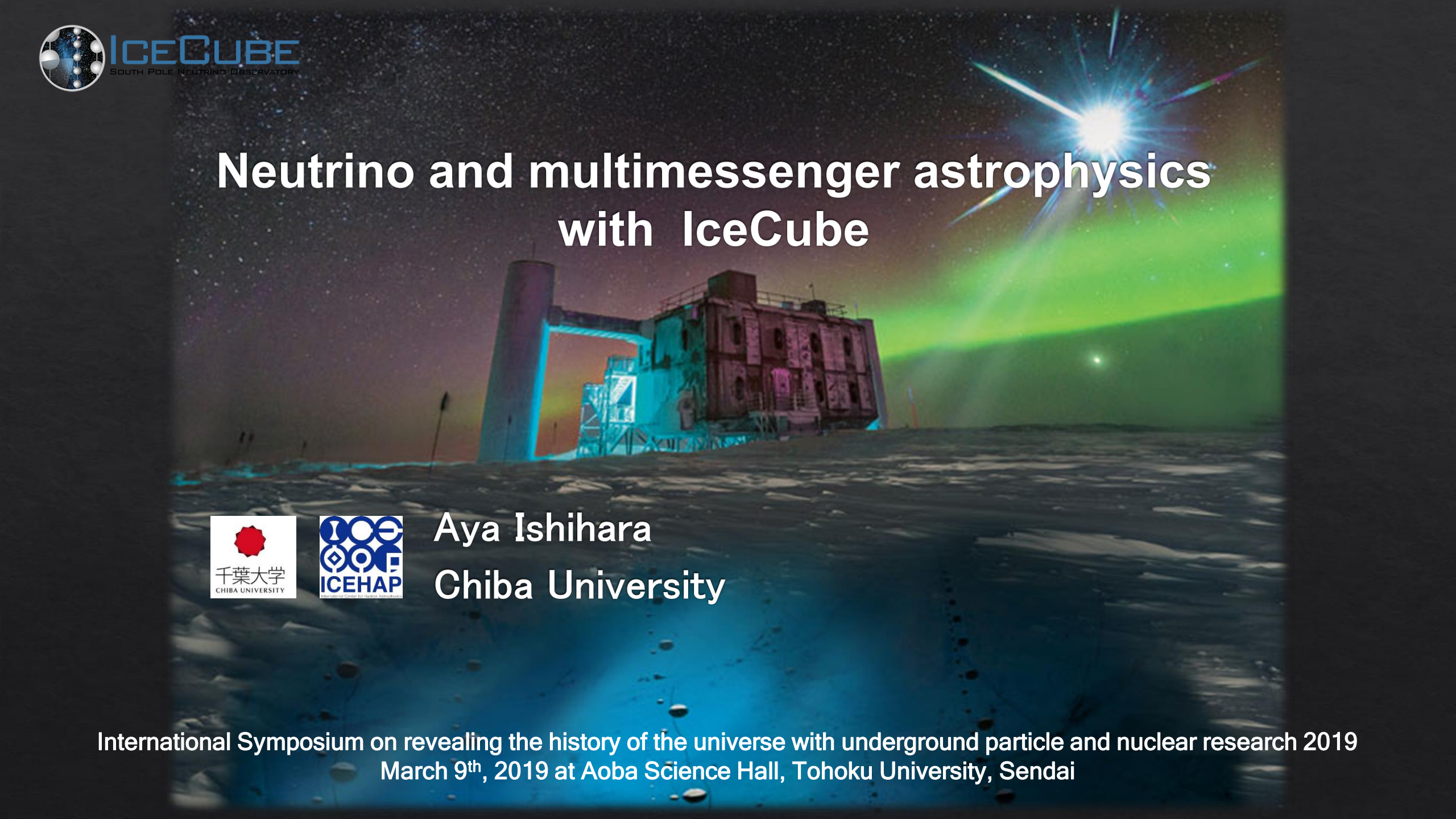
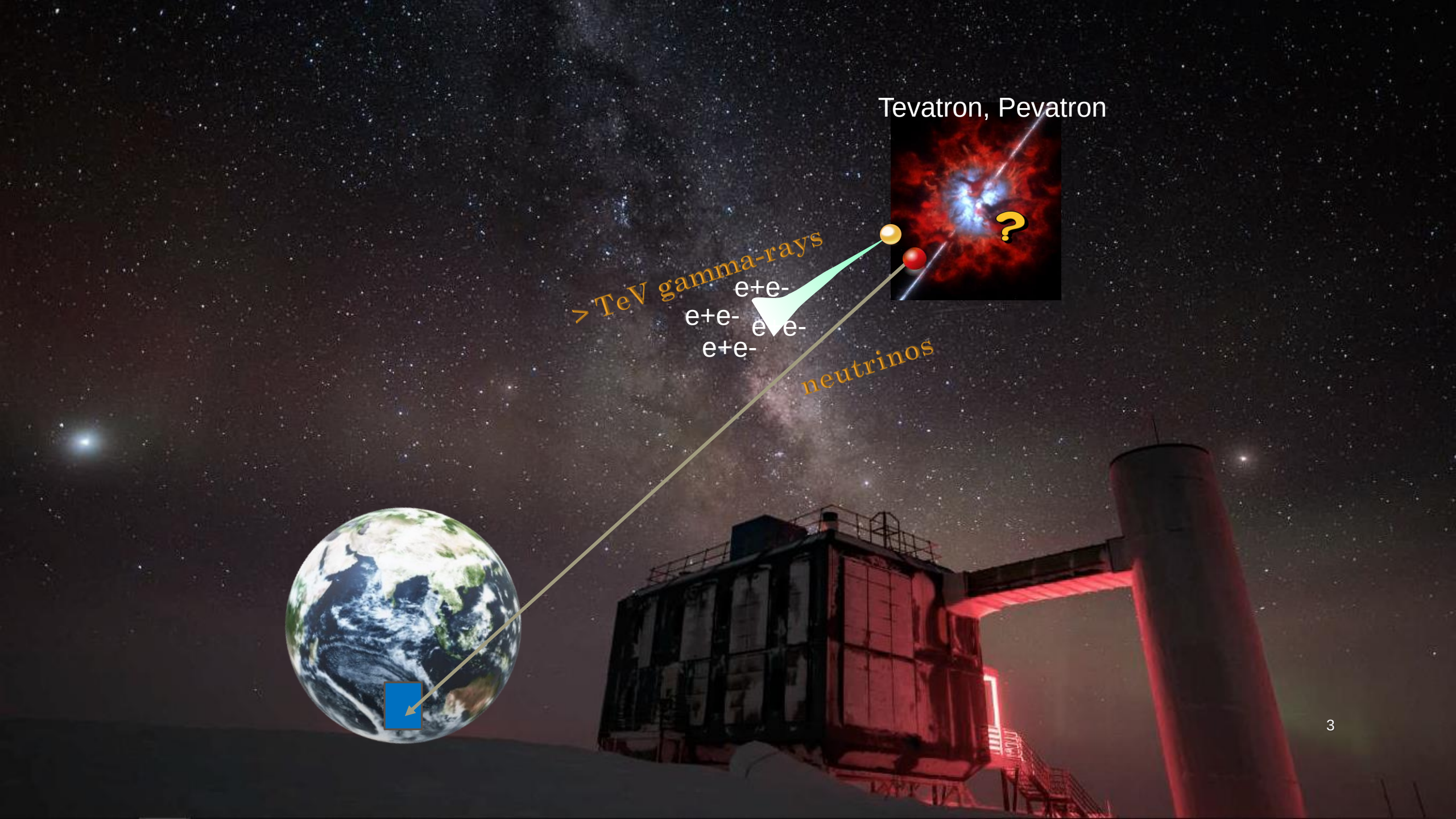


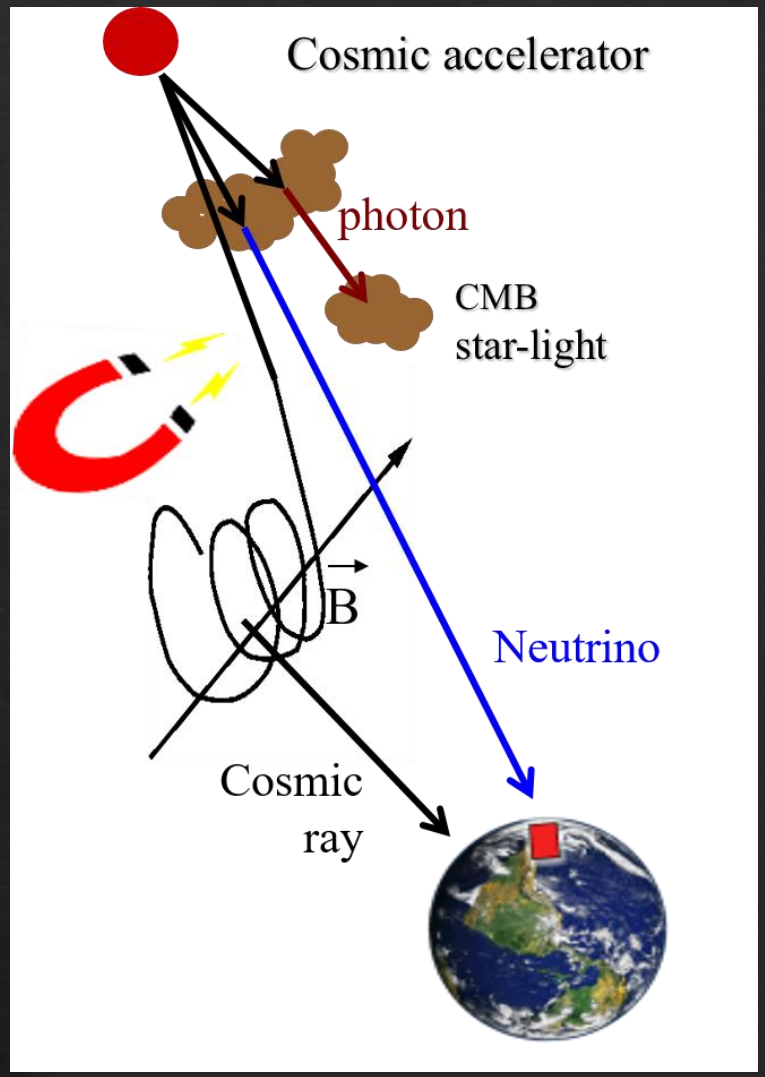
Neutrino and multimessenger astrophysics with IceCube

Aya Ishihara
Chiba University

International Symposium on revealing the history of the universe with underground particle and nuclear research 2019
March 9th, 2019 at Aoba Science Hall, Tohoku University, Sendai


Tevatron, Pevatron
?
> TeV gamma-rays
e+e-
e+e-
e+e-
e+e-
neutrinos

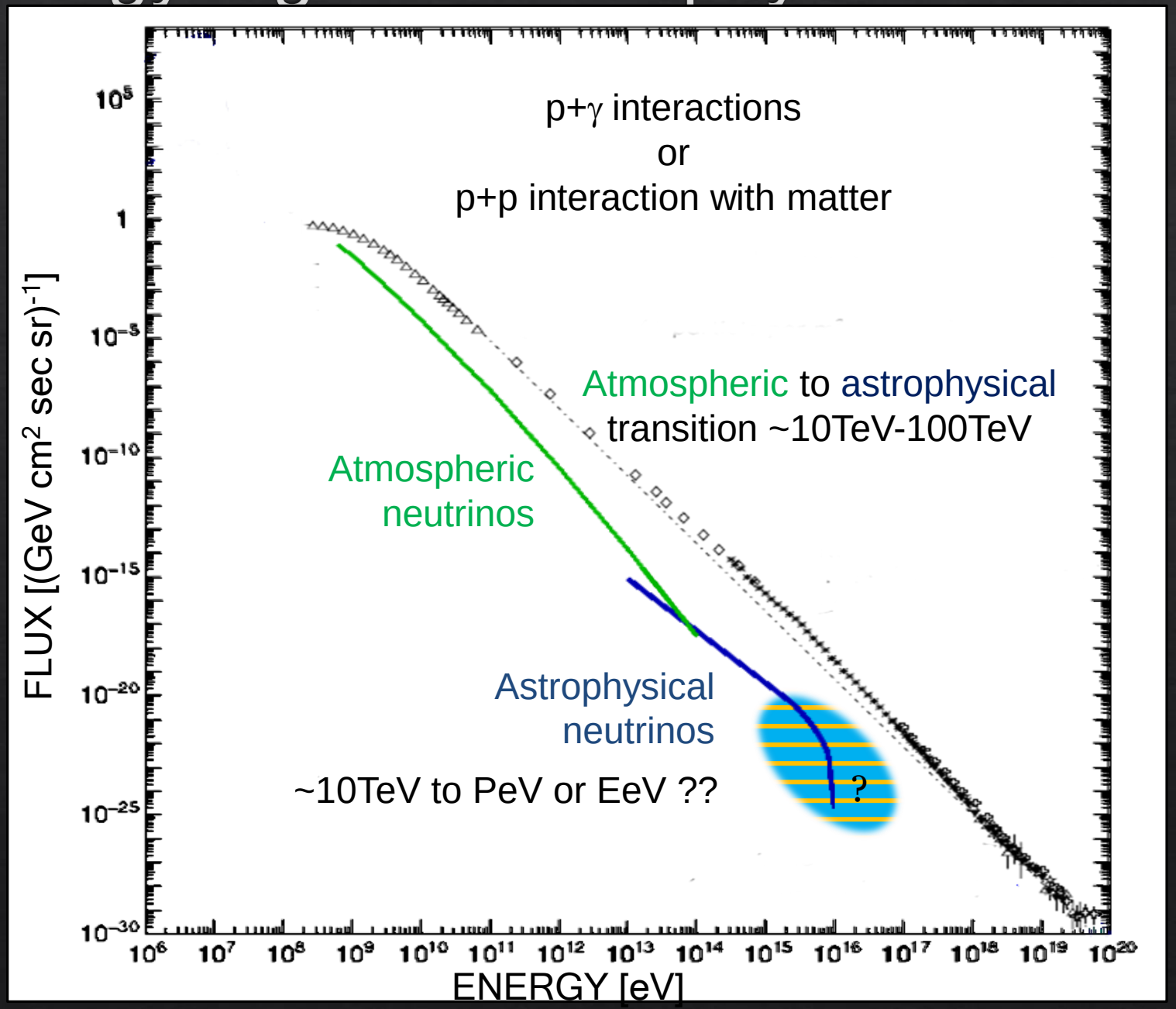
TeV-PeV Neutrino Detector



Catch the cosmic messengers
– only interact weakly during "propagation"

- **Penetration power**
- **Pointing capability**

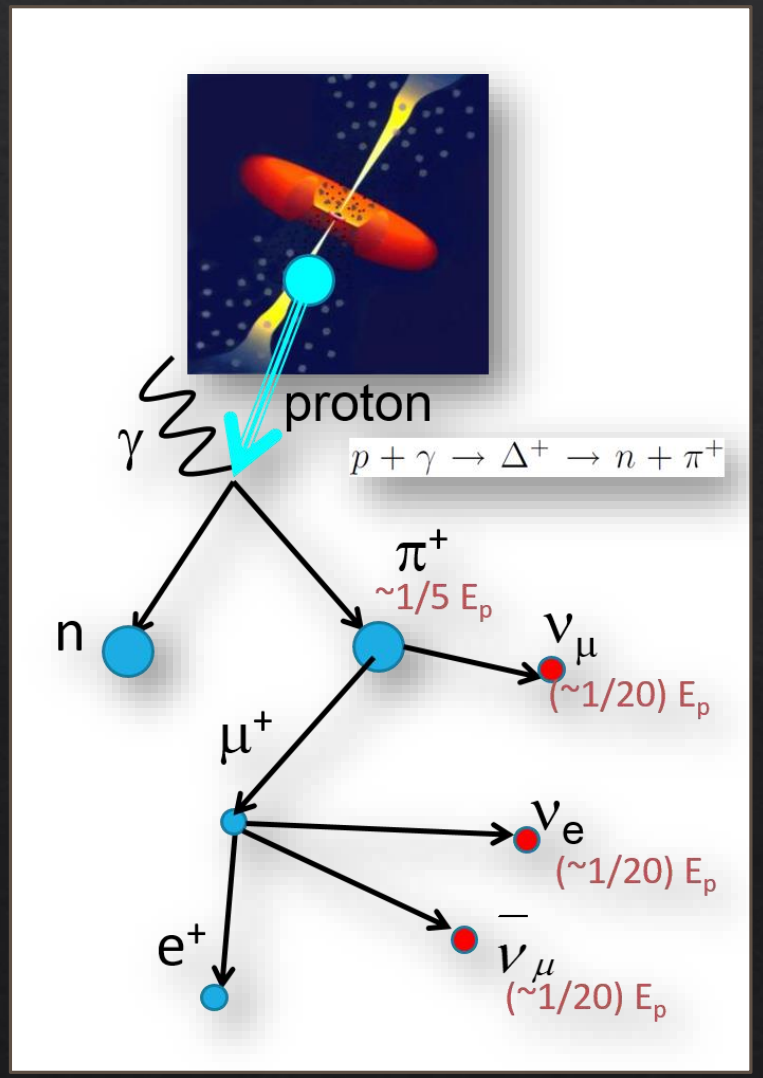
Energy region of astrophysical neutrinos



IceCube found the cosmic neutrino flux close to WB limit: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.59.023002

Connection among ν, γ and CR

$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$



Hadronic "ν creation" only need simple ingredients

- Cosmic-ray and target spectra in source
  - Via pp or pγ interaction

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^- + \ldots$$
$$p + \gamma \rightarrow p + n + \pi^0 + \pi^+ + \ldots$$

$\pi^+ to\ \pi^-$ ratio at source is target (model) dependent

- **Directly accompanying partners**
  - gamma-ray from neutral pions ($\pi^0 \rightarrow \gamma\gamma$ but >TeV γ will cascade down to <TeV via $\gamma\gamma_{CMB} \rightarrow e^+e^- \rightarrow \gamma_{IC}, \gamma_{sync}$ process)
  - parent cosmic-rays (p, nuclei)

$$\pi^0 \rightarrow \boxed{\gamma\gamma}$$
$$\pi^{+,-} \rightarrow \boxed{\mu^{+,-}} + \boxed{\nu_\mu(\bar{\nu}_\mu)}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

alternate models: μ dumping neutron decay

- **Indirectly accompanying partners**
  - radiations, radio, optical, x-ray...
  - Gravitational waves

Multi-messenger !

Neutrino source candidates: pγ interactions

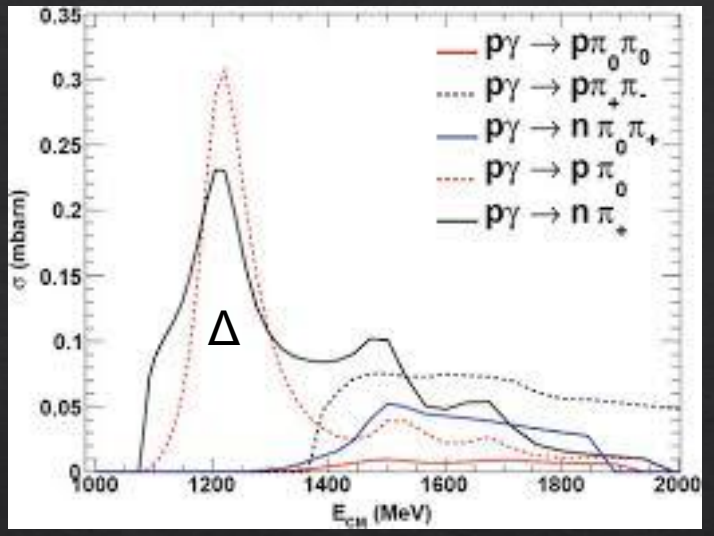
- **Need "target photon" in the energy range which matches to beam energies → neutrino spectral shape**

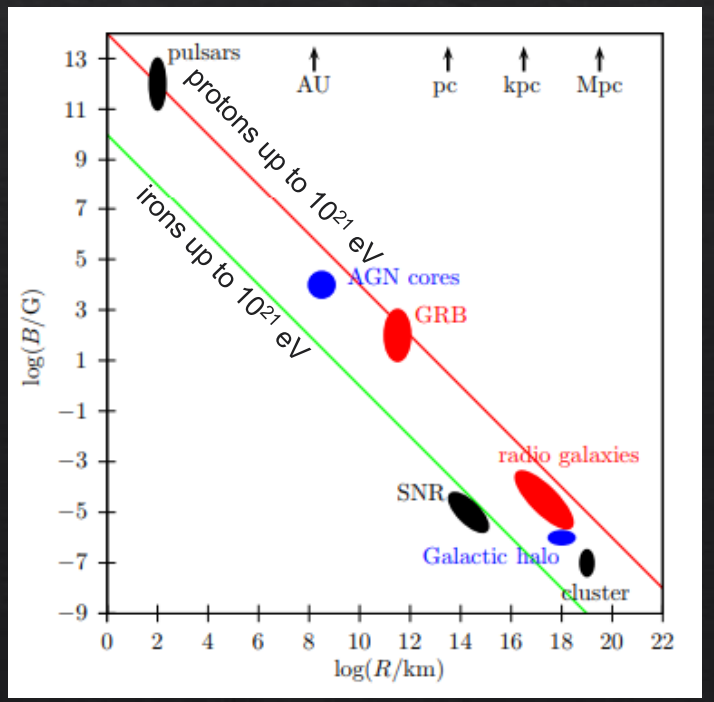
$$E_\nu \approx \frac{1}{20} E_P$$ ← neutrino energy range: 10-100 TeV

$$E_\gamma \sim \frac{0.2 GeV^2}{E_p} \left(\frac{\Gamma}{1+z}\right)^2 \sim \begin{cases} 100 - 1000\ eV\ (\Gamma \sim 1) \\ 10 - 100\ keV\ (\Gamma \sim 10) \\ 1 - 10\ MeV\ (\Gamma \sim 100) \end{cases}$$

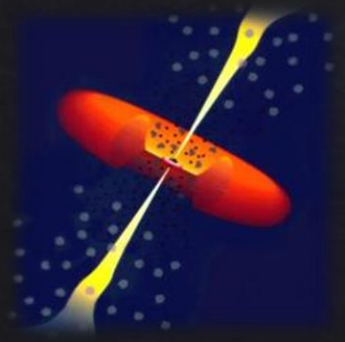
: non-relativistic
: e.g. AGN
: e.g. GRB

- **Need to satisfy Hillas condition $E_p < ZeBR\beta$**





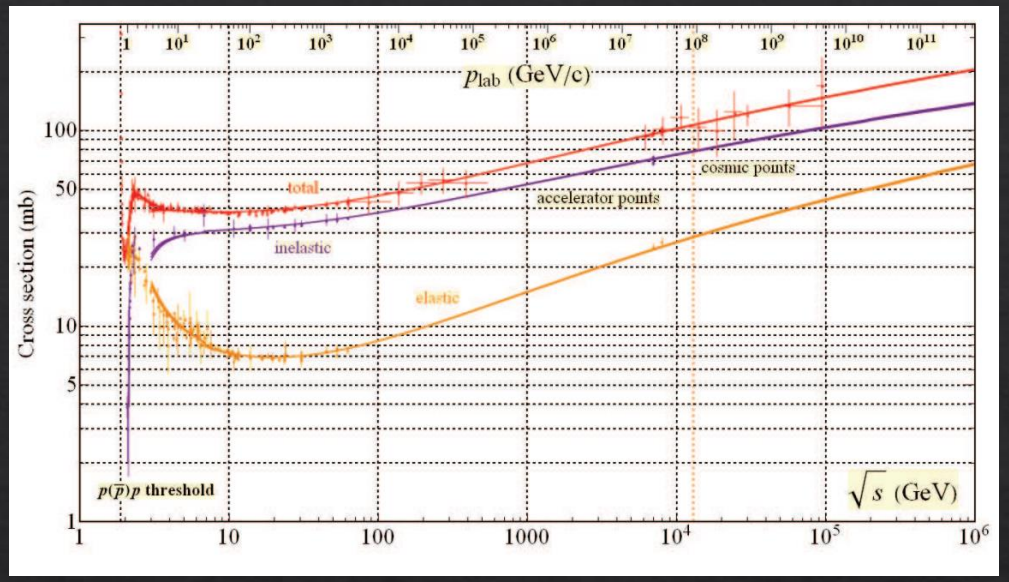
Typical pγ candidate sources such as AGN and GRB exhibit rapid time variation!

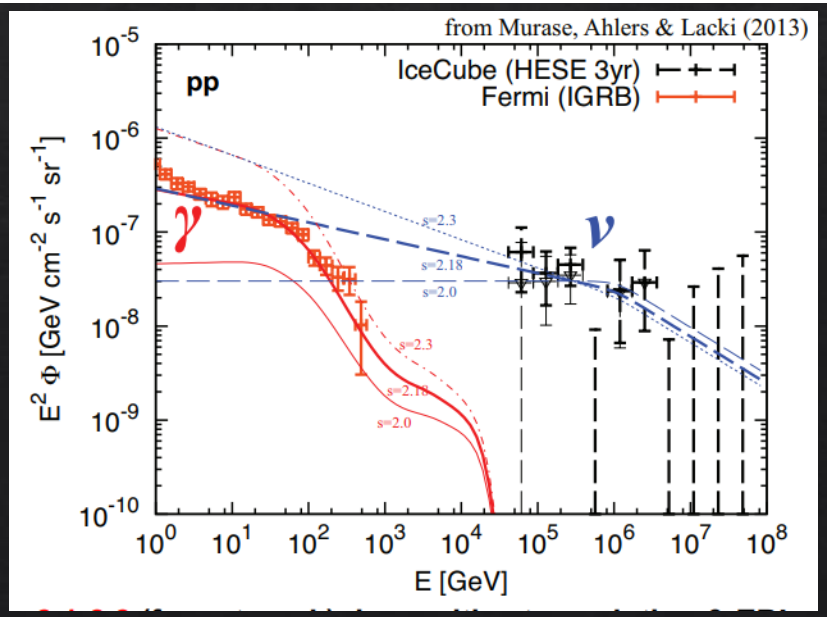


→ Multimessenger observation
→ Their temporal and spatial coincidence

Neutrino source candidates: pp interactions

- **Cosmic-ray reservoirs such as starburst galaxy and galaxy clusters**
  - **CRs could be created in AGN, supernova, hypernova, galaxy mergers**
- **Moderate increase with $\sqrt{s}$ ⇒Neutrino and gamma-ray spectra copy CR spectra ⇒ continues down to TeV**
  - **Induces too much <TeV Background gamma**
- **Need to satisfy Hillas condition E_p<$ZeBR\beta$**
  - starburst galaxy R ~ kpc B~0.1-1 mG
  - galaxy cluster R ~ Mpc B~0.1-1 μG





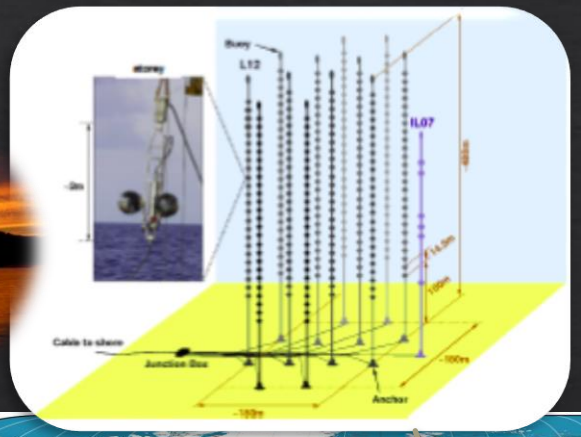
how to distinguish pp and pγ
Spectral shape? Association with candidate object?
Detection of anti nu e from pi (mu) minus decay could be the key!

Neutrino Telescopes

Northern hemisphere

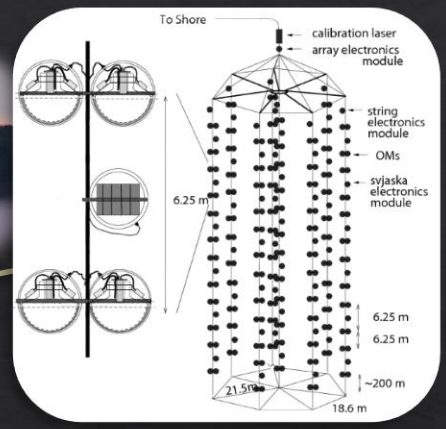
ANTARES

Mediterranean Ocean



BAIKAL-GVD

Lake Bikal



IceCube

South Pole

Glacial ice

Southern hemisphere

BAIKAL-GVD Phase1 (864 PMTs by 2018) 1/100km³

☞ GVD Phase 1(2304 PMTs in 2021) ☞ BAIKAL GVD full scale

ANTARES (12lines 882PMTs) 1/100km³

☞ KM3NET Phase 1 ☞ KM3NET 2.0

IceCube (86lines 5160PMTs) 1km³

☞ IceCube-Gen2 Phase 1 ☞ IceCube-Gen2

http://icecube.wisc.edu

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

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Yale University

FUNDING AGENCIES

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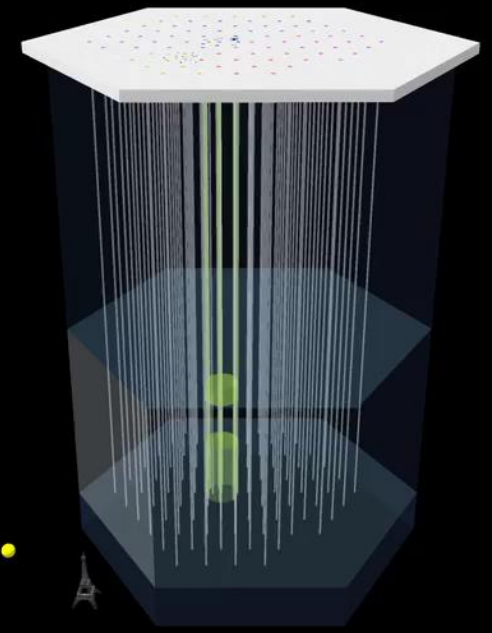
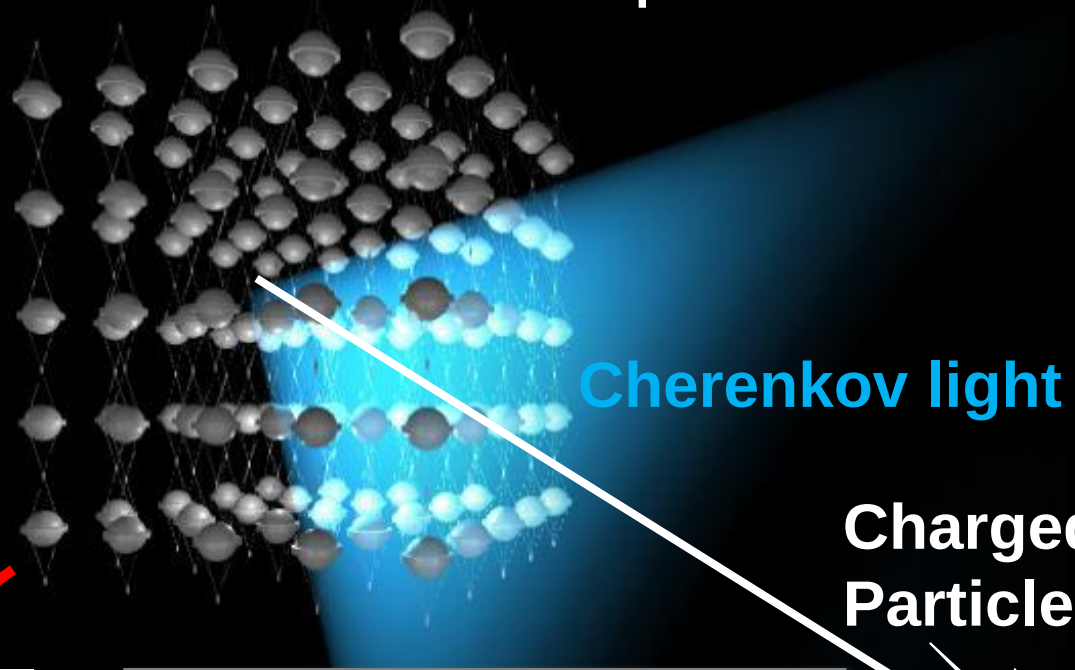
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science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

IceCube South Pole Neutrino Observatory
icecube.wisc.edu

Detection Principle

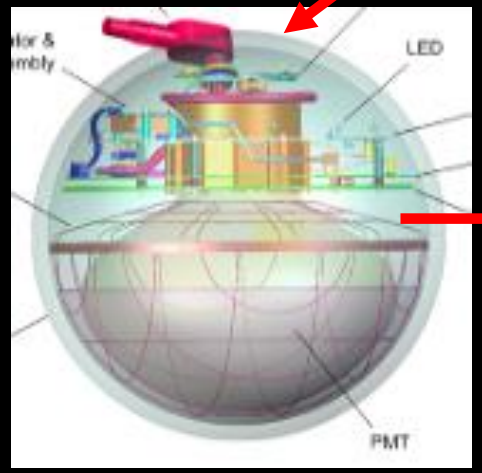
Array of photomultiplier tubes in a dark transparent material

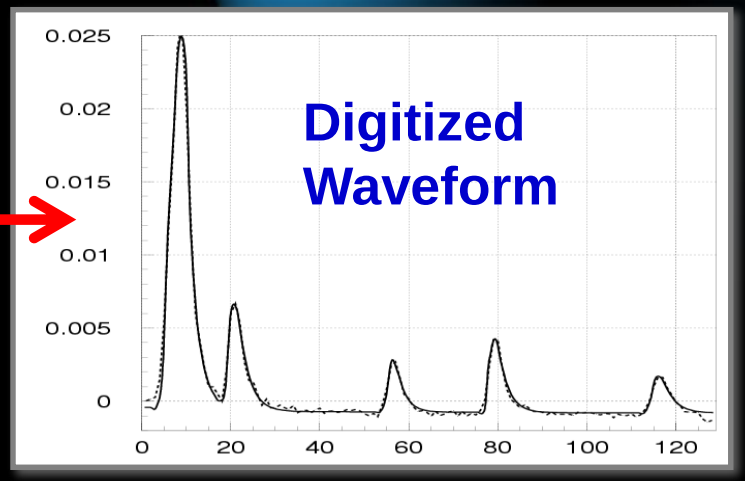


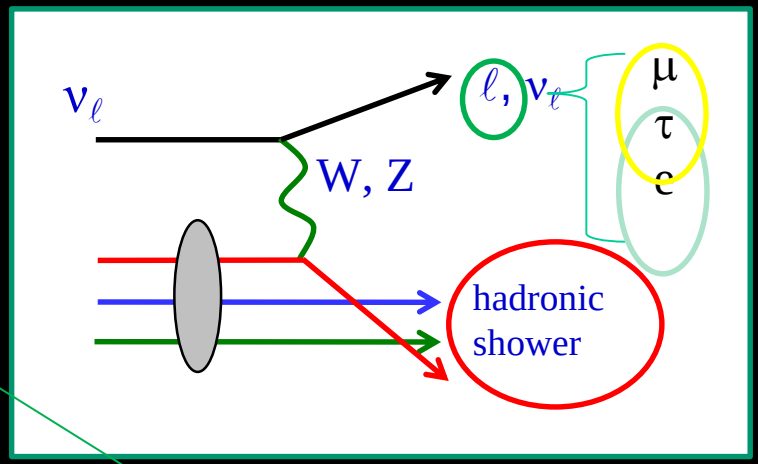


Cherenkov light

Charged Particles

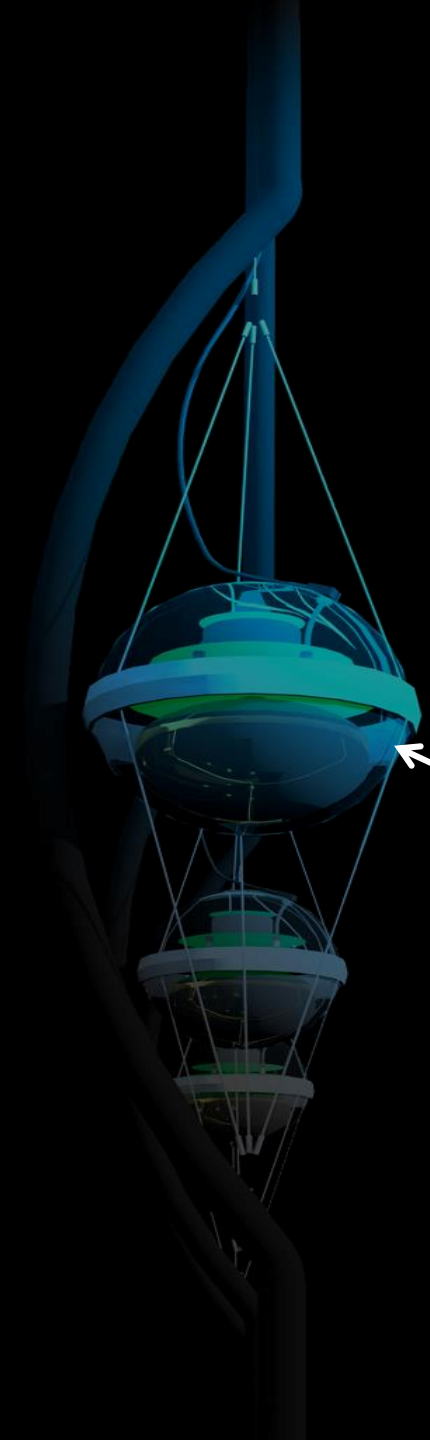


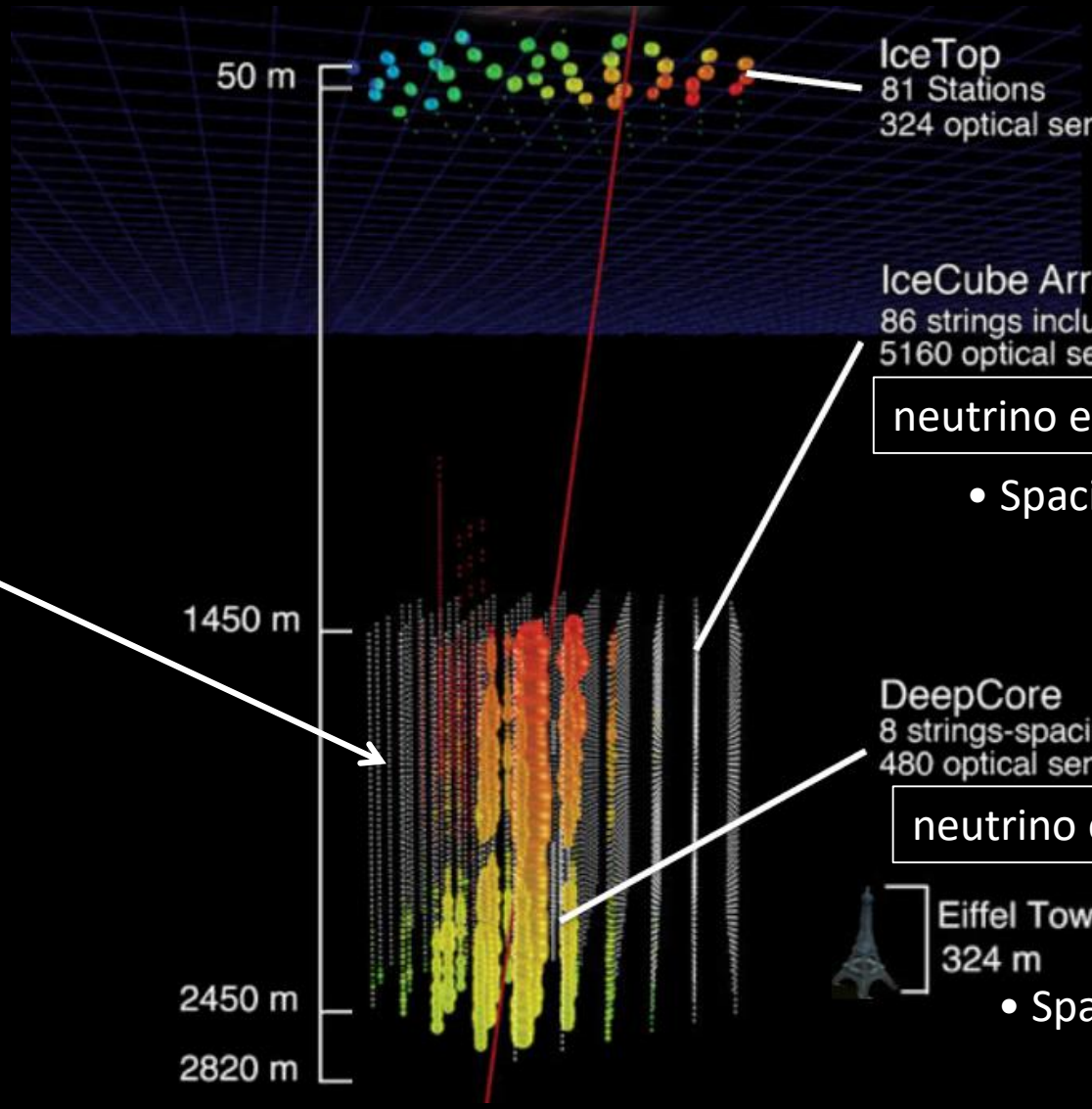




ν

The IceCube Detector





IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

neutrino energy: 1TeV-100EeV

- Spacing: Strings 125 m, DOMs 17 m

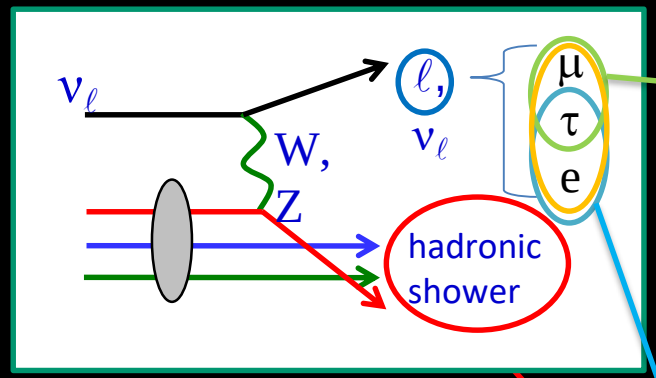
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

neutrino energy: 5GeV-100GeV

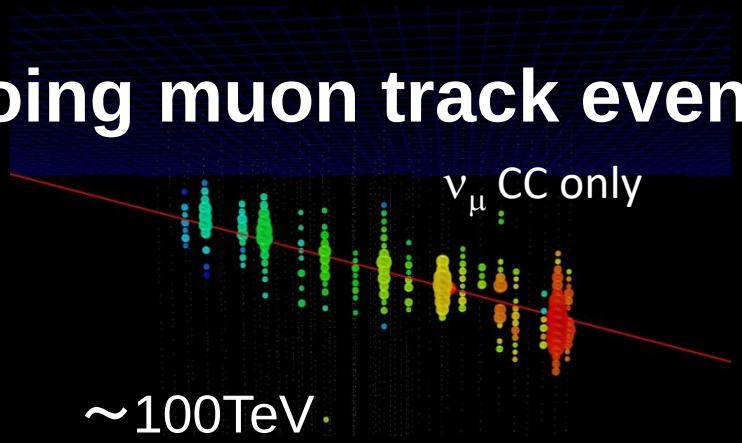
Eiffel Tower
324 m

- Spacing: Strings ~70 m, DOMs 7 m

IceCube Flavor Identifications

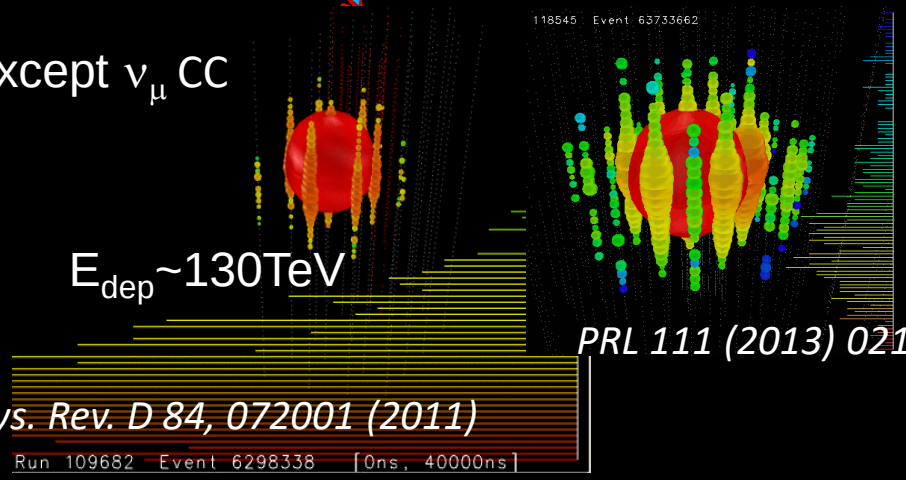


Up-going muon track event



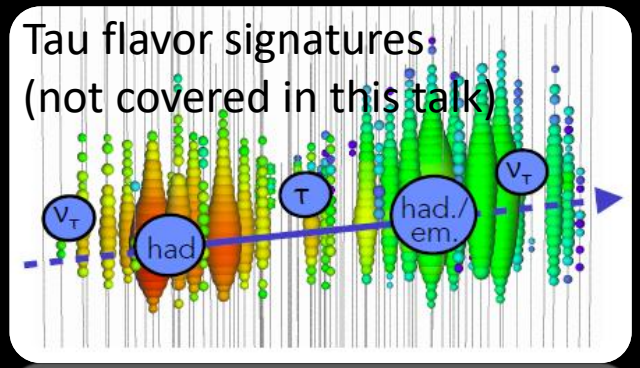
Cascade events

All except ν_μ CC



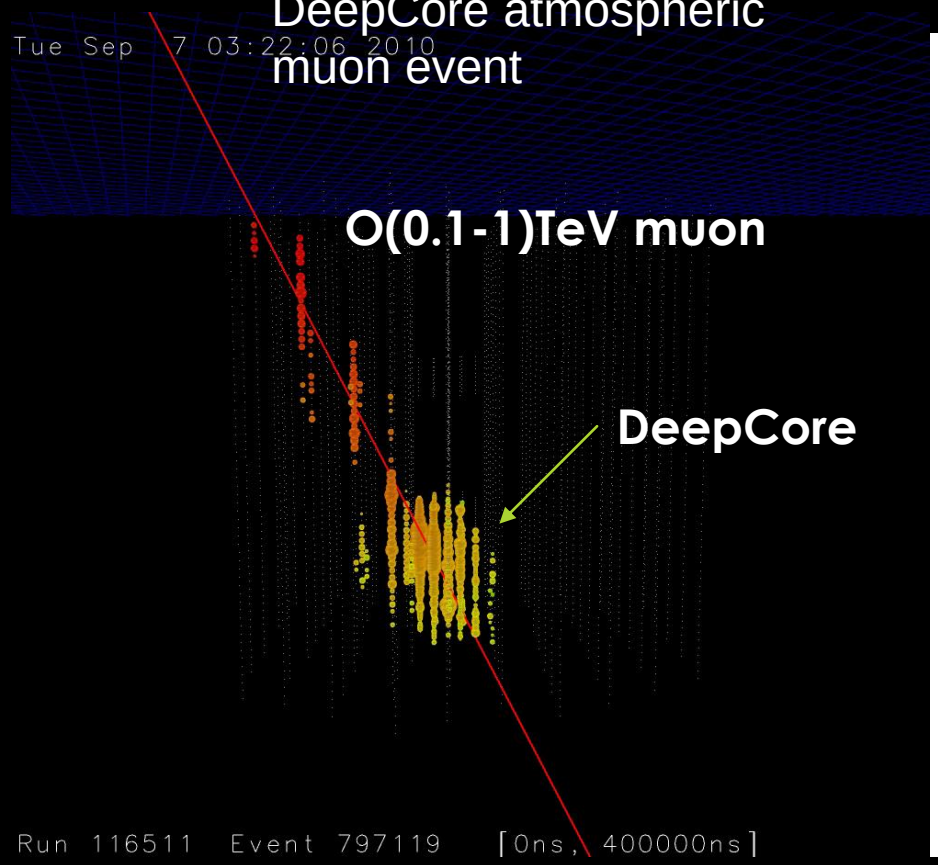
PRL 111 (2013) 021103

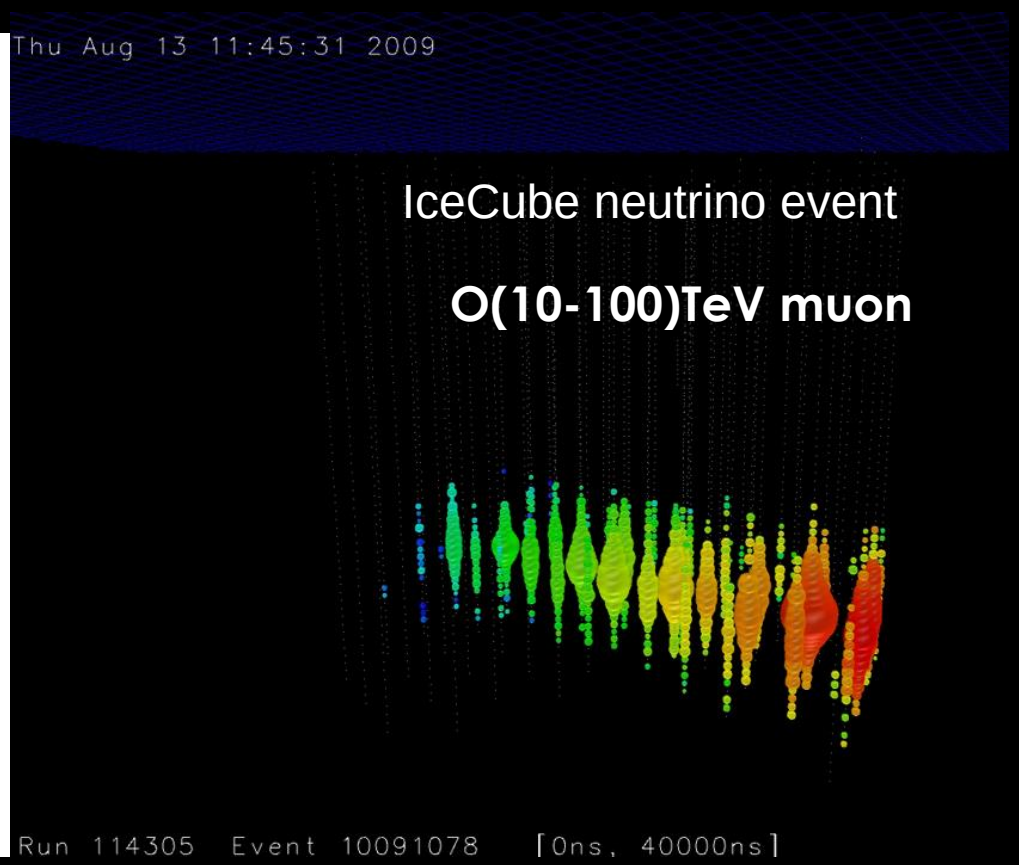
Phys. Rev. D 84, 072001 (2011)



Energy Range for IceCube/DeepCore

Icecube can measure 10GeV – 10^{11}GeV neutrinos !

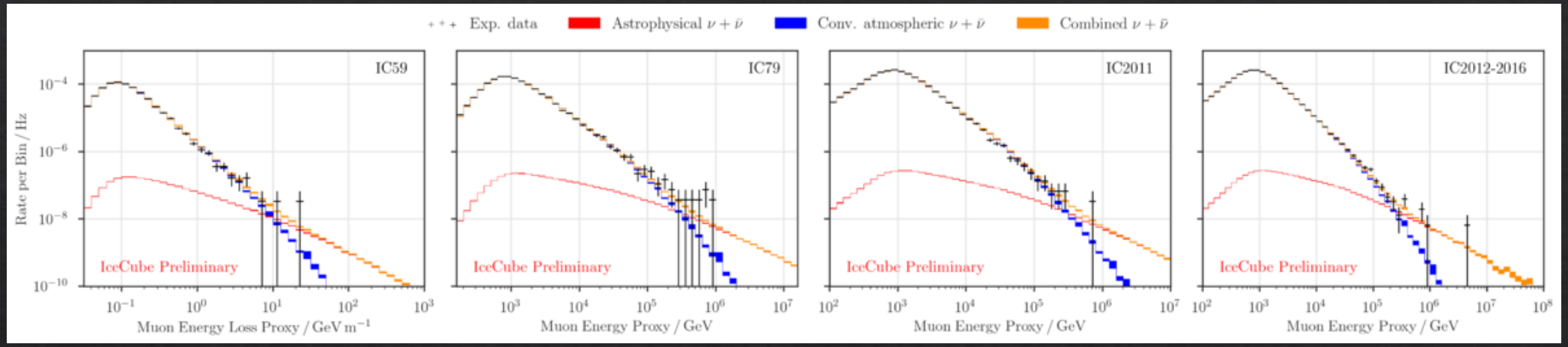




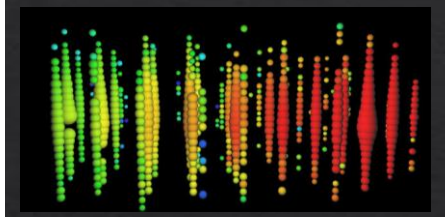
Astrophysical Diffuse Neutrino Flux

Upward going muon* neutrino sample (8 years/2009-2016)

*Select muon induced by muon neutrino CC interactions



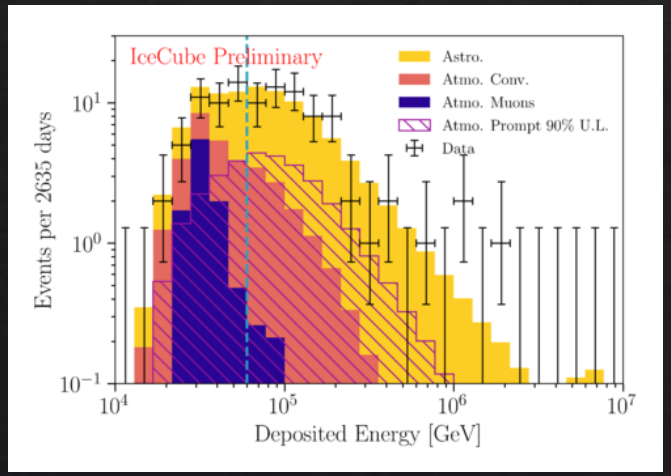
~880TeV upward through-going muon track event

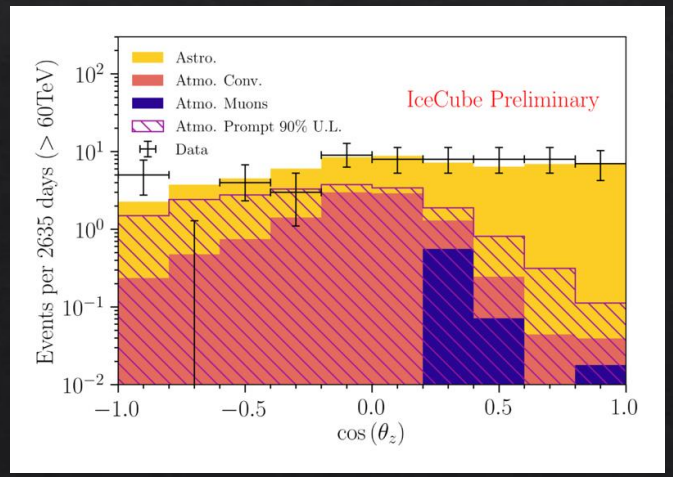


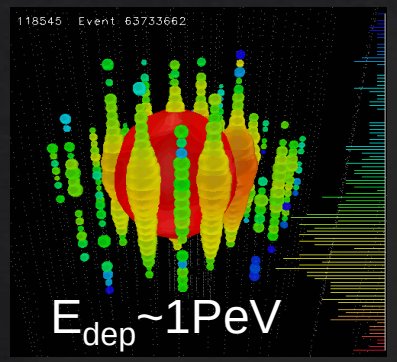
Phys. Rev. Lett. 115, 081102 (2015)

High energy starting event** neutrino sample (7.5 years/2010-2017)

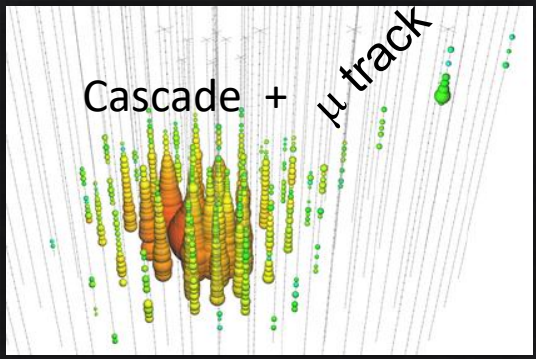
**Select neutrino events with outer layer detector as muon veto







PRL 111 (2013) 021103

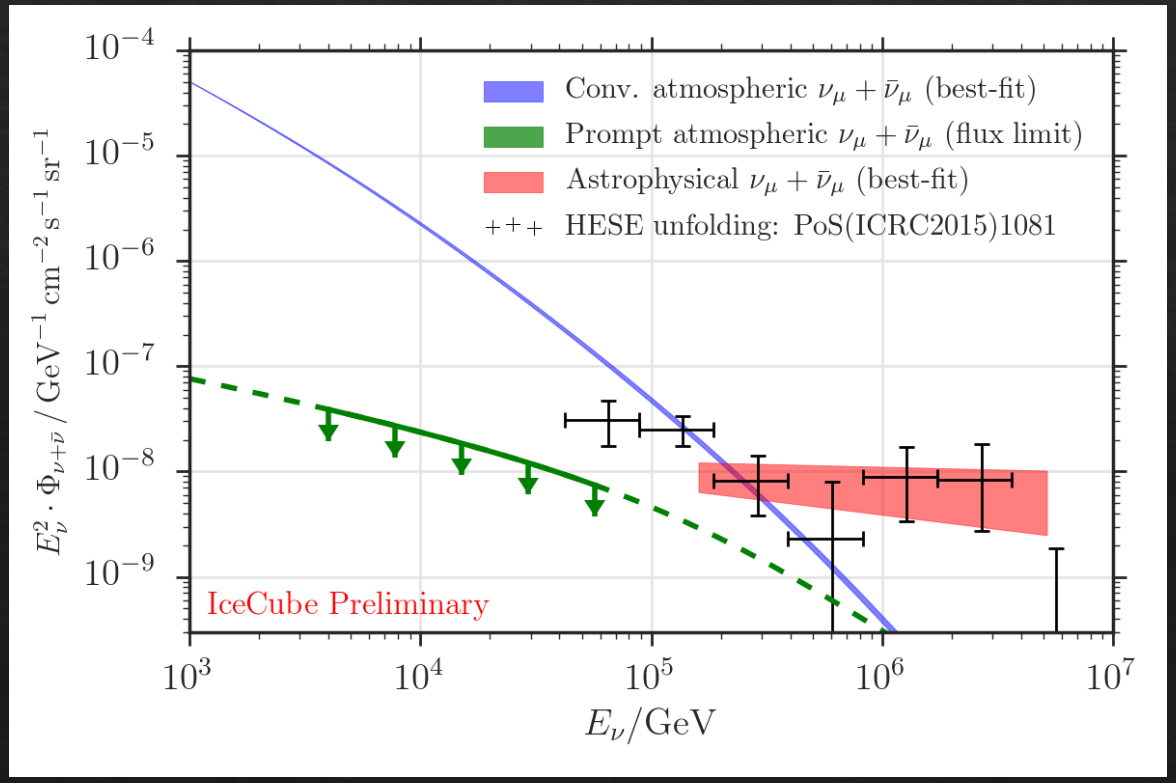


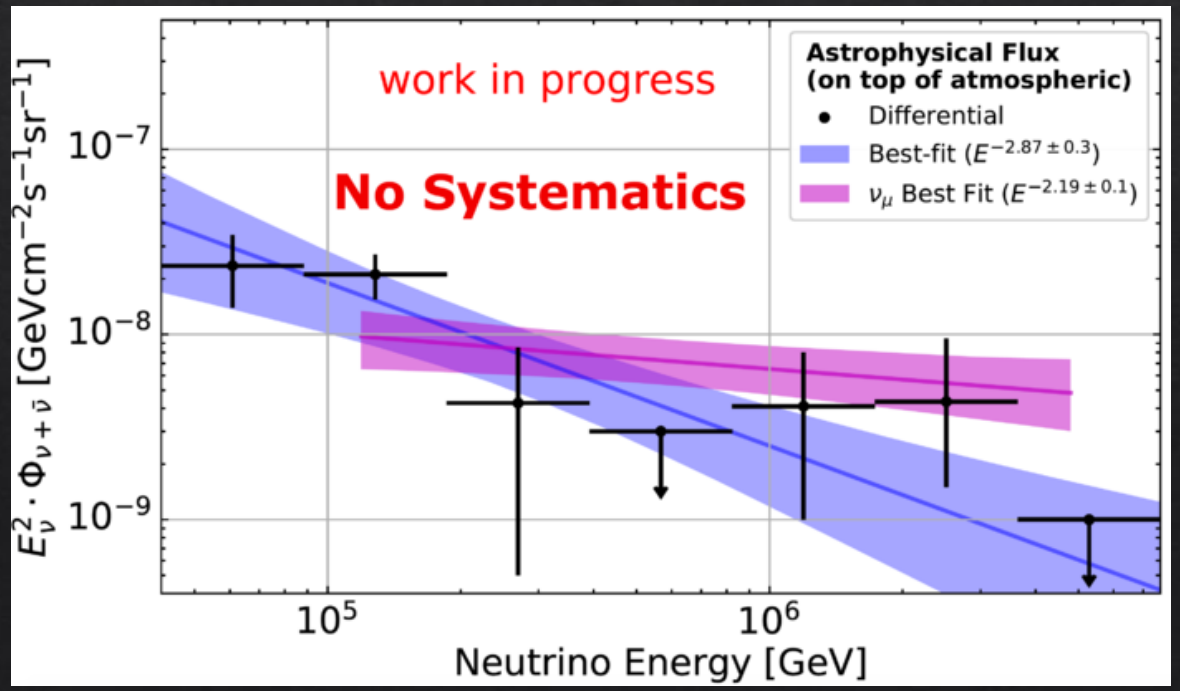
PRL 113, 101101 (2014)

Best Fit Estimate with Independent Samples

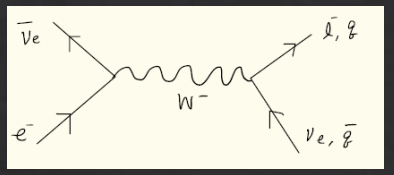
Best single power-law fit results $\Phi_{\text{astro}} = \Phi_0 \left(\frac{E}{E_0} \right)^{-\gamma}$

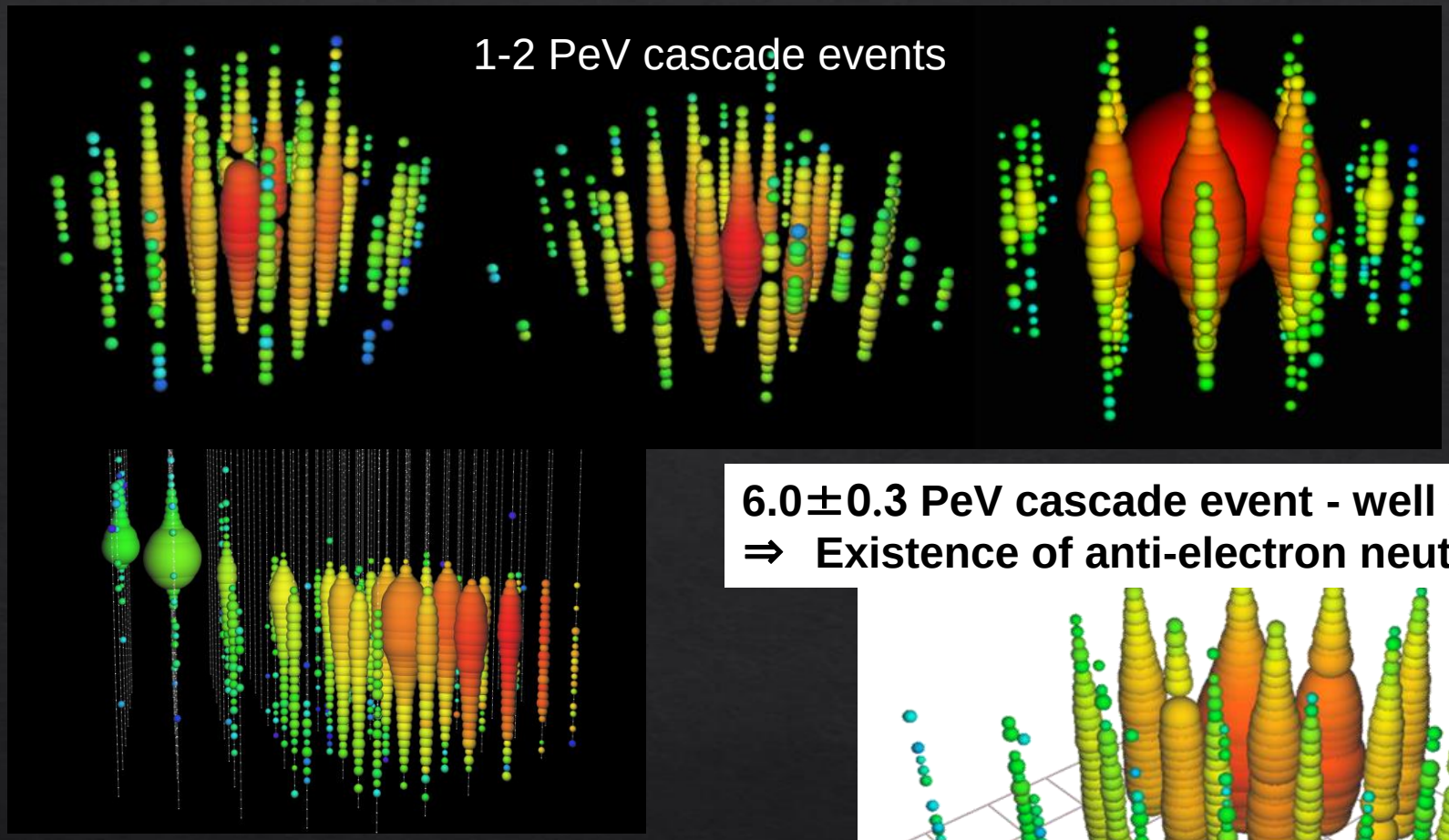
- Good agreements of independent astrophysical neutrino samples above 200TeV
- Detailed consistency studies on <200TeV still on going

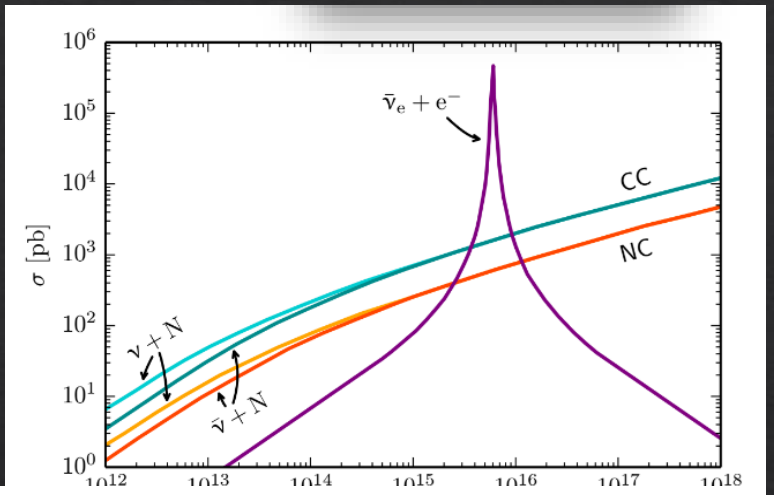




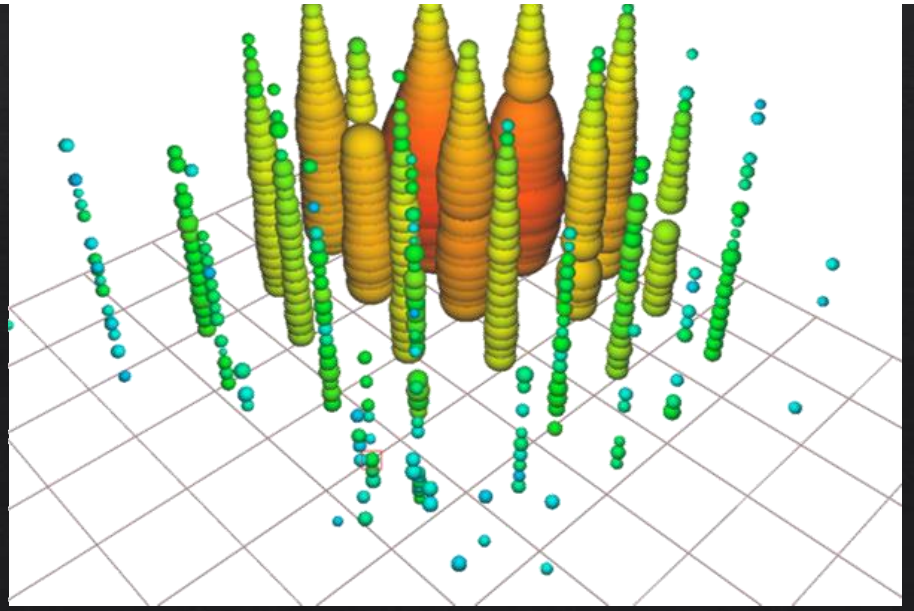
Our Energy Front: PeV energies



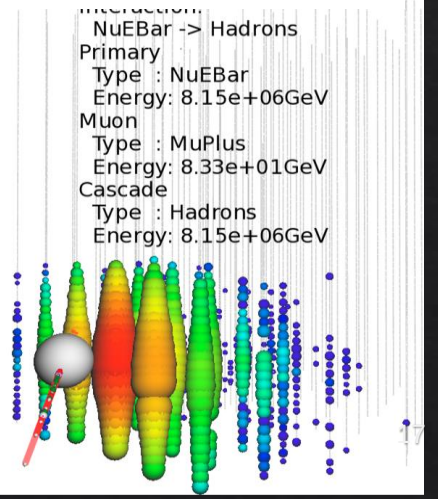




6.0±0.3 PeV cascade event - well compatible with Glashow resonance!
⇒ Existence of anti-electron neutrino



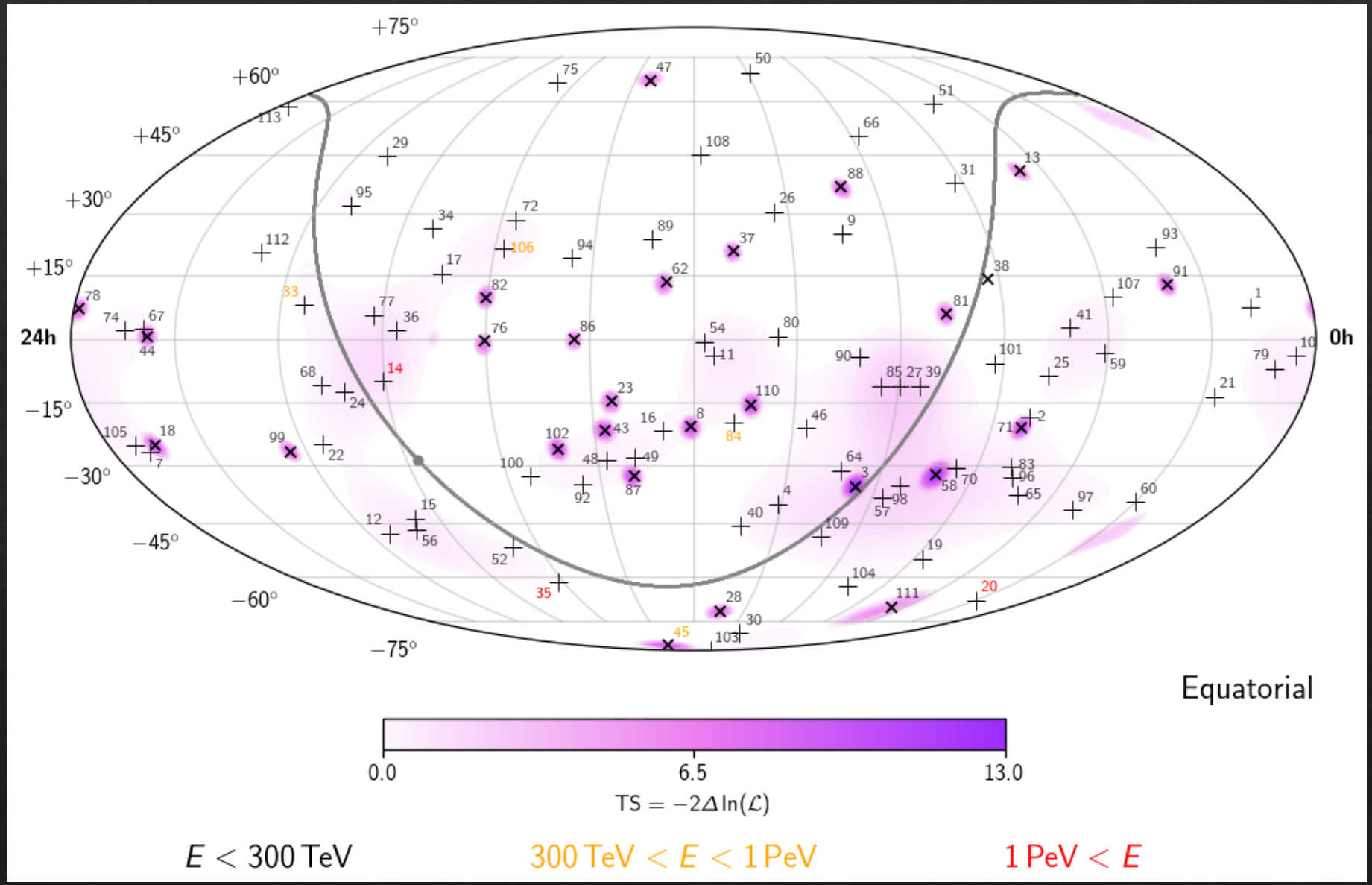
Simulated GR event



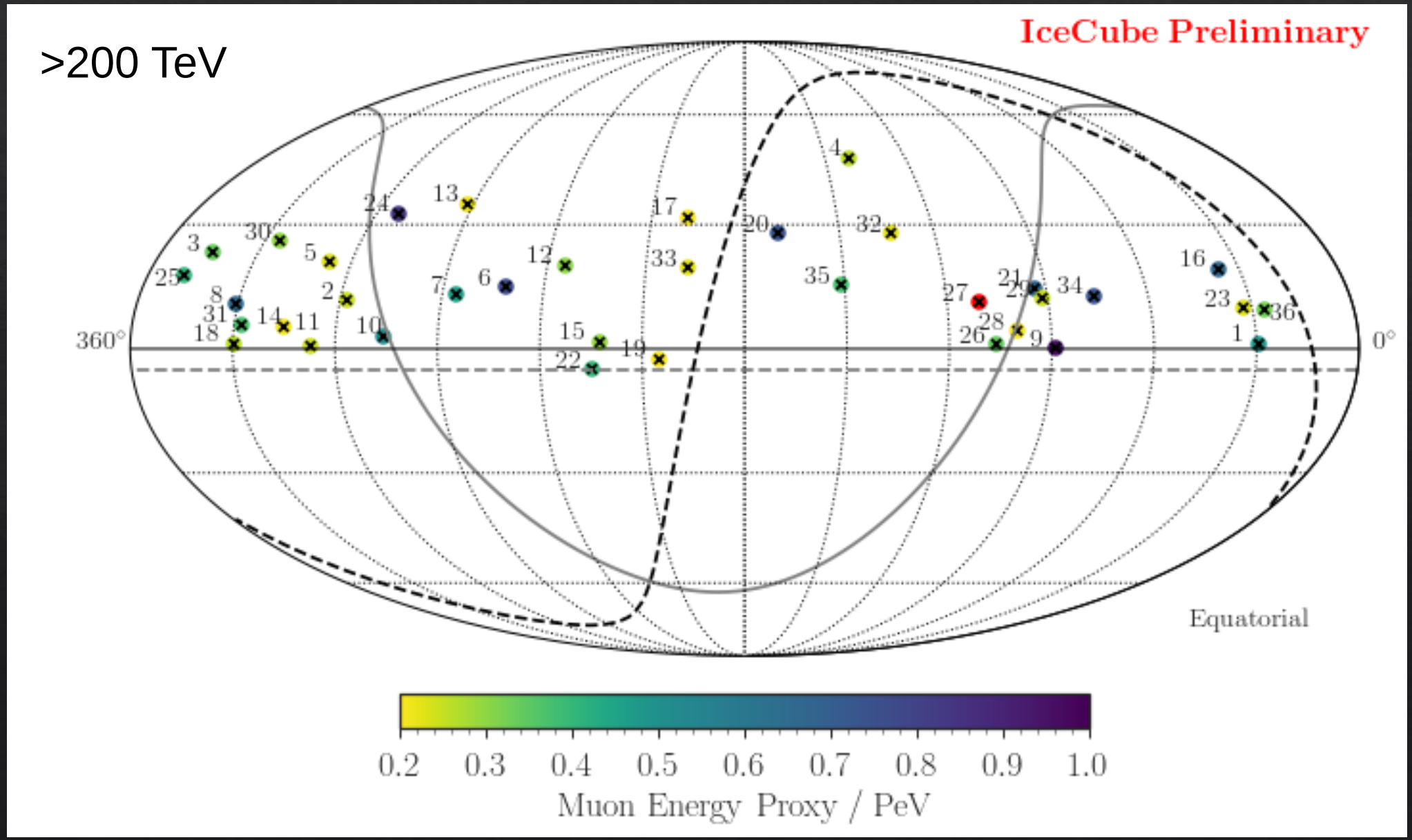
Highest energy event to date,
an upward-going track.

- Deposited energy 2.6±0.3 PeV
- Median neutrino energy 8.7 PeV
- Observed photoelectrons 130,000 pe

No clustering observed in starting events



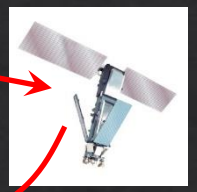
Neither in upward-muon sample



Neutrino Online Alert System

IceCube:
on-site event analysis and alert system has been in operation

Iridium satellites



Before 2016 April, private alert system existed. BUT background dominant

April 2016: Activated public online channel with signal efficiency of >30-50% (EHE and HESE channels)

ν

high energy ν

Flare and exposure in the universe

photon and GW

Alert!

Latency time: a few tens of seconds

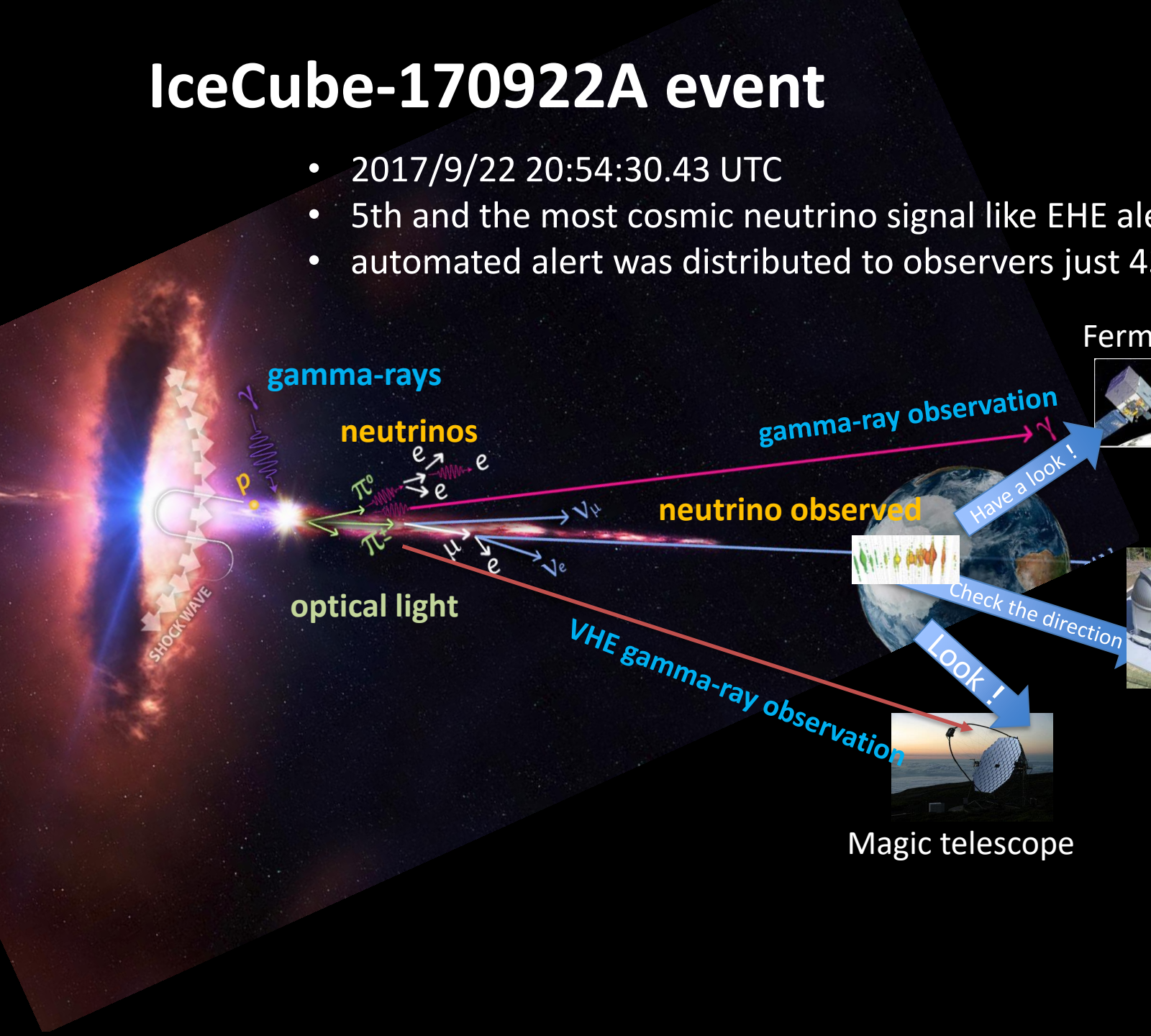
"The IceCube realtime alert system", Astroparticle Physics, 92, 30–41,(2017)

Telescopes over the world!
(Good opportunities for telescopes of all sizes everywhere)

IceCube-170922A event

Science 361 (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

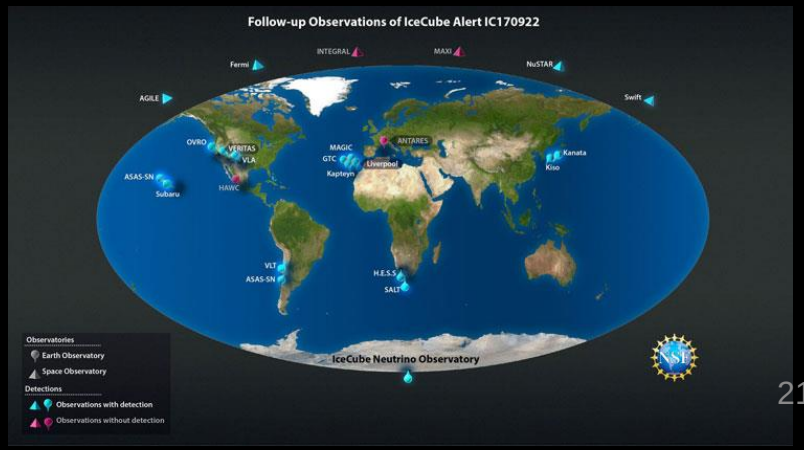


Fermi Telescope

Optical telescopes

Kanata telescope

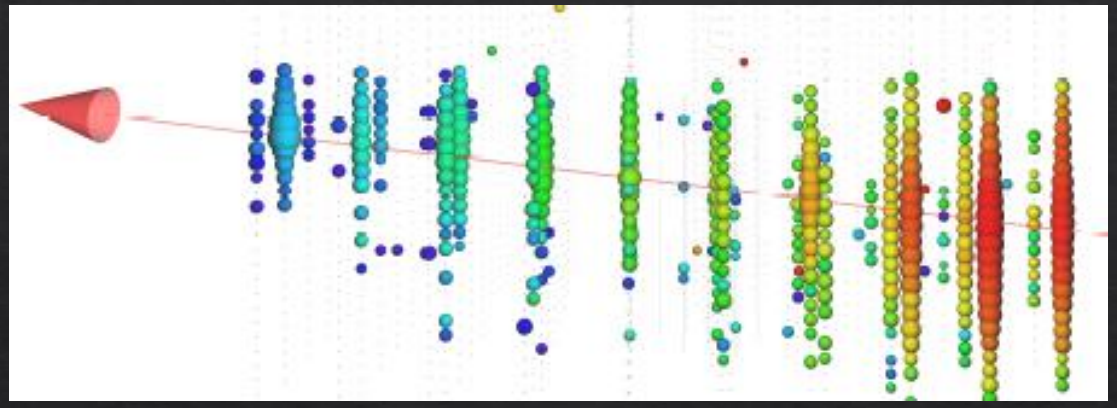
...and many more telescope



Magic telescope

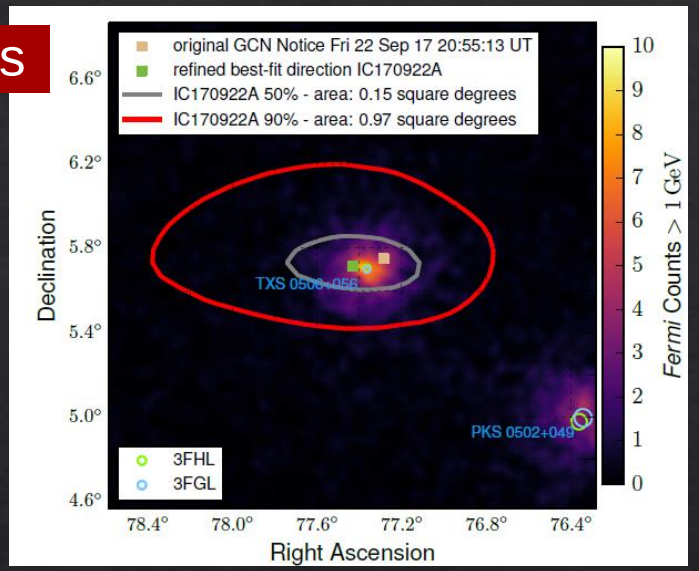
IceCube-170922A Follow up

23.7 ± 2.8 TeV muon energy loss in the detector

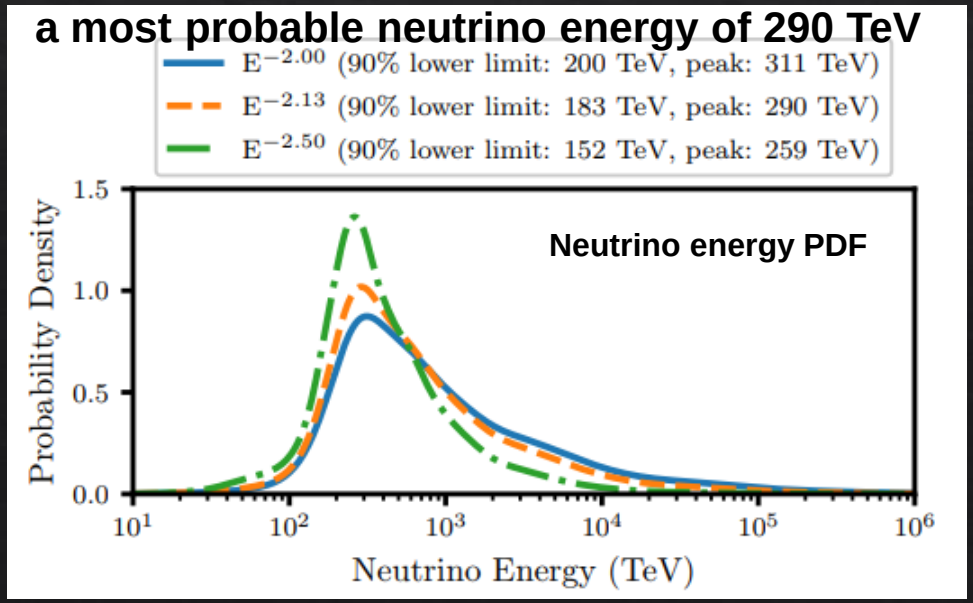


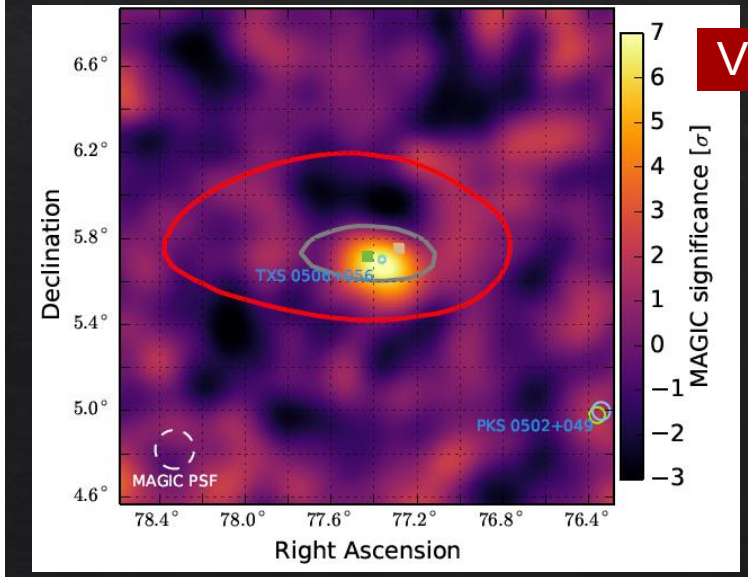
HE gamma-ray observations

- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flaring blazer TXS 0506+056 (ATel#10791)



a most probable neutrino energy of 290 TeV

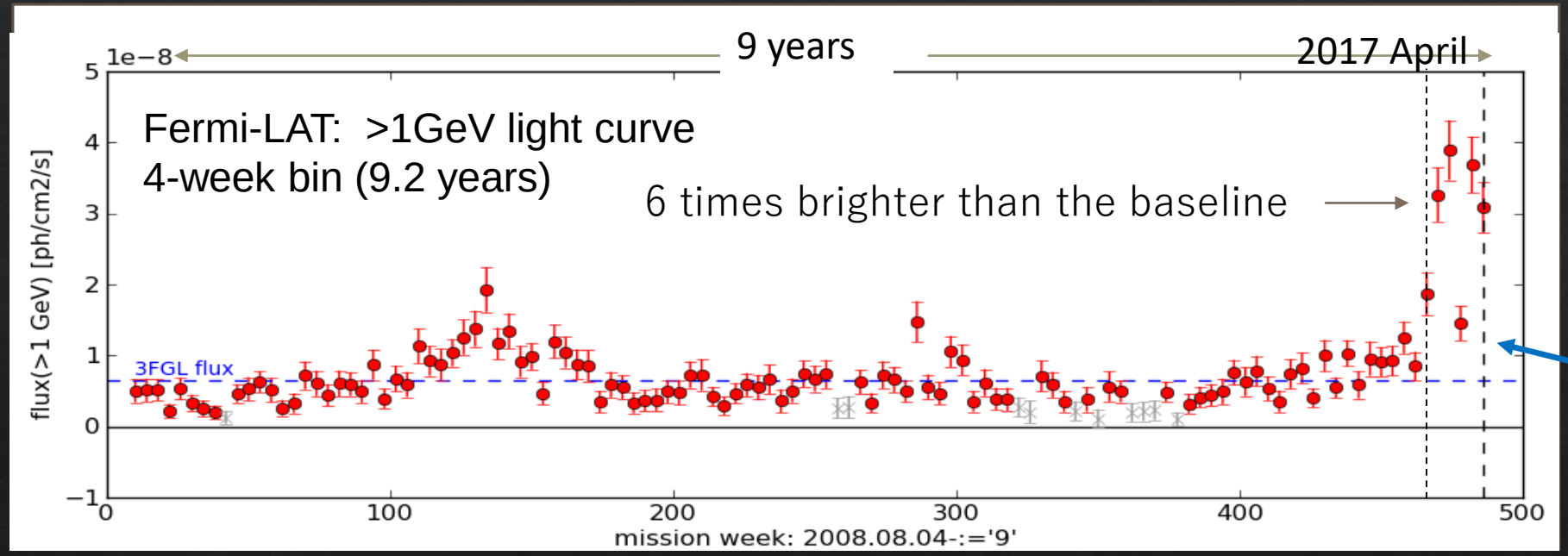




VHE gamma-ray observations

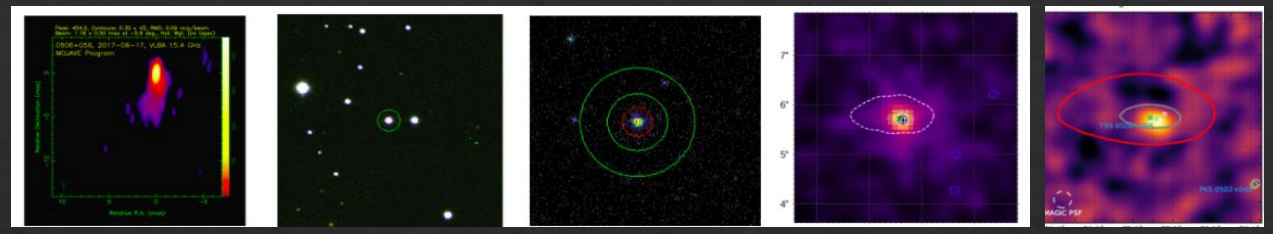
- Furthermore TXS 0506+056 was observed VHE gamma-ray Magic telescope (E > 100GeV) with >6.2σ (ATel#10817)

Light Curve

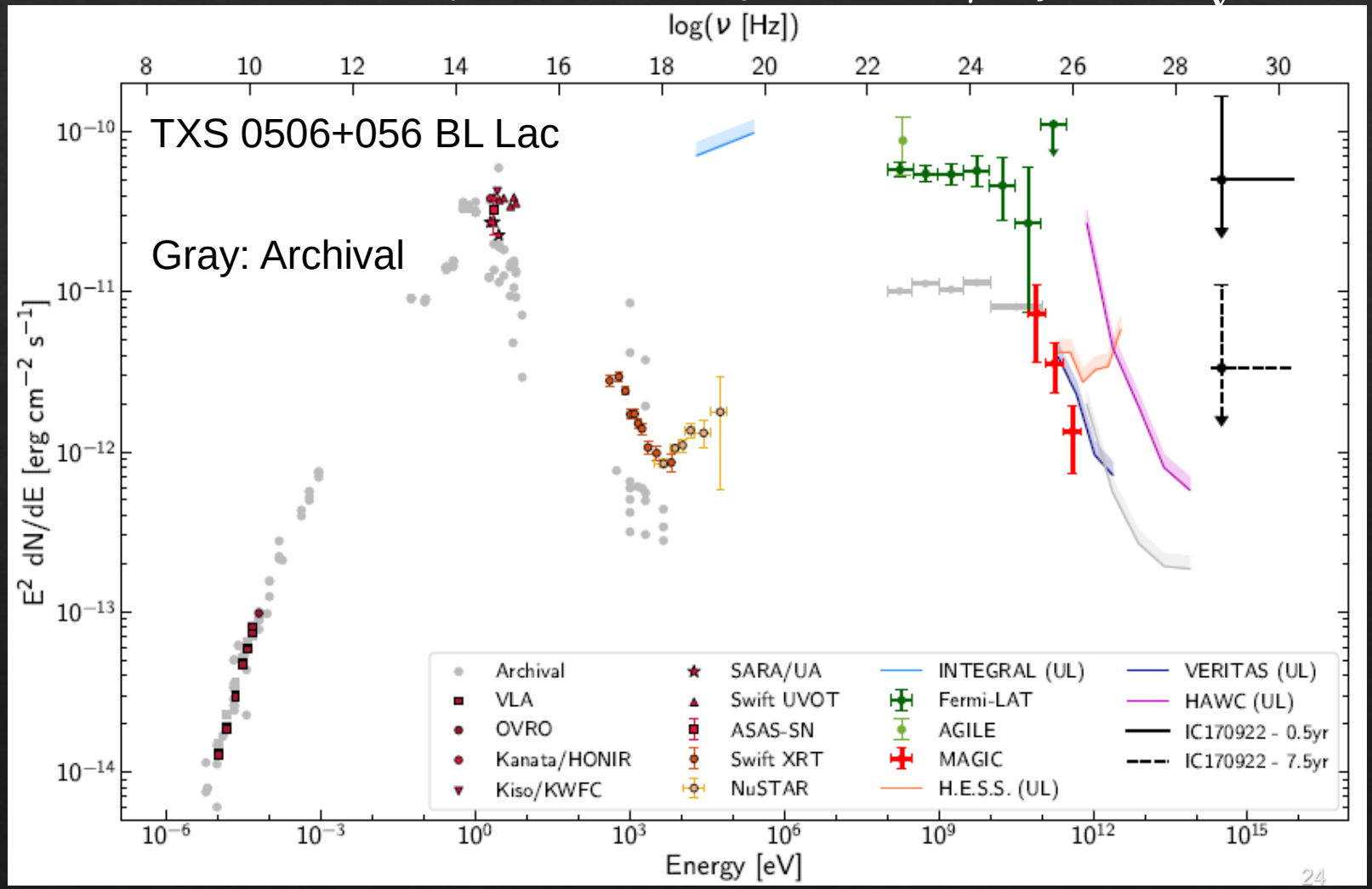

9 years
2017 April
1e−8
Fermi-LAT: >1GeV light curve
4-week bin (9.2 years)
6 times brighter than the baseline
3FGL flux
flux(>1 GeV) [ph/cm2/s]
mission week: 2008.08.04-:='9'
IceCube 170922A

A successful Multiwavelength Campaign with ν!

- Double-bump feature – typical to AGN
- Neutrino flux upper limits to produce 1 detection
  - 1.8×10^{-10} erg cm^{-2} s^{-1} over 0.5yr
  - 1.2×10^{-11} erg cm^{-2} s^{-1} over 7.5yr
- (Paiano et al. 2018) the 10.4m Gran Telescopio Canarias, an optical spectroscopy ⇒ z = 0.3365 +/- 0.0010
- γ-luminosity between 100MeV and 100GeV
  - ~1.7×10^{47} erg s^{-1} at high state
  - ~3.7×10^{46} erg s^{-1} at all time average



radio optical x-ray γ-ray ν



ν-γ Correlation Analysis

- $L = \prod_i^N \left(\frac{n_s}{N} P_S + \frac{n_b}{N} P_B\right) \rightarrow TS(N=1) \propto \log \frac{P_S}{P_B}$

◈ $P_S = P_{spatial}(\vec{x}) \cdot W_{acceptance}(\sin\theta) \cdot W_{temporal}(t)$

2D Gaussian from ν ang resol. | θ-dependent acceptance | from light curve

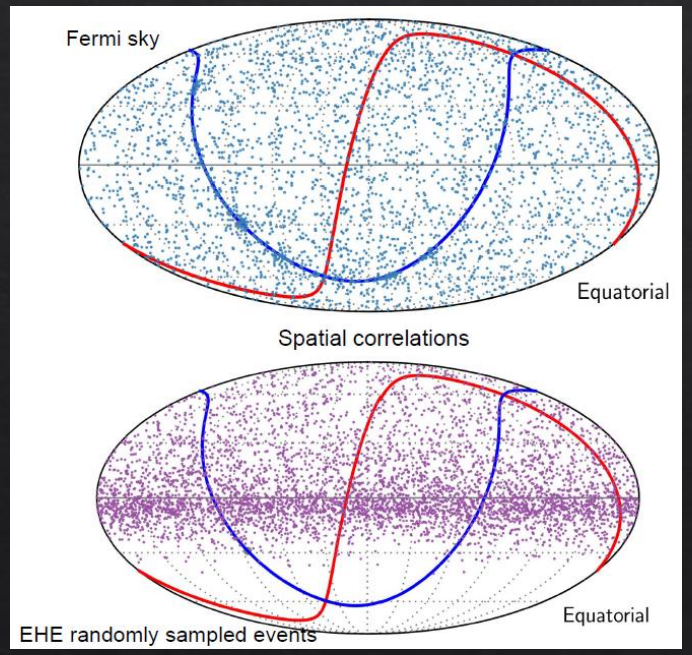
$$P_{spatial} = \frac{1}{2\pi\sigma^2} e^{-(\overrightarrow{x_{TXS}} - \vec{x})^2 / (2\sigma^2)}$$

① flux variability

$$W_{temporal} \propto \frac{I_\gamma(t)}{< I_\gamma(t) >}$$

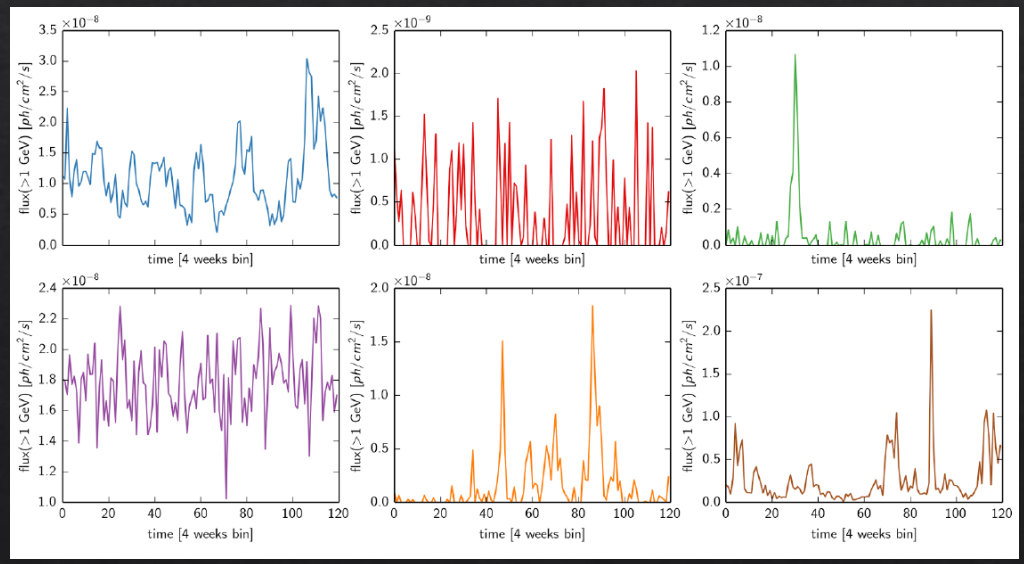
② energy flux

$$W_{temporal} \propto \int_{1GeV}^{100GeV} E_\gamma \frac{dI_\gamma(t)}{dE_\gamma} dE_\gamma$$



≈95.5% seen no gamma-ray

≈4.4% seen one gamma-ray source



3000 fermi light curves from M. Hayashida

Both cases: no correlation vs correlation → 4.1σ → Corrections for all 10 alerts issued previously and the 41 archival events → **≈3σ**

Neutrino only analysis around TXS 0506+56

- $L = \prod_i^N \left(\frac{n_s}{N} P_S + \frac{n_b}{N} P_B \right)$

◈ $P_S = \underline{P_{spatial}(\vec{x})} \cdot \underline{\mathbf{W}_{acceptance}(\sin\theta)} \cdot \underline{W_{temporal}(t)}$

2D Gaussian from n ang resol.

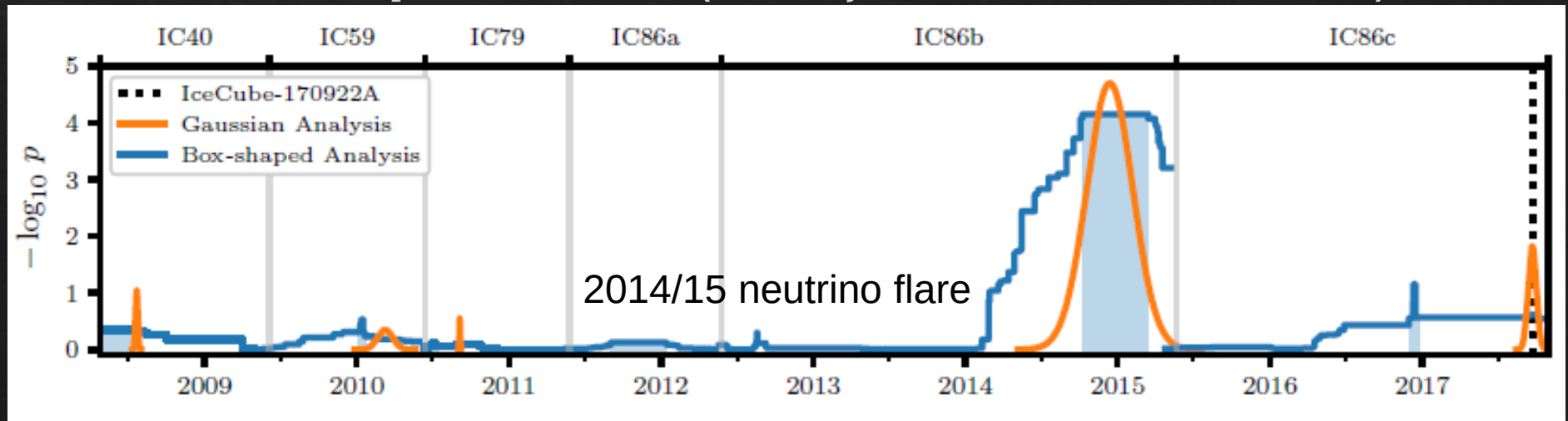
θ-dependent acceptance x power-law signal flux

parameters: spectral index and normalization

square and Gaussian parameters: center time and time window

$$P_{spatial} = \frac{1}{2\pi\sigma^2} e^{-(\vec{x_{TXS}} - \vec{x})^2 / (2\sigma^2)}$$

Signal(n_s, γ, T_0, T_W)+BG vs BG only
Best fit $(n_s = 13.3, \gamma = 2.1, T_0, =$ 2014 Dec 13, $T_W = 110 days)$
$p = 1.0 \times 10^{-4}$, $corresponds\ to\ 3.7\sigma$ $(3.5\sigma\ after\ livetime\ correction)$



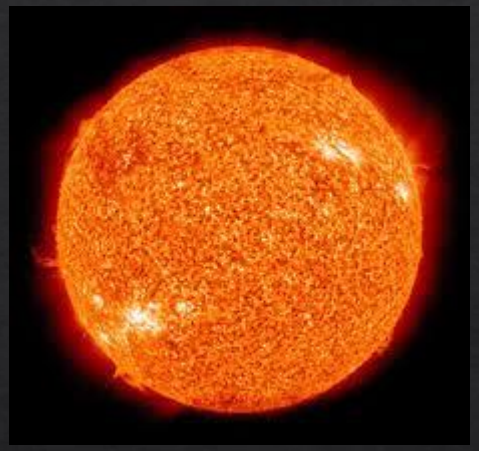
Objects Shining with Neutrinos (so Far)

Earth

typical geo-neutrino energy <4MeV

Distance to the object 0 light years

Sun



typical neutrino energy <20MeV

Distance to the object 0.00001581 light years (149,600,000km)

supernova

typical neutrino energy <100MeV

Distance to the object 160,000 light years

active galactic nuclei (blazar)

likely neutrino energy >100,000,000MeV

Distance to the object 4,000,000,000 light years

Distance from the Earth to Galactic center
28,000 light years

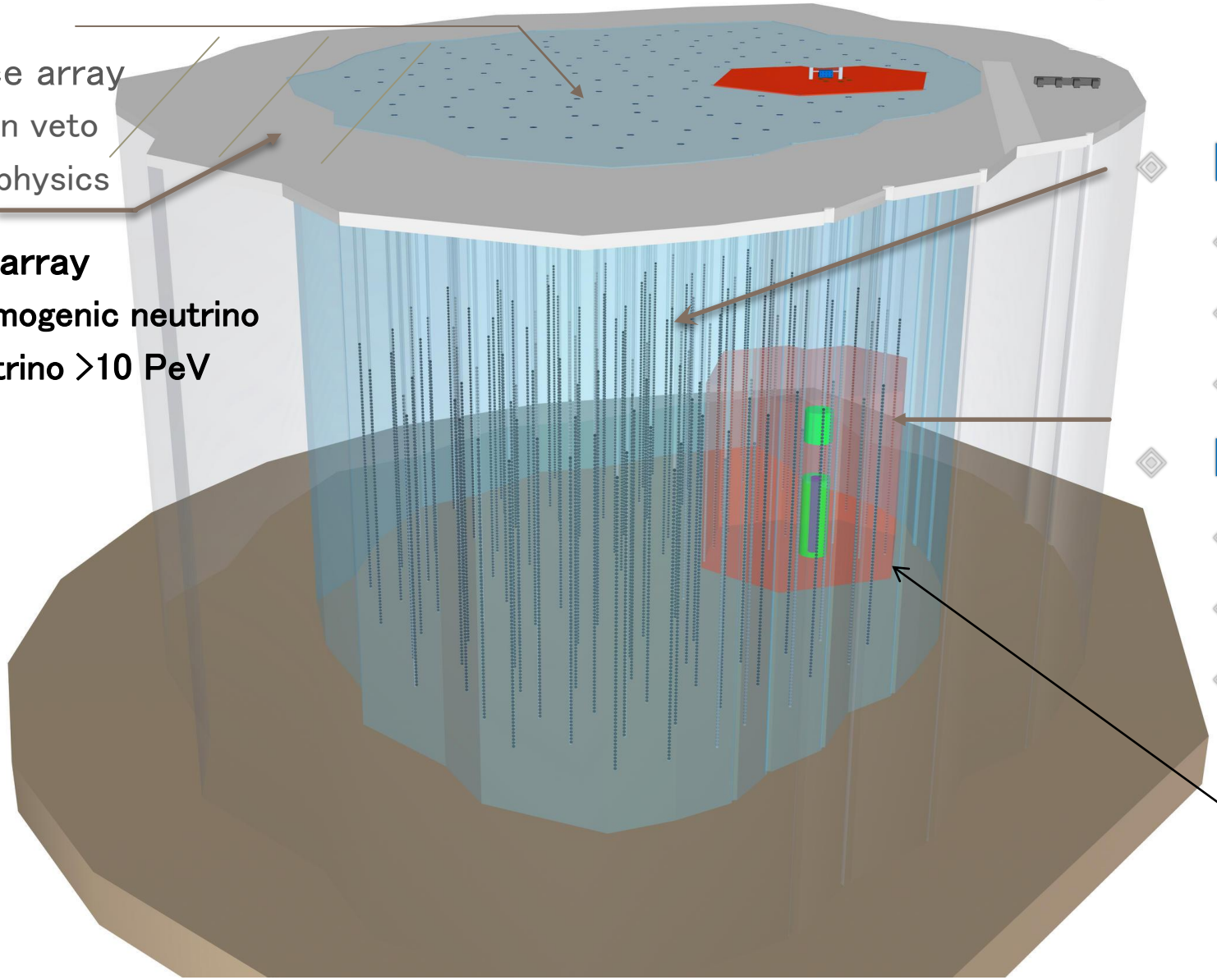
However, Fermi blazer contribution to IceCube diffuse flux is <10%

- What's the other sources?
- What make TXS050-056 special?

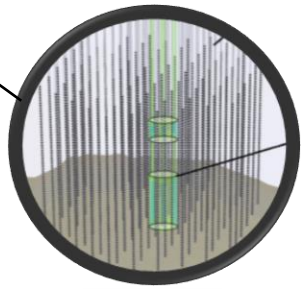
Natural to have observational bias to find from brighter objects

IceCube-Gen2 Facility

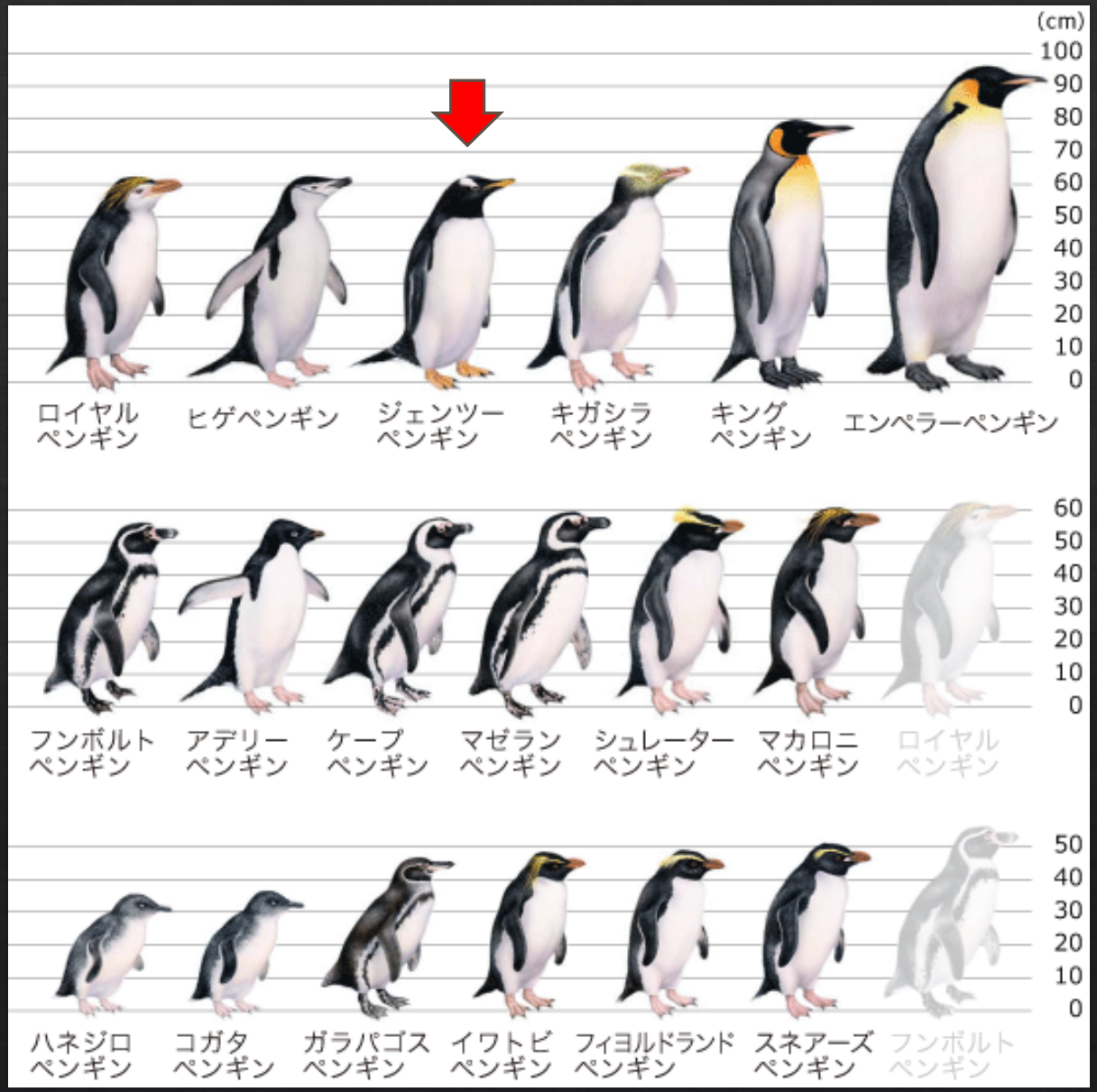
- Surface array
  - muon veto
  - CR physics
- **Radio array**
  - **cosmogenic neutrino**
  - **neutrino >10 PeV**



- **Main array**
  - **≈100 strings**
  - **≈100 sensors/string**
  - **≈240m distance**
- **Dense array**
  - **26 strings**
  - **125-192 sensors/string**
  - **≈25m distance**



Know your Penguin

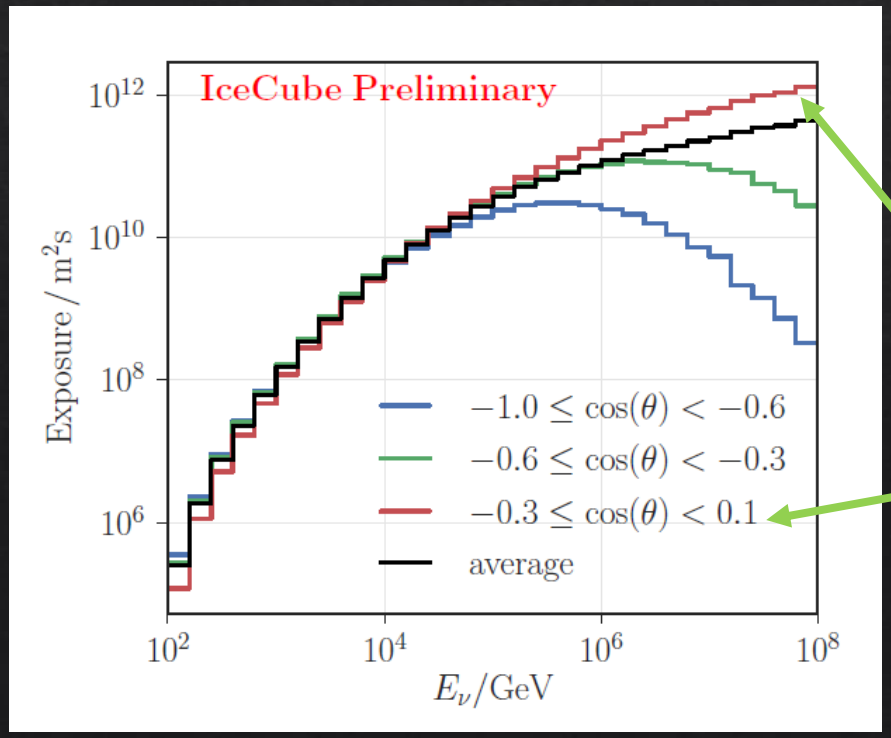


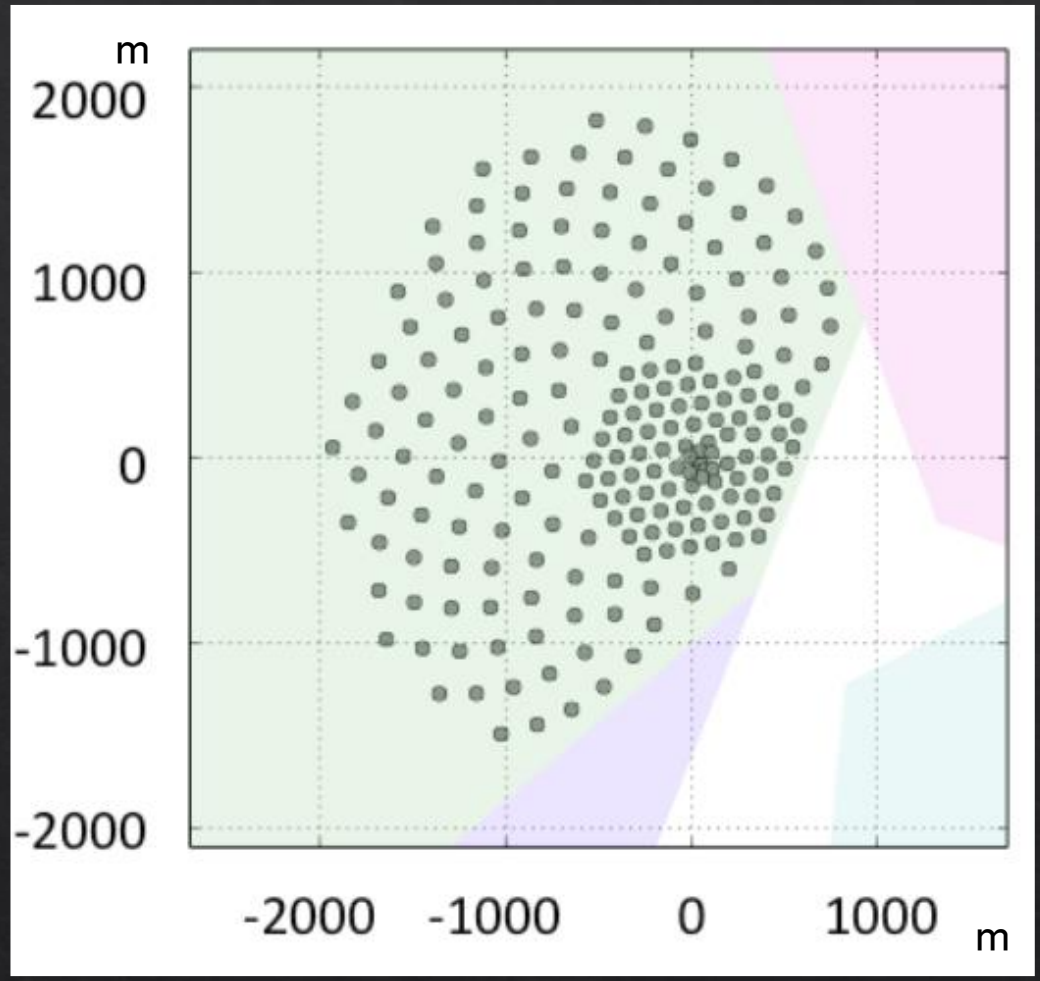
IceCube to Gen2: Point source sensitivity

- ∝sqrt(x): Livetime, Detector size
- ∝x: Angular resolution

} default factor taken into account

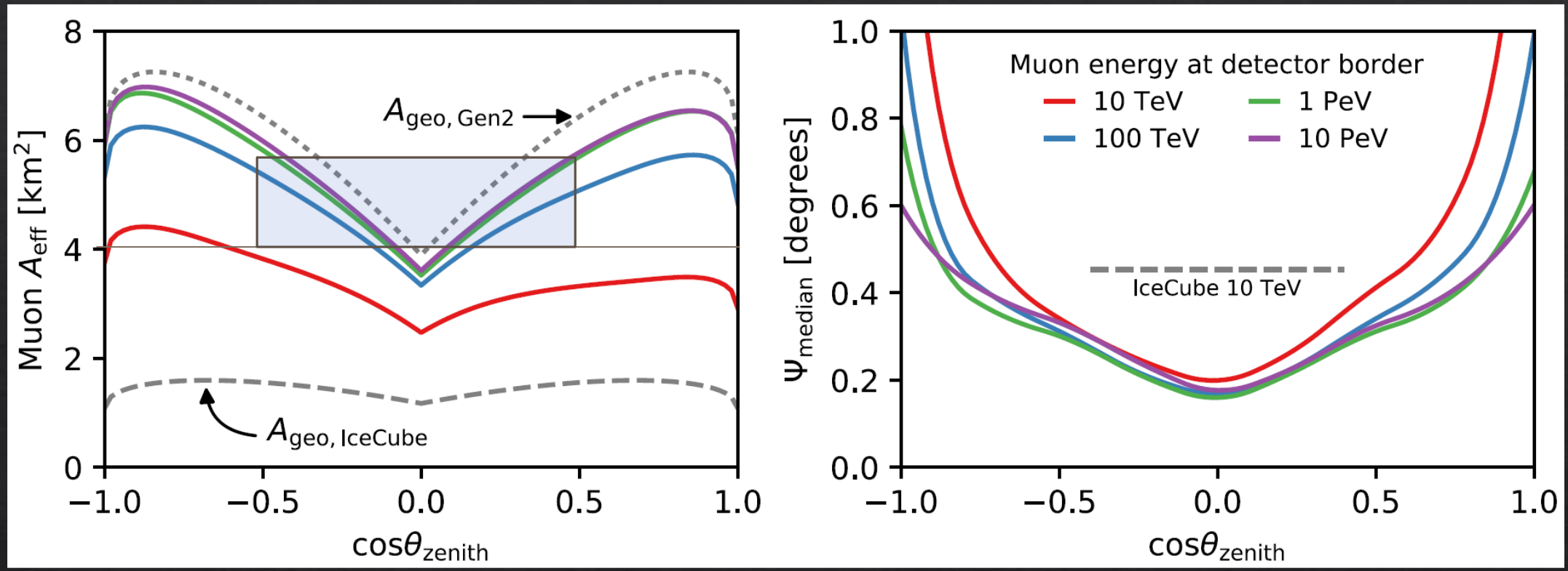
- Signal selection efficiency
- BG rejection efficiency





slightly downgoing horizontal direction is important for >100TeV neutrinos

Gen2 Baseline performance with IceCube DOM

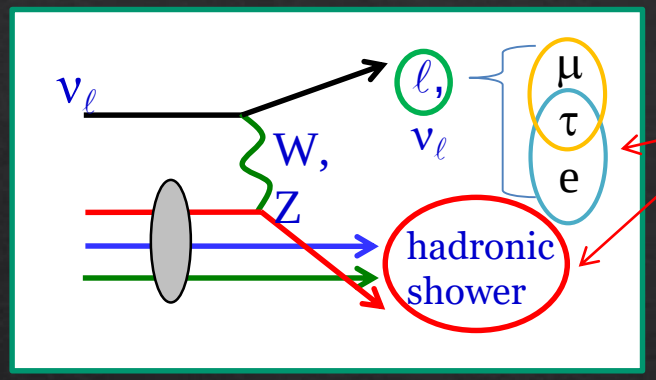


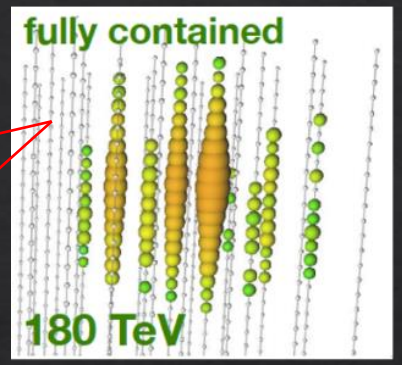
- Detector effective muon area — x 4〜5 (horizontal)
- angular resolution — x ～ 0.45 (horizontal)

} default factor gives a factor of 5 better sensitivity

- **Further signal/bg improvements with new optical sensors (*cascade and muon reconstruction quality and BG reduction, detector/ice systematics*) give even better sensitivity**

Prospects with Cascade Events





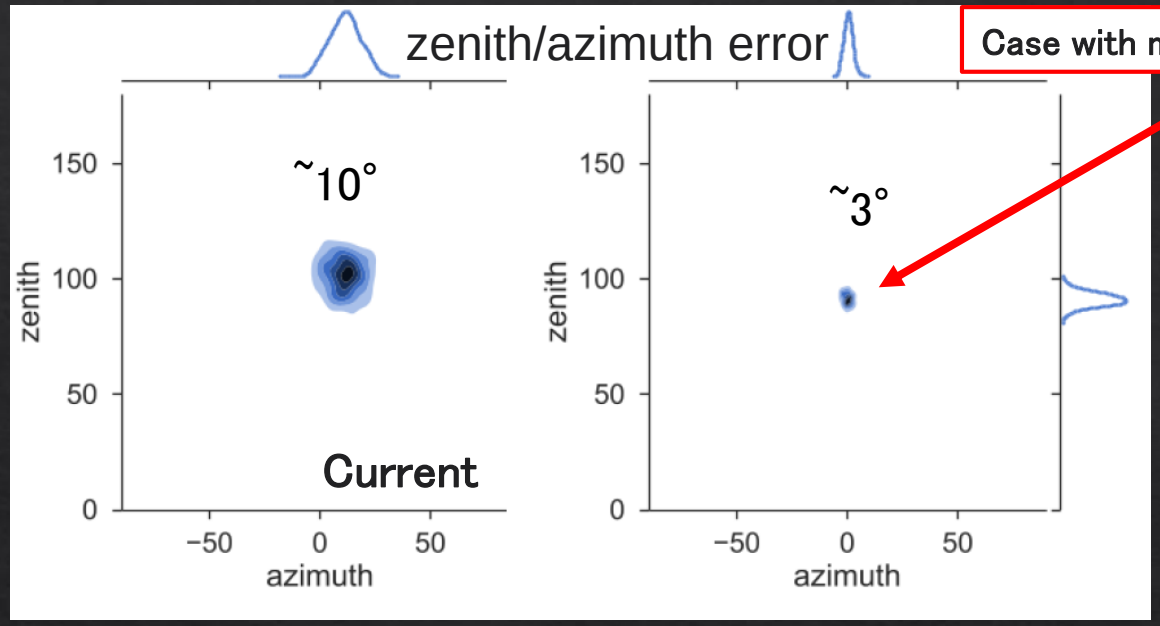
Cascade channel is complementary to upward muon track channel

- Good energy resolution of ~10%
- Directional resolution is ~10° (ice systematic dominant)
- Less atmospheric neutrino background
  - lower energy threshold (10TeV – 100TeV)
- Sensitive to full sky

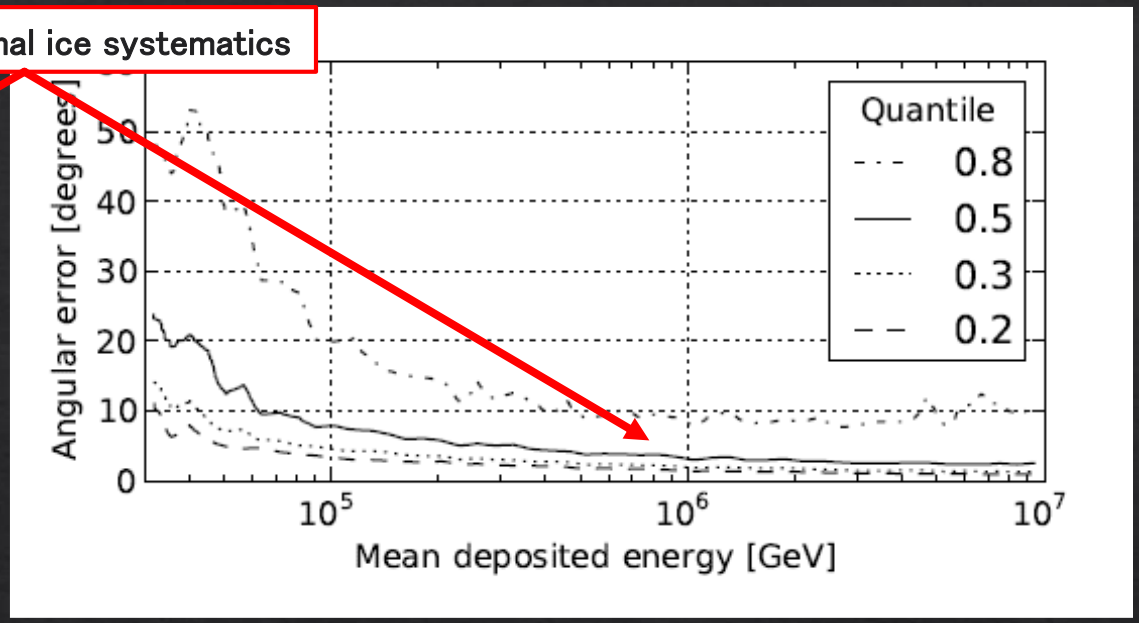
- **Cascade event rates proportional to volume ☞ a factor of 8**
- **Improvements on the reconstruction of cascade *prior to Gen2* construction give us significant benefit**
- **Reduce ice induced systematics with 800 densely (3m) instrumented optical modules**

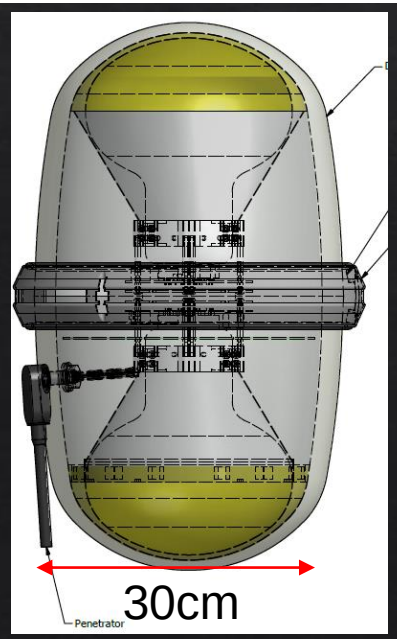
☞ Calibration with Gen2-Phase1

Ice Systematic Challenge with Phase-1

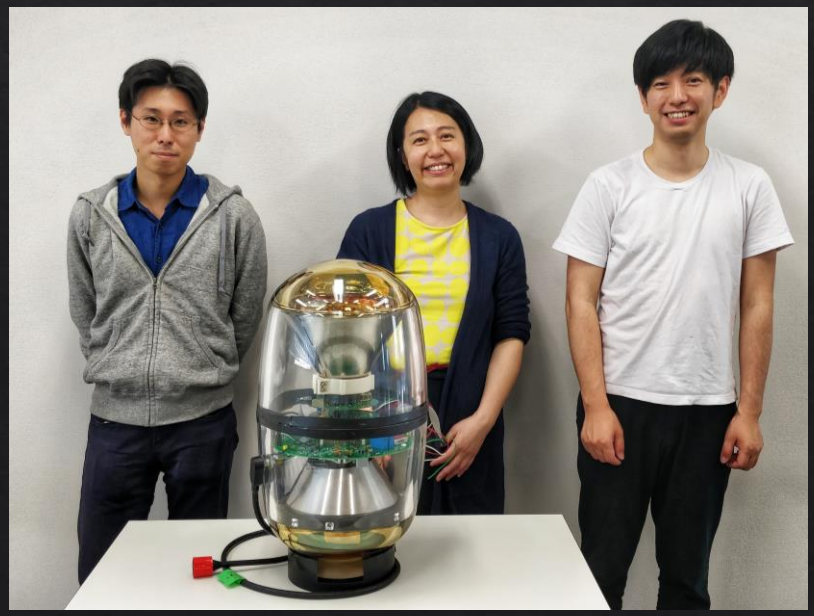


Case with minimal ice systematics





- Chiba IceCube group: Designed new OM “DEgg” with improved sensitivity (x 2 from IceCube optical sensor)
- Responsible for production/calibration of 300 DEgg to be Shipped to South Pole by Sept 2021 (the other 400 oms are from US and Germany)



Summary

- IceCube sees neutrinos created in the atmosphere and also from the far Universe
- IceCube has discovered high energy cosmic neutrinos
- 3σ observation of the first cosmic neutrino and flaring blazer coincidence with multi-messenger techniques
- neutrino only analysis also see
- The ongoing IceCube-Upgrade followed by IceCube-Gen2 construction will significantly improve the performance
- More events – more sources – less biases !