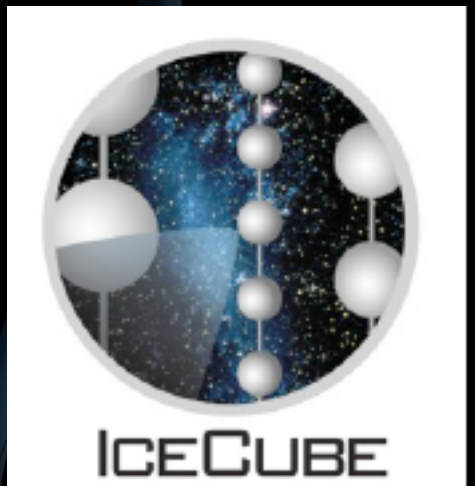


IceCube: sources of cosmic neutrinos

francis halzen

- IceCube
- cosmic neutrinos
- point source searches
- multimessenger observations

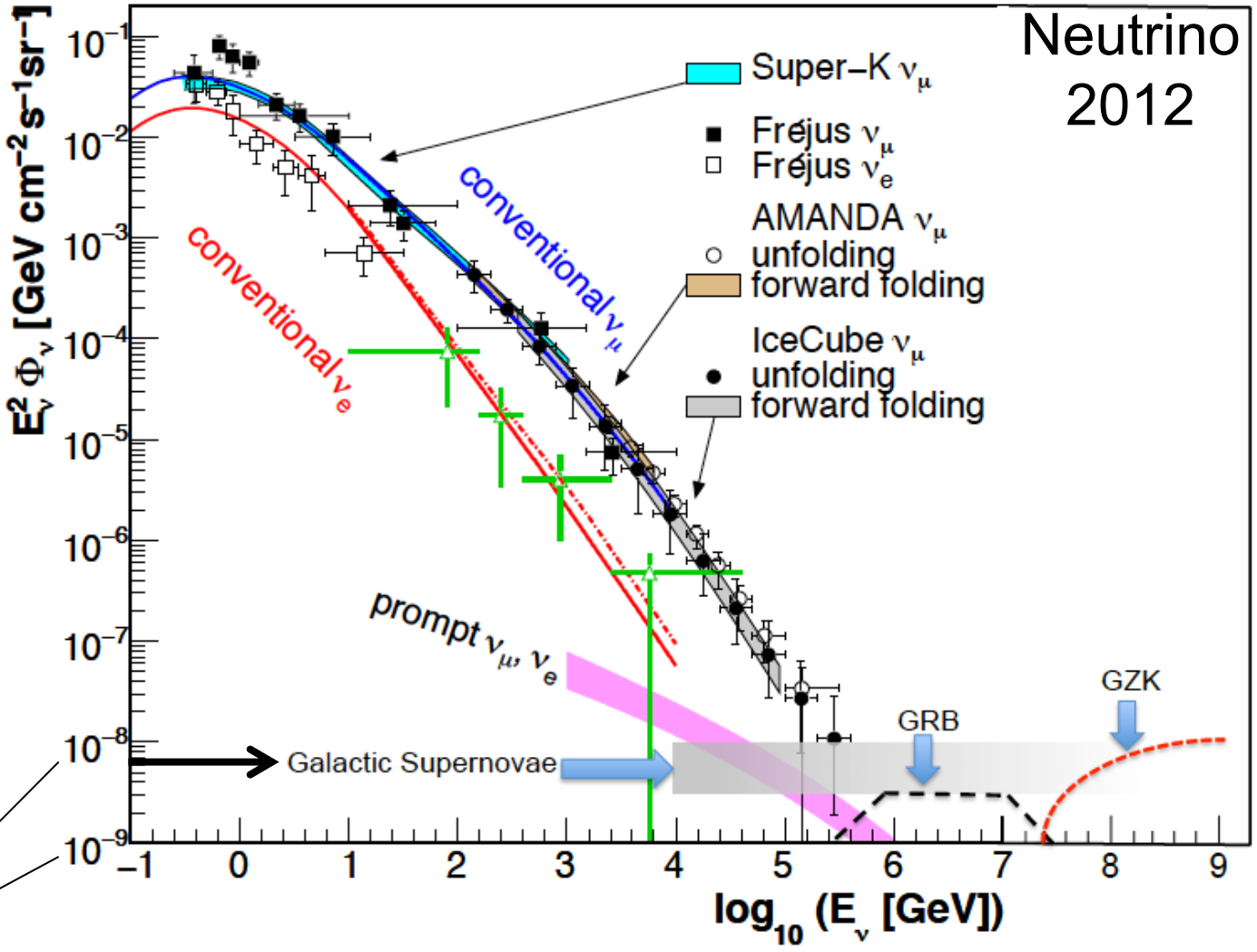
IceCube.wisc.edu

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

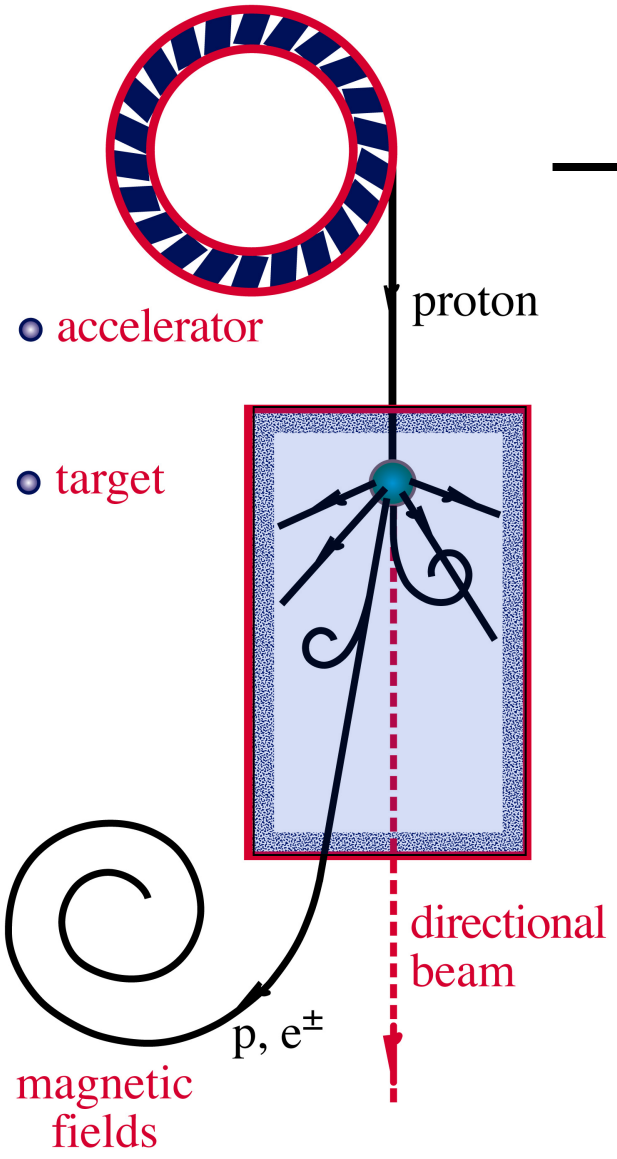


atmospheric

cosmic

100 TeV

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

nearby radiation

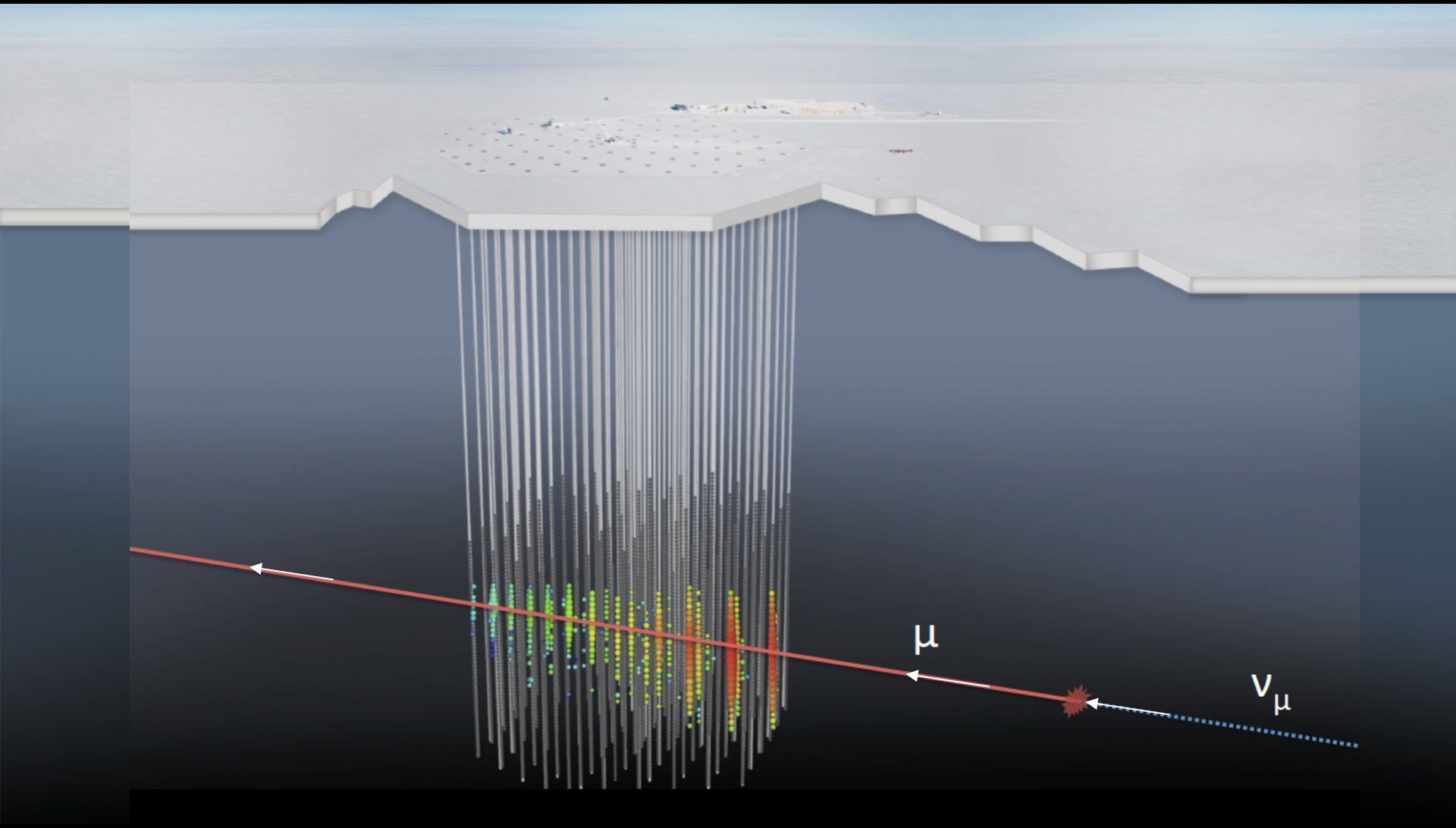
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

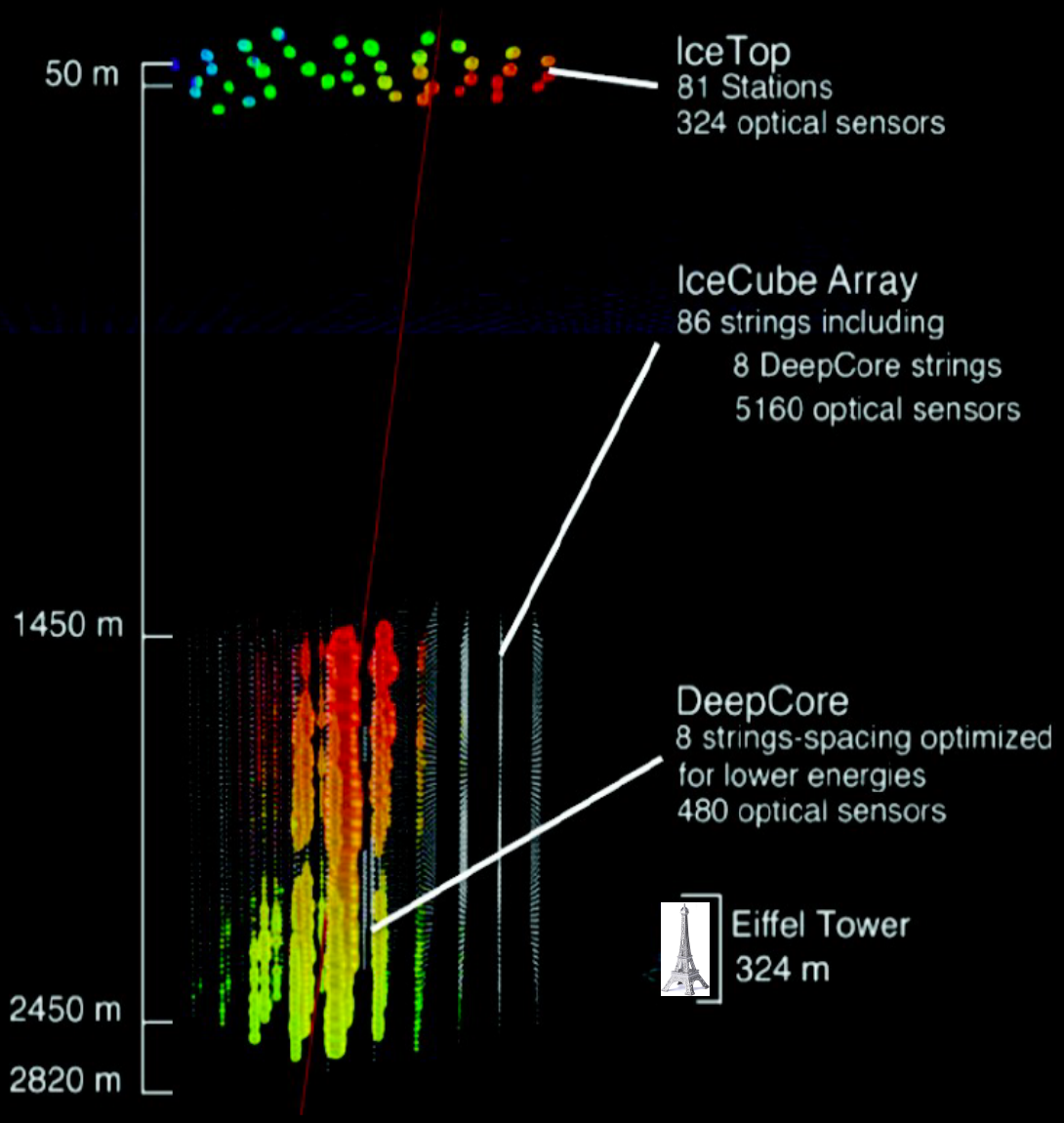
instrument 1 cubic kilometer of natural ice below 1.45 km



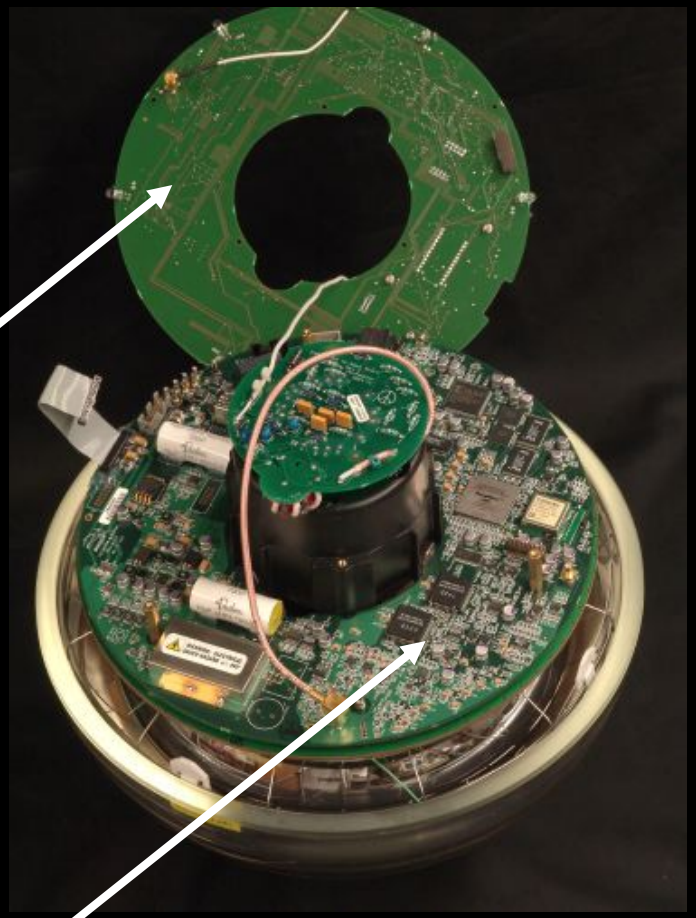
the IceCube Neutrino Observatory

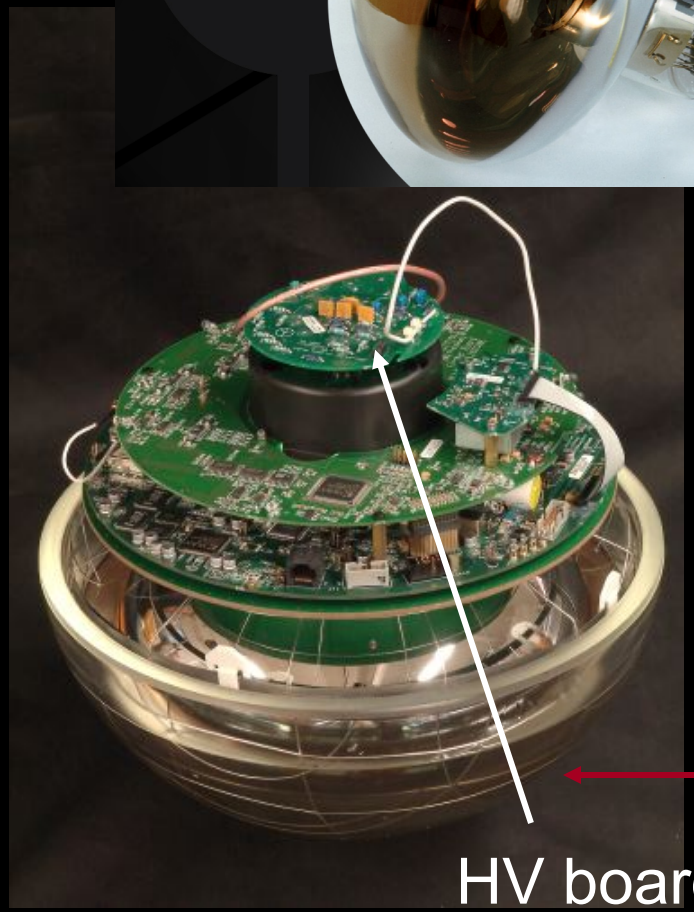
5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution



architecture of independent DOMs





muon neutrinos: signal and background

muons detected per year:

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

* 3000 per second

** 1 every 6 minutes

IceCube: sources of cosmic neutrinos

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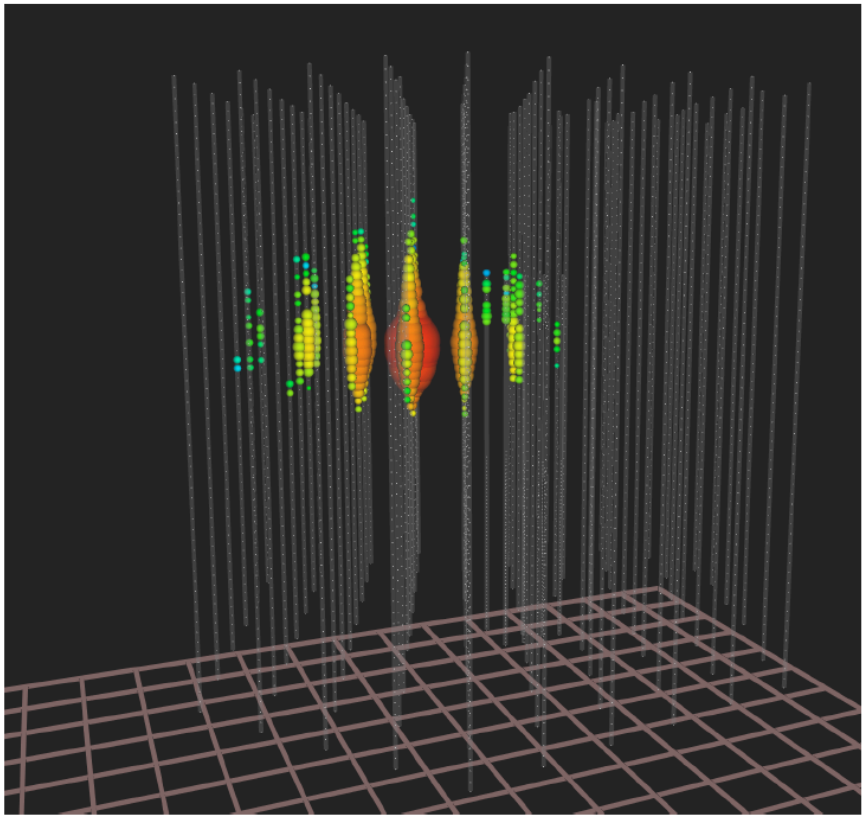
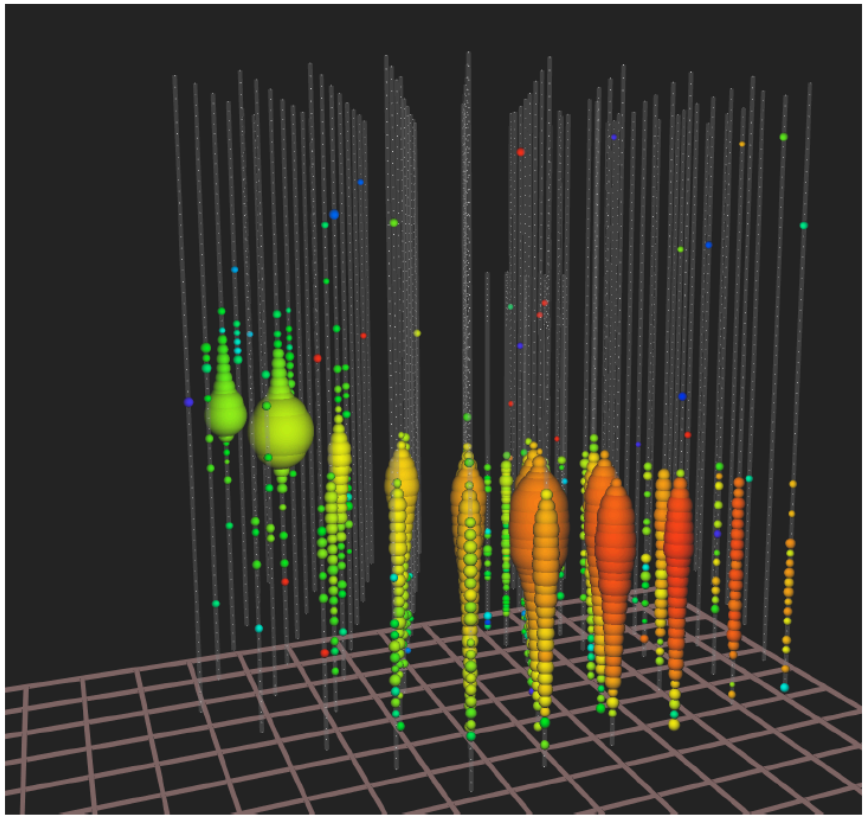
neutrinos interacting
inside the detector

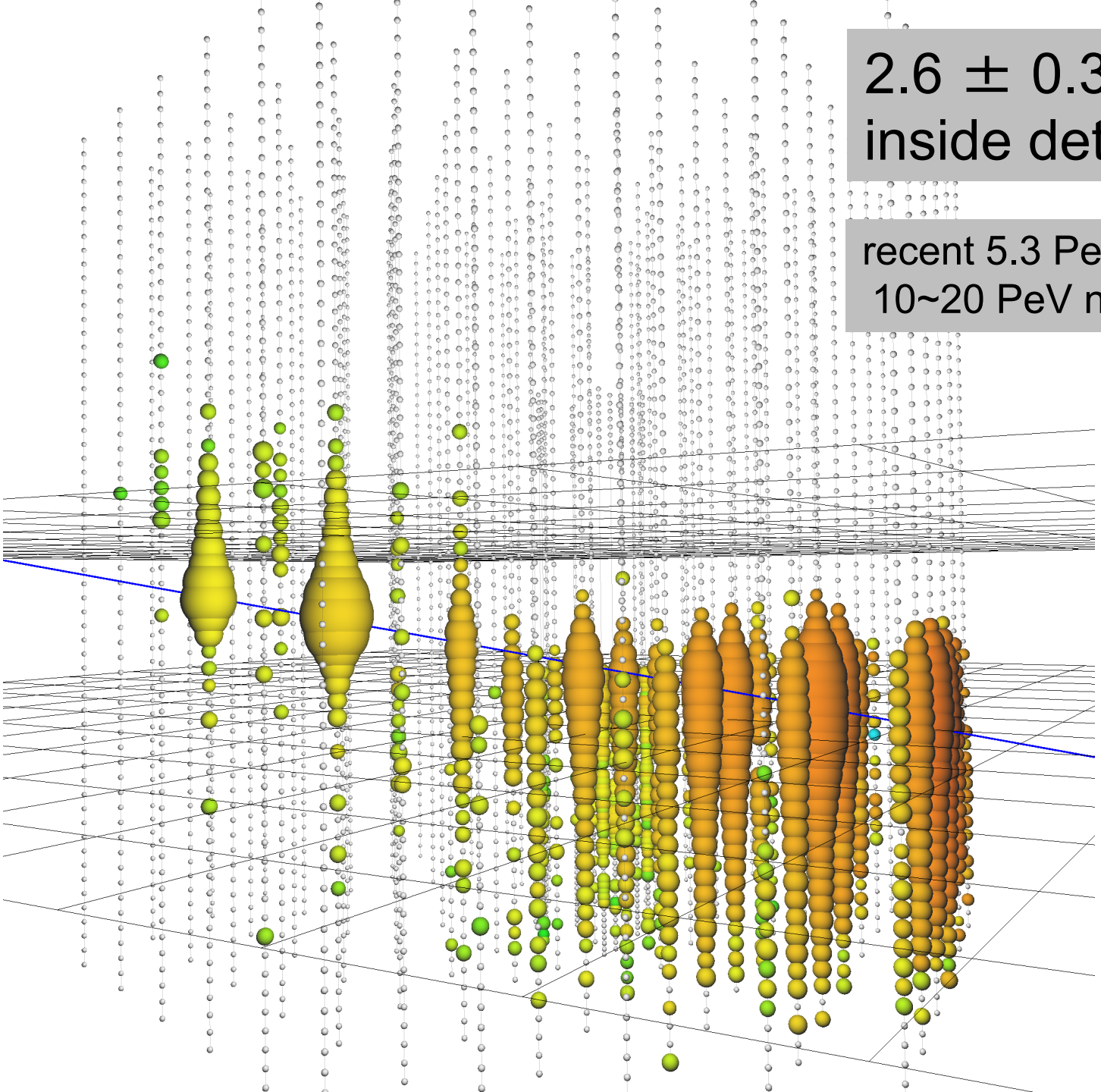


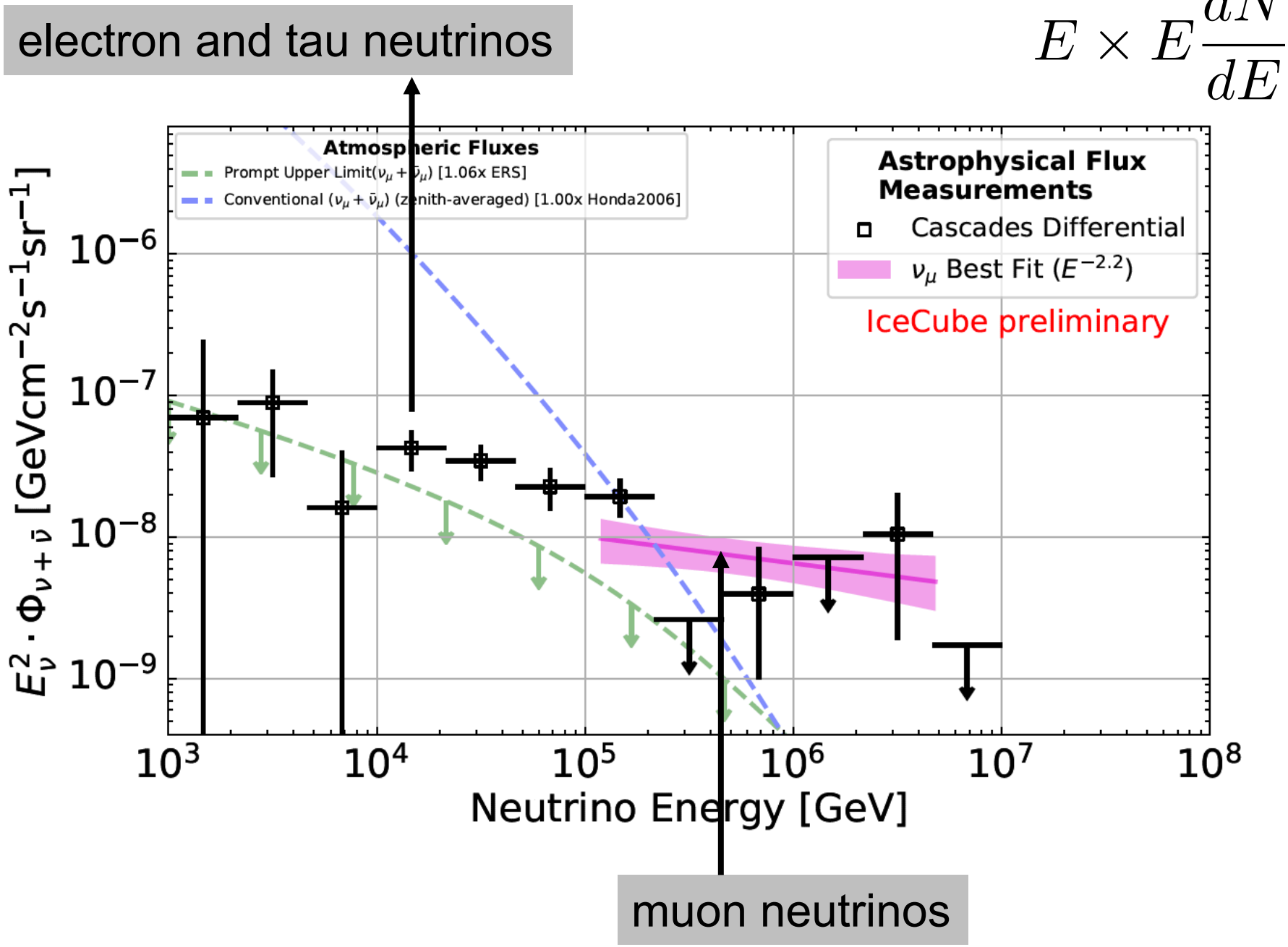
total energy measurement
all flavors, all sky

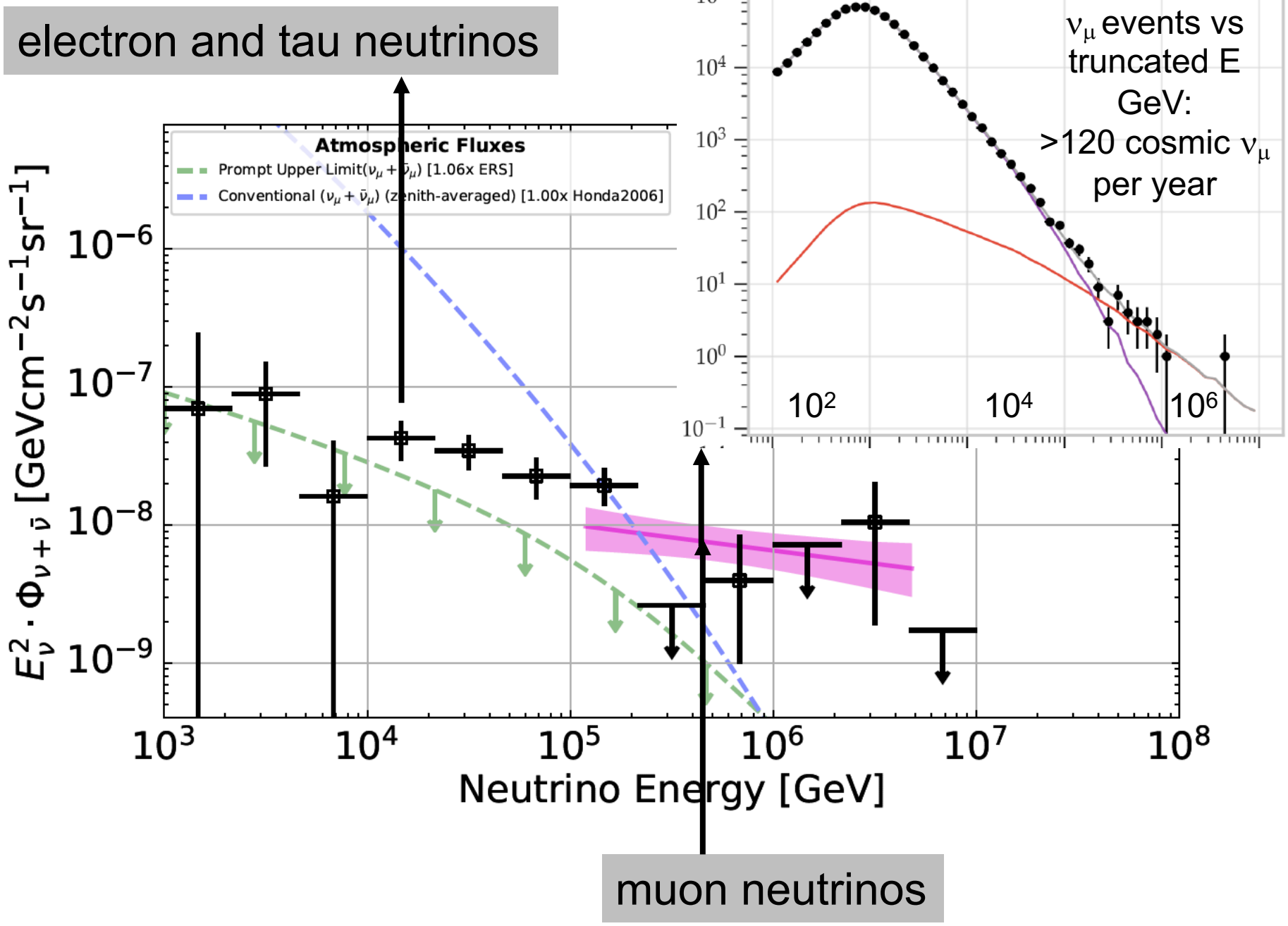
muon neutrinos
filtered by the Earth



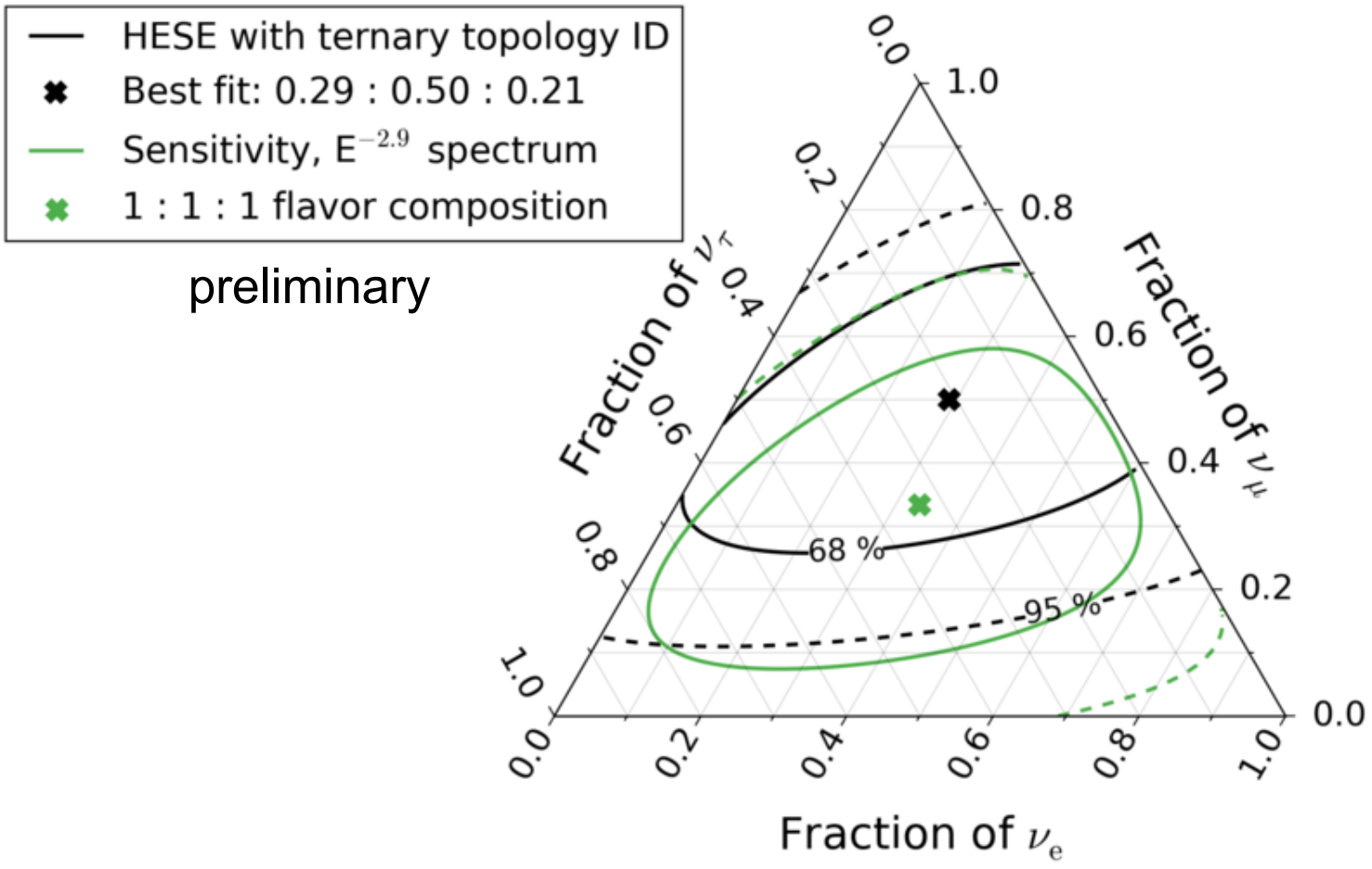
astronomy: angular resolution
superior (0.2~0.4^{o})


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


electron and tau neutrinos
$E \times E \frac{dN}{dE}$
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [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]
muon neutrinos

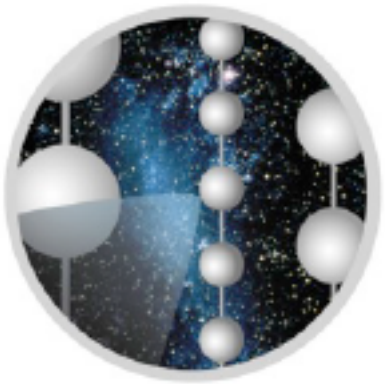

electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7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

high-energy starting events – 7.5 year



preliminary

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

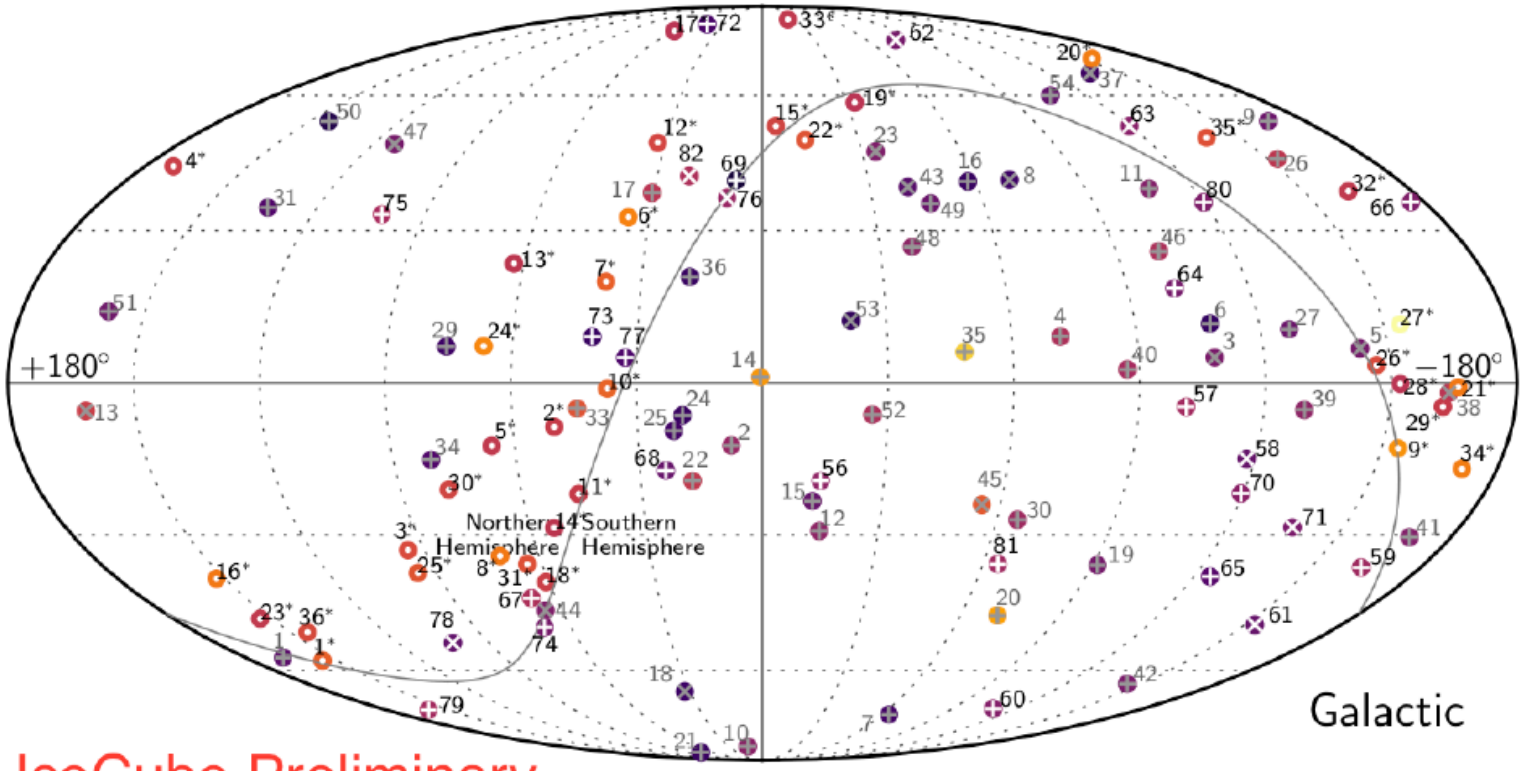


IceCube: sources of cosmic neutrinos

francis halzen

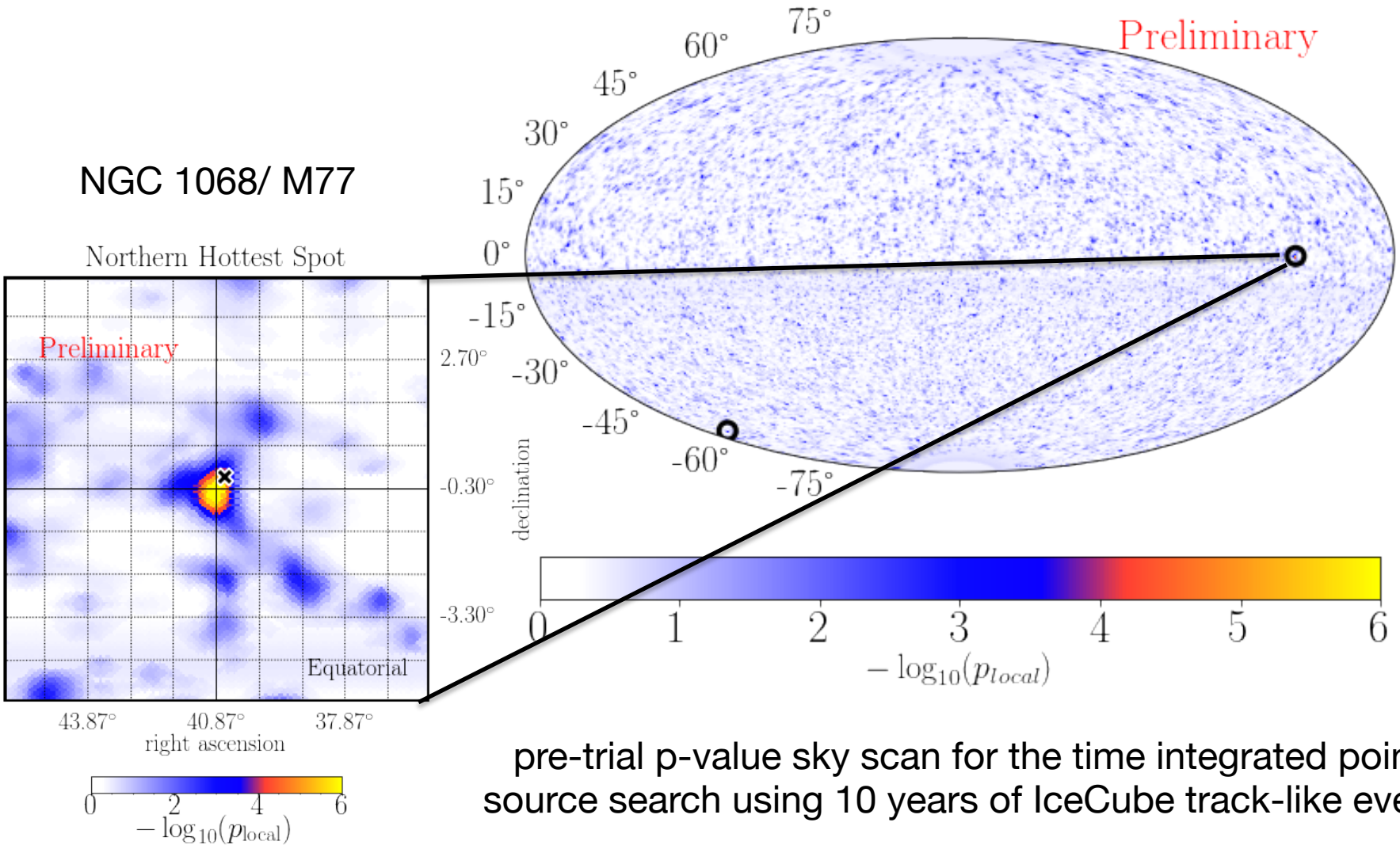
- IceCube
- cosmic neutrinos
- point source searches
- multimessenger observations

where do they come from ?



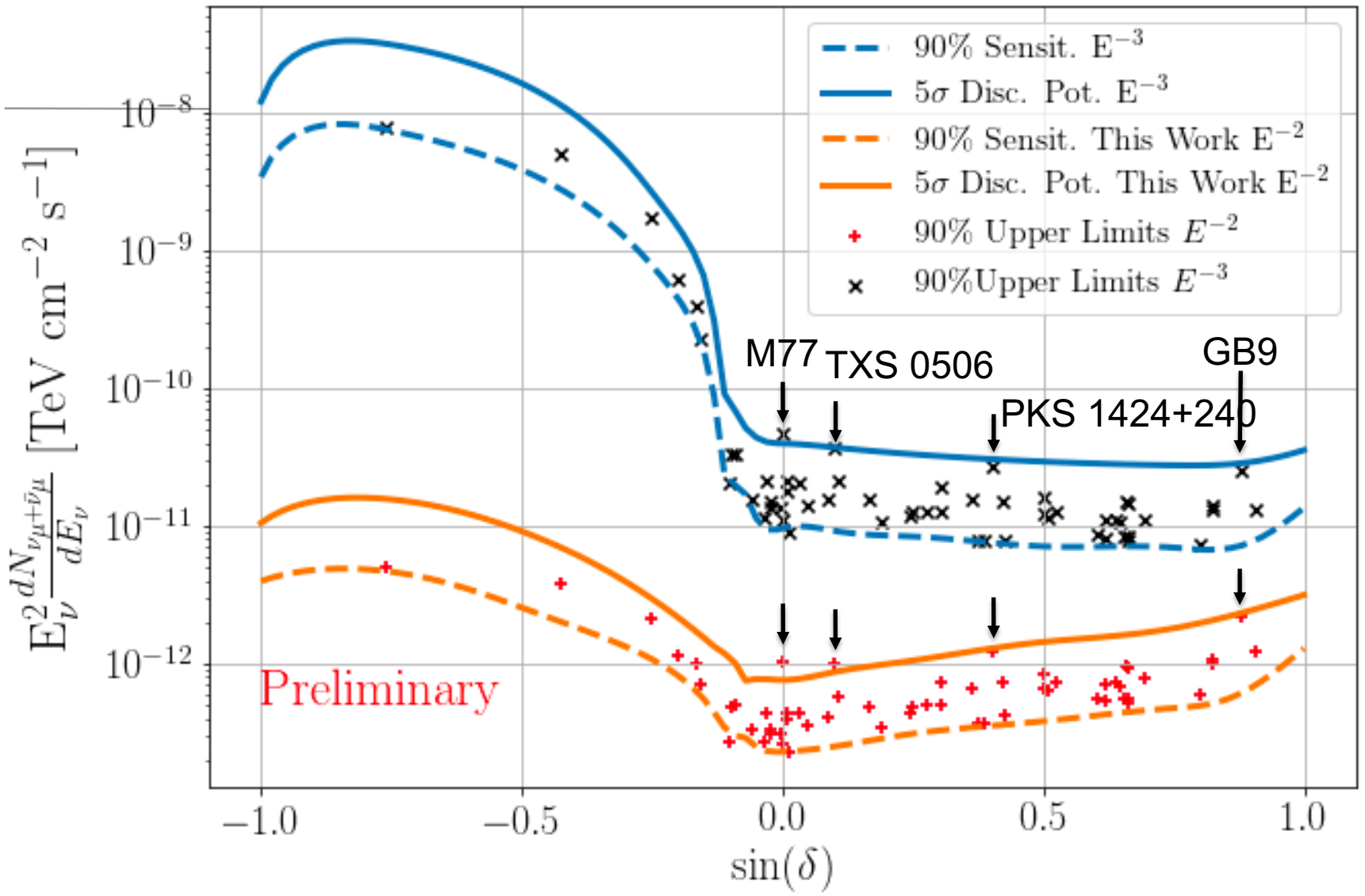
evidence for non-uniform skymap in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates

NGC 1068/ M77

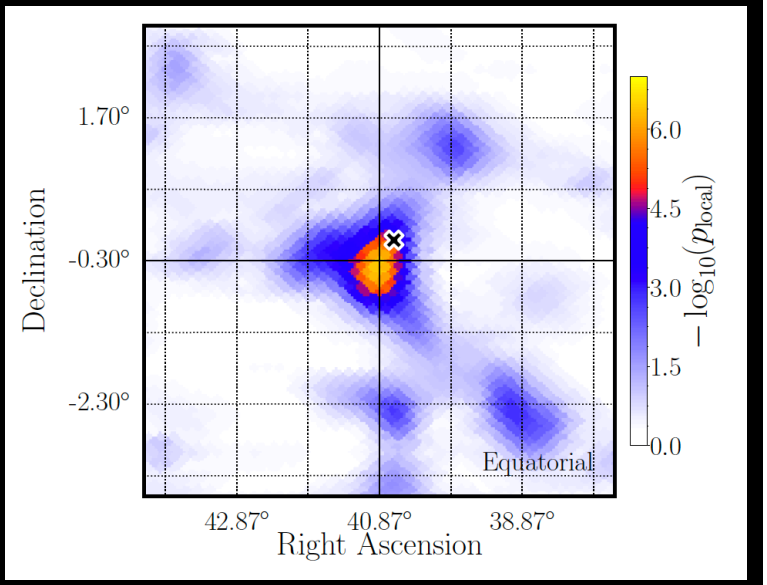


pre-trial p-value sky scan for the time integrated point source search using 10 years of IceCube track-like events

limits and fluctuations (?)



point source analysis with improved methods is forthcoming



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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Received 19 March 2014 / Accepted 4 June 2014

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 ($M_{mol} \sim 2.7^{+0.9}_{-1.2} \times 10^7\ M_\odot$) outflow in all molecular tracers. The tight correlation between the ionized gas outflow, the radio jet, and the occurrence of outward motions in the disk suggests that the outflow is AGN driven.

Conclusions. The molecular outflow is likely launched when the ionization cone of the narrow line region sweeps the nuclear disk. The outflow rate estimated in the CND, $dM/dt \sim 63^{+21}_{-37}\ M_\odot$ 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.

Coming soon: release of 10 years of data and simulation

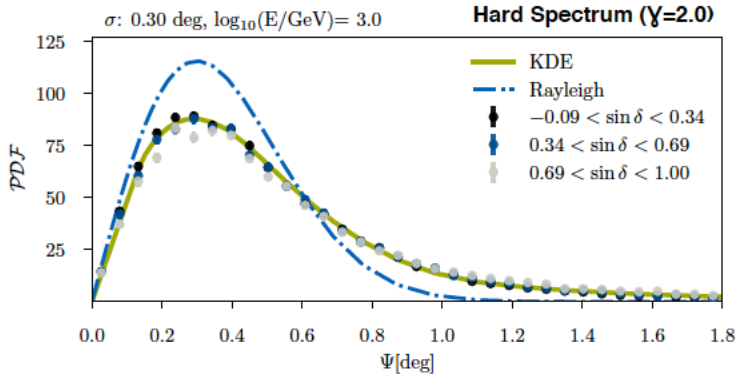
- Data events:
  - MJD to 1ms precision
  - log(10) E-proxy (MuEX)
  - 1 sigma circularized angular error (Paraboloid or Cramer-Rao)
  - RA and DEC (J2000)
  - Zenith and Azimuth

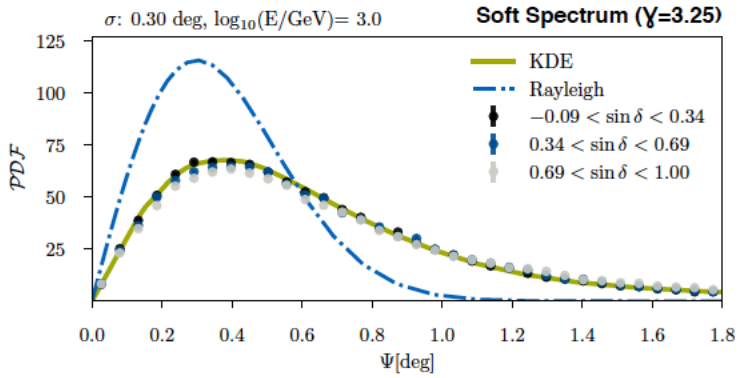
- Final-level GoodRunList start and end times

- Tabulated MC information:
  - Effective area for each year binned in cos(zen) and E
  - Smearing matrix for reconstructed energy, direction, and angular error (not included in 3-yr release)

coming soon: improved muon track reconstruction

- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics



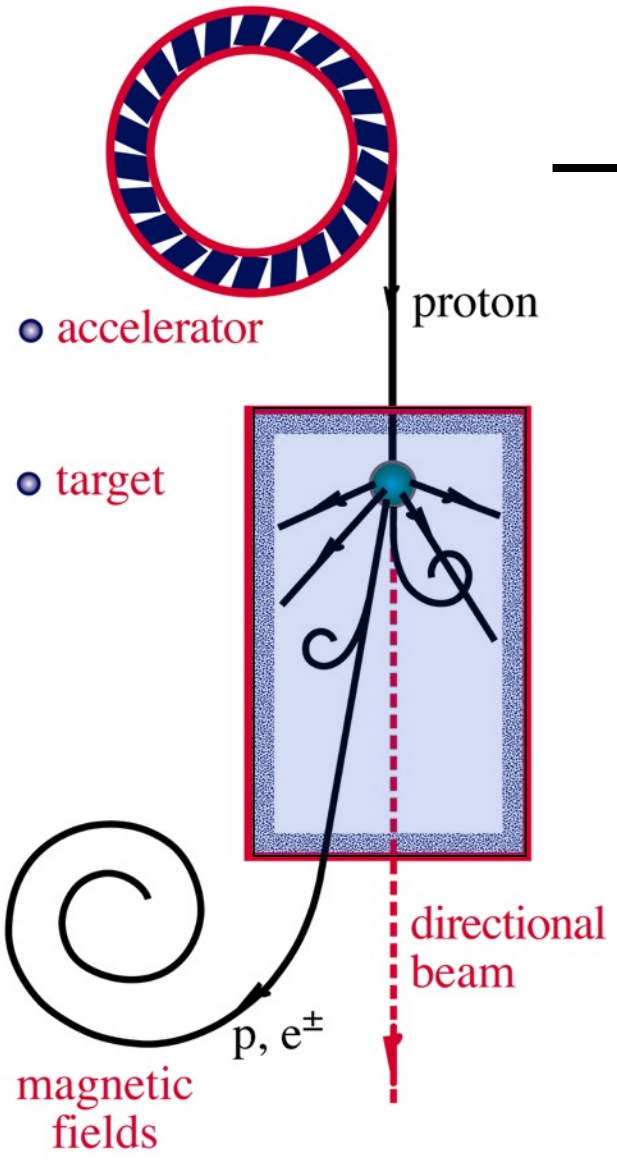


- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation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

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

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

ν and γ beams : heaven and earth



where are the gamma rays ?

supermassive black hole

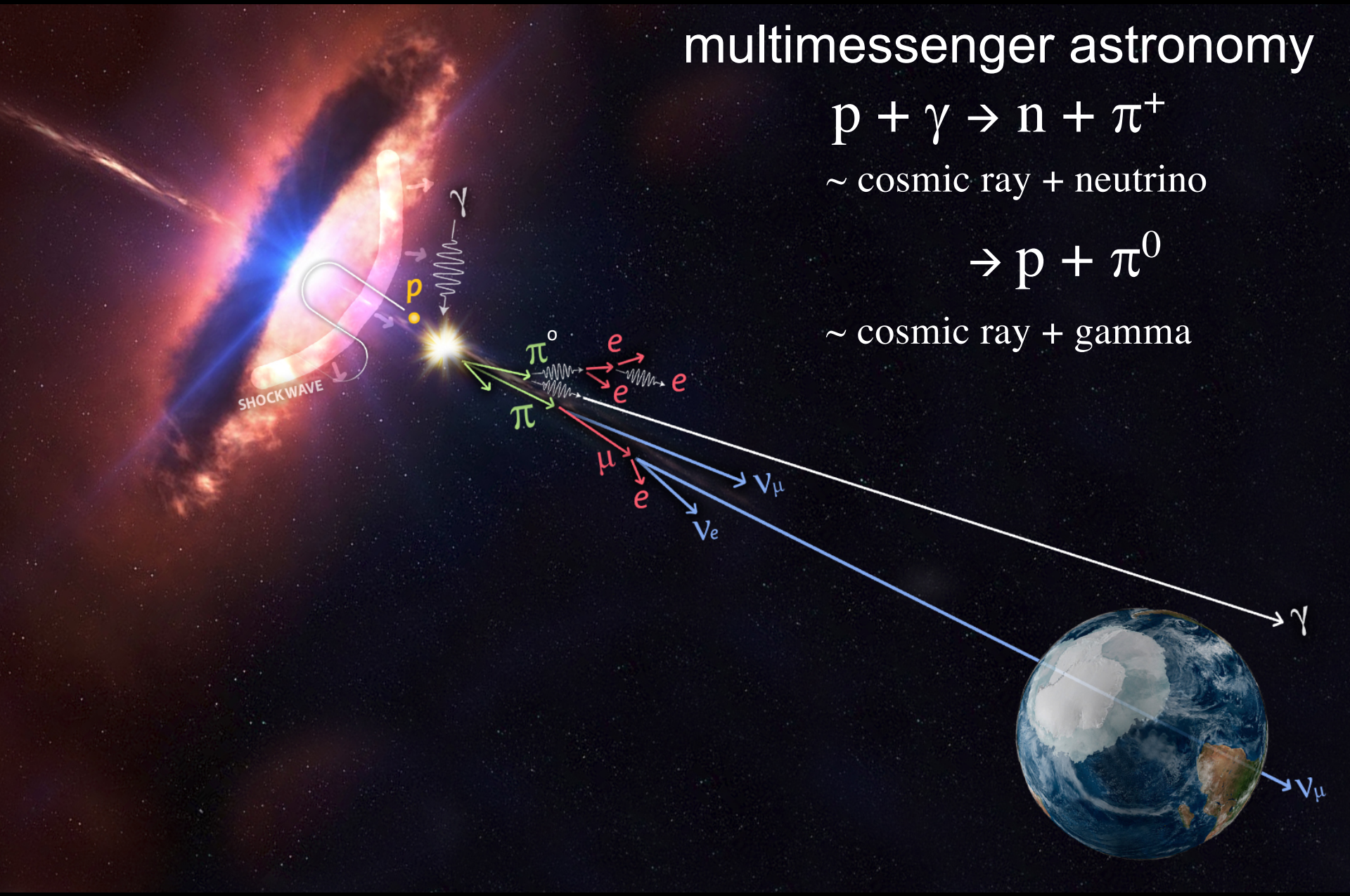
nearby radiation

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma


multimessenger astronomy
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma
γ
p
SHOCK WAVE
π°
e
e
e
π
μ
e
νμ
νe
γ
νμ

IceCube: sources of cosmic neutrinos

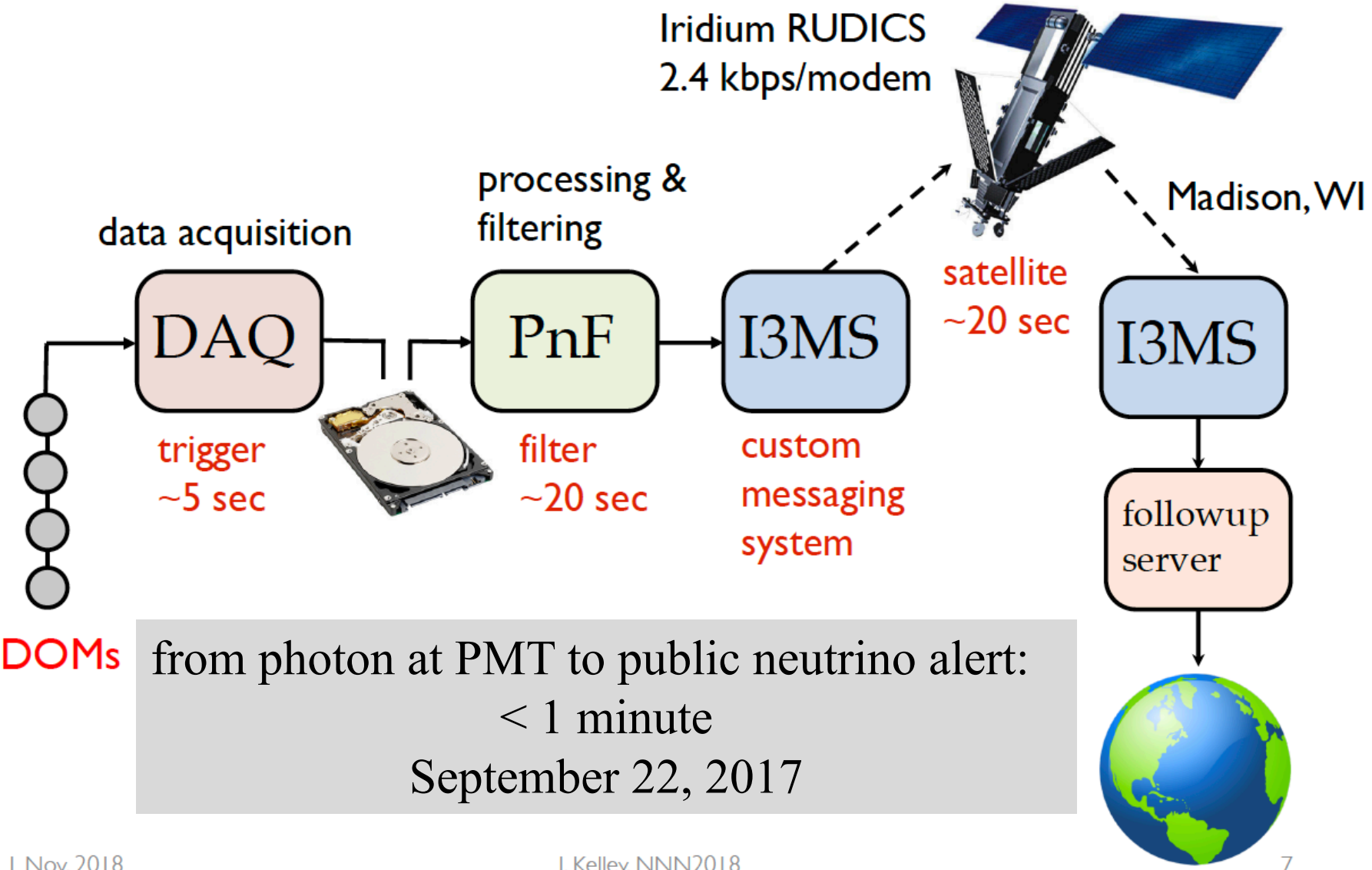
francis halzen

- IceCube
- cosmic neutrinos
- point source searches
- multimessenger observations

IceCube.wisc.edu

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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



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

IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
////////////////////////////////////////////////////////////////////////
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:        AMON ICECUBE EHE
RUN_NUM:            130033
EVENT_NUM:          50579430
SRC_RA:              77.2853d {+05h 09m 08s} (J2000),
                     77.5221d {+05h 10m 05s} (current),
                     76.6176d {+05h 06m 28s} (1950)
SRC_DEC:             +5.7517d {+05d 45' 06"} (J2000),
                     +5.7732d {+05d 46' 24"} (current),
                     +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:          14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:     18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:     75270 SOD {20:54:30.43} UT
REVISION:           0
N_EVENTS:           1 [number of neutrinos]
STREAM:             2
DELTA_T:            0.0000 [sec]
SIGMA_T:            0.0000e+00 [dn]
ENERGY :            1.1998e+02 [TeV]
SIGNALNESS:         5.6507e-01 [dn]
CHARGE:             5784.9552 [pe]
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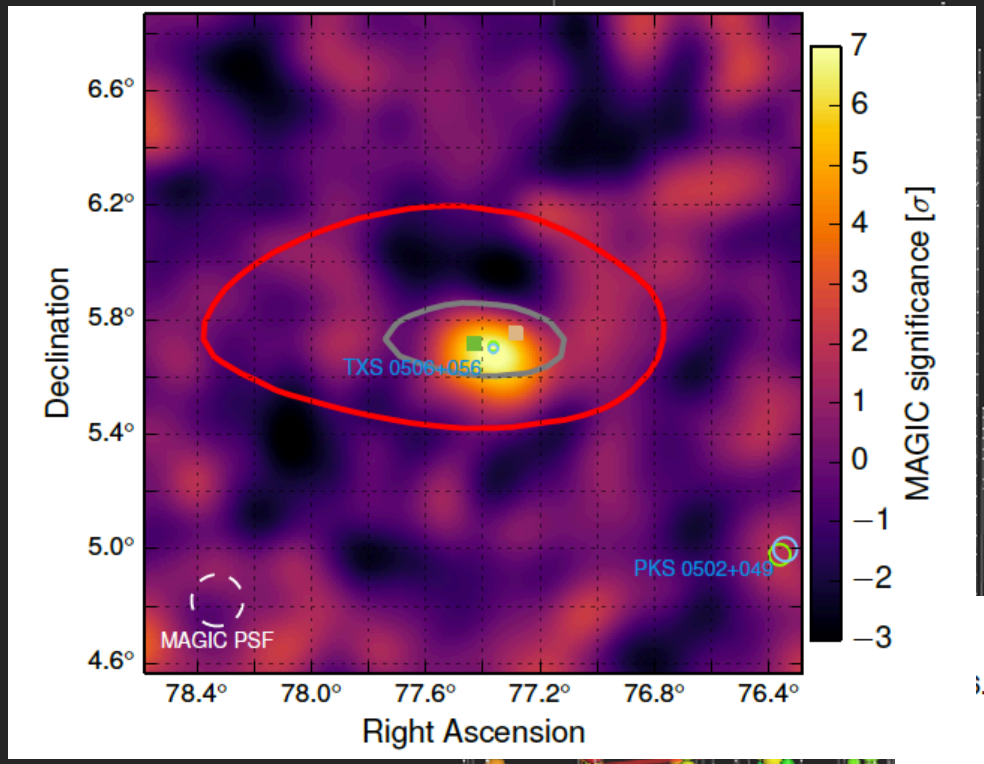
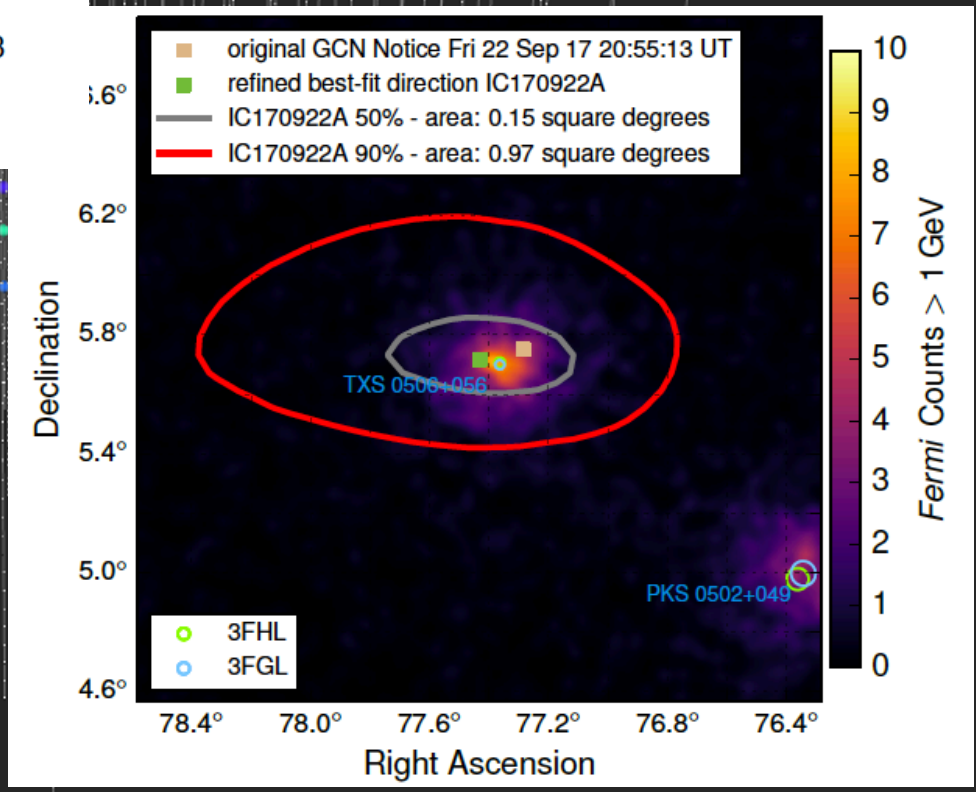


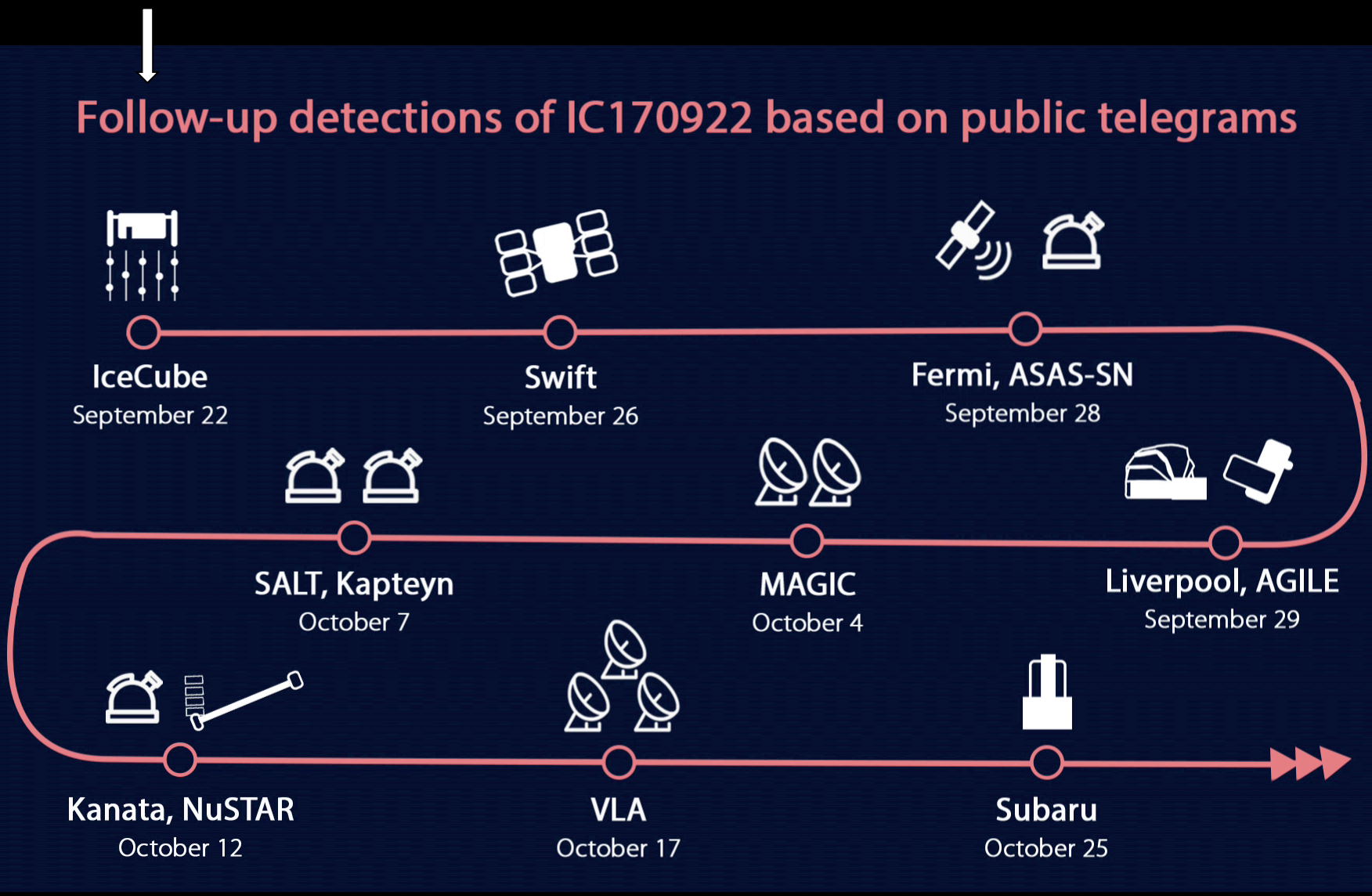
IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas



MASTER robotic optical telescope network: after 73 seconds



THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

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Submitted to ApJL

ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365$\pm$0.0010.

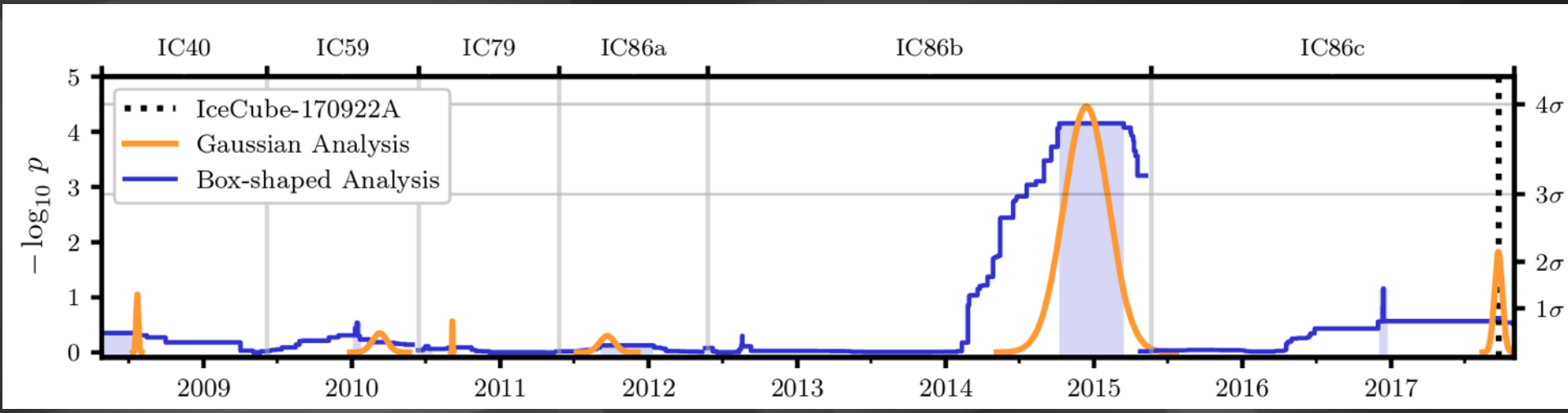
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

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

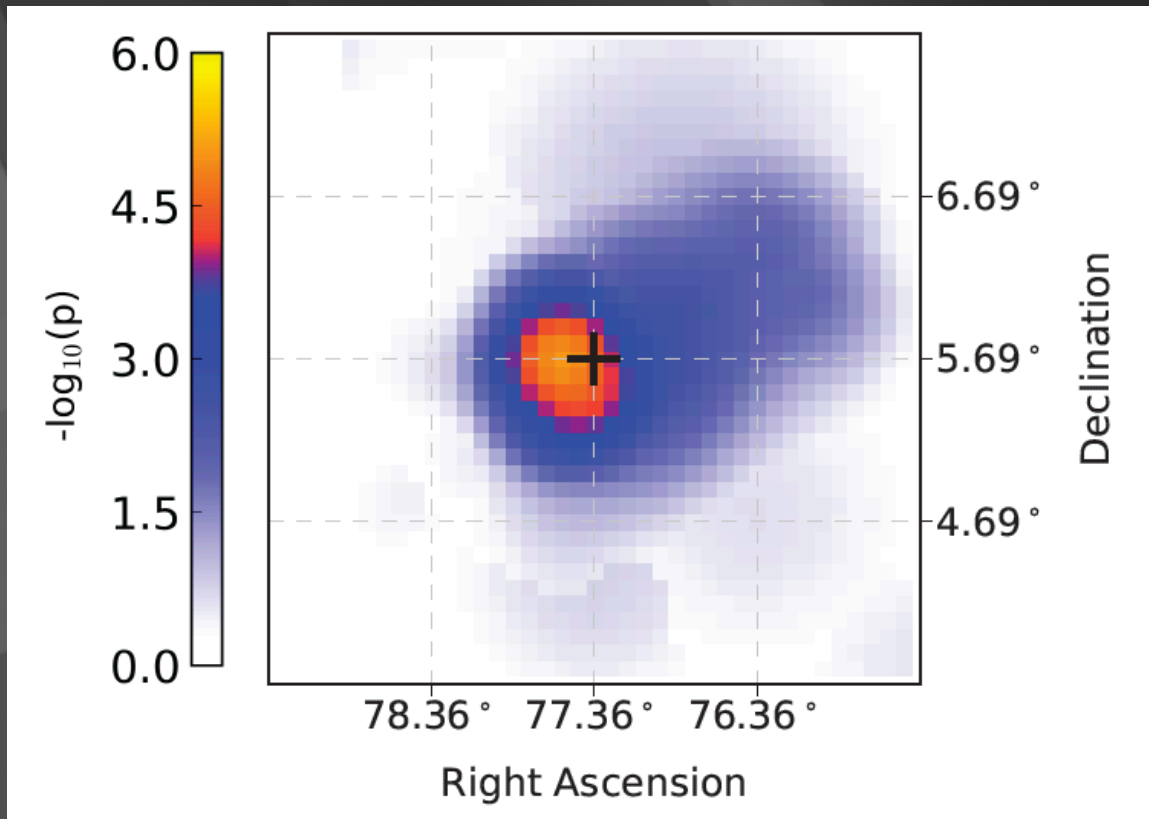
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.06^{o} (7x steady flux, daily variations)
- MAGIC: TeV source in follow-up observations
- follow-up by more telescopes

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



search in archival IceCube data:

- 150-day flare in 2014-15
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
- dominates the total luminosity in ten years



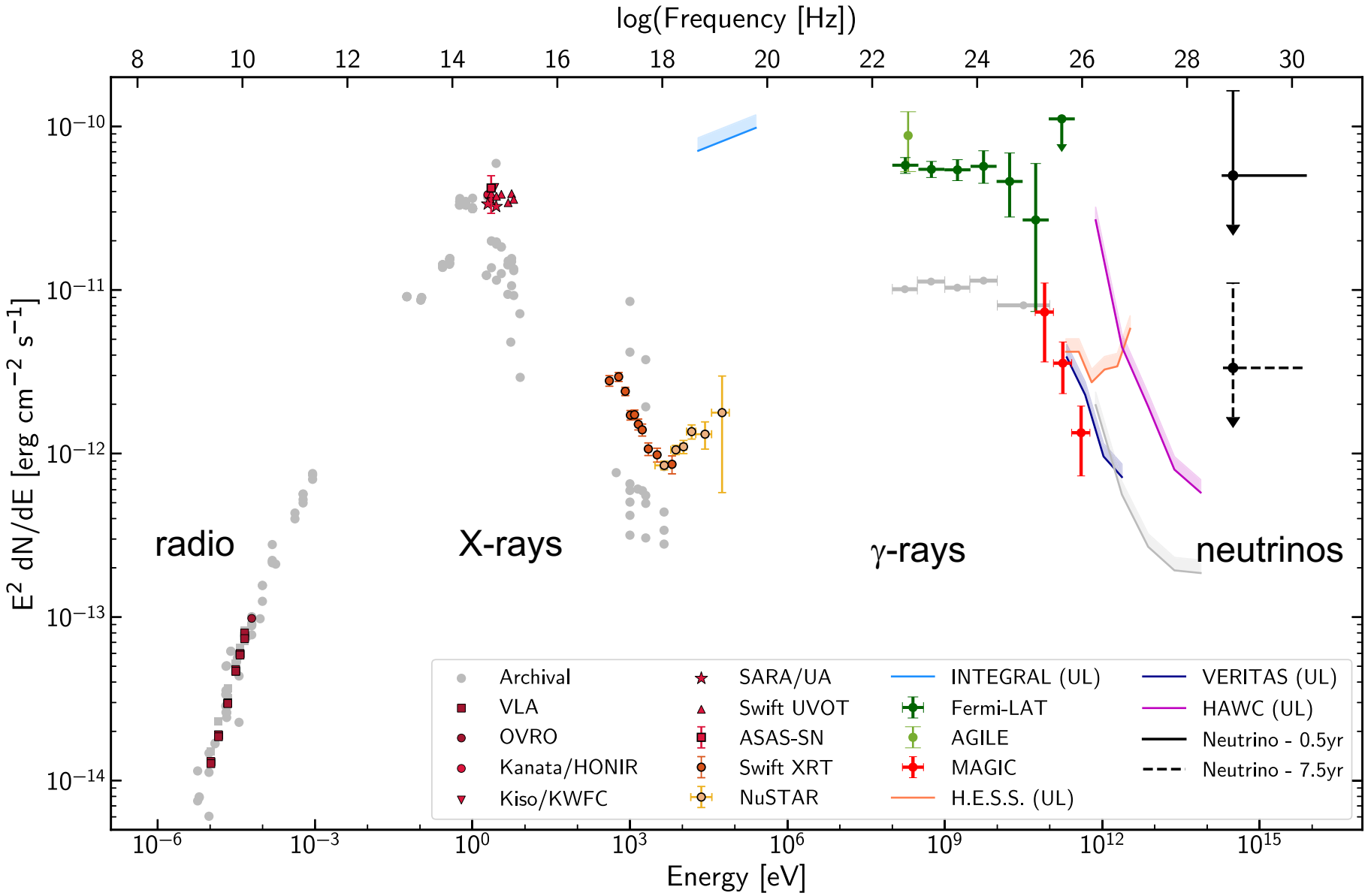
we identified a source of high energy cosmic rays:

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?

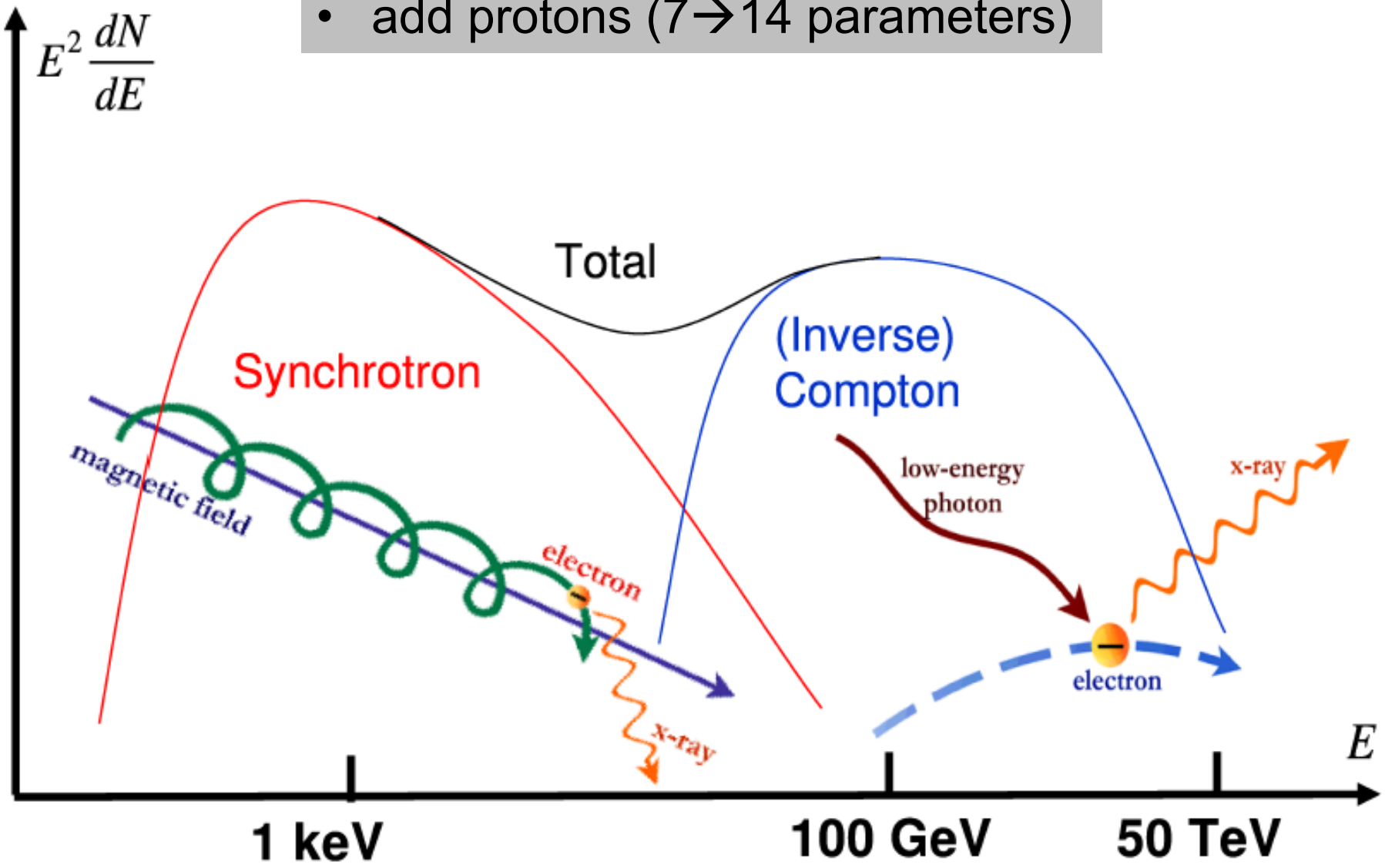
no gamma ray flare accompanying 2014-15 burst (hint of hardening spectrum?)

theory: a problem?



blazar models cannot produce a single neutrino

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



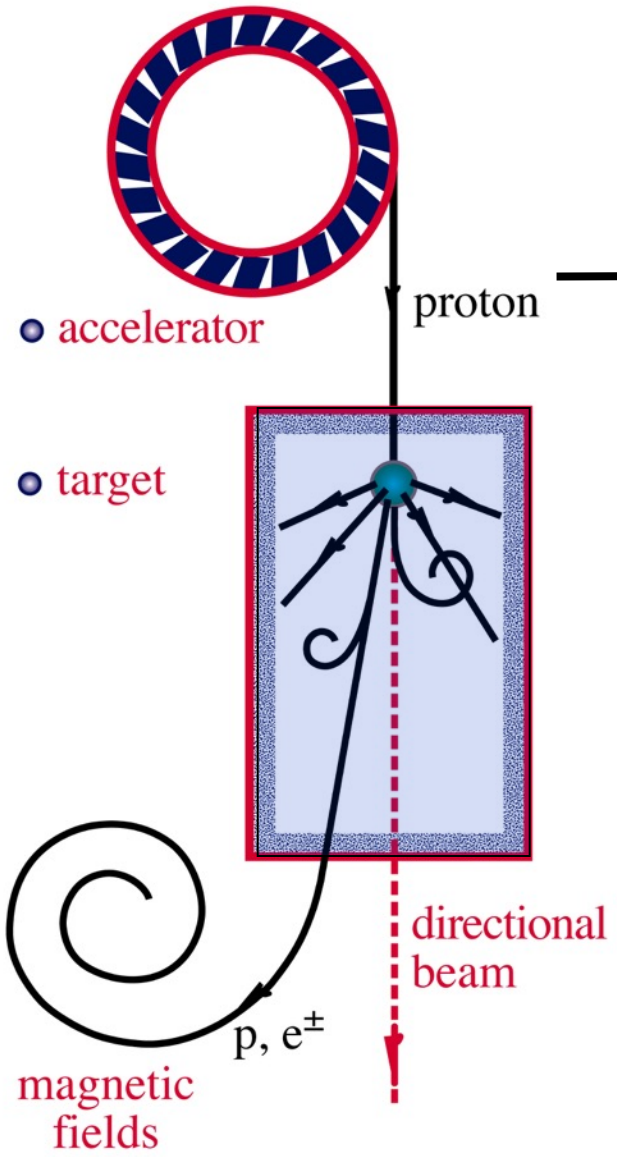
solution:

TXS is *not* a blazar at times that neutrinos are produced, IceCube's neutrinos are detected from temporally gamma-suppressed blazars

when a source is transparent to high energy gamma rays there is an insufficient photon or matter target density to produce neutrinos. Opacity to photons is ~100 times that to protons.

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

ν and γ beams : heaven and earth



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

→ cosmic ray + neutrino

supermassive black hole

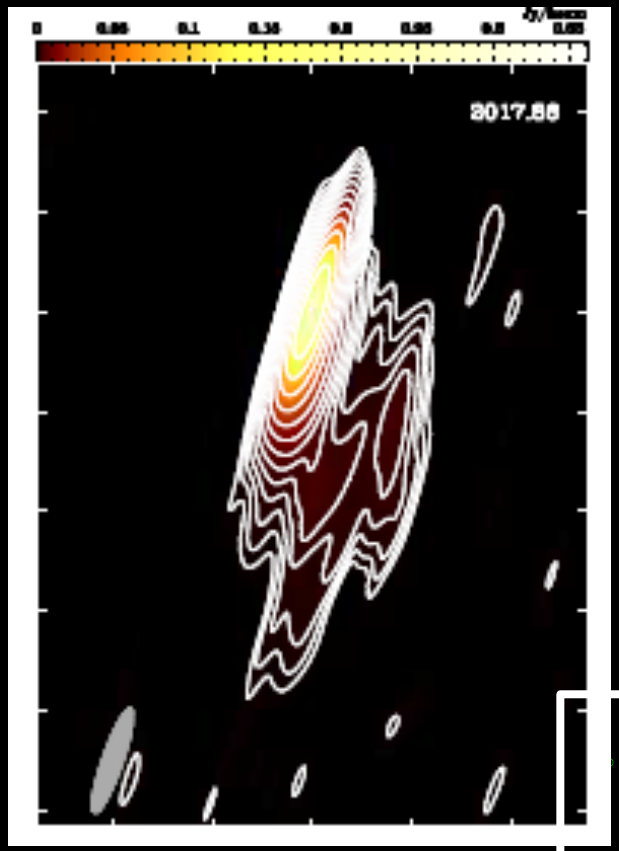
target ?

→ a neutrino source needs an accelerator and a target

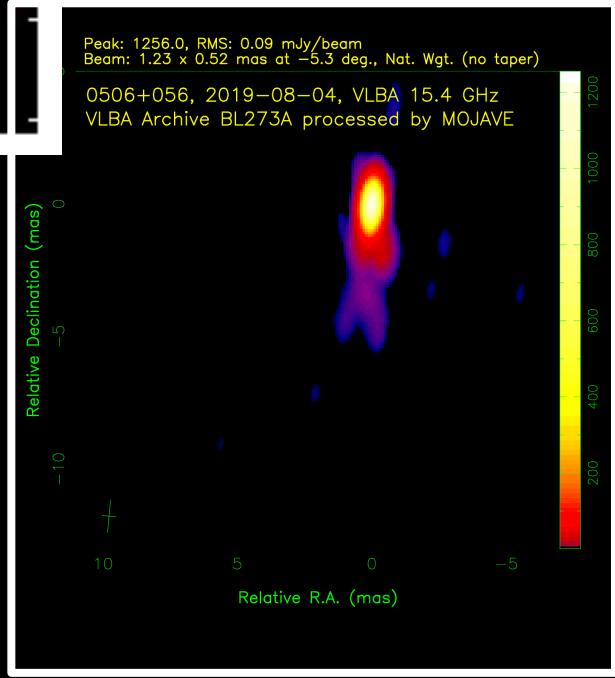
→ the target is likely opaque to gamma rays

radio interferometry images show the target

- 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

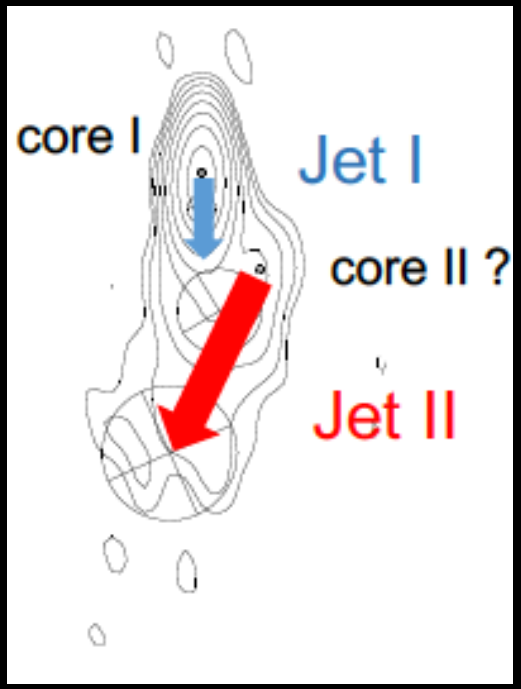


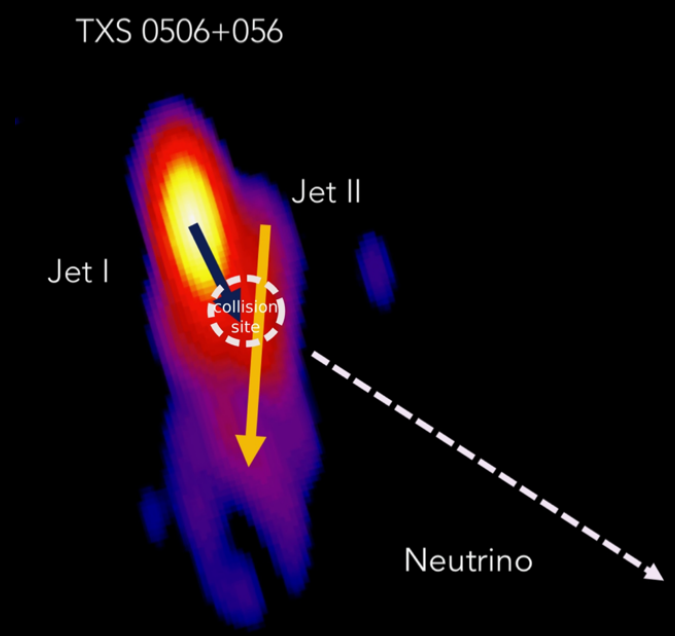
1912.01743v1
[astro-ph.GA]

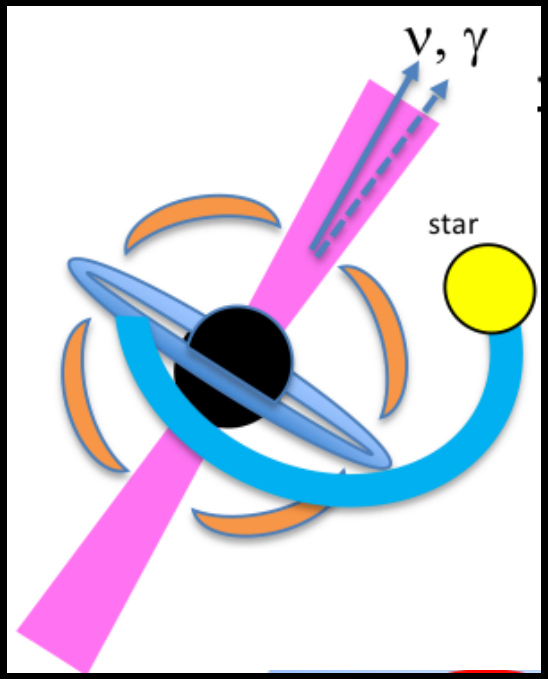
TXS 0506+056

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

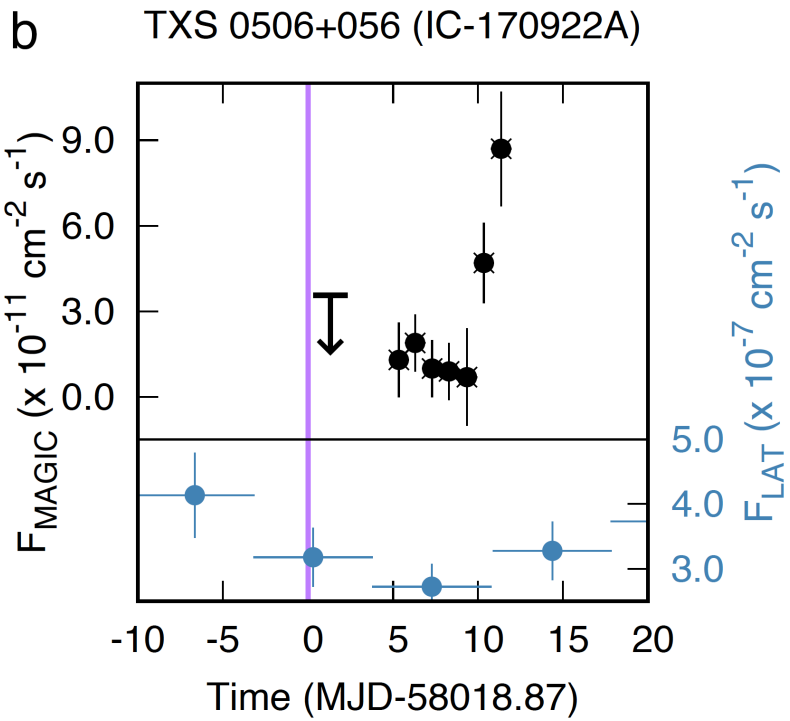
- *radio interferometry images show that the jet interacts with a target close to the core of the galaxy*
- a massive star in the host galaxy, the jet of a merging galaxy?
- the gamma rays accompanying the neutrinos lose their energy in the target that produces them







no TeV gamma rays at the time the neutrino



- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- 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

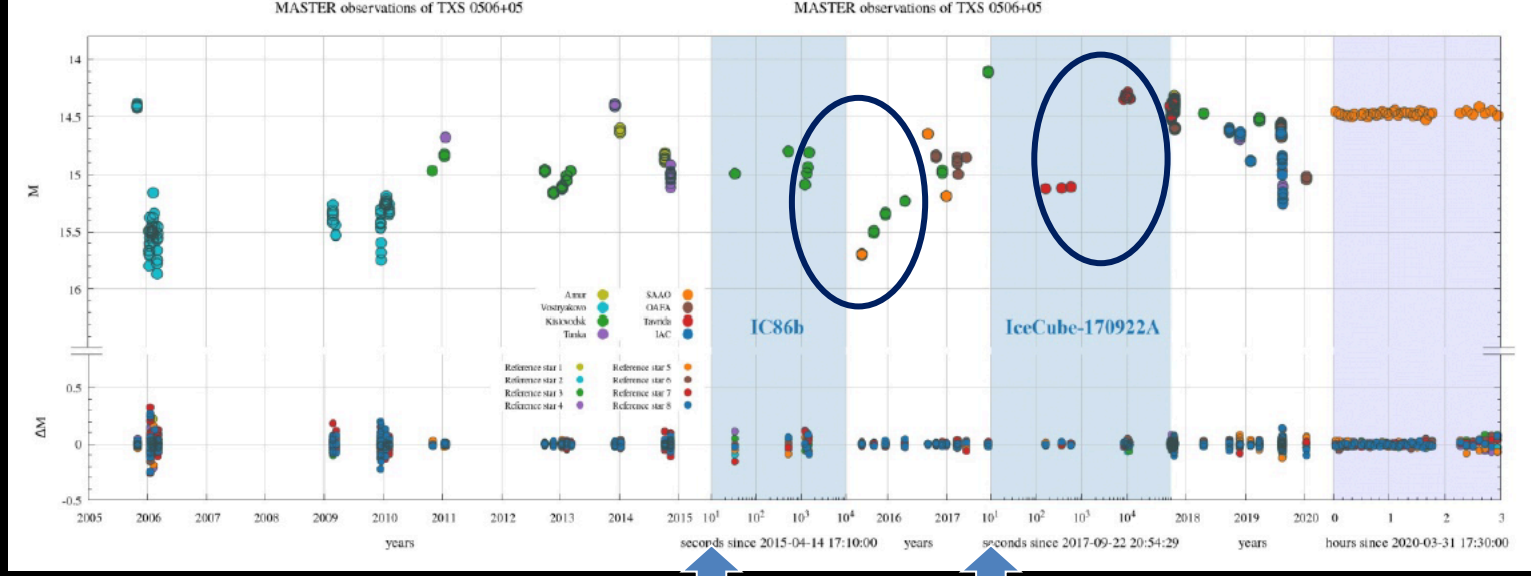
V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8] , P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2],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

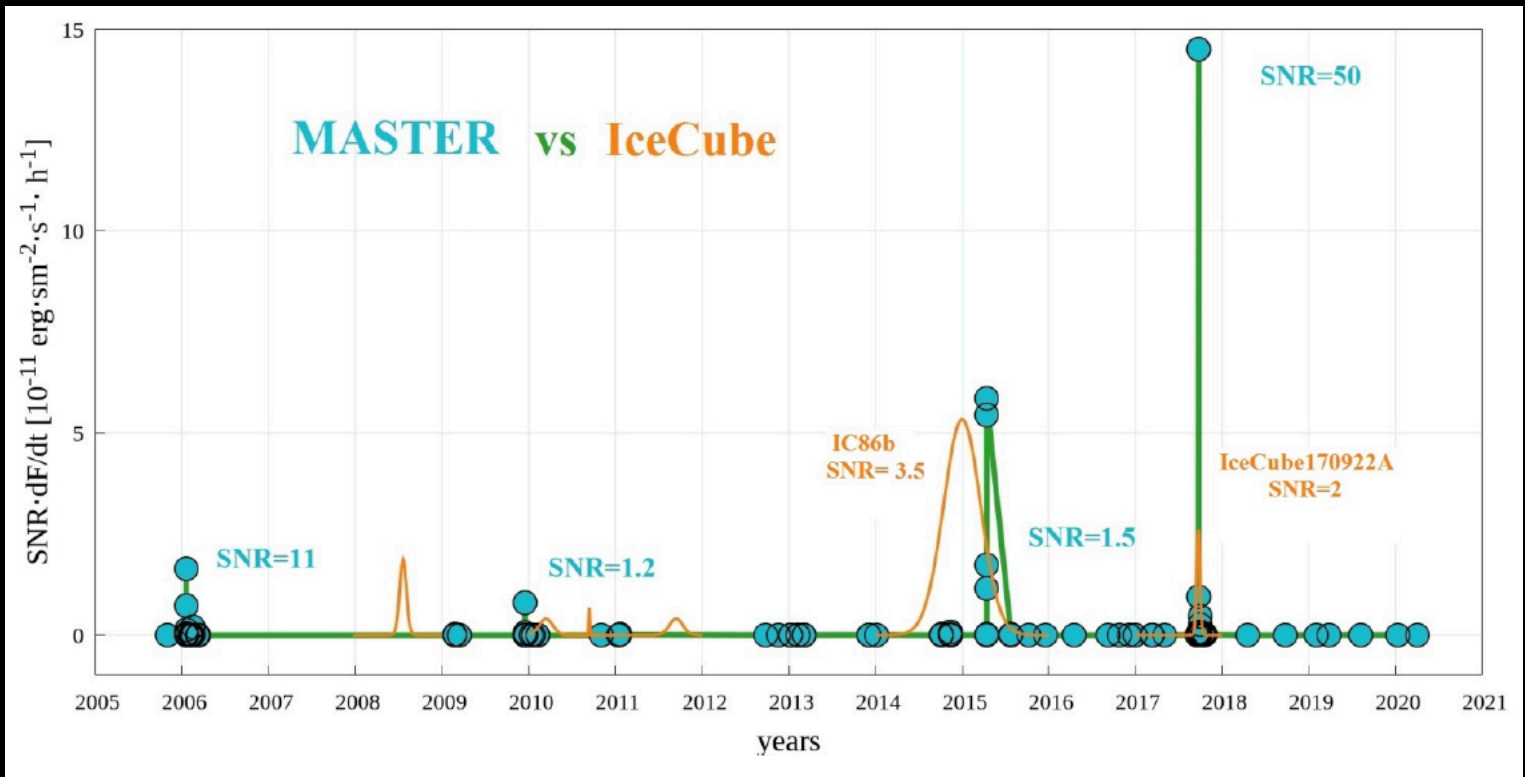


seconds after 2014-15 burst

seconds after IC170922

time variation of flux
times
signal-to-noise

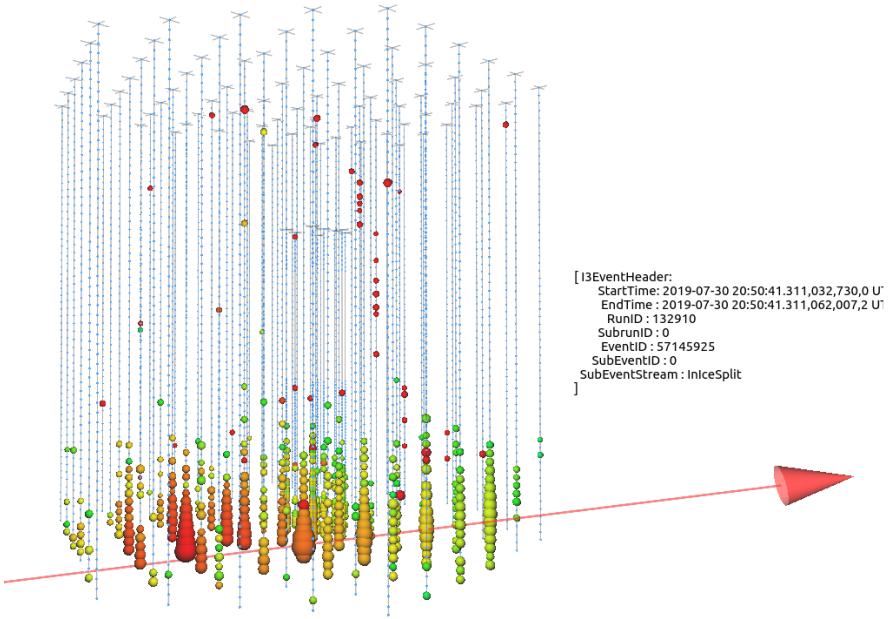
hour-scale variability of the source after neutrino emission

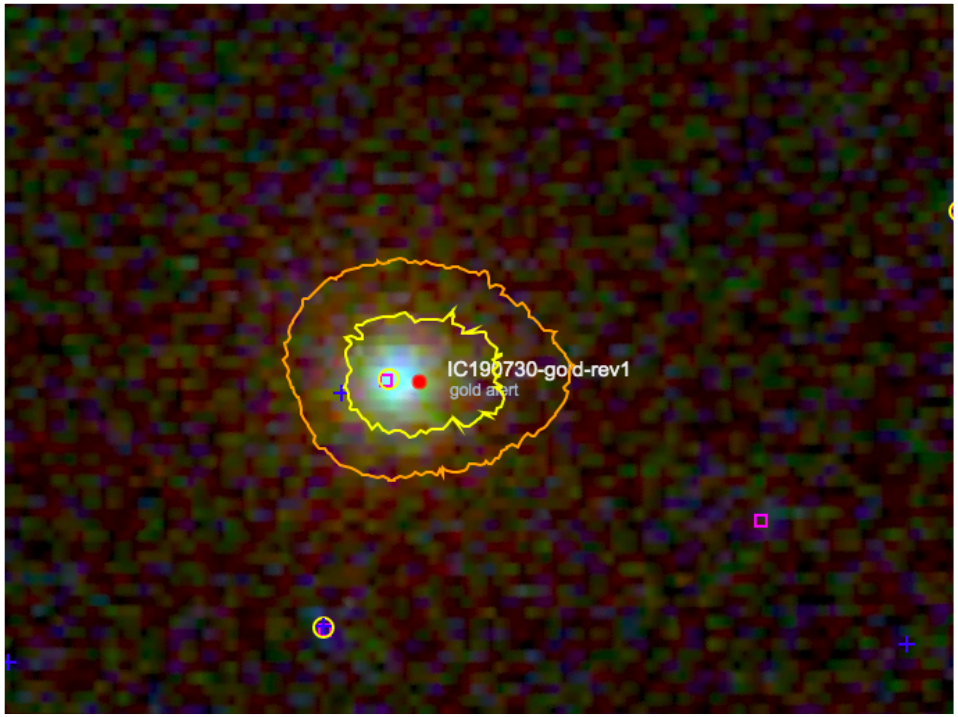


IceCube's neutrinos are detected from temporally gamma-suppressed blazars

- what is the target found in the radio and optical images?
- multimessenger astronomy is “subtle but not malicious”
- some other intriguing events: 190730, 191001, 200107…

a second cosmic ray source





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[Previous | Next]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

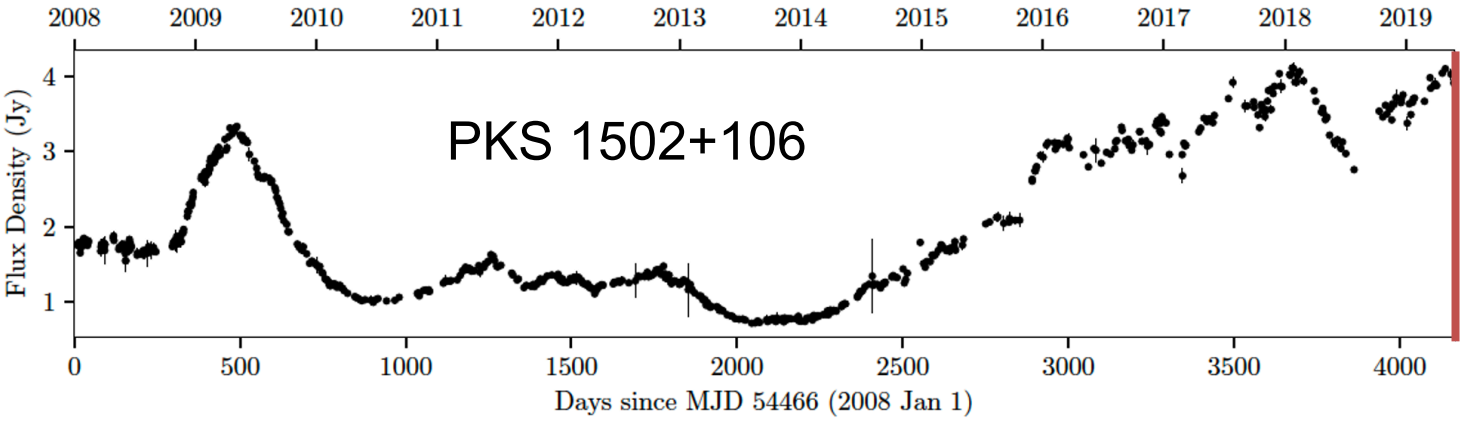
Tweet

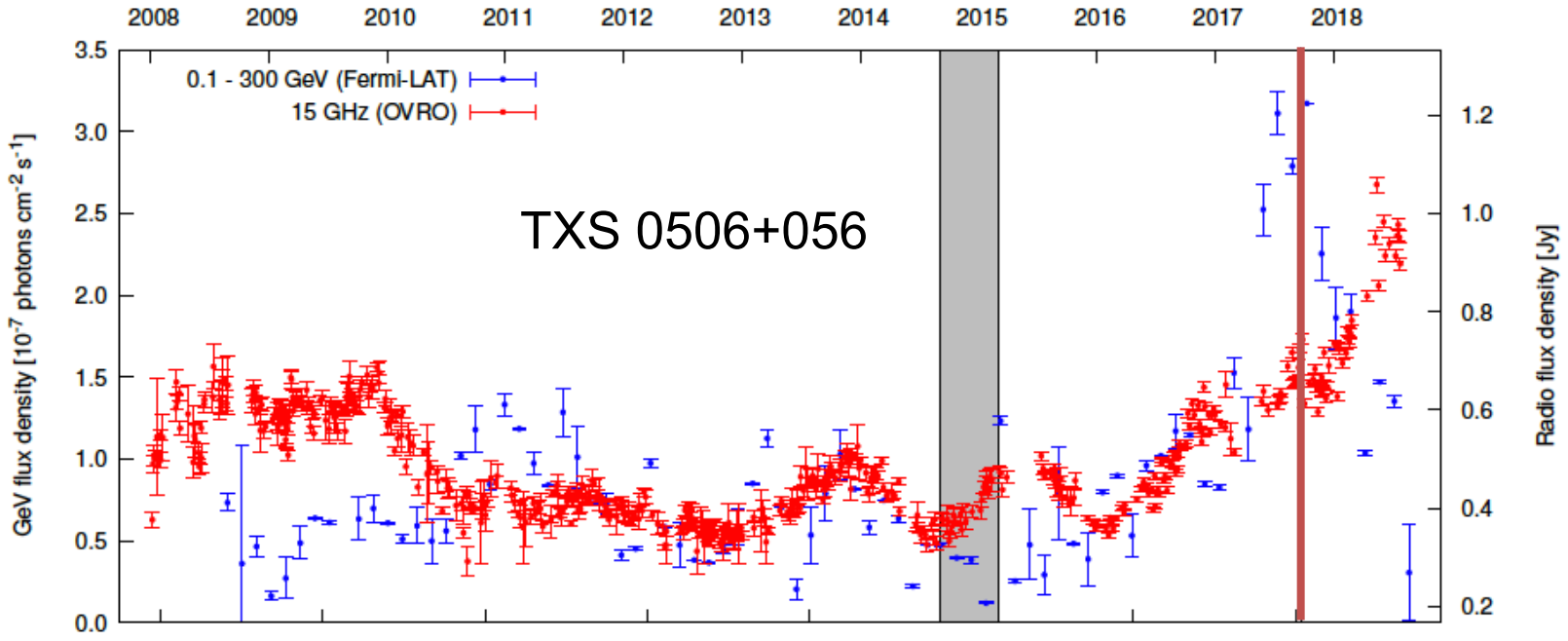
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

Related

12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974	Optical follow-up of IceCube-190730A with ZTF
12971	IceCube-190730A: MASTER alert observations and analysis
12967	IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926	VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

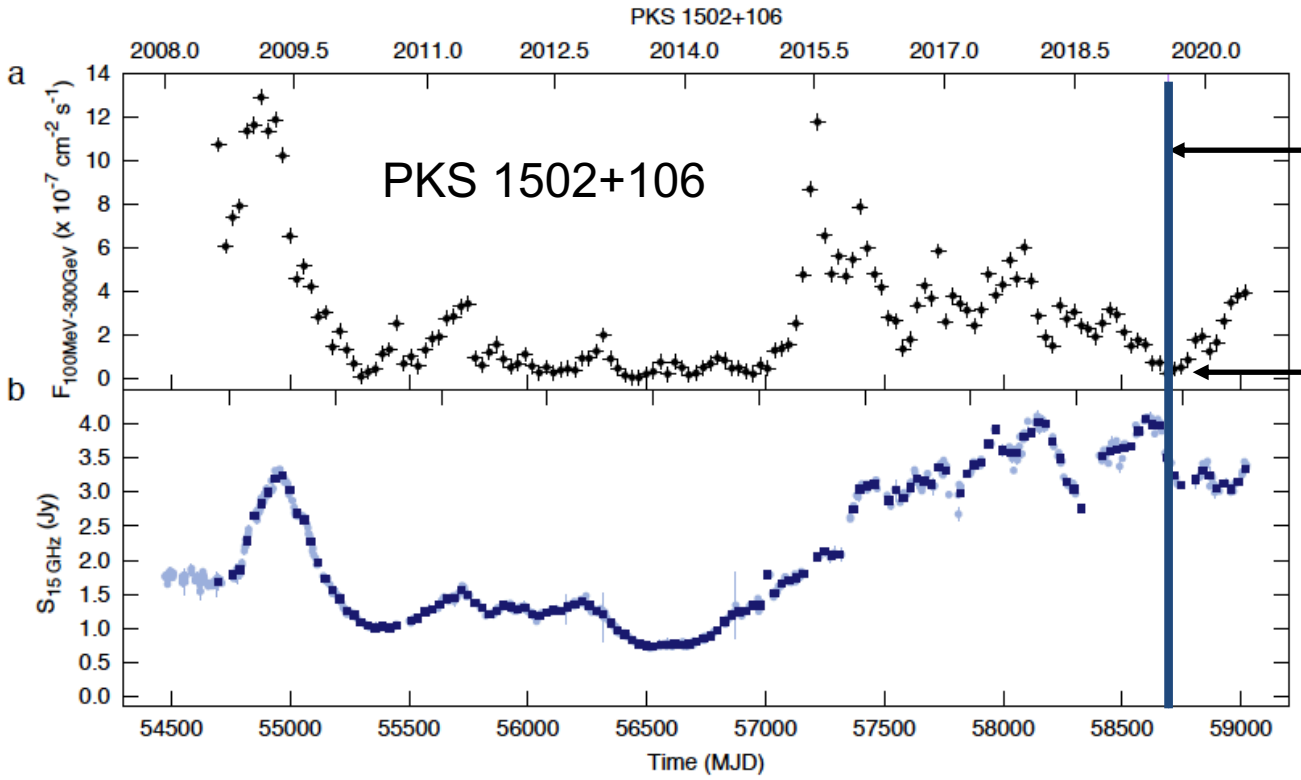
the two highest energy (300 TeV ν_μ) IceCube neutrino alerts are coincident with radio flares





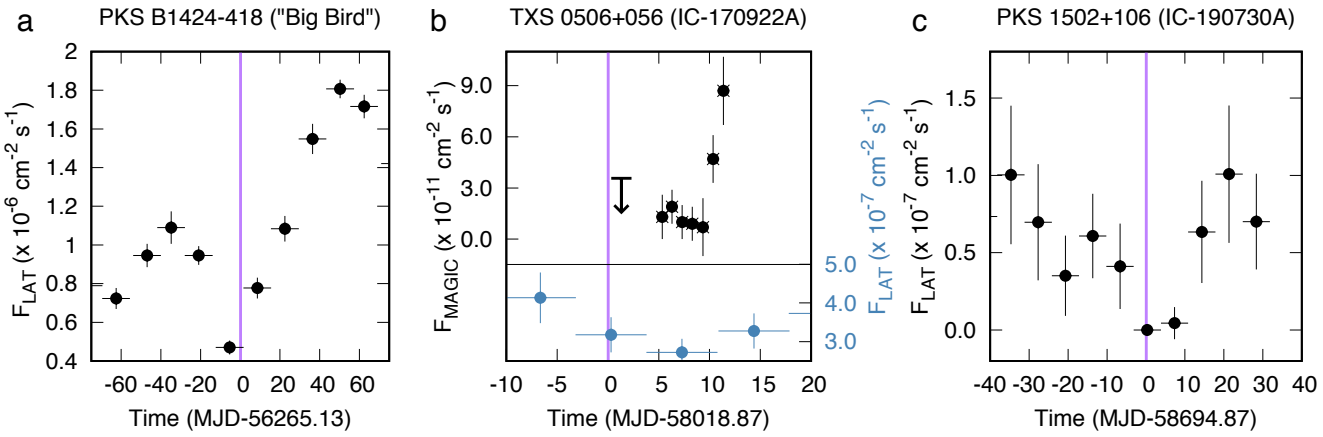
γ-ray

radio



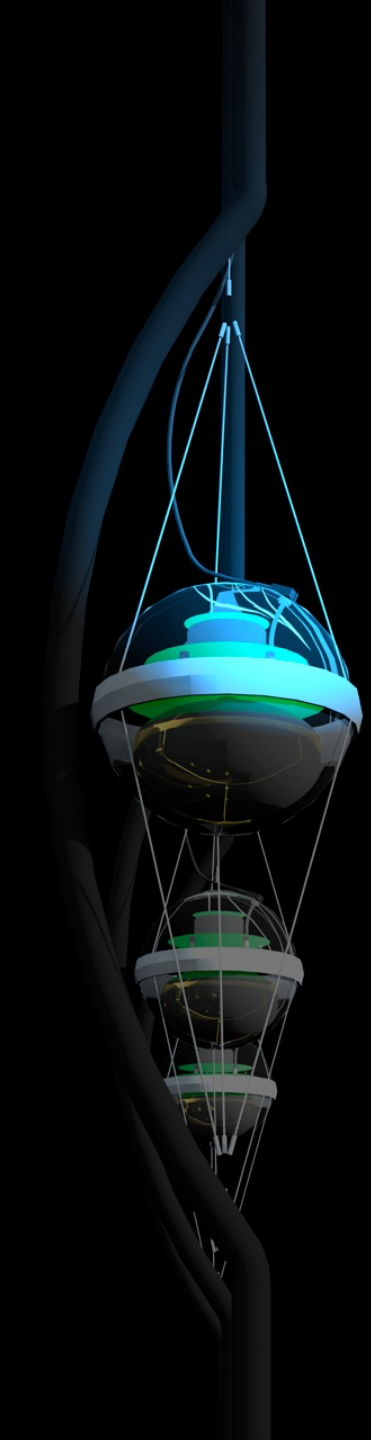
300 TeV neutrino produced

target moves through the jet blocks photons



other examples

2009.09792 [astro-ph.HE]



neutrino astronomy 2020

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

icecube.wisc.edu

THE ICECUBE COLLABORATION

THE ICECUBE COLLABORATION

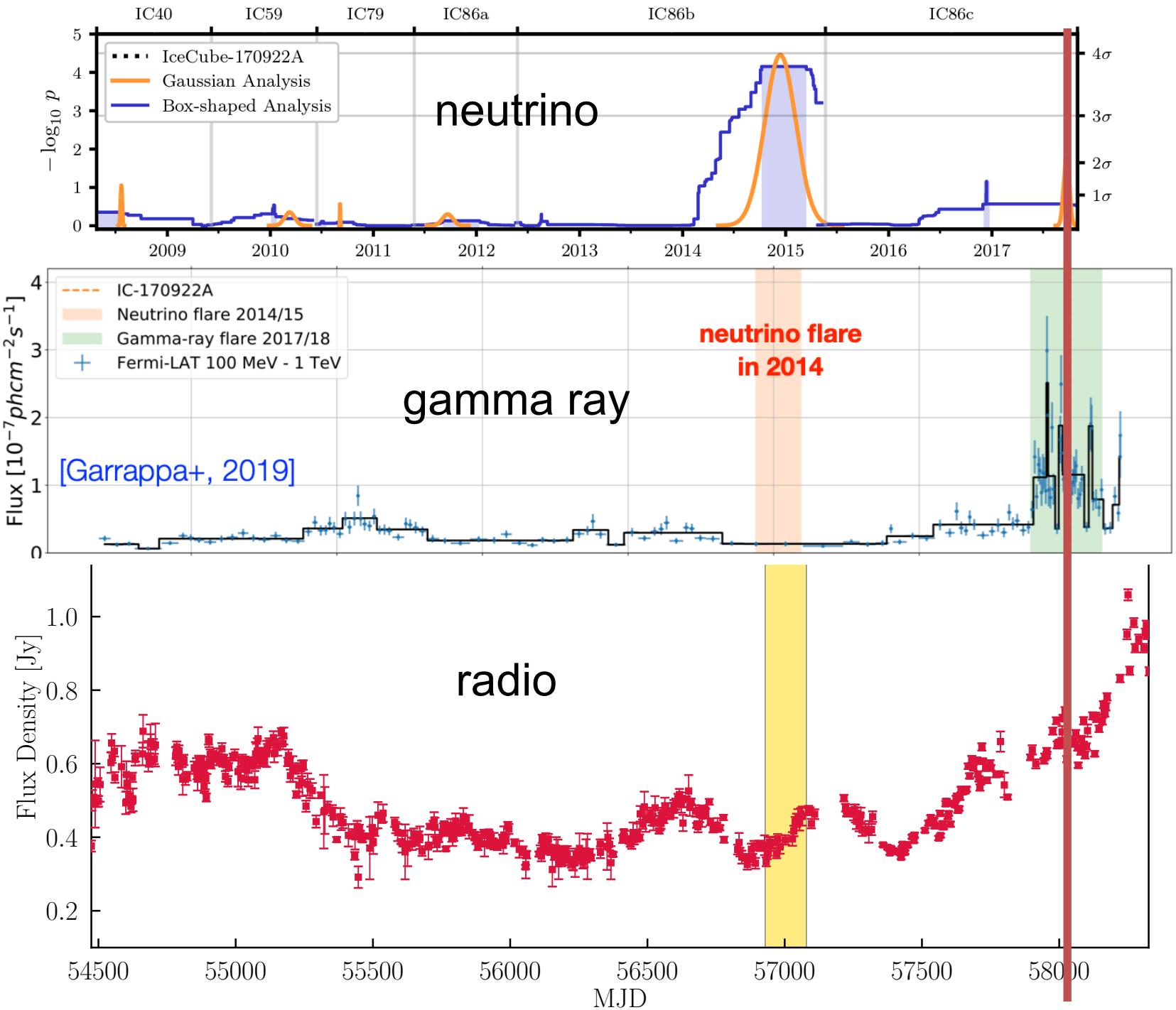
...STRALIA 1

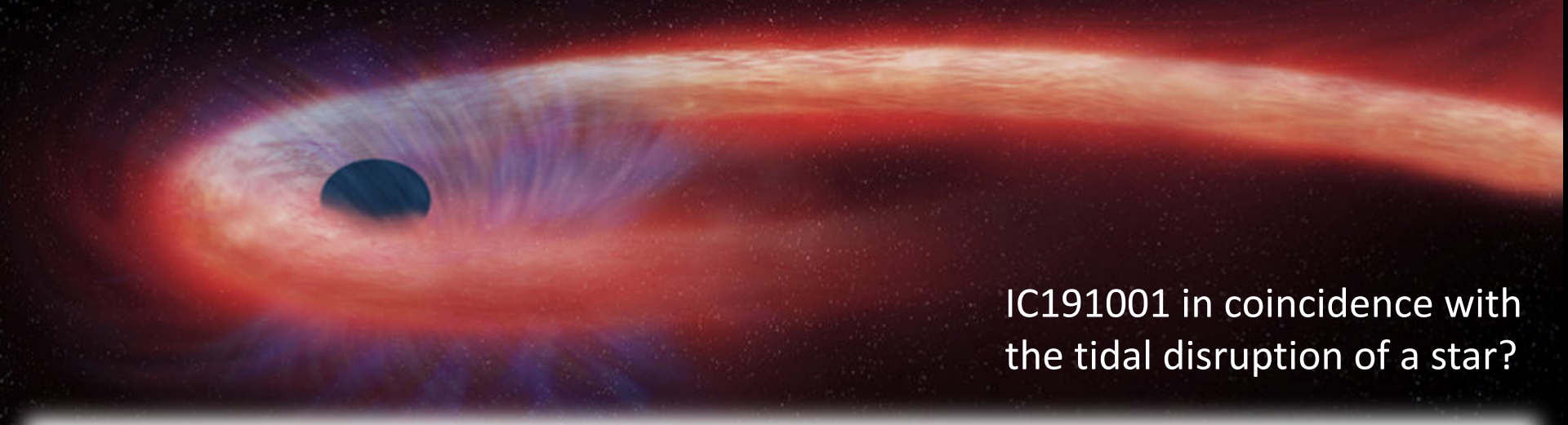
...NGDOM 1

UNITED STATES 25

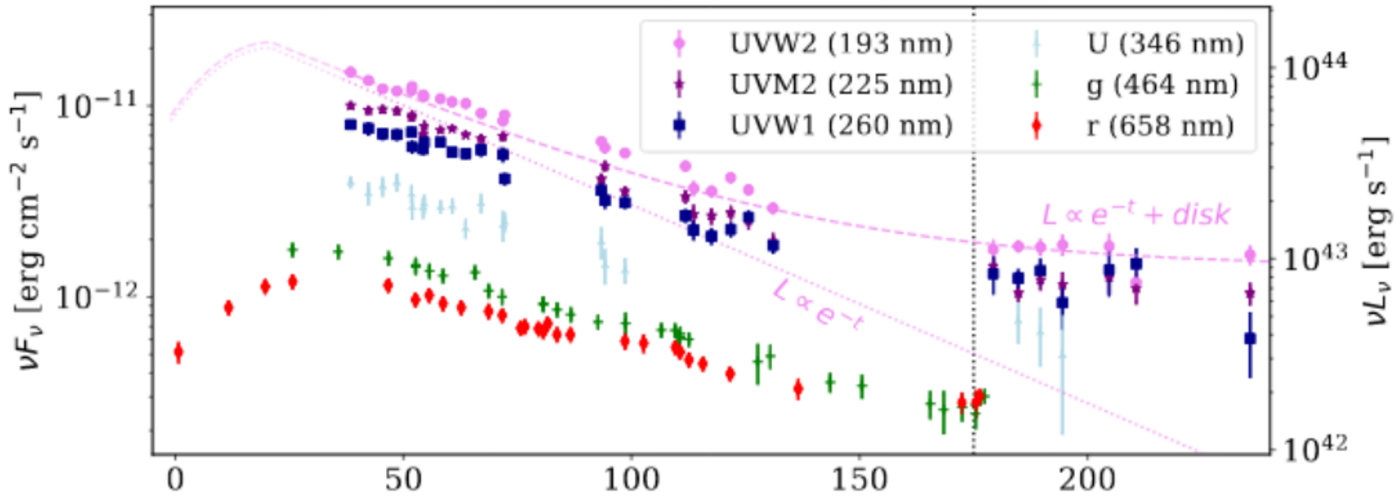
IceCube
South Pole Neutrino Observatory

overflow sides


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
neutrino flare
in 2014
gamma ray
[Garrappa+, 2019]
Flux [$10^{-7} phcm^{-2}s^{-1}$]
radio
Flux Density [Jy]
MJD
54500
55000
55500
56000
56500
57000
57500
58000



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})