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# HIGH ENERGY NEUTRINO ASTRONOMY

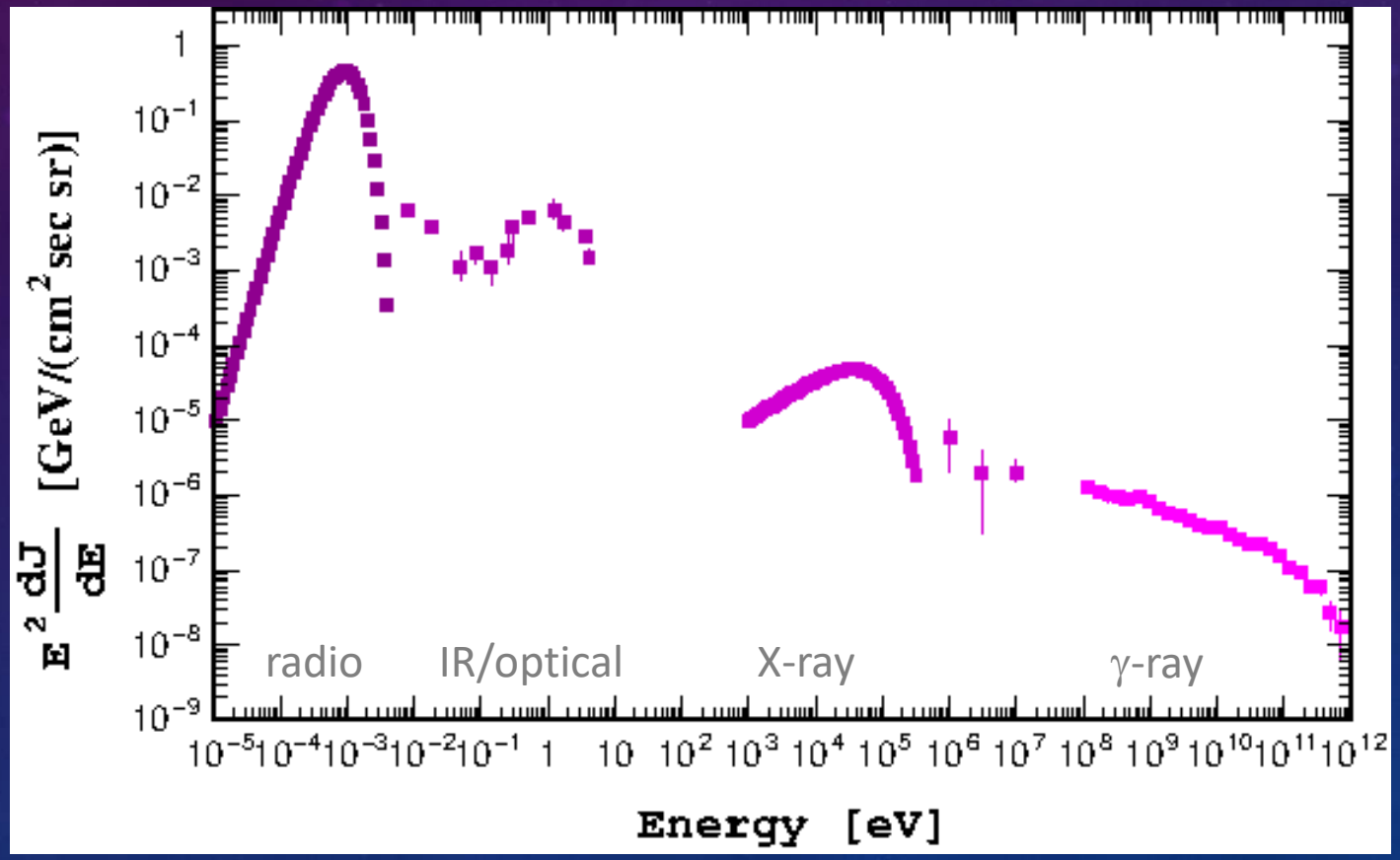
## IN THE ERA OF MULTI-MESSENGER OBSERVATIONS

ICEHAP & DEPARTMENT OF PHYSICS, CHIBA UNIVERSITY

SHIGERU YOSHIDA

# COSMIC BACKGROUND RADIATION

## from μ-wave to γ-rays



# THE END PART OF BACKGROUND RADIATION

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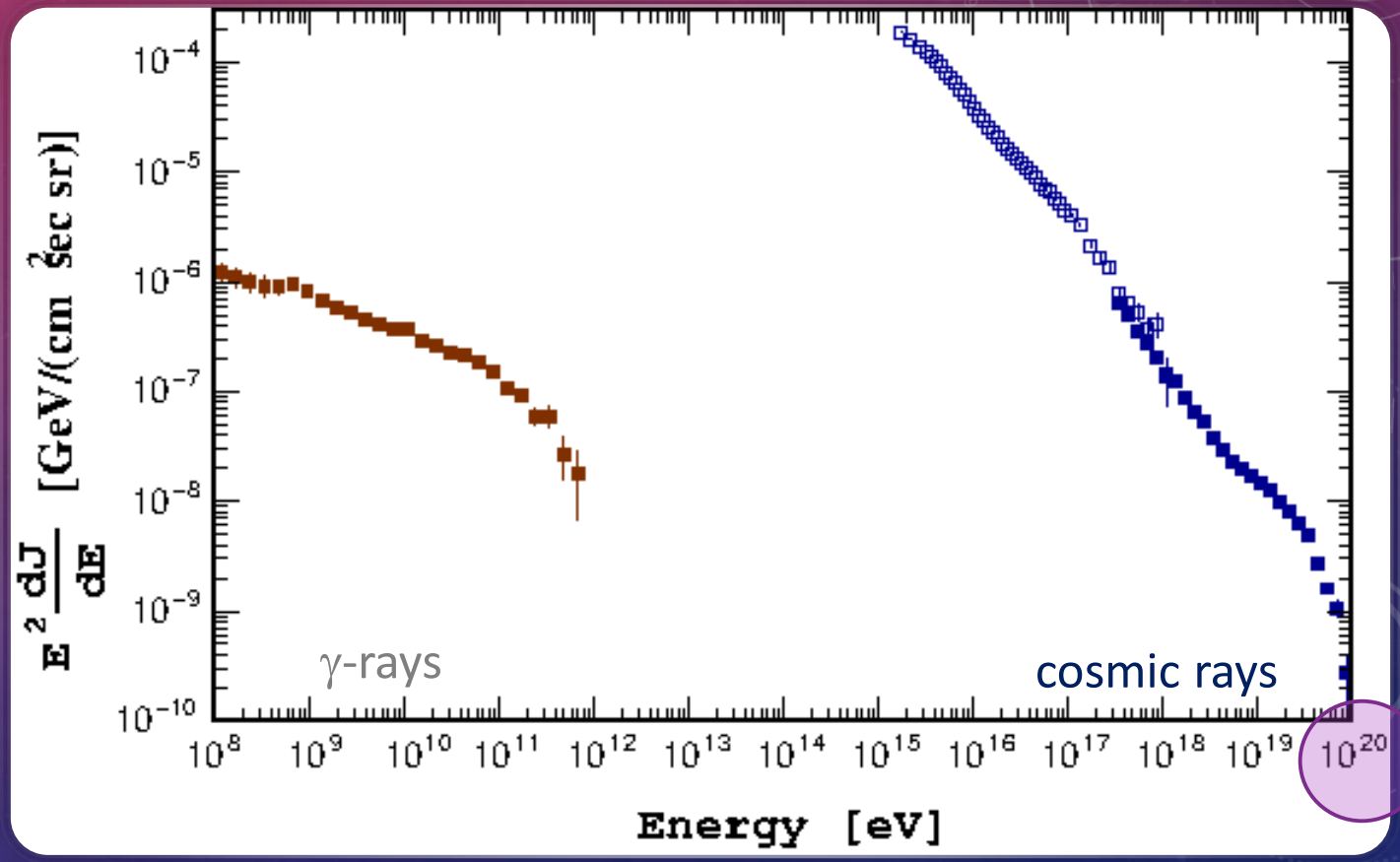
## Cosmic Rays

protons & nuclei with energies even up to $10^{20}$ eV!



# COSMIC ACCELERATORS?

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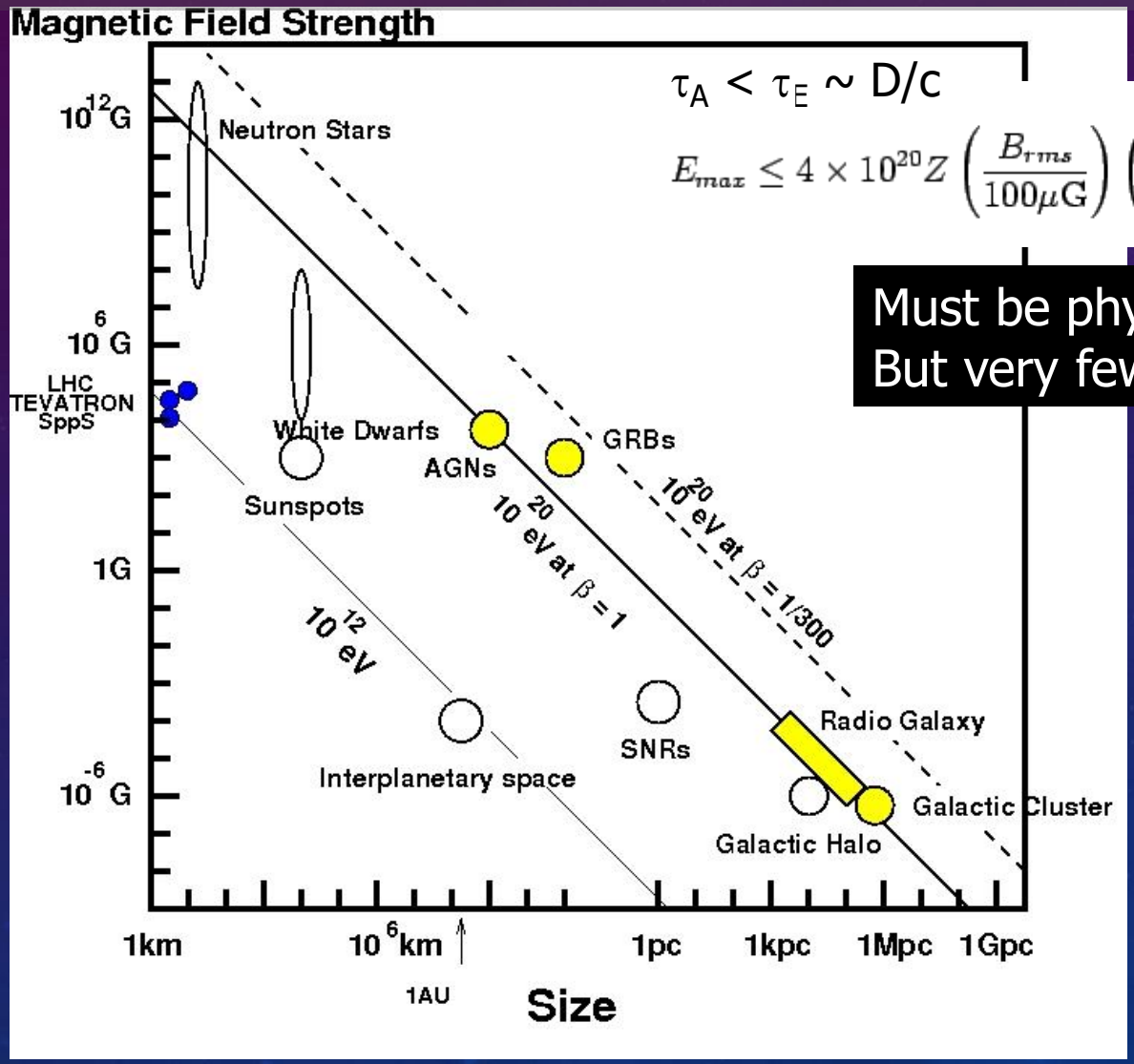



$\tau_A < \tau_E \sim D/c$

$$E_{max} \leq 4 \times 10^{20} Z \left(\frac{B_{rms}}{100\mu\mathrm{G}}\right)\left(\frac{\beta_1}{0.3}\right)\left(\frac{D}{100\mathrm{kpc}}\right) \quad \mathrm{eV}.$$

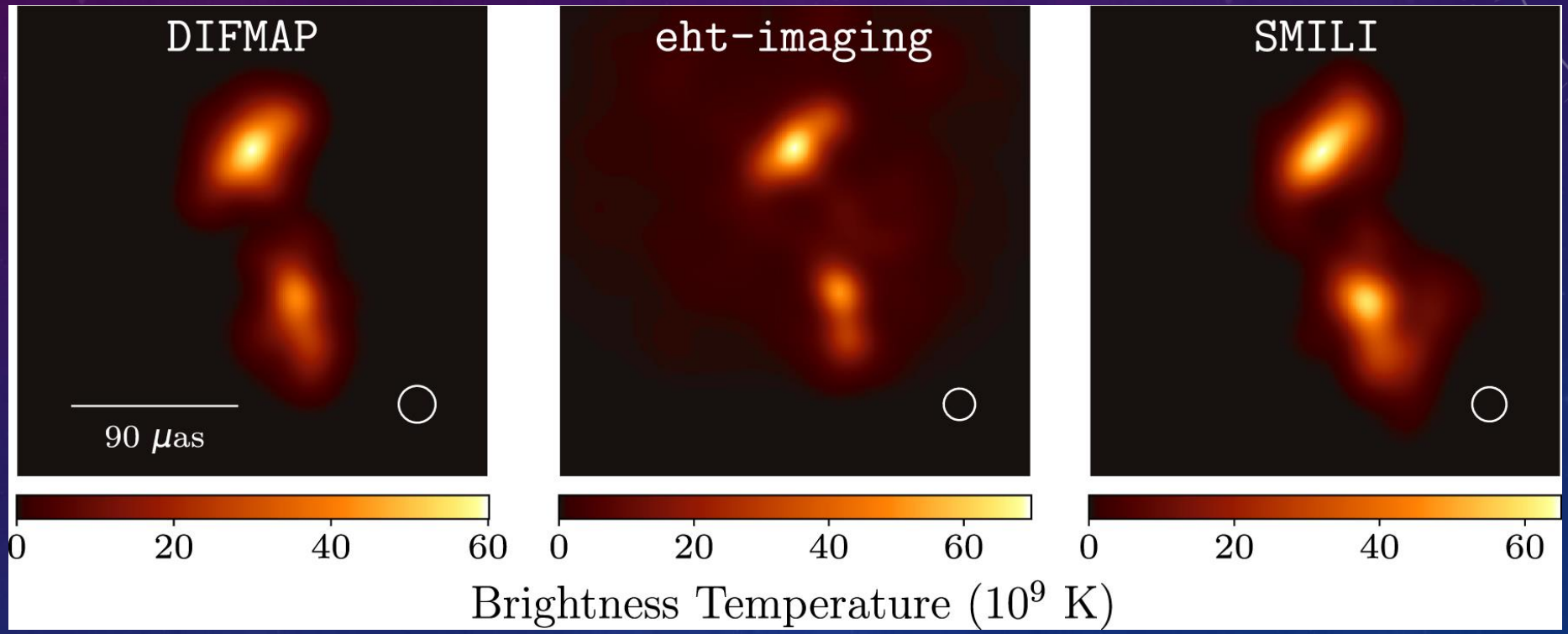
Must be physically large,
But very few satisfies the requirements

Very likely
Extra-galactic

But no observational evidence to identify cosmic ray sources even after more than *100 yrs* of discovery of cosmic rays!

# 3C279 – A POWERFUL QUASAR

It *was* a strong candidate to stream out ultra high energy cosmic rays



# FORNAX CLUSTER – A CLUSTER OF GALAXIES

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## another type of cosmic accelerator candidates

a still viable candidate of high energy cosmic ray hometown

but hard to prove it – why?

# CHARGED PARTICLES ARE *NOT* GOOD MESSENGERS

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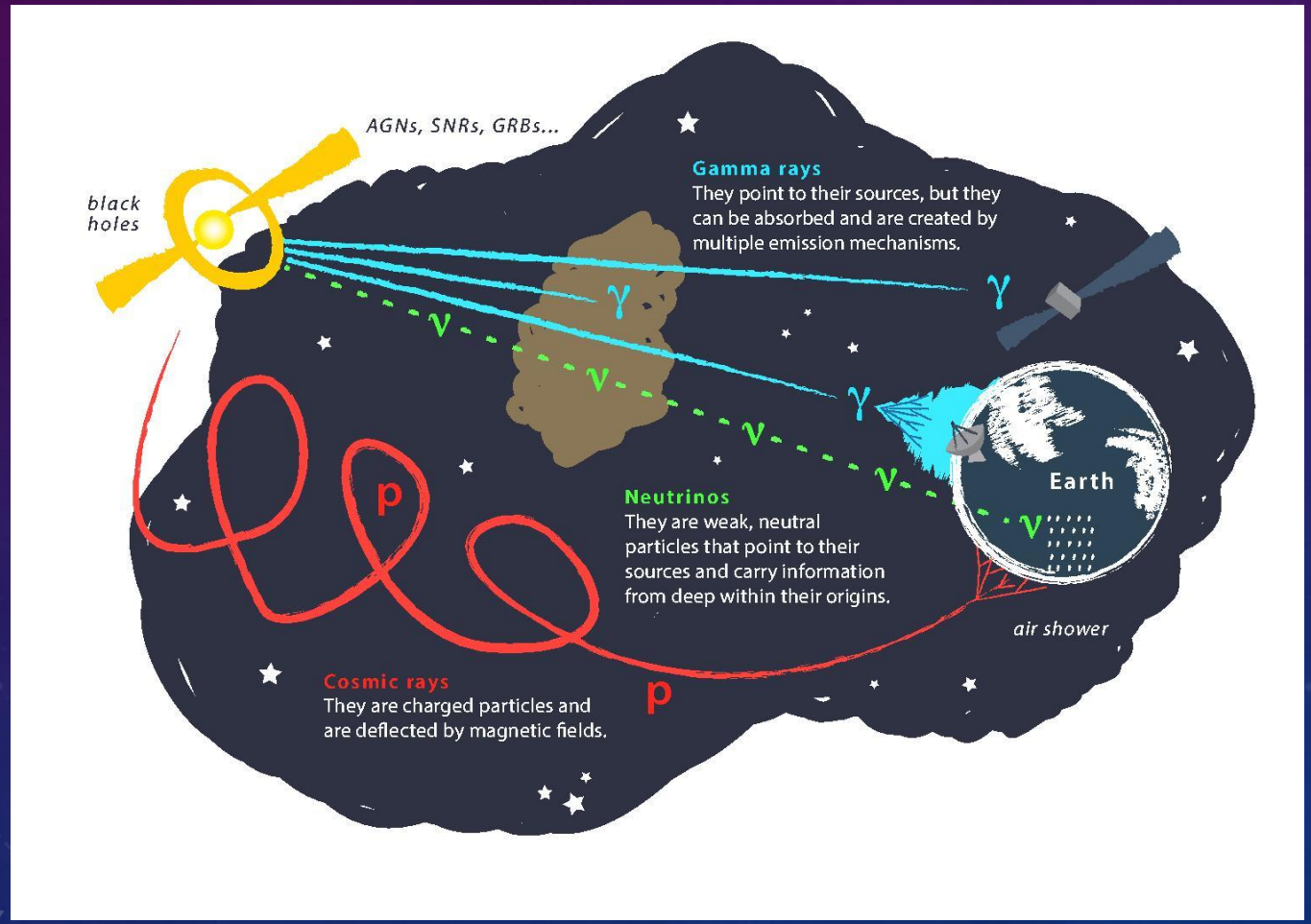
cosmic rays are unfortunately charged




Neutrinos are Savior

# NEUTRINO ARE EVEN MORE POWERFUL TO EXPLORE HIGH ENERGY UNIVERSE

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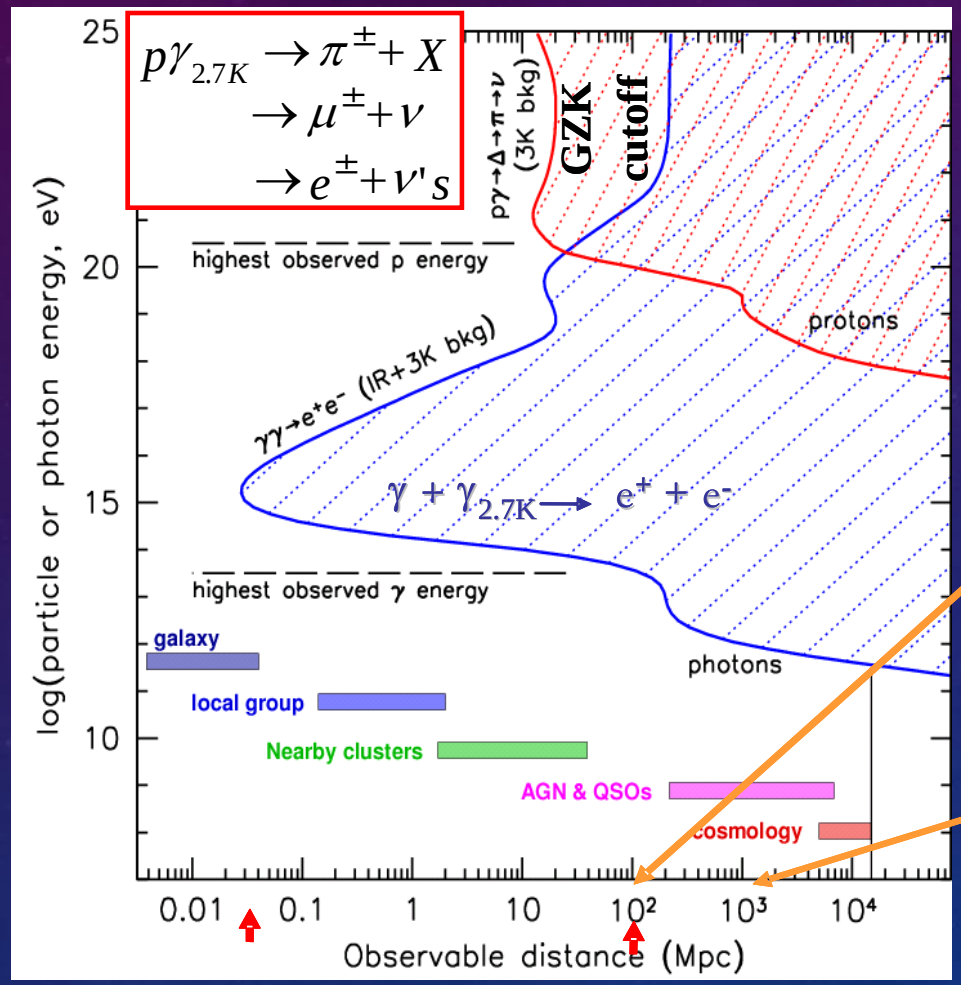


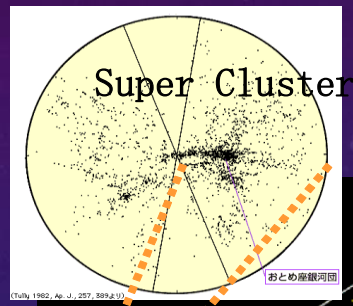


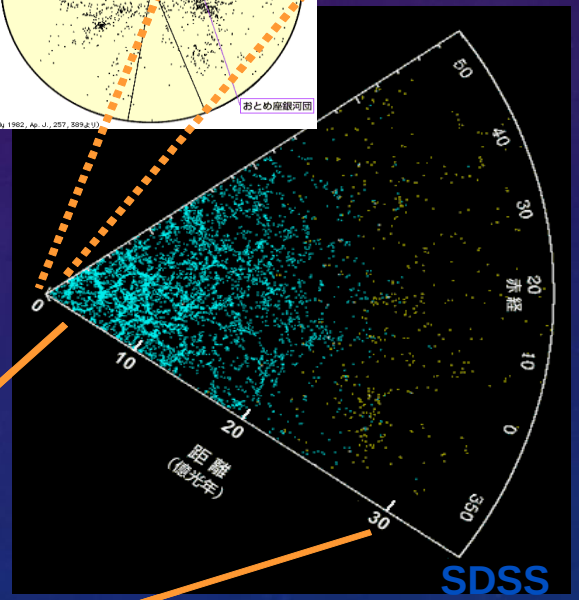


Distant Young Universe

Our Galaxy

Super Cluster

# HOW COSMIC RAYS PRODUCE NEUTRINO MESSENGERS TO TELL HOW AND WHERE THEY ARE BORN

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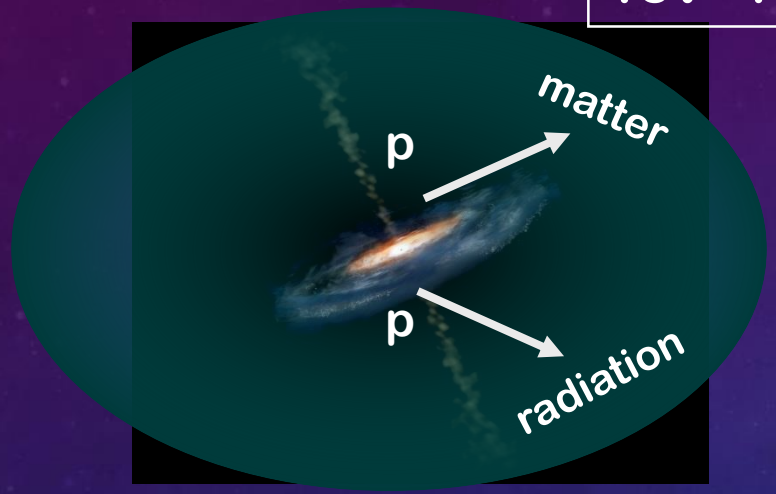
"On-source" ν

**TeV - PeV**



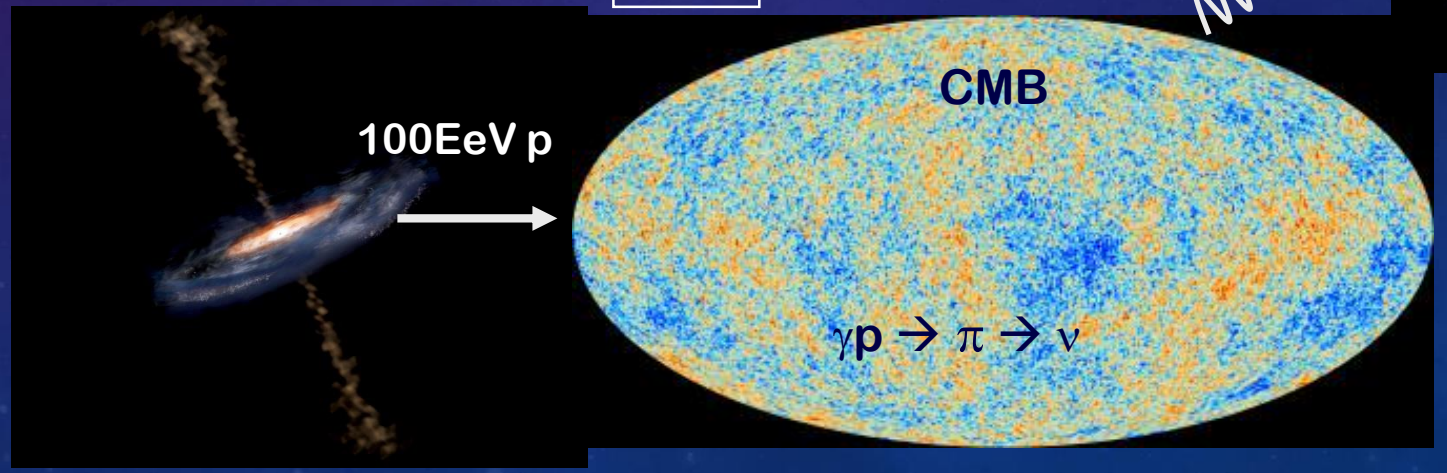

$pp \rightarrow \pi \rightarrow \nu$

$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production


"GZK" cosmogenic ν

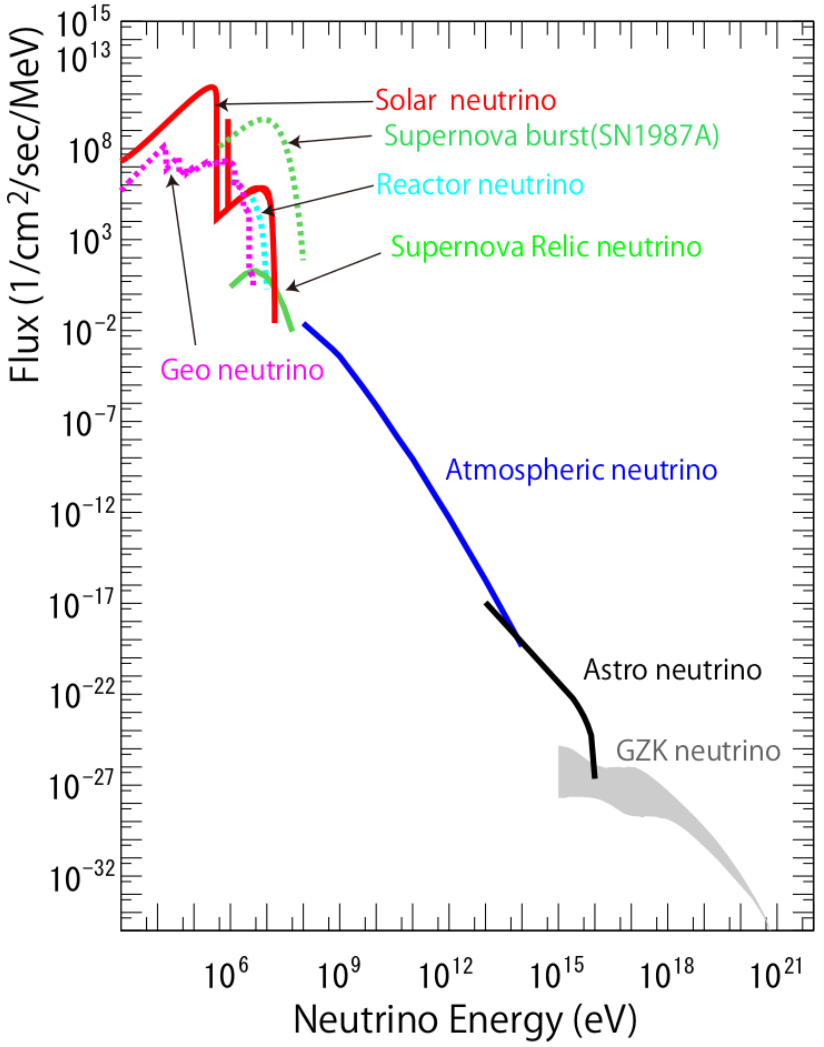
**EeV**



# A BIG CHALLENGE

## HIGH ENERGY NEUTRINO FLUXES ARE SO LOW

you need a huge detector
to catch them up

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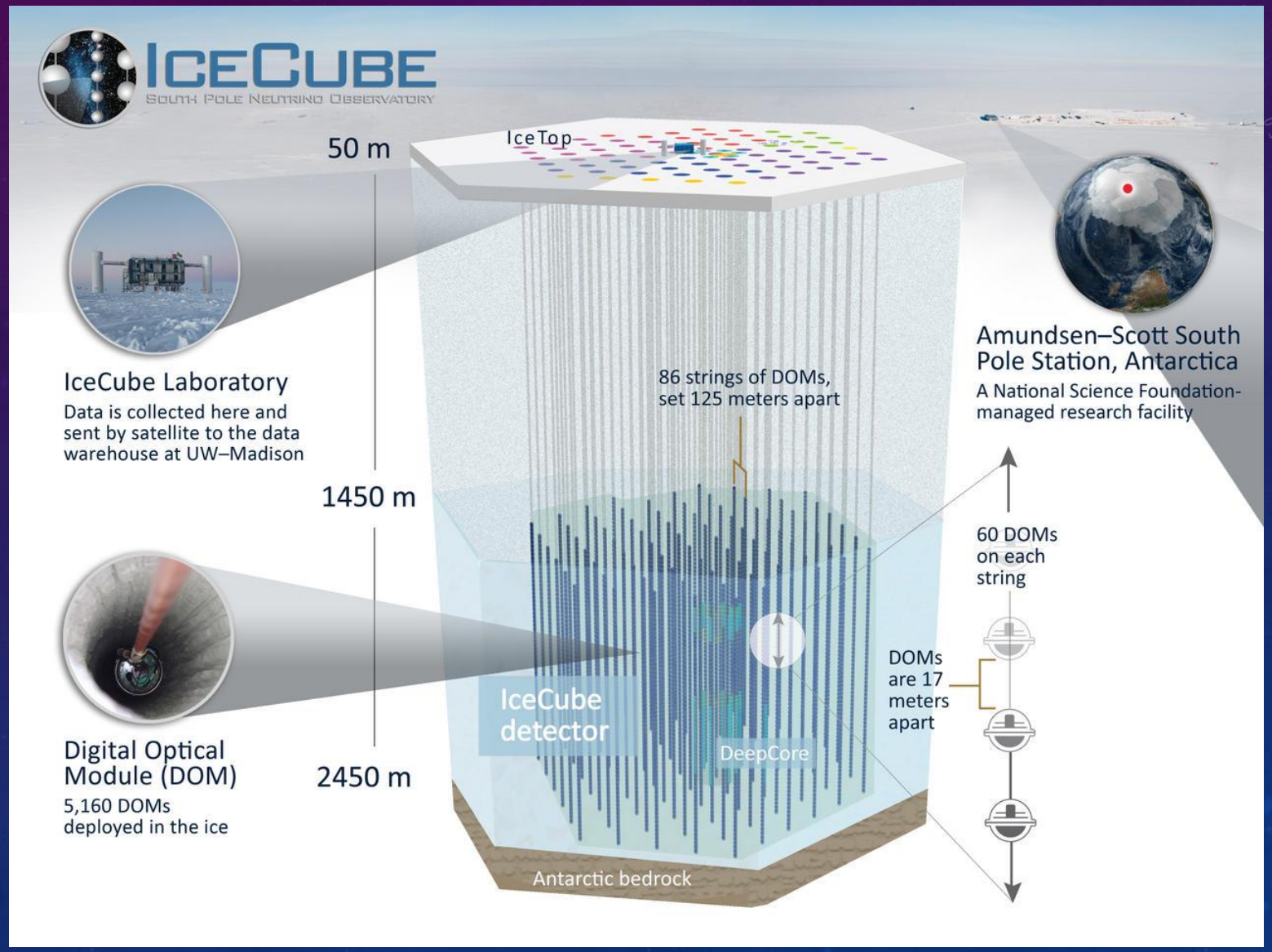
# THAT IS WHY ICECUBE NEUTRINO OBSERVATORY WAS BUILT



# THE ICECUBE COLLABORATION

**AUSTRALIA**
University of Adelaide

**BELGIUM**
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

**CANADA**
SNOLAB
University of Alberta–Edmonton

**DENMARK**
University of Copenhagen

**GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

**JAPAN**
Chiba University

**NEW ZEALAND**
University of Canterbury

**REPUBLIC OF KOREA**
Sungkyunkwan University

**SWEDEN**
Stockholms Universitet
Uppsala Universitet

**SWITZERLAND**
Université de Genève

**UNITED KINGDOM**
University of Oxford

**UNITED STATES**
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University


FUNDING AGENCIES

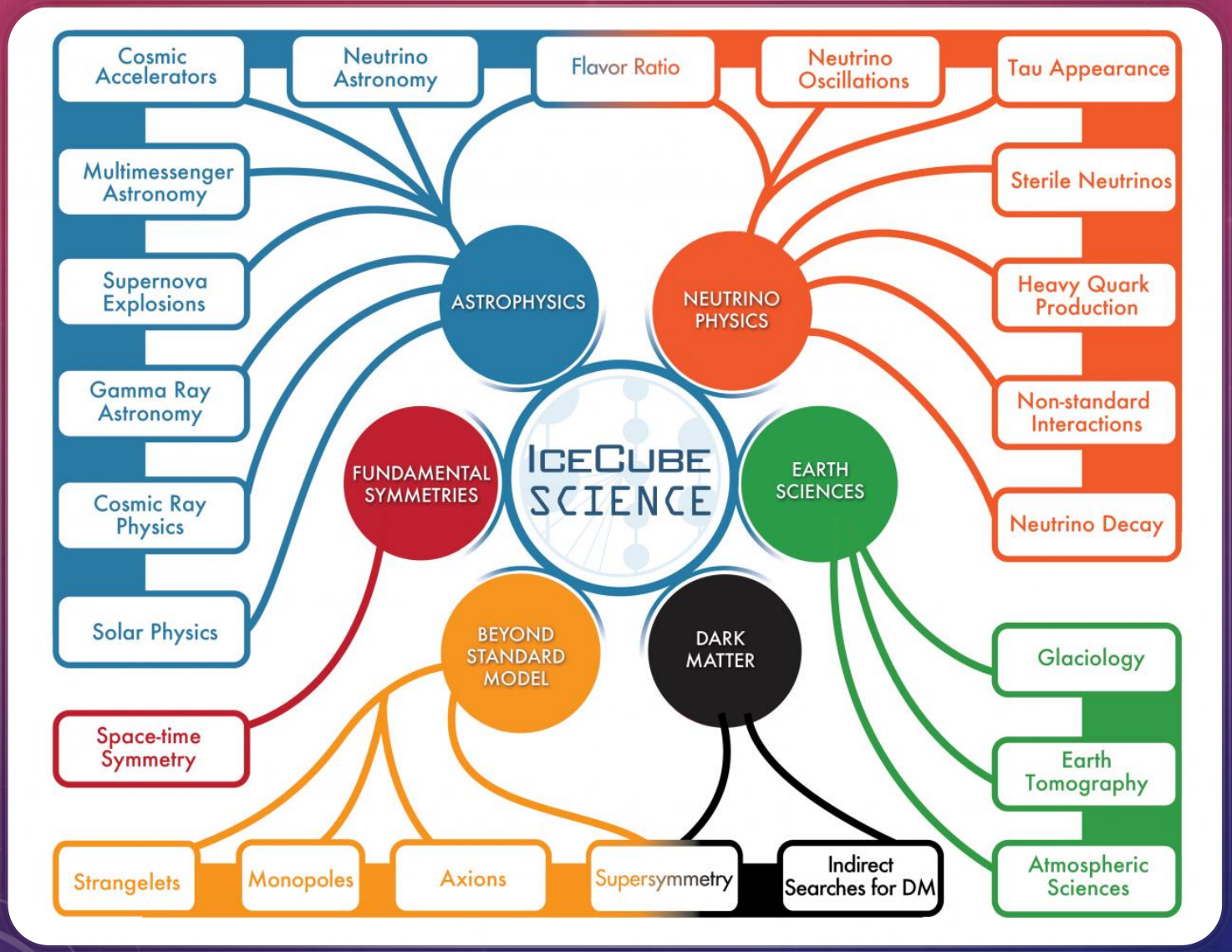
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)




IceCube South Pole Neutrino Observatory

icecube.wisc.edu

# ICECUBE'S SCIENCE MISSION



# NEUTRINO AS COSMIC MESSENGERS

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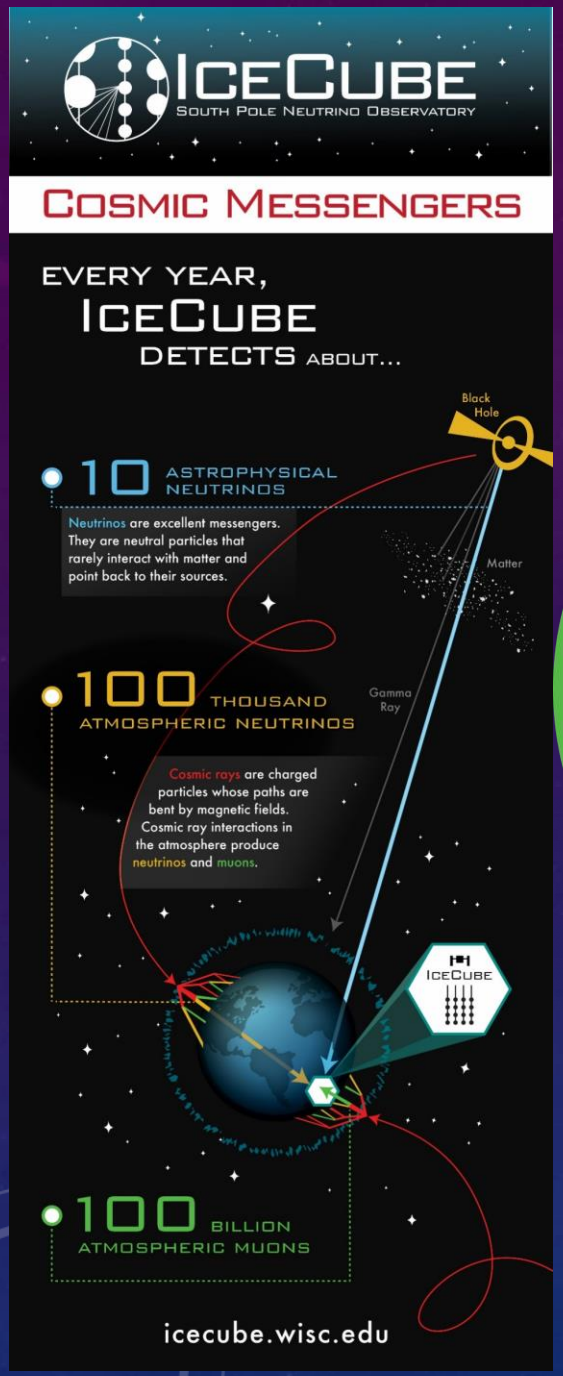
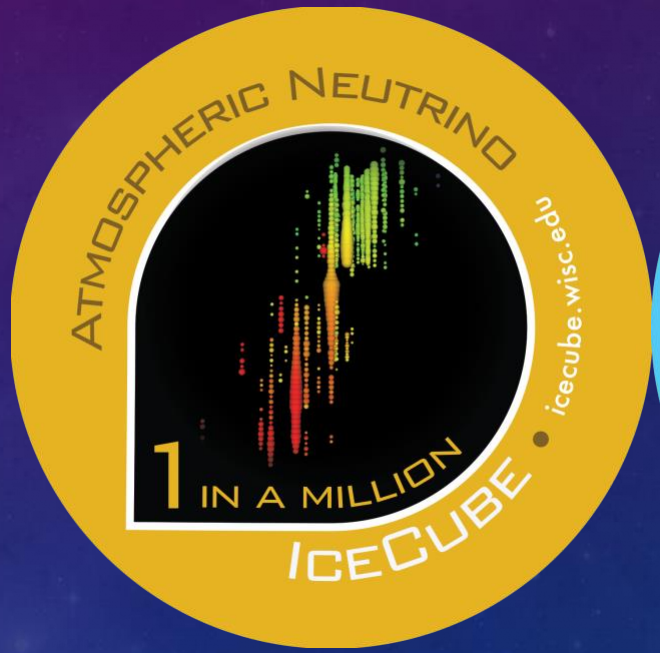
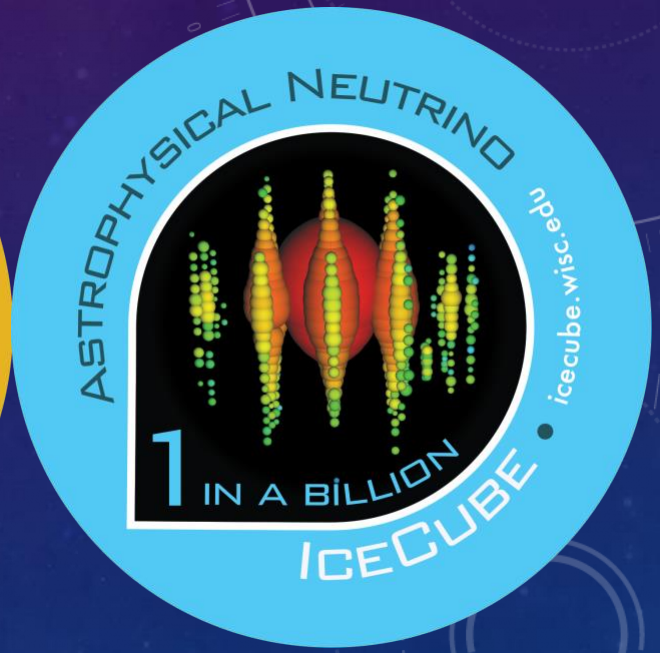
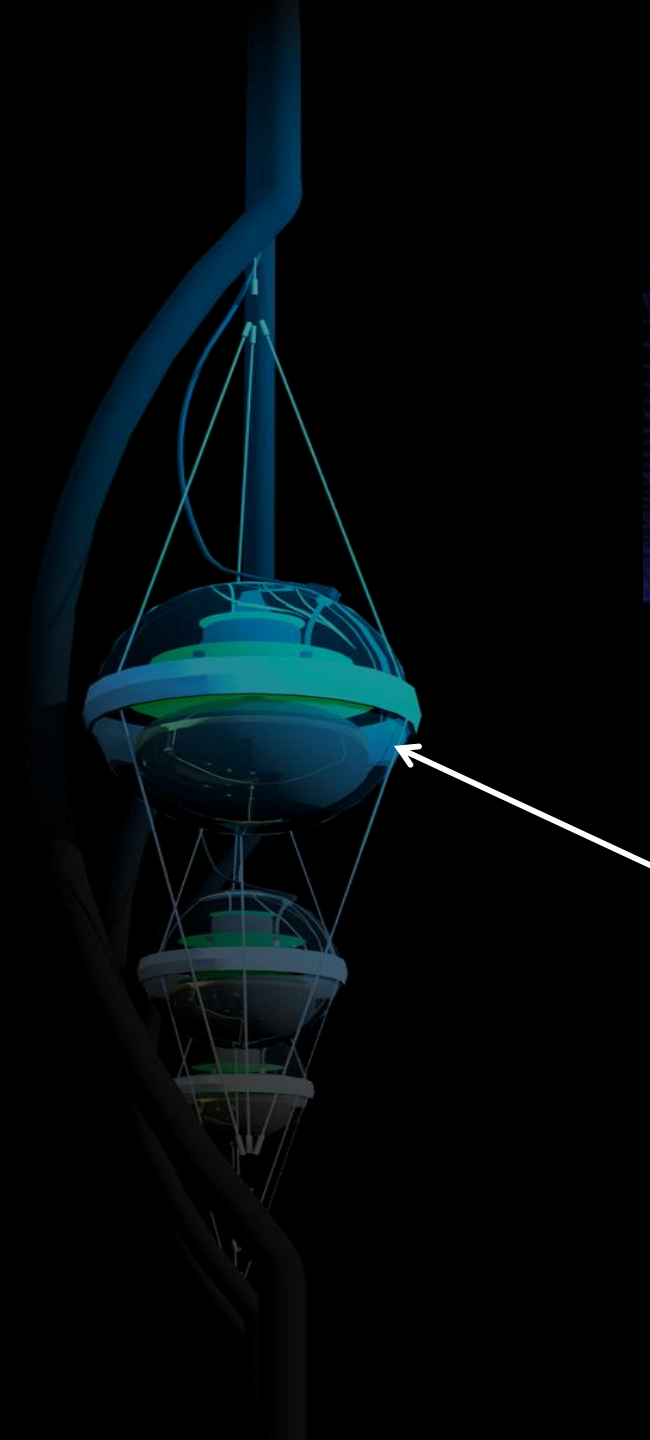


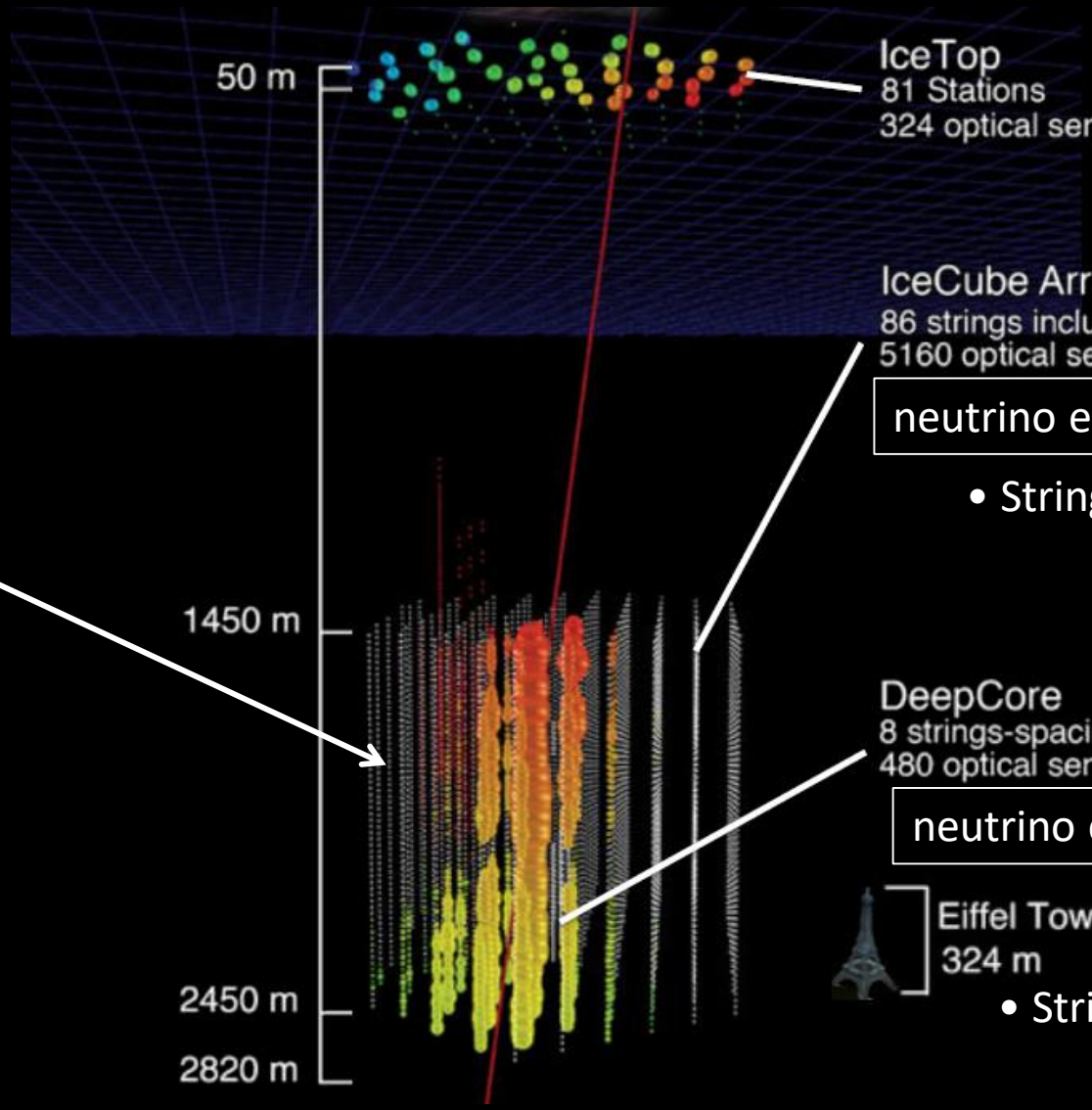




# The IceCube Detector






**IceTop**
81 Stations
324 optical sensors

**IceCube Array**
86 strings including 8 DeepCore strings
5160 optical sensors

neutrino energy: 1TeV-100EeV

- String spacing 125 m, DOM spacing of 17 m

**DeepCore**
8 strings-spacing optimized for lower energies
480 optical sensors

neutrino energy: 5GeV-100GeV



Eiffel Tower
324 m

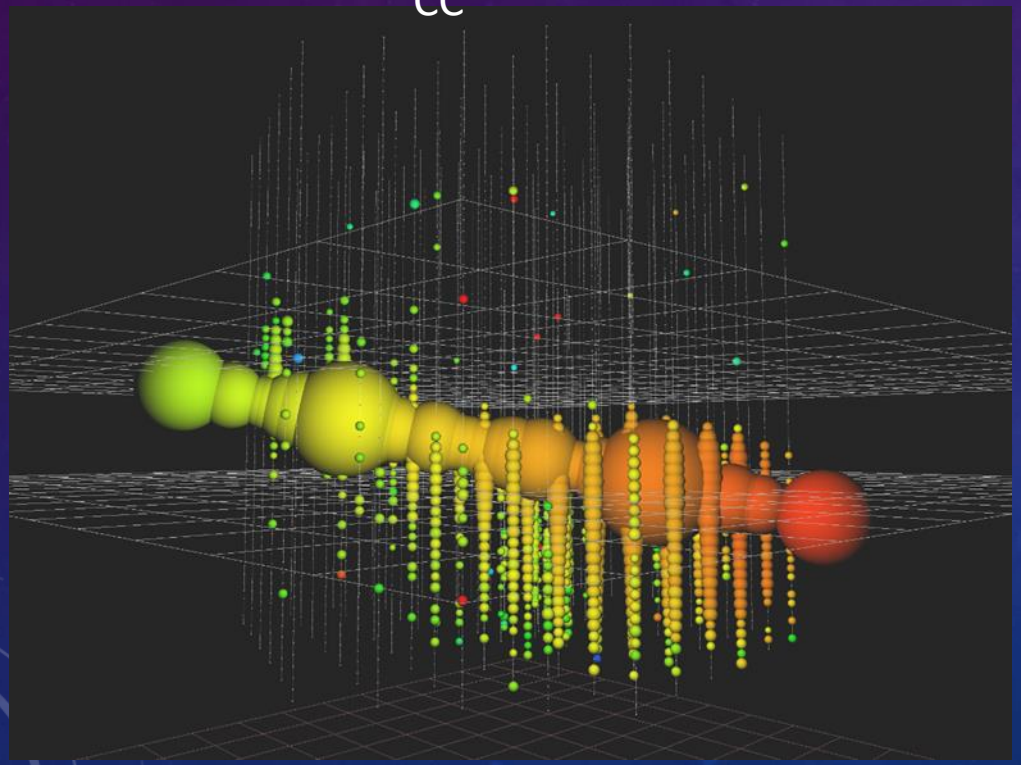
- String spacing ~70 m, DOM spacing of 7 m

# ICECUBE EVENT TOPOLOGY

## Track

$\nu_\mu \xrightarrow[CC]{} \mu$

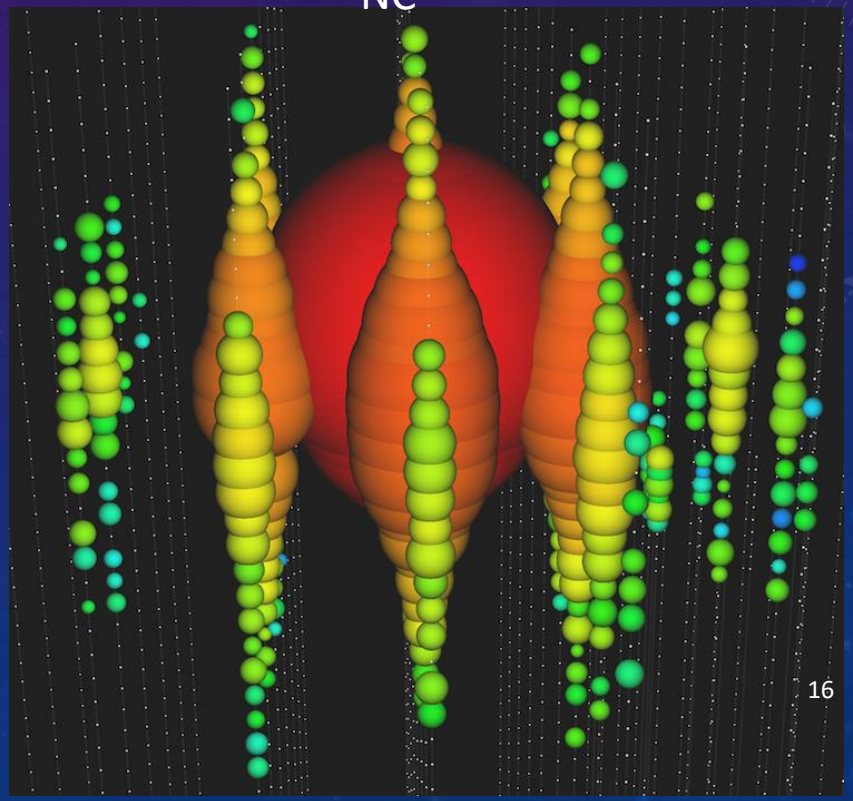
$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)



## Cascade (shower)

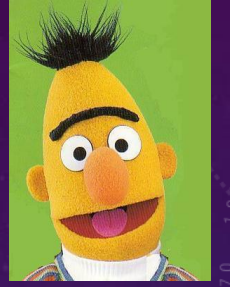
$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$ x=e, μ, τ



# BERT & ERNIE KICKS OFF HIGH-E NEUTRINO ASTRONOMY

## the Discovery of Cosmic $\nu$ flux



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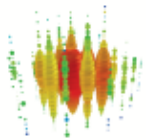
NEWSPAPER



Observation of a high-energy particle shower event from August 2011, identified as a PeV-energy neutrino. Each sphere represents a digital optical module sensor in the IceCube detector. Sphere size is a measure of the recorded number of photoelectrons. Colors represent arrival times of photons (red, early; blue, late). Selected for a Synopsis in *Physics* and an Editors' Suggestion. [M. G. Aartsen *et al.*, IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)]

**IceCube collaboration**
**Phys. Rev. Lett. 111, 081801 (2013)**

PHYSICAL REVIEW LETTERS

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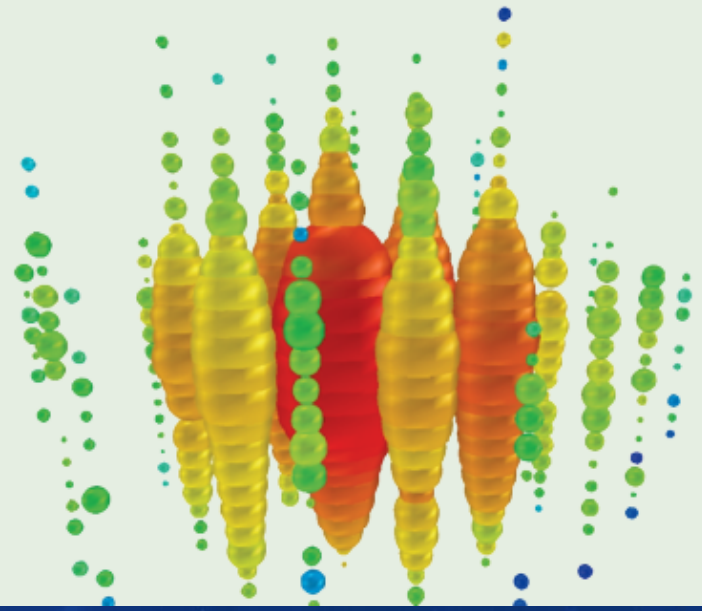
*Articles published 6 July–12 July 2013*

VOLUME 111, NUMBER 2 — 12 July 2013



PHYSICAL REVIEW LETTERS

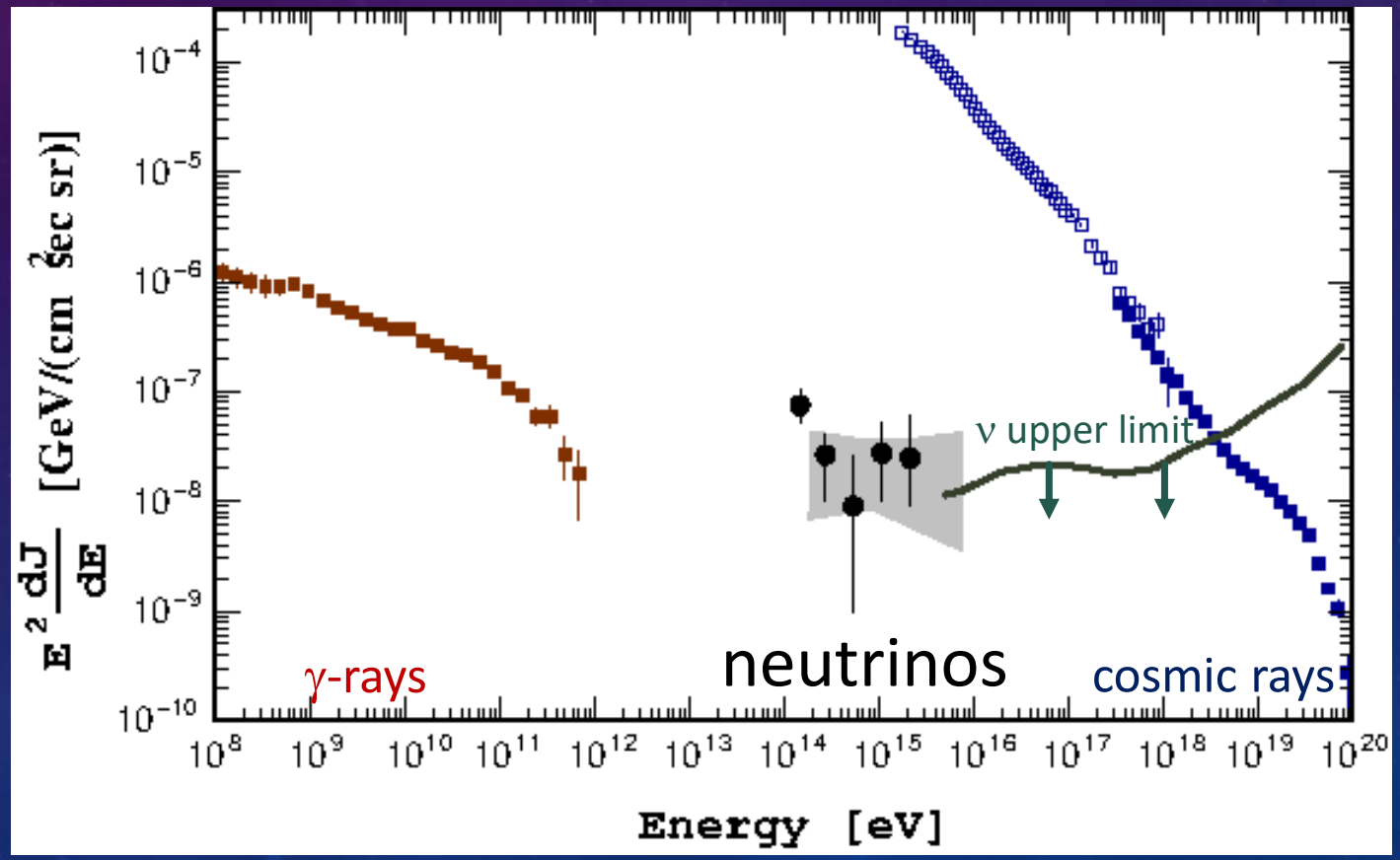
Articles published week ending 12 JULY 2013



PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

# NOW WE HAVE *MEASURED* COSMIC NEUTRINO BACKGROUND RADIATION

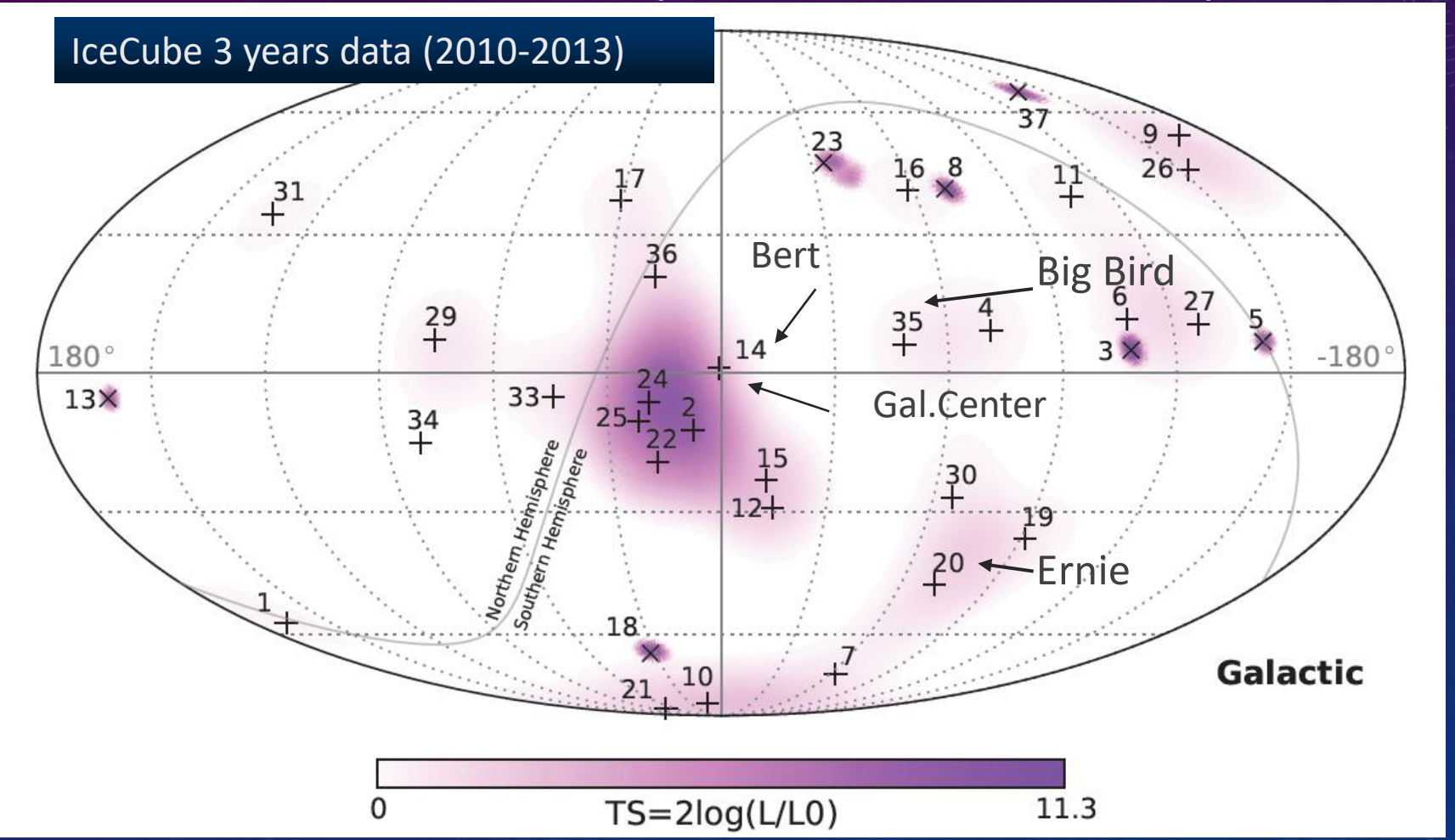
after a decade of the big efforts with IceCube



TeV PeV EeV

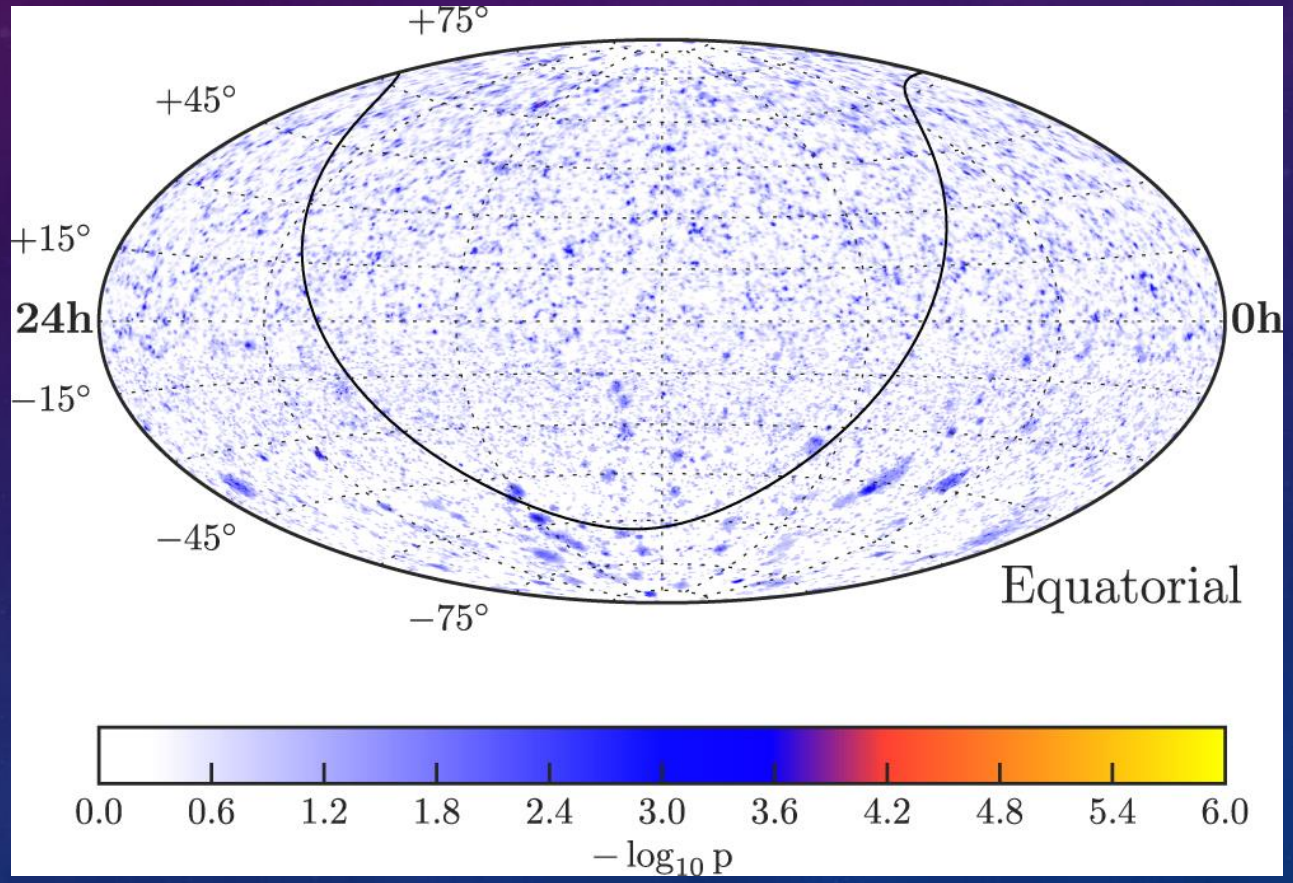
# MOSTLY EXTRA GALACTIC

## but cannot find any remarkable counterparts



# NEUTRINO POINT SOURCE SEARCH MAP

found no sources yet



# ONE THING WE CAN TELL

## neutrino flux is a marker to trace history of comic ray radiation

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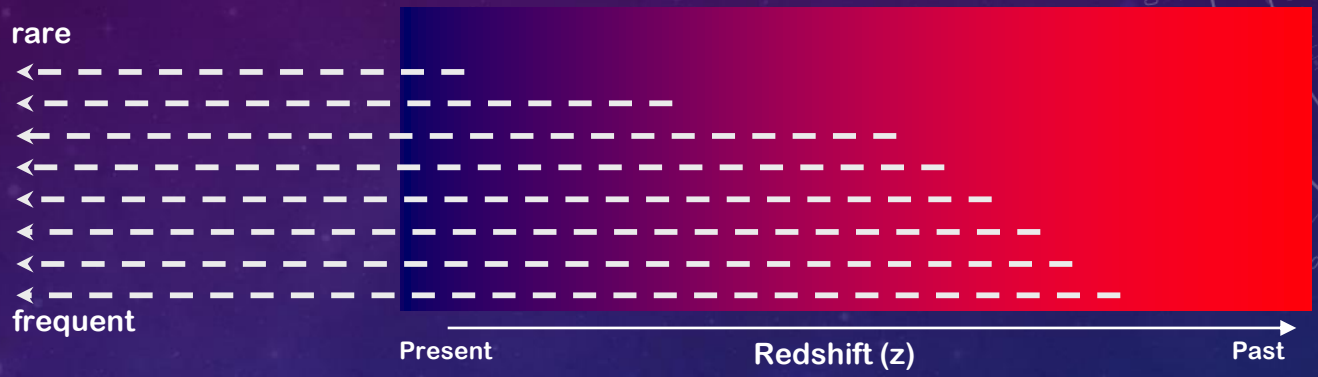
Intensity gets higher if the emission is more active in the past

because ν beams are penetrating over cosmological distances




The cosmological evolution

Many indications that the past was more active.

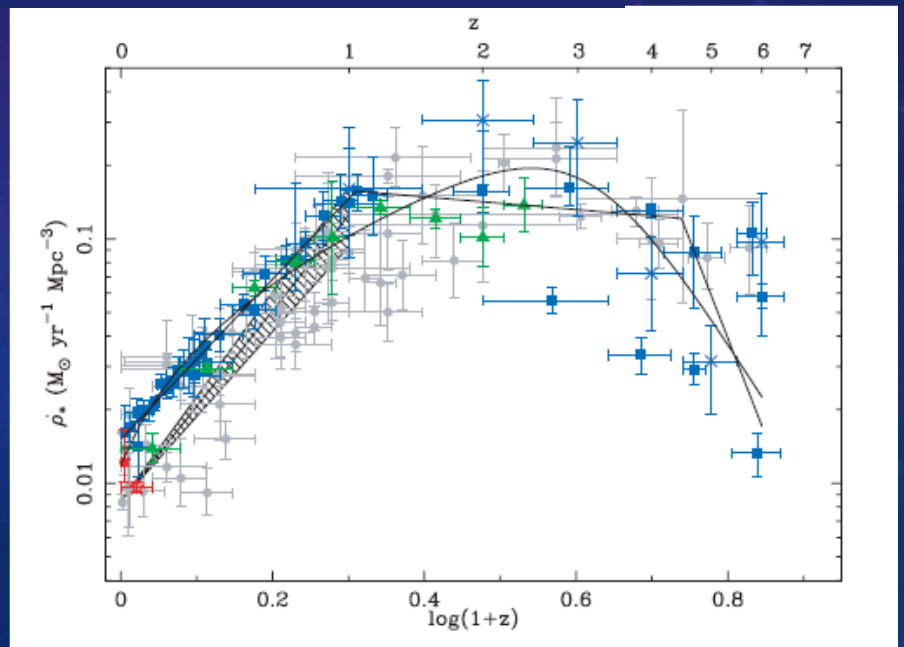
Star formation rate→

The spectral emission rate

$\rho(z) \sim (1+z)^m$

m= 0 : No evolution

Hopkins and Beacom, Astrophys. J. **651** 142 (2006)



TeV PeV EeV

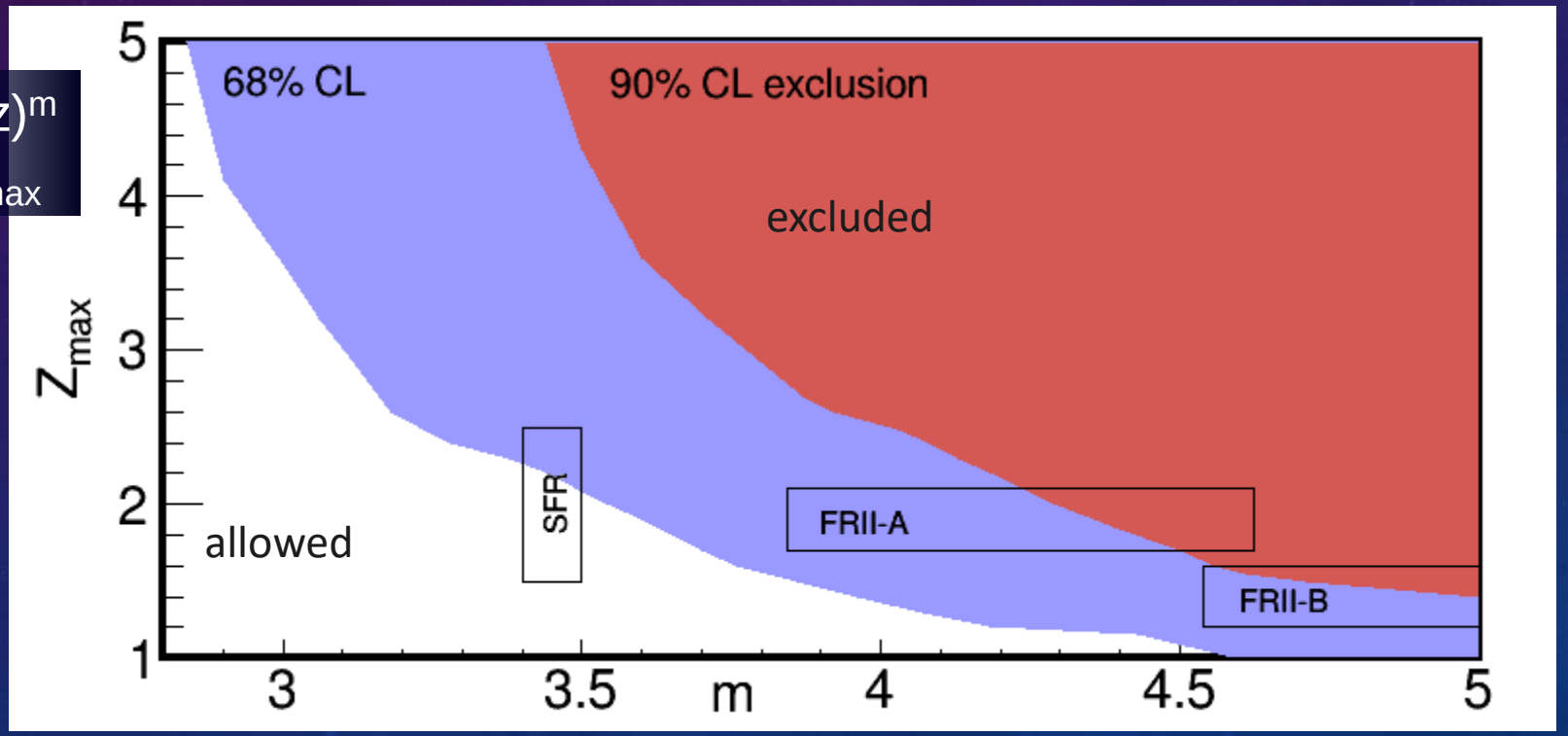
# The Constraints on evolution (emission history) of ultra high cosmic ray (UHECR) sources

**UHECR source is cosmologically LESS evolved**

Any sources with evolution compatible or stronger than star formation rate are disfavored

IceCube collaboration
Phys.Rev.Lett.**117** 241101(2016)

$\rho \sim (1+z)^m$
$0<z<z_{max}$




~~FRII (FSRQs)~~

~~GRBs~~

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# we want to discover $\nu$ and cosmic ray sources!

where are they?

# NEUTRINO SOURCE HUNTING WITH MULTI-MESSENGER DETECTION

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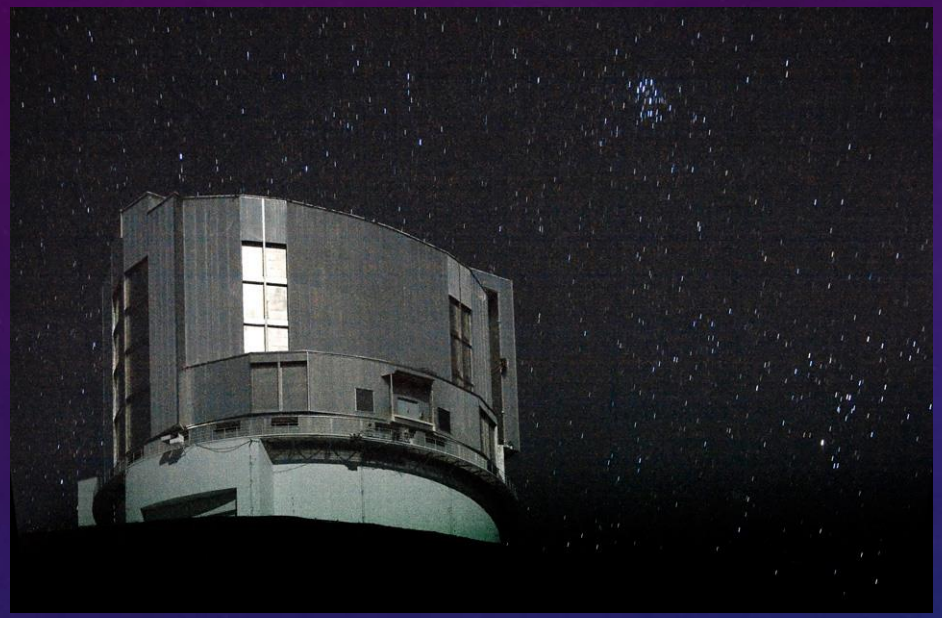
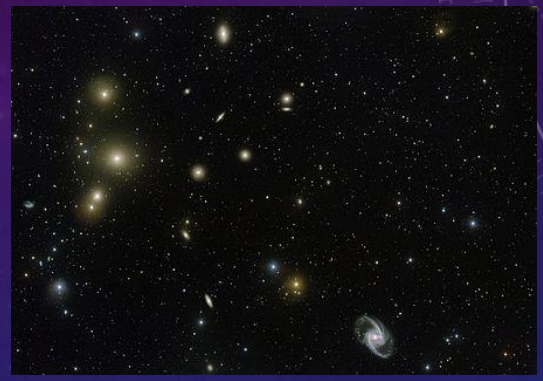


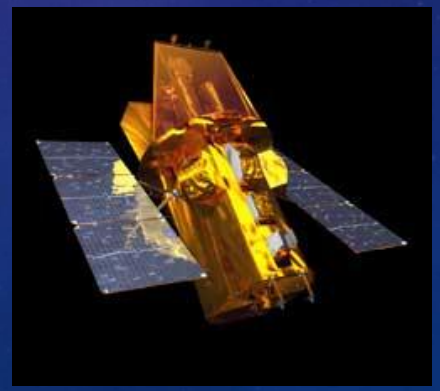


optical

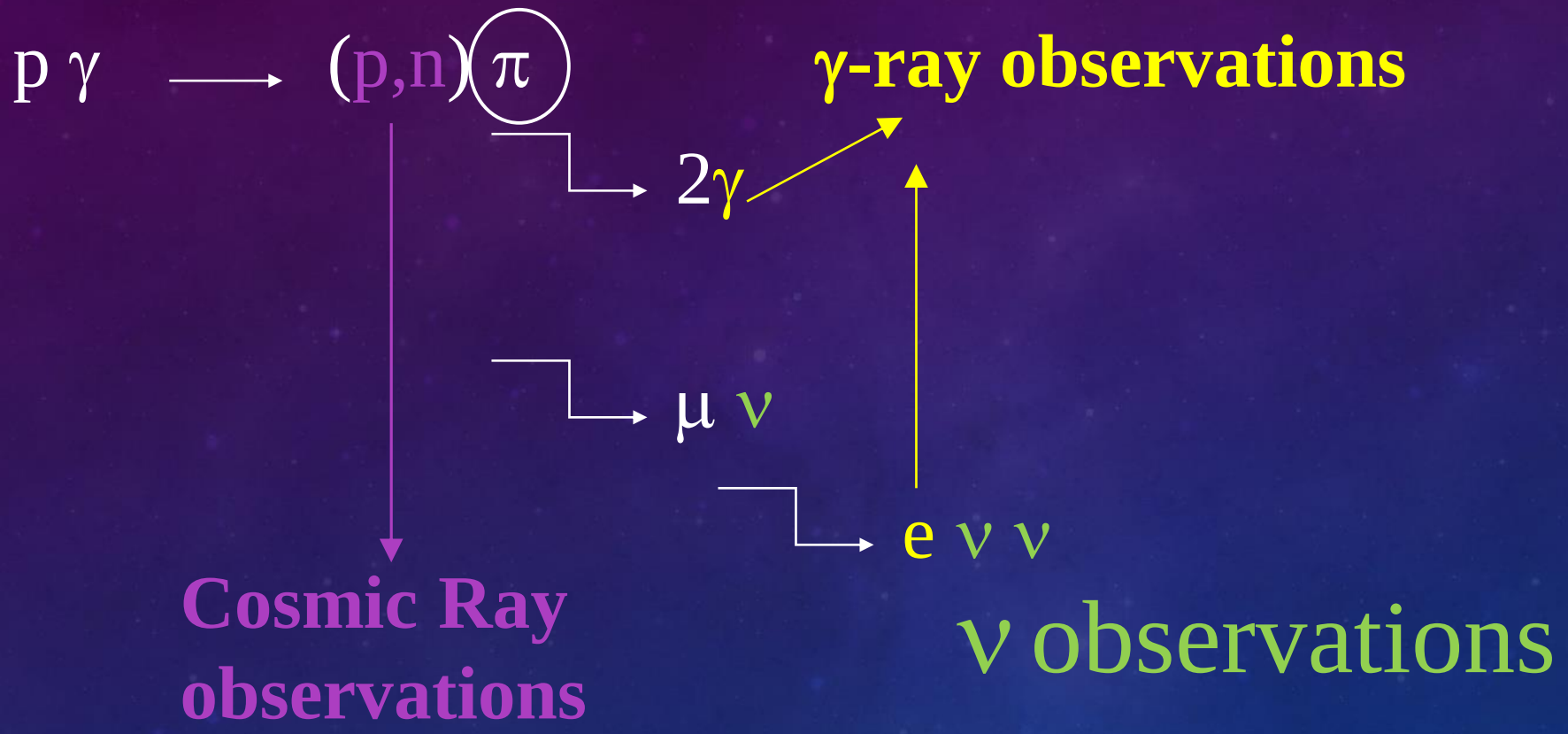
$\gamma$-ray

X-ray

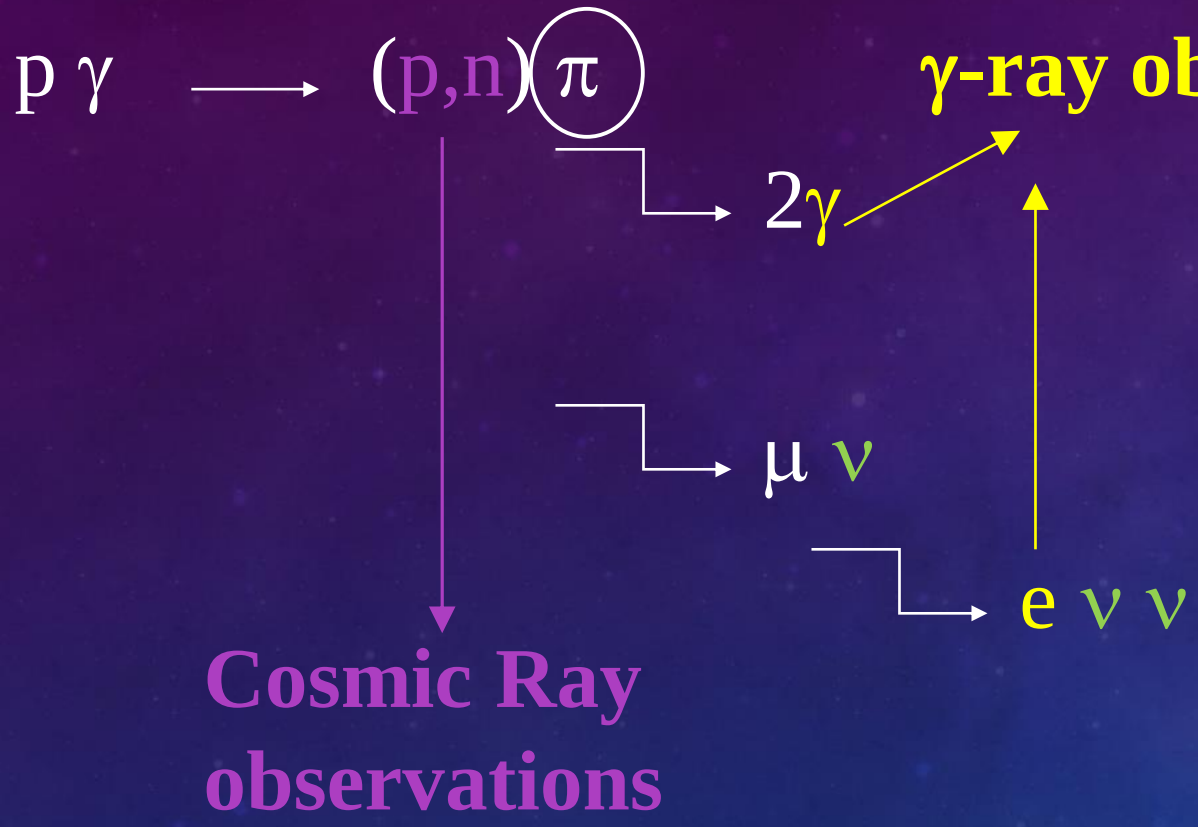
$\nu$



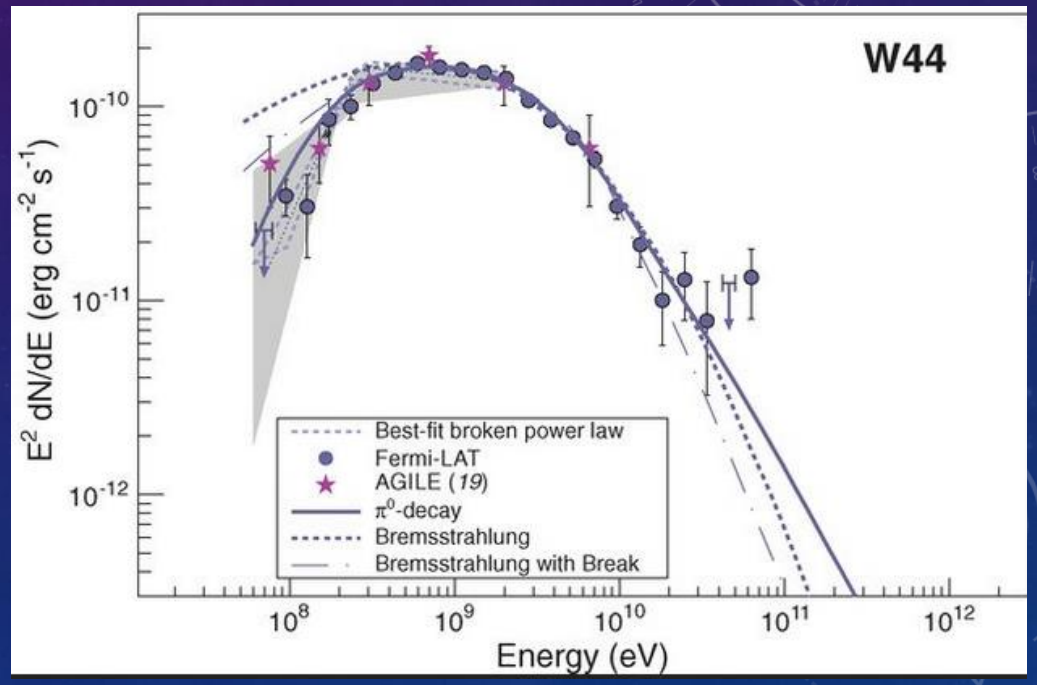
# MULTI-MESSENGER FRAMEWORK



# MULTI-MESSENGER FRAMEWORK




Fermi-LAT collaboration, Science **339**, 807 (2013)



# MULTI-MESSENGER FRAMEWORK

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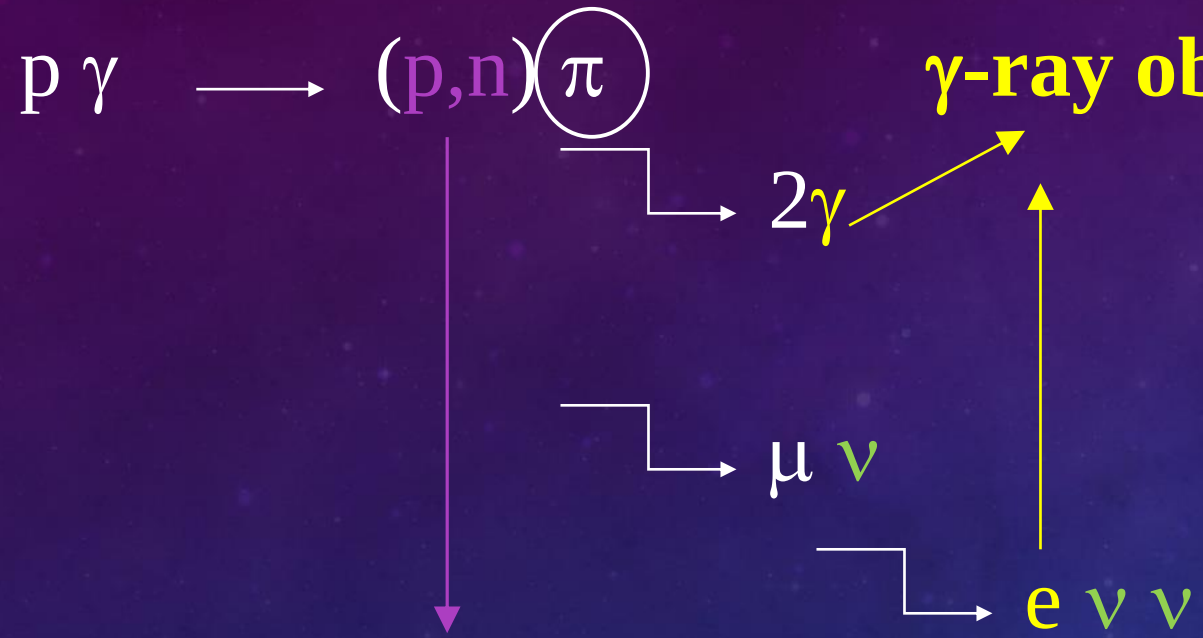
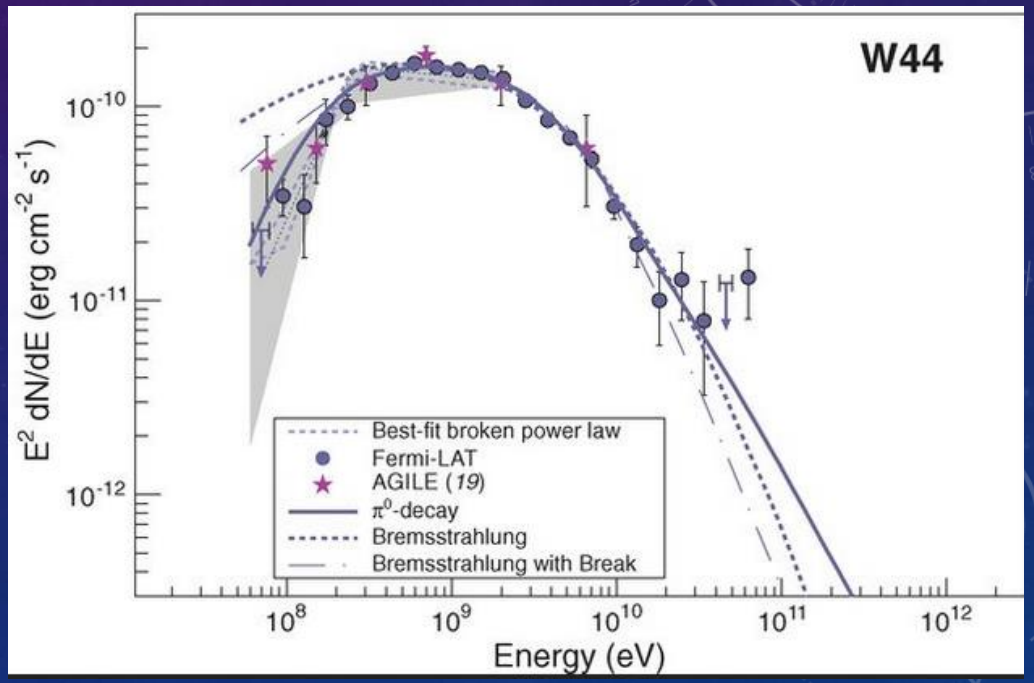
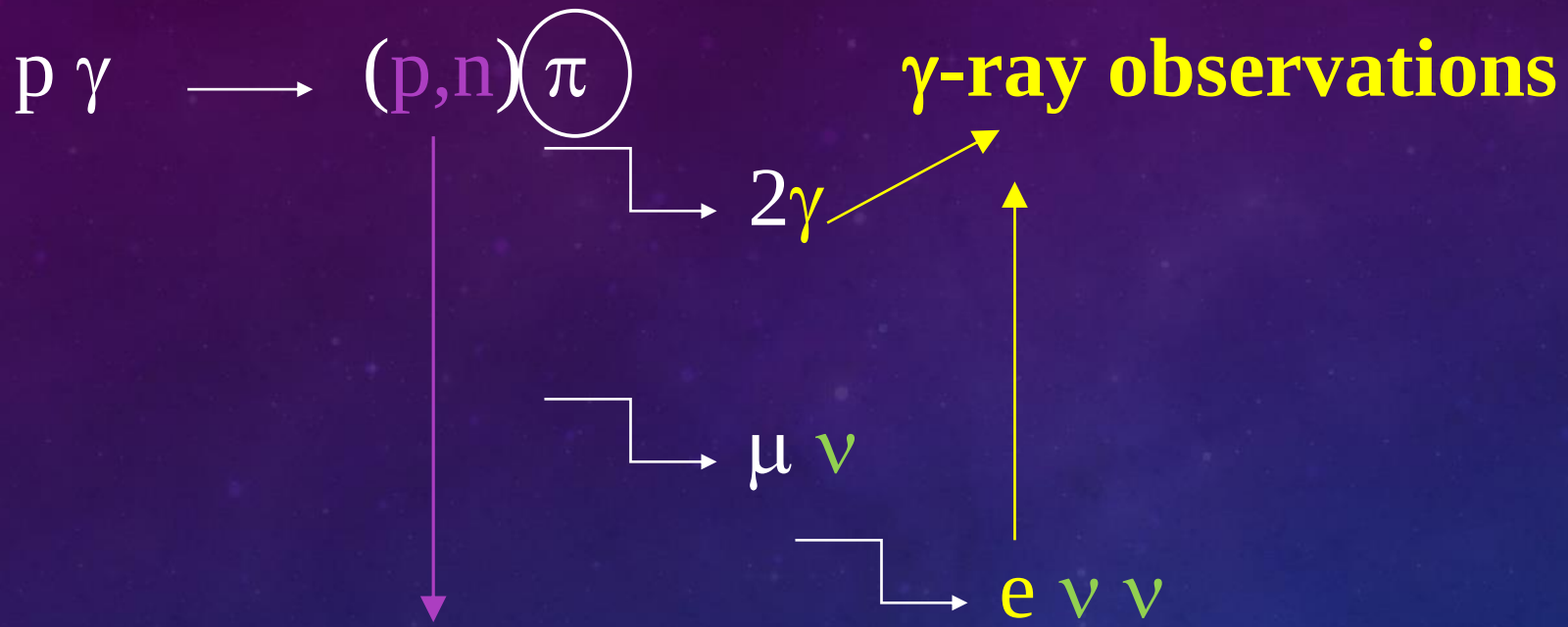



Fermi-LAT collaboration, Science **339**, 807 (2013)




But eZ → eγZ (Bremsstrahlung)
eγ → eγ (inverse Compton)
could produce γ-ray

# MULTI-MESSENGER FRAMEWORK




ν observations
||
The smoking gun

# REALTIME MULTI-MESSENGER

**South Pole**

< 3 minutes time lag

**Northern Hemisphere**

WIPAC
Wisconsin IceCube Particle Astrophysics Center

GCN-TAN

# ICECUBE REALTIME ANALYSIS CHAIN

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## Deliver of public alerts via GCN

High cosmic ν purity samples.
Launched in 2016!

veto-based HESE


all neutrino flavor sensitive
high chance of real cosmic neutrino signals
angular resolutions so-so

EHE (Ultra-High Energies)

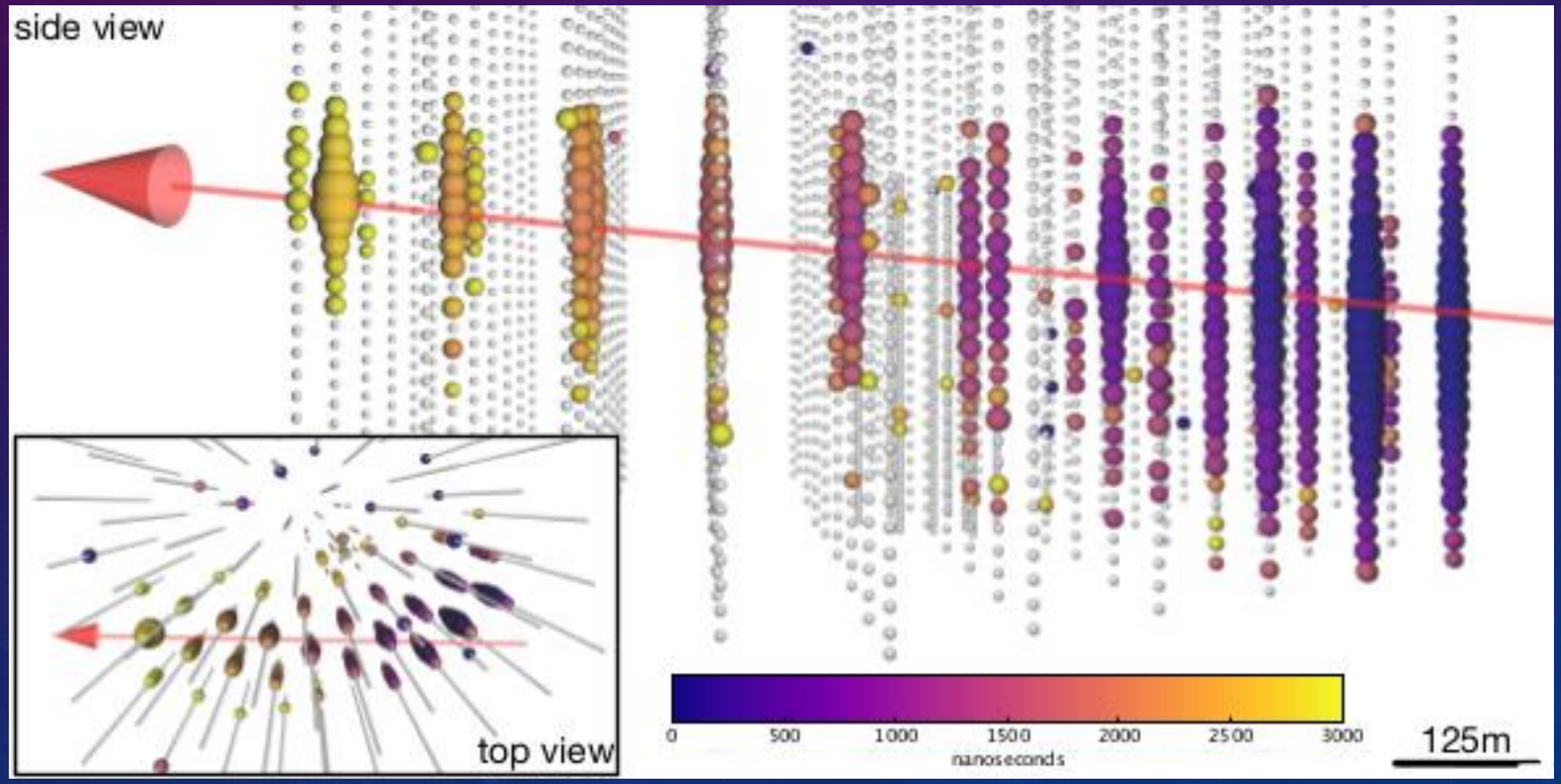

all neutrino flavor sensitive
high chance of real cosmic neutrino signals
good angular resolutions
signal flux highly uncertain

The breakthrough event detected in this channel

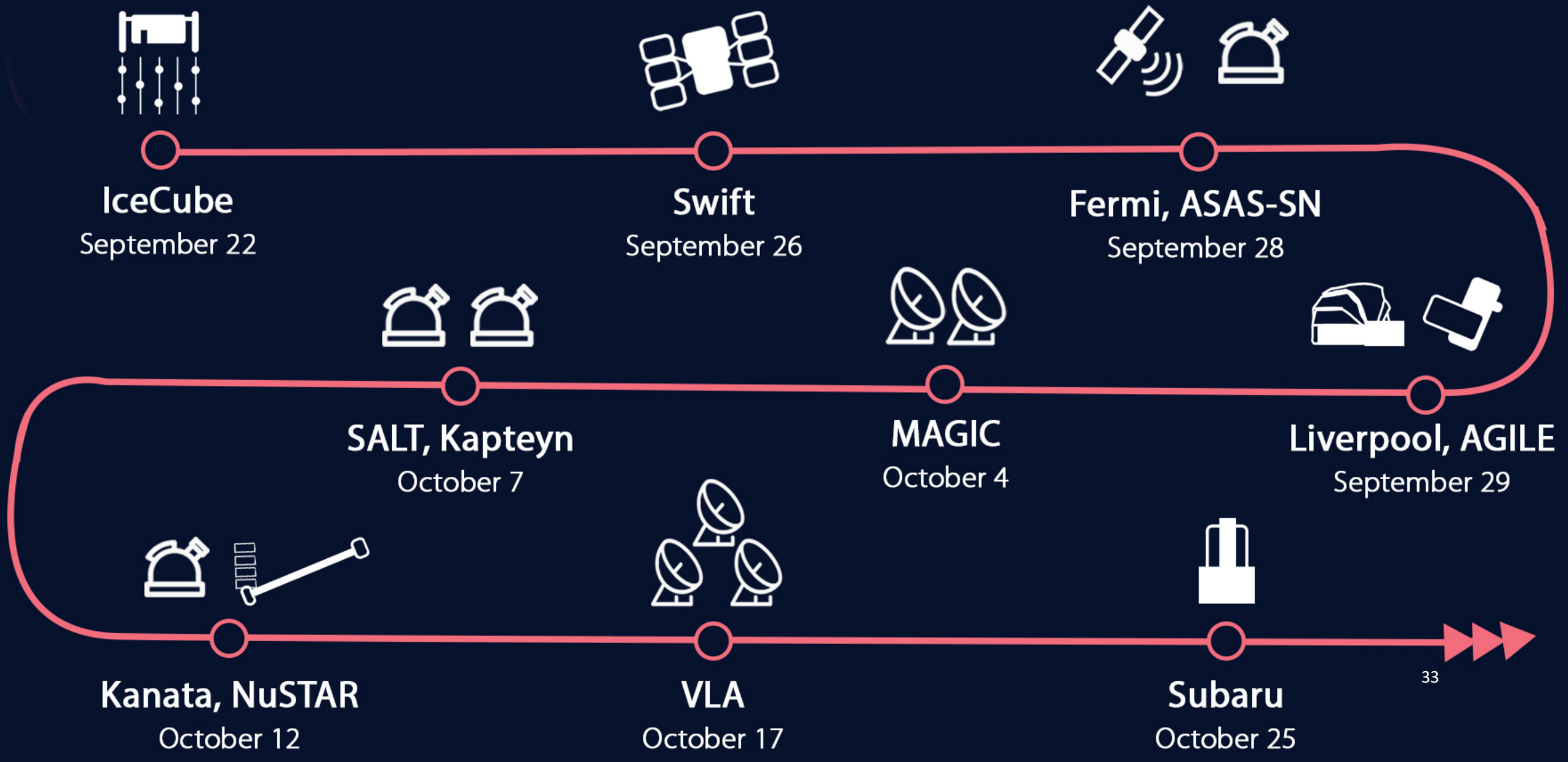

Chasing the ammonia economy p. 120
Time invested matters for mice, rats, and humans pp. 124 & 178
Two spindles are better than one pp. 128 & 189
Science
$15
13 JULY 2018
sciencemag.org
AAAS
NEUTRINOS FROM A BLAZAR
Multimessenger observations of an astrophysical neutrino source pp. 115, 146, & 147

# AND THE MESSENGER ARRIVED!

IceCube-170922A



# Follow-up detections of IC170922 based on public telegrams

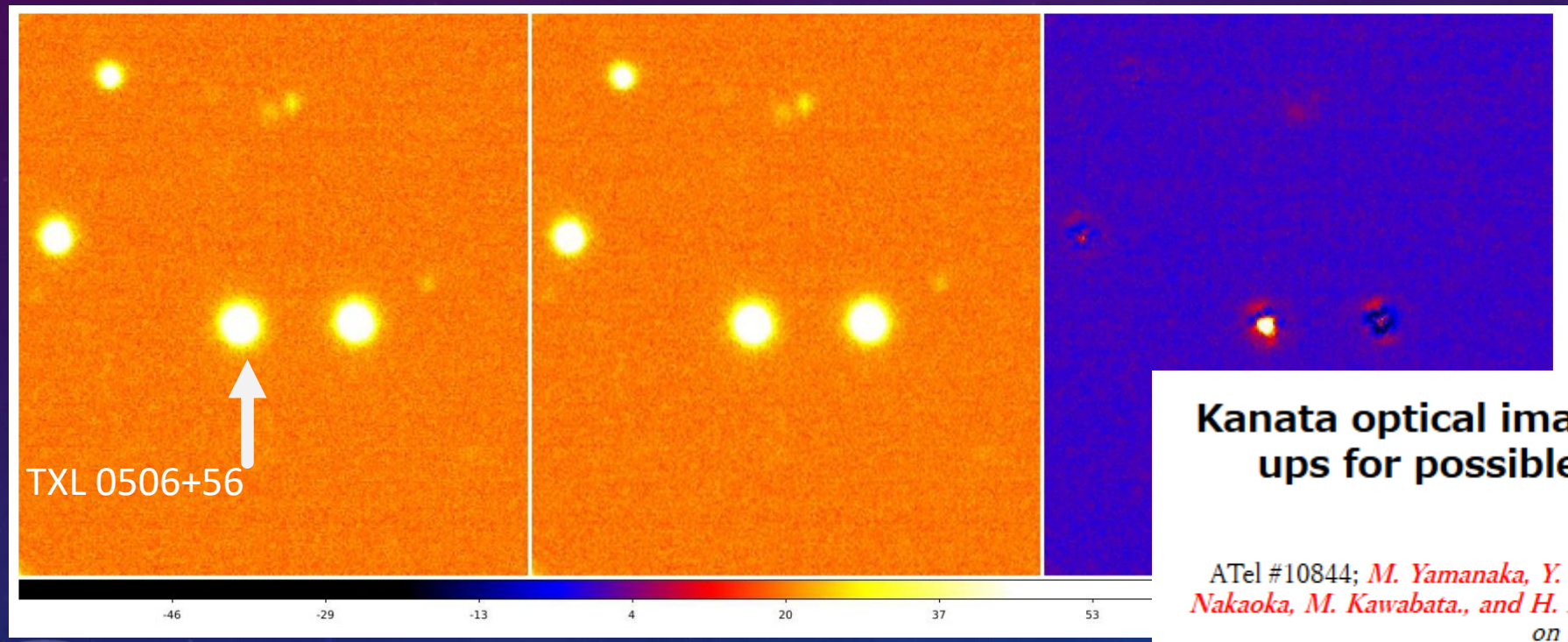


# OPTICAL FOLLOW-UP

## Kanata's follow-up

1.5 m dish at Hiroshima, Japan

September 23 September 24 Residual




**Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056**

ATel #10844; *M. Yamanaka, Y. T. Tanaka, H. Mori, K. S. Kawabata, Y. Utsumi, T. Nakaoka, M. Kawabata., and H. Nagashima on behalf of Kanata and OISTER teams.*
*on 12 Oct 2017; 15:50 UT*
*Distributed as an Instant Email Notice Transients*
*Credential Certification: Masayuki Yamanaka (masyamanaka@hiroshima-u.ac.jp)*

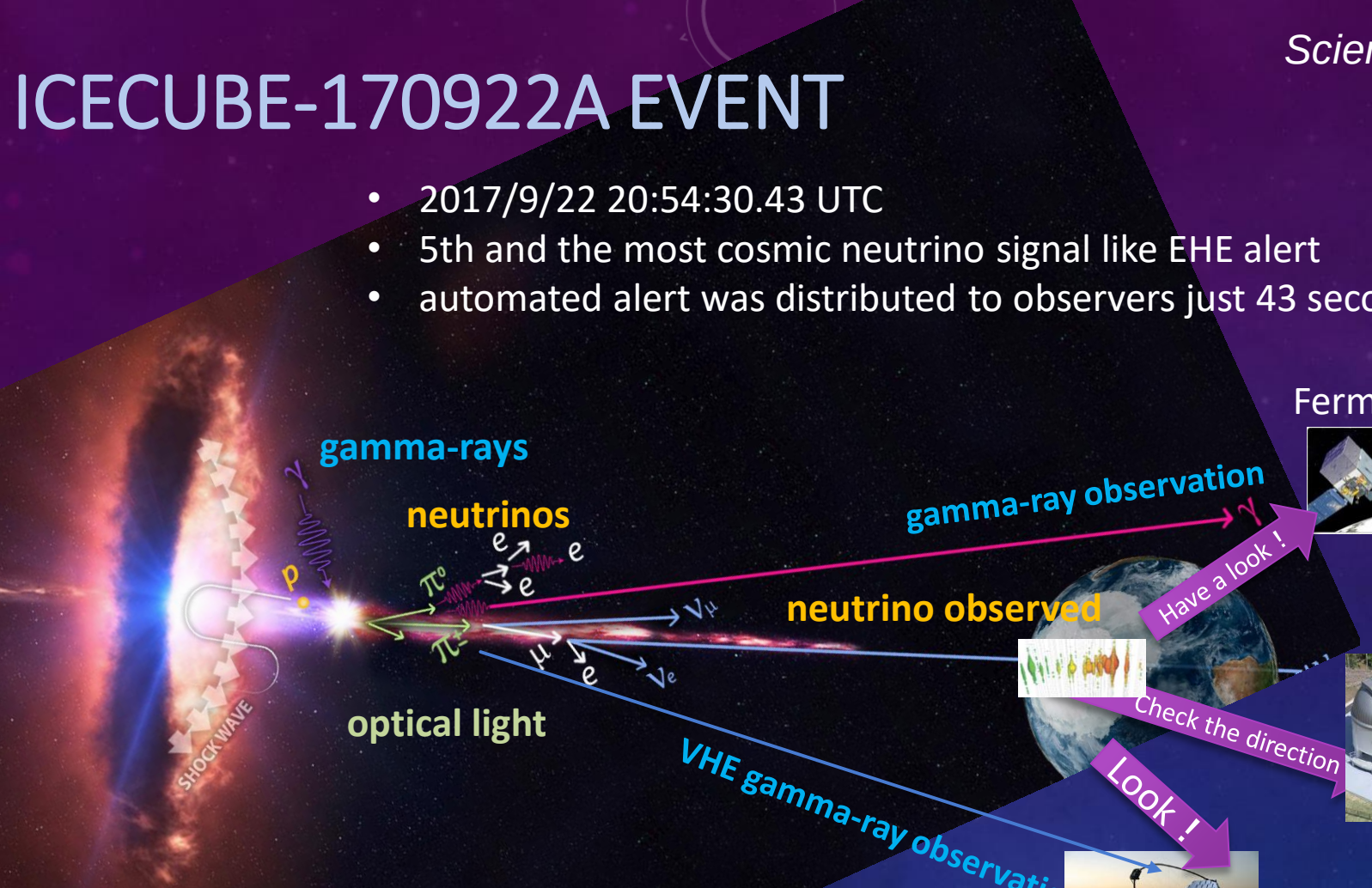
Subjects: Infra-Red, Optical, Blazar, Transient

Referred to by ATel #: 10861, 11430, 11489

# ICECUBE-170922A EVENT

*Science* 361, eaat1378 (2018)


- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later




Blazar TXS0506+056

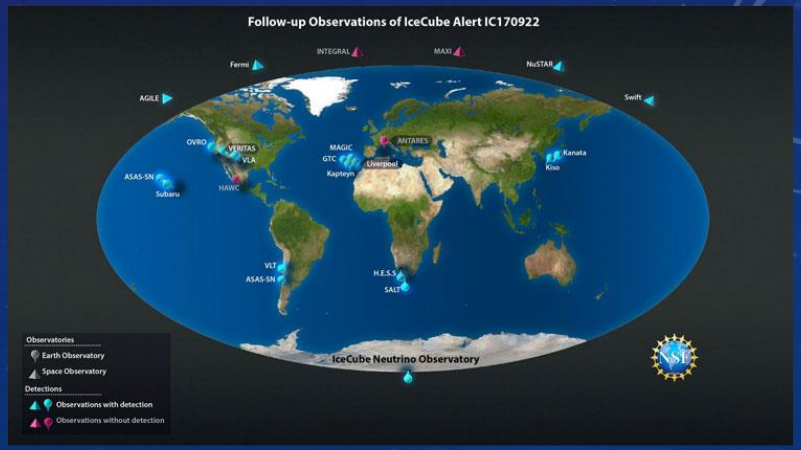
Fermi Telescope


Optical telescopes

Kanata telescope

Magic telescope

...and many more telescope



# ASSOCIATION WITH G-RAY FLARE FROM TXS0506+056

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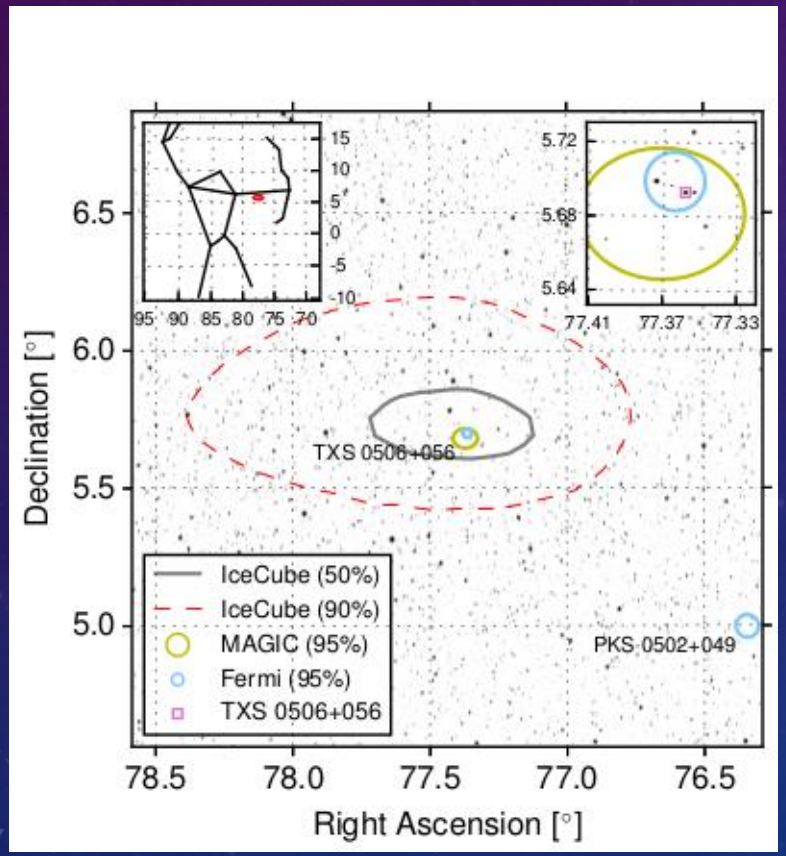
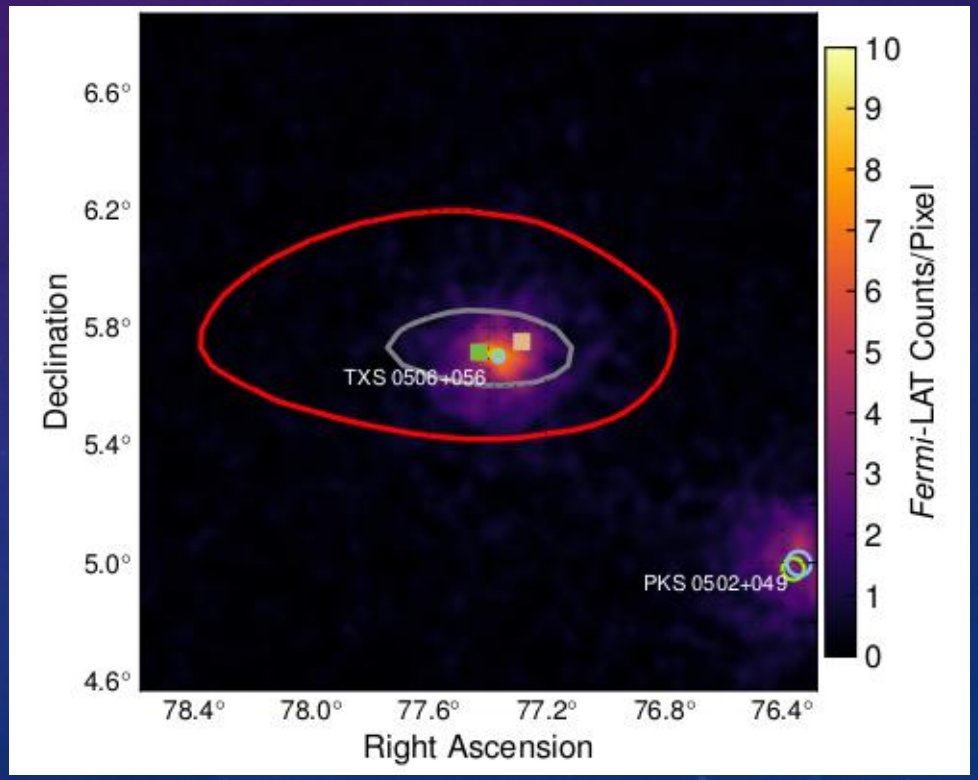
~ 4σ significance of association

(~ 3σ post-trial)



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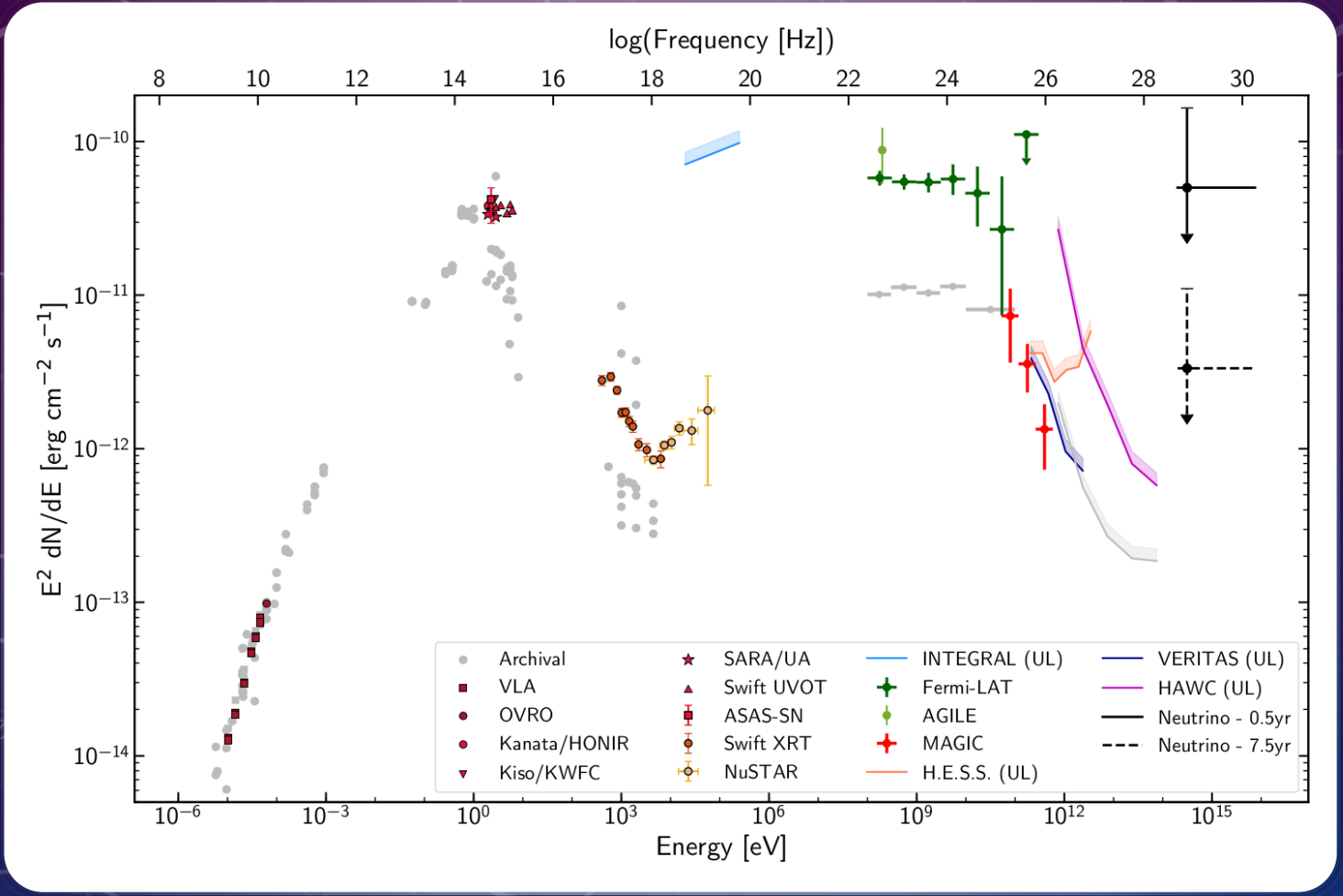
# SED

## MEASURED BY MULTI-WAVE MESSENGERS




## A mystery

This is a typical SED of γ-ray blazars

X-ray band is dim

# THE SOURCE IMAGES IN MULTI-WAVELENGTH BANDS

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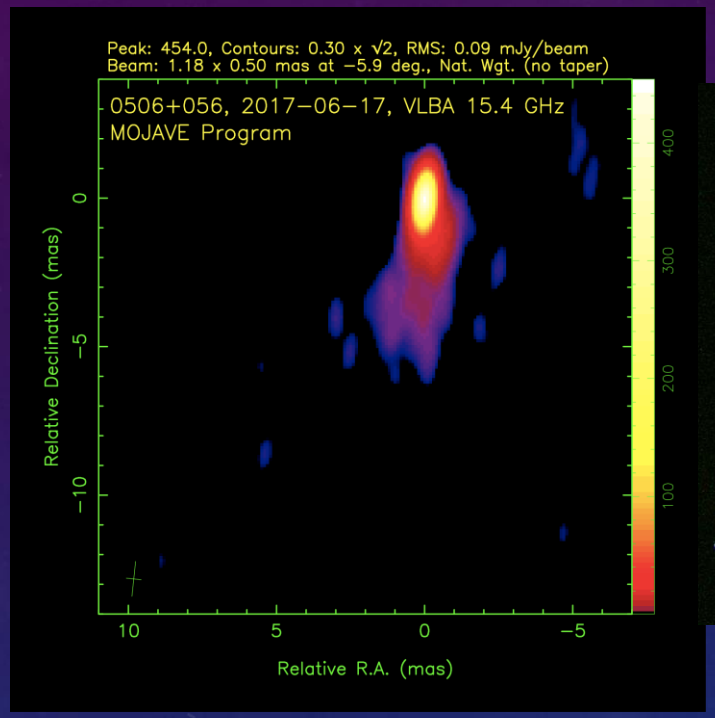
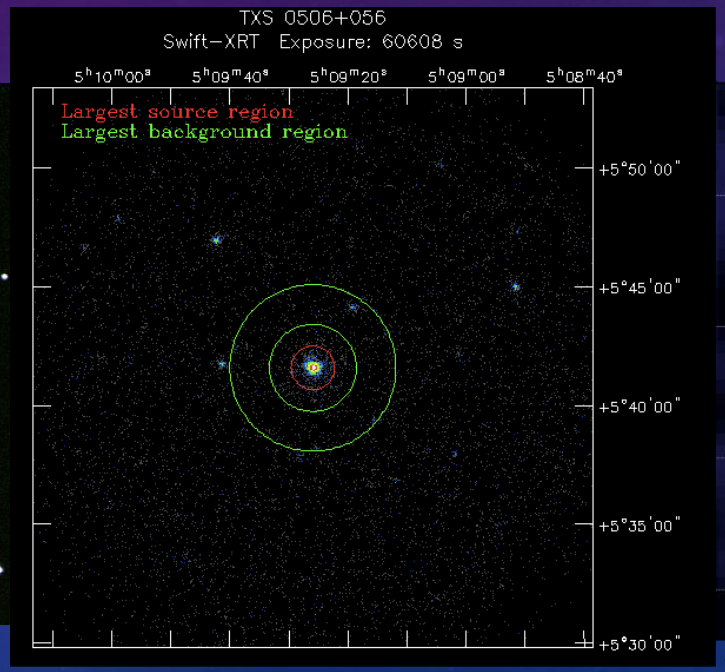
radio

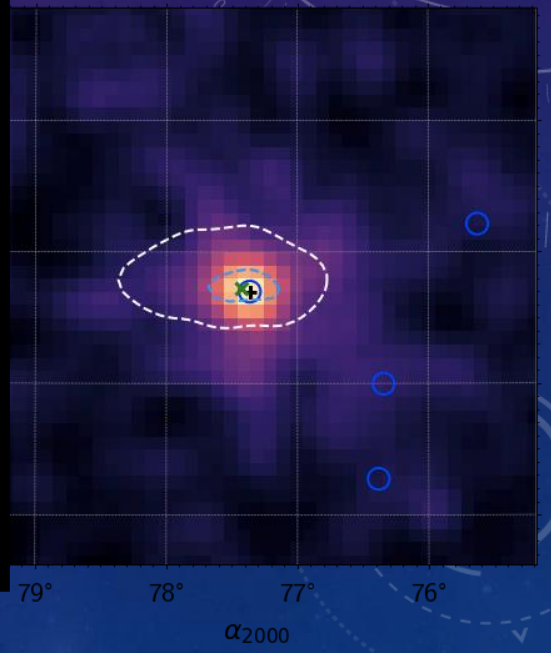



optical

x-ray




γ-ray



# ICECUBE REALTIME ANALYSIS CHAIN

## version 2 now online!

inheritance from the version 1

veto-based HESE

EHE (Ultra-High Energies)

new addition!

GFU (Gamma-ray Follow Ups)

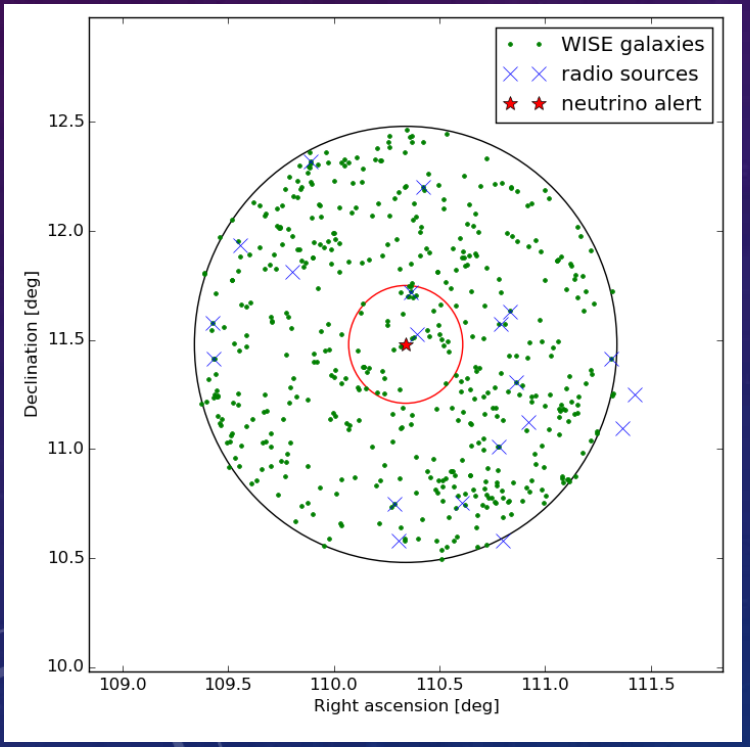

purity of cosmic neutrinos

>50%


>30%

# FUTURE MOVE ON THE ICECUBE SIDE

**Which one is Cosmic Pevatron ??**




So many counterparts as neutrinos are ***penetrating*** messengers even from even z ~ 1

We need to limit number of counterpart candidate!

# FUTURE MOVE: INTRODUCING MULTIPLETS

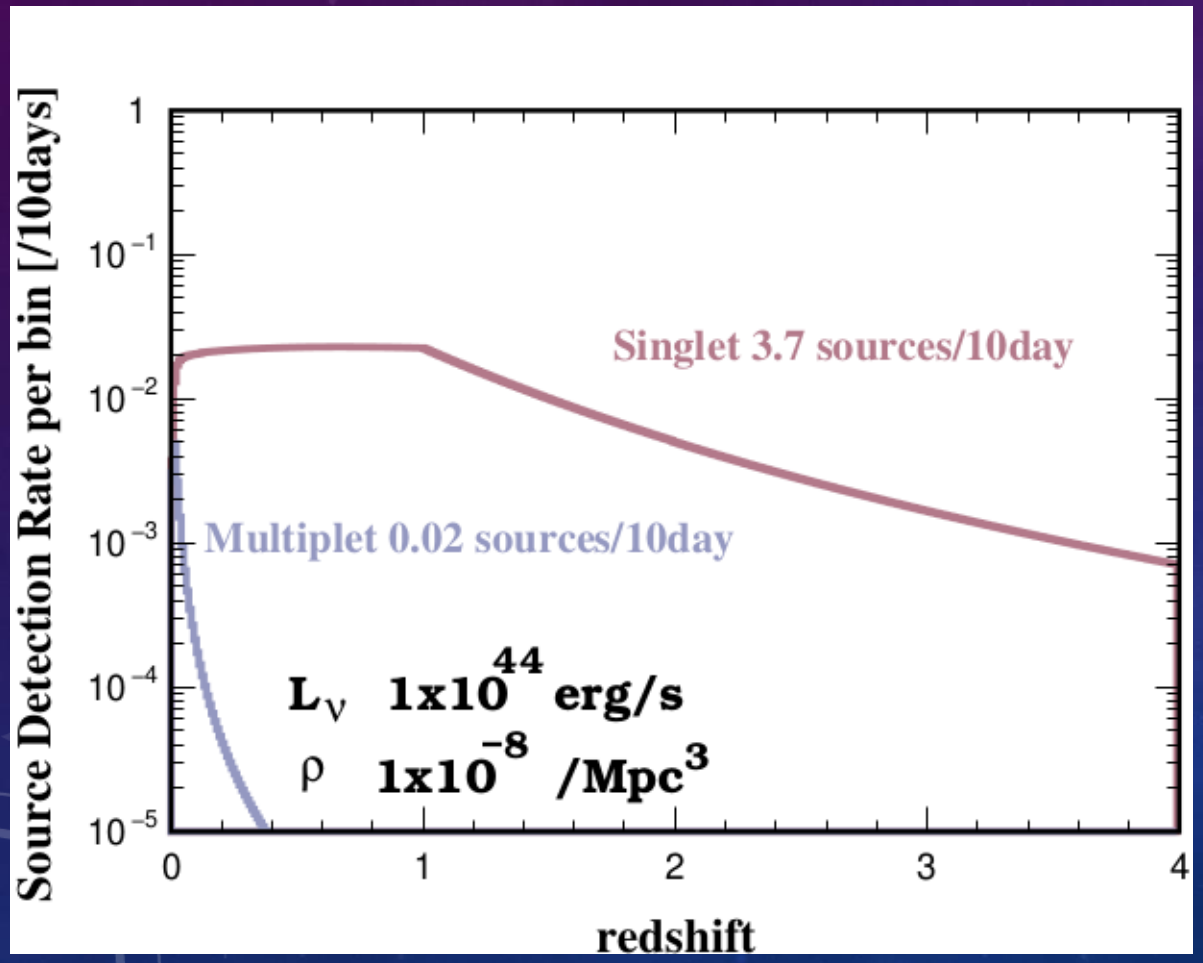
singlet : A high energy $\nu$


multiplet: multi high-E $\nu$'s within O(days)

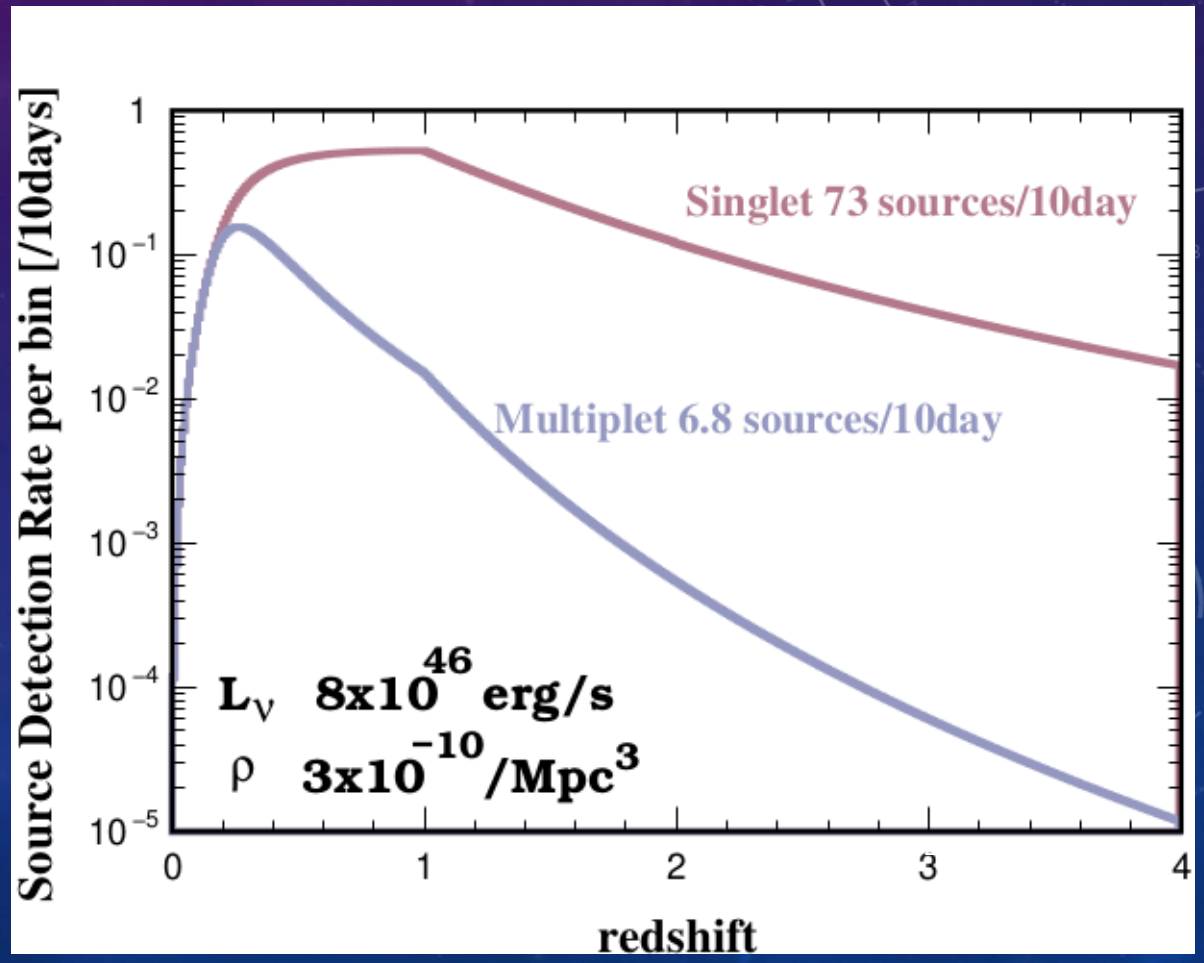
# MULTIPLET WOULD CERTAINLY LIMIT REDSHIFT

## examples – still toy calculations

SNe like : well populated, so-so luminous




(yet-unknown) ultrahigh energy CR source-like
rare, but super luminous



# NEUTRINO ASTRONOMY IS BLOOMING

Multi-messenger observations will answer key questions of high energy universe

- neutrino sources
- cosmic accelerators
- physics beyond SM