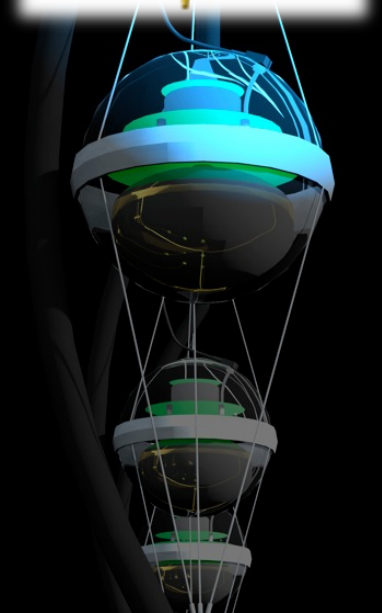


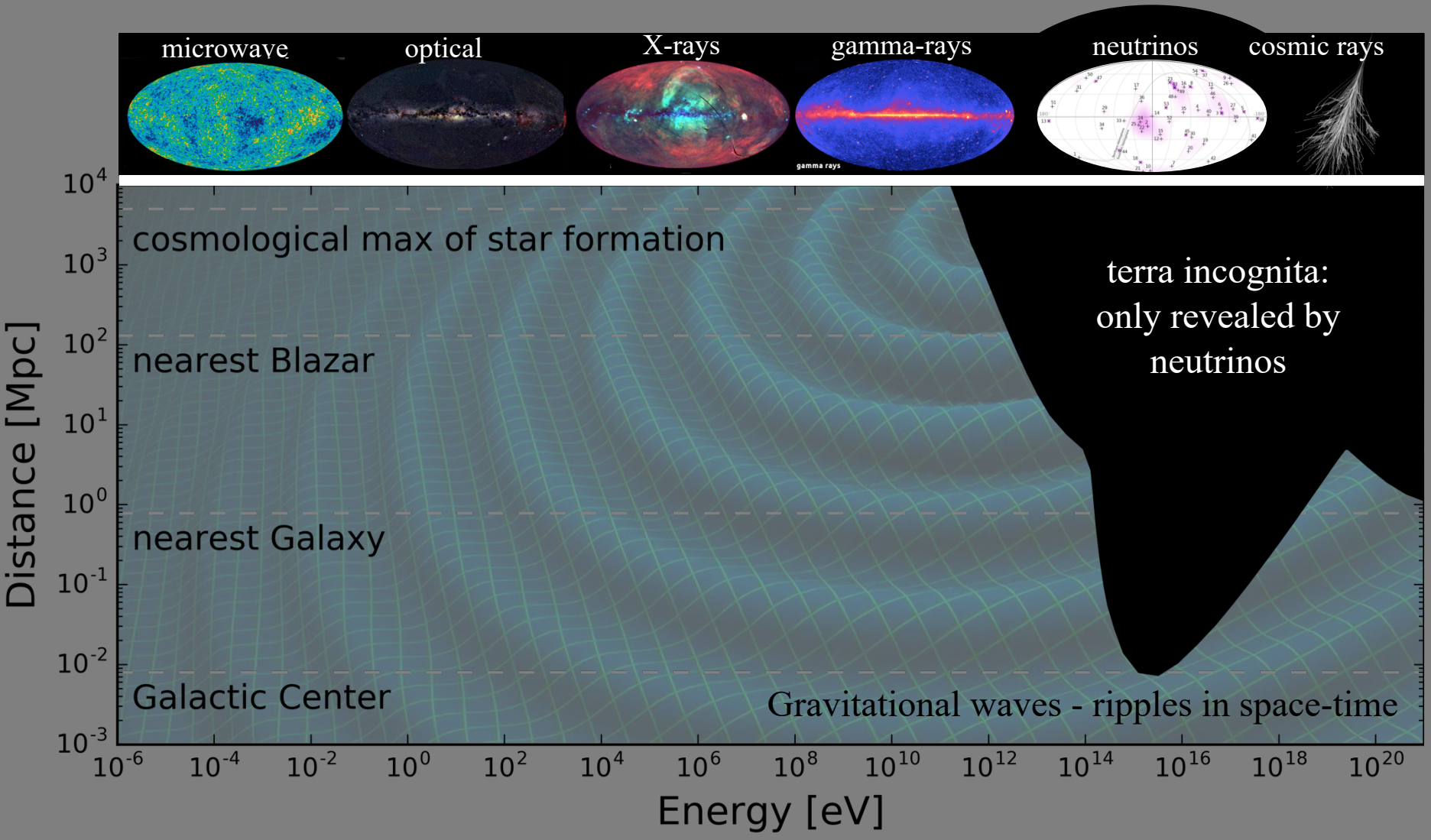
Neutrinos in the Era of Multimessenger Astronomy

francis halzen

- cosmic neutrinos: many independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments
- also, a beam for PeV neutrino physics

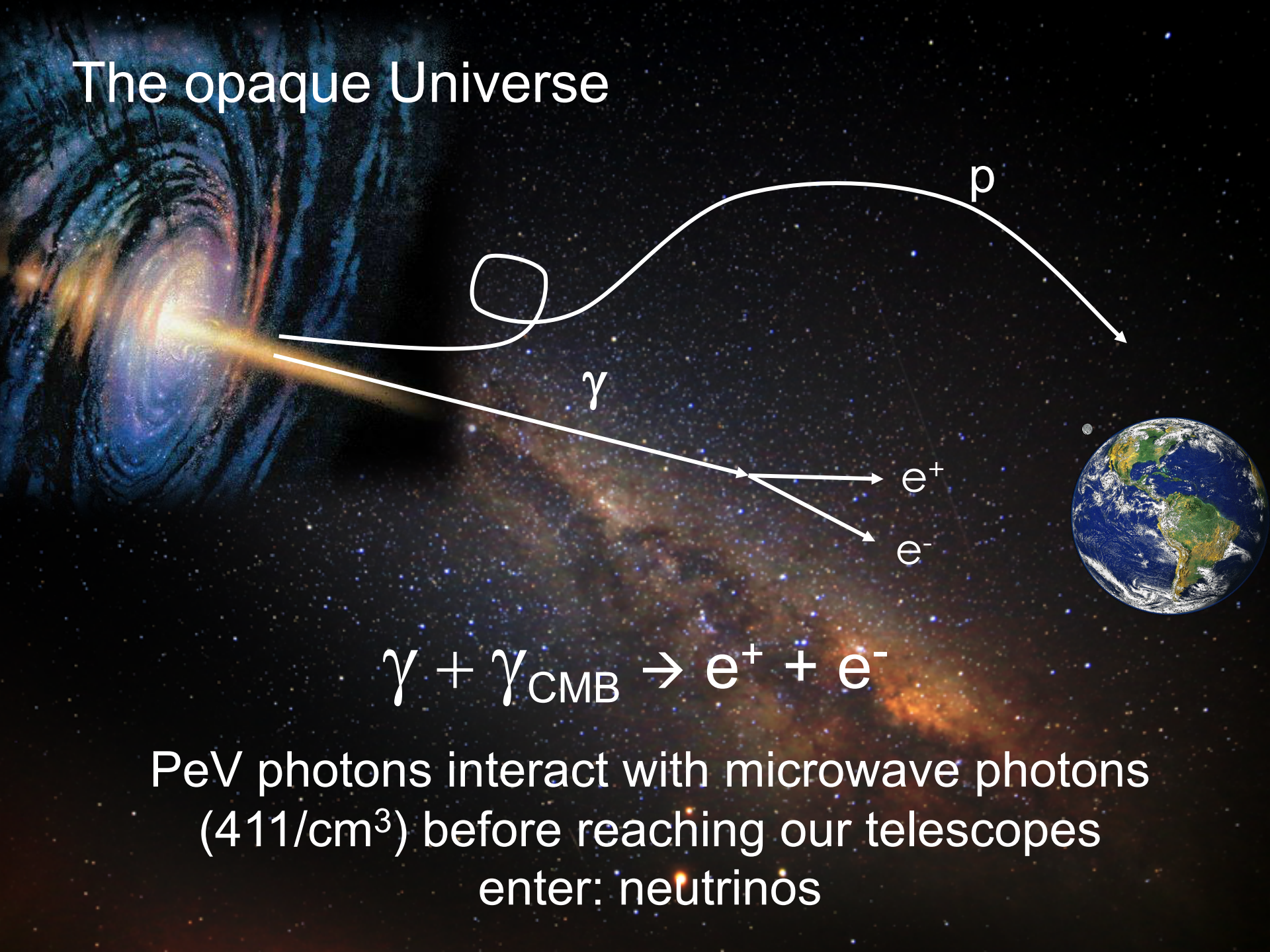
icecube.wisc.edu

Multi-Messenger Astronomy



> 20% of the Universe is opaque to the EM spectrum

The opaque Universe



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

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

enter: neutrinos

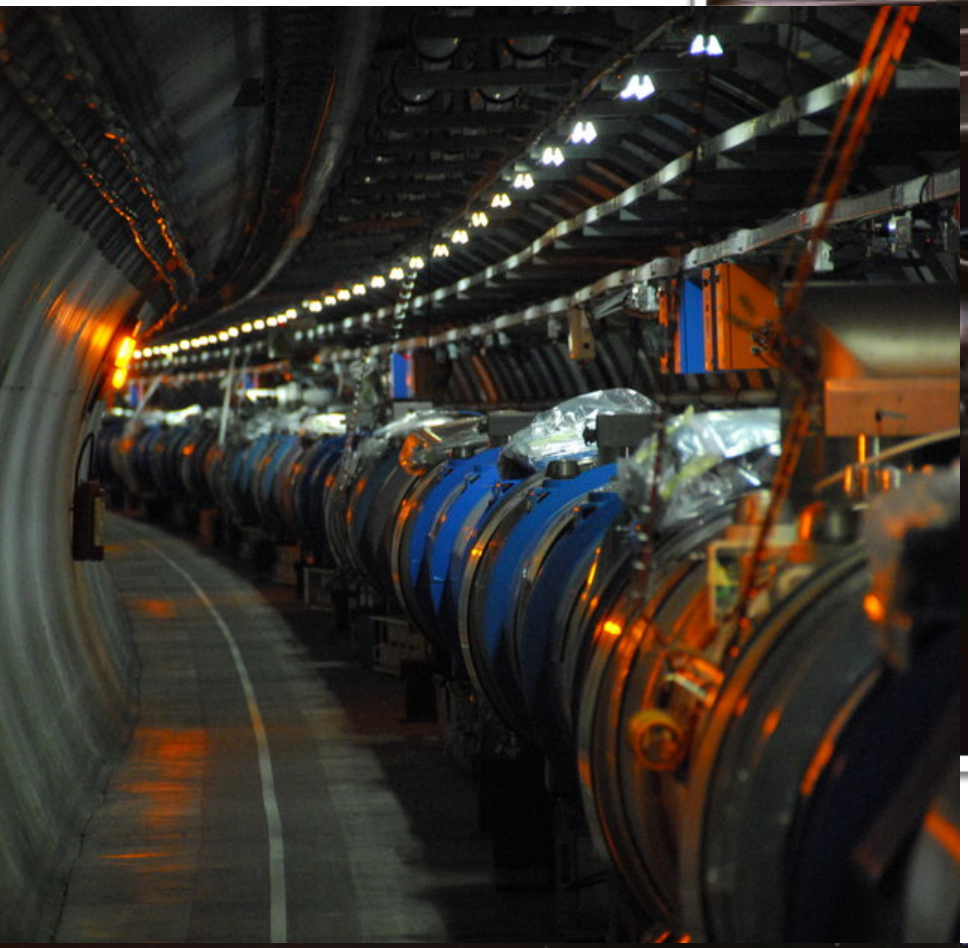
Neutrinos? Perfect Messenger

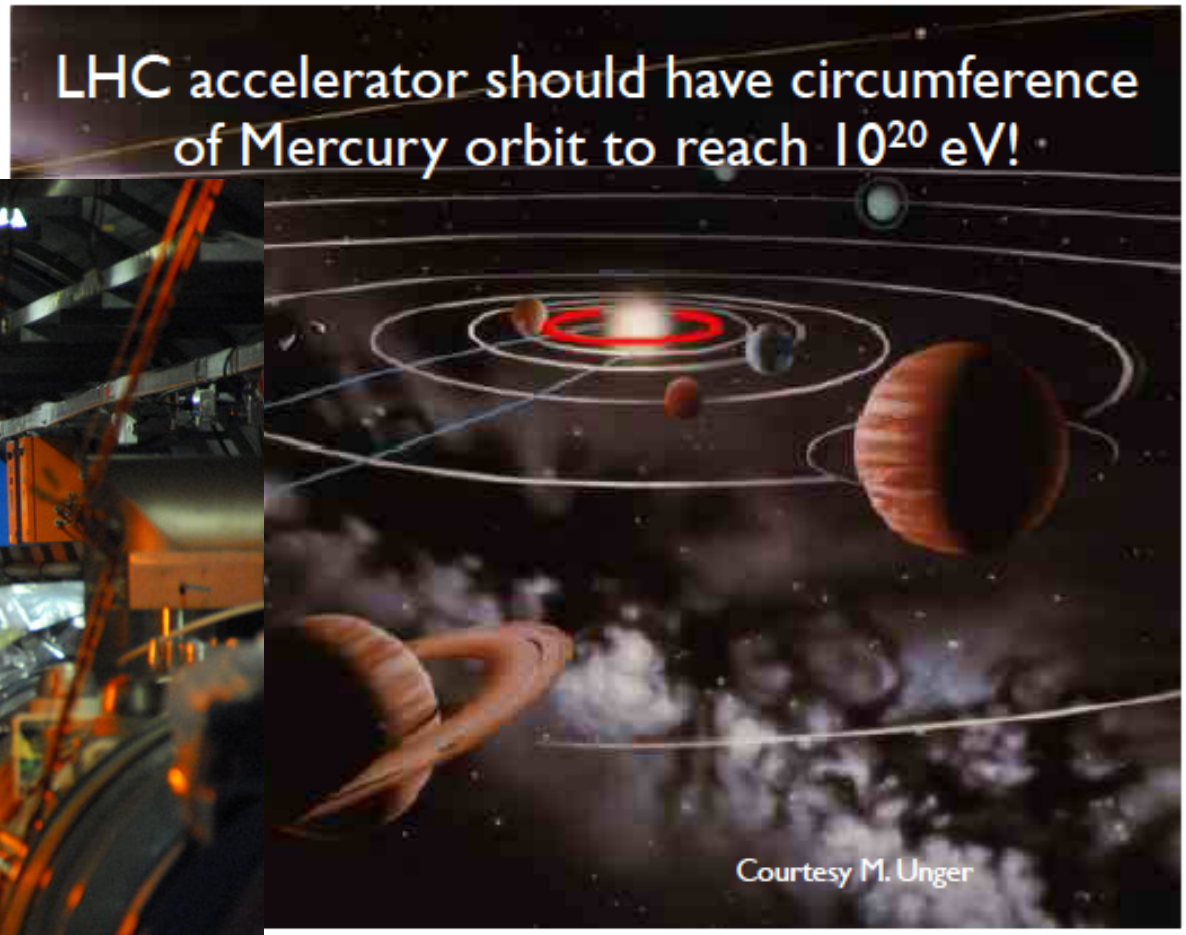
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

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

highest energy radiation from the Universe: protons!

high energy
high luminosity

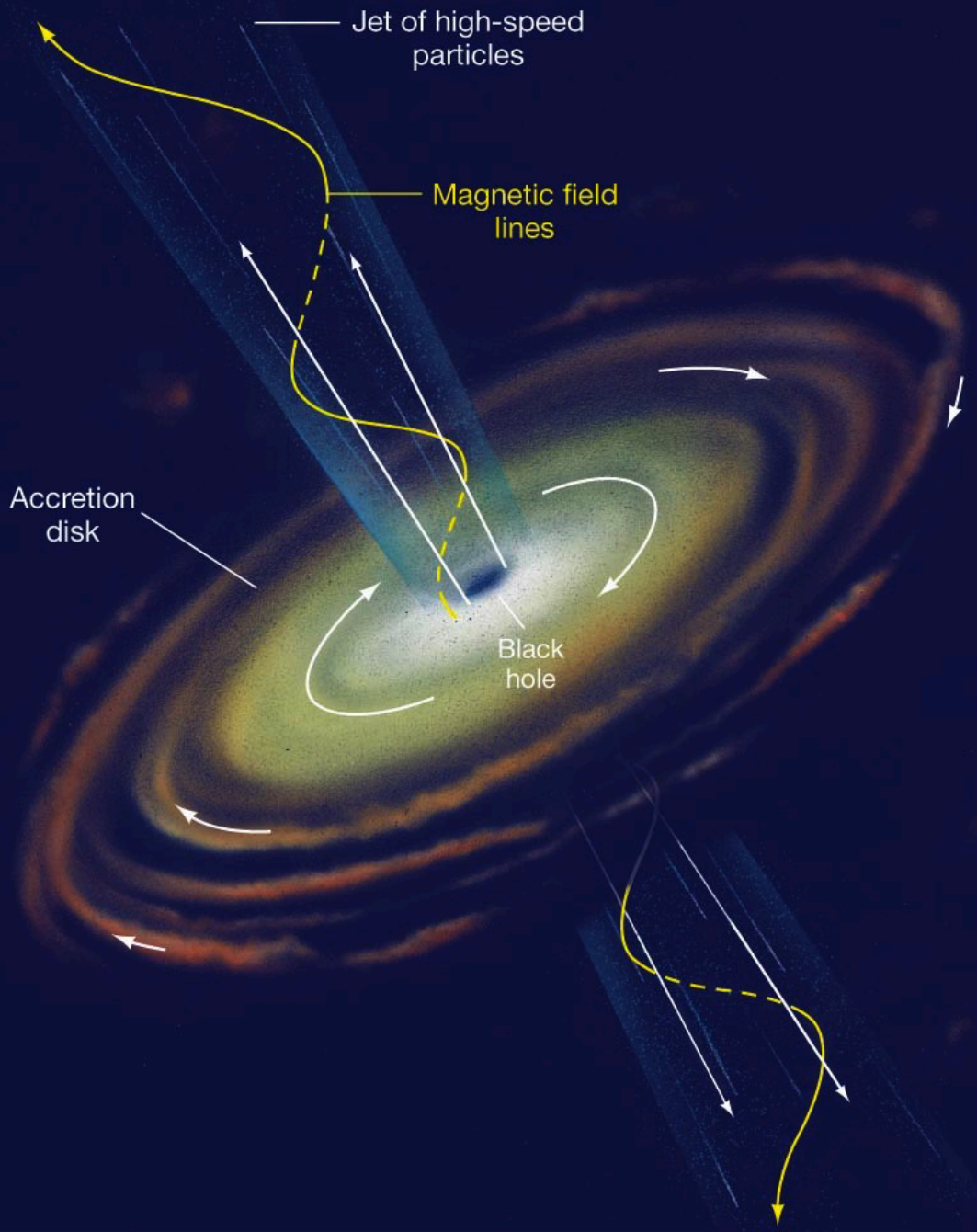


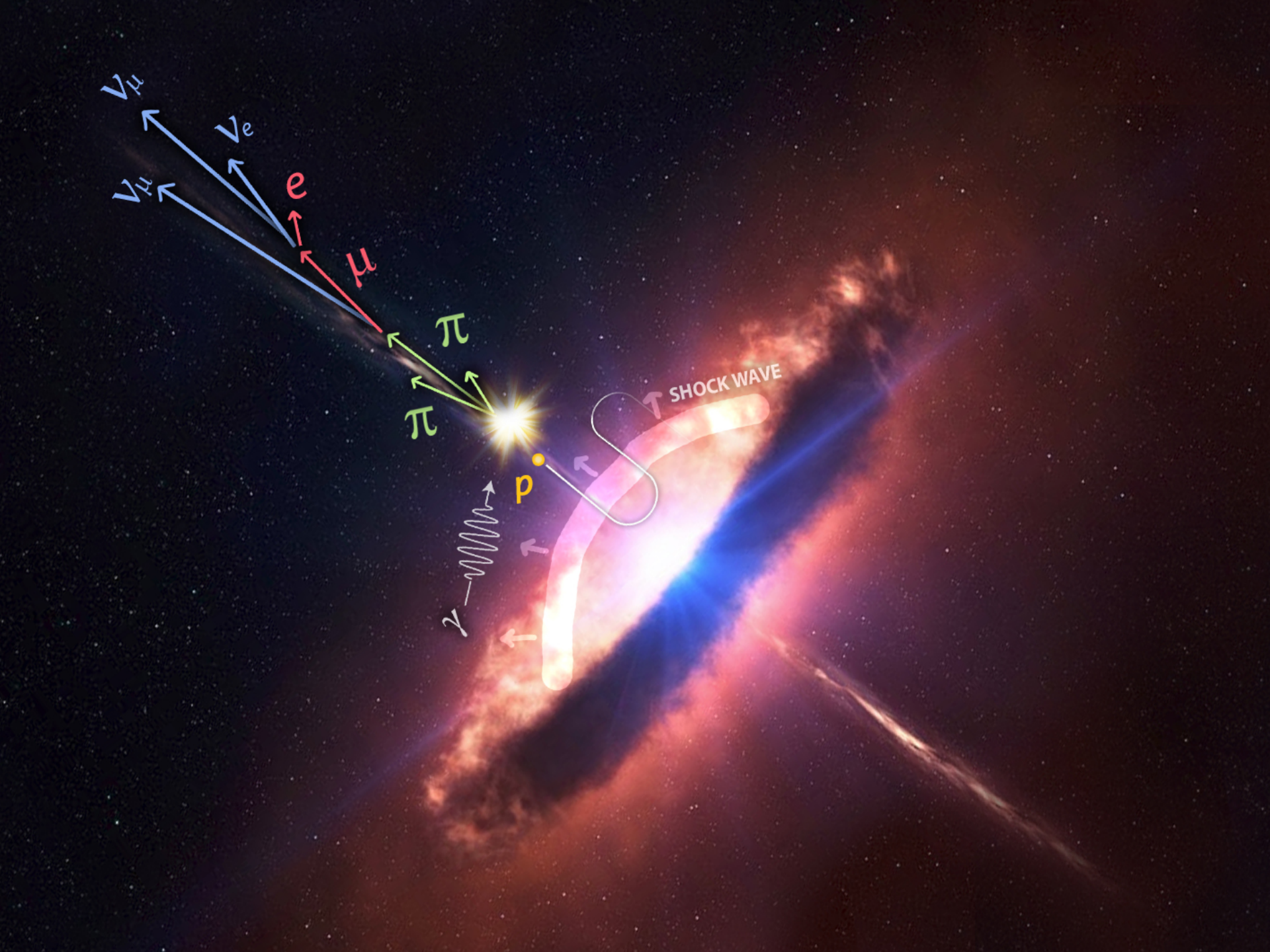


Fly's Eye 1991
3,000,000,000 TeV

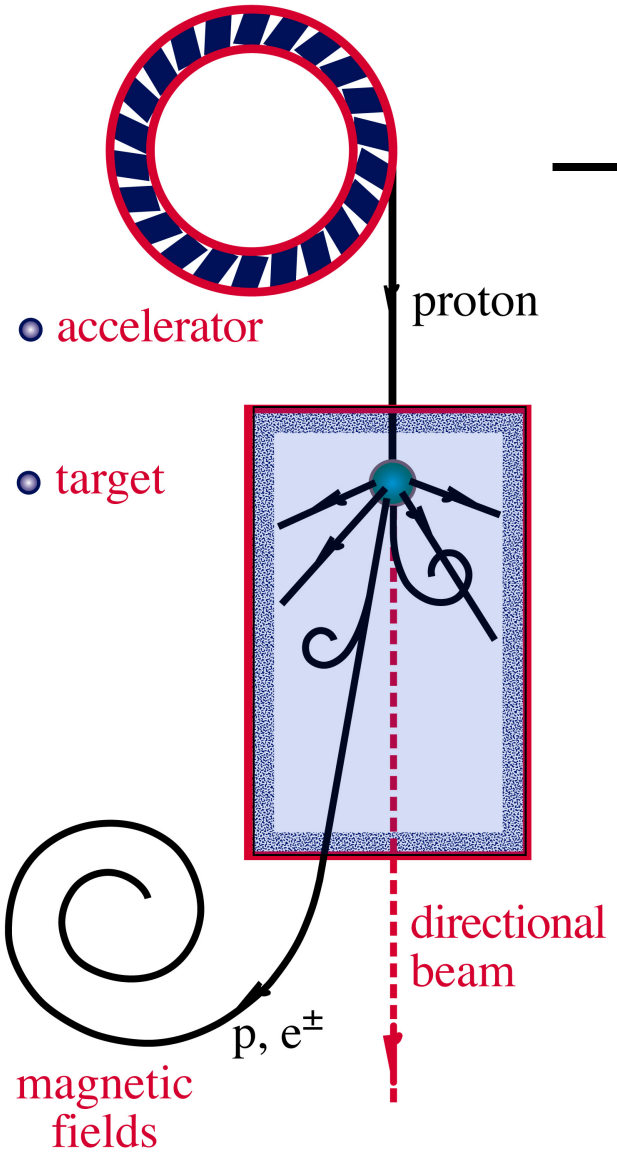

matter falling into a supermassive black is
accelerated in a jet along its rotation axis

- 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




ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

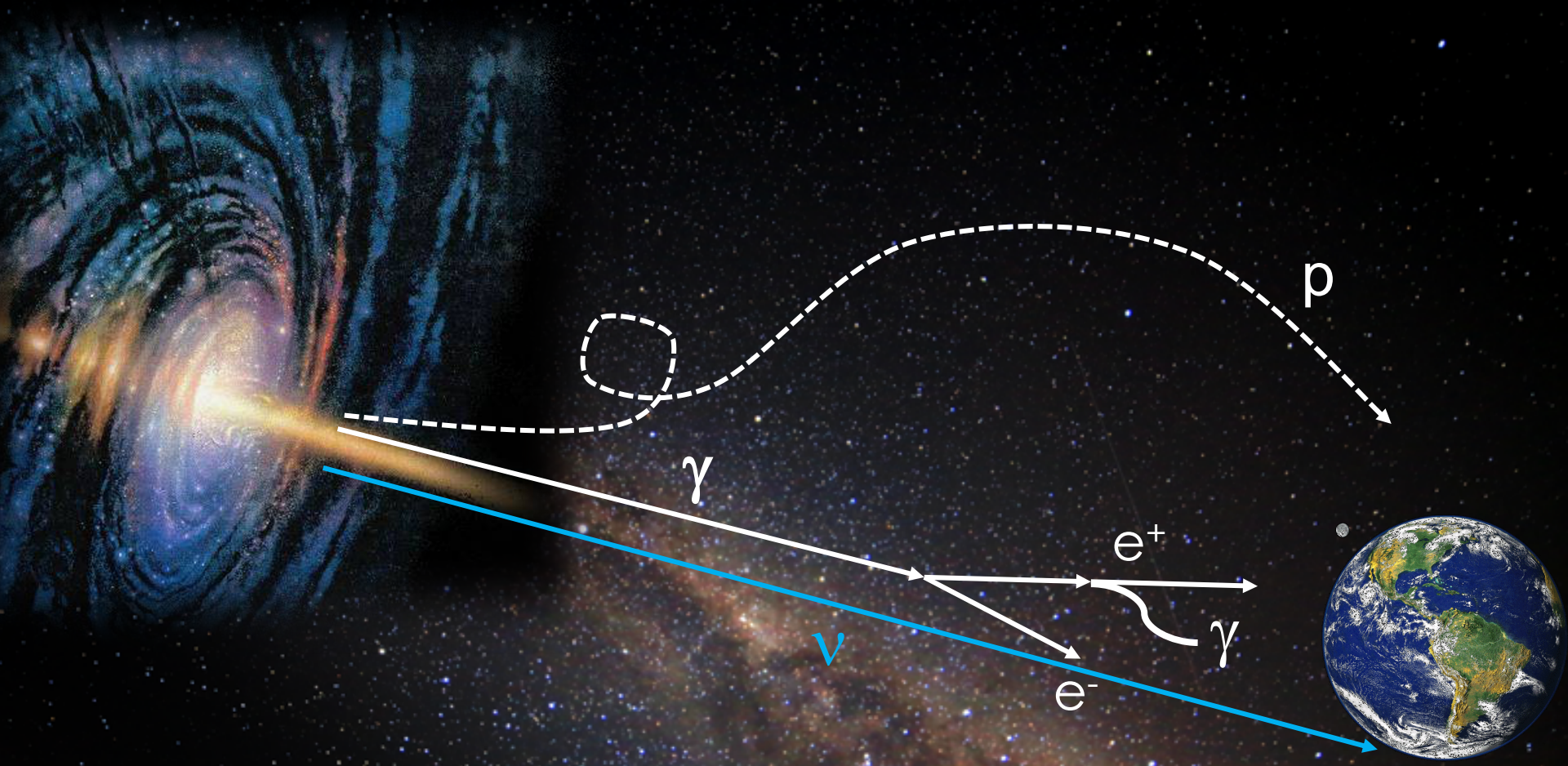
nearby radiation

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

~ cosmic ray + neutrino

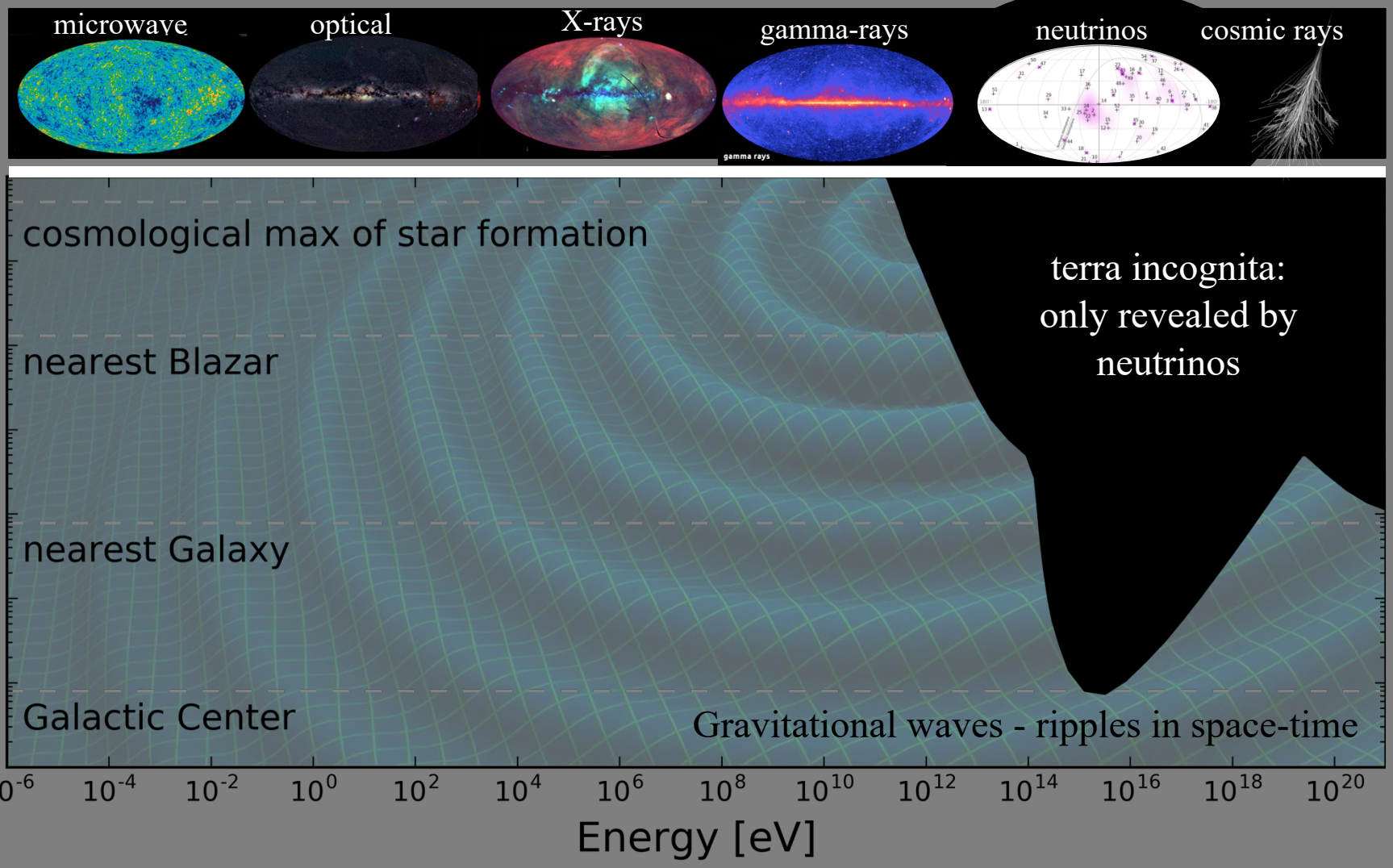
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

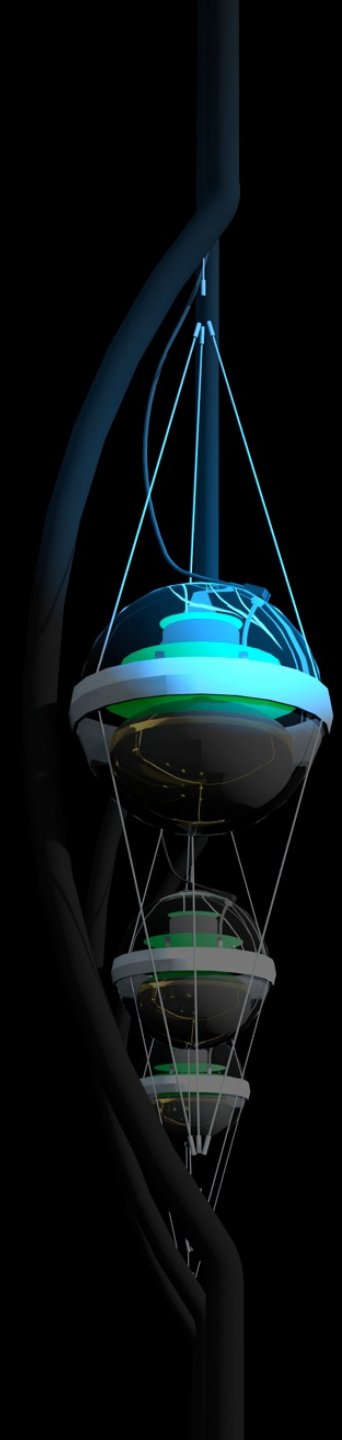


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

the energy of gamma rays accompanying PeV neutrinos is distributed over the electromagnetic spectrum



multimessenger astronomy



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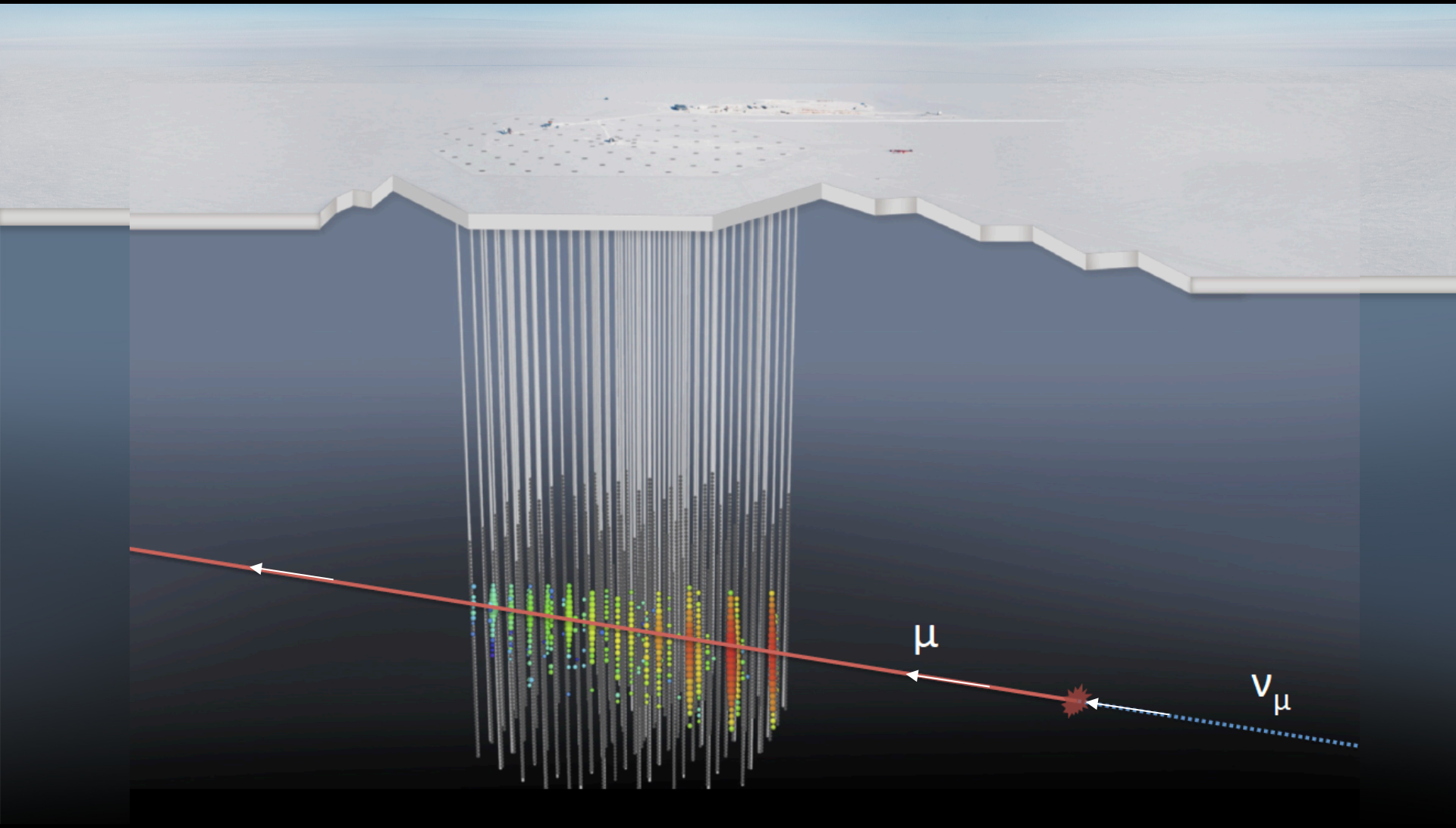
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole

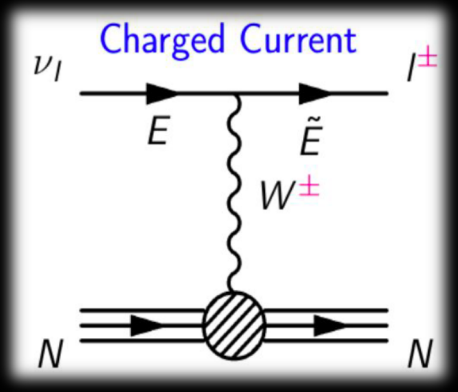
- from discovery to astronomy: next-generation instruments

- also, a beam for PeV neutrino physics


ultra-transparent ice below 1.35 km

instrument 1 cubic kilometer of natural ice below 1.45 km



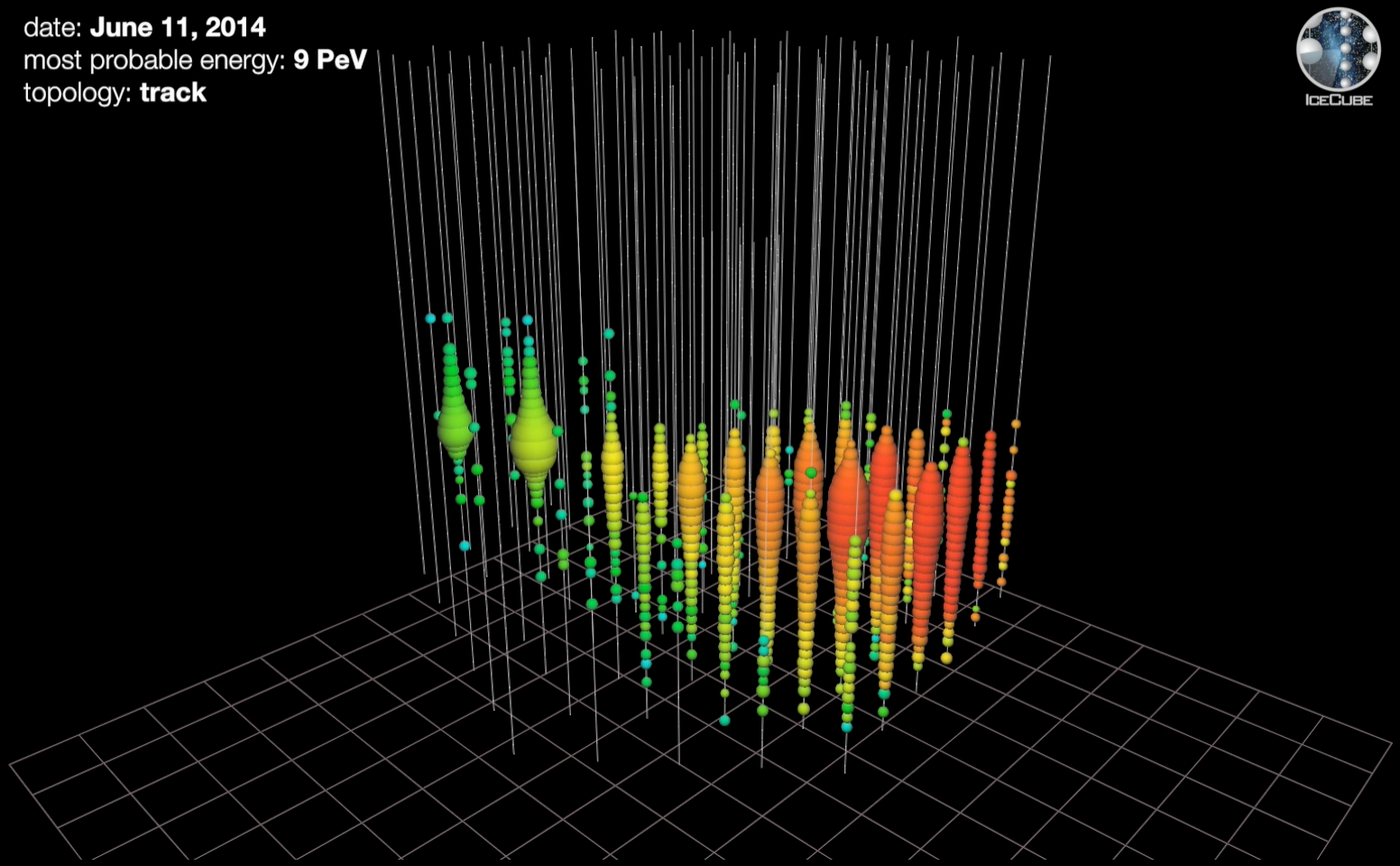


a muon neutrino produces a muon with a range of kilometers

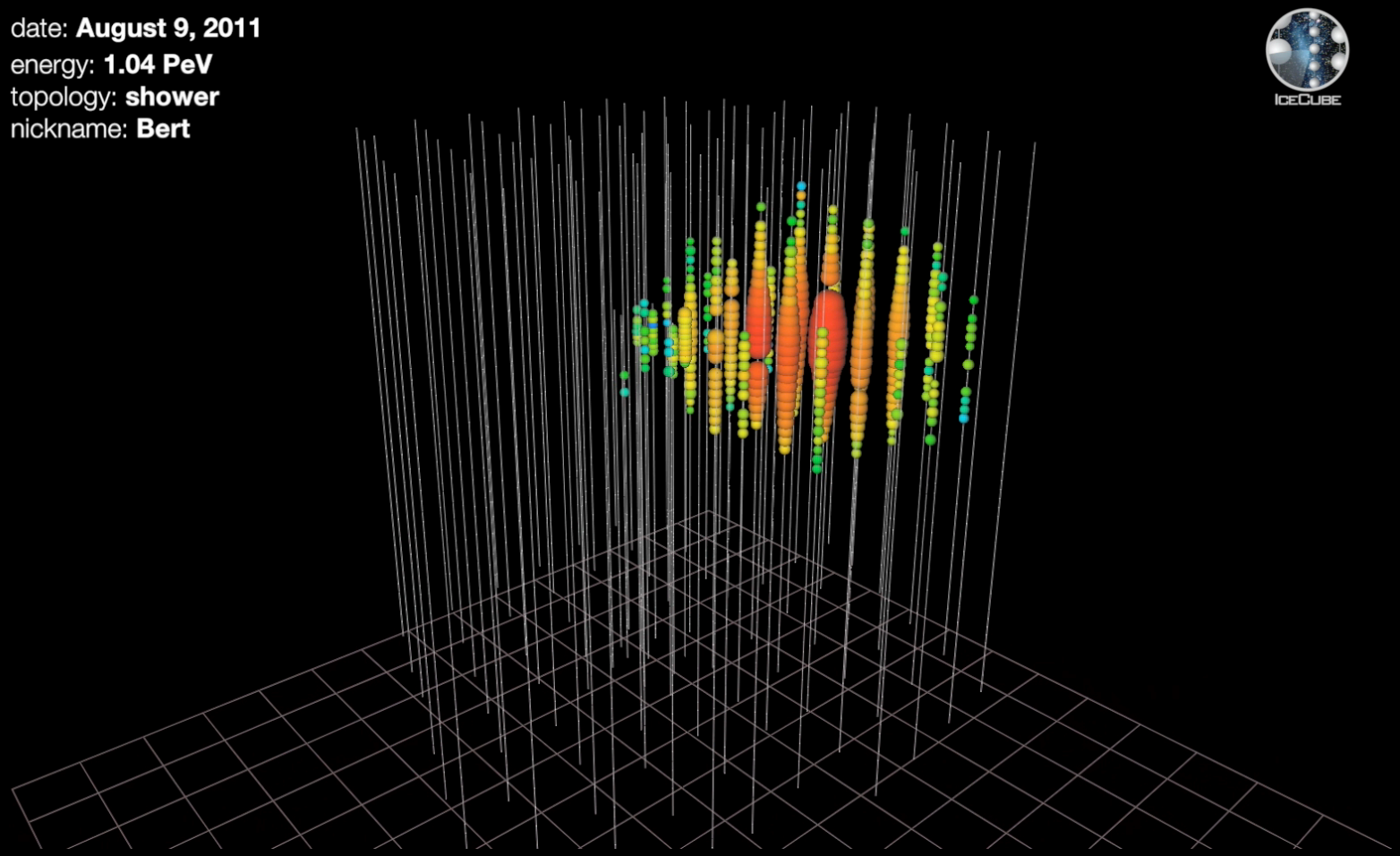
- lattice of photomultipliers

neutrino

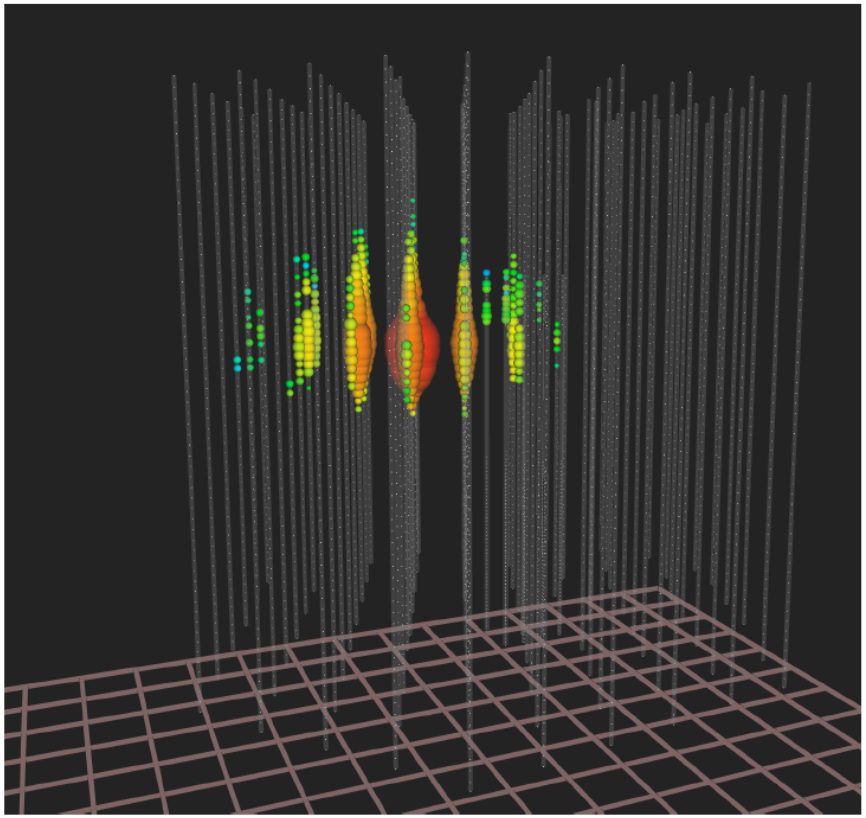
muon neutrinos observed through the Earth



electron and tau neutrinos: contained events

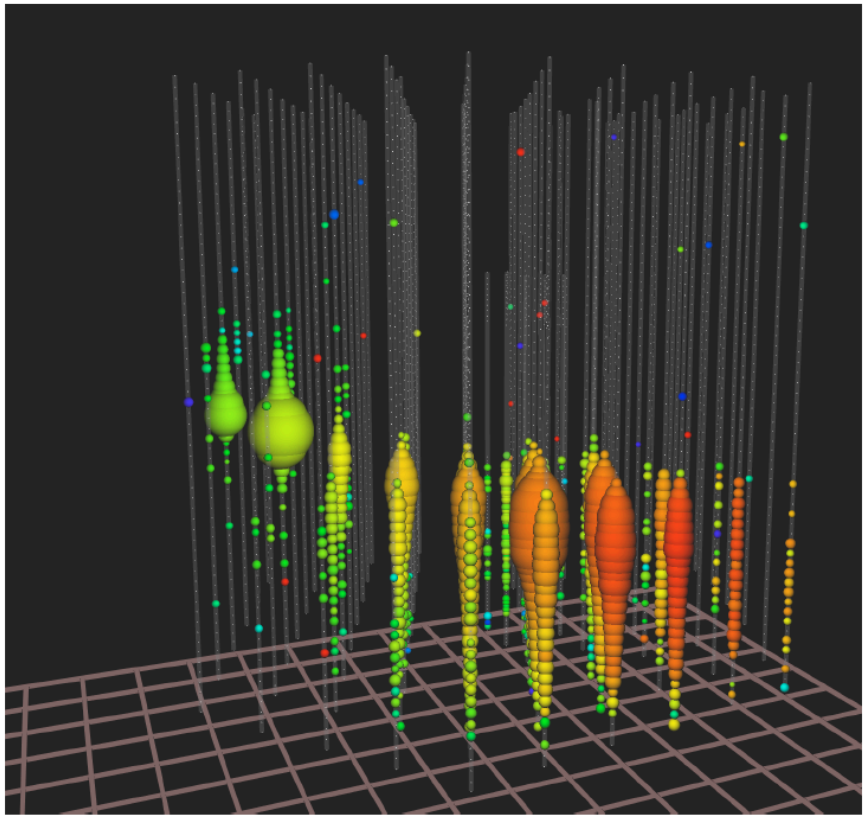


neutrinos interacting
inside the detector



total energy measurement
all flavors, all sky

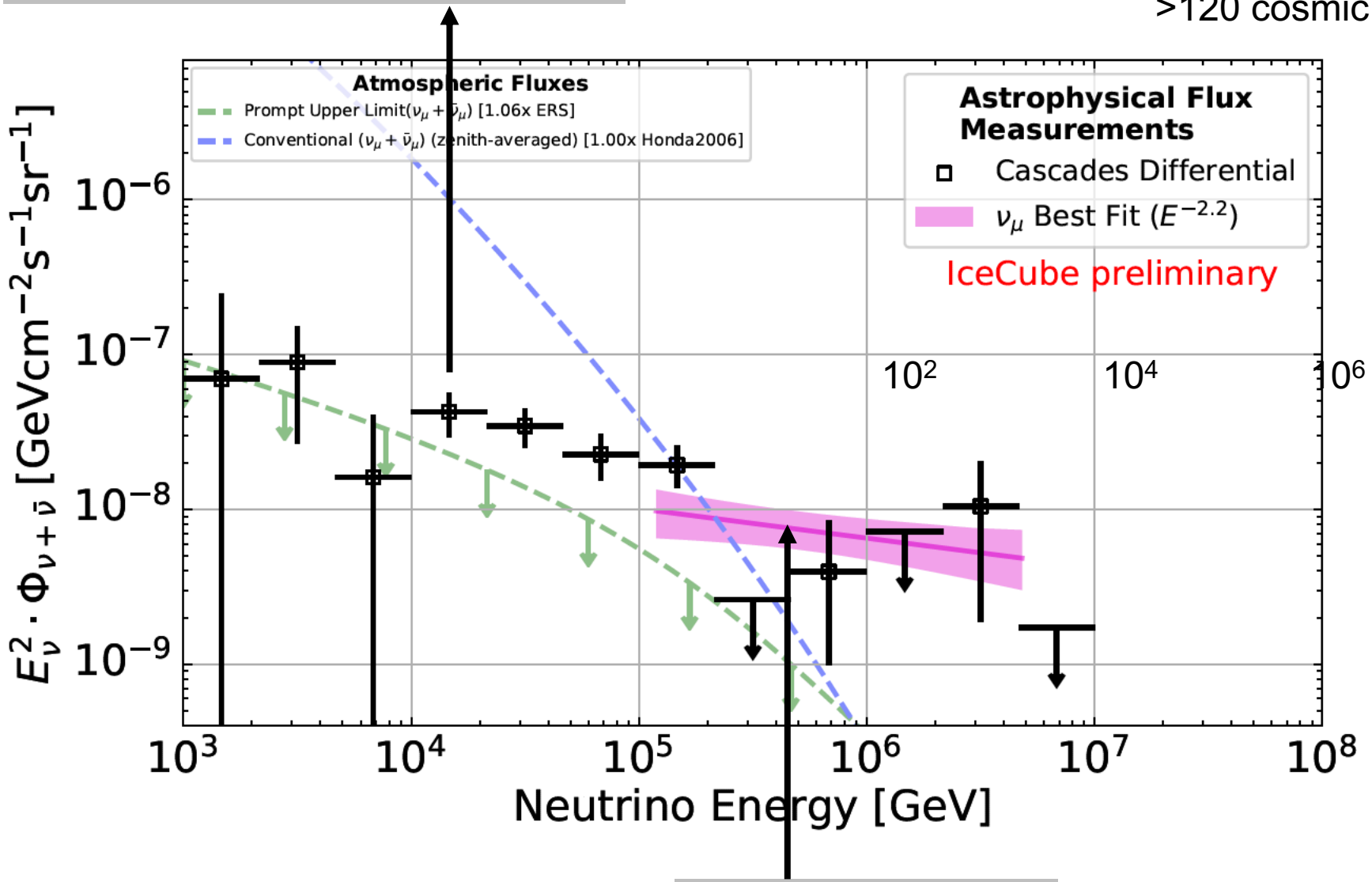
muon neutrinos
filtered by the Earth



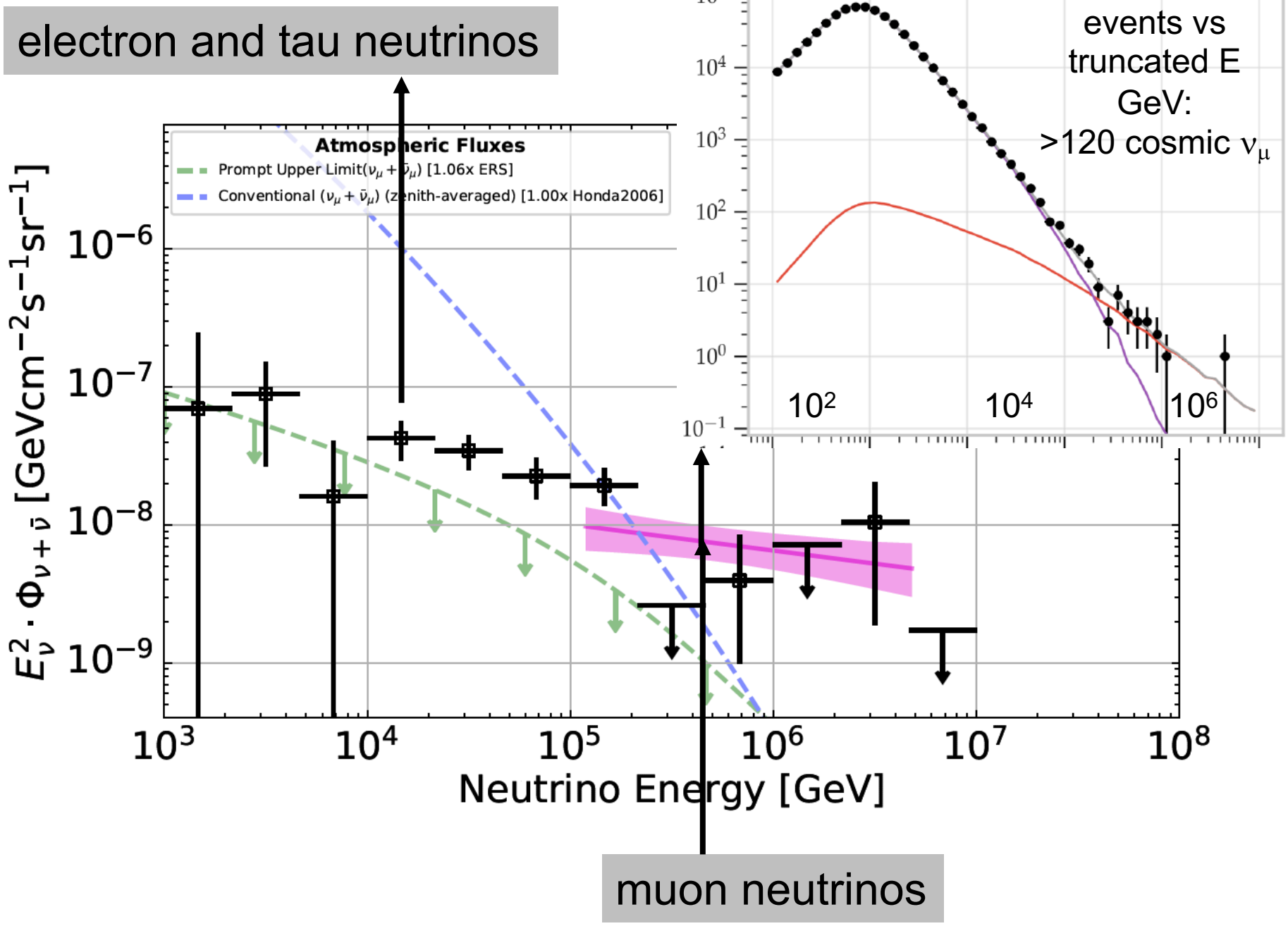
astronomy: angular resolution
superior (<0.4^{o})

electron and tau neutrinos

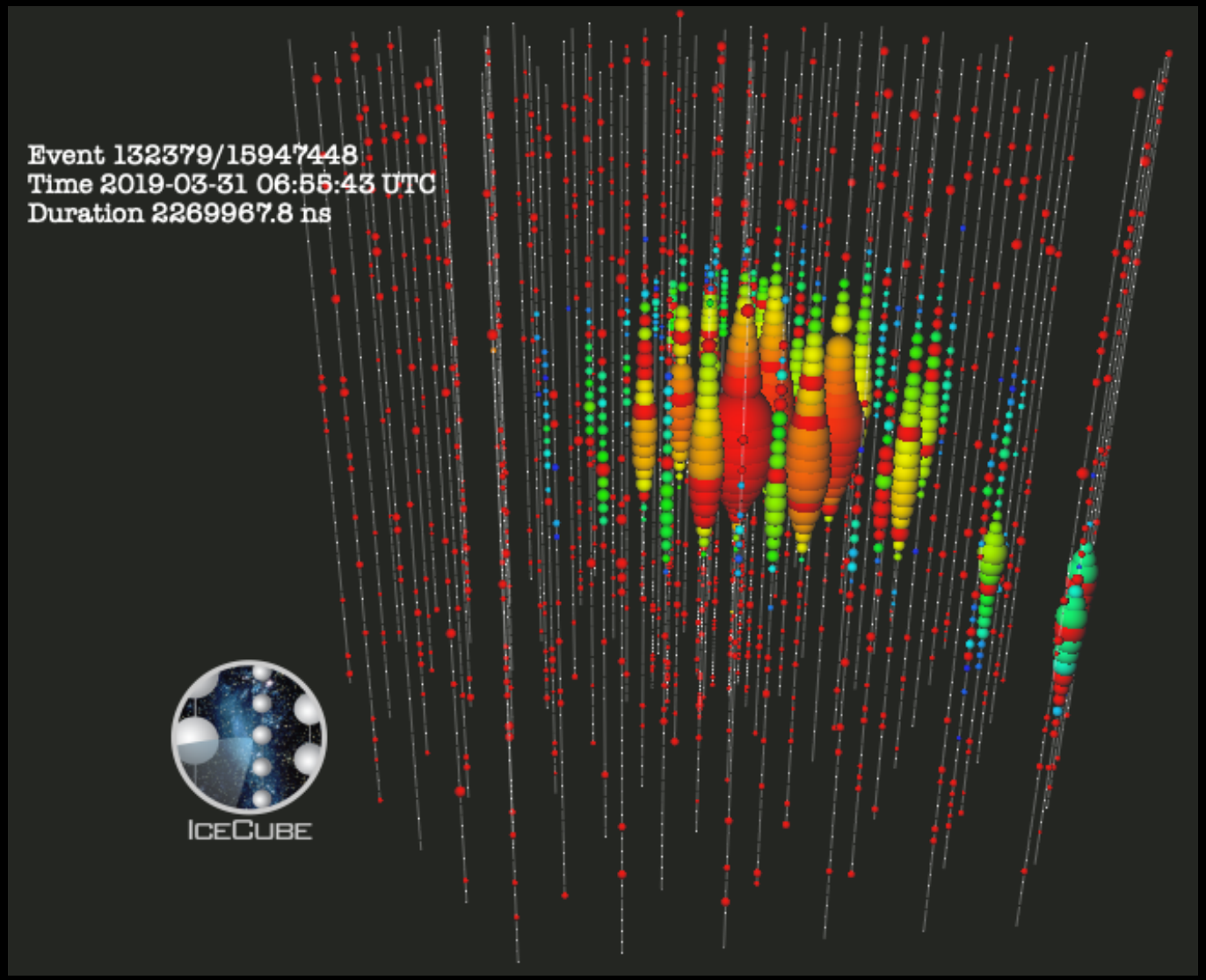
>120 cosmic ν_μ



muon neutrinos

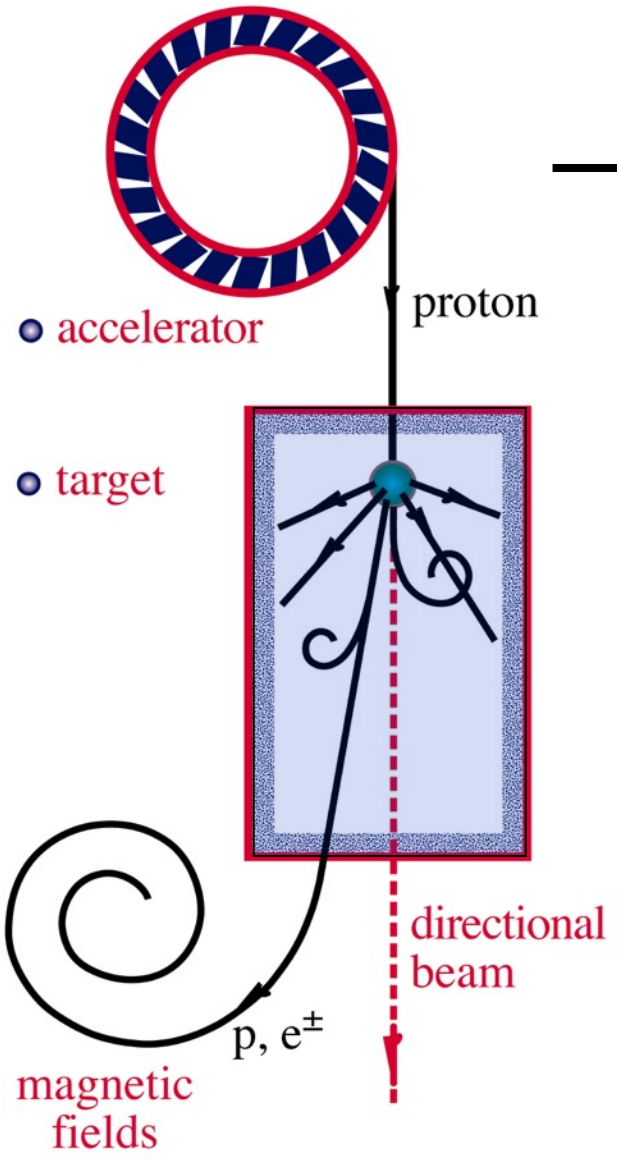

electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
events vs truncated E GeV: >120 cosmic ν_μ
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^2
10^4
10^6
muon neutrinos

IC190331: 5300 TeV deposited inside the detector



initial neutrino energy 10~20 PeV

ν and γ beams : heaven and earth



where are the gamma rays ?

supermassive black hole

nearby radiation

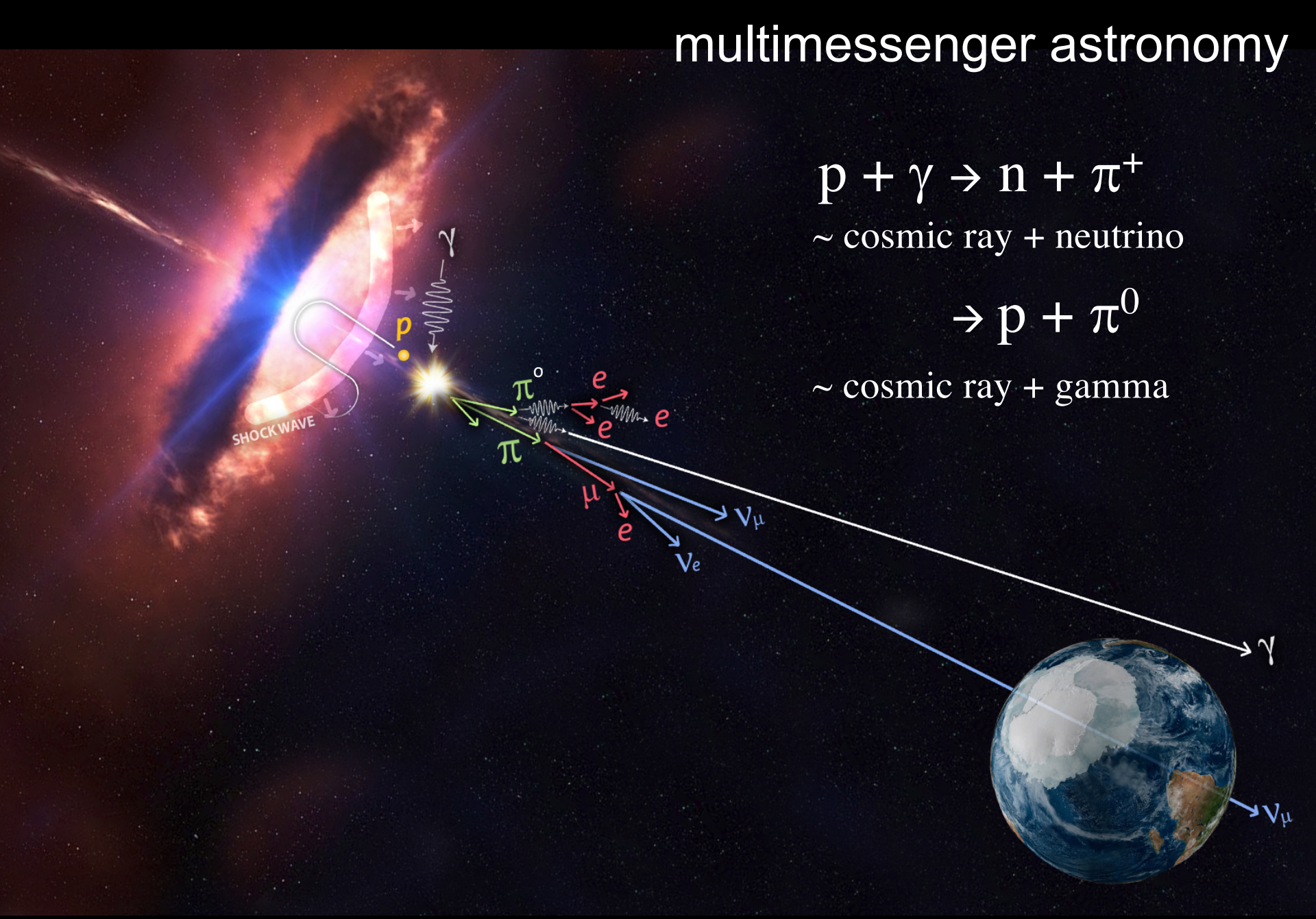
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

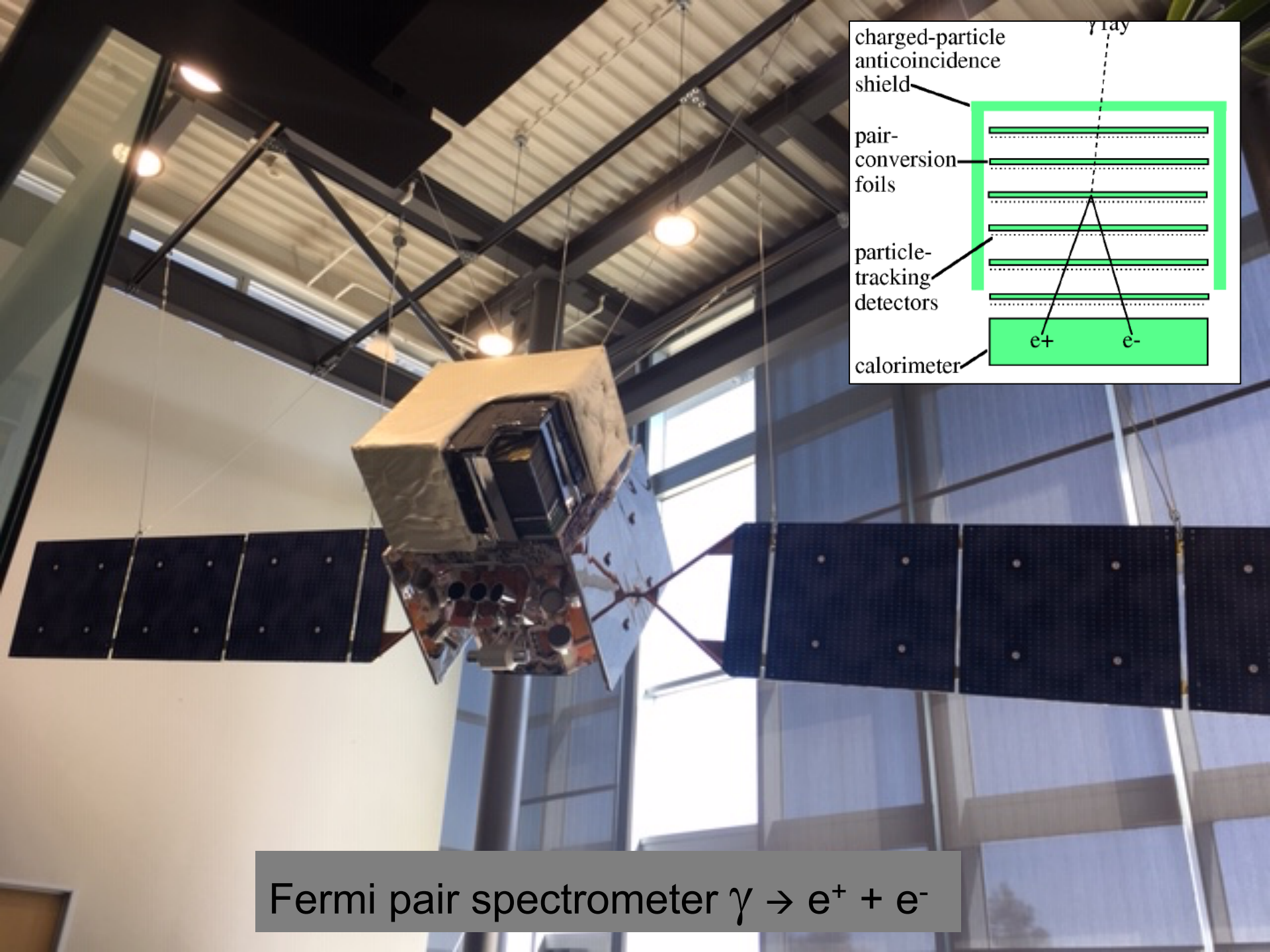
multimessenger astronomy



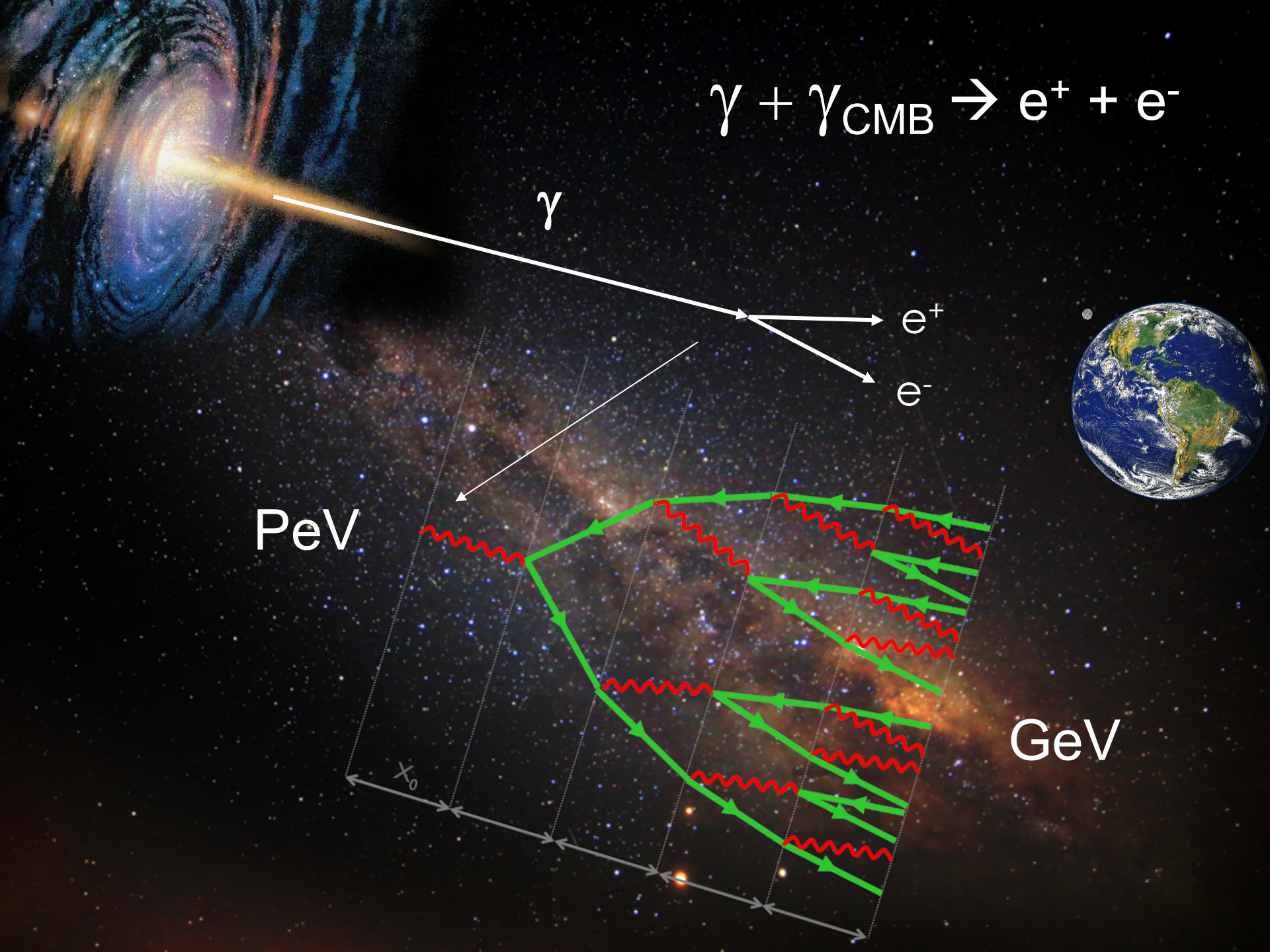
gamma ray

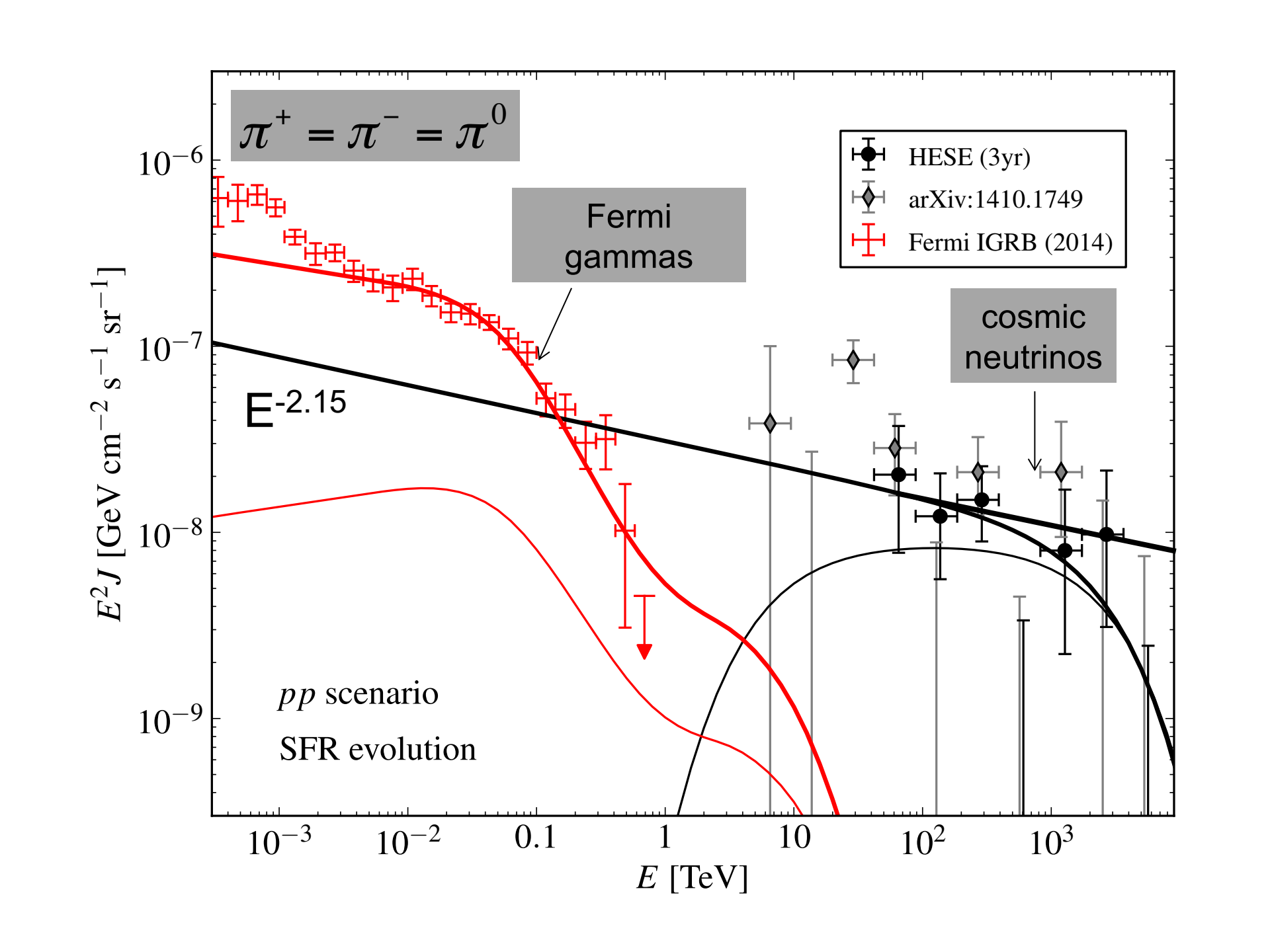
TeV
atmospheric Cherenkov
telescopes

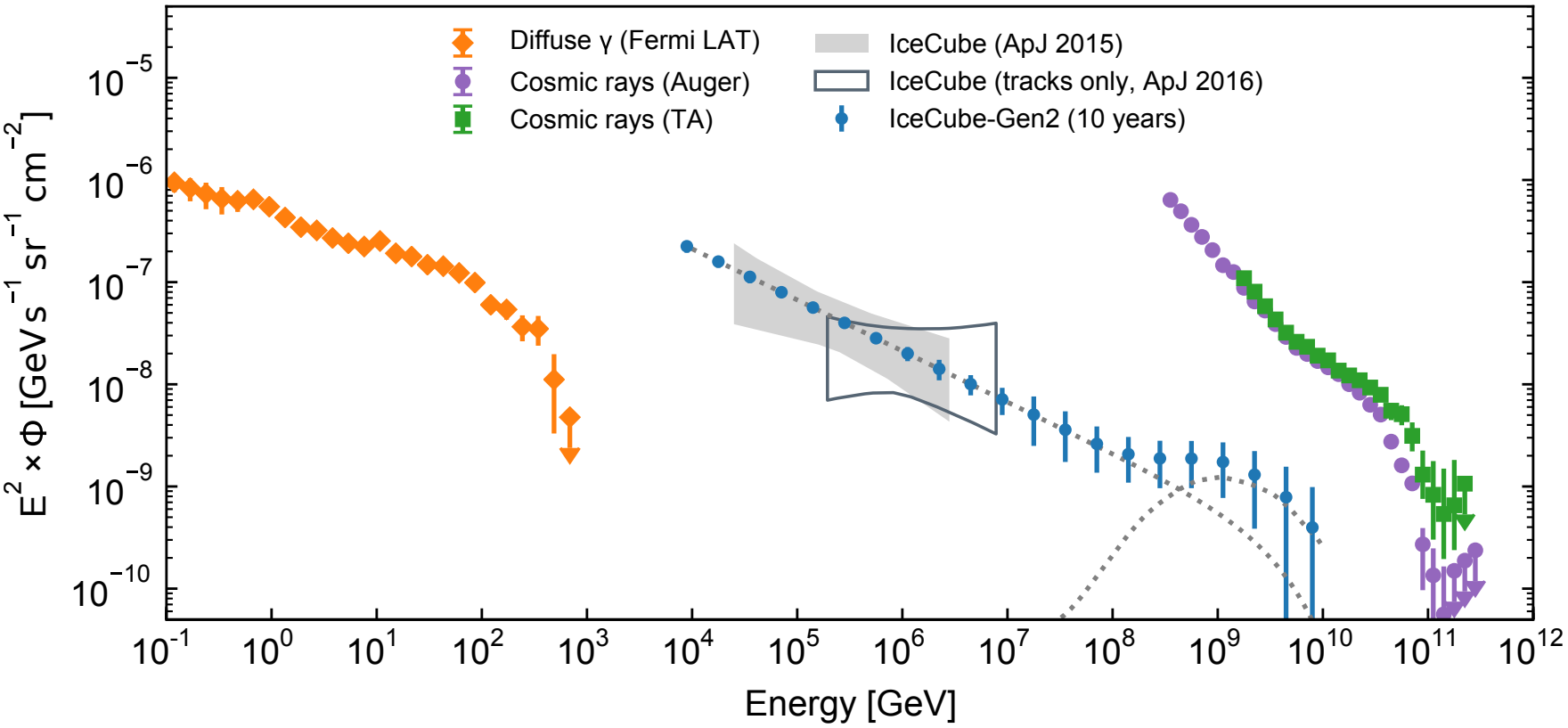
HESS, MAGIC, VERITAS



Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$

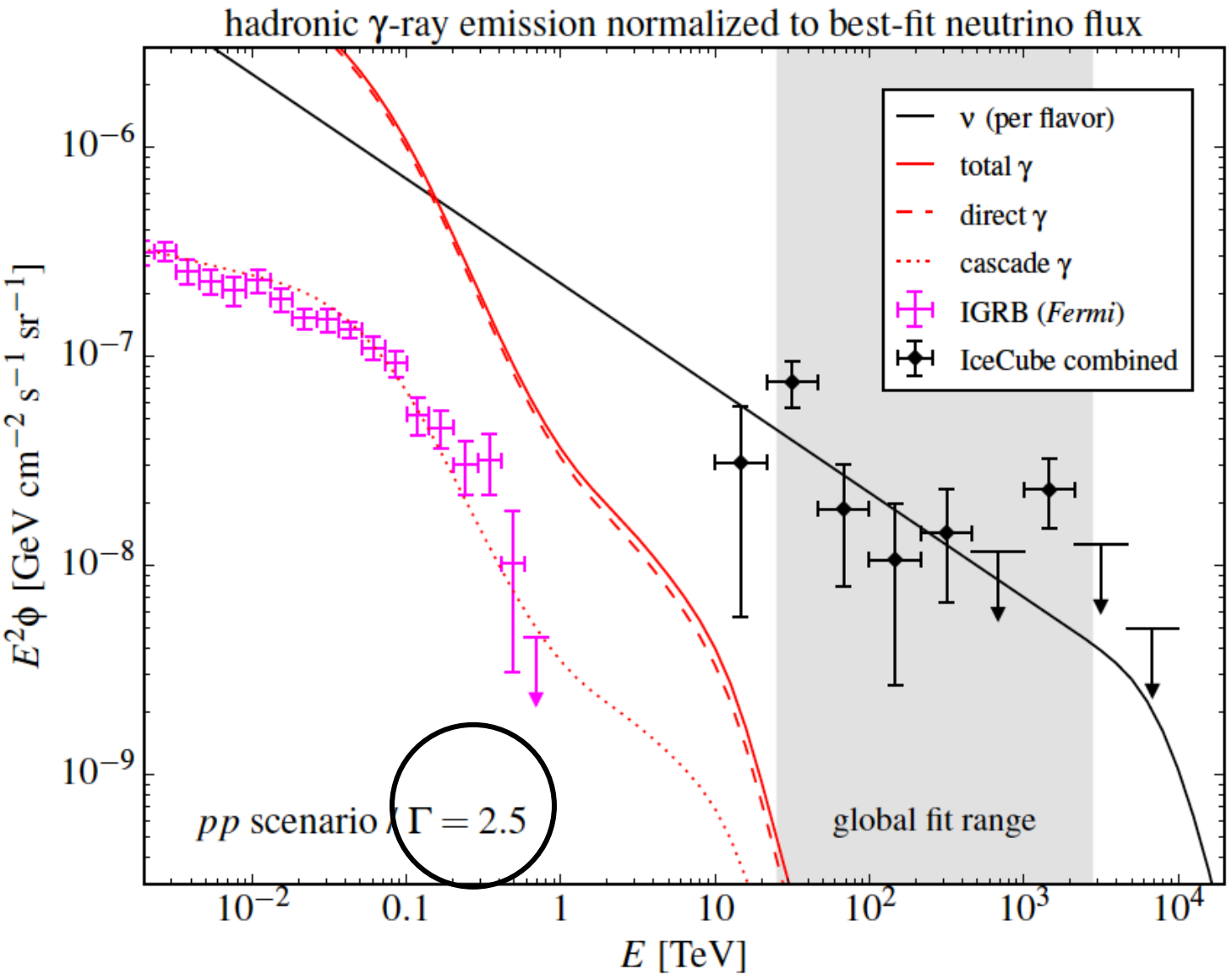

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0


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

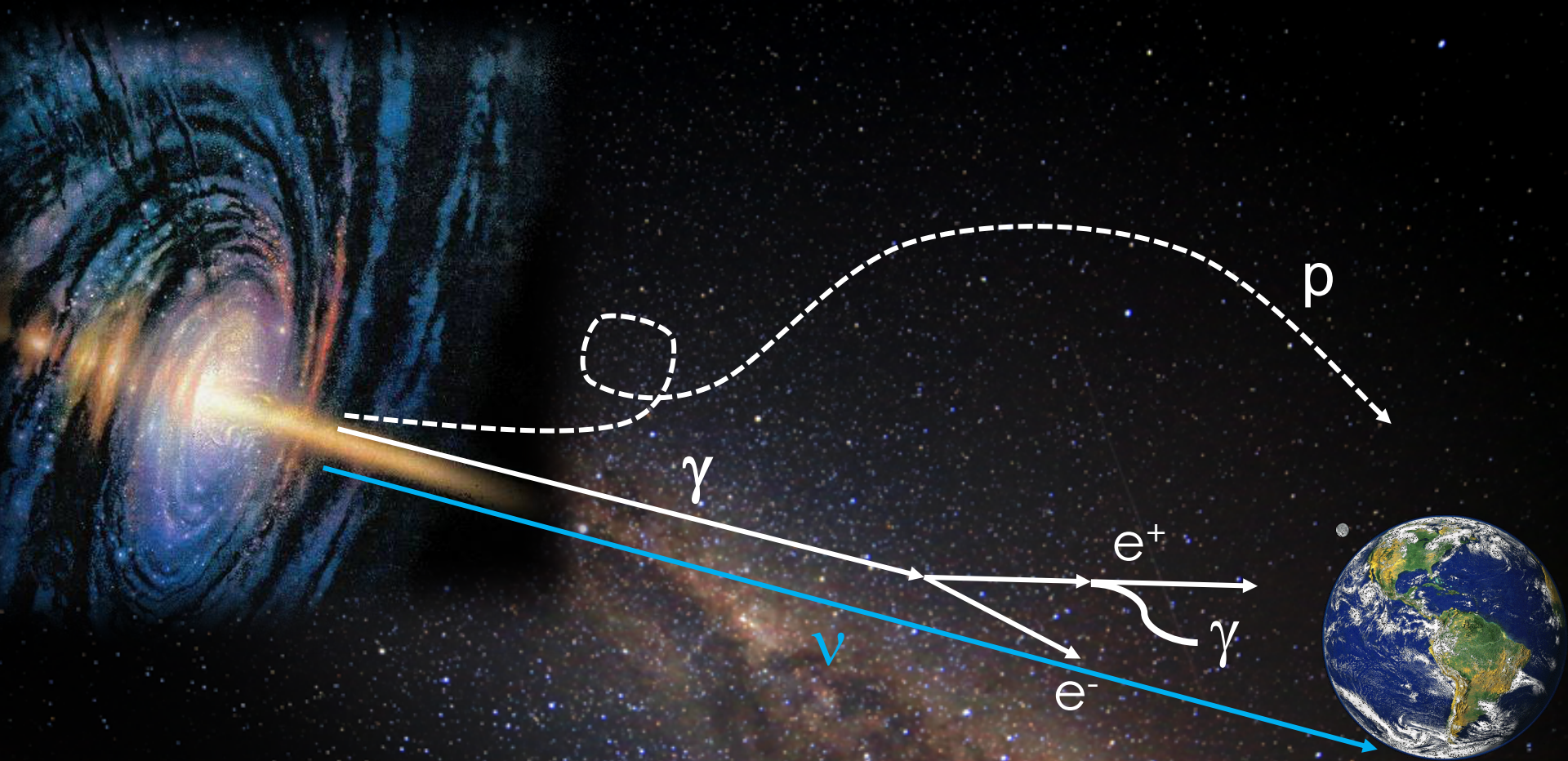


energy in the Universe in gamma rays, neutrinos and cosmic rays

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

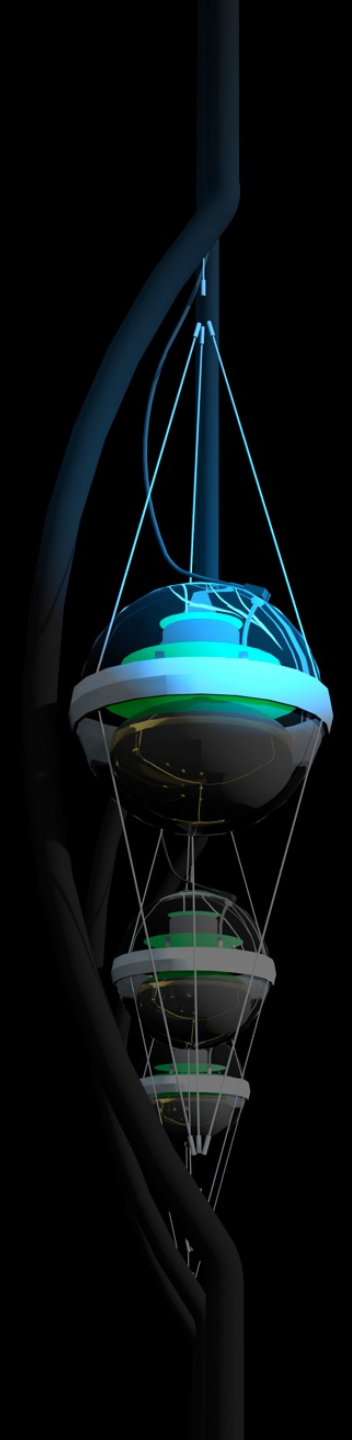


dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to lower energy



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

multimessenger astronomy: radio to TeV gamma rays



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francis halzen

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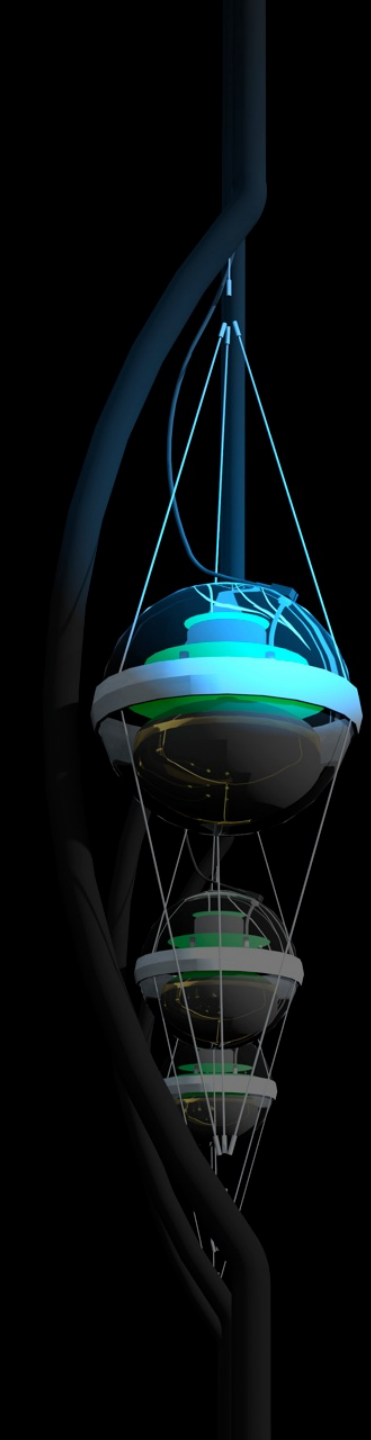
  → muon neutrinos through the Earth
  → starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments
- also, a beam for PeV neutrino physics

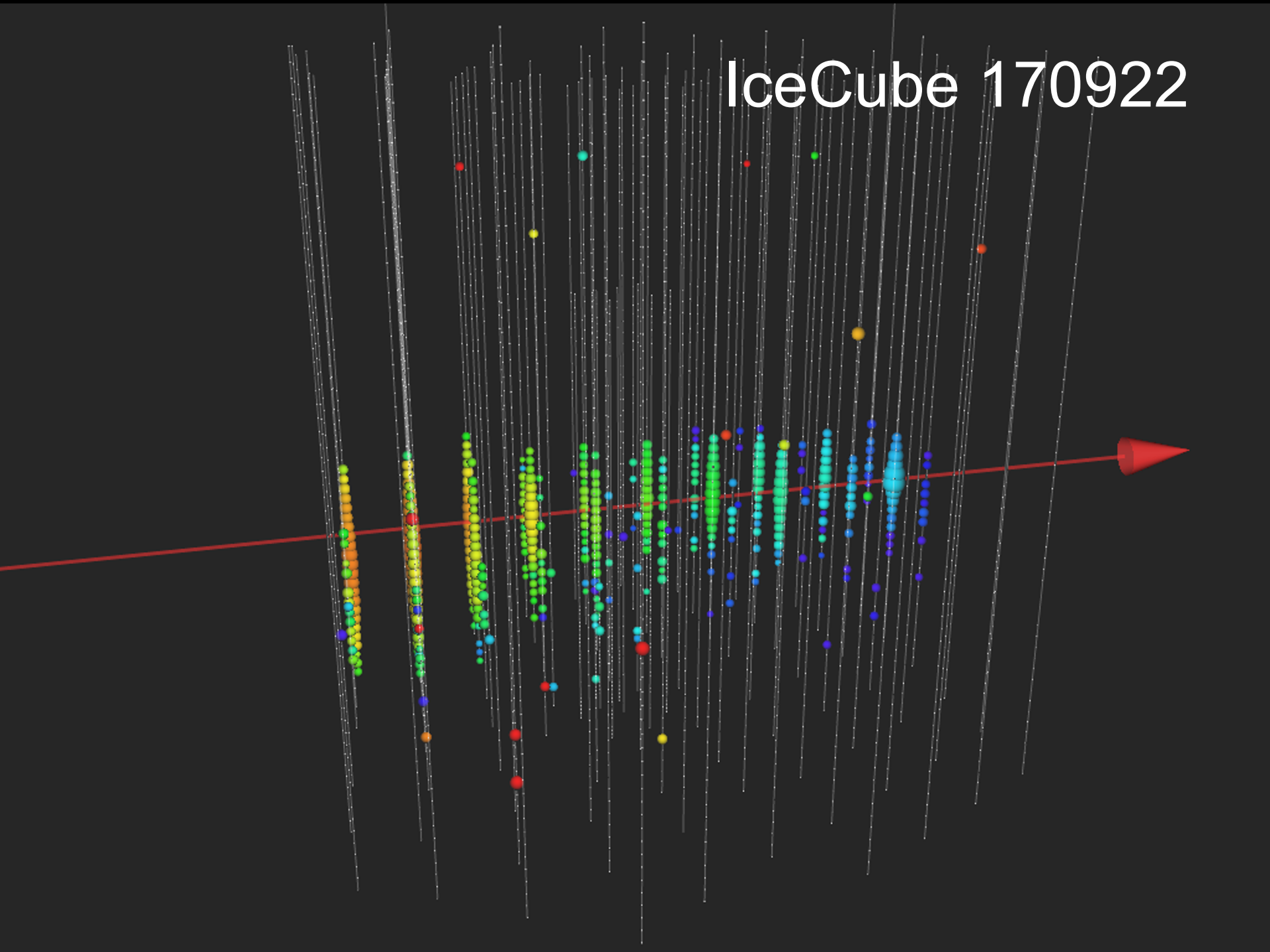


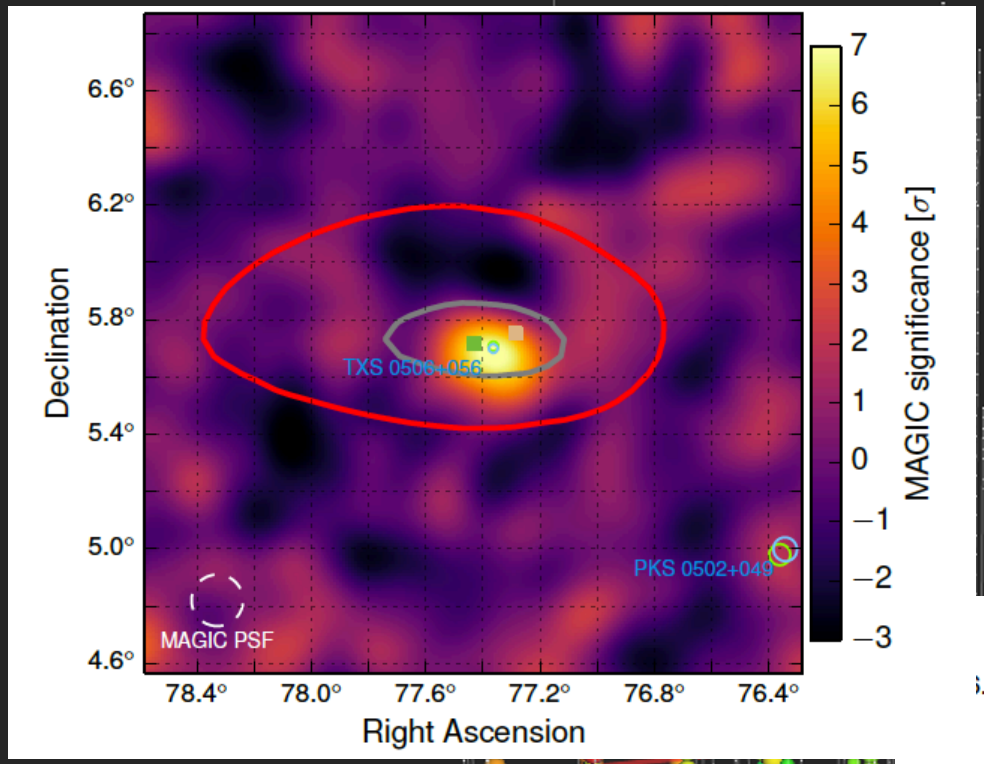
IceCube:

Closing in on Cosmic Ray Accelerators

francis halzen

- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → high energy tau neutrinos
  - → a Glashow event
- where do they come from?
- the first high-energy cosmic ray accelerator

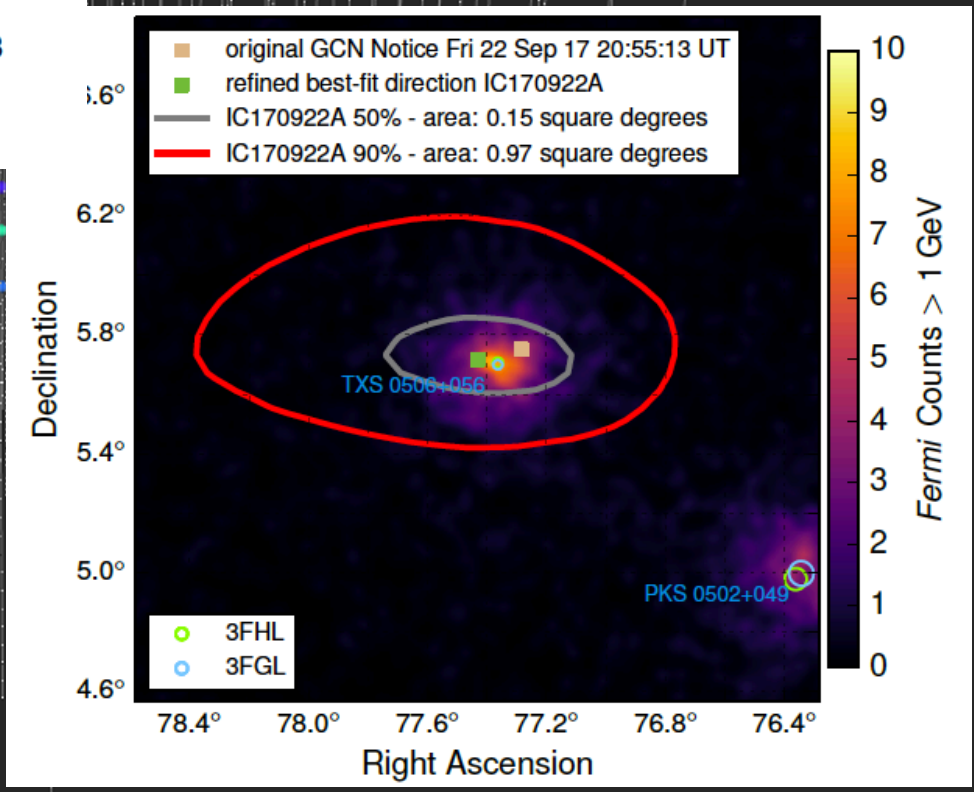

IceCube 170922

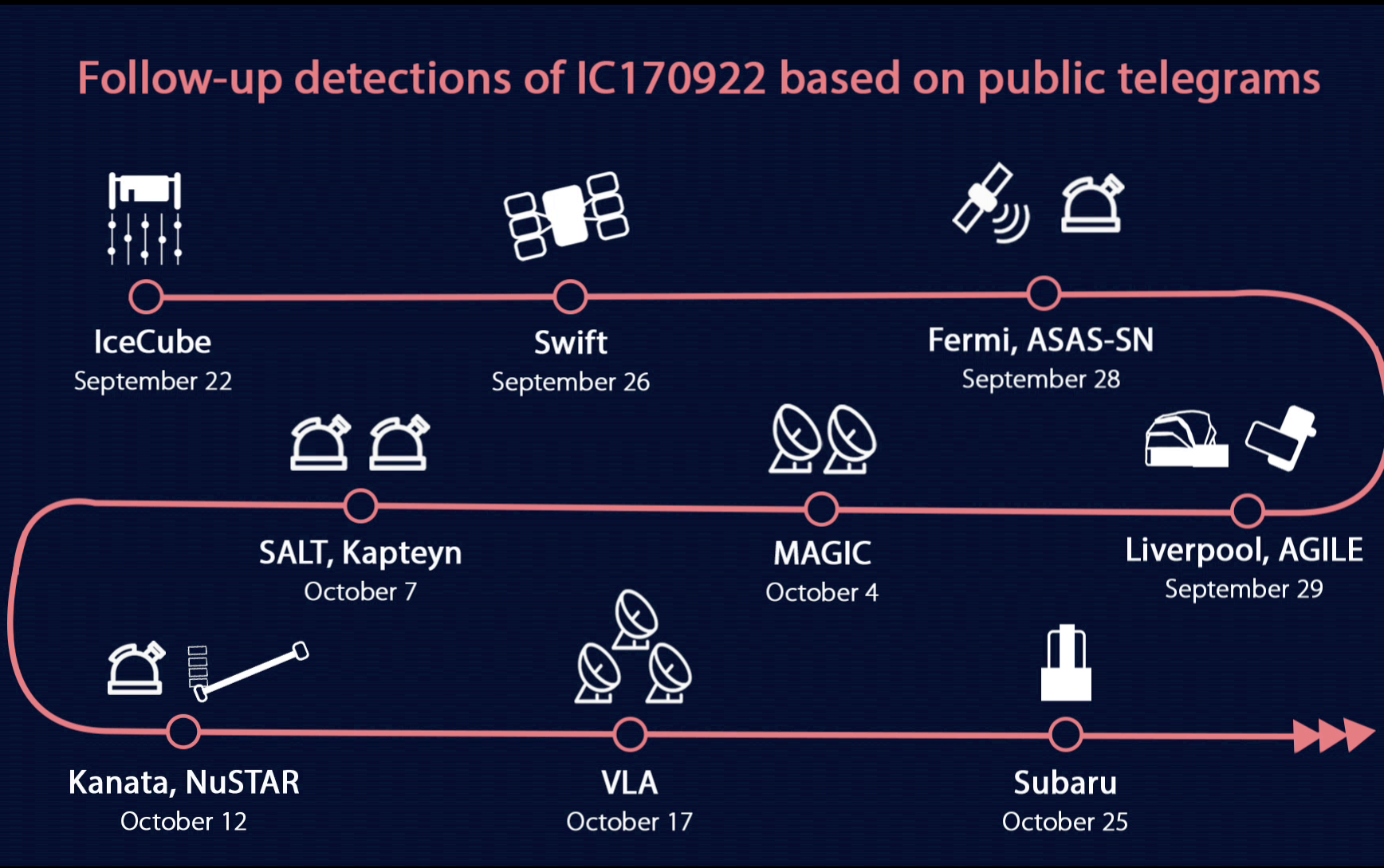


IceCube 170922

Fermi
detects a flaring
blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas



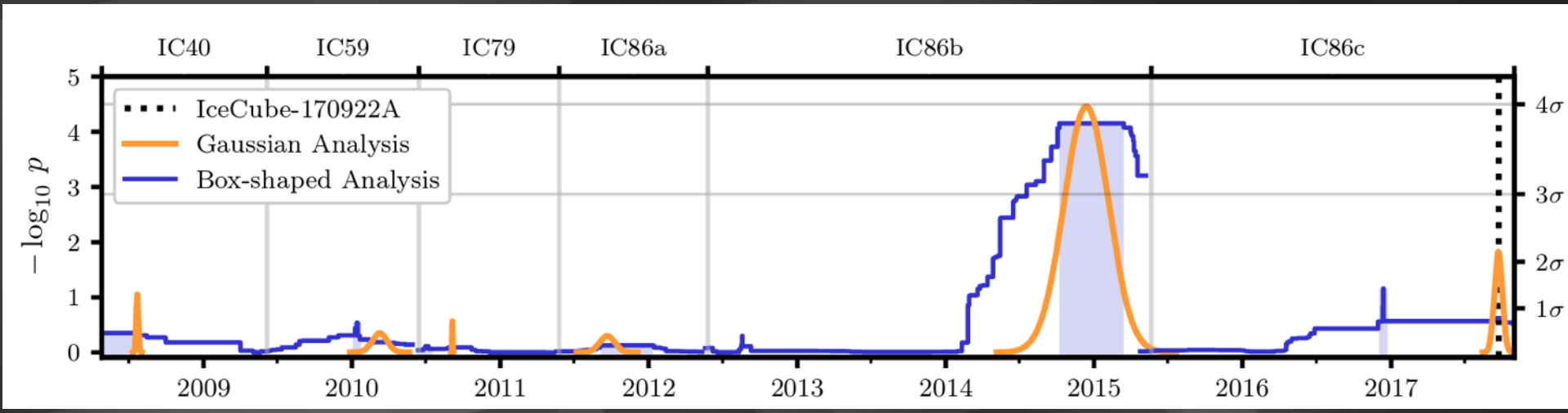

Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25

multiwavelength campaign launched by IC 170922

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

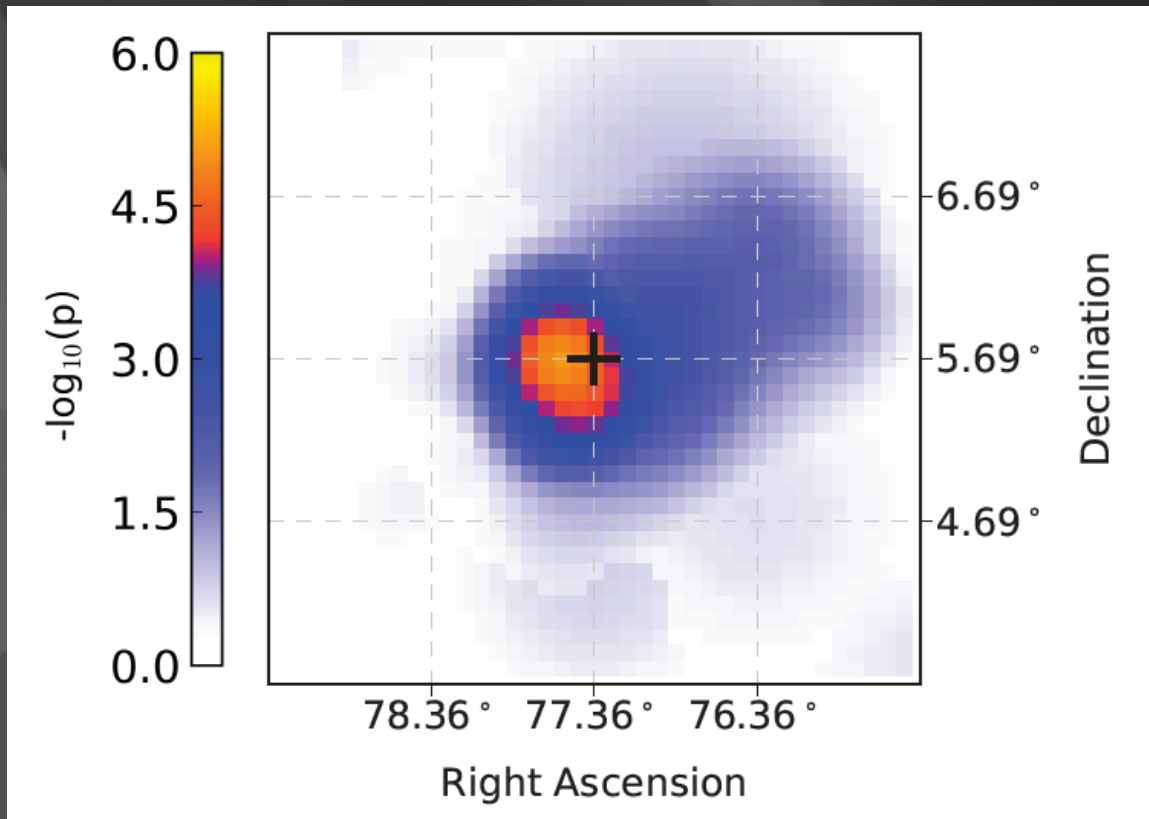
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.06^{o} (7x steady flux, daily variations)
- MAGIC: TeV source in follow-up observations
- follow-up by more telescopes

- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data



search in archival IceCube data:

- 150-day flare in December 2014 of 19 events (bkg < 6)
- spectrum $E^{-2.1}$
- $L_\nu > 10^{47}$ erg/s



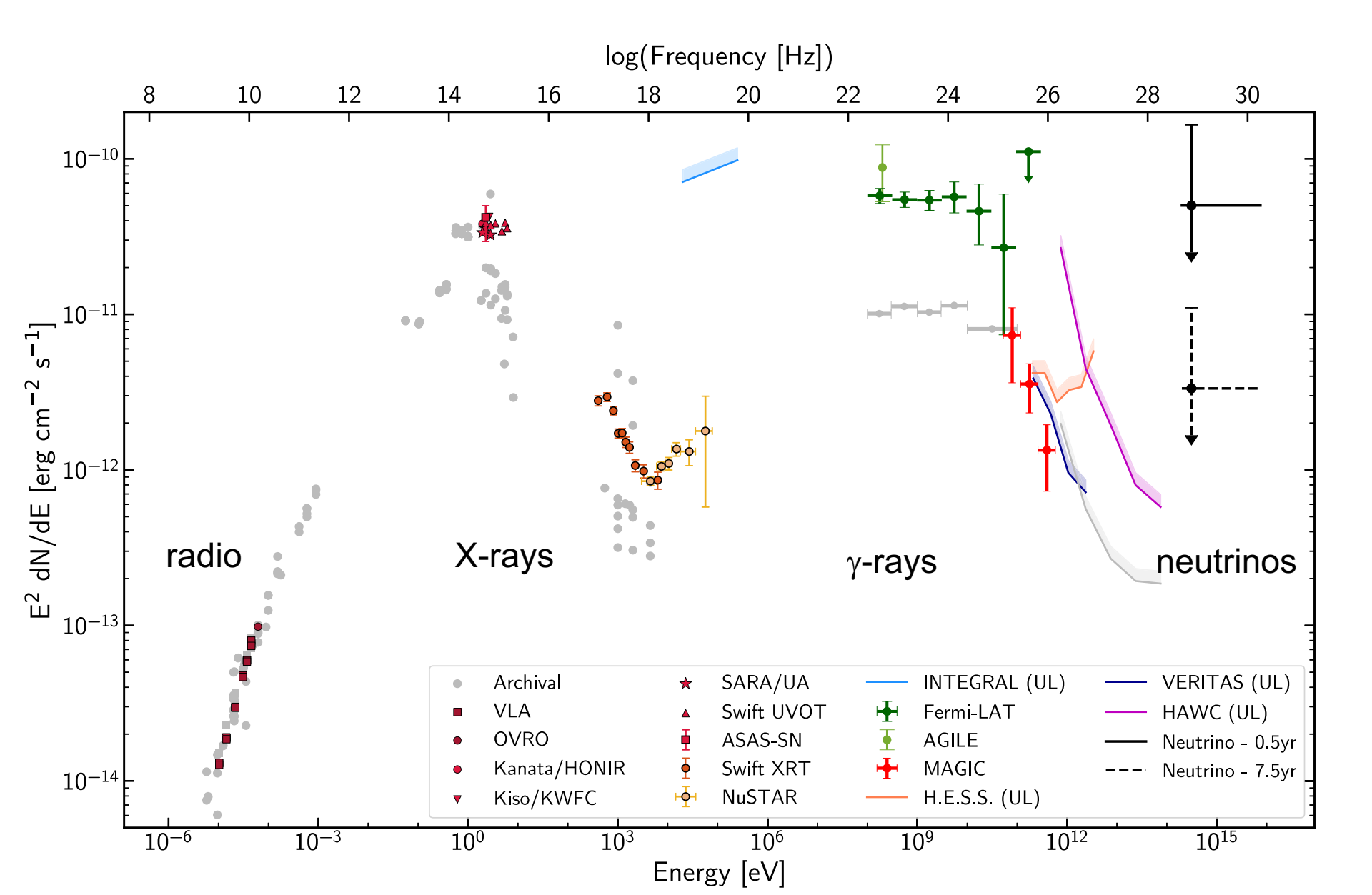
we identified a source of high energy cosmic rays:

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

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

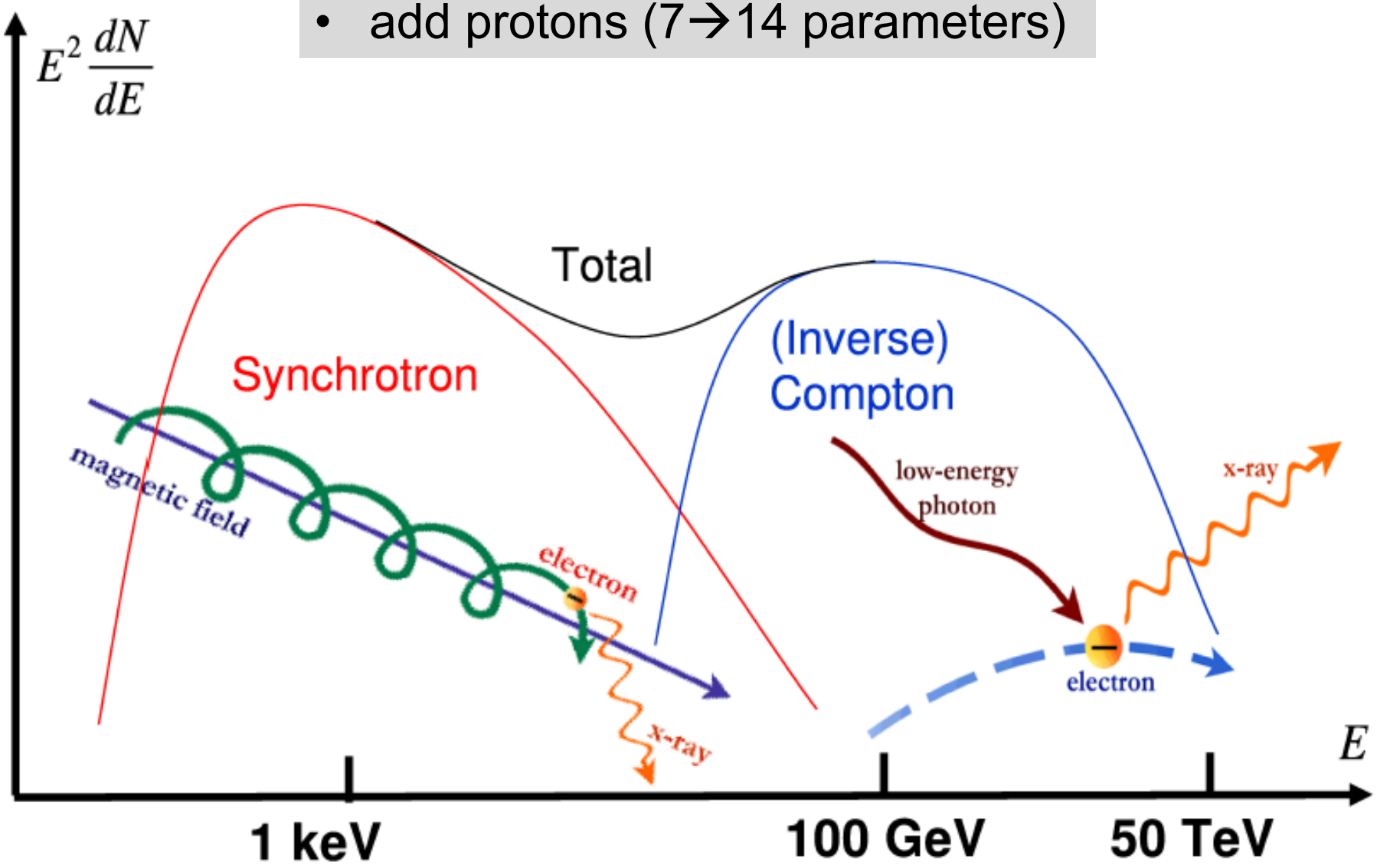
extensive multiwavelength campaign allows us to study the first cosmic accelerator

a problem: theory

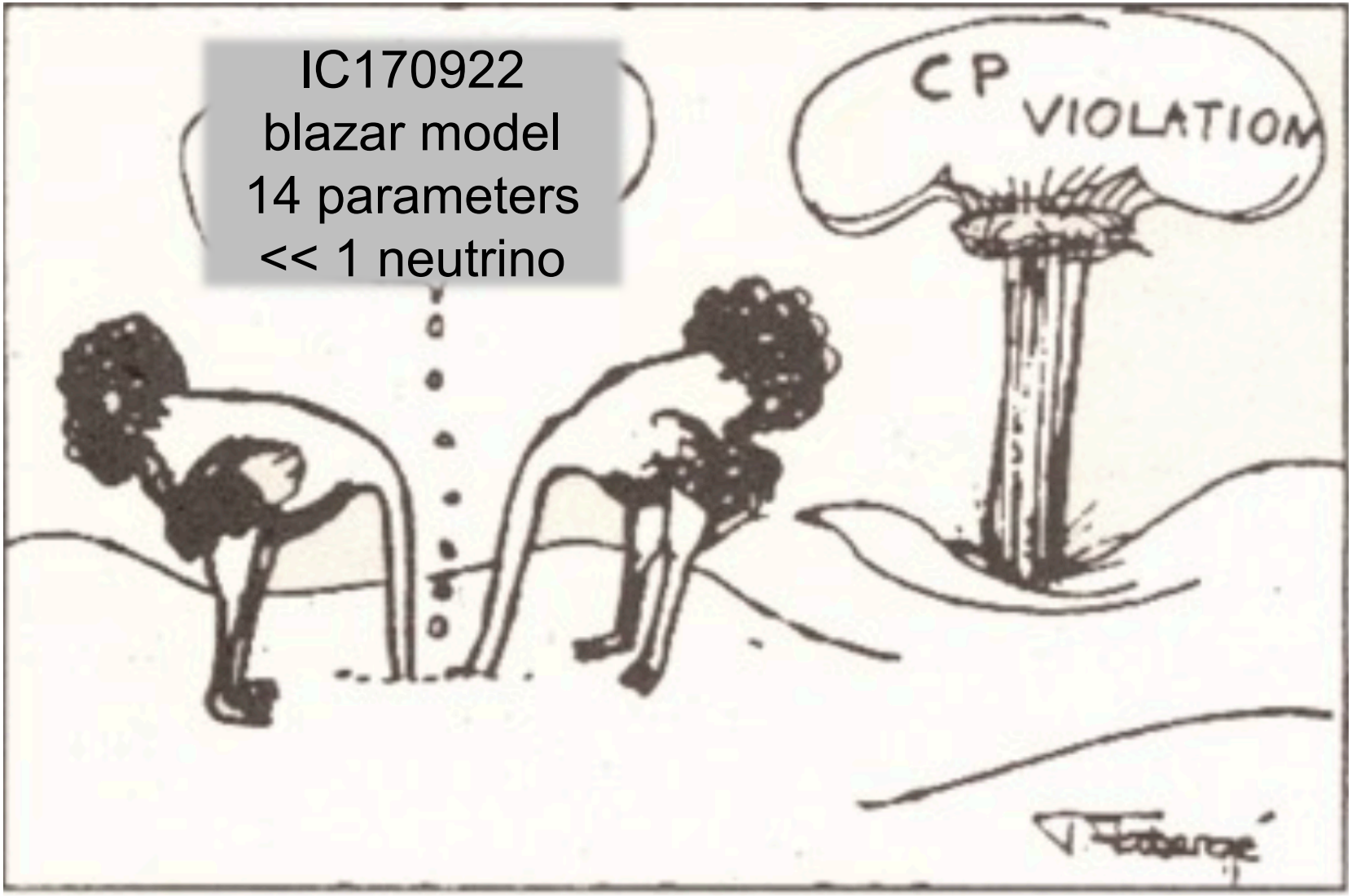


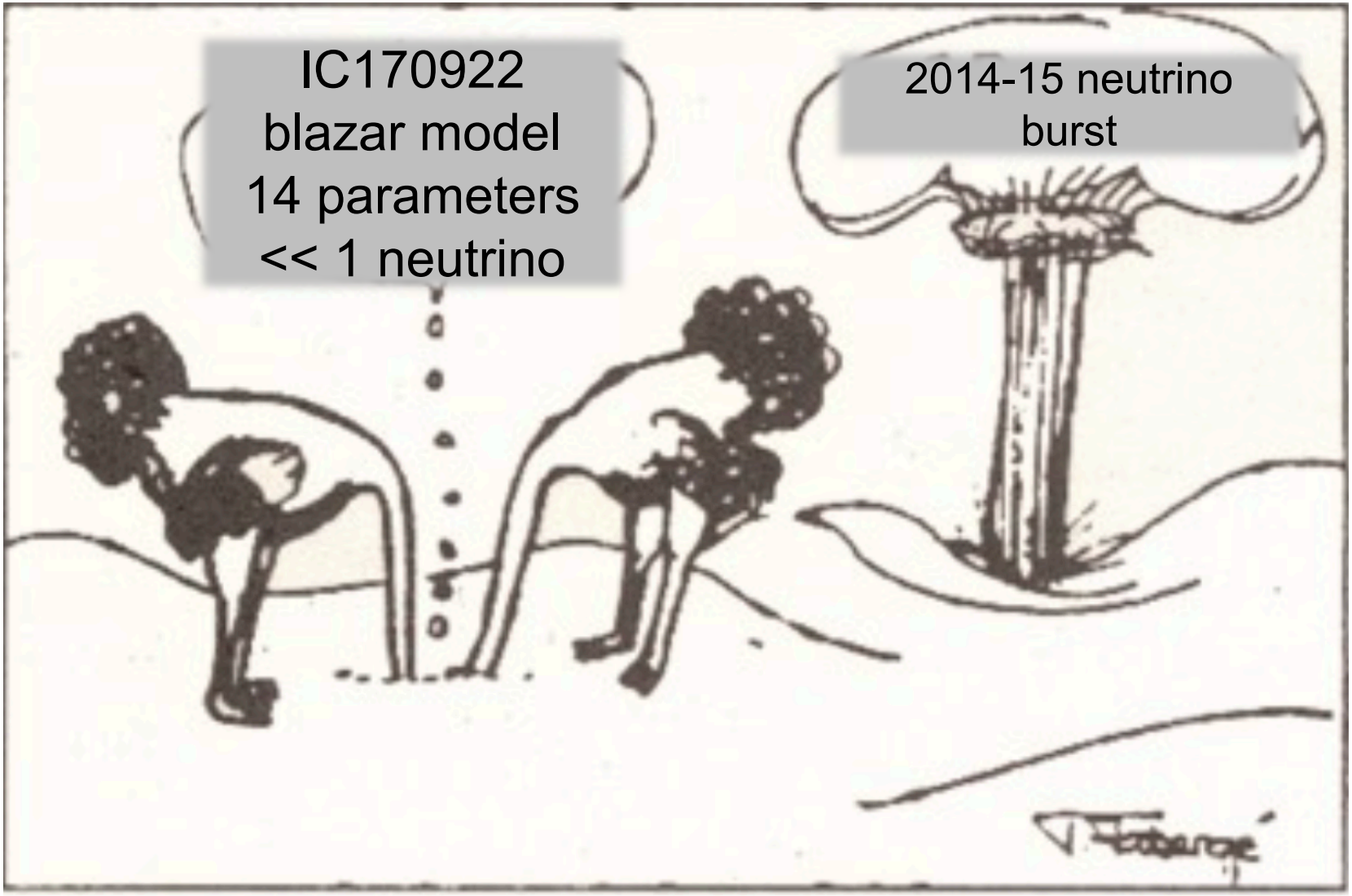
we know that this one is a cosmic ray source

- blazar modeling well understood
- add protons (7→14 parameters)

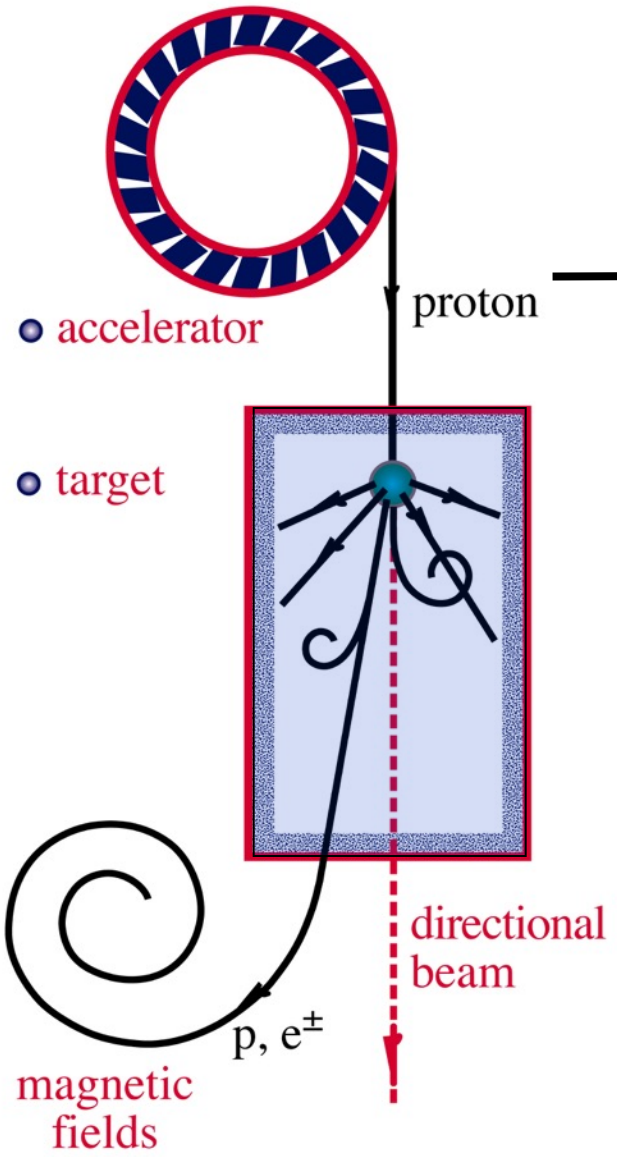


Cabibbo 1966


IC170922
blazar model
14 parameters
<< 1 neutrino
CP VIOLATION


IC170922
blazar model
14 parameters
<< 1 neutrino
2014-15 neutrino
burst

ν and γ beams : heaven and earth



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

$\rightarrow$ cosmic ray + neutrino

supermassive black hole

target ?

neutrino source
needs an accelerator
and
a target
source opacity?

an efficient neutrino source is opaque to gamma rays

- efficiency for producing neutrinos: $L_\nu \sim \tau_{p\gamma}\, L_p$
  opacity of the target $\tau_{p\gamma}$
- requires large opacity of the target $\tau_{p\gamma} \sim n_\gamma$
  to protons and large target density
- source is opaque to gamma rays $\tau_{\gamma\gamma} \simeq 10^2\ \tau_{p\gamma}$
- blazars are highly efficient gamma ray emitters!
- radio interferometry images and optical robotic telescopes
  to the rescue

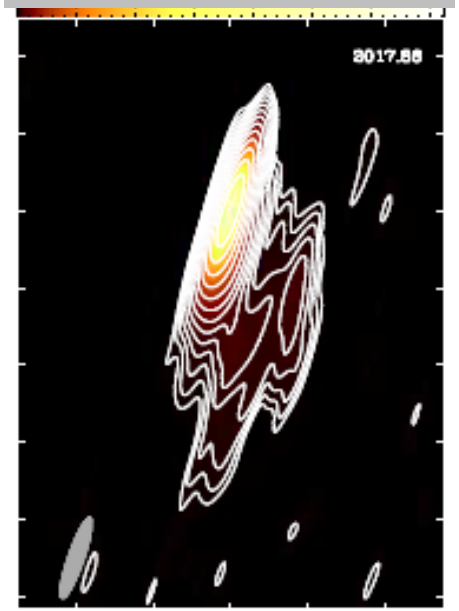
TXS 0506+056

"beyond 5 mas the core loses its tight collimation…"

jet found a target after ~tens of pc

jet star interaction?

theory confirms observation?



Astronomy & Astrophysics manuscript no. 0506
December 5, 2019

LETTER TO THE EDITOR

Apparent superluminal core expansion and limb brightening in the candidate neutrino blazar TXS 0506+056

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[4] Observatori Astronòmic, Universitat de València, c/ Catedràtic José Beltrán Martínez 2, E-46980 Paterna, València, Spain
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[6] Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16801, USA
[7] National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771, USA
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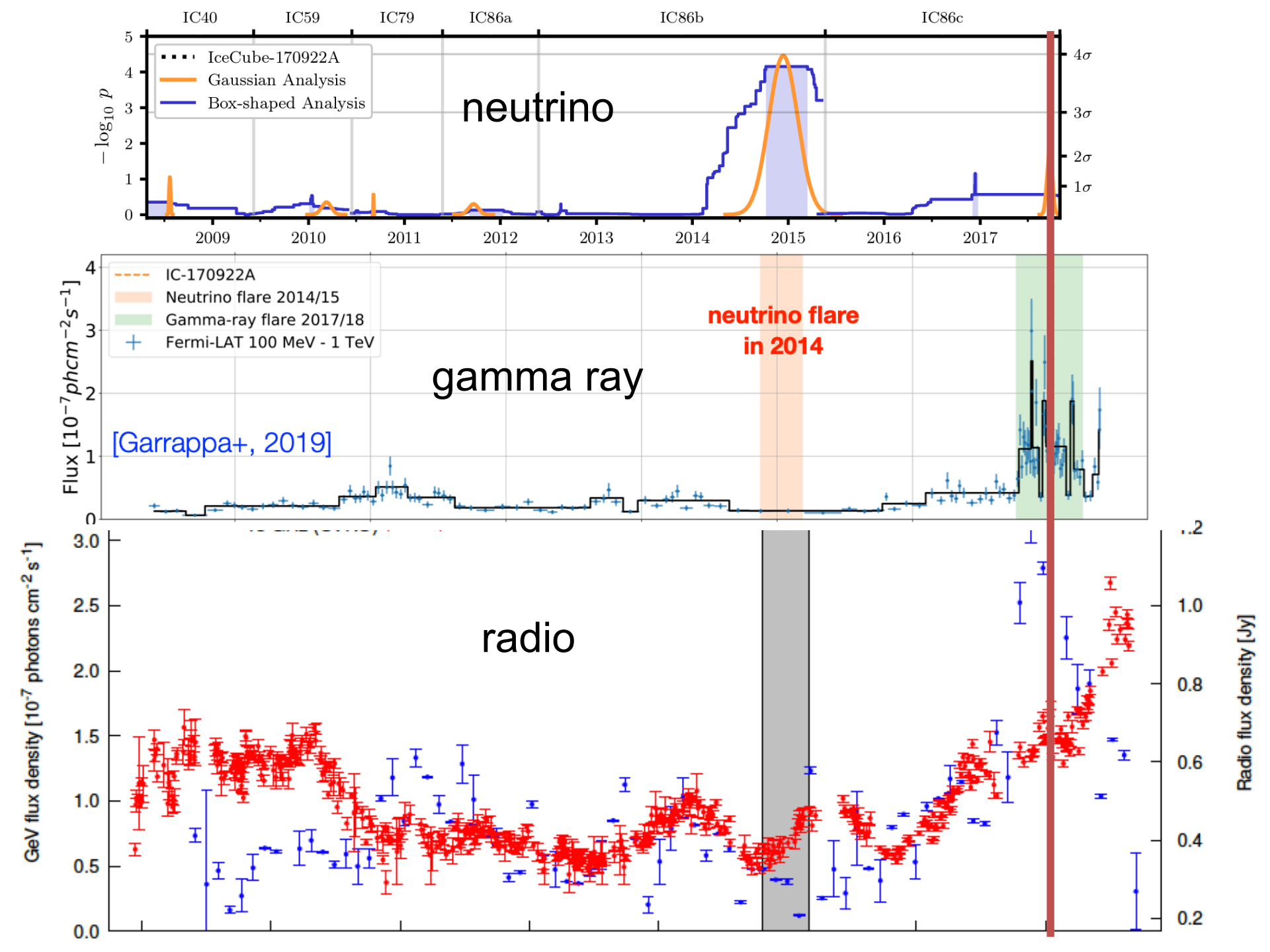
[9] Catholic University of America, Washington, DC, 20064, USA

Submitted: November 28, 2019; Accepted: December 3, 2019

ABSTRACT

Context. IceCube has reported a very-high-energy neutrino (IceCube-170922A) in a region containing the blazar TXS 0506+056. Correlated gamma-ray activity has led to the first high-probability association of a high-energy neutrino with an extragalactic source. This blazar has been found to be in a radio outburst during the neutrino event.
Aims. Our goal is to probe the sub-milliarcsecond properties of the radio jet right after the neutrino detection and during the further evolution of the radio outburst.
Methods. We have performed target-of-opportunity very-long-baseline interferometry imaging observations at 43 GHz frequency, corresponding to 7 mm in wavelength, with the Very Long Baseline Array two and eight months, respectively, after the neutrino event.
Results. We produced two images of the radio jet of TXS 0506+056 at 43 GHz with angular resolutions of (0.2 × 1.1) mas and (0.2 × 0.5) mas, respectively. The source shows a compact, high brightness temperature core (albeit not approaching the equipartition limit, Readhead 1994) and a bright and originally very collimated inner jet. Beyond about 0.5 mas from the mm-VLBI core, the jet loses this tight collimation and expands rapidly. During the months after the neutrino event associated with this source, the overall flux density is rising. This flux density increase happens solely within the core. Notably, the core expands in size with apparent superluminal velocity during these six months so that the brightness temperature drops by a factor of three in spite of the strong flux density increase.
Conclusions. The radio jet of TXS 0506+056 shows strong signs of deceleration and/or a spine-sheath structure within the inner 1 mas (corresponding to about 70 pc to 140 pc in deprojected distance) from the mm-VLBI core. This structure is consistent with theoretical models that attribute the neutrino and gamma-ray production in TXS 0506+056 to interactions of electrons and protons in the highly-relativistic jet spine with external photons originating from a slower-moving jet region. Proton loading due to jet-star interactions in the inner host galaxy is suggested as the possible cause of deceleration.

Key words. Radiation mechanisms: non-thermal – Neutrinos – Techniques: interferometric – Radio continuum: galaxies – Galaxies: quasars: individual: TXS 0506+056


IC40
IC59
IC79
IC86a
IC86b
IC86c
IceCube-170922A
Gaussian Analysis
Box-shaped Analysis
neutrino
$-\log_{10} p$
4σ
3σ
2σ
1σ
2009
2010
2011
2012
2013
2014
2015
2016
2017
IC-170922A
Neutrino flare 2014/15
Gamma-ray flare 2017/18
Fermi-LAT 100 MeV - 1 TeV
gamma ray
neutrino flare
in 2014
[Garrappa+, 2019]
Flux [$10^{-7} phcm^{-2}s^{-1}$]
radio
GeV flux density [10^{-7} photons cm^{-2} s^{-1}]
Radio flux density [Jy]

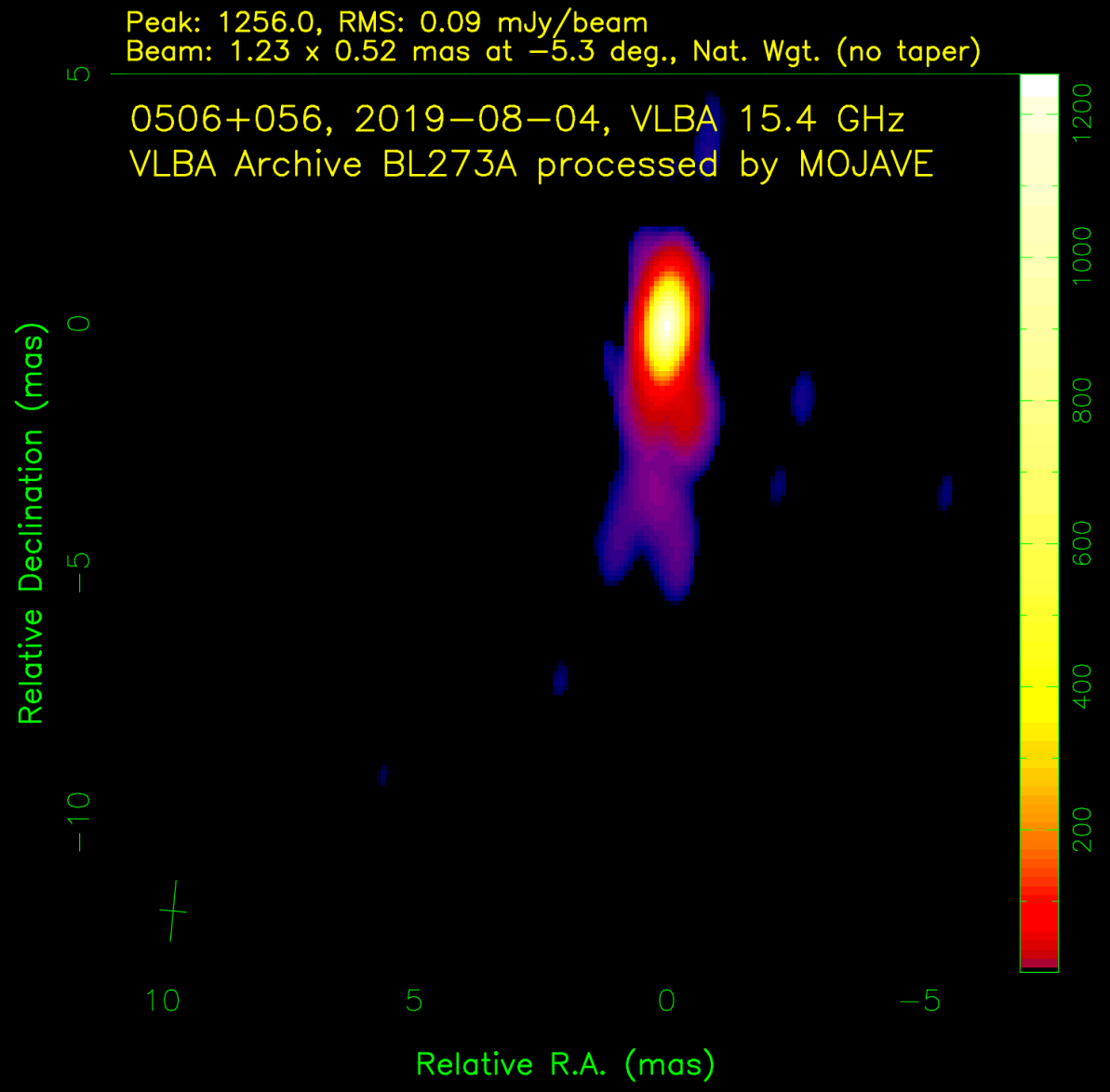
TXS 0506+056 a galaxy merger?

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

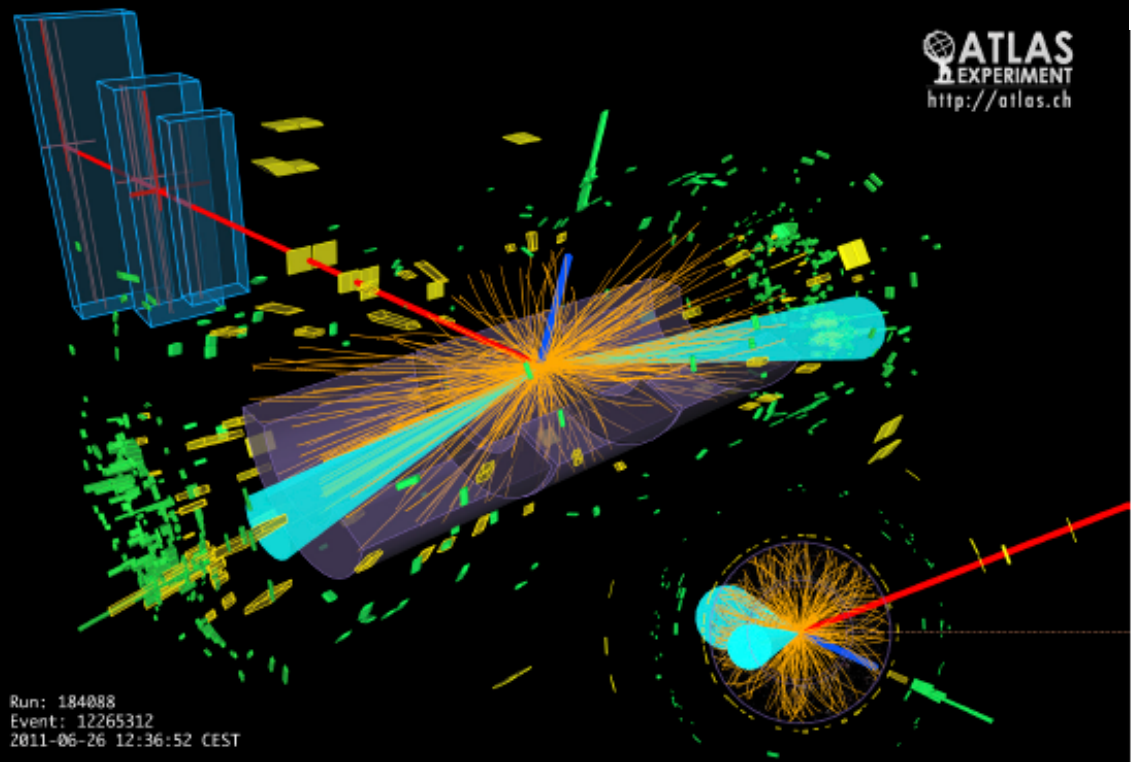
core expands with superluminal velocity

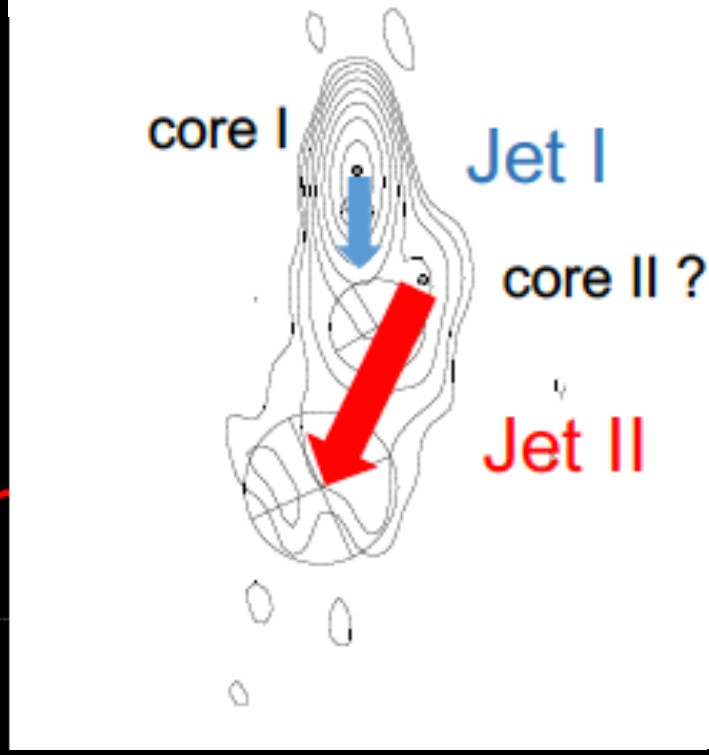
beyond 5 mas the core loses its tight collimation…

theory confirms observation?



analysis of 16 VLBA observations
MOJAVE 15 GHz
2009-18





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

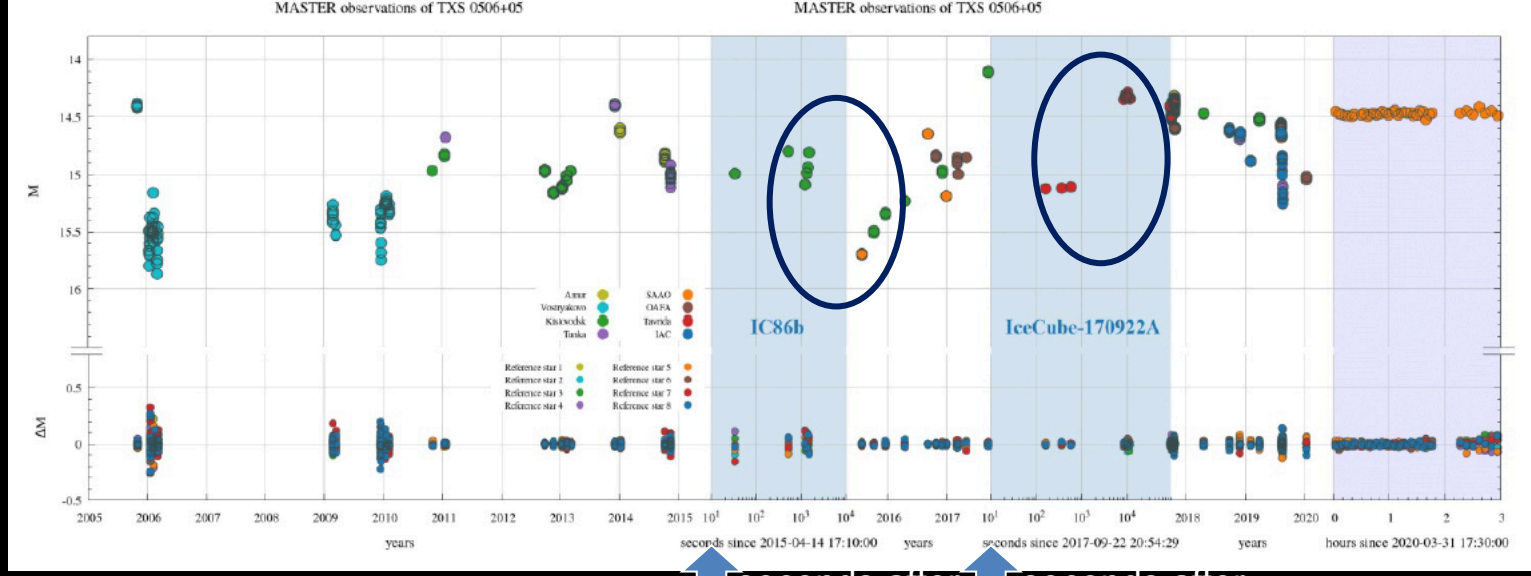
V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8] , P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], 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

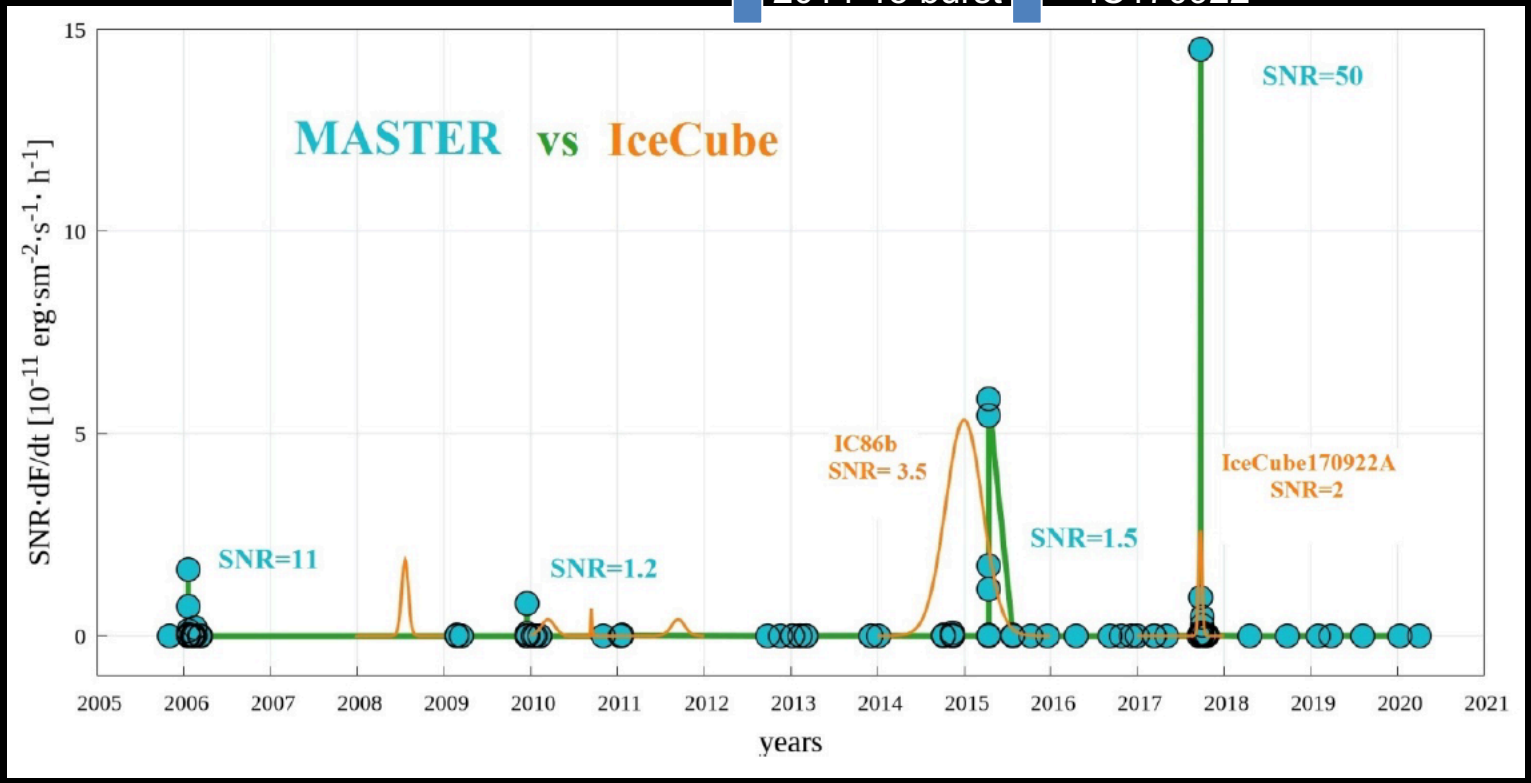
blue panels:
expanded time axis
years → seconds



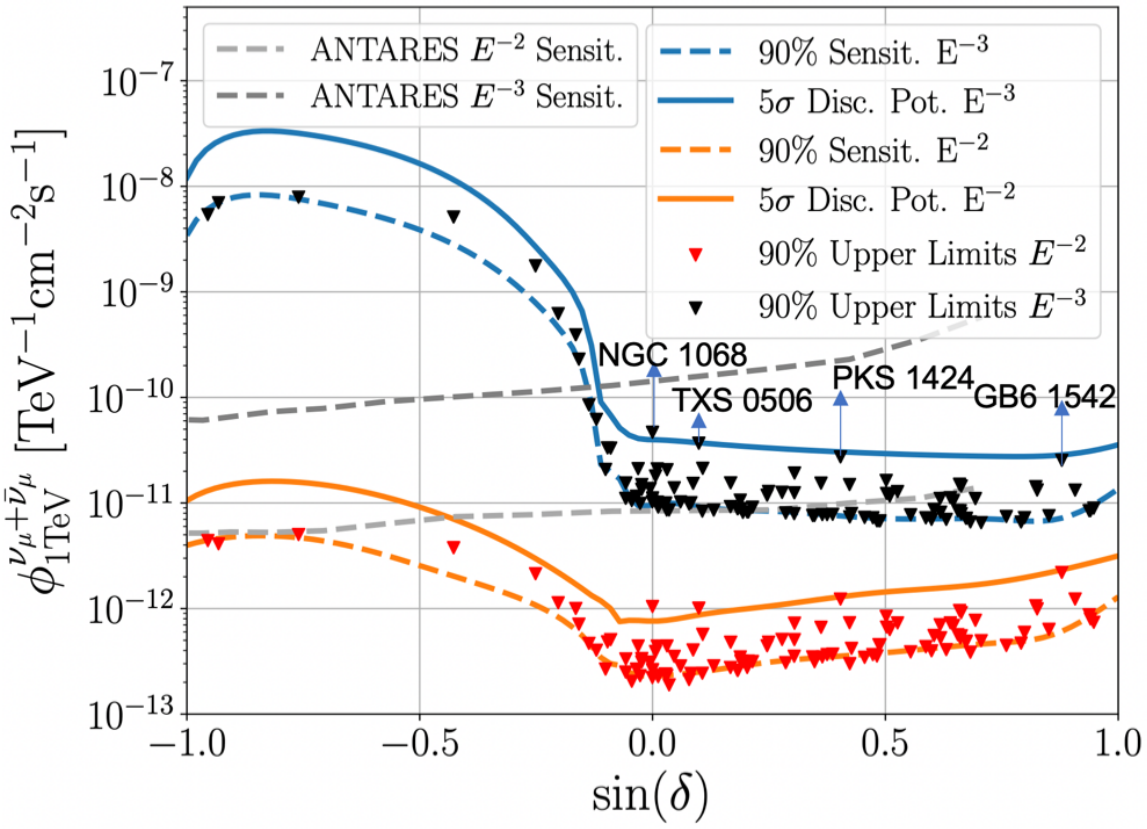
seconds after 2014-15 burst

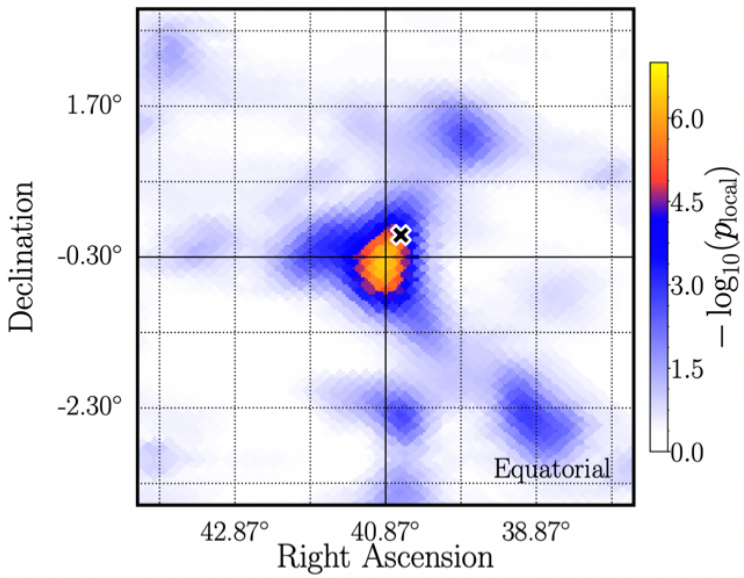
seconds after IC170922

time variation of flux
times
signal-to-noise



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





why not seen before?

theory: not a “vanilla” blazar

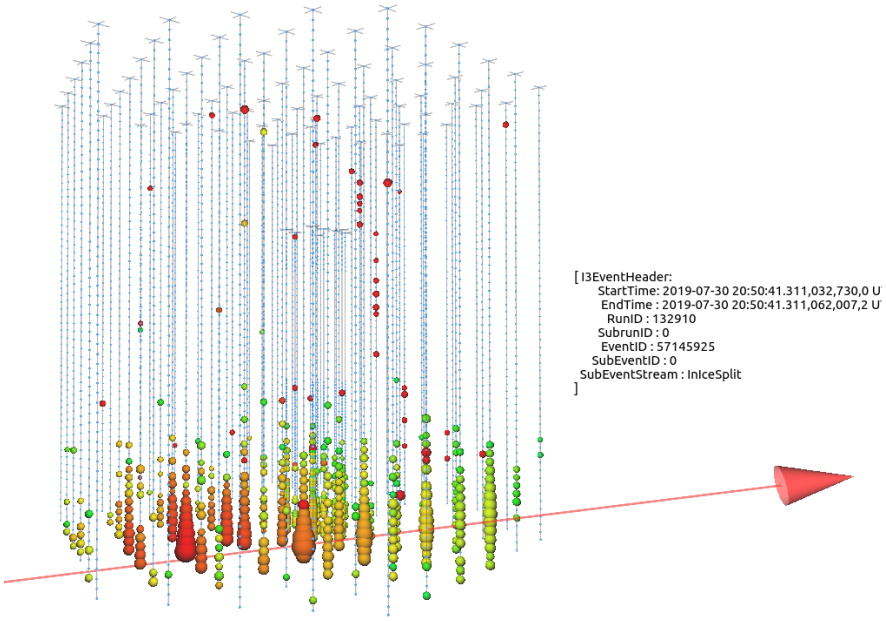
what is the target found in the radio and optical images

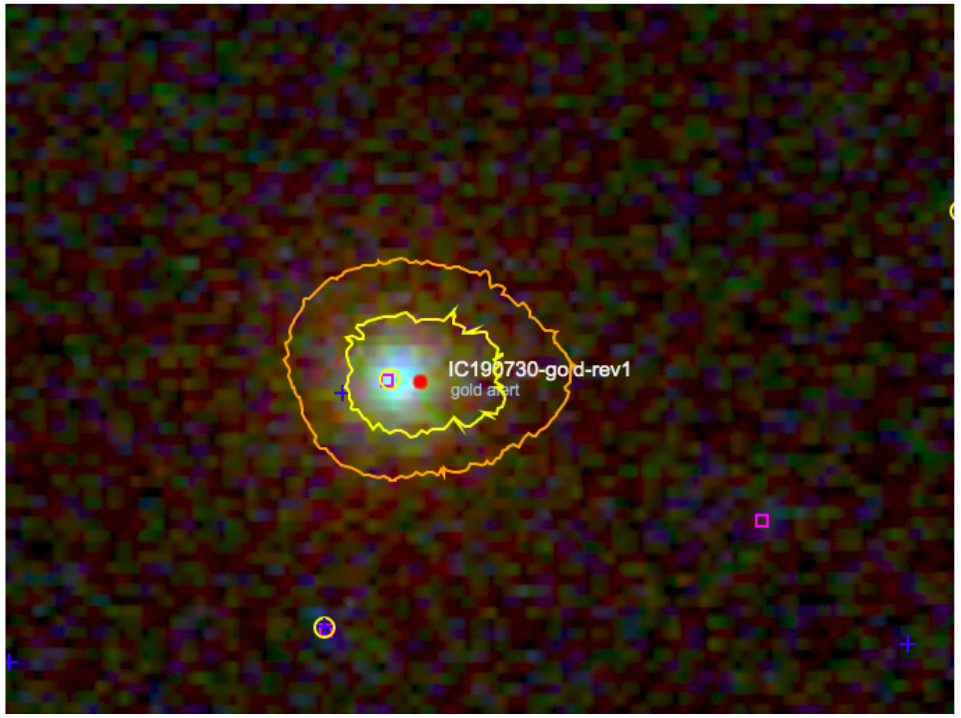
blueprint of TXS accelerator still evolving

is cosmic ray origin connected to blazars or do other sources also turn into TXS-type neutrino beam dumps?

multimessenger astronomy is “subtle but not malicious”

some other intriguing events





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

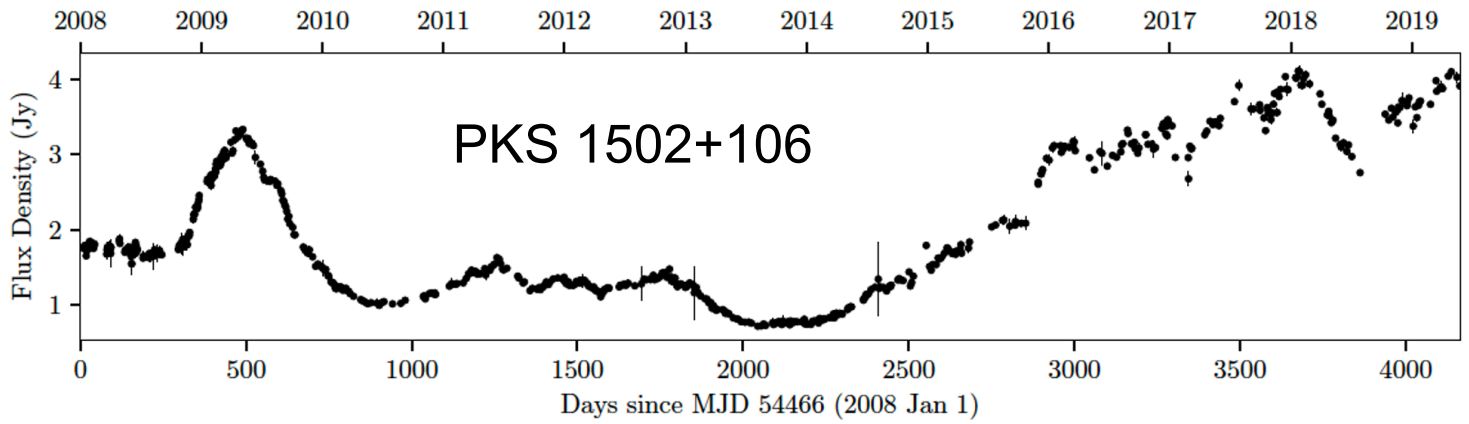
Tweet

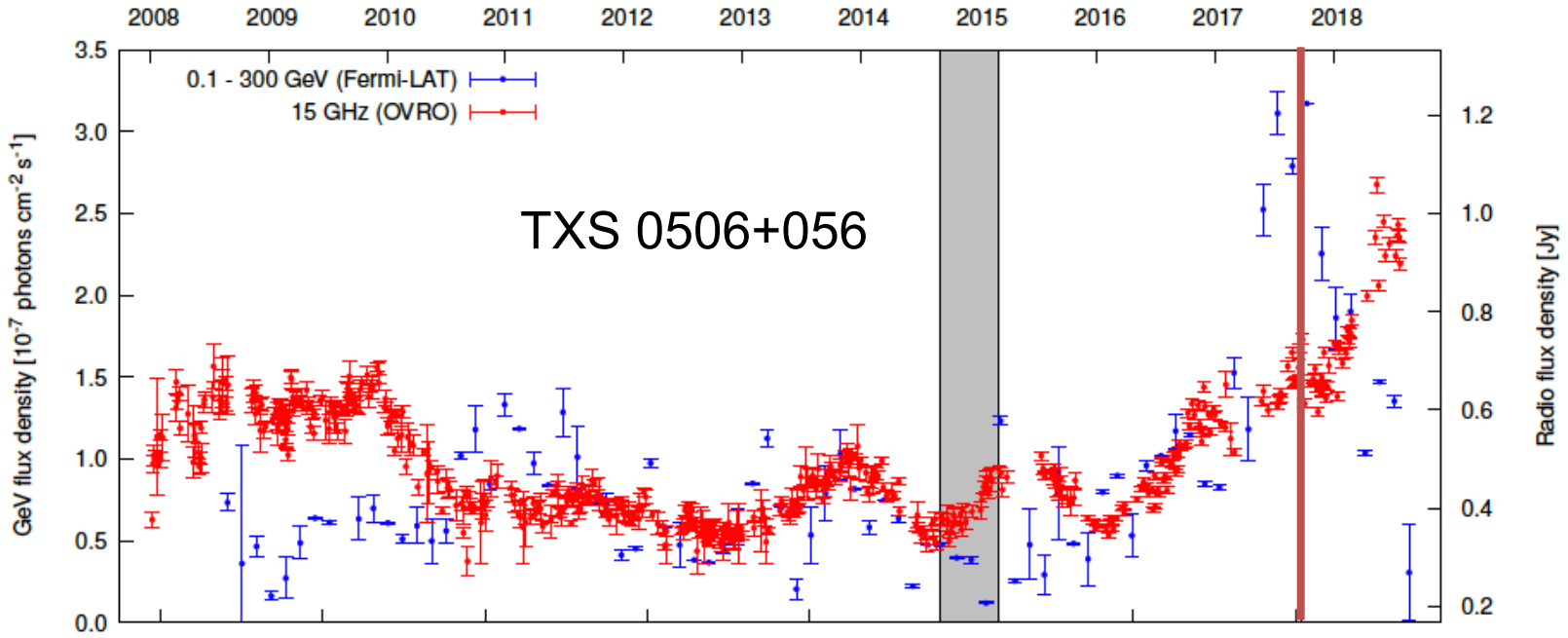
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started 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.

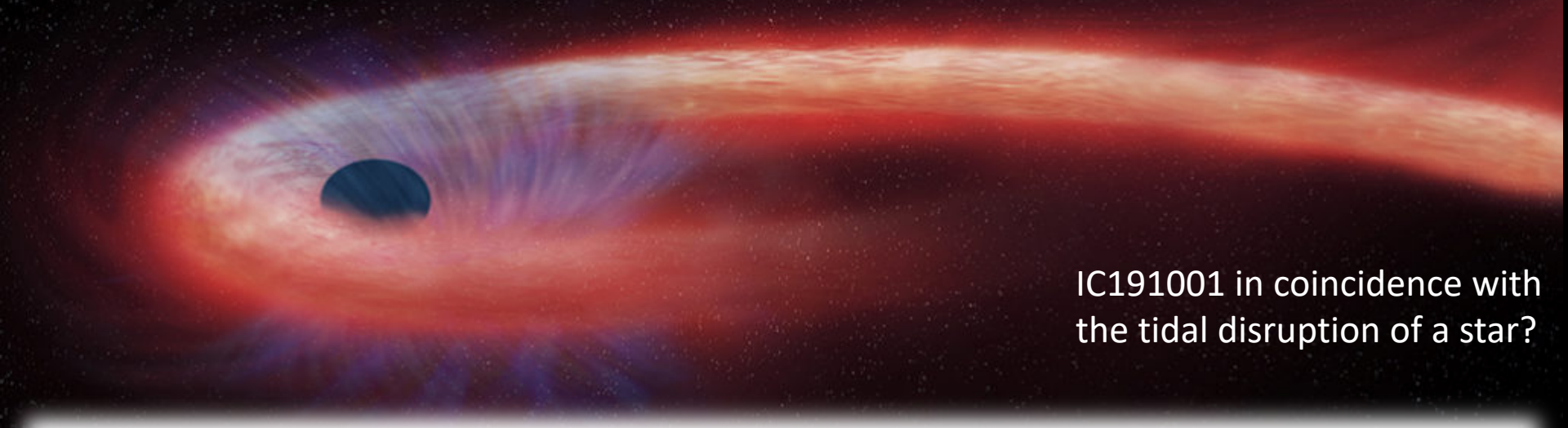
Related

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

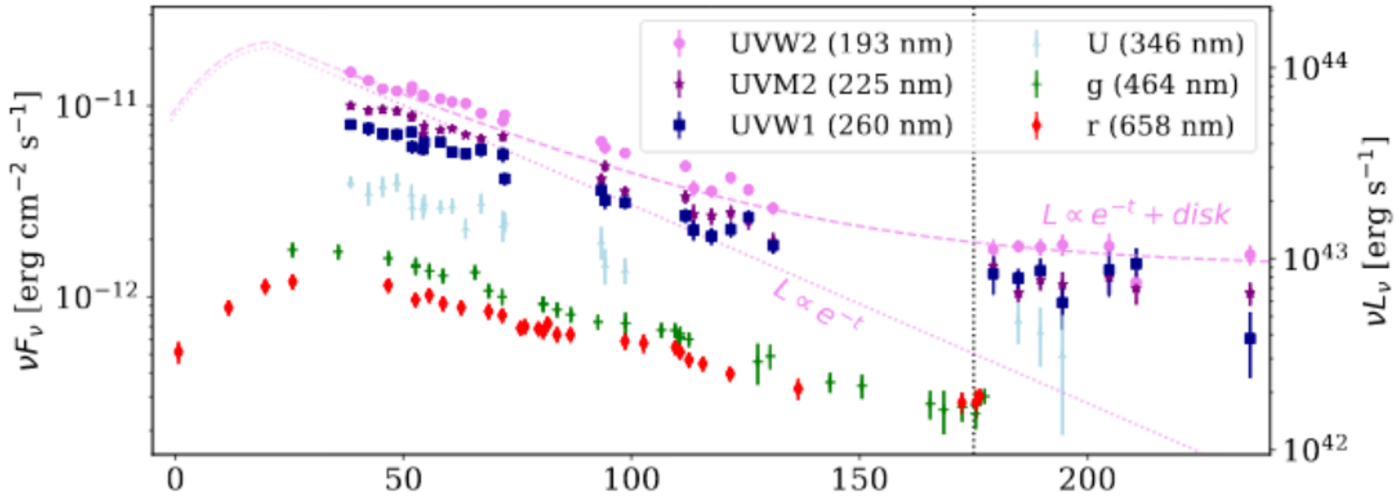
the two highest energy IceCube alerts are coincident with radio flares







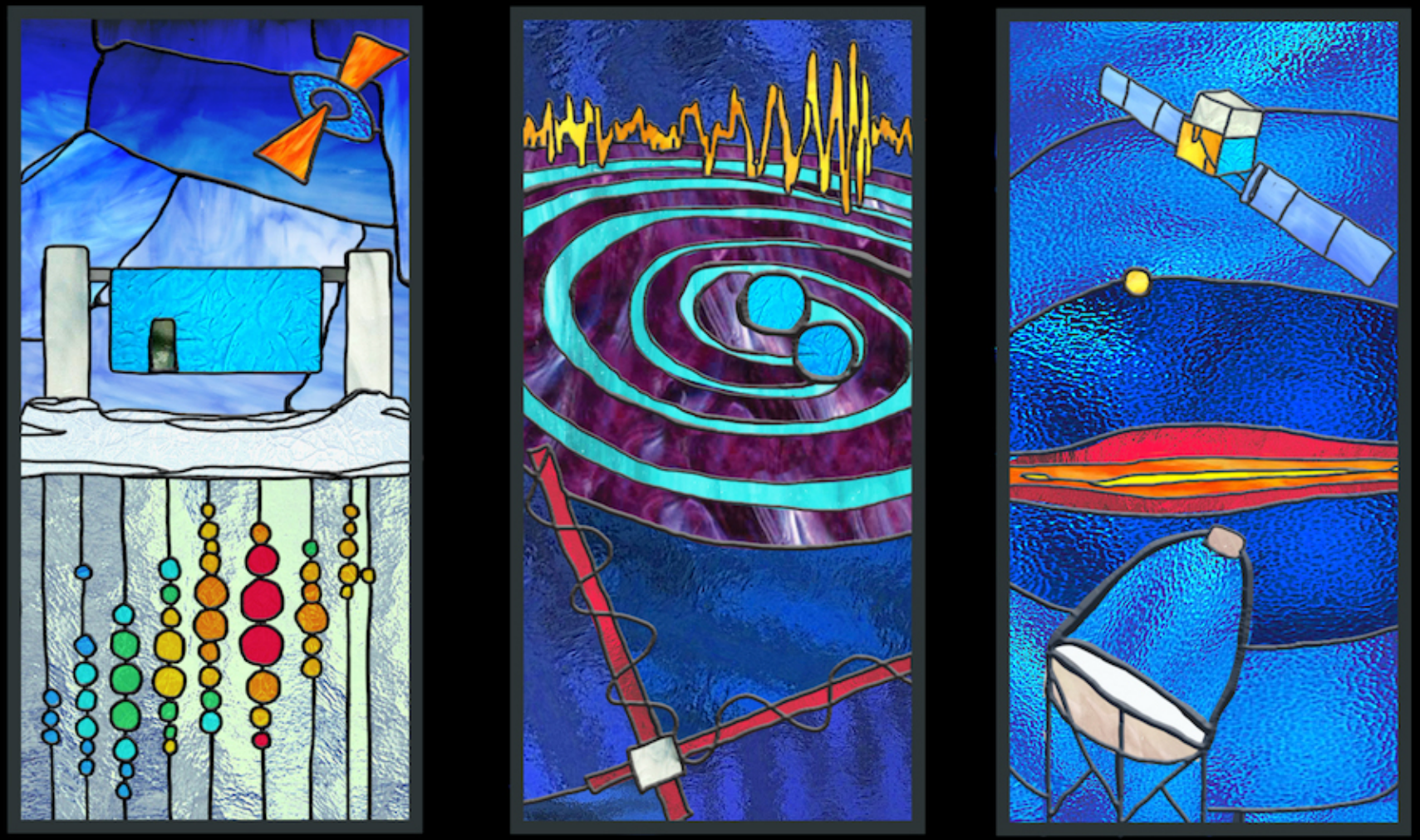
IC191001 close to luminous TDE of the Zwicky Transit Factory



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})

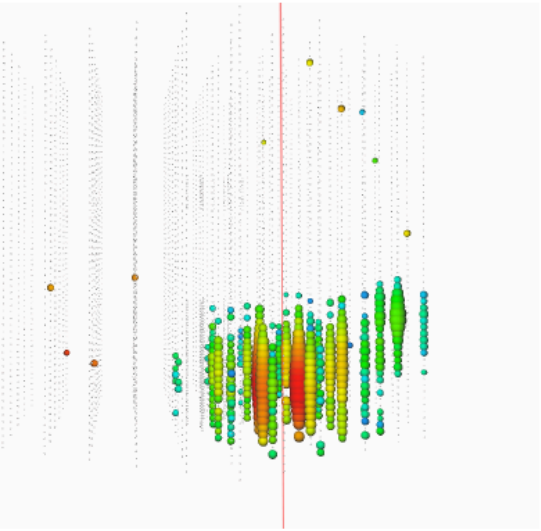


next: gravitational waves + neutrinos

August 17, 2017 neutron star merger jet not aligned

IC200107A: The "DNN-starting-track Neutrino"

DNN (HESE V3)



High-charge HESE event, did not qualify as alert (see SplineMPE direction…)

Good starting track, confirmed by Theo's DNN

Signalness ~65% (Not reported).

Posted in GCN circular.

Coincident with "extreme blazar".

Followed Up In 7 GCNs + 3 ATELs + 3 Papers:

ZTF

(Non-detection)

Fermi GBM

(Non-detection)

Integral

(Non-detection)

HAWC

(Non-detection)

IceCube (FRA)

(p_2 = 0.04)

Fermi-LAT

(Nothing coincident, no new sources)

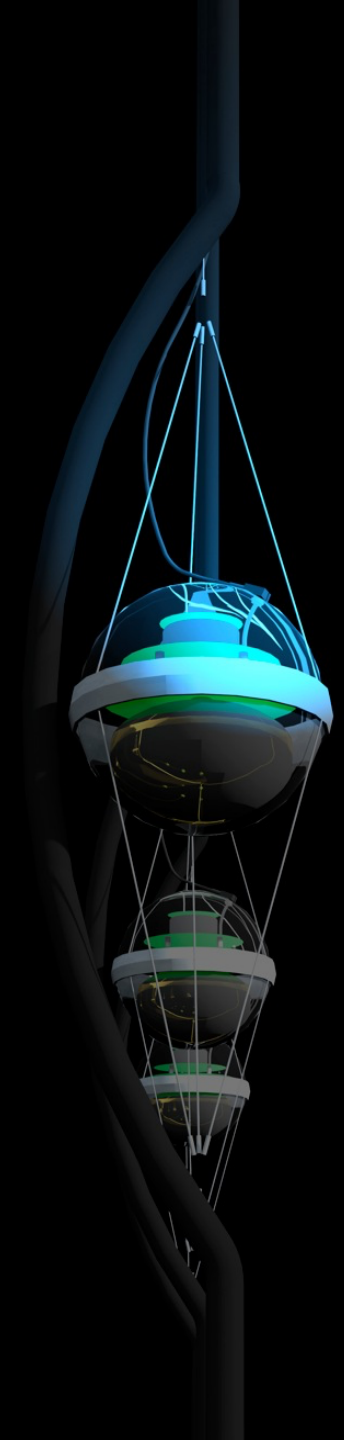
→ Swift

(ATEL, ATEL)

(Coincident Extreme Blazar, flaring)

→ LBT

(Redshift)

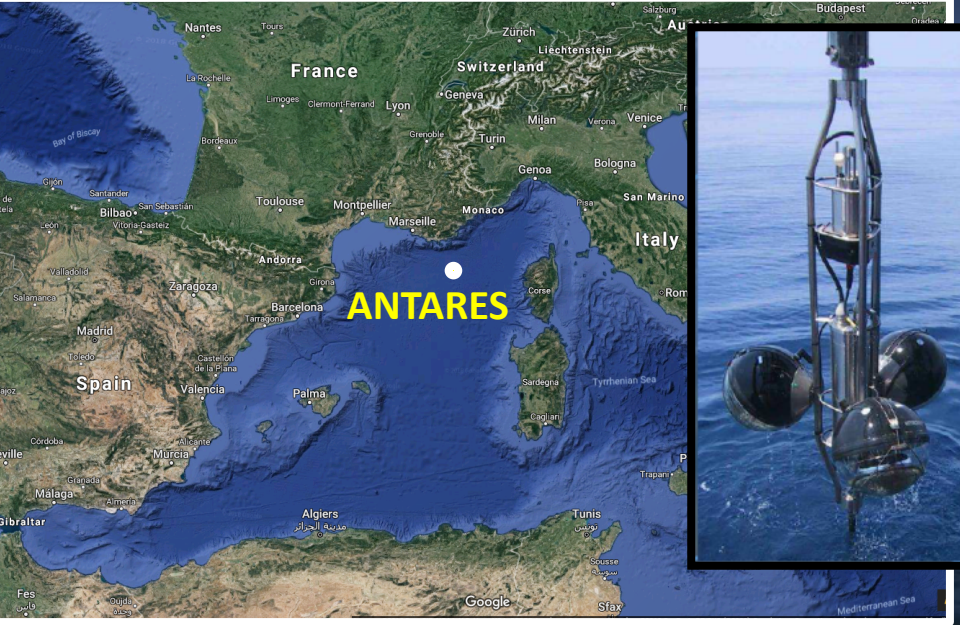


Neutrinos in the Era of Multimessenger Astronomy

francis halzen

- cosmic neutrinos: many independent observations
  → muon neutrinos through the Earth
  → starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments
- also, a beam for PeV neutrino physics

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

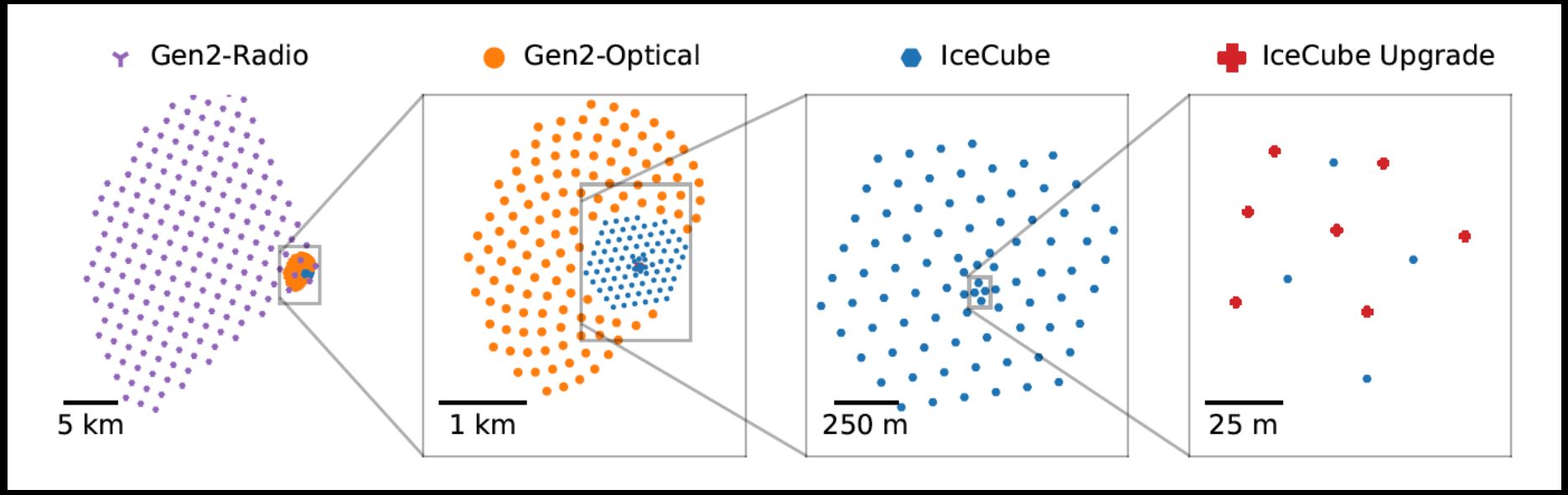
70 m

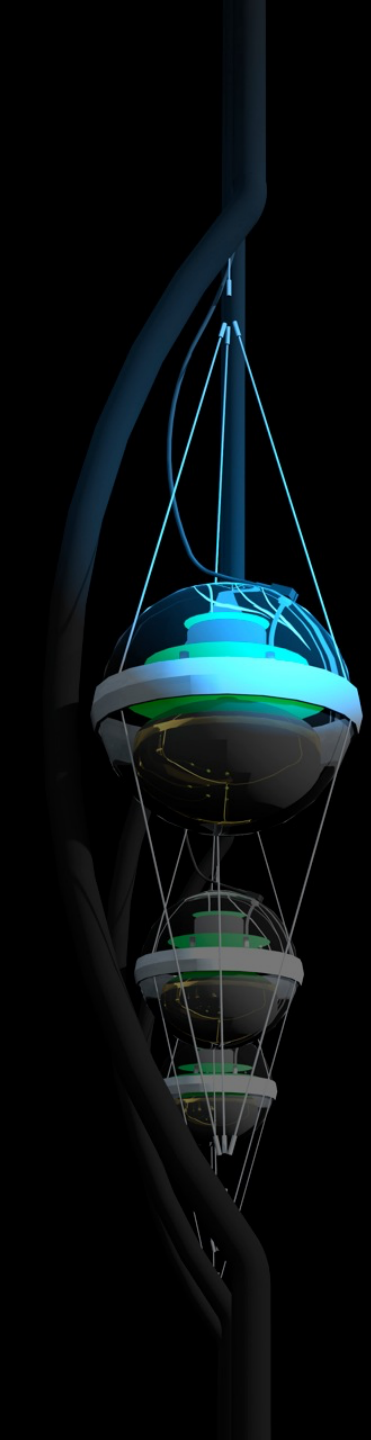
Interlink cables

Lake Baikal experiment reaches 0.35 km^3

next-generation detectors

sensitivity improved by 5 to more than 100





neutrino astronomy 2020

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

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...STRALIA 1

...NGDOM 1

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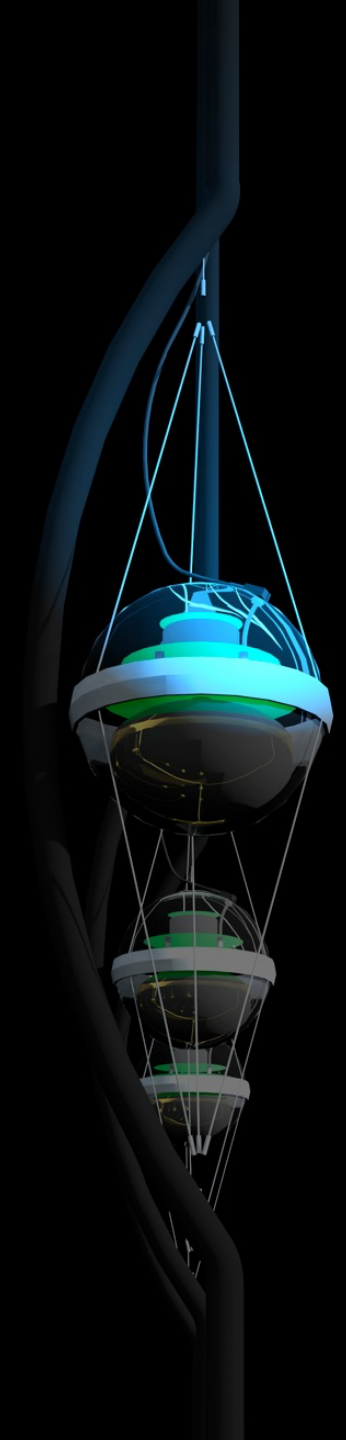
South Pole Neutrino Observatory



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- also, a beam for PeV neutrino physics

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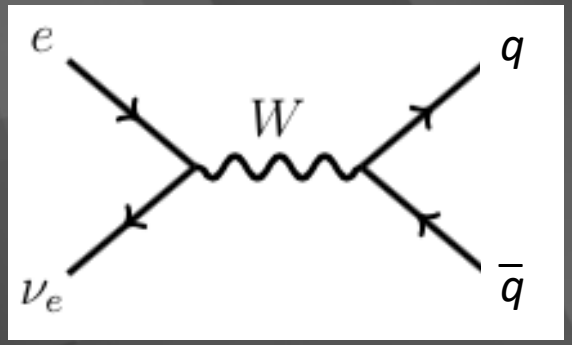
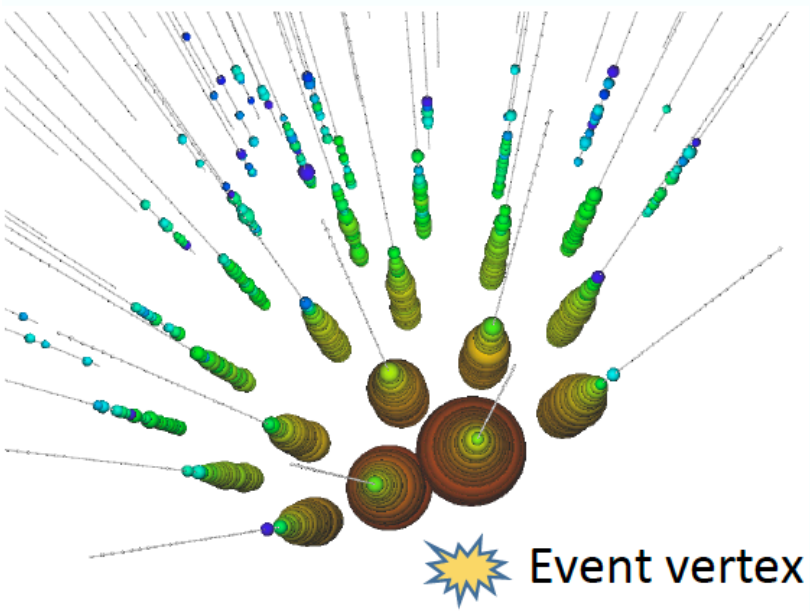
the first Glashow resonance event:

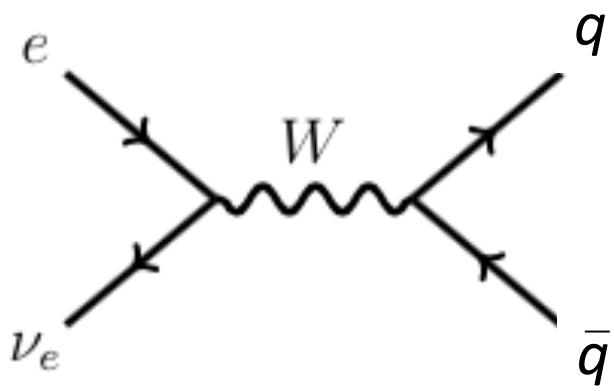
anti-ν_e + atomic electron → real W at 6.3 PeV

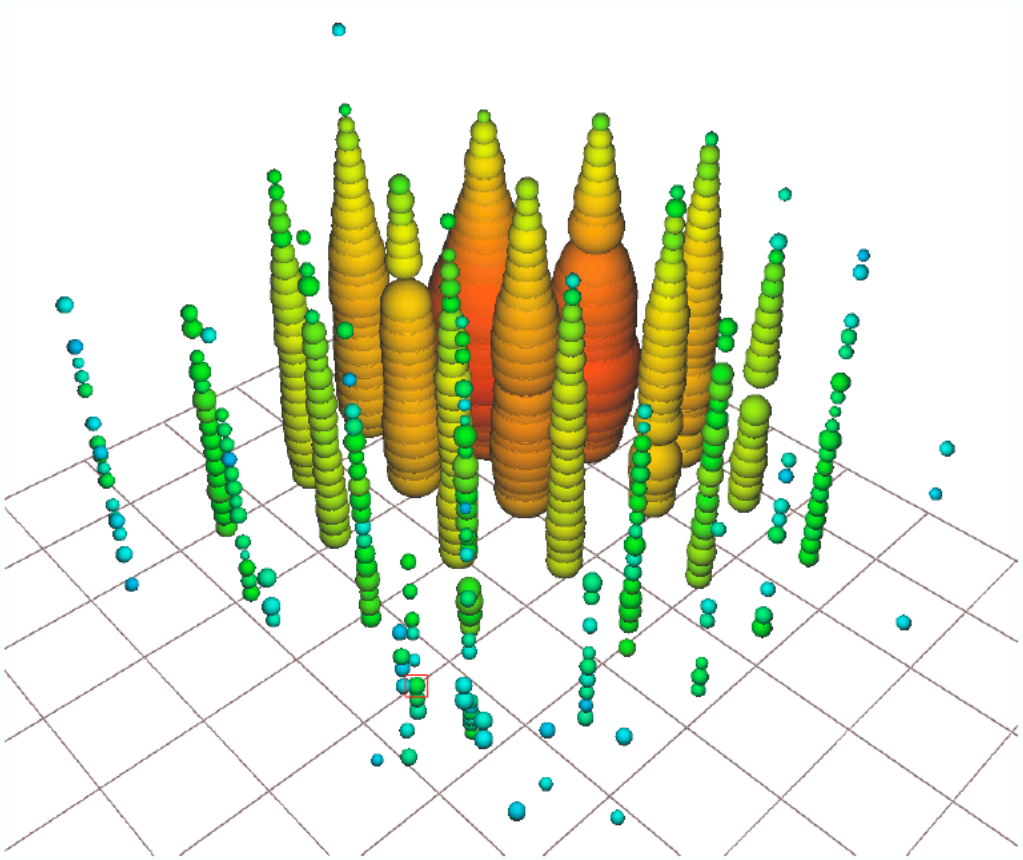


partially contained event with energy 6.3 PeV

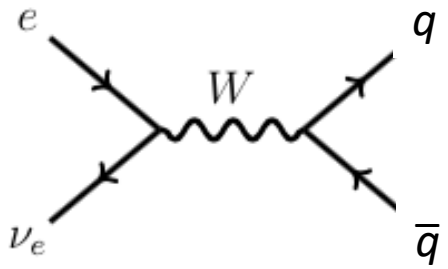


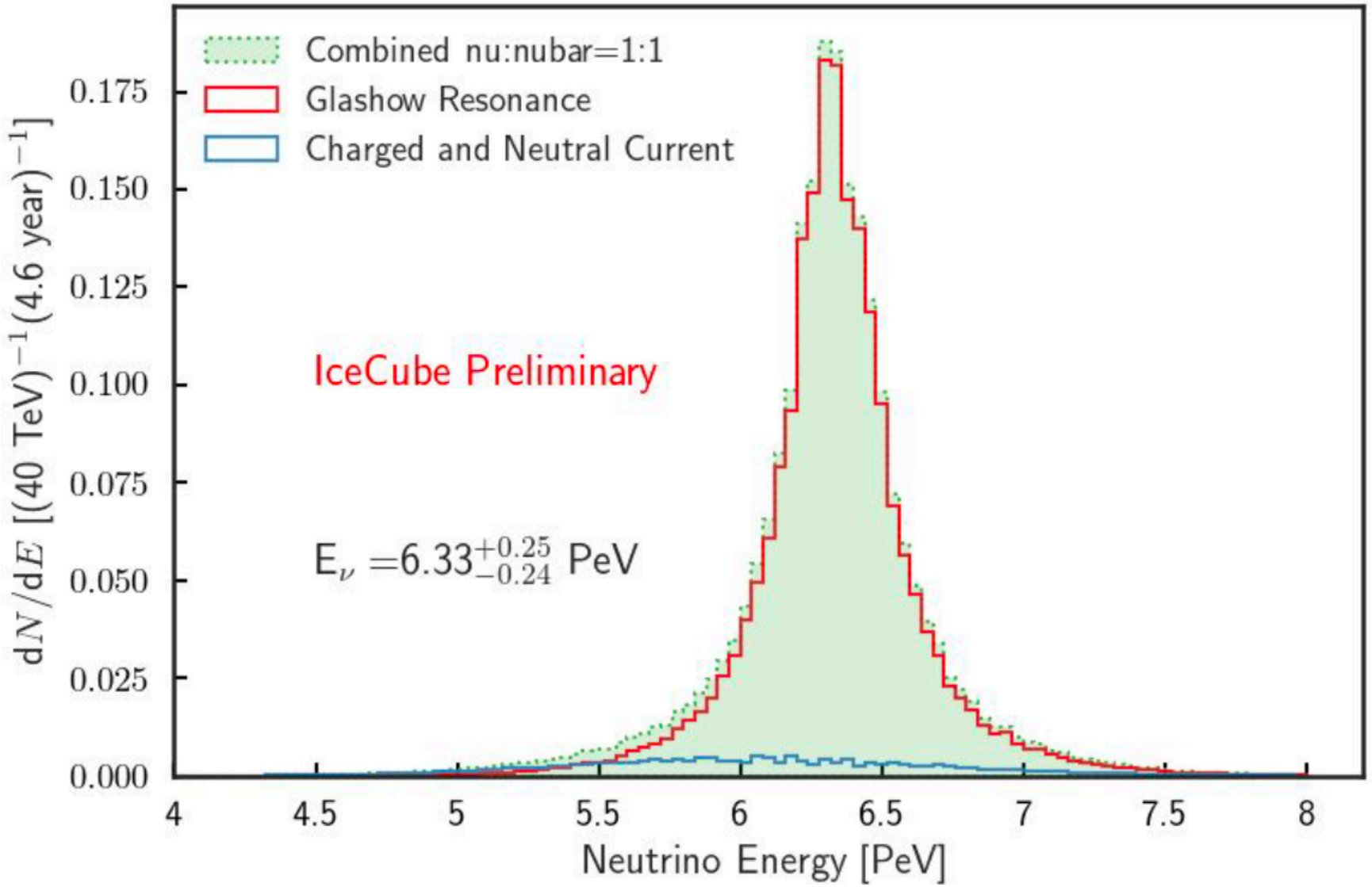
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron





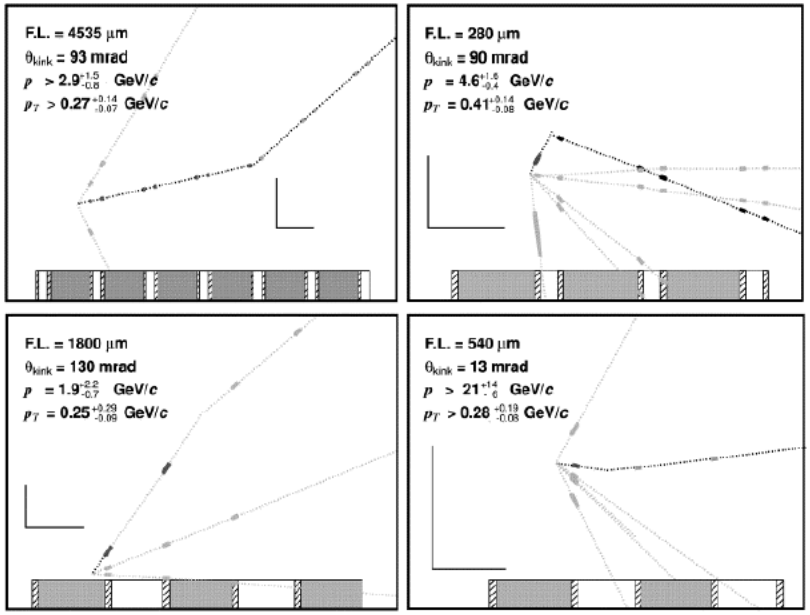
- energy measurement understood
- identification of anti-electron neutrinos





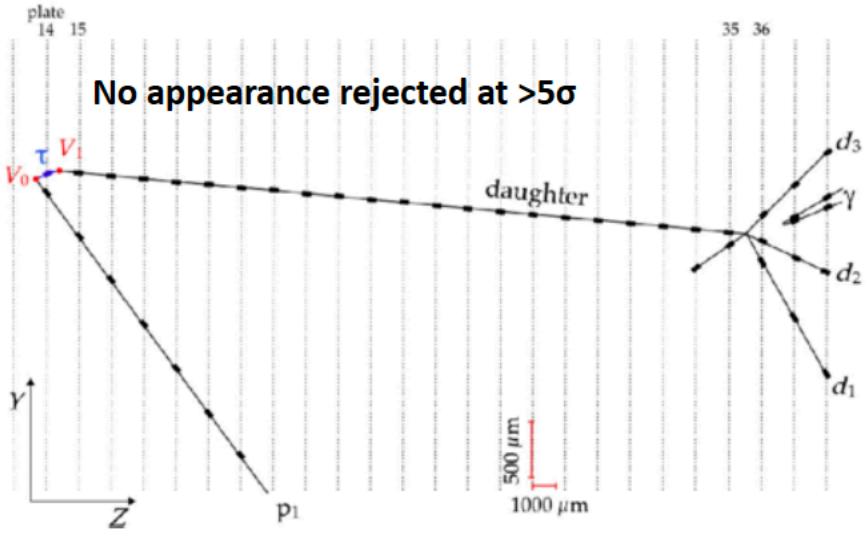
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



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

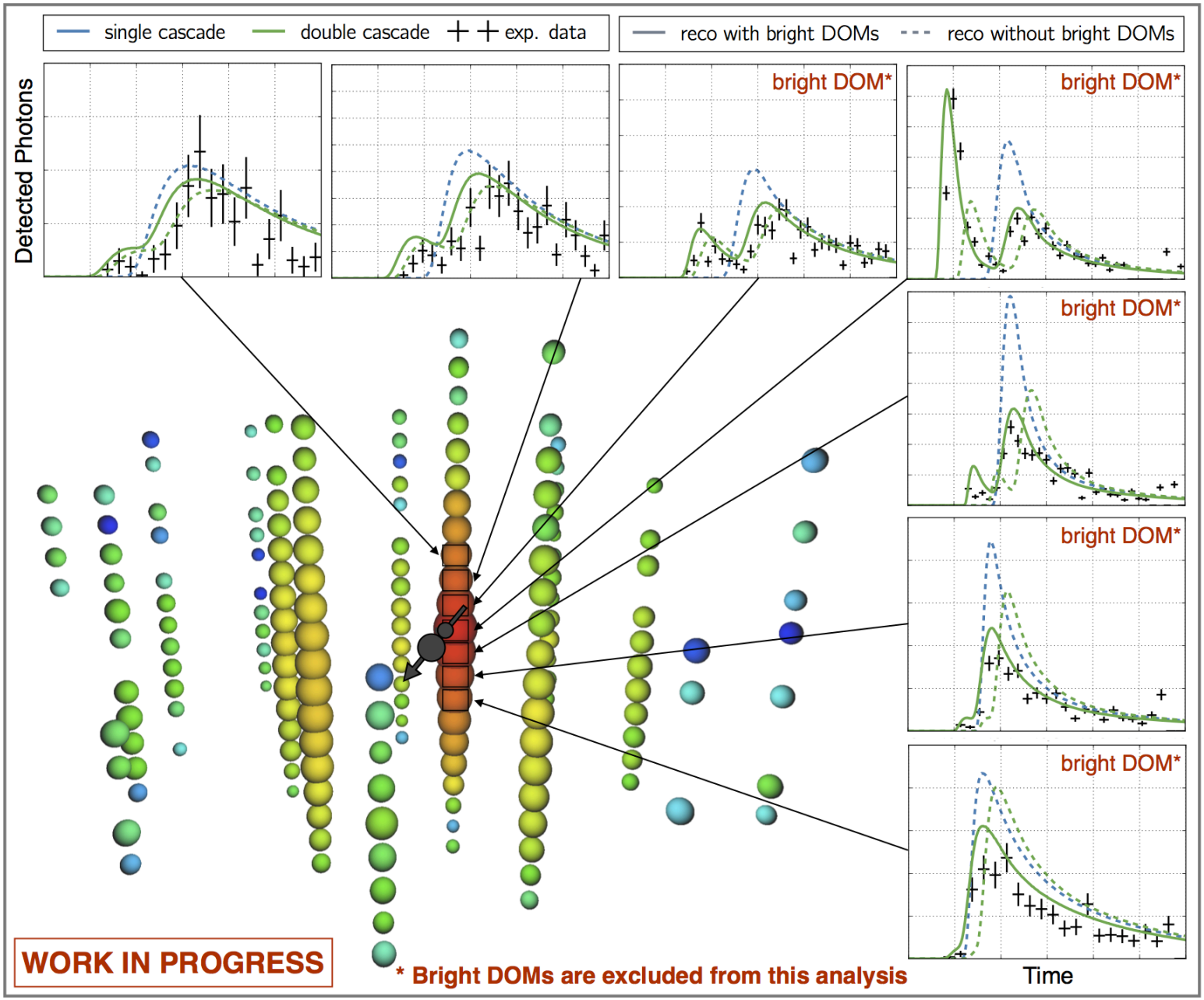
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



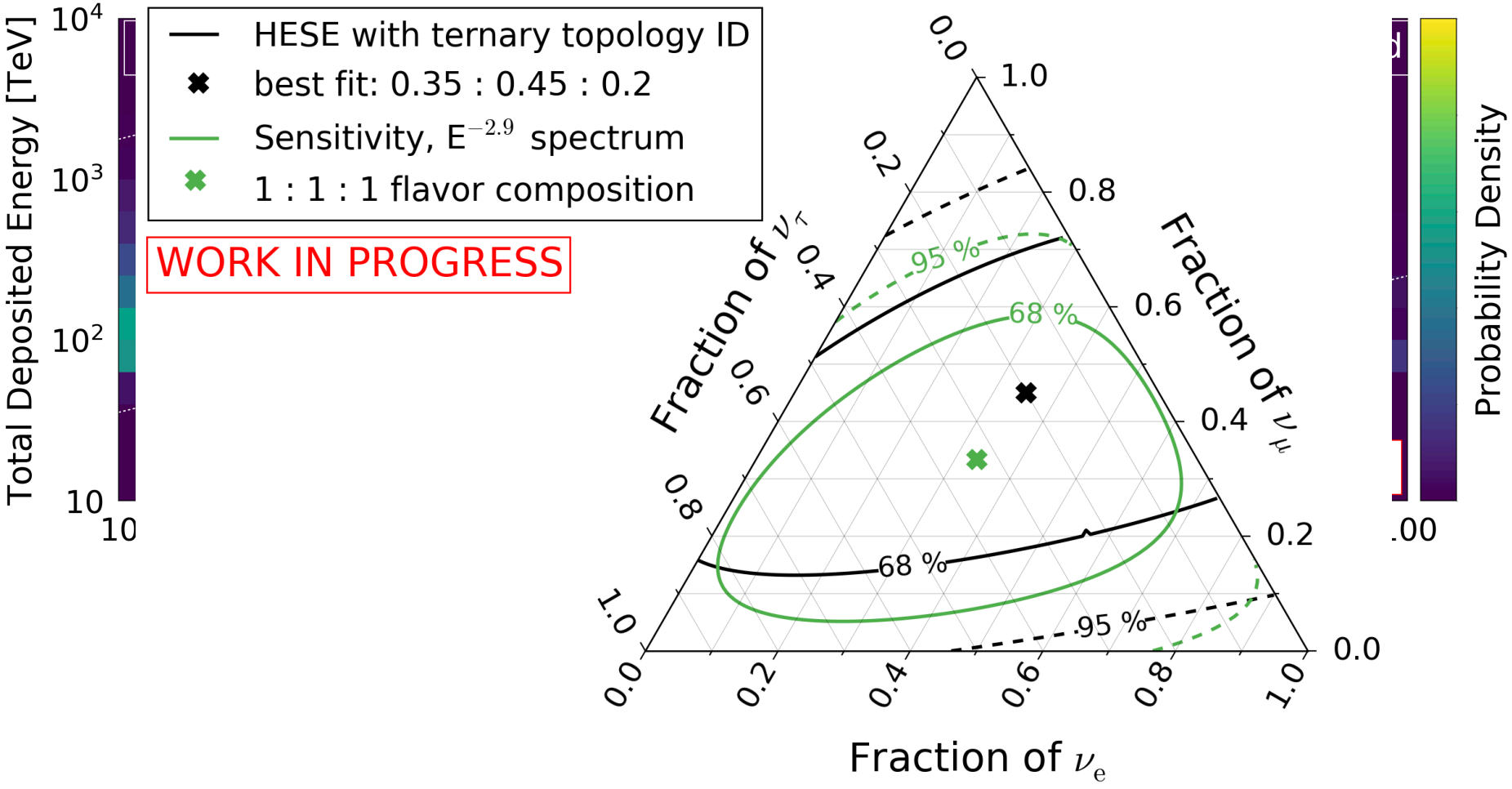
OPERA Phys. Rev. Lett. 115, 121802 (2015)

tau decay length = γ c τ = 50m per PeV

a cosmic tau neutrino: livetime 17m



high-energy starting events – 7.5 yr

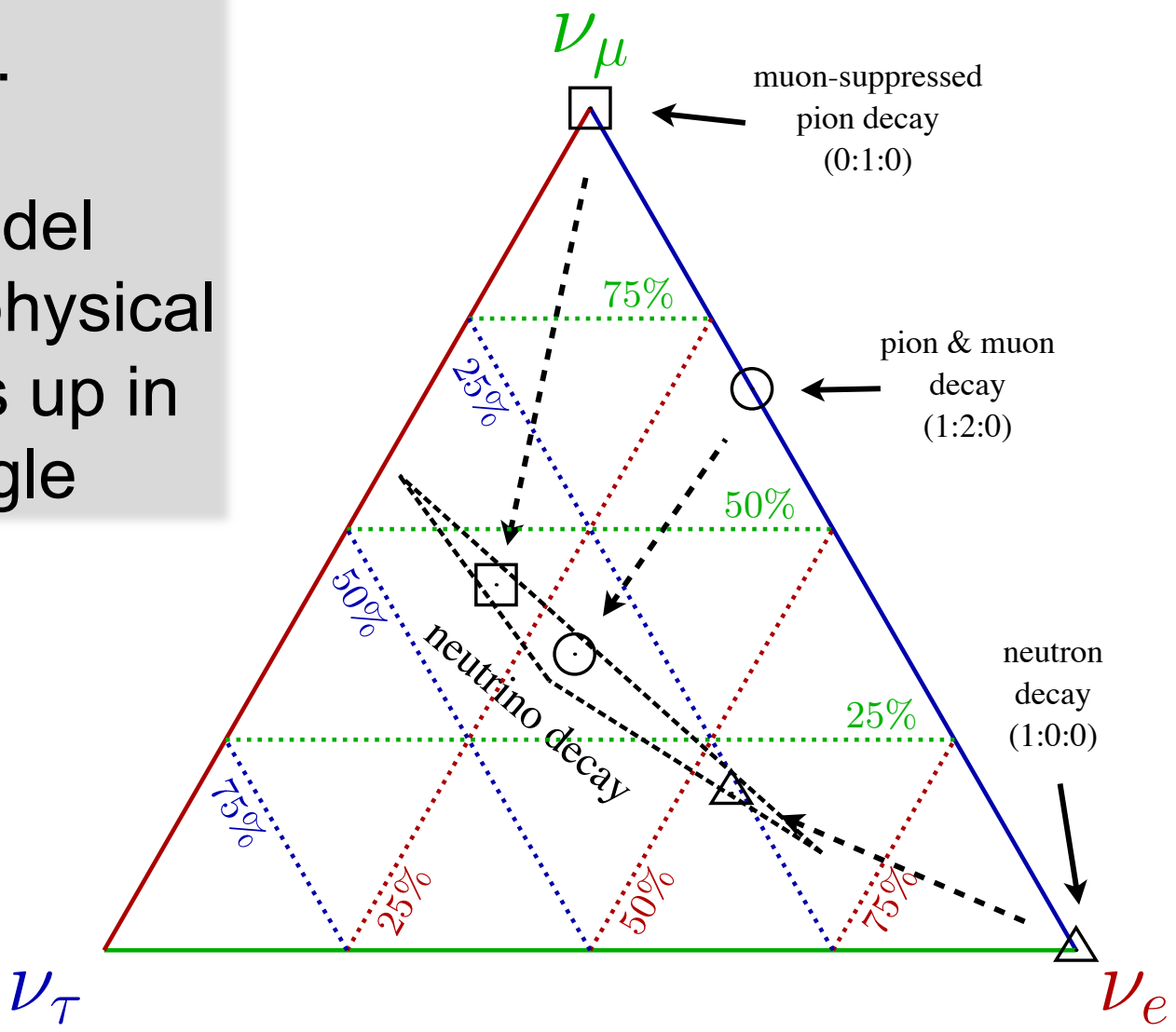


oscillations of PeV neutrinos over cosmic distances to 1:1:1

new physics ?

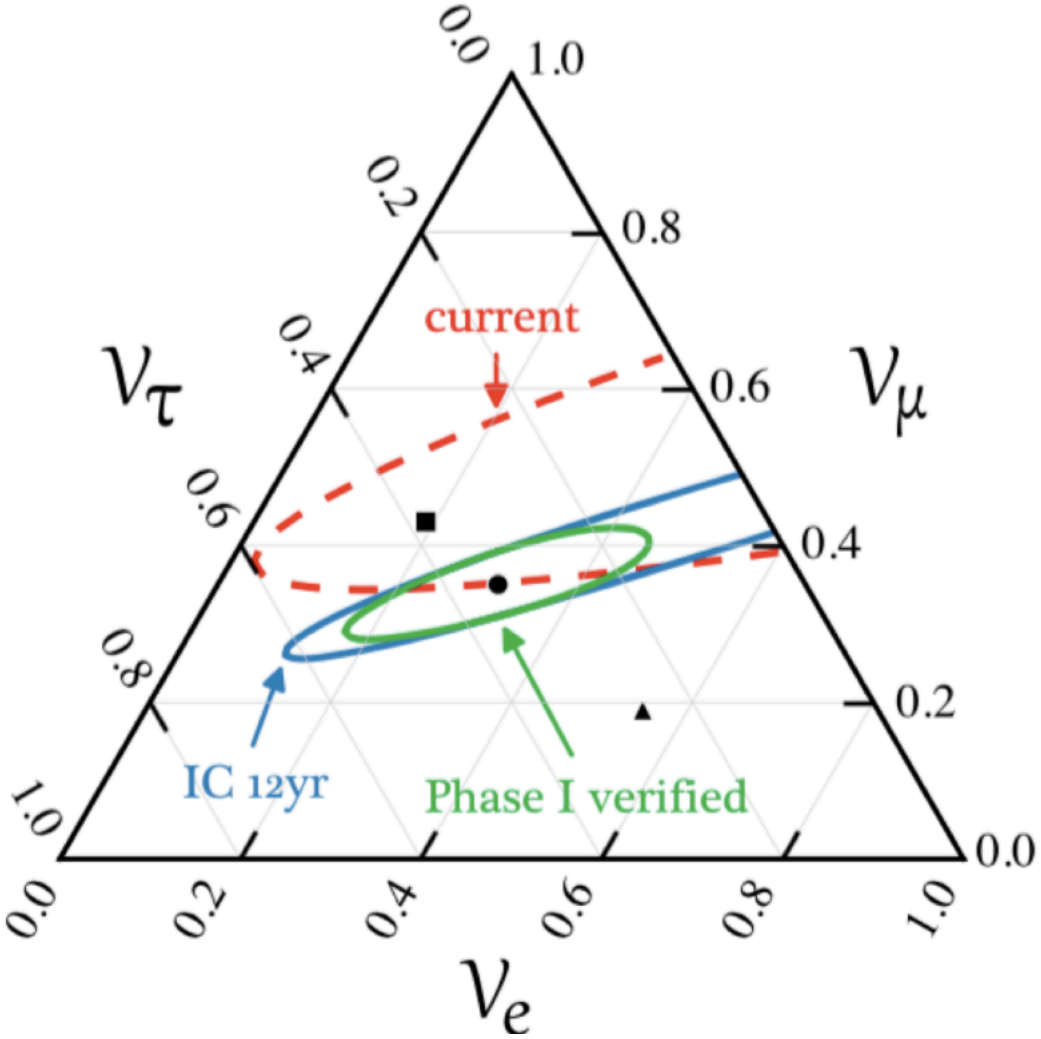
if not…

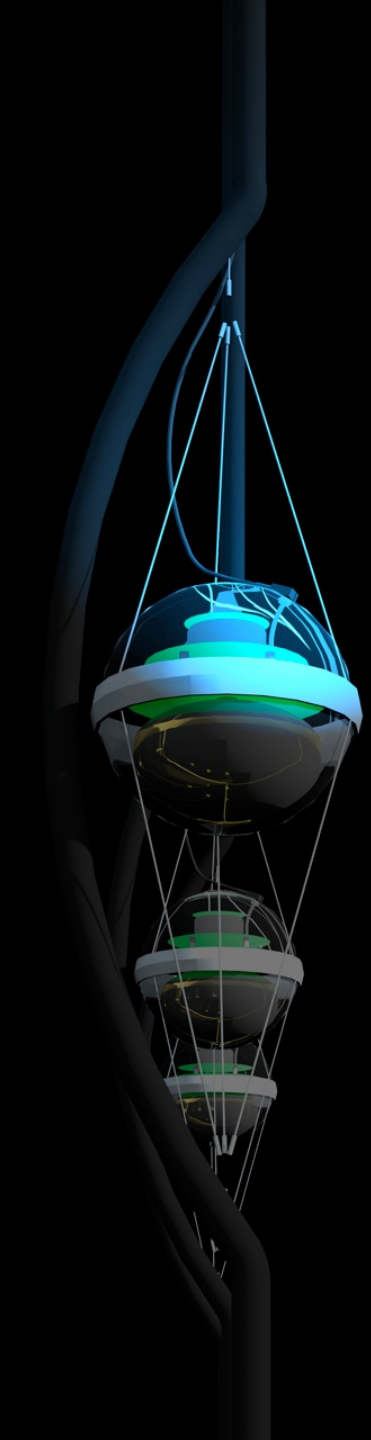
every model
for the astrophysical
source ends up in
the triangle



upgrade/Gen2

- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM





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...NGDOM 1

UNITED STATES 25

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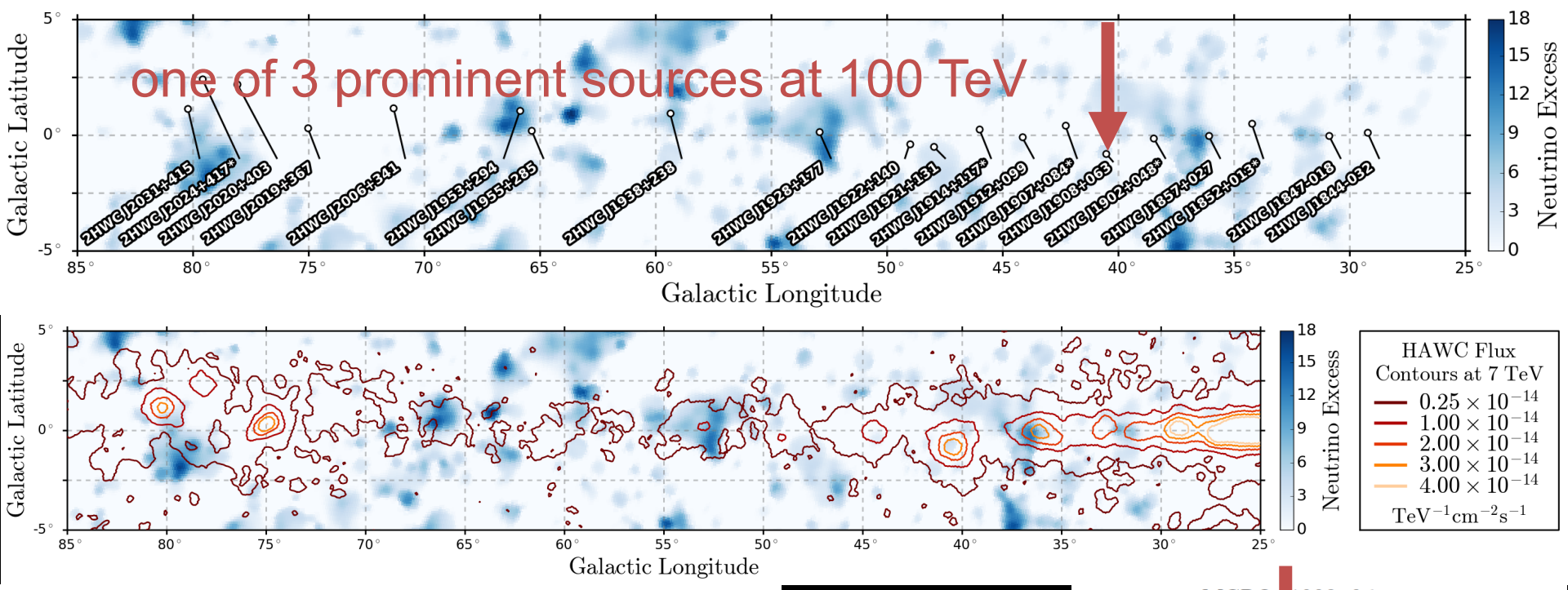
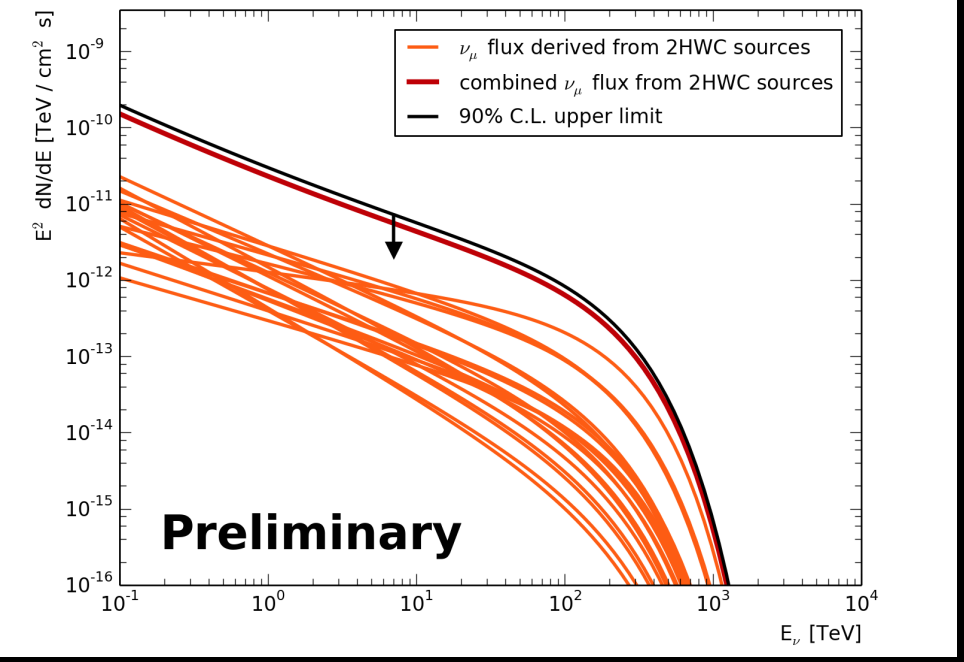
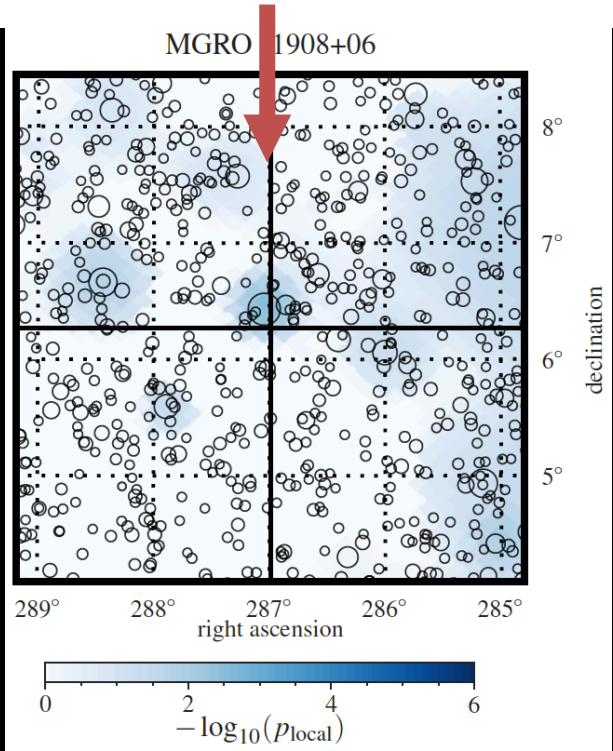
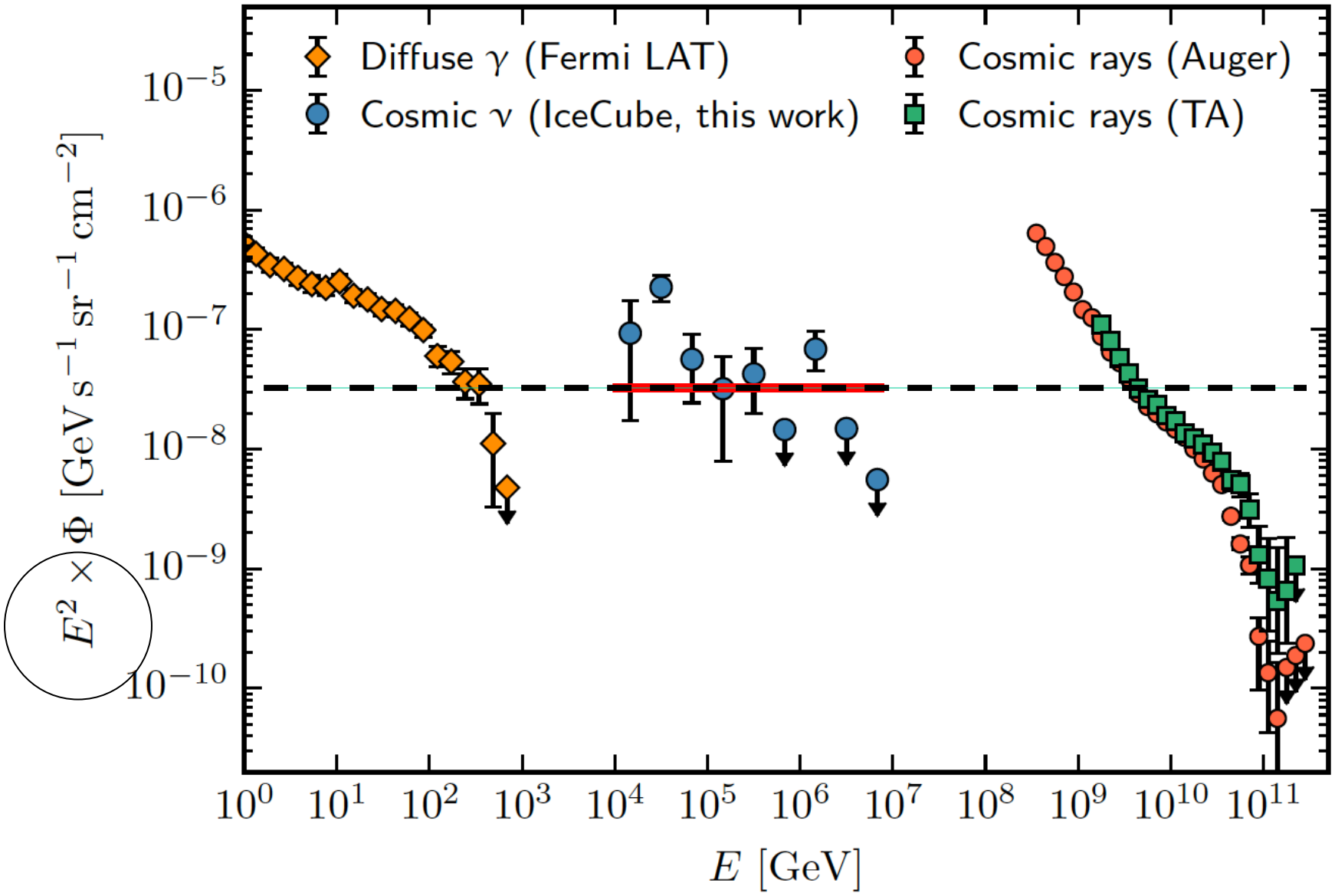

one of 3 prominent sources at 100 TeV
Galactic Latitude
Galactic Longitude
Neutrino Excess
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*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

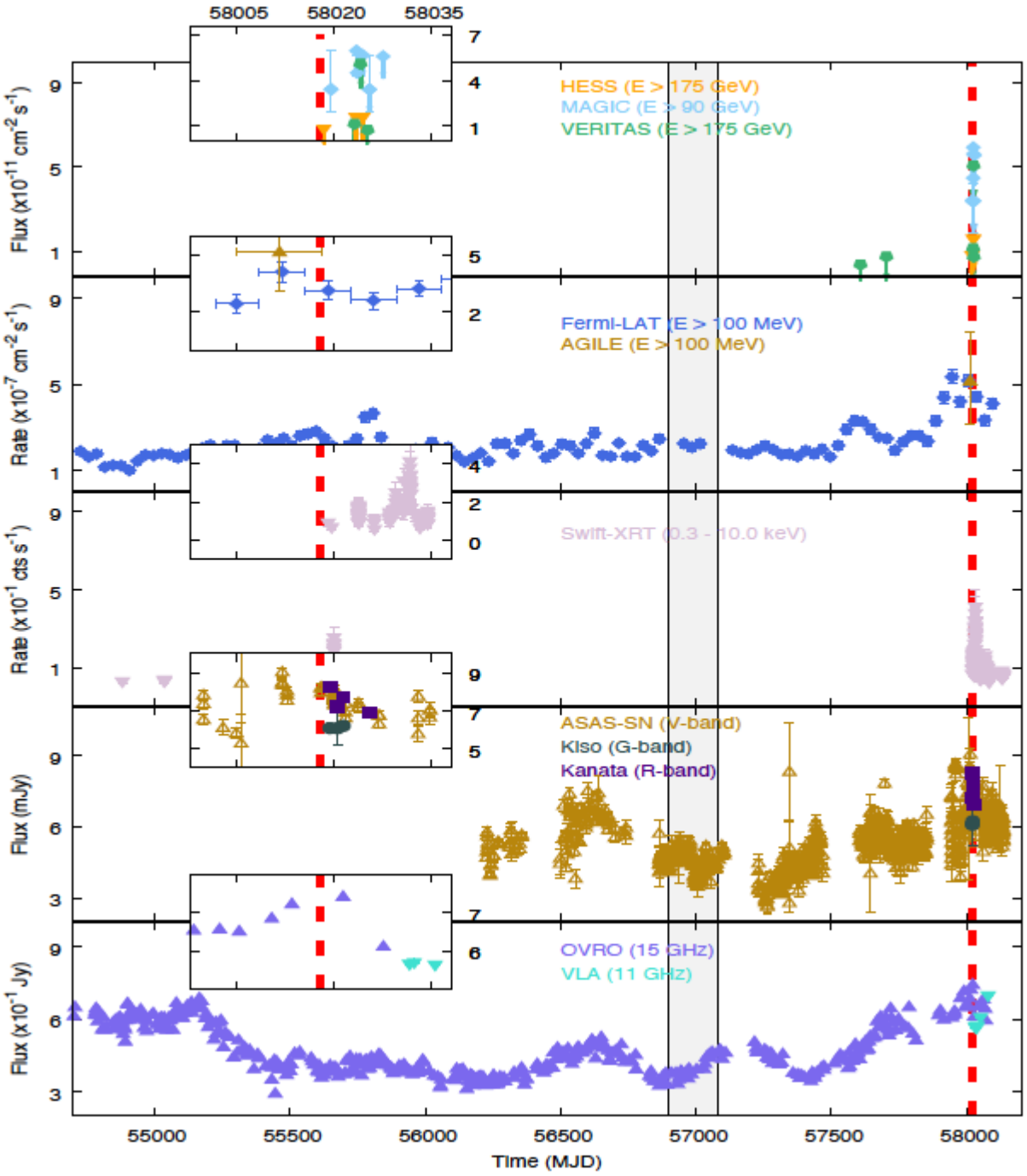
Galactic Latitude
Galactic Longitude
Neutrino Excess
HAWC Flux
Contours at 7 TeV
0.25×10^{-14}
1.00×10^{-14}
2.00×10^{-14}
3.00×10^{-14}
4.00×10^{-14}
$\mathrm{TeV^{-1} cm^{-2} s^{-1}}$

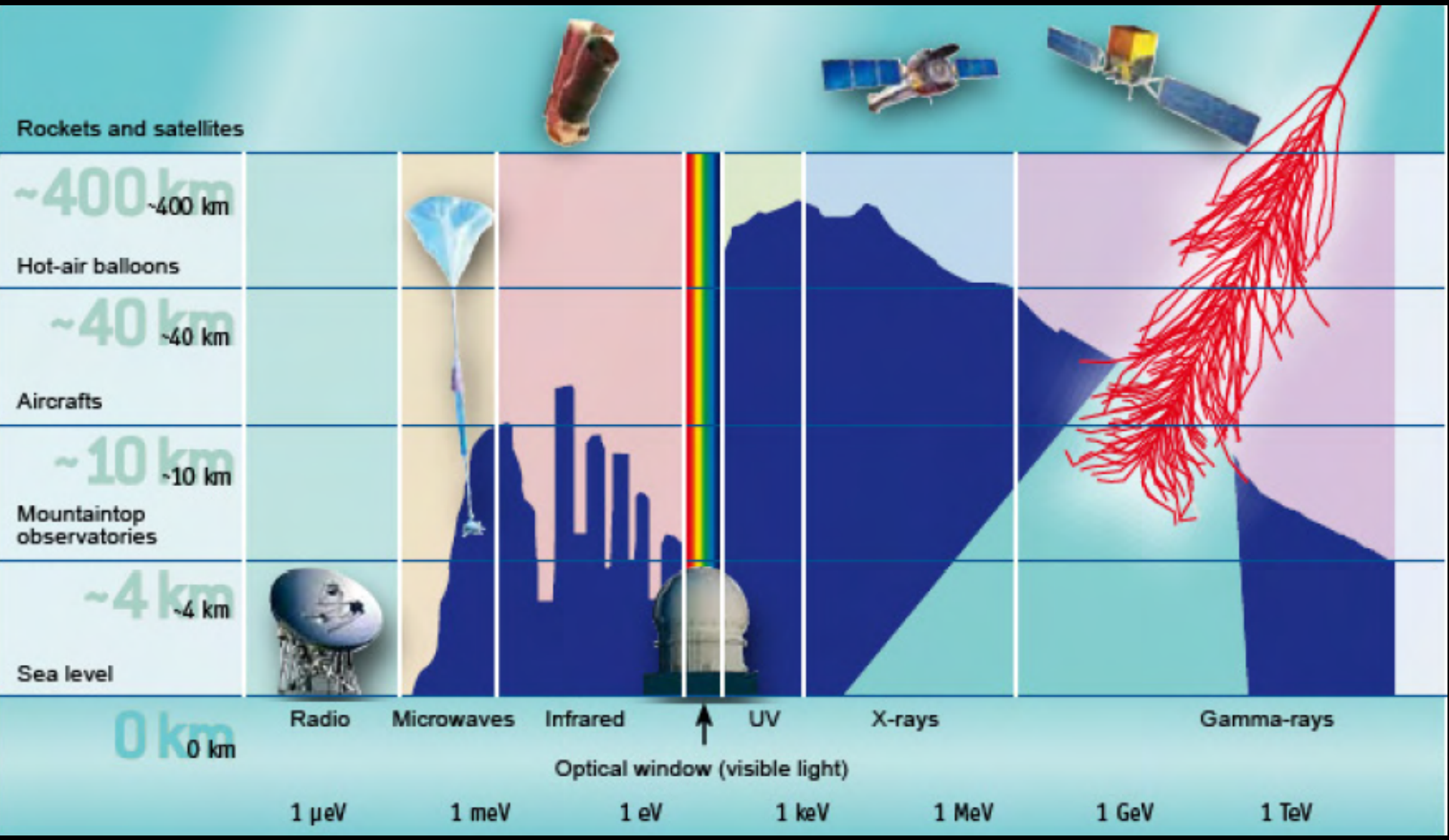

ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]
Preliminary


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



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


58005
58020
58035
HESS (E > 175 GeV)
MAGIC (E > 90 GeV)
VERITAS (E > 175 GeV)
Flux (x10^-11 cm^-2 s^-1)
Fermi-LAT (E > 100 MeV)
AGILE (E > 100 MeV)
Rate (x10^-7 cm^-2 s^-1)
Swift-XRT (0.3 - 10.0 keV)
Rate (x10^-1 cts s^-1)
ASAS-SN (V-band)
Kiso (G-band)
Kanata (R-band)
Flux (mJy)
OVRO (15 GHz)
VLA (11 GHz)
Flux (x10^-1 Jy)
55000
55500
56000
56500
57000
57500
58000
Time (MJD)


Rockets and satellites
~400 km
Hot-air balloons
~40 km
Aircrafts
~10 km
Mountaintop observatories
~4 km
Sea level
0 km
Radio
Microwaves
Infrared
UV
X-rays
Gamma-rays
Optical window (visible light)
1 μeV
1 meV
1 eV
1 keV
1 MeV
1 GeV
1 TeV