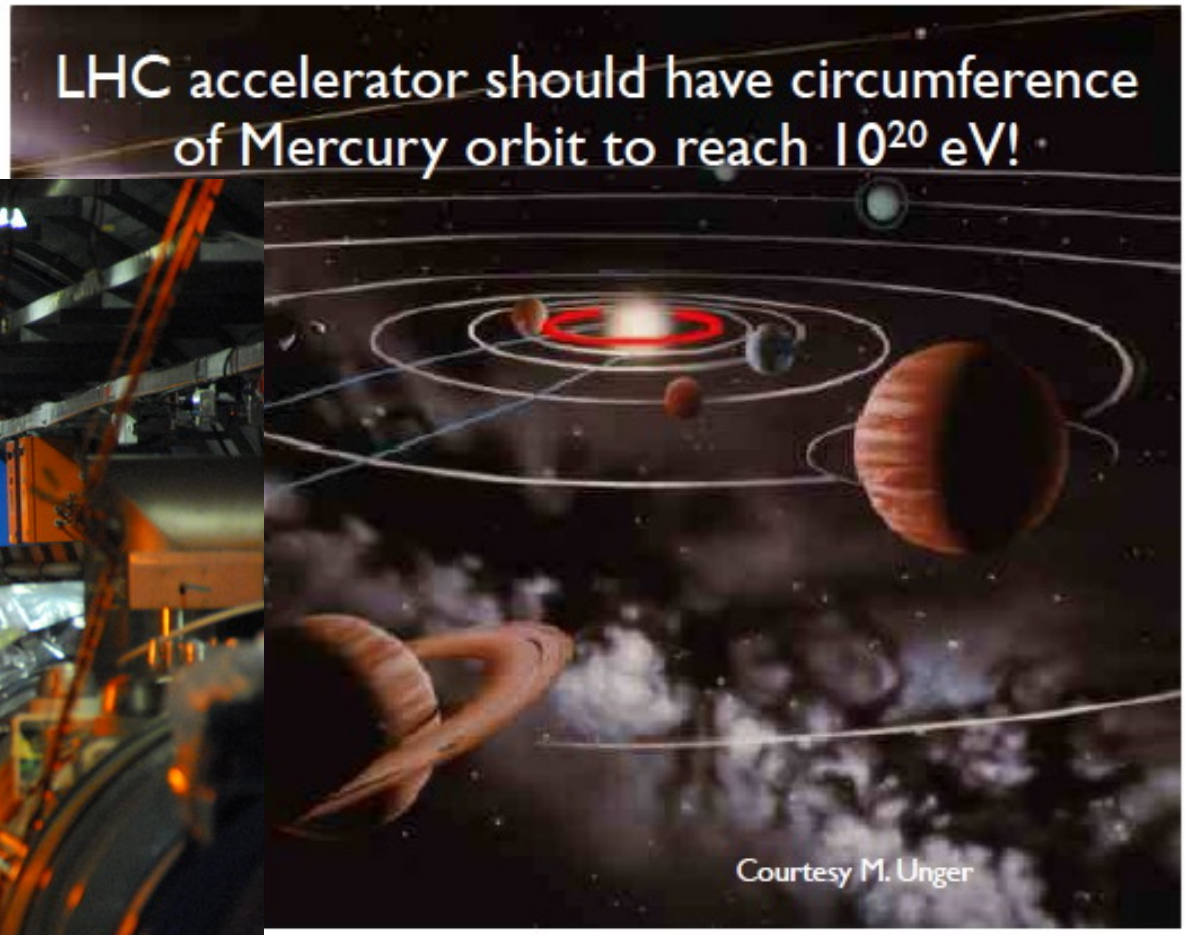
- electrically neutral
- massless (in this talk)
- unabsorbed
- tracks protons (that produce pions that decay into neutrinos)
- reveal the sources of cosmic rays

- … but difficult to detect

highest energy radiation from the Universe: protons!

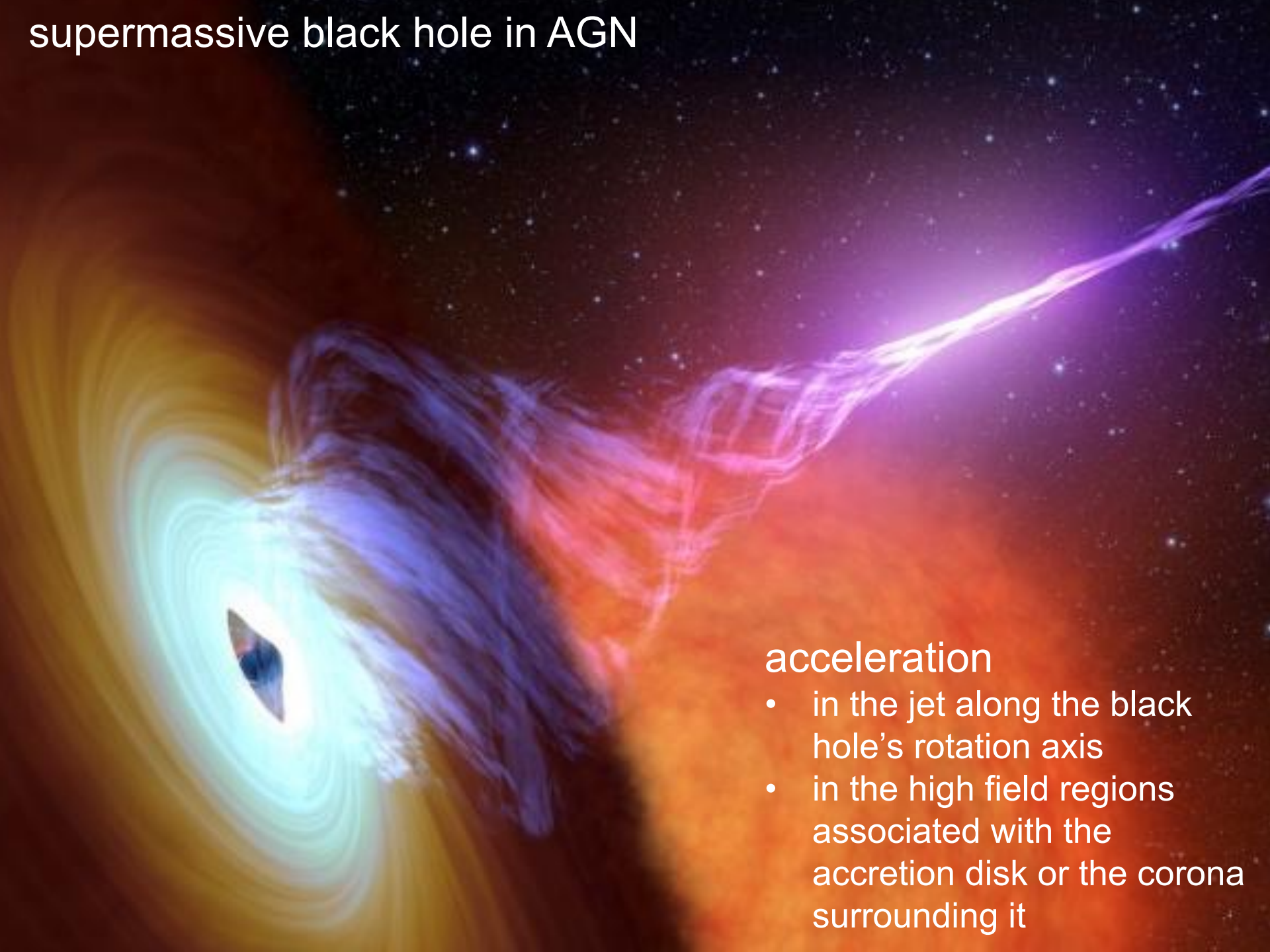
high energy
high luminosity





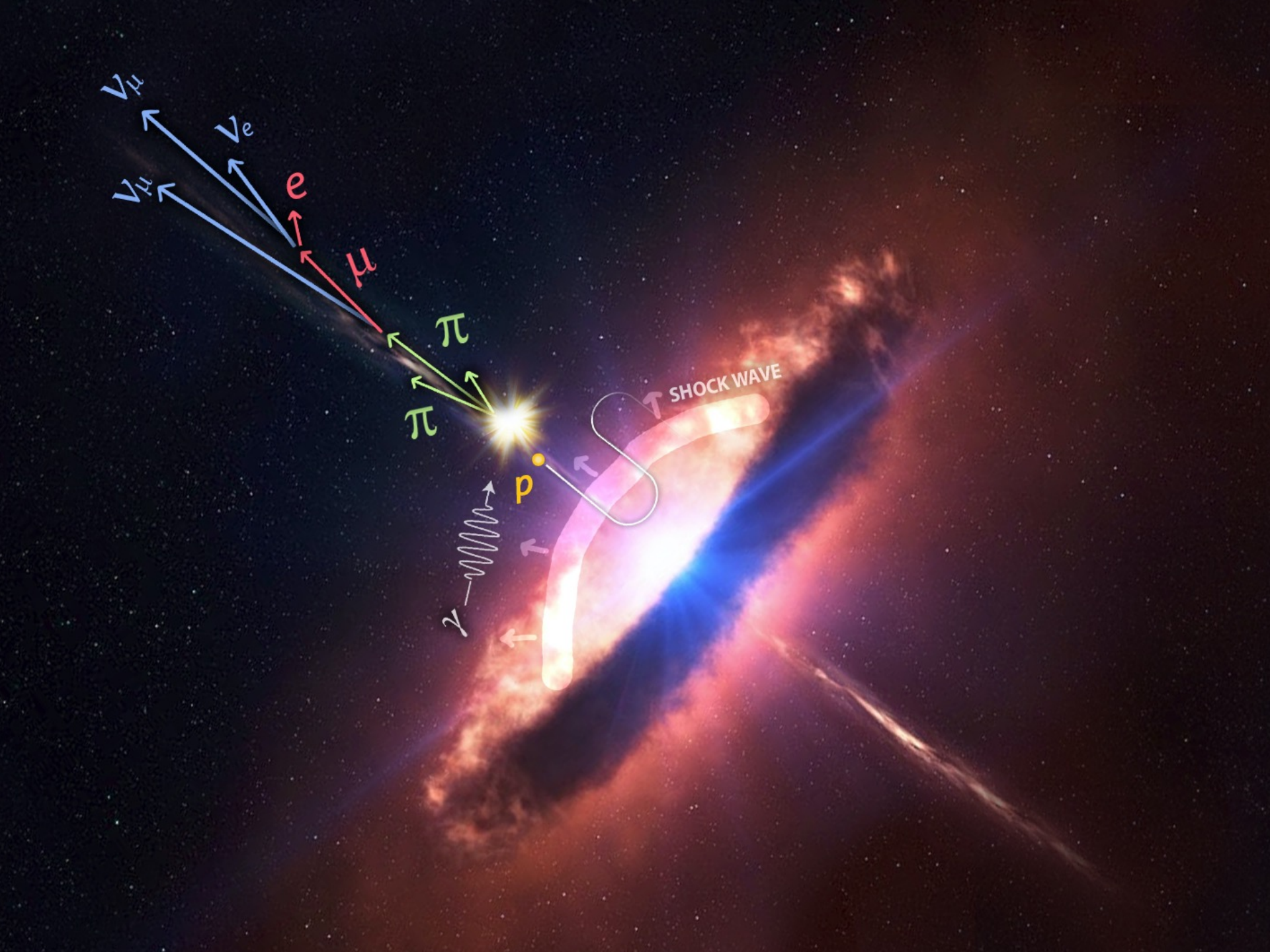
Fly's Eye 1991
300,000,000 TeV

supermassive black hole in AGN

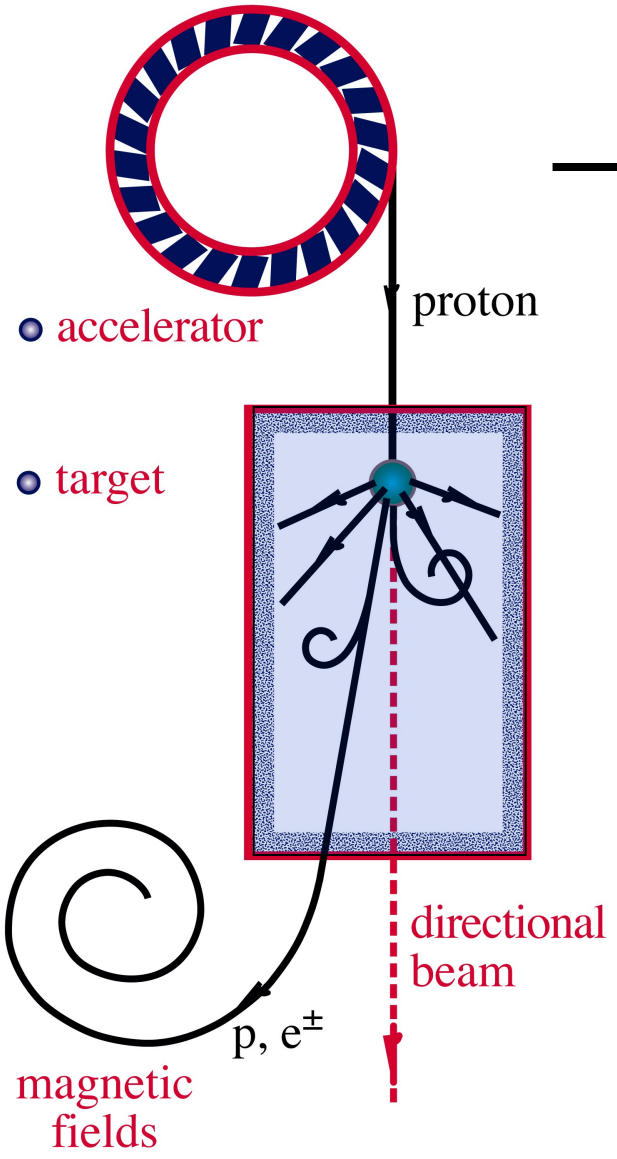


acceleration

- in the jet along the black hole's rotation axis
- in the high field regions associated with the accretion disk or the corona surrounding it


ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

ν and γ beams : heaven and earth



supermassive black hole

nearby radiation

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

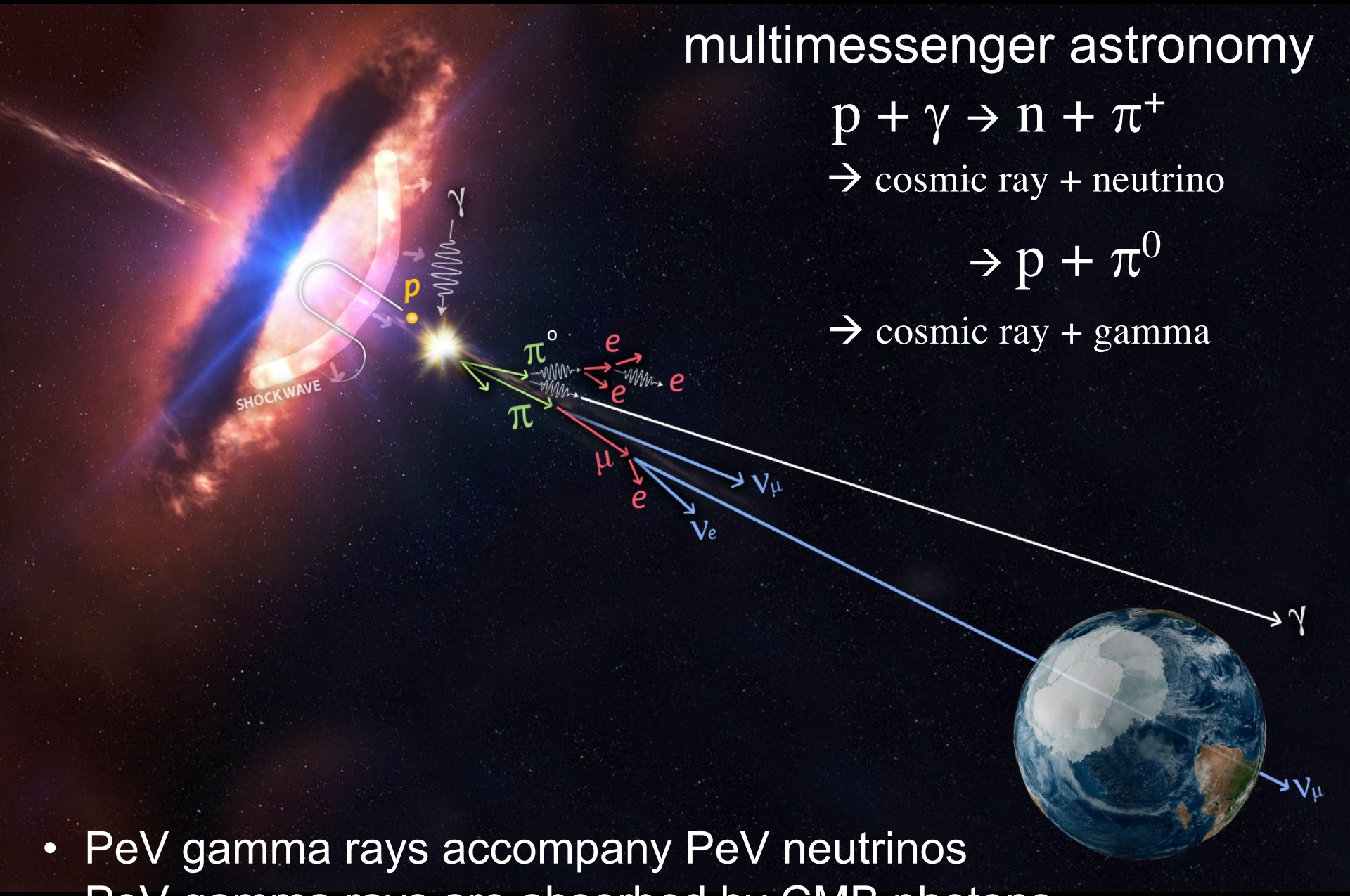
multimessenger astronomy

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

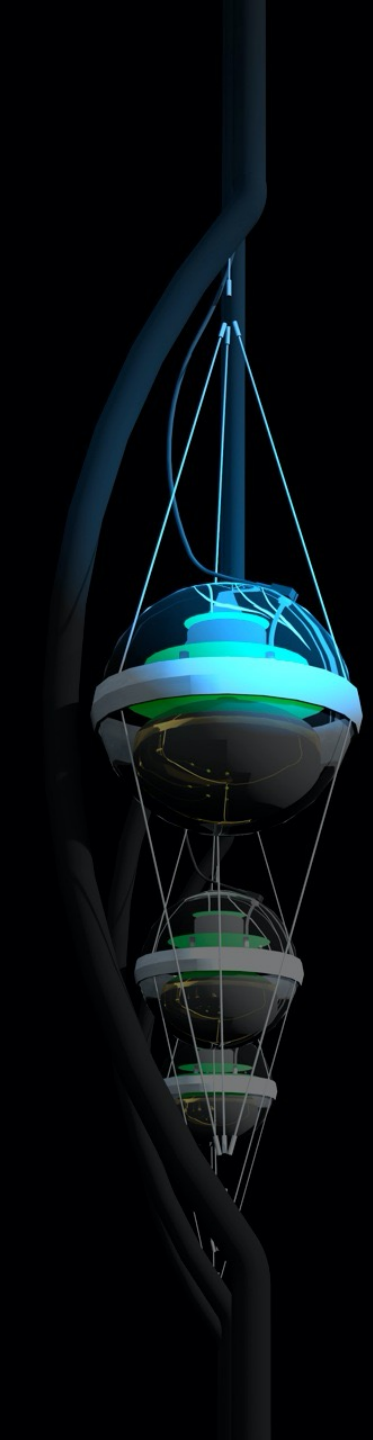
→ cosmic ray + neutrino

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

→ cosmic ray + gamma



- PeV gamma rays accompany PeV neutrinos
- PeV gamma rays are absorbed by CMB photons



PeV neutrinos
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extragalactic cosmic neutrinos

the large diffuse neutrino flux

the first cosmic ray accelerator(s)

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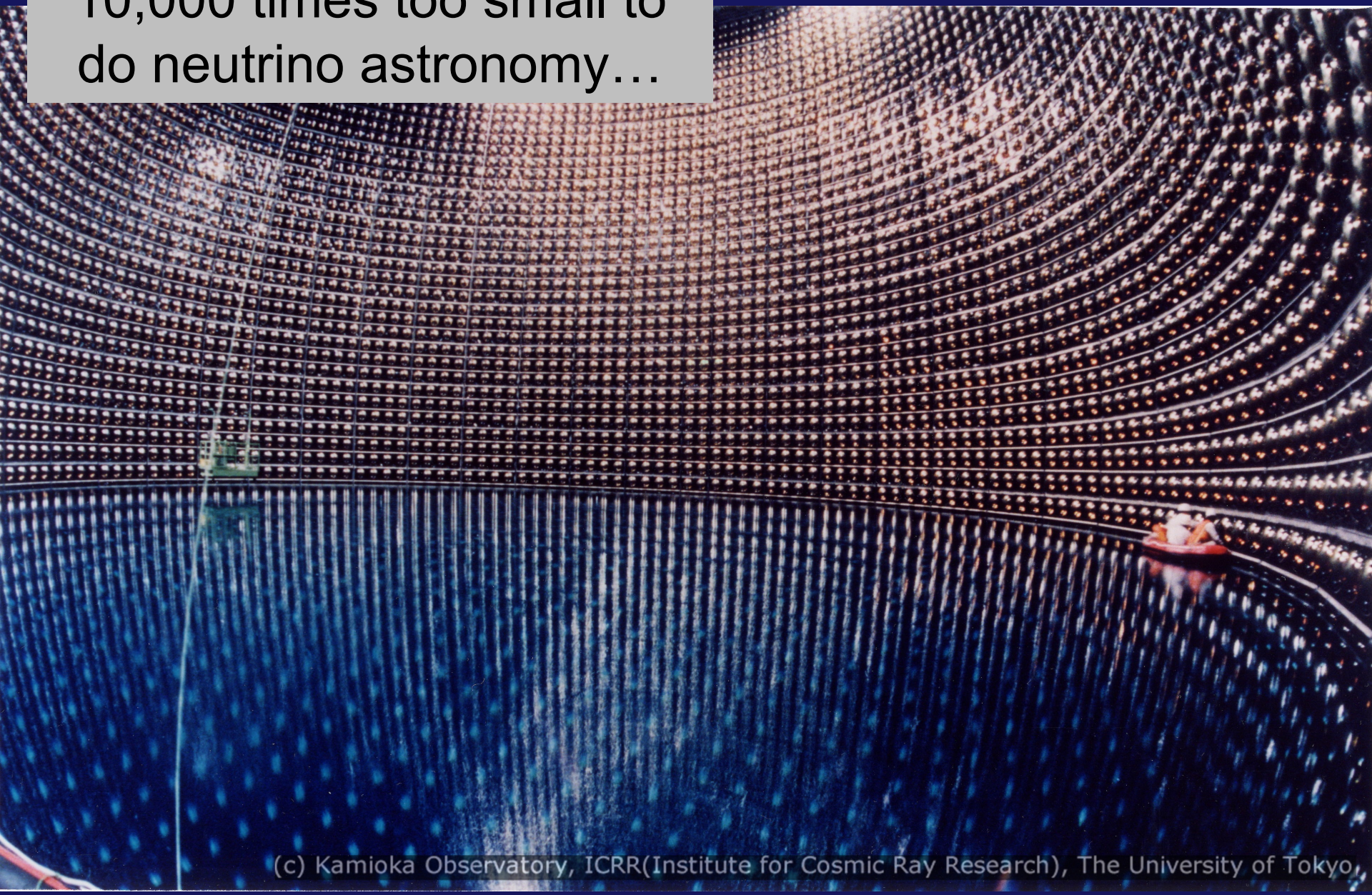
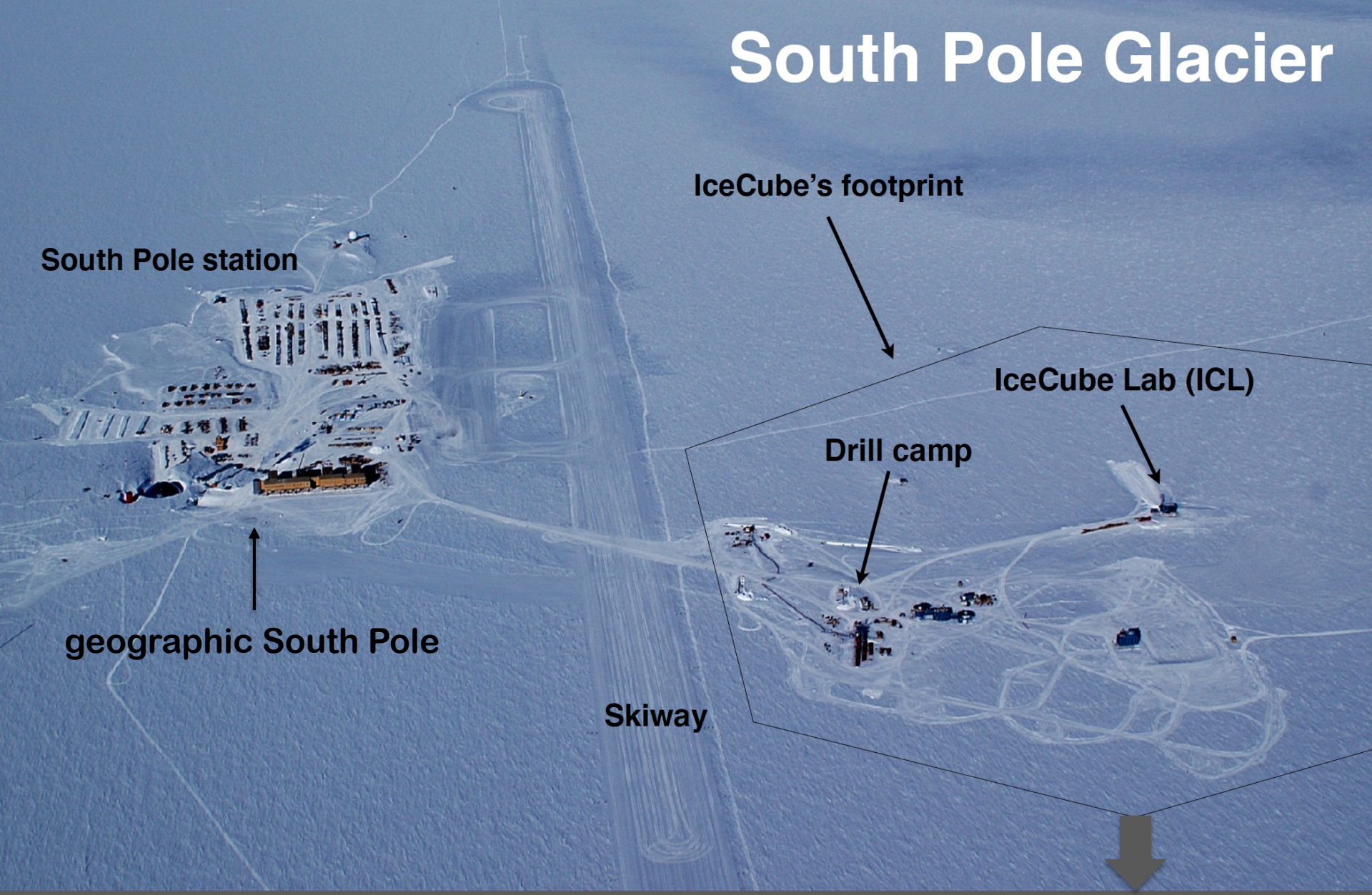
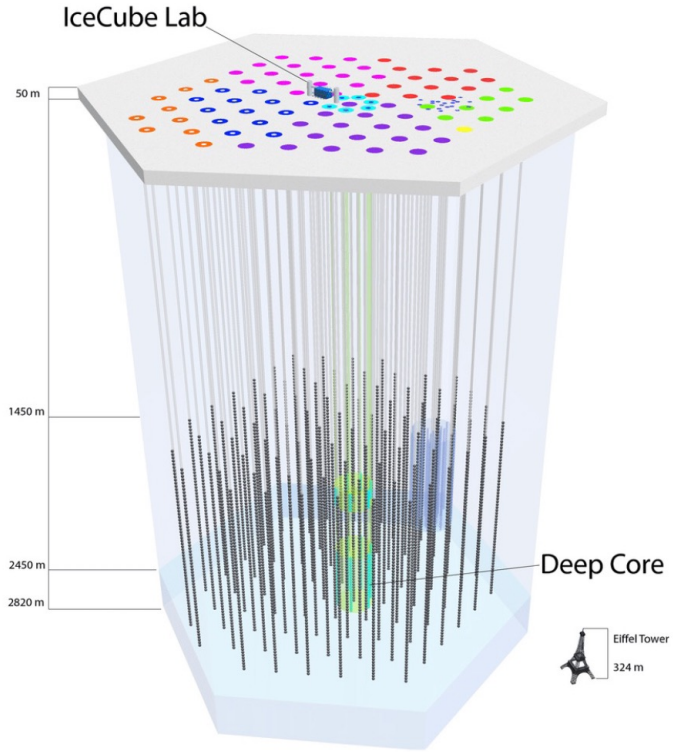
10,000 times too small to do neutrino astronomy…





instrument 1 cubic kilometer of natural ice below 1.45 km
with 5160 10-inch photomultiplier tubes

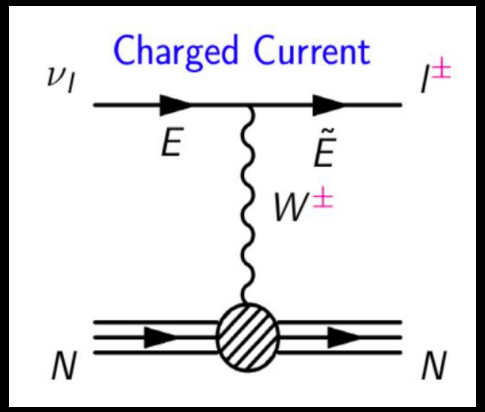
IceCube architecture

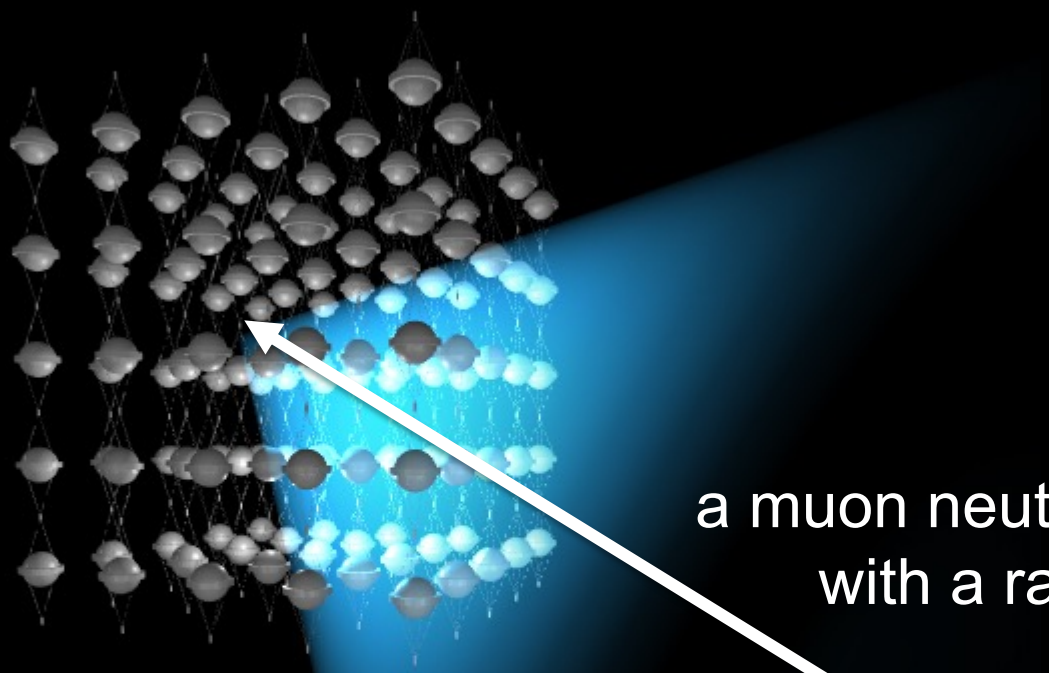


instrument 1 cubic kilometer of natural ice below 1.45 km
with 5160 10-inch photomultiplier tubes

photomultiplier tube -10 inch

events that have come through the Earth





a muon neutrino produces a muon with a range of kilometers

lattice of photomultipliers in deep and transparent sea water

muon neutrino

signal and background

muons detected per year:

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

(12 cosmic neutrinos per year above 100 TeV)

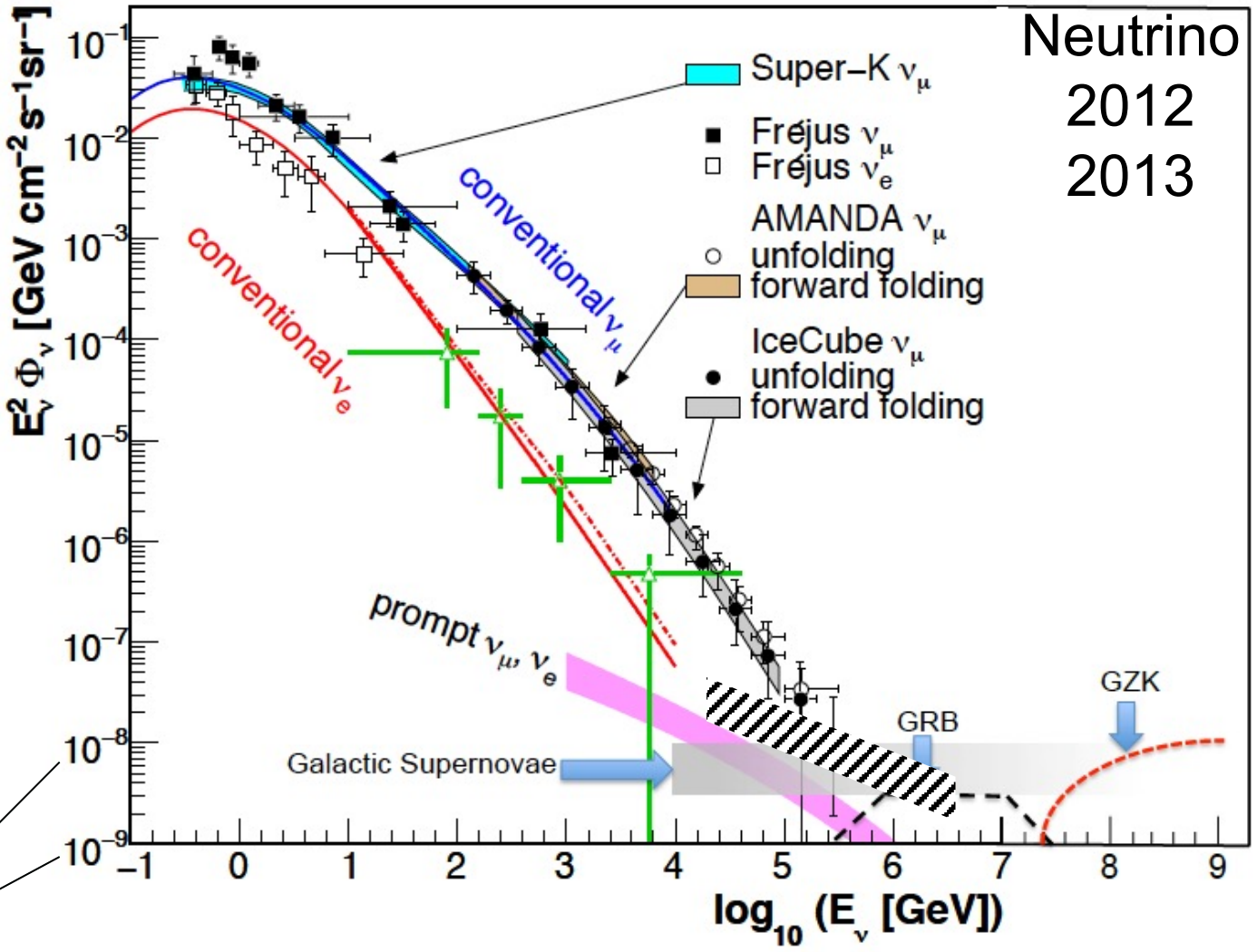
* 3000 per second ** 1 every 5 minutes

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

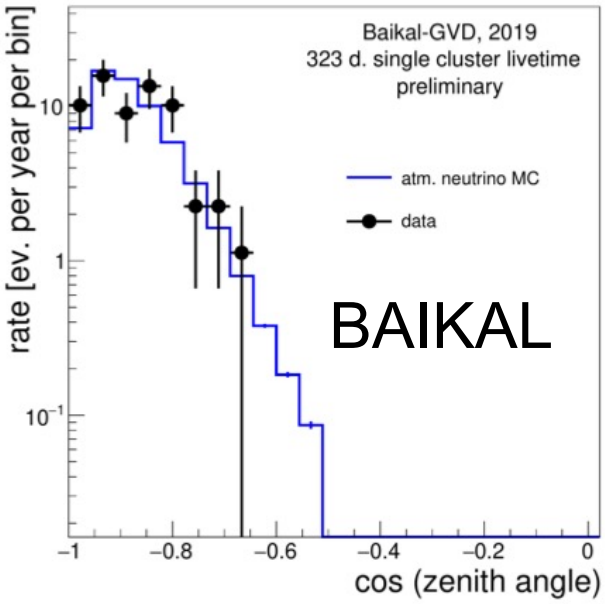


atmospheric

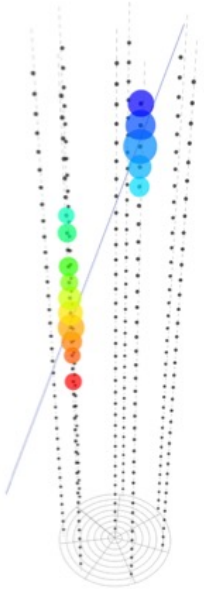
cosmic

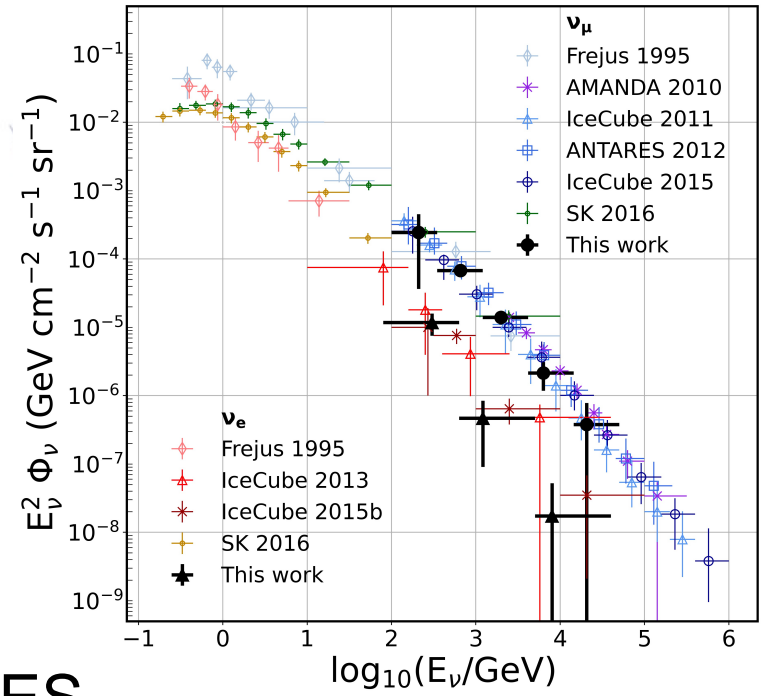
100 TeV

atmospheric neutrinos : calibration well understood.

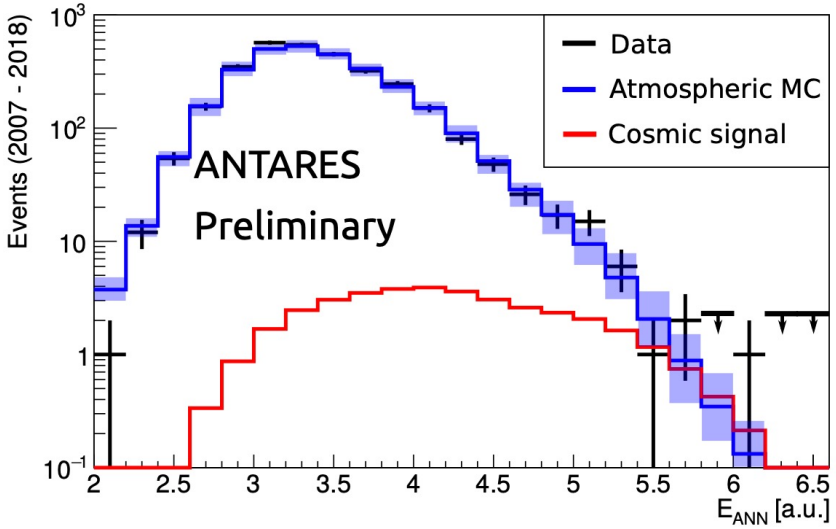


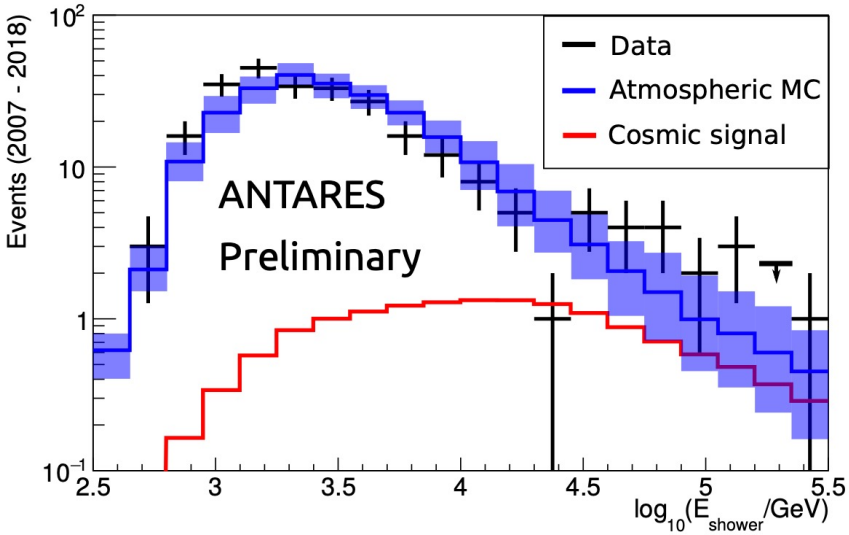
BAIKAL

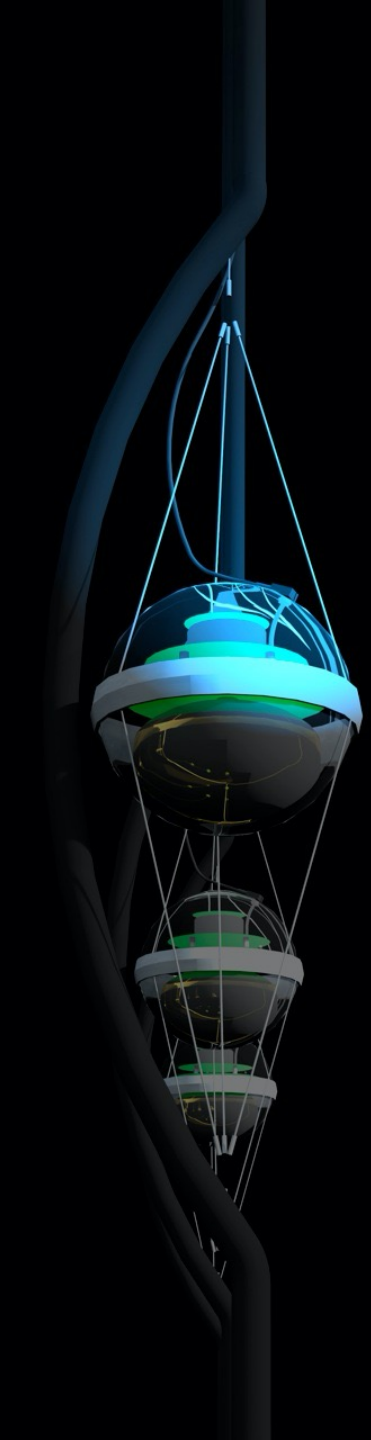




ANTARES







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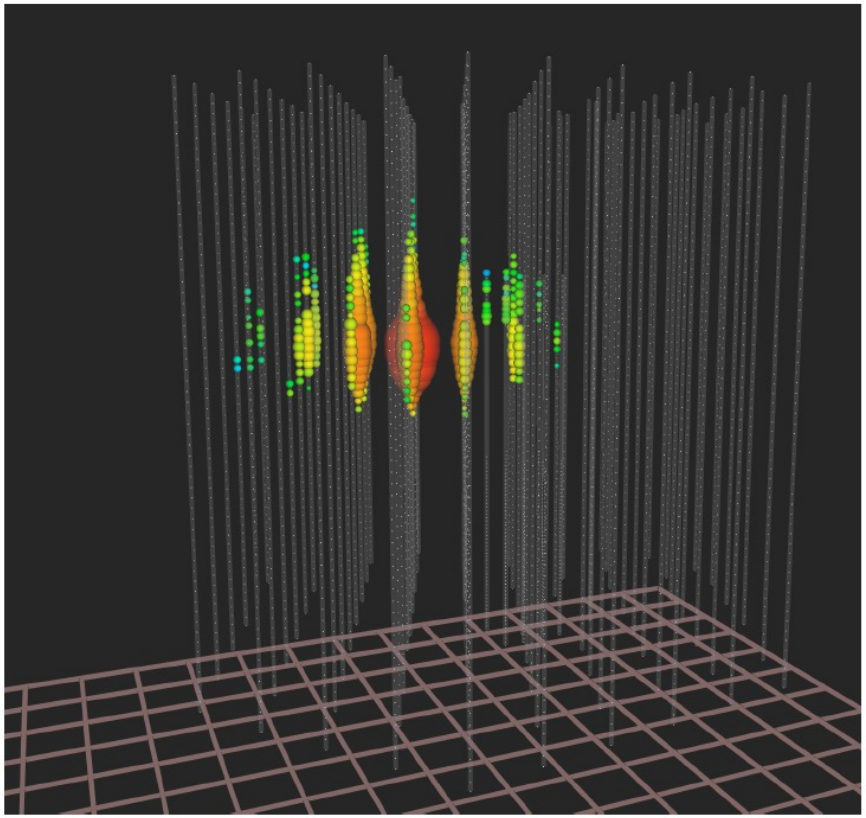
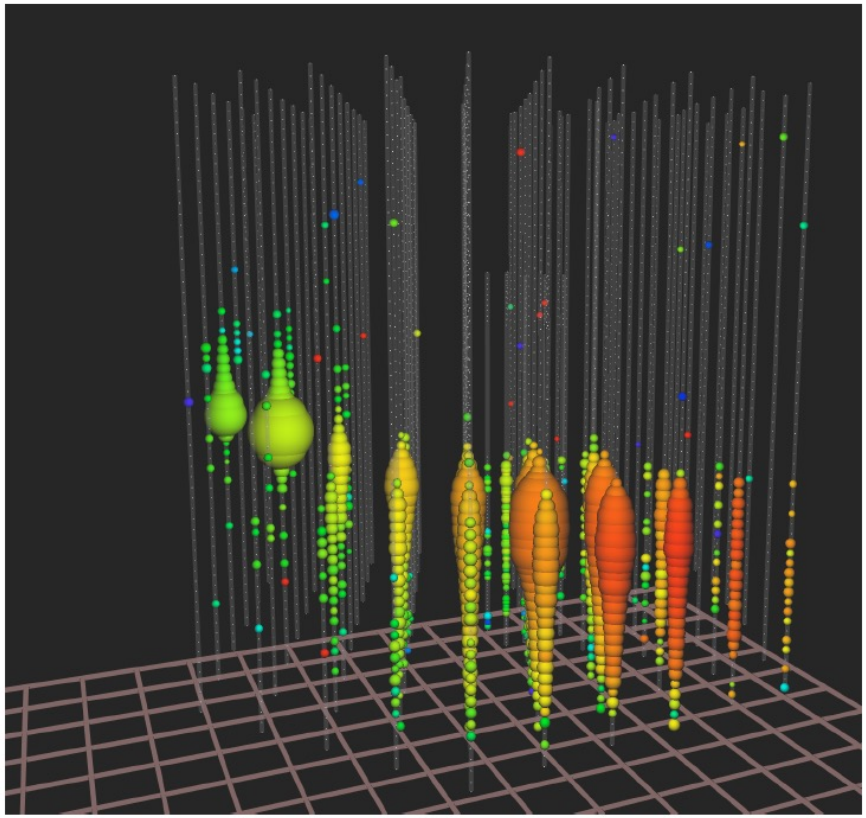
neutrinos interacting
inside the detector

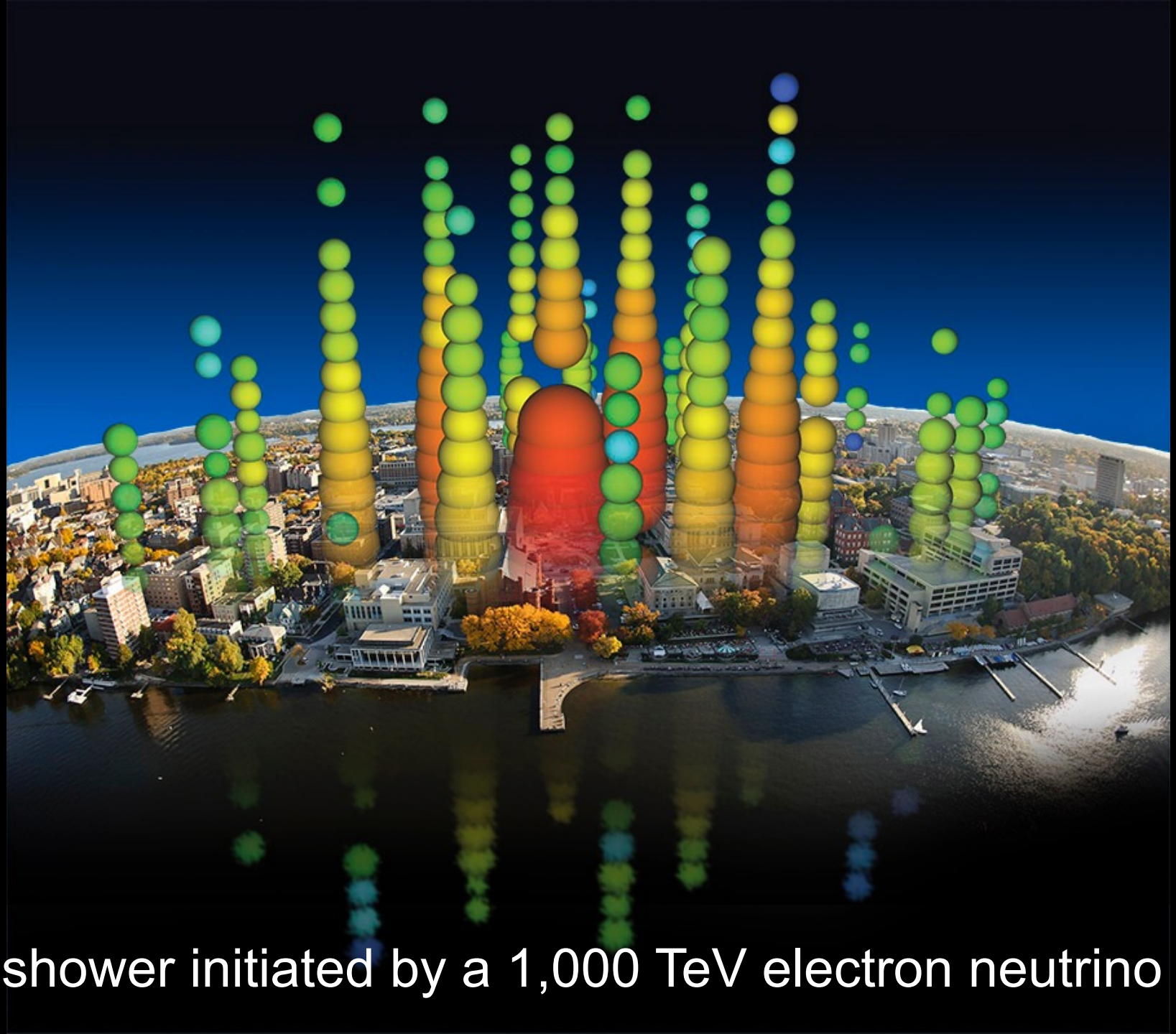


muon neutrinos
filtered by the Earth

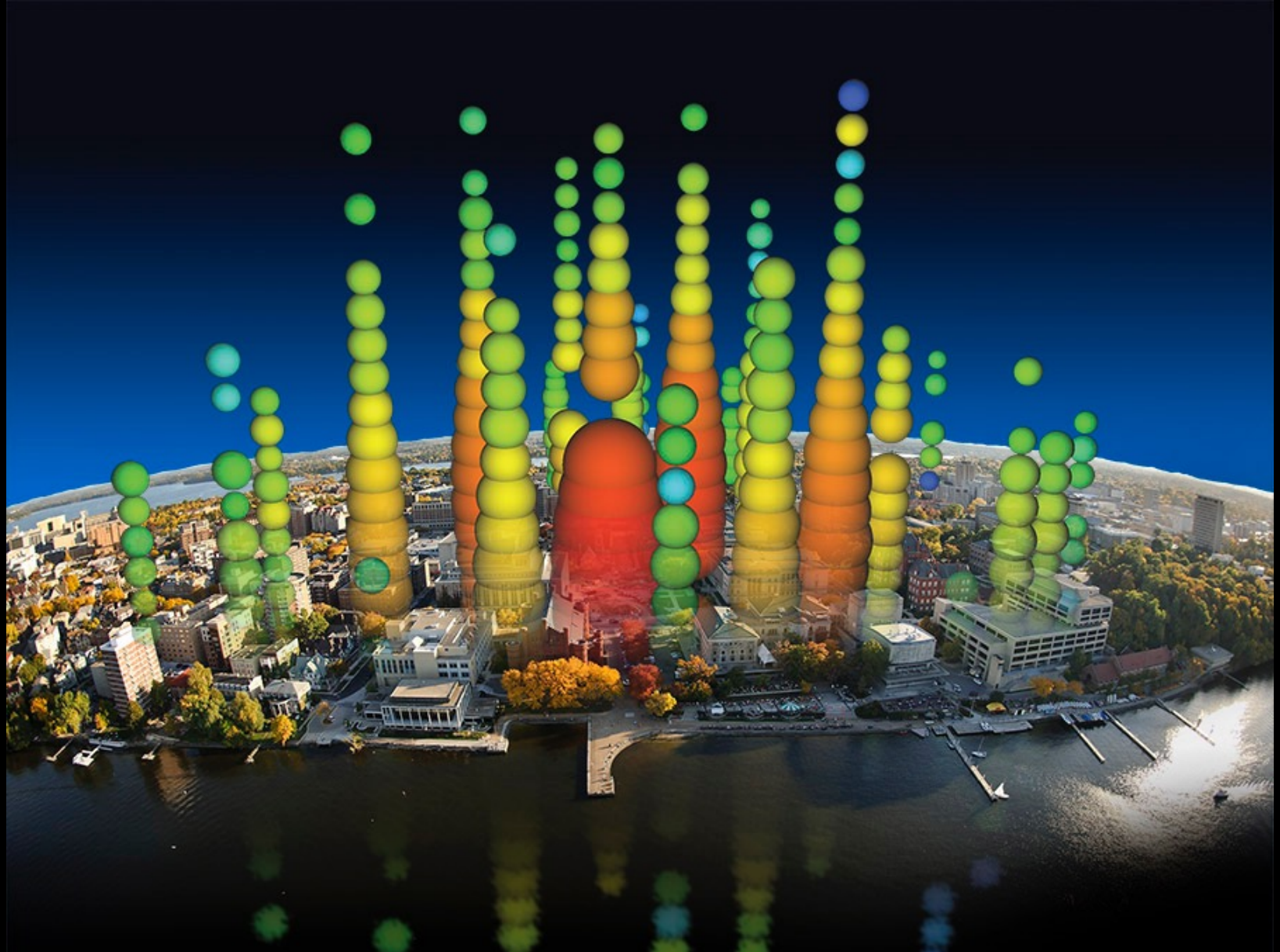


total energy measurement
to 10%, all flavors, all sky

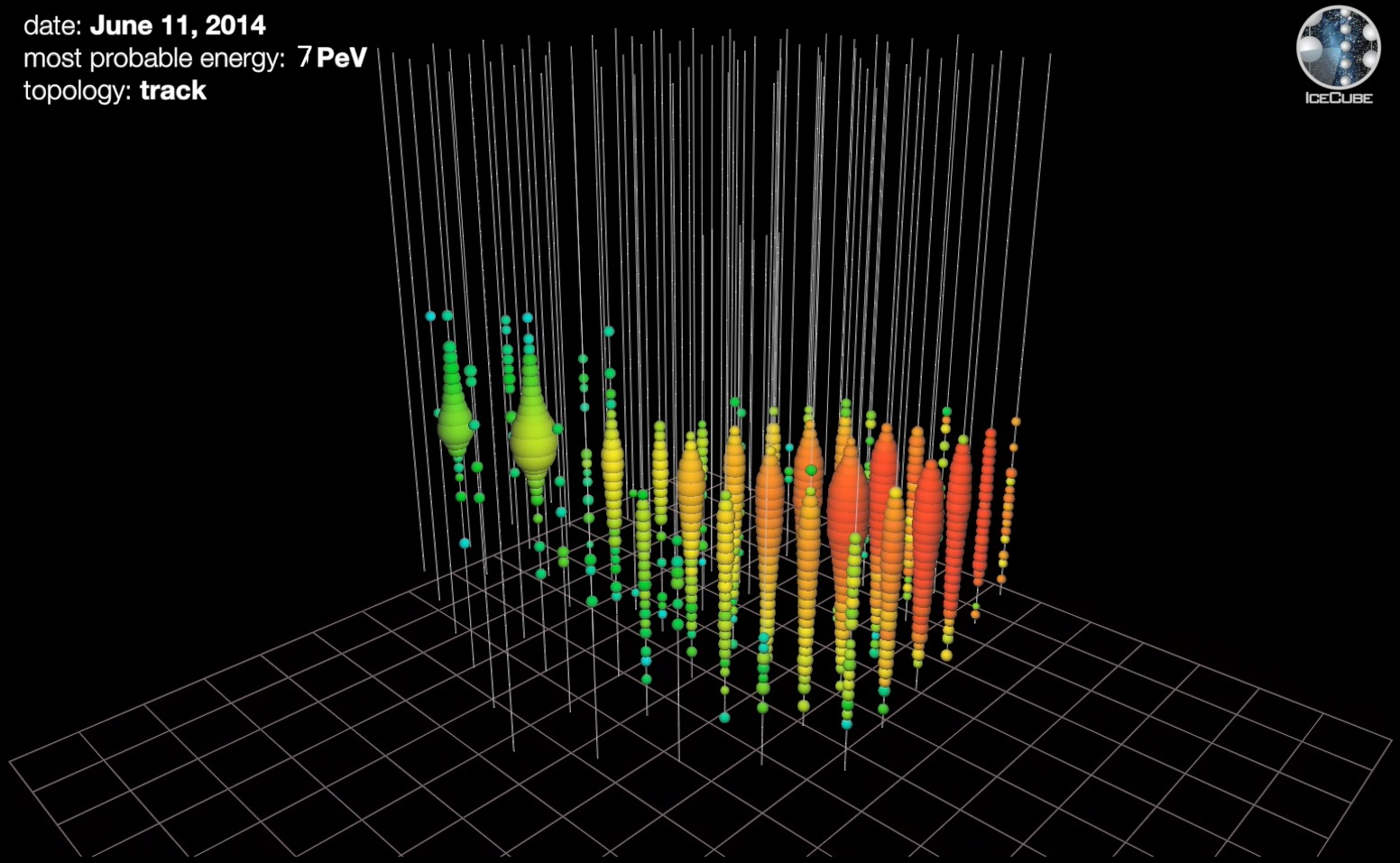
astronomy: angular resolution
superior (0.2~0.4^{o})

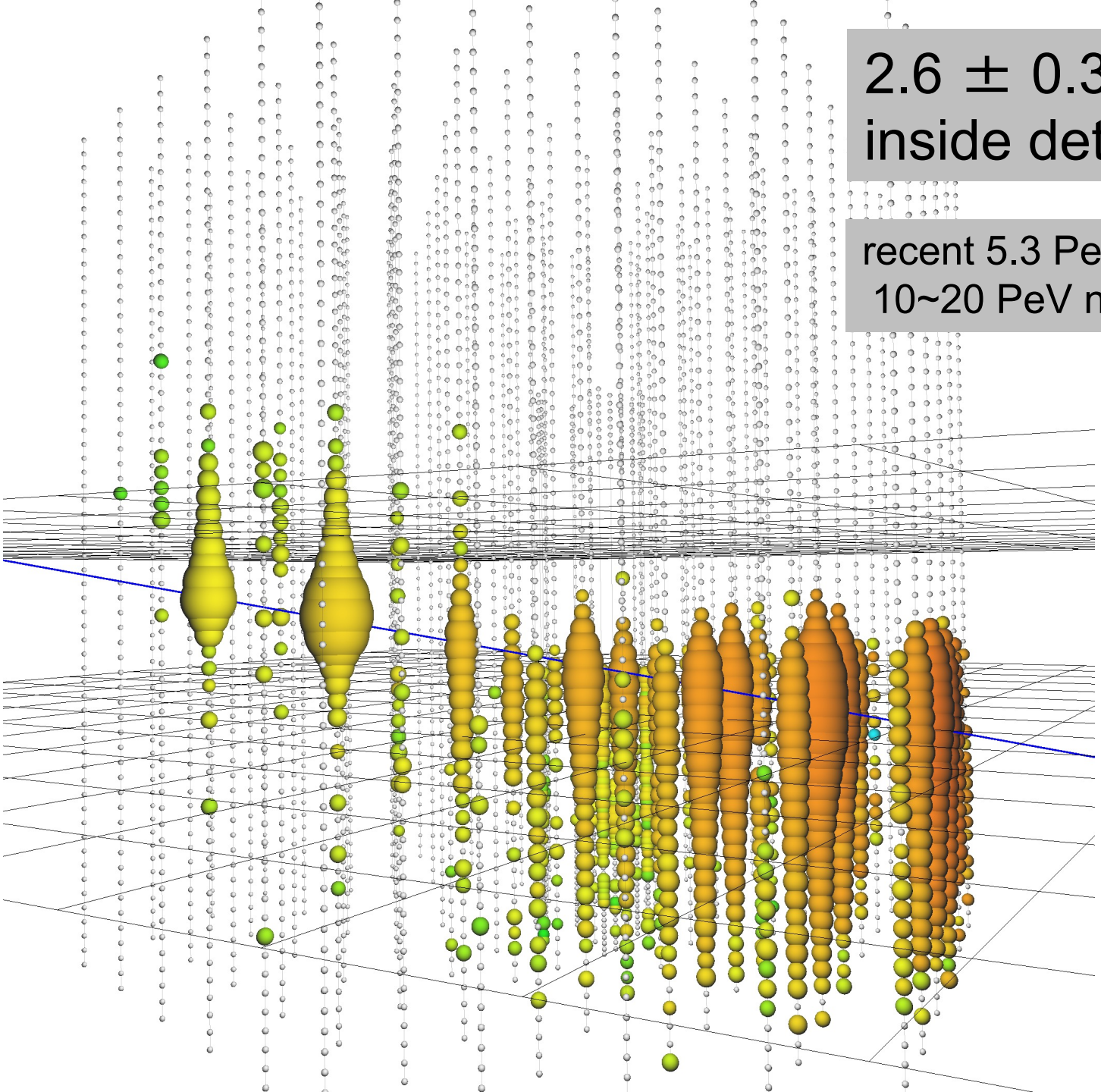


shower initiated by a 1,000 TeV electron neutrino

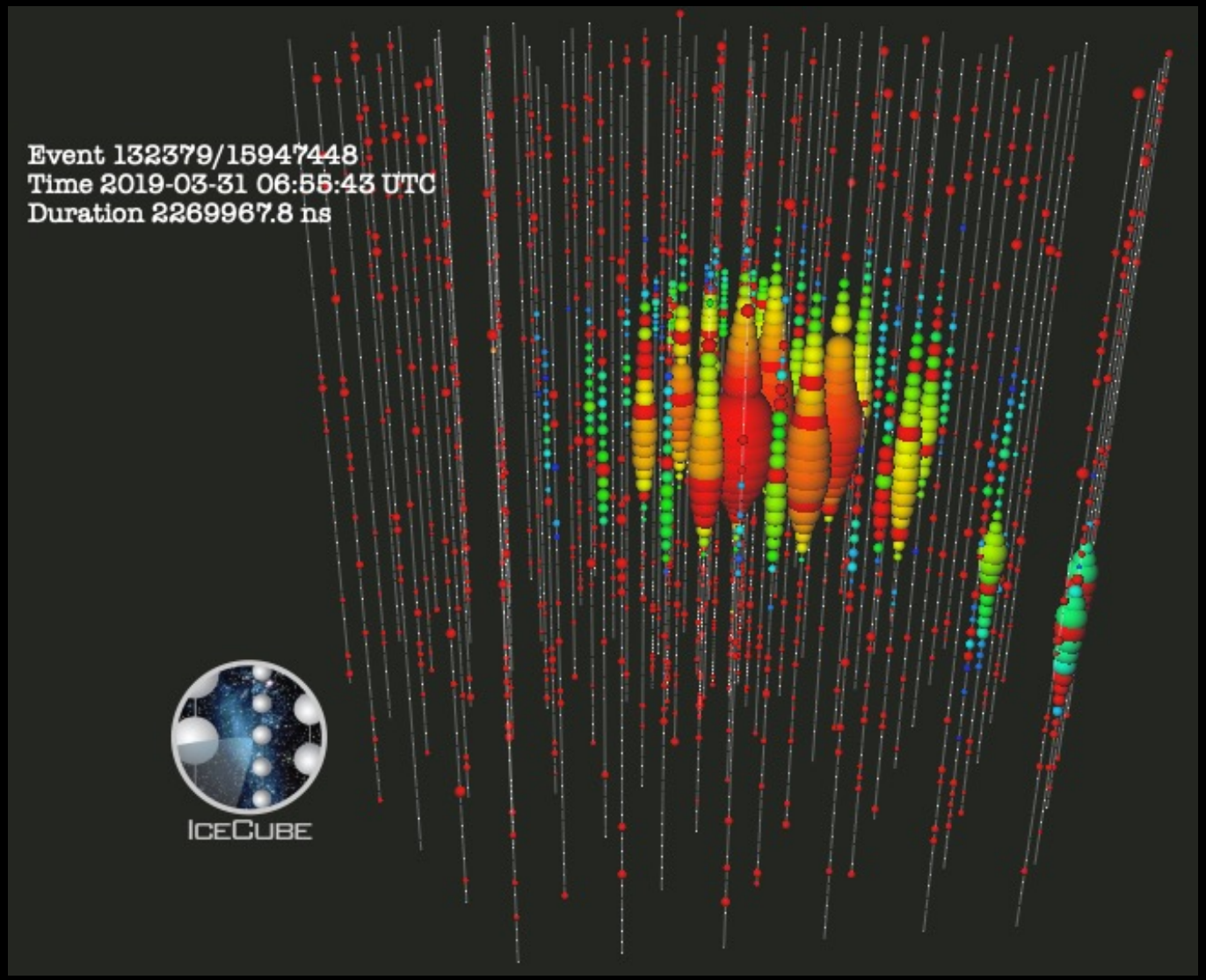


Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec


date: **June 11, 2014**
most probable energy: **7 PeV**
topology: **track**
IceCube


2.6 ± 0.3 PeV
inside detector
recent 5.3 PeV event
10~20 PeV neutrino

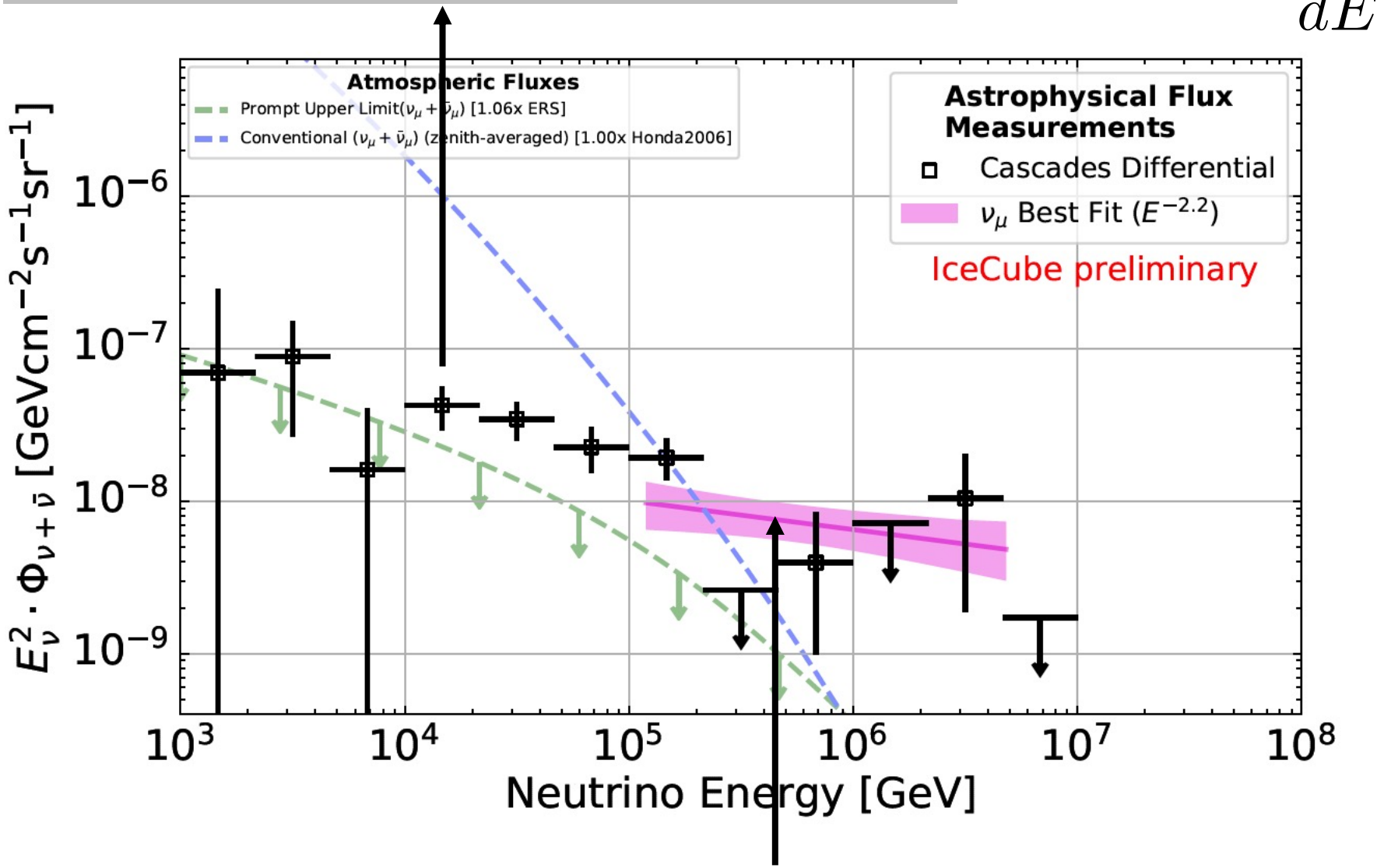
IC190331: 5300 TeV deposited inside the detector



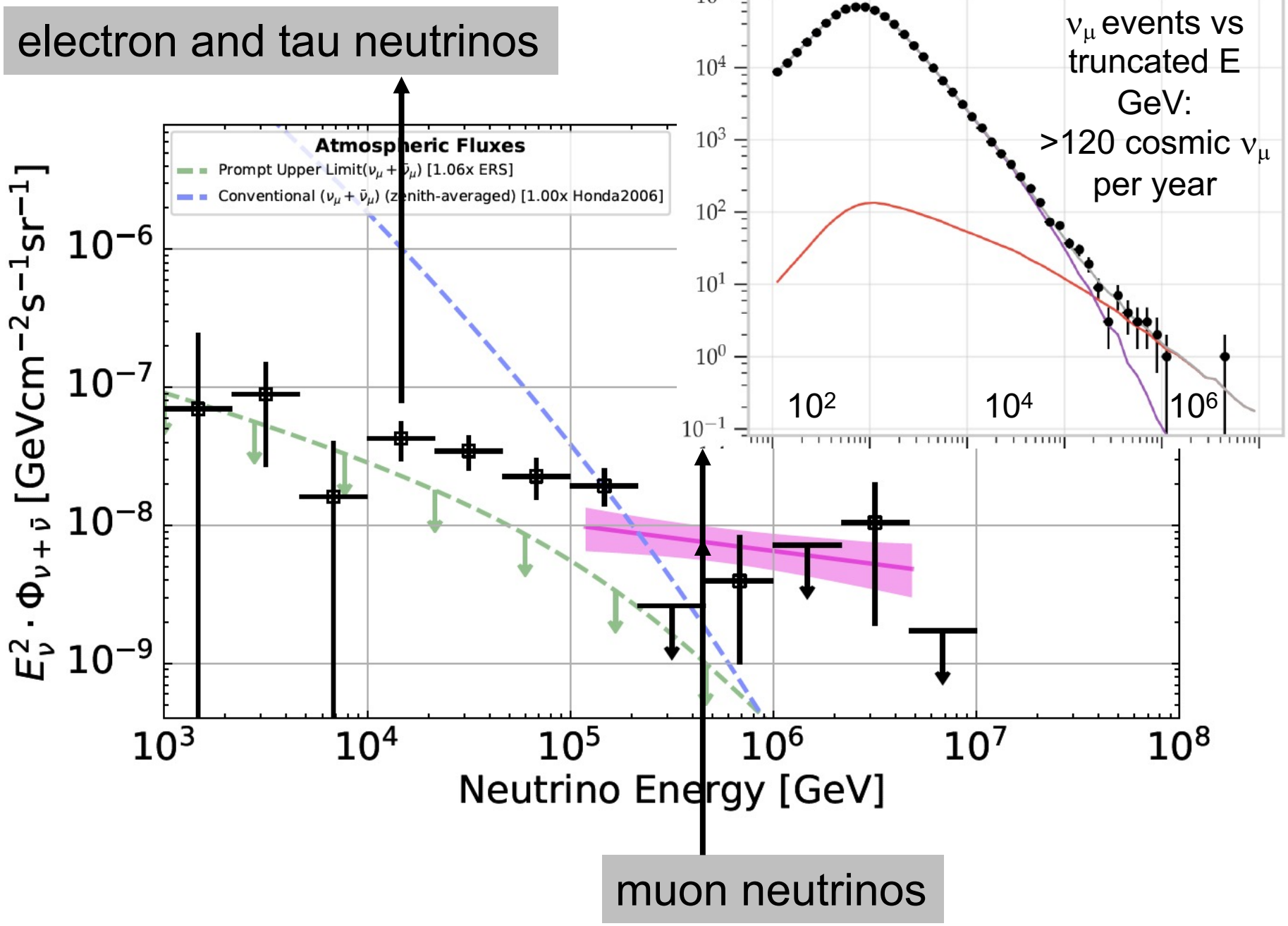
initial neutrino energy > 10 PeV

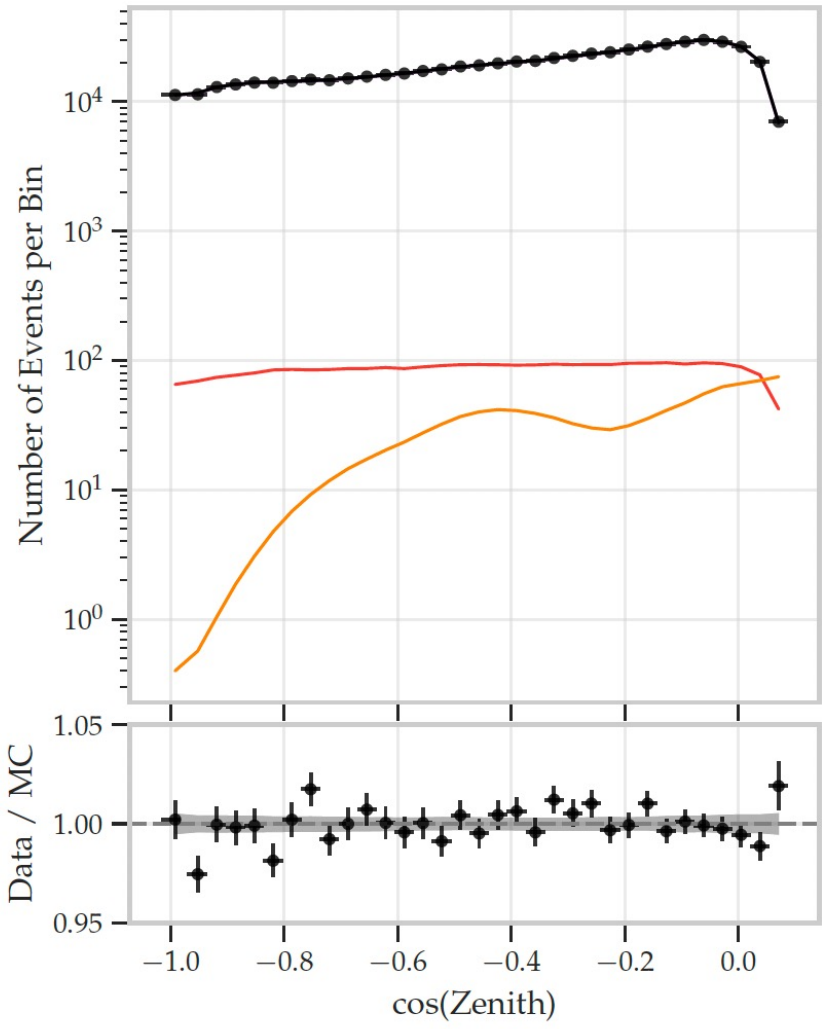
electron and tau neutrinos (showers only)

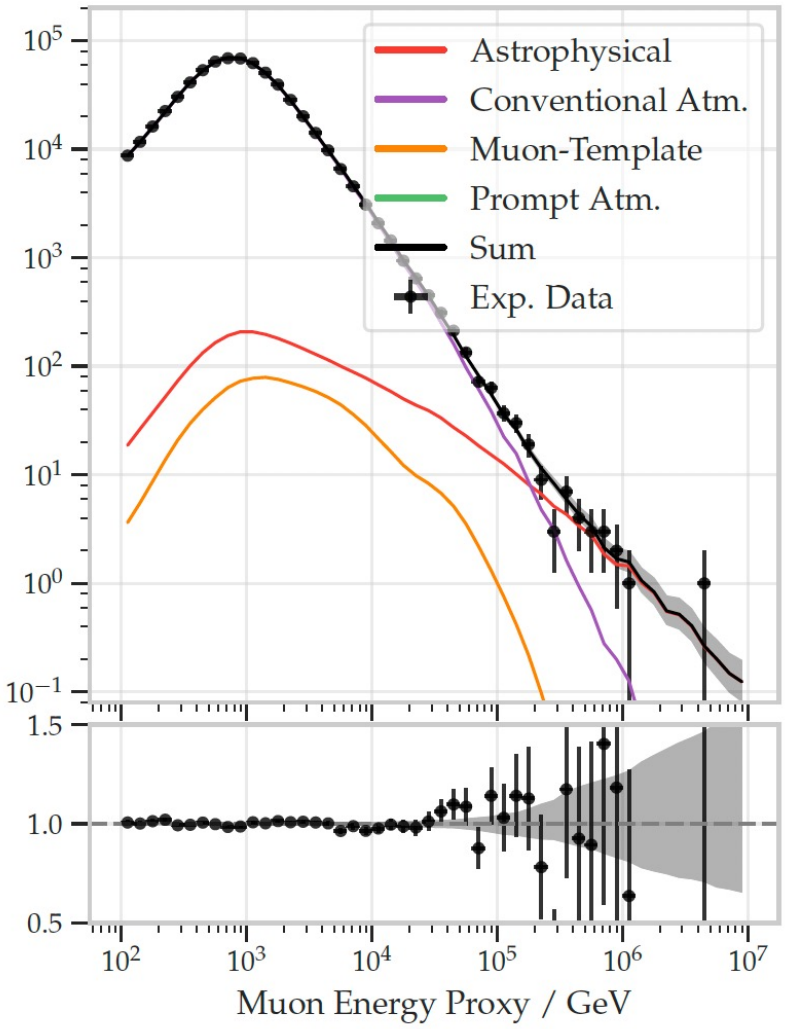
$$E \times E \frac{dN}{dE}$$

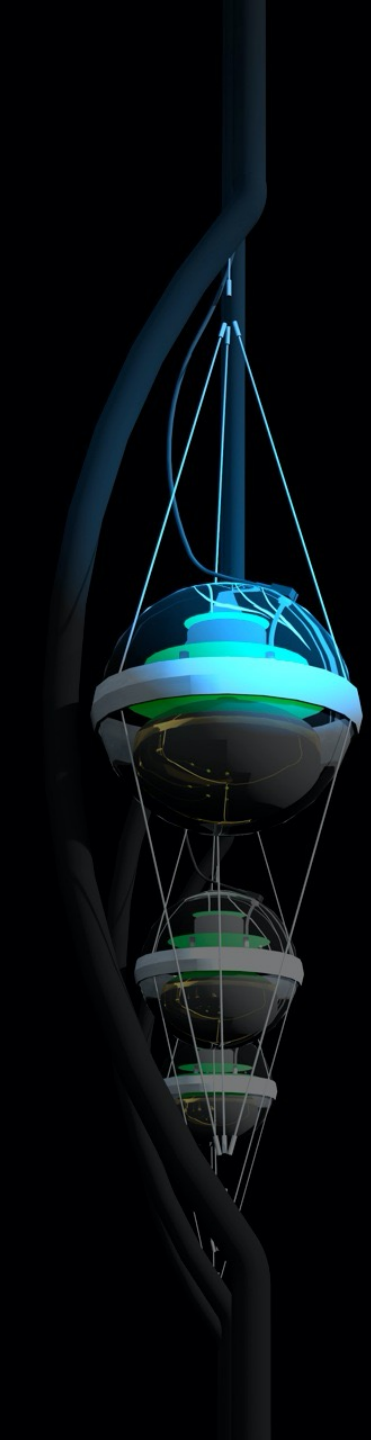


muon neutrinos (tracks through Earth)


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]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [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]
ν_μ events vs truncated E GeV: >120 cosmic ν_μ per year
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^2
10^4
10^6
muon neutrinos


Number of Events per Bin
10^4
10^3
10^2
10^1
10^0
Data / MC
1.05
1.00
0.95
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
cos(Zenith)


Astrophysical
Conventional Atm.
Muon-Template
Prompt Atm.
Sum
Exp. Data
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
1.5
1.0
0.5
10^2
10^3
10^4
10^5
10^6
10^7
Muon Energy Proxy / GeV



cosmic neutrinos: four independent observations

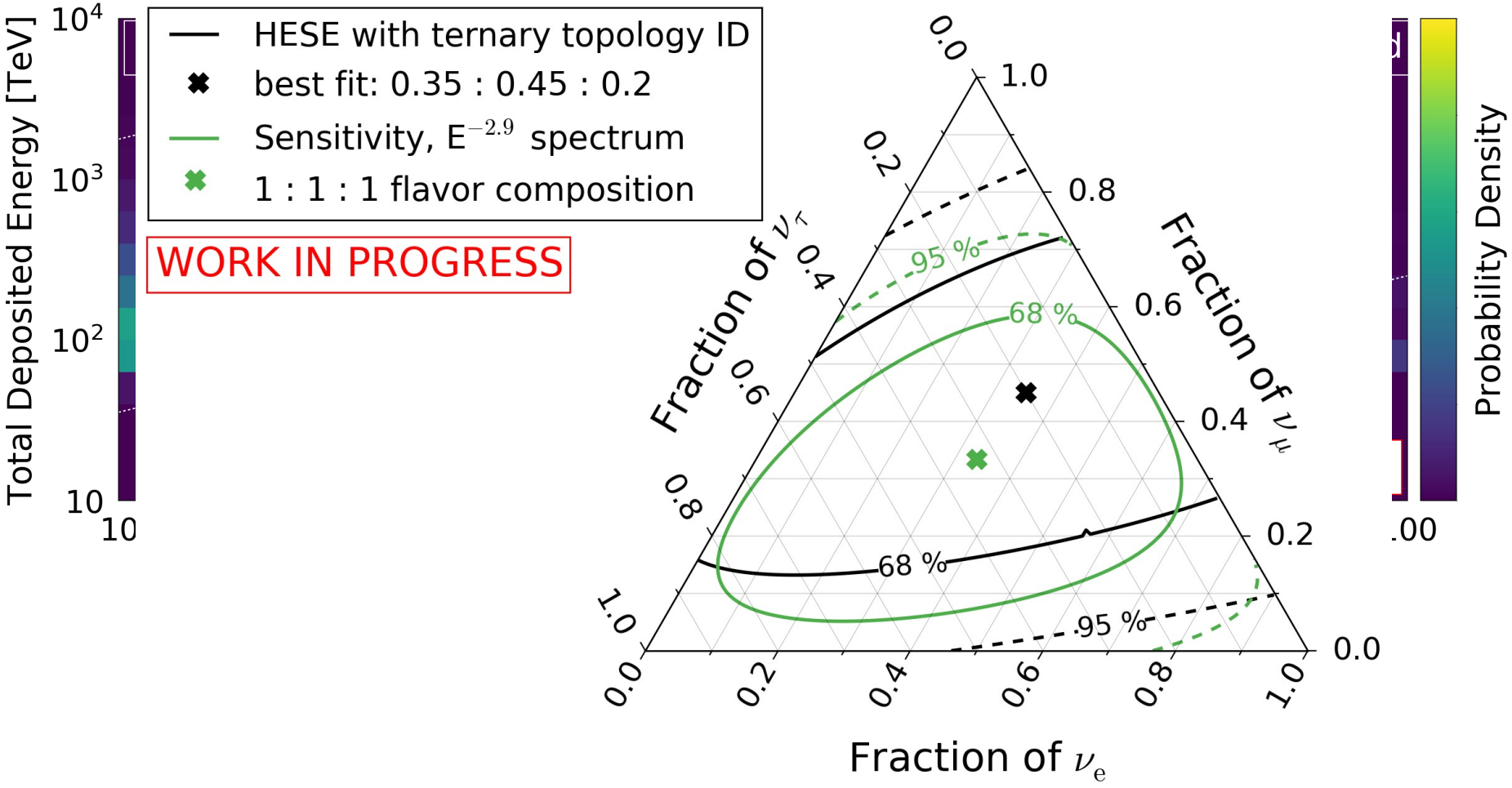
→ muon neutrinos through the Earth

→ starting neutrinos: all flavors

→ tau neutrinos produced by oscillation over cosmic distances

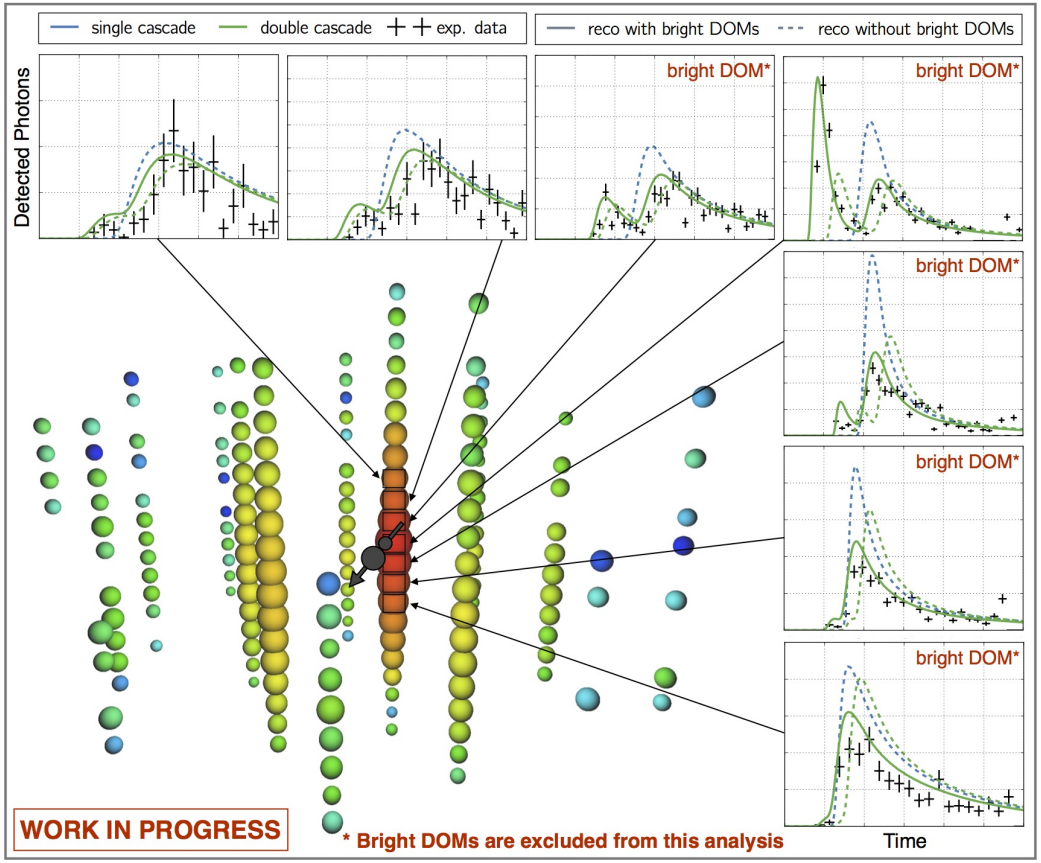
→ Glashow resonance event

high-energy starting events – 7.5 yr

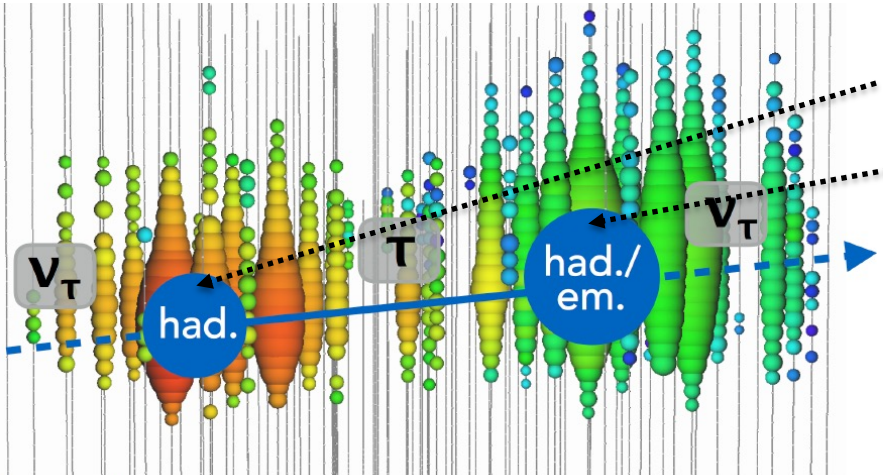


oscillations of PeV neutrinos over cosmic distances to 1:1:1

a cosmic tau neutrino: livetime 17m



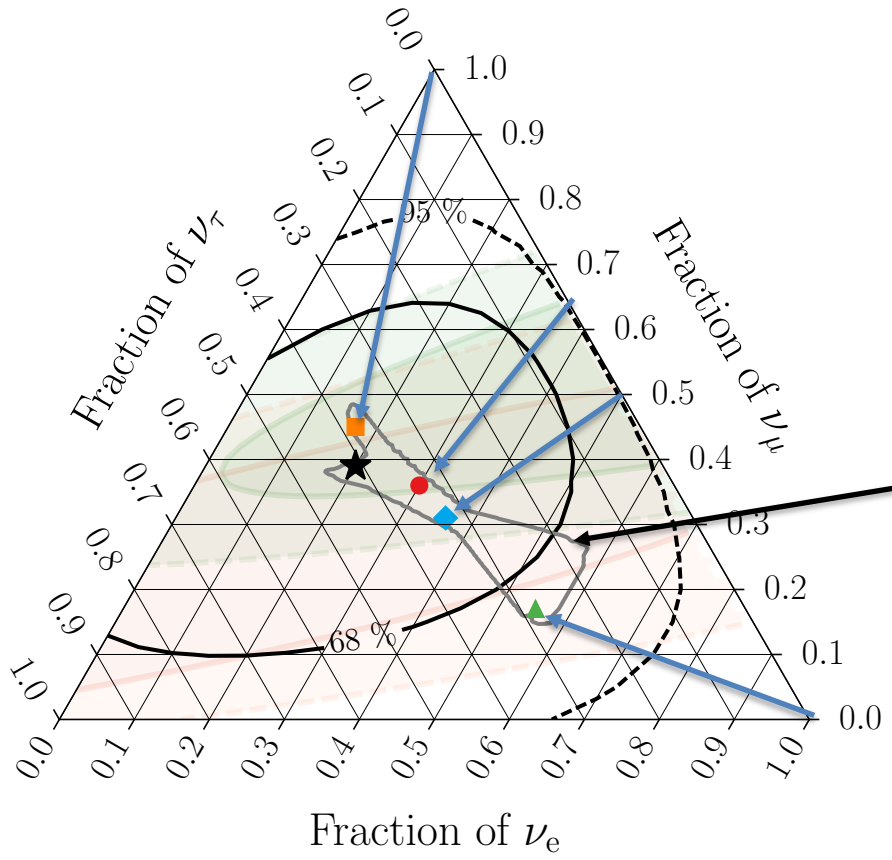
tau decay length:
$\gamma c\tau$ = 50m per PeV



tau production
and decay

oscillating PeV neutrinos

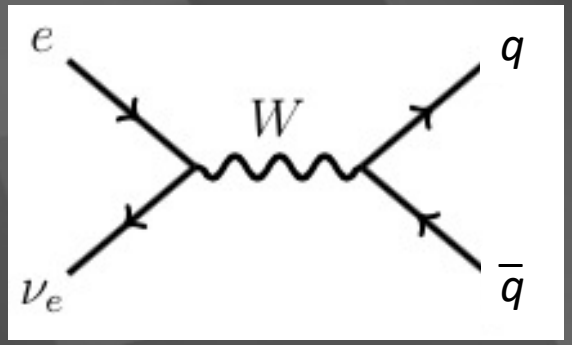
- 7.5 years of events starting inside the detector
- tau events



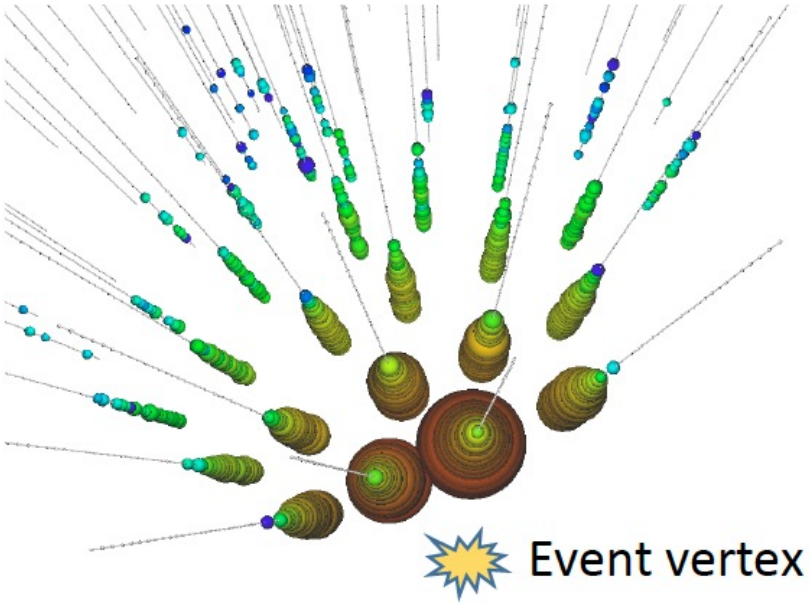
star outside the butterfly: neutrino physics beyond the SM!

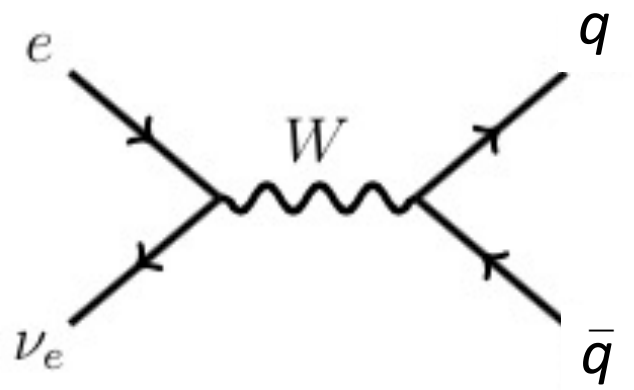
the first Glashow resonance event:

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

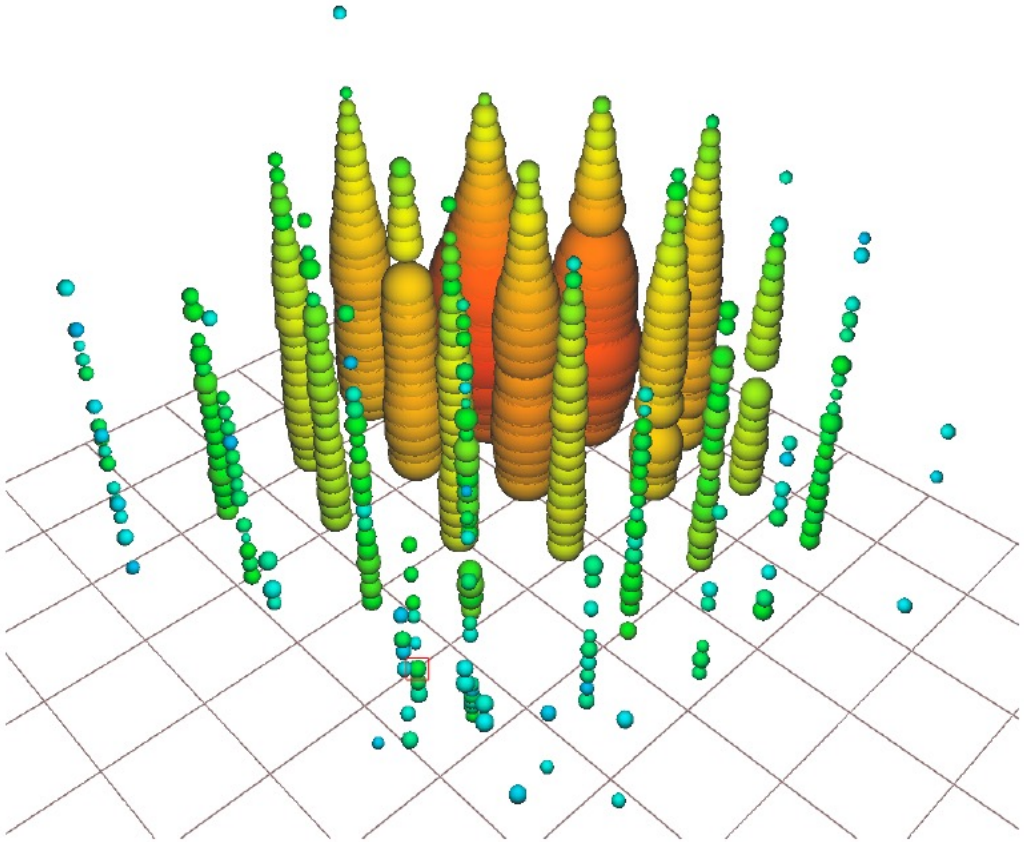


partially contained event with energy 6.3 PeV

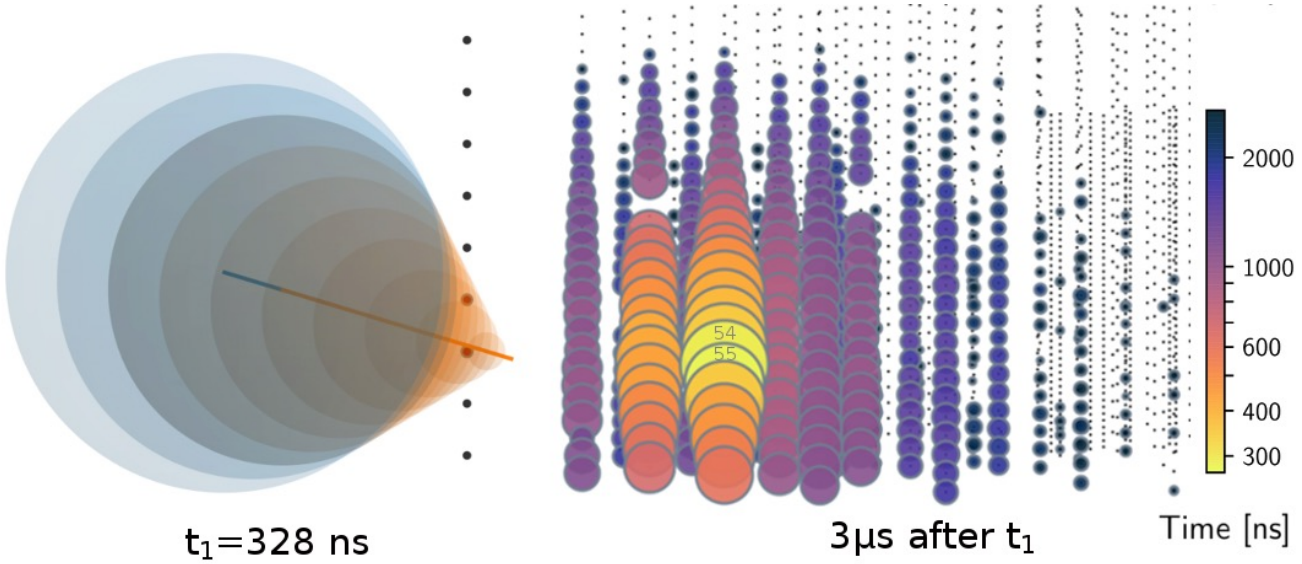


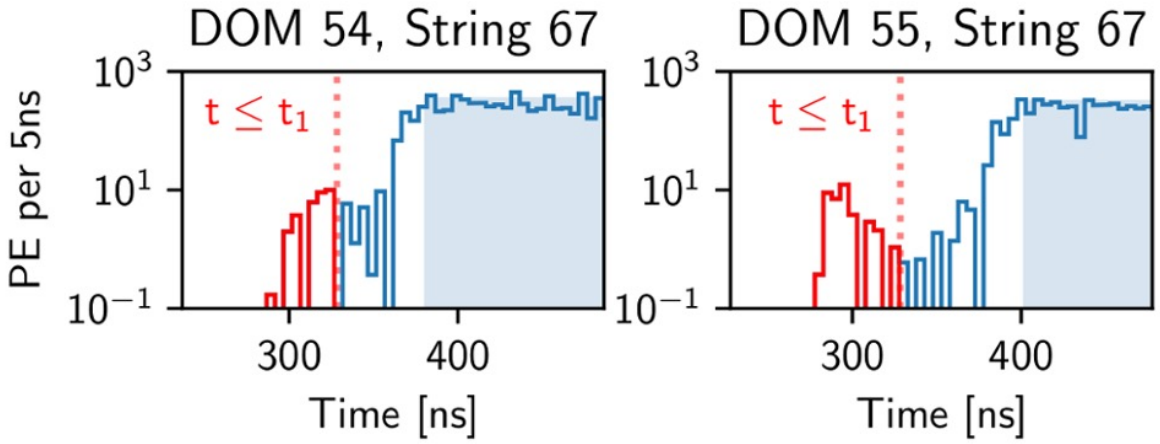


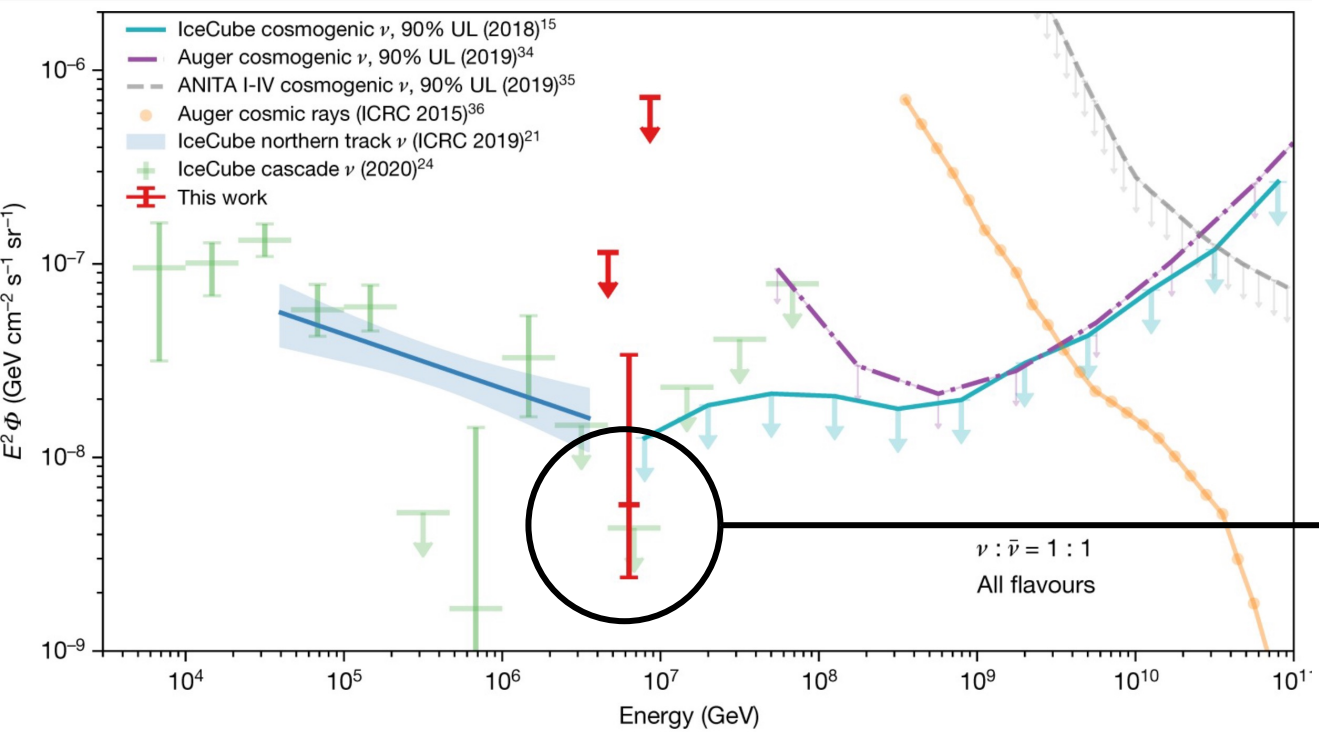
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron



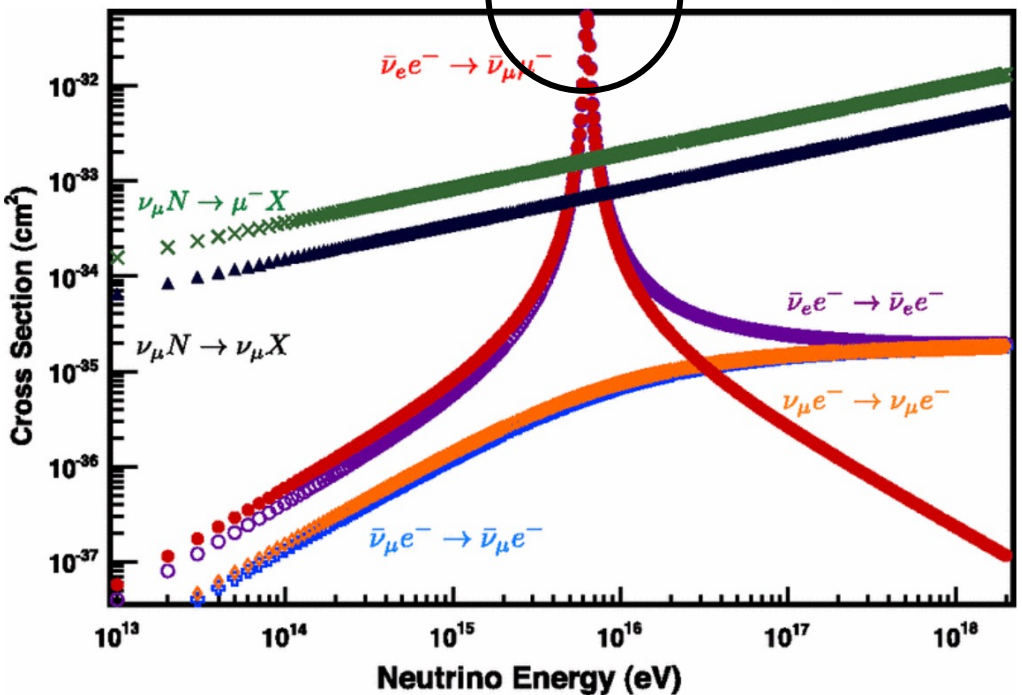
hadronic shower from W-decay: early muons followed by electromagnetic shower



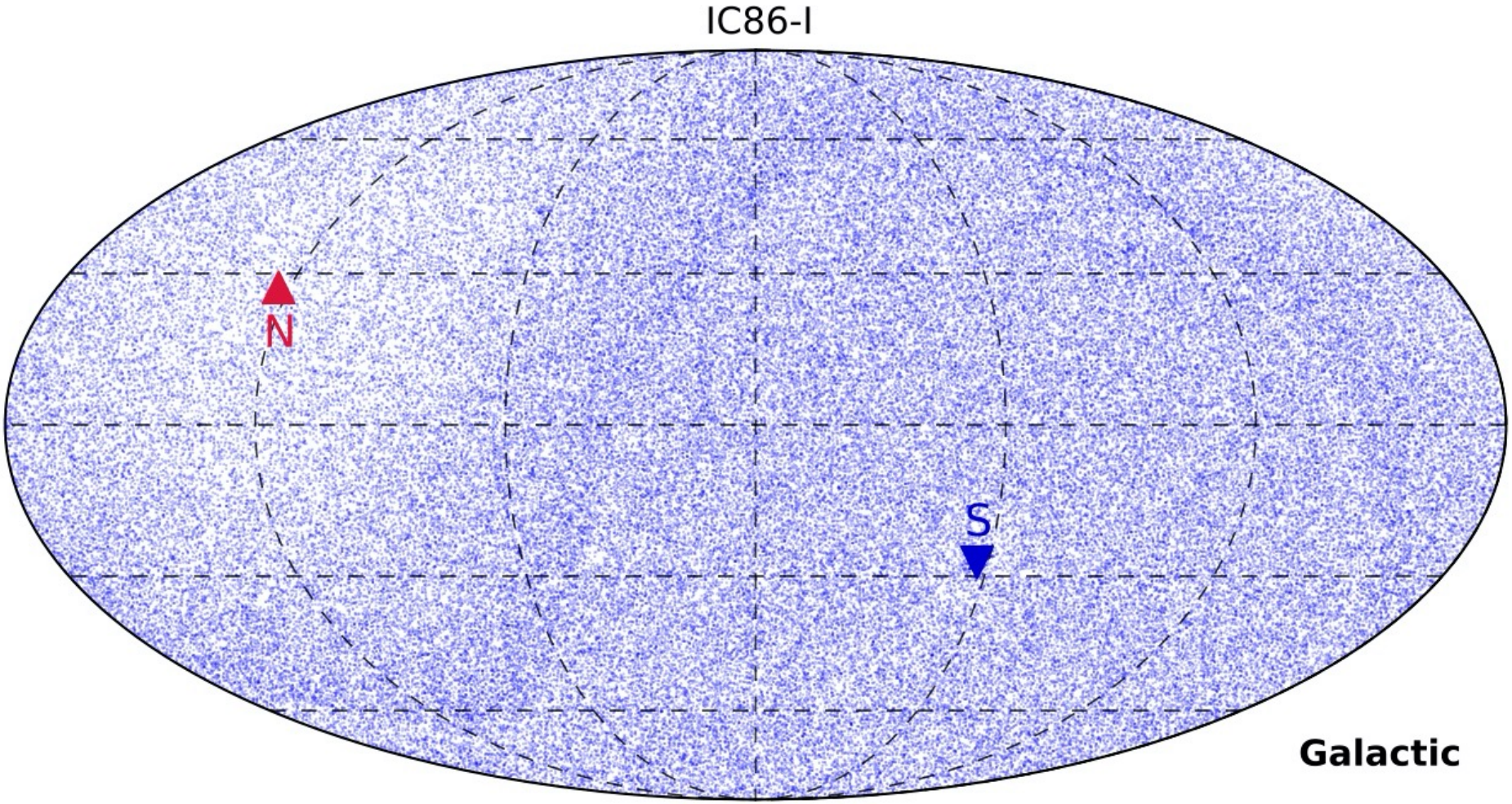




RevModPhys. 84 1307



where do they come from?



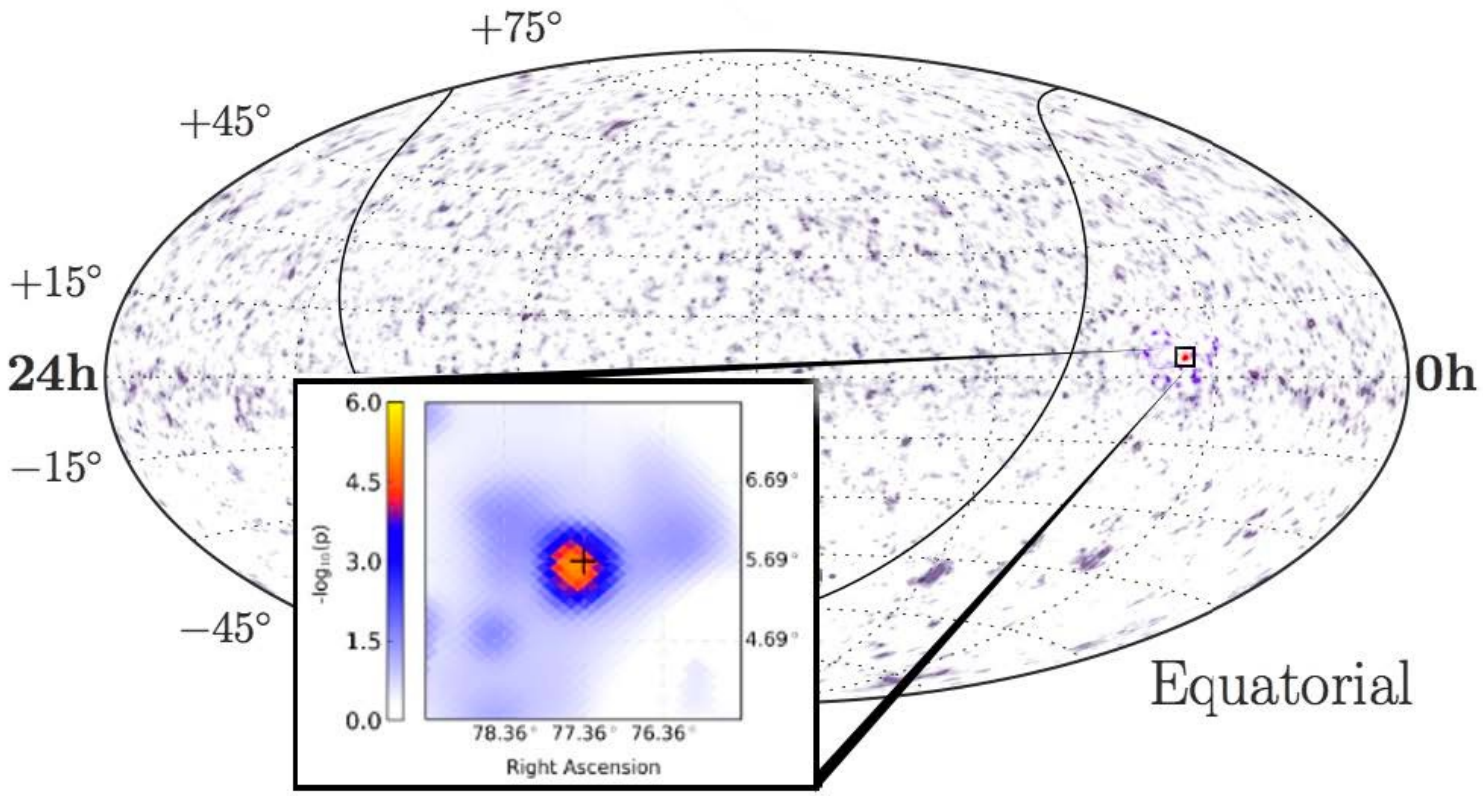
138322 neutrino candidates in one year

>120 cosmic neutrinos (depending on the spectrum)

~12 separated from atmospheric background with E>60 TeV

structure in the map results from neutrino absorption by the Earth

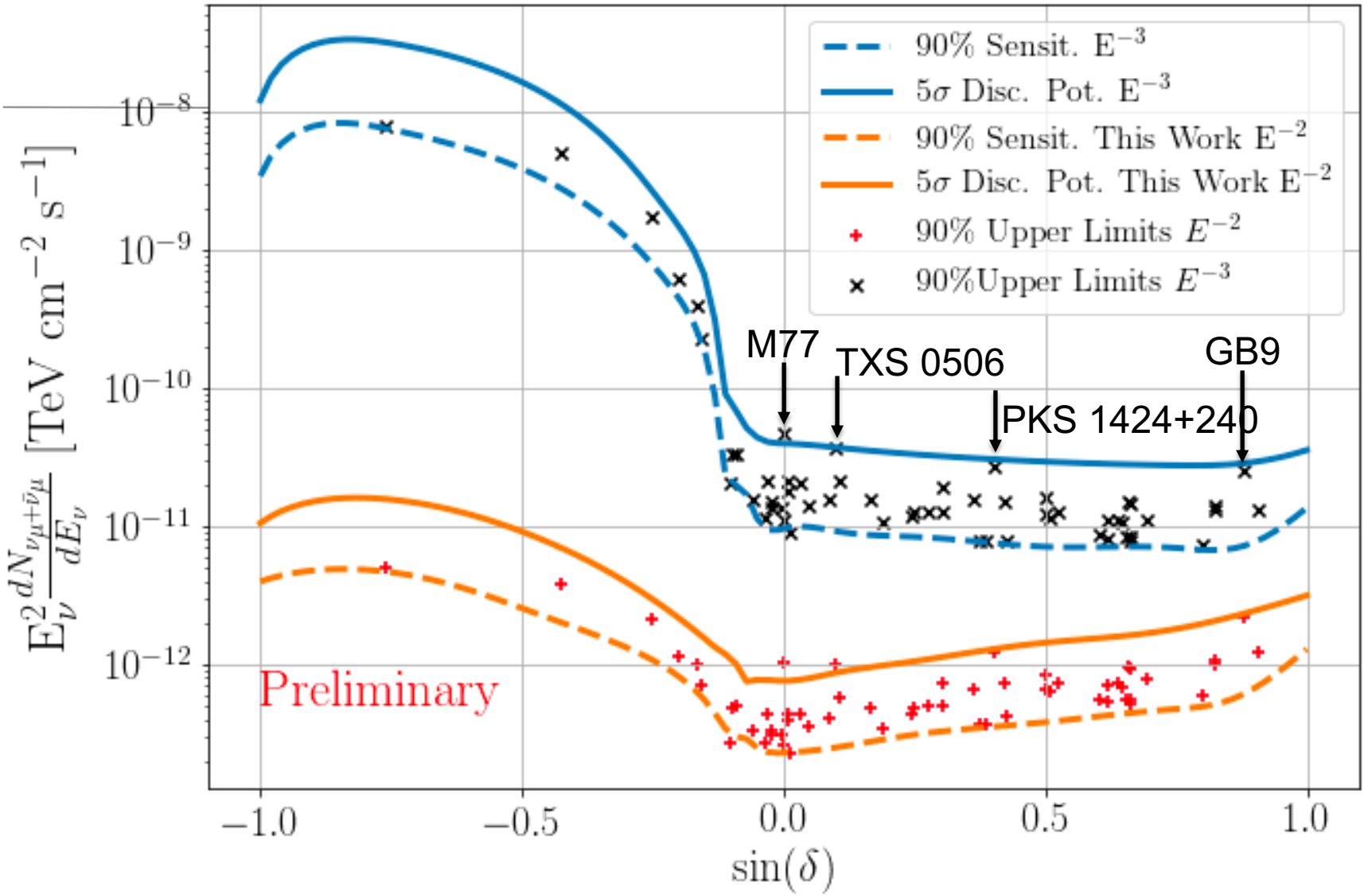
pre-trial p-value for clustering of high energy neutrinos



- hottest spot coincident with the active galaxy NGC 1068 (M77)
- also hottest of 100 pre-selected sources

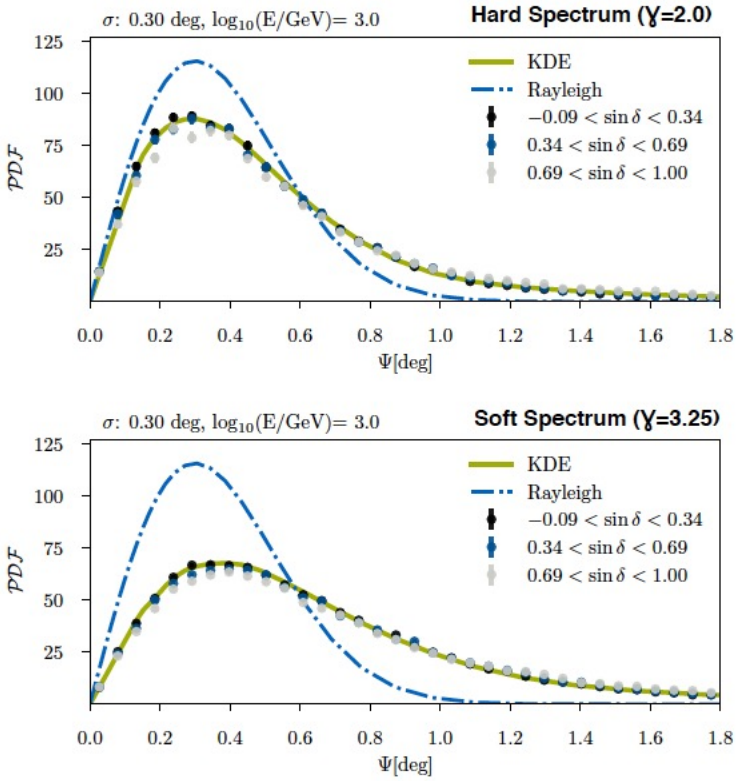
- evidence for non-uniform skymap in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates

limits and interesting fluctuations (?)



data and simulation released: https://arxiv.org/abs/2101.09836

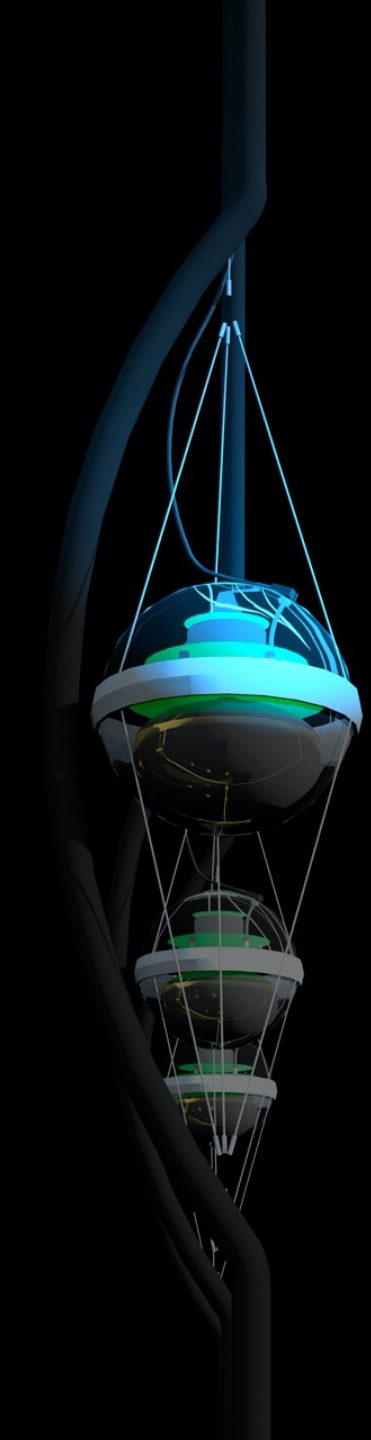
- improved detector calibration (pass 2)
- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics
- improved modeling of the optics of the ice



- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the γ-dependent spatial term from MC simulation (for example using KDEs)

$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}\left(\psi \,|\, \sigma,\, E_\mu,\, \gamma\right)$$

very soon!



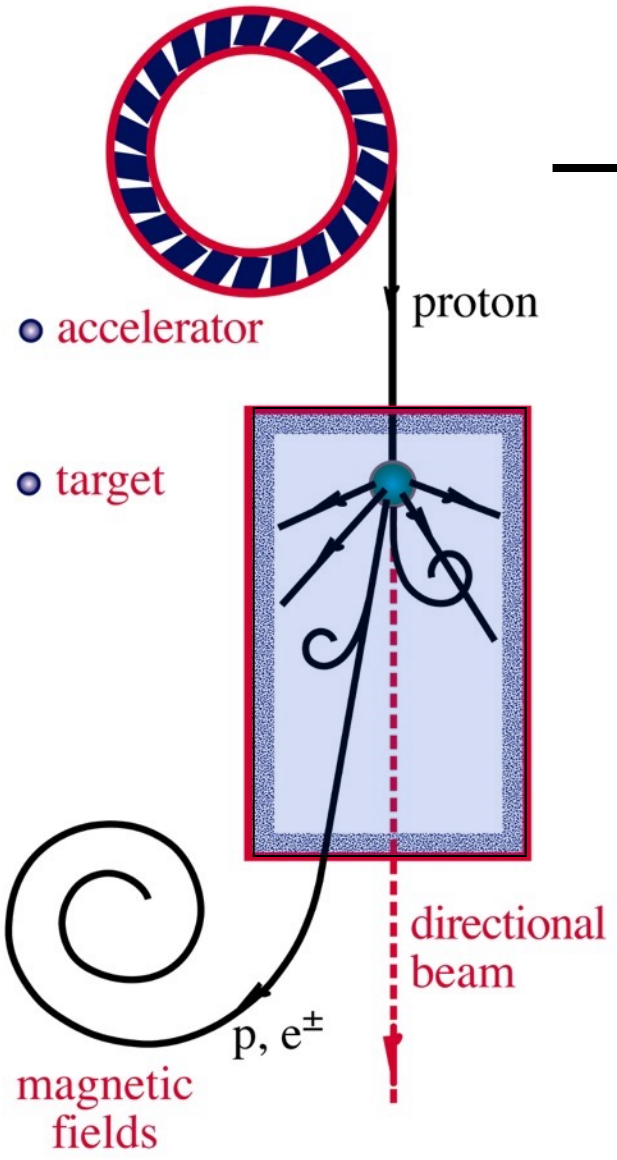
Cosmic Neutrinos and Multimessenger Astronomy

francis halzen

- neutrino astronomy and the origin of cosmic rays
- IceCube
- extragalactic cosmic neutrinos
- the large diffuse neutrino flux
- the first cosmic ray accelerator(s)

IceCube.wisc.edu

ν and γ beams : heaven and earth



where are the gamma rays ?

supermassive black hole

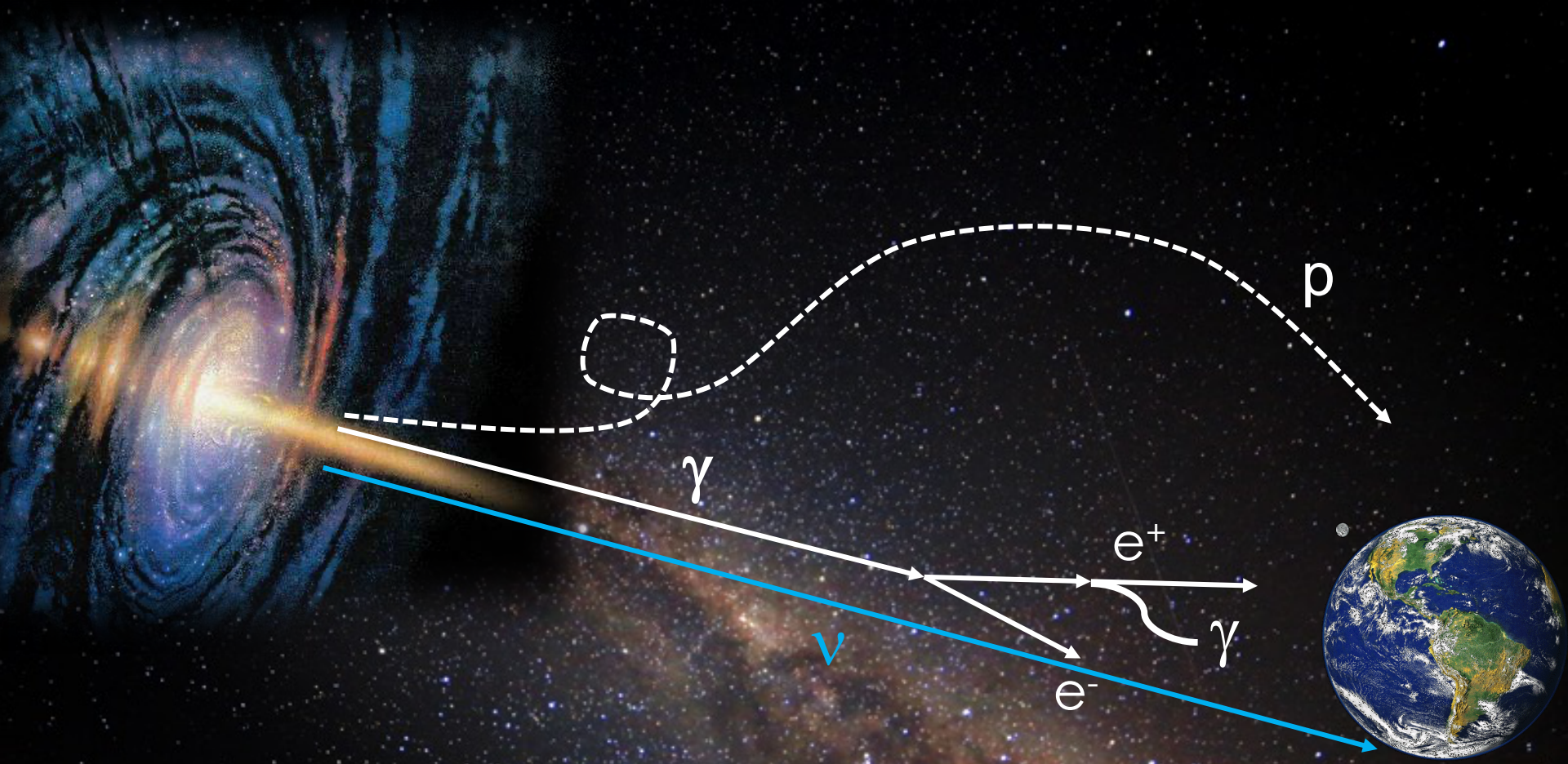
nearby radiation

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

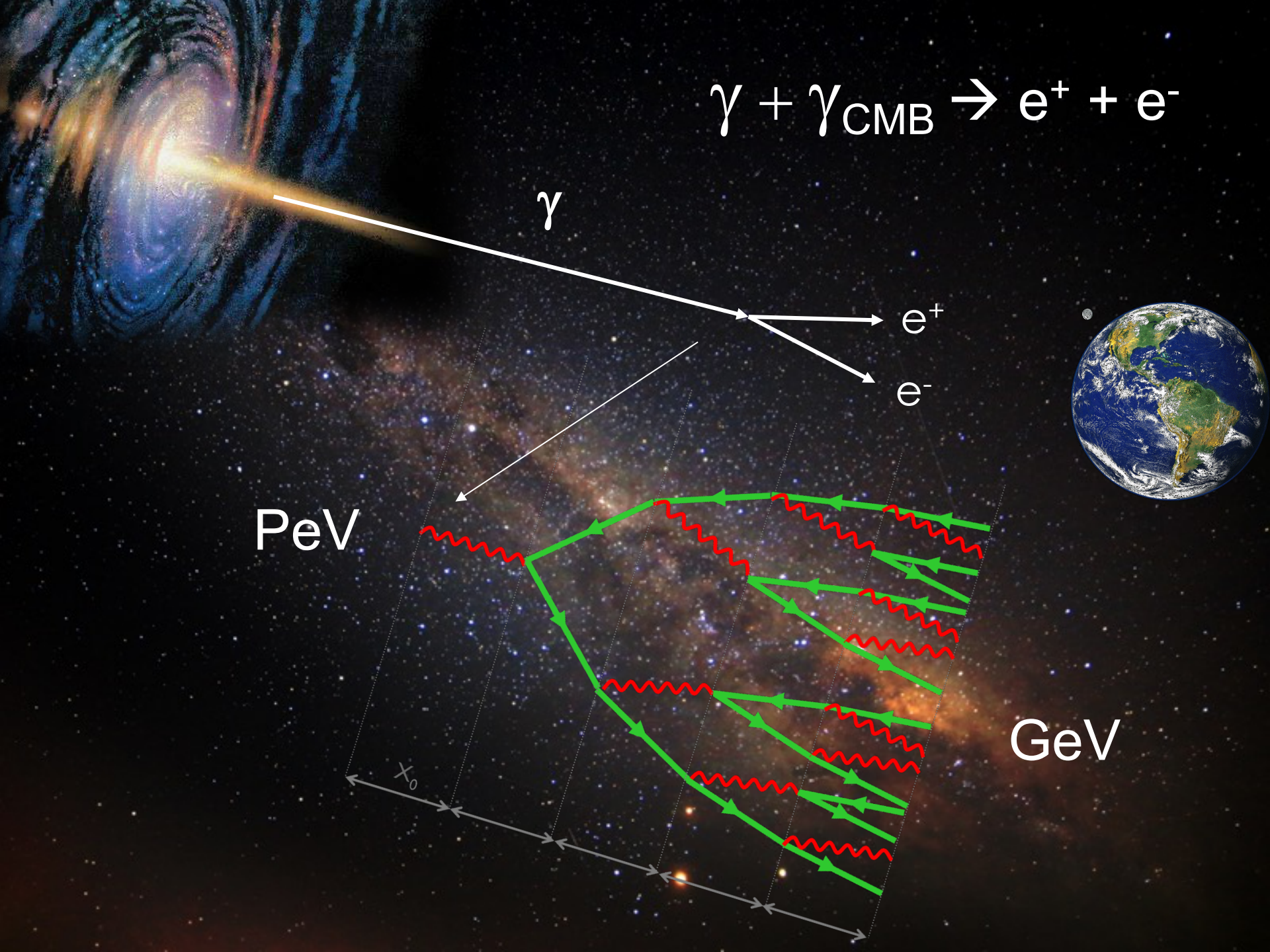
~ cosmic ray + neutrino

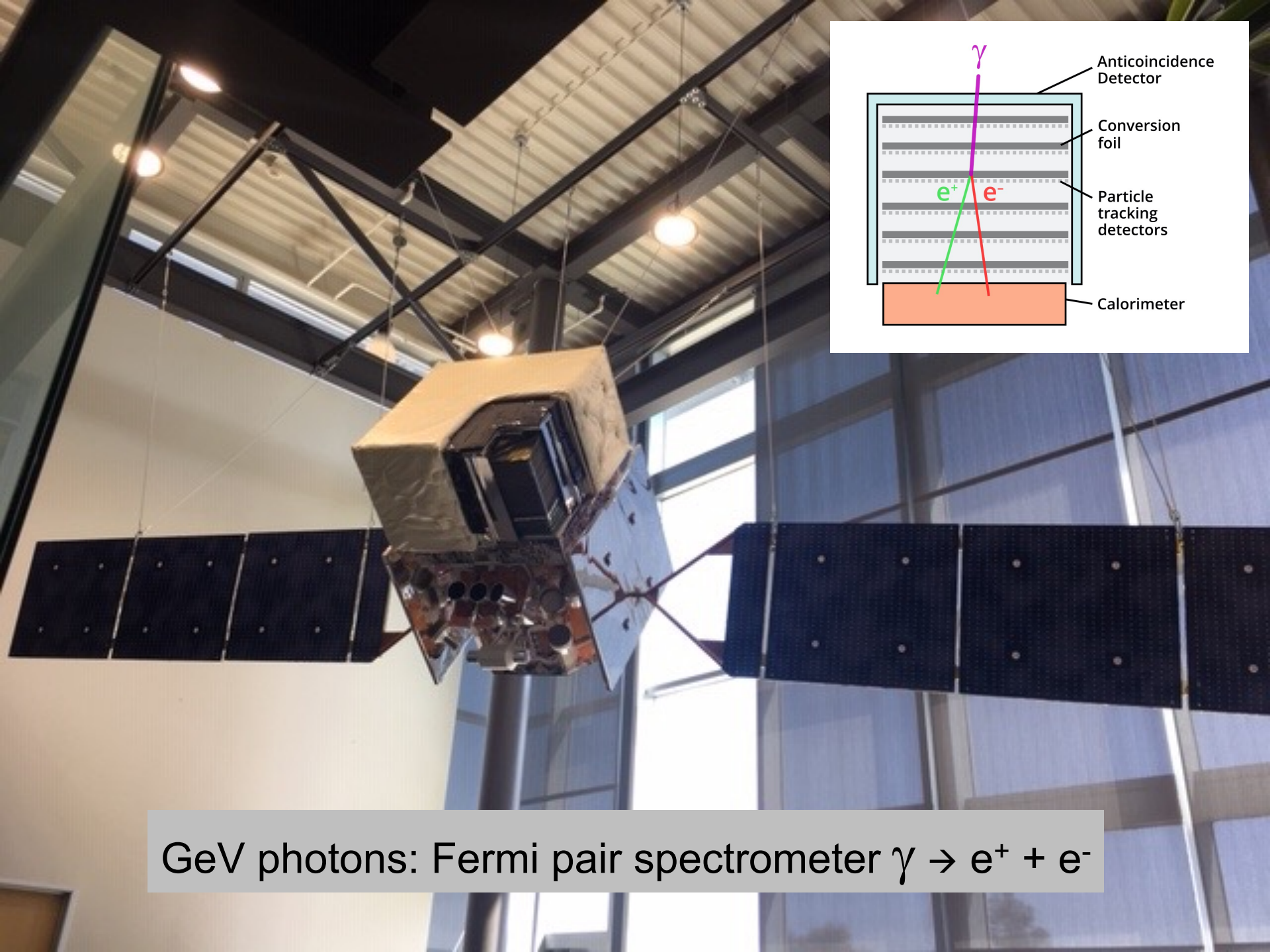
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

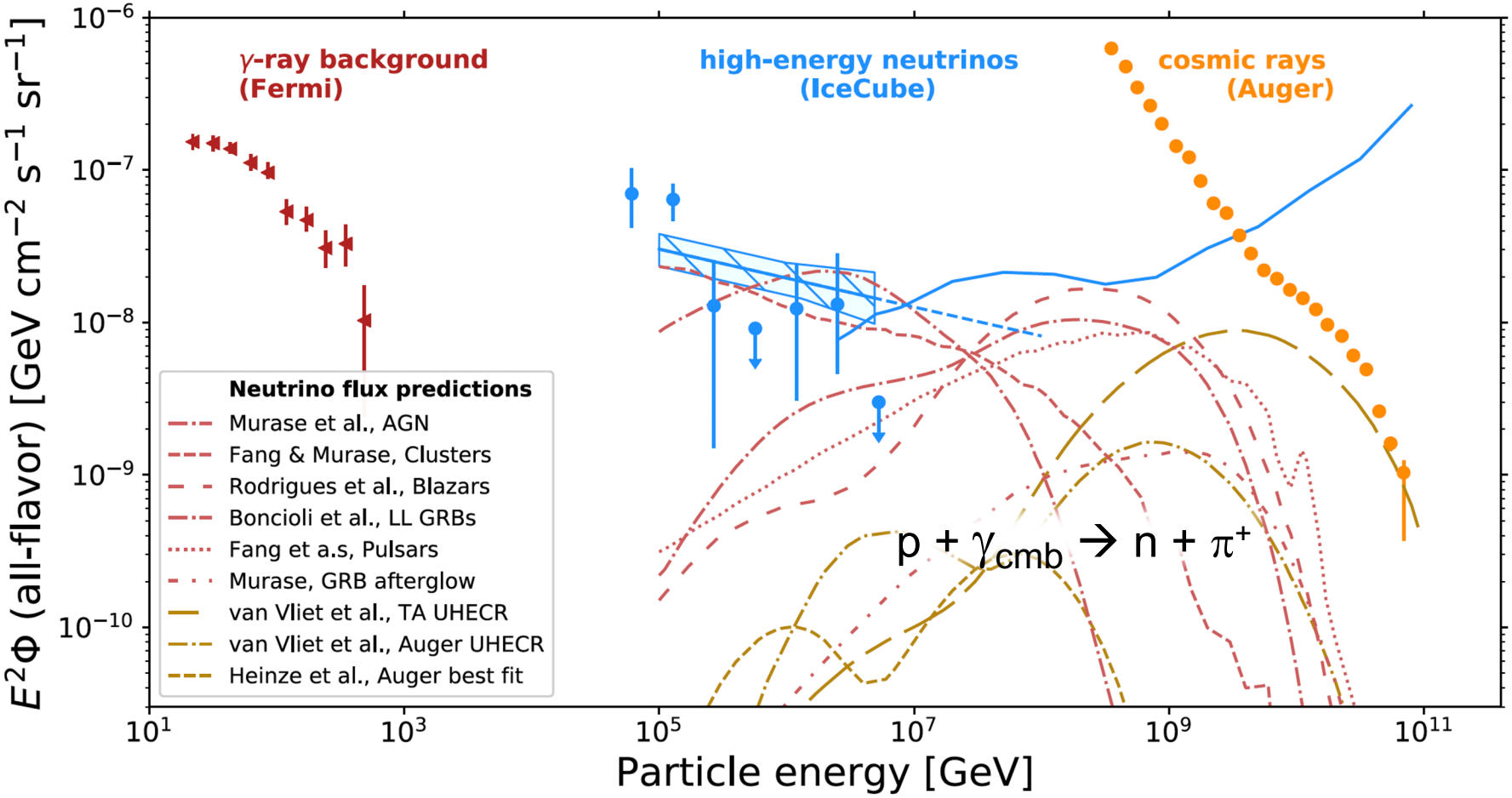


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

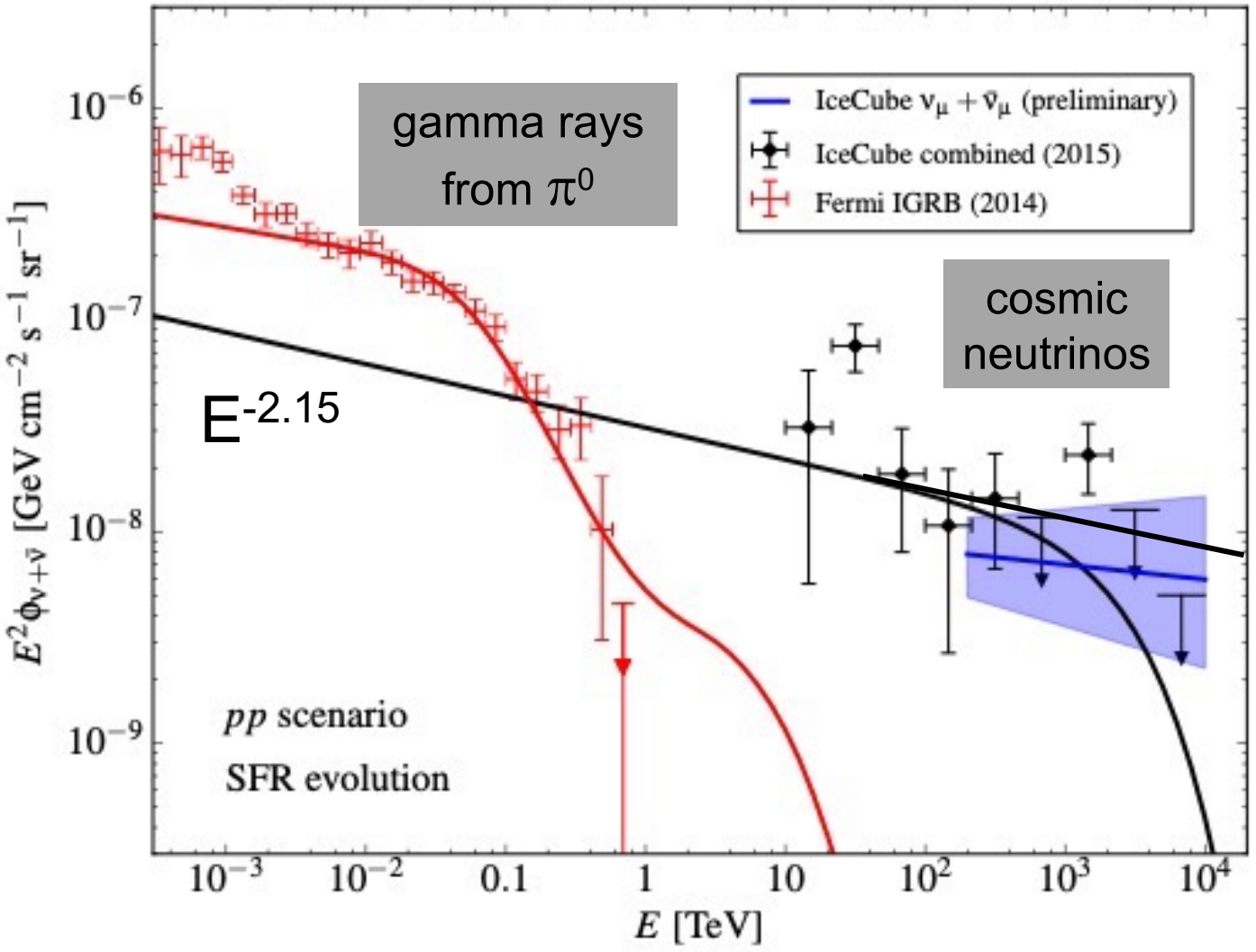

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0



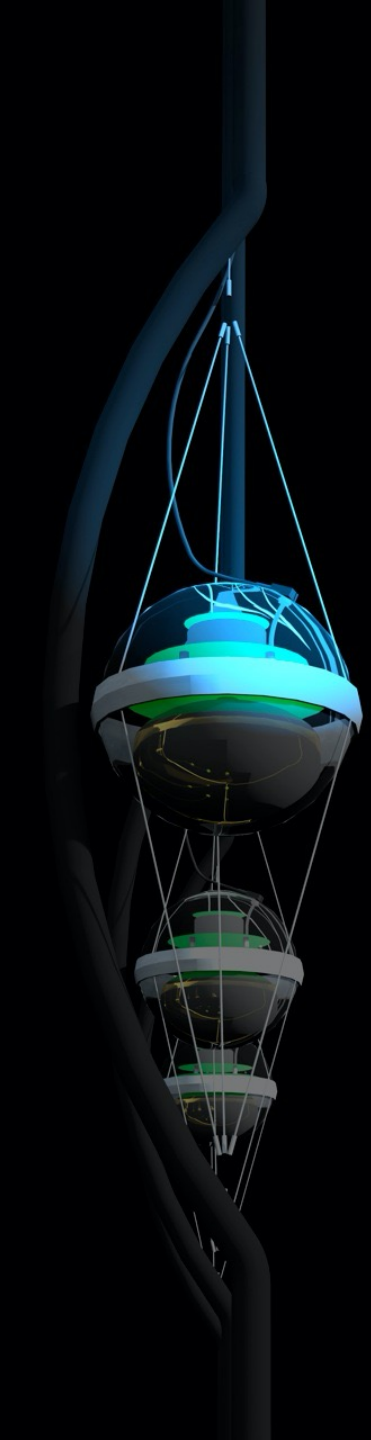
GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$


γ-ray background
(Fermi)
high-energy neutrinos
(IceCube)
cosmic rays
(Auger)
Neutrino flux predictions
Murase et al., AGN
Fang & Murase, Clusters
Rodrigues et al., Blazars
Boncioli et al., LL GRBs
Fang et a.s, Pulsars
Murase, GRB afterglow
van Vliet et al., TA UHECR
van Vliet et al., Auger UHECR
Heinze et al., Auger best fit
p + γcmb → n + π+
E2Φ (all-flavor) [GeV cm−2 s−1 sr−1]
Particle energy [GeV]
10−6
10−7
10−8
10−9
10−10
101
103
105
107
109
1011

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


gamma rays from π^0
cosmic neutrinos
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
$E^{-2.15}$
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

- we observe a diffuse flux of neutrinos from extragalactic sources
- energy in the non-thermal Universe in neutrinos is the same as that in gamma-rays
- (a subdominant Galactic component cannot be excluded)



Cosmic Neutrinos and Multimessenger Astronomy

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- neutrino astronomy and the origin of cosmic rays
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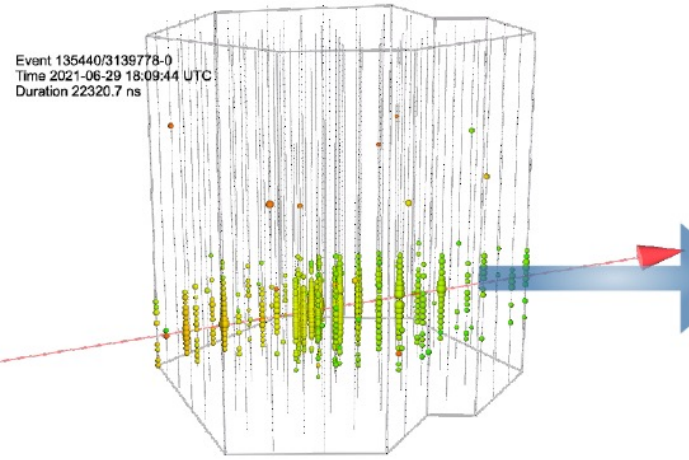
- extragalactic cosmic neutrinos
- the large diffuse neutrino flux
- the first cosmic ray accelerator(s)

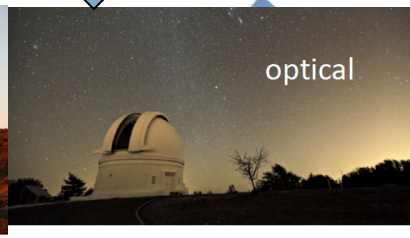
IceCube.wisc.edu

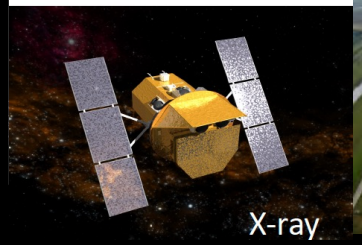
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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



from photon at PMT to public neutrino alert:
< 1 minute
September 22, 2017

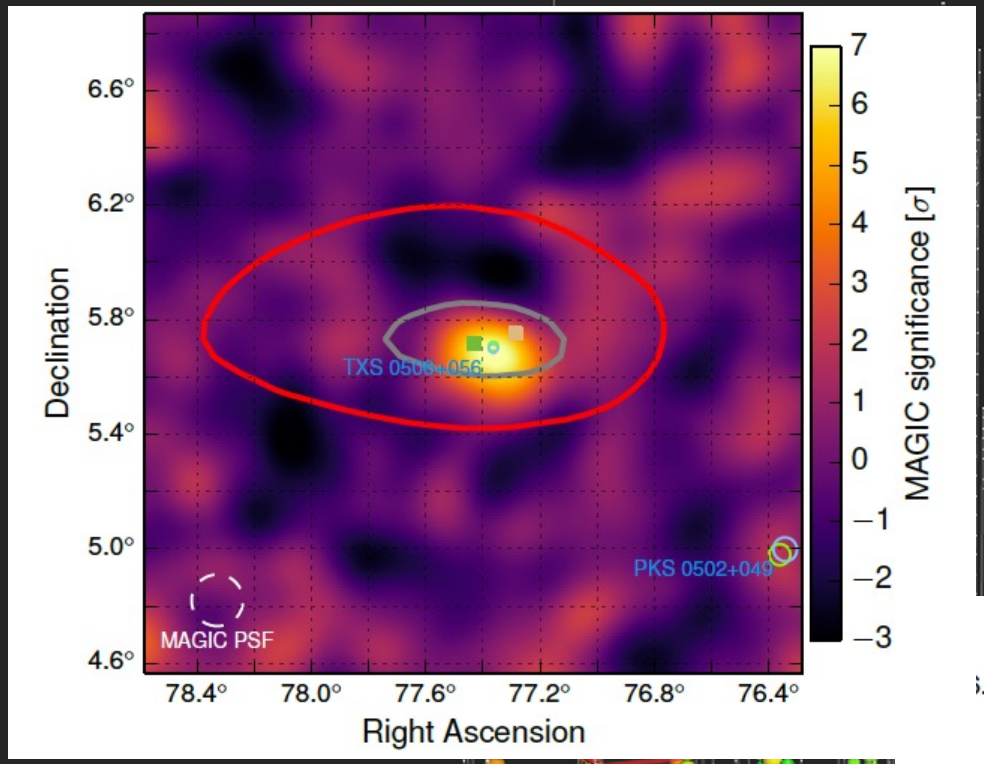




IceCube Trigger

43 seconds after trigger, GCN notice was sent

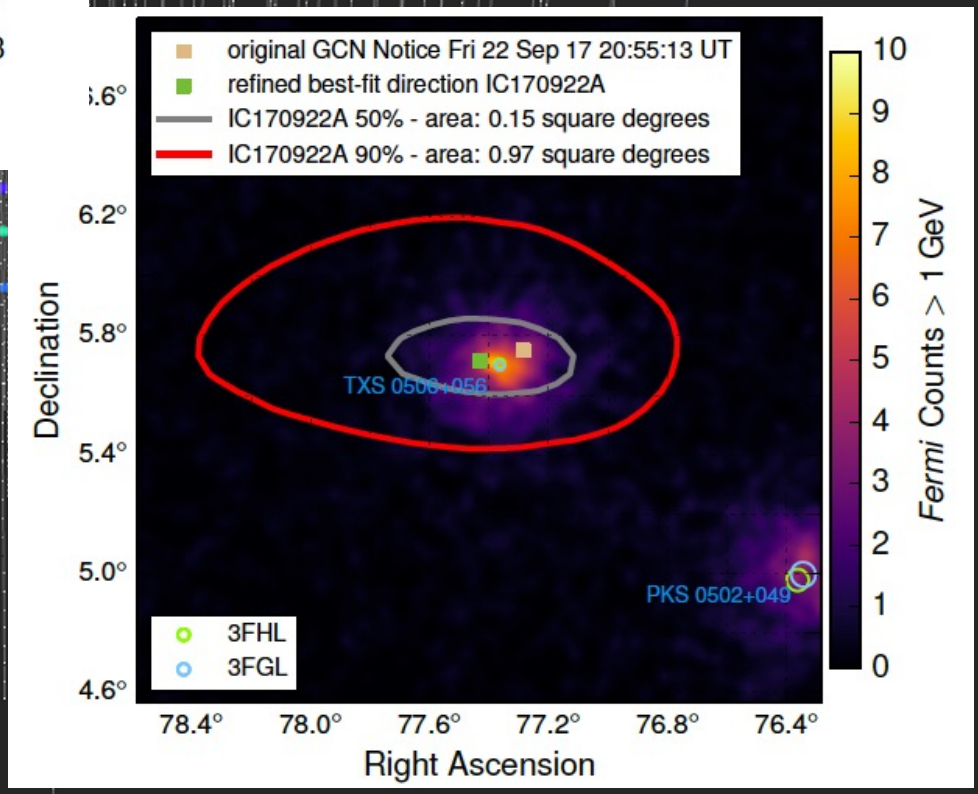
```
////////////////////////////////////////////////////////////////////////
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:        AMON ICECUBE EHE
RUN_NUM:            130033
EVENT_NUM:          50579430
SRC_RA:              77.2853d {+05h 09m 08s} (J2000),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

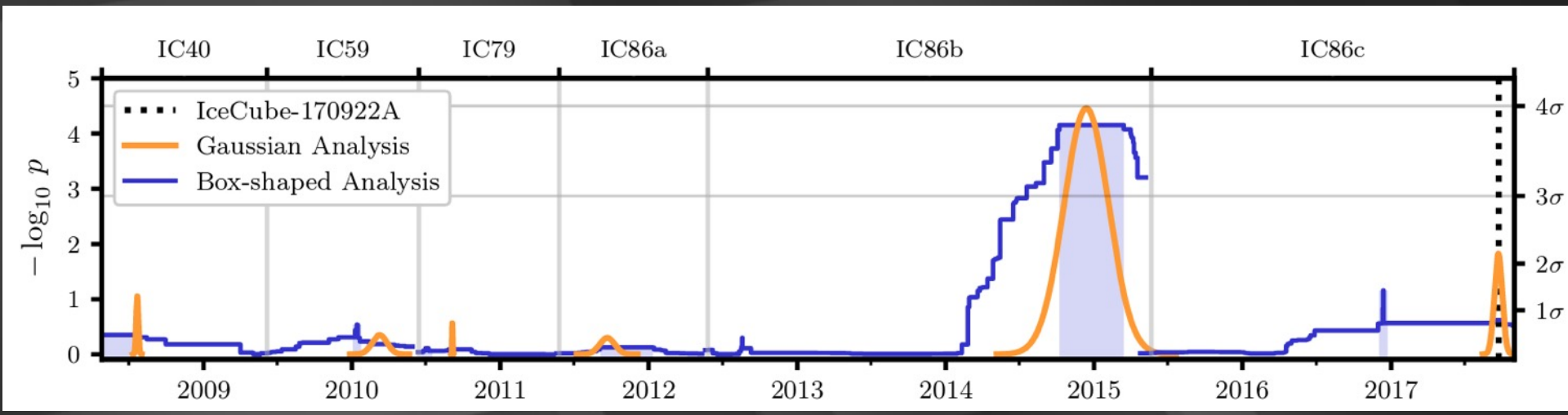


IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°

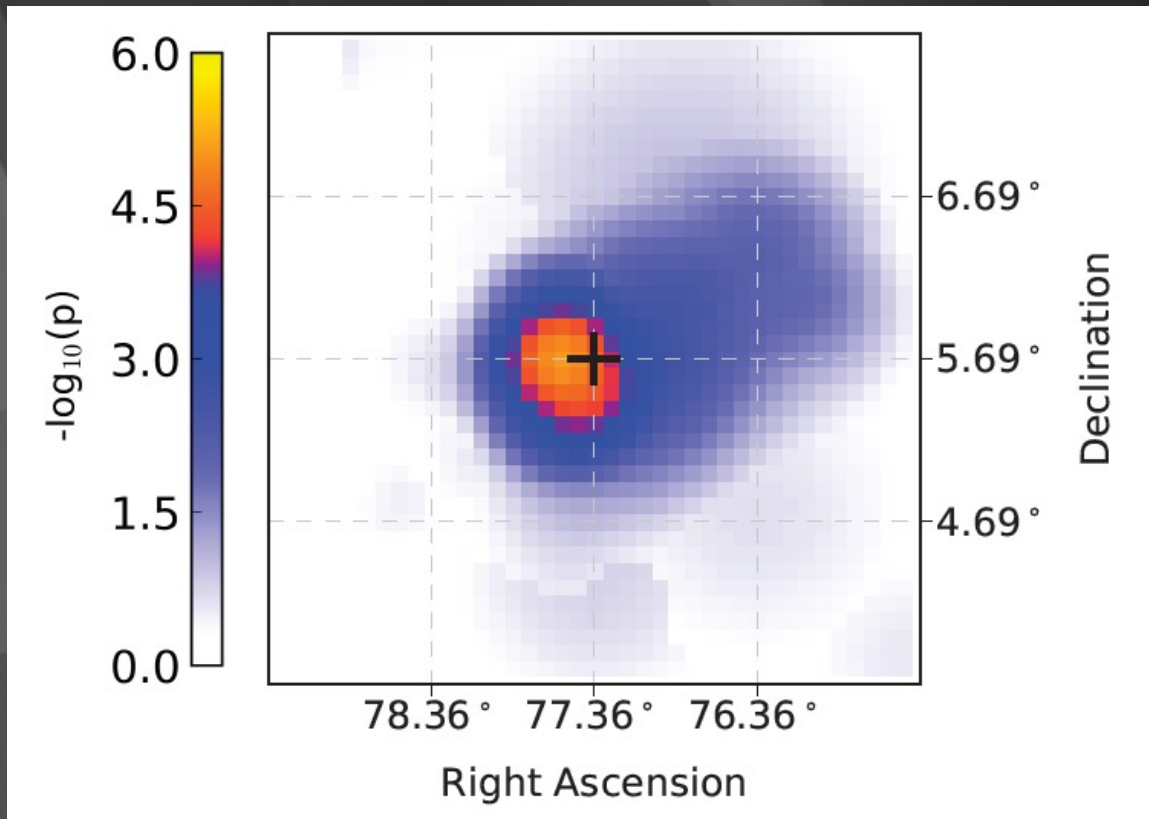
MAGIC
detects emission of
> 100 GeV gammas



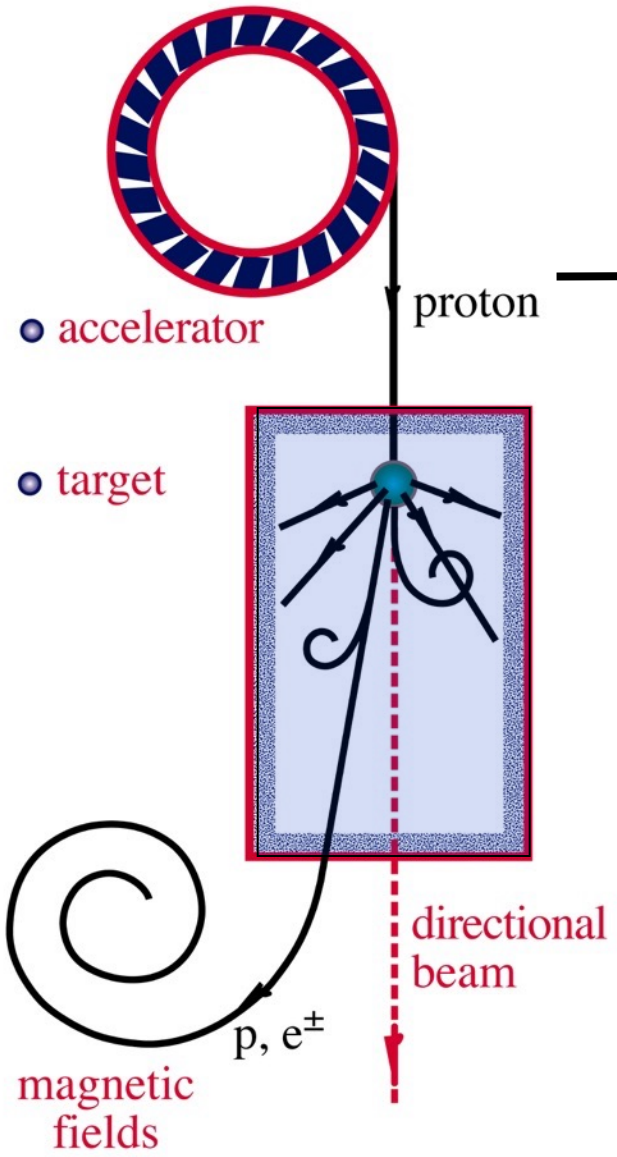


search in archival IceCube data:

- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
- no gamma ray flare!



ν and γ beams : heaven and earth



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

→ cosmic ray + neutrino

supermassive black hole

target ?

→ a neutrino source needs an accelerator and a target

→ the target is likely opaque to gamma rays

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

- two statistically independent observations at the > 3σ level → 4.2σ
- optical observations and radio interferometry imaging indicate that there is no gamma ray emission when neutrinos are produced

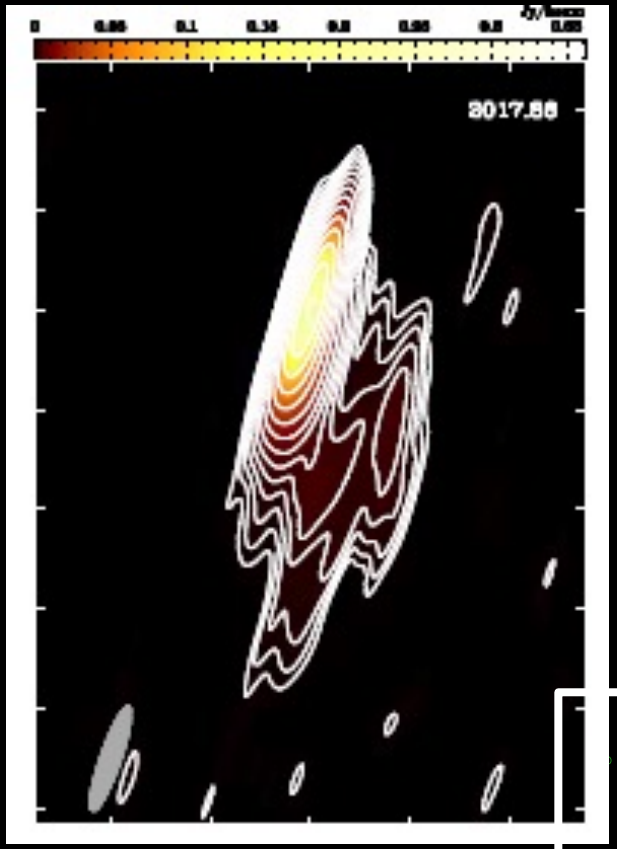
global robotic network of optical telescopes connects TXS 0506+056 to IC170922A

"MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

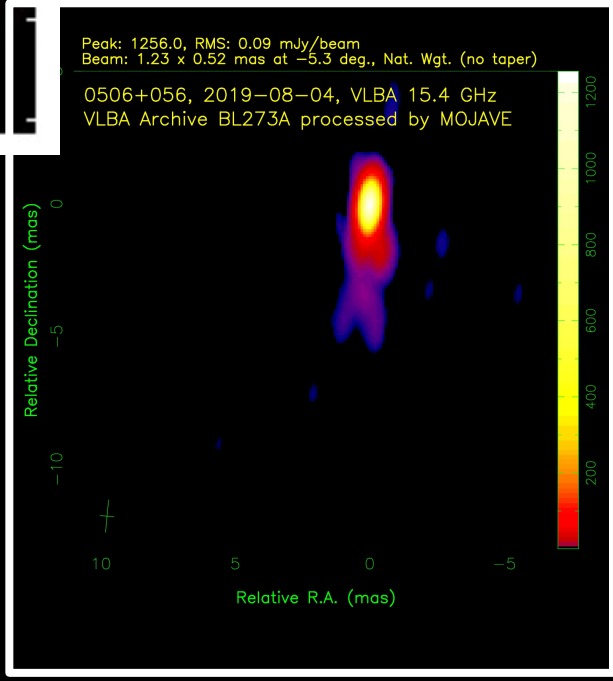
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8] , P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], V.Topolev[1], A.Pozdnyakov[1], A.Kuznetsov[2], V.Vladimirov[2], A. Chasovnikov[1], D. Kuvshinov[1,2], V.Grinshpun[1,2], E.Minkina [1,2], V.B.Petkov [7], S.I.Svertilov[2,6] , C. Lopez[9], F. Podesta[9], H.Levato[10], A. Tlatov[11] B. Van Soelen[12], S. Razzaque[13], M. Böttcher[14]

radio interferometry images of TXS 0506+056 show the target that produces the neutrinos and obscures the gamma rays



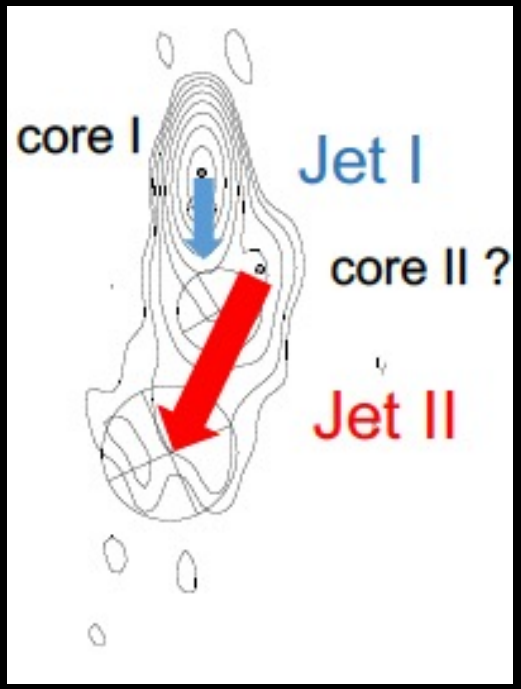
A&A. 630 A103
A&A. 632 C3

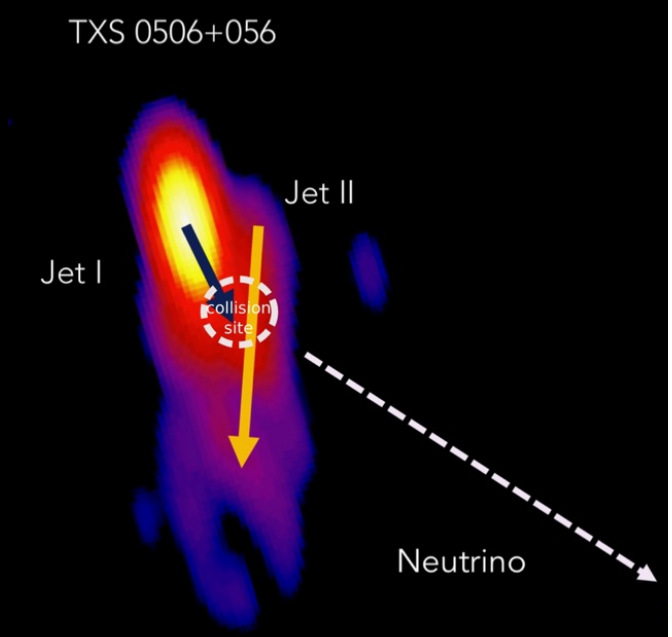


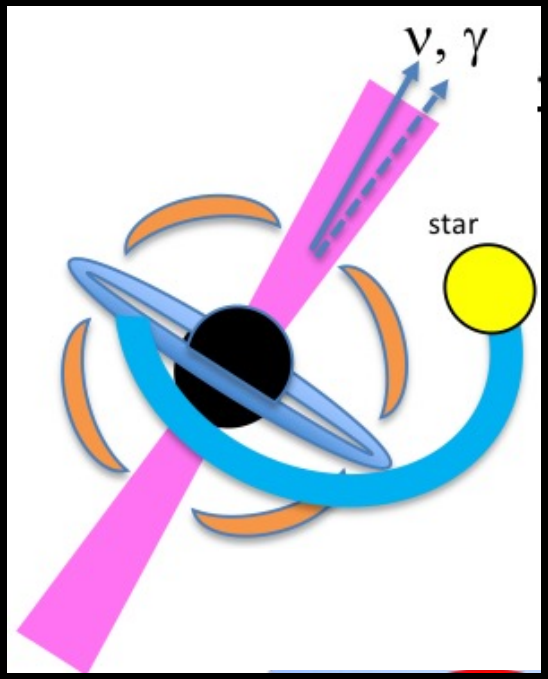
1912.01743v1
[astro-ph.GA]

- core brightening observed in a radio burst that started 5 years ago
- core expands with superluminal velocity
- beyond 5 milliarcseconds the jet loses its tight collimation
- jet found a target after ~ tens of pc to produce neutrinos

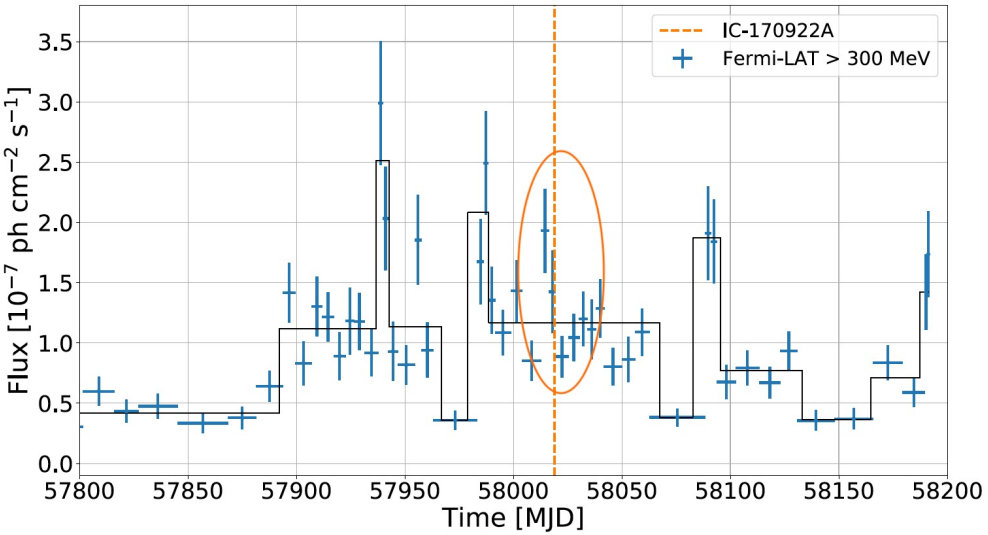
- radio interferometry images show that the jet interacts with a target close to the base of the jet
- a massive star in the host galaxy, the jet of a merging galaxy, warped jet, structured jet…
- the gamma rays accompanying the neutrinos lose their energy in the target that produces them

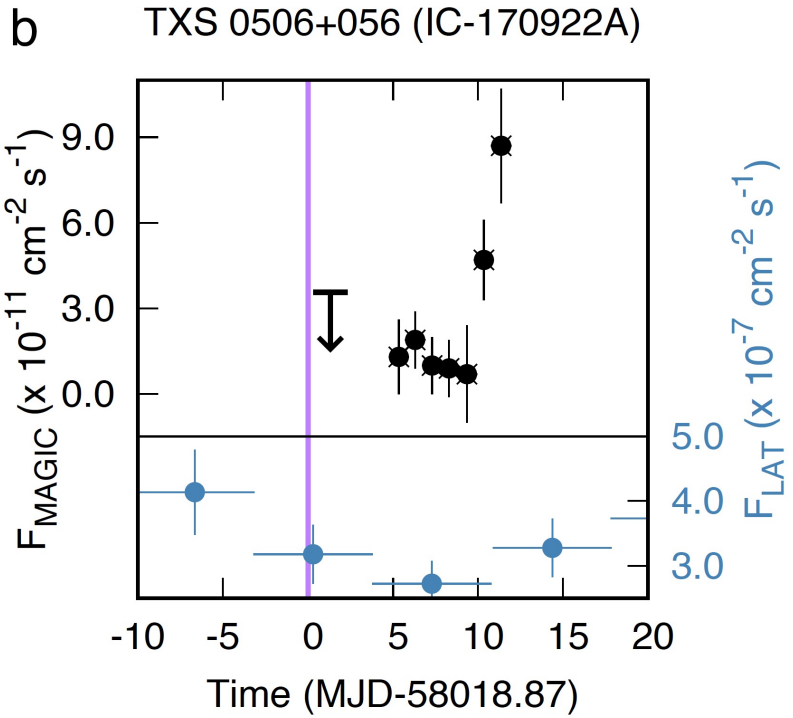






gamma rays in 2017 at the time the neutrino is produced ?

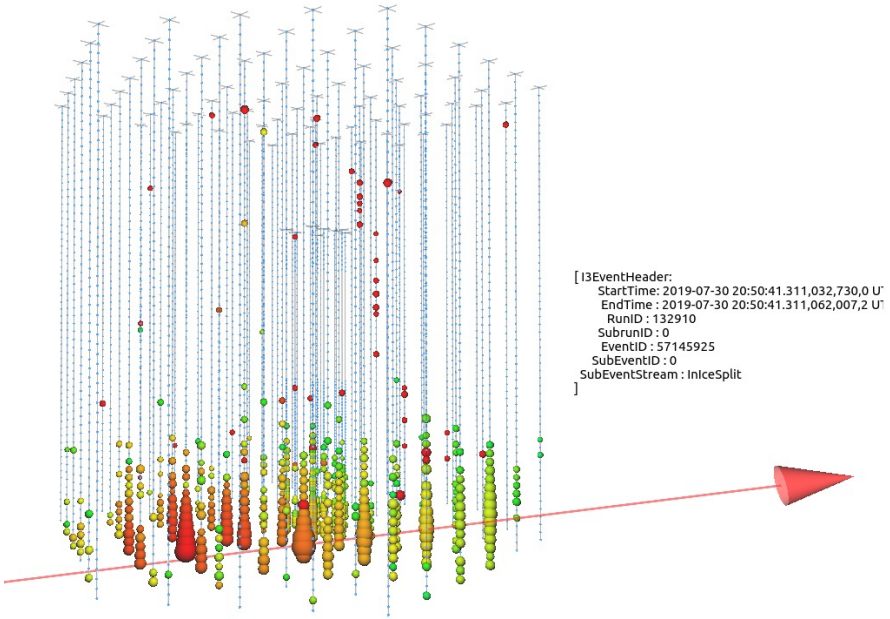


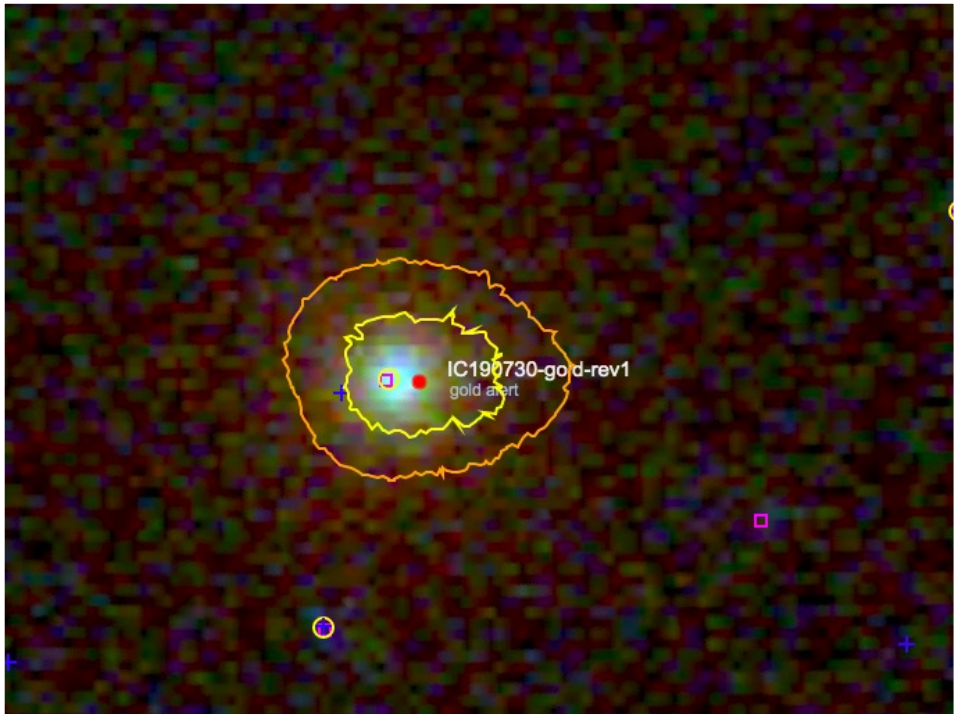


- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

- TXS is *not* a gamma ray blazar during the times that neutrinos are produced
- TXS belongs to a special class of sources with density 10^{-10} / Mpc^3 in order to match the IceCube diffuse flux
- the typical opacity of the target to $\gamma+\gamma$ is one hundred times the opacity for $p+\gamma$: pionic photons lose energy in the source, to emerge below gamma ray energies, at MeV and below
- the stronger neutrino sources are more likely to be gamma-ray obscured
- another intriguing event supporting this picture: IC190730

a second cosmic ray source?





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[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.

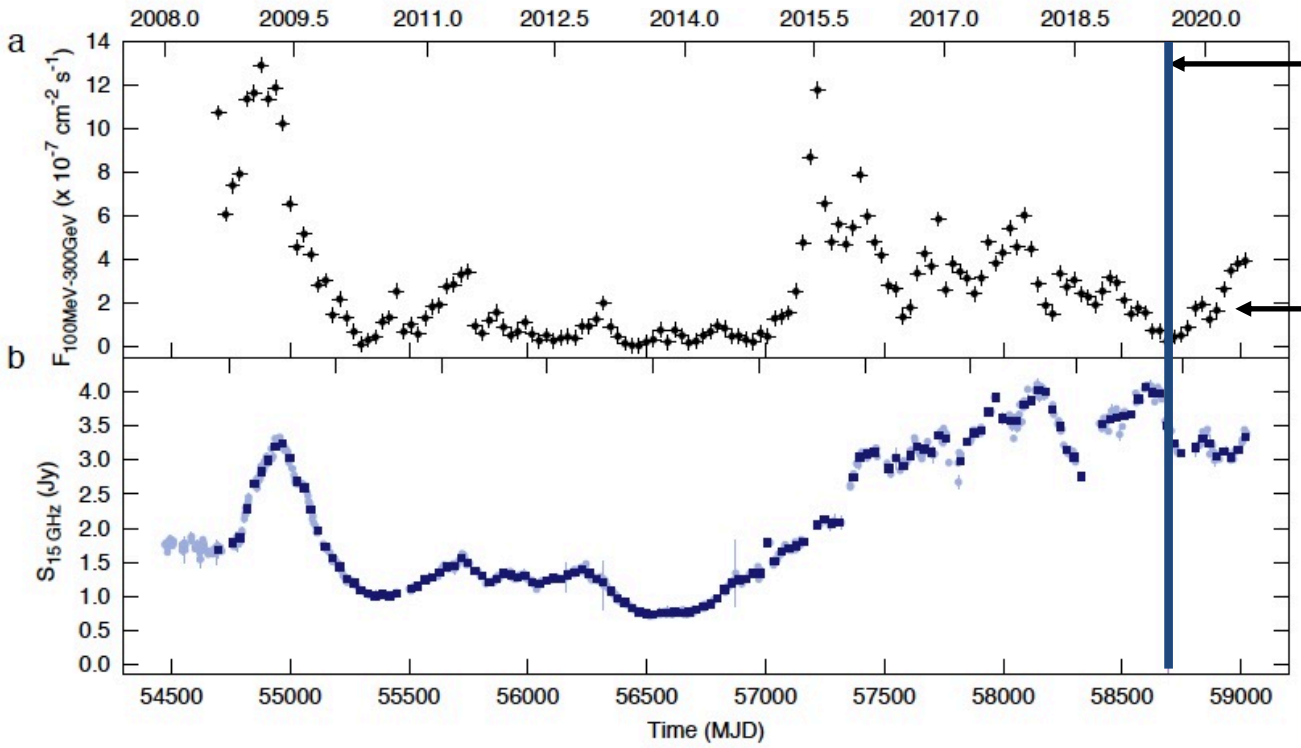
Related

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

PKS 1502+106

γ-ray

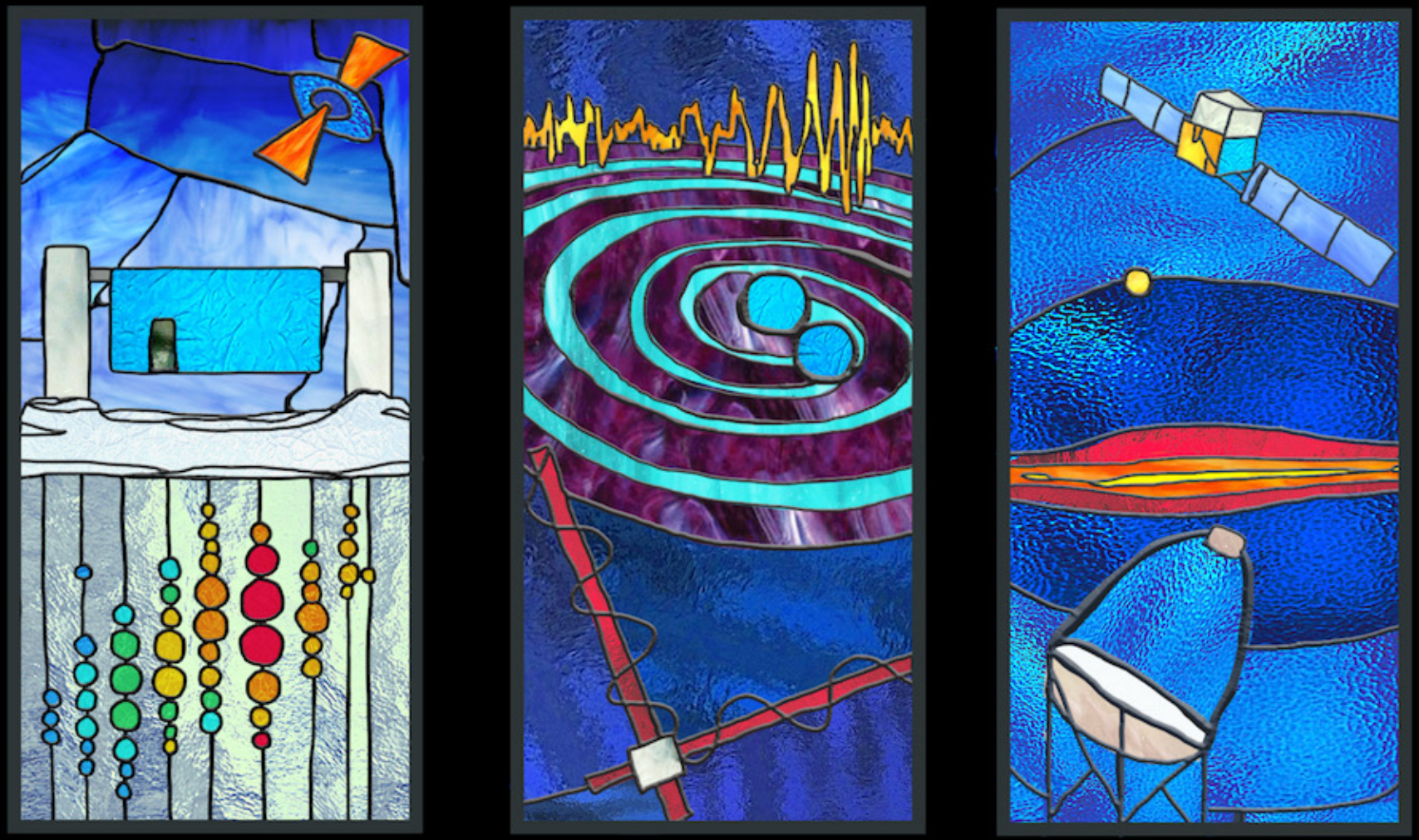
radio



300 TeV neutrino produced

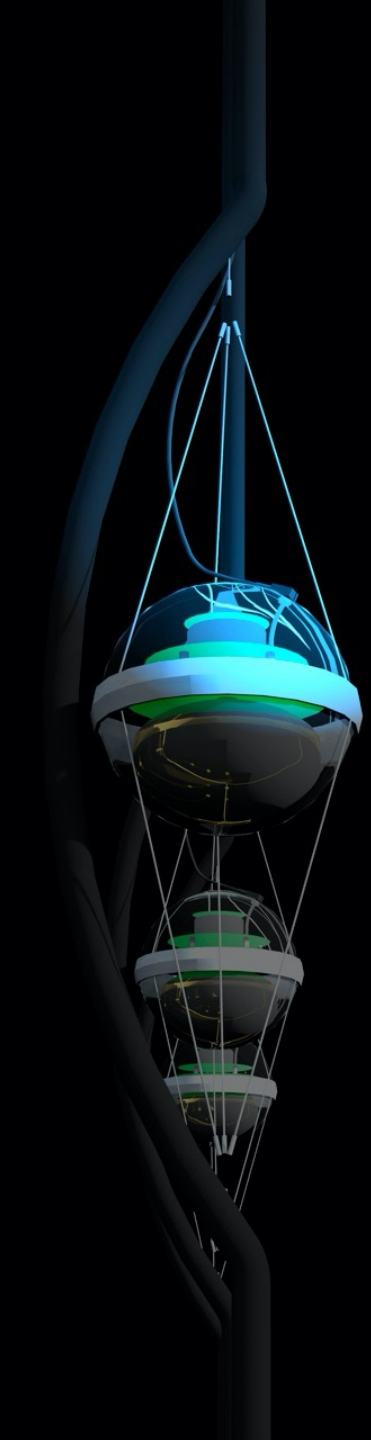
target moves through the jet: blocks photons

2009.09792 [astro-ph.HE]



next attraction: gravitational waves + neutrinos?

(August 17, 2017 neutron star merger: jet not aligned)



neutrino astronomy 2021

- it exists
- more neutrinos, better neutrinos
- closing in on cosmic ray sources

icecube.wisc.edu

THE ICECUBE COLLABORATION

THE ICECUBE COLLABORATION

ISTRALIA 1

NGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory

overflow sides

standing on the shoulder of giants

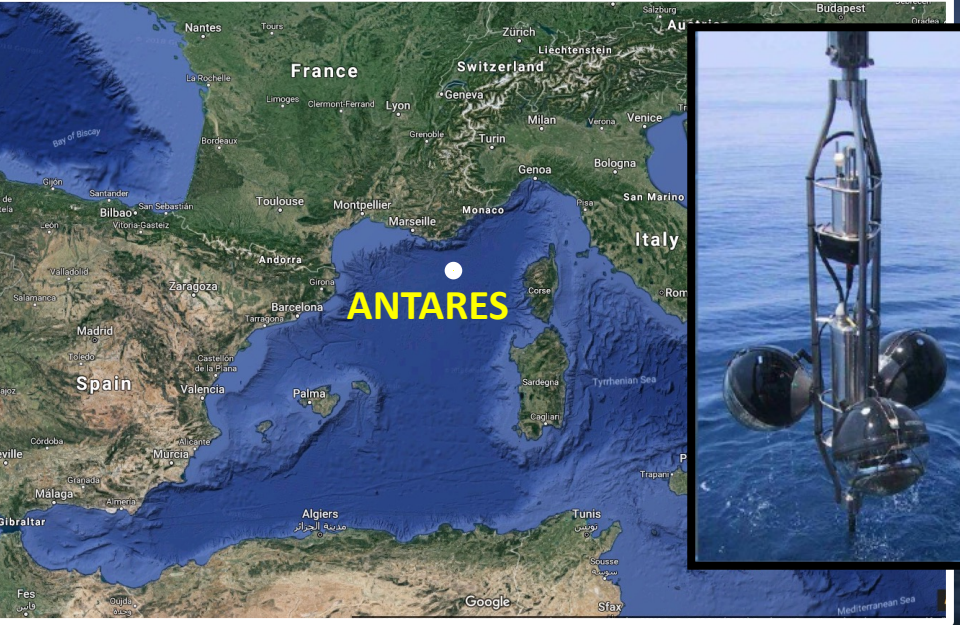
1987: DUMAND test string

… success with Baikal and Antares

Lake Baikal experiment reaches ~ 0.5 km^3

ANTARES

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



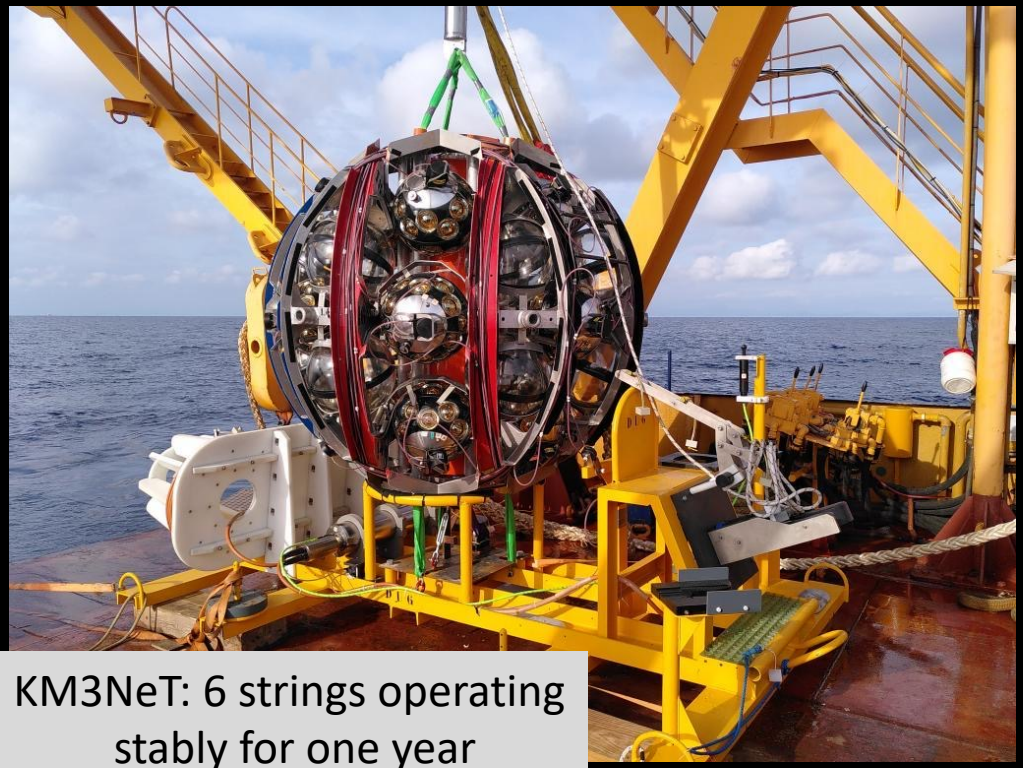
450 m

40 km to shore

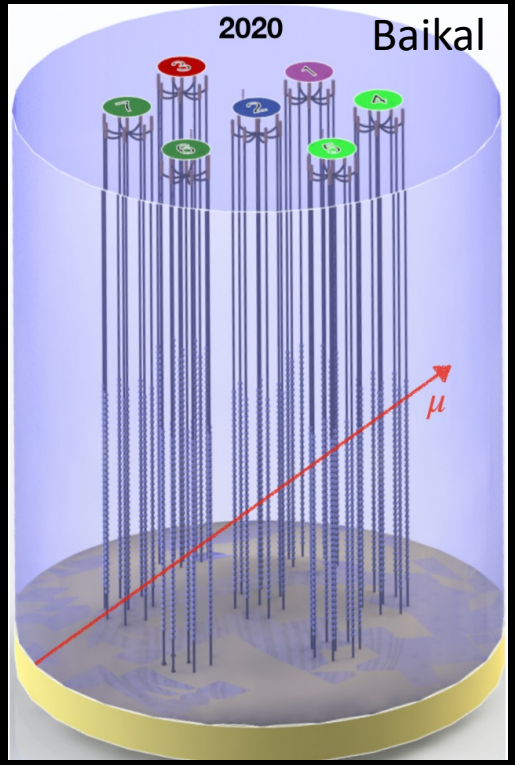
Junction Box

70 m

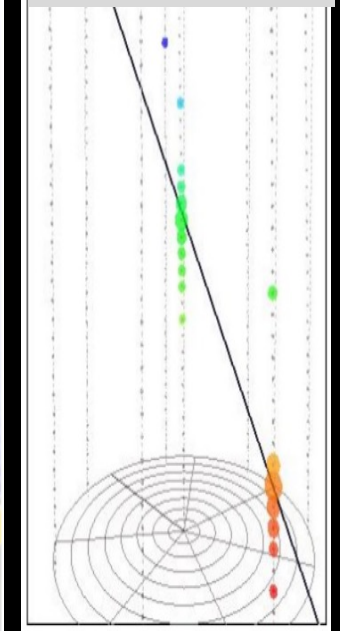
Interlink cables

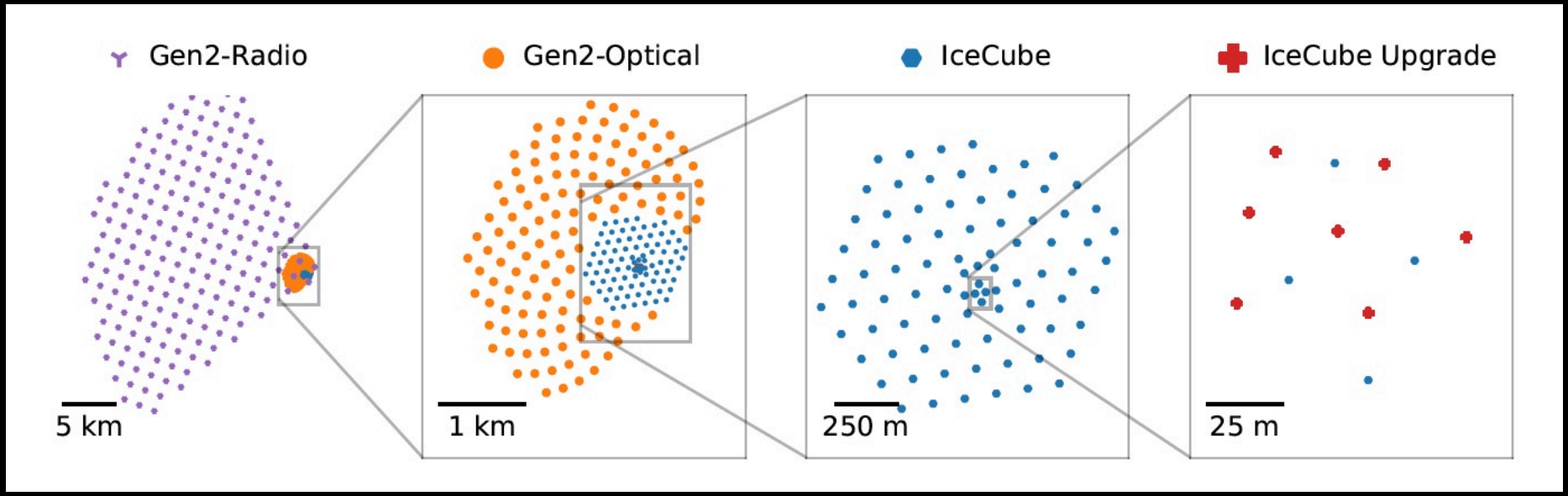


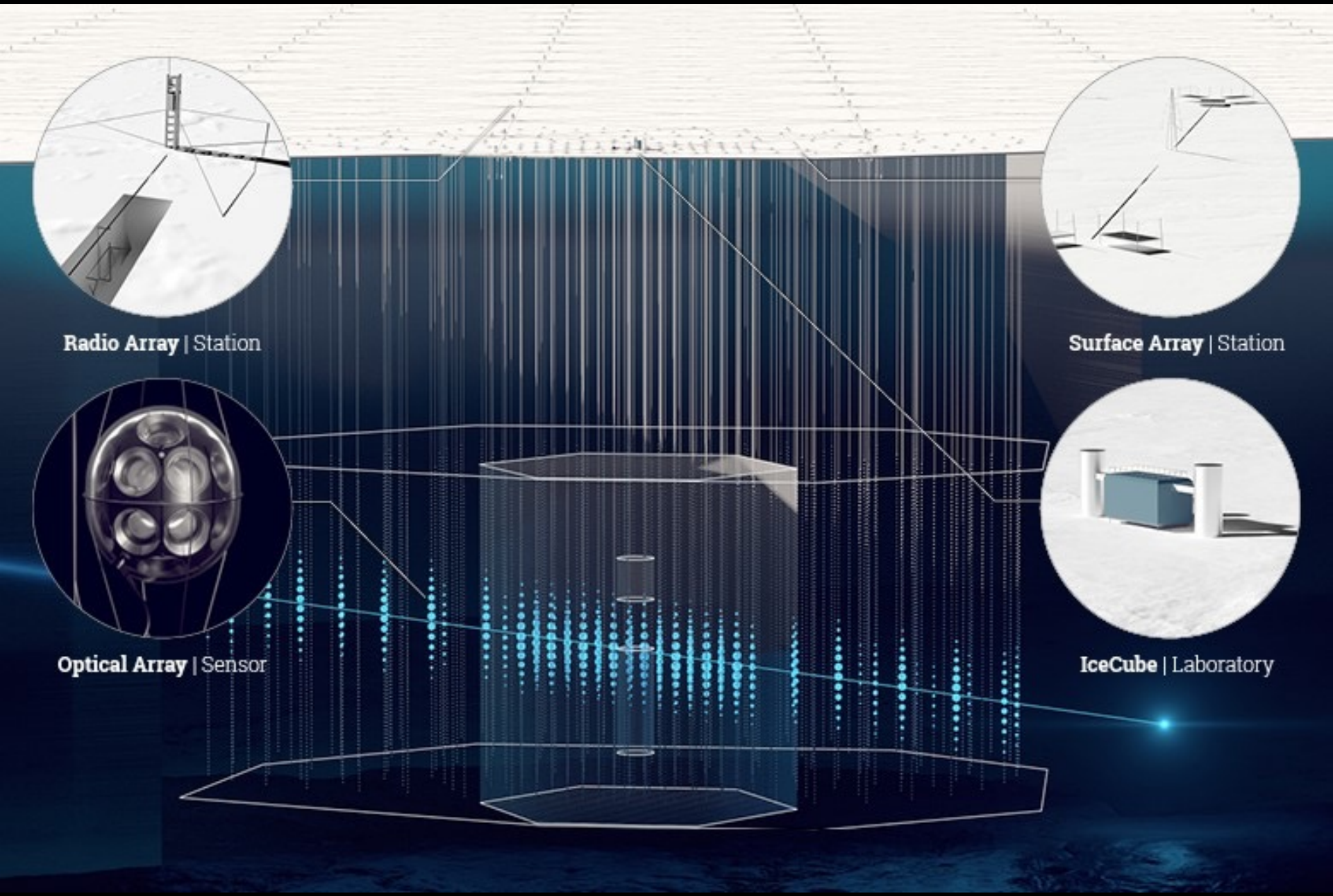
KM3NeT: 6 strings operating stably for one year

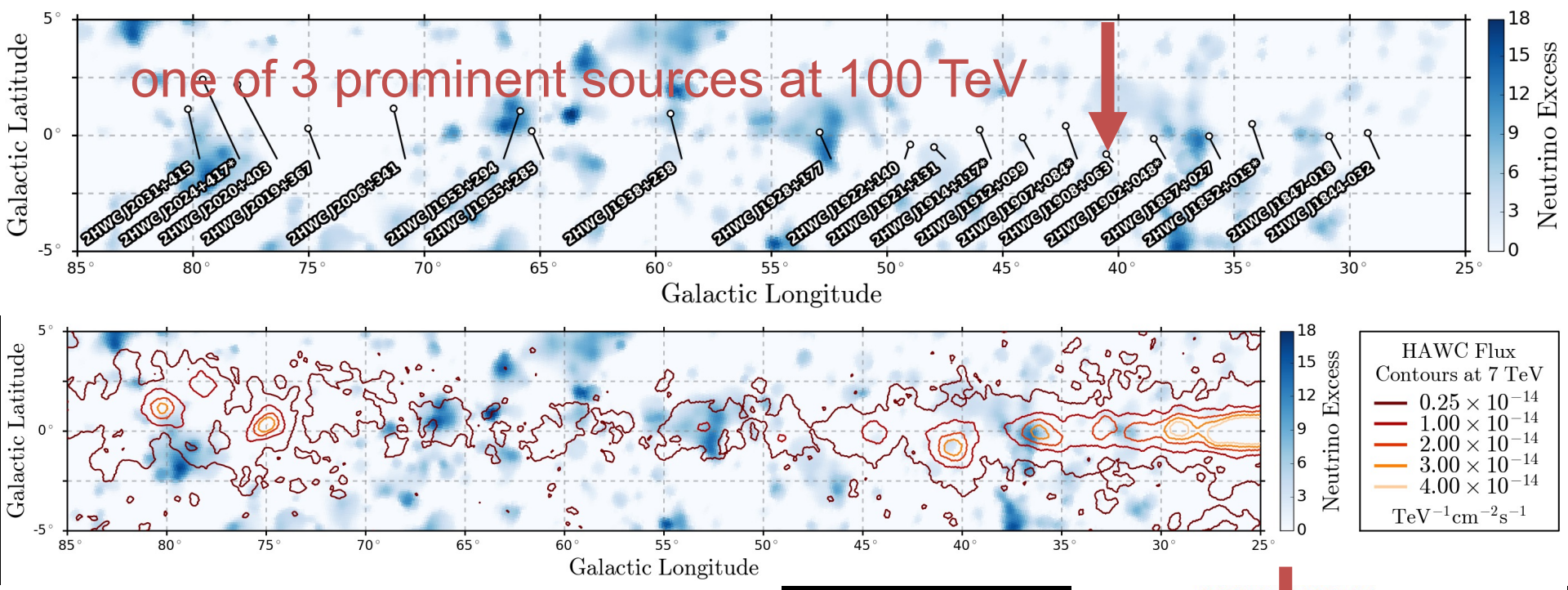


completion:
14 units 2024

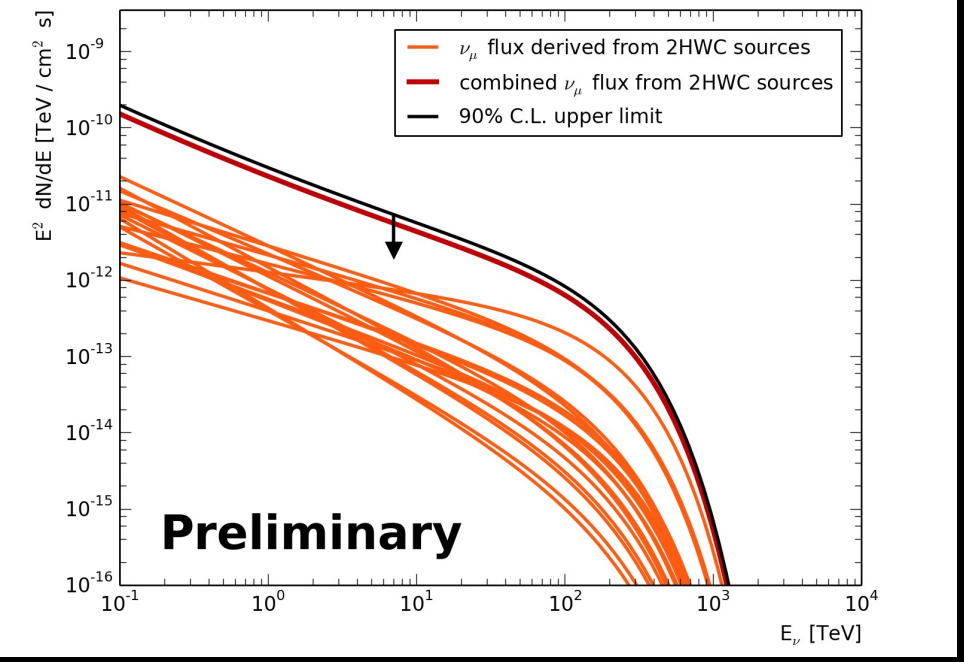


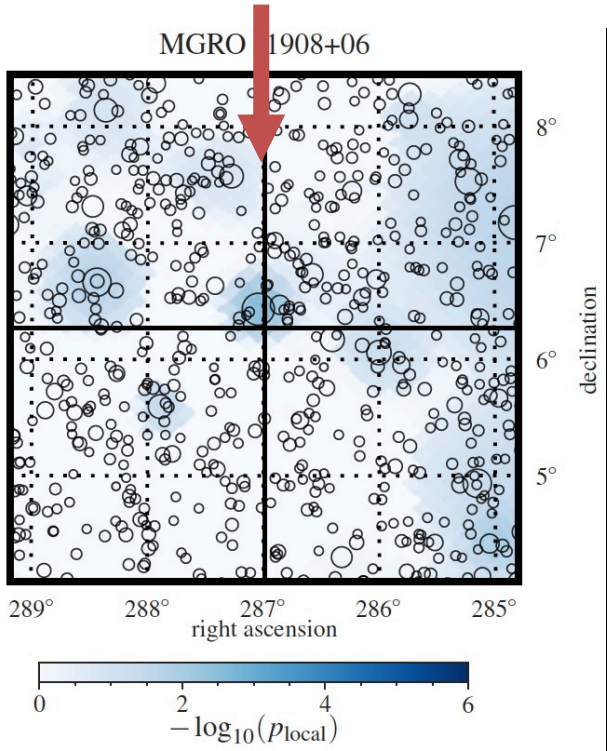


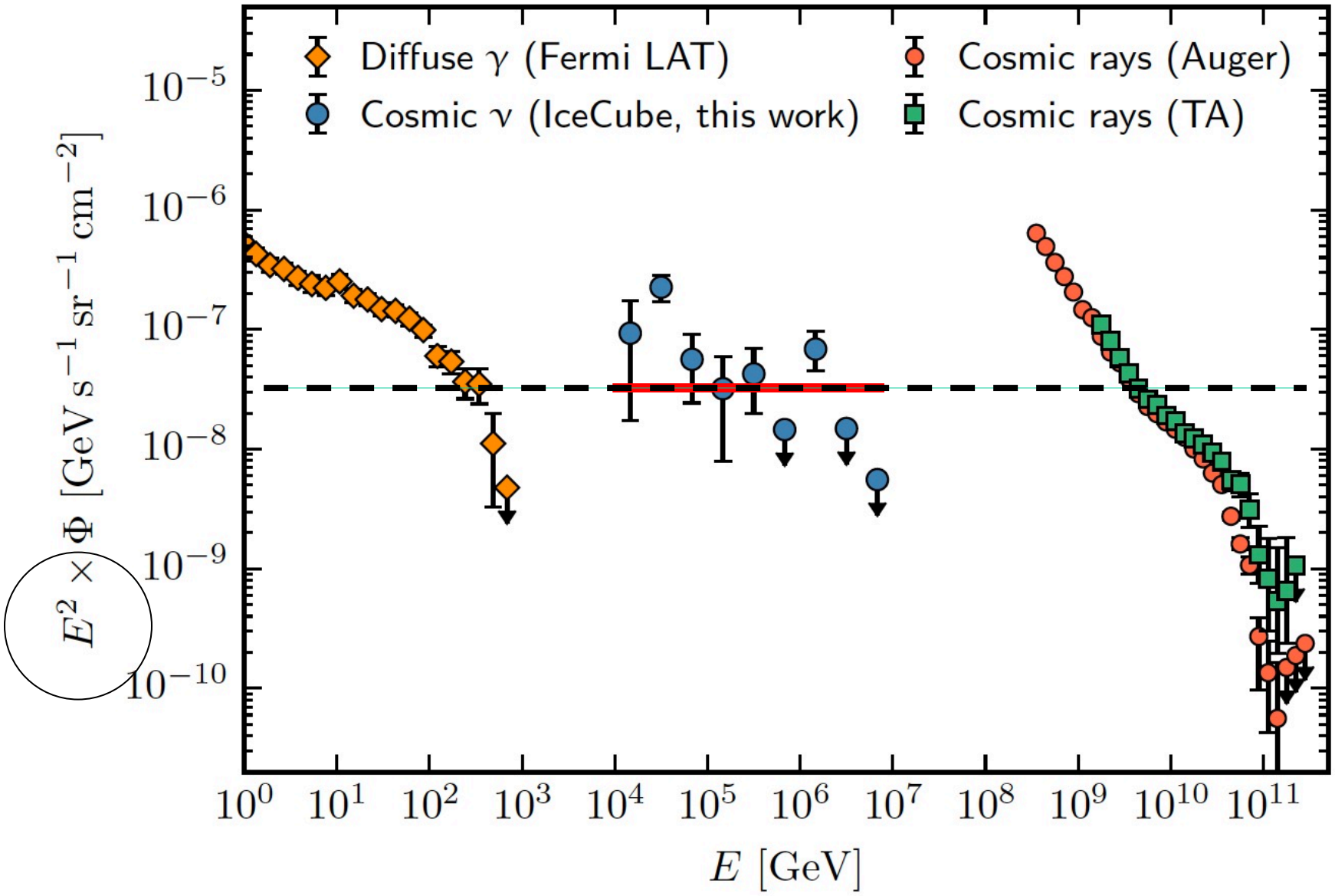

Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory


one of 3 prominent sources at 100 TeV
Galactic Latitude
Galactic Longitude
Neutrino Excess
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
2HWC J1903+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1847+018
2HWC J1844+032

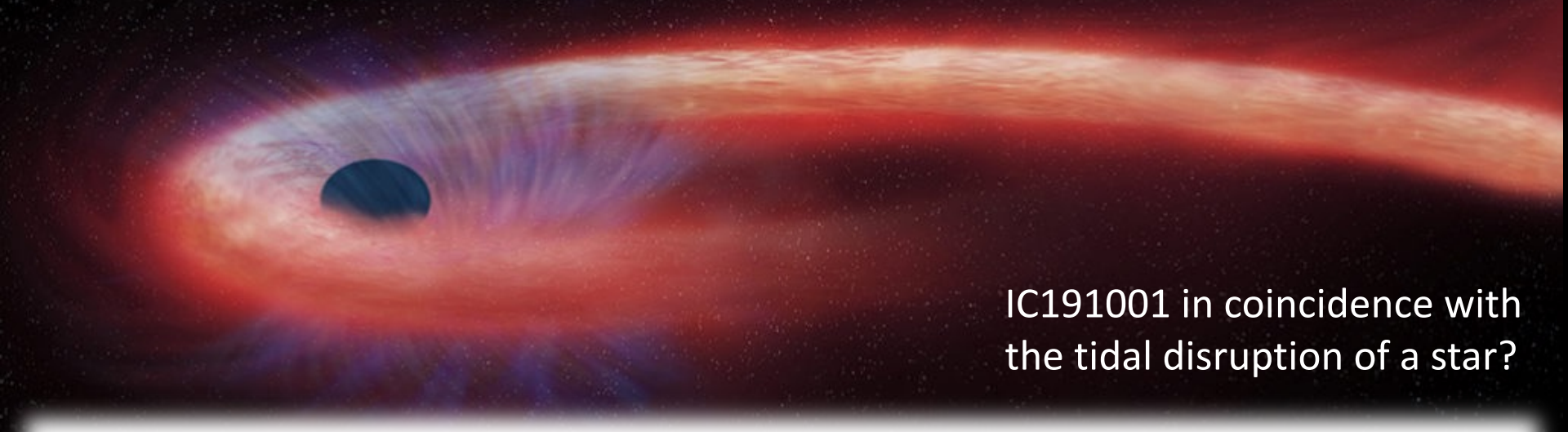
Galactic Latitude
Galactic Longitude
Neutrino Excess
HAWC Flux
Contours at 7 TeV
0.25×10^{-14}
1.00×10^{-14}
2.00×10^{-14}
3.00×10^{-14}
4.00×10^{-14}
$\mathrm{TeV^{-1} cm^{-2} s^{-1}}$


ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]
Preliminary

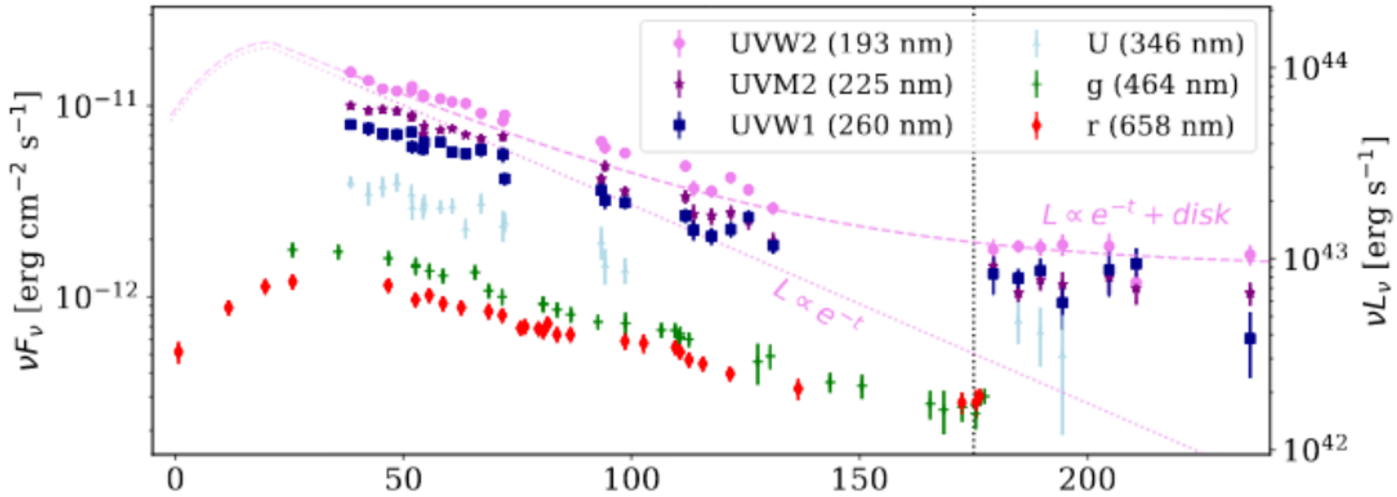

MGRO J1908+06
declination
right ascension
$-\log_{10}(p_{\mathrm{local}})$



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



IC191001 close to luminous TDE of the Zwicky Transit Factory

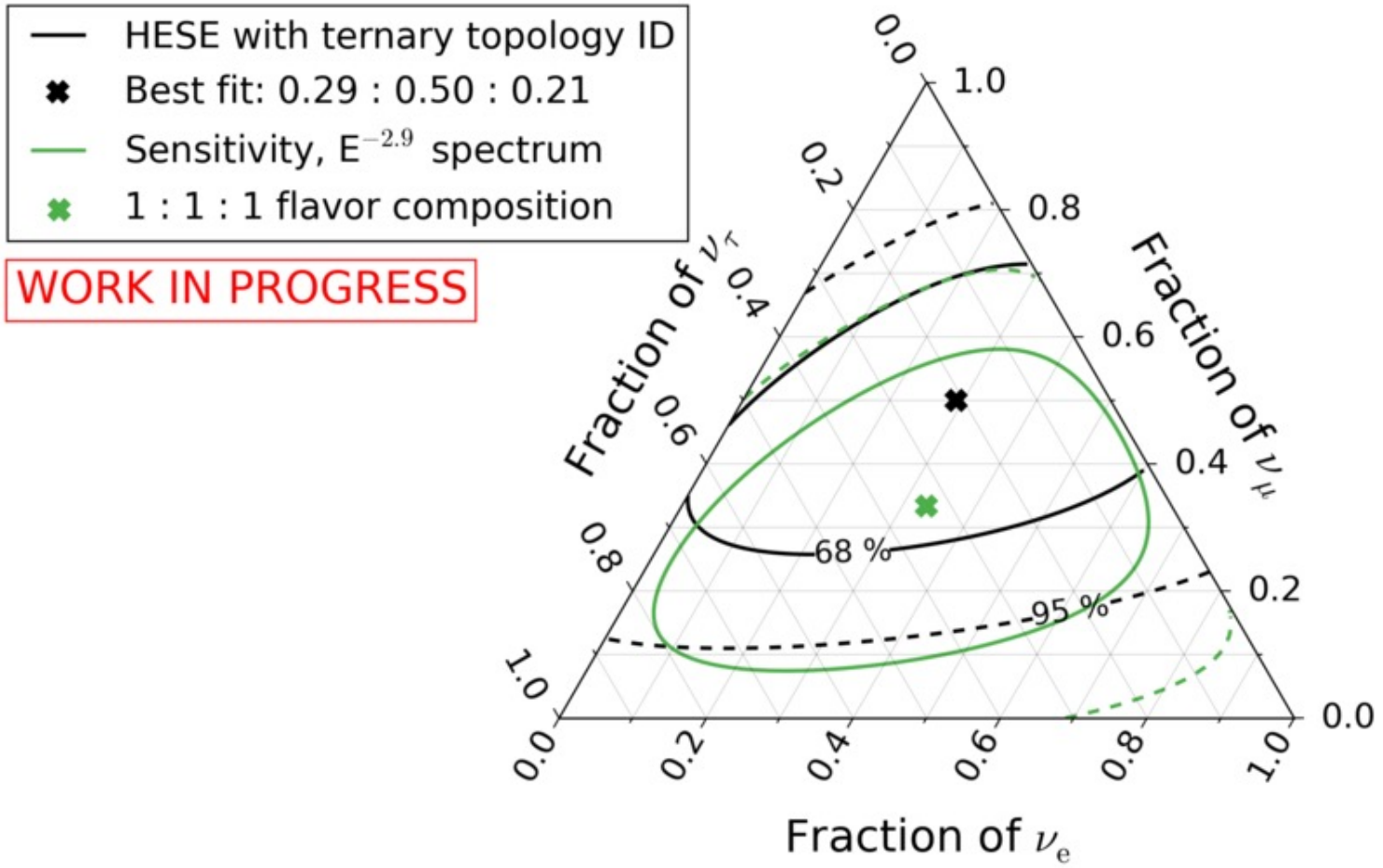


Discovered in April 2019 by ZTF, lots of data! Neutrino arrived ~175 days post-discovery.

Relatively early/bright plateau, consistent with accretion disk formation.

As for most TDEs, well-described by thermal emission ($T \sim 10^{4.6}$ K, $R \sim 10^{14.5}$ cm, $L_{peak} \sim 10^{44.5}$ erg s^{-1})

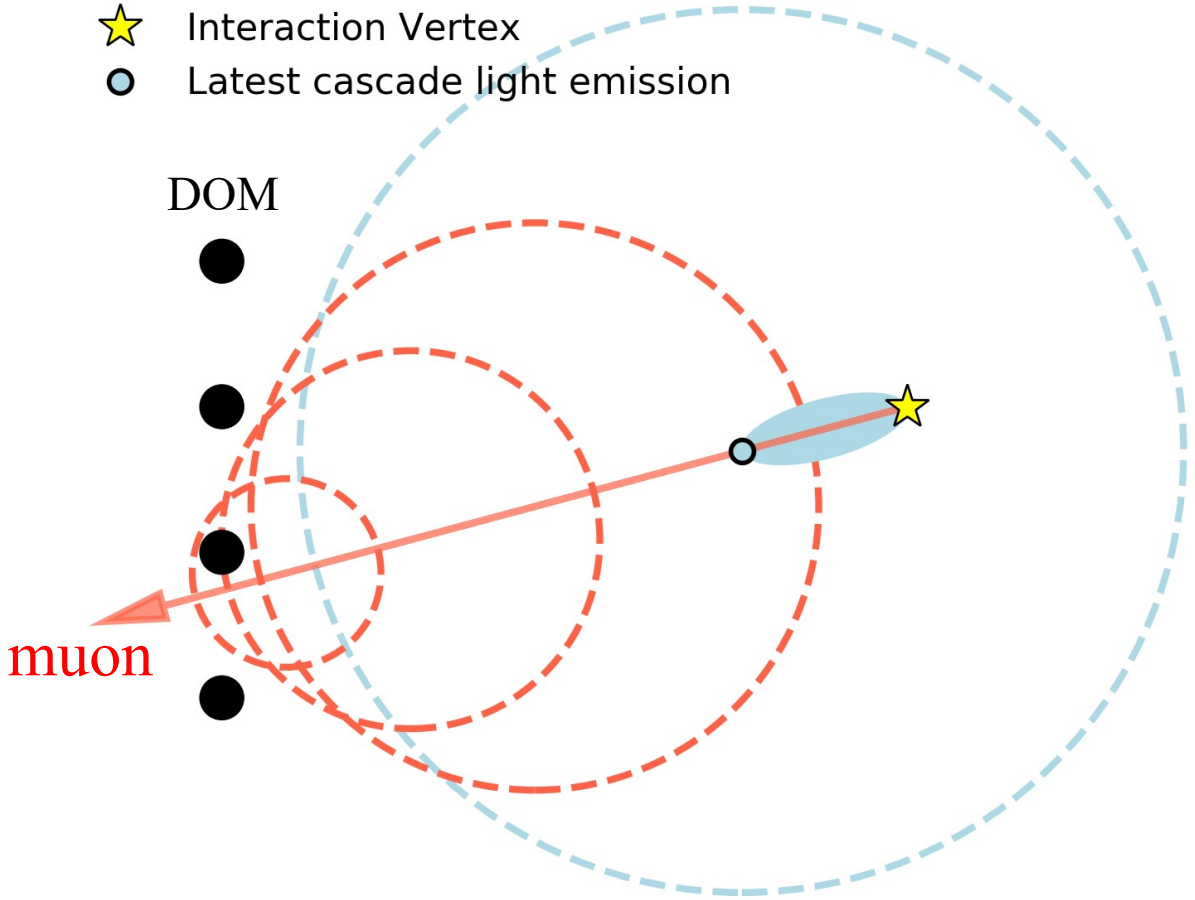
high-energy starting events – 7.5 yr

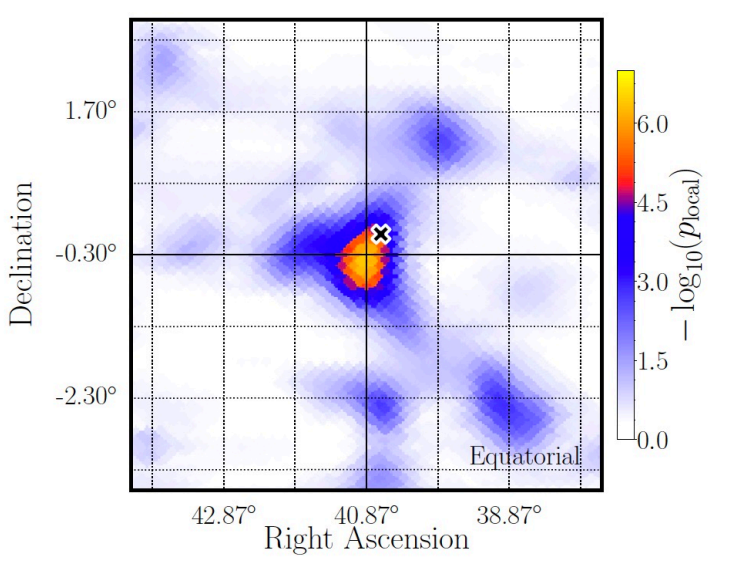


oscillations of PeV neutrinos over cosmic distances to 1:1:1

- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)





evidence for M77 (NGC1086)

- agn activity
- dense molecular clouds near black hole
- merger (with a star-forming region or satellite galaxy)

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

S. García-Burillo[1], F. Combes[2], A. Usero[1], S. Aalto[3], M. Krips[4], S. Viti[5], A. Alonso-Herrero[6,⋆⋆], L. K. Hunt[7], E. Schinnerer[8], A. J. Baker[9], F. Boone[10], V. Casasola[11], L. Colina[12], F. Costagliola[13], A. Eckart[14], A. Fuente[1], C. Henkel[15,16], A. Labiano[1,17], S. Martín[4], I. Márquez[13], S. Muller[3], P. Planesas[1], C. Ramos Almeida[18,19], M. Spaans[20], L. J. Tacconi[21], and P. P. van der Werf[22]

[1] Observatorio Astronómico Nacional (OAN)-Observatorio de Madrid, Alfonso XII, 3, 28014 Madrid, Spain
e-mail: s.gburillo@oan.es
[2] Observatoire de Paris, LERMA, CNRS, 61 Av. de l'Observatoire, 75014 Paris, France
[3] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Observatory, 439 94 Onsala, Sweden
[4] Institut de Radio Astronomie Millimétrique (IRAM), 300 rue de la Piscine, Domaine Universitaire de Grenoble, 38406 St.Martin d'Hères, France
[5] Department of Physics and Astronomy, UCL, Gower Place, London WC1E 6BT, UK
[6] Instituto de Física de Cantabria, CSIC-UC, 39005 Santander, Spain
[7] INAF – Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
[8] Max-Planck-Institut für Astronomie, Königstuhl, 17, 69117 Heidelberg, Germany
[9] Department of Physics and Astronomy, Rutgers, The State University of New Jersey, Piscataway, NJ 08854, USA
[10] Université de Toulouse, UPS-OMP, IRAP, 31028 Toulouse, France
[11] INAF – Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
[12] Centro de Astrobiología (CSIC-INTA), Ctra de Torrejón a Ajalvir, km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[13] Instituto de Astrofísica de Andalucía (CSIC), Apdo 3004, 18080 Granada, Spain
[14] I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
[15] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[16] Astronomy Department, King Abdulazizi University, PO Box 80203, 21589 Jeddah, Saudi Arabia
[17] Institute for Astronomy, Department of Physics, ETH Zurich, 8093 Zurich, Switzerland
[18] Instituto de Astrofísica de Canarias, Calle vía Láctea, s/n, 38205 La Laguna, Tenerife, Spain
[19] Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
[20] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
[21] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany
[22] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

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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 ($n(\mathrm{H_2}) \simeq 10^{5-6}$ 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).

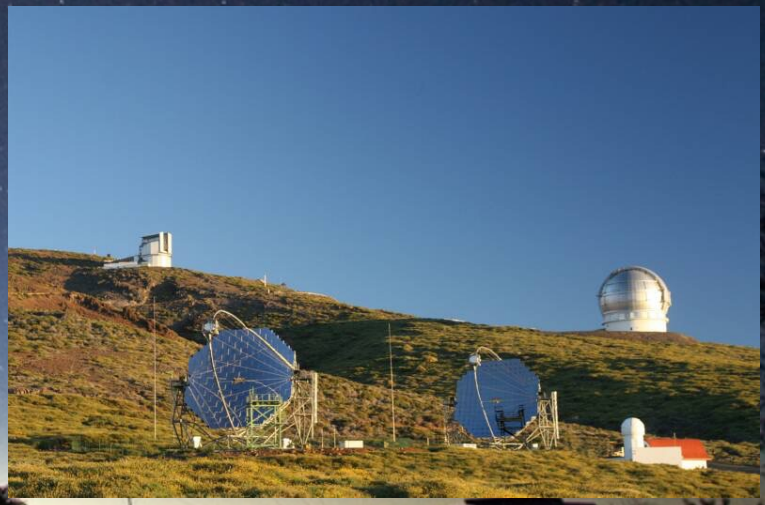
Results. The sensitivity and spatial resolution of ALMA give an unprecedented detailed view of the distribution and kinematics of the dense molecular gas ($n(\mathrm{H_2}) \geq 10^{5-6}$cm^{-3}) in NGC 1068. Molecular line and dust continuum emissions are detected from a $r \sim 200$ pc off-centered 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.

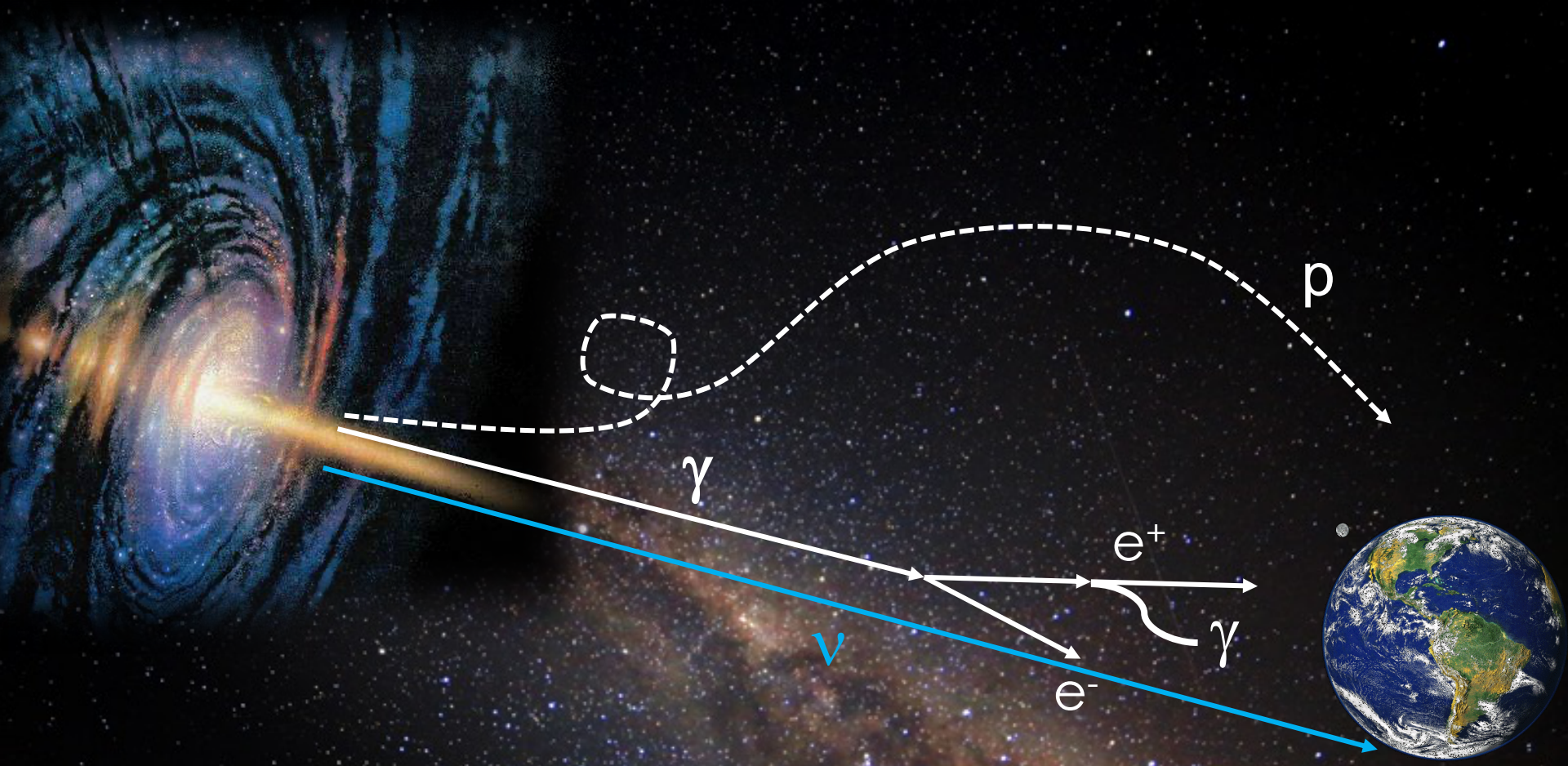
Conclusions. The molecular outflow is likely launched when the ionization cone of the narrow line region sweeps the nuclear disk. The outflow rate estimated in the CND, $dM/dt \sim 63^{+21}_{-37}\ M_\odot\ \mathrm{yr}^{-1}$, is an order of magnitude higher than the star formation rate at these radii, 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.

gamma ray

TeV
atmospheric Cherenkov
telescopes

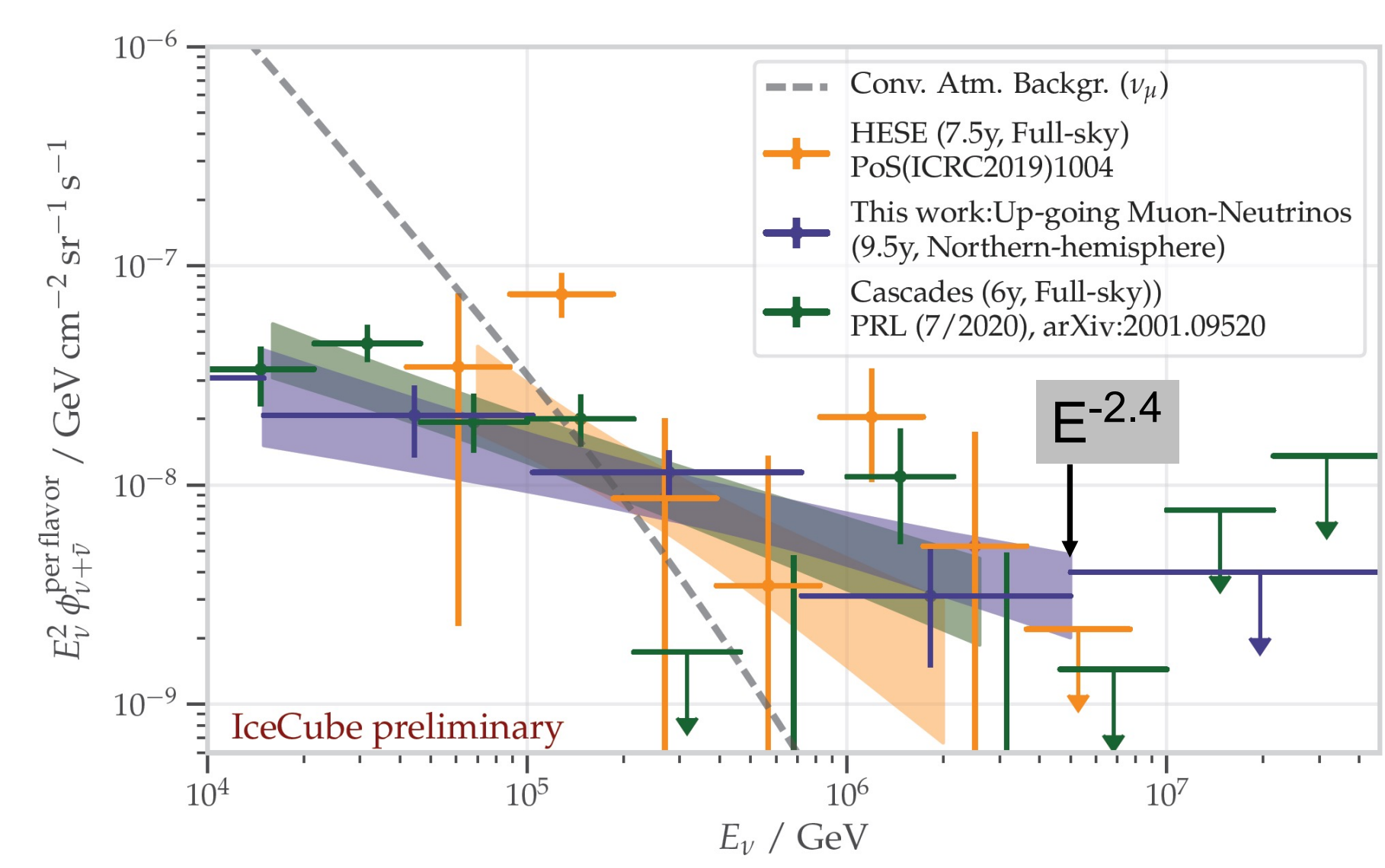
HESS, MAGIC, VERITAS





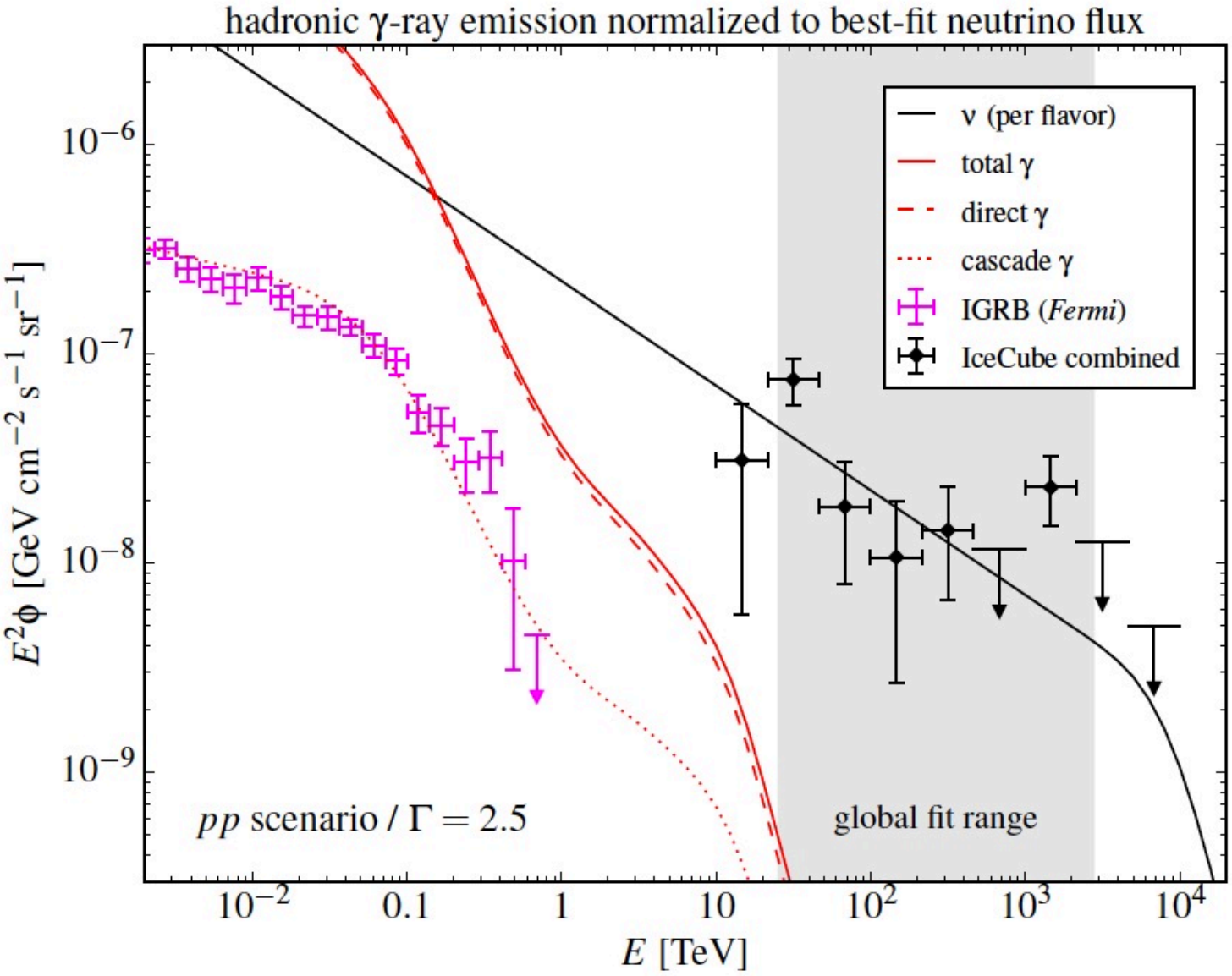
target may not be transparent to gamma rays:

gamma rays accompanying IceCube neutrinos lose energy in the source and in the interstellar medium and fragment into lower energy gamma rays, X-rays… that reach earth



coming soon:

- superior calibration of the detector (pass 2),
- improved simulation, and
- better energy and directional reconstruction with better neural nets



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

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]

[1] *INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5 I-35122 Padova - ITALY*
[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*
[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!

multiwavelength campaign launched by IC 170922

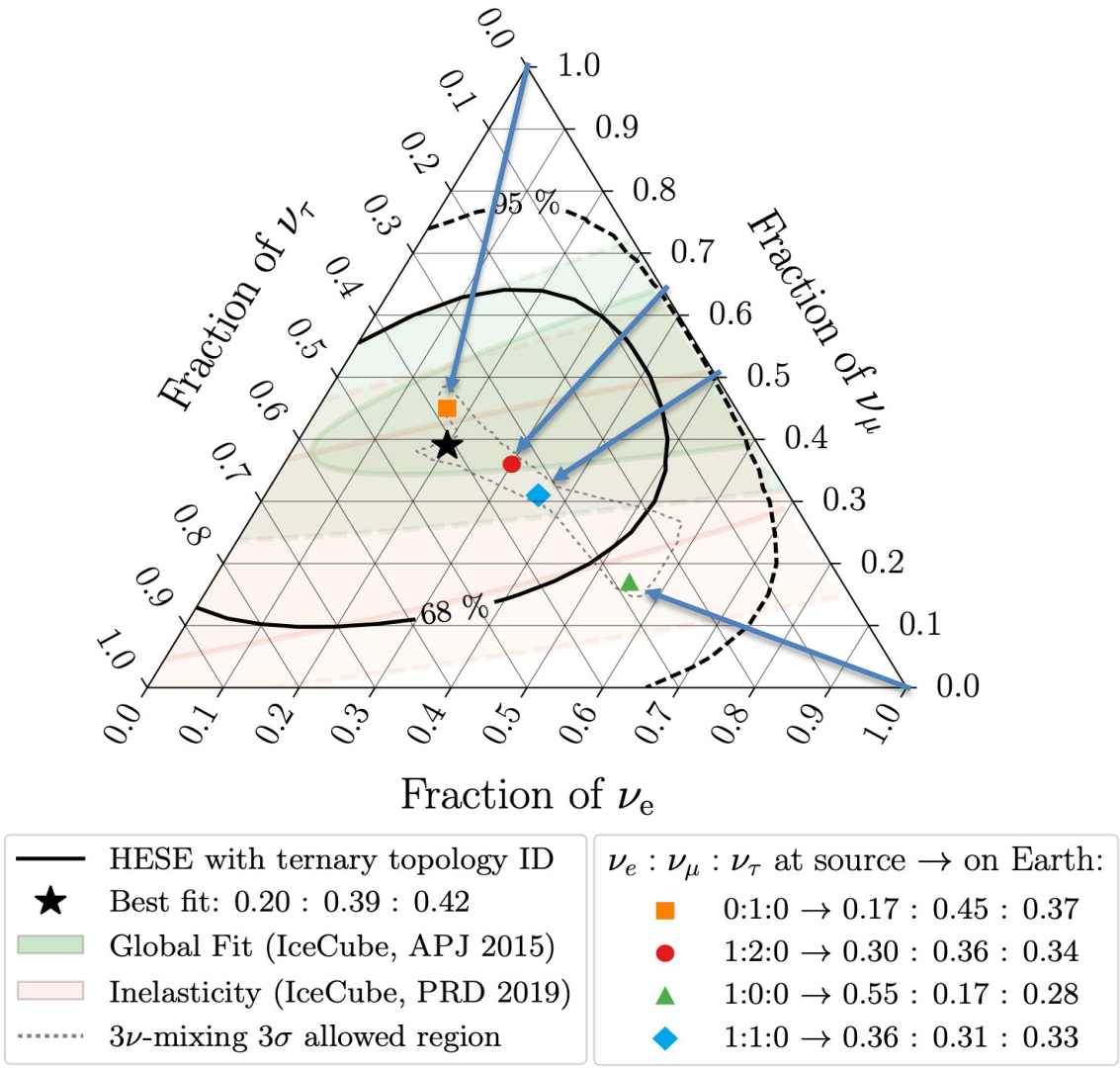
Science 361 (2018) 6398 and 361 (2018) 6398

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 (daily variations)
- follow-up by more telescopes

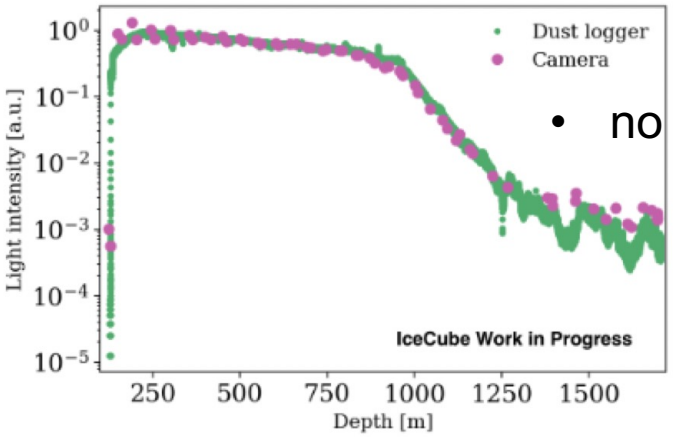
new neutrino physics ?

oscillating PeV neutrinos (7.5 years HESE)



ice: step by step

- hole ice ?

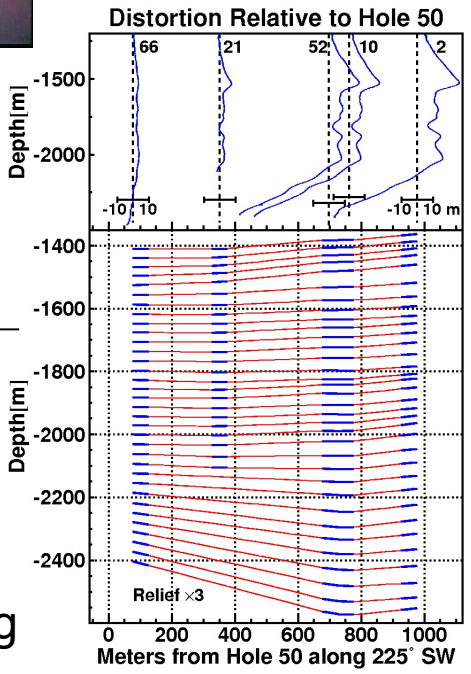


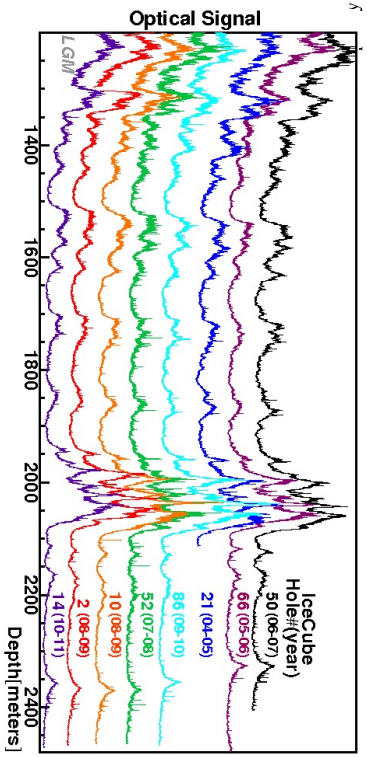
- no air bubbles/hydrates below 1350 m

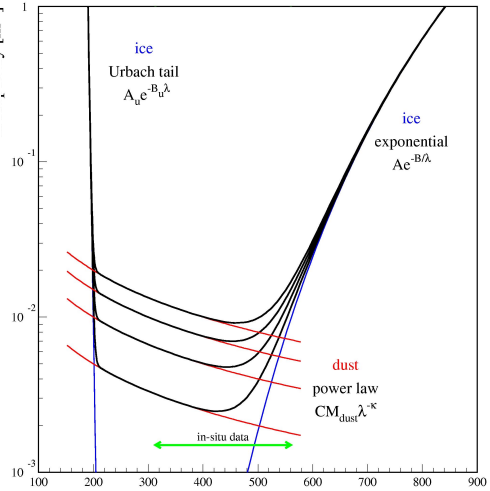
- > 100 m absorption length limited by dust

- ice layers

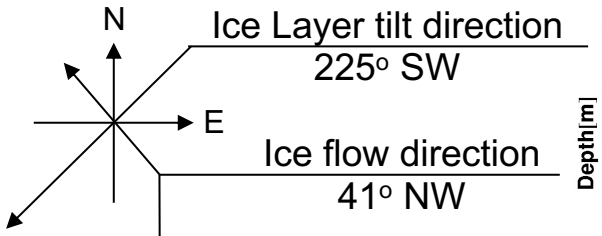
- tilted ice layers







- birefringence of the crystal boundaries ?



Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

- anisotropy
~8% less scattering
41° NW

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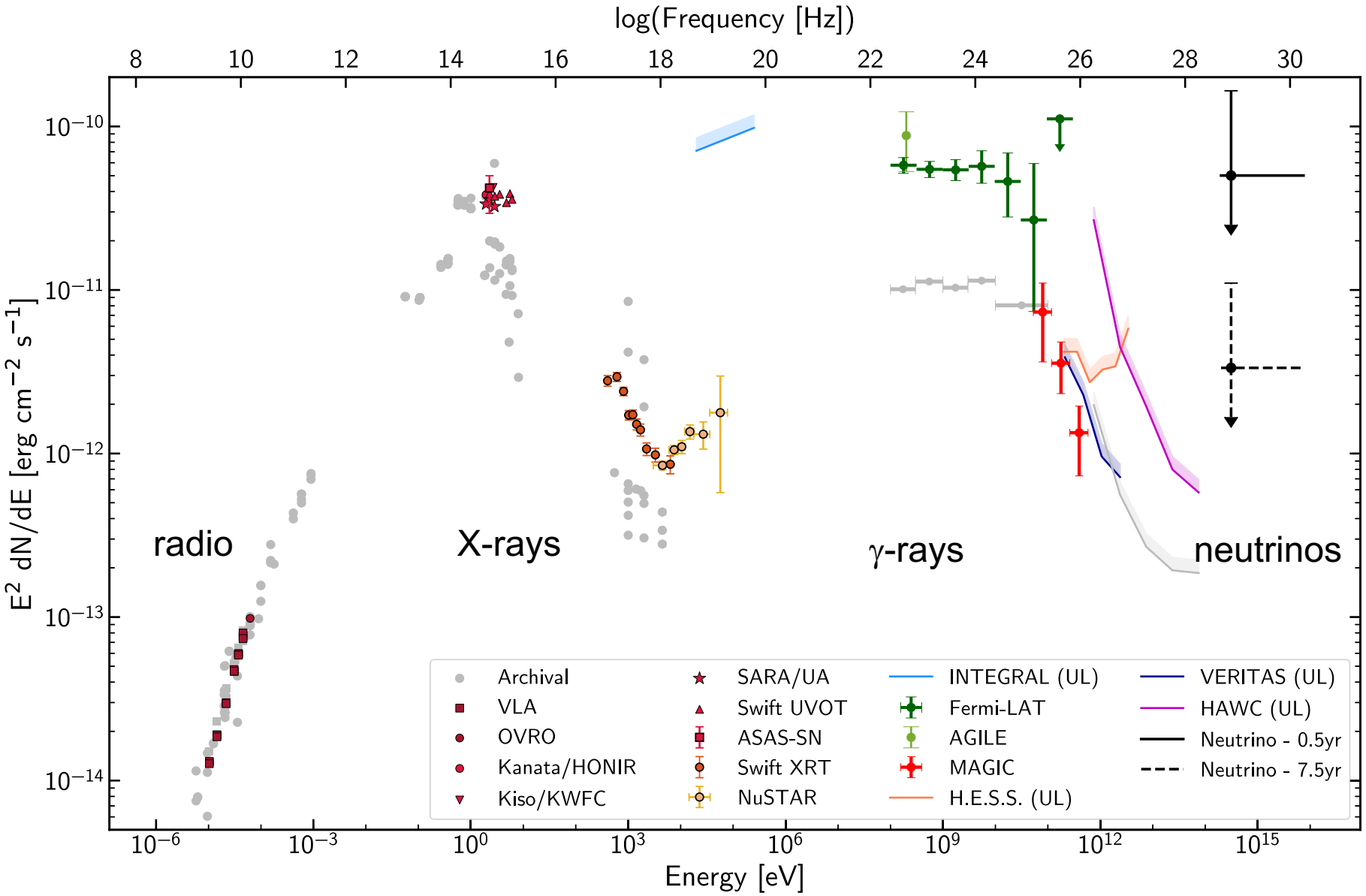
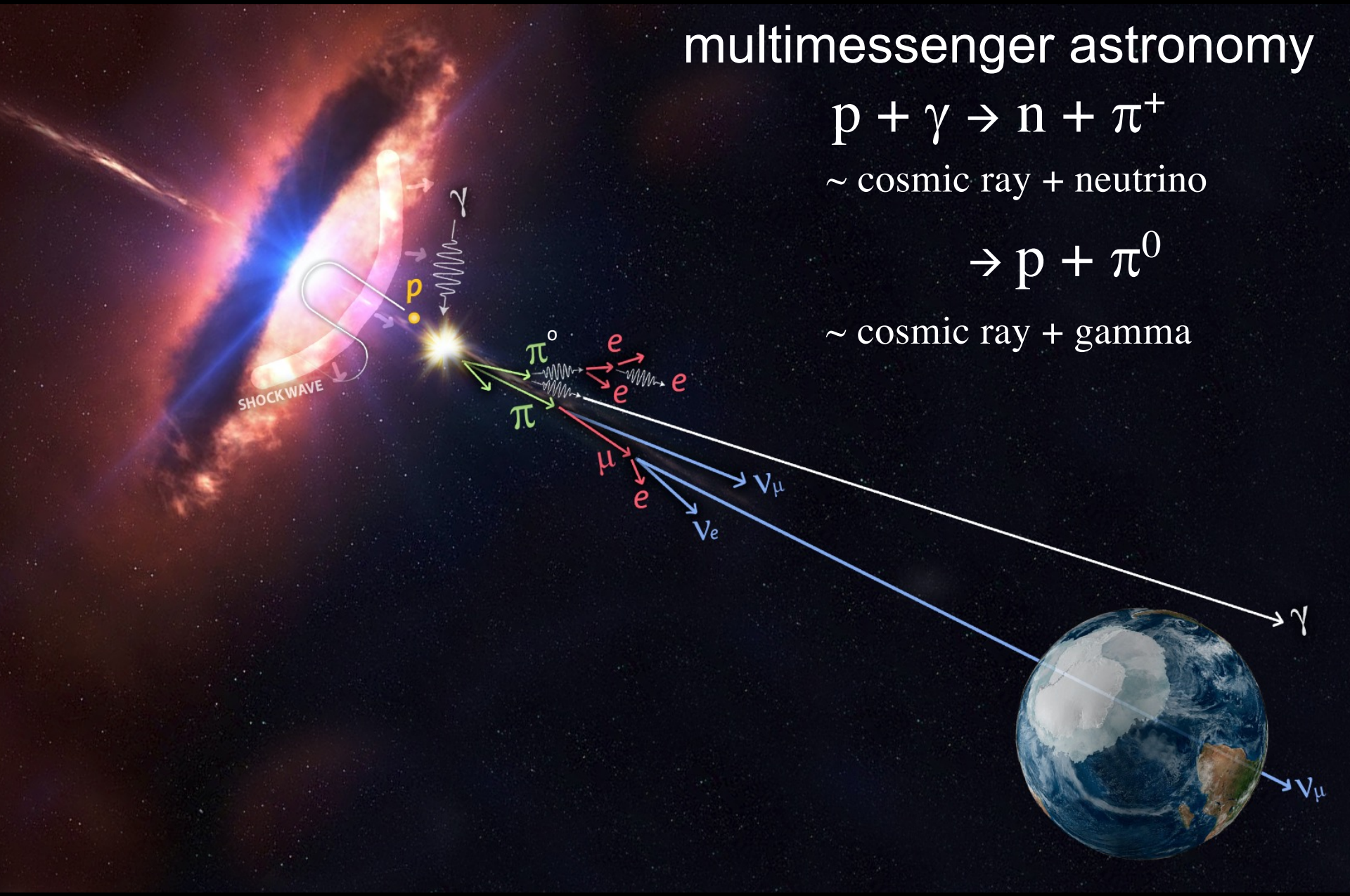
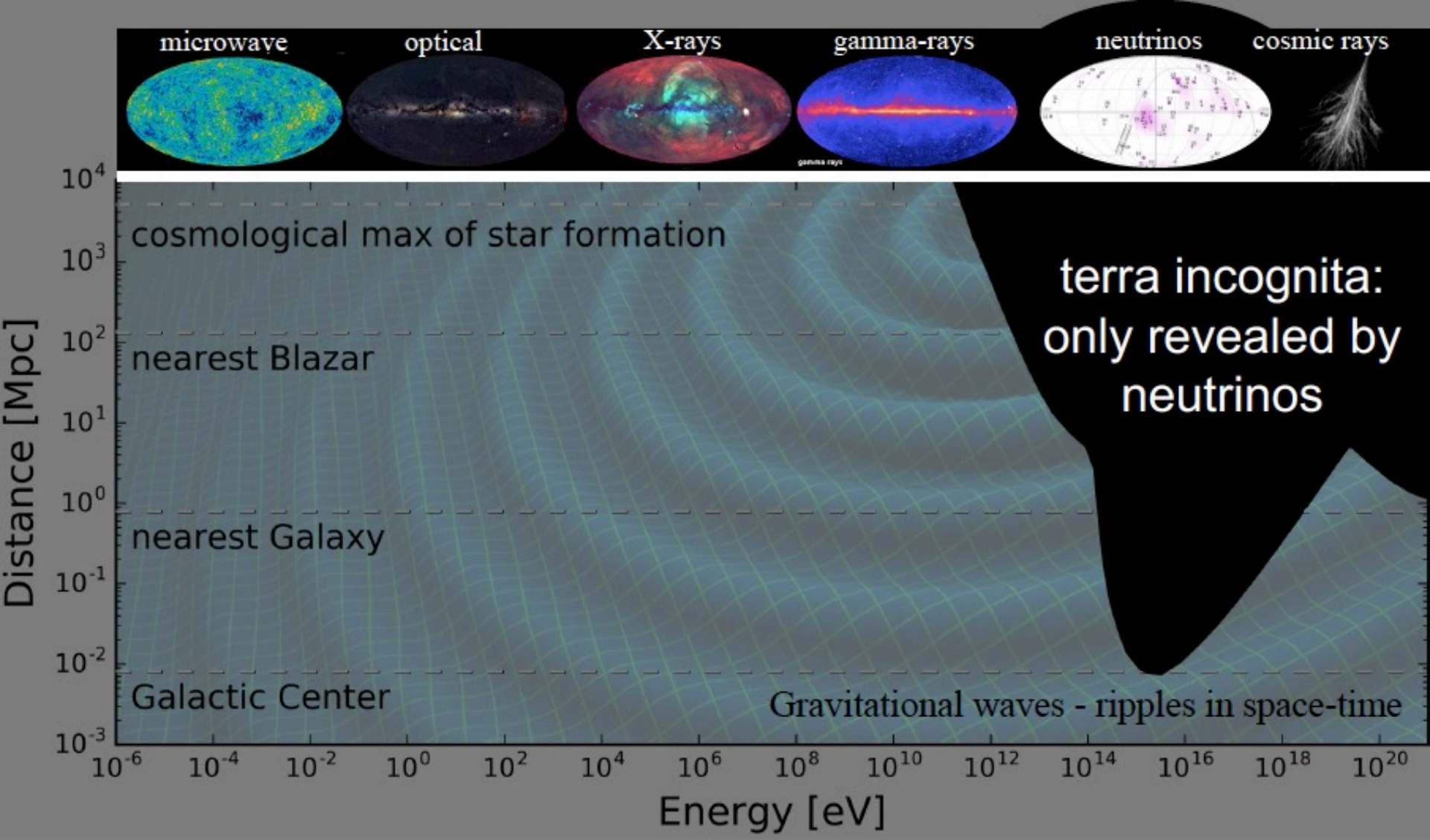


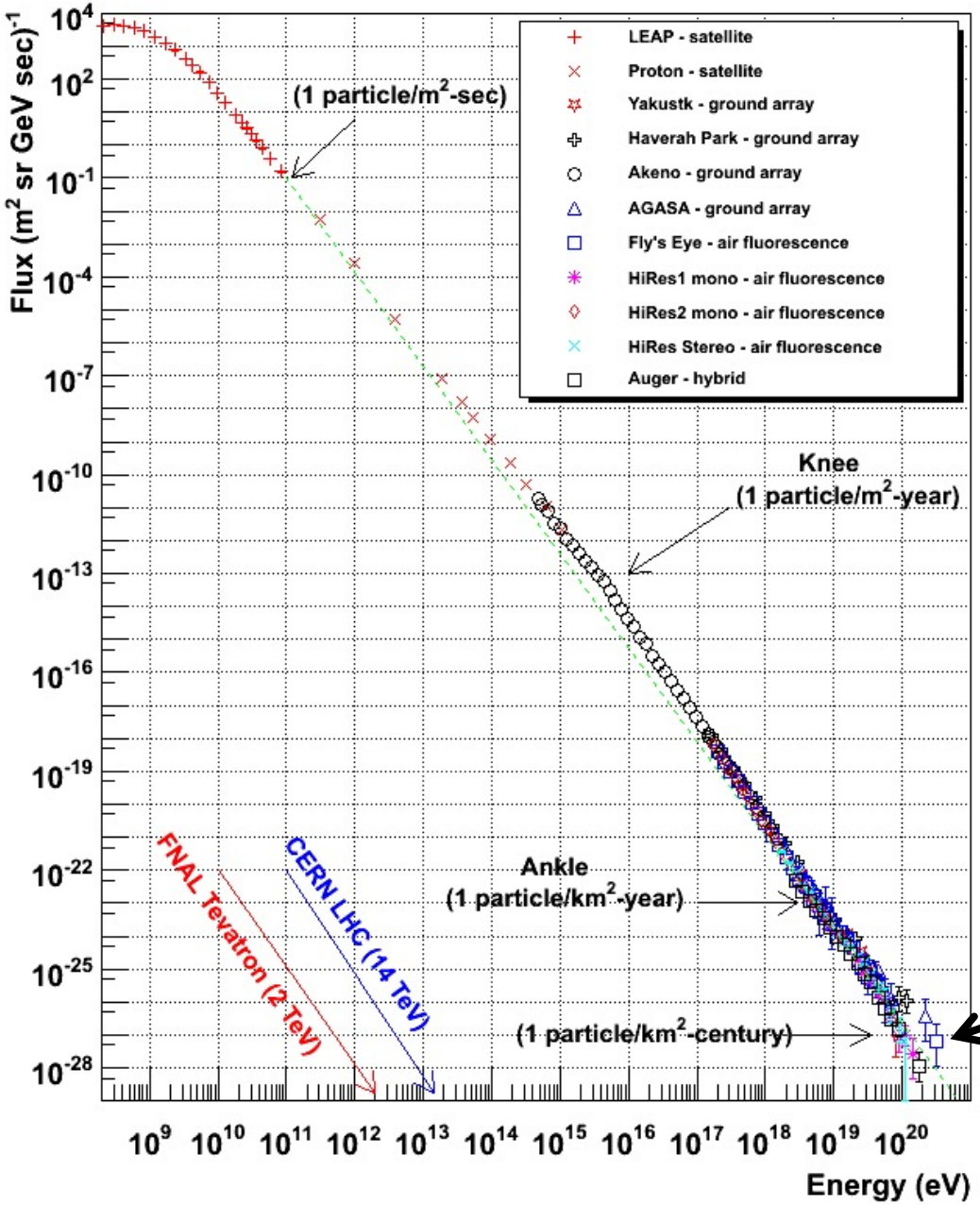
blazar models cannot produce a single neutrino at this level


multimessenger astronomy
$p + \gamma \rightarrow n + \pi^+$
~ cosmic ray + neutrino
$\rightarrow p + \pi^0$
~ cosmic ray + gamma
SHOCK WAVE
p
γ
π°
e
e
e
π
μ
e
ν_μ
ν_e
γ
ν_μ



- the extreme Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos

origin of cosmic rays: oldest problem in astronomy



cosmic ray challenge

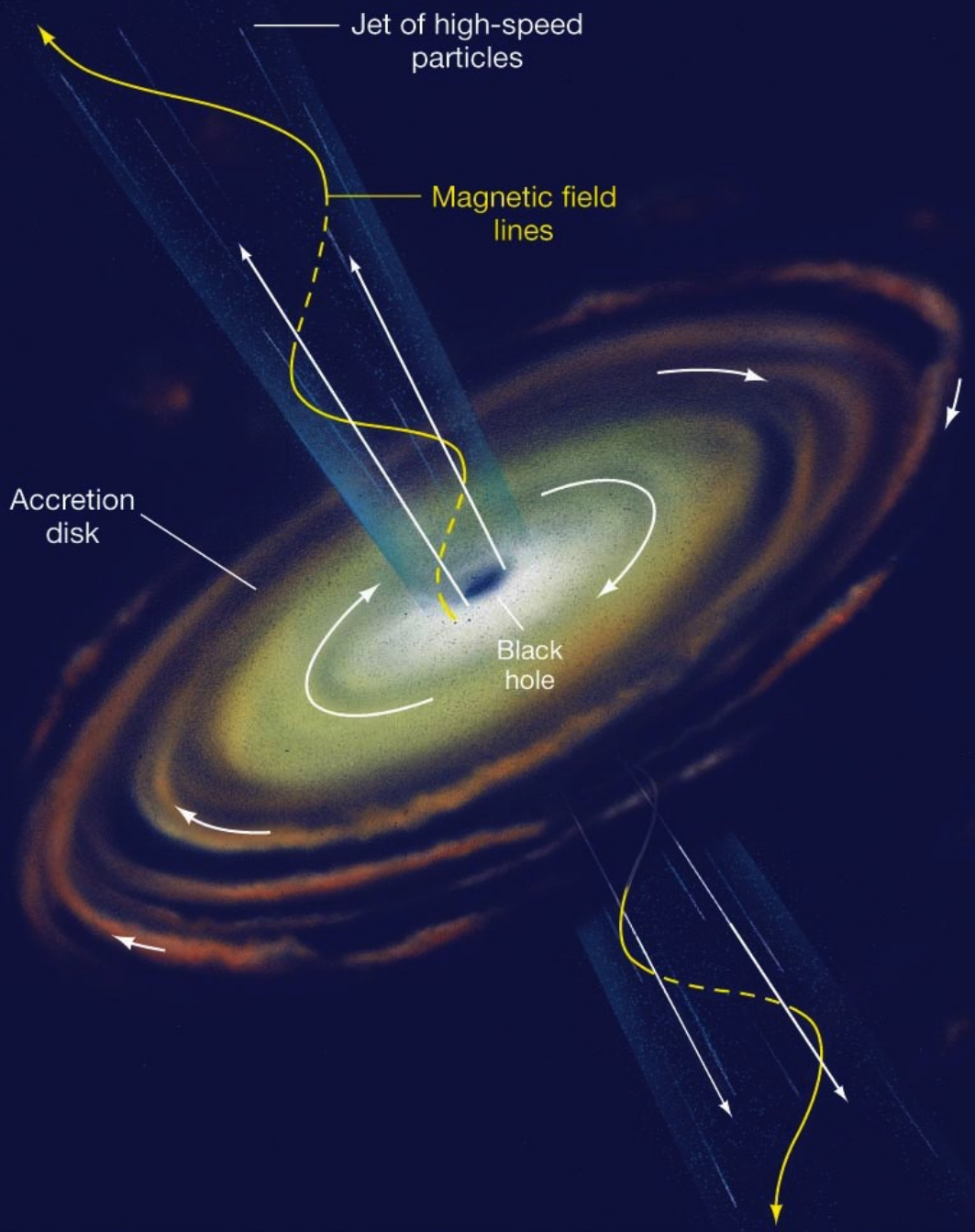
both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

- supernova remnants
- gamma ray bursts

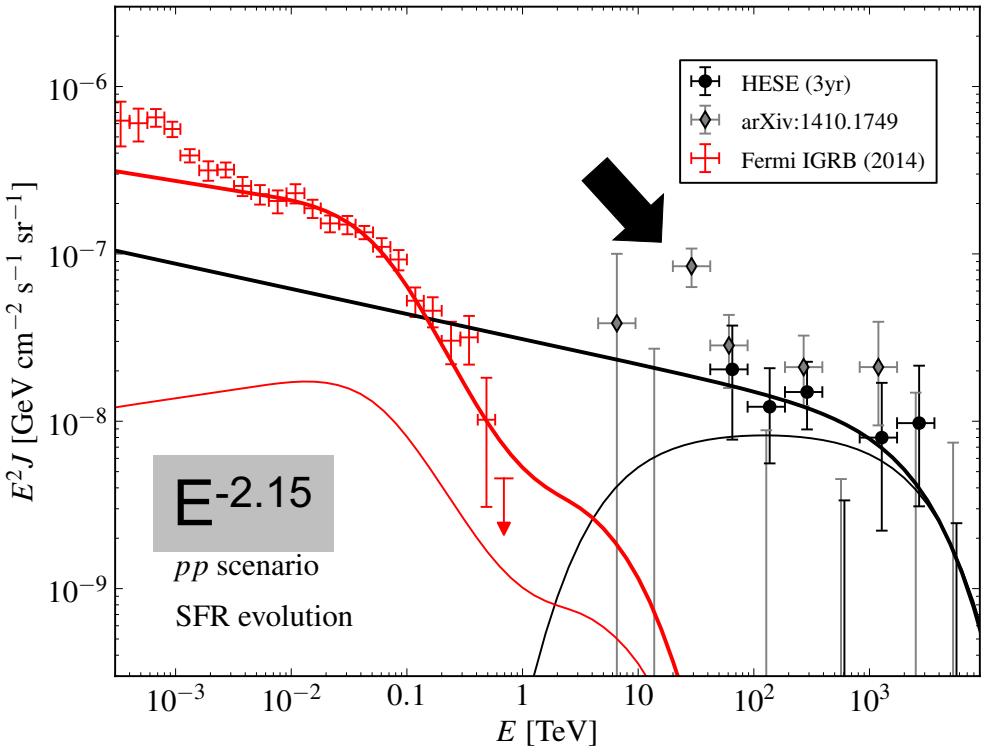
… or active galaxies?

- fast spinning infalling matter comes in contact with rotating black hole
- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes
- plasma from the accretion disk is then flung out along these lines

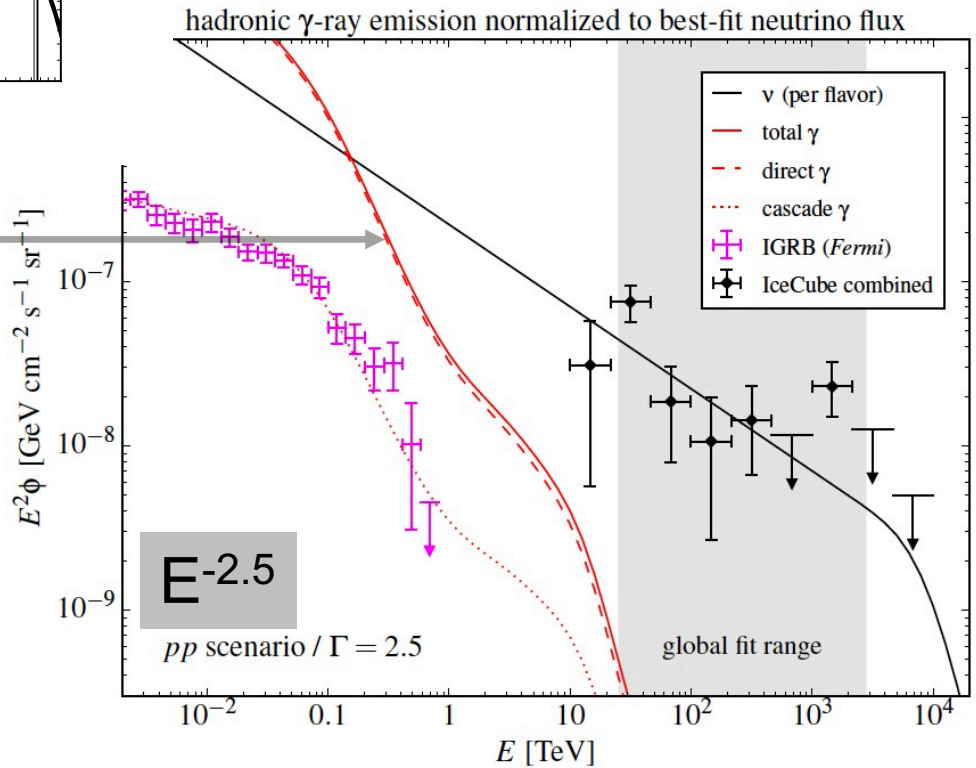


a source opaque to protons that efficiently produces neutrinos is opaque to gamma rays

dark sources with opacity $\tau_{\gamma\gamma} \sim 1$?

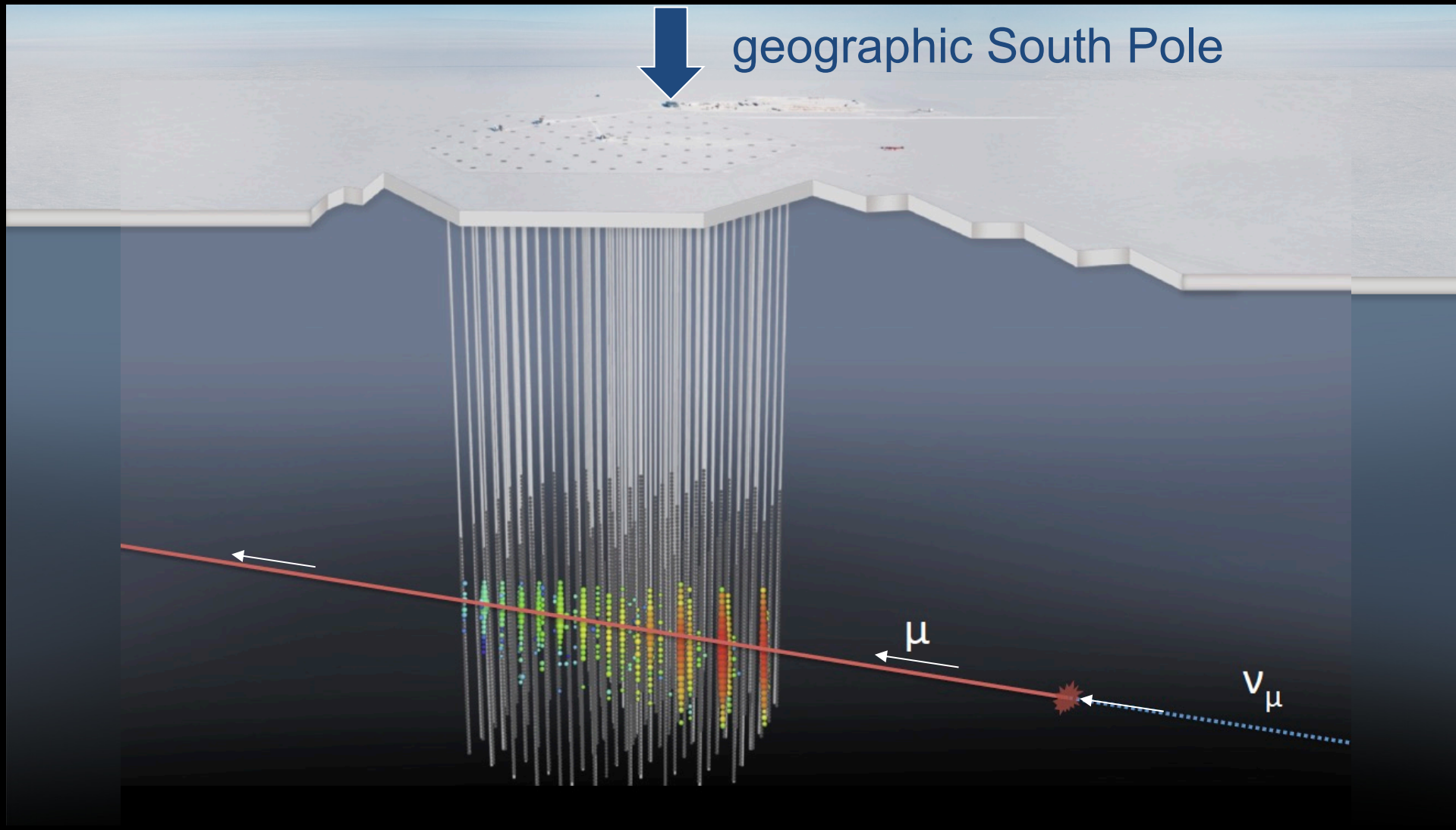


- the pionic photons accompanying the neutrinos lose energy in the source even before reaching the extragalactic background.
- as a result, the photons emerge below Fermi threshold, at MeV energies and below, in X-rays, … radio.




ultra-transparent ice below 1.35 km

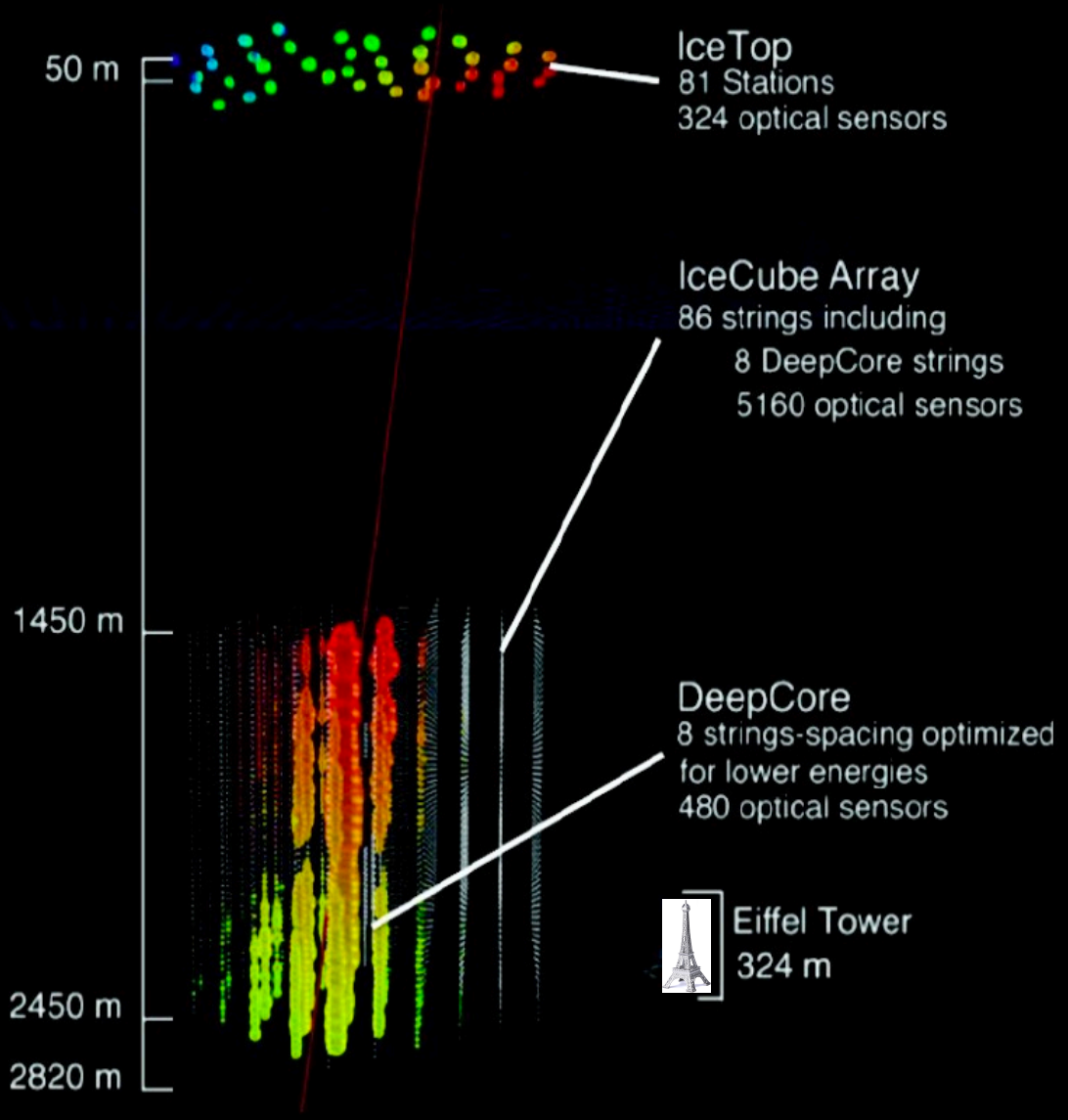
instrument 1 cubic kilometer of natural ice below 1.45 km
with 5160 10-inch photomultiplier tubes



the IceCube Neutrino Observatory

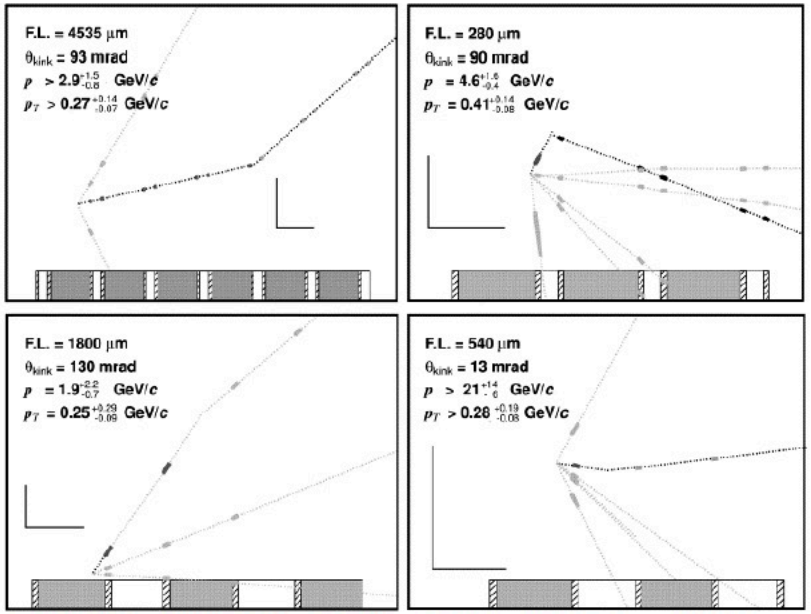
5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution



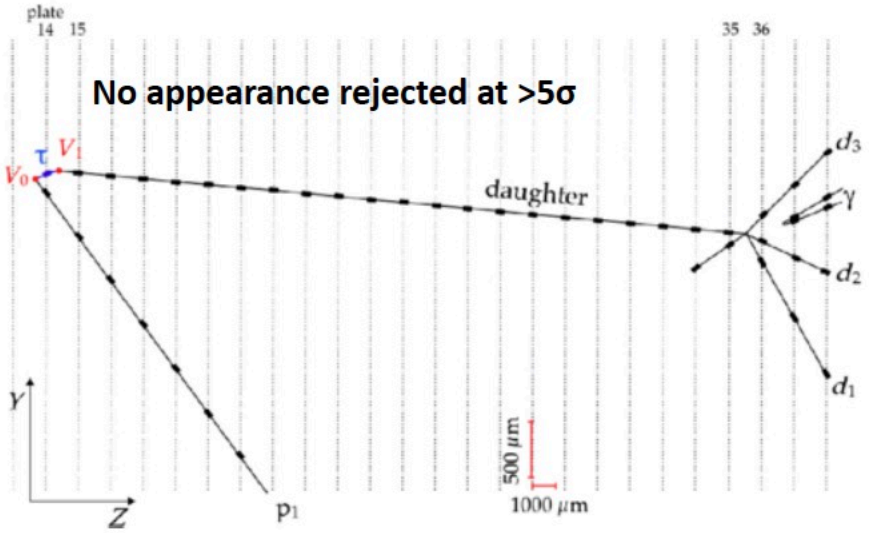
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



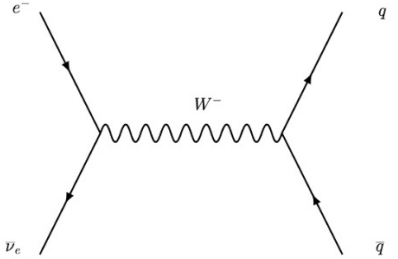
DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

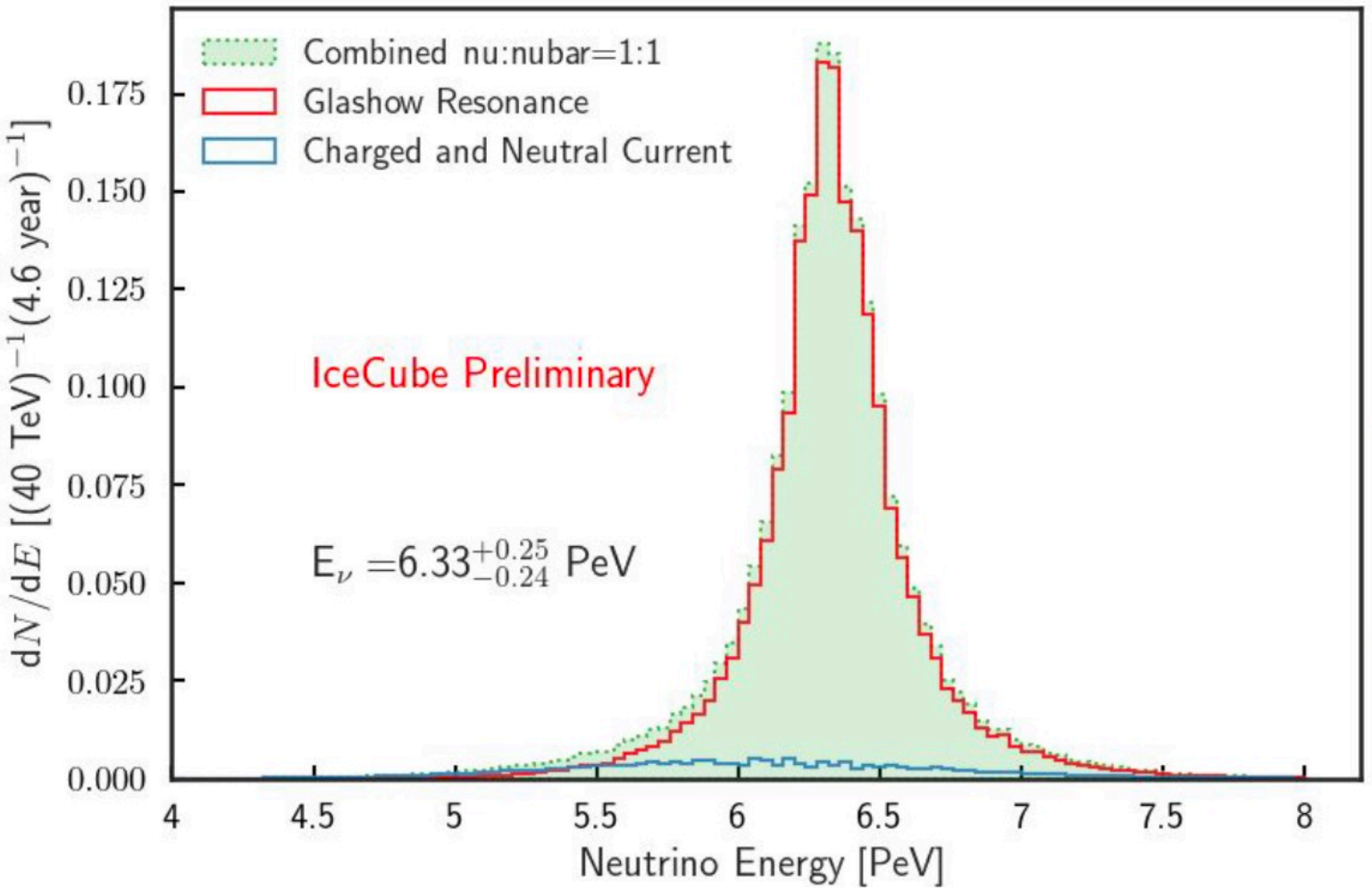
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



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

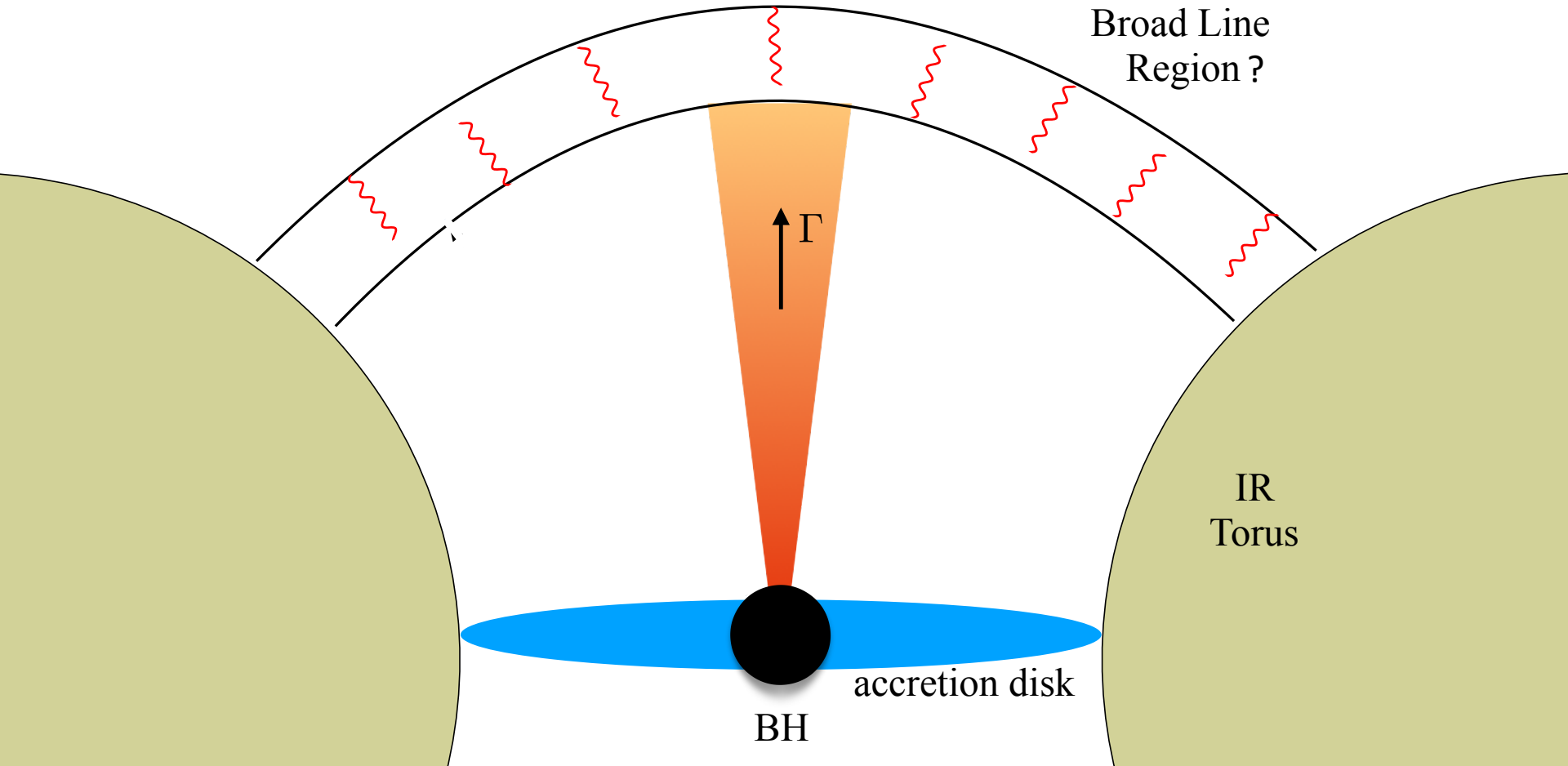
- energy measurement understood
- identification of anti-electron neutrinos

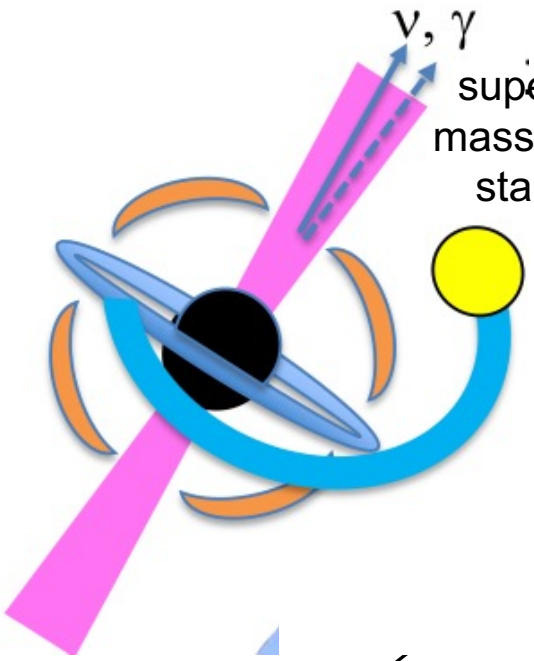




blazar modeling was spectacularly unsuccessful and should be:

- no target to produce neutrinos because the jet is transparent to photons
- neutrinos are produced in bursts




ν, γ
super
massive
star

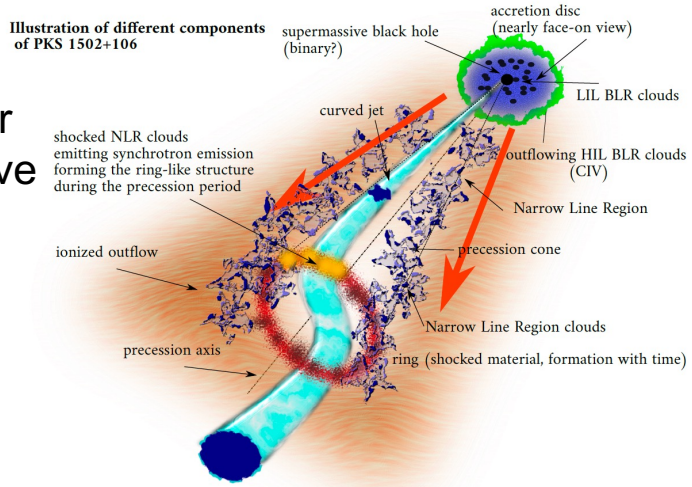
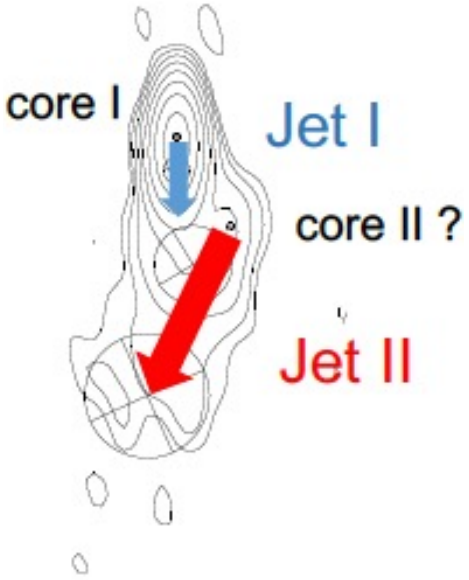
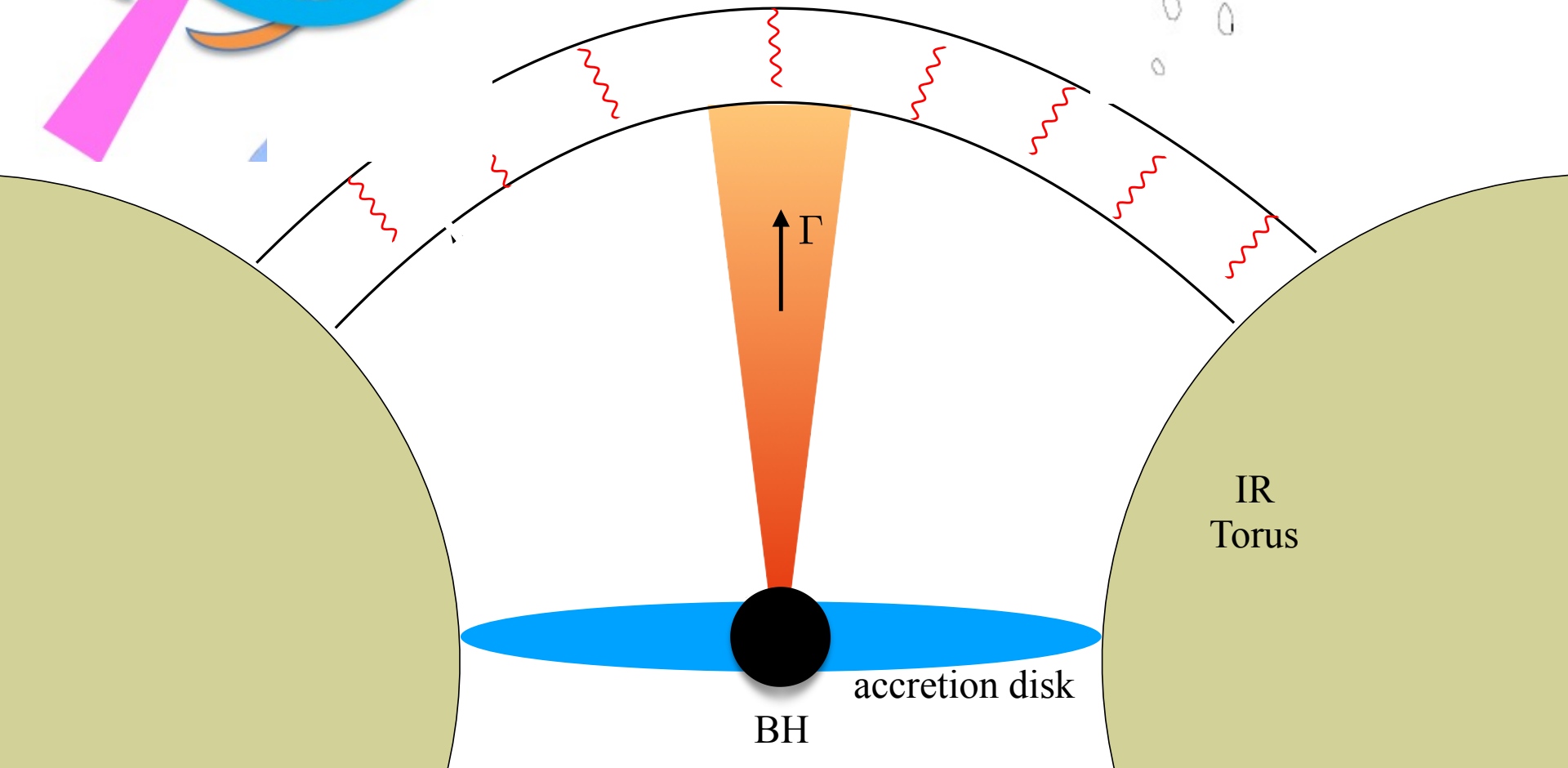


Illustration of different components
of PKS 1502+106
supermassive black hole
(binary?)
accretion disc
(nearly face-on view)
LIL BLR clouds
curved jet
shocked NLR clouds
emitting synchrotron emission
forming the ring-like structure
during the precession period
outflowing HIL BLR clouds
(CIV)
Narrow Line Region
ionized outflow
precession cone
Narrow Line Region clouds
precession axis
ring (shocked material, formation with time)


core I
Jet I
core II ?
Jet II


Γ
IR
Torus
accretion disk
BH

injection rate of cosmic rays in the universe: $\rho L_p = \frac{dE}{dt}$

$$(4\pi t_H)\, E^2_{\nu_\mu}\, \Phi_{\nu_\mu} = \frac{1}{2}\, \tau_{p\gamma}\, [\rho\, L_p] = [\rho\, L_\nu]$$

diffuse flux measured by IceCube

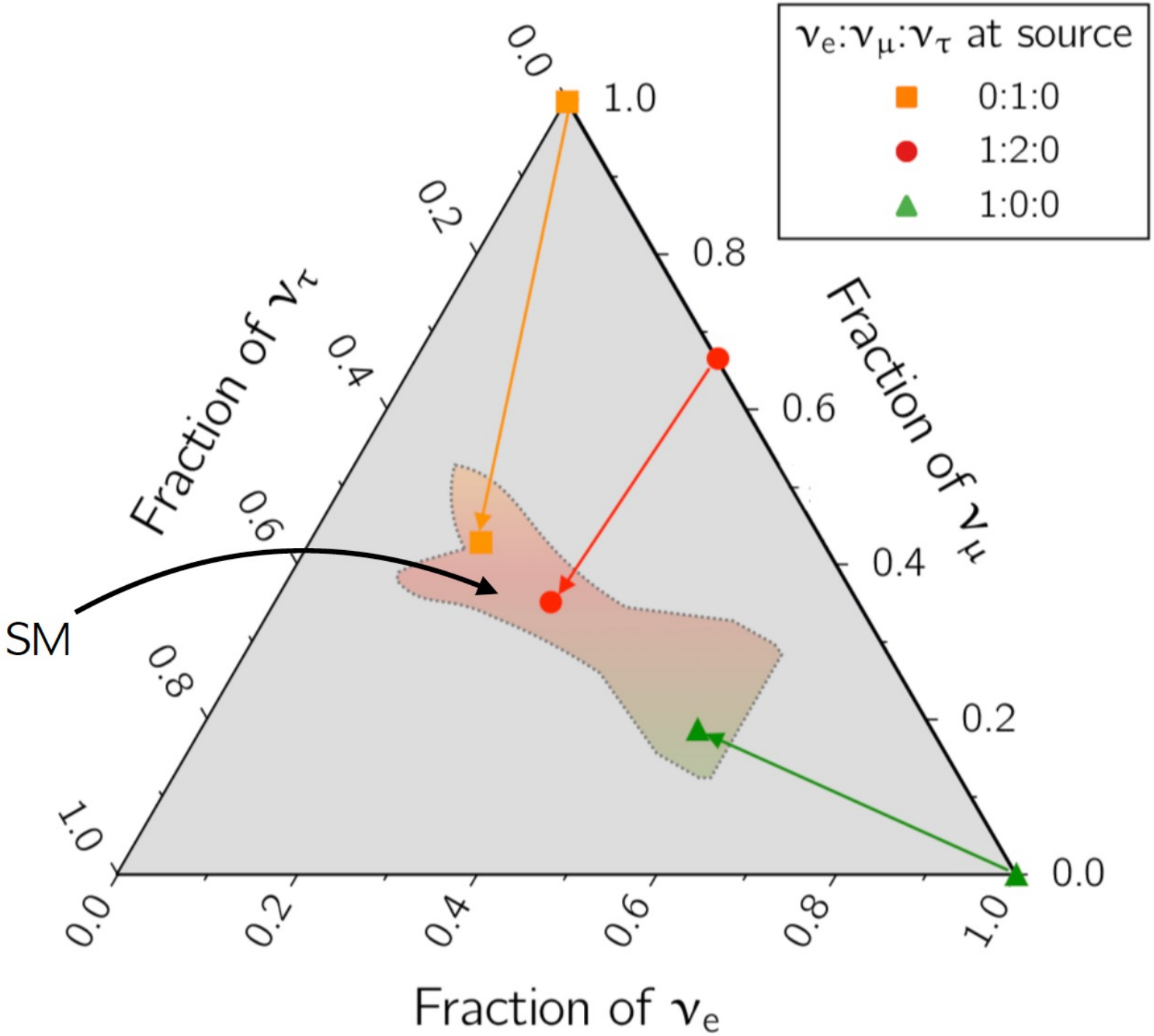
opacity of the source to protons (f_π)

TXS flux (10y average)

solution:

$$\rho \simeq 10^{-11} \mathrm{per\,Mpc}^3 \ \text{ and } \ \tau_{\mathrm{p}\gamma} \geq 0.4$$

- sources are opaque to gamma rays with $\tau_{\gamma\gamma} >> \tau_{p\gamma} \geq 0.4$
- for instance, ~ few % of blazars


ν_e:ν_μ:ν_τ at source
0:1:0
1:2:0
1:0:0
SM
Fraction of ν_e
Fraction of ν_μ
Fraction of ν_τ
0.0
0.2
0.4
0.6
0.8
1.0