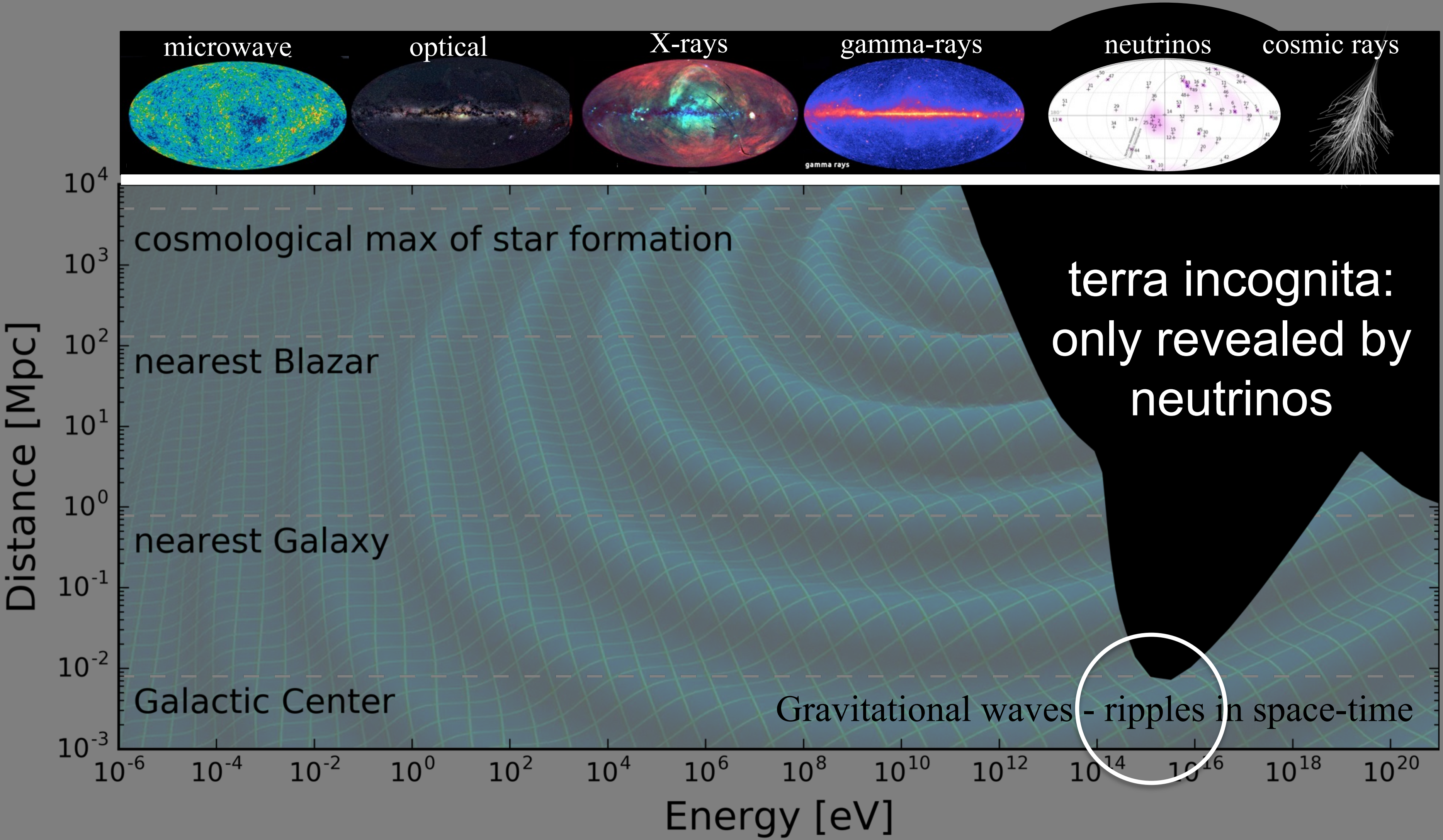
IceCube: the discovery of cosmic neutrinos
francis halzen

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

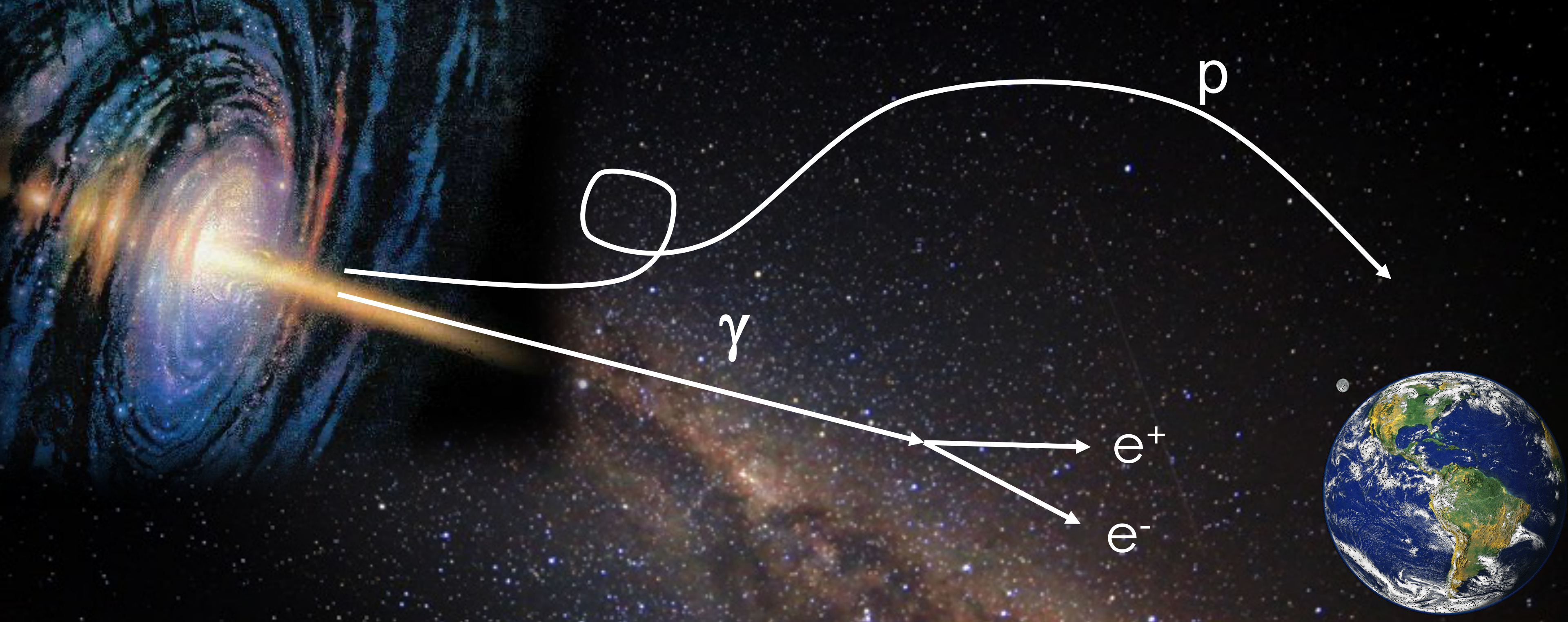
IceCube.wisc.edu

highest energy "radiation" from the Universe: neutrinos and cosmic rays



Universe is opaque above ~100 TeV energy

The opaque Universe

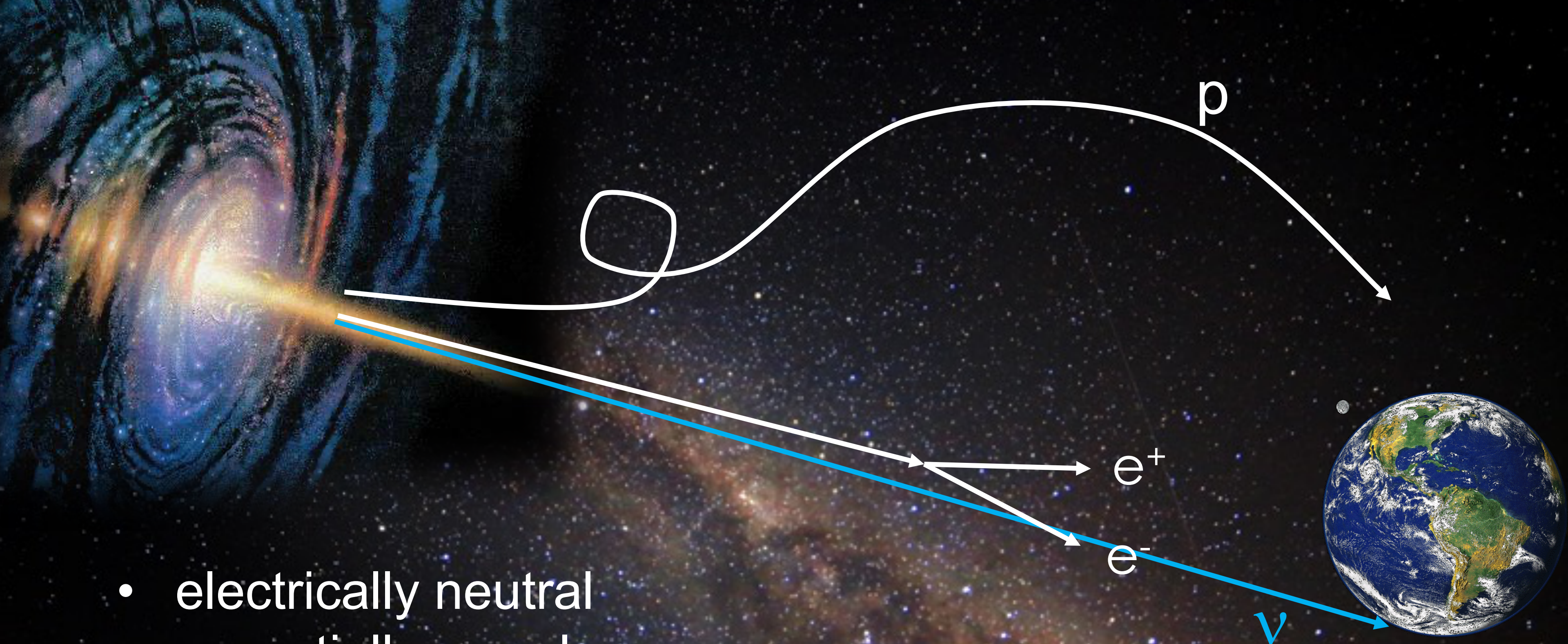


$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

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

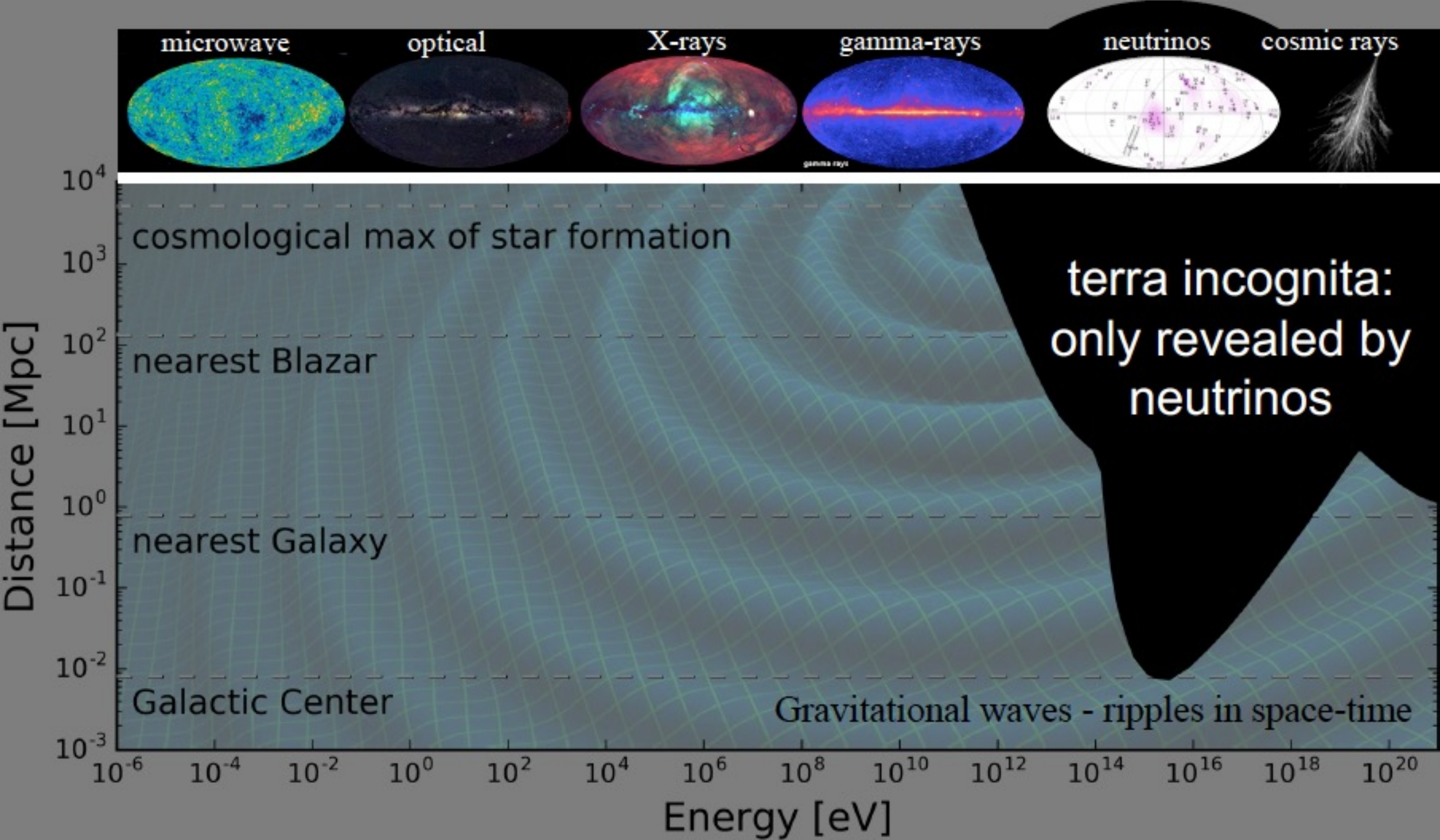
enter: neutrinos

Neutrinos? Perfect Messenger



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

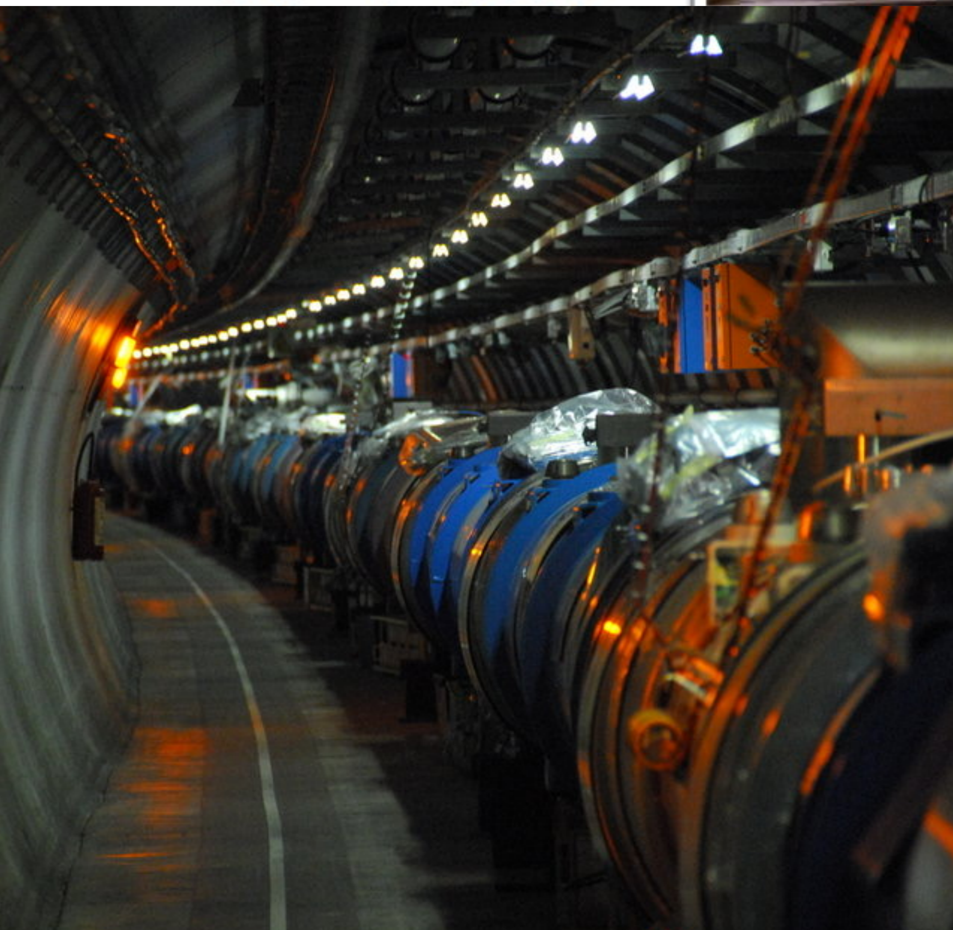
- … but difficult to detect

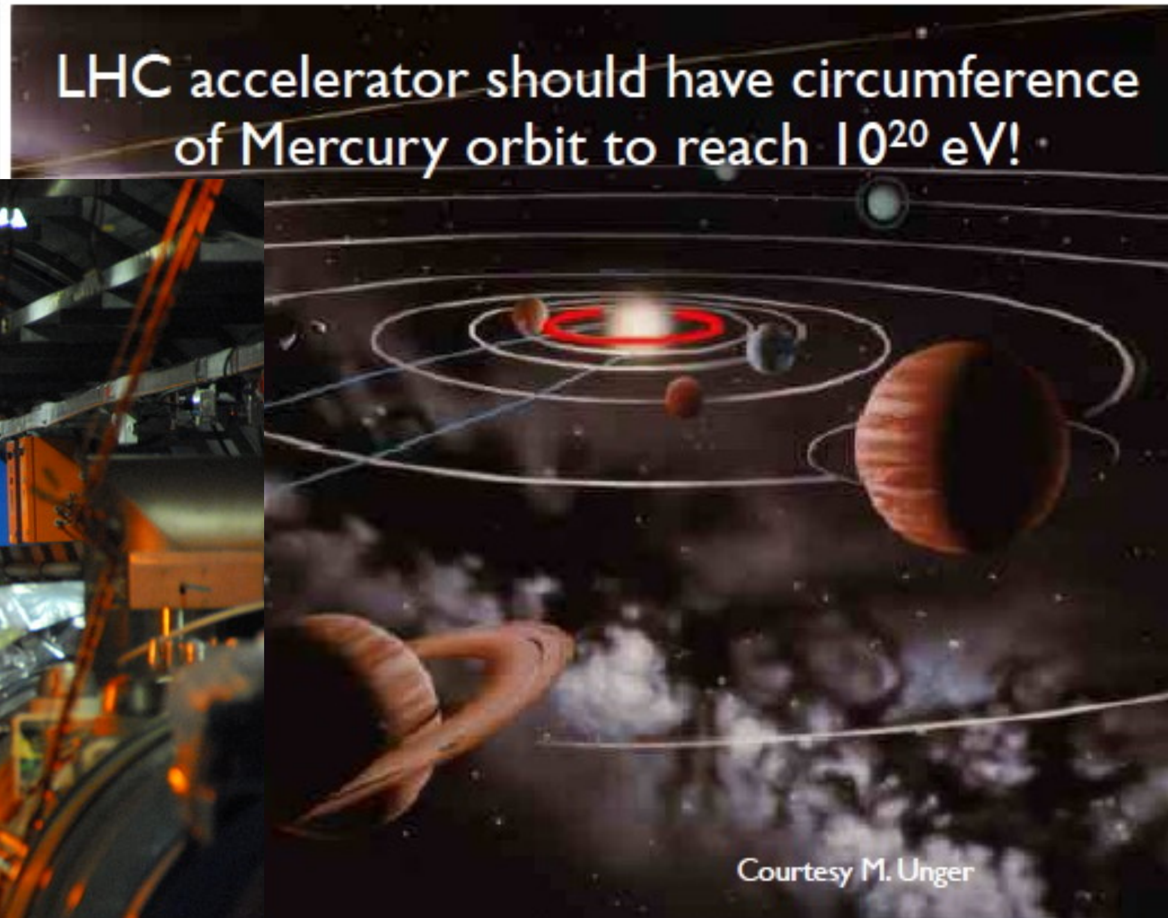


- the extreme Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos

highest energy radiation from the Universe: protons!

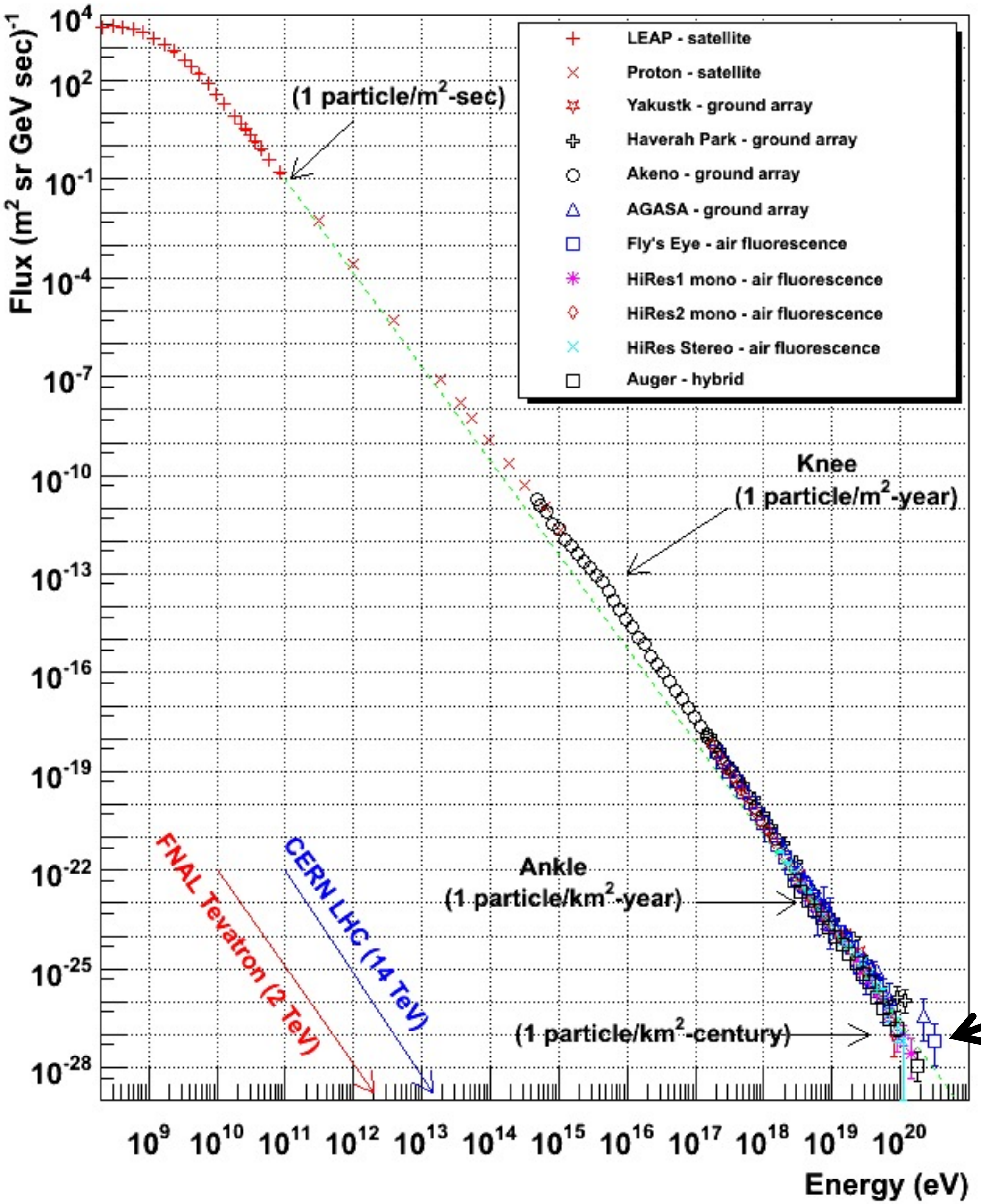
high energy
high luminosity





Fly’s Eye 1991
300,000,000 TeV

origin of cosmic rays: oldest problem in astronomy



cosmic ray challenge

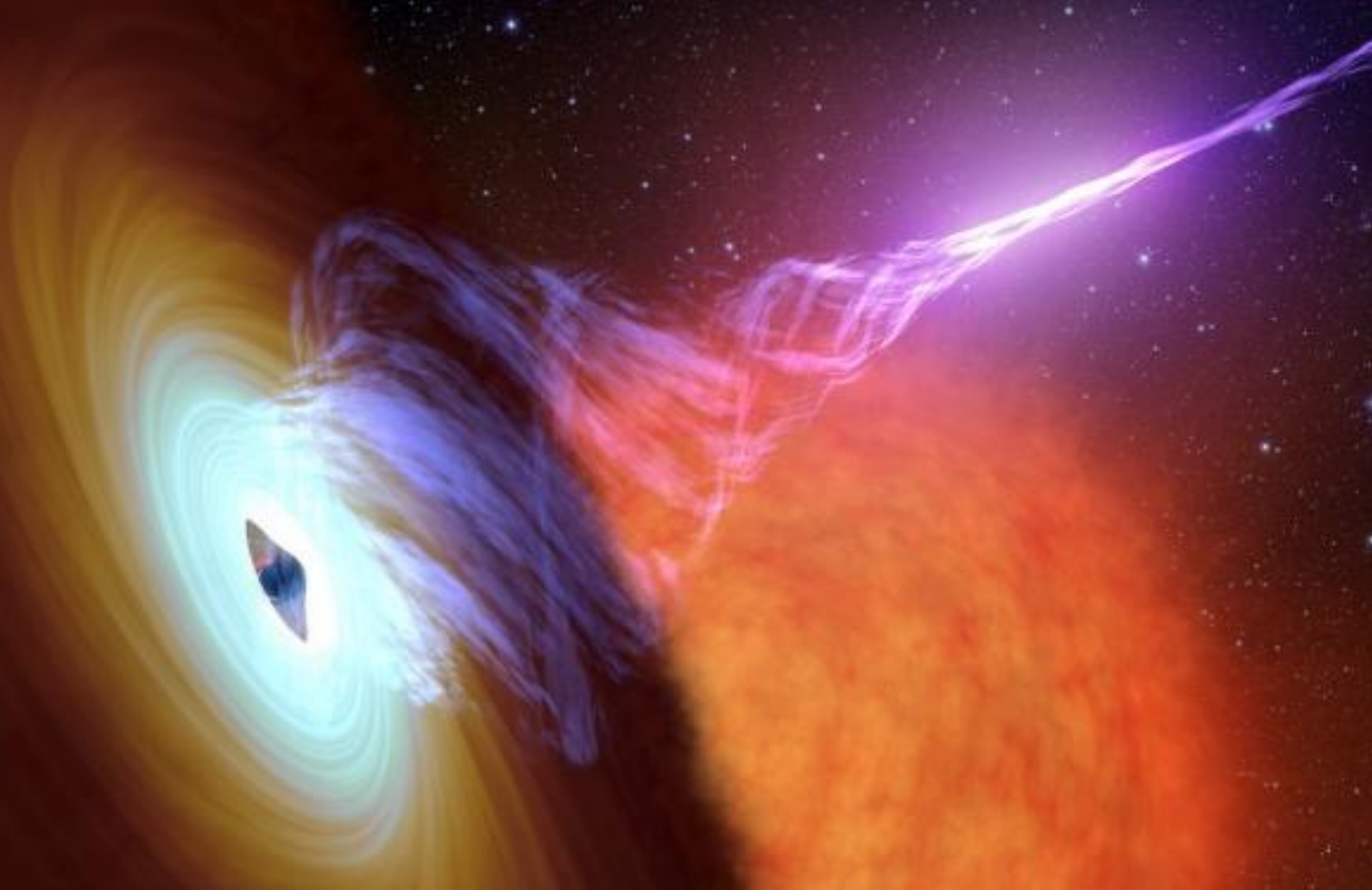
both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

- supernova remnants
- gamma ray bursts

… or active galaxies?

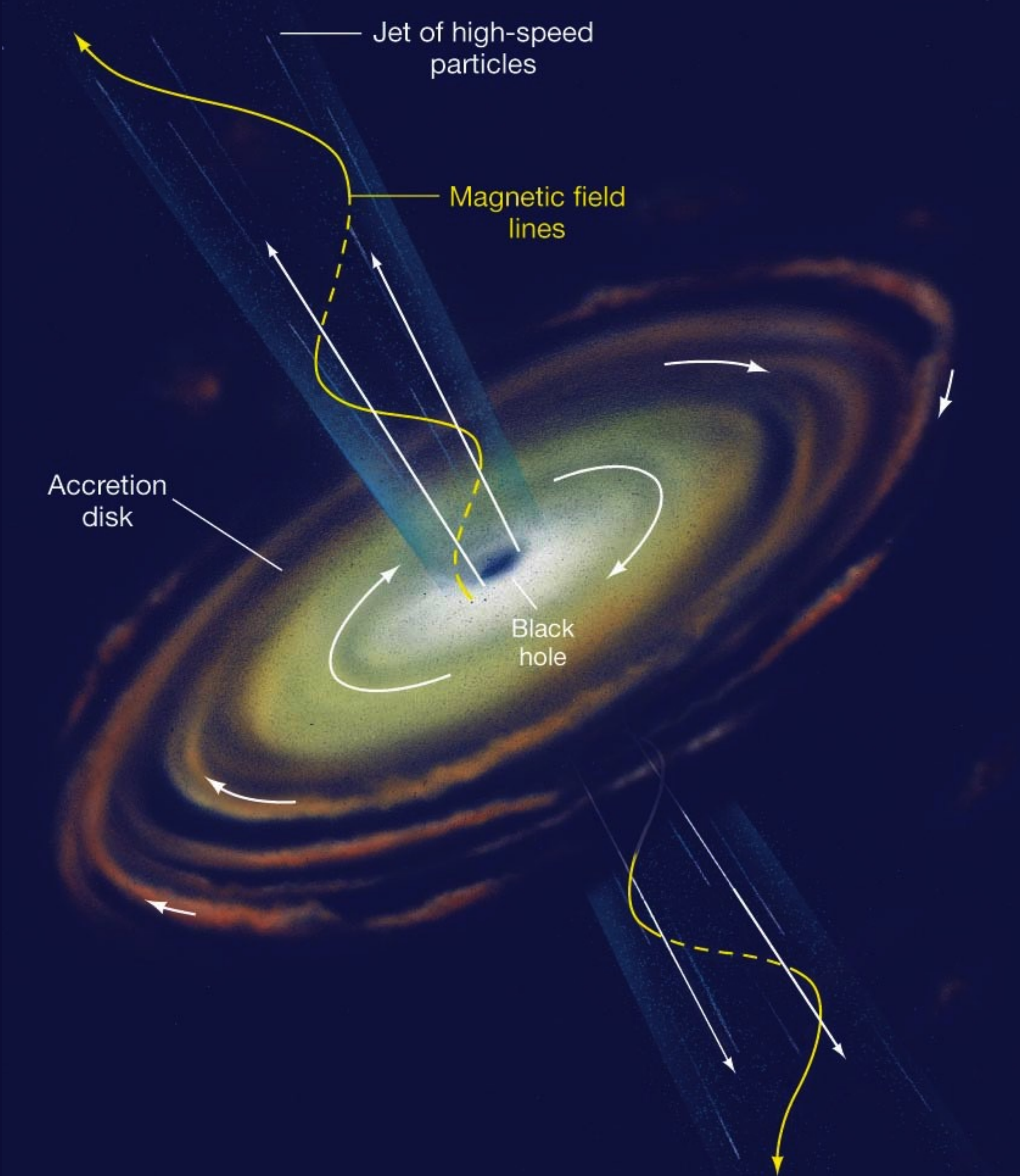
some of the matter falling into a supermassive black is accelerated in a jet along its rotation axis

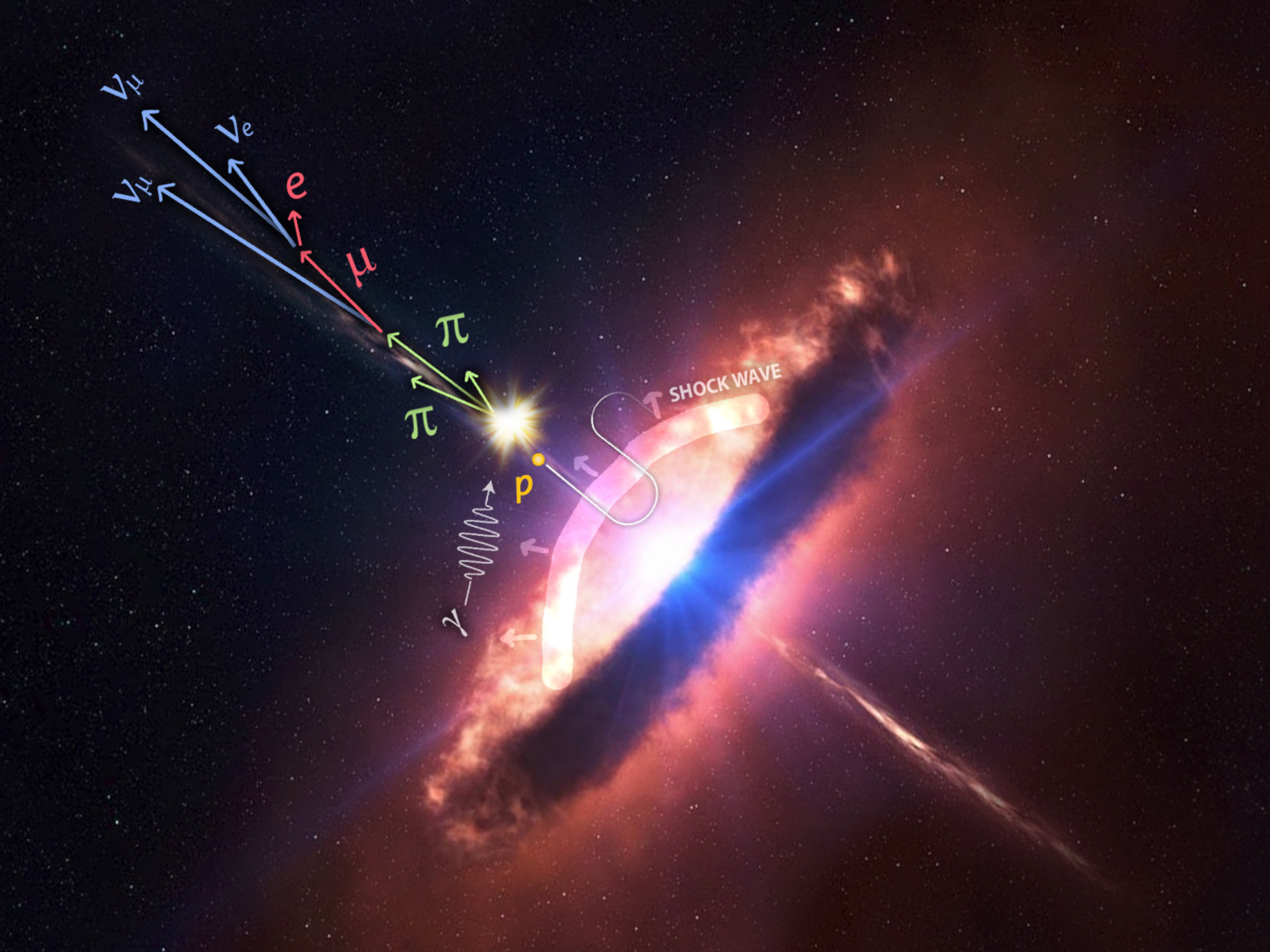


- fast spinning infalling matter comes in contact with rotating black hole

- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes

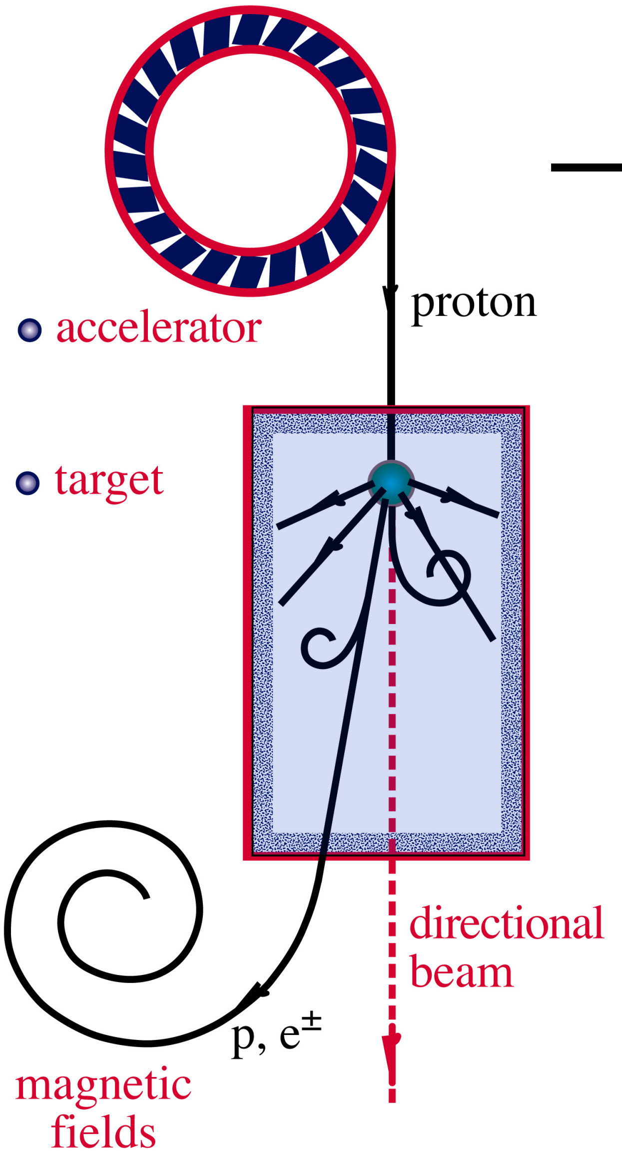
- plasma from the accretion disk is then flung out along these lines





νμ
νe
e
νμ
μ
π
π
SHOCK WAVE
p
γ

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

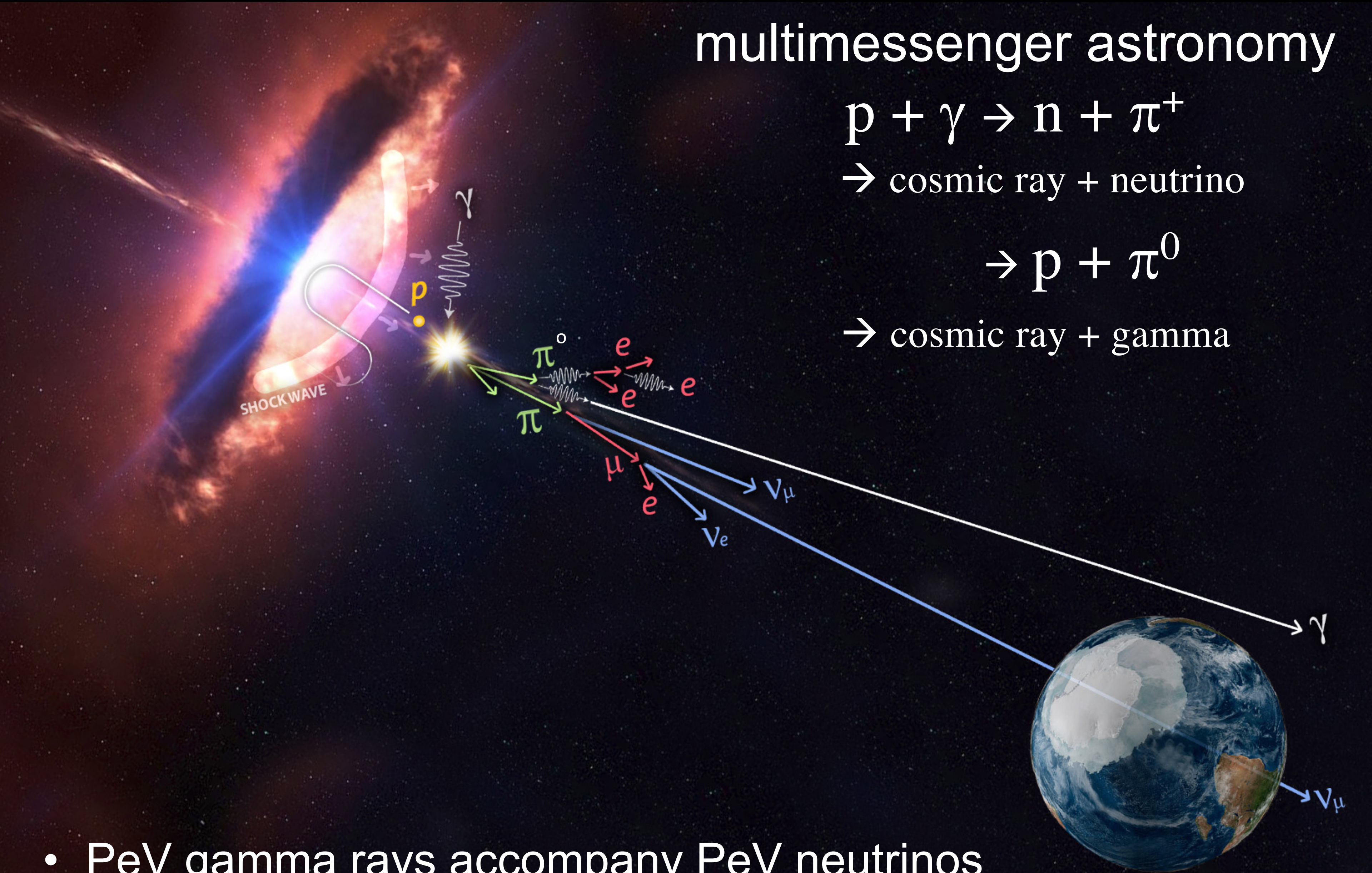
multimessenger astronomy

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

→ cosmic ray + neutrino

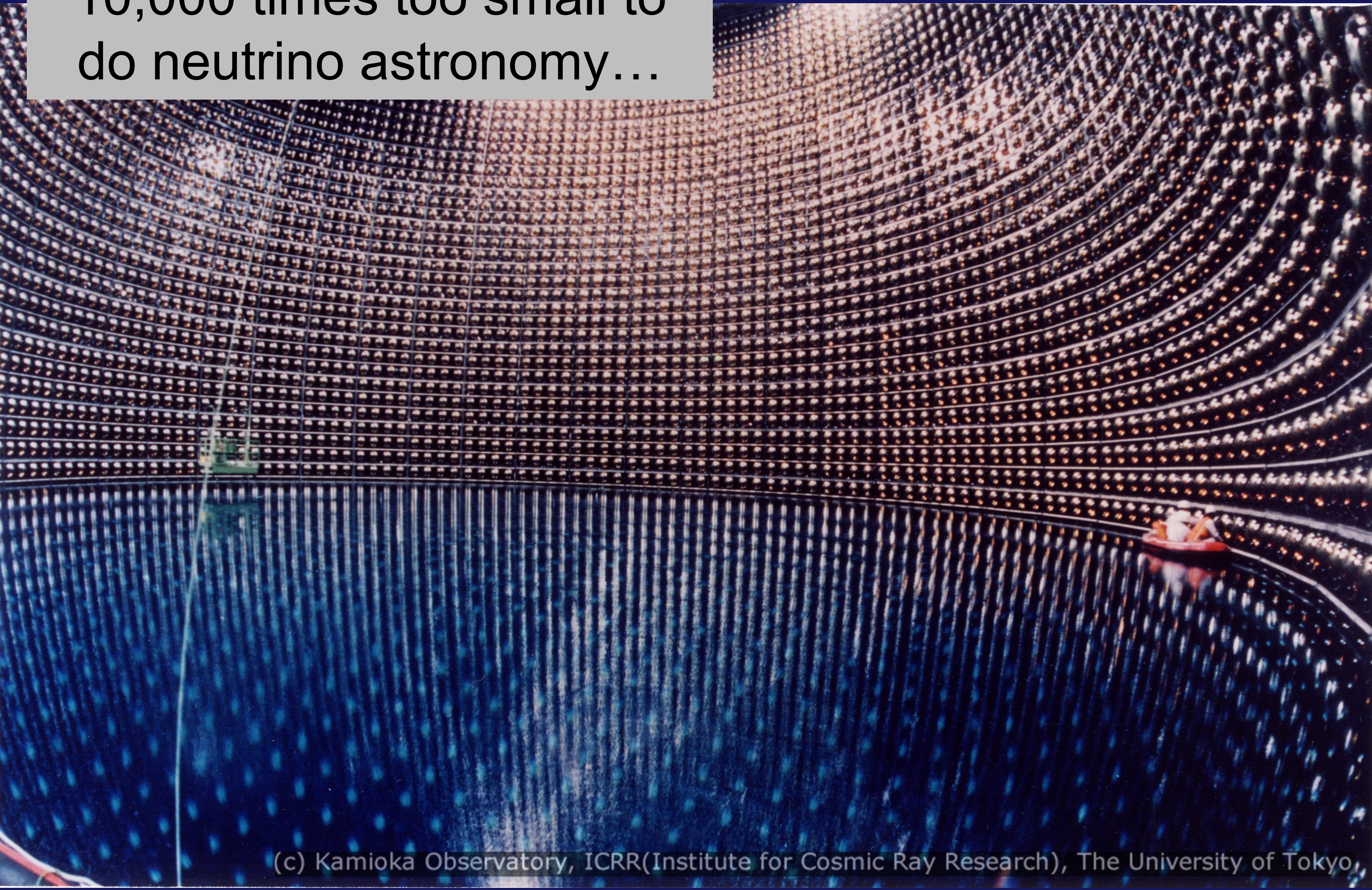
$$\rightarrow p + \pi^{0}$$

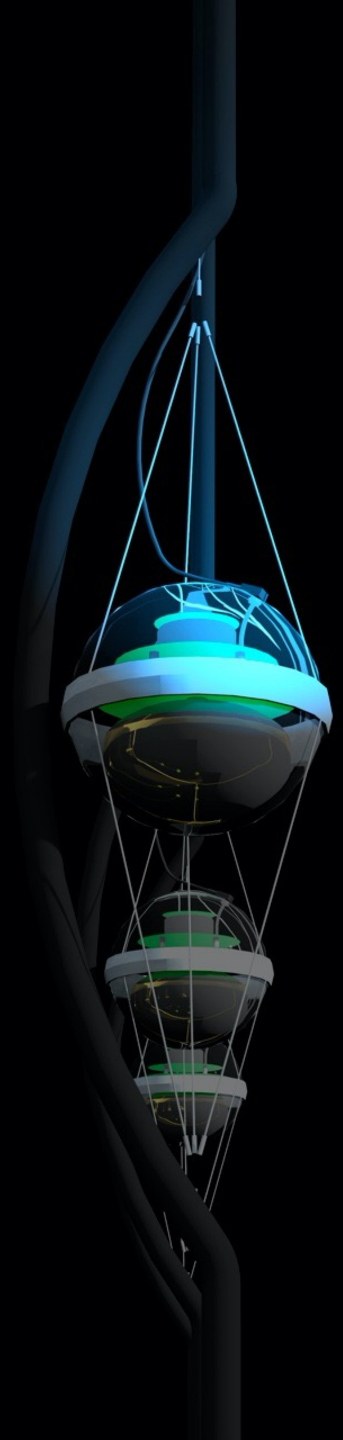
→ cosmic ray + gamma



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

10,000 times too small to do neutrino astronomy…





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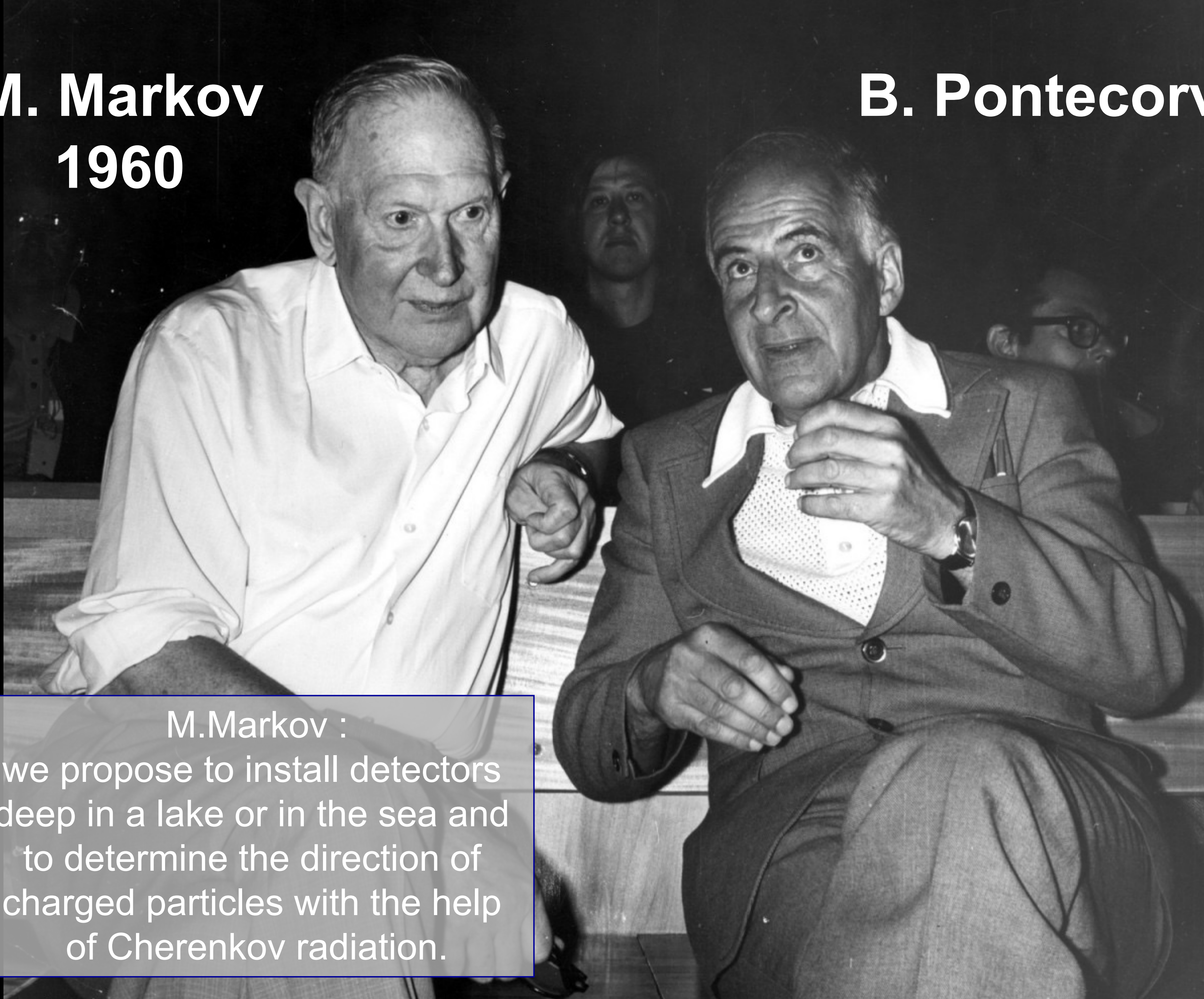
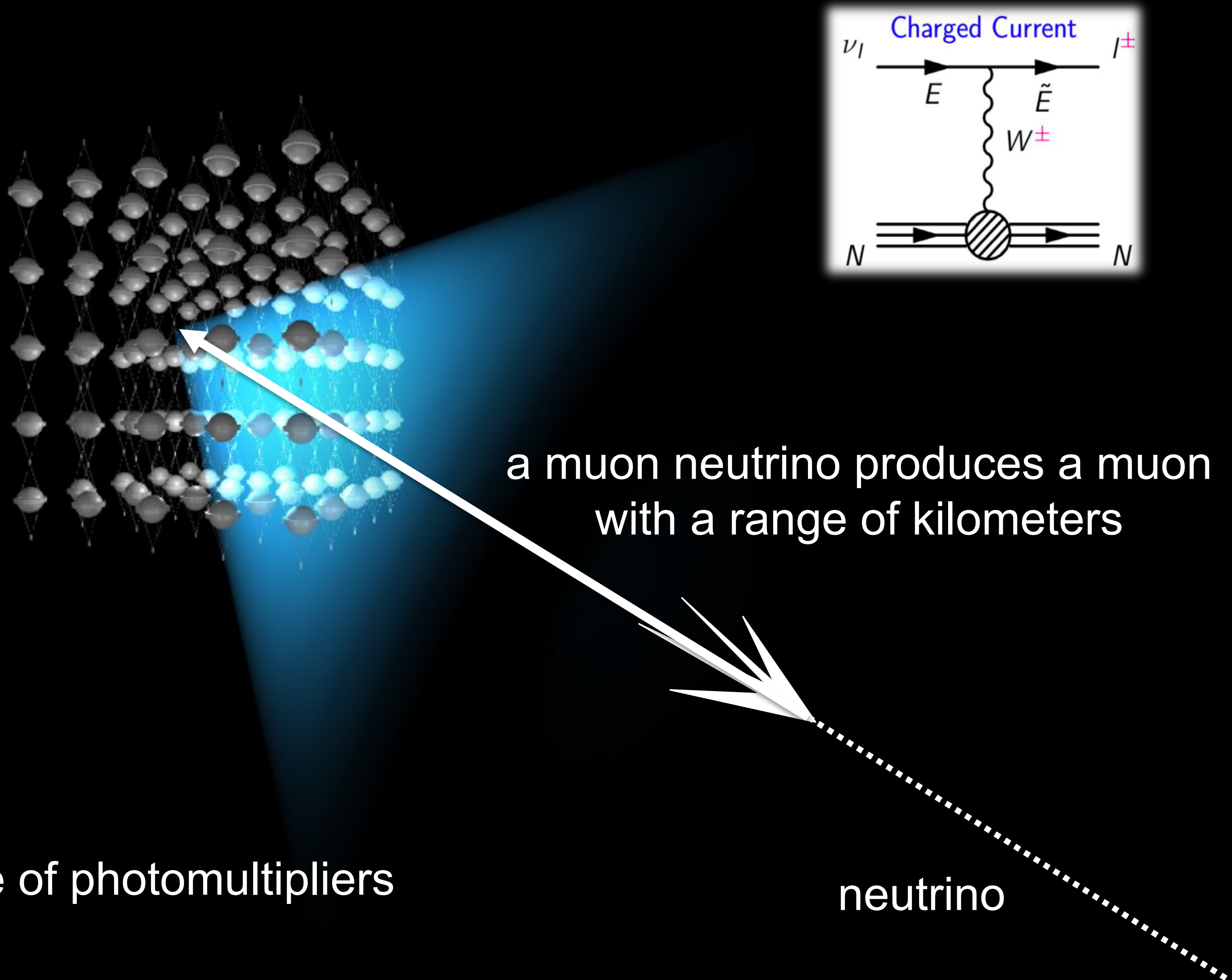


M. Markov
1960

B. Pontecorvo

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



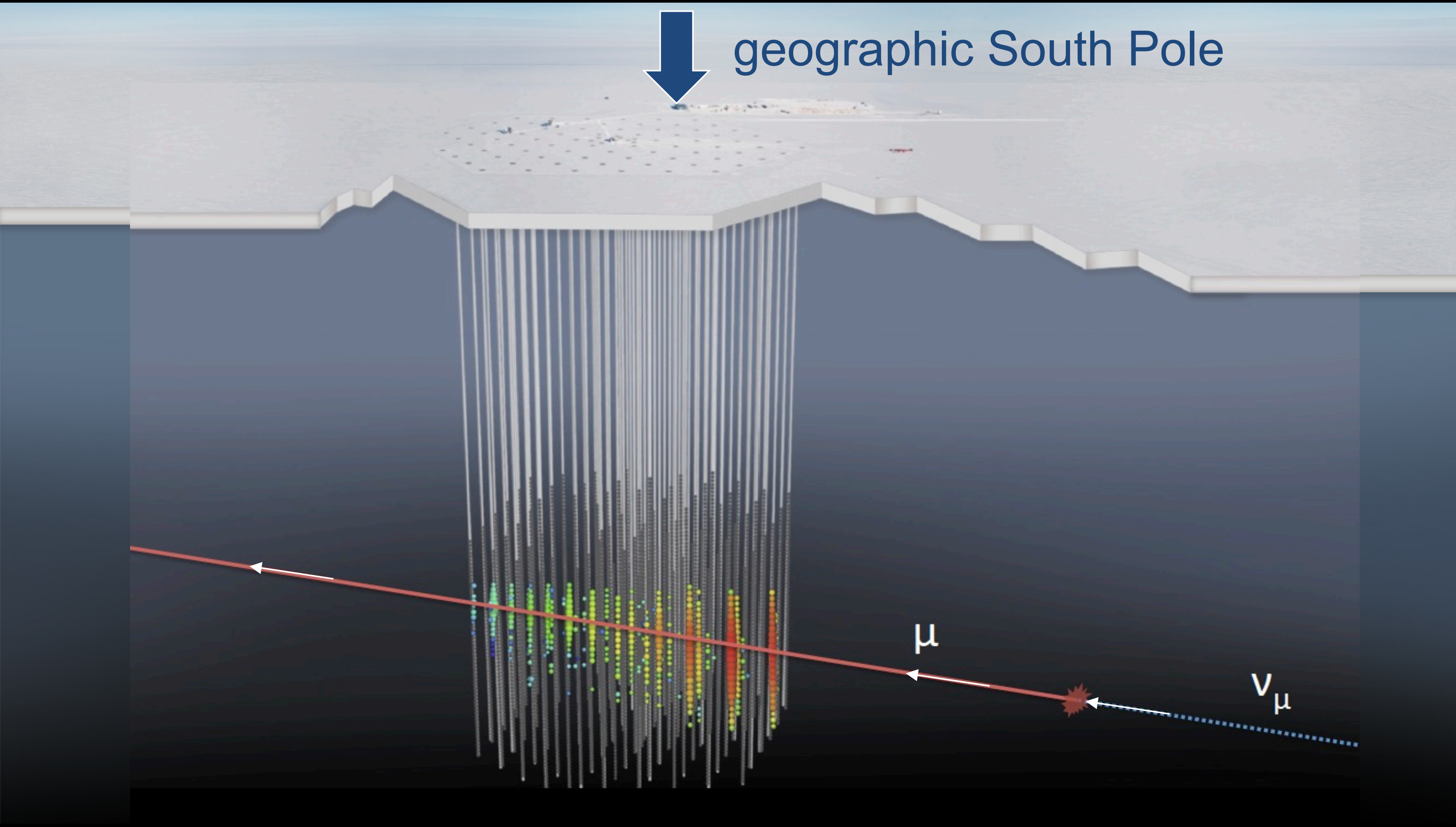
- lattice of photomultipliers

standing on the shoulder of giants

- 1987: DUMAND test string
- Lake Baikal experiment

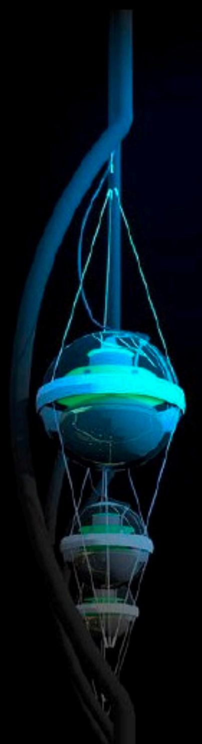
… success with Baikal and Antares

instrument 1 cubic kilometer of natural ice below 1.45 km



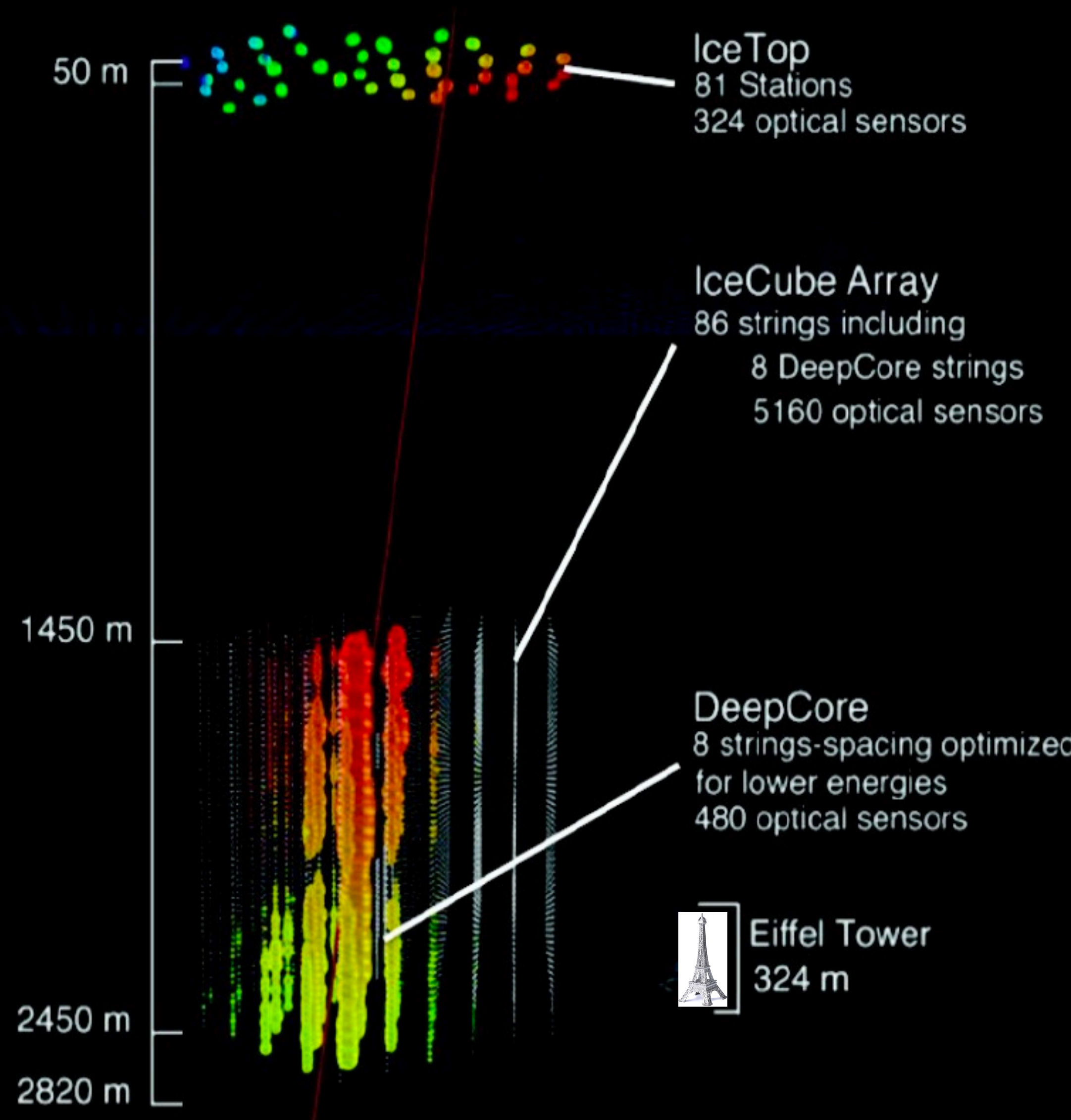

ultra-transparent ice below 1.35 km

the IceCube Neutrino Observatory

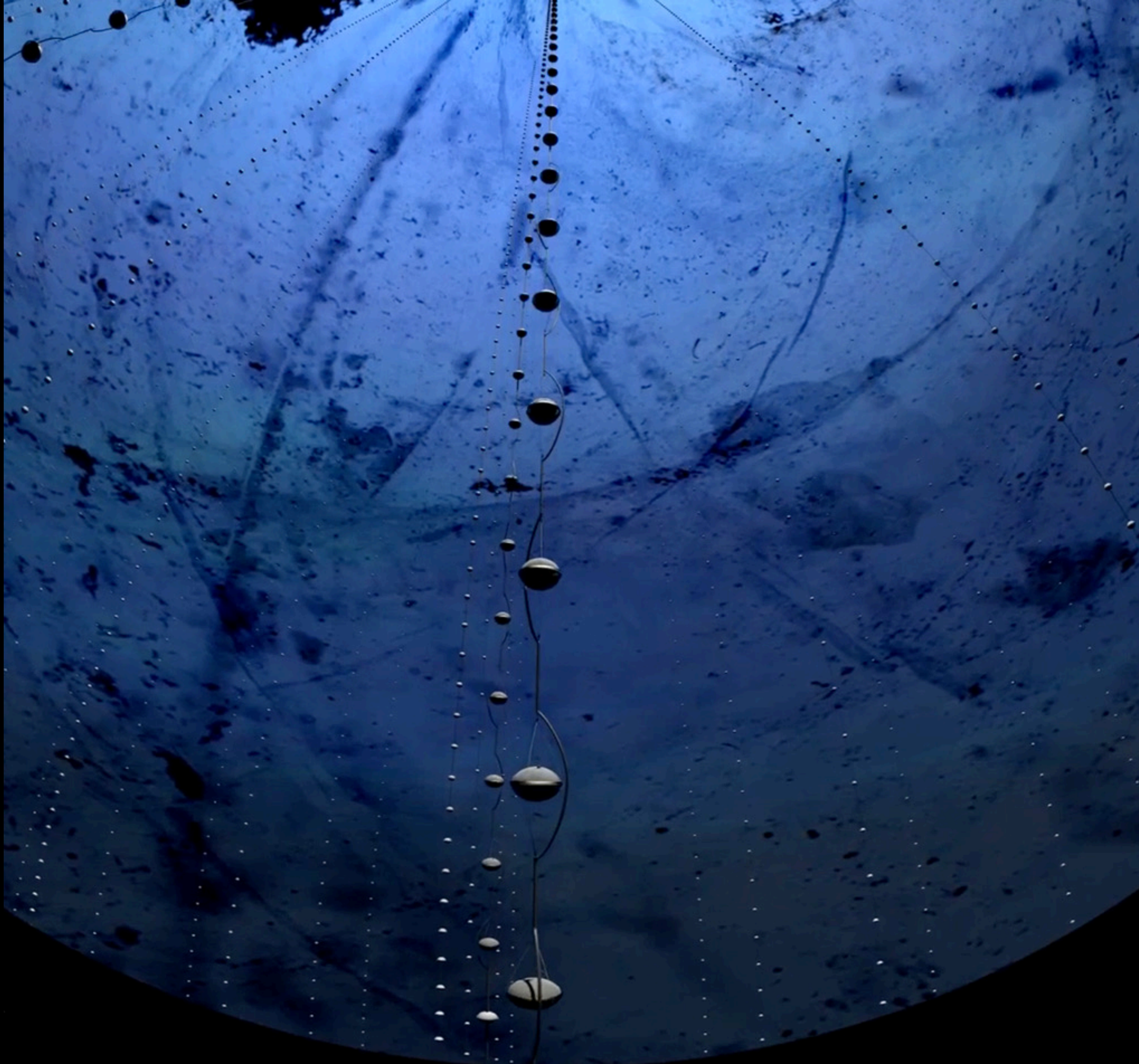


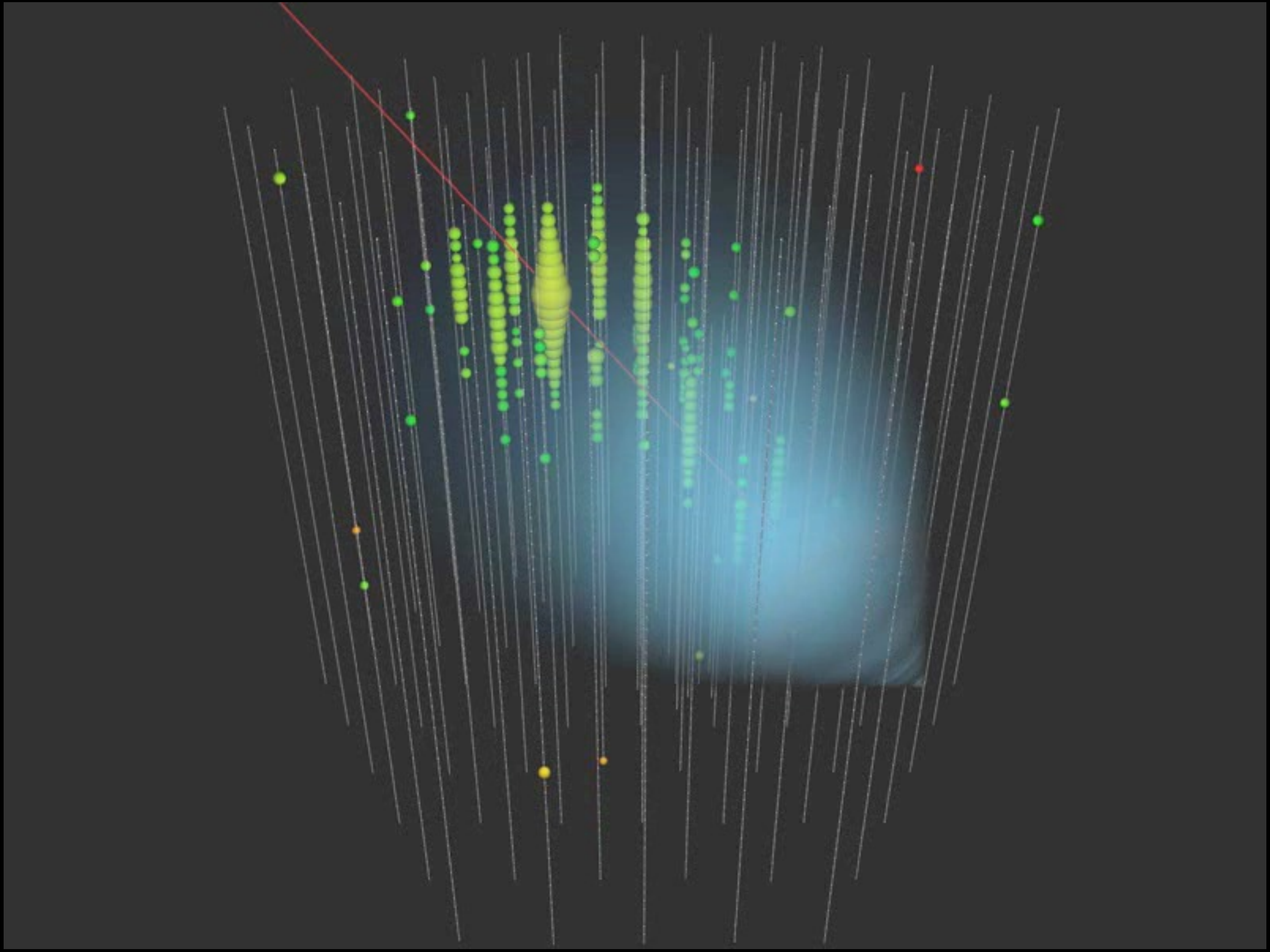
5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution



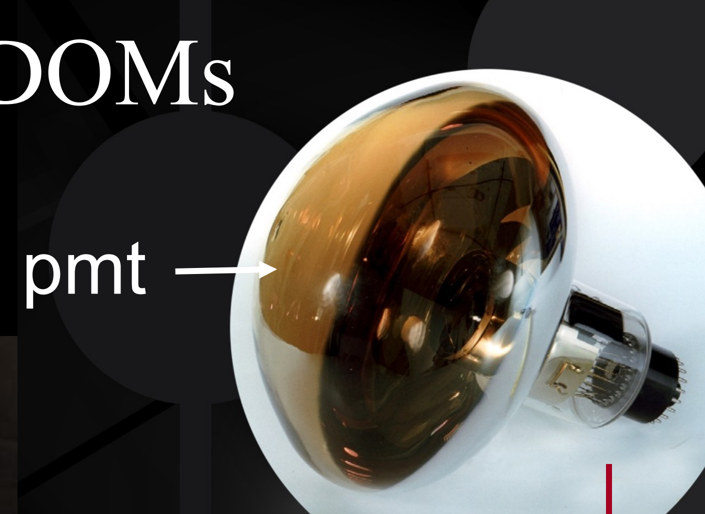
photomultiplier tube -10 inch

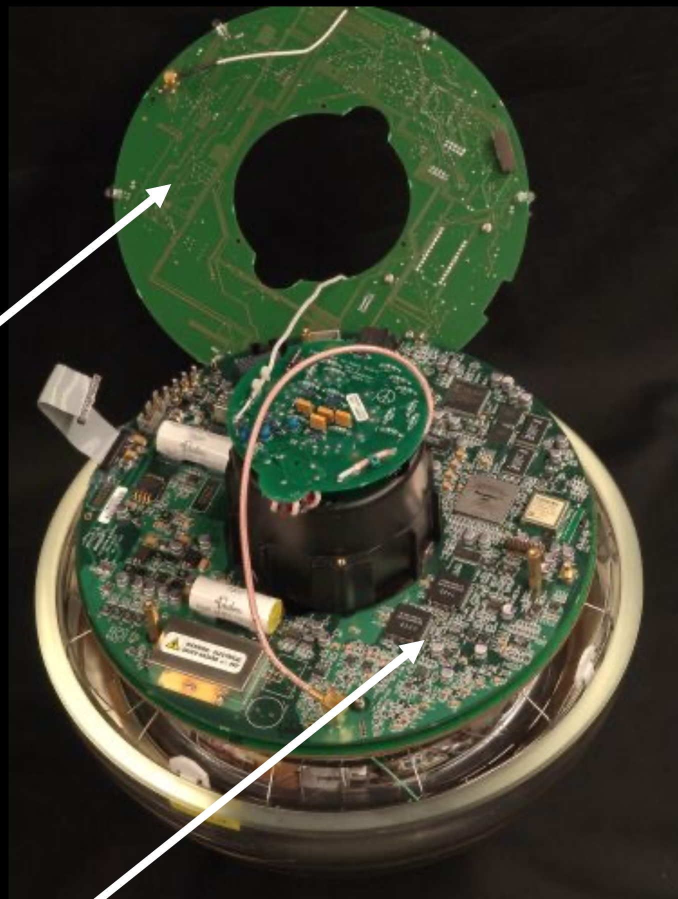


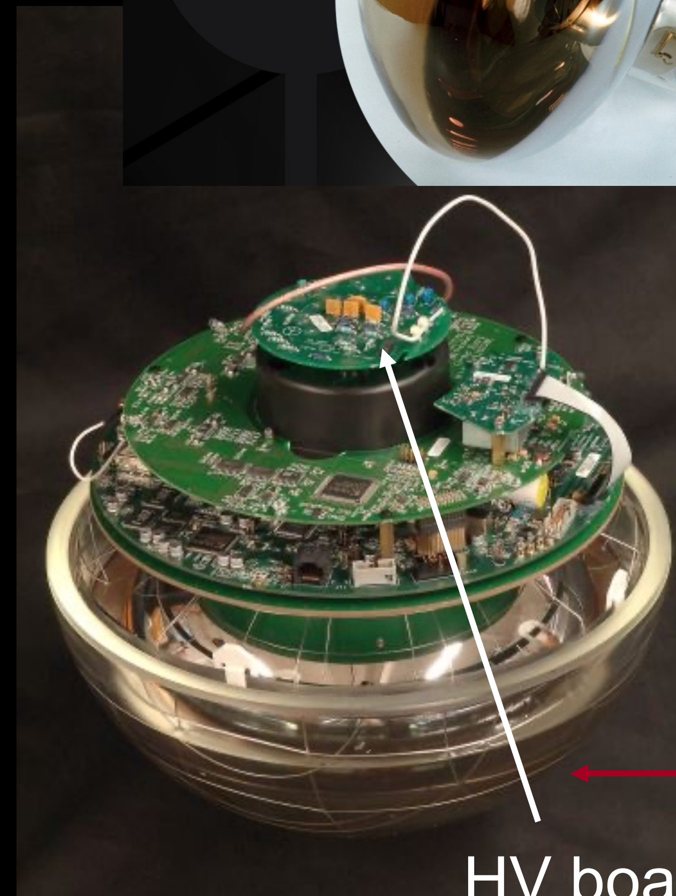


muon track: color is time; number of photons is energy

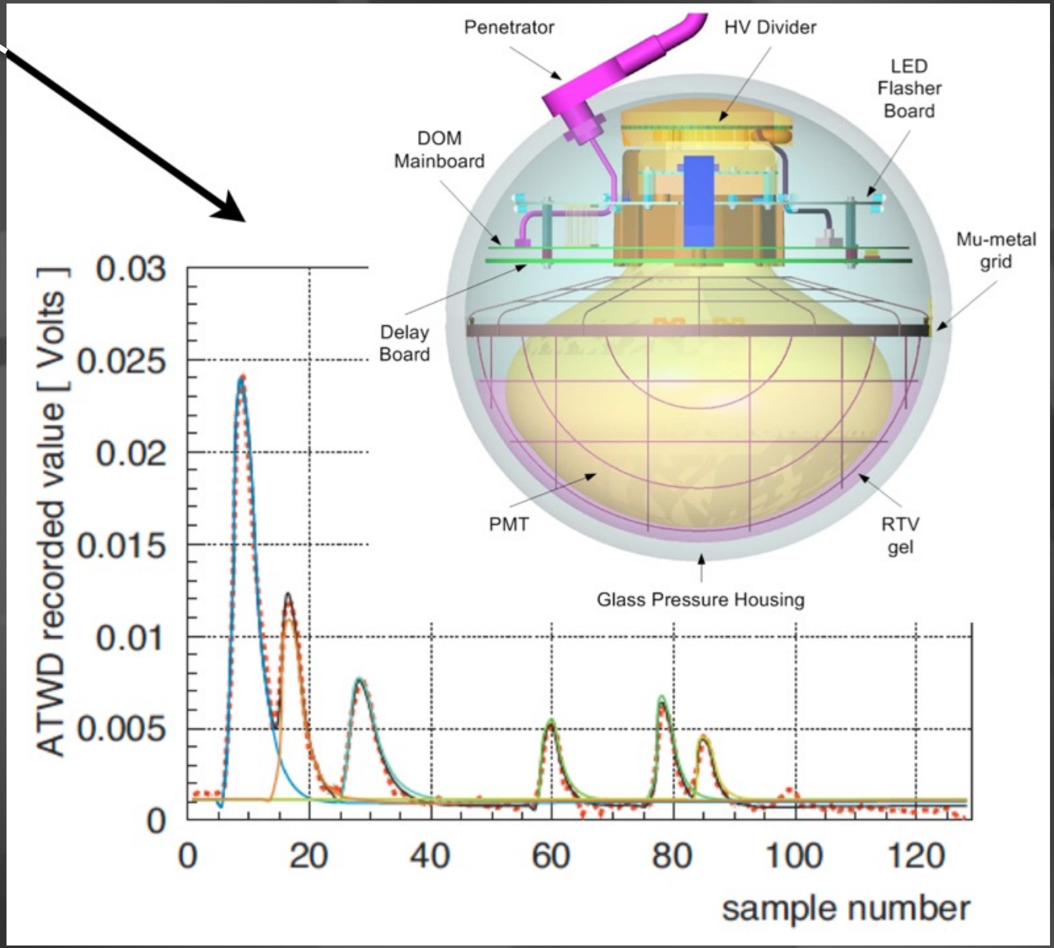
architecture of independent DOMs



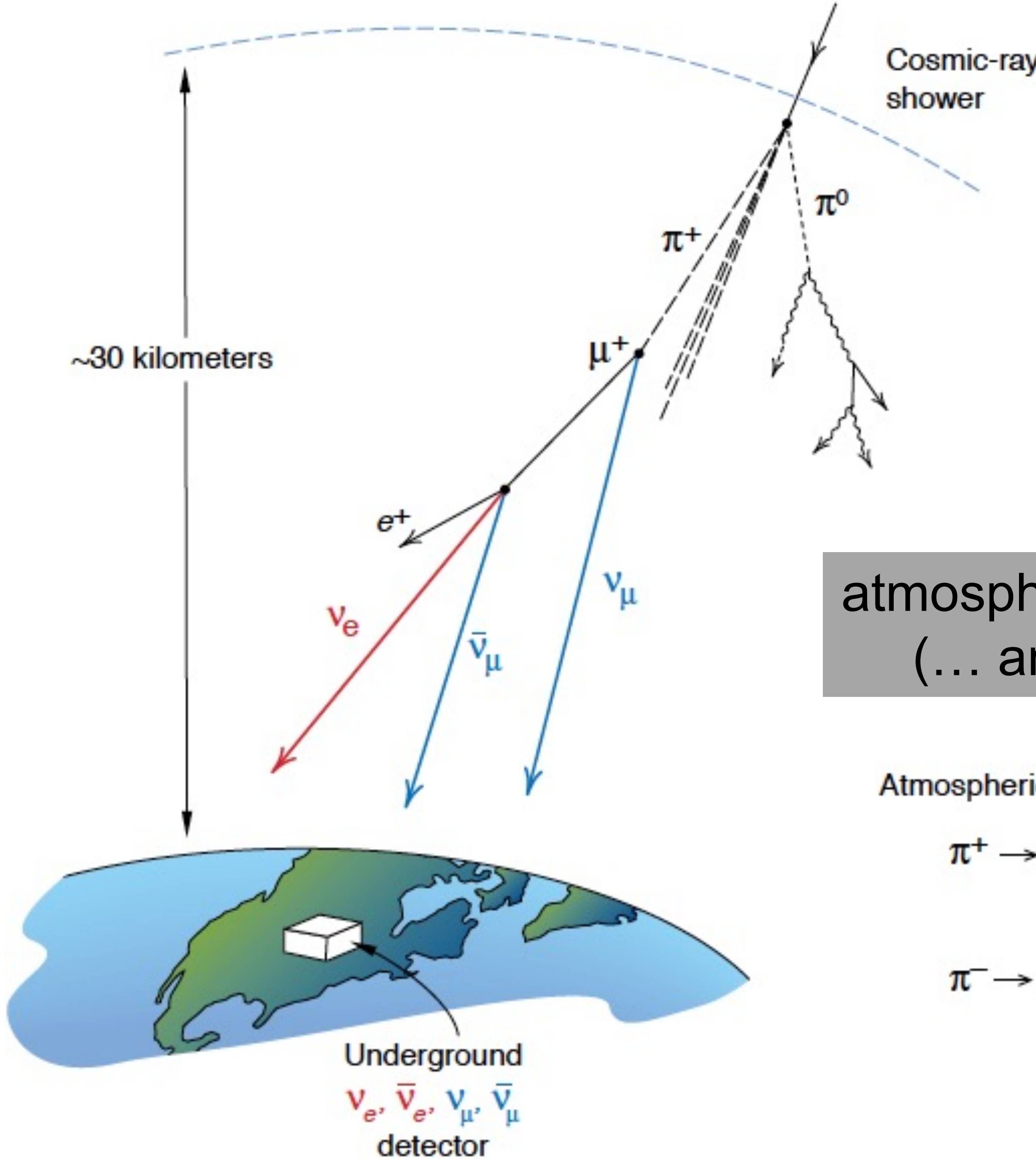




… each Digital Optical Module independently collects light signals like this, digitizes them,



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



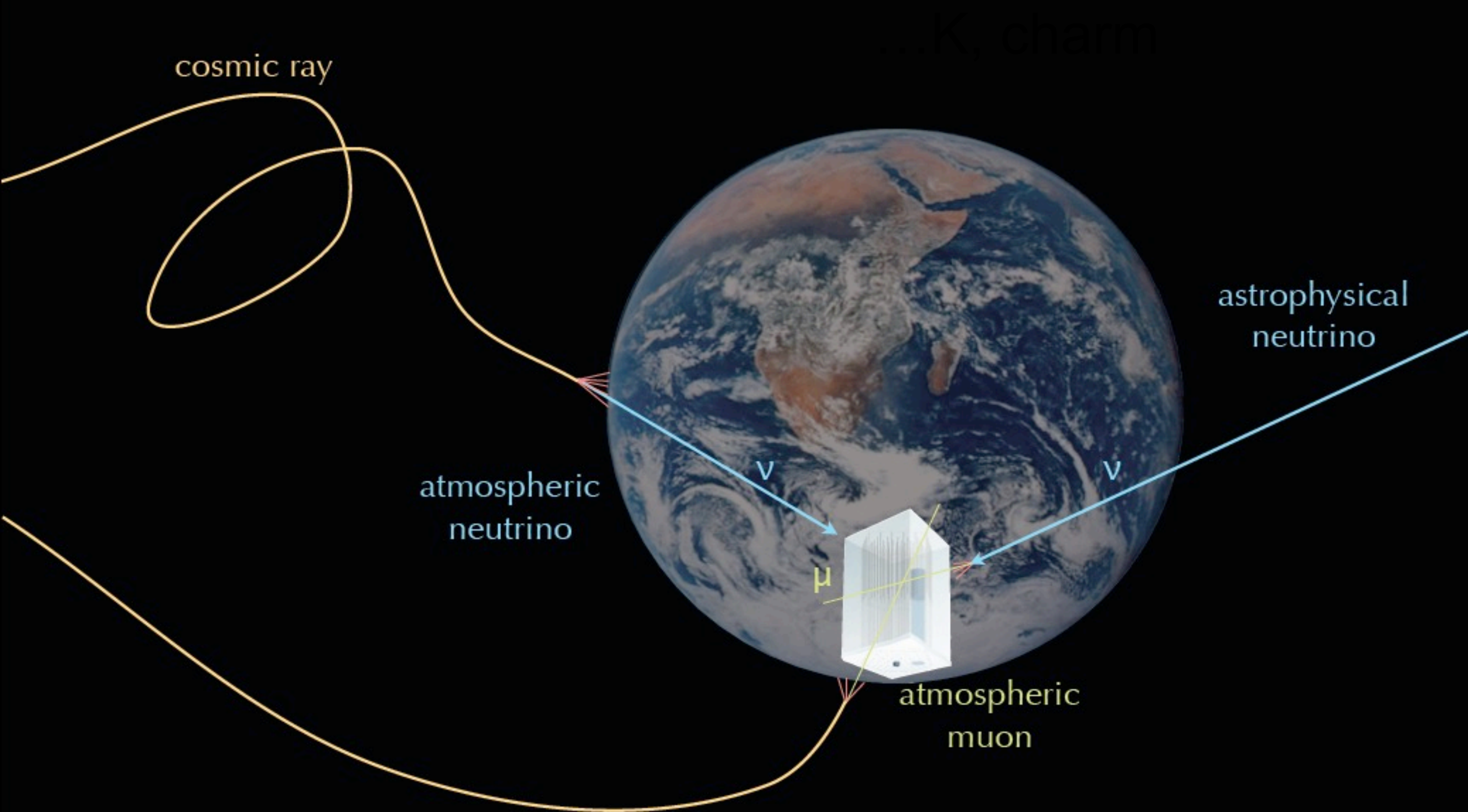
atmospheric neutrinos
(… and muons!)

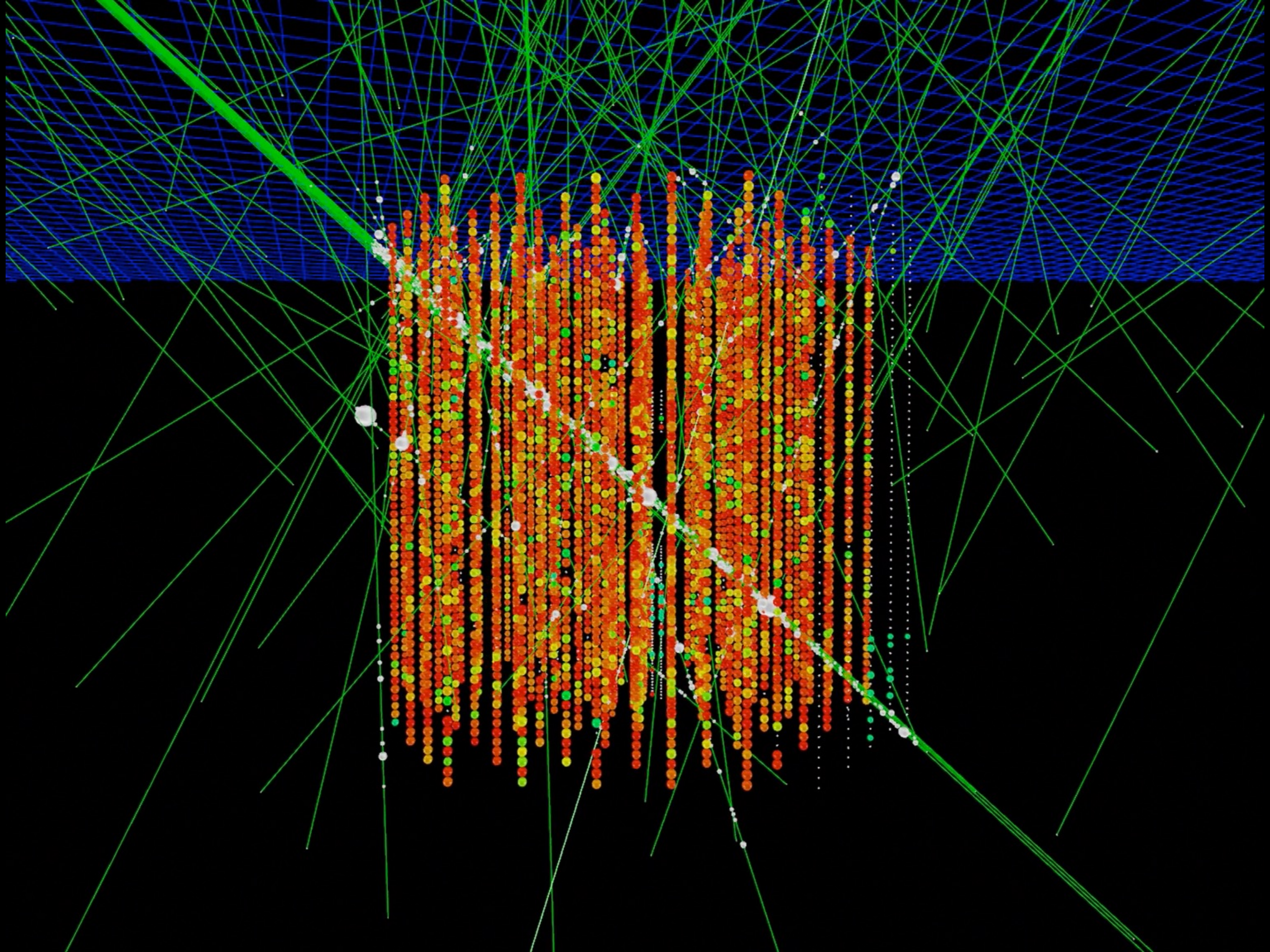
Atmospheric neutrino source

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

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

Signals and Backgrounds





… you looked at 10msec of data !

muons detected per year:

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

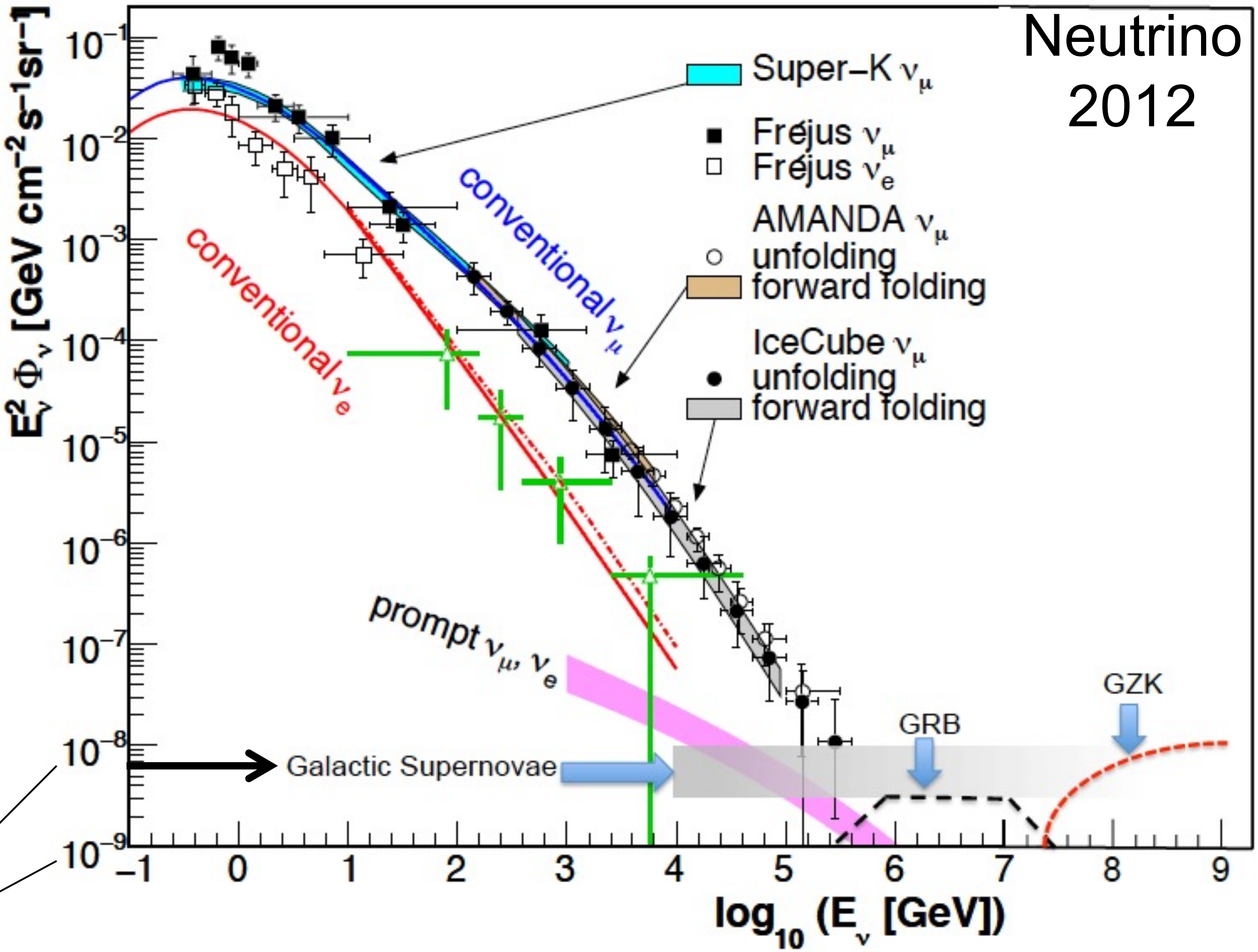
* 3000 per second

** 1 every 6 minutes

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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



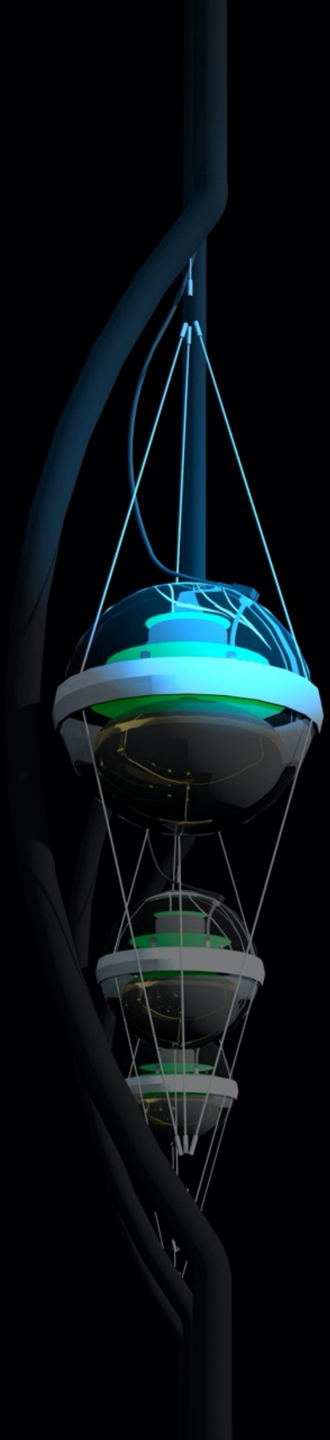
10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV


the IceCube Project
has developed very
efficient and reliable
deployment methods



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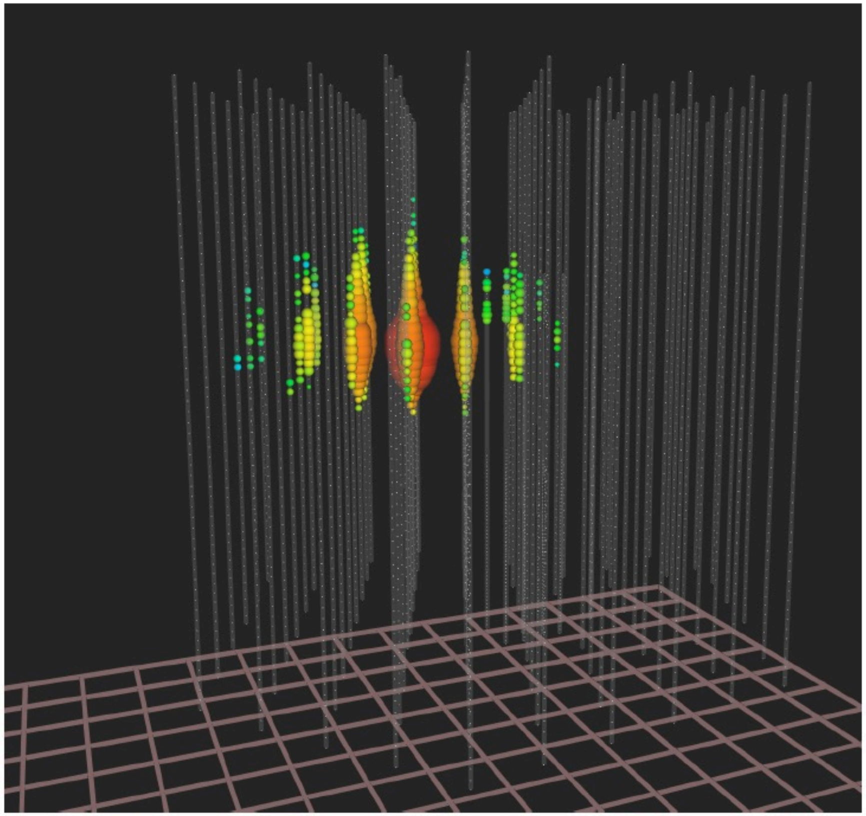
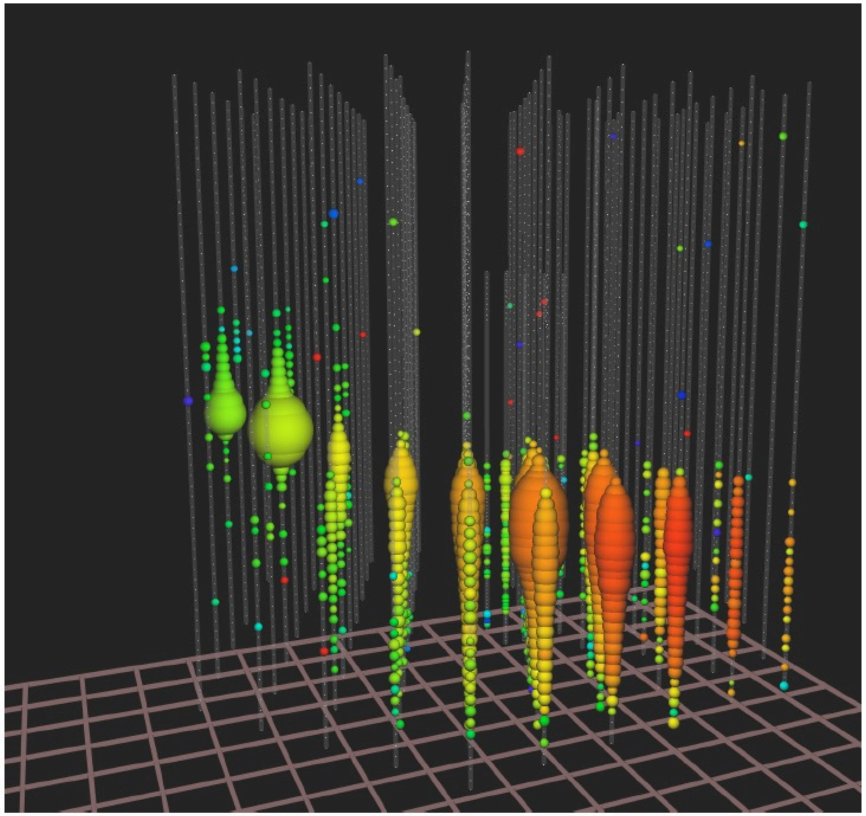
neutrinos interacting inside the detector

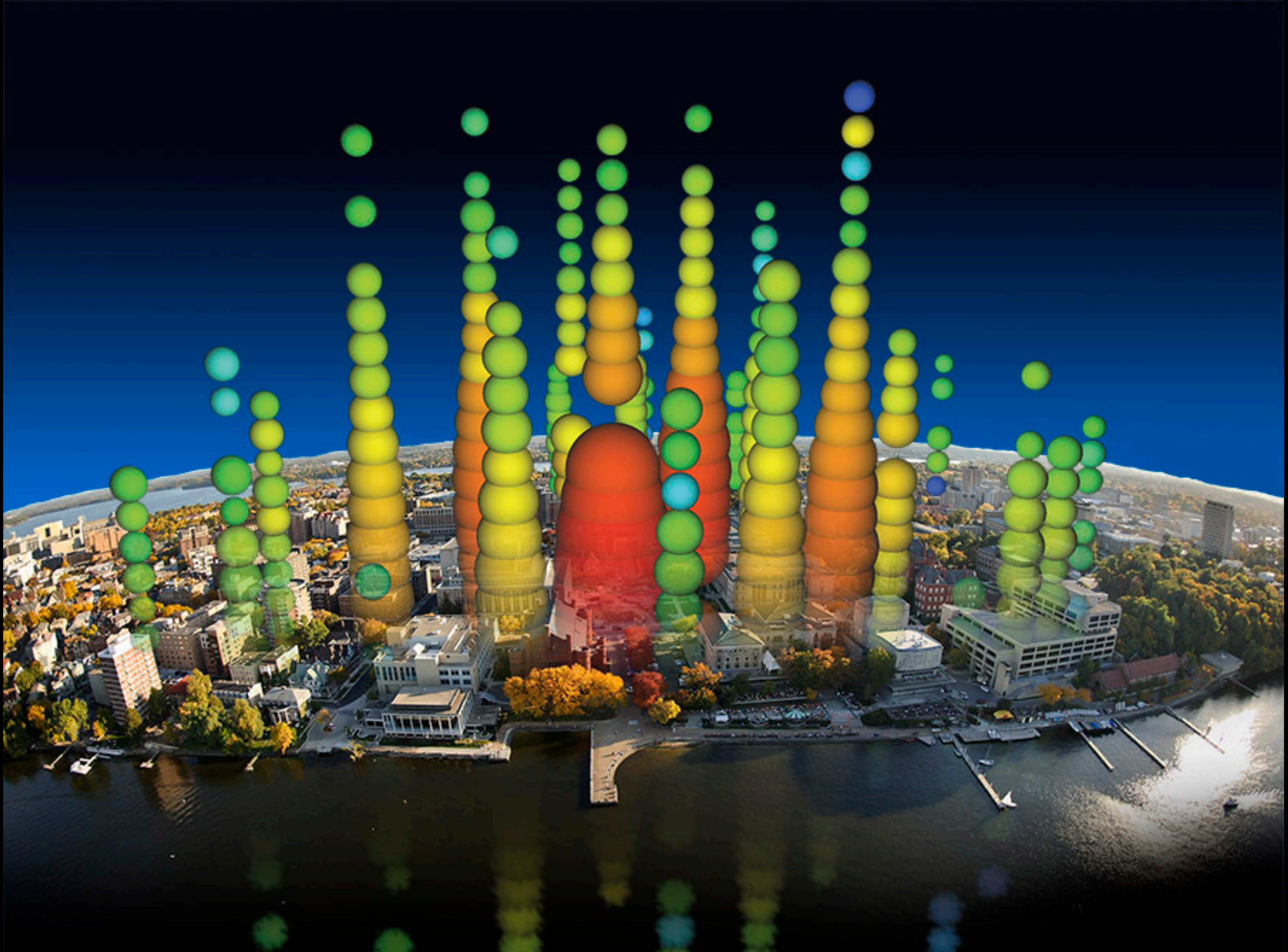
muon neutrinos filtered by the Earth





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

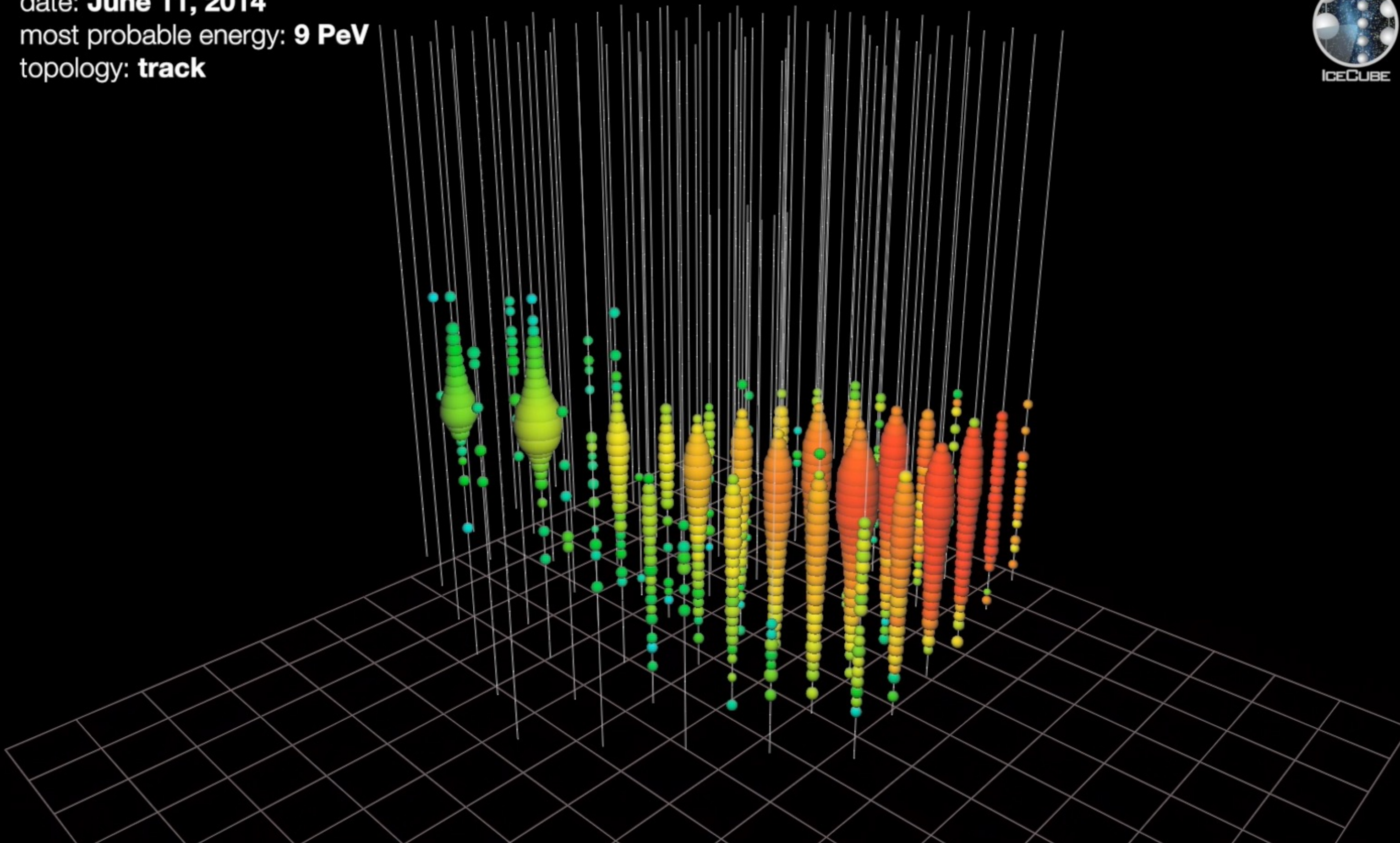
astronomy: angular resolution superior (0.2~0.4°)

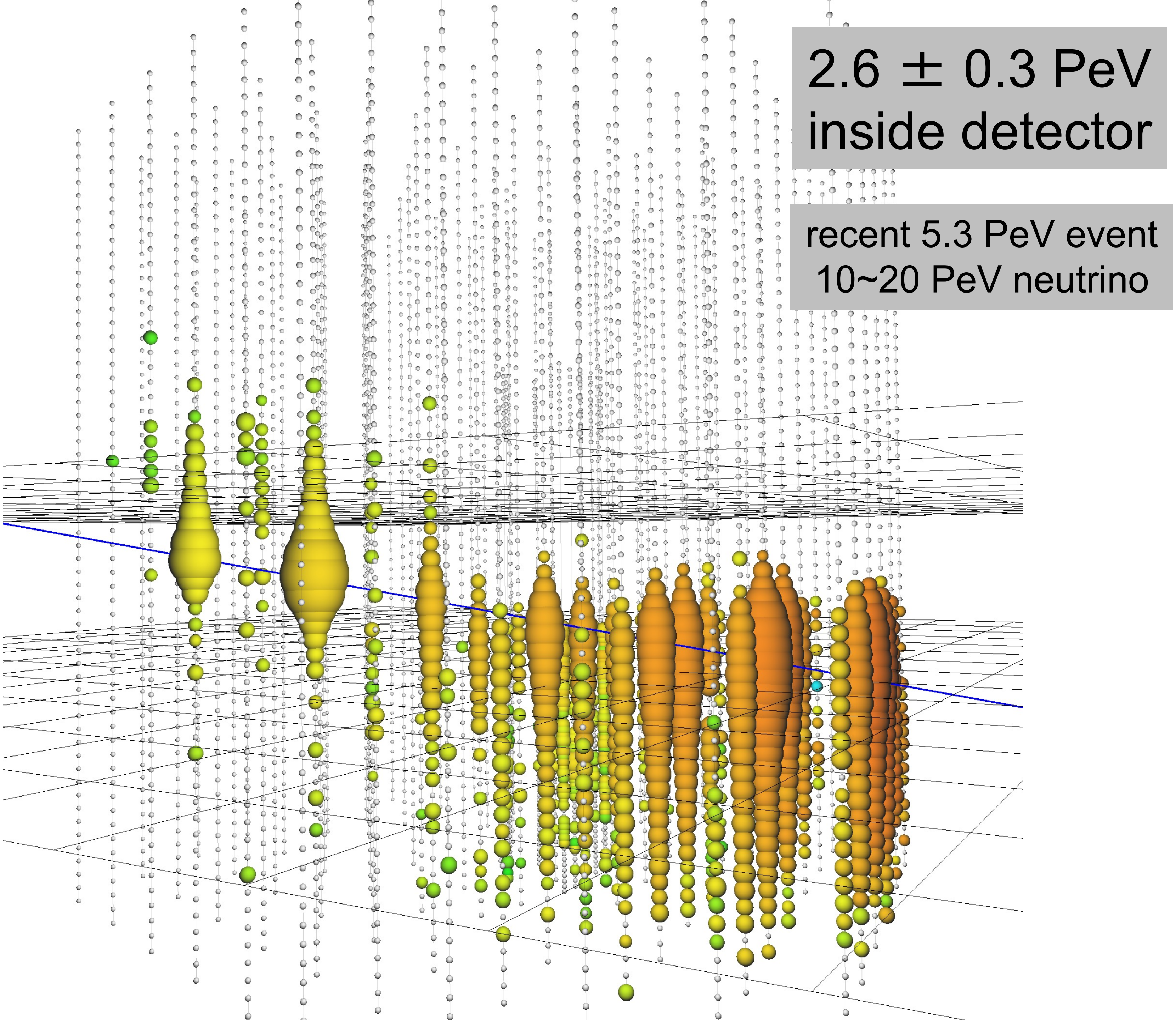


Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

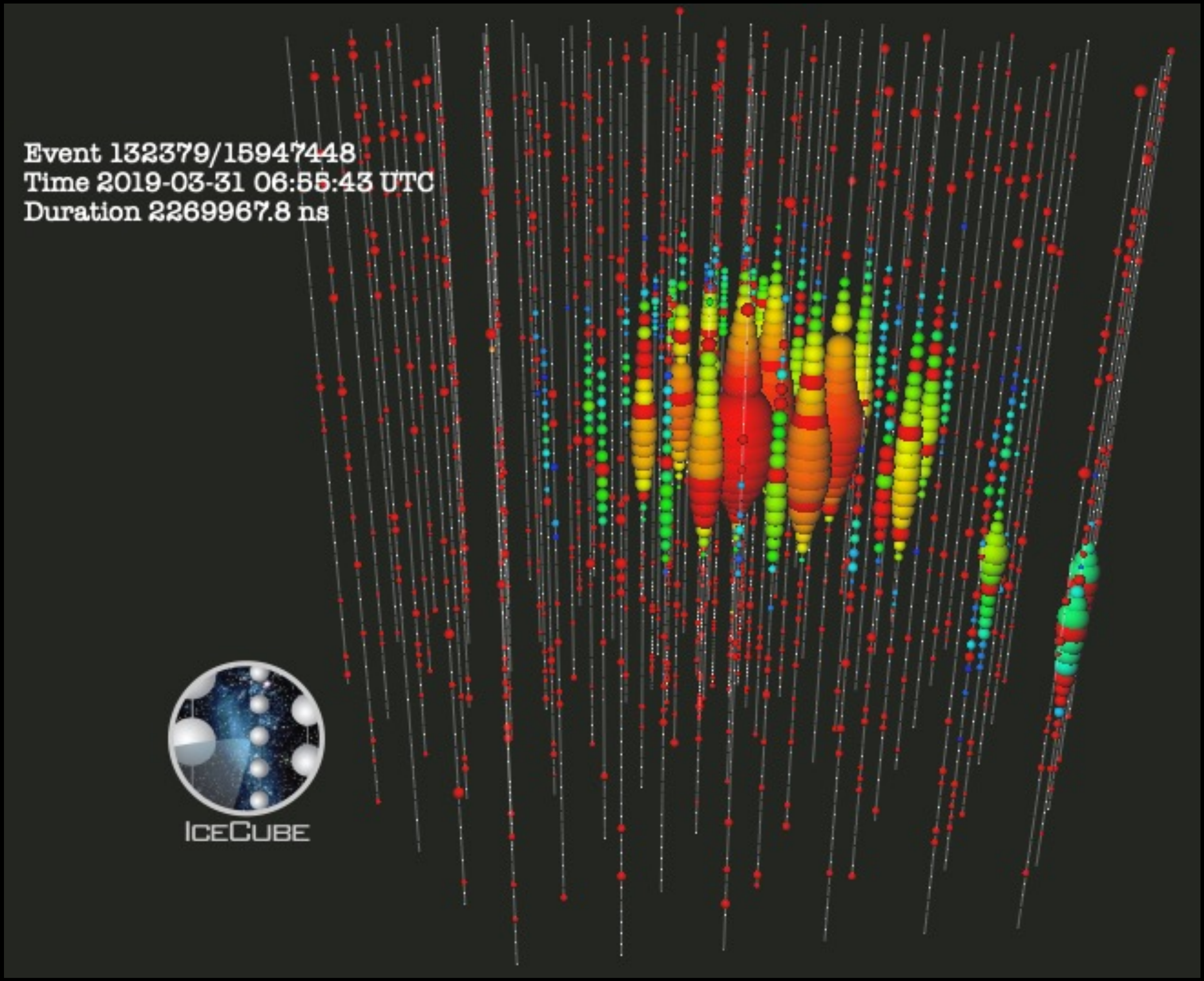
date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**

ICECUBE



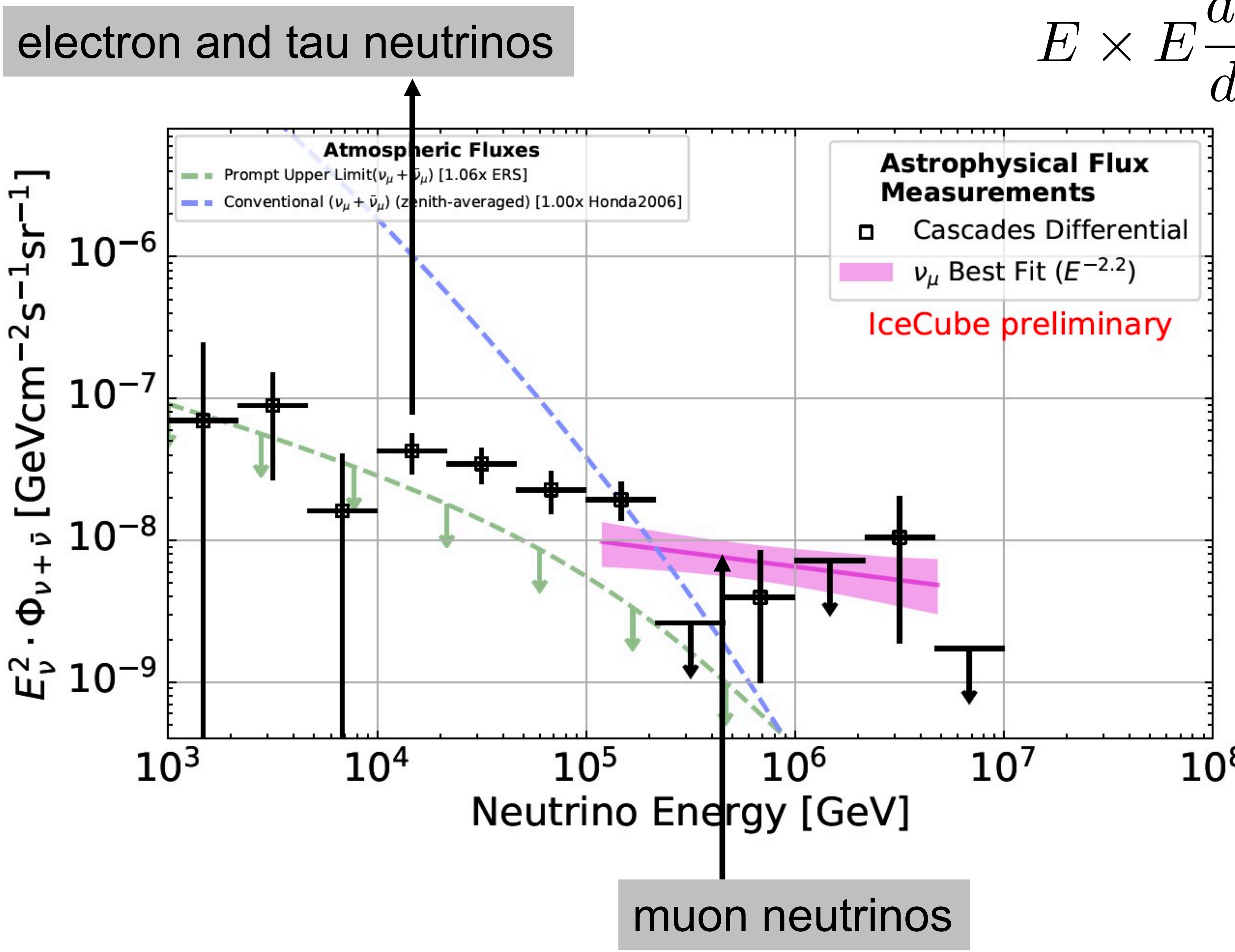

2.6 ± 0.3 PeV
inside detector
recent 5.3 PeV event
10~20 PeV neutrino

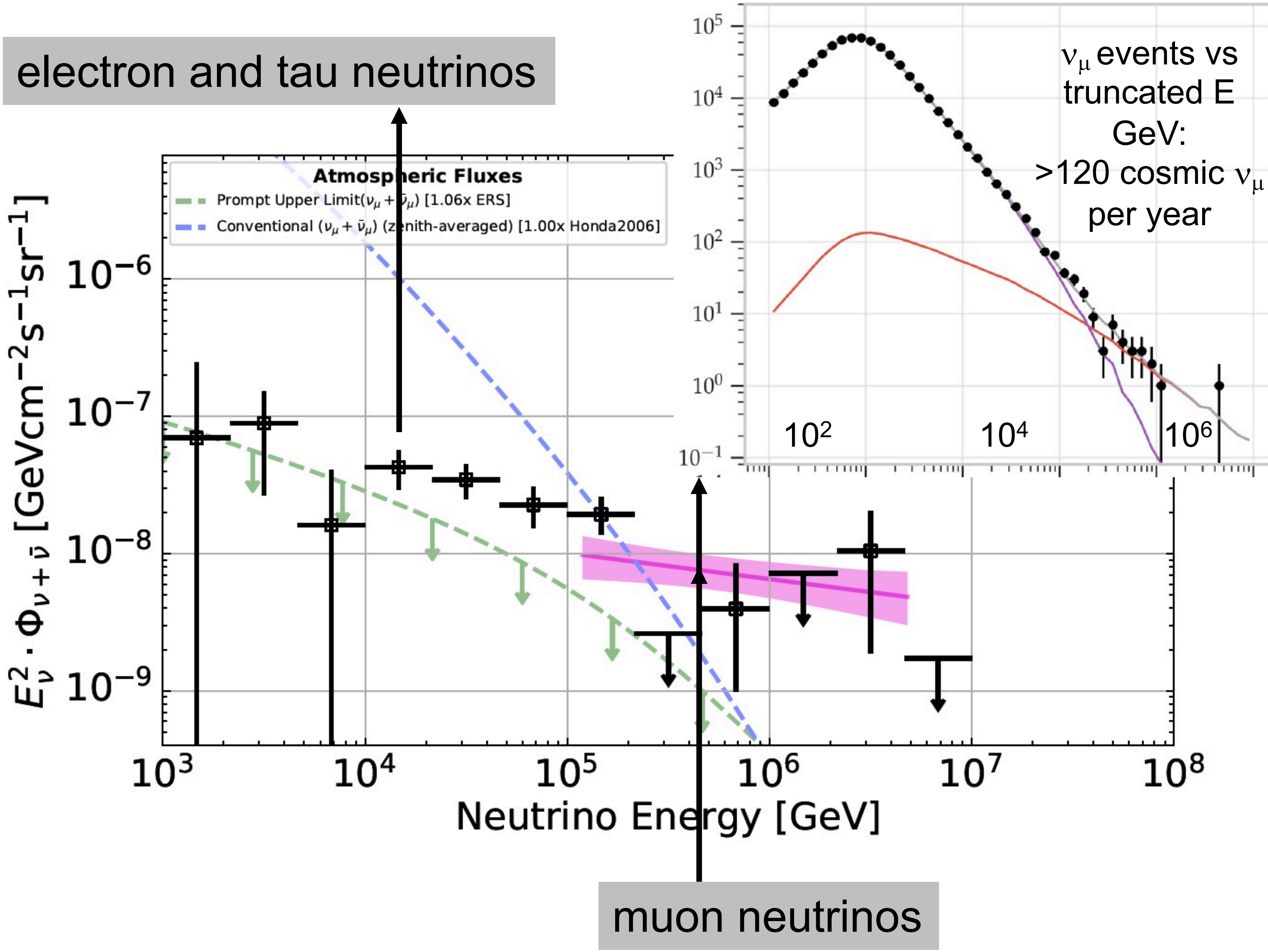
IC190331: 5300 TeV deposited inside the detector



initial neutrino energy 10~20 PeV

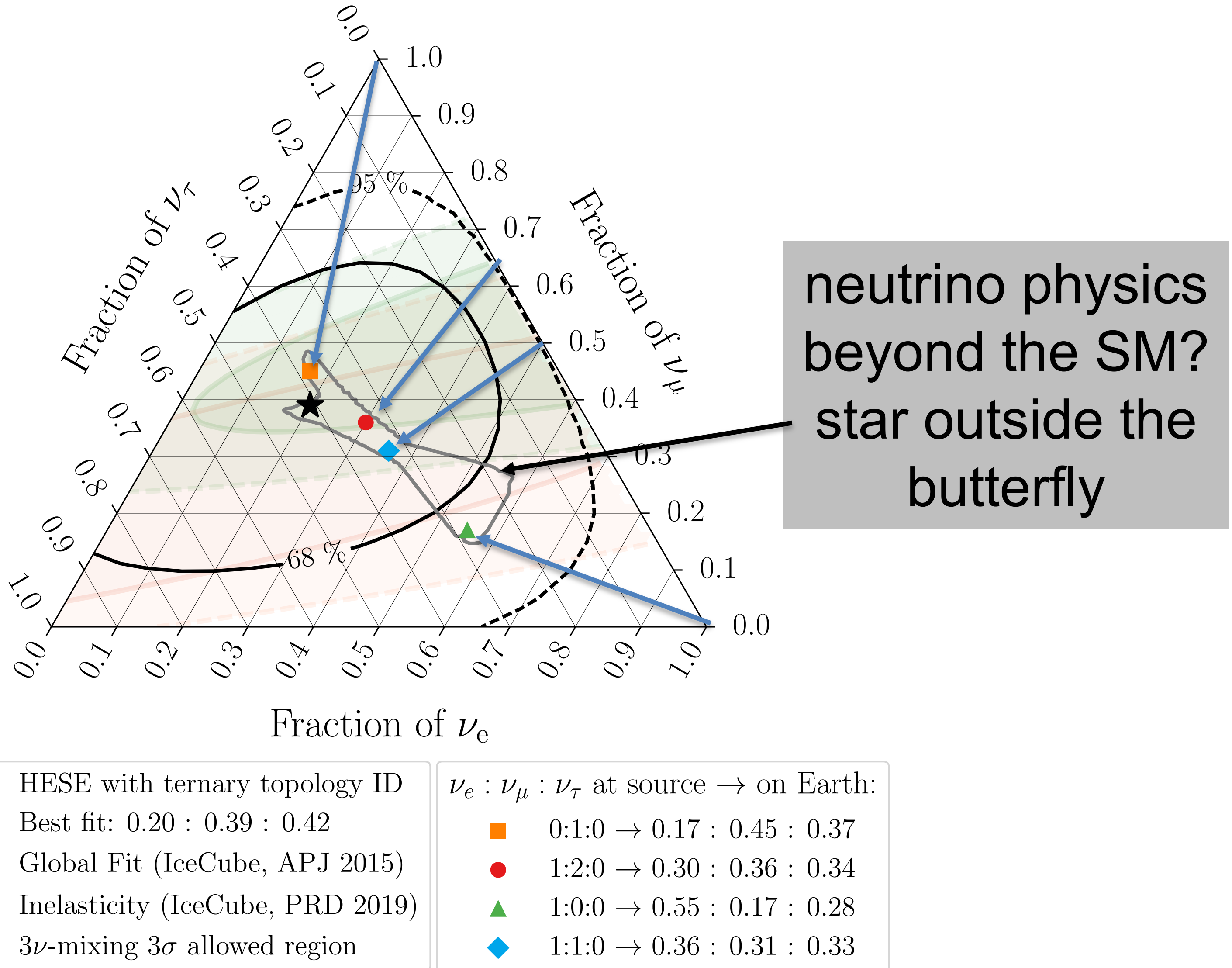
$$E \times E\frac{dN}{dE}$$

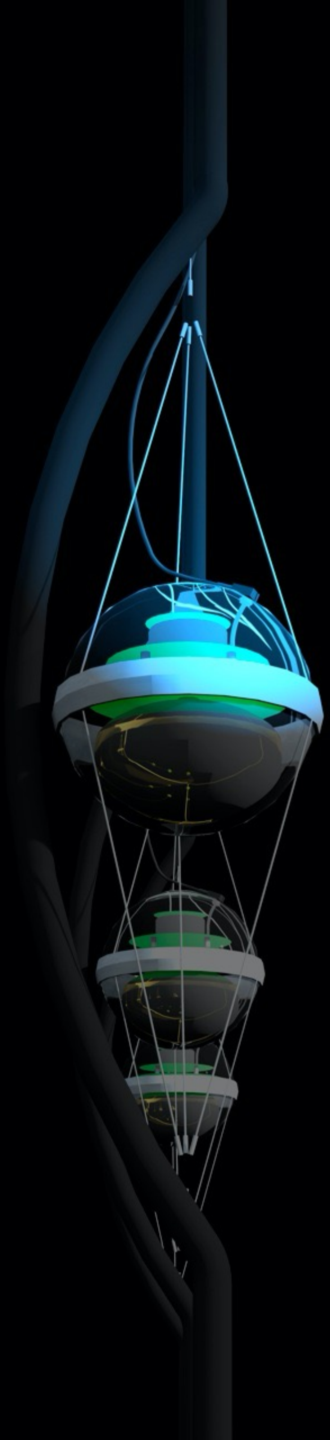



electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
ν_μ events vs truncated E GeV:
>120 cosmic ν_μ per year
muon neutrinos

new neutrino physics ?

oscillating PeV neutrinos (7.5 years HESE)





cosmic neutrinos: four independent observations

→ muon neutrinos through the Earth

→ starting neutrinos: all flavors

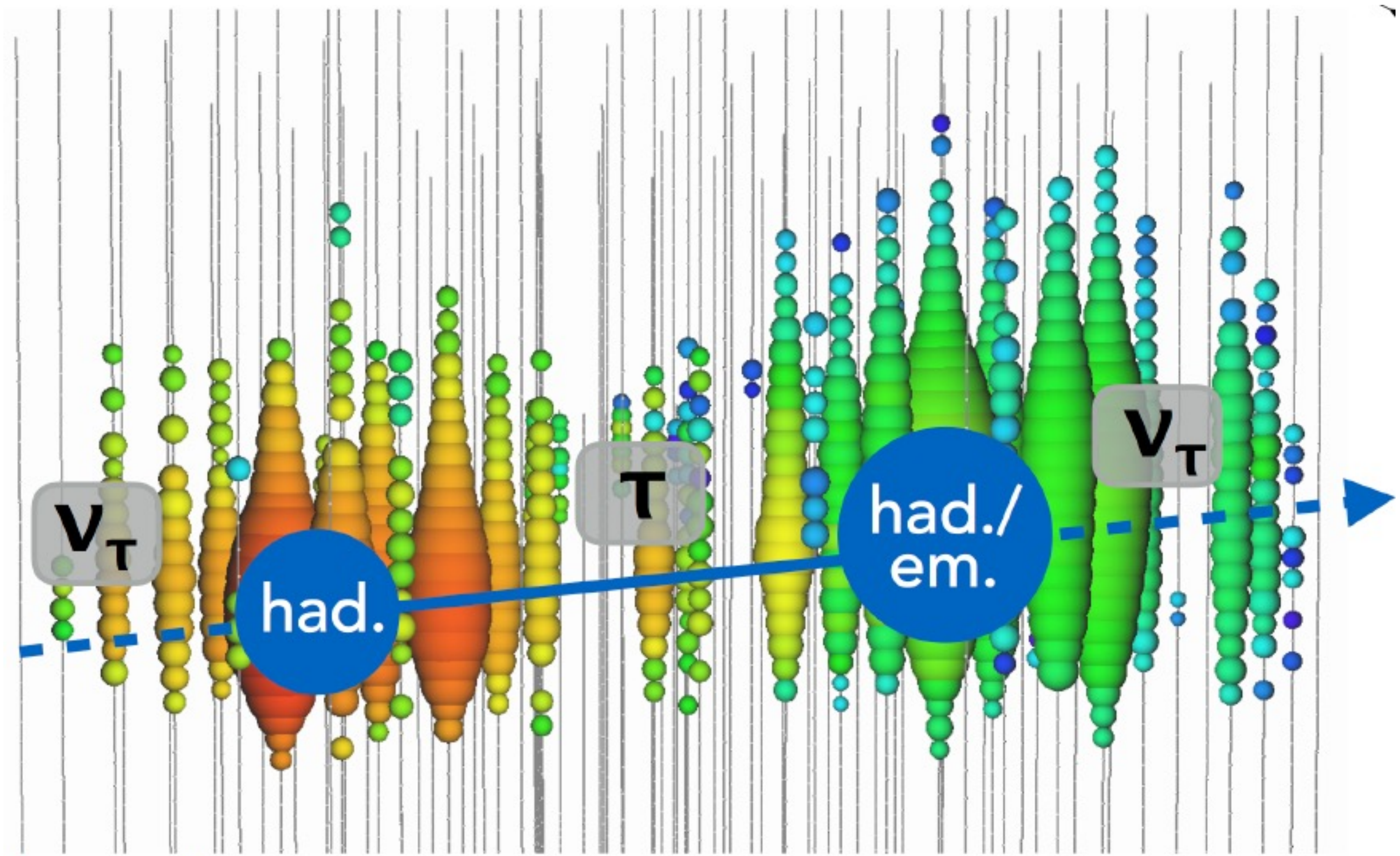
→ tau neutrinos produced by oscillation over cosmic distances

→ Glashow resonance event

icecube.wisc.edu

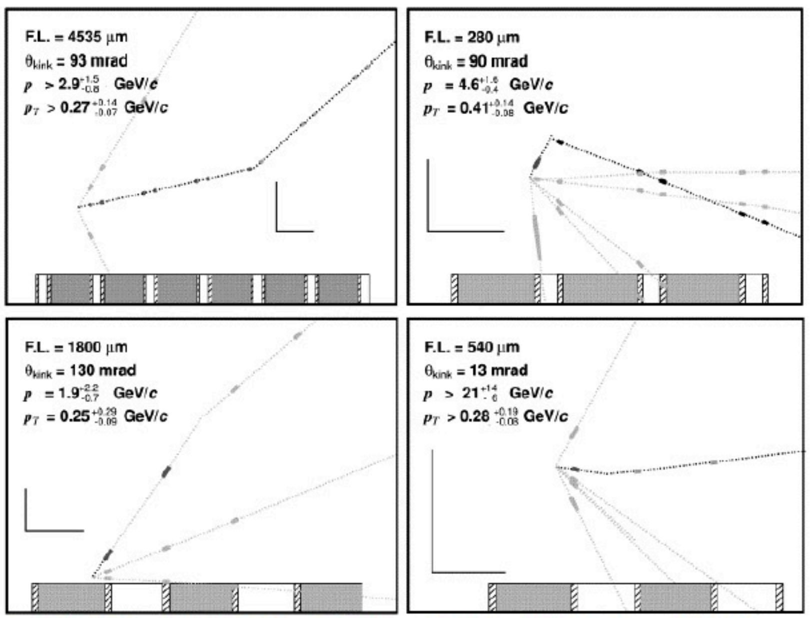
tau production and decay

tau decay length:
50m per PeV



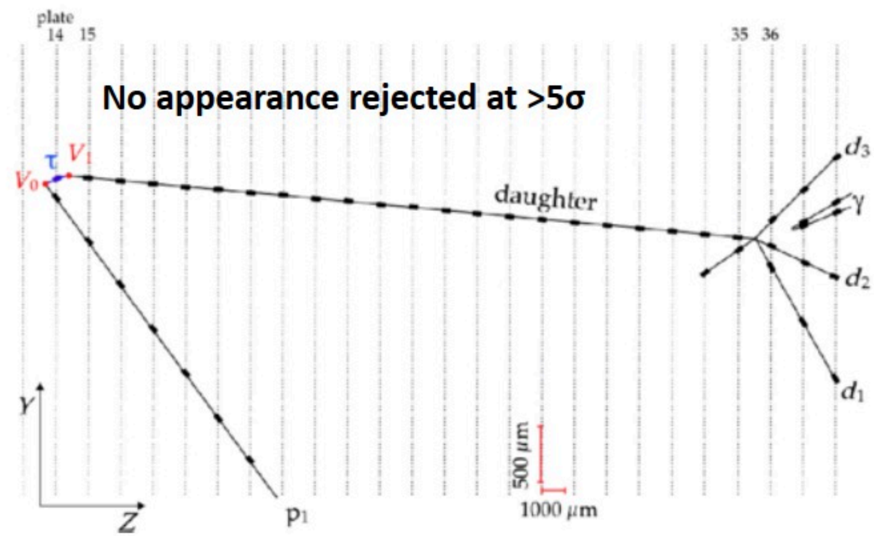
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



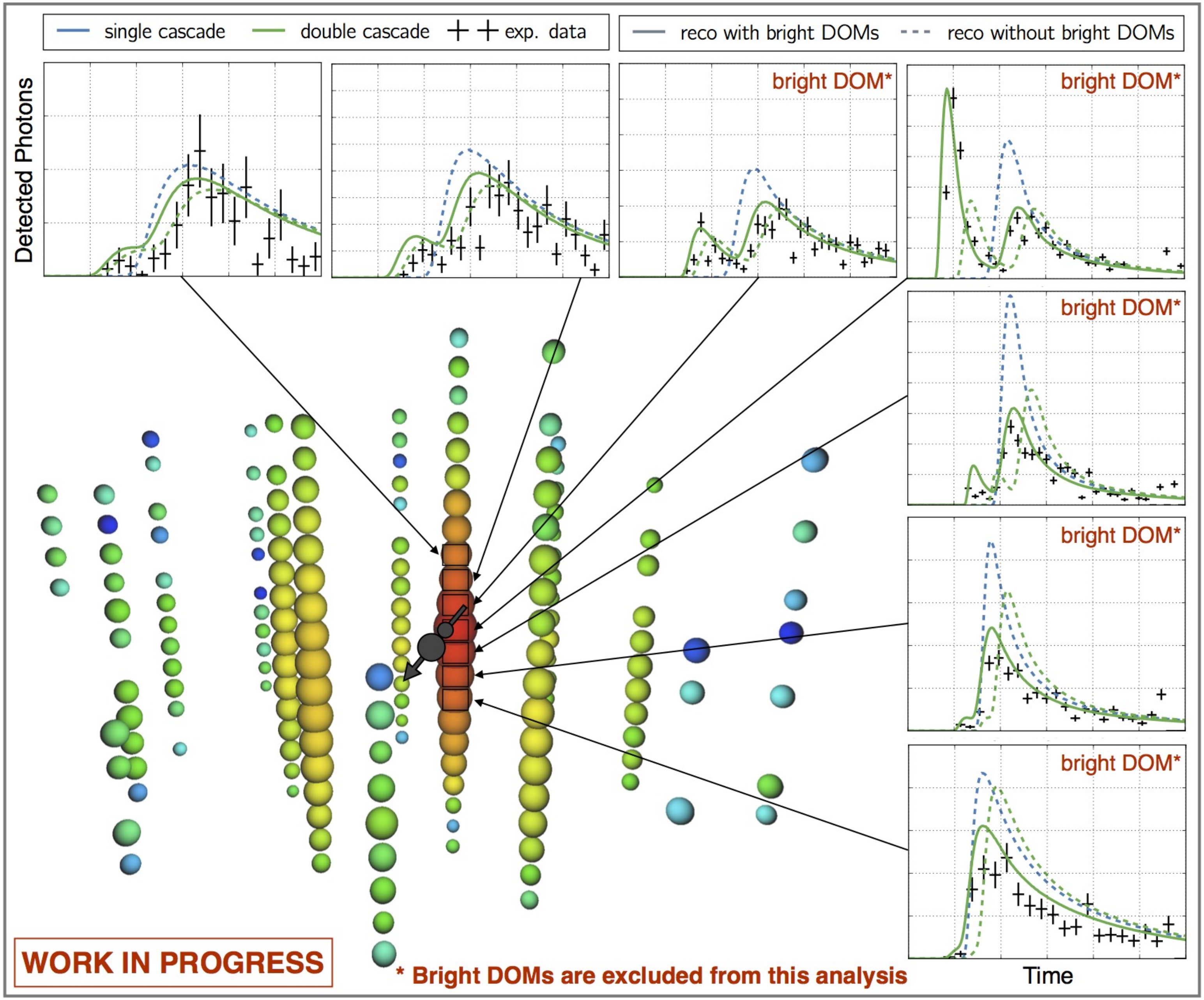
DONUT Phys. Lett. B, [Volume 504, Issue 3](), 12 April 2001, Pages 218-224

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



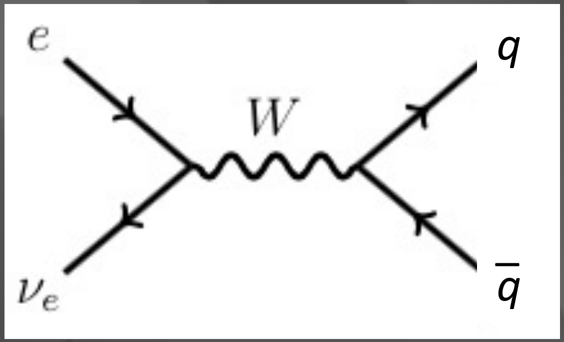
OPERA Phys. Rev. Lett. 115, 121802 (2015)

a cosmic tau neutrino: livetime 17m

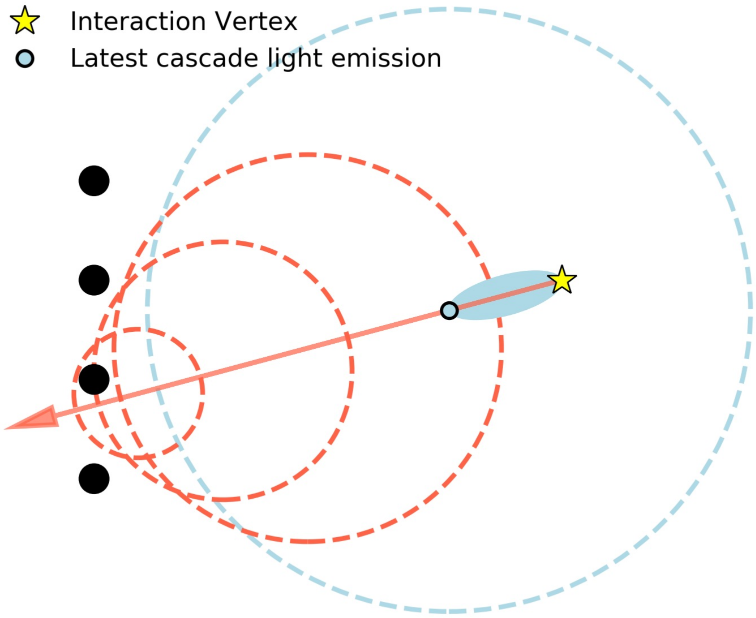


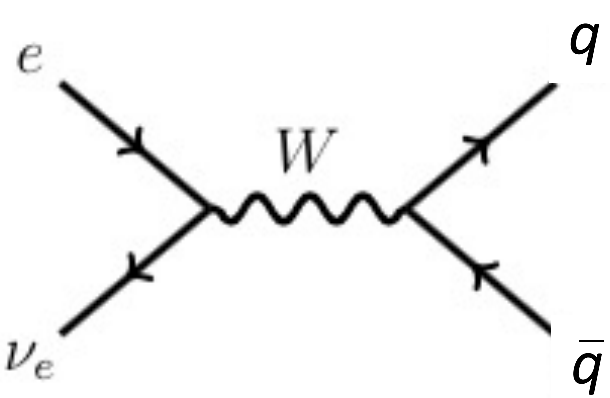
the first Glashow resonance event:

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

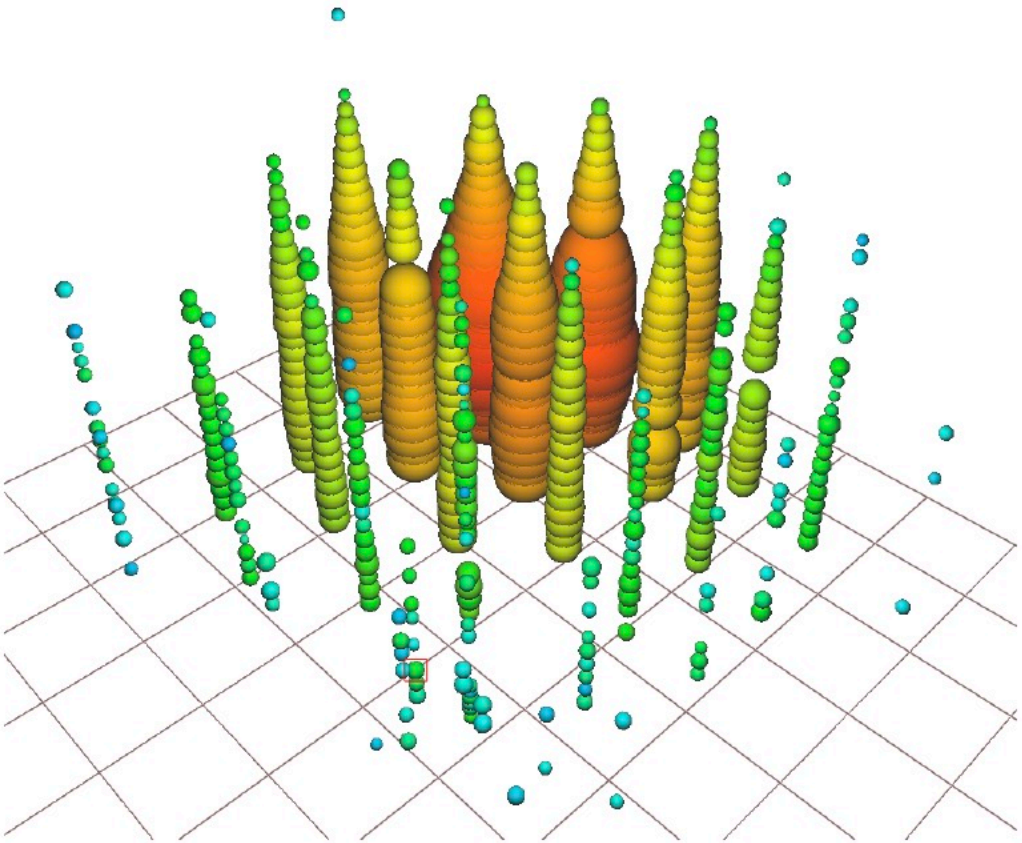


partially contained event with energy 6.3 PeV

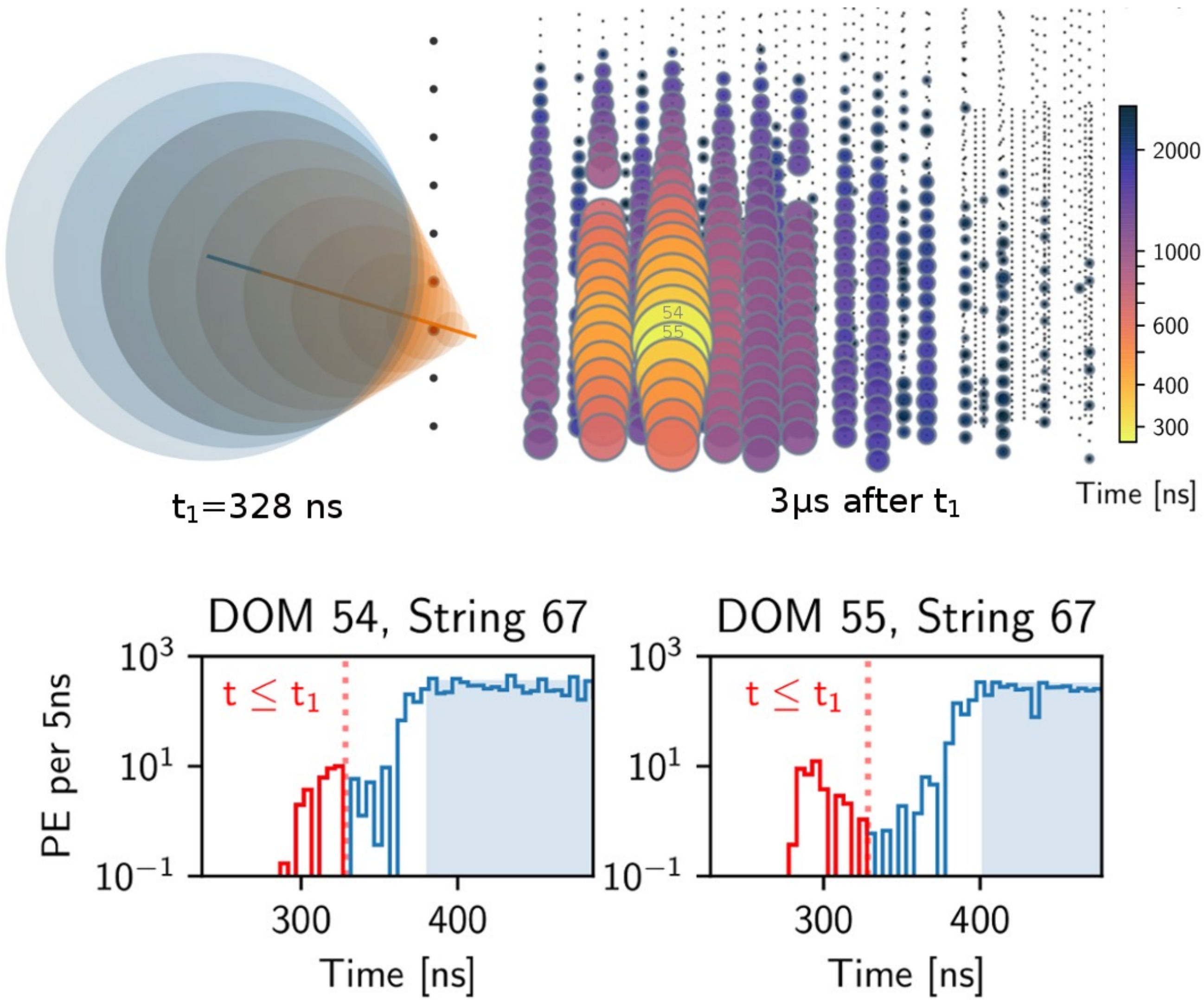




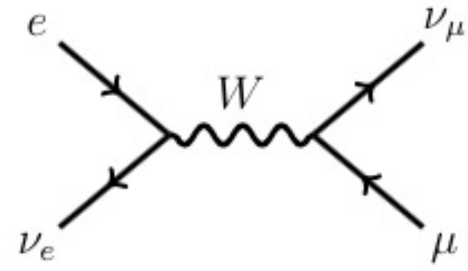
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

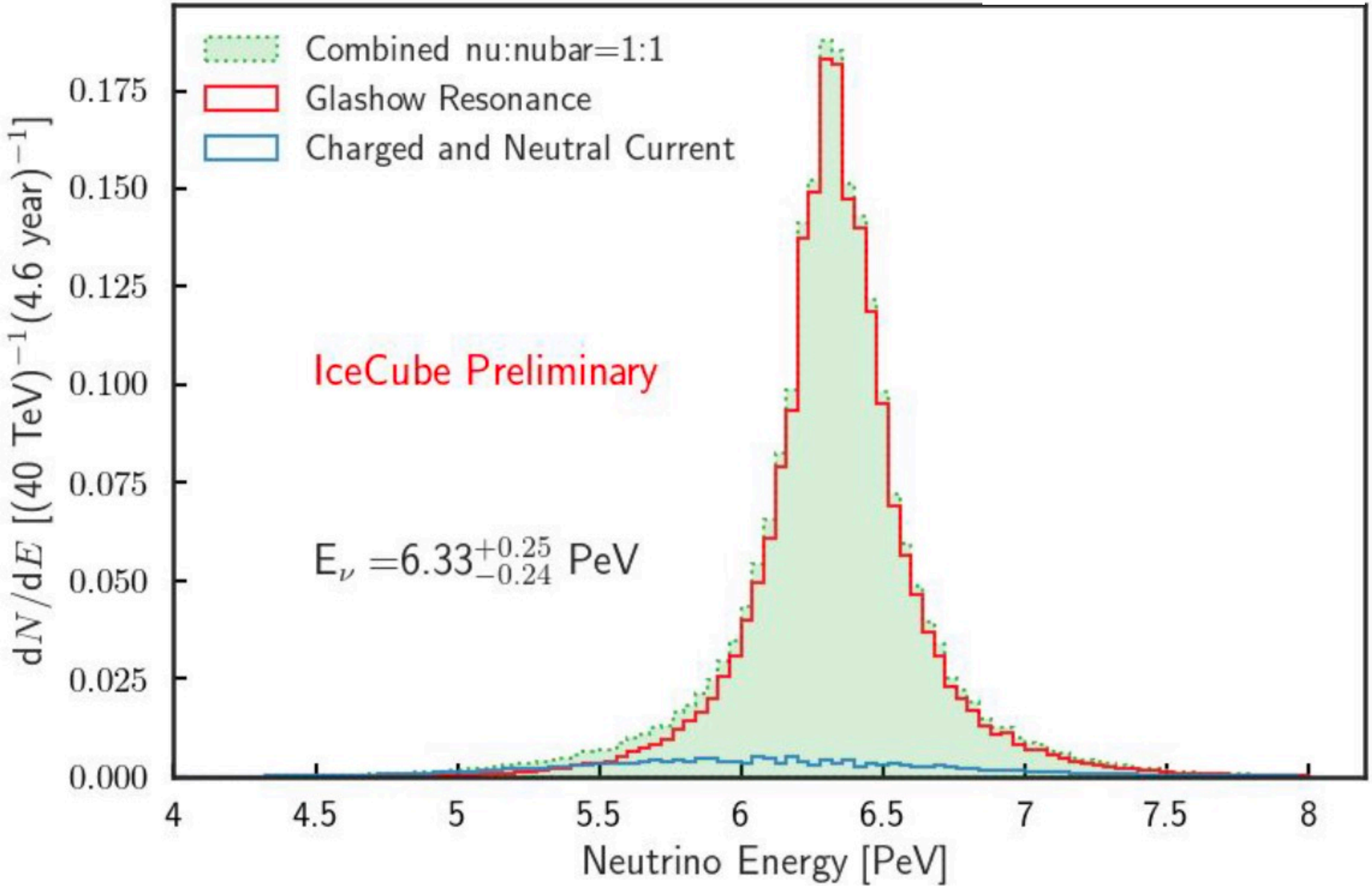


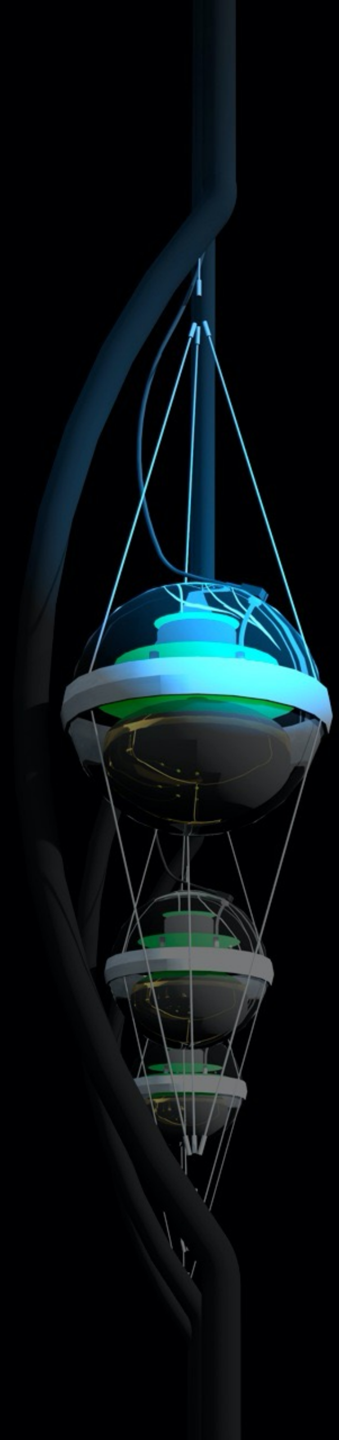
hadronic shower from W-decay:
early muons followed by electromagnetic shower



- energy measurement understood
- identification of anti-electron neutrinos







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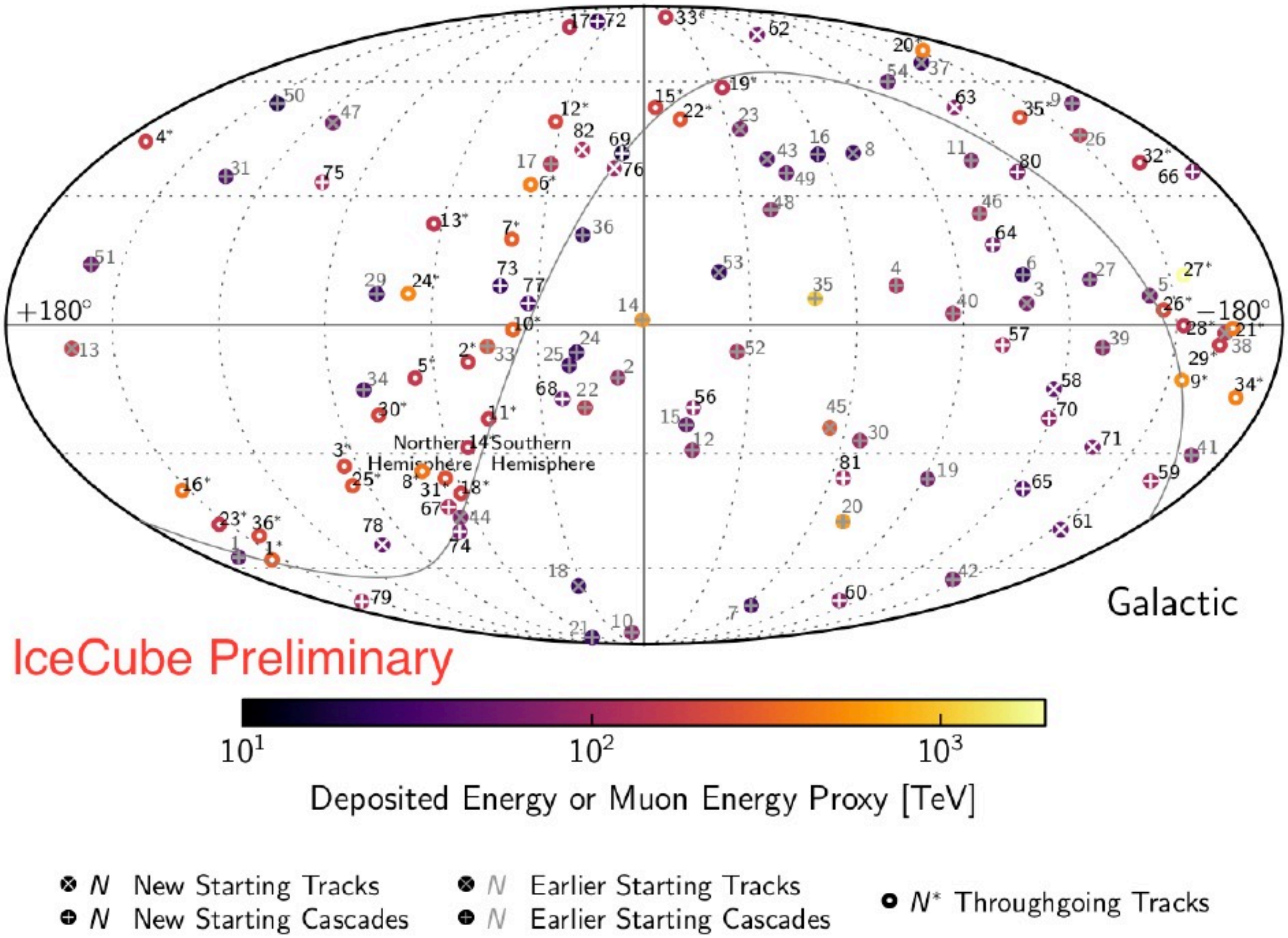
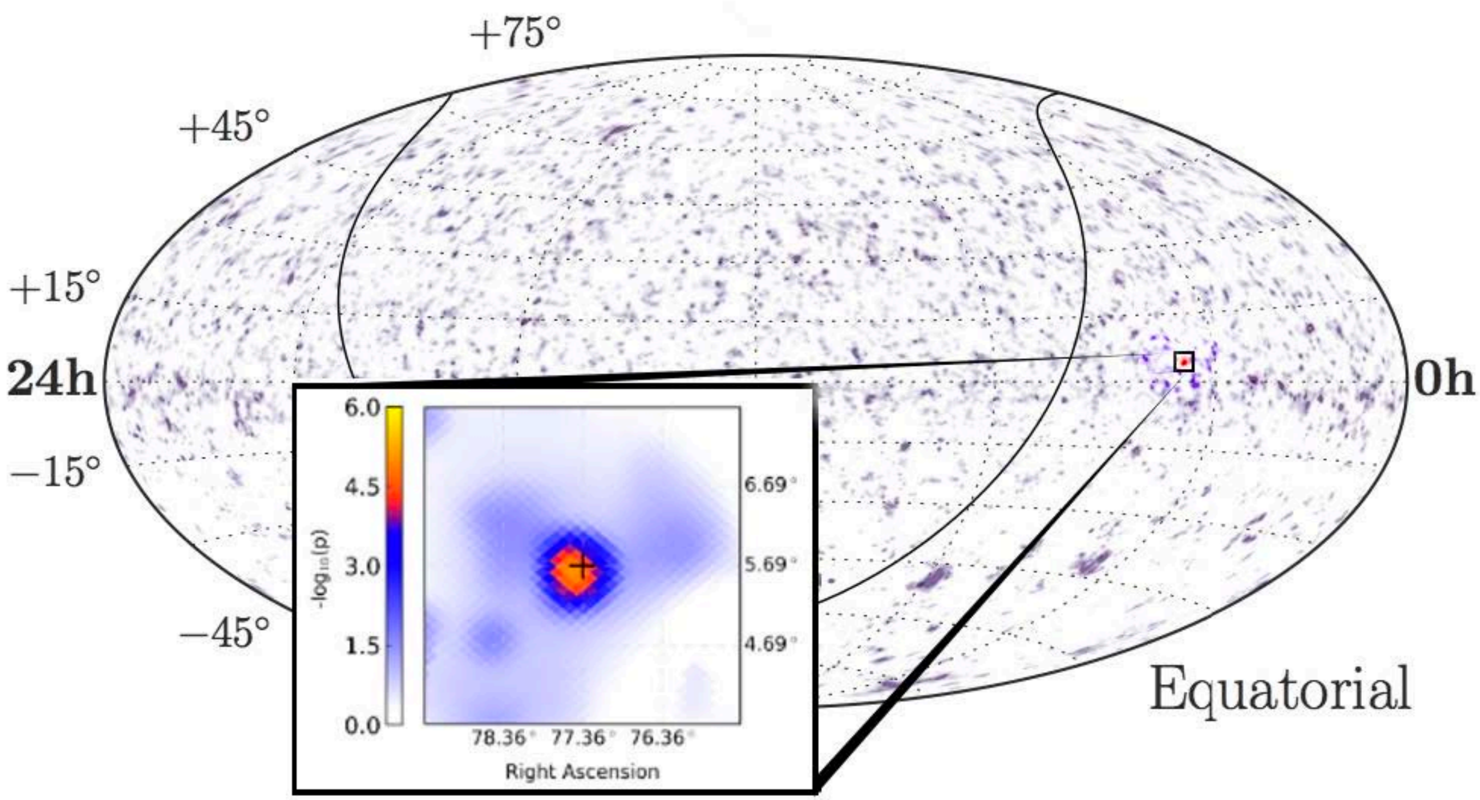
where do they come from?



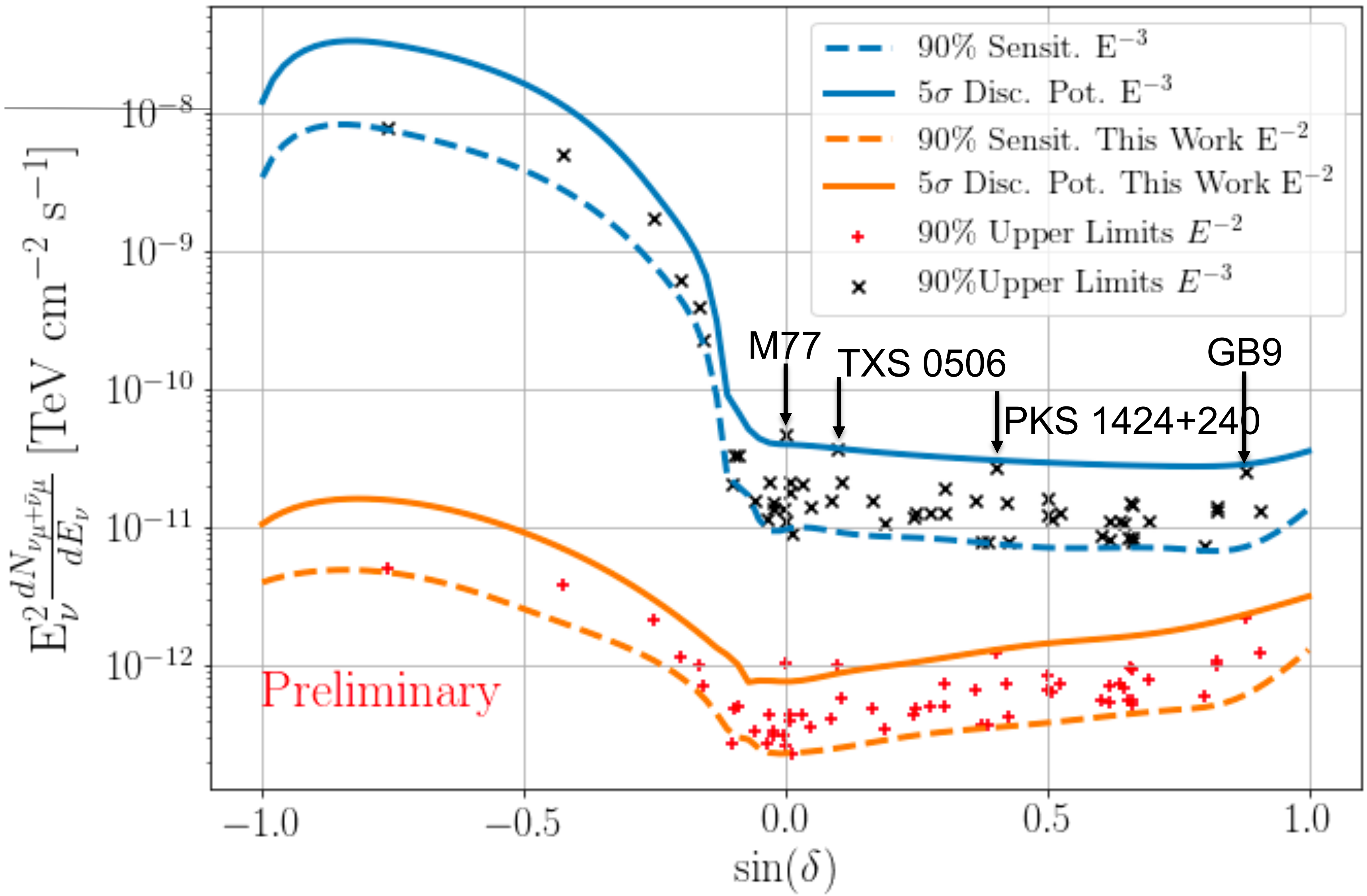
pre-trial p-value for clustering of high energy neutrinos



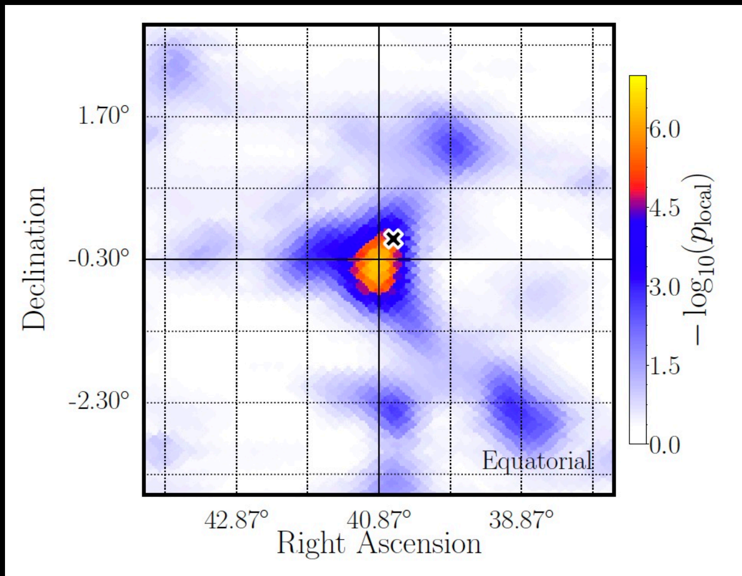
hottest spot coincident with
NGC 1068 (M77)

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



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

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ABSTRACT

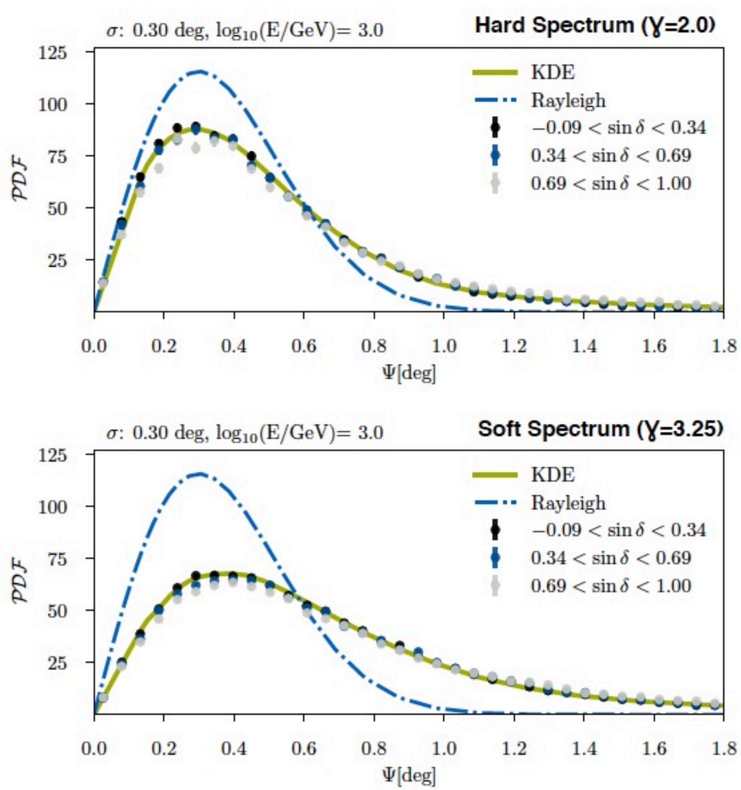
Aims. We investigate the fueling and the feedback of star formation and nuclear activity in NGC 1068, a nearby (D = 14 Mpc) Seyfert 2 barred galaxy, by analyzing the distribution and kinematics of the molecular gas in the disk. We aim to understand if and how gas accretion can self-regulate.

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

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

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

- 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

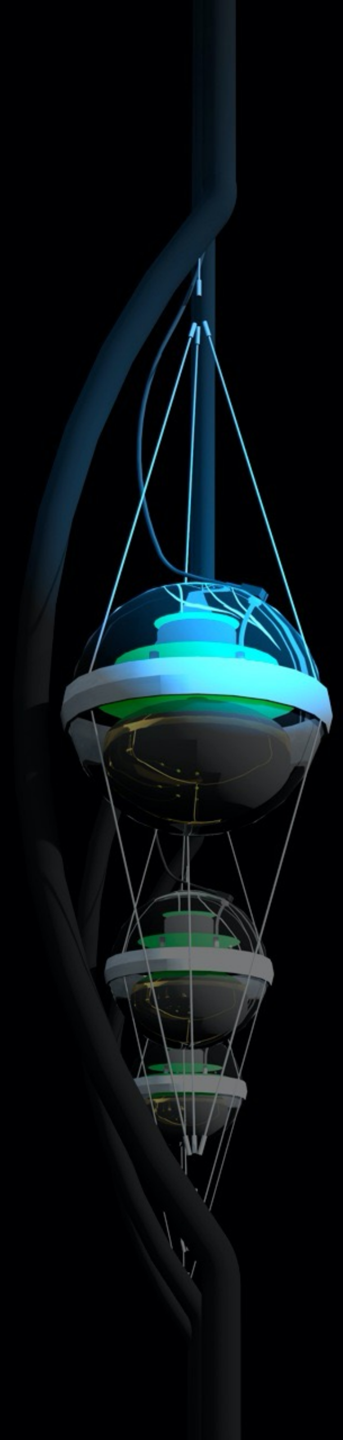


- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation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

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



IceCube: the discovery of cosmic neutrinos
francis halzen

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

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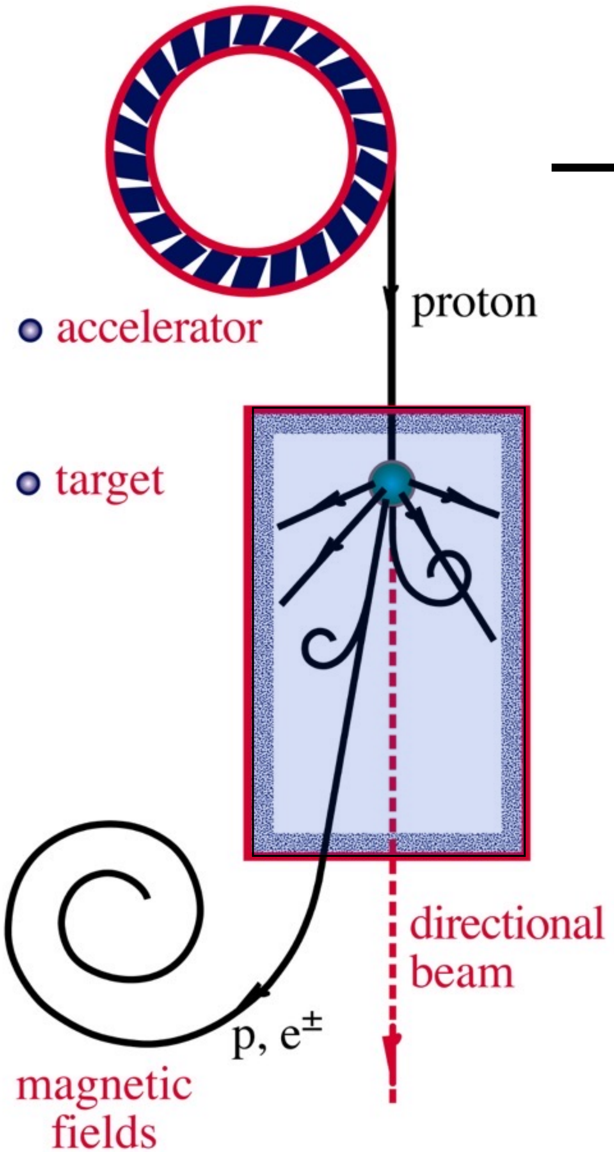
ν and γ beams : heaven and earth



where are the gamma rays ?

supermassive black hole

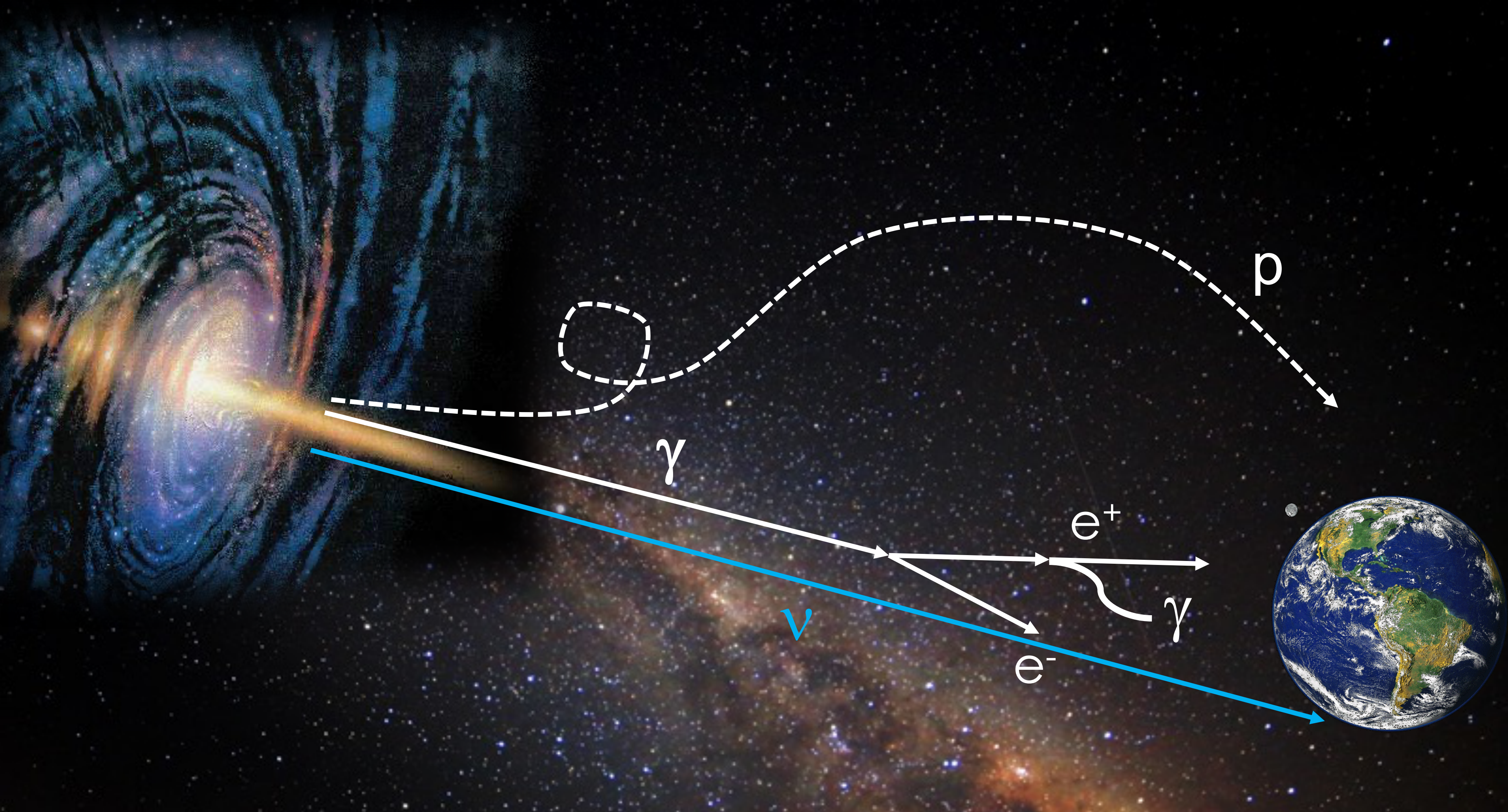
nearby radiation

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

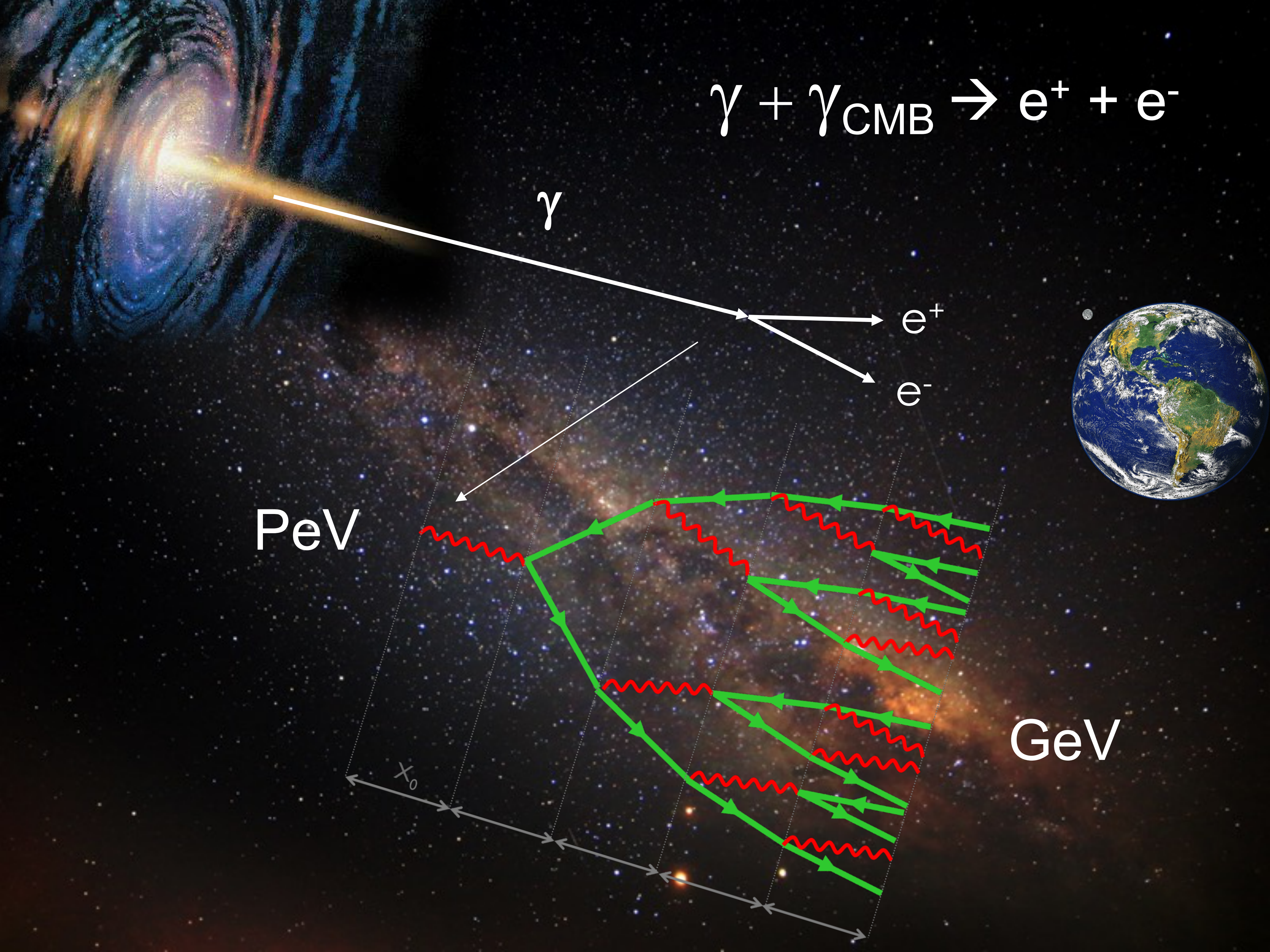
~ cosmic ray + neutrino

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

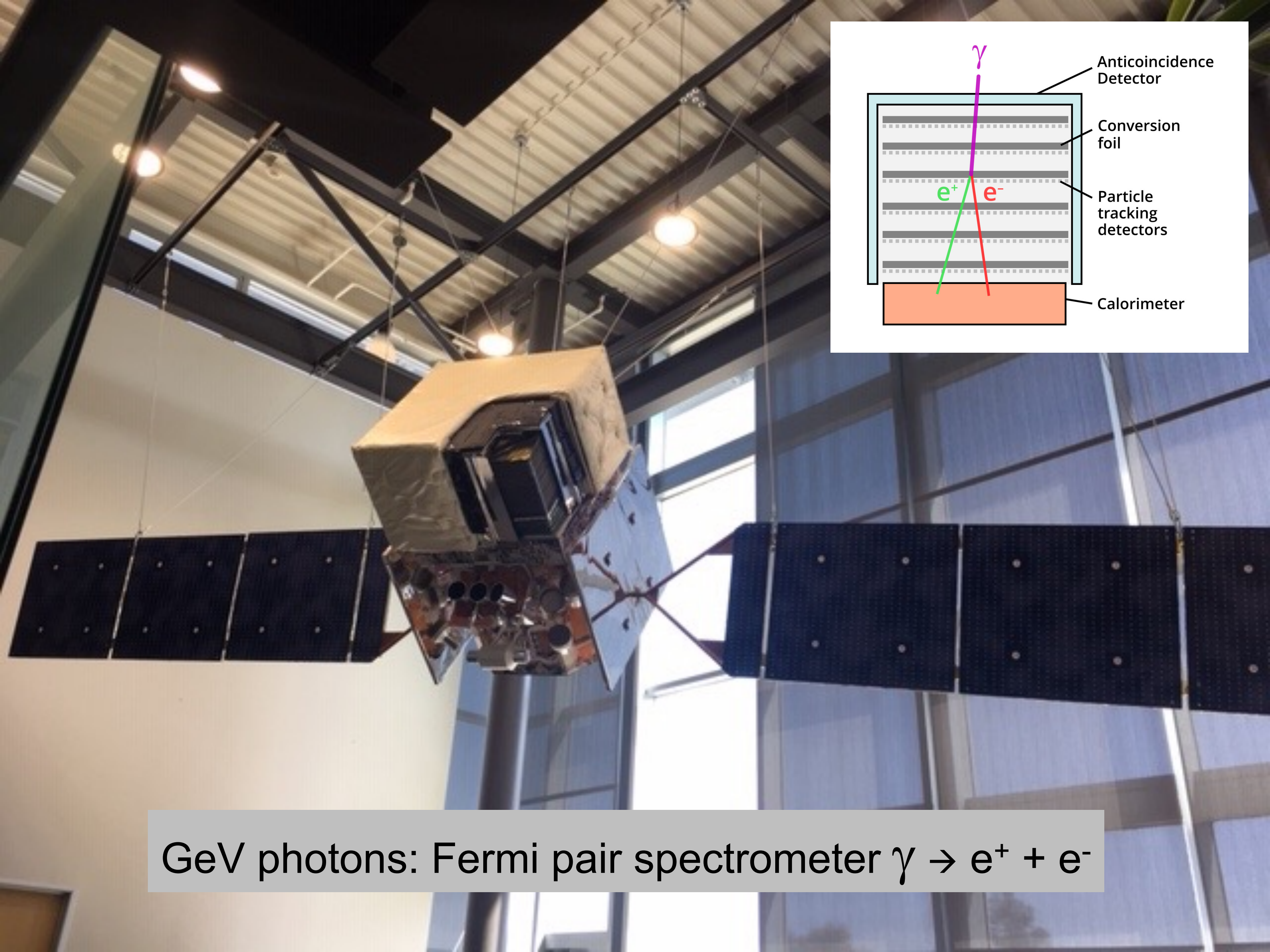
~ cosmic ray + gamma



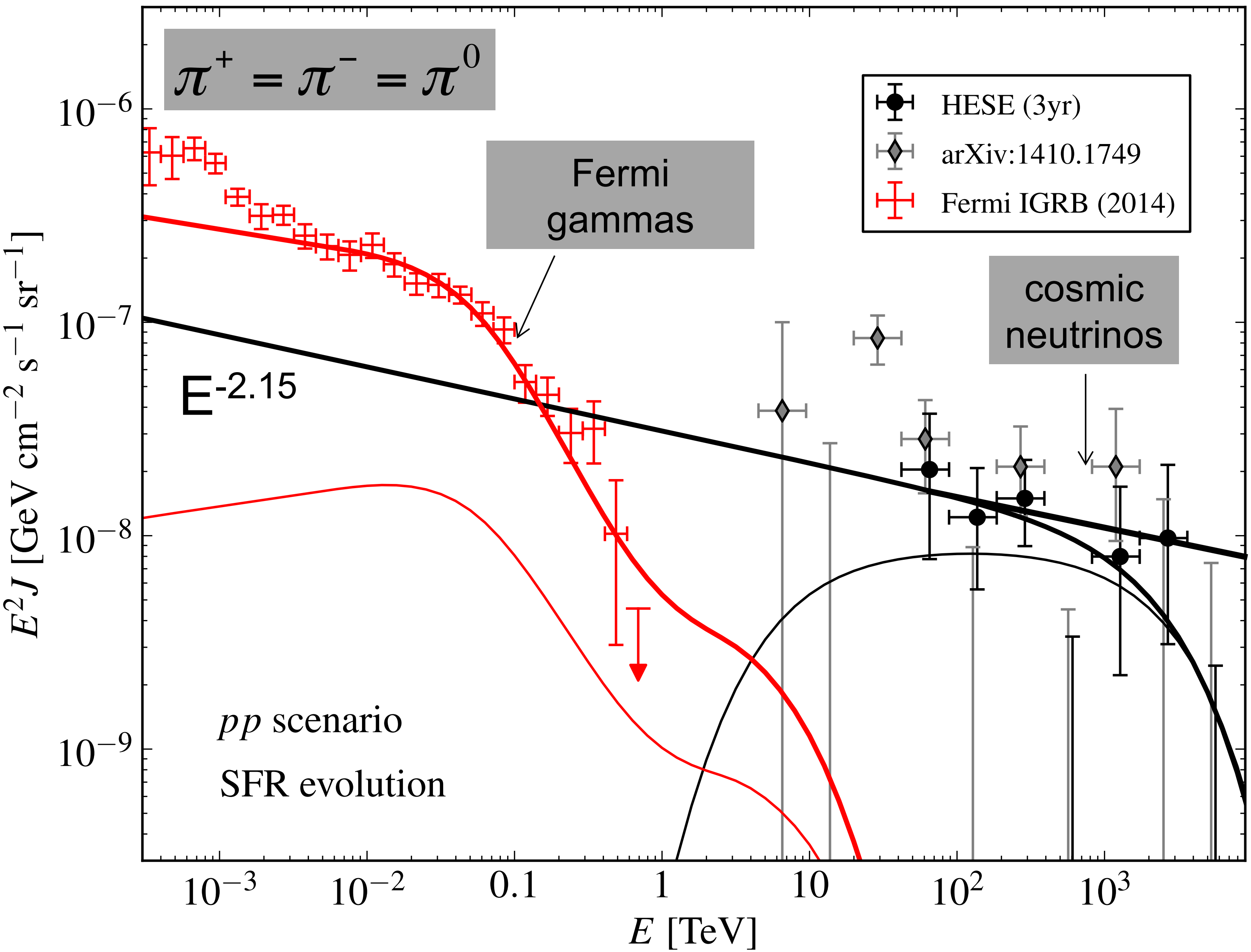
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



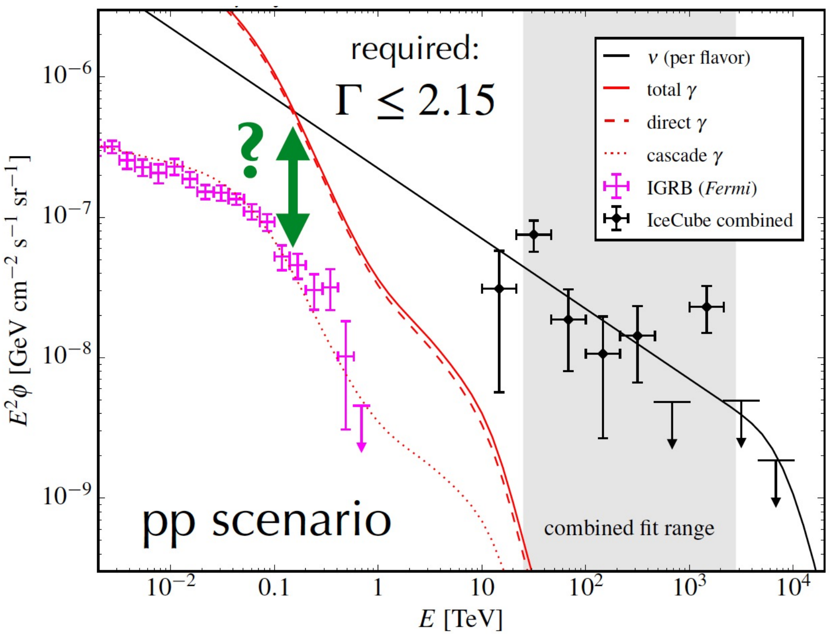
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

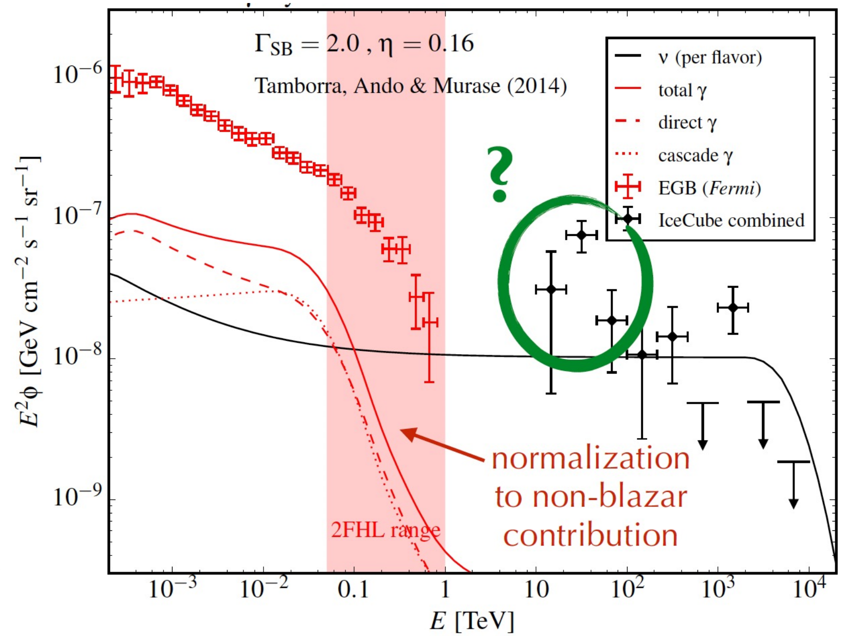


GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^{+} + e^{-}$



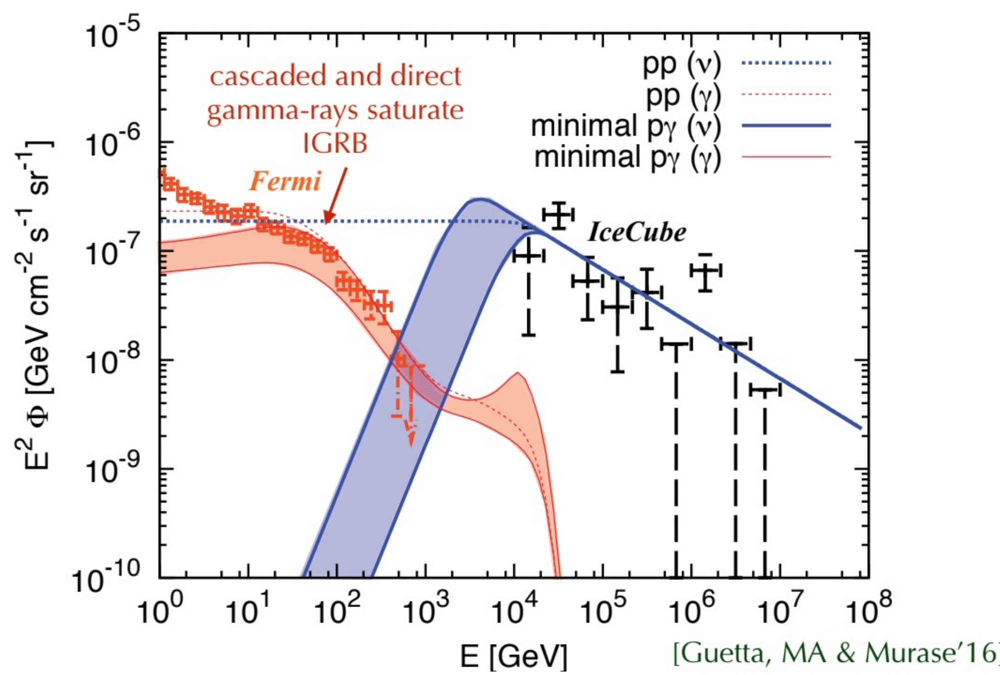
$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

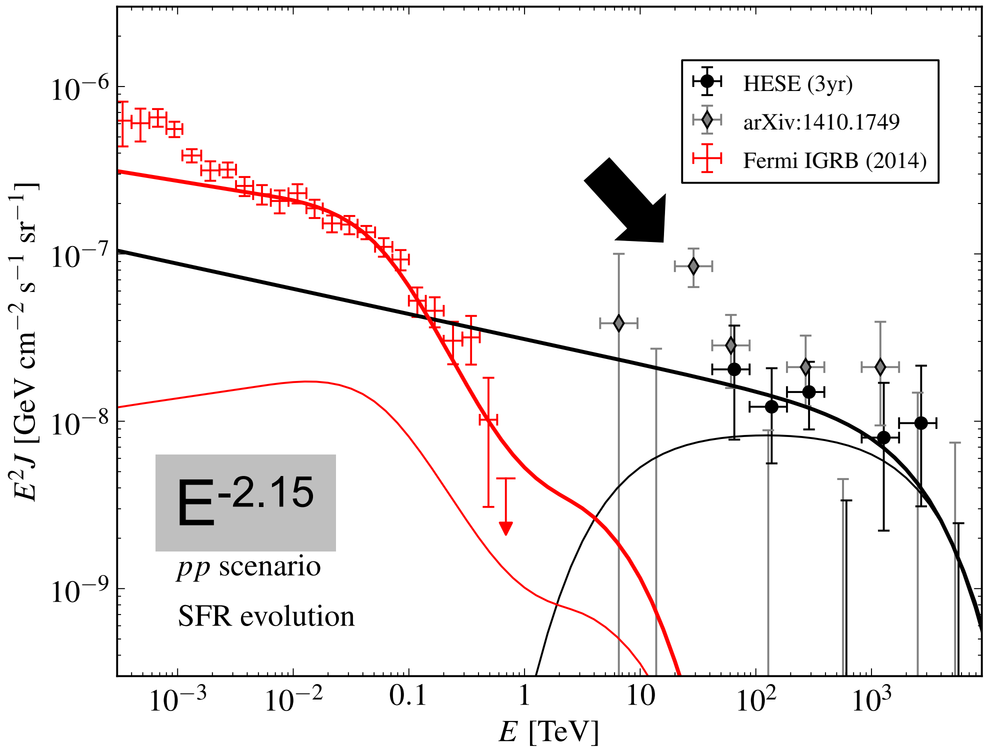




pγ scenario

for instance proton jet interacting with 10 eV ~ 1KeV photons near black hole in agn



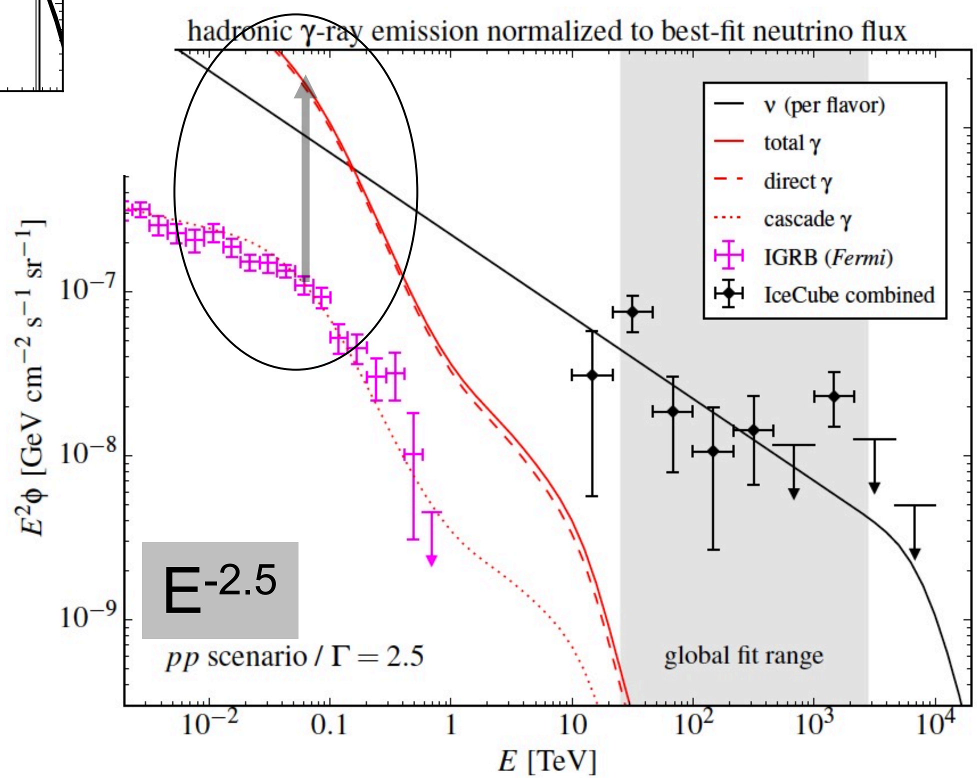


- a source opaque to protons that efficiently produces neutrinos with $\tau_{p\gamma} \sim 1$, is opaque to gamma rays

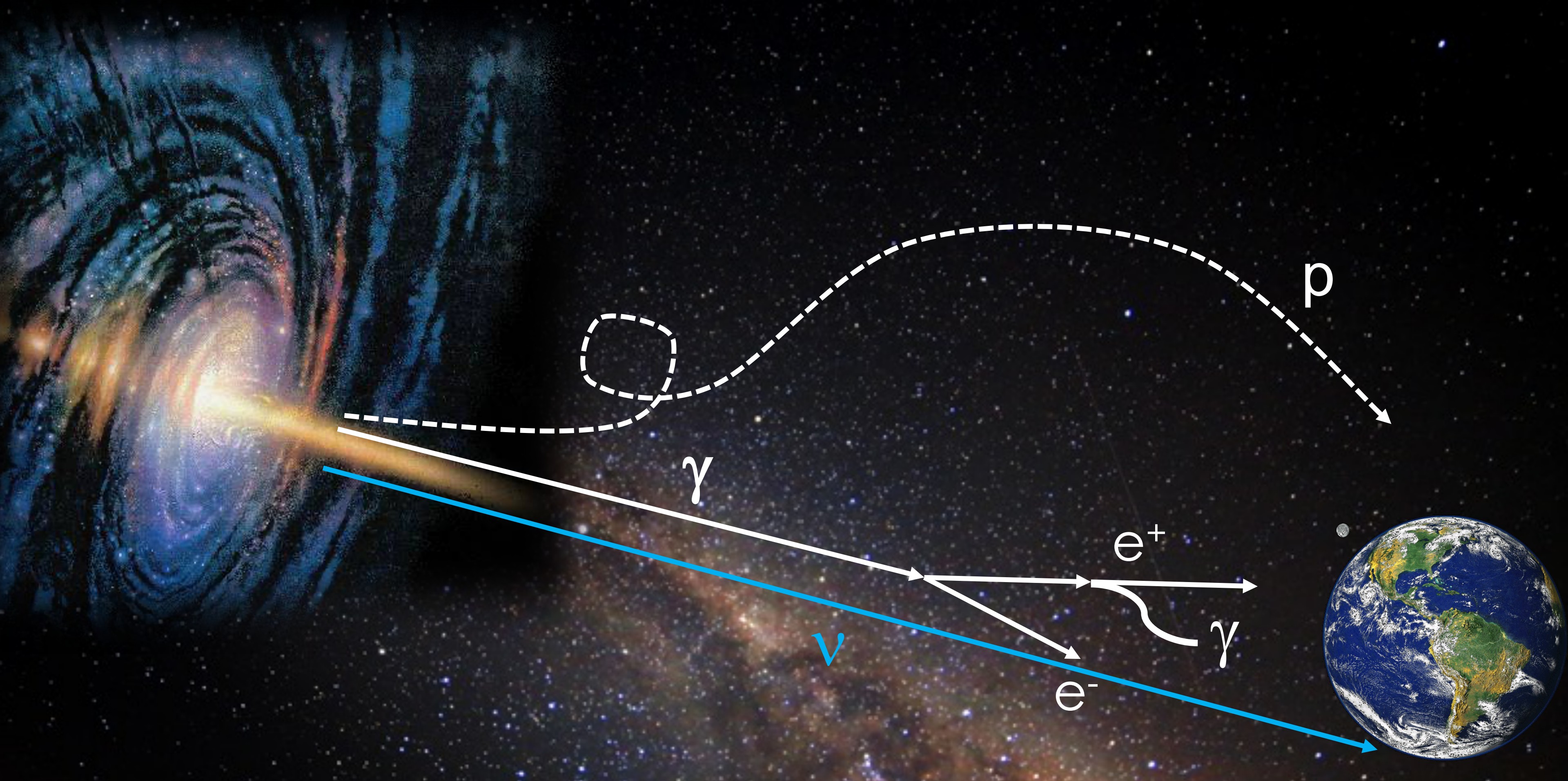
- dark sources with opacity $\tau_{\gamma\gamma} \sim 1$?

- 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.

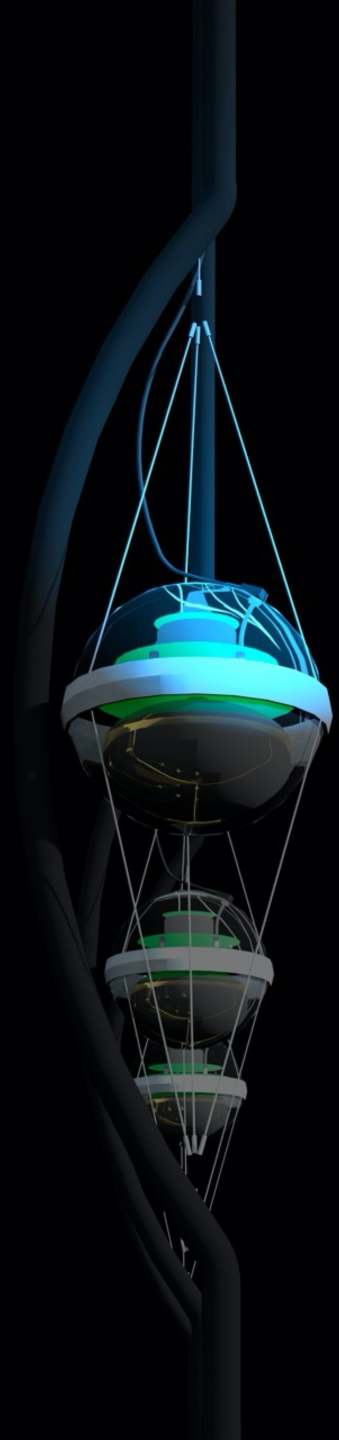


- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



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



IceCube: the discovery of cosmic neutrinos
francis halzen

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

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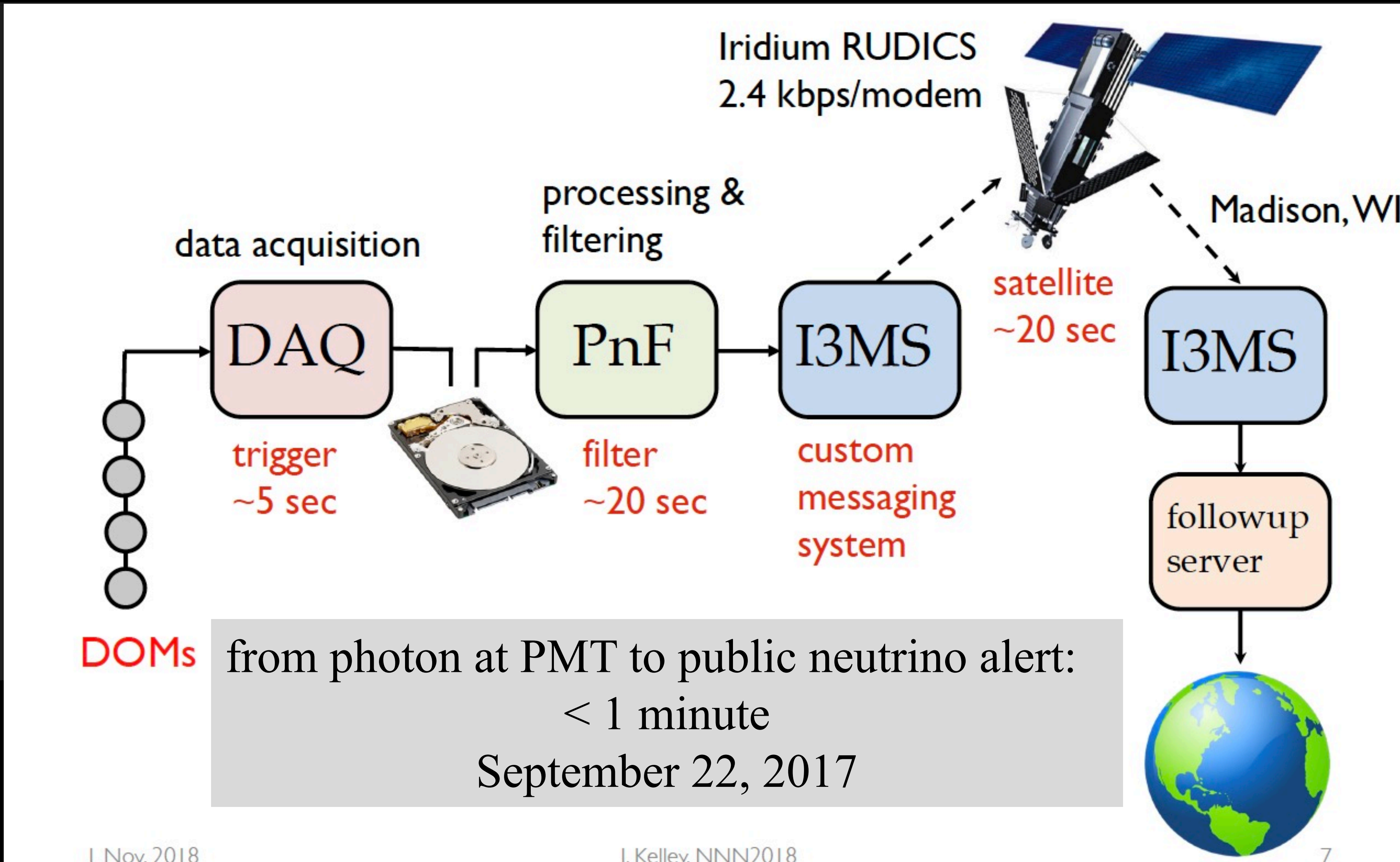
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

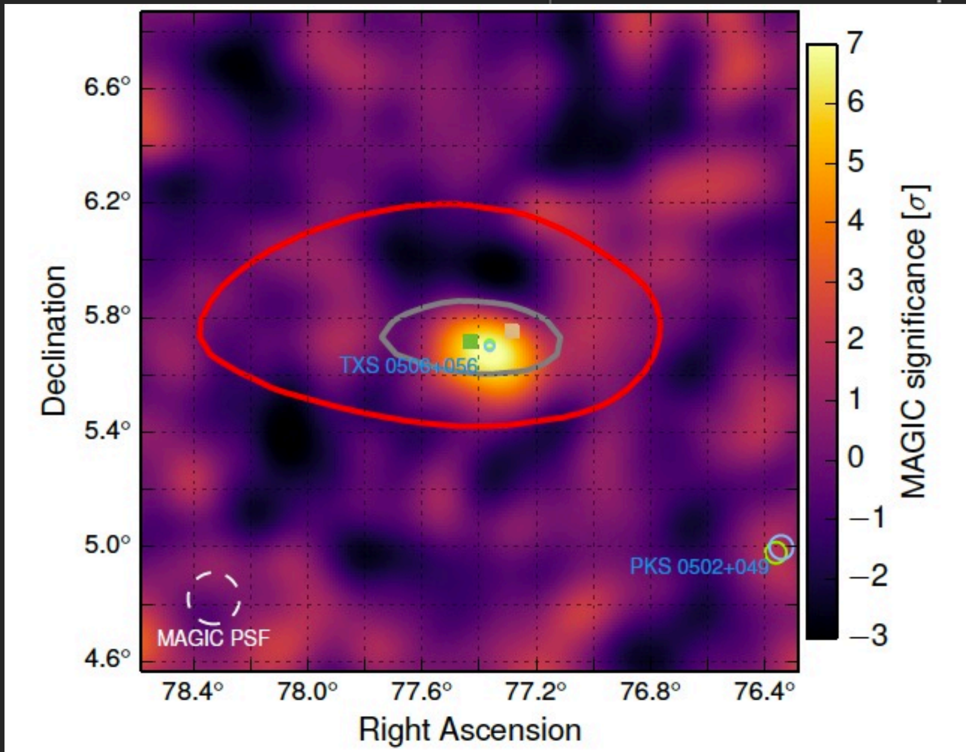
We send our high-energy events in real-time as public GCN alerts now!



IceCube Trigger

43 seconds after trigger, GCN notice was sent

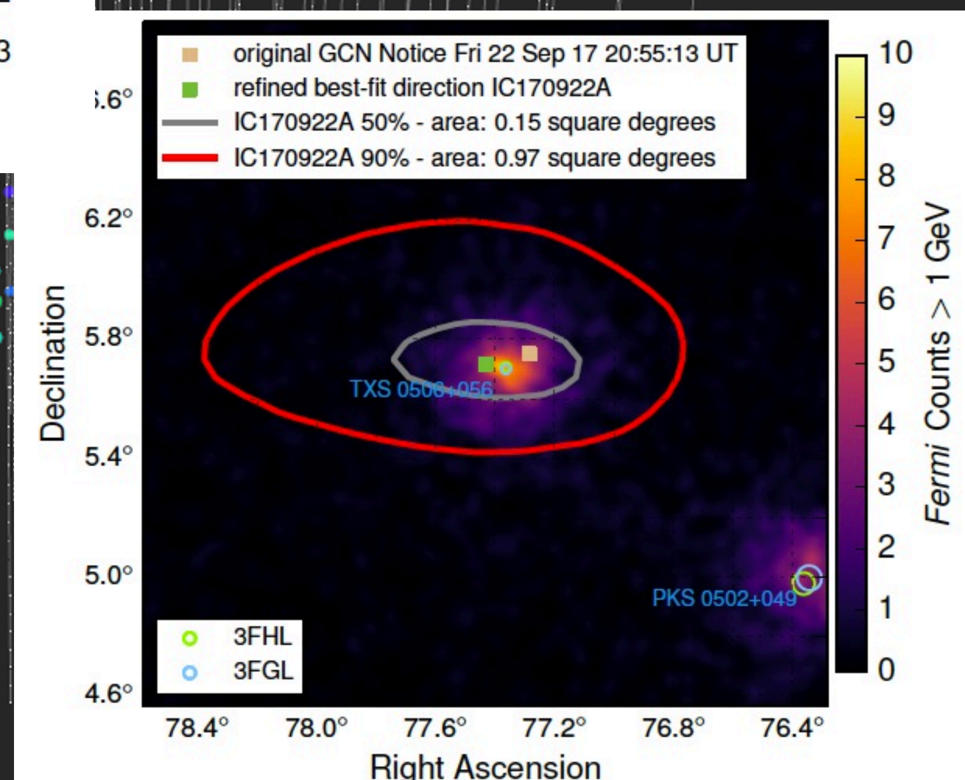
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
        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



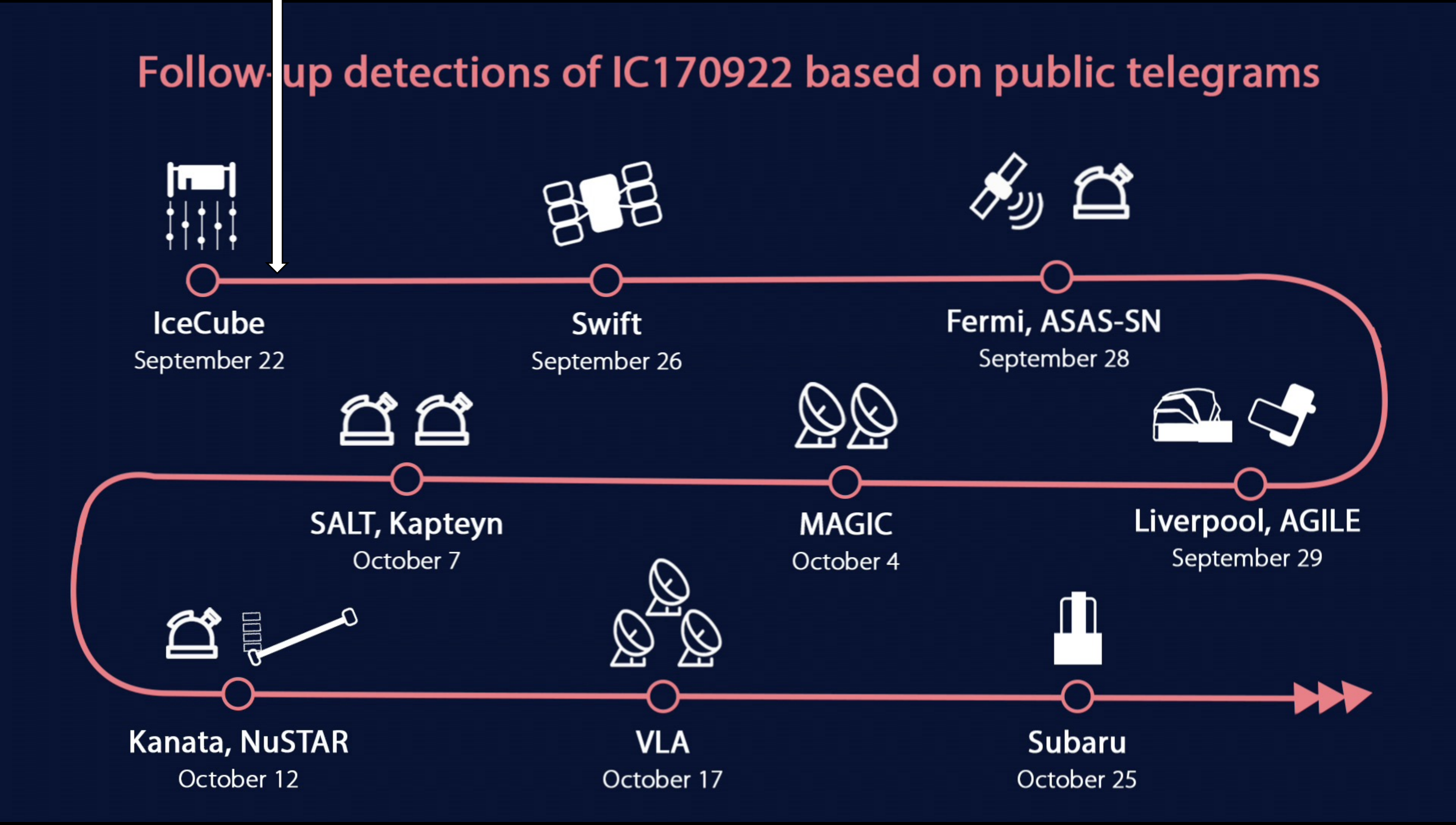
IceCube 170922
290 TeV

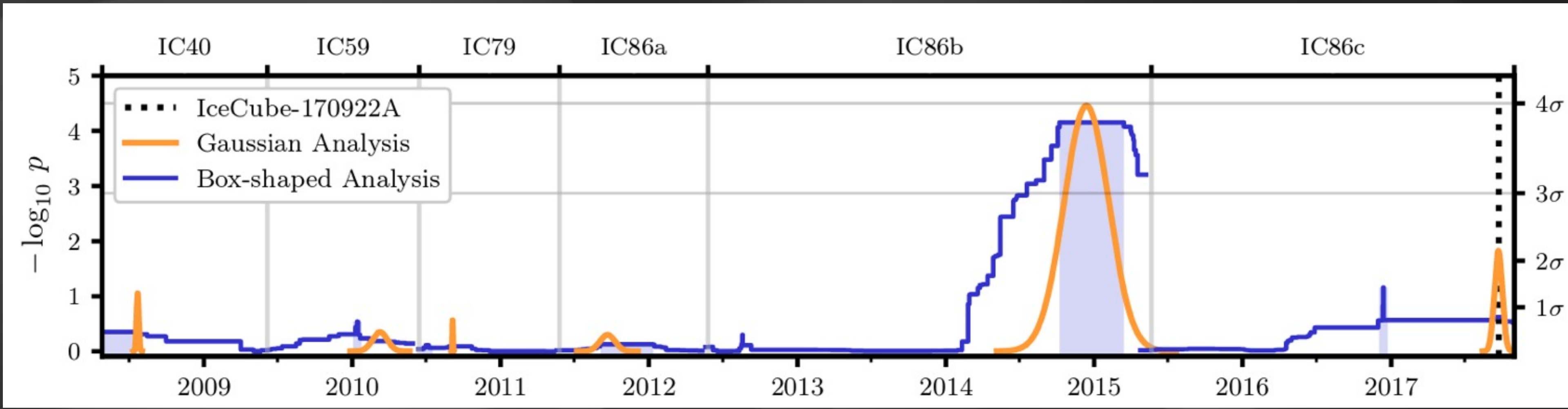
Fermi
detects a flaring
blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas



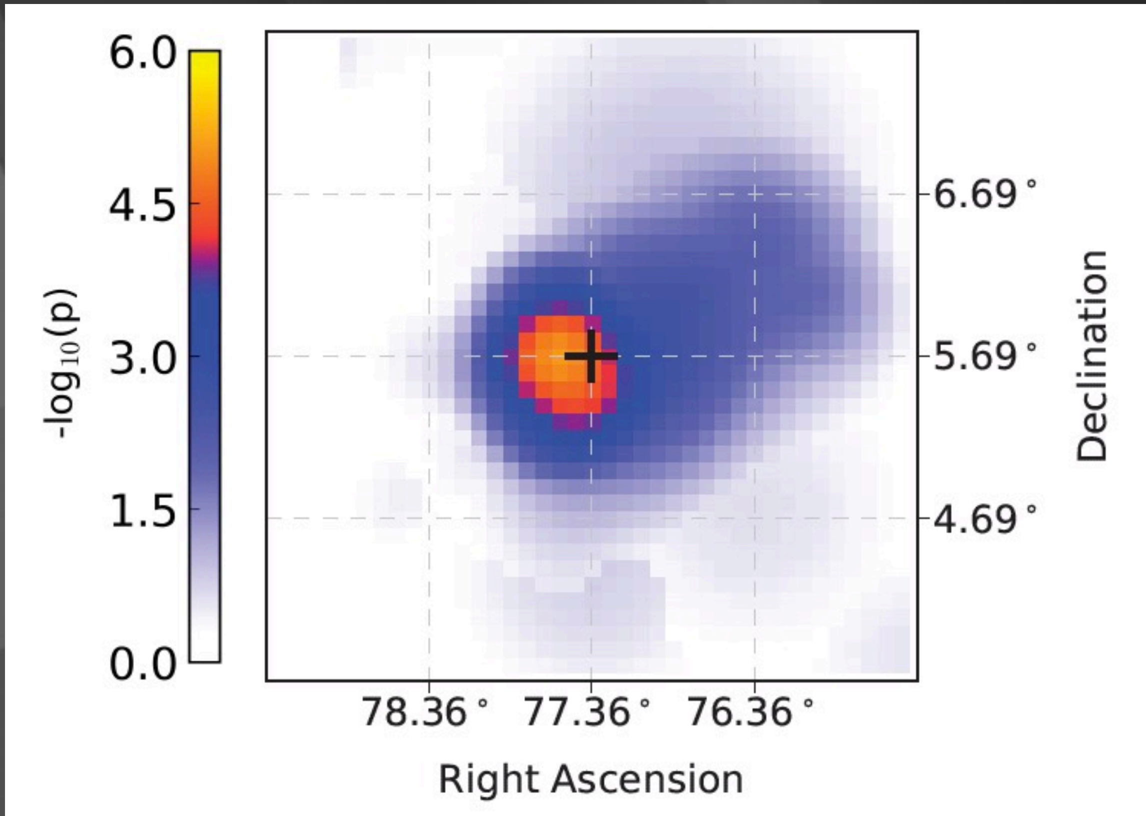
MASTER robotic optical telescope network: after 73 seconds





search in archival IceCube data:

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



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

IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations
M.G. Aartsen(Canterbury U.) et al. (Jul 12, 2018) Published in: *Science* 361 (2018) 6398, eaat1378
e-Print: 1807.08816 [astro-ph.HE]

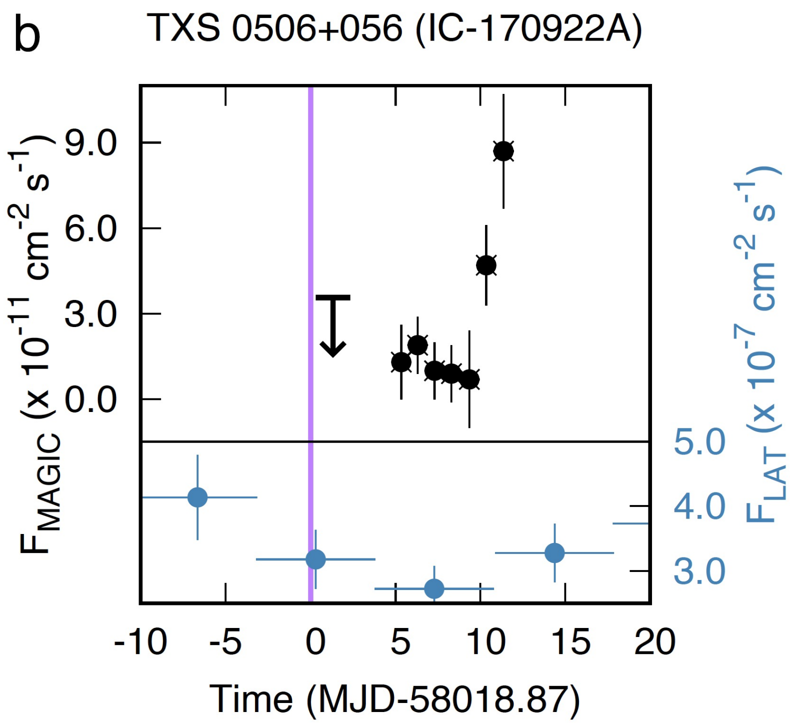
- Neutrino emission from the direction of the blazar TXS 0506+05 prior to the IceCube-170922A alert

IceCube Collaboration
M.G. Aartsen(Canterbury U.) et al. (Jul 12, 2018) Published in: *Science* 361 (2018) 6398, 147-151
e-Print: 1807.08794 [astro-ph.HE]

- two totally independent observations at the > 3σ level

- next: optical observation and radio interferometry imaging

no gamma rays in 2017 at the time the neutrino is produced ?



- MAGIC, HESS and VERITAS: source exhibited daily variations with no TeV gamma rays observed 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 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"

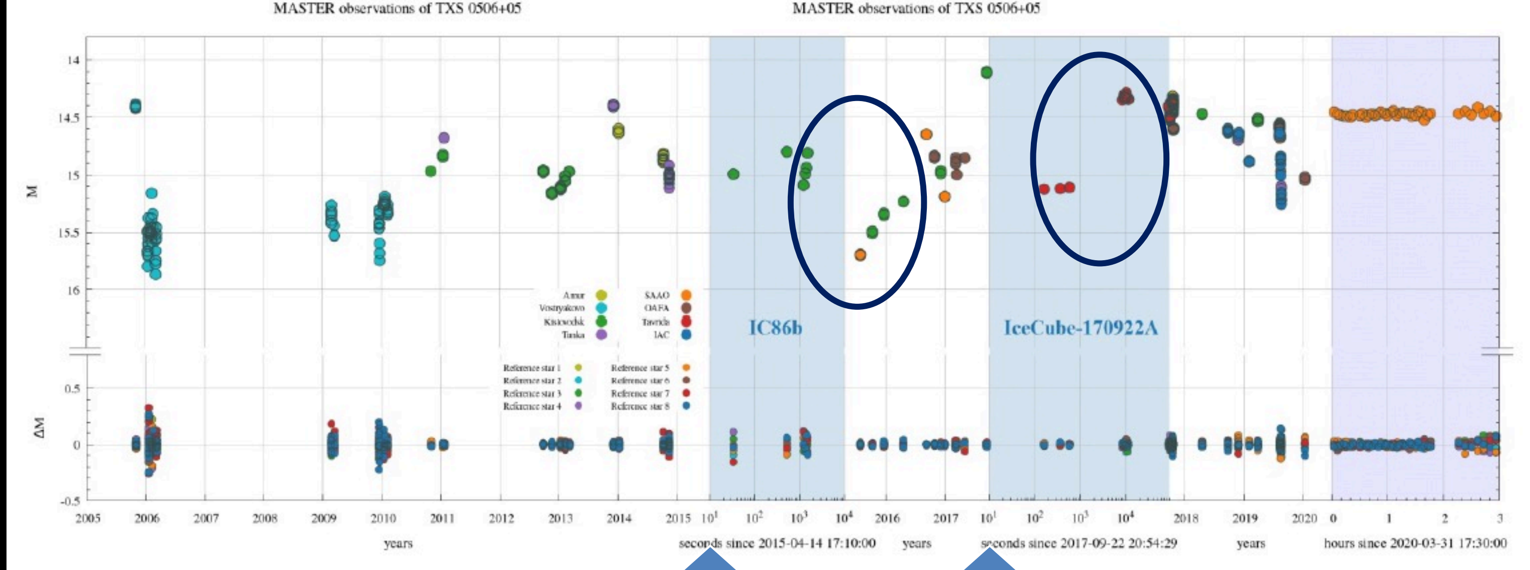
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

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]

MASTER
robotic network

optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years → seconds

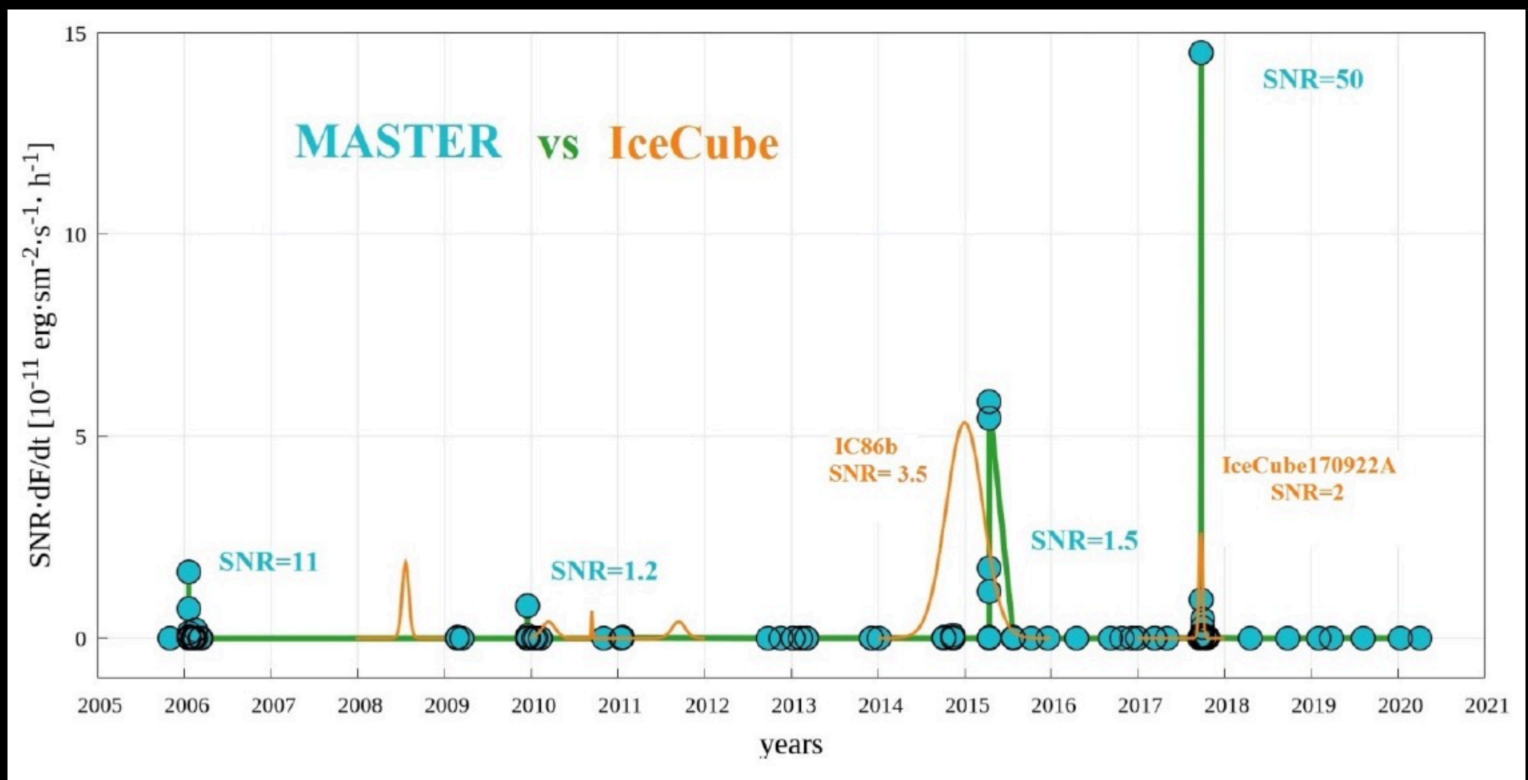


seconds after
2014-15 burst

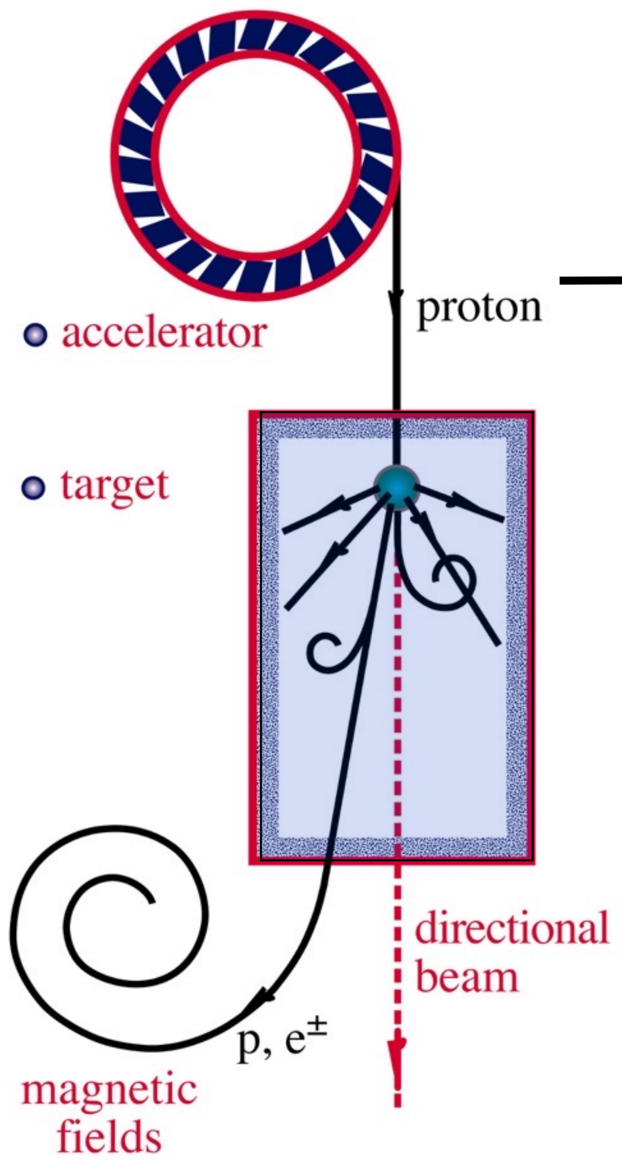
seconds after
IC170922

time variation of flux
times
signal-to-noise

hour-scale
variability of the
source after
neutrino emission



ν and γ beams : heaven and earth



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

→ cosmic ray + neutrino

supermassive black hole

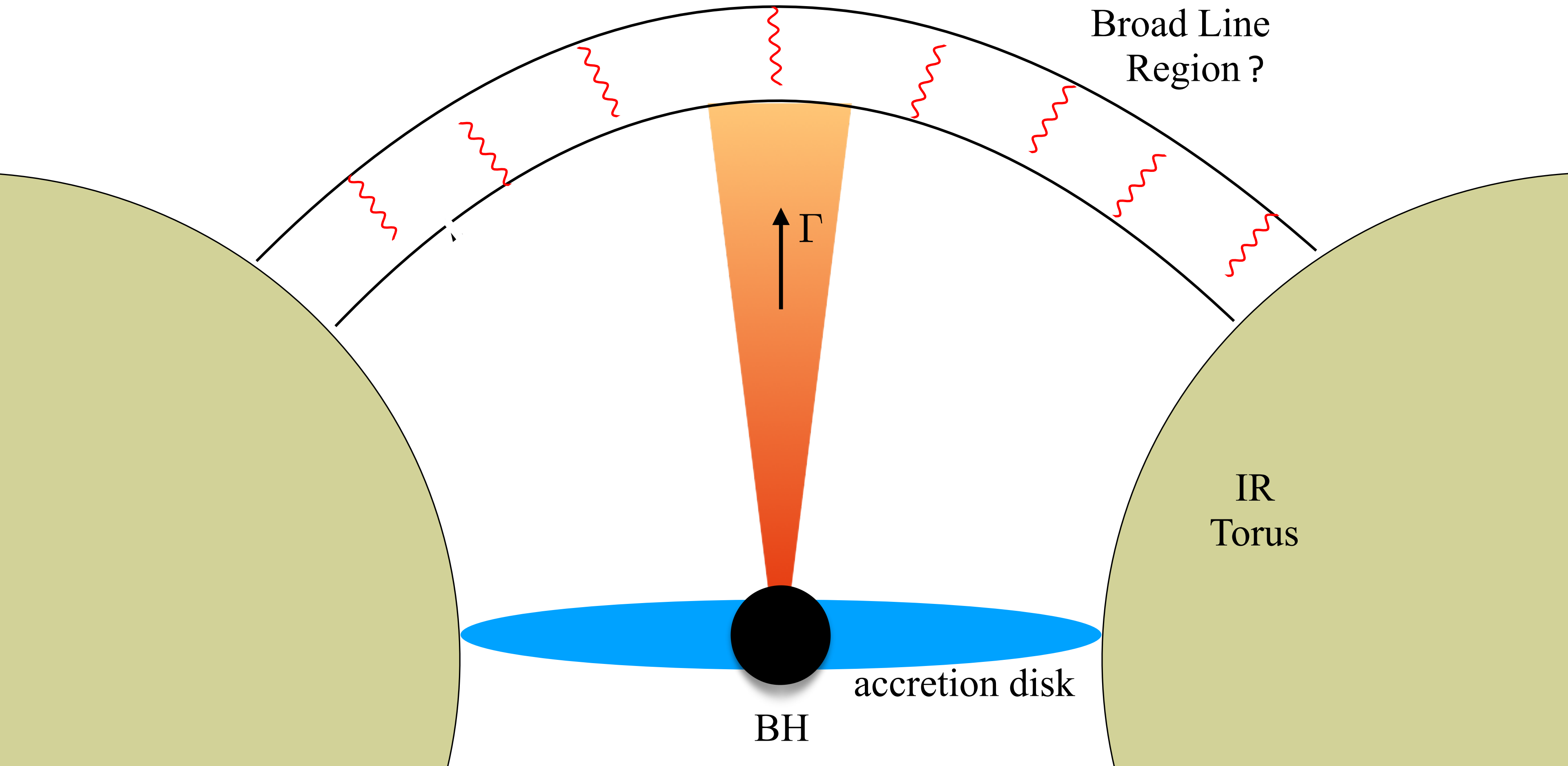
target ?

→ a neutrino source needs an accelerator and a target

→ the target is likely opaque to gamma rays

BLAZAR MODEL: spectacularly unsuccessful and should be

- there is no target to produce neutrinos because the jet is transparent to photons ($\tau_{\gamma\gamma} \sim 10^2\ \tau_{p\gamma}$)
- neutrinos are produced in bursts



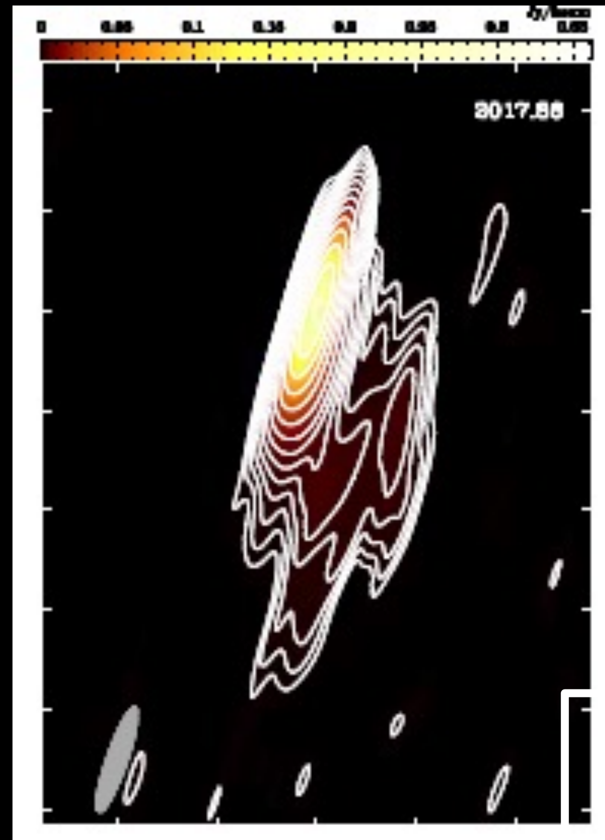
RADIO INTERFEROMETRY

images show the target that produces the neutrinos and obscures the gamma rays

- core brightening observed in a radio burst that started 5 years ago

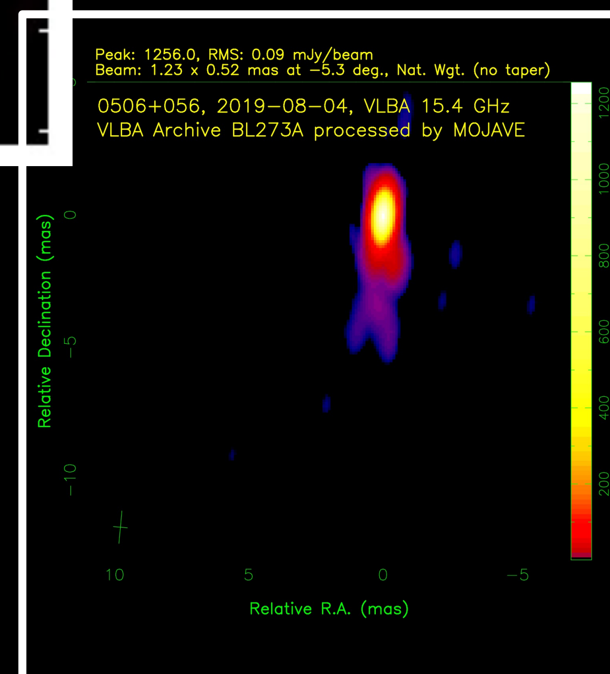
TXS 0506+056

- beyond 5 milliarcseconds the jet loses its tight collimation…
- jet found a target after ~ tens of pc to produce neutrinos

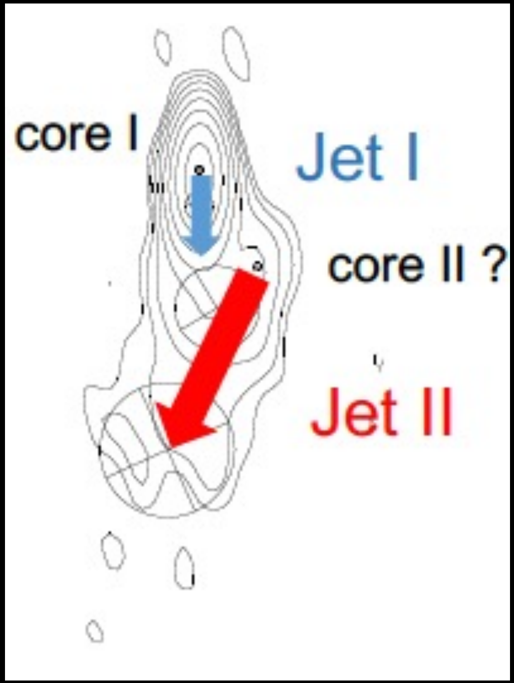


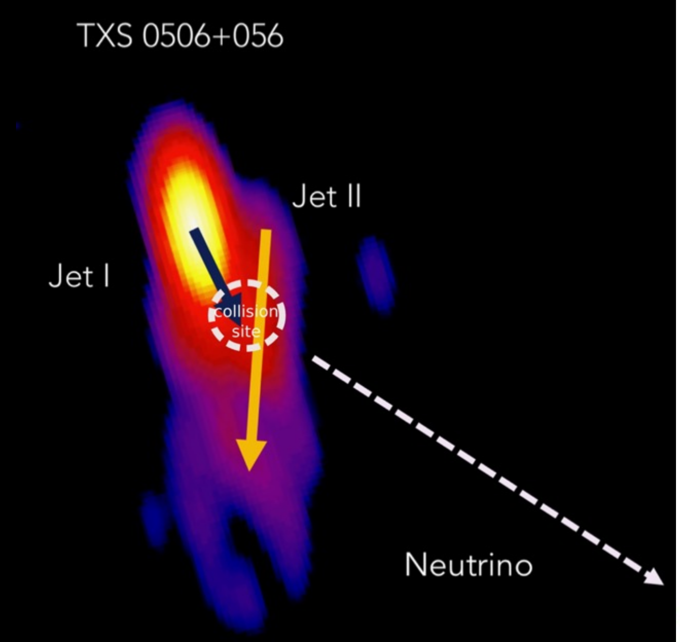
1912.01743v1 [astro-ph.GA]

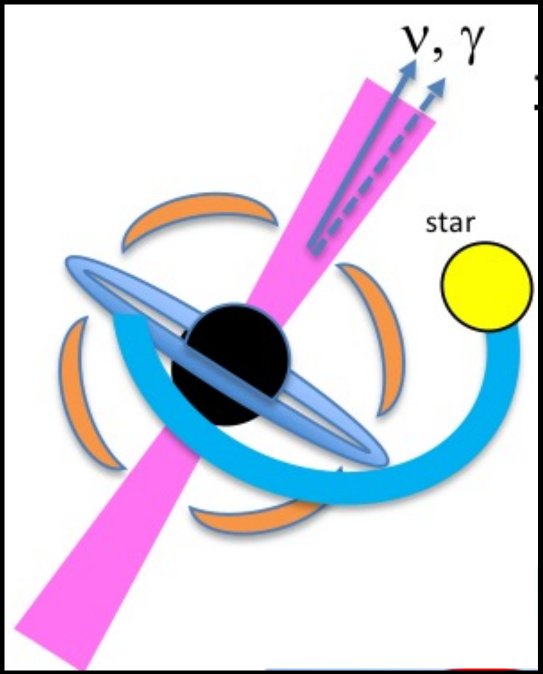
A&A. 630 A103
A&A. 632 C3

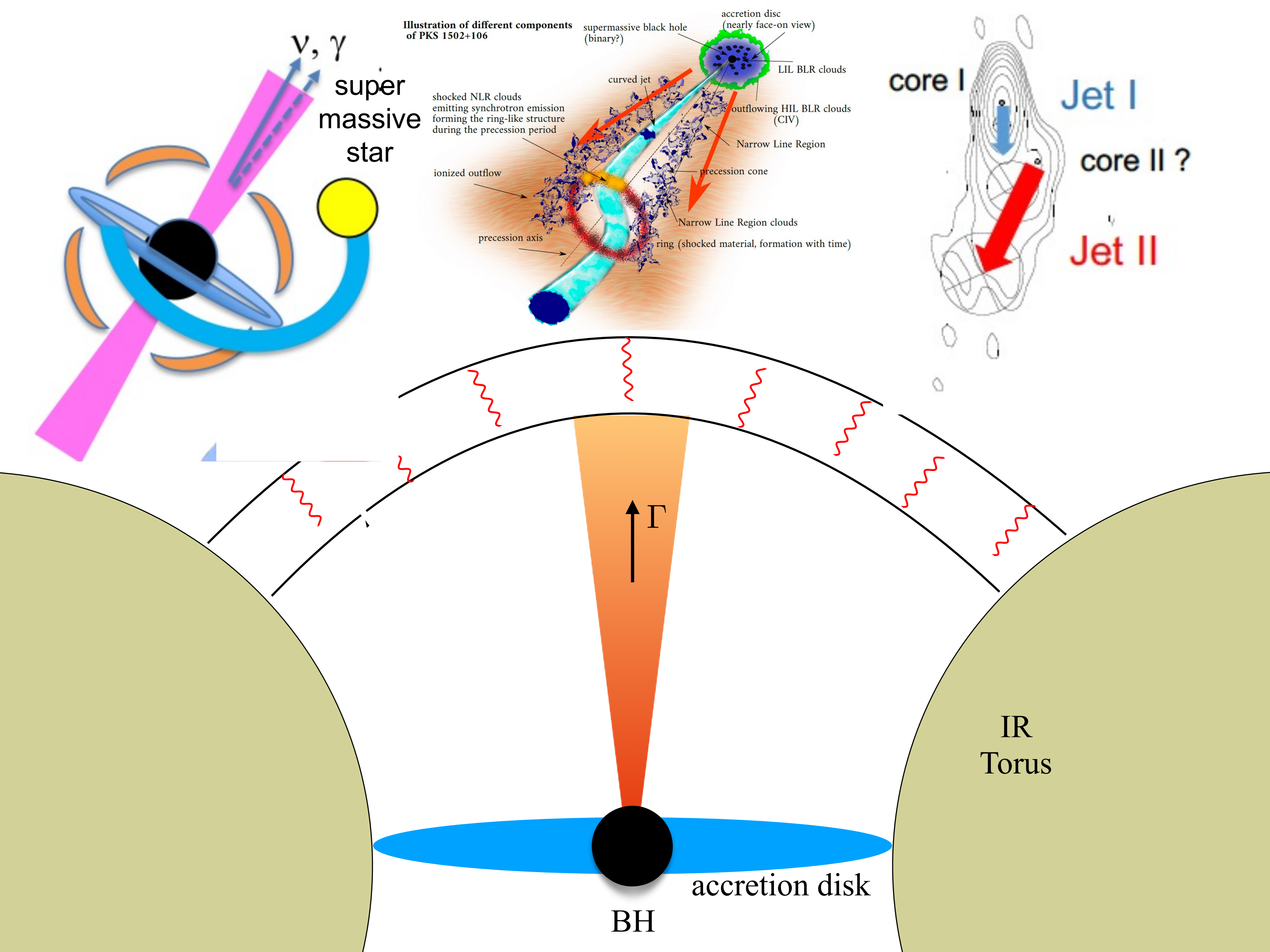


- radio interferometry images show that the jet interacts with a target close to the base of the jet
- a massive star in the host galaxy, the jet of a merging galaxy, warped jet, structured jet…
- the gamma rays accompanying the neutrinos lose their energy in the target that produces them









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

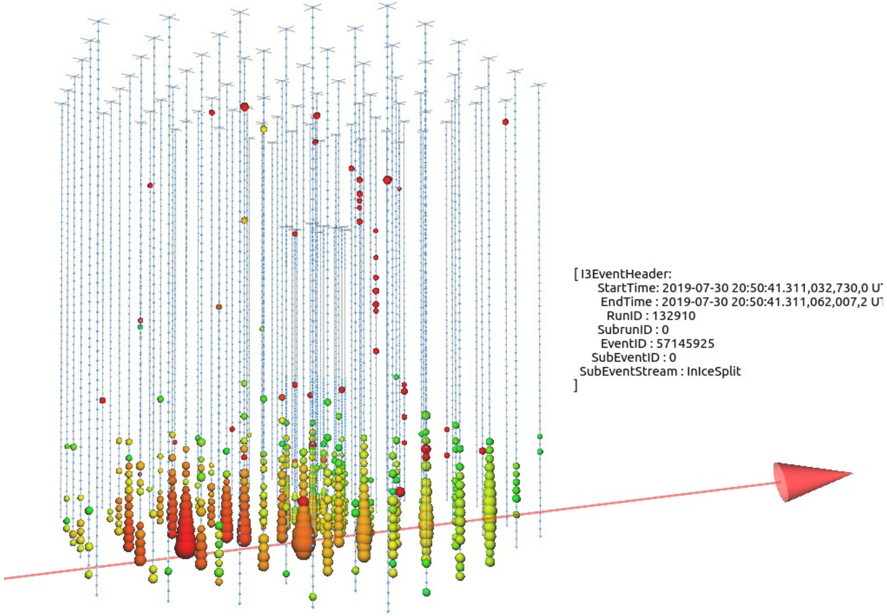
- TXS is *not* a blazar during the short times that neutrinos are produced: IceCube's neutrinos are detected from temporally gamma-suppressed blazars.

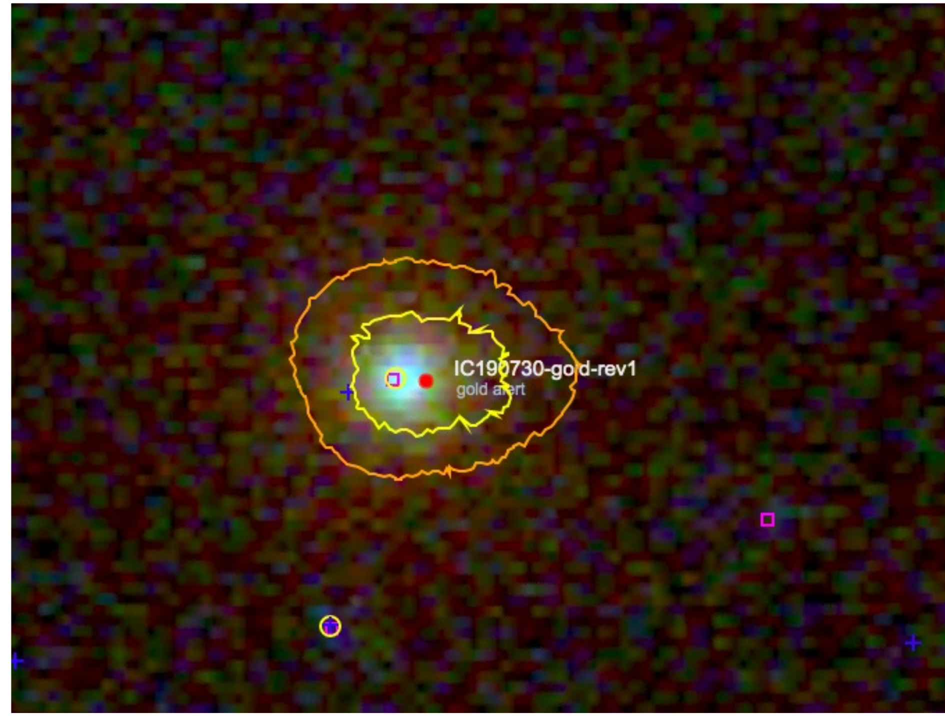
- TXS cannot be a “vanilla” blazar, otherwise blazars would overproduce the IceCube diffuse flux 1605.06119 [astro-ph.HE]

- special sources like TXS, at the density of 5% of the number of blazars in the Universe, can accommodate the cosmic neutrino flux, and the high energy cosmic ray flux

- 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***
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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.

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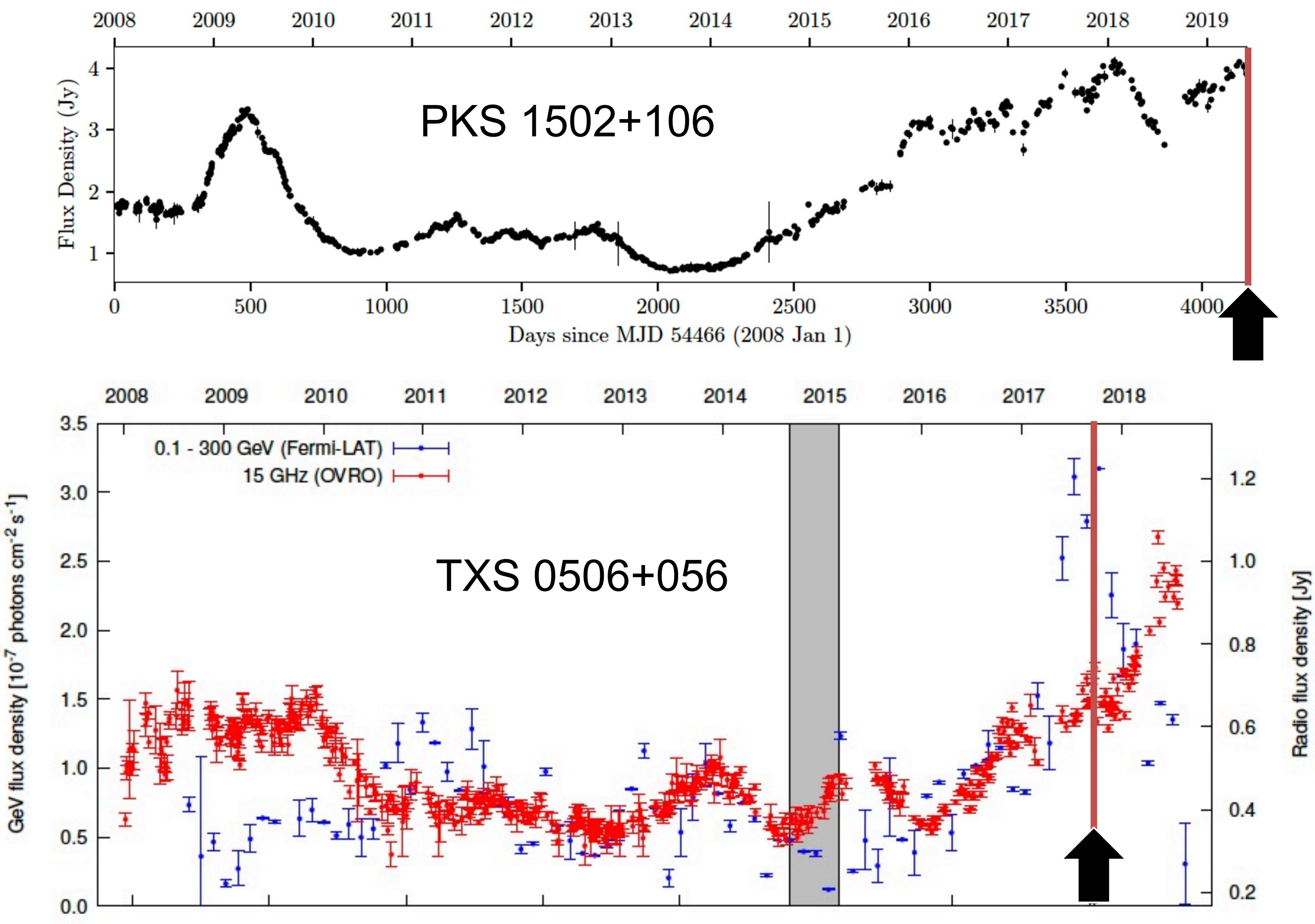
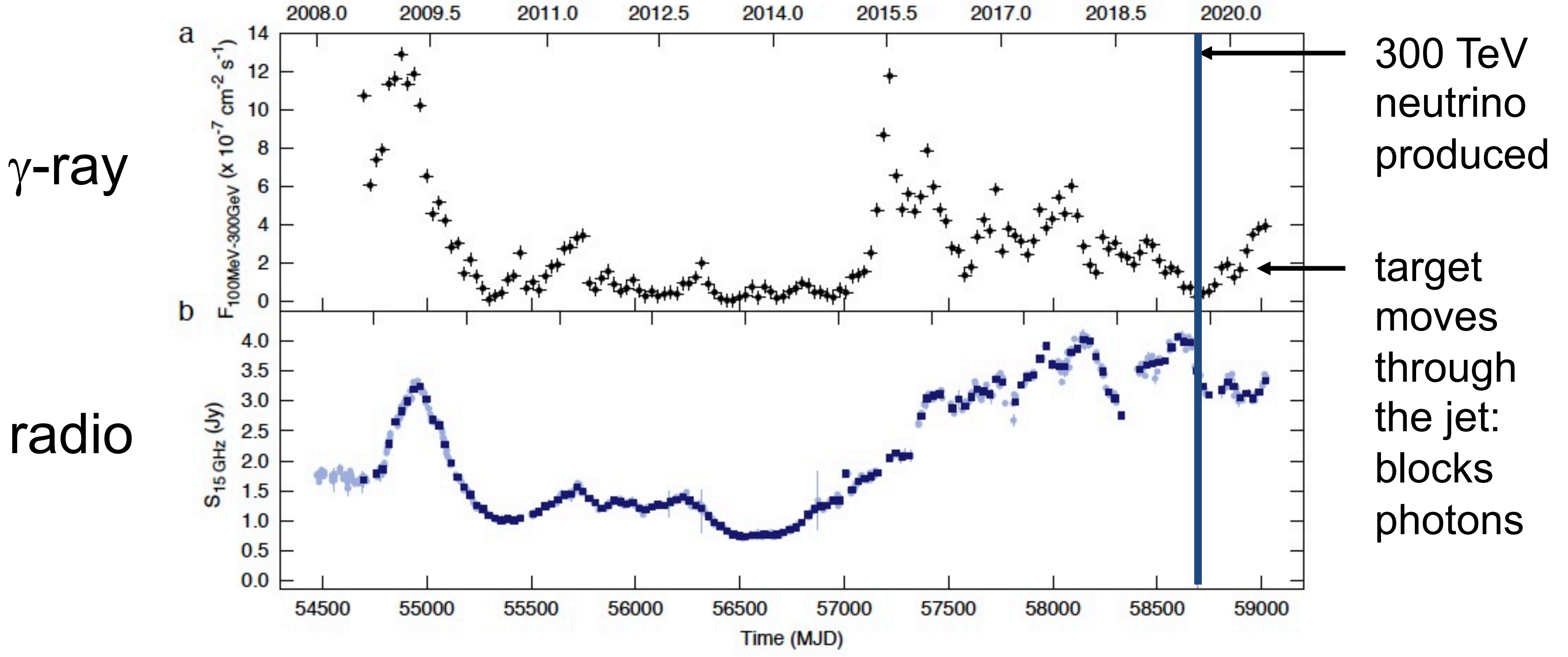
the two highest energy (300 TeV ν_μ) IceCube neutrino alerts are coincident with radio flares (→ core agn activity)

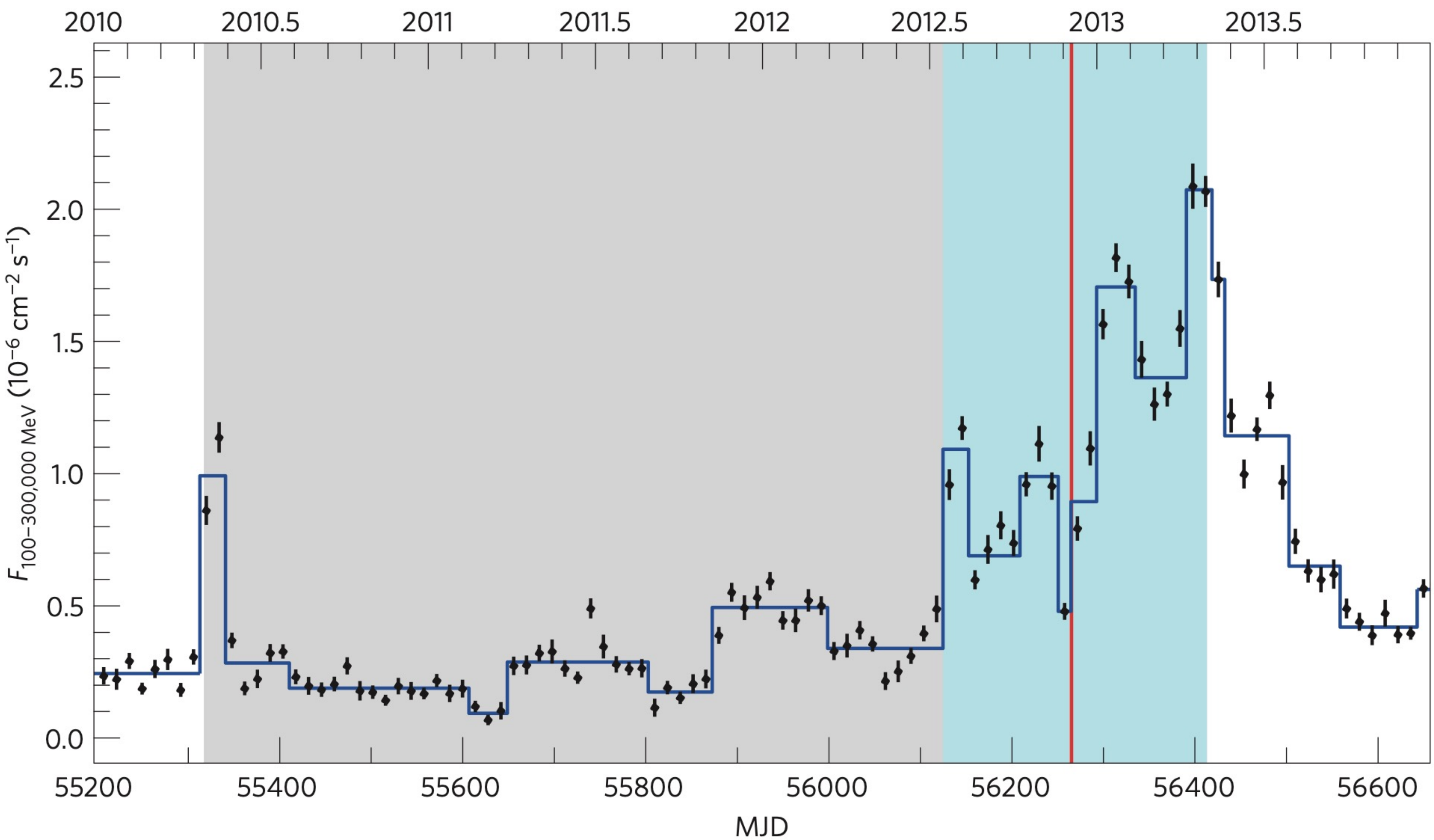


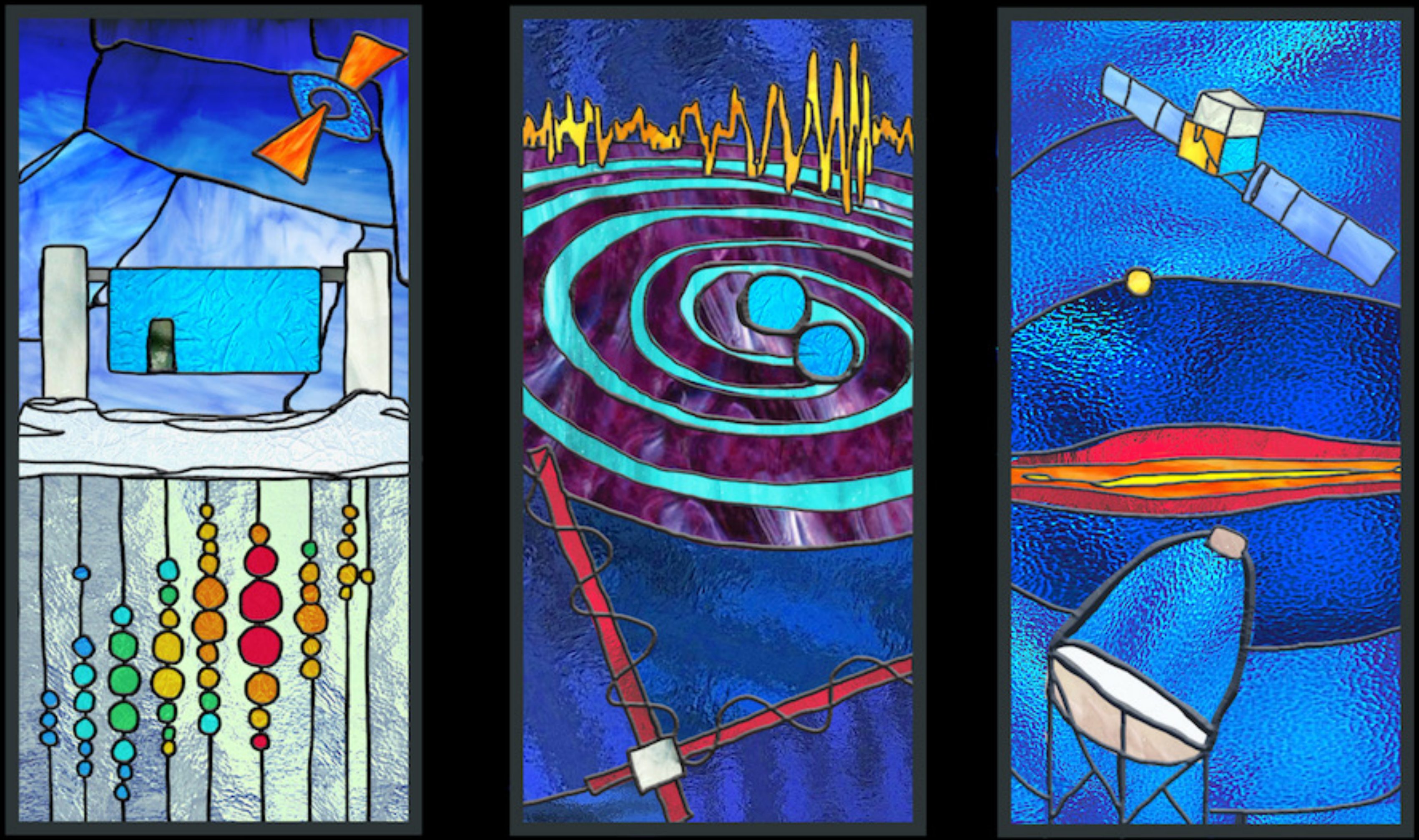
PKS 1502+106



2009.09792 [astro-ph.HE]

big bird (~ 2 PeV) and PKS 1424+240

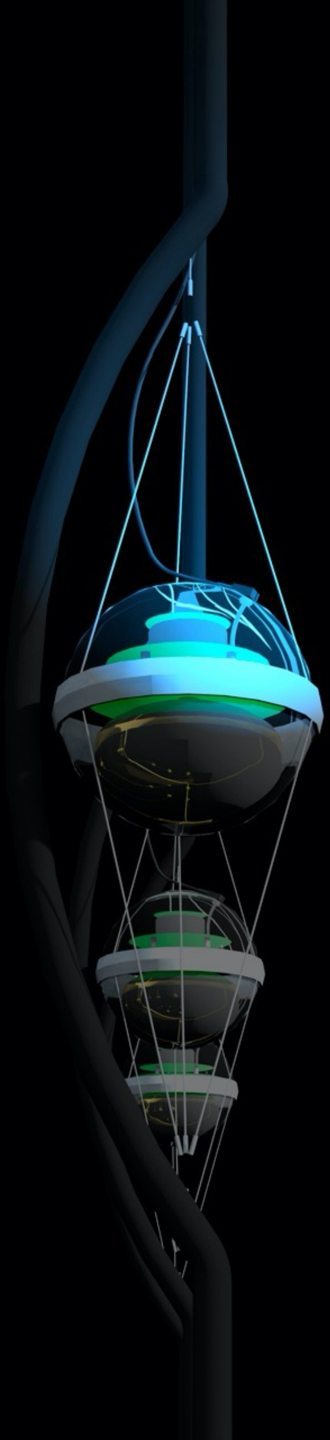




next attraction: gravitational waves + neutrinos?

(August 17, 2017 neutron star merger: jet not aligned) neutrino astronomy 2021

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



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NGDOM 1

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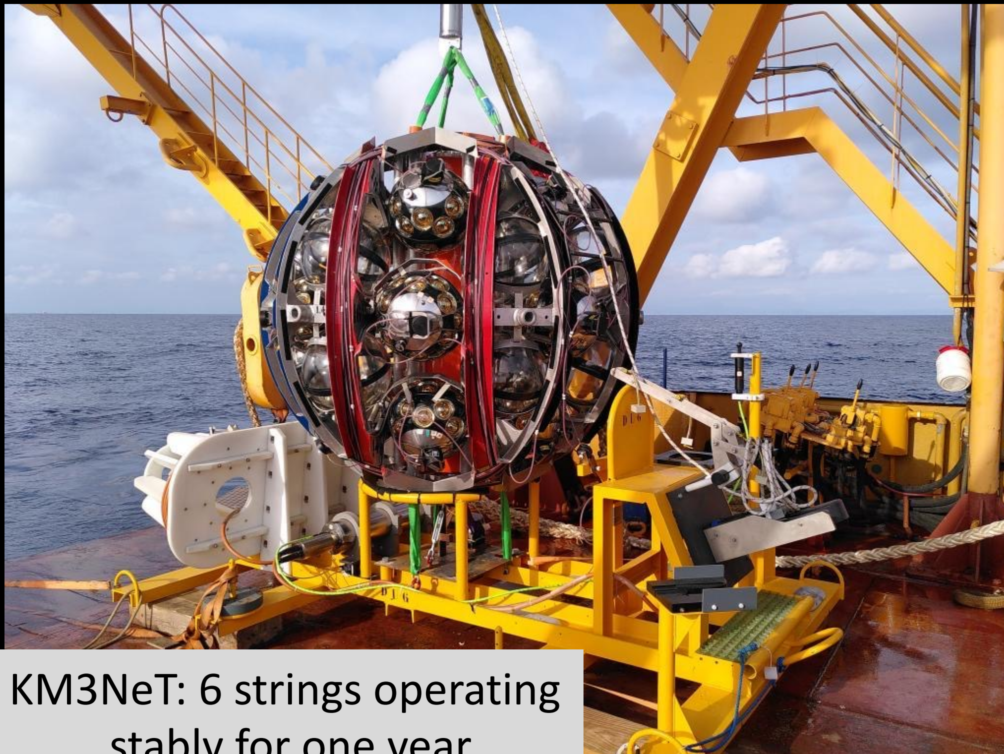
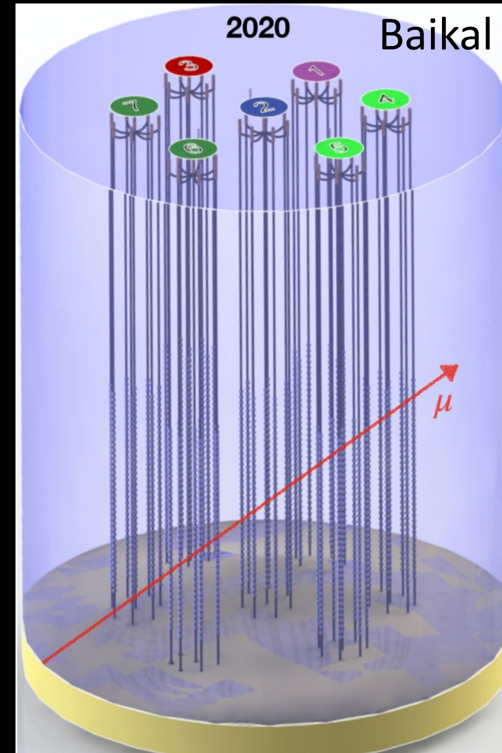
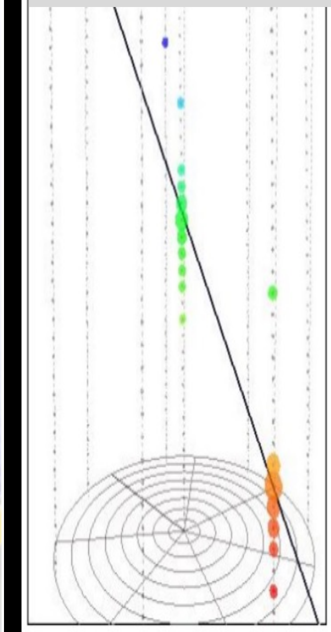
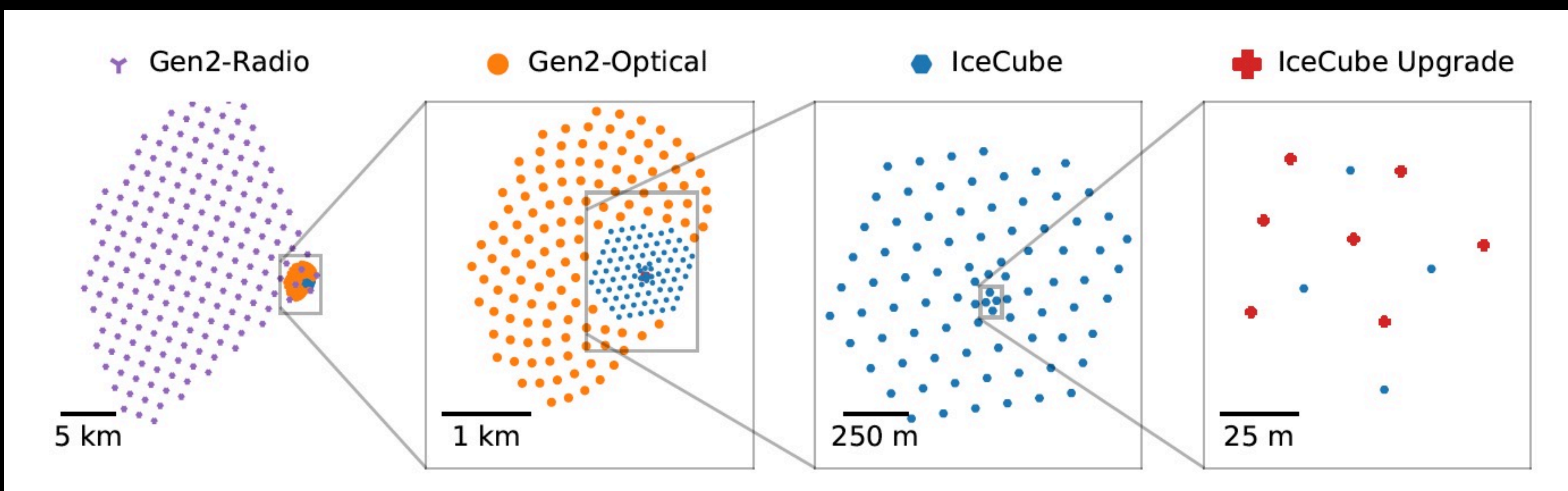


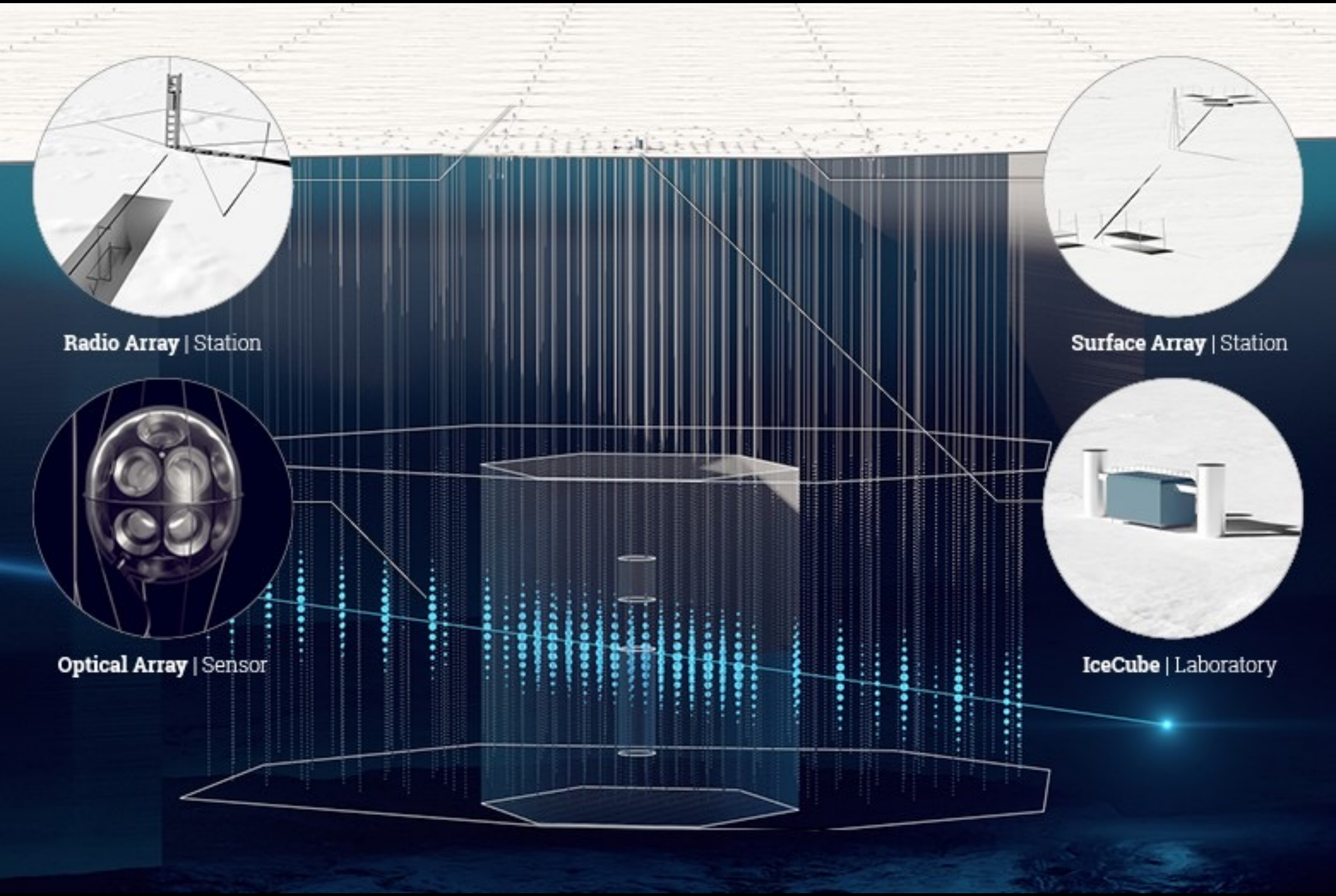
KM3NeT: 6 strings operating stably for one year



completion: 14 units 2024






Radio Array | Station
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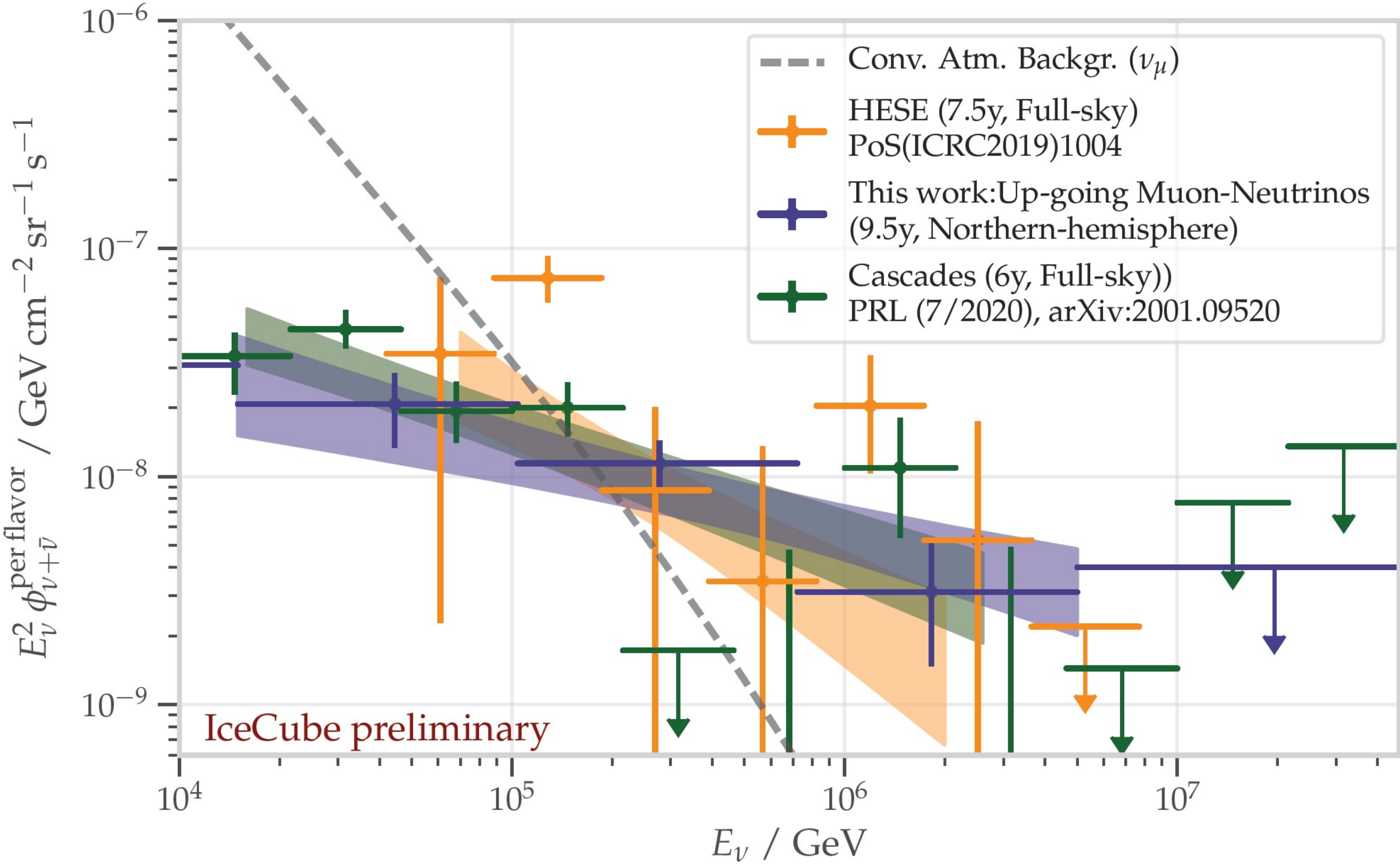
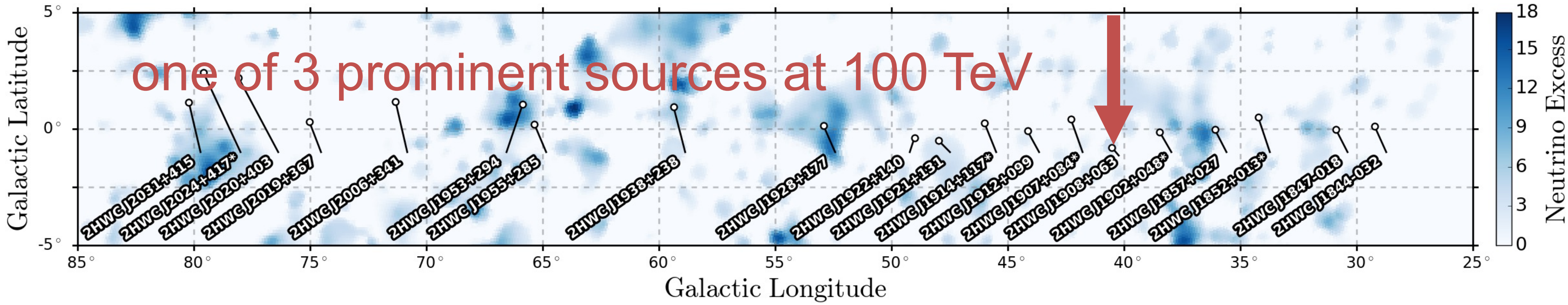
Optical Array | Sensor
IceCube | Laboratory

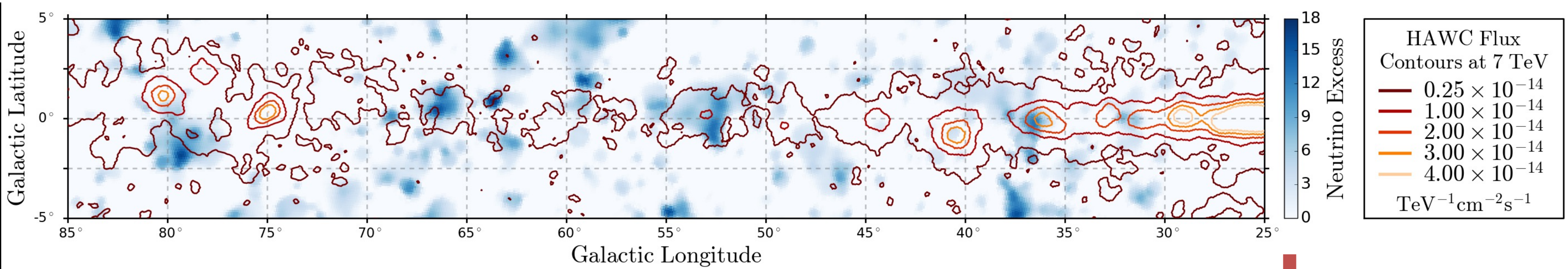


coming soon:

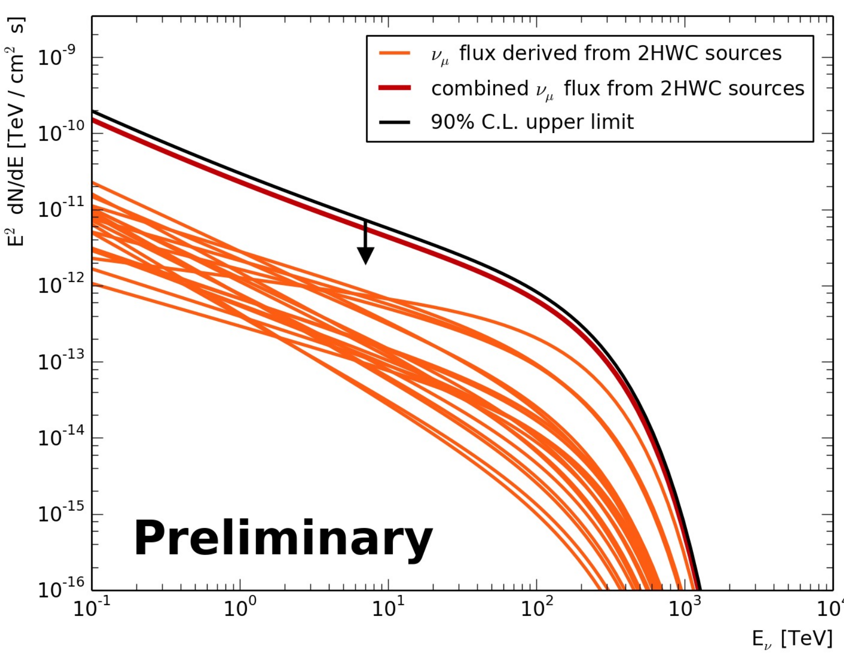
superior calibration of the detector, improved simulation and better energy and directional reconstruction with better neural nets



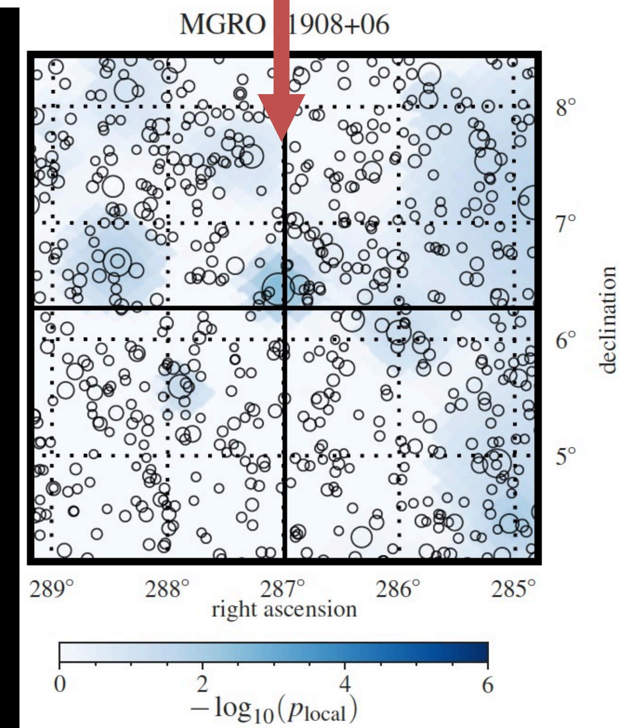
one of 3 prominent sources at 100 TeV
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1847-018
2HWC J1844-032
Galactic Latitude
Galactic Longitude
Neutrino Excess



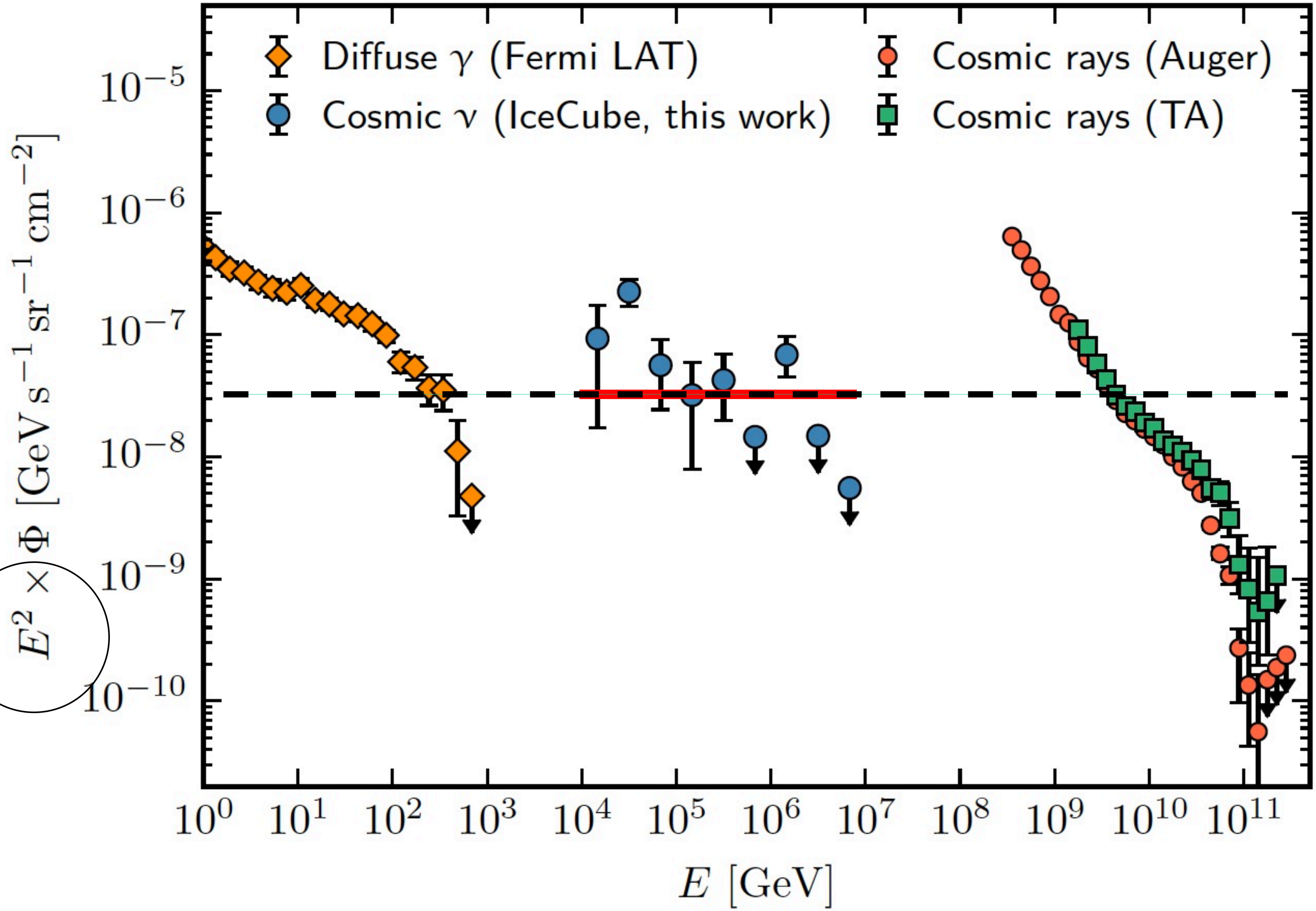
Galactic Latitude
Galactic Longitude
Neutrino Excess
HAWC Flux
Contours at 7 TeV
0.25×10^{-14}
1.00×10^{-14}
2.00×10^{-14}
3.00×10^{-14}
4.00×10^{-14}
$TeV^{-1}cm^{-2}s^{-1}$



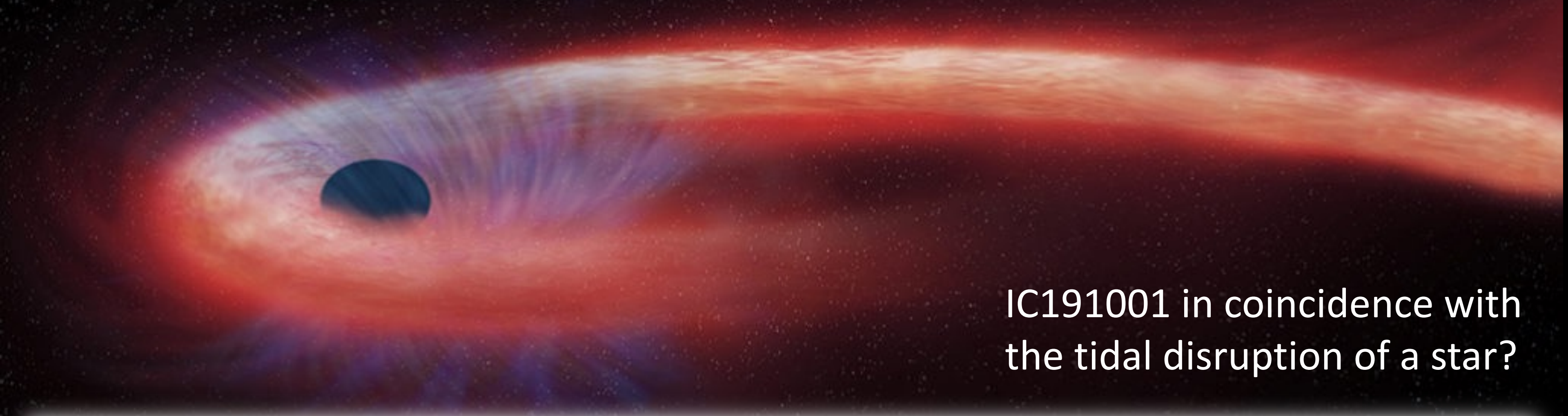
ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]
Preliminary



MGRO 1908+06
right ascension
declination
$-\log_{10}(p_{local})$

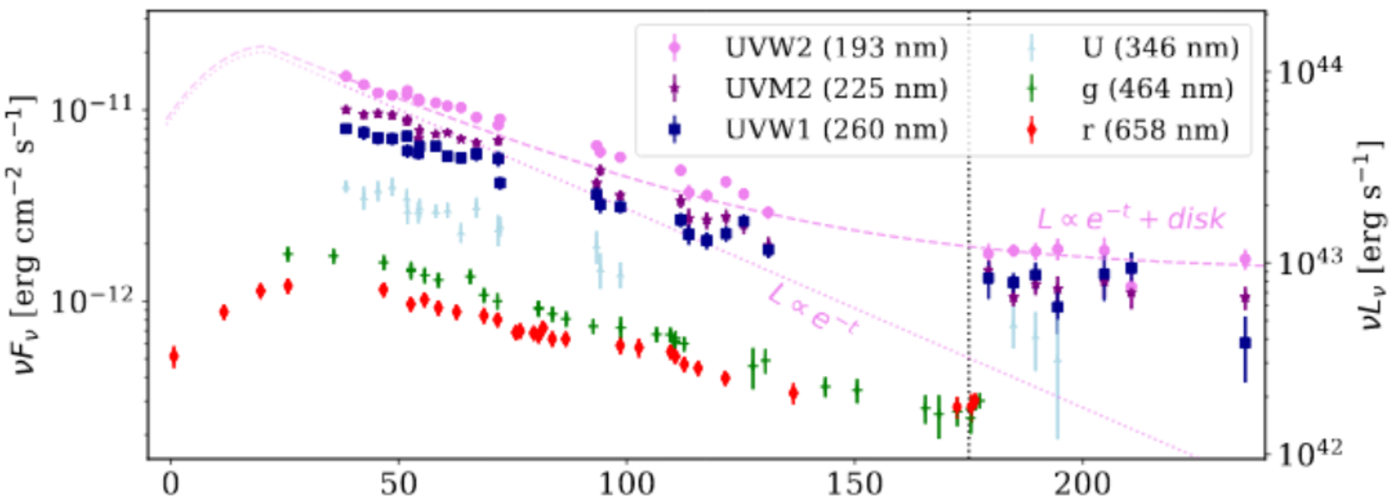


energy in the Universe in gamma rays, neutrinos and cosmic rays



IC191001 in coincidence with the tidal disruption of a star?

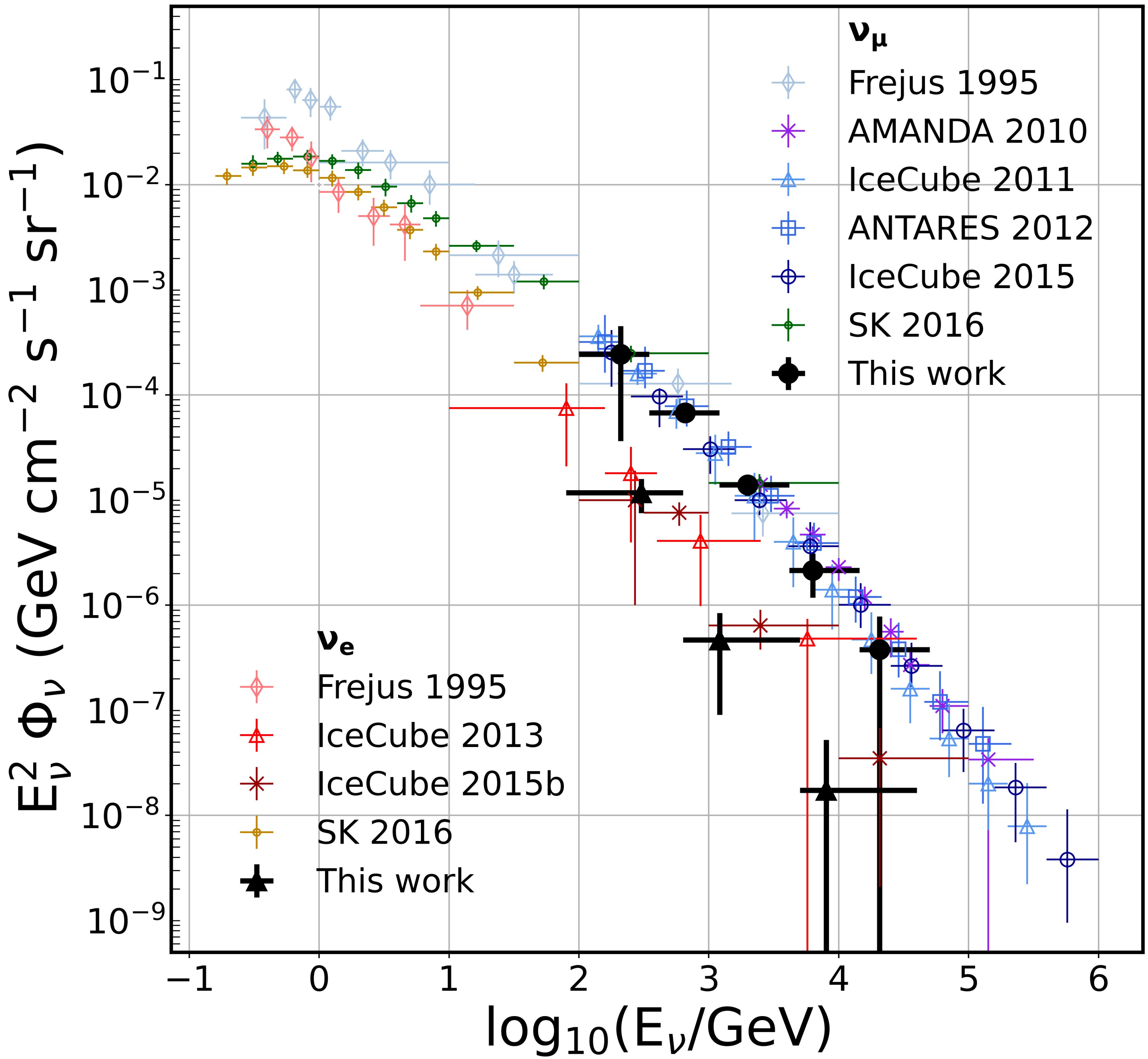
IC191001 close to luminous TDE of the Zwicky Transit Factory



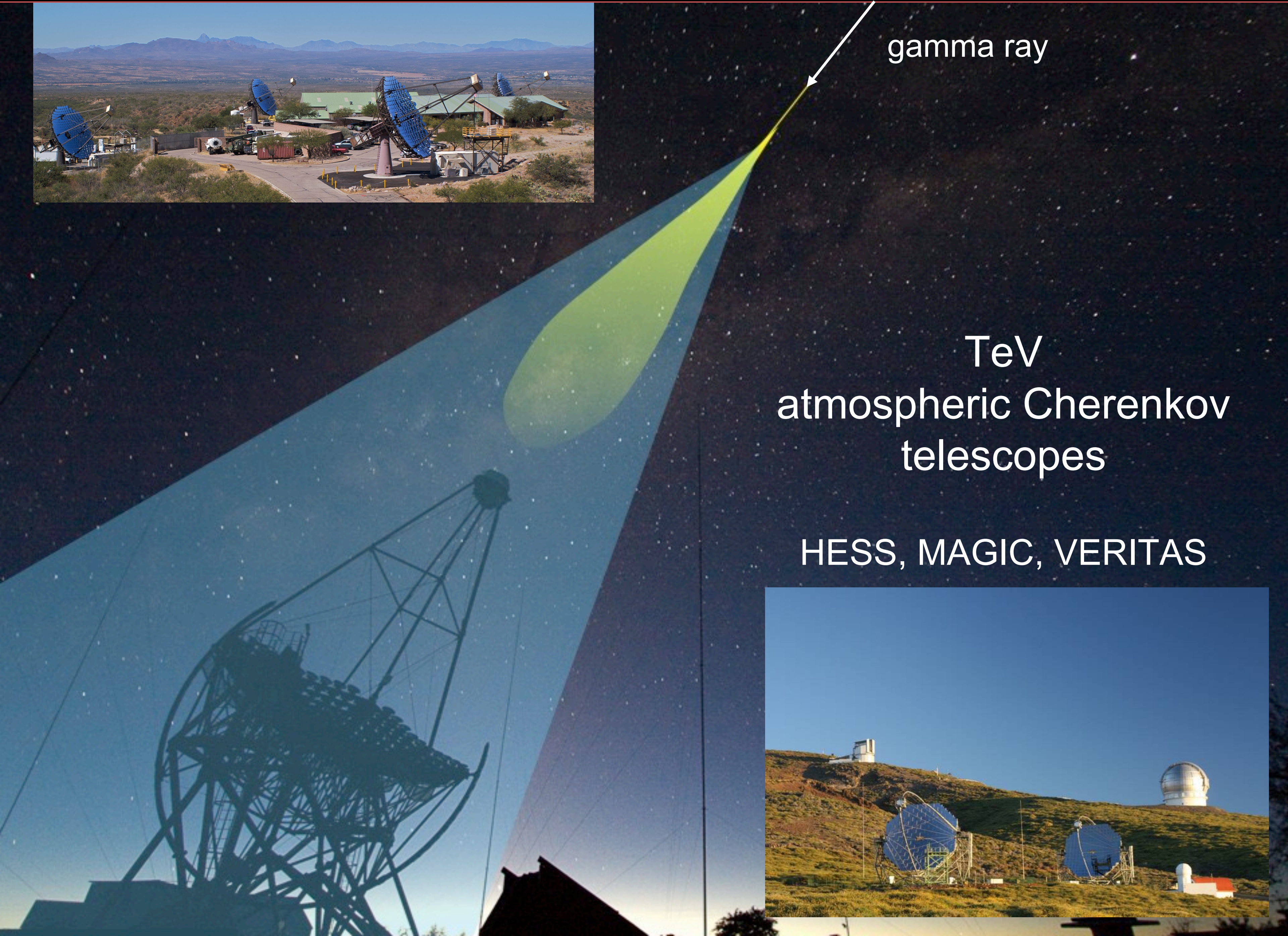
Discovered in April 2019 by ZTF, lots of data! Neutrino arrived ~175 days post-discovery.

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})



$E_\nu^2\,\Phi_\nu$ (GeV cm^{-2} s^{-1} sr^{-1})
$\log_{10}(E_\nu/\mathrm{GeV})$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
−1
0
1
2
3
4
5
6
ν_μ
Frejus 1995
AMANDA 2010
IceCube 2011
ANTARES 2012
IceCube 2015
SK 2016
This work
ν_e
Frejus 1995
IceCube 2013
IceCube 2015b
SK 2016
This work



TeV atmospheric Cherenkov telescopes

HESS, MAGIC, VERITAS

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

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

diffuse flux measured by IceCube

TXS flux (10y average)

opacity of the source to protons (f_π)

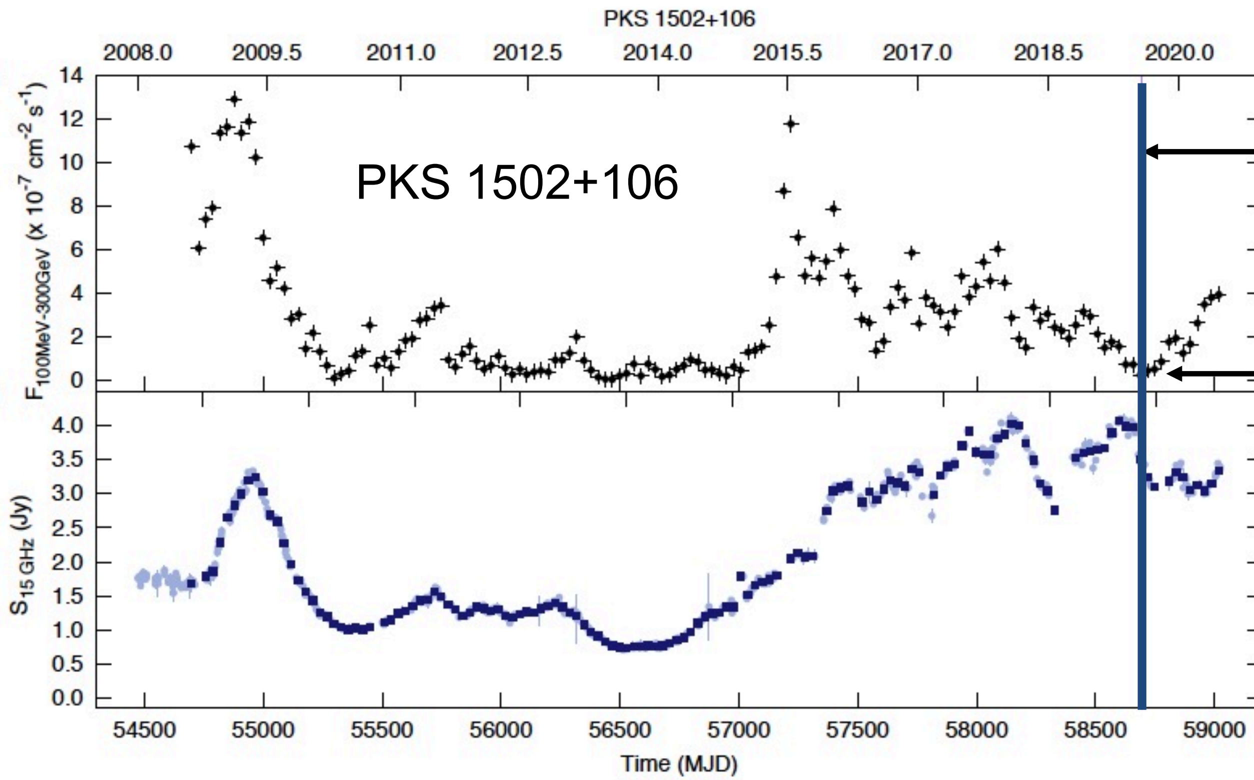
solution:

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

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

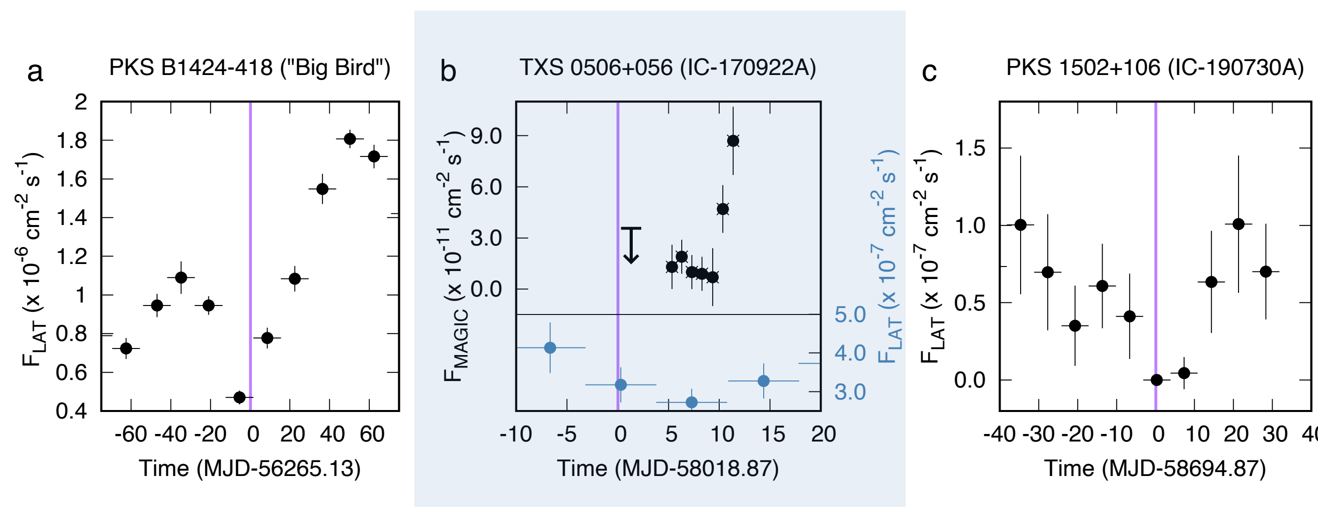
γ-ray

radio



300 TeV neutrino produced

target moves through the jet blocks photons



other examples