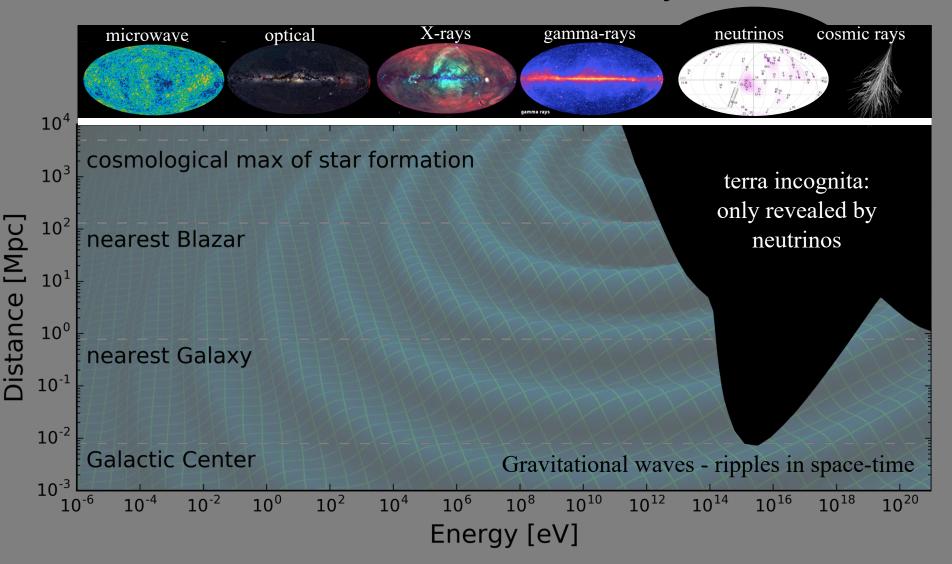


Neutrinos in the Era of Multimessenger Astronomy francis halzen

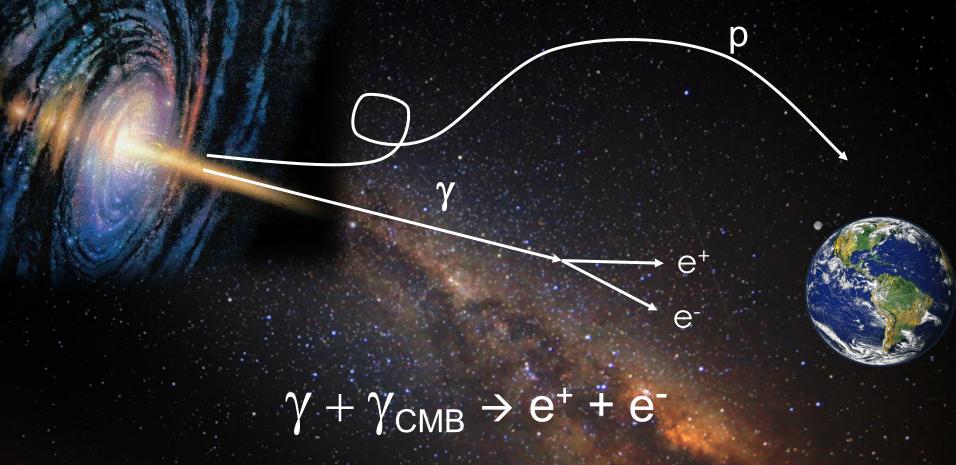
- cosmic neutrinos: many independent observations
 - → muon neutrinos through the Earth
 - → starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments
- also, a beam for PeV (1,000 TeV) neutrino physics

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



Universe is opaque above ~100 TeV energy

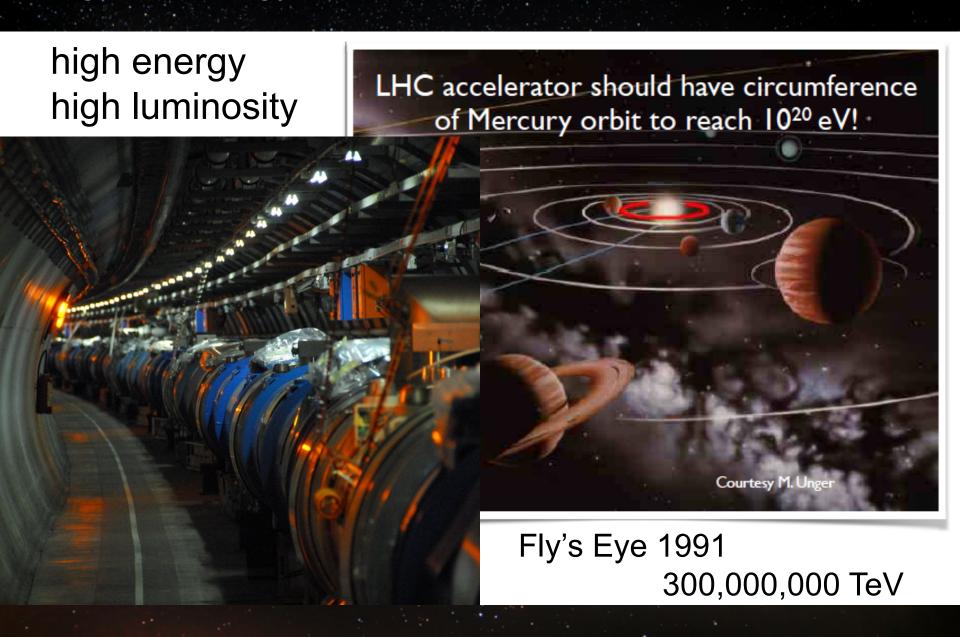


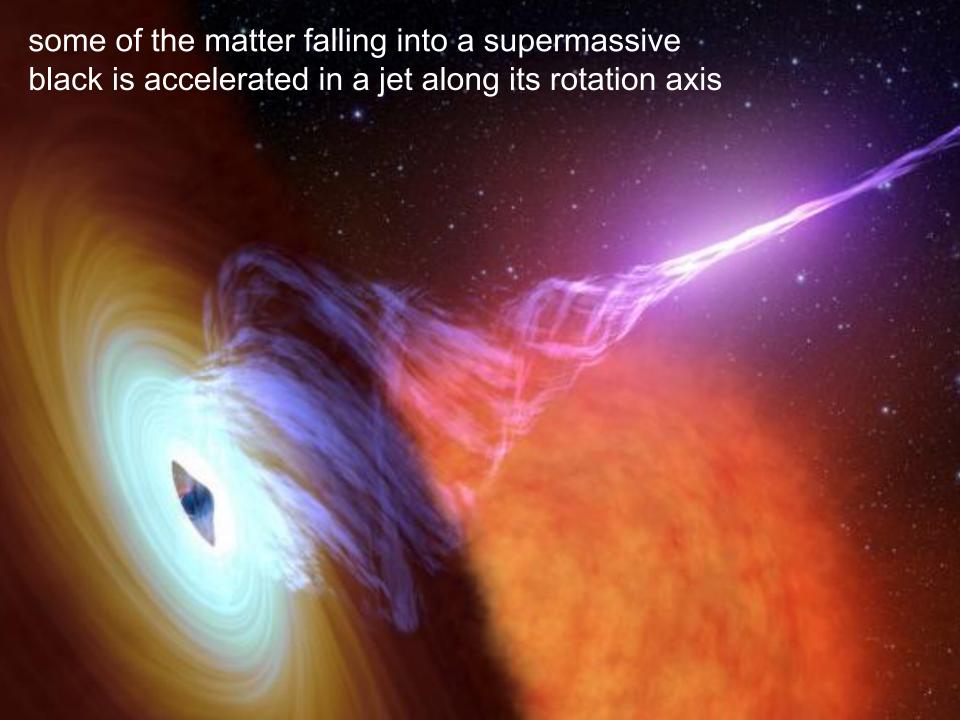


PeV photons interact with microwave photons (411/cm³) before reaching our telescopes enter: neutrinos

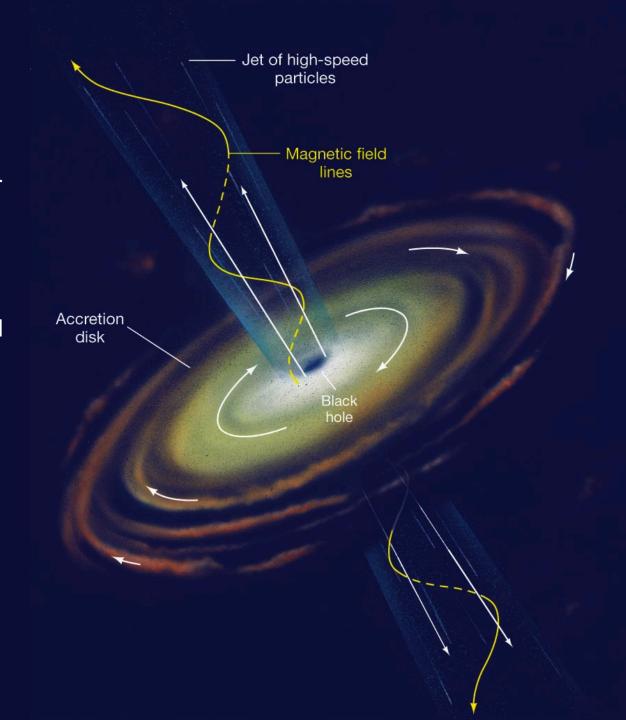
Neutrinos? Perfect Messenger electrically neutral essentially massless essentially unabsorbed tracks nuclear processes reveal the sources of cosmic rays but difficult to detect

highest energy radiation from the Universe: protons!





- 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



Z Je SHOCK WAVE T 2-wmm

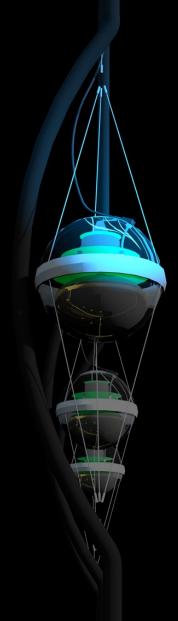
 ν and γ beams : heaven and earth proton accelerator target directional beam magnetic fields

accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

$$p + \gamma \rightarrow n + \pi^{+}$$
 $\sim cosmic ray + neutrino$
 $\rightarrow p + \pi^{0}$
 $\sim cosmic ray + gamma$

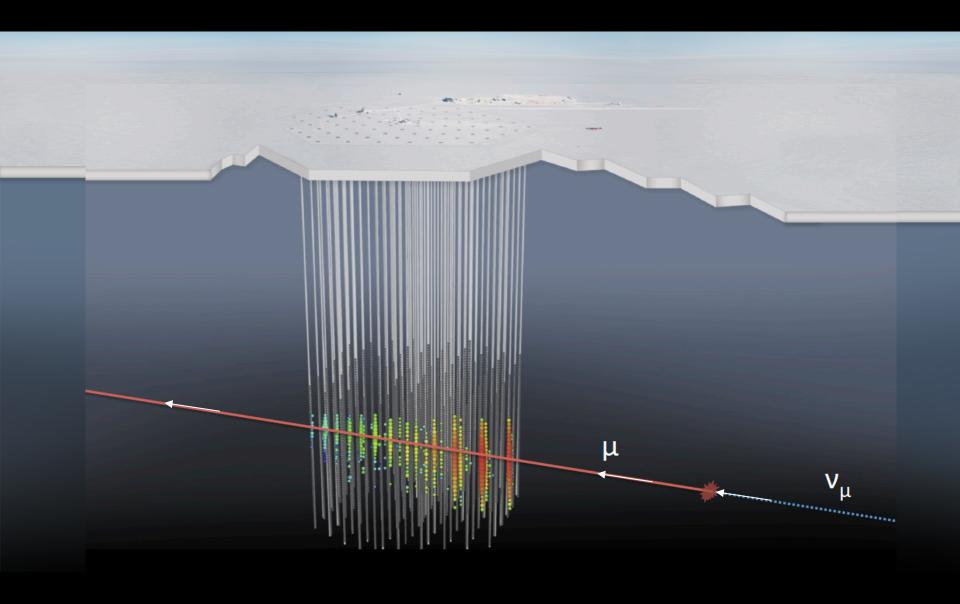


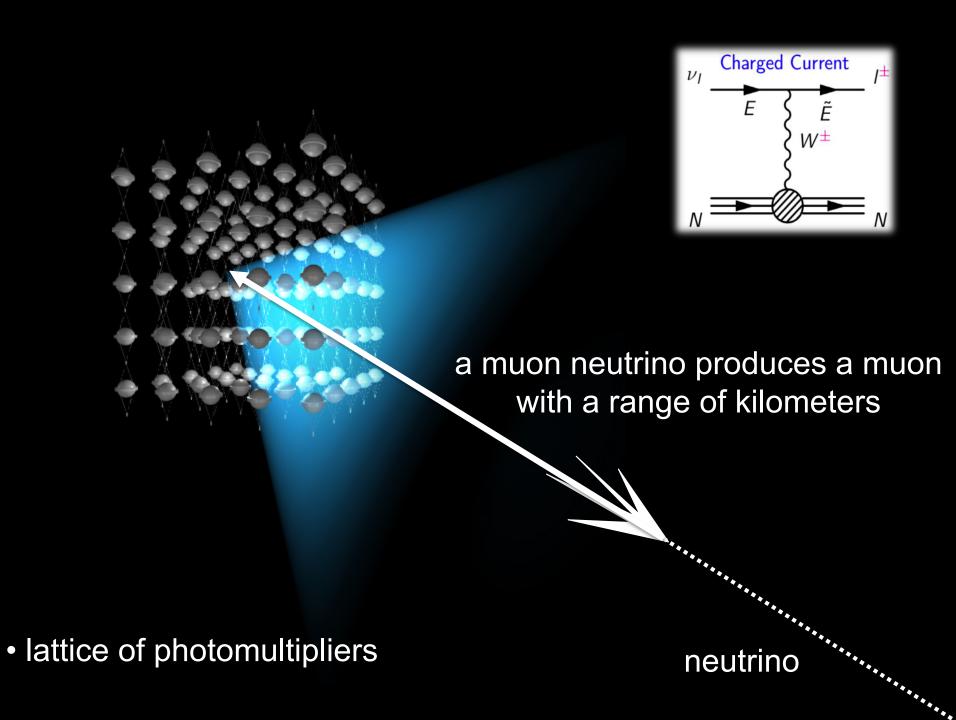
Neutrinos in the Era of Multimessenger Astronomy francis halzen

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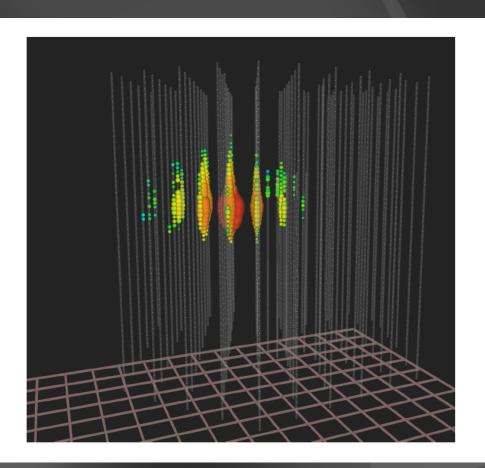
instrument 1 cubic kilometer of natural ice below 1.45 km

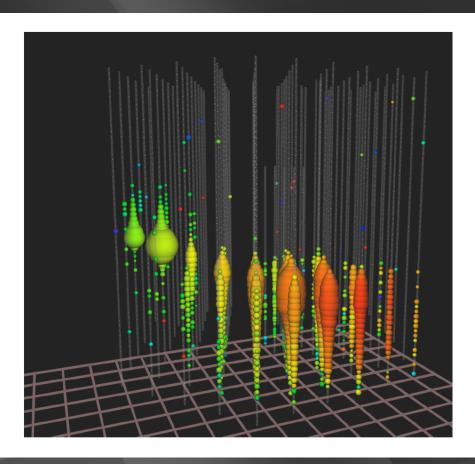




neutrinos interacting inside the detector

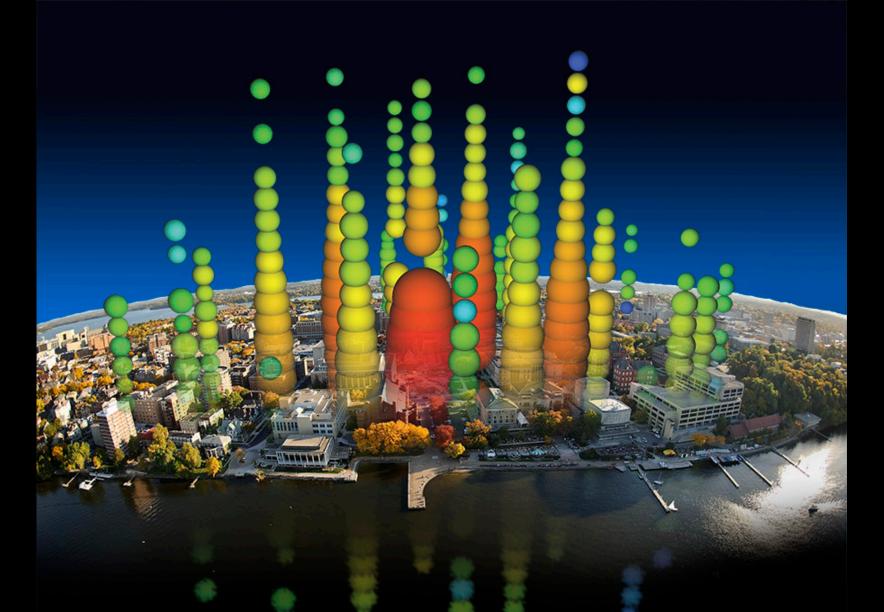
muon neutrinos filtered by the Earth





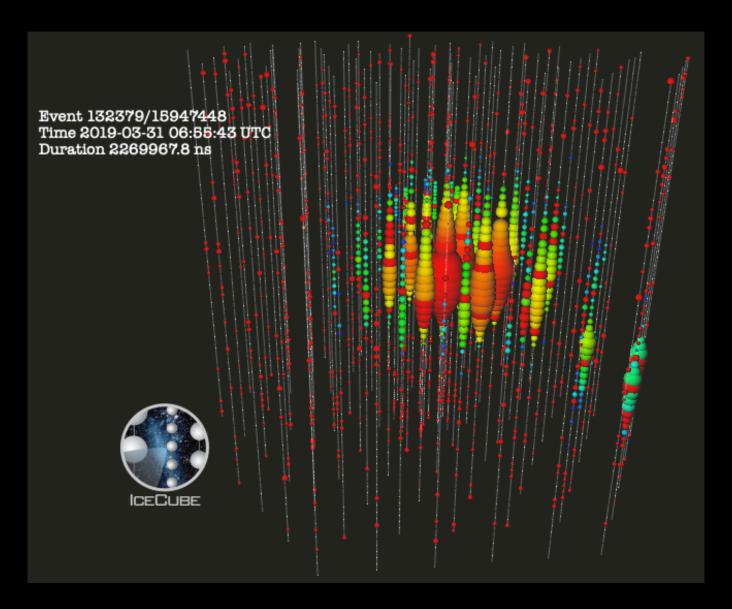
total energy measurement all flavors, all sky

astronomy: angular resolution superior (0.2~0.4°)

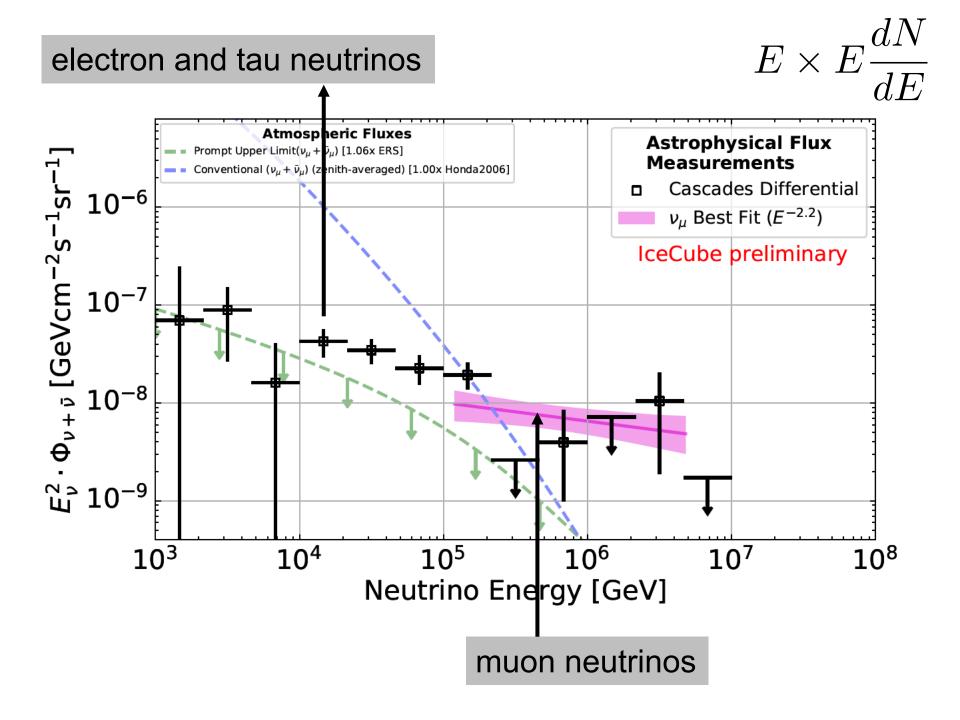


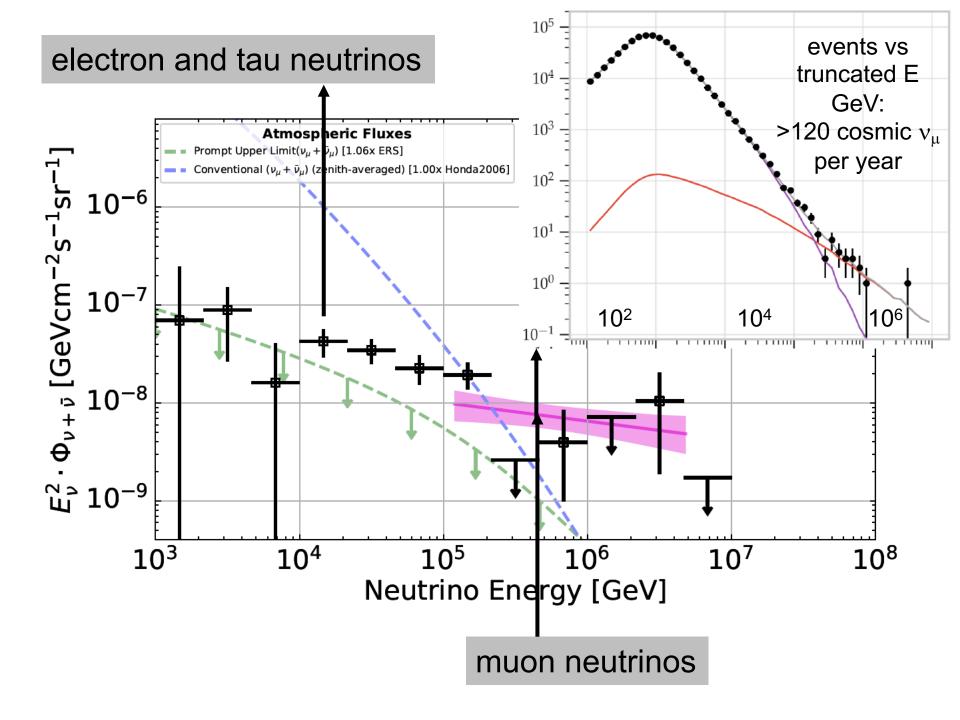
Cherenkov radiation from PeV electron (tau) shower > 300 sensors > 100,000 pe reconstructed to 2 nsec

IC190331: 5300 TeV deposited inside the detector

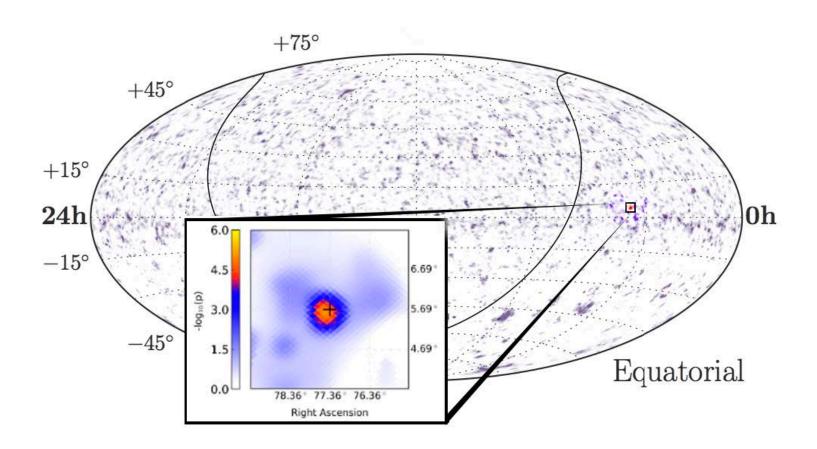


initial neutrino energy 10~20 PeV





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



no evidence for neutrinos associated with Galactic sources

 ν and γ beams : heaven and earth proton accelerator target directional beam magnetic fields

where are the gamma rays ?

supermassive black hole

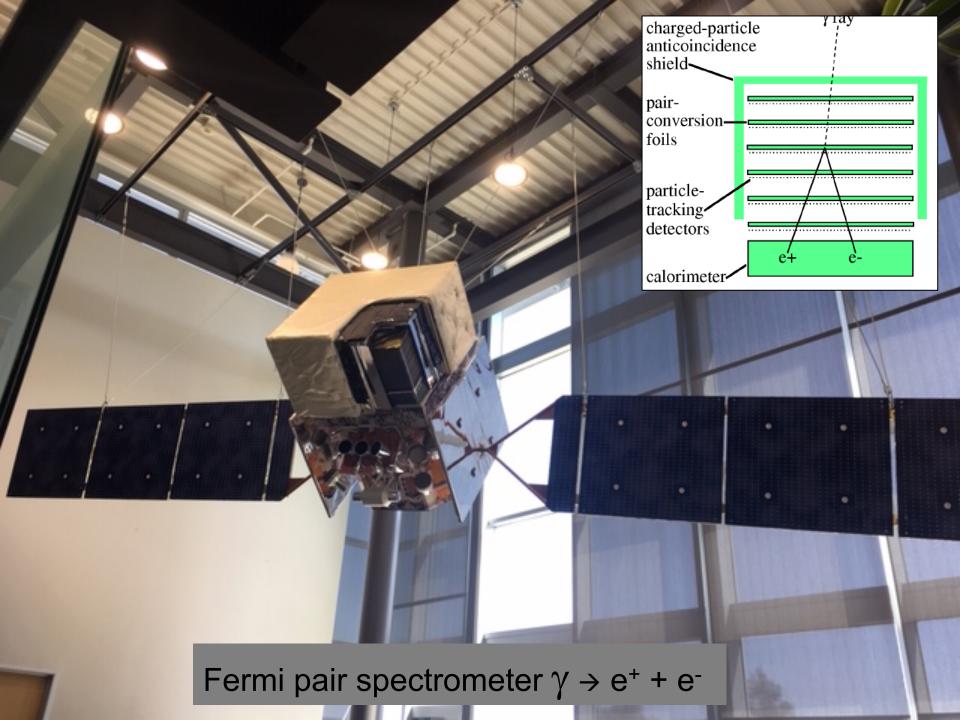
nearby radiation

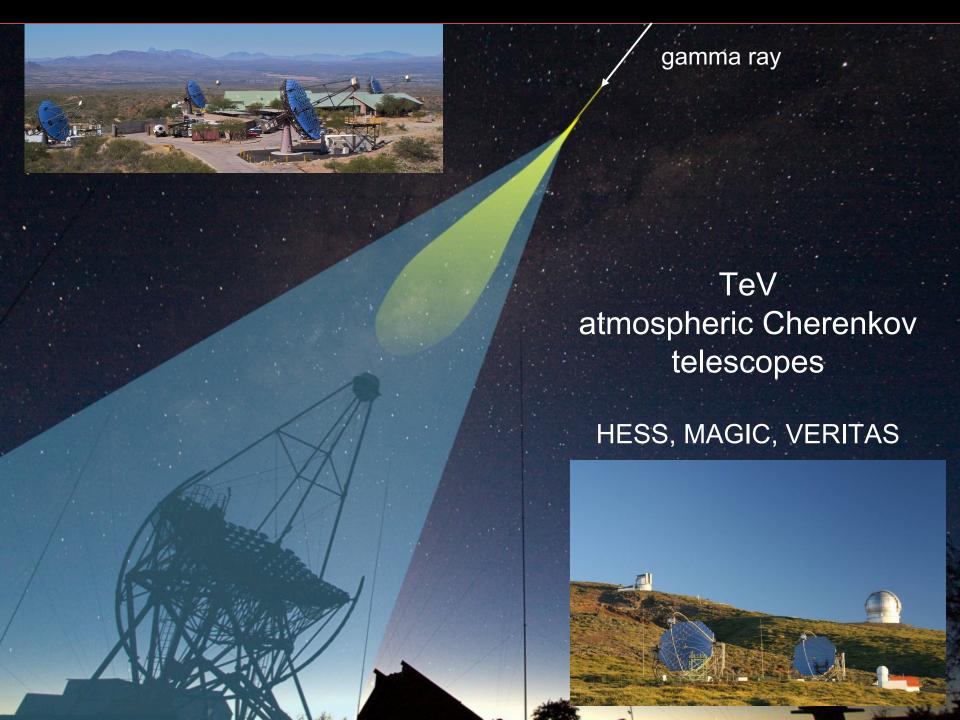
$$p + \gamma \rightarrow n + \pi^{+}$$

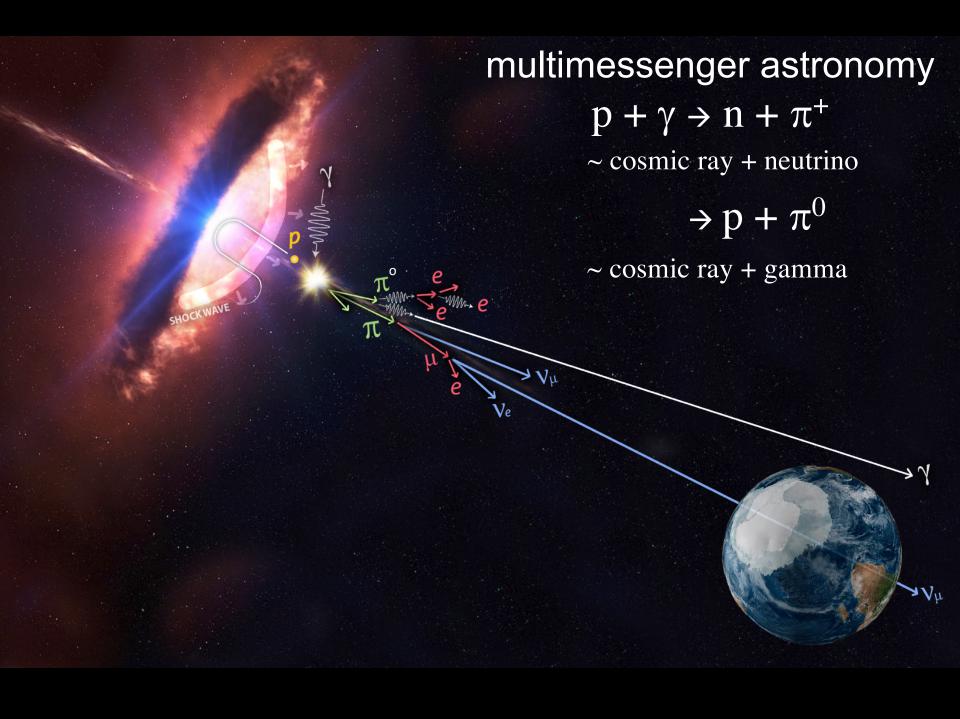
$$\sim cosmic ray + neutrino$$

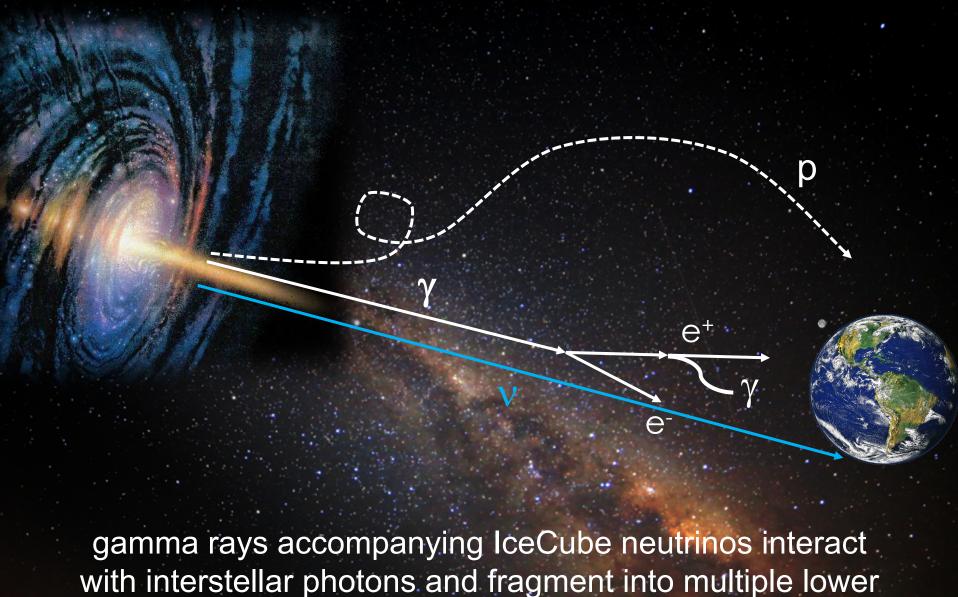
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

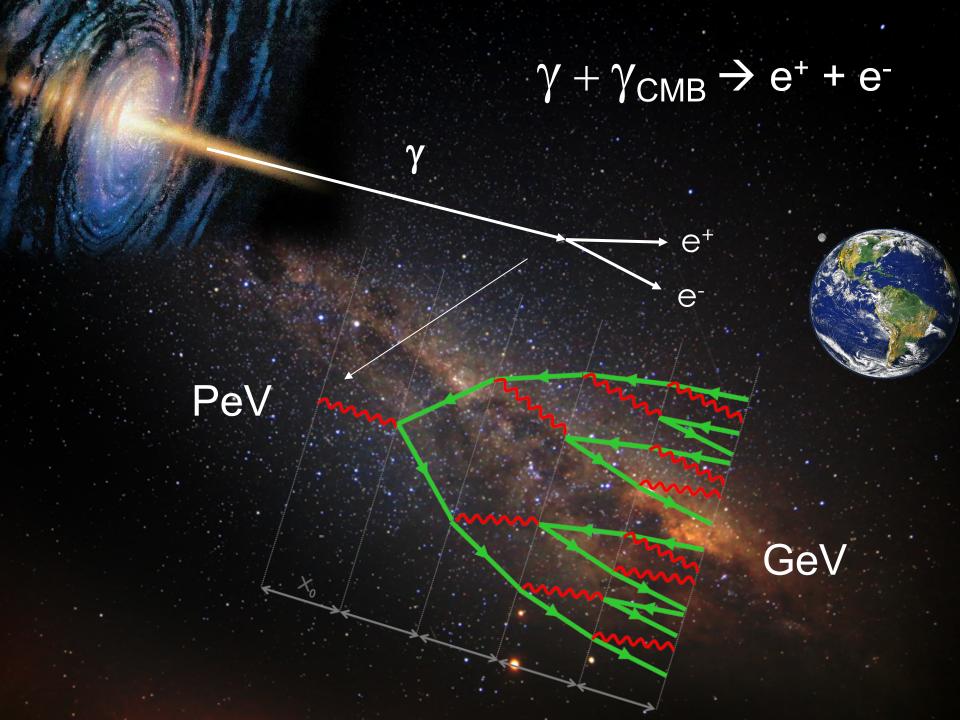




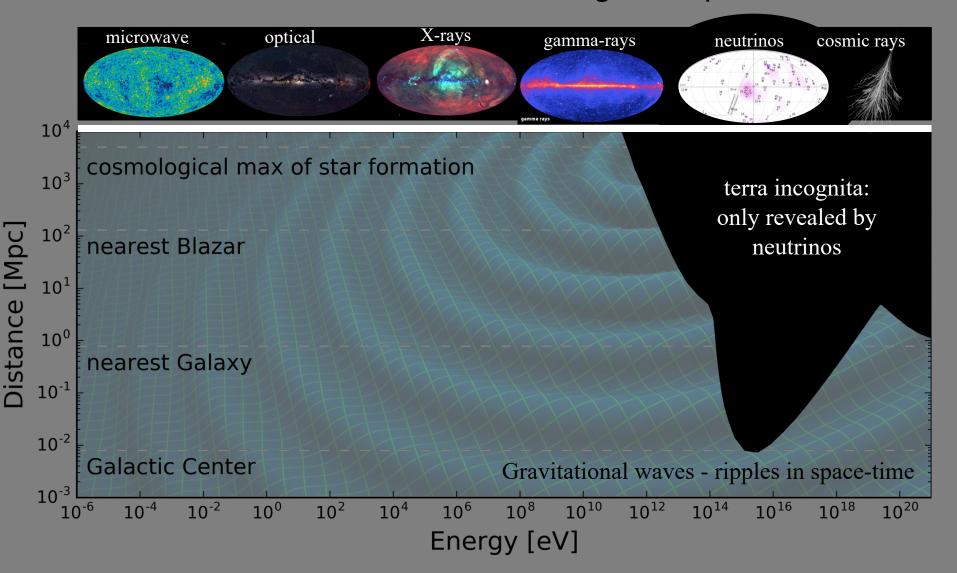




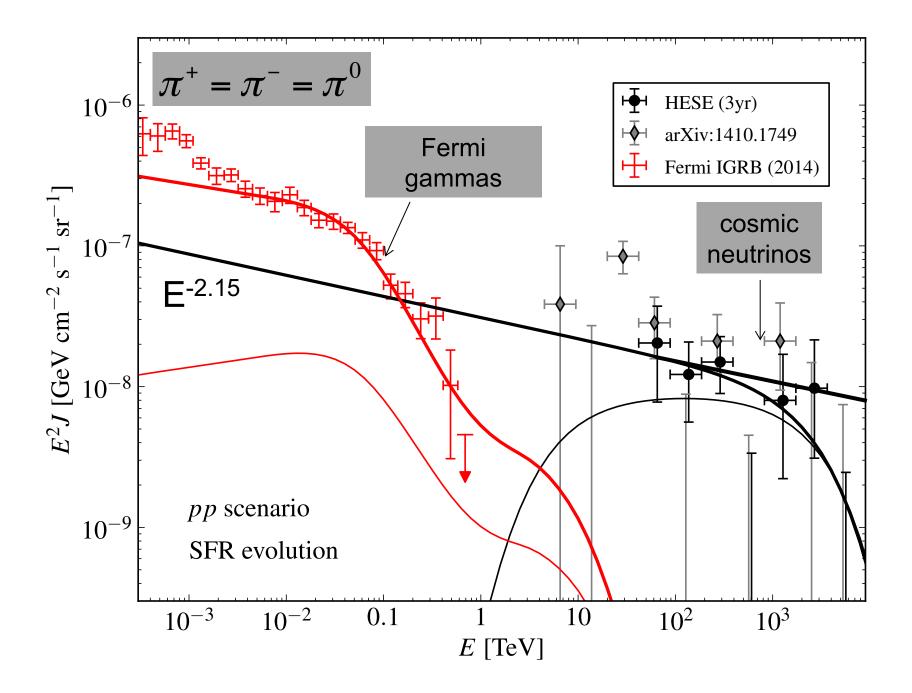
with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



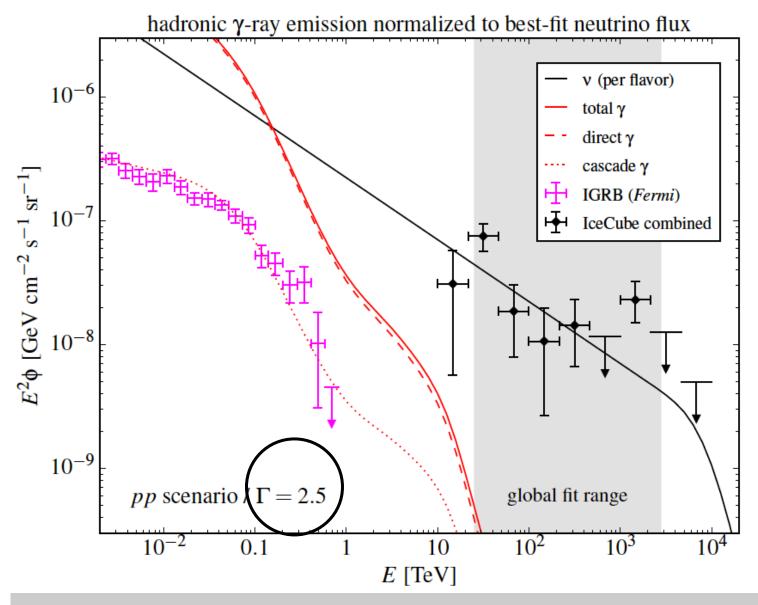
the energy of gamma rays accompanying PeV neutrinos is distributed over the electromagnetic spectrum



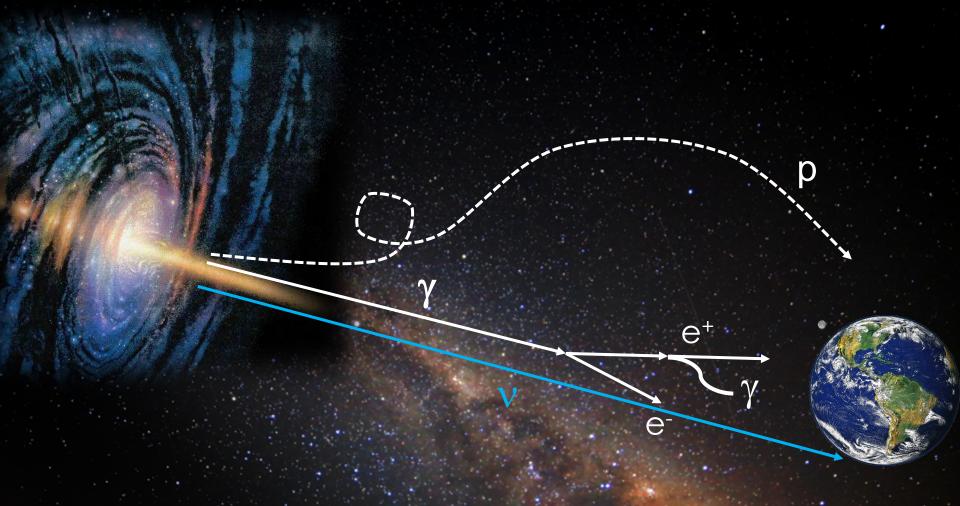
multimessenger astronomy



 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



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



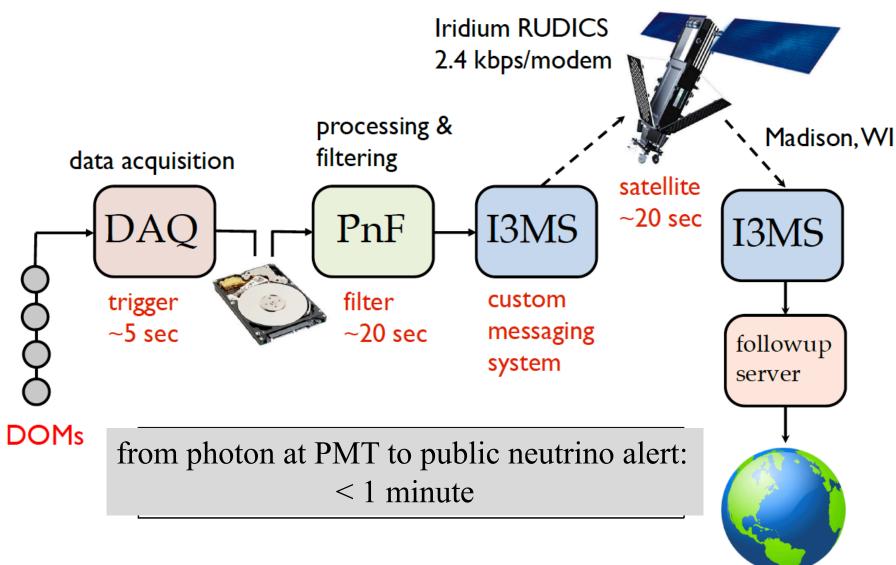
Neutrinos in the Era of Multimessenger Astronomy francis halzen

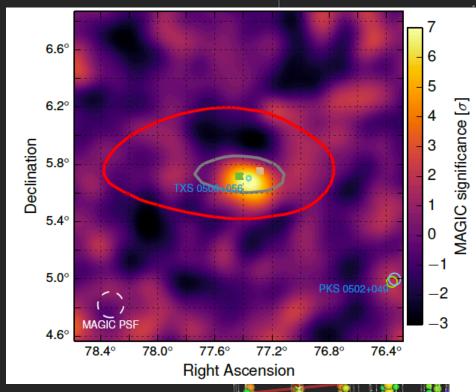
- cosmic neutrinos: many independent observations
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- also, a beam for PeV neutrino physics



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

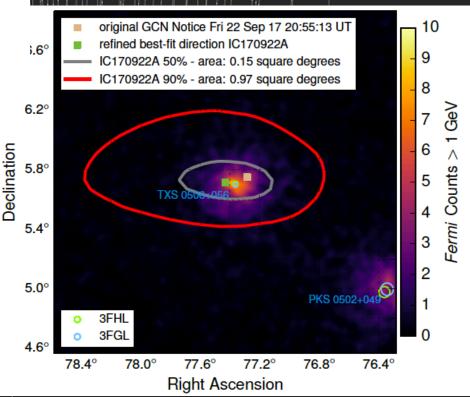
We send our high-energy events in real-time as public GCN alerts now!





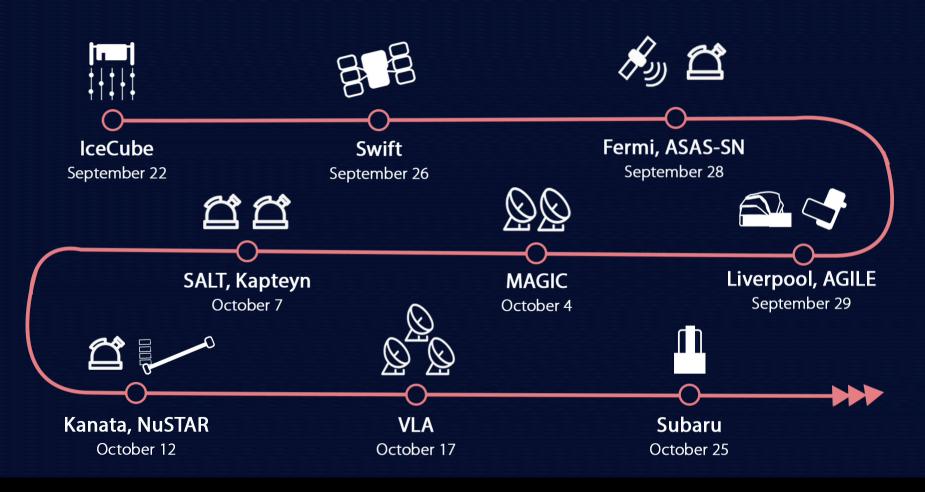
MAGIC
detects emission of > 100 GeV gammas

IceCube 170922 290 TeV Fermi detects a flaring blazar within 0.06°



MASTER robotic telescope: after 73 seconds

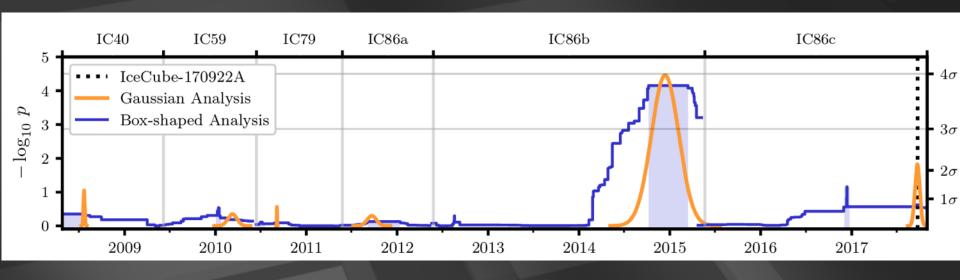
Follow-up detections of IC170922 based on public telegrams



multiwavelength campaign launched by IC 170922

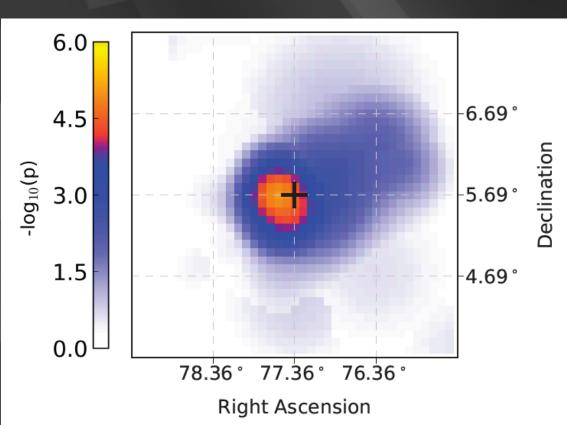
IceCube, *Fermi*—LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC energy 290 TeV direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.06° (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 lceCube data:

- 150-day flare in
 December 2014 of
 19 events (bkg < 6)
- spectrum E^{-2.2}
- $L_v > 10^{47} \text{ erg/s}$



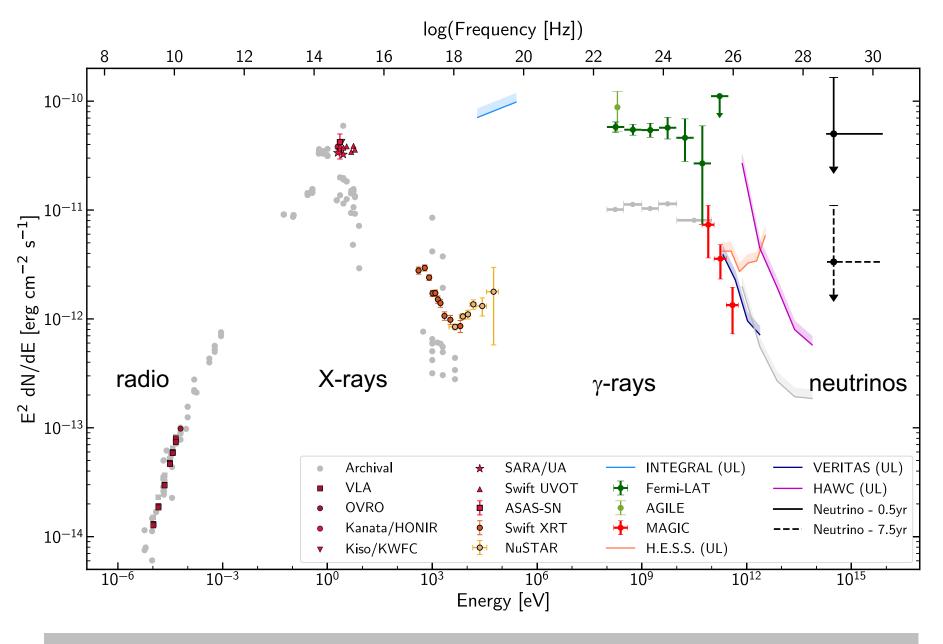
we identified a source of high energy cosmic rays:

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?

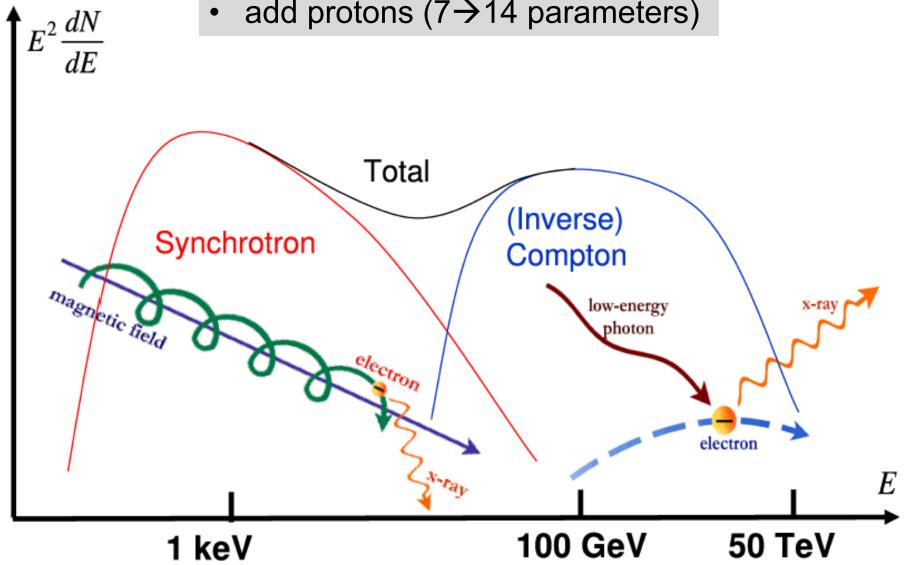
extensive multiwavelength campaign allows us to study the first cosmic accelerator

a problem: theory



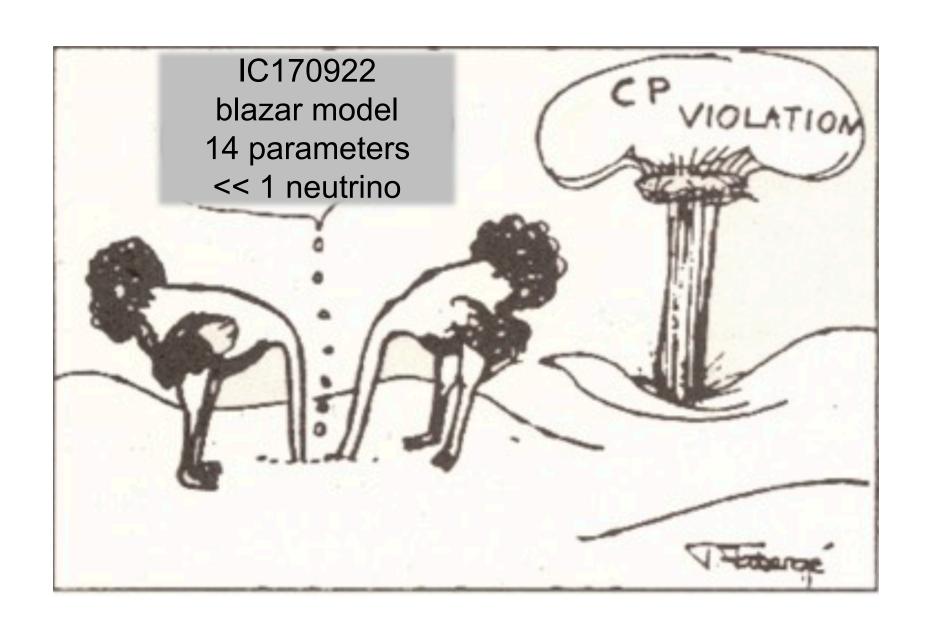
we know that this cosmic accelerator is a cosmic ray source

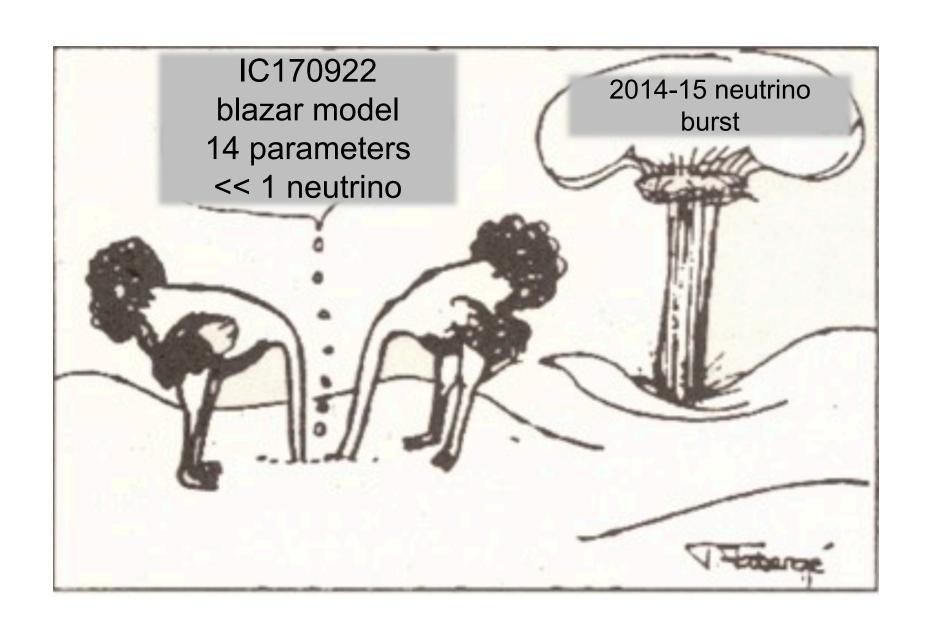
- blazar modeling well understood
- add protons $(7 \rightarrow 14 \text{ parameters})$

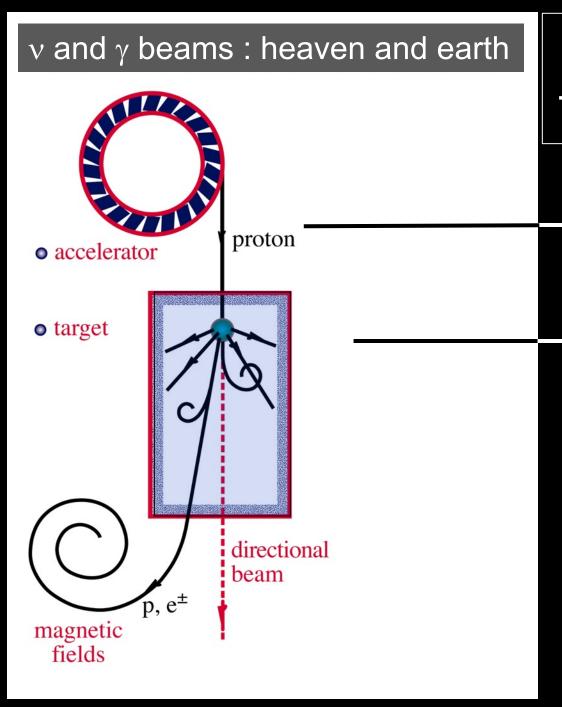




Cabibbo 1966







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

→ cosmic ray + neutrino

supermassive black hole

• target ?

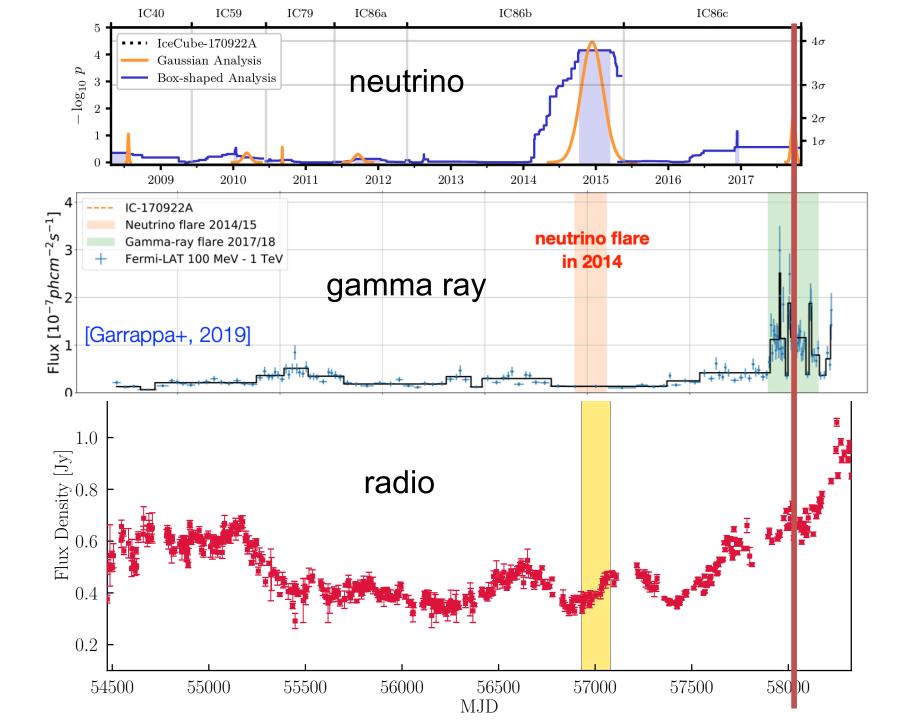
- → a neutrino source needs an accelerator and a target
- the target may be opaque to gamma rays

an efficient neutrino source is opaque to gamma rays

- efficiency for producing neutrinos: $L_{
 u} \sim au_{p\gamma}\,L_{p}$ opacity of the target's proton $au_{p\gamma}$
- requires large opacity of the target to protons and large target density

$$au_{p\gamma} \sim n_{\gamma}$$

- gamma ray opacity is 10² times higher $au_{\gamma\gamma} \simeq 10^2 \,\, au_{p\gamma}$
- blazars are highly efficient gamma ray emitters, cannot be efficient neutrino sources
- imaging by radio interferometry and optical robotic telescopes to the rescue!

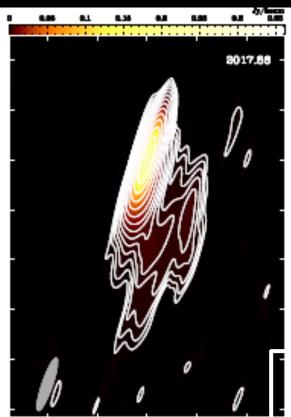


TXS 0506+056

- beyond 5 mas the jet loses its tight collimation...
- jet found a target after ~tens of pc

Theory confirms observations:

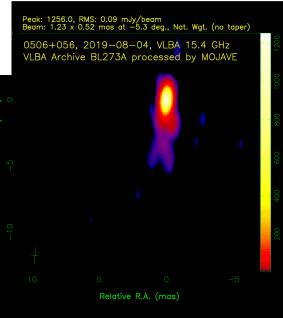
- jet star interaction?
- jet-jet encounter in a galaxy merger?



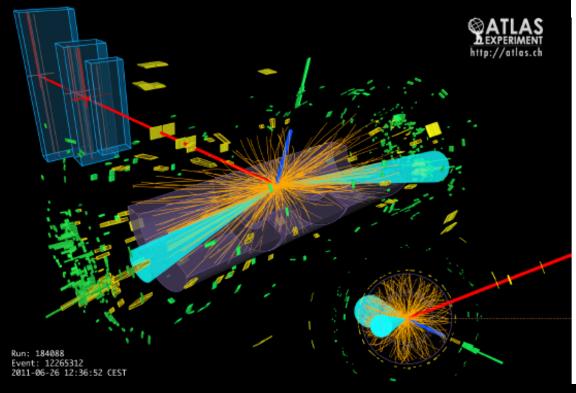
1912.01743v1 [astro-ph.GA]

- core brightening observed in a radio burst that started 5 years ago
- core expands with superluminal velocity

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



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.Zhirkov¹, E. Gorbovskoy², N.M. Budnev⁴, D.A.H.Buckley³, R. Rebolo⁵, M. Serra-Ricart⁵, R. Podesta^{9,10}, N. Tyurina², O. Gress^{4,2}, Yu.Sergienko⁸, V. Yurkov⁸, A. Gabovich⁸, P.Balanutsa², I.Gorbunov², D.Vlasenko^{1,2}, F.Balakin^{1,2}, V.Topolev¹, A.Pozdnyakov¹, A.Kuznetsov², V.Vladimirov², A. Chasovnikov¹, D. Kuvshinov^{1,2}, V.Grinshpun^{1,2}, E.Minkina^{1,2}, V.B.Petkov⁷, S.I.Svertilov^{2,6}, C. Lopez⁹, F. Podesta⁹, H.Levato¹⁰, A. Tlatov¹¹
B. Van Soelen¹², S. Razzaque¹³, M. Böttcher¹⁴

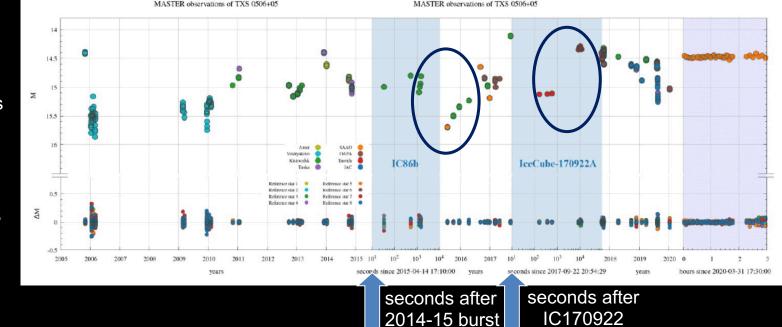
MASTER robotic network

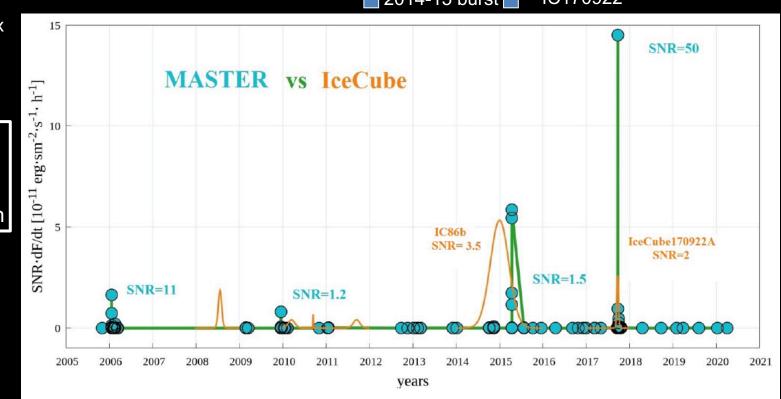
optical observations TXS 0506+056 since 2005

blue panels: expanded time axis years → seconds

time variation of flux times signal-to-noise

hour-scale
variability of the
source after
neutrino emission





theory: not a "vanilla" blazar

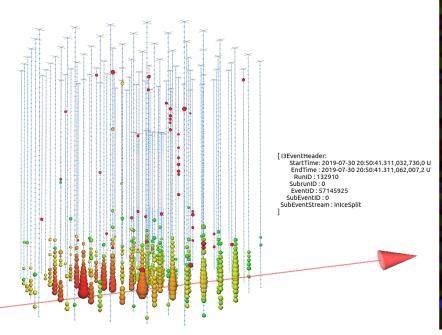
what is the target found in the radio and optical images?

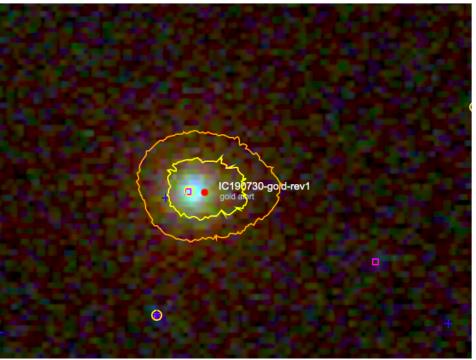
blueprint of TXS accelerator still evolving

is cosmic ray origin really 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:190730, 191001, 200107...





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. Würzburg), 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

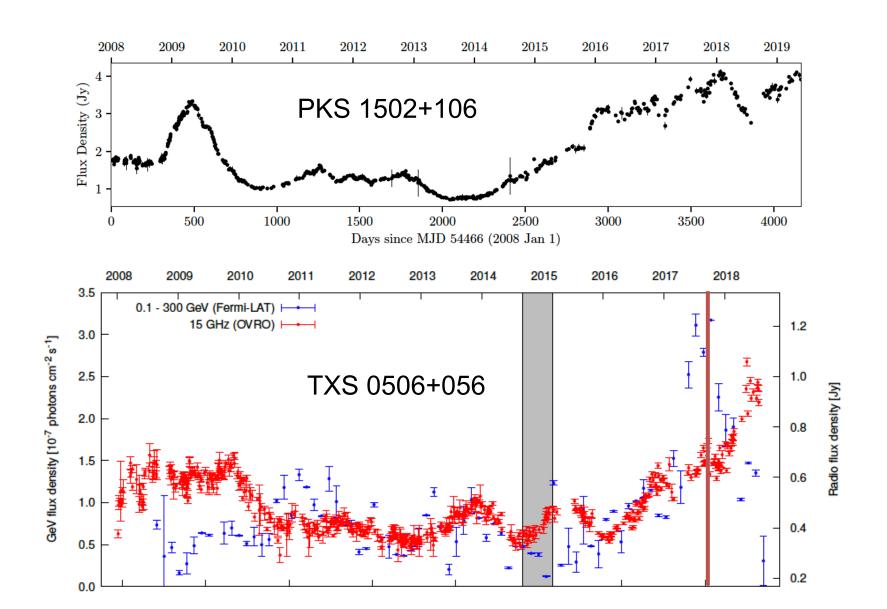


On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started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

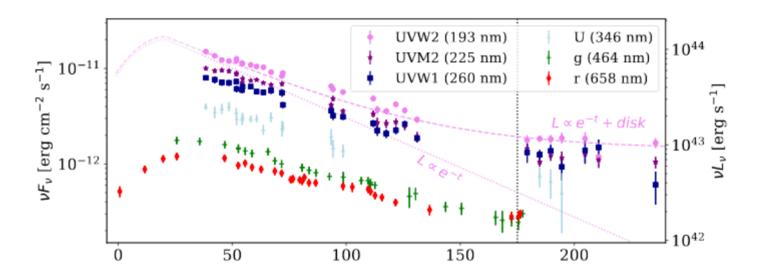
- 12996 Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
- 2985 IceCube-190730A: Swift XR and UVOT Follow-up and prompt BAT Observations
- 12983 Optical fluxes of candidate neutrino blazar PKS 1502+106
- 12981 ASKAP observations of blazars possibly associated with neutrino 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



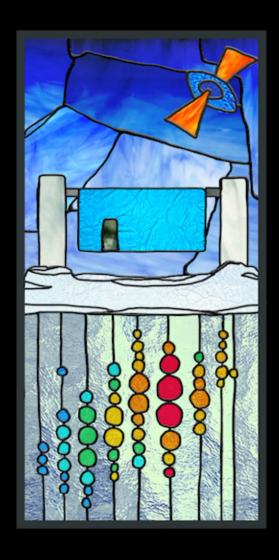
IC191001 in coincidence with the tidal disruption of a star?

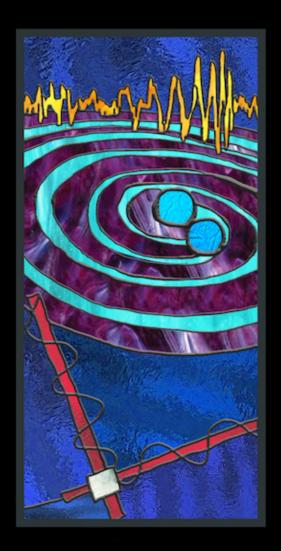
IC191001 close to luminous TDE of the Zwicky Transit Factory



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)

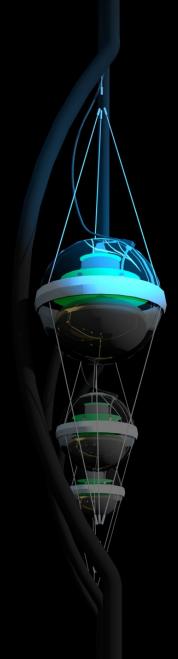






next attraction: gravitational waves + neutrinos?

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



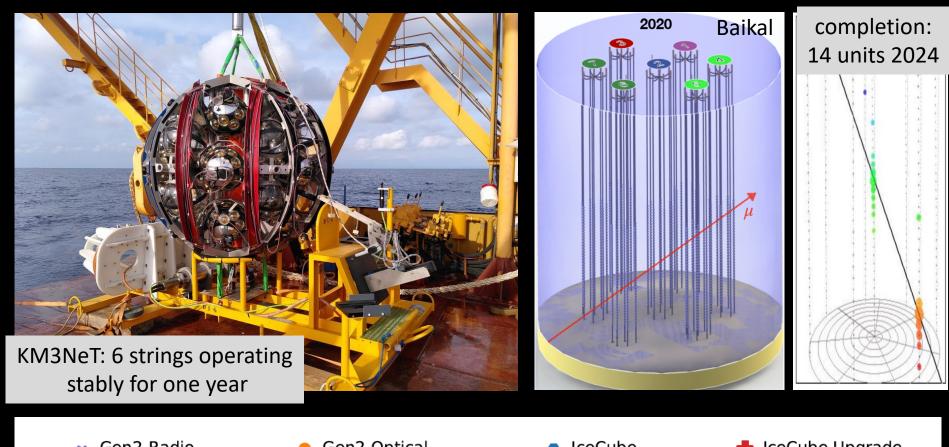
Neutrinos in the Era of Multimessenger Astronomy francis halzen

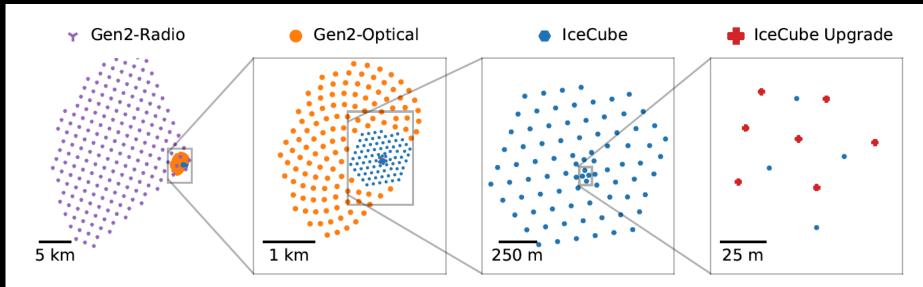
- cosmic neutrinos: many independent observations
 - → muon neutrinos through the Earth
 - → starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments: x 5~10 (PeV) and x100 (EeV)
- also, a beam for PeV neutrino physics

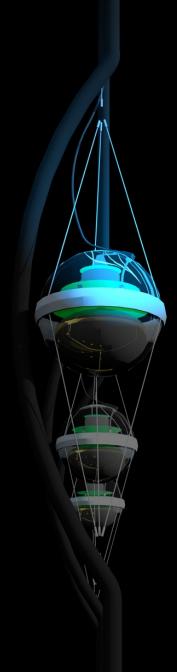


Lake Baikal experiment reaches 0.35 km³





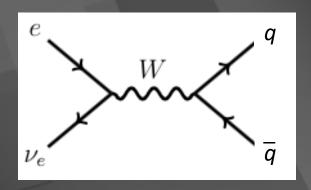




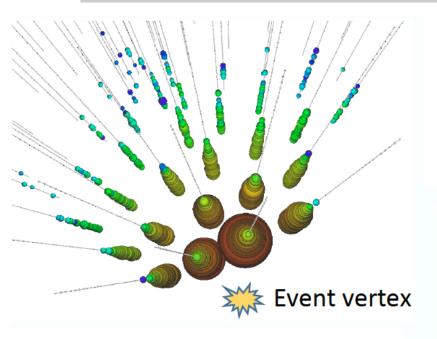
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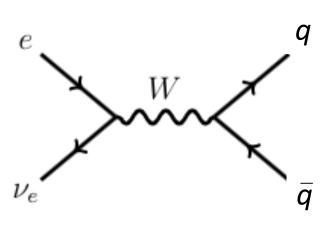
the first Glashow resonance event: anti-v_e + atomic electron → real W at 6.3 PeV

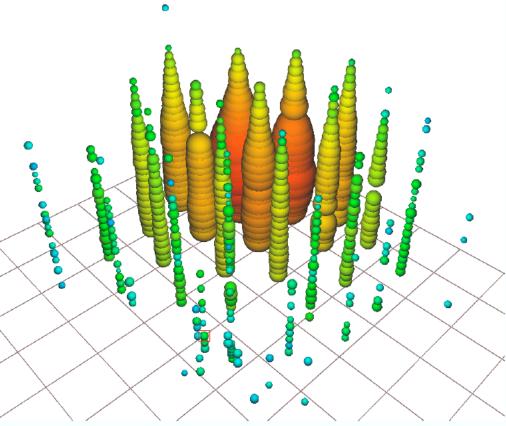


partially contained event with energy 6.3 PeV

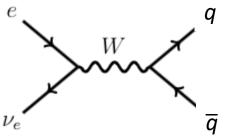


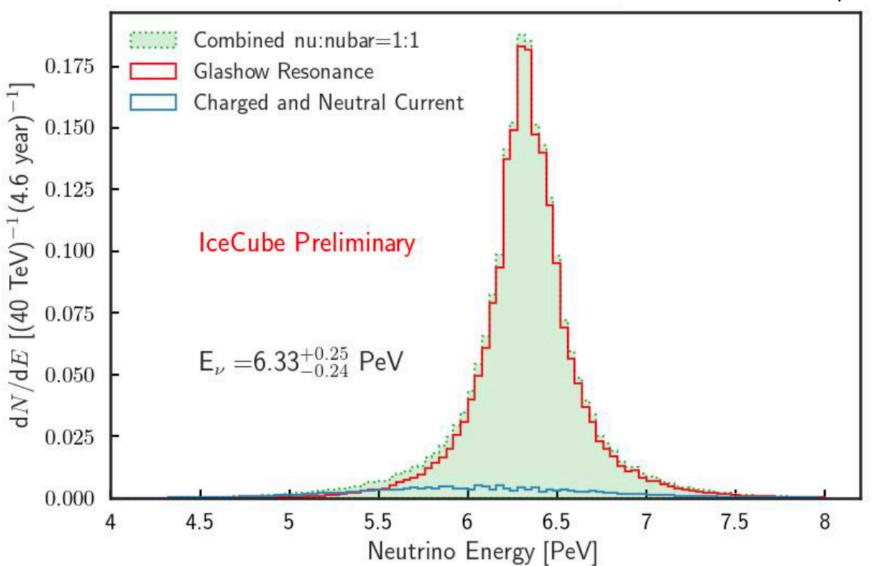
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron





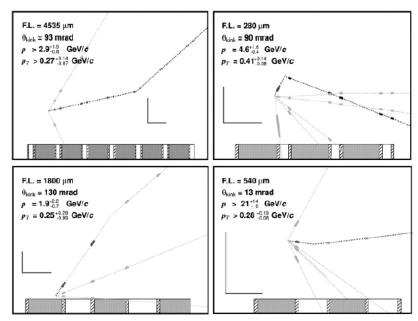
- energy measurement understood
- identification of anti-electron neutrinos





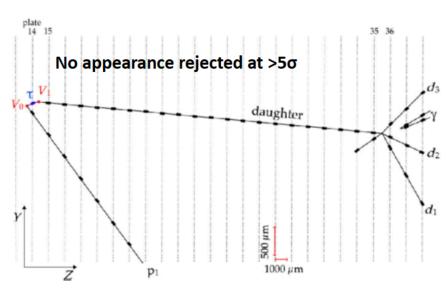
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



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

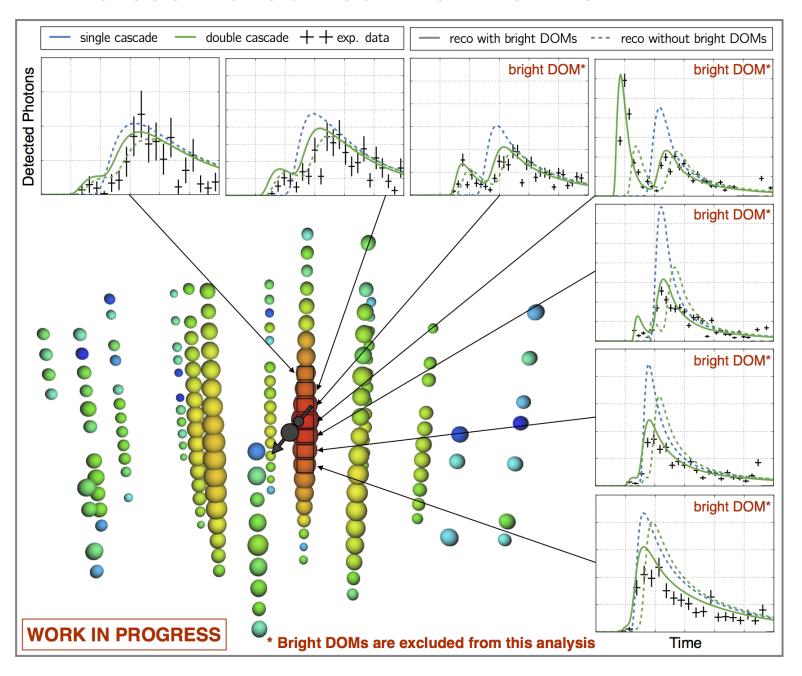
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



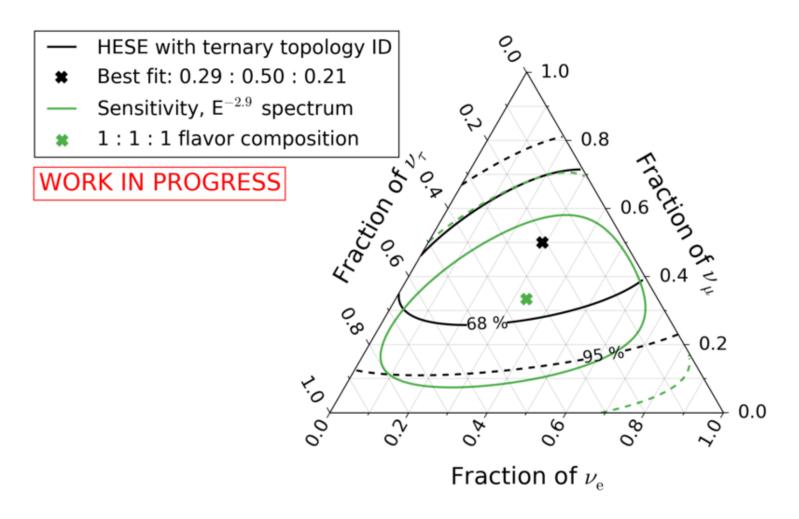
OPERA Phys. Rev. Lett. 115, 121802 (2015)

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

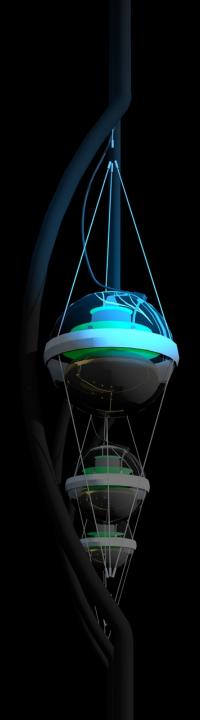
a cosmic tau neutrino: livetime 17m



high-energy starting events – 7.5 yr



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



neutrino astronomy 2020

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

THE ICECUBE COLLABORATION



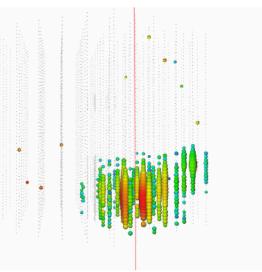
THE ICECUBE COLLABORATION



overflow sides

IC200107A: The "DNN-starting-track Neutrino"

DNN (HESE V3)



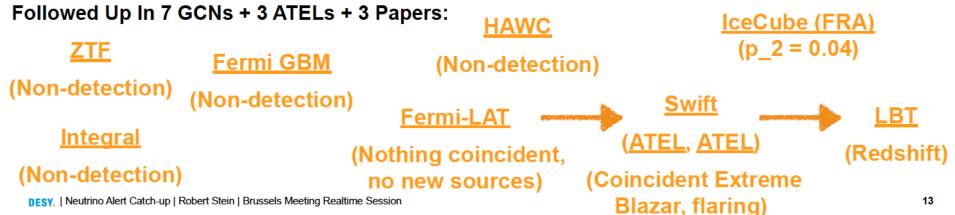
High-charge HESE event, did not qualify as alert (see SplineMPE direction...)

Good starting track, confirmed by Theo's DNN

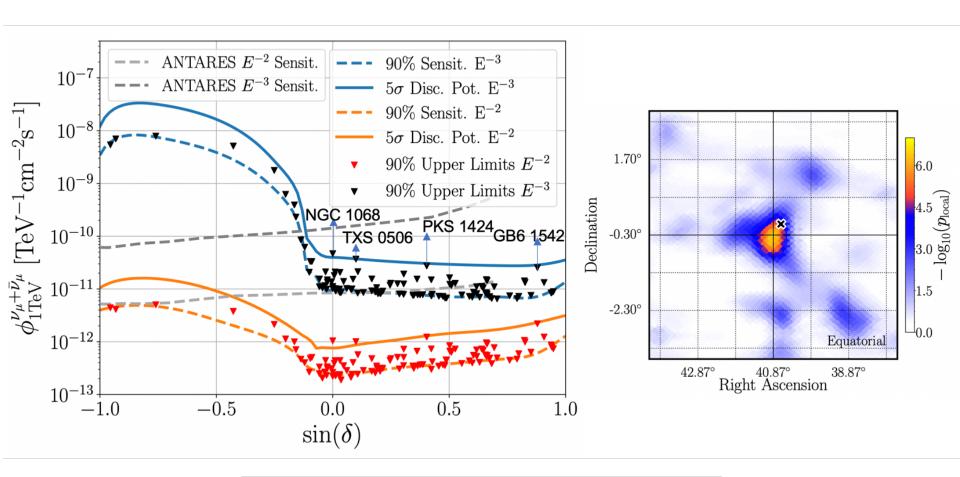
Signalness ~65% (Not reported).

Posted in GCN circular.

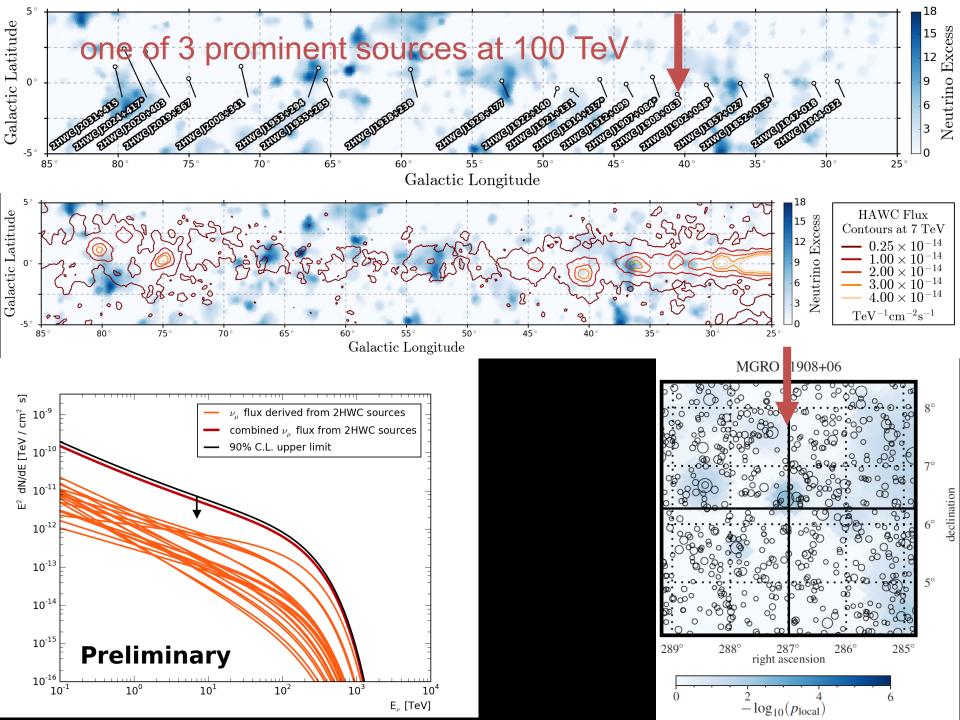
Coincident with "extreme blazar".

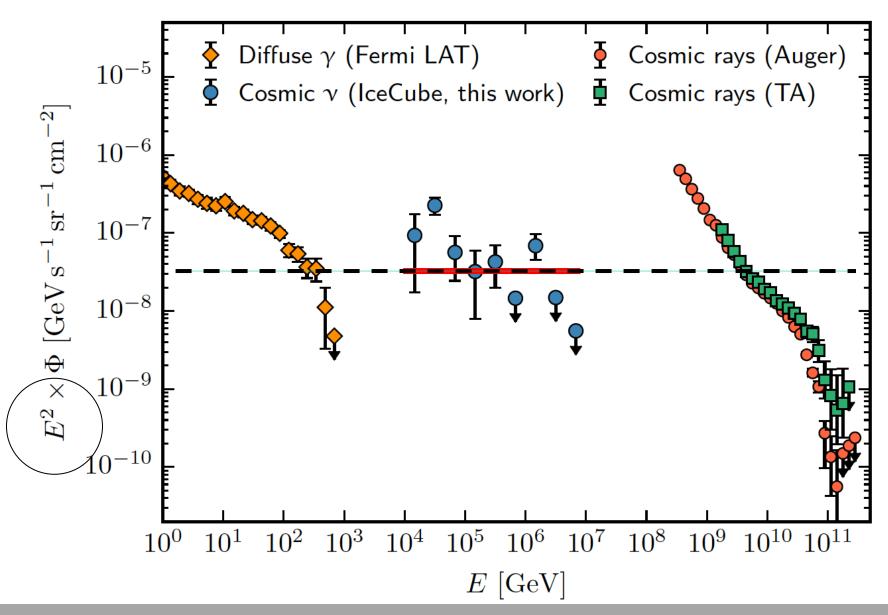


10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates

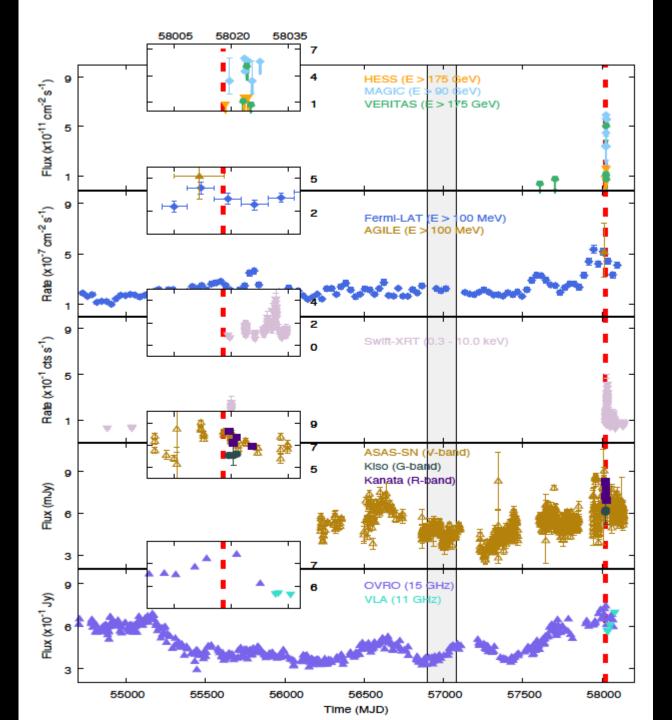


why not seen before?





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



TXS 0506+056

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

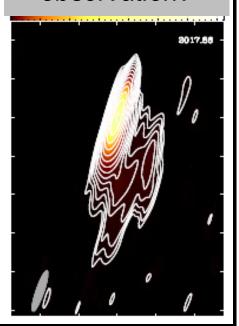
jet found a target after ~tens of pc

jet star interaction?

theory confirms observation?

Dec 2019

912.01743v1 [astro-ph.GA]



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LETTER TO THE EDITOR

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

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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.

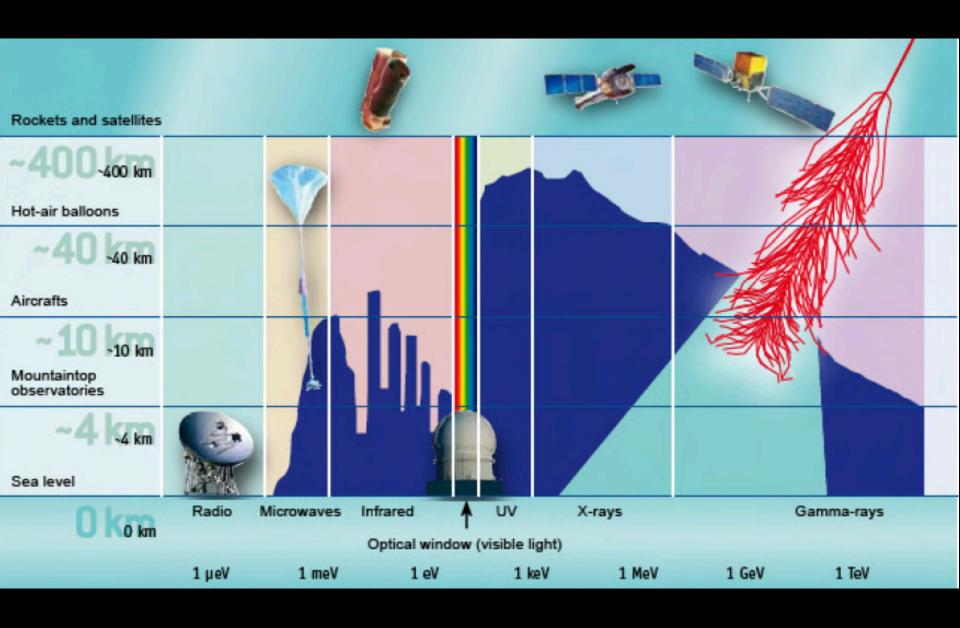
Aims. Our goal is to probe the sub-milliarcsecond properties of the radio jet right after the neutrino detection and during the further evolution of the radio outburst.

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

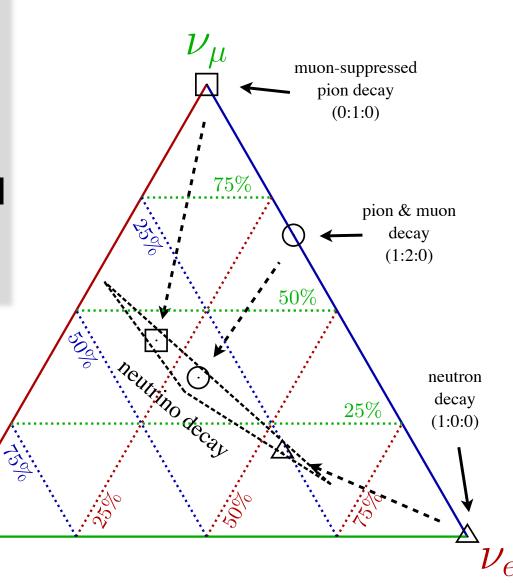


new physics?

if not...

every model for the astrophysical source ends up in the triangle

 $u_{ au}$



upgrade/Gen2

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

