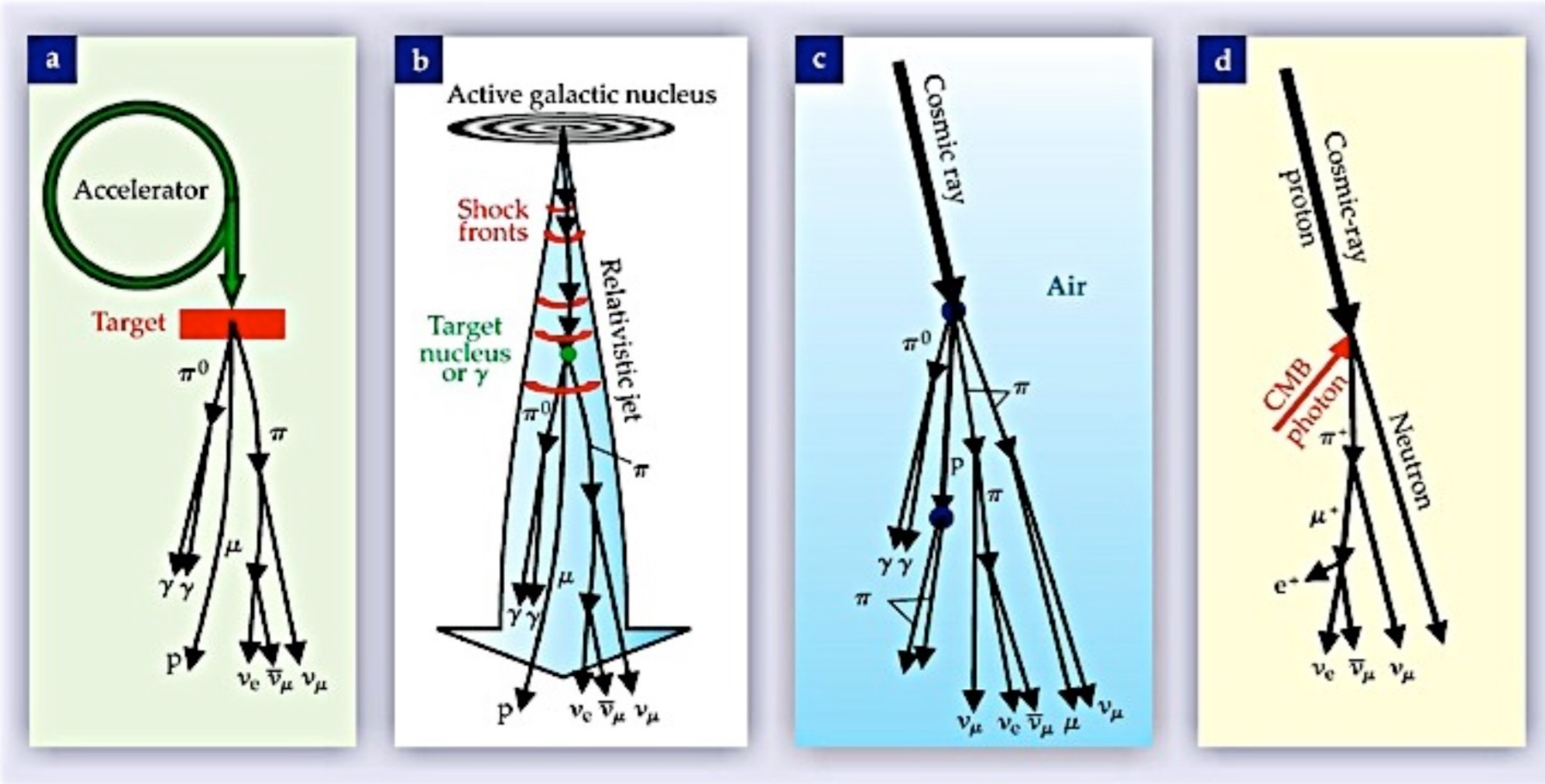
Astrofisica Nucleare e Subnucleare

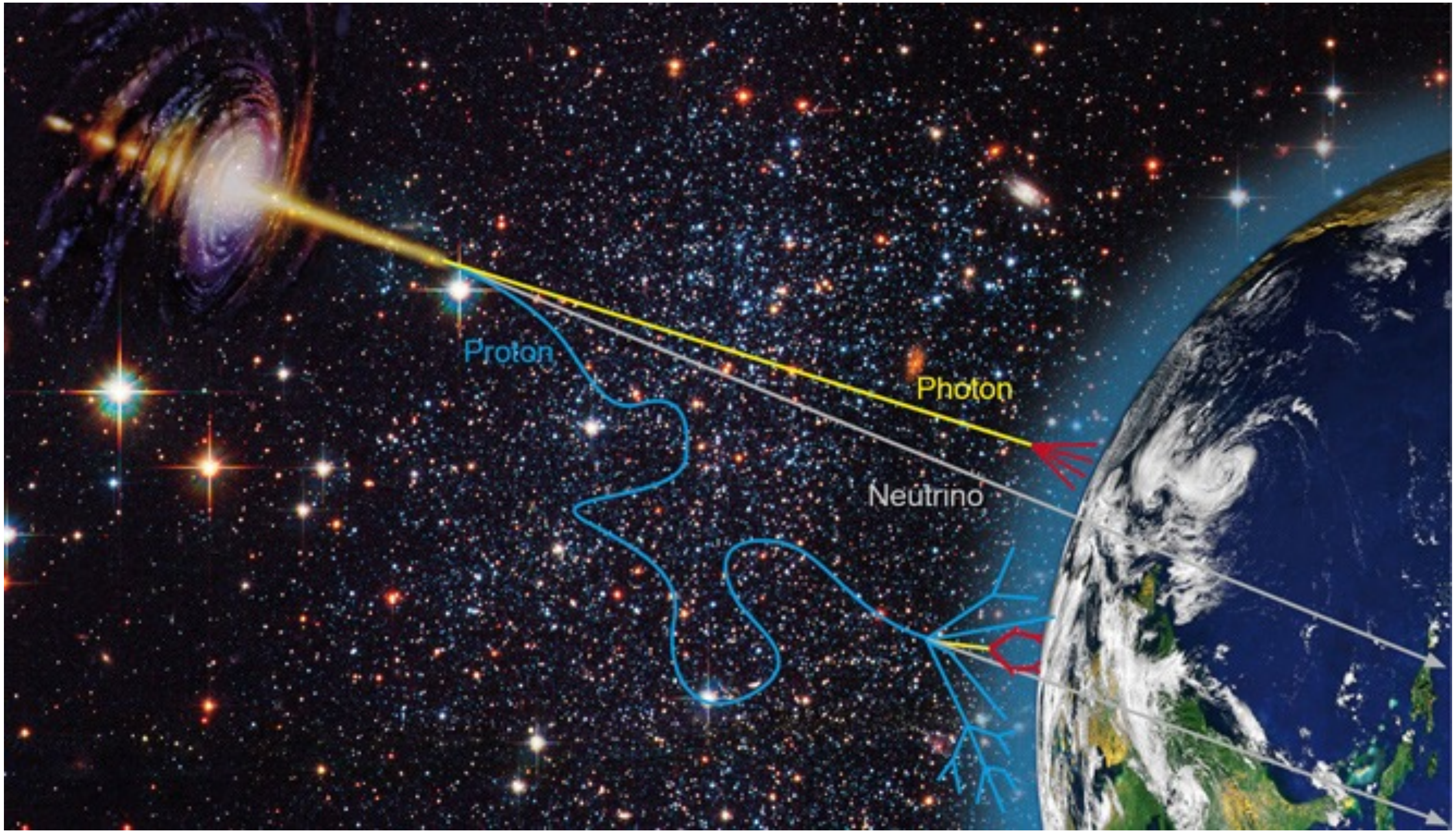
Astrophysical Neutrinos

Summary of neutrino production modes



From Physics Today

Astrophysical Neutrinos



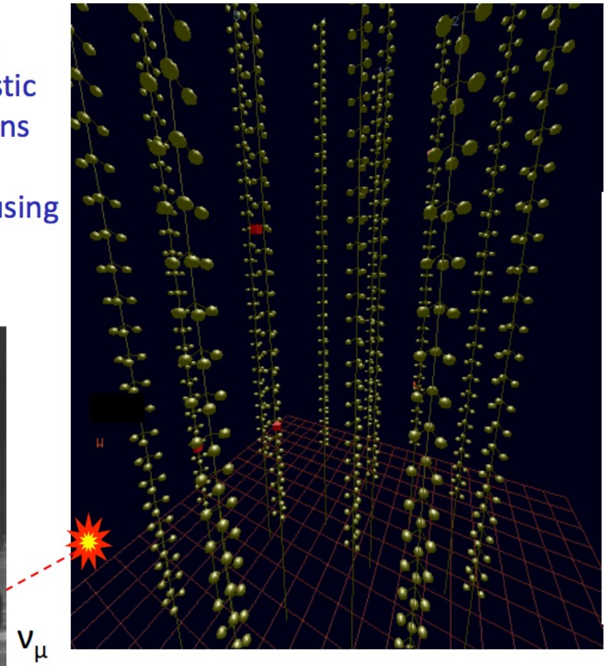
The ANTARES neutrino telescope

A.Margiotta
Dipartimento di Fisica e Astronomia
Alma Mater Studiorum, Università Bologna
and
INFN Bologna
on behalf of the ANTARES Collaboration

XII International Conference on New Frontiers in Physics - Crete, 10-23 July 2023

The concept of Cherenkov neutrino telescopes

- Photomultipliers (PMTs) collecting Cherenkov photons due to relativistic charged particles from ν interactions
- Parent ν direction reconstructed using time & position of optical sensors



First tentative in water mid '70s:
Deep **U**nderwater **M**uon **A**nd **N**eutrino **D**etector **Project**
(https://www.phys.hawaii.edu/~dumand/dumacomp.html)
about 4800 m under the sea - Hawaii island

DUMAND-II Progress Report

R. J. Wilkes, for
The DUMAND Collaboration :
C.M. Alexander[4], T. Aoki[11], U. Berson[1], P. Bosetti[1], J. Bolesta[4], P.E. Boynton[14], H. Bradner[9], U. Camerini[15], S.T. Dye[3], E. Gergin[3], P.W. Gorham[4], P.K.F. Grieder[2], W. Grogan[15], H. Hanada[10], D. Harris[4], T. Hayashino[10], E. Hazen[3], M. Ito[10], M. Jaworski[11], M. Jenko[3], H. Kawamoto[10], T. Kitamura[7], K. Kobayakawa[6], S. Kondo[4], P. Koske[5], J.G. Learned[4], C. Ley[1], J.J. Lord[14], R. Lord[14], T. Lozic[3], R. March[15], T. Matsumoto[10], S. Matsuno[4], A. Mavretic[3], L. McCourry[14], M. Mignard[4], K. Miller[13], P. Minkowski[2], R. Mitiguy[4], K. Mitsui[11], S. Narita[10], D. Nicklaus[15], Y. Ohashi[11], A. Okada[11], D. Orlov[3], V.Z. Peterson[4], A. Roberts[4], M. Sakuda[12], V.J. Stenger[4], H. Suzuki[10], S. Tanaka[10], S. Uehara[12], C. Wiebusch[1], G. Wilkins[4], M. Webster[13], R.J. Wilkes[14], G. Wurm[1], A. Yamaguchi[10], I. Yamamoto[8], K.K. Young[14]

1) Technische Hochschule Aachen, Germany; 2) University of Bern, Switzerland; 3) Boston University, USA; 4) University of Hawaii, USA; 5) University of Kiel, Germany; 6) Kobe University, Japan; 7) Kinki University, Japan; 8) Okayama Science University, Japan; 9) Scripps Institution of Oceanography, USA; 10) Tohoku University, Japan; 11) ICRR, University of Tokyo, Japan; 12) NLHEP, Tsukuba, Japan; 13) Vanderbilt University, USA; 14) University of Washington, USA; 15) University of Wisconsin, USA.

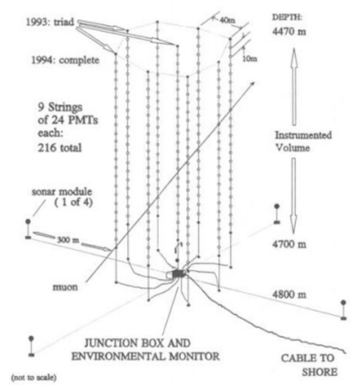
Abstract

The design, scientific goals, and capabilities of the DUMAND II detector system are described. Construction was authorized by DOE in 1990, and construction of various detector subsystems is under way. Current plans include deployment of the shore cable, junction box and three strings of optical detector modules in 1993, with expansion to the full 9-string configuration about one year later.

640 DUMAND-II Progress Report

DUMAND II Neutrino Telescope

Instrumented volume: 230 m high, 106 m diameter



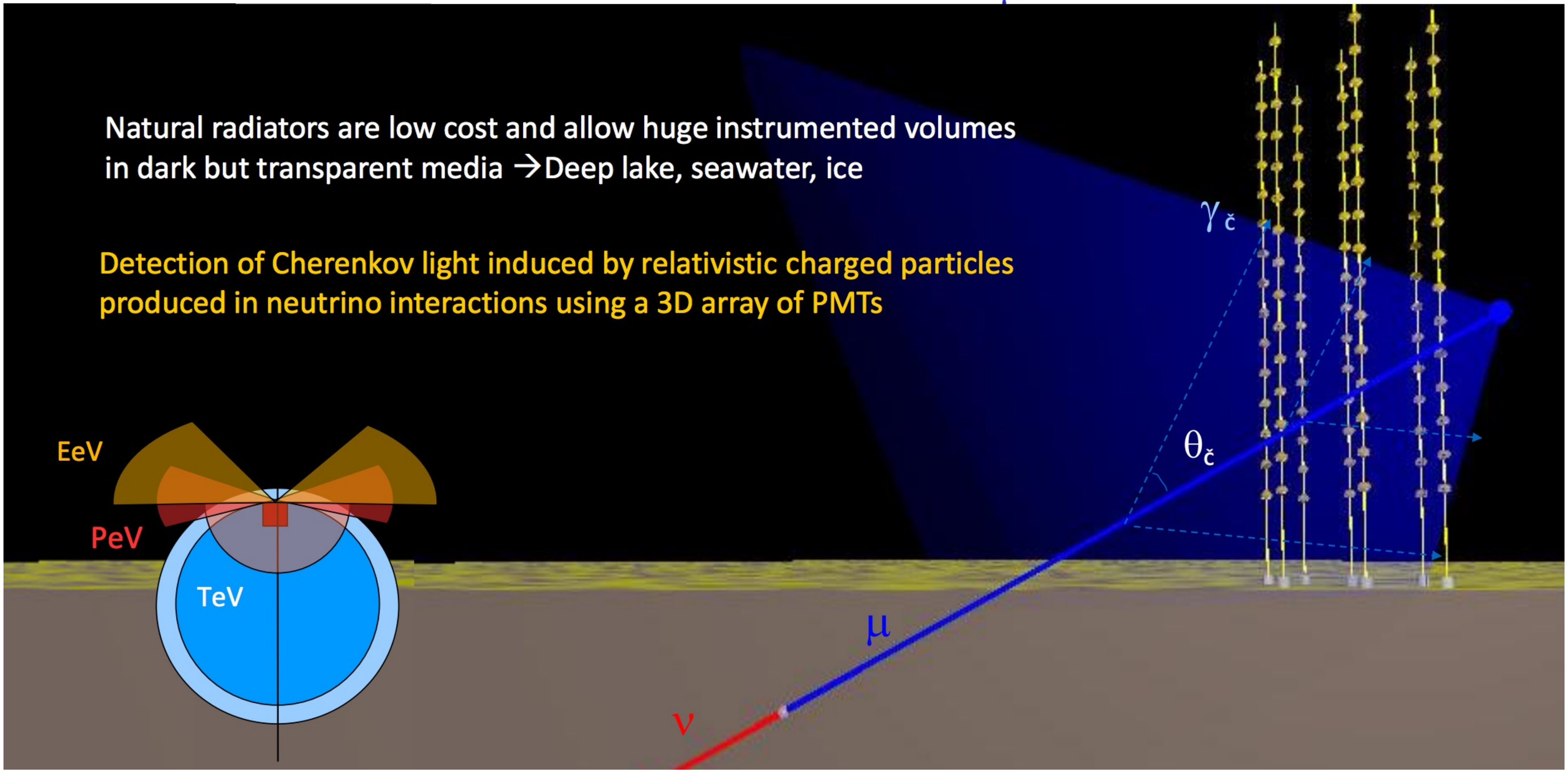
ISVHECRI 1992

DUMAND Project canceled in 1996 because of technological problems

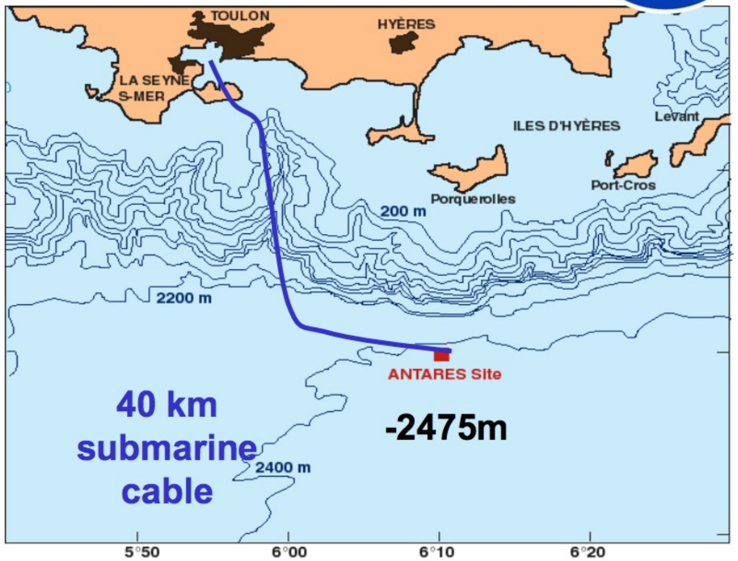
Precursor of the present neutrino telescopes, under water and ice

ANTARES accepted the challenge - the present and the future undersea neutrino telescopes shall exploit the ANTARES experience

Detection principle: muon tracks ($CC\nu_\mu$)+ cascades ($NC+\nu_e$)



The ANTARES site

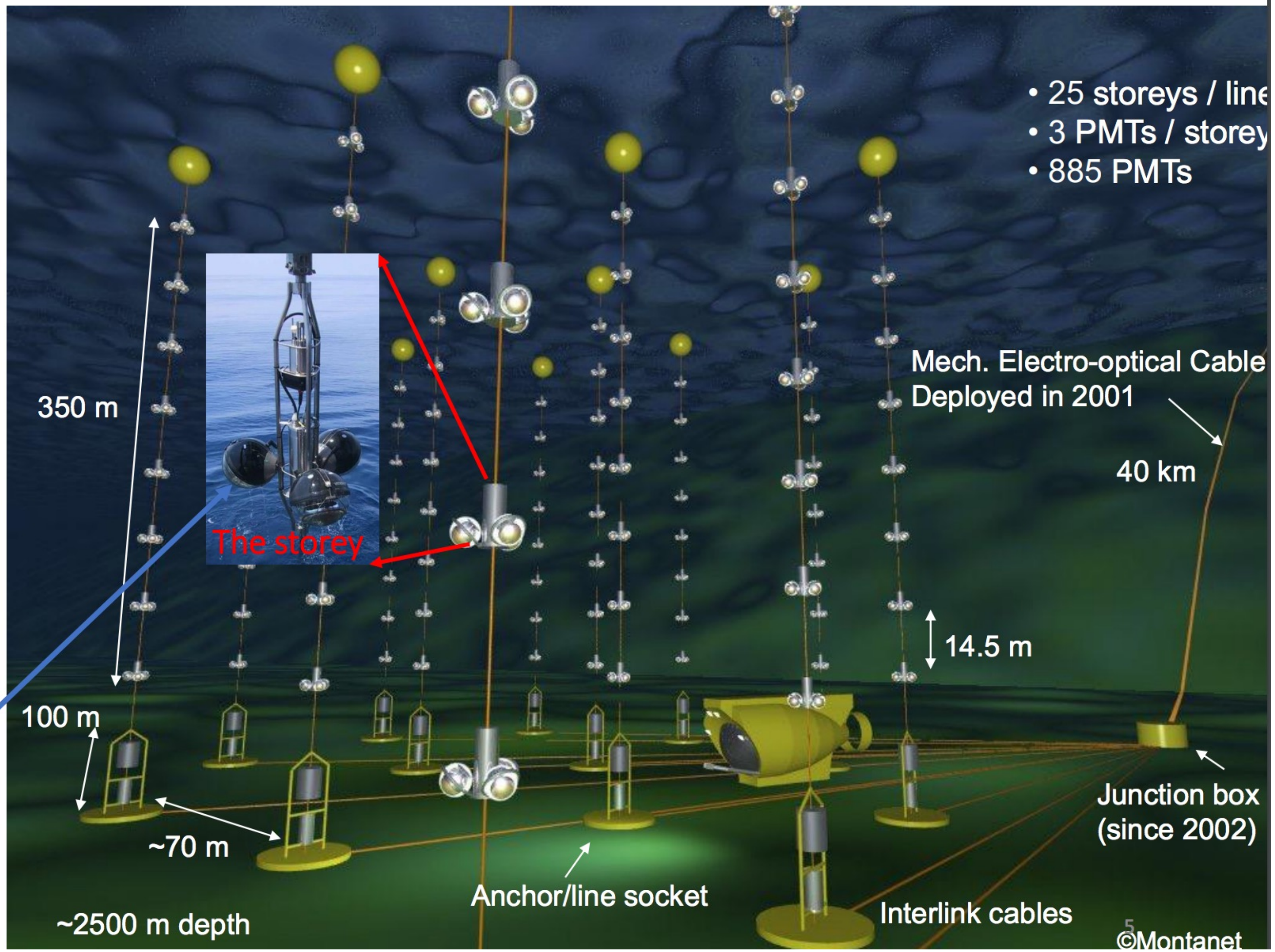


The ANTARES detector

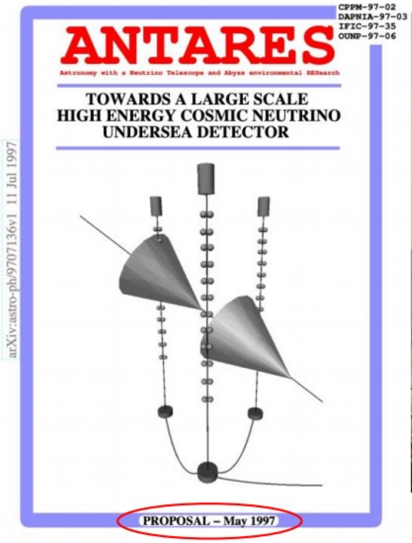
NIM A 656 (2011) 11

The Optical Module

NIM A 484 (2002) 369



ANTARES 2001-2022


CPPM-97-02
DAPNIA-97-03
IFIC-97-35
OUNP-97-06

ANTARES

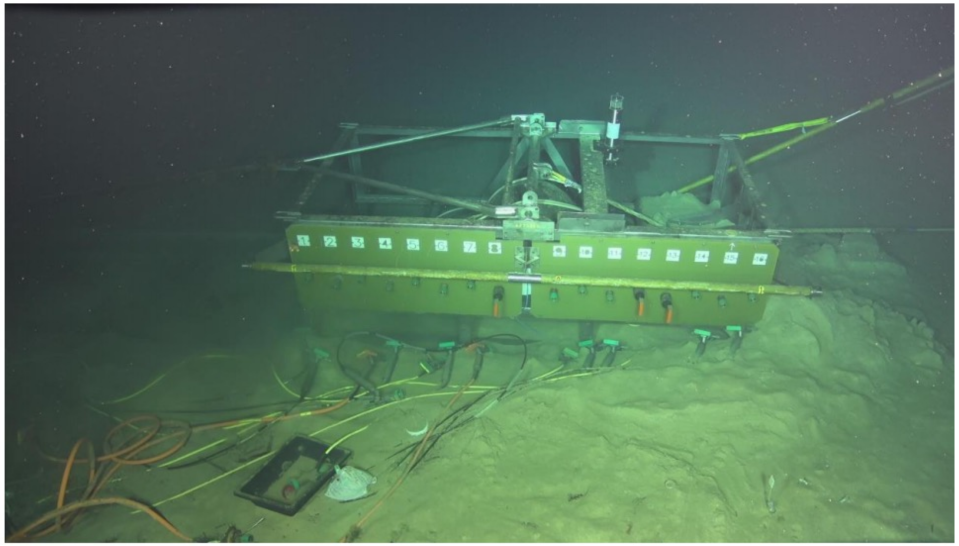
Astronomy with a Neutrino Telescope and Abyss environmental RESearch

TOWARDS A LARGE SCALE
HIGH ENERGY COSMIC NEUTRINO
UNDERSEA DETECTOR

PROPOSAL – May 1997

arXiv:astro-ph/9707136v1 11 Jul 1997

2002 Junction Box deployment:
no failure in 20 years



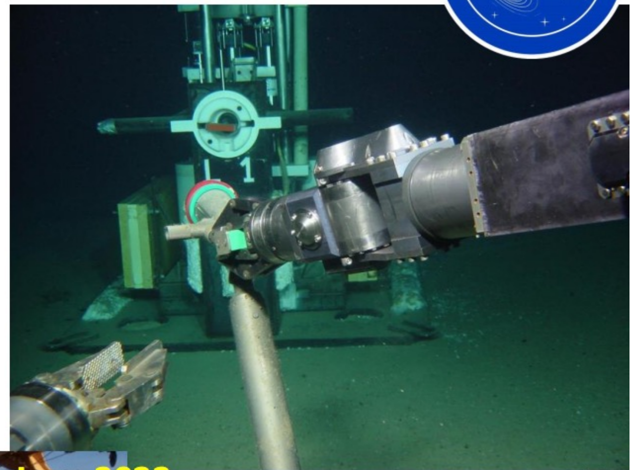
1997 Proposal
2001 Main Electro-Optical Cable deposition
2002 Junction box deployment
2003 Prototype Sector Line - First data
2005 Mini Instrumentation Line with OMs - environmental data
2006 First complete detector line
2008 Detector with 12 lines completed - complete configuration
2016 Running (almost) without common funds

February 2022 Data taking terminated

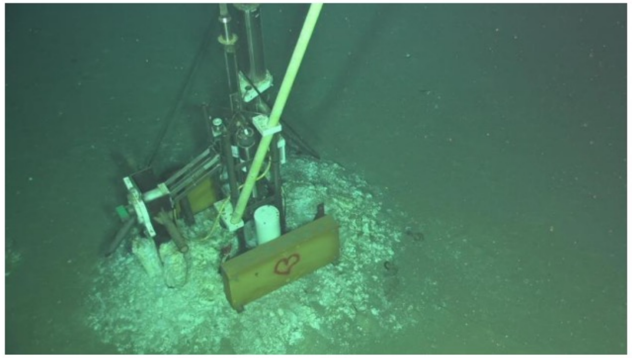
First detector line

Deployment
14/02/2006

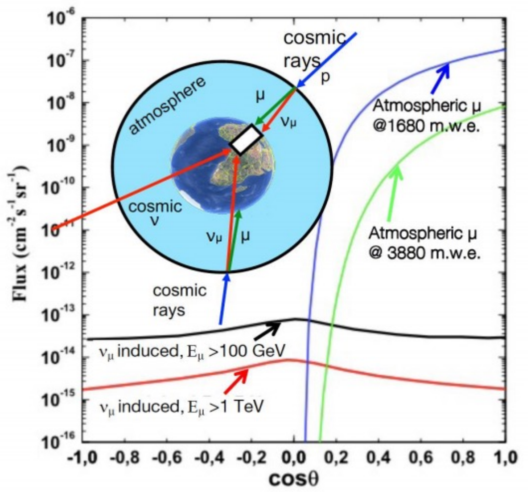
Connection
march 2006



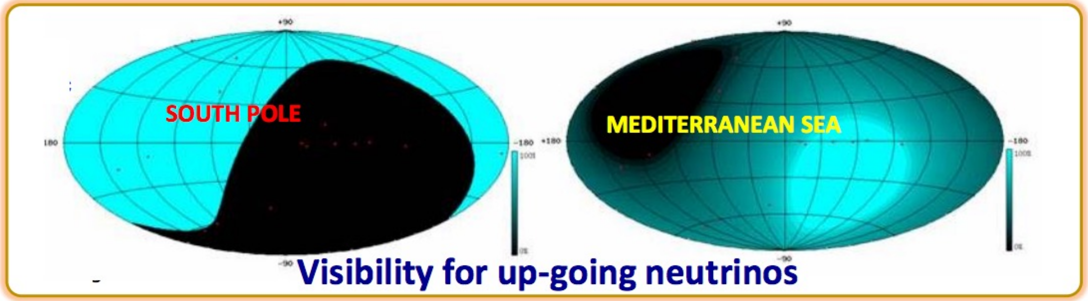
Disconnection after 16 years



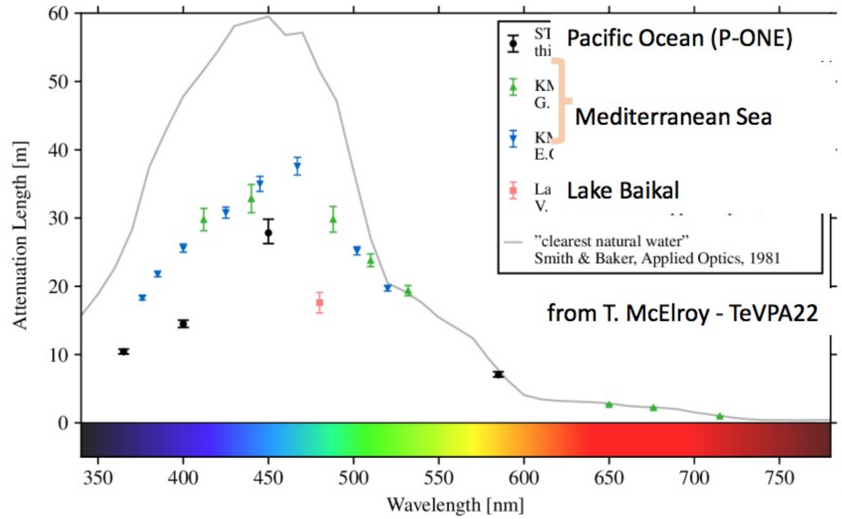
Why the Mediterranean Sea



- excellent water optical properties → excellent reconstruction performance
- angular resolution
  - **tracks: ~0.4° [< 0.1 ° KM3NeT] @ 10TeV; (IceCube : 0.3° @ >100 TeV)**
  - **showers: ~4° [2° KM3NeT] @10 TeV ; (IceCube: 10° @ > 100 TeV)**
- Visibility of the Galactic region ➔ ~ 70 % for the Galactic Centre
- Investigation of the IceCube diffuse flux from another point of view



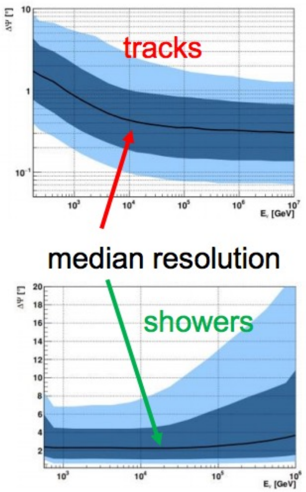
Visibility for up-going neutrinos



Event topologies - reconstruction performances

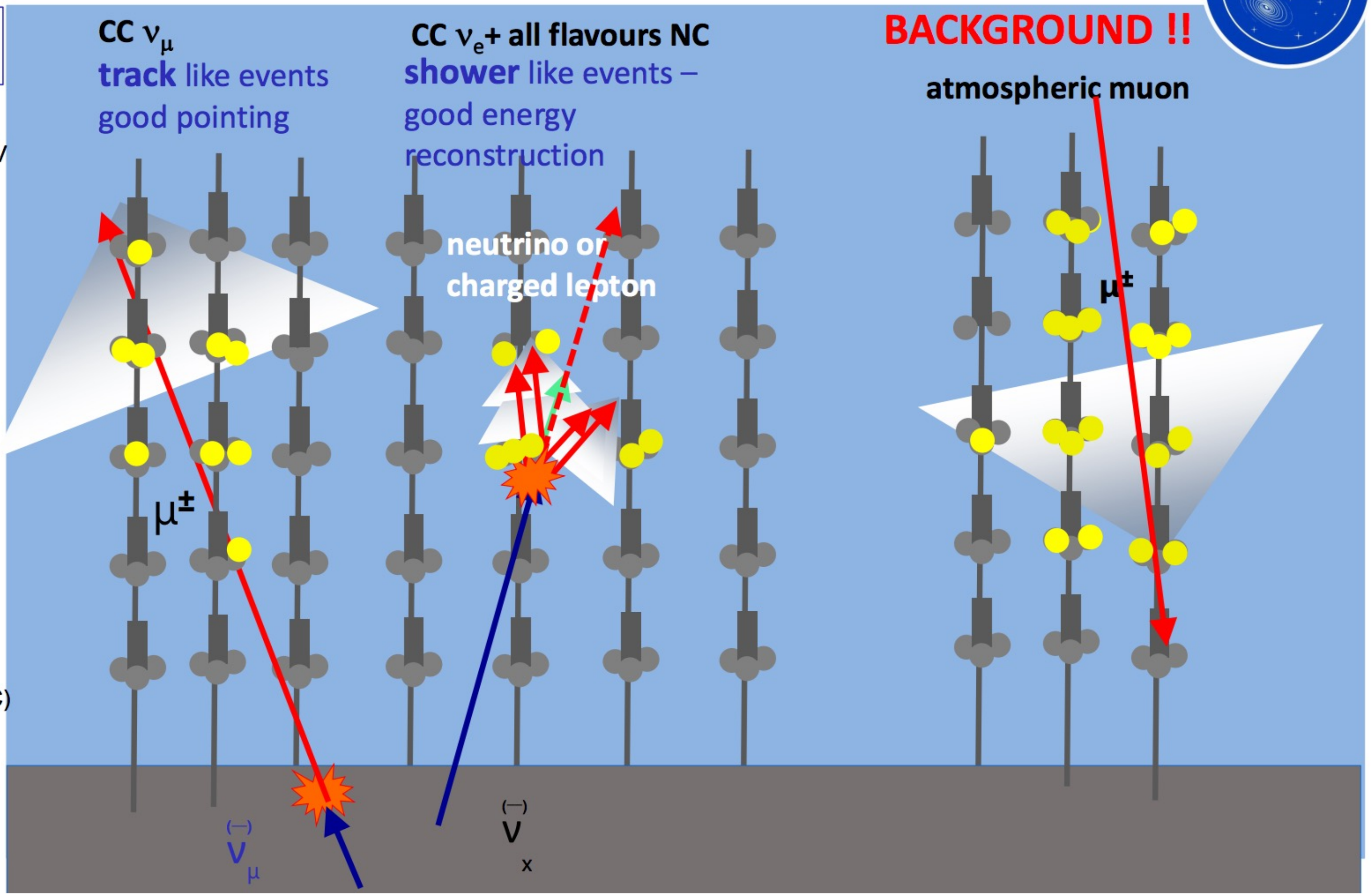
track channel = the golden channel for source identification

- Upgoing track events (νμCC)
- Angular resolution <0.4° for Eν>10 TeV
- 90% purity
- Energy resolution ~ factor 2



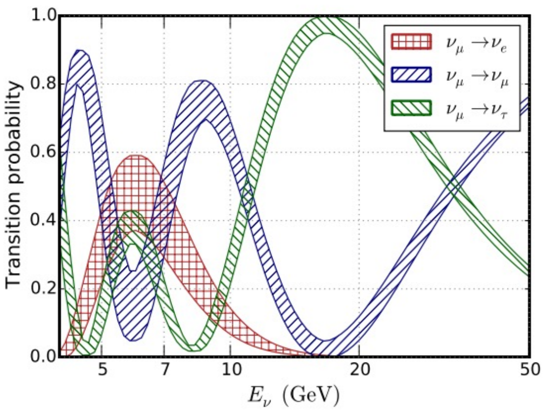
- Upgoing shower events (ve / vt CC, NC)
- Angular resolution < 4°
- Energy resolution for better than 10%

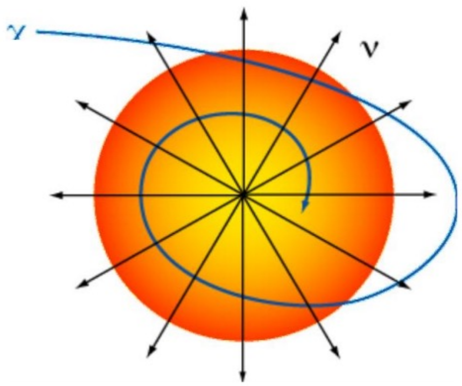
shower channel = good energy resolution
(IceCube discovery channel)

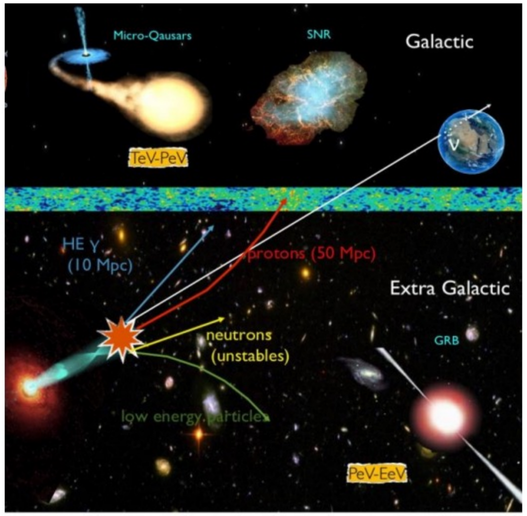


Science with ANTARES

Neutrinos: undeflected and unabsorbed → perfect probes







Low Energy
> 10 GeV

Medium Energy
10 GeV < E_ν < 10 TeV

Galactic → Extragalactic
High Energy, E_ν > TeV → PeV

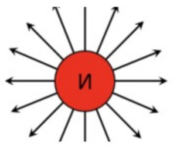
Energy

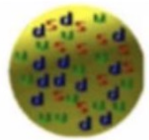
ν Oscillations

Dark matter search

ν from cosmic sources
origin and production
mechanism of HE CRs

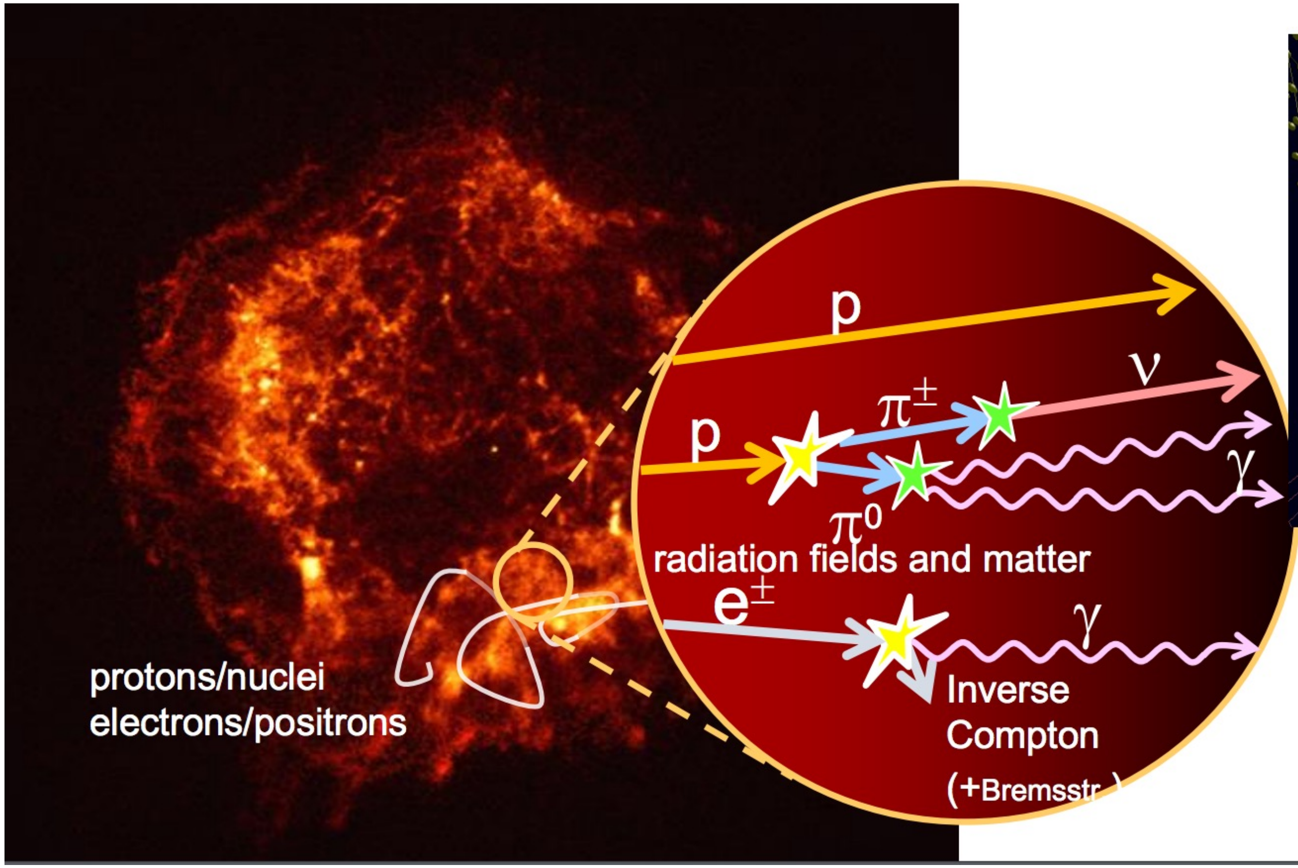
+ Exotic searches - Nuclearites, Magnetic monopoles...

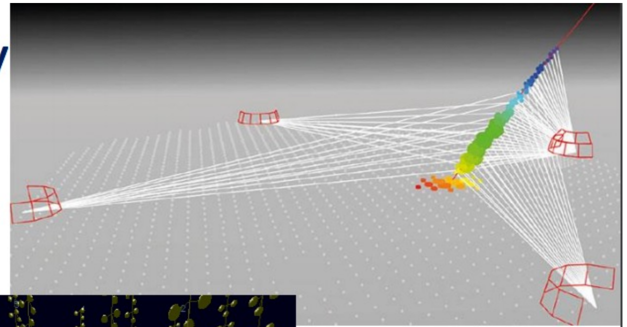


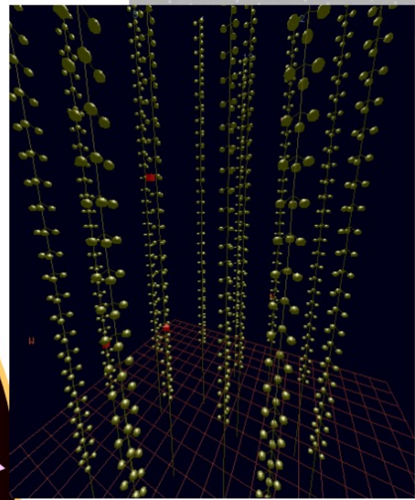


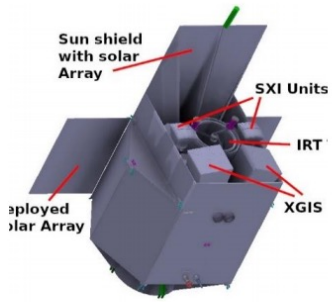
11

ν, CRs, γs and multimessenger astronomy

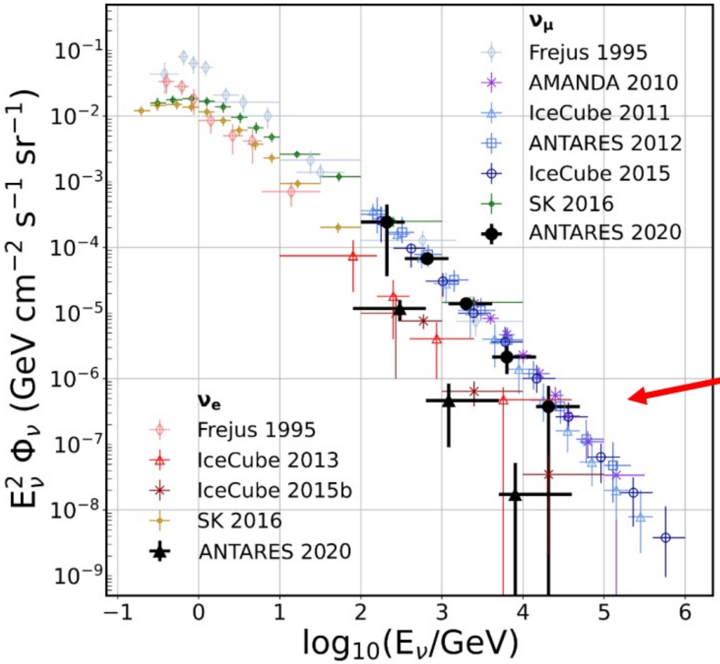


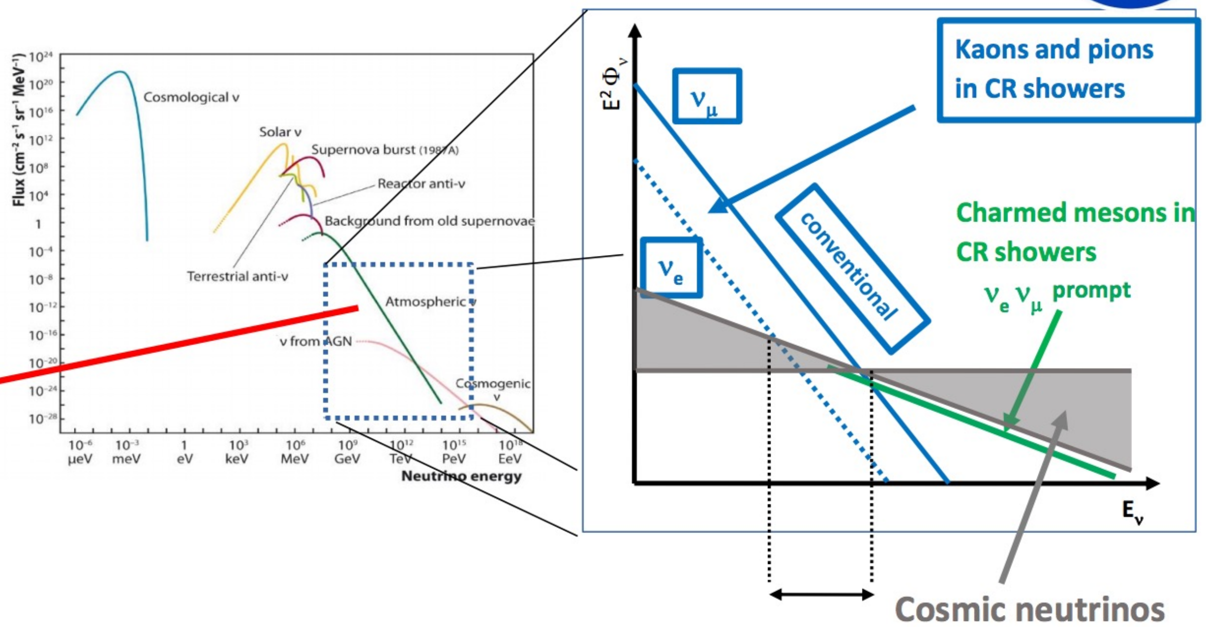






Atmospheric neutrino background





Atmos-to-Cosmic transition
30-200 TeV

measured using an energy estimator
accounting for detector systematics

EPJ 73: 2606 (2013)
PLB 816: 136228 (2021)

13

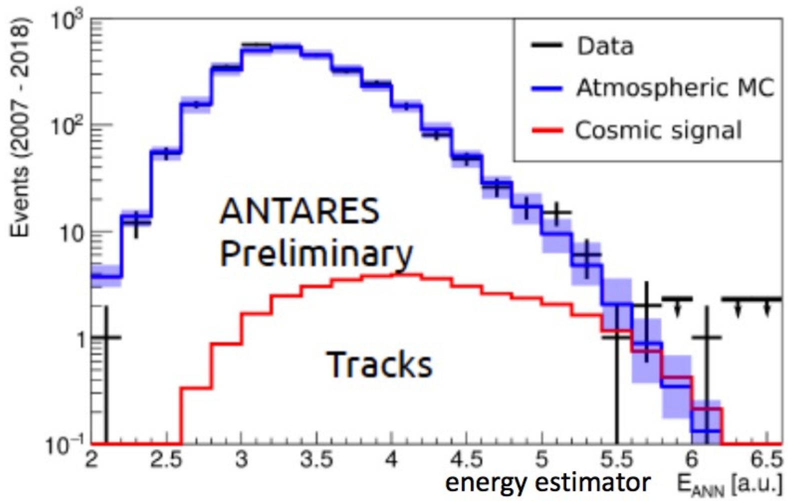
Diffuse flux of cosmic neutrinos in ANTARES

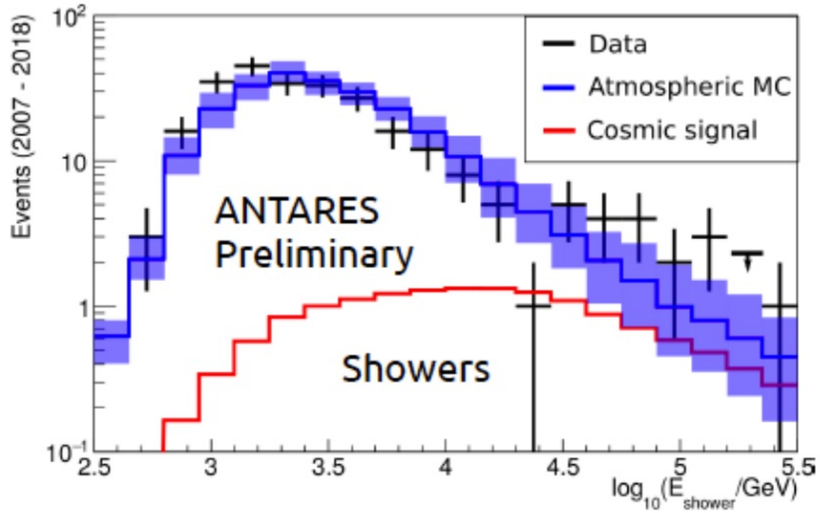
📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

Search for an excess of high-energy events w.r.t atmospheric neutrinos

- Selection cuts optimized with MRF procedure (assumed spectral index Γ=2.5)
- Look for event excess above a given E_{th} both for track & shower samples
- Data with E> E_{th} : **50 events (27 tracks + 23 showers)**
- Background with E> E_{th} (atm. Flux=HONDA + Enberg): **36.1 ± 8.7 (19.9 tracks +16.2 showers)**
- → **1.8σ excess** of events with E> E_{th}**,** assumed as cosmic flux (red histogram)

DATA sample 2007-2018





14

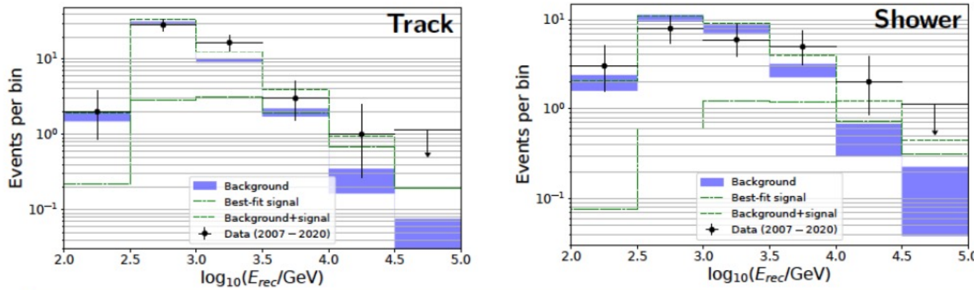
Flux from the Galactic ridge - new analysis ON/OFF

- neutrino signal expected from the Galactic Ridge (gamma-ray data)
- Cosmic ray interactions → π^0 → γ $\pi^{\pm}$ → ν
- extension of a previous analysis ----

  Data period: 2007–2013 → 2007–2020
- sample of events: tracks-only → tracks + showers

Galactic ridge region : $|l| < l_{ridge} \approx 30°$ and $|b| < b_{ridge} \approx 2°$

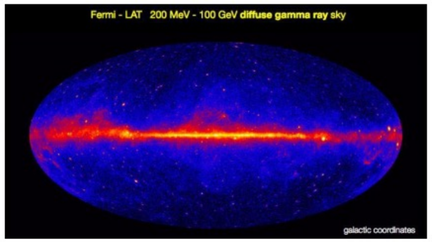
previous analyses
- PLB 760 (2016) 143
- Phys. Rev. D 96, 062001 (2017)
- ApJL 868, L20 (2018)

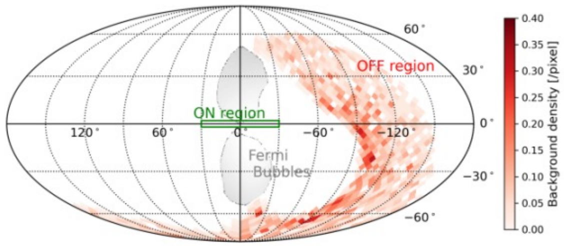


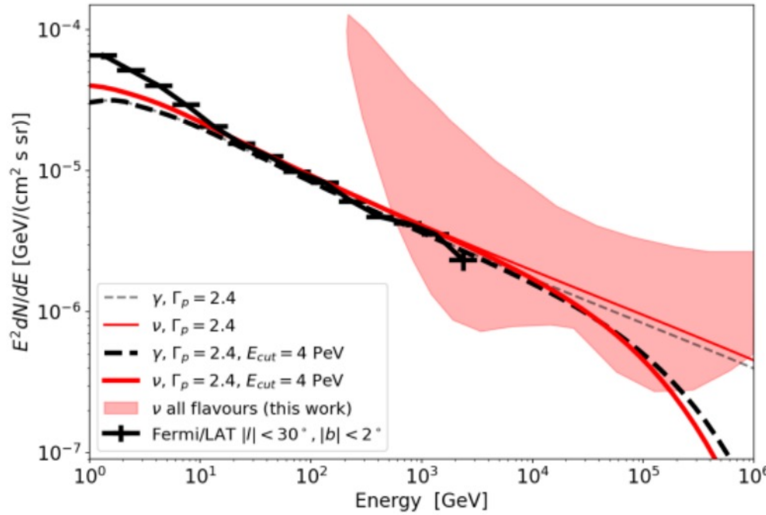
- Comparison of the neutrino flux coming from the ON region to the expected background neutrino flux
- **Background**: *scrambled* data from OFF regions [excluding Fermi bubbles]

hints of an excess of a neutrino flux from the Galactic Plane

A. Albert et al., PLB 841 (2023) 137951





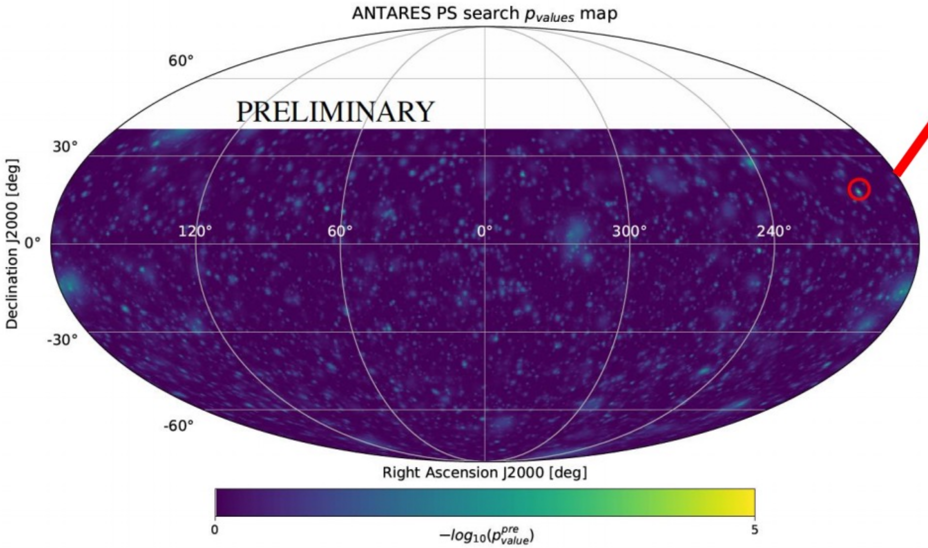


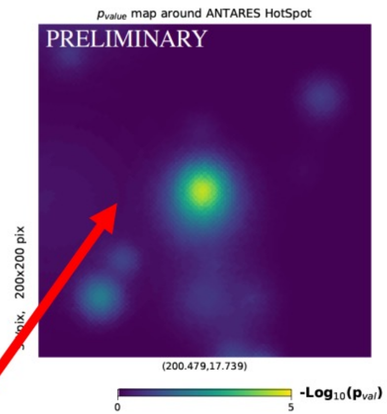
Search for cosmic sources: tracks+cascades

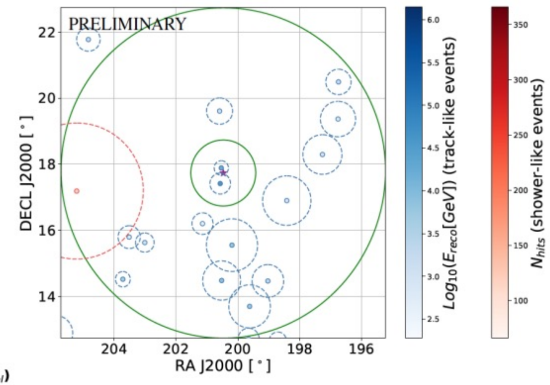
📖 PRD 96, 082001 (2017)
📖 PoS(ICRC2021)1161
📖 PoS(ICRC2023)

Data set 15 year (from Jan 2007 to Feb 2022); Livetime: 4541 days; 11029 tracks + 239 showers
Search for an excess of events (cluster) from any direction

full-sky







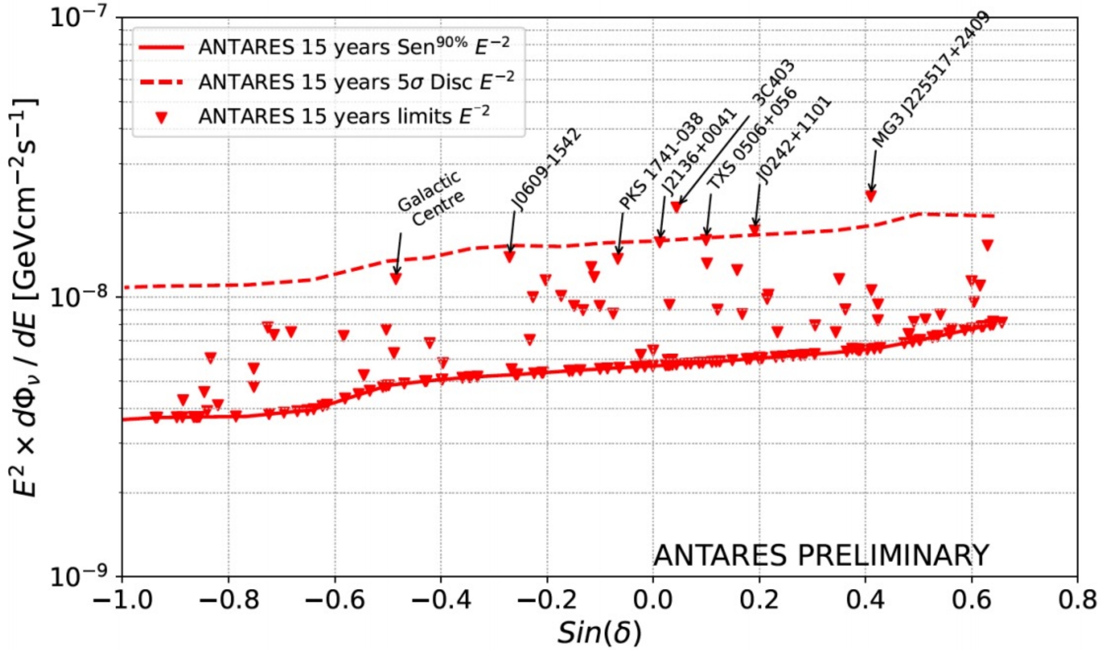
Highest significance hot spot (α, δ) = (200.5°, 17.7°)
pre-trial p-value=3x 10^{-5} → 4σ
post-trial p-value=1.1%→1.2σ

Search for cosmic sources: tracks+cascades

📖 PRD 96, 082001 (2017)
📖 PoS(ICRC2021)1161
📖 PoS(ICRC2023)

Data set 15 year (from Jan 2007 to Feb 2022); Livetime: 4541 days; 11029 tracks + 239 showers
Search for an excess of events (cluster) from any direction

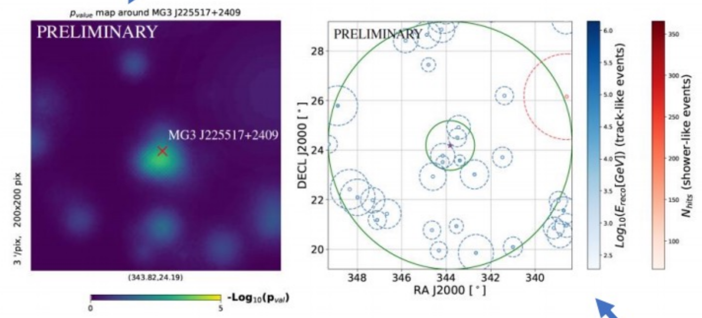
search over a predefined list of 163 candidates



No significant evidence of cosmic neutrino sources has been found

Blazar MG3 J225517+2409 is the most significant source (post-trial p-value: 1.7 σ)

pre-trial p-value map



location of events

Search for neutrinos from radio-blazars

The notable case of the J0242+1101 blazar

Search for neutrino - blazar association in the data sample collected between 2007-2020

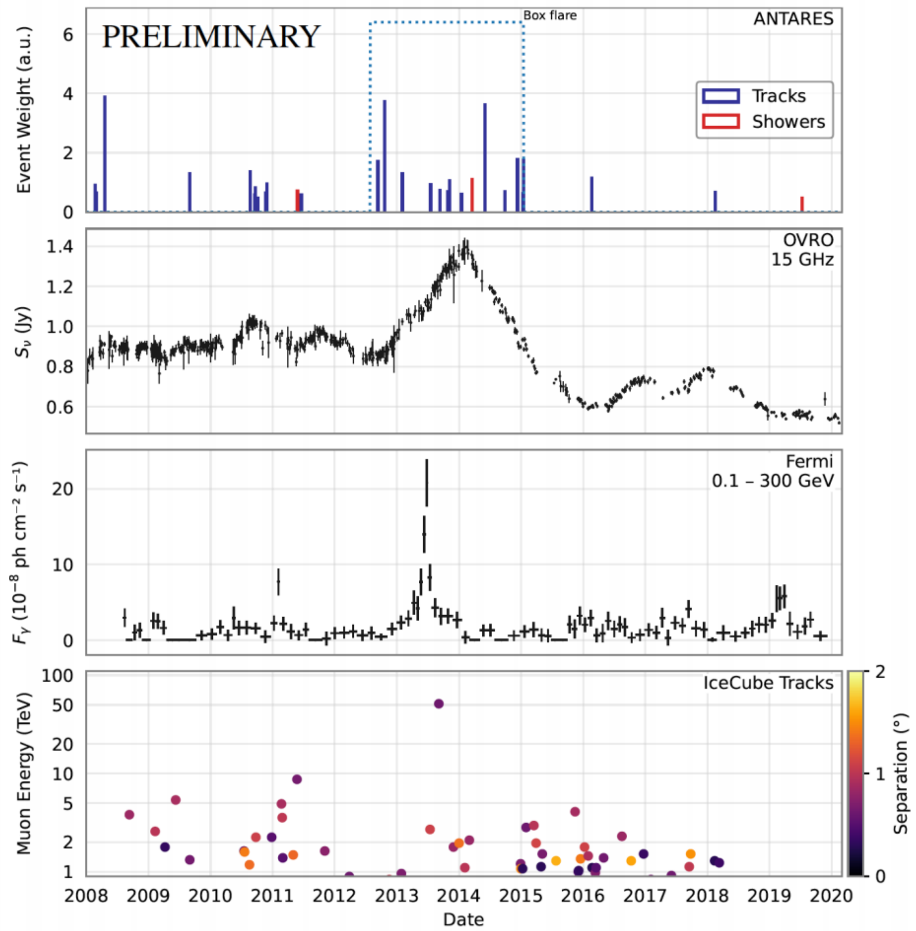
3845 days, 10504 track-like events + 227 shower-like events

Different strategies:

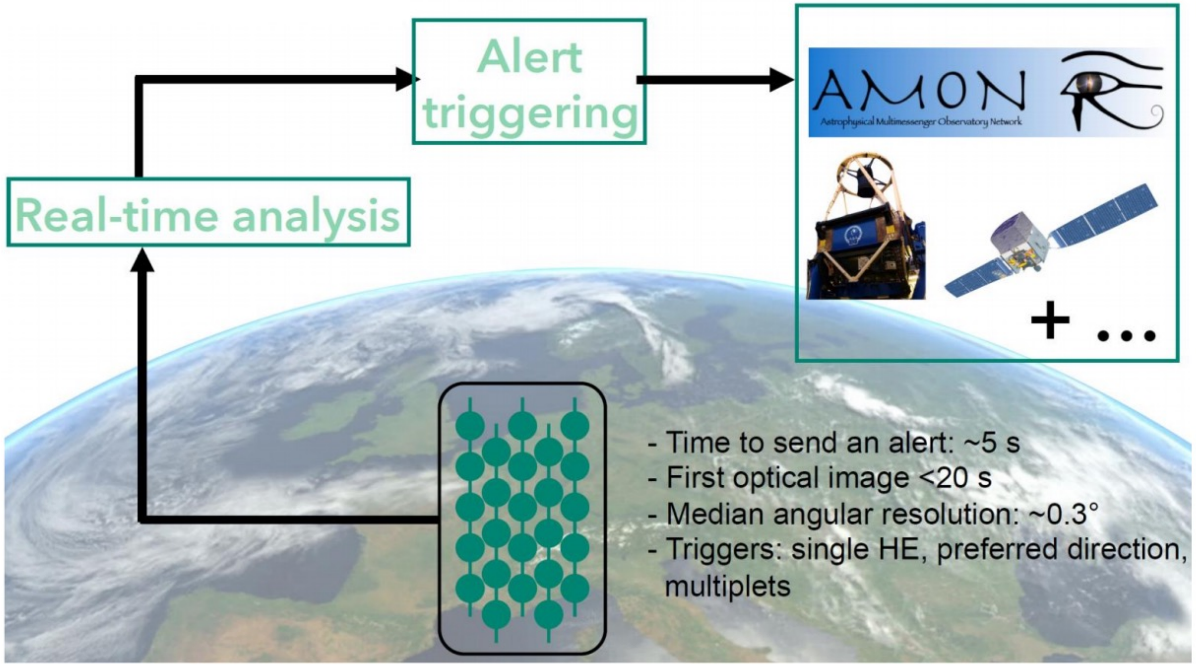
- neutrino-blazar pair counting method
- time integrated likelihood analysis
- time dependent likelihood scan
- multi-messenger flares comparison

No significant excess - only hints of possible correlation

Paper in preparation



Multi-messenger approaches - **sending alerts**



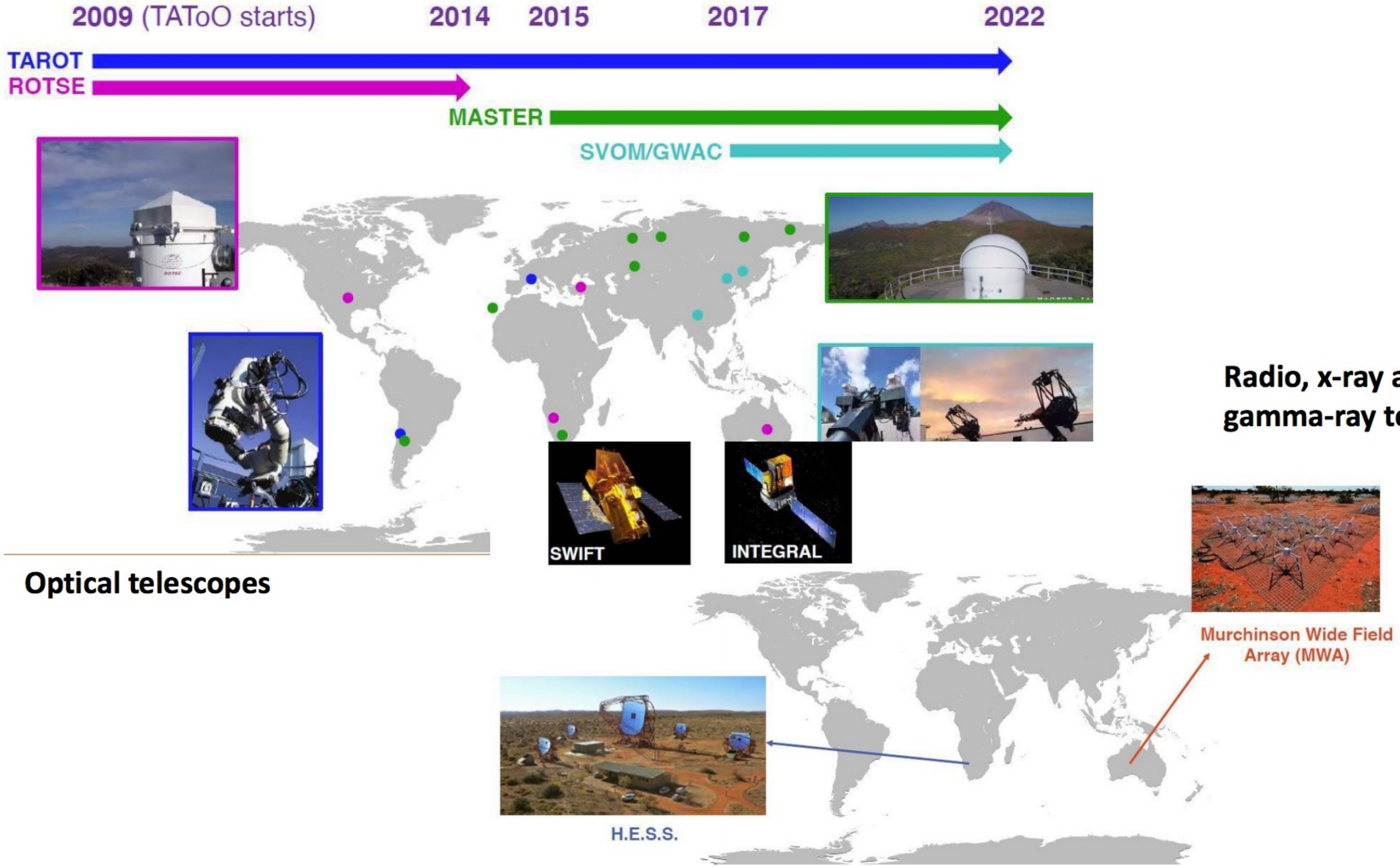
Alert system (**TAToO**: Telescopes and Antares Target of Opportunity) active since 2009
📖APP 35 (2012) 530

What triggers an alert:

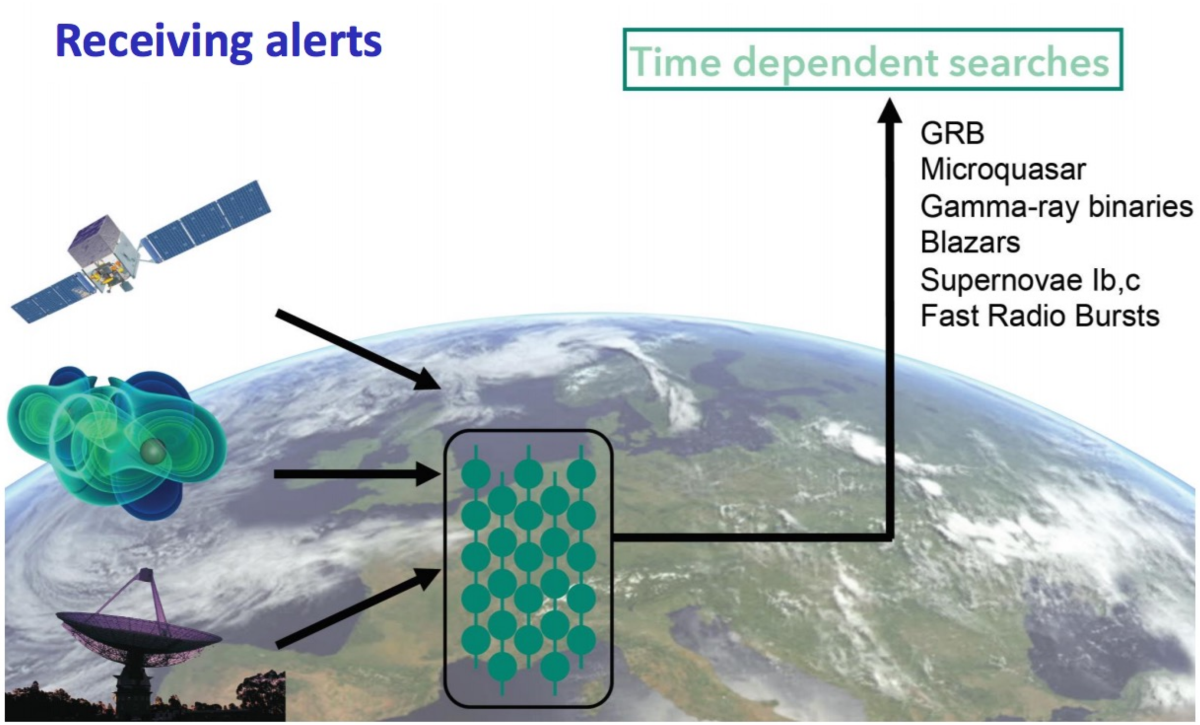
- **High energy (HE):** single neutrino with energy ≥ 5 TeV. Rate: ~1/month
- **Very high energy (VHE):** single neutrino with energy ≥ 30 TeV. Rate: ~3-5/year
- **Directional trigger:** single neutrino from the direction (≤ 0.4°) of a local galaxy (≤ 20 Mpc). Introduced to increase the chance to detect a local CCSN. Rate: ~1/month
- **Doublet trigger**: at least two neutrinos coming from close directions (≤ 3°) within a predefined timewindow (15 min). **No doublet trigger ever**

20

Multi-messenger approaches - **sending alerts**



Multi-messenger approaches - **receiving alerts**



Follow-up of IceCube neutrinos:

- 115 IceCube events received, 37 analyzed (7 HESE, 3 EHE, 10 gold and 17 bronze)
- No ANTARES candidates compatible with any of the IceCube alerts
- 90% confidence level upper limits on the neutrino fluence

Dedicated offline follow-up of IC events:

TXS0506+056 (📖 **ApJL863 (2018) 2, L30**)
AT2019dsg and AT2019fdr (📖 **ApJ920 (2021) 1, 50**)
HESE and EHE events (📖 **ApJ. 879 (2019)2, 108**)

Follow-up of LIGO/Virgo GWs

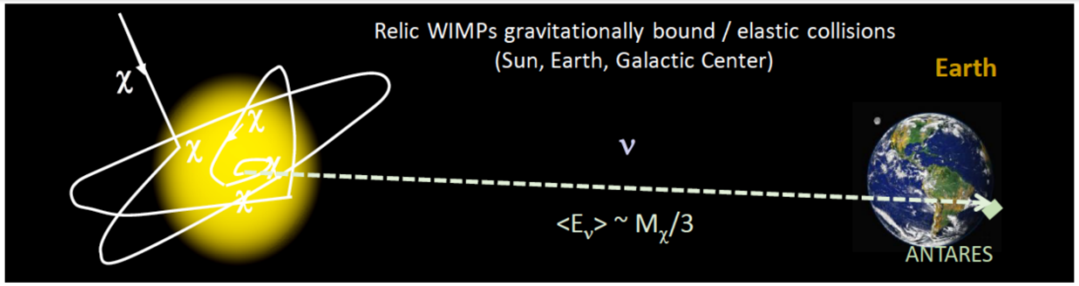
No candidates associated with GWs
📖 **JCAP04 (2023) 004** (neutrinos associated to O3 Run events of Virgo/Ligo)

Follow-up of Fermi-GBM and Swift GRBs
Follow-up of HAWC alerts

📖 **ApJ 944 (2023) 166**

22

Indirect search for Dark Matter



Neutrino telescopes are very versatile and good for different search channels

Search for an excess of neutrinos - as final product of annihilation - from the core of astrophysical objects were WIMPS could have accumulated

Earth

Physics of the Dark Universe, 16 (2017) 41

Sun

Phys.Lett. B759 (2016) 69

JCAP 05 (2016) 016

JCAP11 (2013) 032

Galactic Center

JCAP 10 (2015) 068

Phys. Lett. B 769 (2017) 249

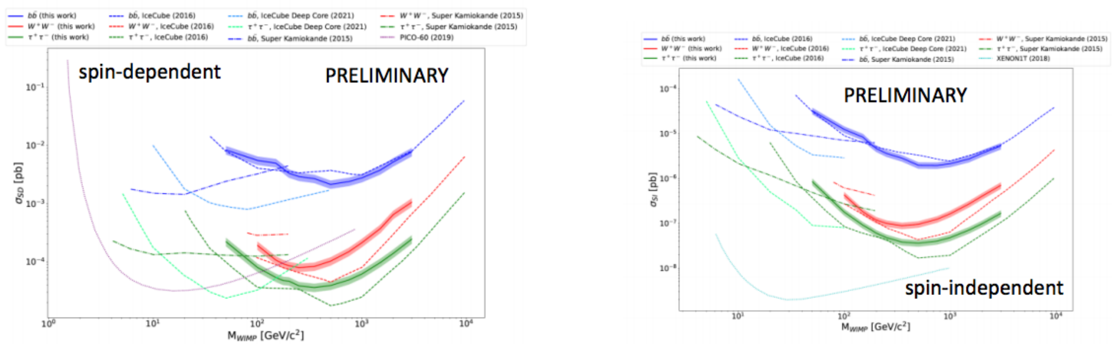
Phys. Rev. D 102 (2020) 082002 (with IceCube)

JCAP06 (2022) 028 (secludedDM)

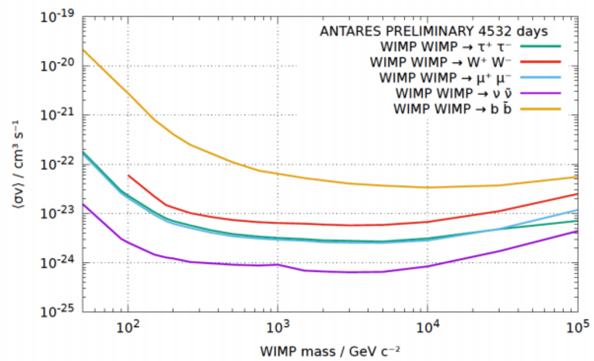
Phys. Lett. B 805 (2020) 135439

The Sun

- equilibrium between capture and annihilation
- The Sun has known isotopic abundance ⇒sensitive to WIMP-nucleon cross section for spin-dependent and spin-independent case (odd or even atomic number)
- Competitive limits to direct experiment for spin-dependent



Galactic Center



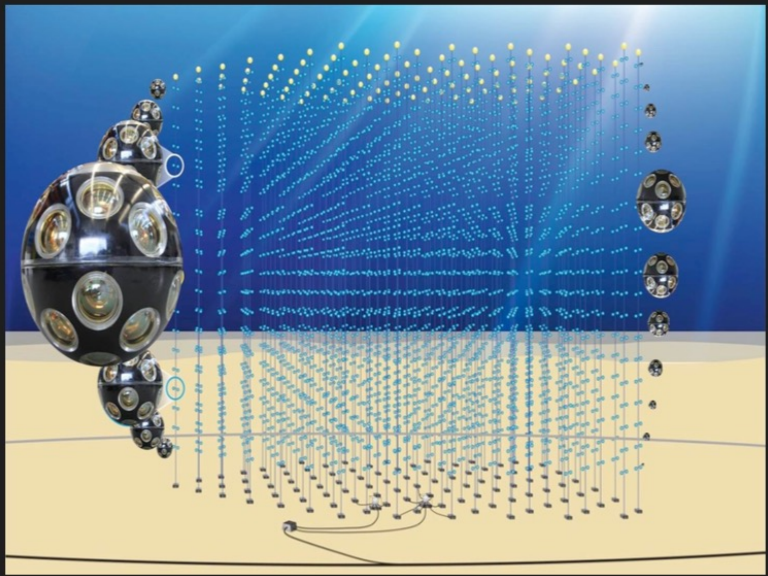
data 2007 - 2022 compatible with background

23

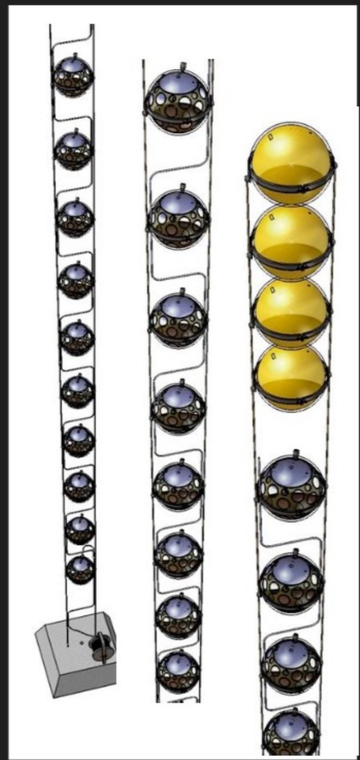
THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction

61



KM3NeT "building block"



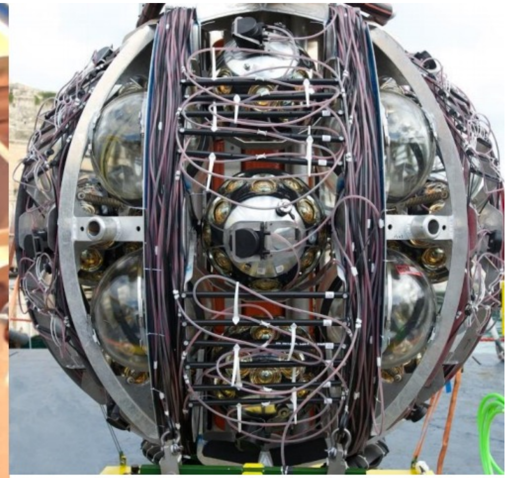
string with OMs

Multi-PMT digital optical module ("DOM")

ANTARES → KM3NeT

- ANTARES was the first and largest NT in the Mediterranean Sea.
- Fundamental lesson learned from ANTARES: undersea Cherenkov technique is feasible and reliable for long time data taking.
- Multi disciplinary observatory (Earth and Sea sciences).
- Competitive physics results & intriguing hints.
- Constraints on neutrinos as seen by IceCube.
- Extensive multi-messenger program.
- Joint studies with several partners (electromagnetic+ GWs + Cosmic Rays + Neutrinos).
- more than 100 papers published & 100 PhD.

- AN EXCITING ADVENTURE ! To be continued with **KM3NeT** (Talk by A. Romanov, this conference July 12th)



Oscillation **R**esearch with **C**osmics In the **A**byss

Astroparticle **R**esearch with **C**osmics in the **A**byss

25

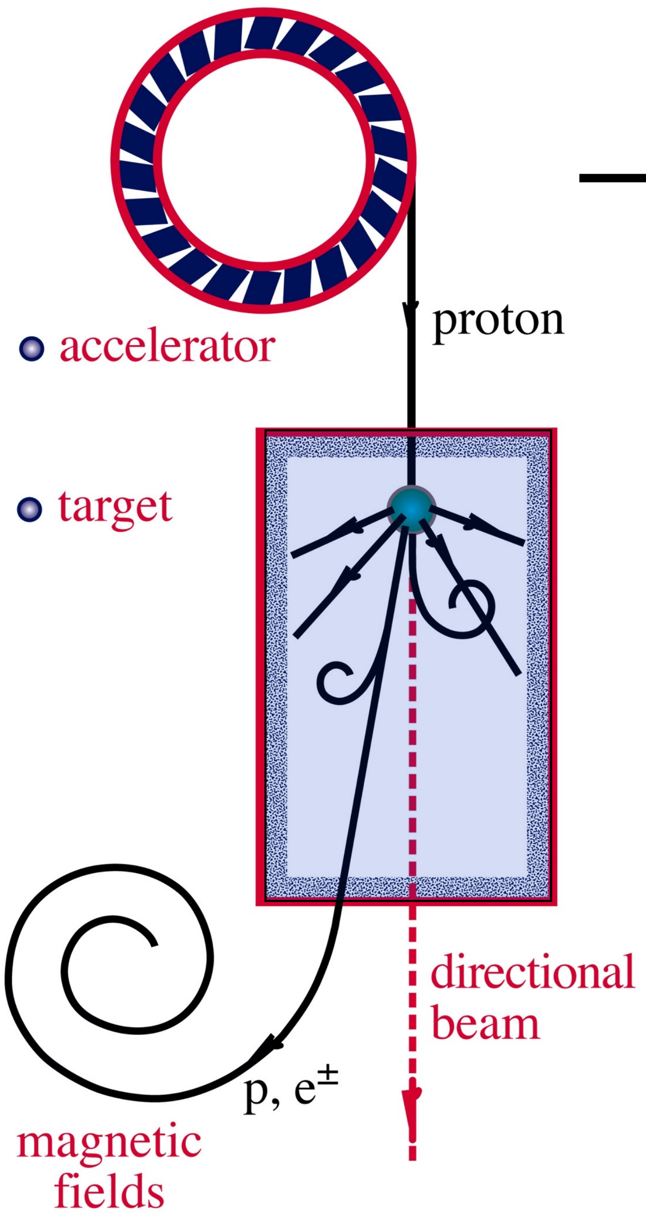
Cosmic Neutrinos in Louvain-la-Neuve

francis halzen

- ANTARES, Baikal GVD, IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation or hydrogen, or…

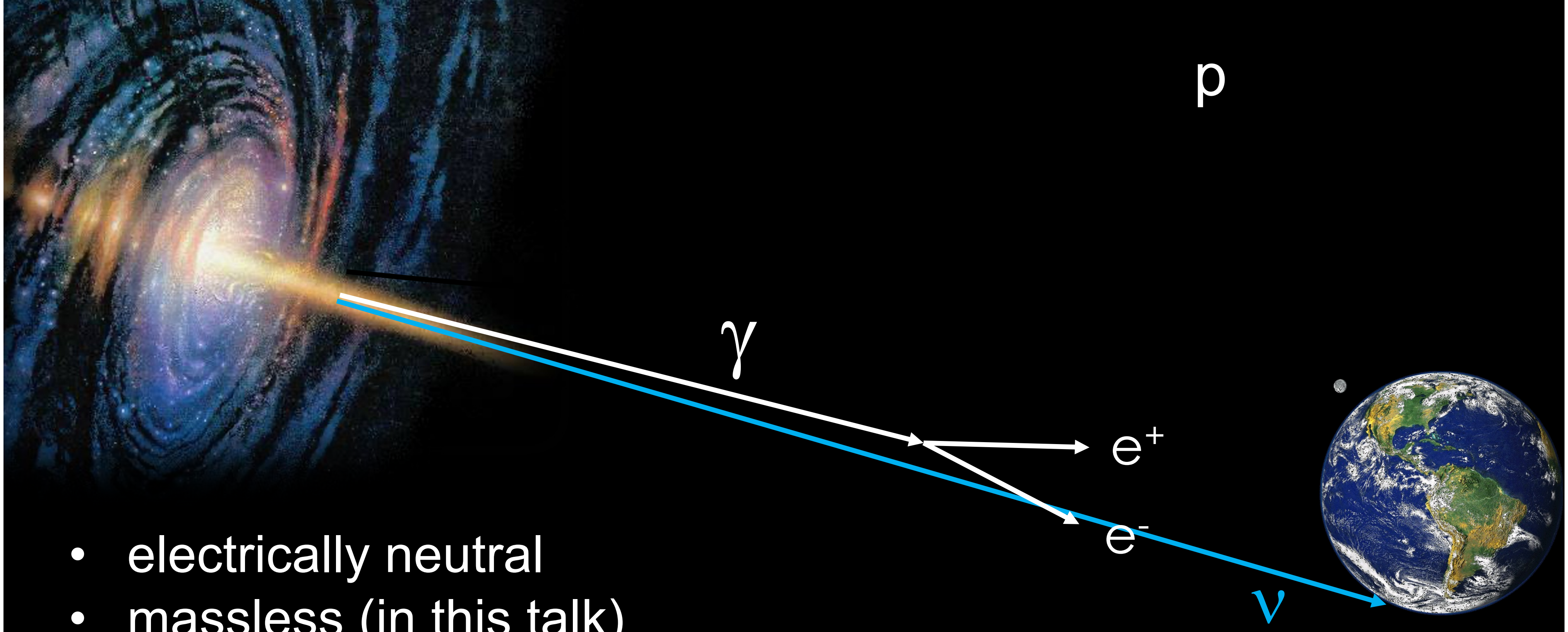
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

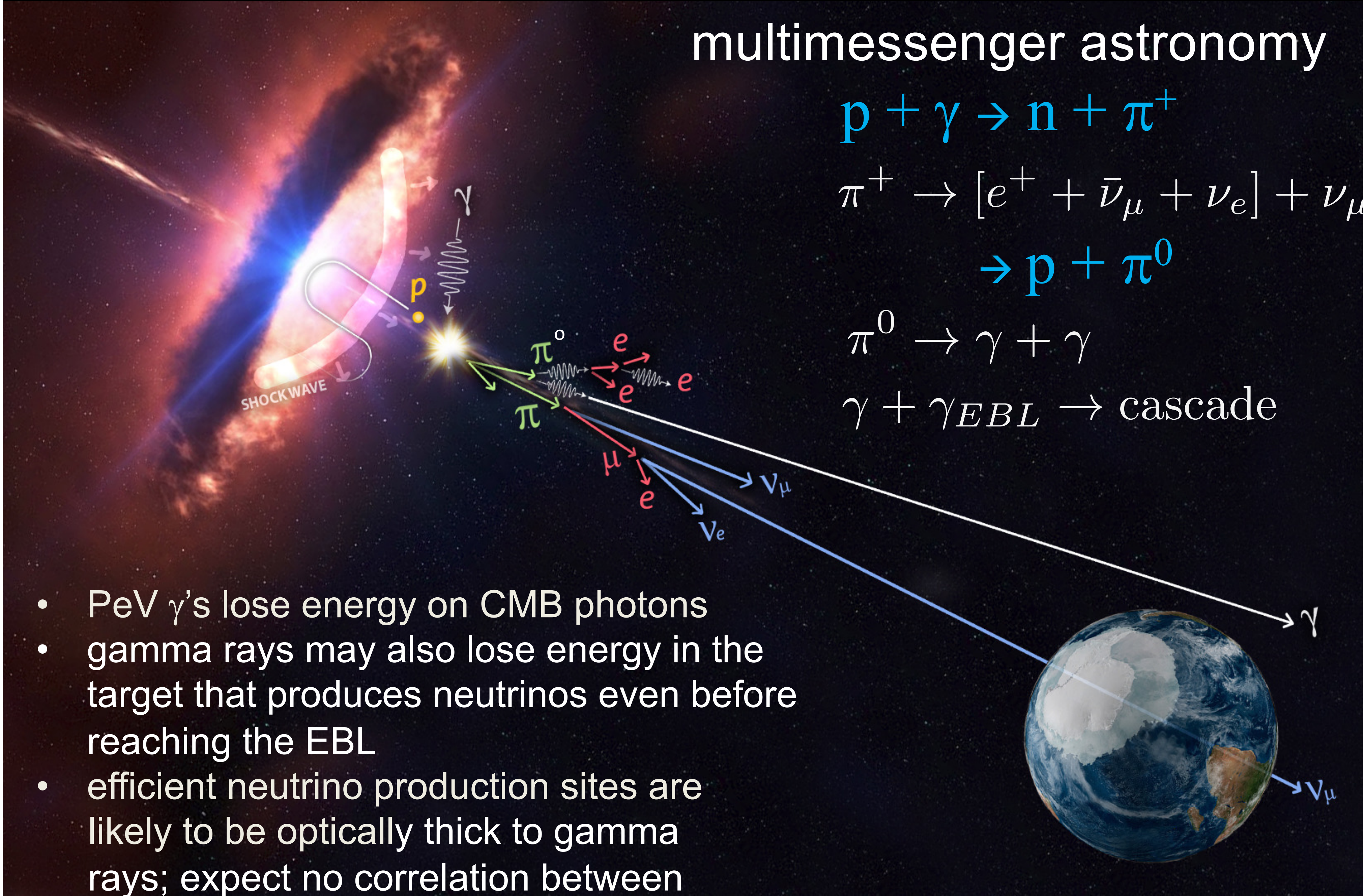
Neutrinos? Perfect Messengers



- electrically neutral
- massless (in this talk)
- unabsorbed

- unlike γ rays, neutrinos are solely created in processes involving cosmic rays

- … but difficult to detect



multimessenger astronomy

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

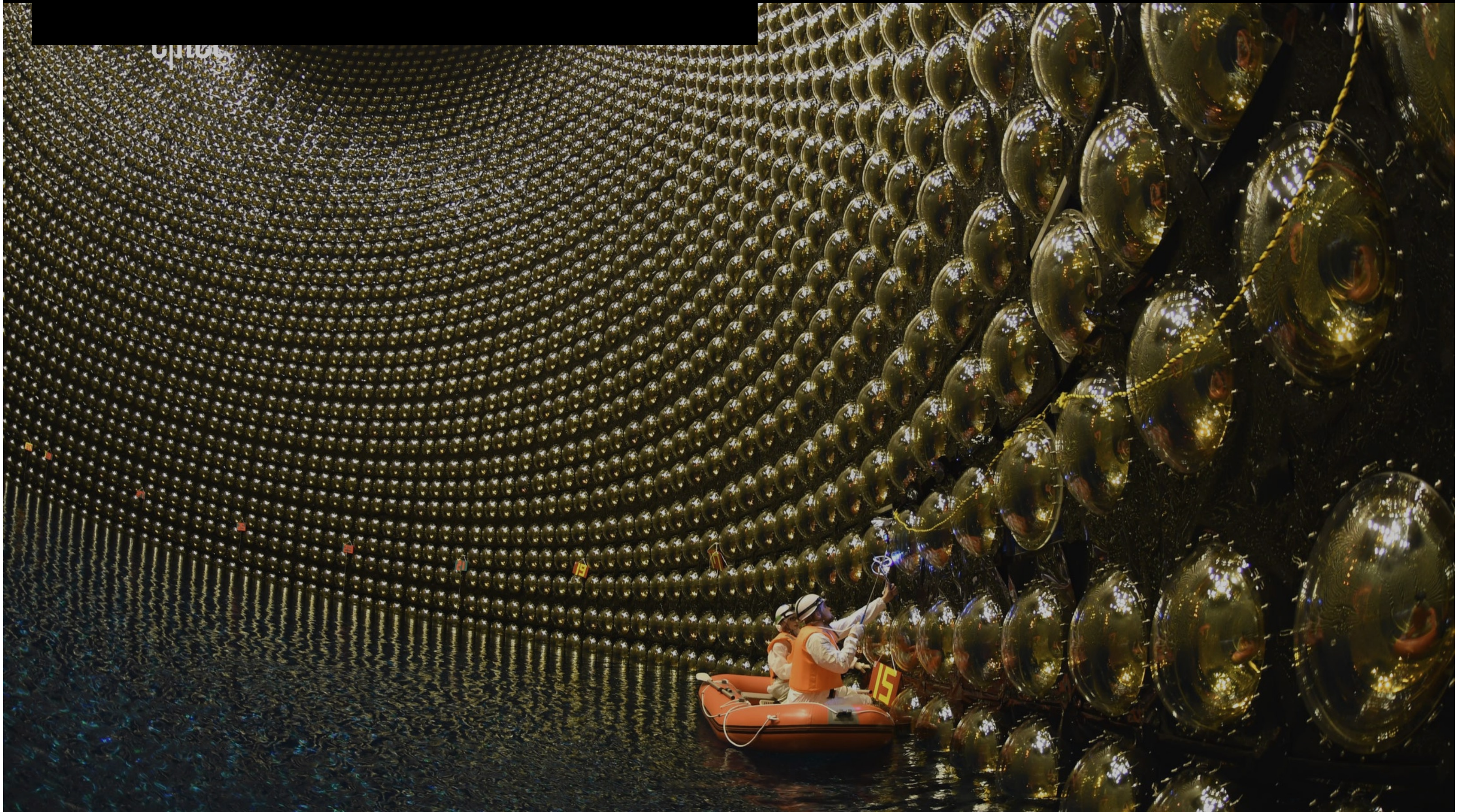
$$\pi^+ \rightarrow [e^+ + \bar{\nu}_\mu + \nu_e] + \nu_\mu$$

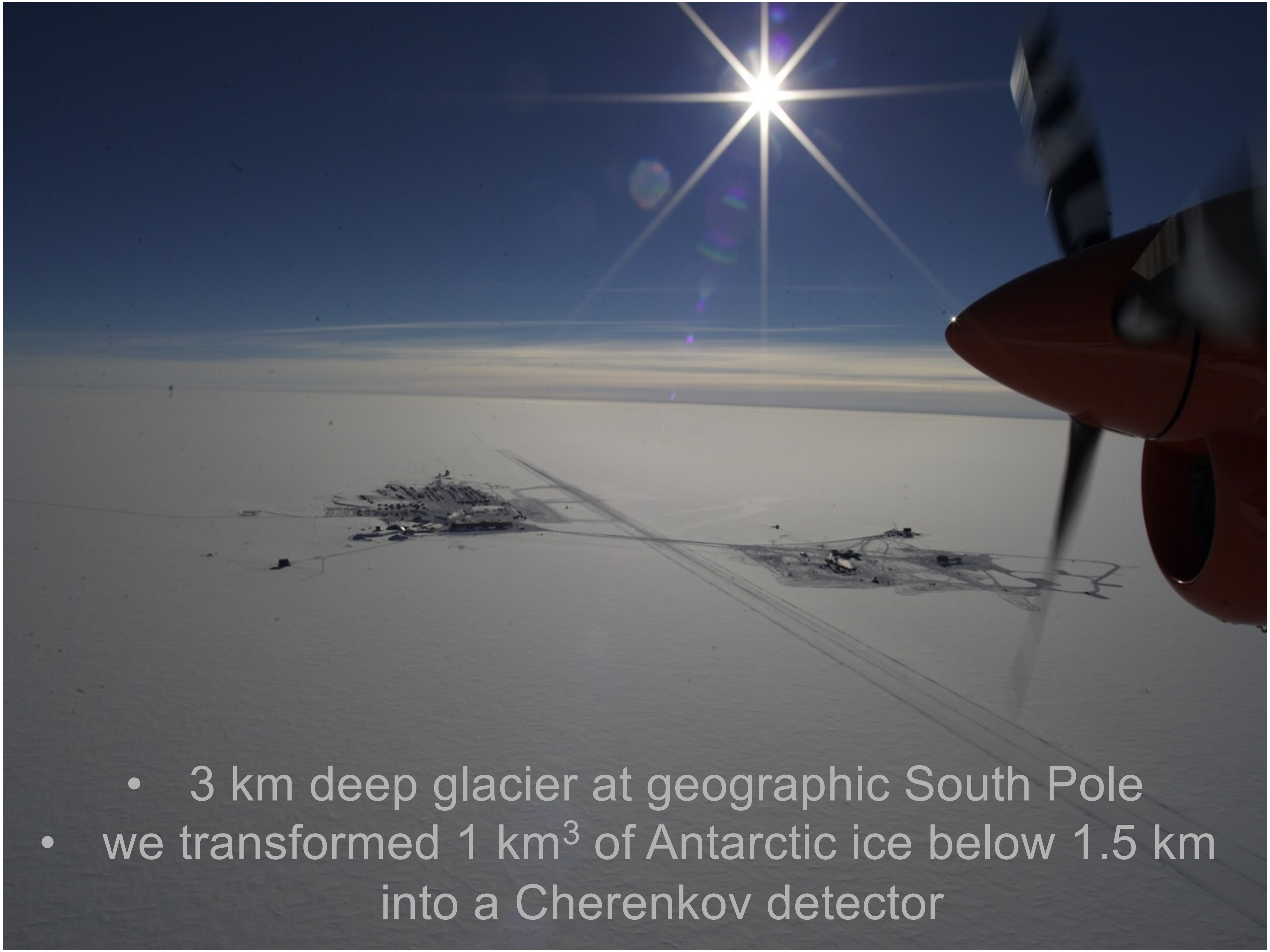
$$\rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

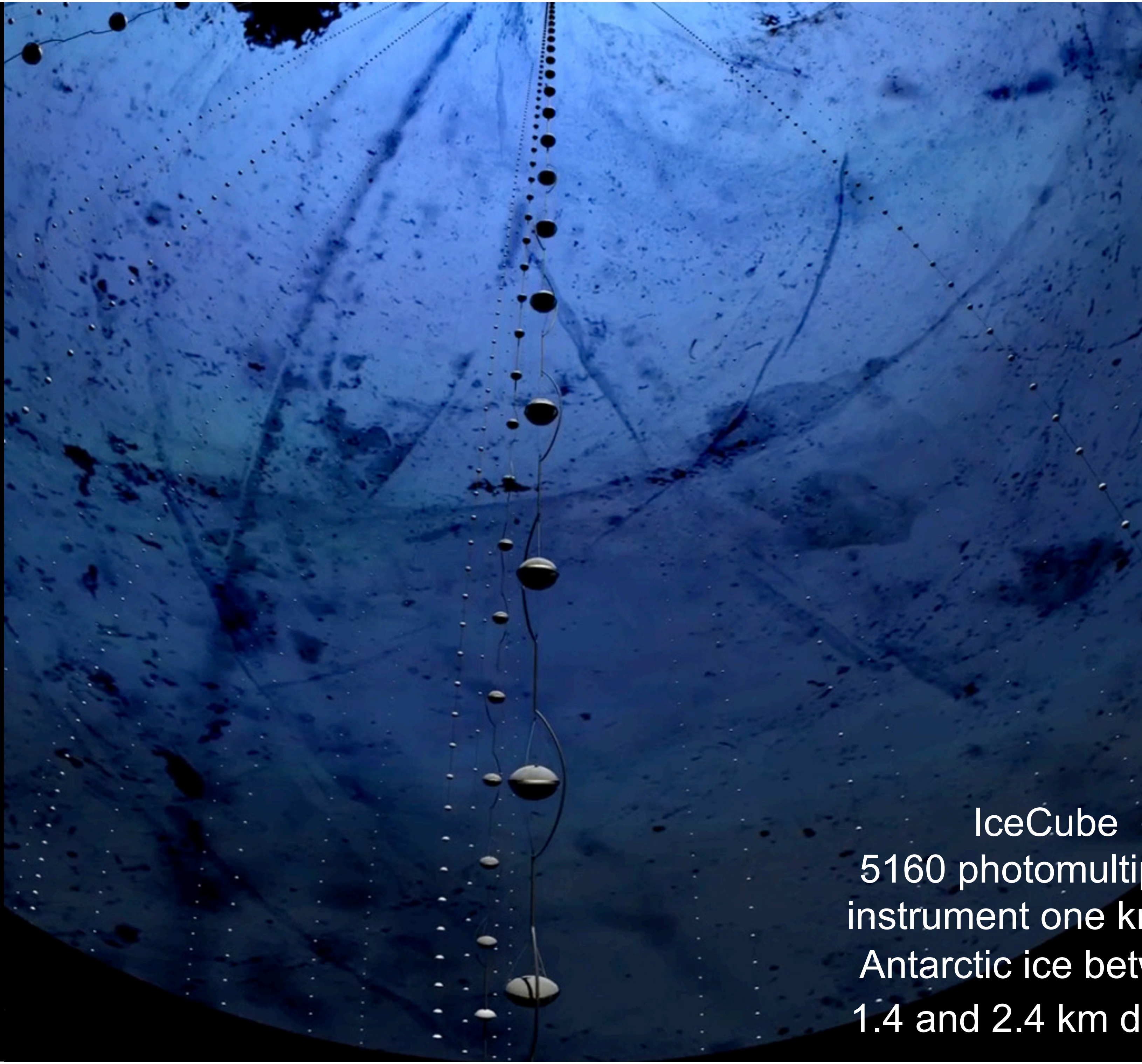
$$\gamma + \gamma_{EBL} \rightarrow \text{cascade}$$

- PeV γ's lose energy on CMB photons
- gamma rays may also lose energy in the target that produces neutrinos even before reaching the EBL
- efficient neutrino production sites are likely to be optically thick to gamma rays; expect no correlation between gamma-ray and neutrino activity


[redacted]



- 3 km deep glacier at geographic South Pole
- we transformed 1 km^3 of Antarctic ice below 1.5 km into a Cherenkov detector



IceCube
5160 photomultipliers
instrument one km3 of
Antarctic ice between
1.4 and 2.4 km depth

photomultiplier tube -10 inch

THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

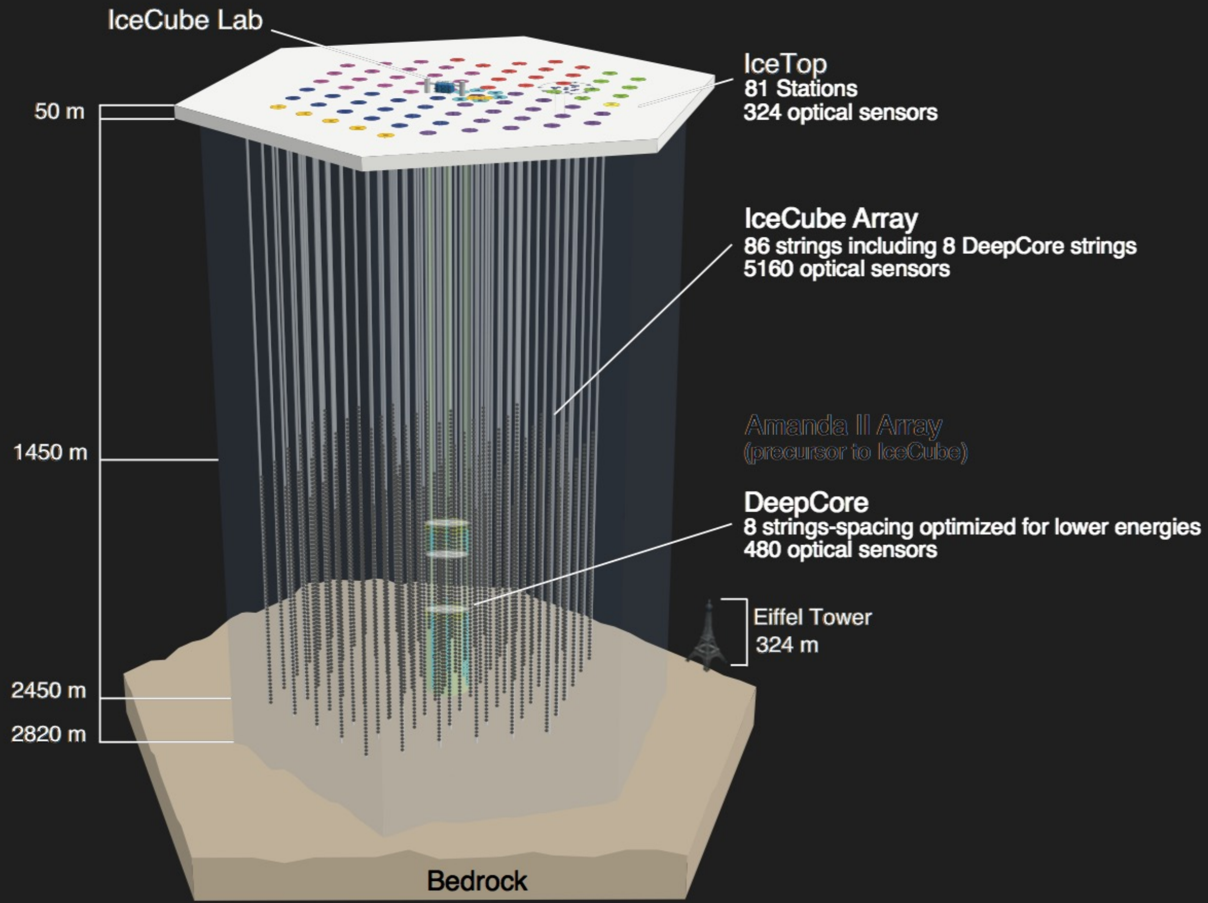
1 km³ volume

86 strings

17 m vertical spacing

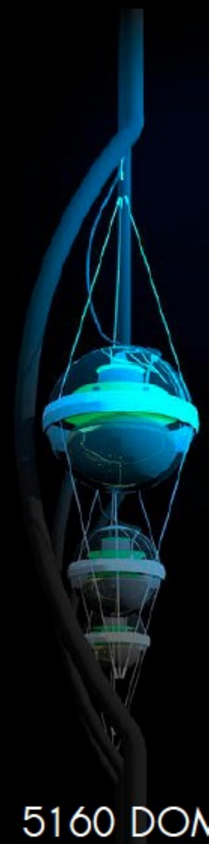
125 m string spacing

Completed **2010**



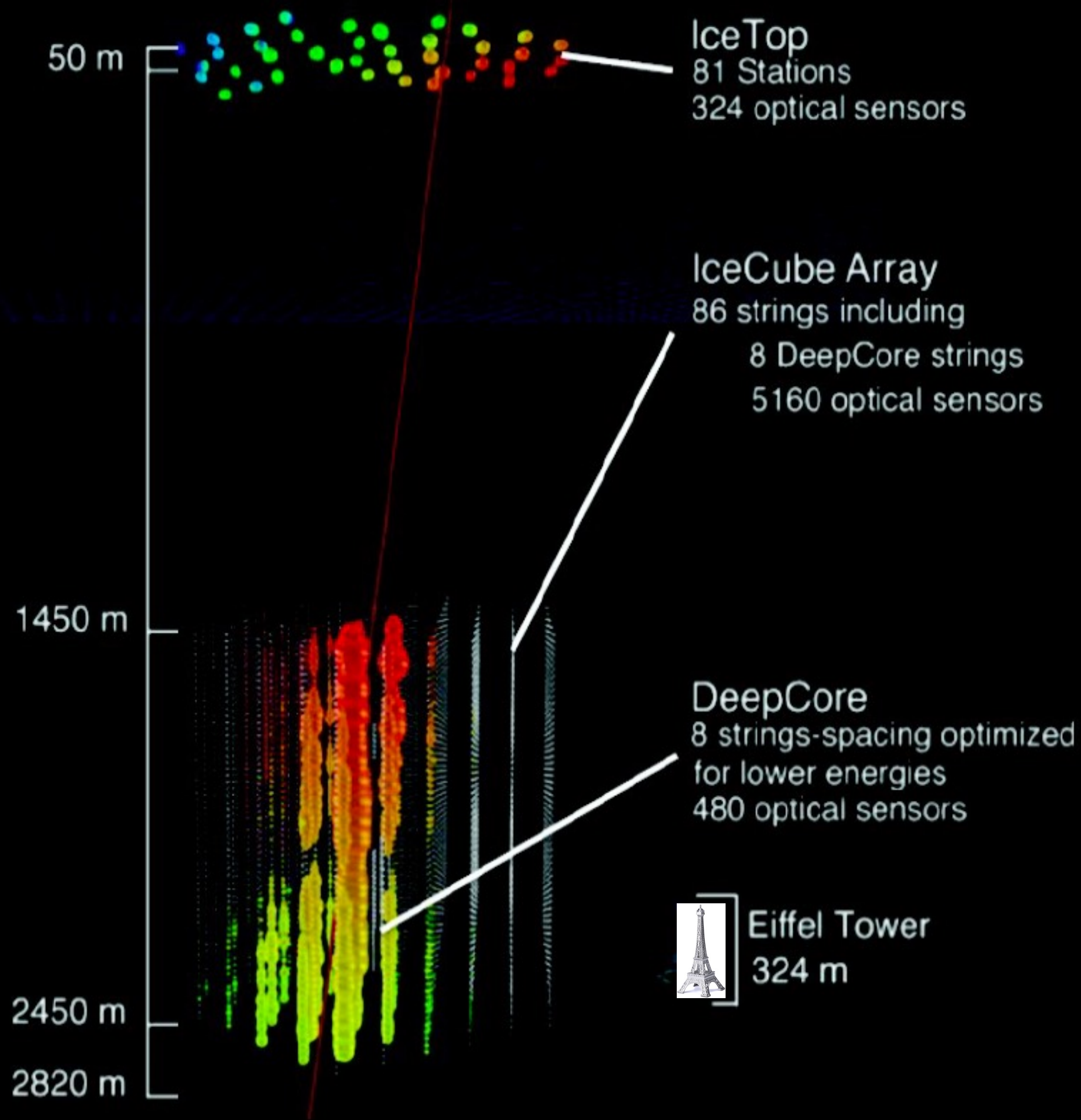
THE ICECUBE COLLABORATION

the IceCube Neutrino Observatory

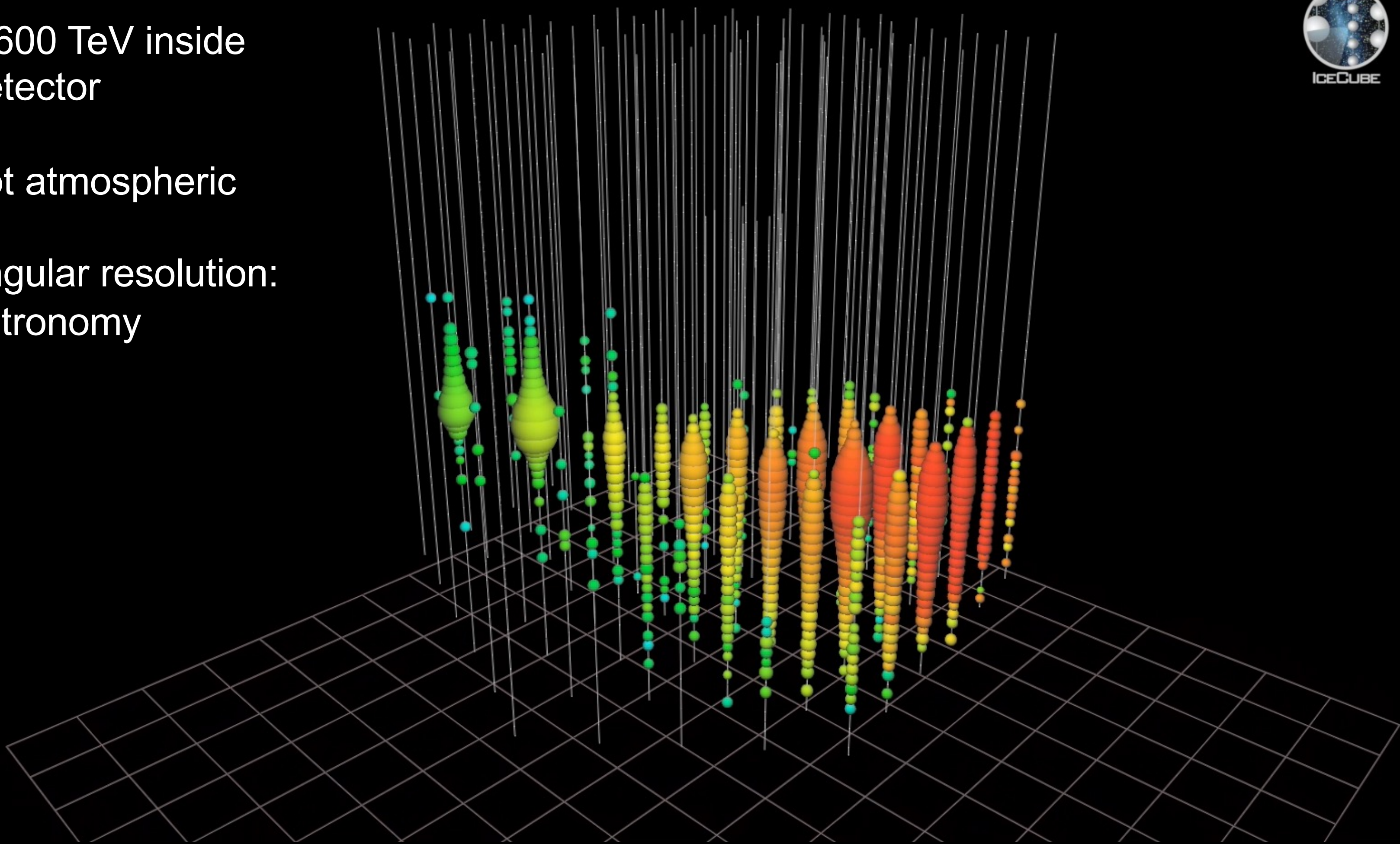


5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution

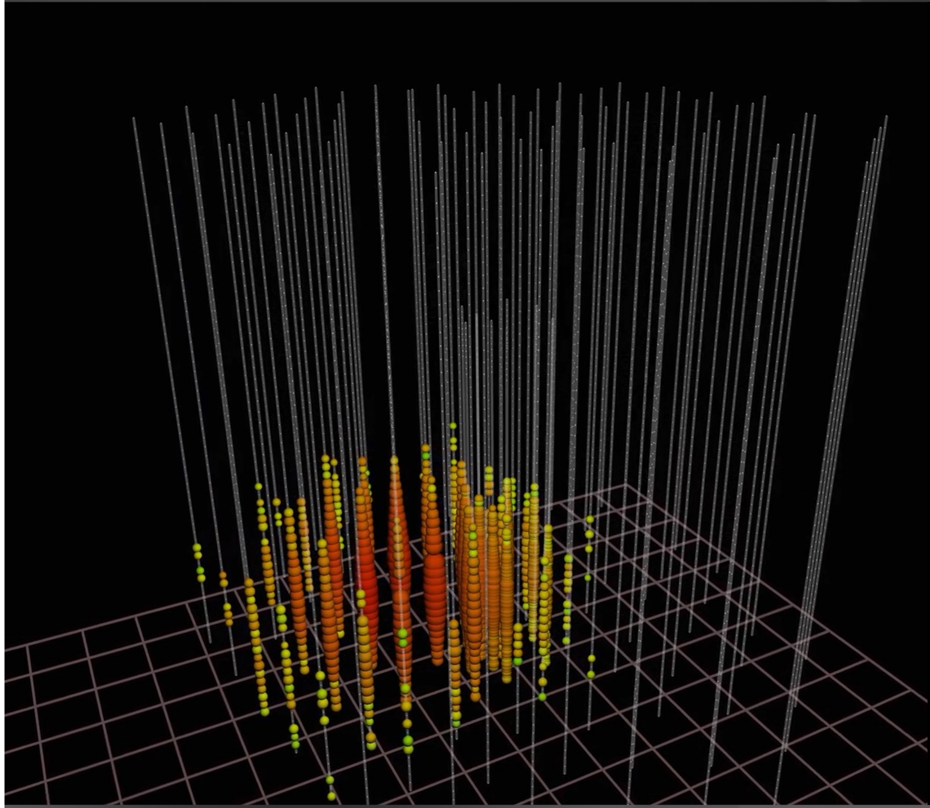


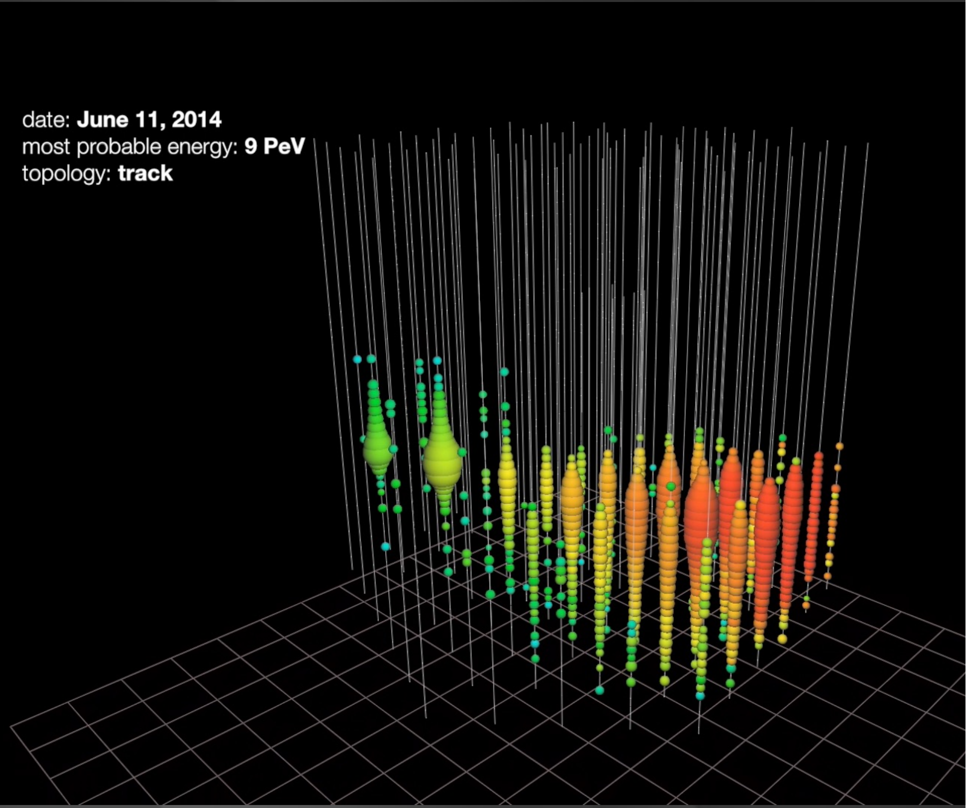
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: astronomy



neutrinos interacting inside the detector

muon neutrinos filtered by the Earth





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

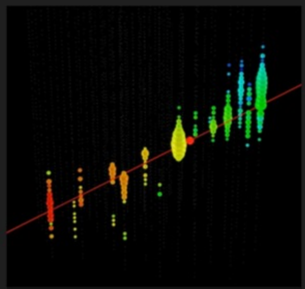
astronomy: superior angular resolution superior (0.3^{o})

NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

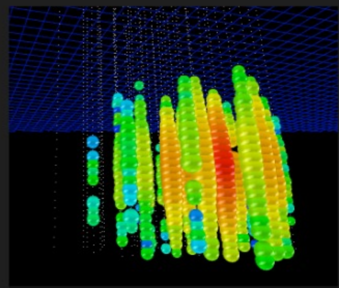


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



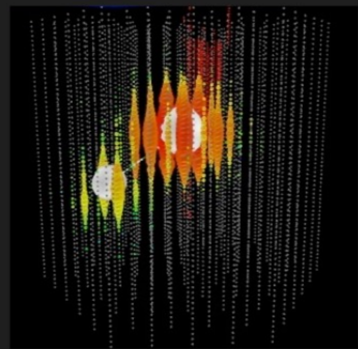
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

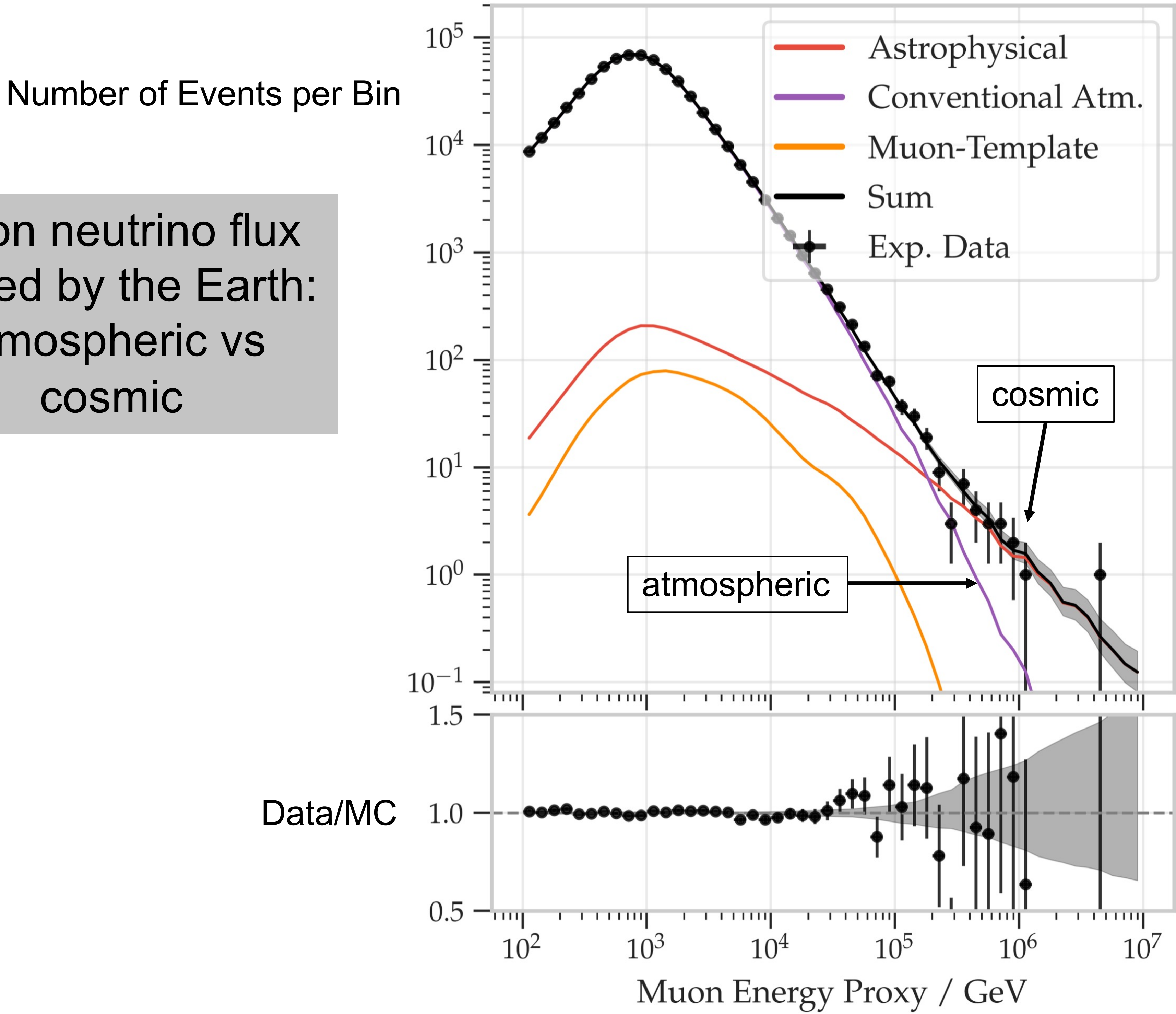
CC Tau Neutrino



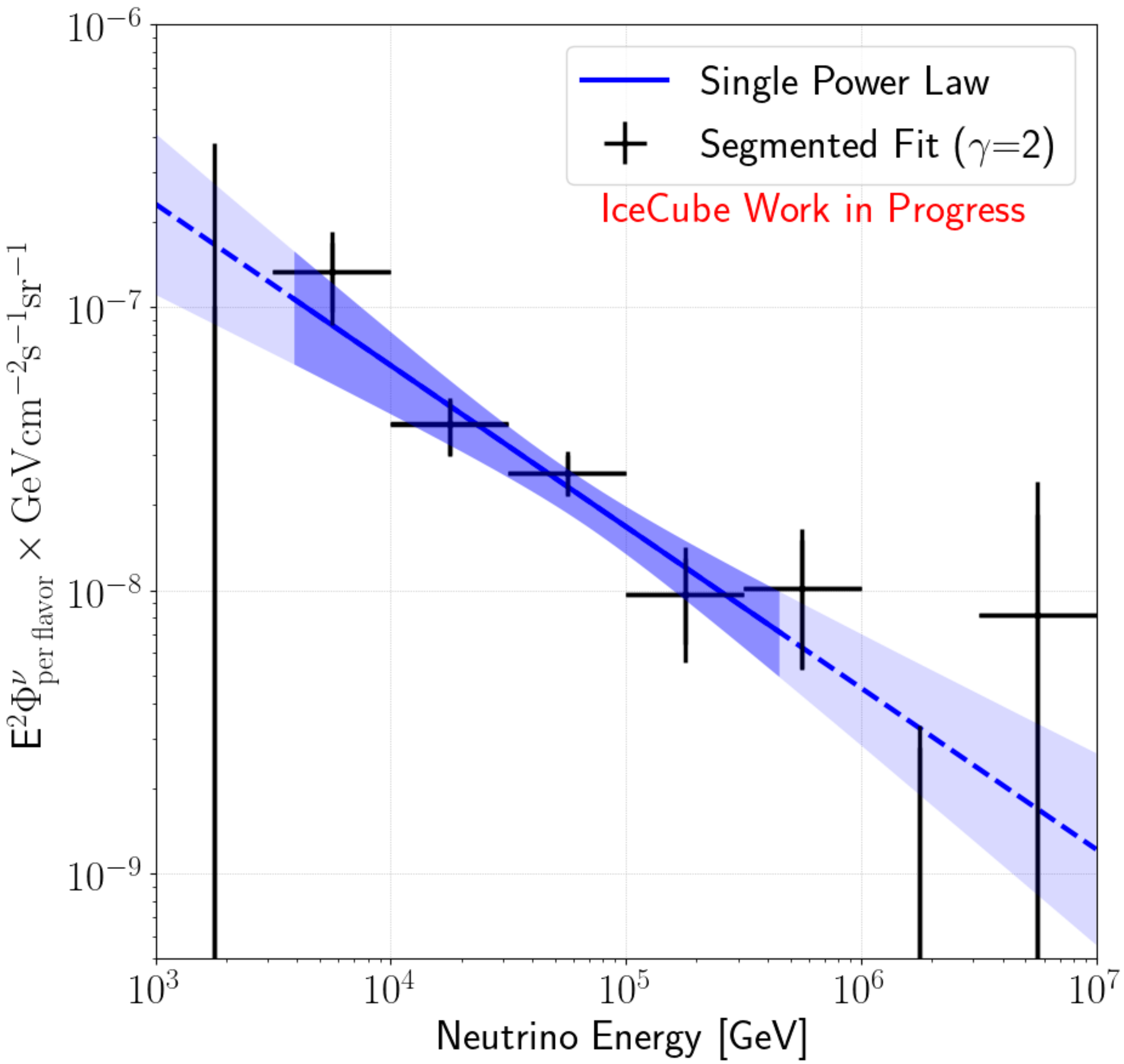
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (≳10PeV) and other signatures (simulation)

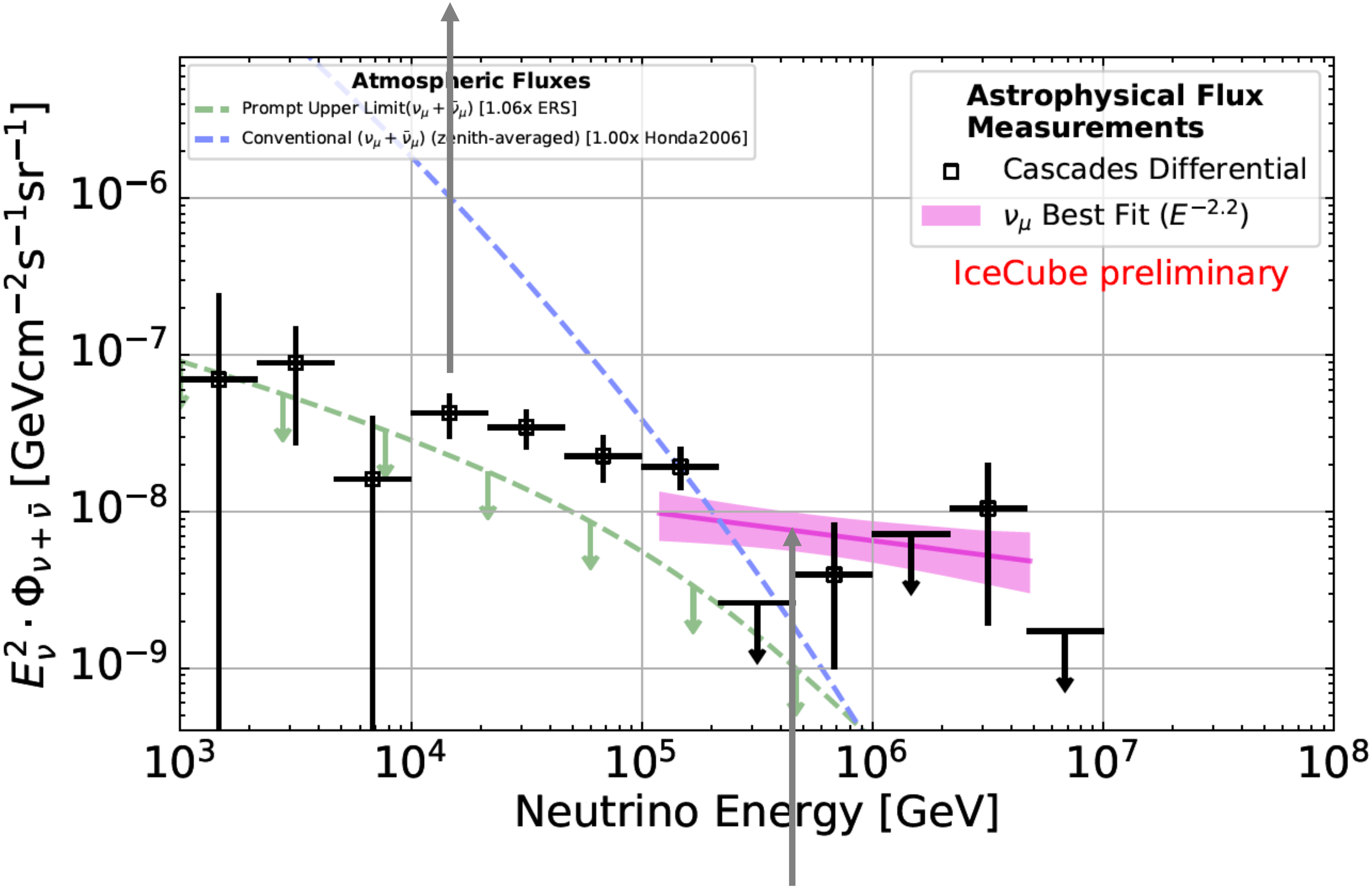
(not observed yet: τ decay length is 50 m/PeV) muon neutrino flux filtered by the Earth: atmospheric vs cosmic



update: multi-year starting ν_μ track analysis

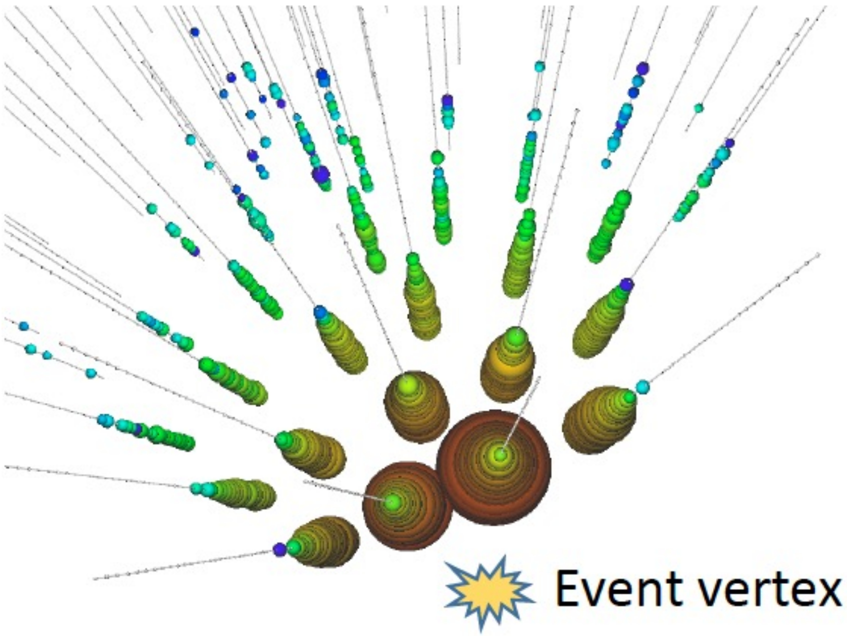


electron and tau neutrinos (showers)

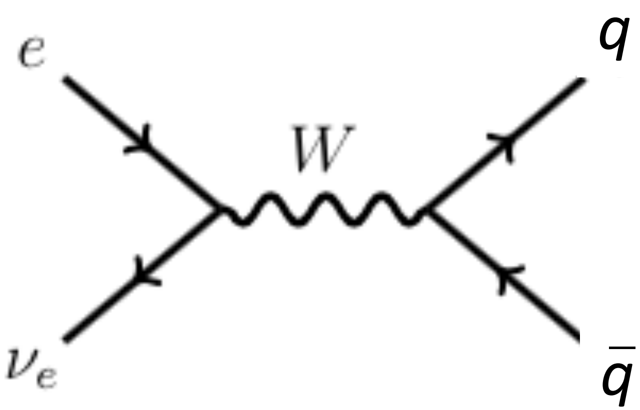


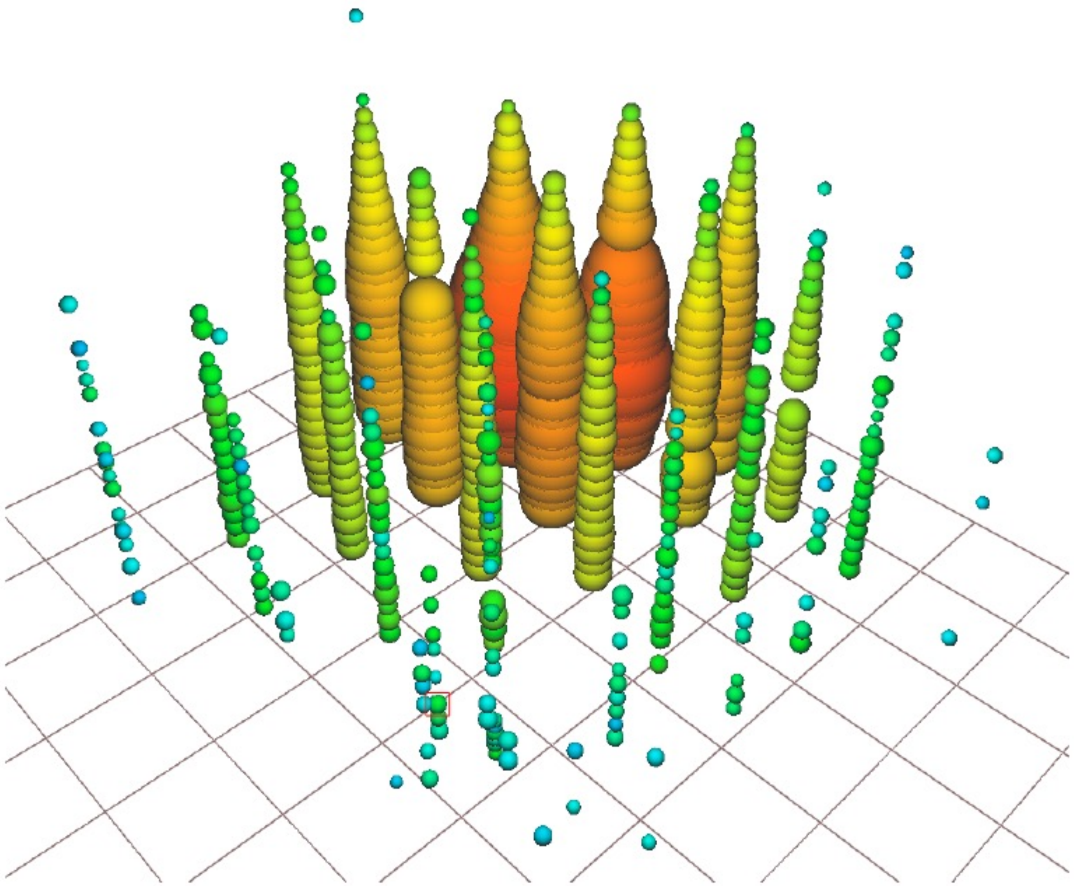
muon neutrinos through Earth (tracks)

partially contained event with energy 6.3 PeV

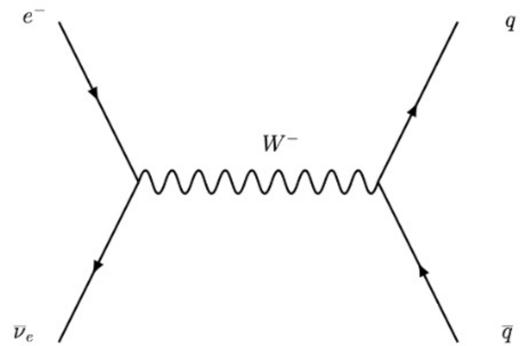


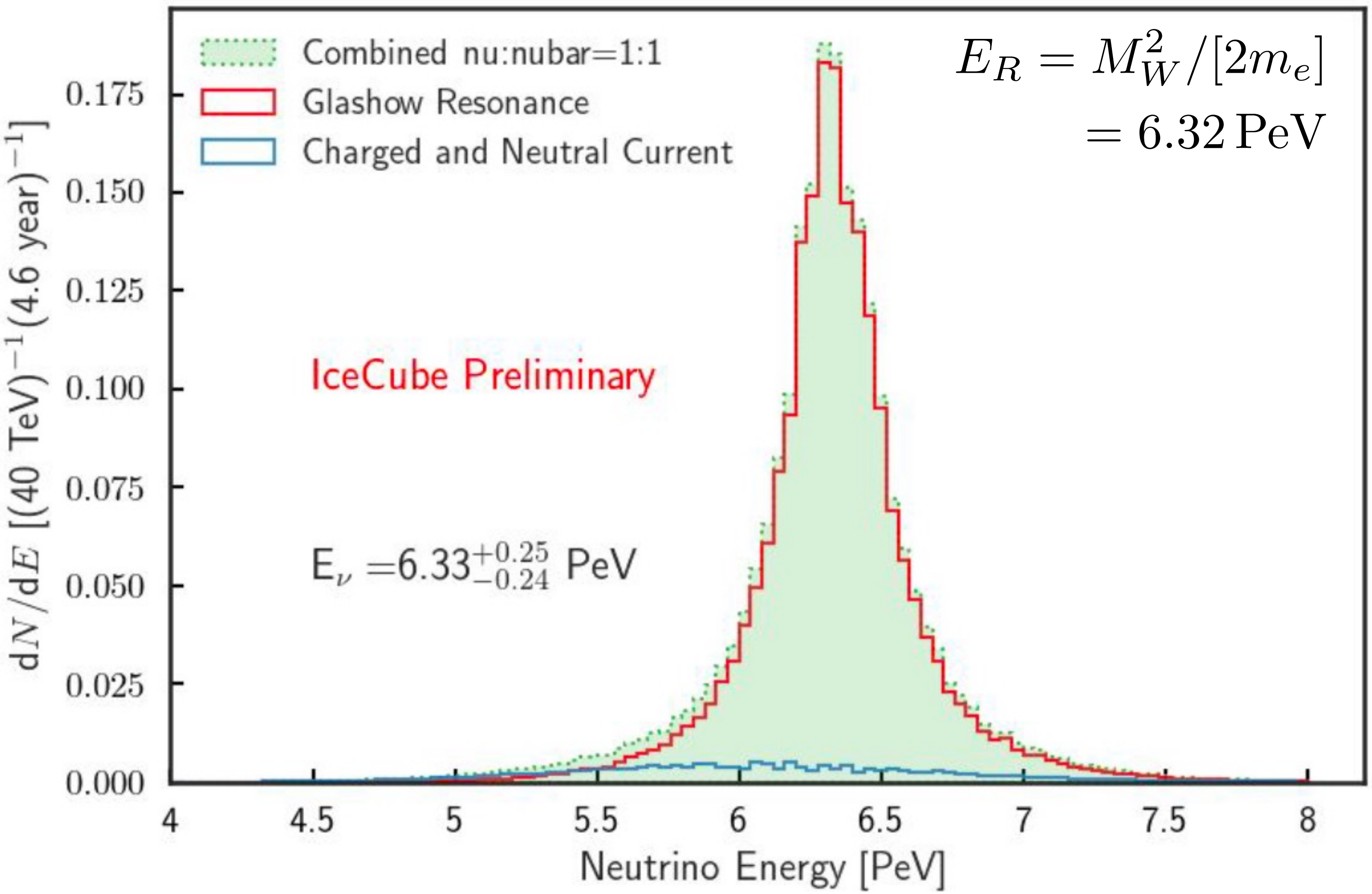
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

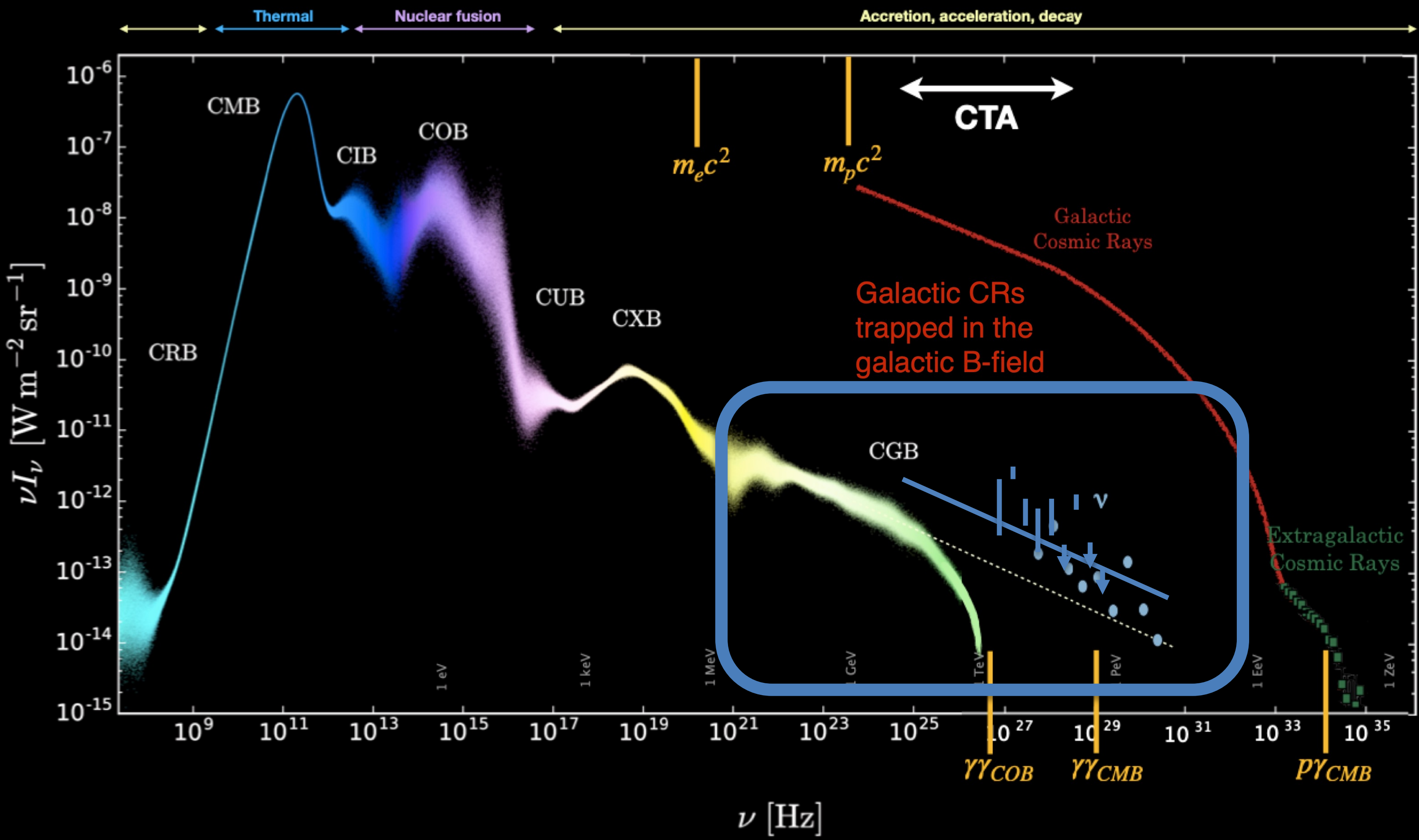




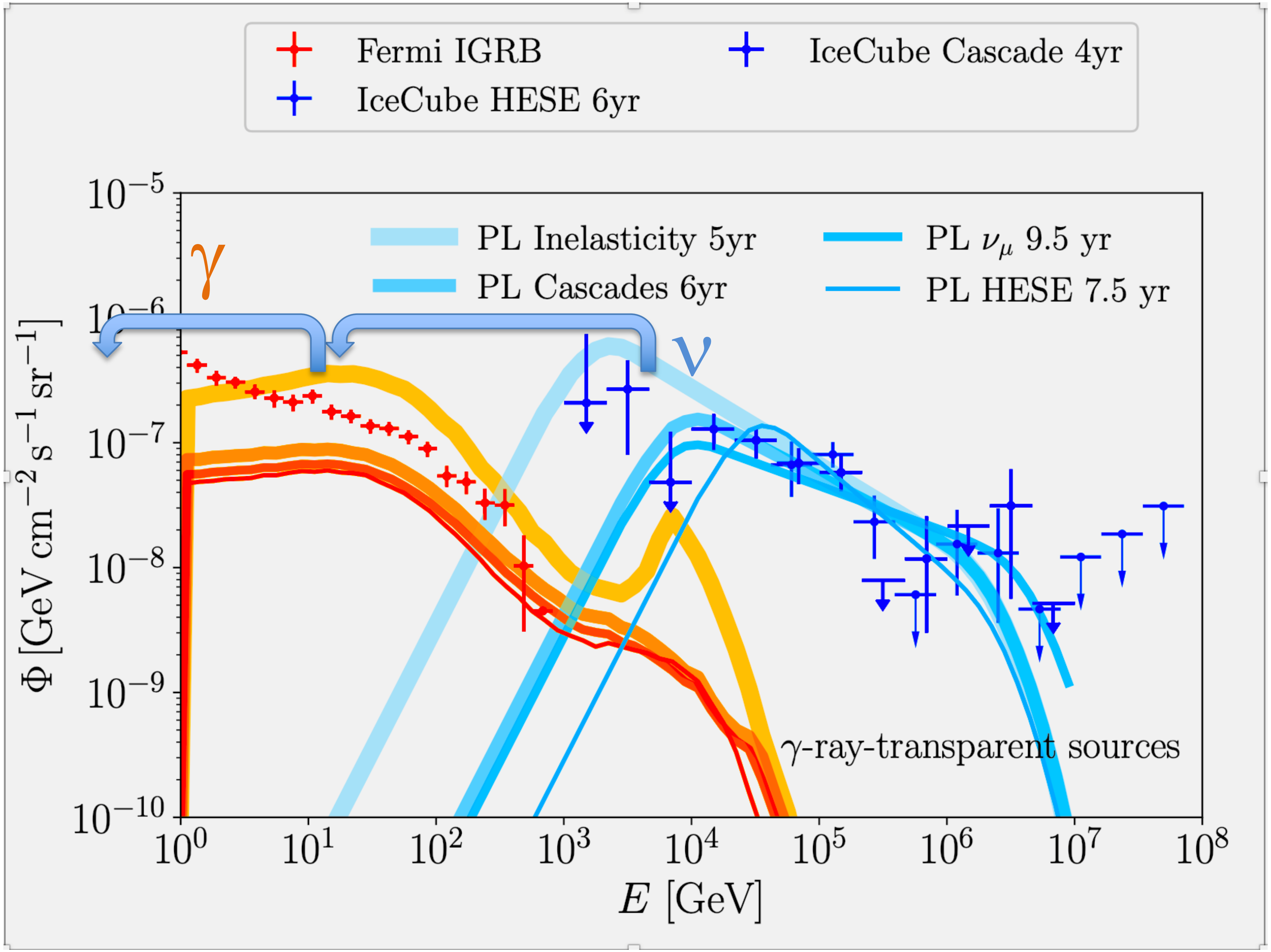
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino







in the extreme universe the energy in neutrinos is larger than the energy in gamma rays



the neutrino sources are likely opaque to gamma rays

- we do not see our own Galaxy, we see the Universe
- Our Galaxy is a neutrino desert
- in the extreme universe more energy is emitted in neutrinos than in gamma rays
- neutrinos are produced in obscured sources
- this was totally unexpected and represents a great opportunity for a “new” astronomy

High-Energy Cosmic Neutrinos

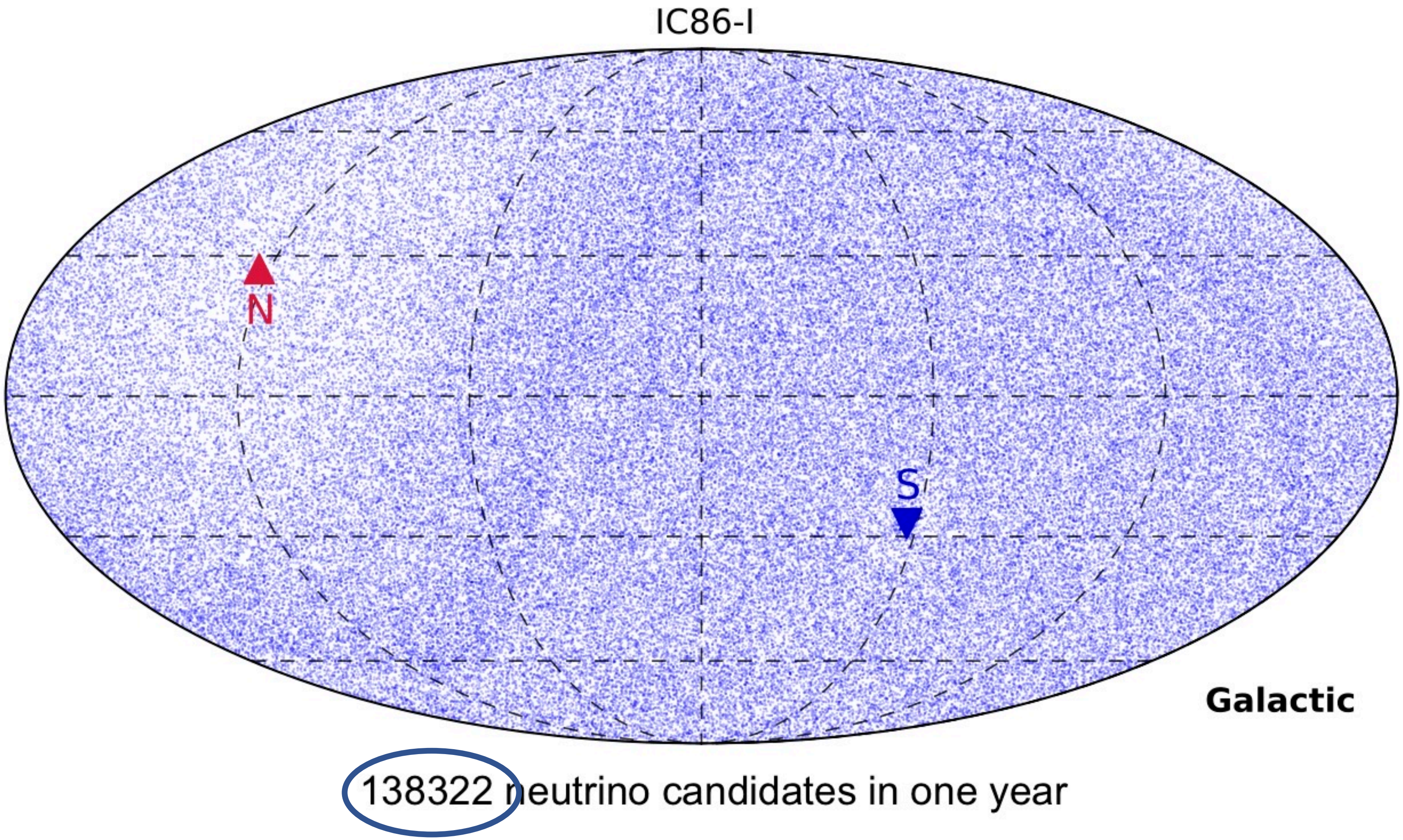
francis halzen

- ANTARES, Baikal-GVD,IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu

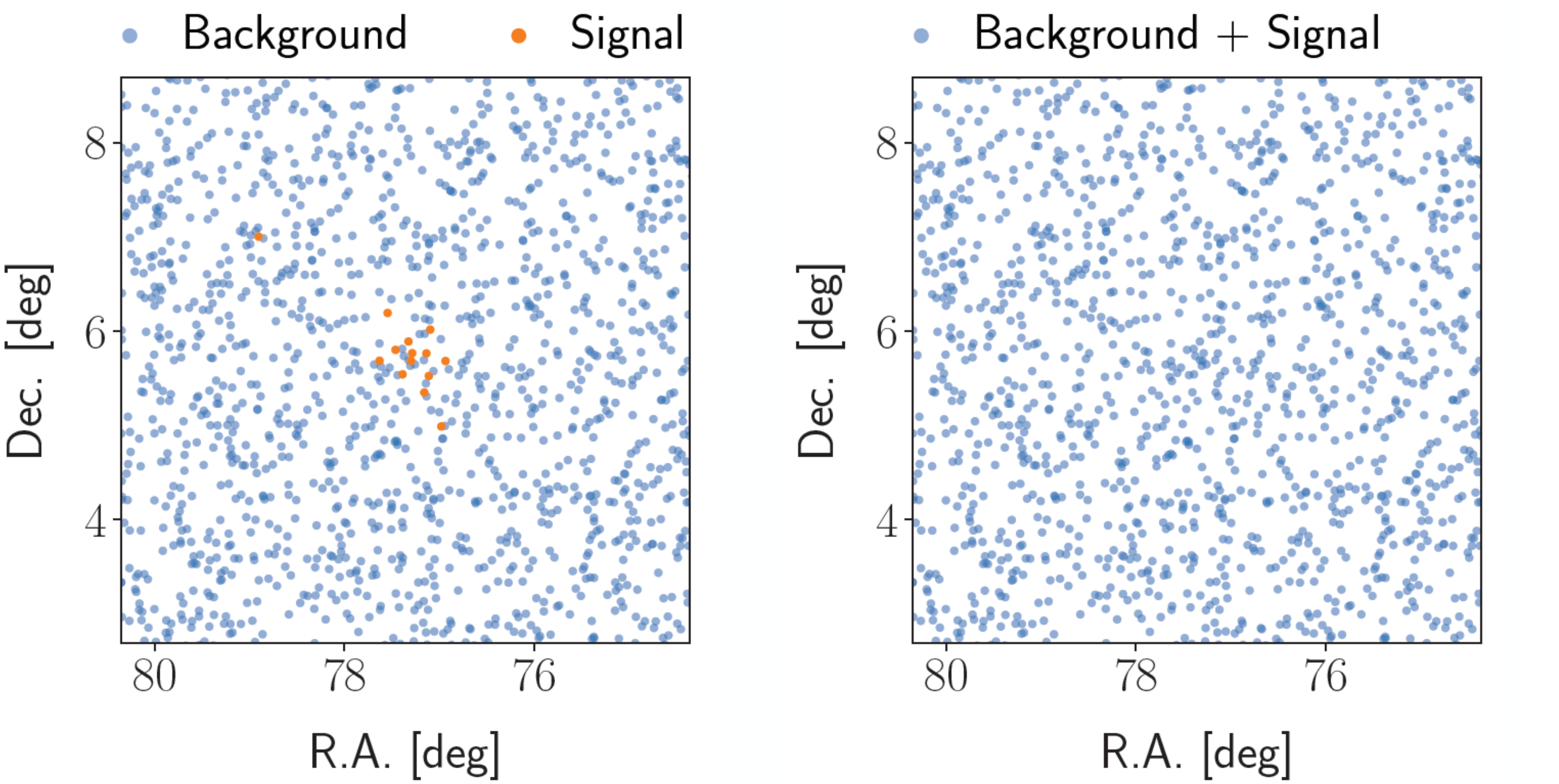
one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)



~ 200 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV



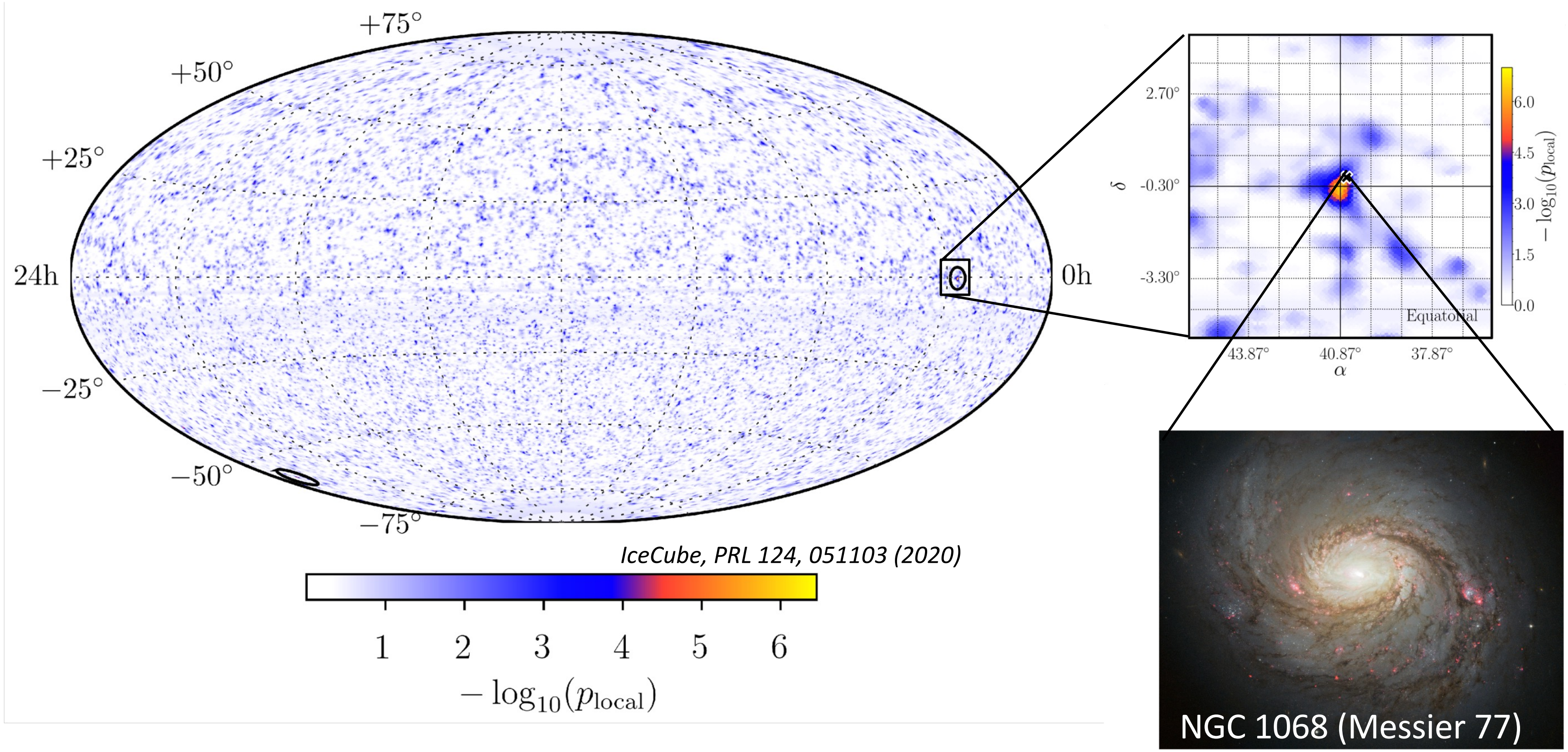
- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

$$L(n_s, x_s, \gamma) = \prod_i^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s|\sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i)\right)$$

$$\downarrow$$

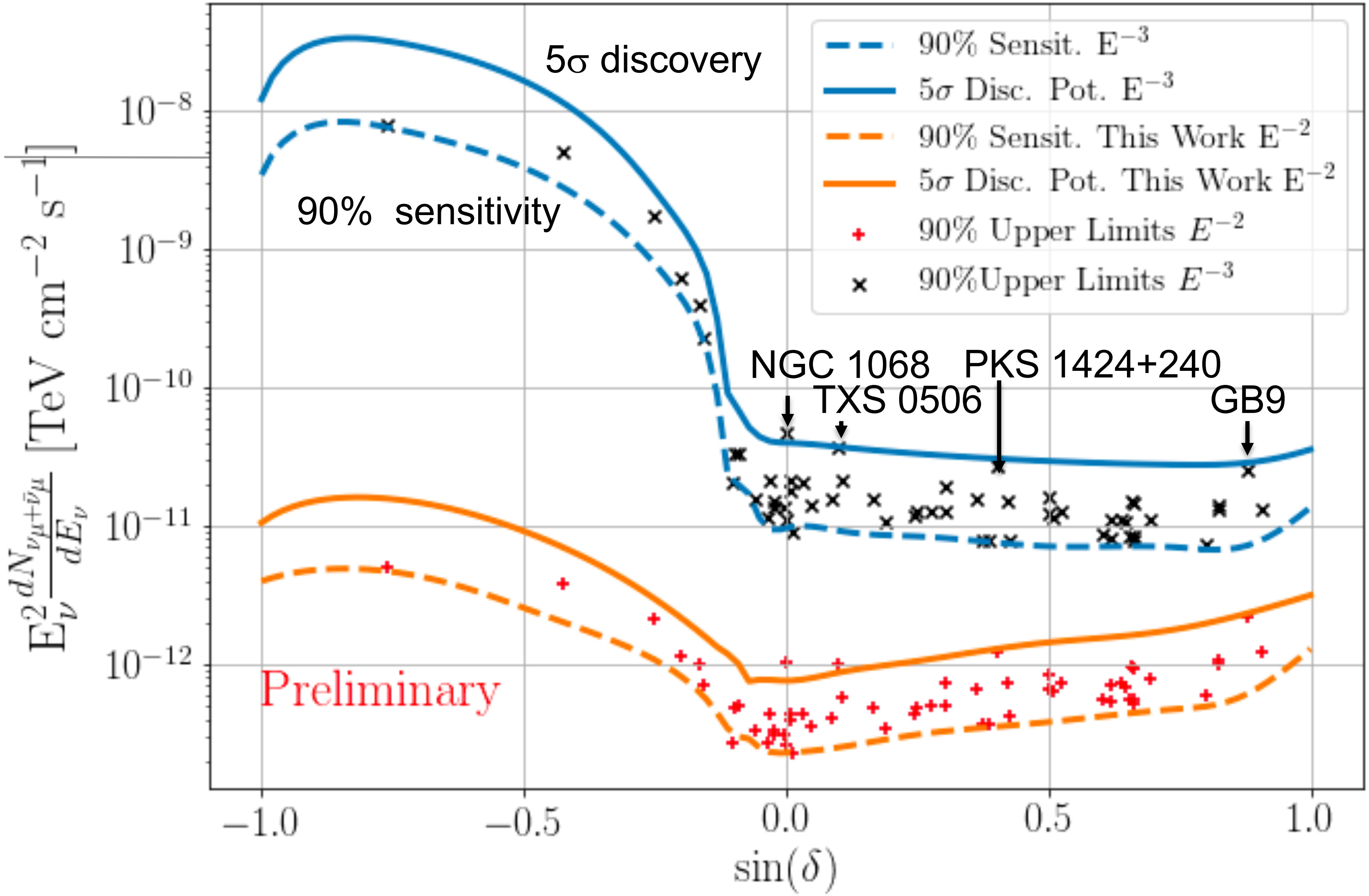
$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right)$$

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

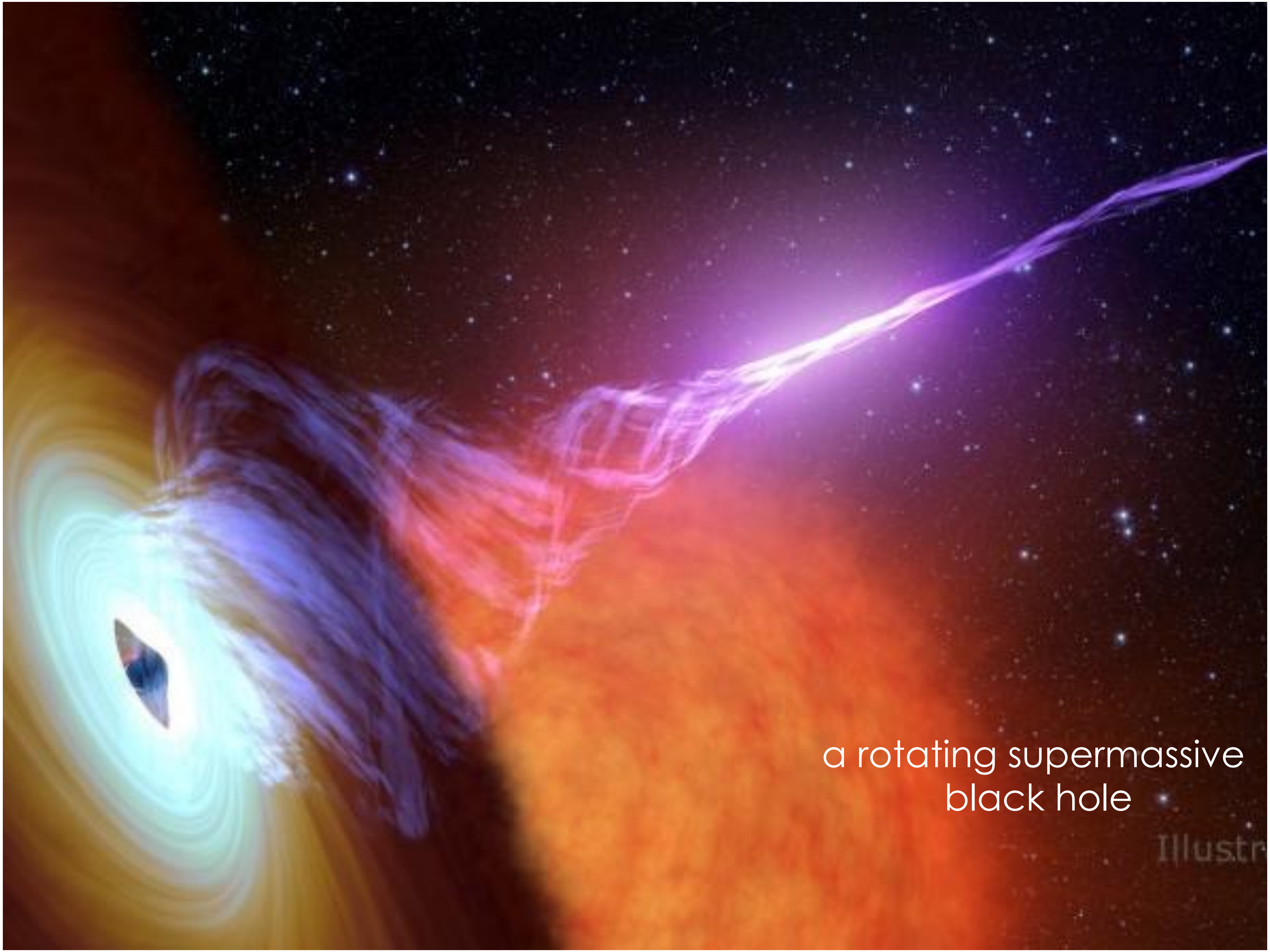


pre-trial p-value for clustering of high energy neutrinos

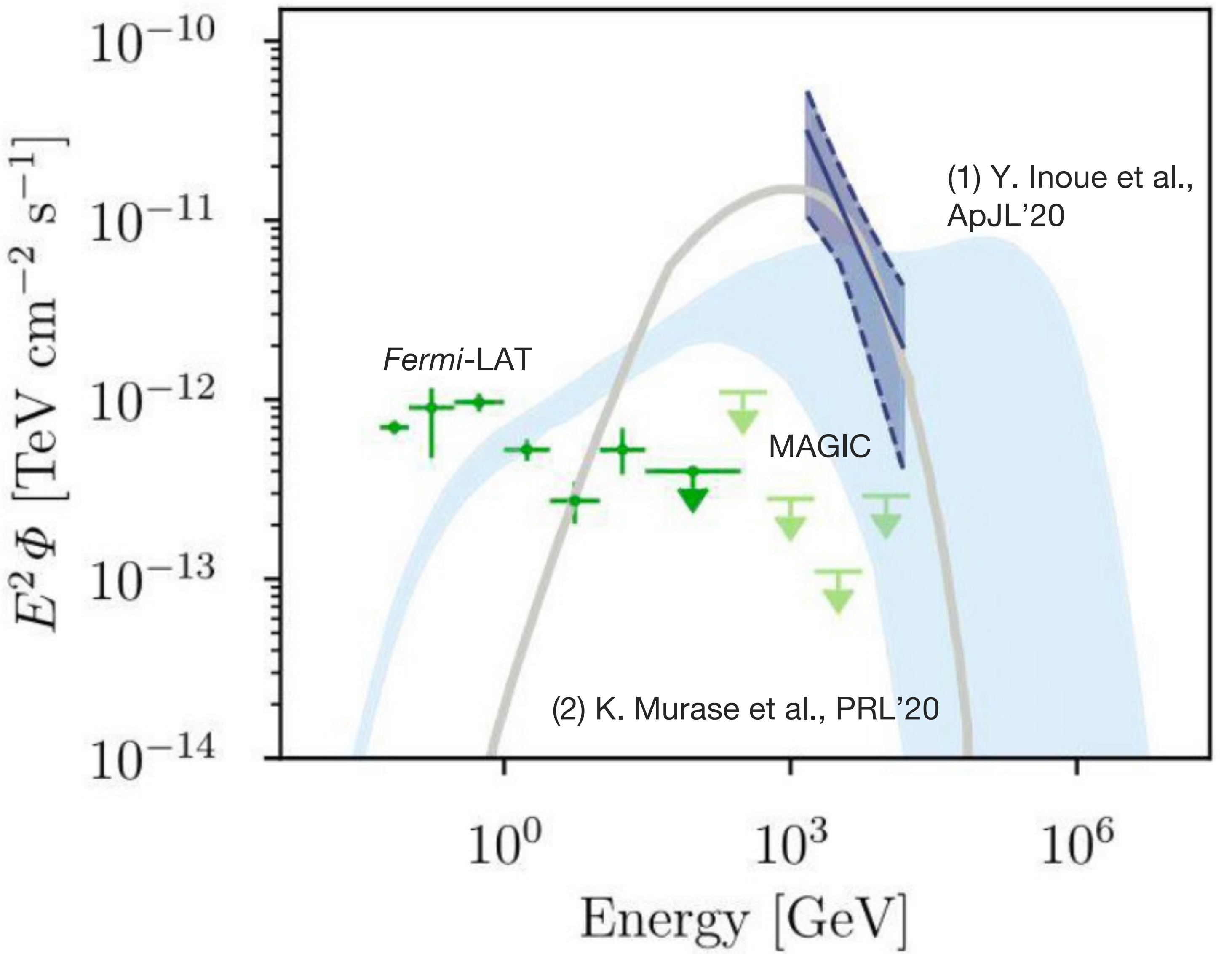
IceCube, PRL 124, 051103 (2020)



limits and interesting fluctuations ?

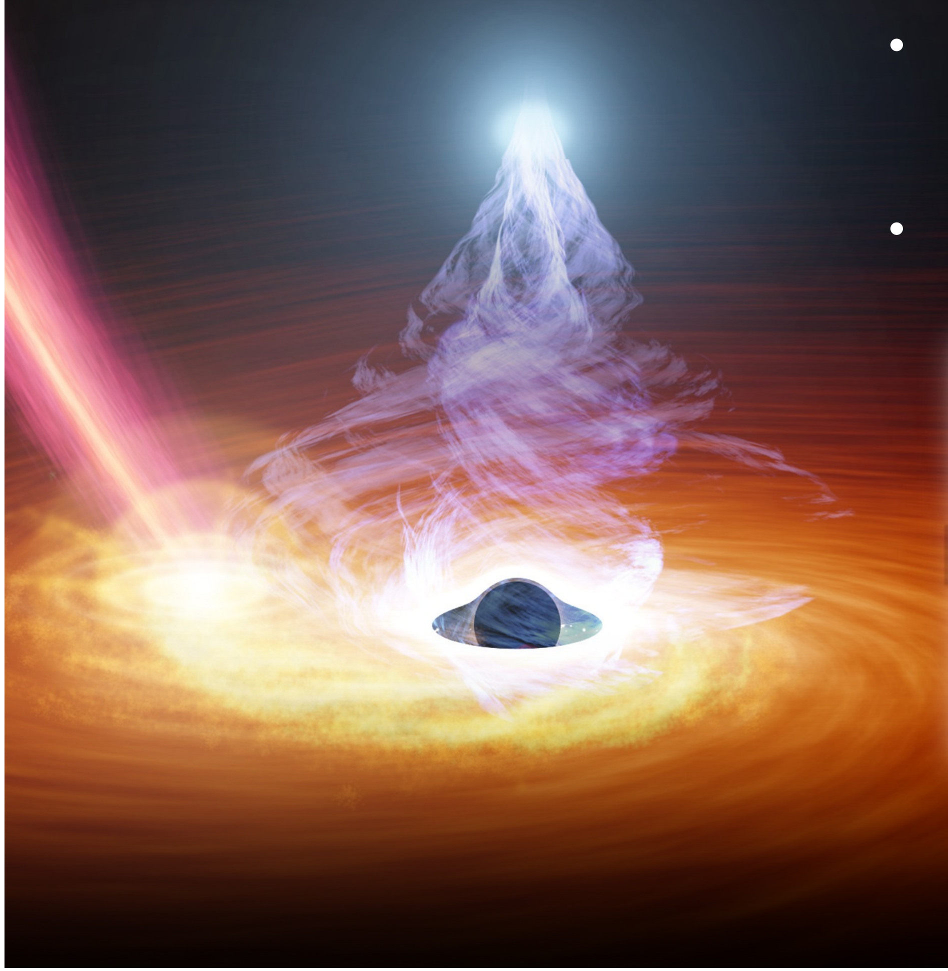

a rotating supermassive
black hole
Illustr

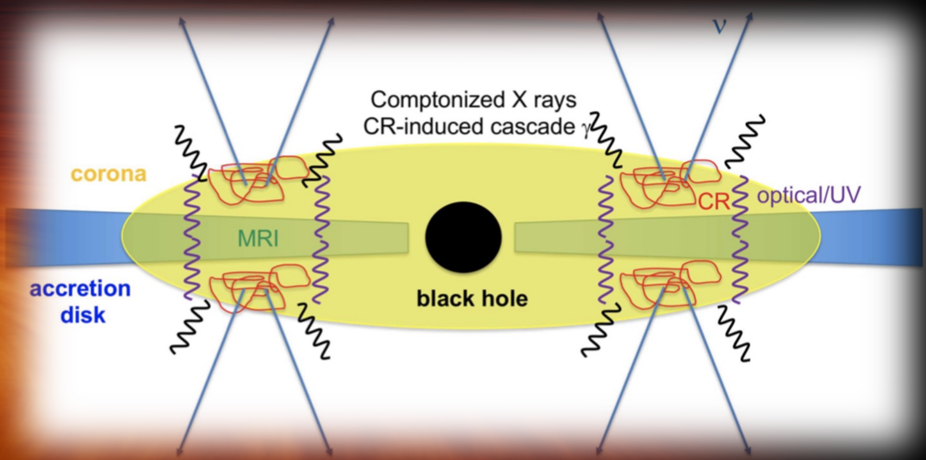
NGC 1068: an obscured cosmic accelerator



neutrino production in obscured cores of active galaxies

- electrons and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- produce neutrinos in the optically thick corona





NGC 1068 neutrinos: the disk corona model

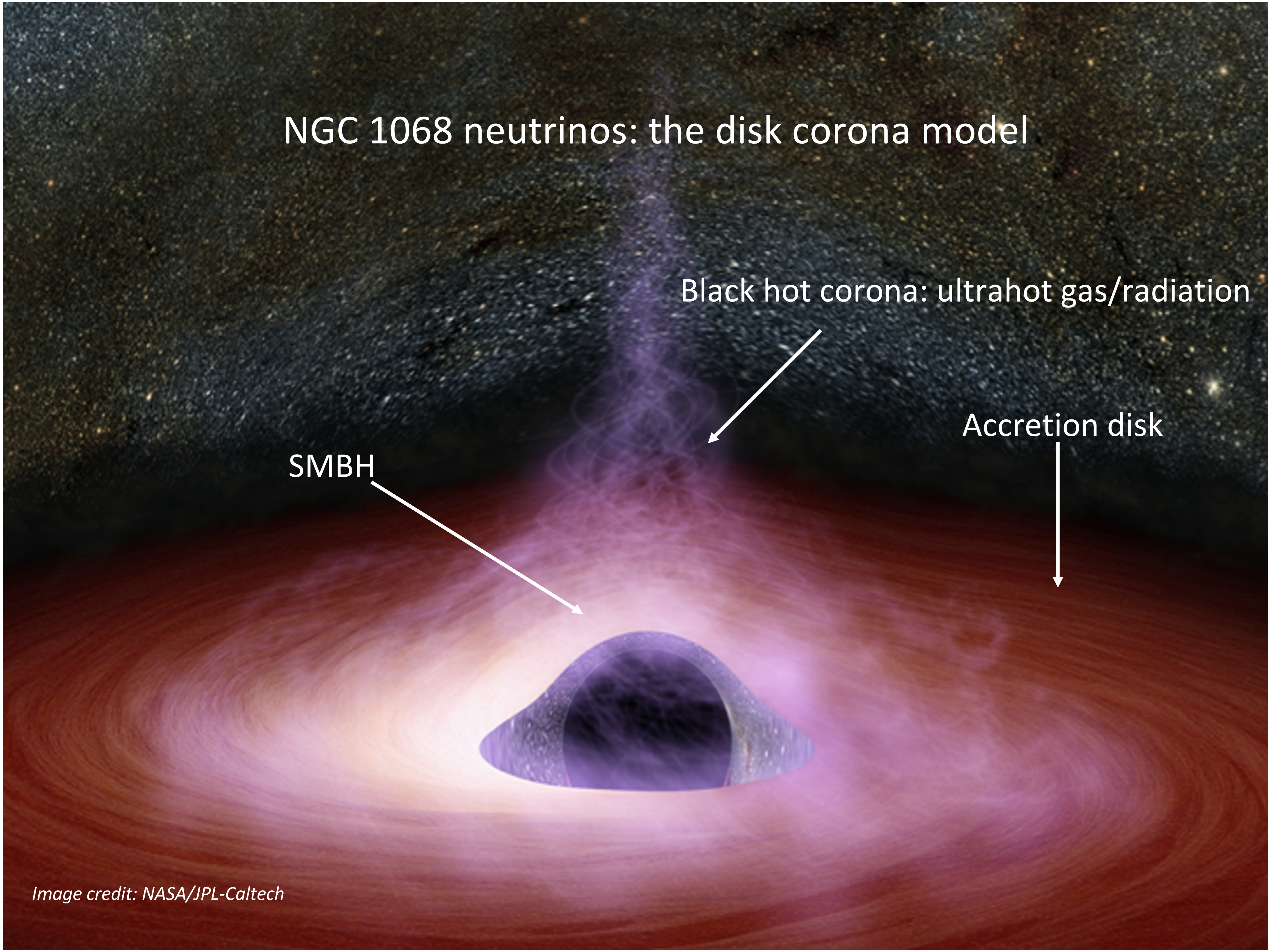
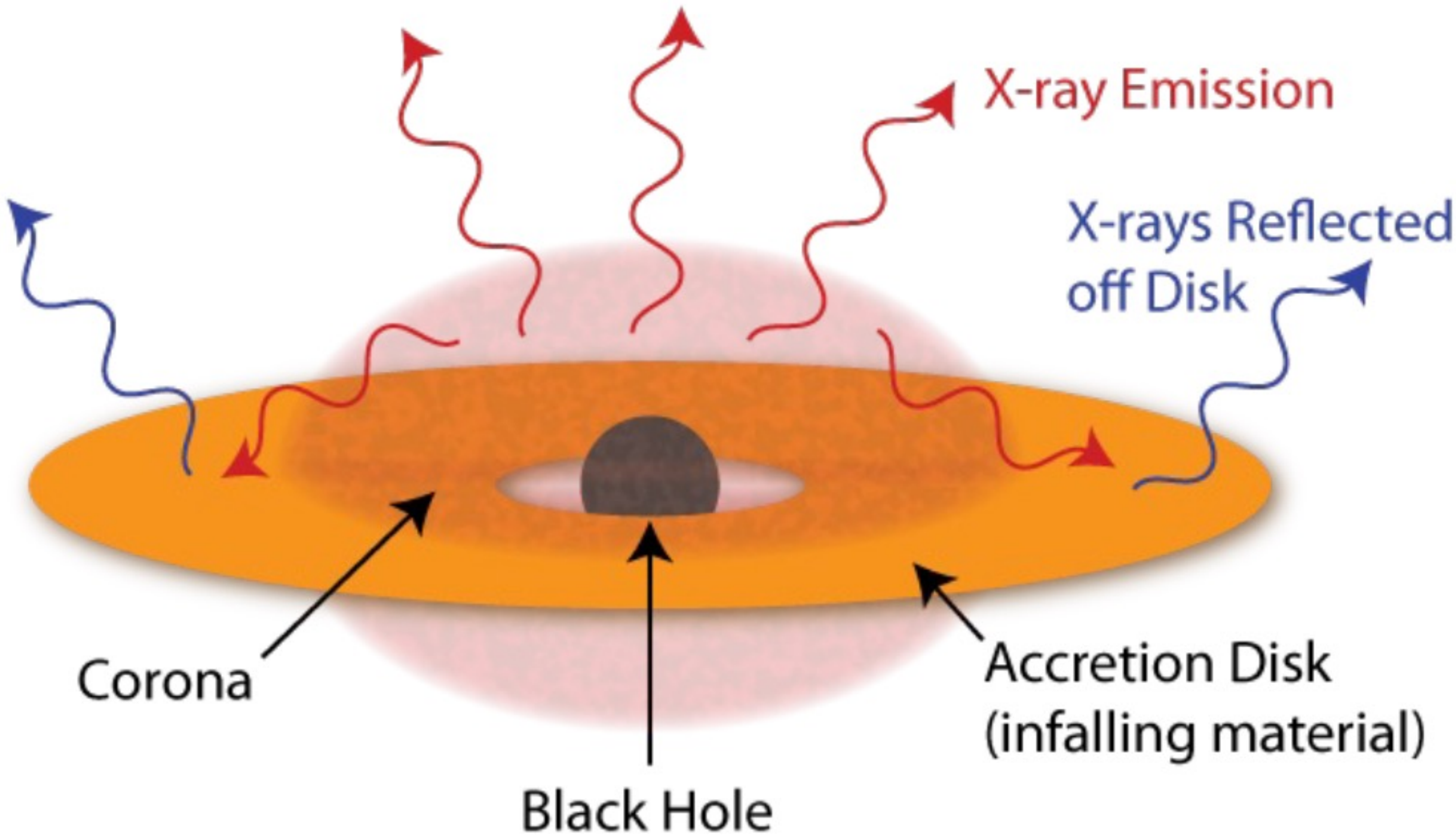


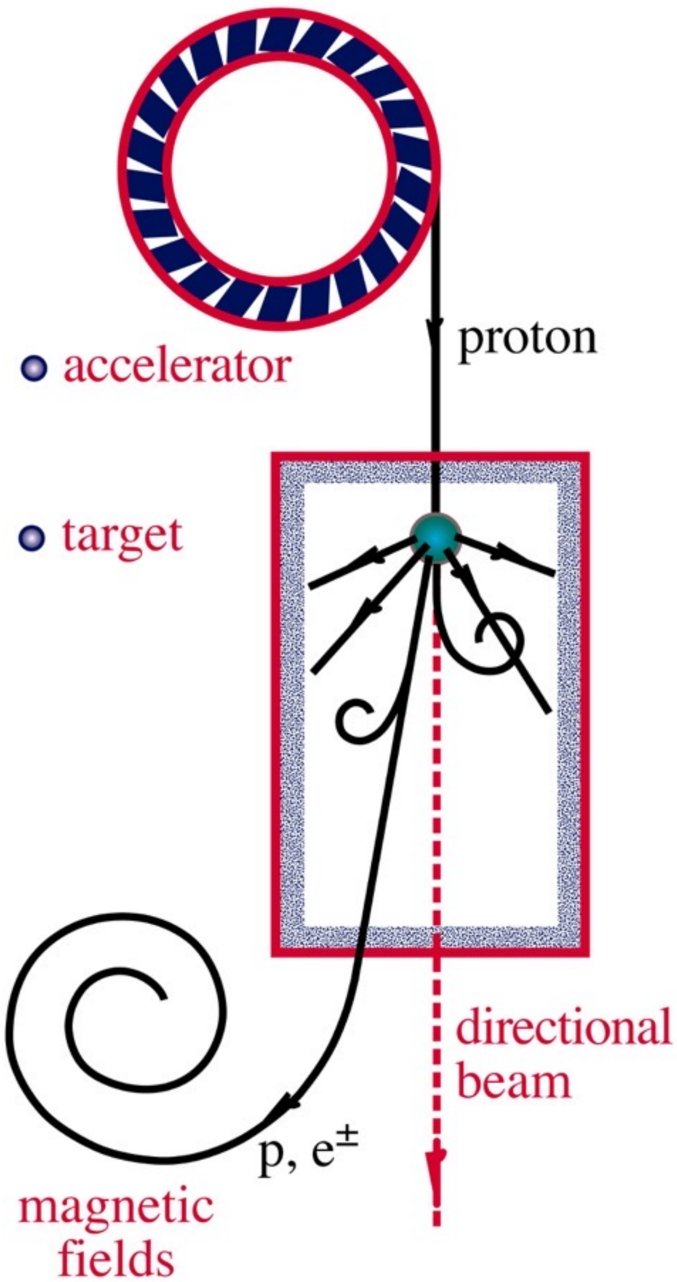
Image credit: NASA/JPL-Caltech

the radiatively obscured core of an active galaxy: opaque to γ-rays



[PS: the neutrinos are not produced by star formation because they are not accompanied by gamma rays]

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{\mathrm{p}\gamma} \simeq \frac{\kappa_{\mathrm{p}\gamma} \mathrm{R}_{\mathrm{escape}}}{\lambda_{\mathrm{p}\gamma}} \simeq \mathrm{R}_{\mathrm{escape}}\, \sigma_{\mathrm{p}\gamma}\, \mathrm{n}_{\mathrm{photons}}$$

- likelihood of the multimessenger photons to be absorbed in target

$$\tau_{\gamma\gamma} \simeq \mathrm{R}_{\mathrm{target}}\, \sigma_{\gamma\gamma}\, \mathrm{n}_{\mathrm{photons}}$$

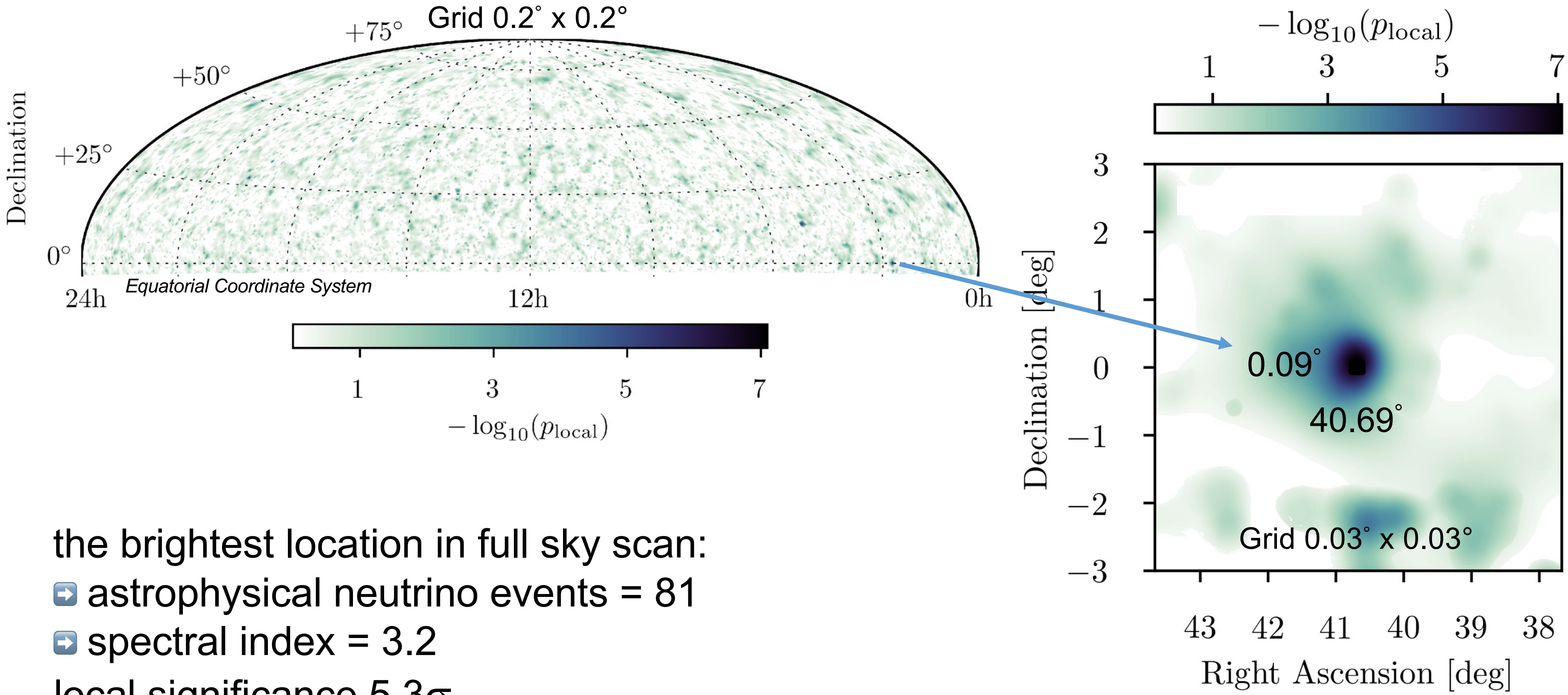
→ therefore, with $\mathrm{R}_{\mathrm{escape}} \sim \mathrm{R}_{\mathrm{target}}$

$$\tau_{\gamma\gamma} \sim \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \tau_{p\gamma} \sim 300\, \tau_{p\gamma}$$

→ do not expect high energy gamma rays to accompany cosmic neutrinos

→ blazar jets are out

the new IceCube neutrino map

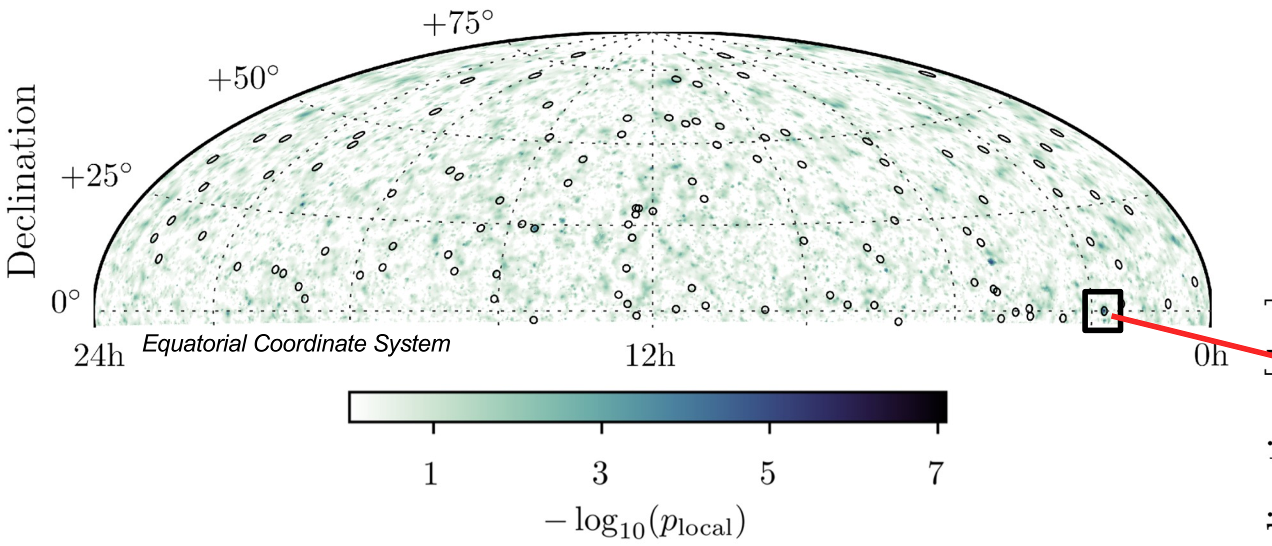


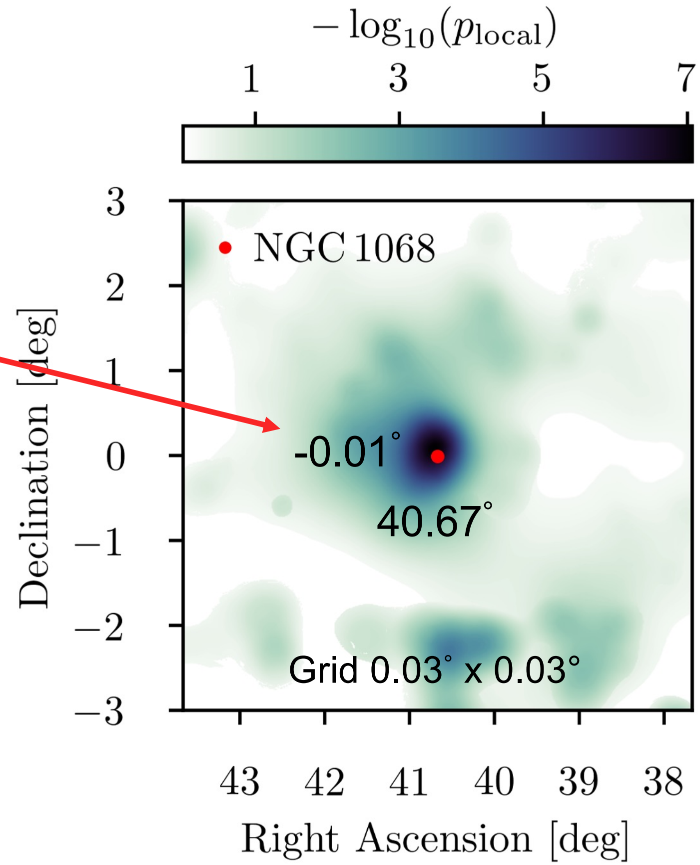
the brightest location in full sky scan:

- astrophysical neutrino events = 81
- spectral index = 3.2

local significance 5.3σ

1% of scrambled data sets have a spot ≥ 5.3**σ** is the hot spot coincident with one of the 110 preselected sources?





at the NGC1068 location:

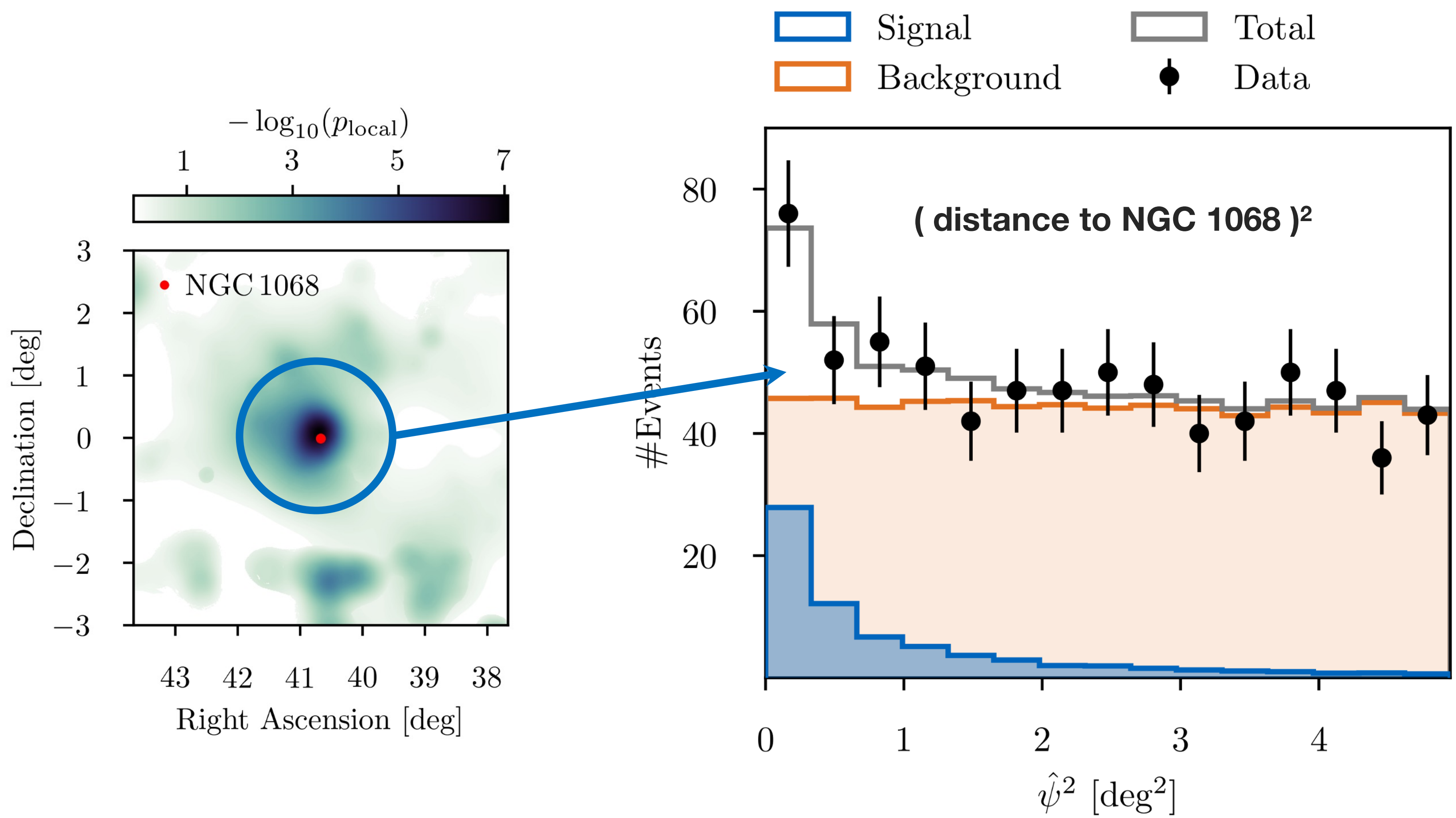
astrophysical neutrino events = 79^{+22}_{-20}

spectral index = 3.2 ± 0.2

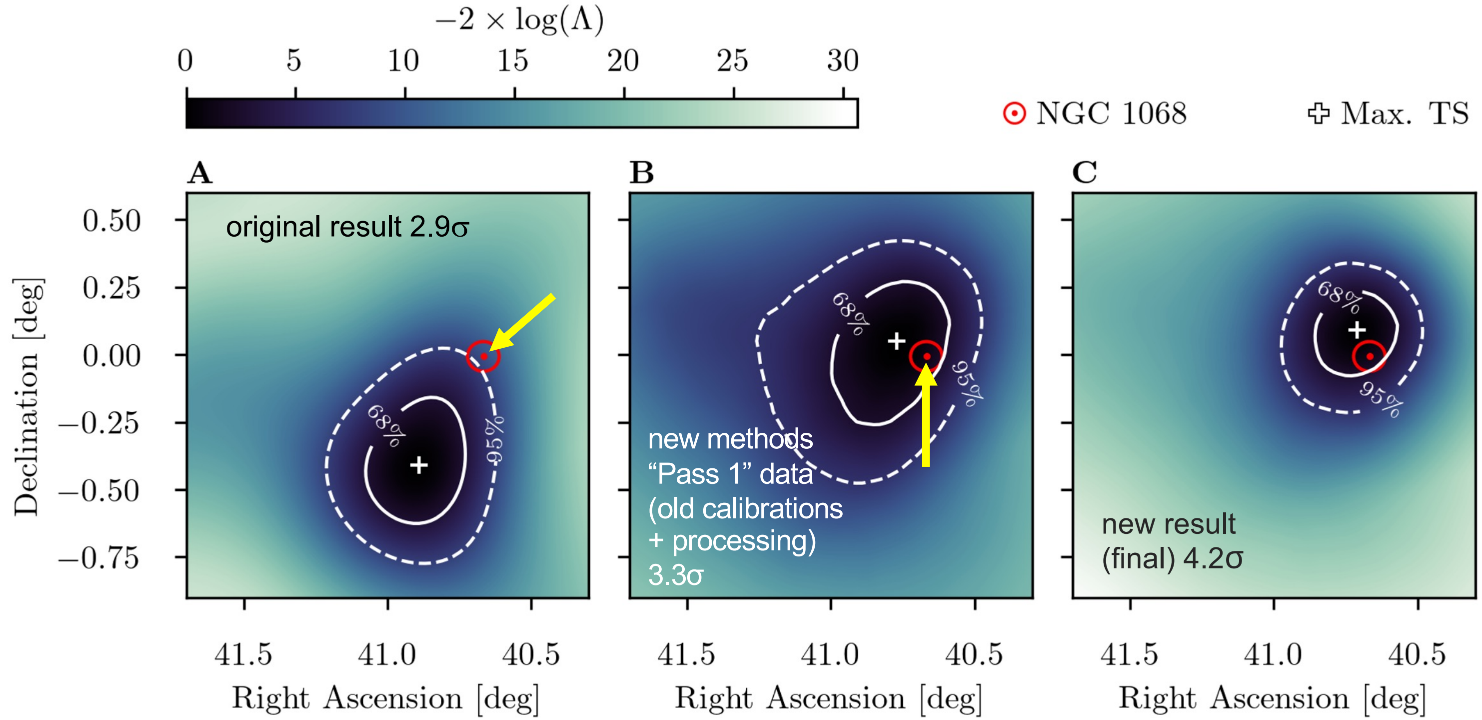
single source significance 5.2σ

1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ** evidence

another look at the result



- measured astrophysical neutrino events = 79^{+22}_{-20}
- the angular distribution of the events matches simulation



$-2 \times \log(\Lambda)$
0
5
10
15
20
25
30
NGC 1068
Max. TS
A
B
C
original result 2.9σ
new methods
“Pass 1” data
(old calibrations
+ processing)
3.3σ
new result
(final) 4.2σ
68%
95%
Declination [deg]
0.50
0.25
0.00
−0.25
−0.50
−0.75
41.5
41.0
40.5
Right Ascension [deg]

How are neutrinos produced in non-jetted AGN?

1982

R. Silberberg and M. M. Shapiro

Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D.C. 20375

We conclude that active galactic
accelerating particles to cosmic
galactic cosmic rays is likely to
particular, in the Virgo supercl
NGC 4151 and NGC 1068 are likely
"local" metagalactic cosmic rays,
the ultra-high energy ($E \gtrsim 10^{19}$ eV) air showers. The energy density of photons in the immediate vicinity of a black hole may be too high (Blumenthal, 1970) to permit the acceleration of protons beyond $\sim 10^{14}$ eV, (except by beaming processes). The highest energy protons hence are accelerated somewhat farther out, or else by beaming (Lovelace, 1976). Gamma rays from the ergosphere of a black hole are degraded at energies above ~ 1 MeV, and from a spinar, above ~ 1 GeV. Neutrinos are not thus affected and would provide information on very high energy particles in active galactic nuclei.

High-Energy Cosmic Neutrinos
francis halzen

- ANTARES, Baikal-GVD, IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

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

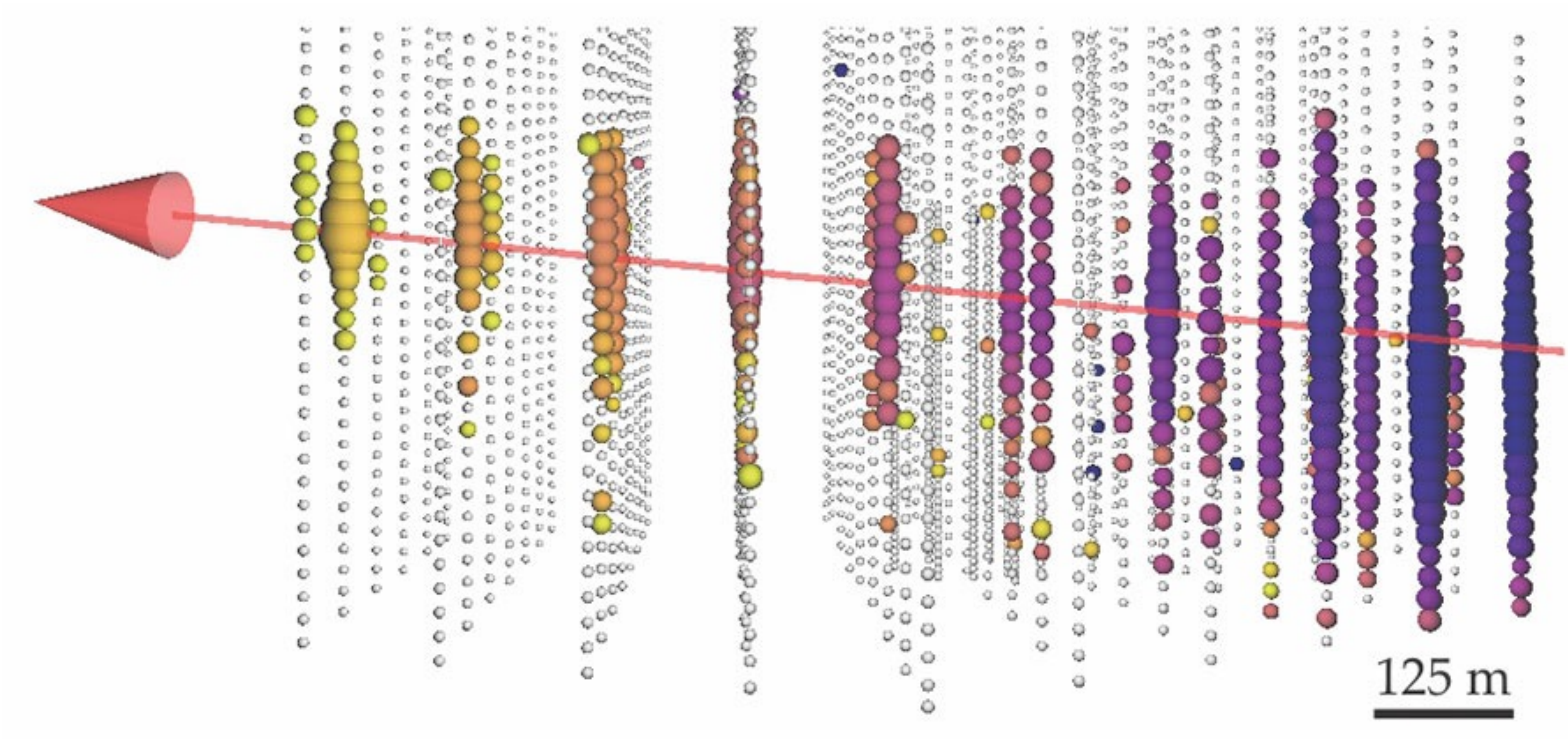
RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

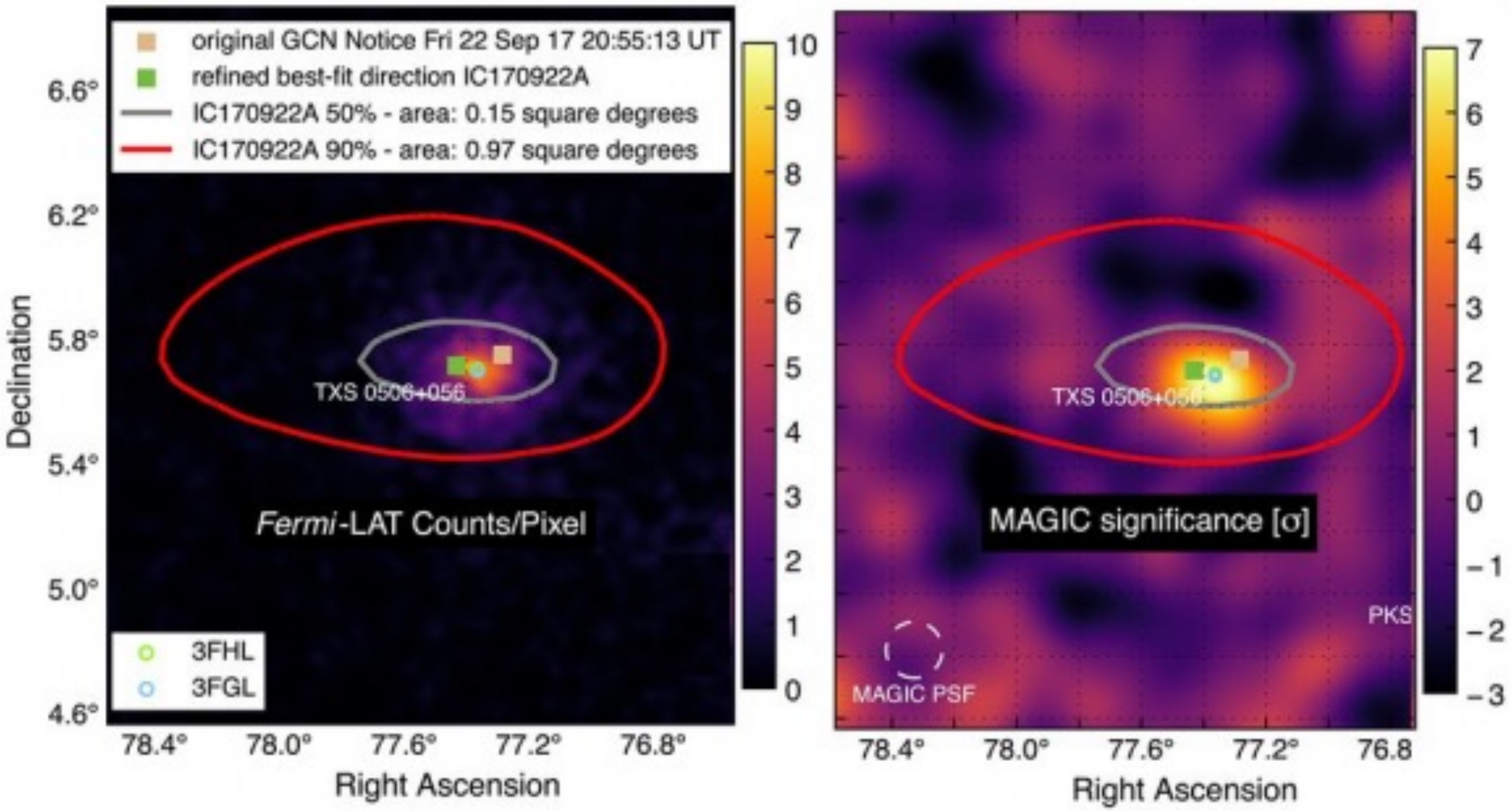
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

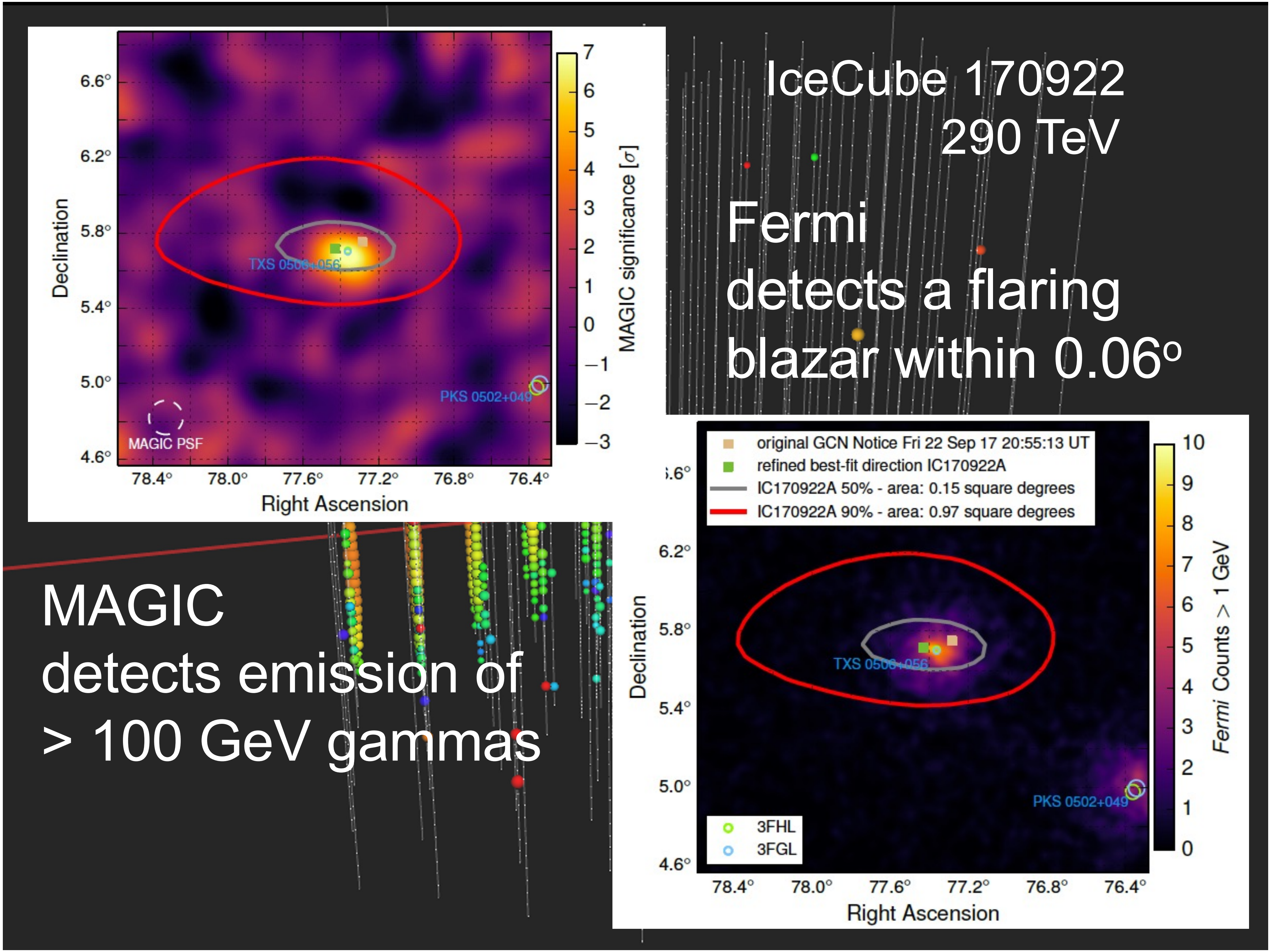
“The” neutrino …



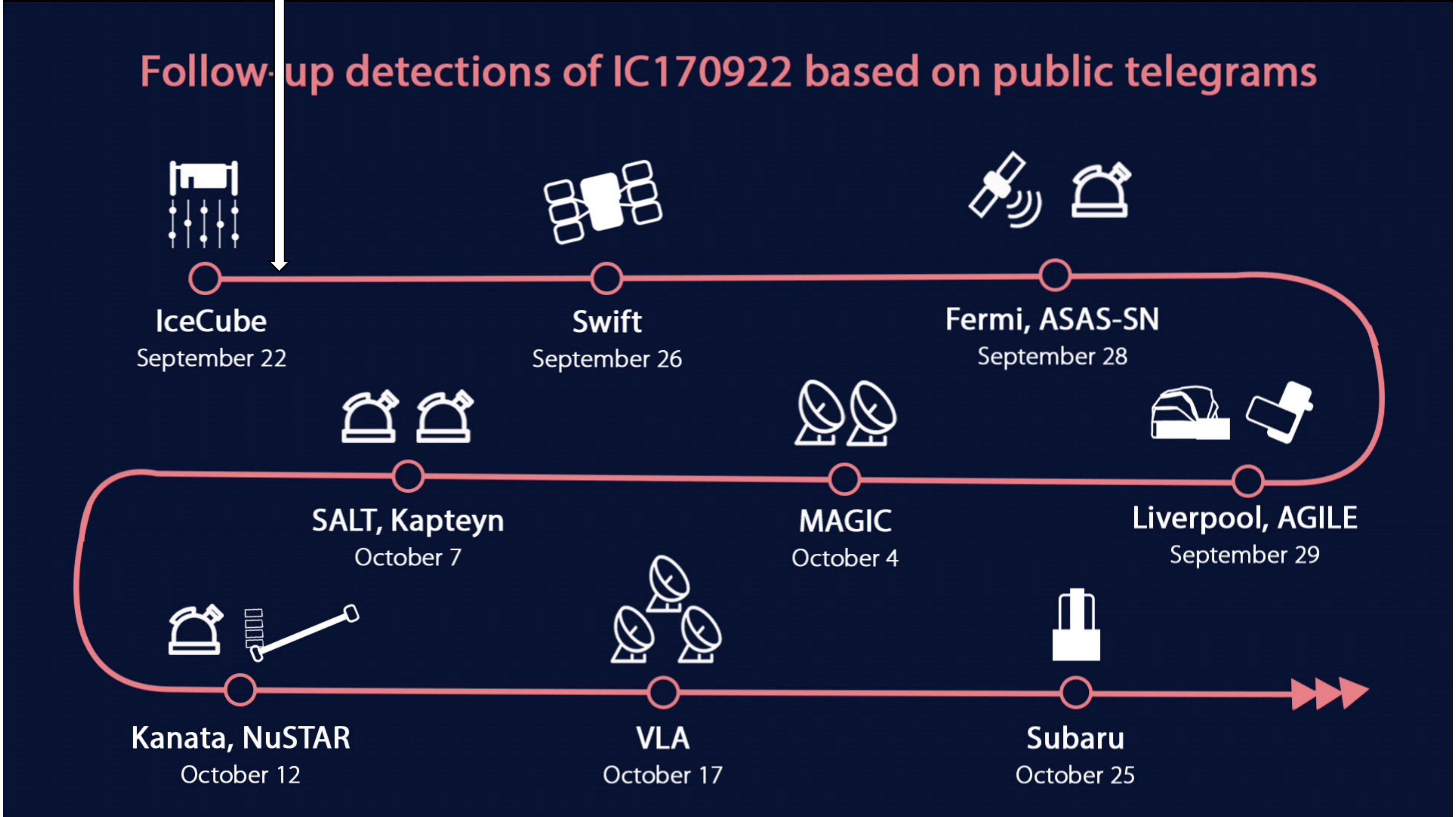
TXS 0506+056

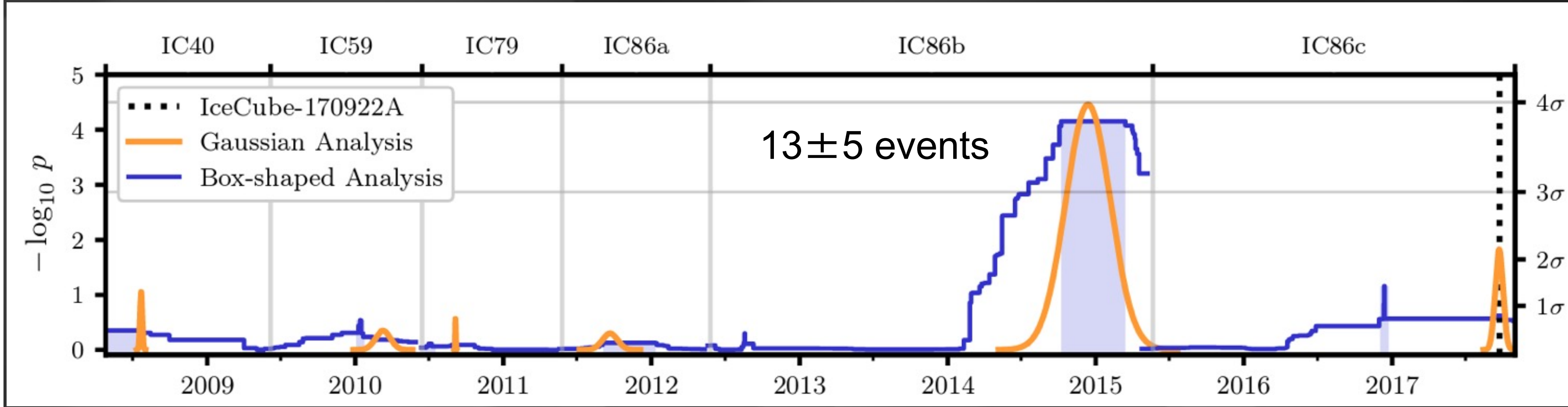


original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
TXS 0506+056
Fermi-LAT Counts/Pixel
3FHL
3FGL
Declination
Right Ascension
MAGIC significance [σ]
MAGIC PSF
PKS


IceCube 170922
290 TeV
Fermi
detects a flaring
blazar within 0.06°
MAGIC
detects emission of
> 100 GeV gammas
Declination
Right Ascension
MAGIC significance [σ]
TXS 0506+056
PKS 0502+049
MAGIC PSF
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
78.4°
78.0°
77.6°
77.2°
76.8°
76.4°
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
3FHL
3FGL
Fermi Counts > 1 GeV

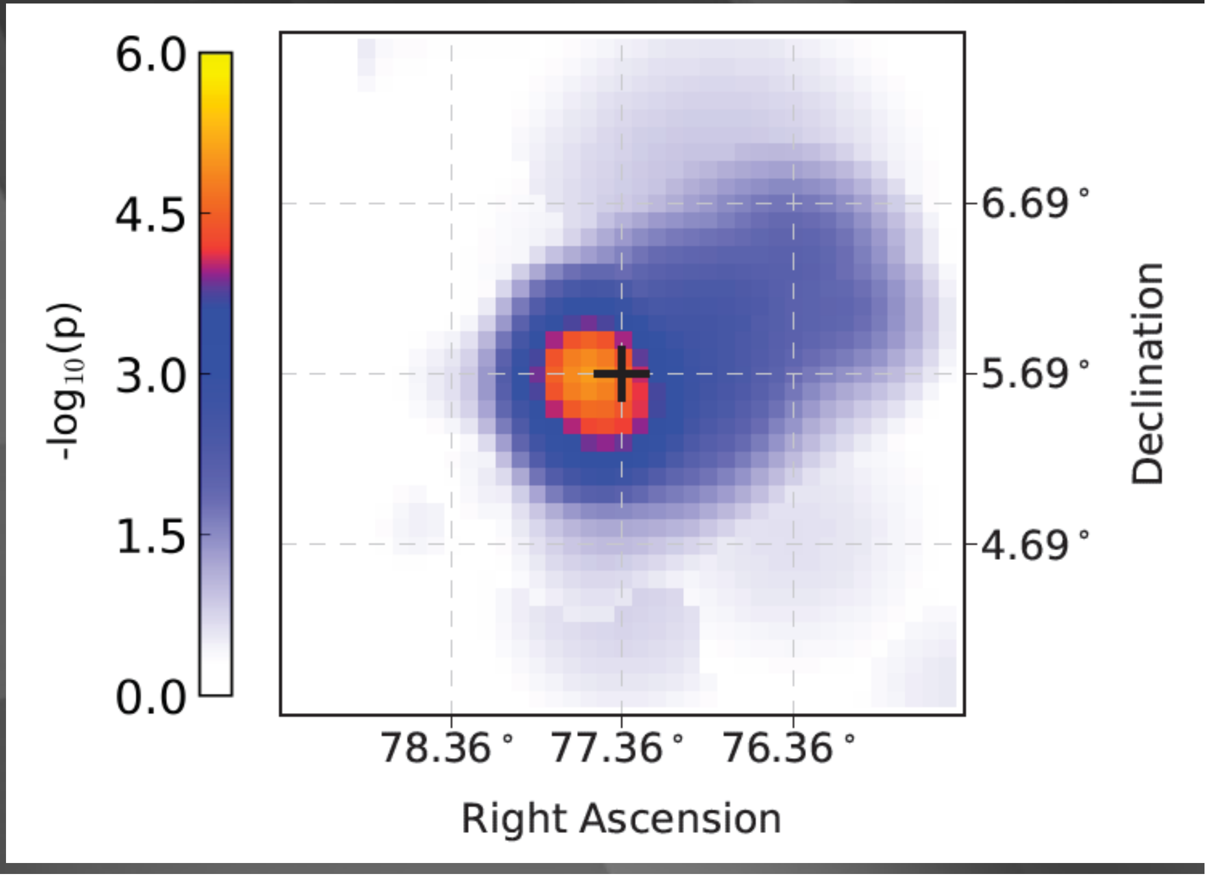
MASTER robotic optical telescope network: after 73 seconds





search in archival IceCube data:

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

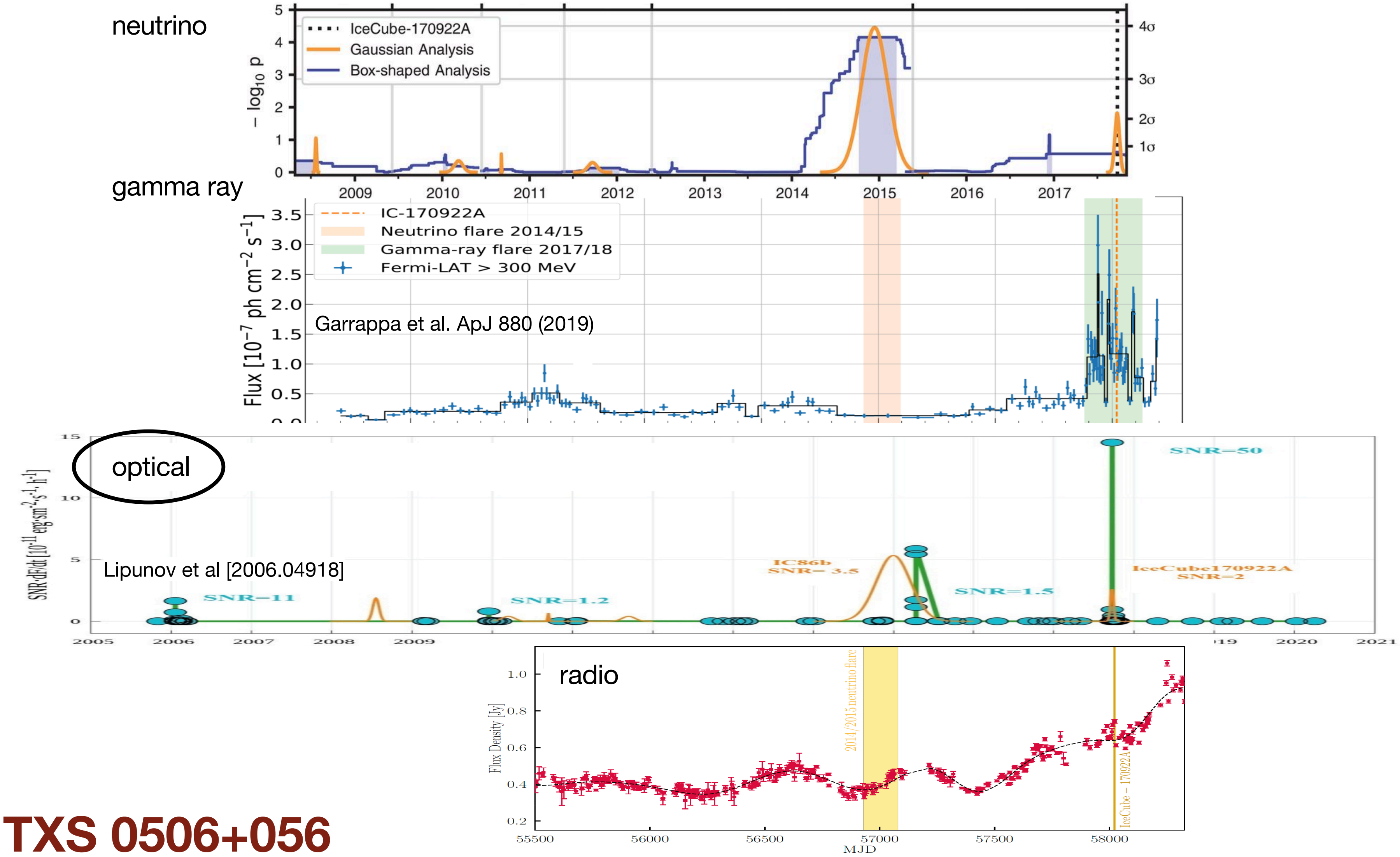


global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"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"

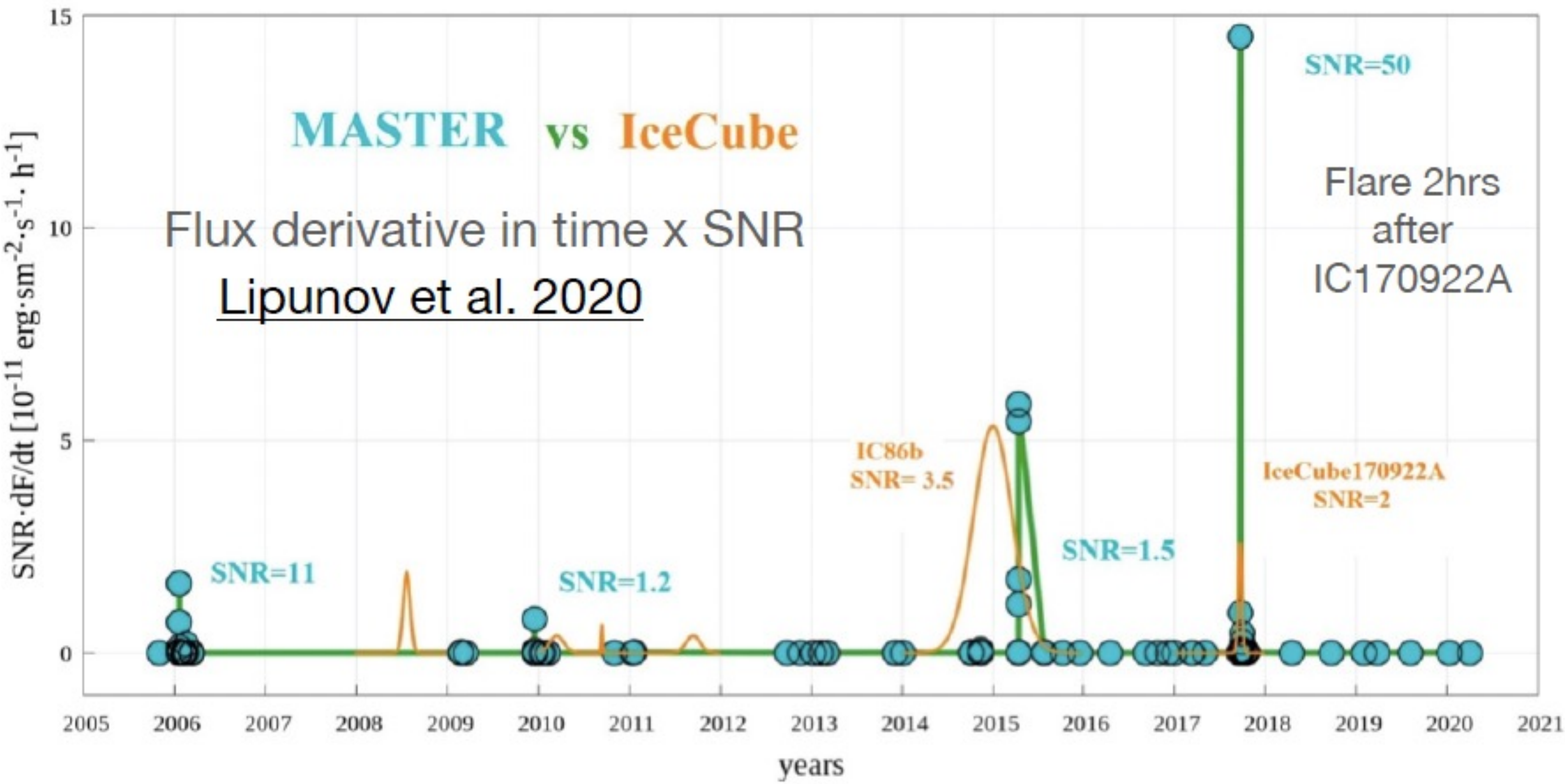
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

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]



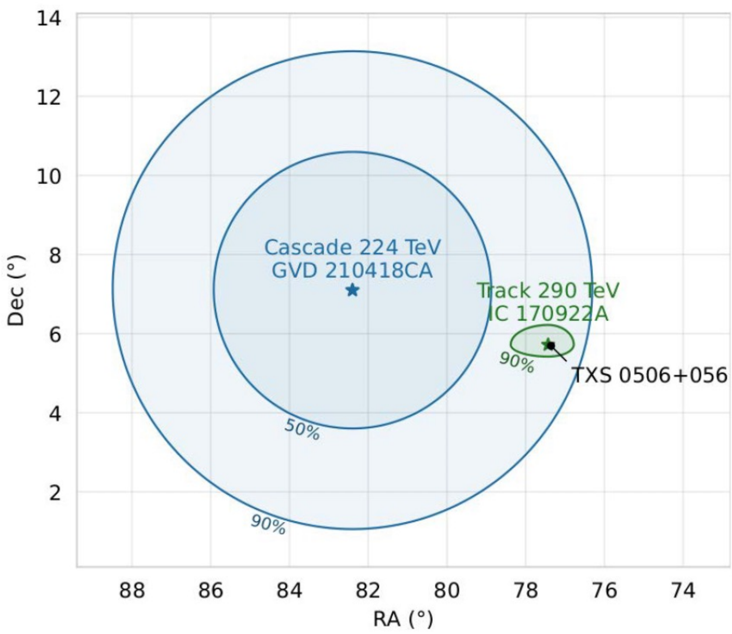
TXS 0506+056

multimessenger observations of TXS 0506 + 056


MASTER vs IceCube
Flux derivative in time x SNR
Lipunov et al. 2020
Flare 2hrs after IC170922A
SNR=50
SNR=11
SNR=1.2
IC86b SNR= 3.5
SNR=1.5
IceCube170922A SNR=2
SNR·dF/dt [10^-11 erg·sm^-2·s^-1·h^-1]
years
0
5
10
15
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

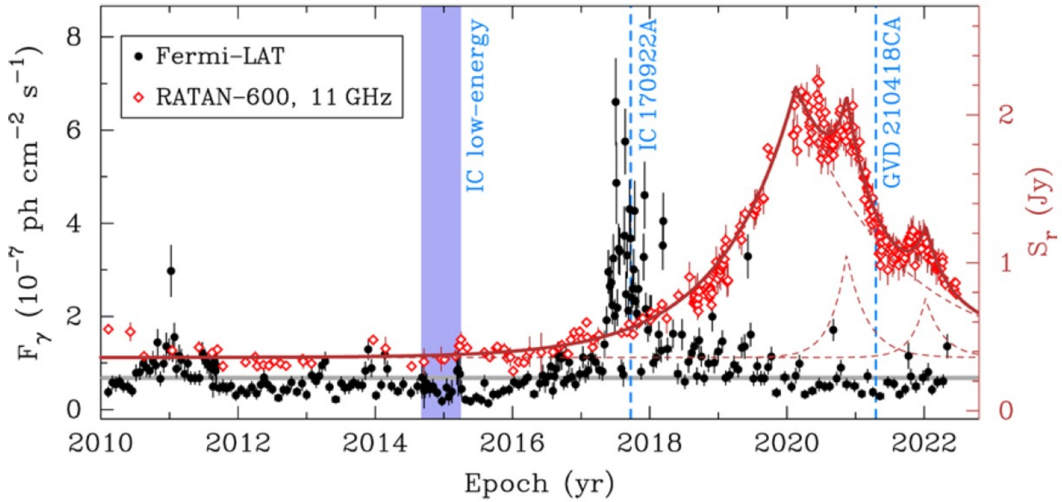
A high energy neutrino from the direction of TXS 0506+056

GVD210418CA (97% signalness) lies within 90% error circle from TXS 0506+056



The chance probability for such an association to occur randomly due to the background is p = 0.0074

Radio and gamma-ray light curves of TXS 0506+056.

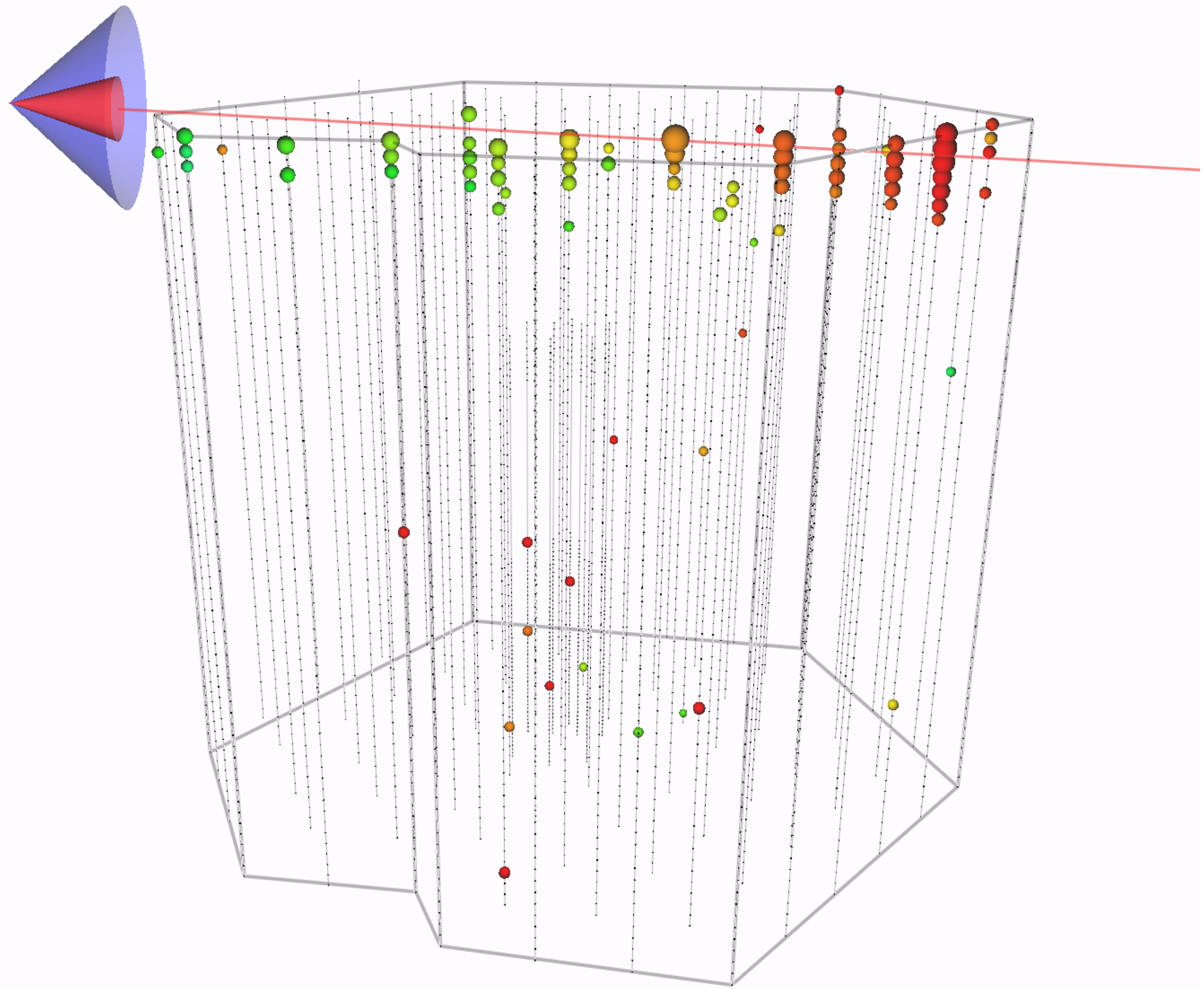


Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare and radio activity
- Baikal-GVD event during radio activity
- Probability of IC non-observation: 11%

arXiv:2210.01650

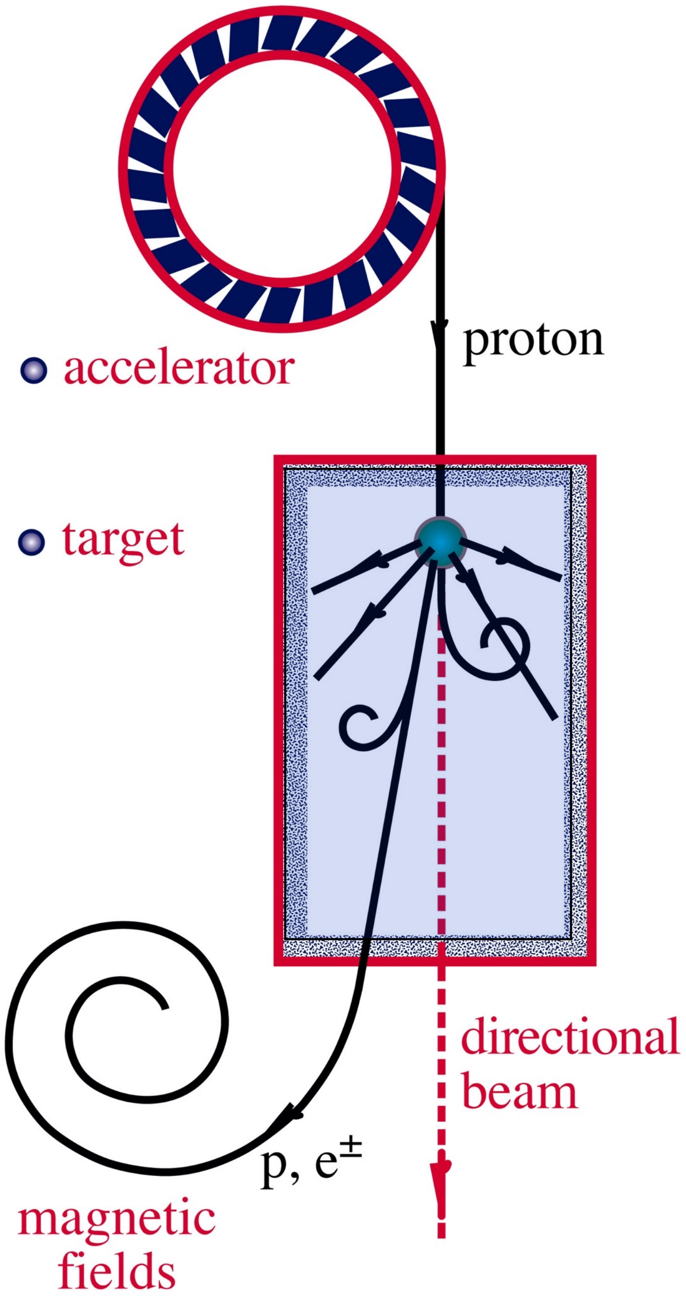
[I3EventHeader:
StartTime: 2022-09-18 12:46:05.322,758,760,8 UTC
EndTime : 2022-09-18 12:46:05.322,778,378,4 UTC
RunID : 137065
SubrunID : 0
EventID : 22012496
SubEventID : 0
SubEventStream : InIceSplit
]



IC220918

within 90% error circle of TXS 0506+056

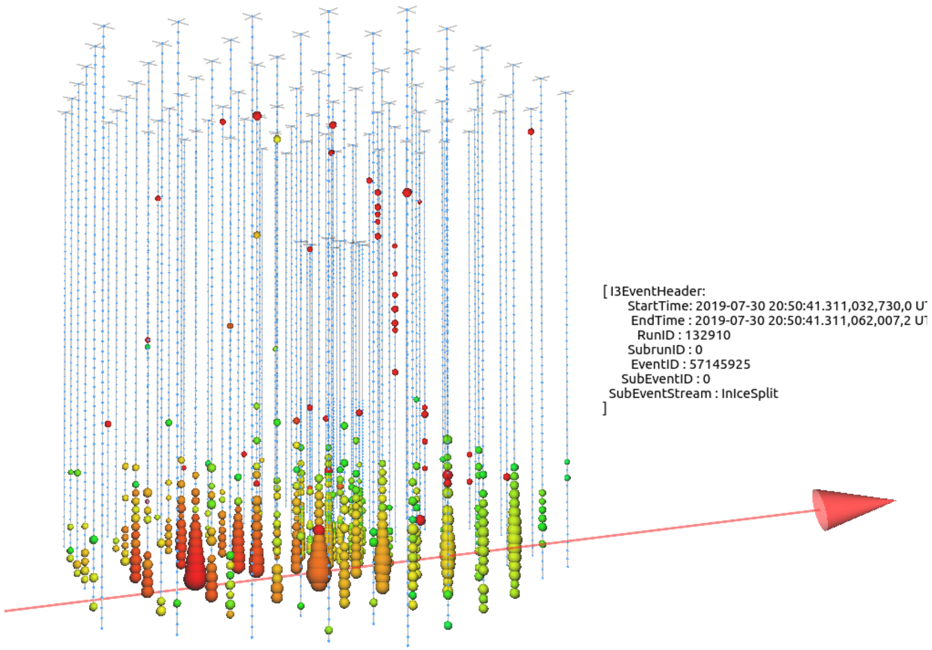
NEUTRINO BEAMS: HEAVEN & EARTH

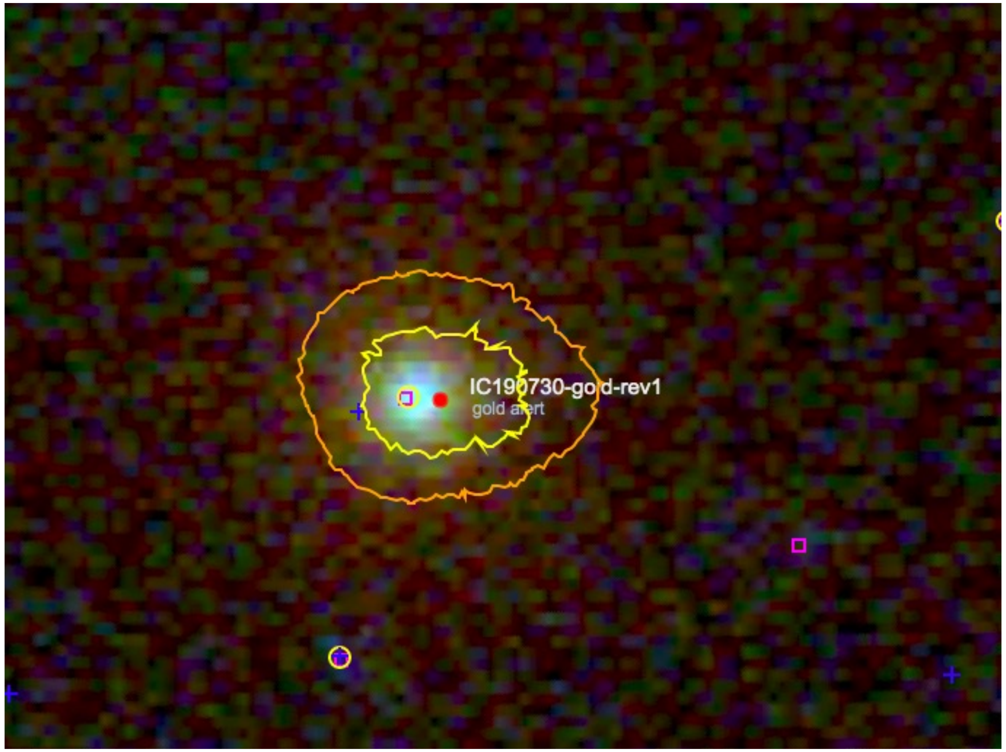


→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

→ IC170922? TXS 0506+056 is not a blazar when neutrinos are emitted as confirmed by gamma ray, optical and radio observations

a second cosmic ray source ?





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[Previous | Next]

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

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

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

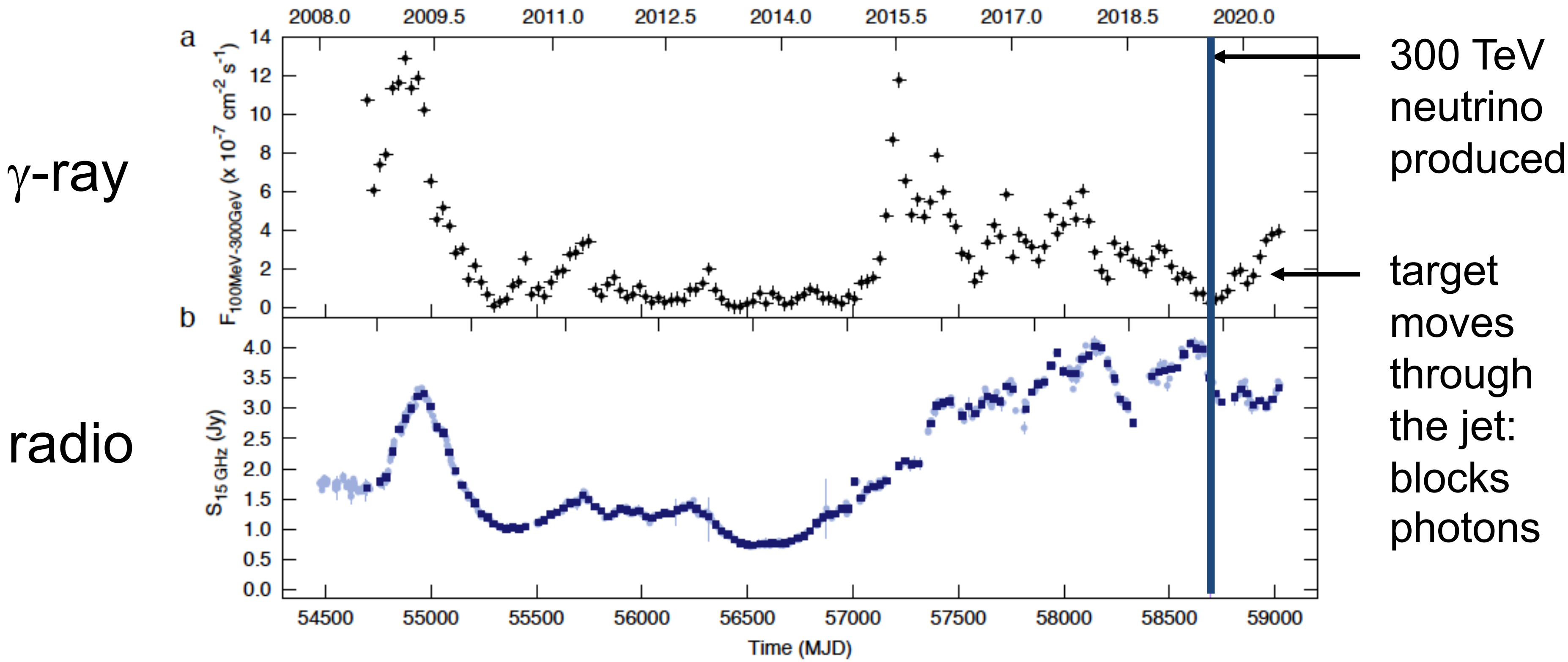
Tweet

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

Related

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

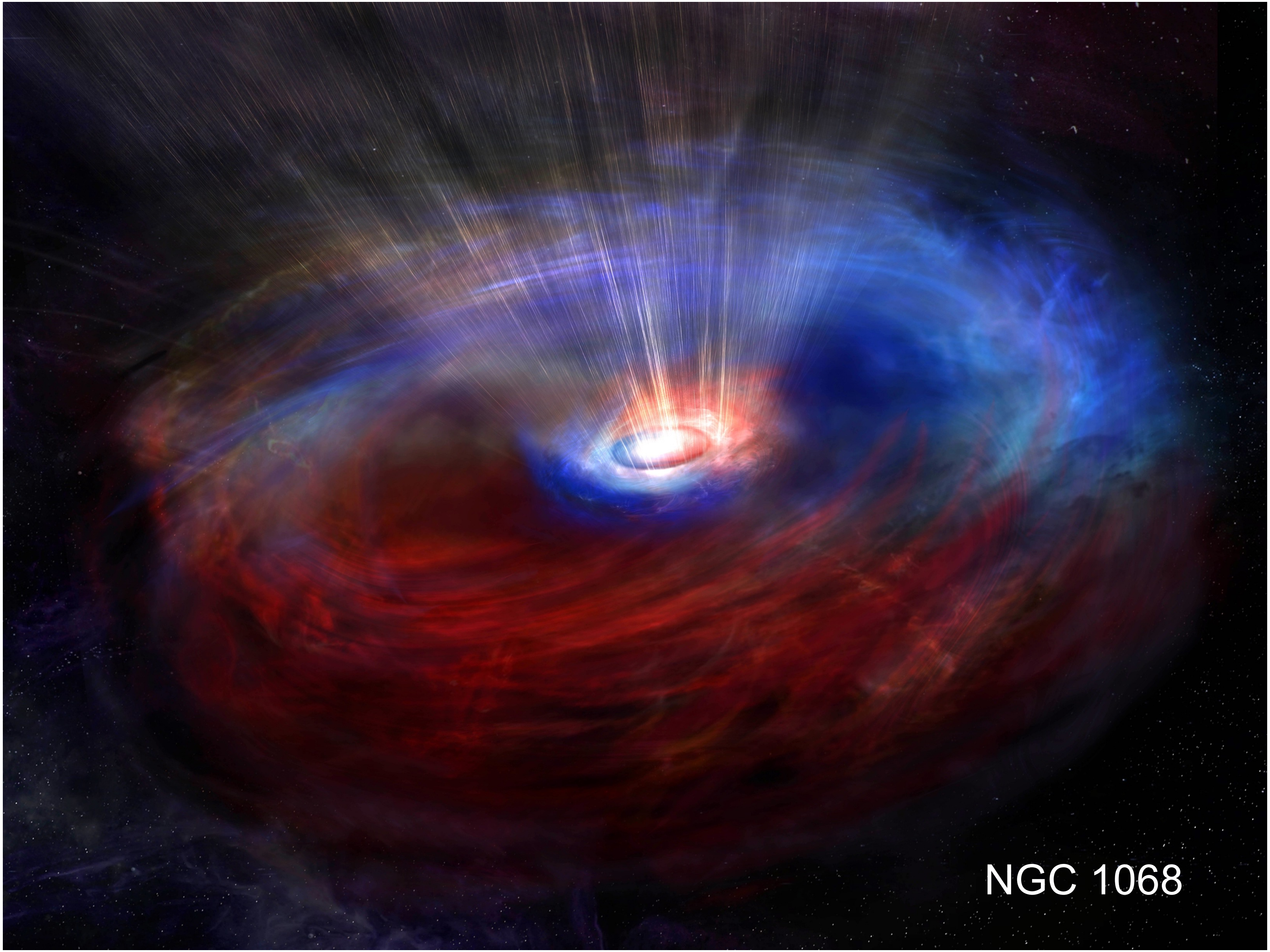
PKS 1502+106



2009.09792 [astro-ph.HE]

TXS 0506+056

- two statistically independent observations above the > 3σ level
- it is also the second source in the all-sky search at 3.7σ
- high-statistic association of IC170922 with optical variation in time domain
- TXS 0506+056 within the error circle of IC220918 and the highest energy event observed by Baikal-GVD
- supported by TeV gamma ray and by radio imaging of the core (jet loses its tight collimation after 5 milliarcseconds)


NGC 1068

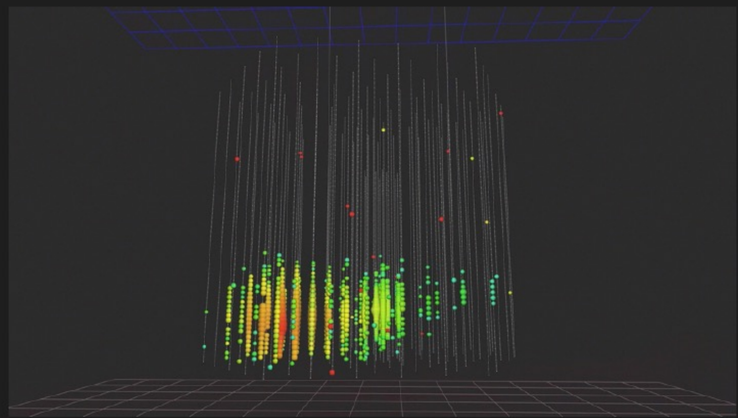
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

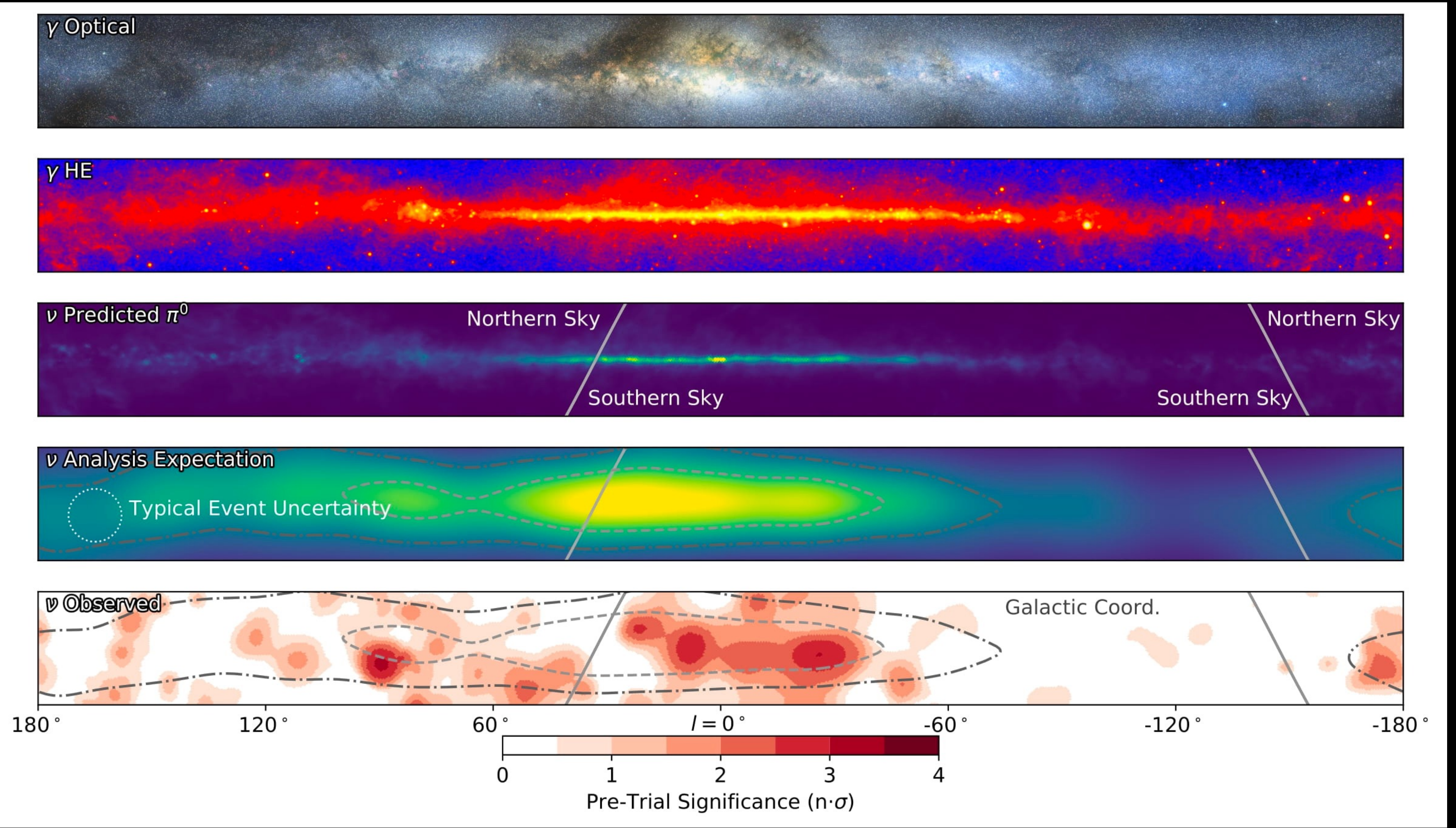
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;    118 DOY;    16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them.**



from light in the ice to astronomer in less than one minute



γ Optical
γ HE
ν Predicted π^0
Northern Sky
Southern Sky
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
ν Observed
Galactic Coord.
180°
120°
60°
$l = 0°$
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)