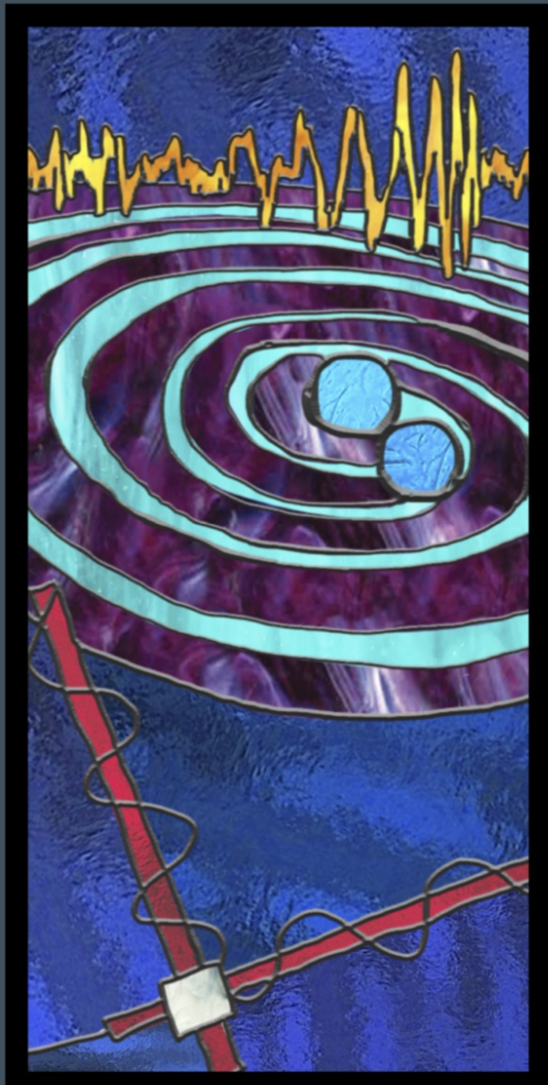
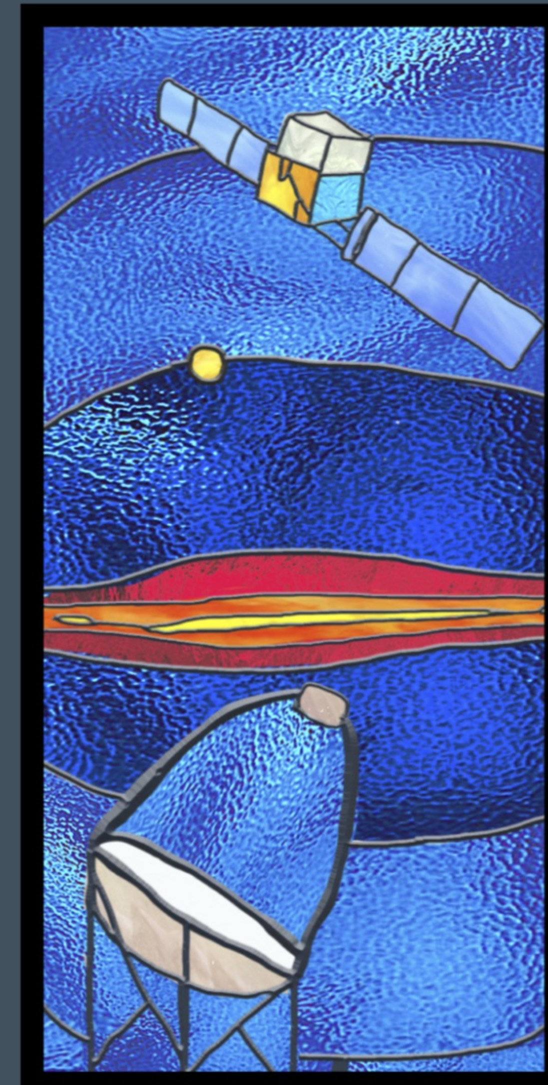
High Energy Neutrino Observations

Based on the transparencies of Markus Ahlers

Paolo Lipari (INFN, Roma)

Auger 20th anniversary celebration
Malargue 14th November 2019





High-Energy Neutrino Observations

Markus Ahlers, NBI Copenhagen

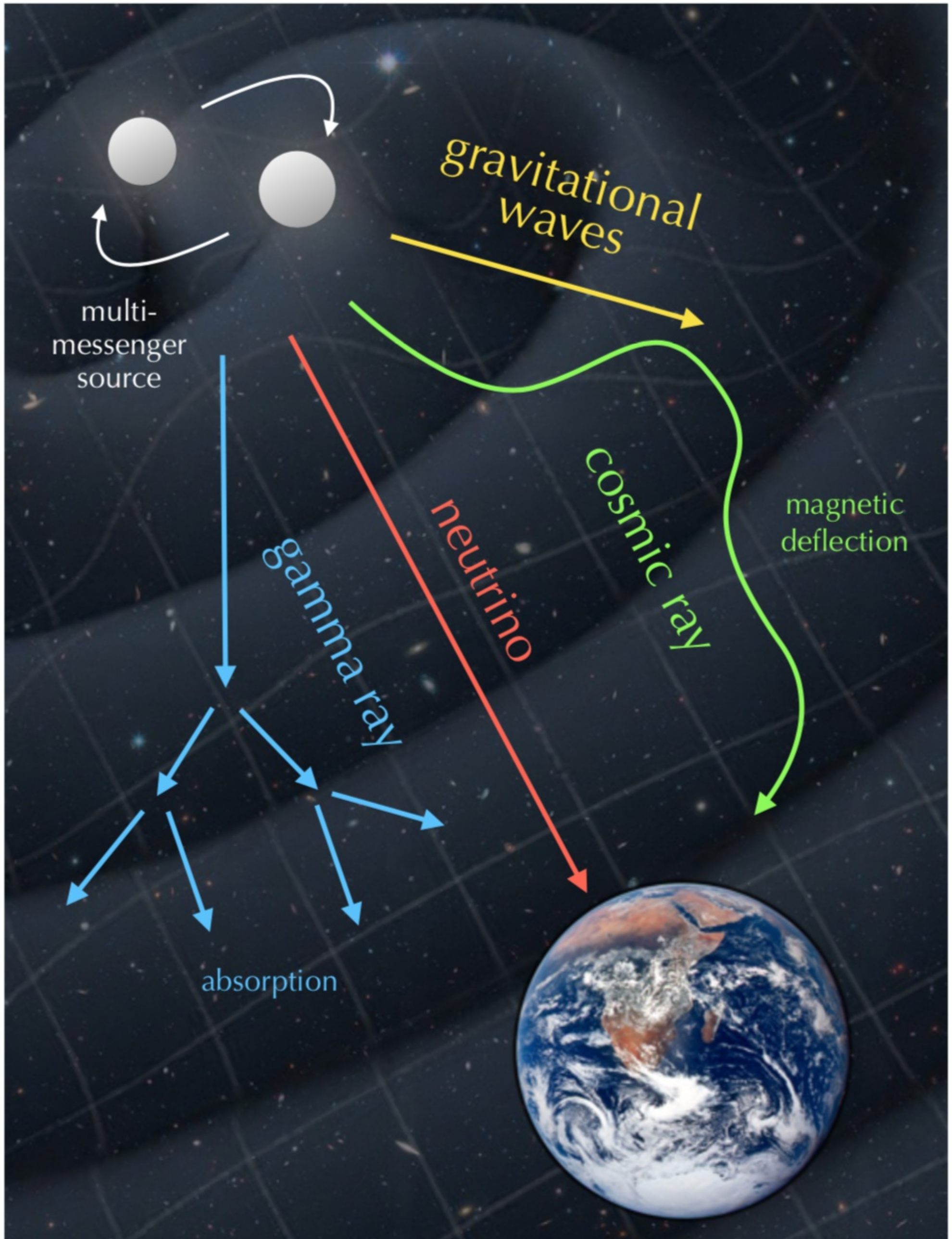
Scientific Symposium

November 14, 201

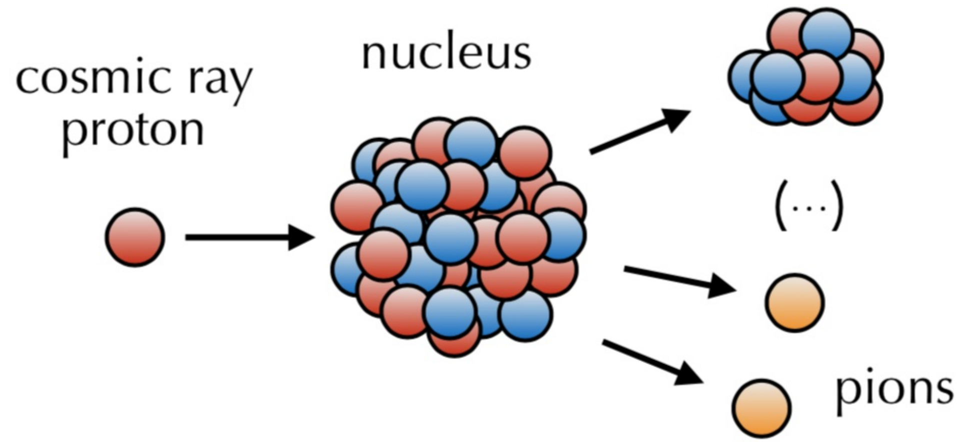
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

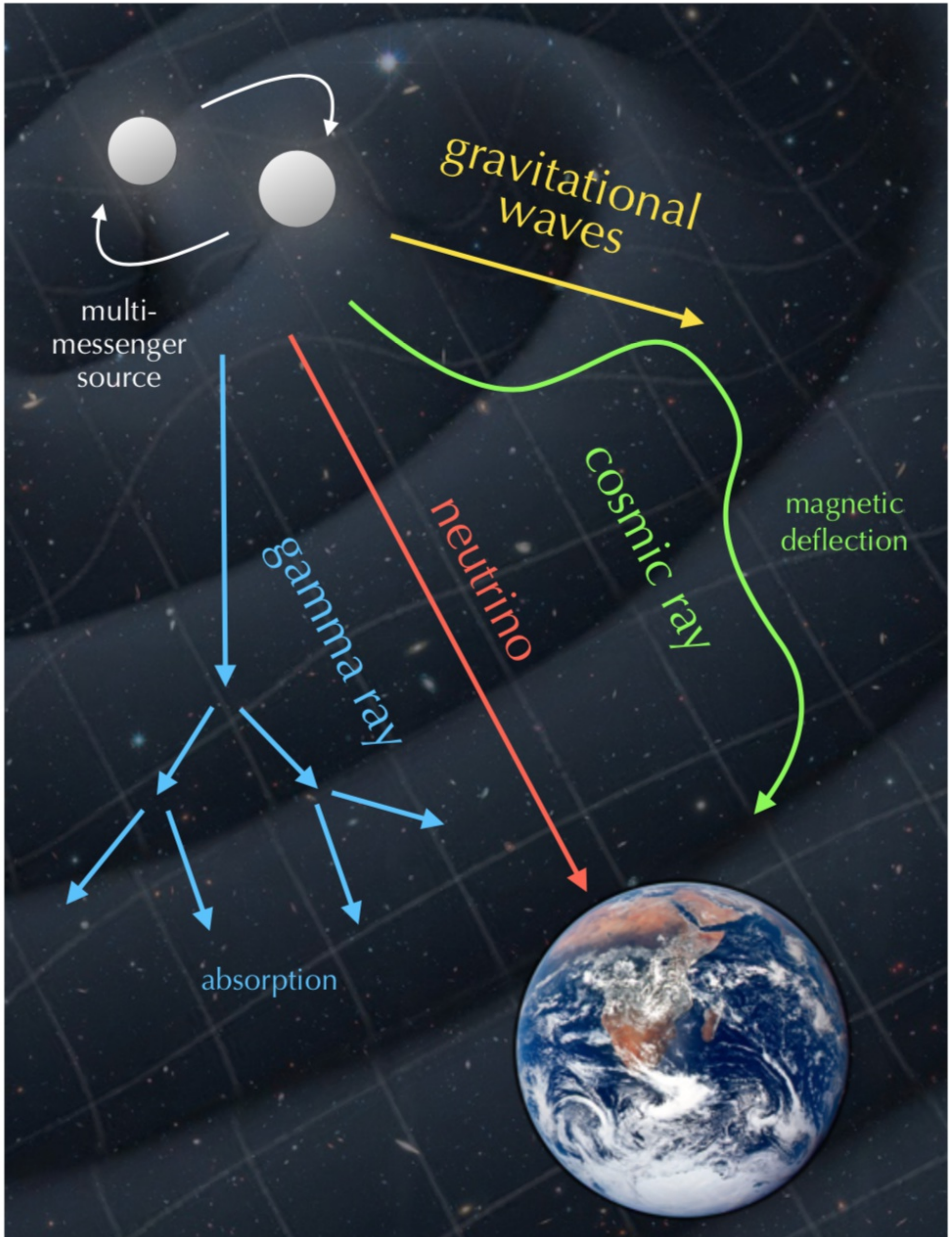


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

Multi-Messenger Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

no absorption in cosmic backgrounds
(unlike gamma-rays)

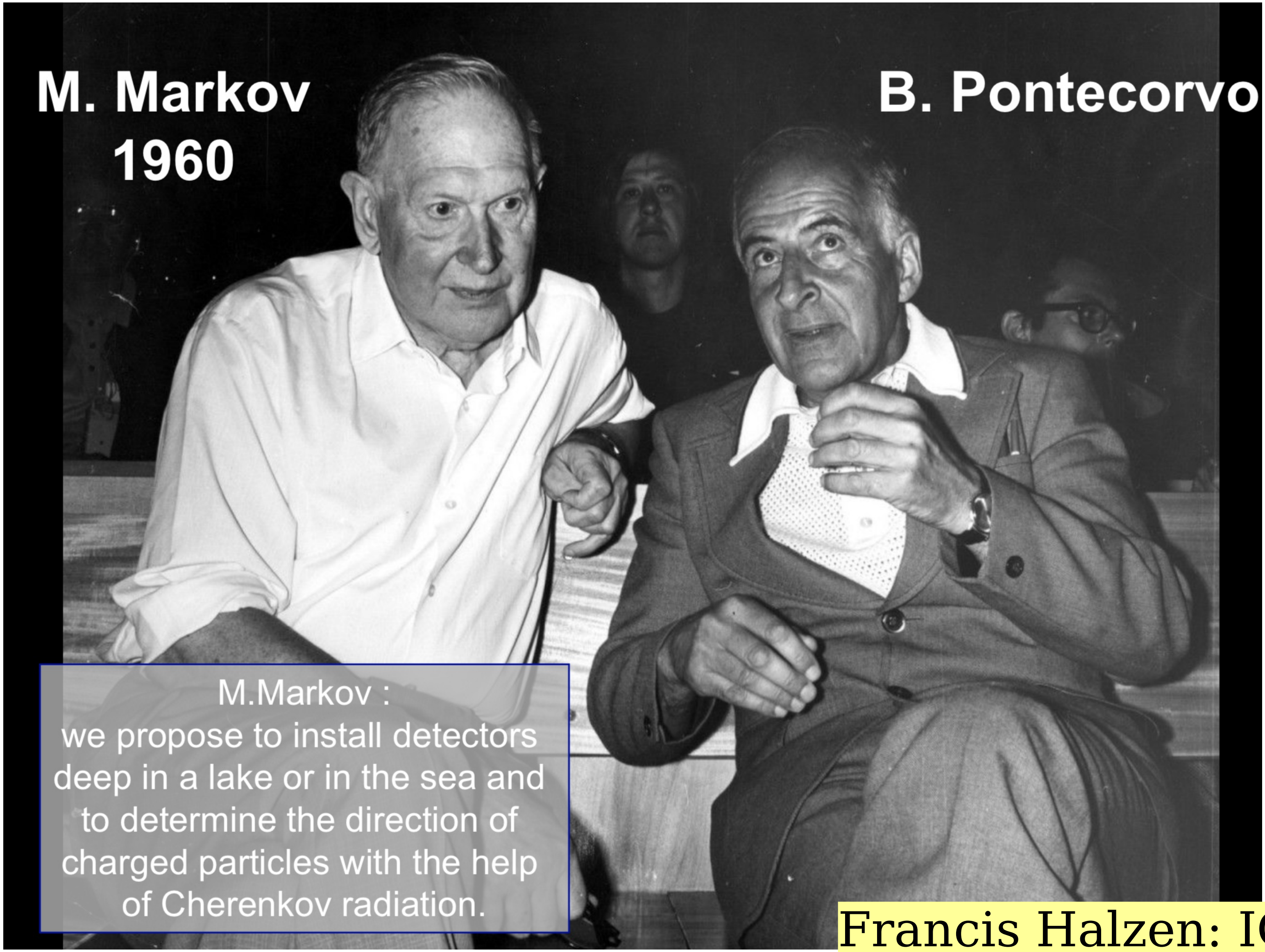
smoking-gun of
unknown sources of cosmic rays

coincident with
photons and gravitational waves

BUT, very difficult to detect!

The development of Cherenkov High Energy Neutrino Telescopes

"Dreamers" and pioneers in the Soviet Union



IMB detector (proton decay)

SuperKamiokande detector

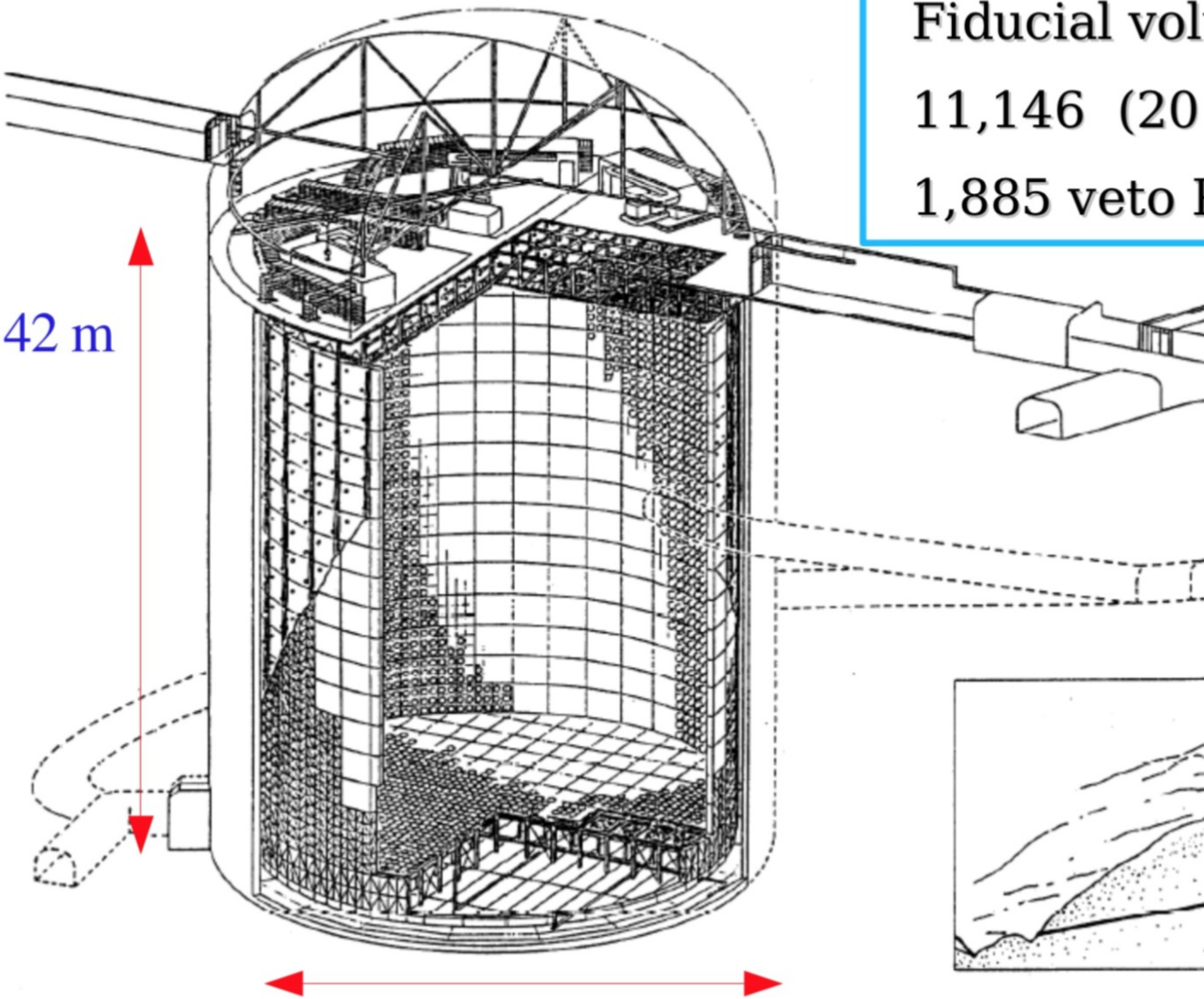
50,000 tons of ultrapure water

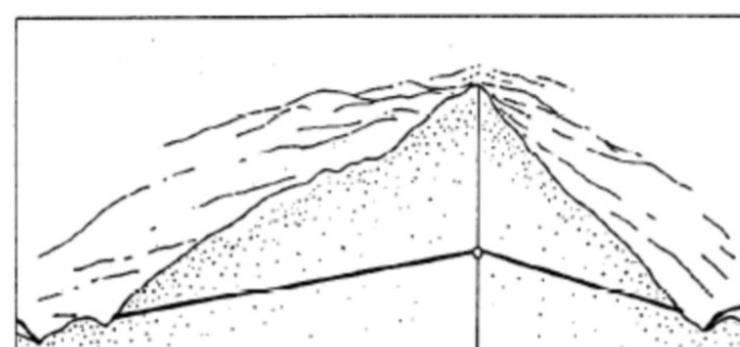
2 m of water = veto counter

Fiducial volume = 22,500 tons

11,146 (20 inch) PMT's

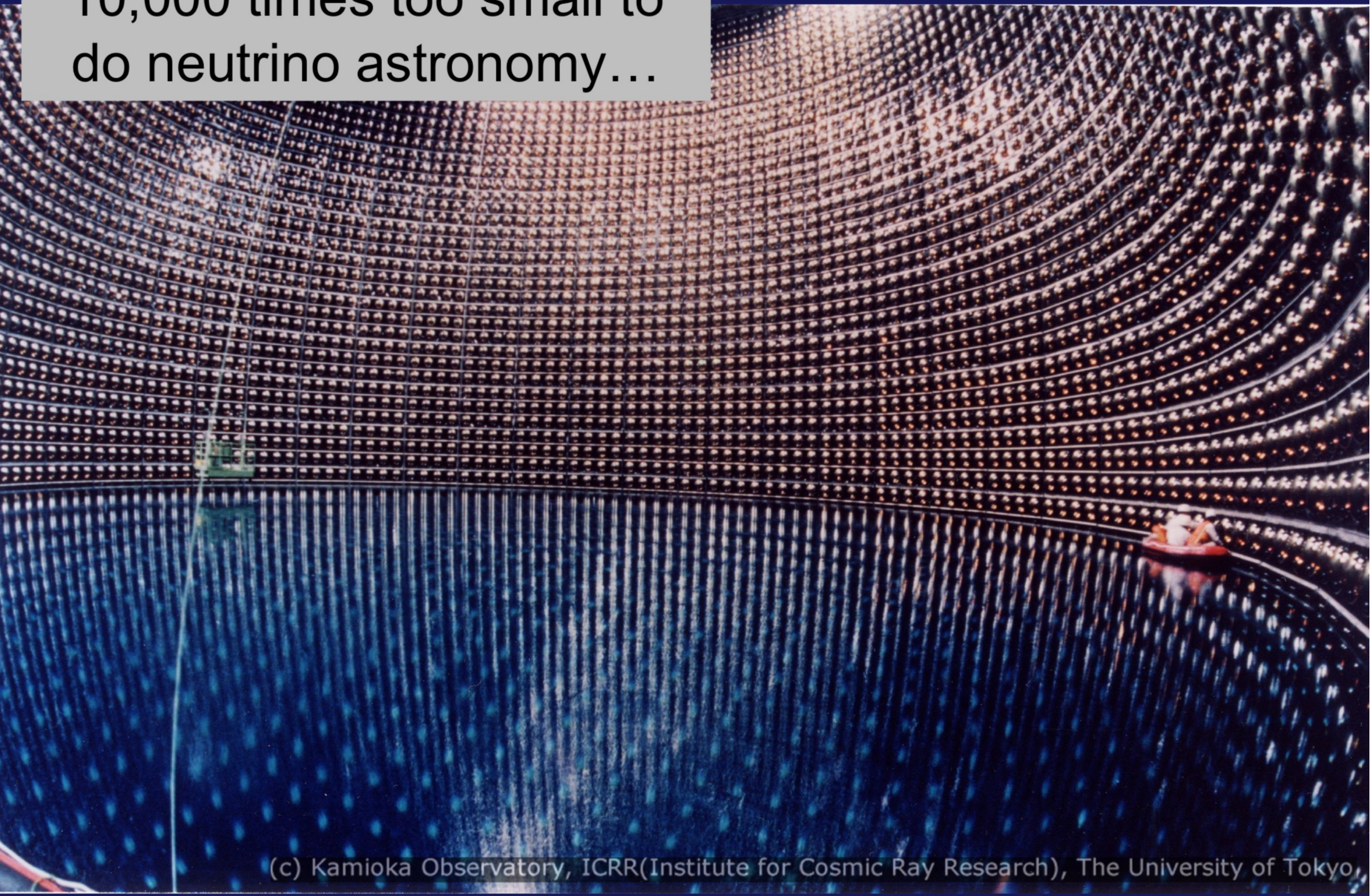
1,885 veto PMT's



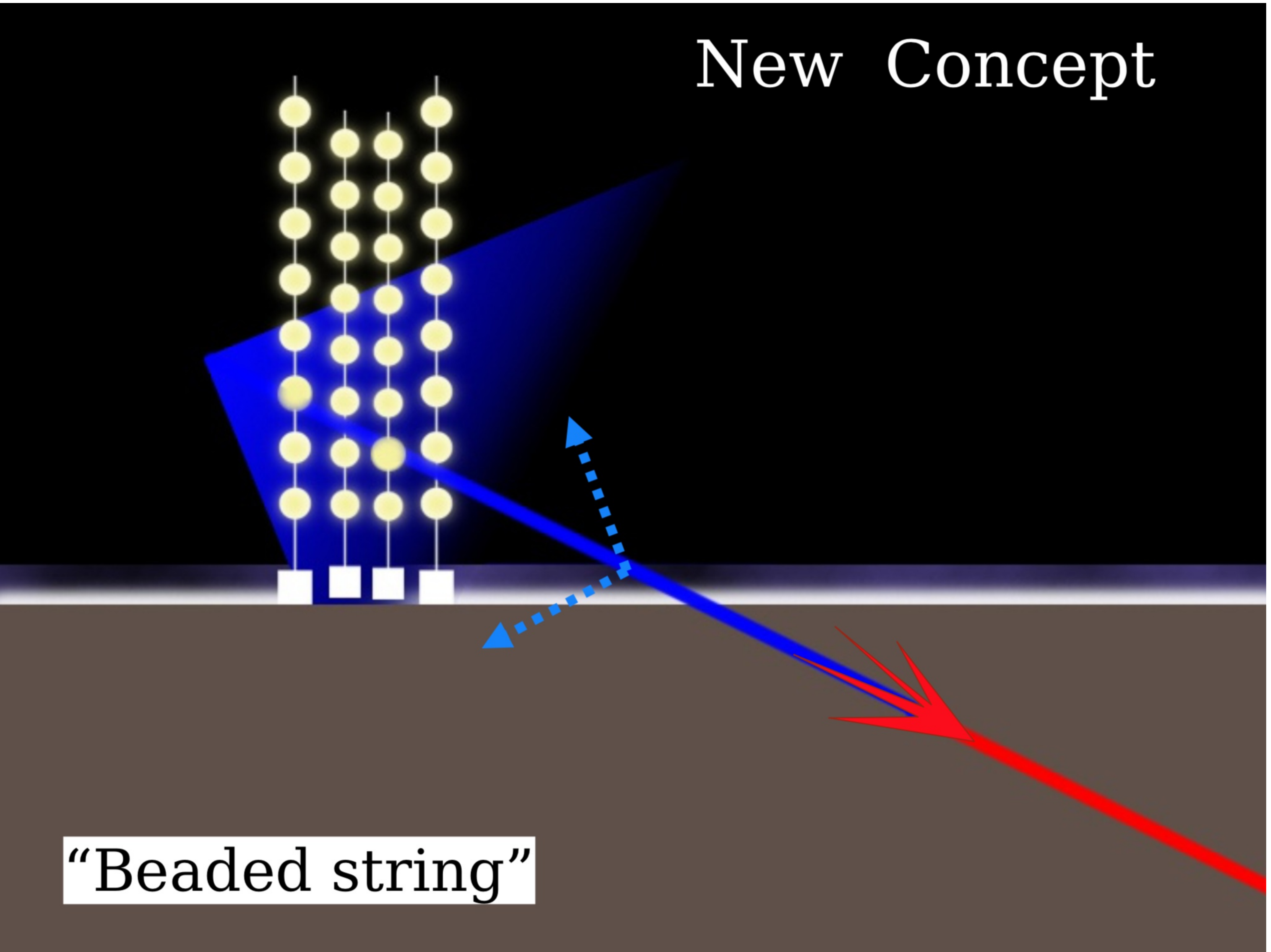


1 Km underground

10,000 times too small to do neutrino astronomy…

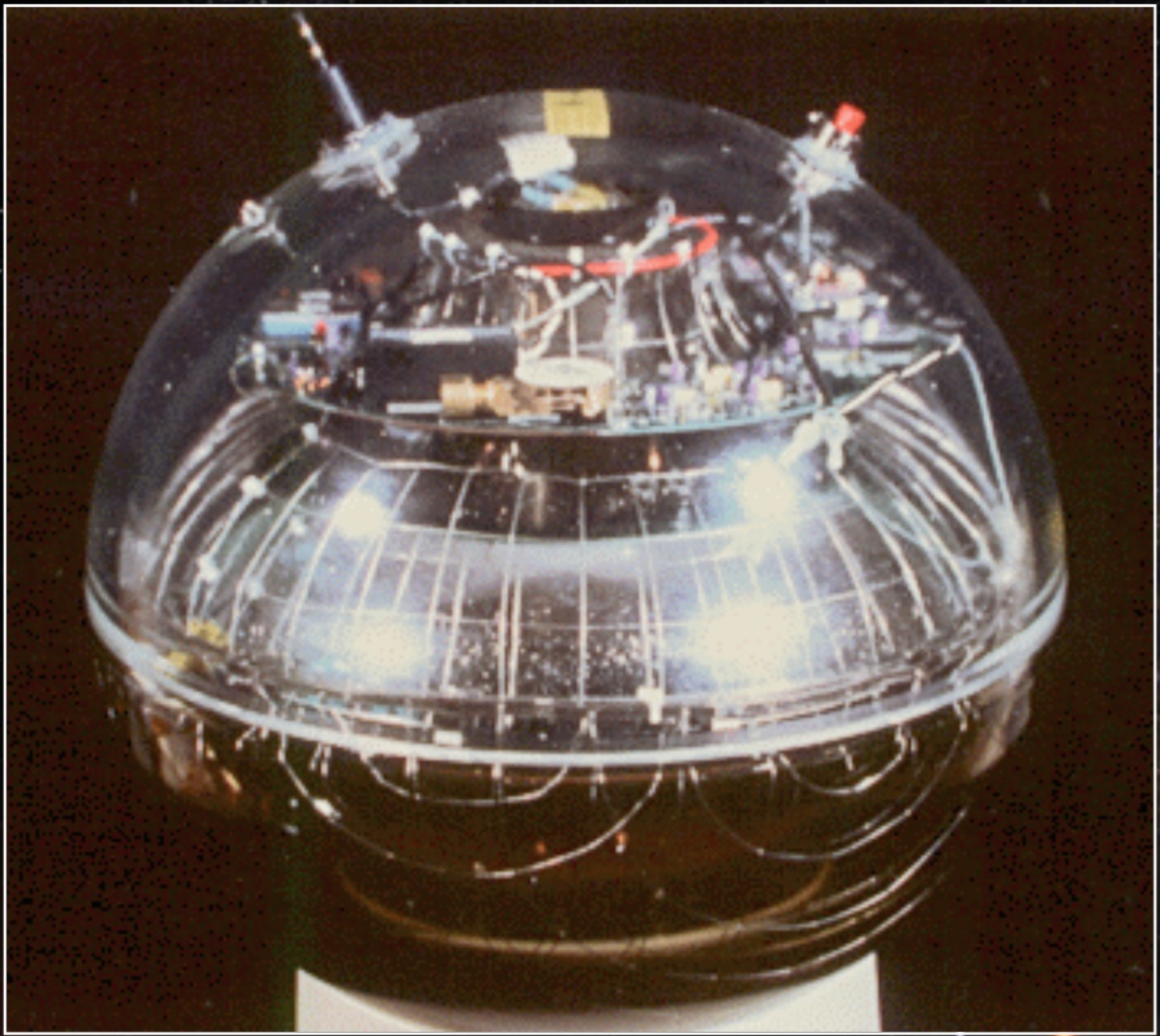


Super-Kamiokande


New Concept
“Beaded string”

standing on the shoulder of giants

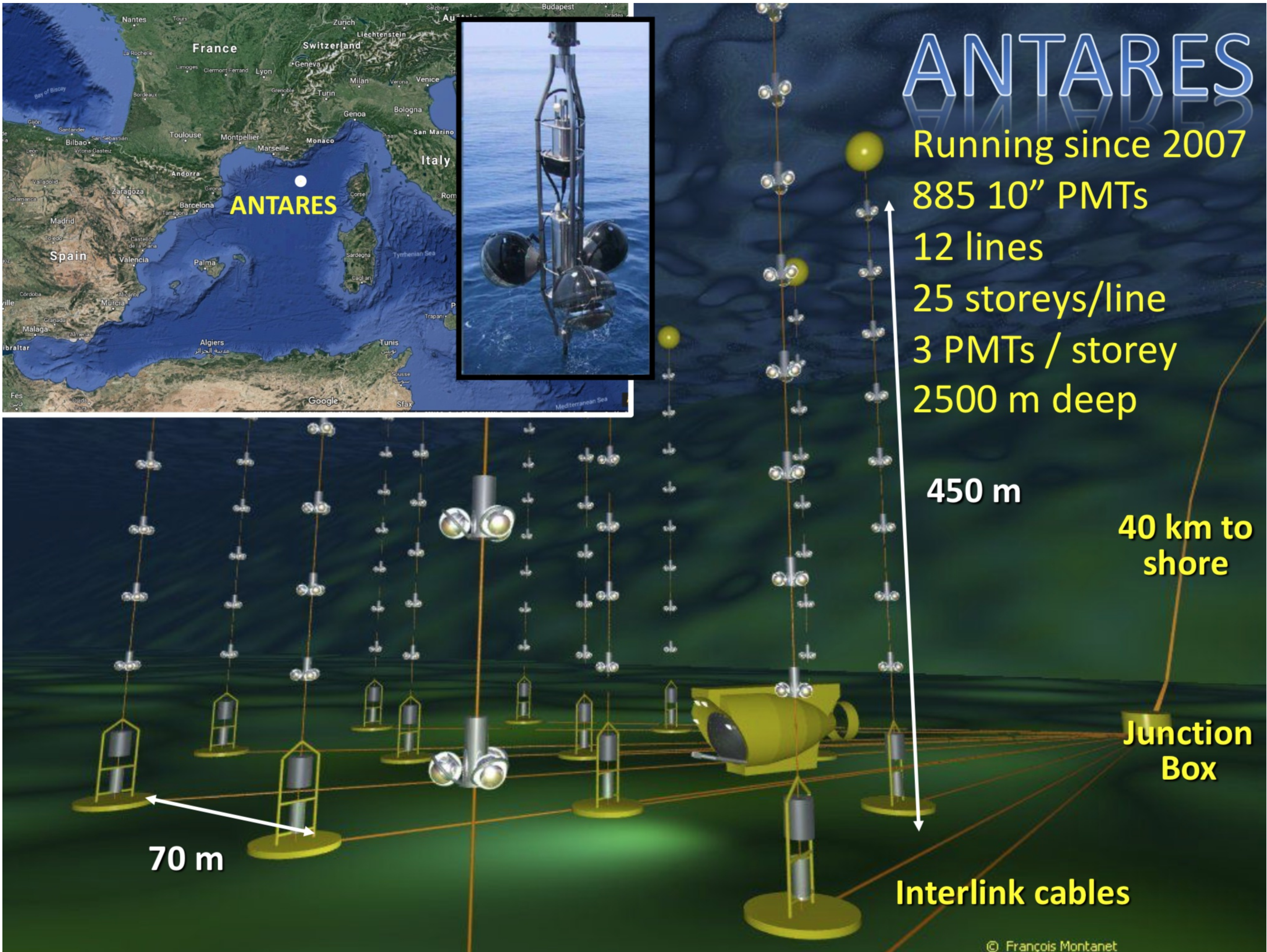
1987: DUMAND test string



Francis Halzen: ICRC-2019

Lake Baikal experiment observes atmospheric neutrinos

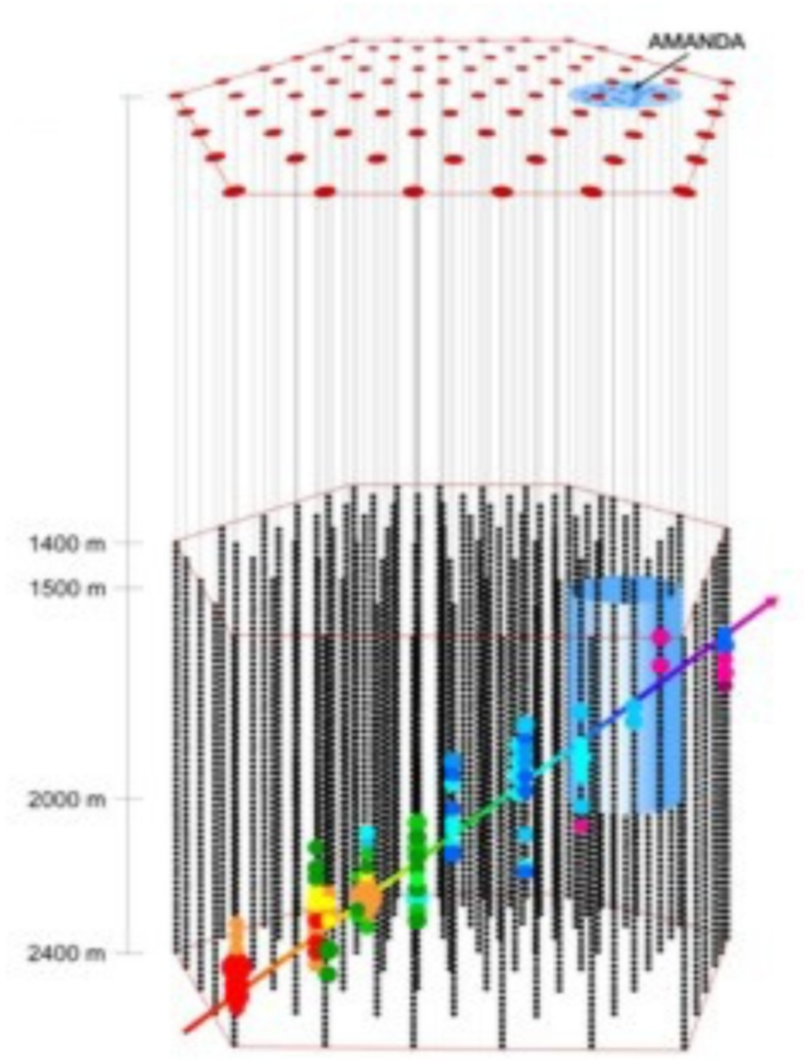
Francis Halzen: ICRC-2019



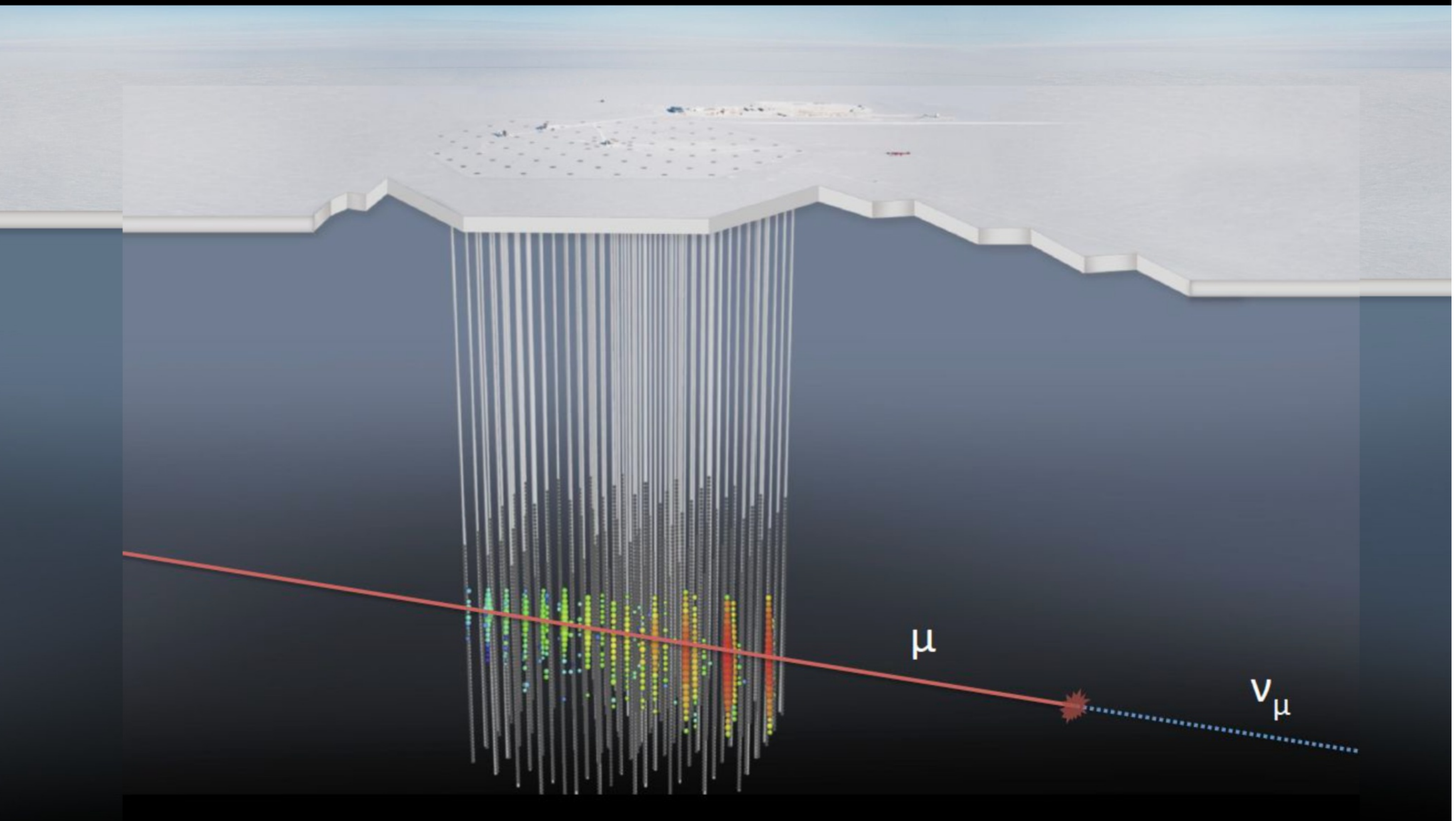
ANTARES
Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
450 m
40 km to shore
Junction Box
70 m
Interlink cables
© François Montanet
France
Switzerland
Italy
Spain
ANTARES
Marseille
Monaco
Barcelona
Toulouse
Montpellier
Lyon
Genoa
Milan
Turin
Bologna
Venice
Madrid
Valencia
Palma
Algiers
Tunis
Google


Francis Halzen: ICRC-2019
ultra-transparent ice below 1.35 km

Deployment of the strings

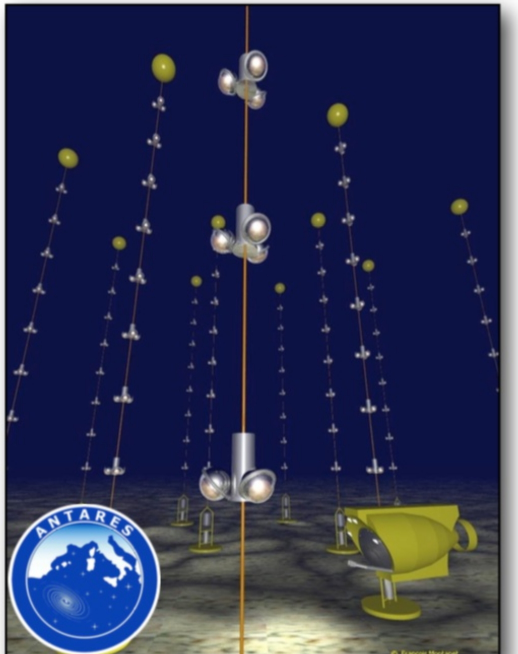


instrument 1 cubic kilometer of natural ice below 1.45 km

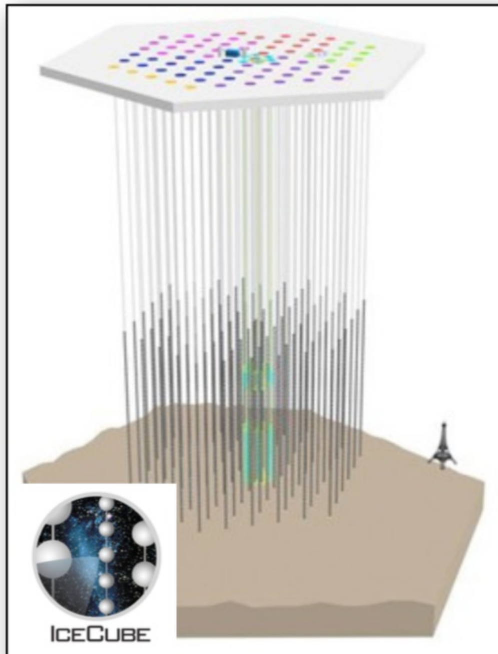


Cherenkov Observatories

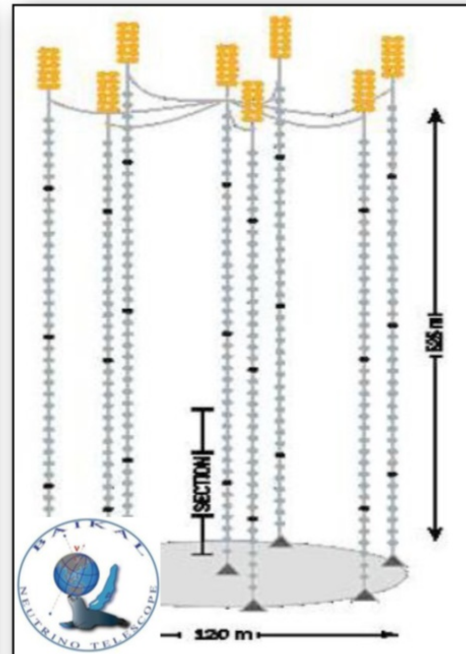
Antares



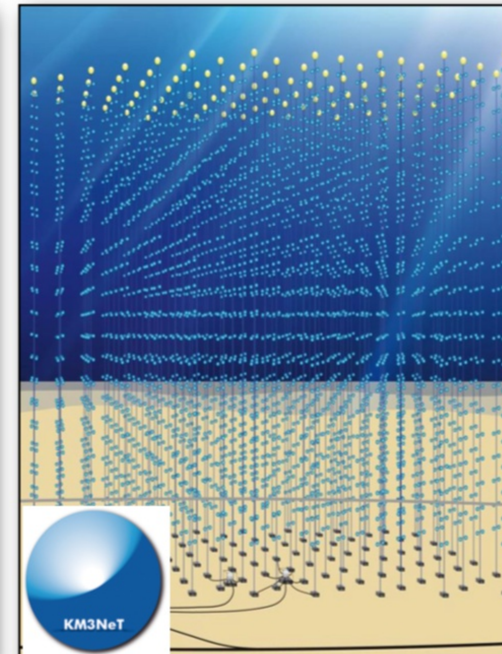
IceCube



Baikal-GVD

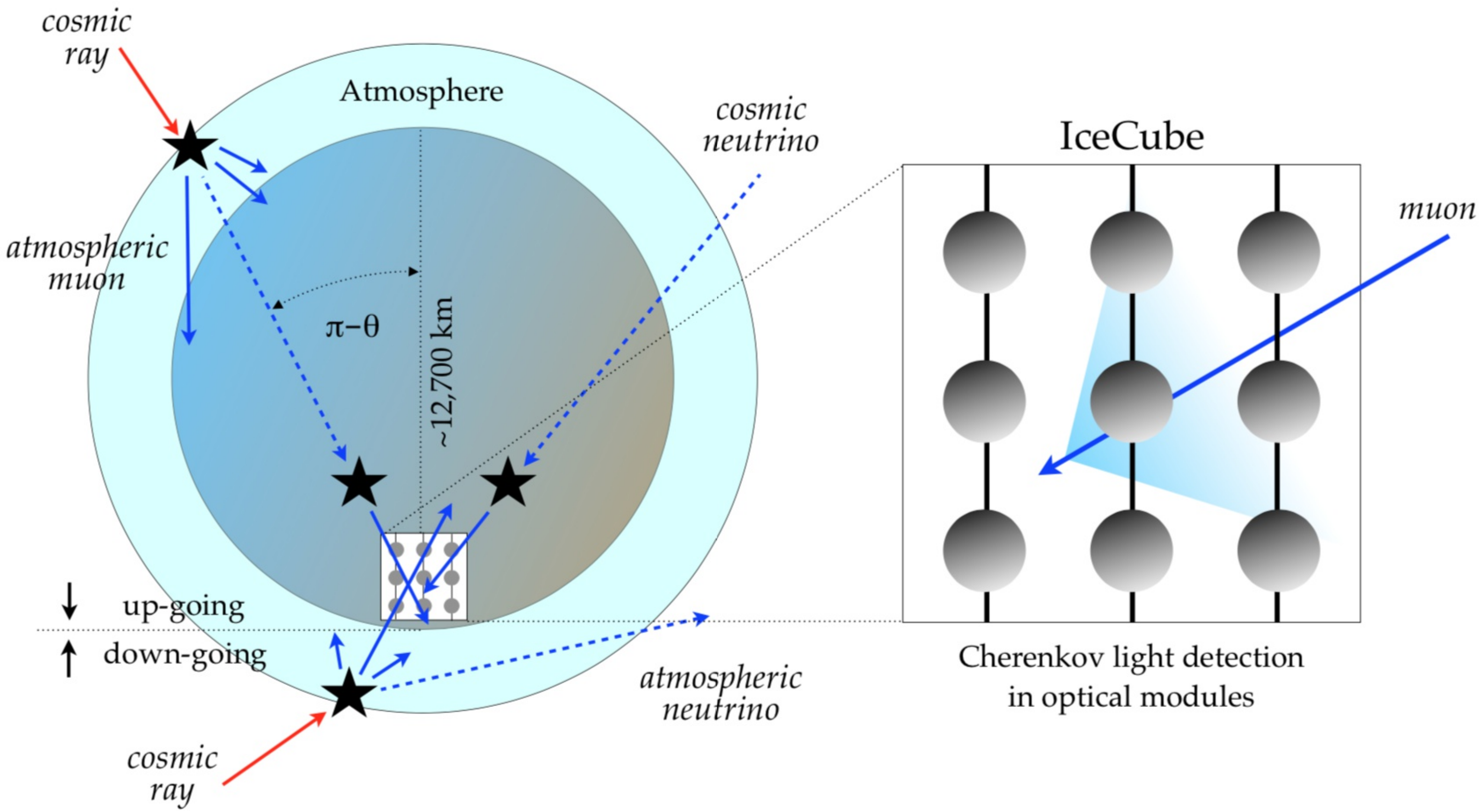


KM3NeT/ARCA



Antares	IceCube	Baikal-GVD	KM3NeT/ARCA
Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (5 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km^3	~1 km^3	~0.4 km^3 (Phase 1) ~1km^3	~0.1 km^3 (Phase 1) ~1 km^3
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

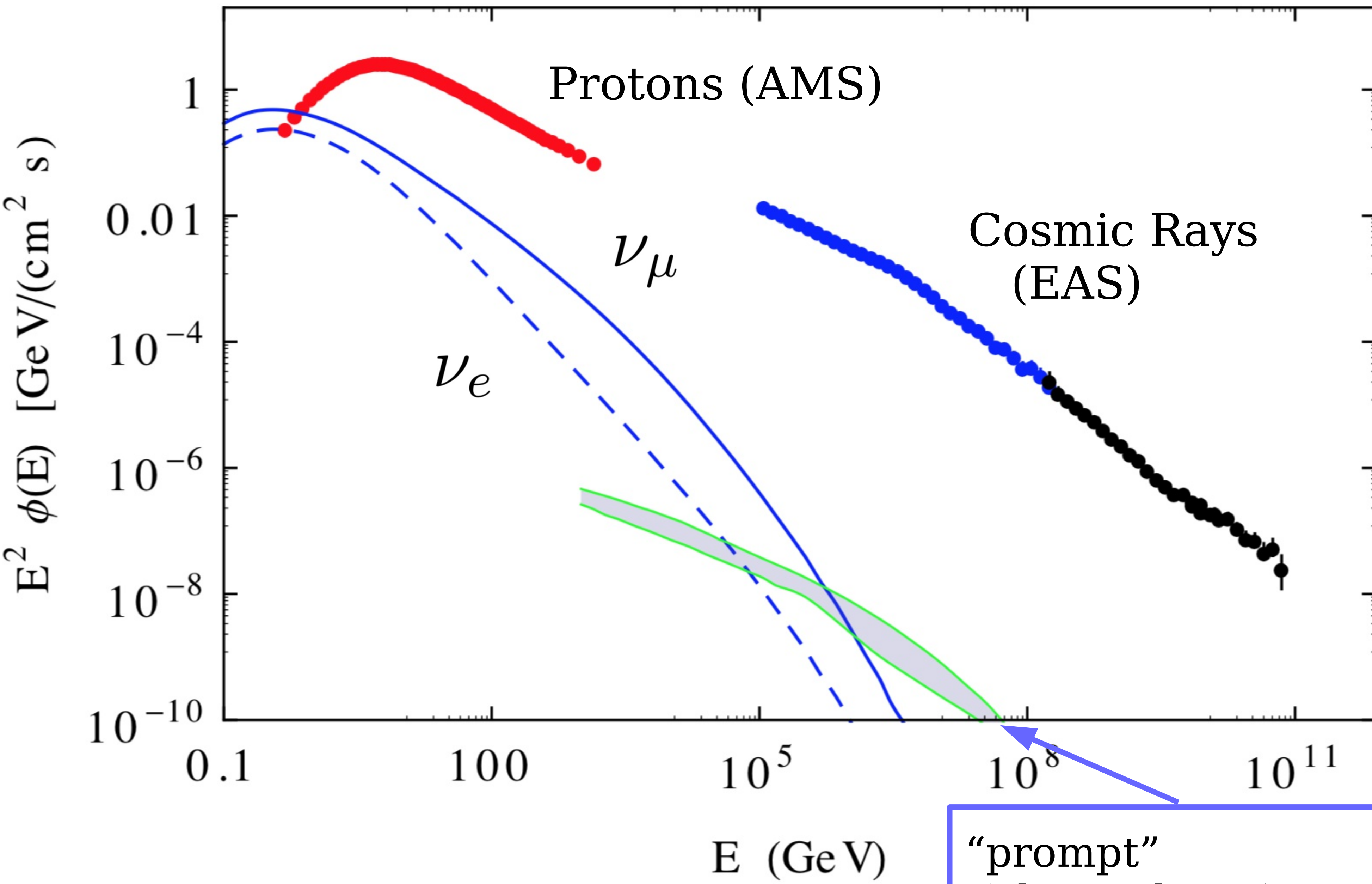
Detection Methods I



➜ Selecting **up-going muon tracks** reduces atmospheric muon background:

$\underbrace{10,000,000,000}_{\text{atmospheric muons (from above)}}$: $\underbrace{100,000}_{\text{atmospheric neutrinos}}$: $\underbrace{10}_{\text{cosmic neutrinos}}$

Atmospheric Neutrinos (pi/K decay)

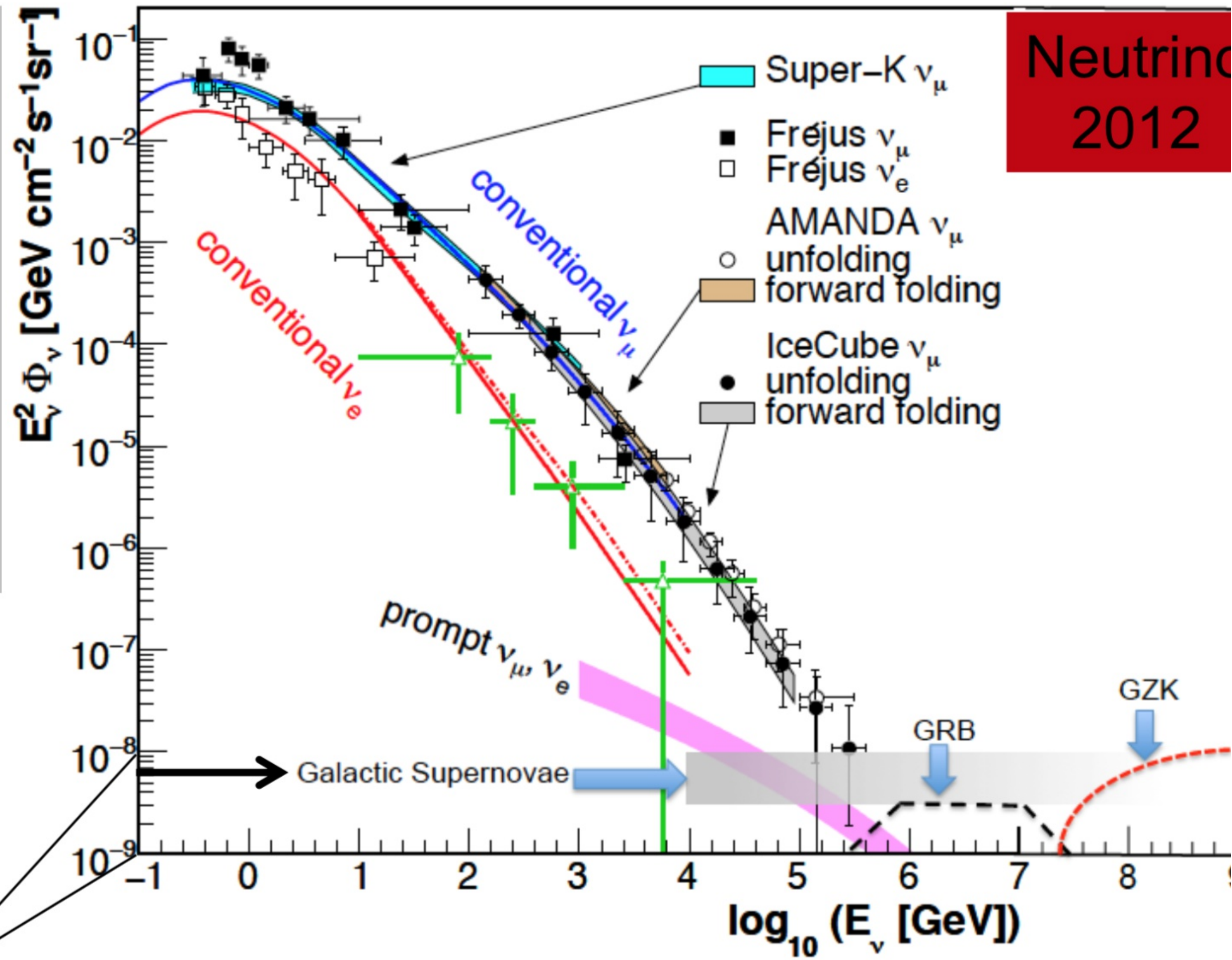


"prompt"
(charm decay) nu's

(Angle integrated Spectra)

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



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

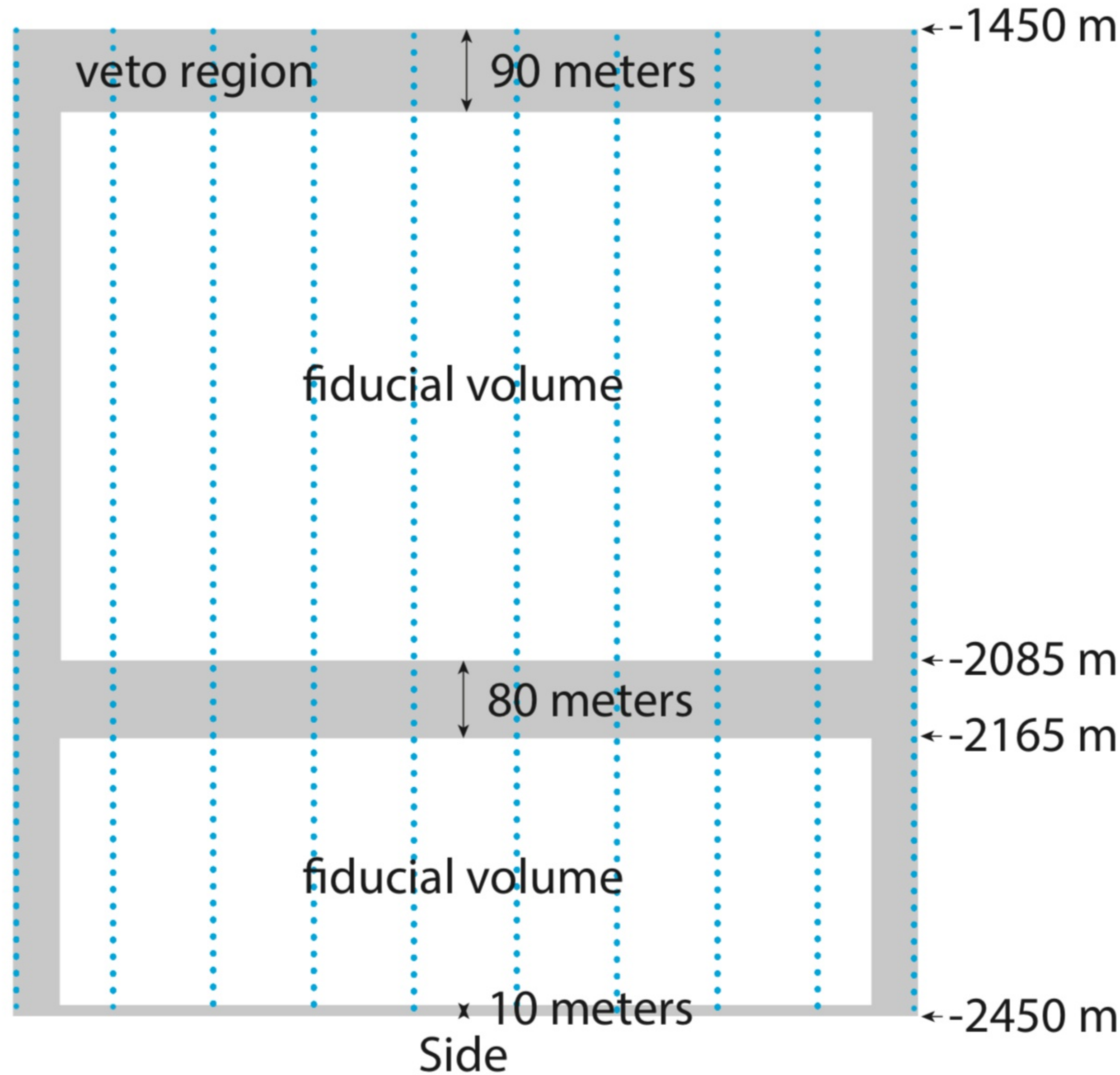
10-10^2 events per year for a fully efficient km^3 detector

atmospheric | cosmic

100 TeV

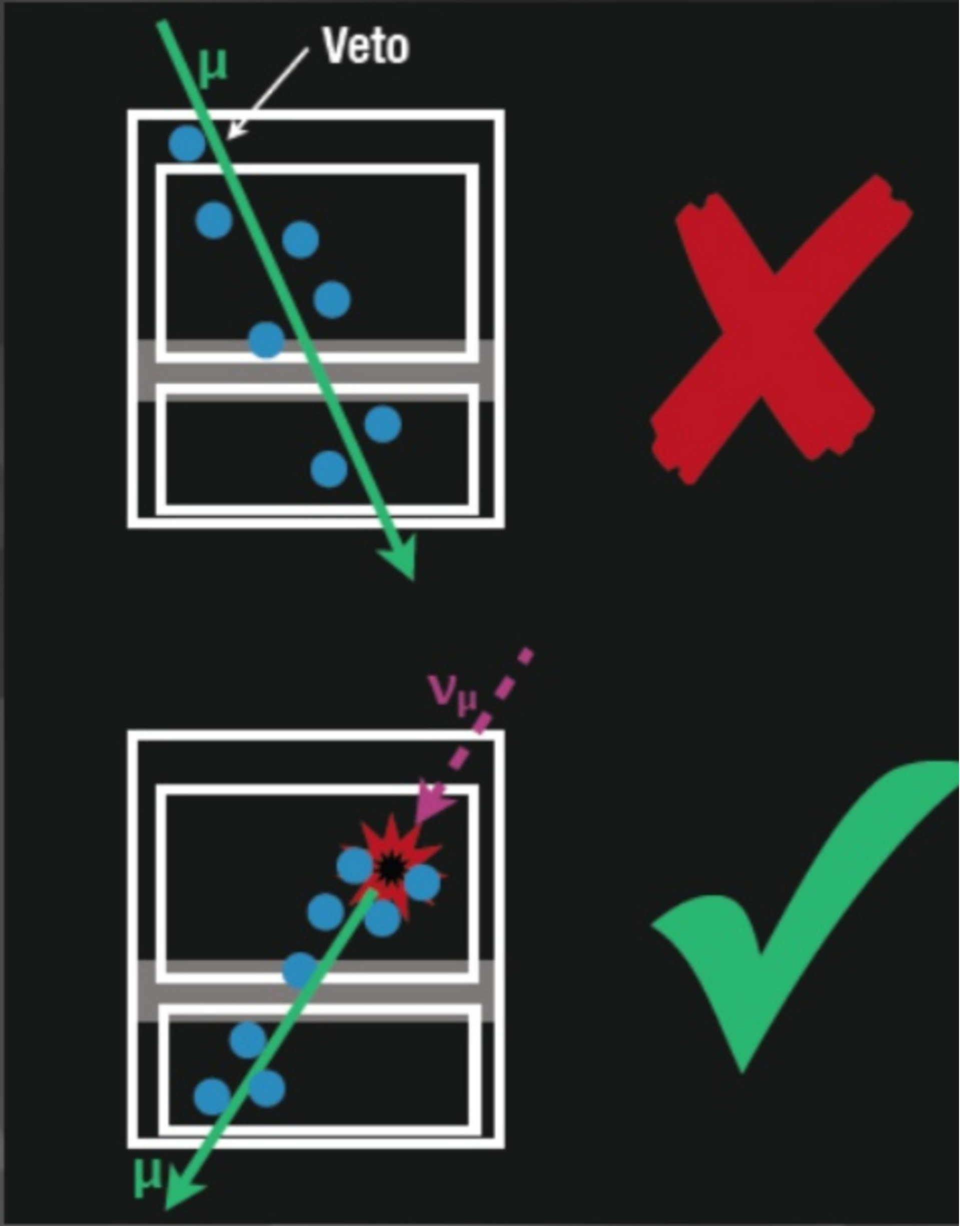
Detection Methods II

- Outer layer of optical modules used as virtual **veto region** (gray area)
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



High Energy Starting Events

- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

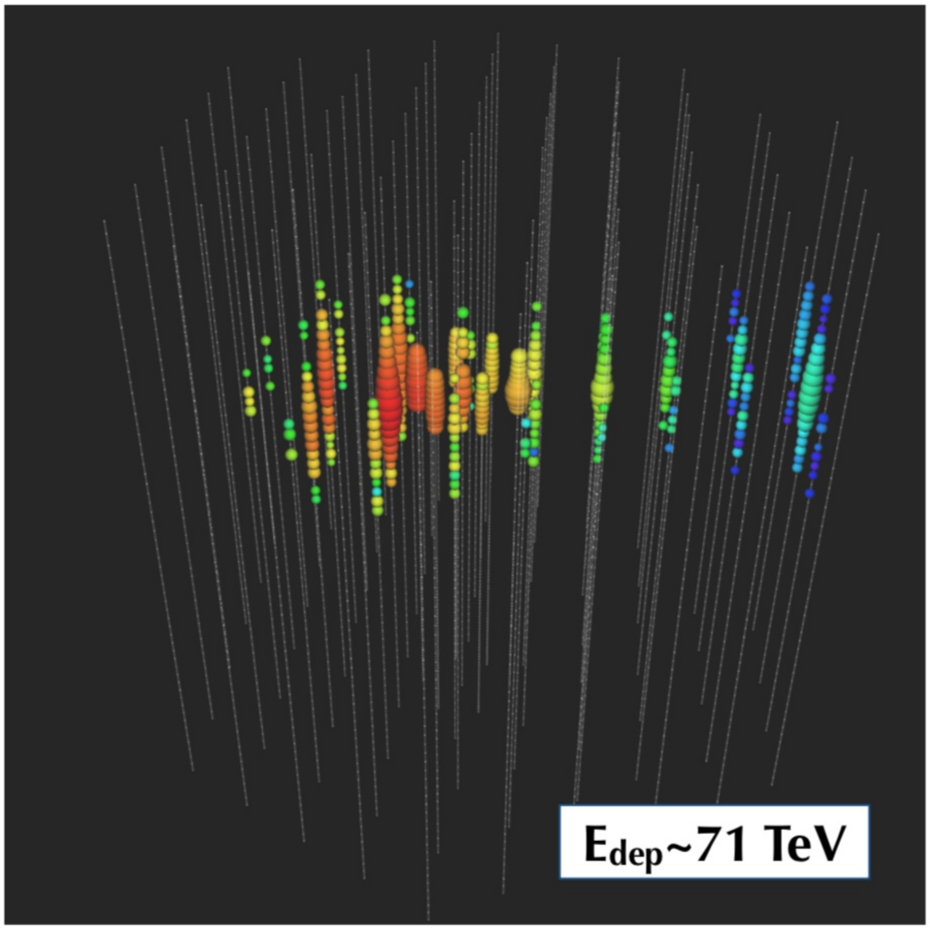


loss in statistics is compensated by event definition

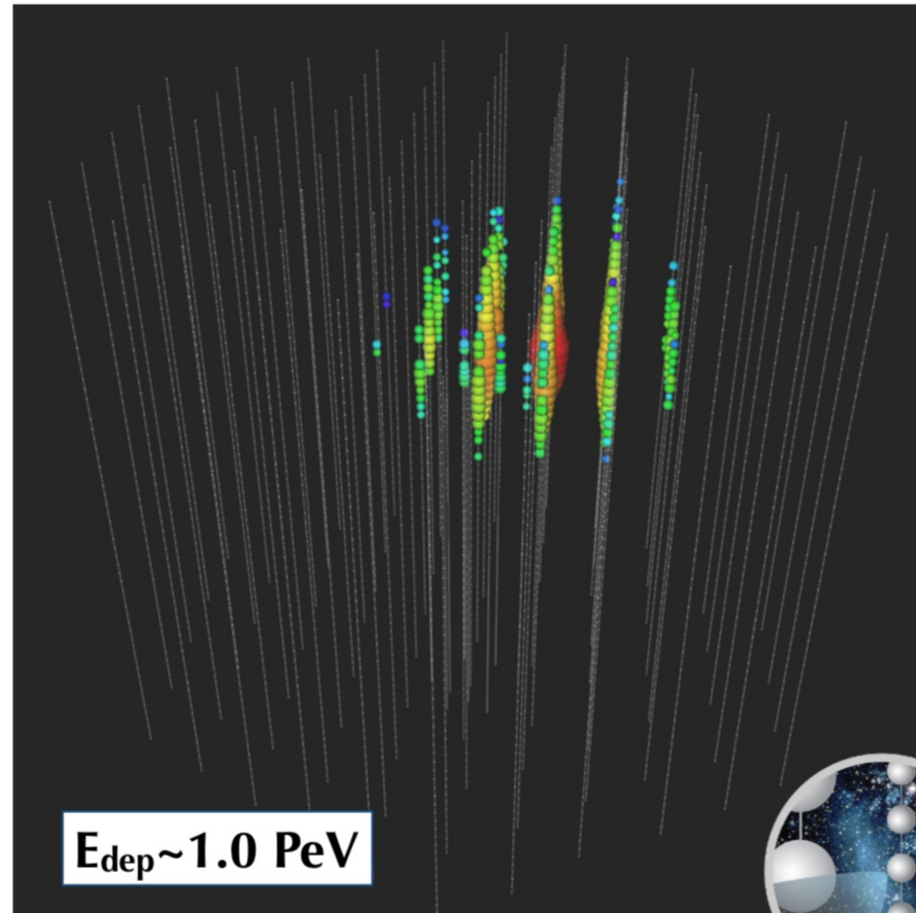
Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering)



"cascade event" (from all flavours)

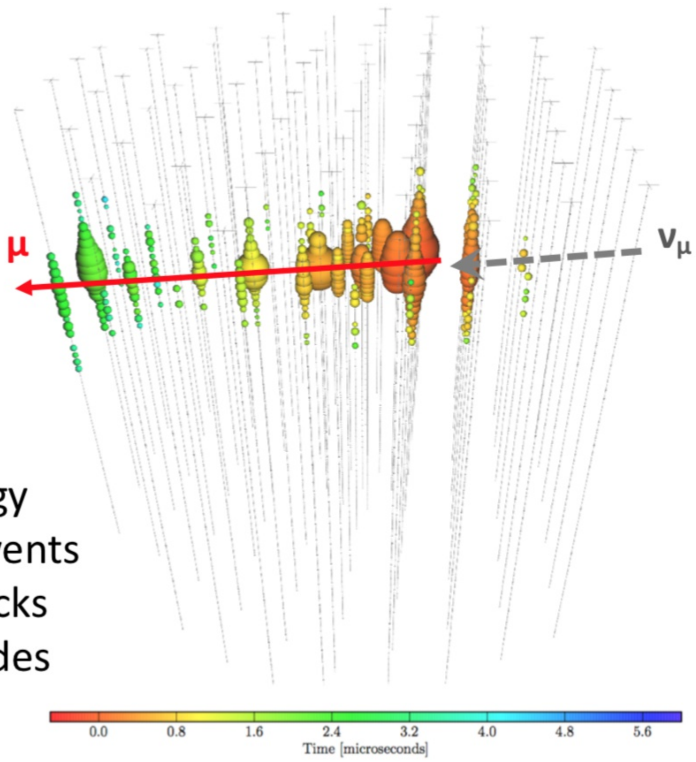


["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

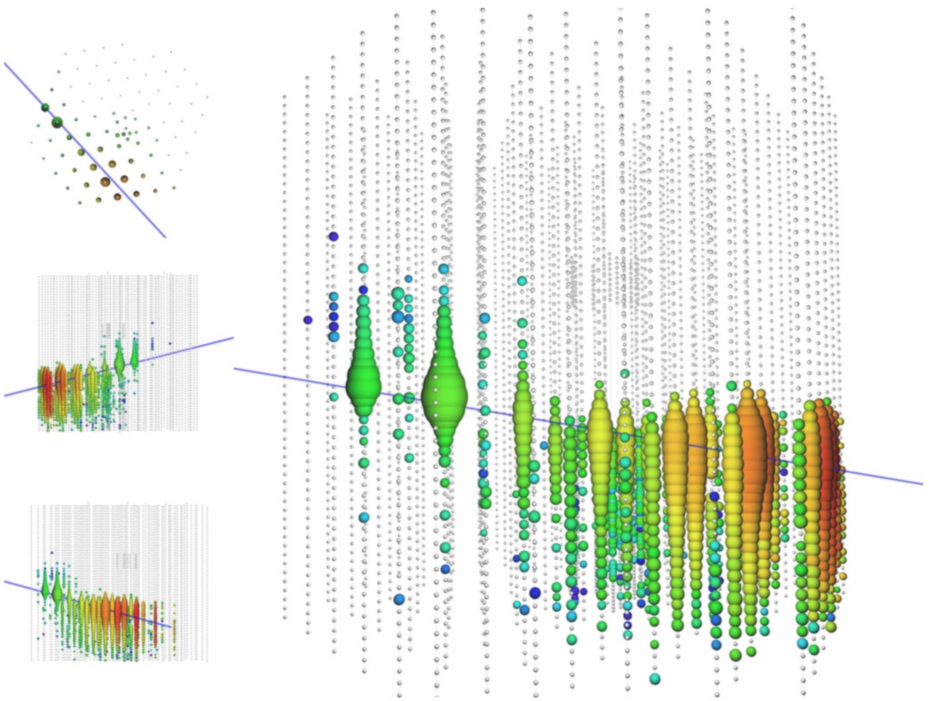
ICECUBE

HESE track

Through-going track



High energy starting events (HESE) tracks and cascades



Through-going tracks

Disentangling an

Astrophysical Neutrino signal

from

Atmospheric neutrino foreground

1. Angular distribution

2 Energy distribution

3. Flavor Content

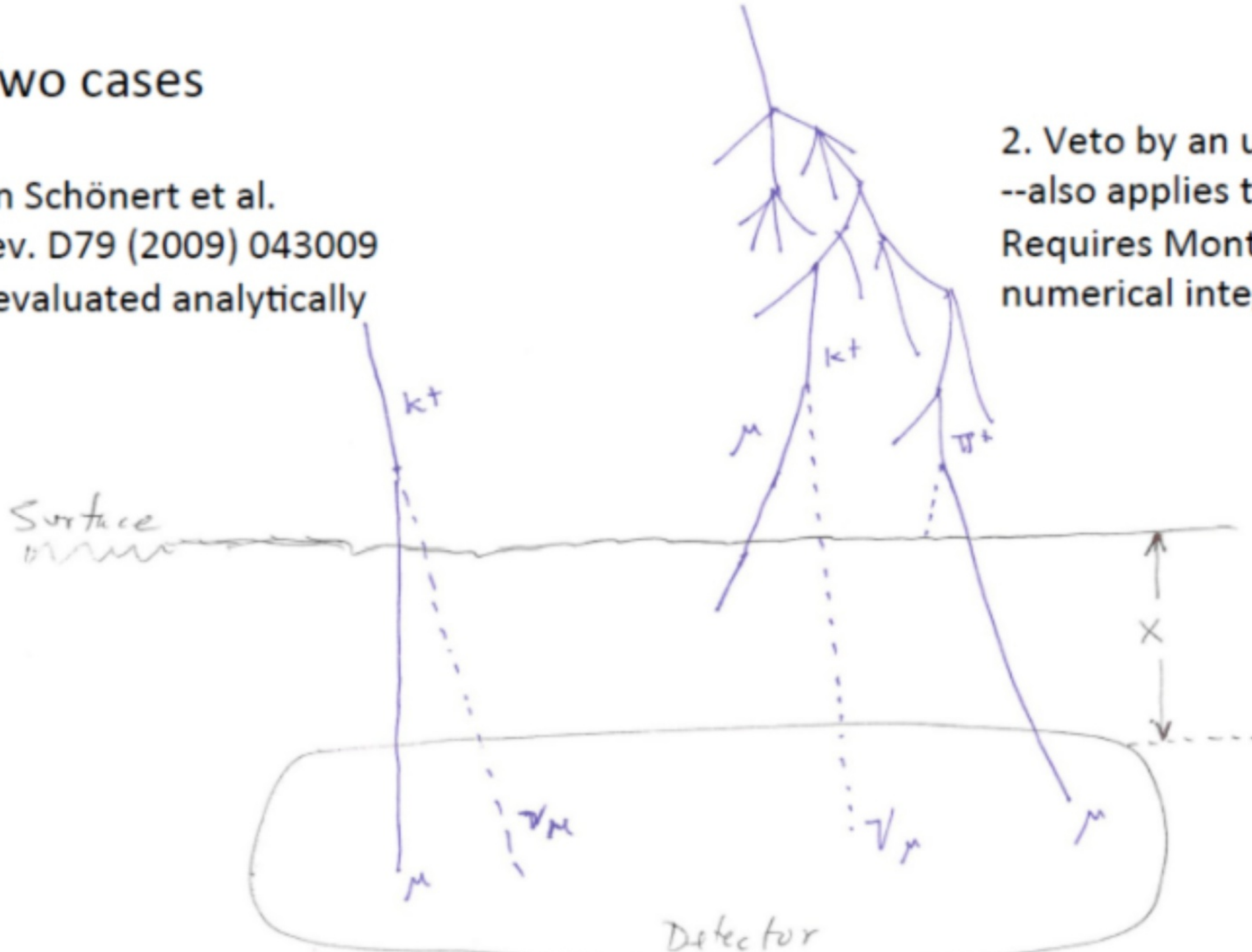
4. Use of "Veto" [for down-going neutrinos]

Atmospheric neutrino self veto

Two cases

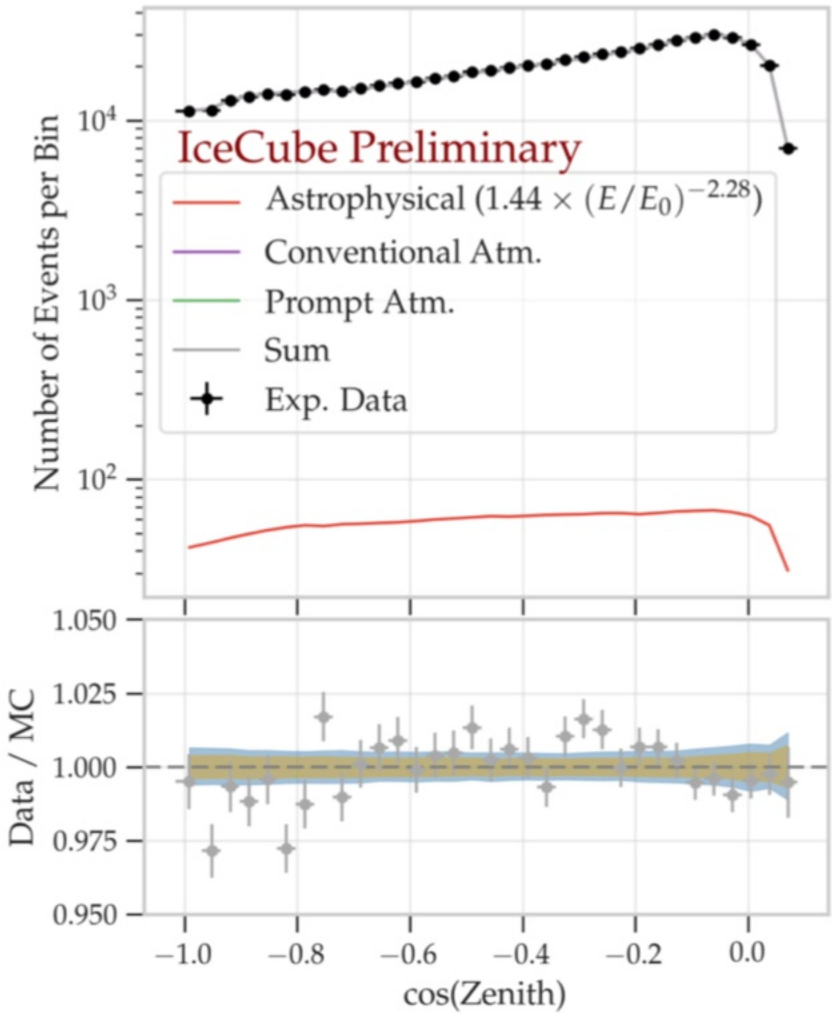
1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

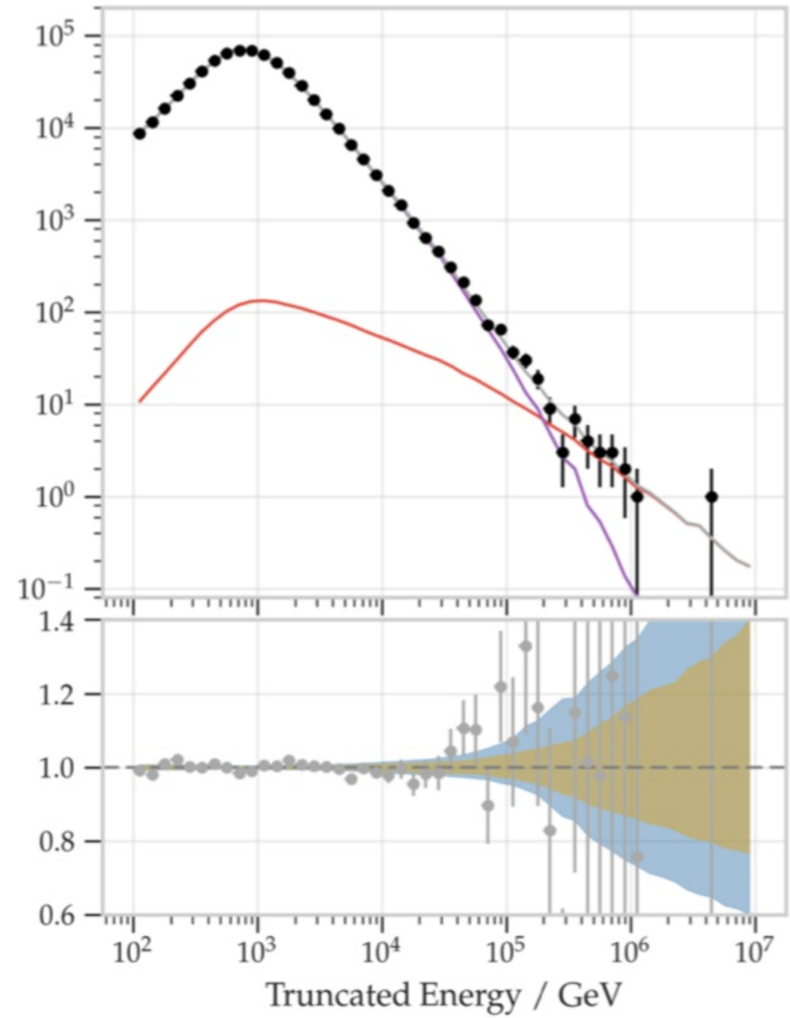
2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or
numerical integration



Zenith angle

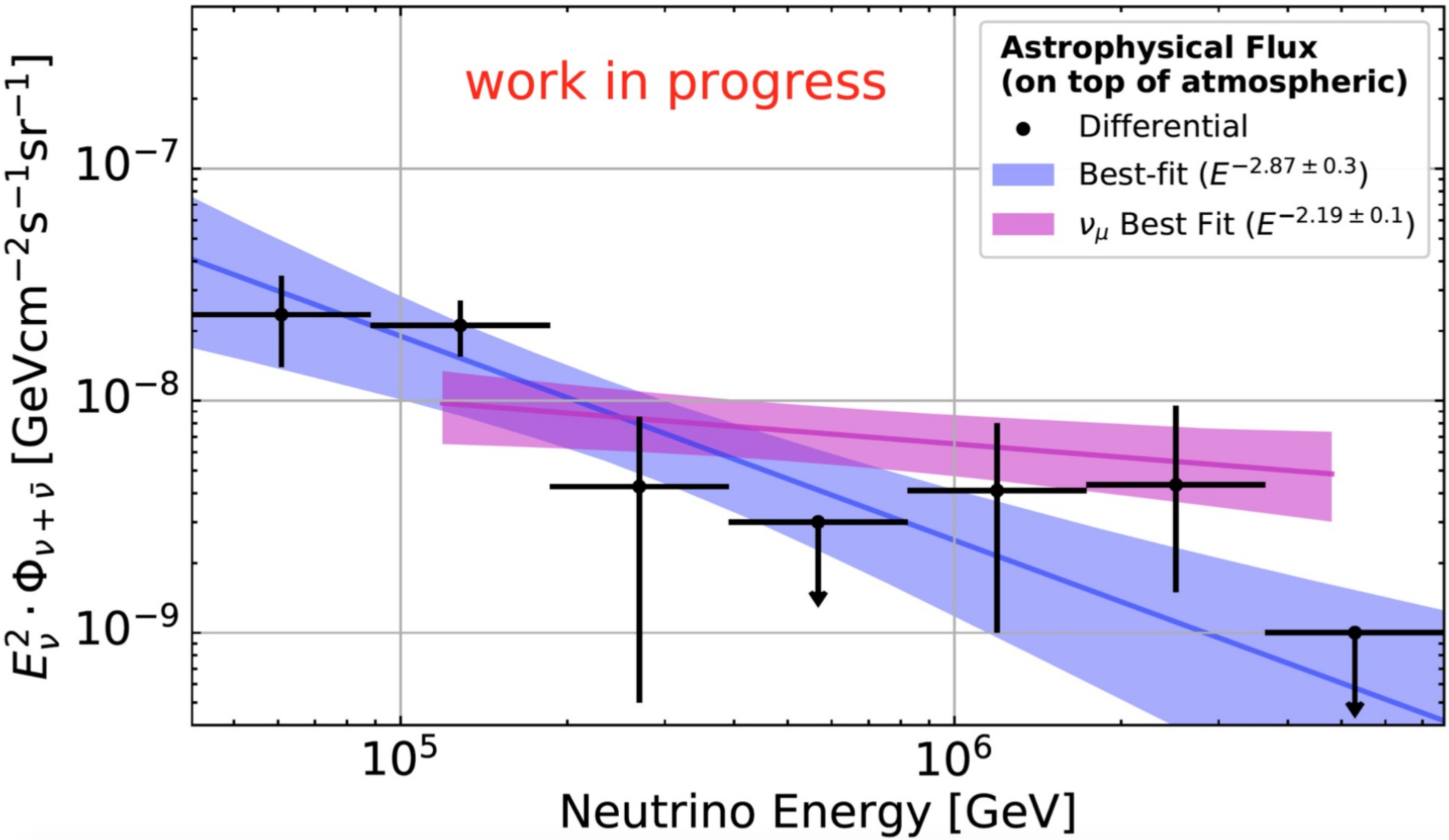
Energy



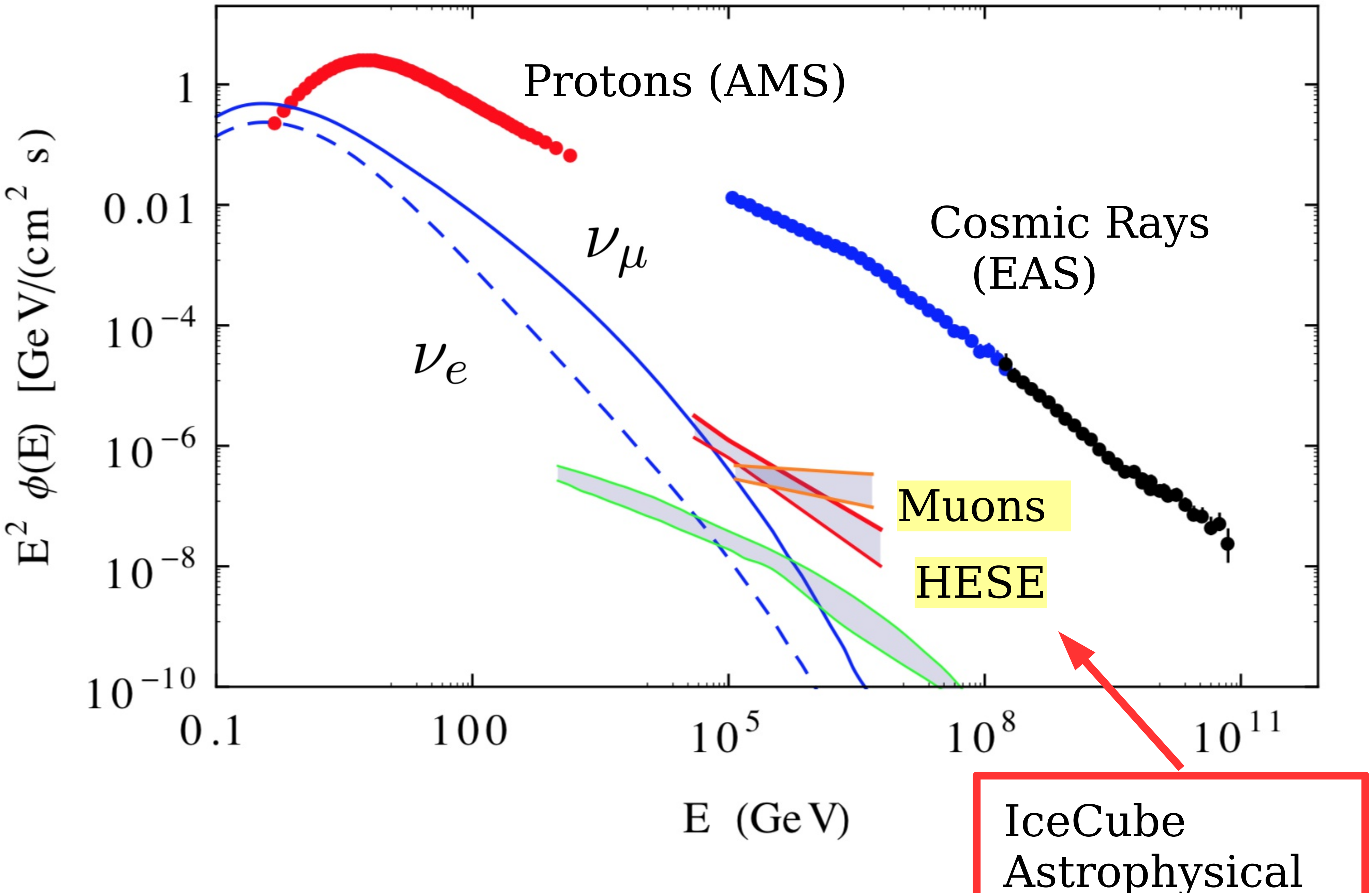


Through-going muons

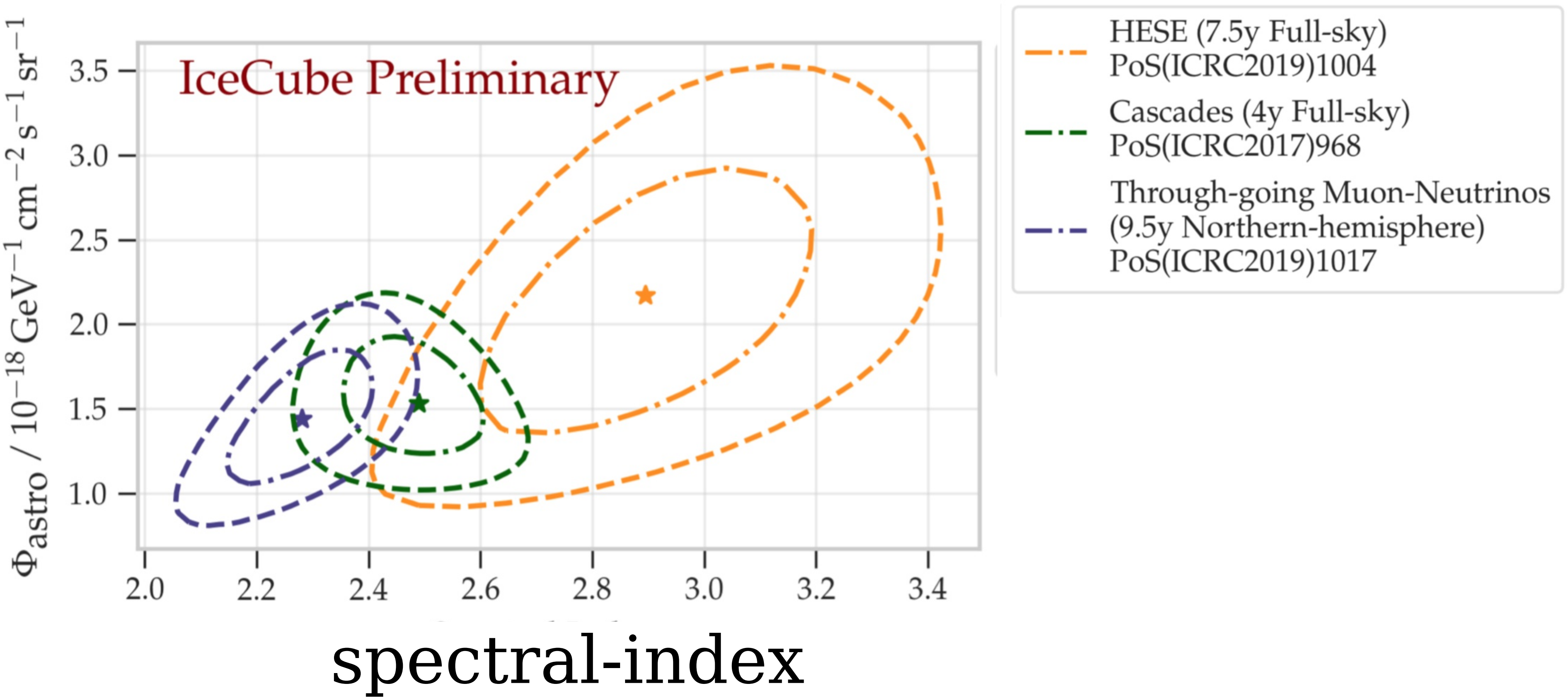
High-Energy Starting Events (HESE) – 7.5 yr



Ignacio Taboada: Neutrino 2018



(Angle integrated Spectra)


IceCube Preliminary
Φ_{astro} / 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
3.5
3.0
2.5
2.0
1.5
1.0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
HESE (7.5y Full-sky)
PoS(ICRC2019)1004
Cascades (4y Full-sky)
PoS(ICRC2017)968
Through-going Muon-Neutrinos
(9.5y Northern-hemisphere)
PoS(ICRC2019)1017
spectral-index

Neutrino Flavor at the source.

[usual “benchmark examples”]

1. “Standard Production”

$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{1,\ 2,\ 0\}$$

$$\pi^+ \to \mu^+ \ \nu_\mu$$
$$\hookrightarrow e^+ \ \nu_e \ \overline{\nu}_\mu$$

2. “Muon damped"

$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{0,\ 1,\ 0\}$$

$$-\frac{dE}{dt} = \frac{4}{9}\frac{e^4\,B^2}{m^4}\ E^2$$

$$E_{\rm syn} = \frac{3}{2}\frac{m^{5/2}}{e^2\,B\,\sqrt{\tau}} = \frac{5.8\times 10^{18}\ {\rm eV}}{B_{\rm Gauss}}$$

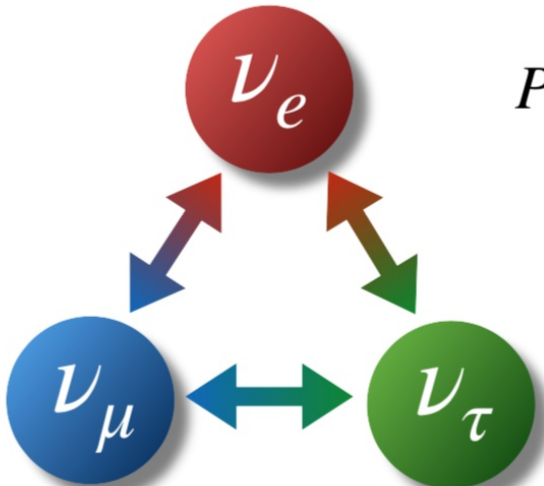
3. Neutron decay

$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{1,\ 0,\ 0\}$$

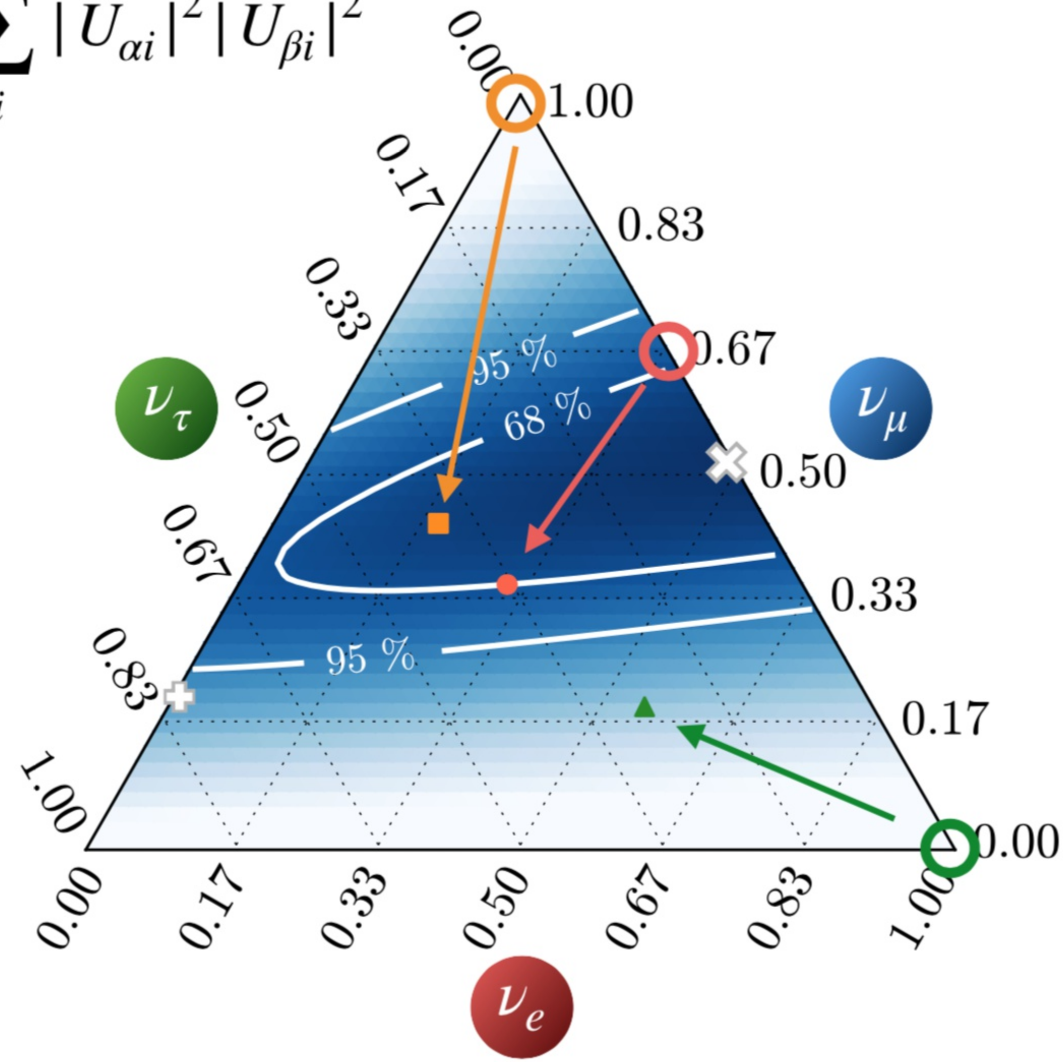
Difficult to produce neutrons without charged pions

Astrophysical Flavours

Oscillation of neutrino flavours between source and observatory.

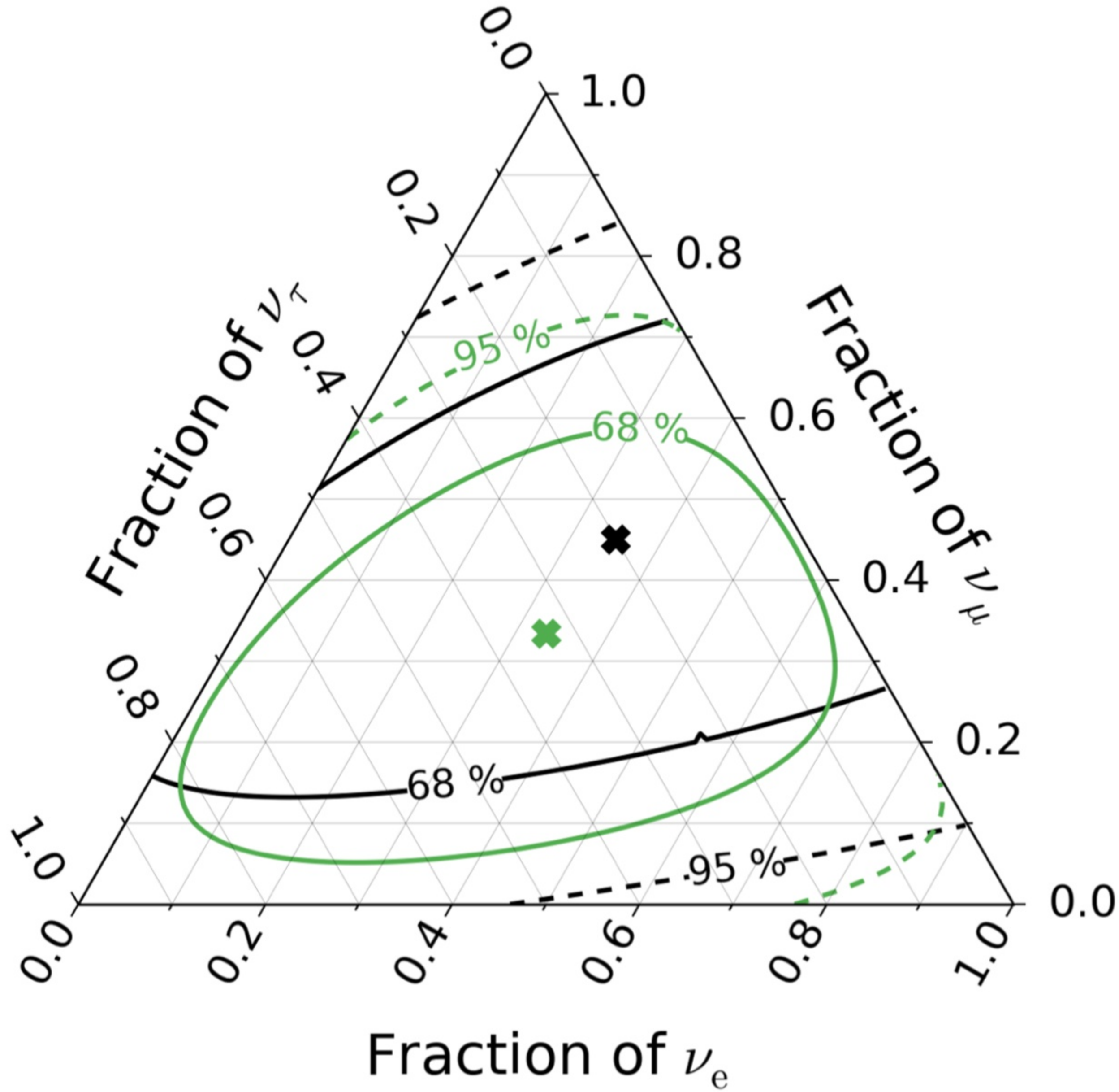


$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$



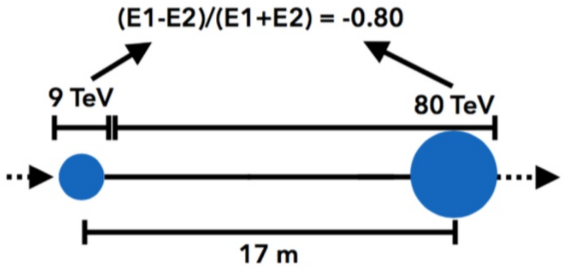
- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  - *pion & muon decay:* 1 : 2 : 0
  - *muon-damped decay:* 0 : 1 : 0
  - *neutron decay:* 1 : 0 : 0

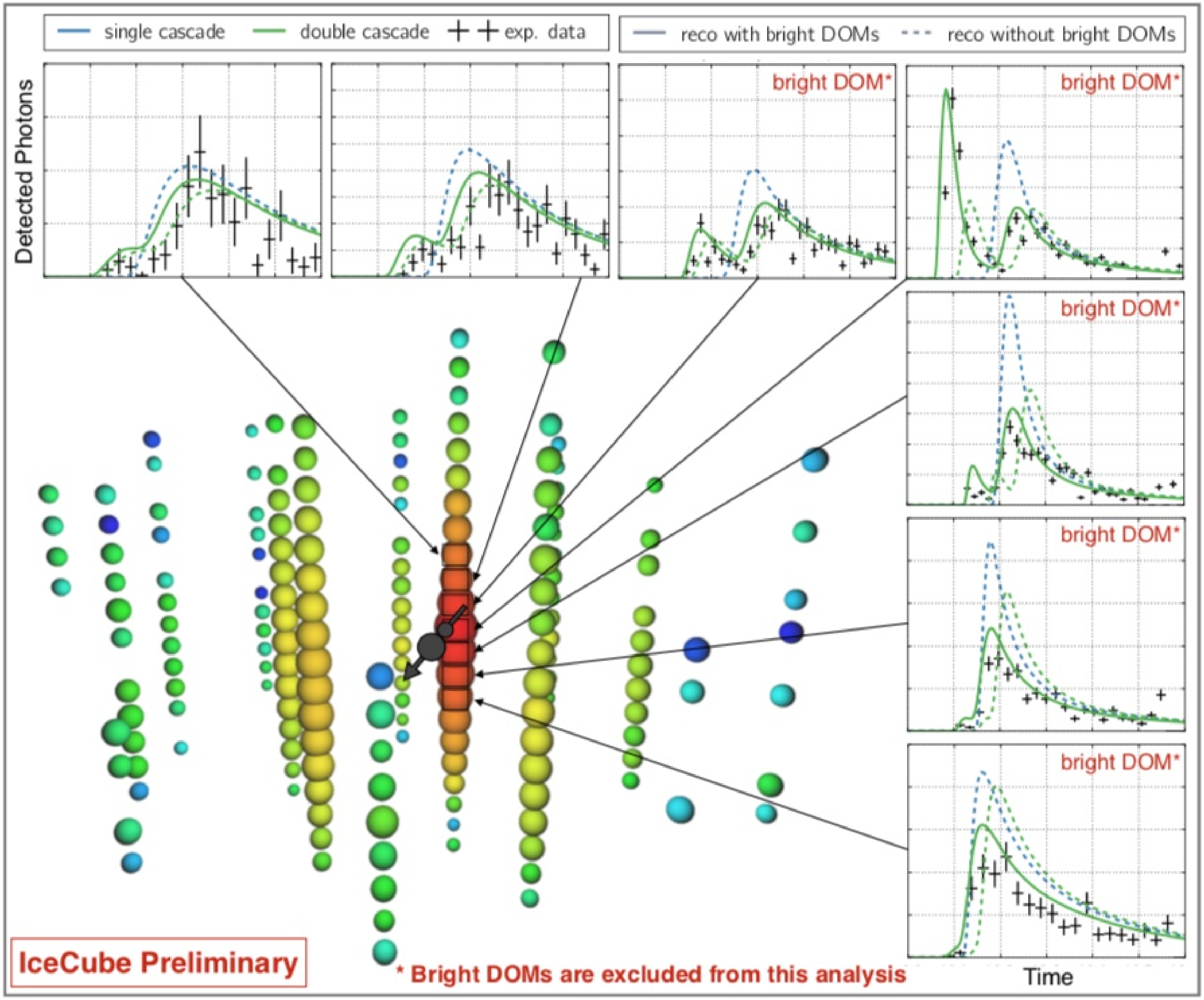
Cosmic neutrinos visible via their oscillation-averaged flavour.



Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
95 %
68 %
68 %
95 %
0.0
0.2
0.4
0.6
0.8
1.0

“Double-Double” tau-neutrino event
[double- cascade + double pulse waveform]





Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

Very High Energy $\sim$ PeV

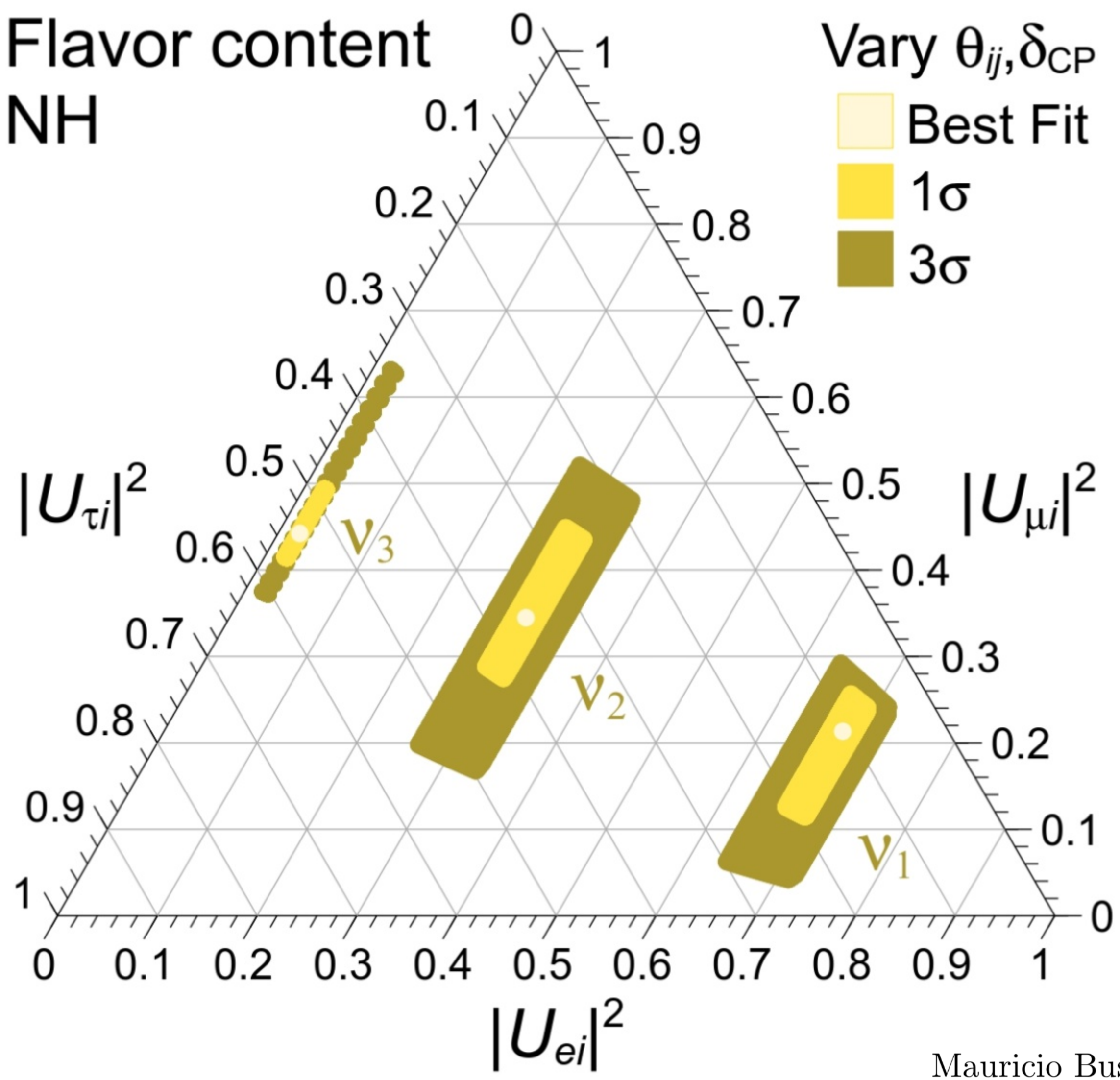
10^6 GeV

Very Long Path-length (extragalactic) $\sim$ Gpc

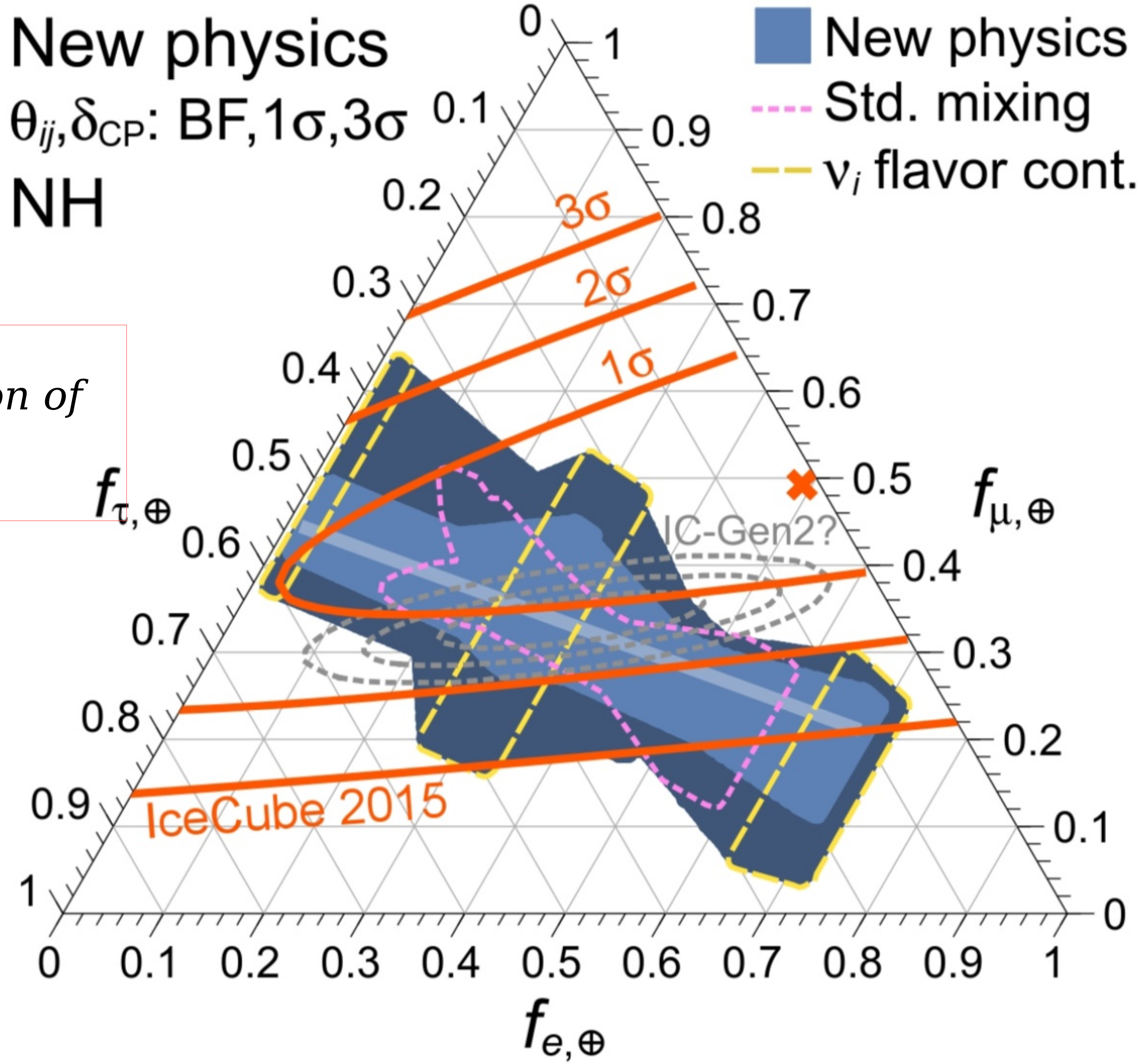
10^{27} cm

Very large (astrophysical) uncertainties about source spectra

Potential to study non-standard neutrino propagation properties



Mauricio Bustamante, John F. Beacom, and Walter Winter, "Theoretically palatable flavor combinations of astrophysical neutrinos", Phys. Rev. Lett. 115, 161302 (2015), arXiv:1506.02645 [astro-ph.HE].



General superposition of

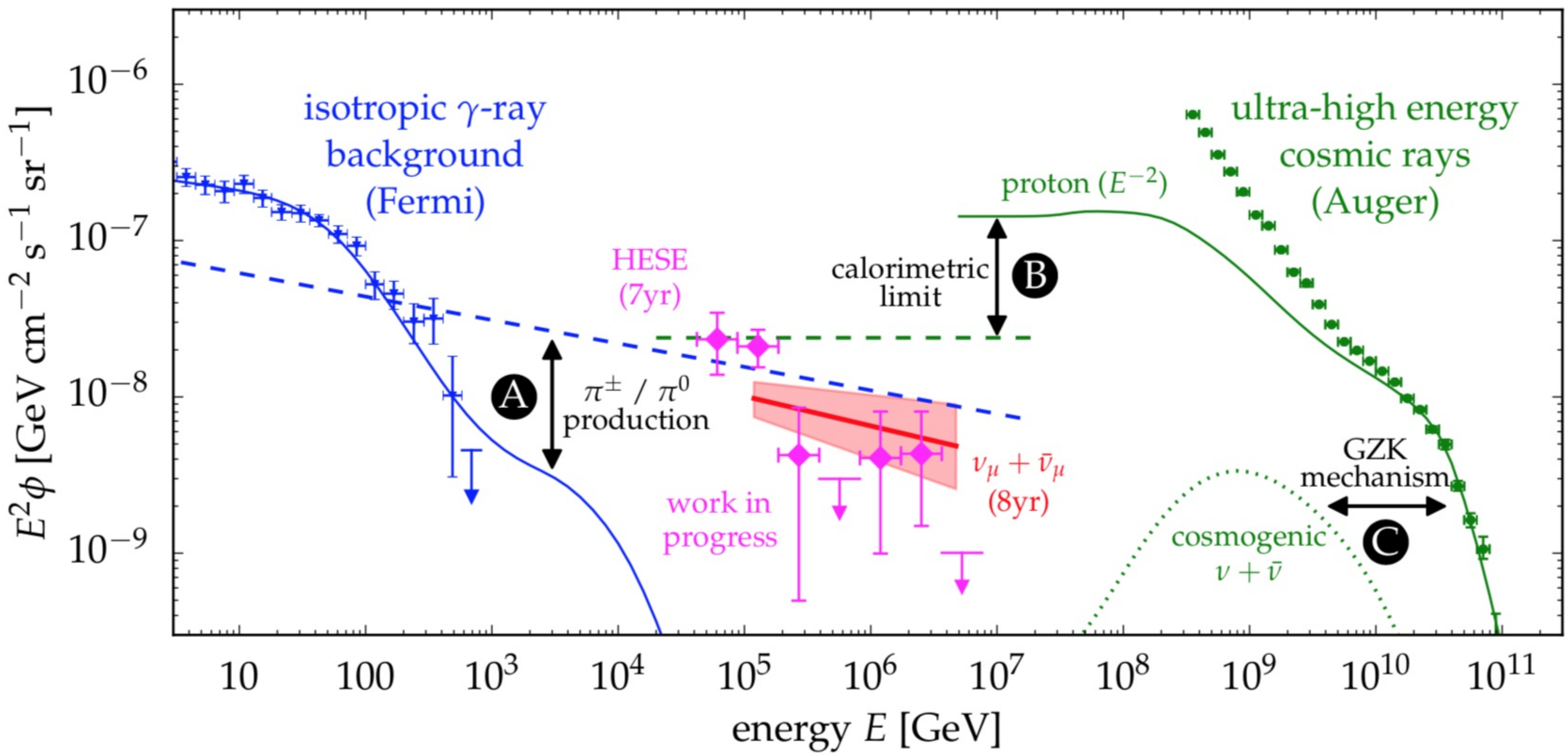
$\nu_1 \quad \nu_2 \quad \nu_3$

New physics effects can fill the “forbidden” area

$$\propto k\ E^n\ L$$

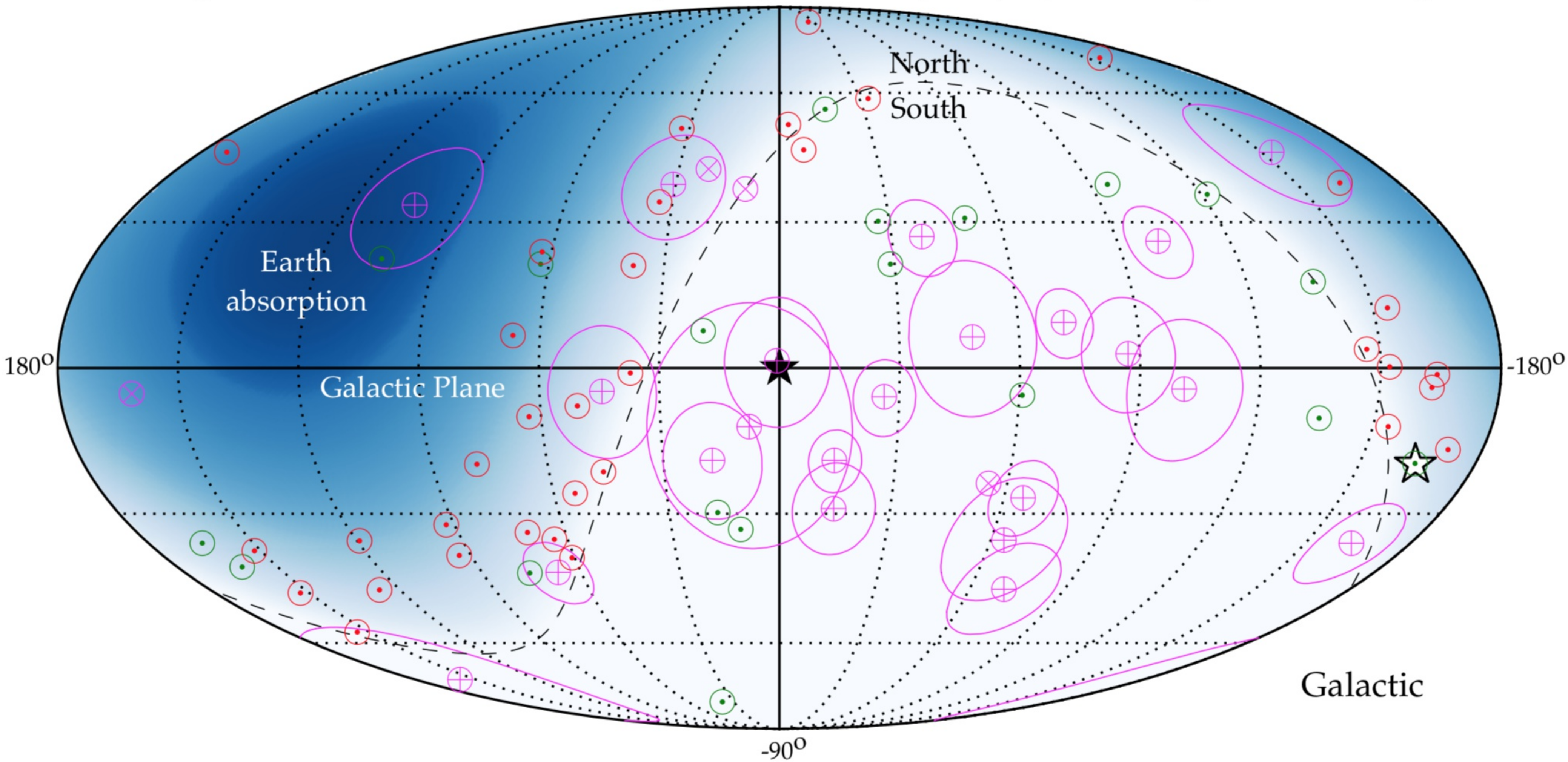
Diffuse TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (7yrs):** [Science 342 (2013); work in progress]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (8yrs):** [Astrophys.J. 833 (2016); update ICRC 2017]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption

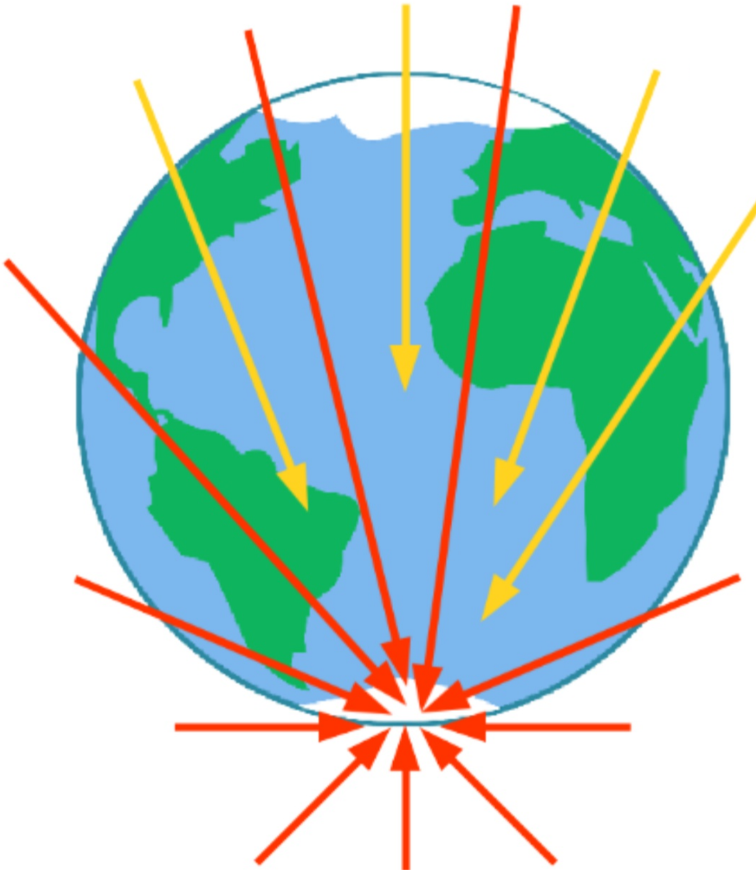


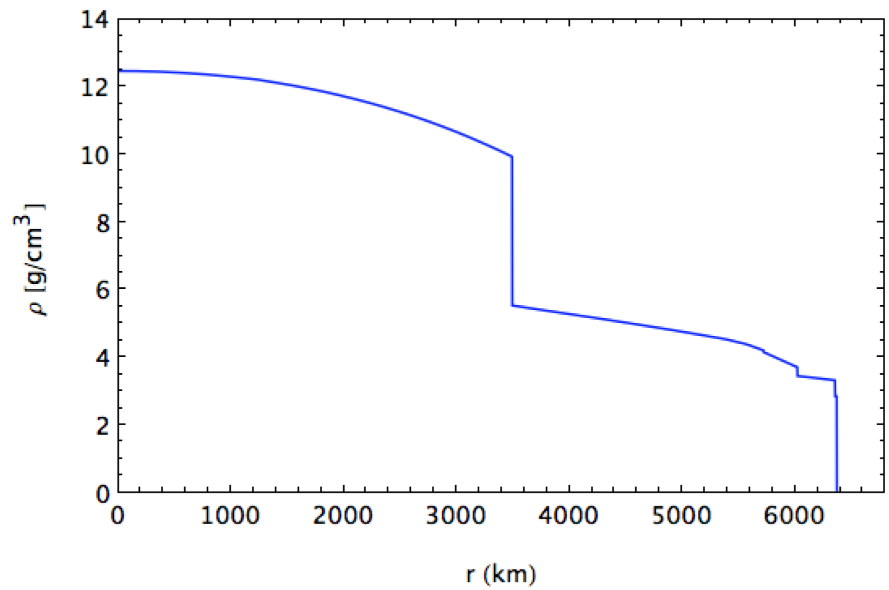
Status of Neutrino Astronomy

Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red) + public alerts (green))

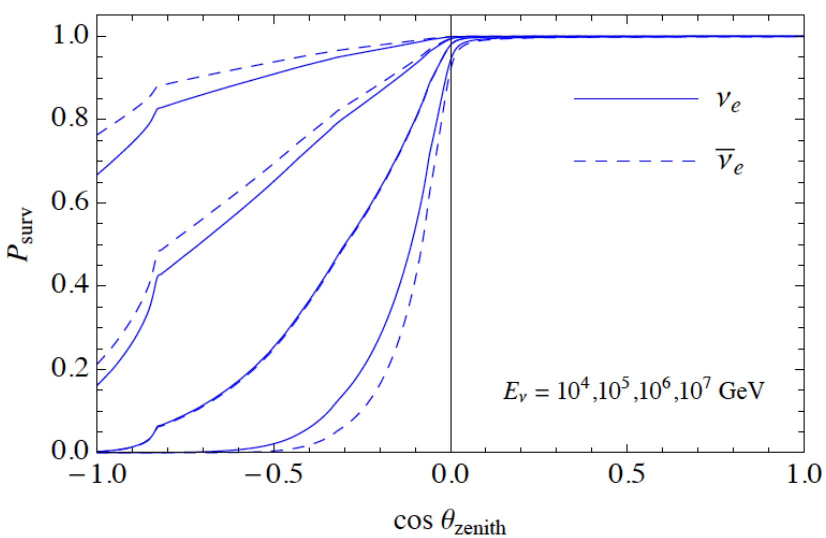


No significant steady or transient emission from known Galactic and extragalactic high-energy sources (except for one candidate).





$$P_{\rm surv} = e^{-\tau(E,\Omega)}$$

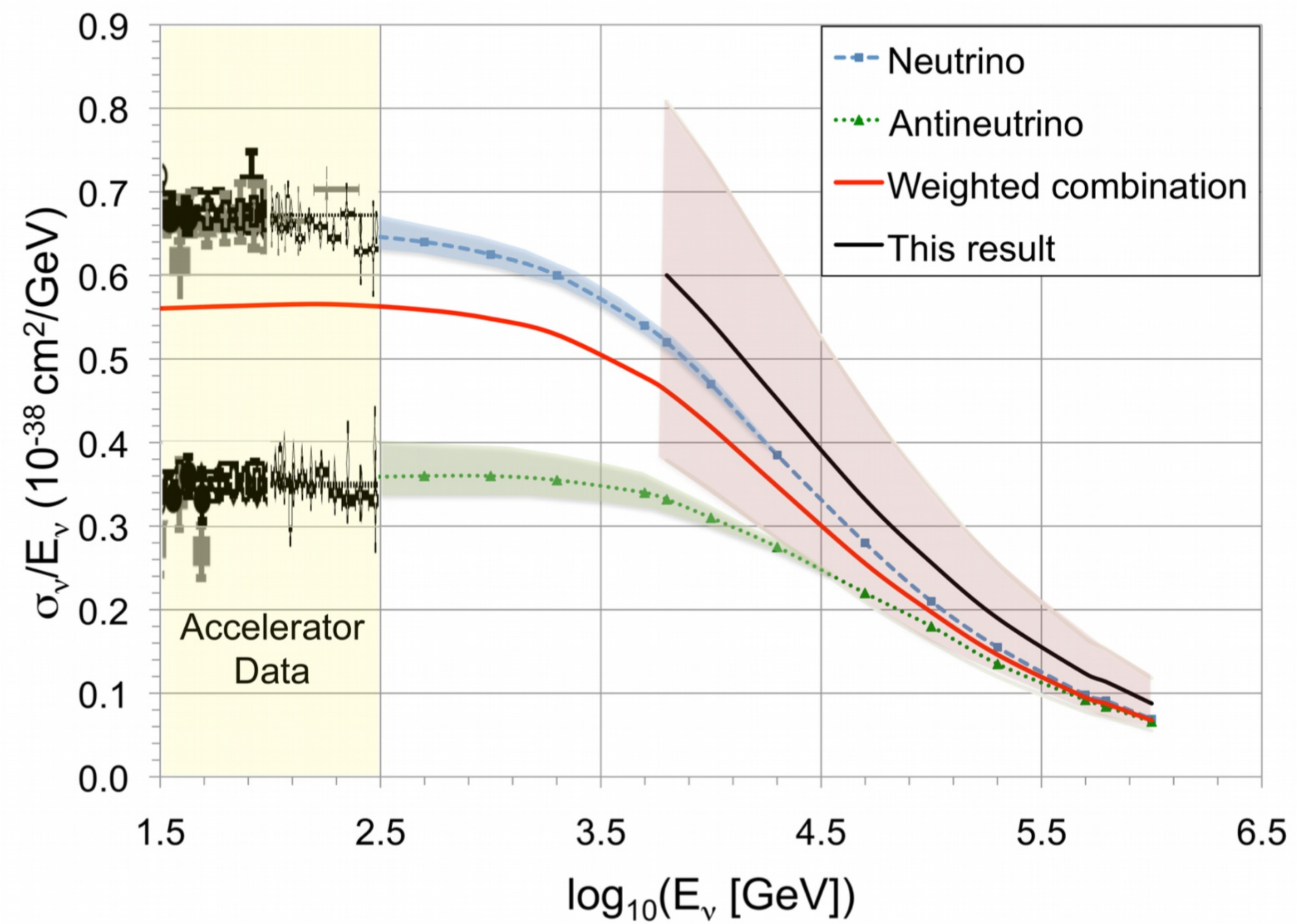


$$\tau = \frac{X}{m_p}\,\sigma_\nu$$

$$\frac{X_\oplus}{m_p} \simeq 6.5\ \mathrm{nb}^{-1}$$

$$\tau = 1 \Longleftrightarrow E \simeq 40\ \mathrm{TeV}$$

IceCube result

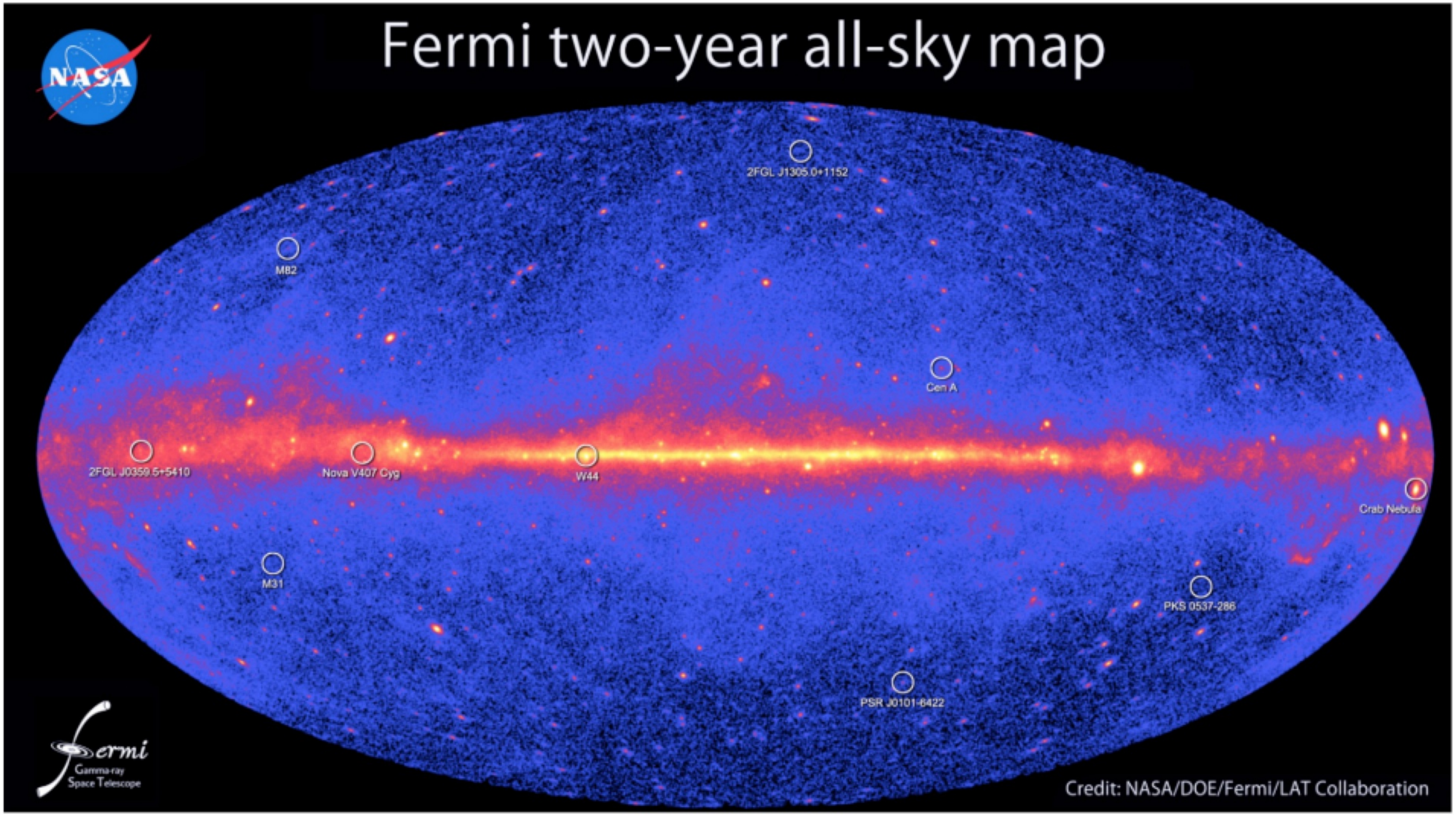


Based on up-going muons

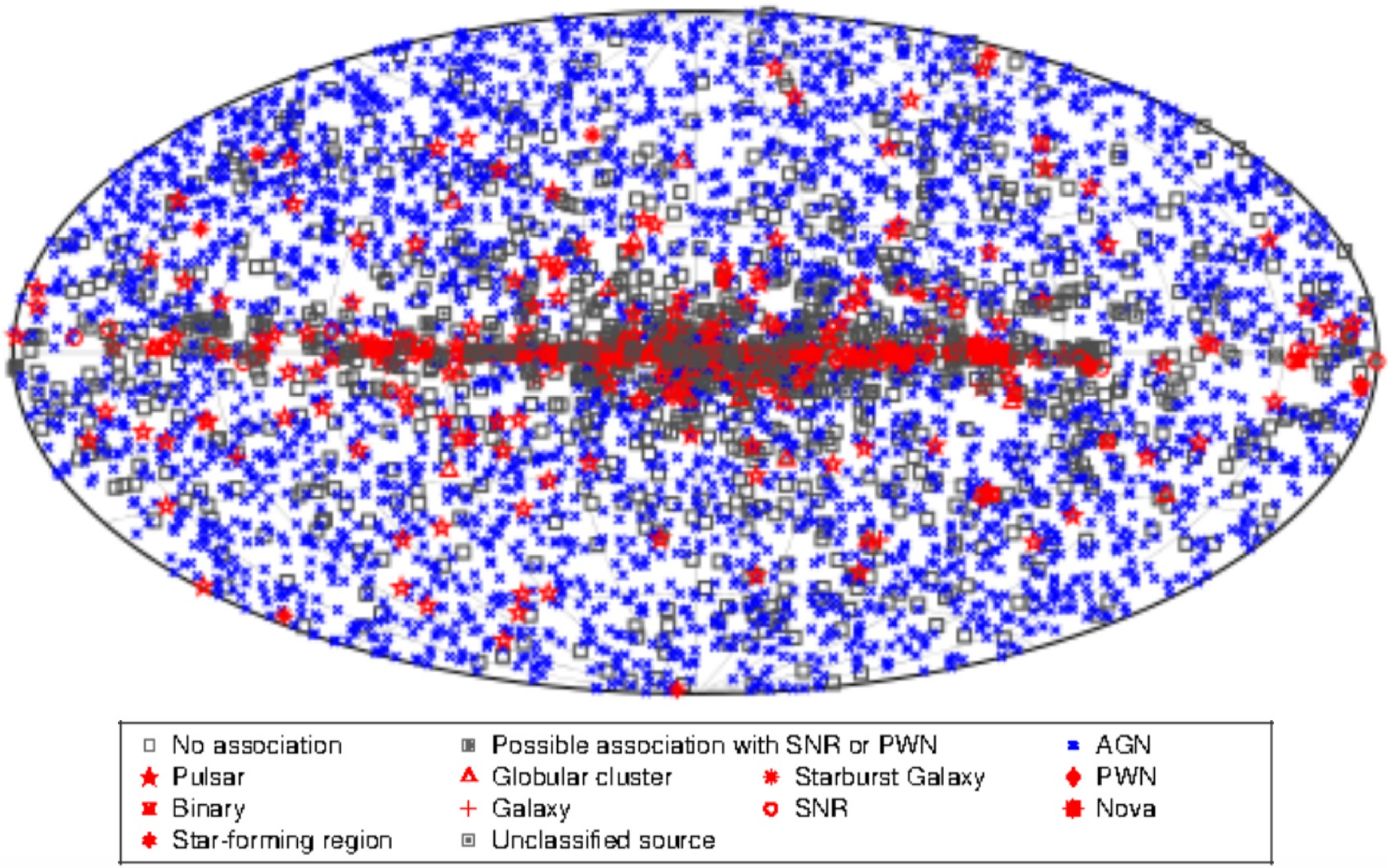
$$E_\mu \gtrsim 6 \text{ TeV}$$

$$\frac{\sigma_{\rm obs}}{\sigma_{\rm SM}} \simeq 1.30^{+0.21}_{-0.19} \text{ (stat.) } {}^{+0.39}_{-0.43} \text{ (syst.)}$$

$E_\gamma \geq 100$ MeV



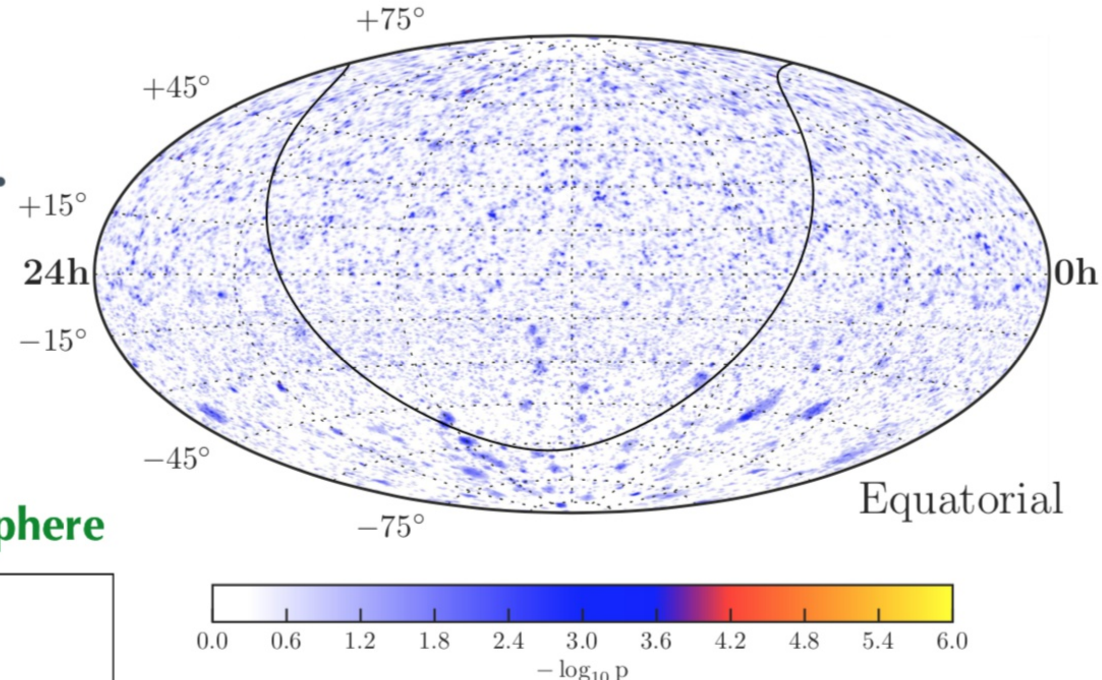
Comparing the Gamma-ray and the Neutrino sky


No association
Possible association with SNR or PWN
AGN
Pulsar
Globular cluster
Starburst Galaxy
PWN
Binary
Galaxy
SNR
Nova
Star-forming region
Unclassified source

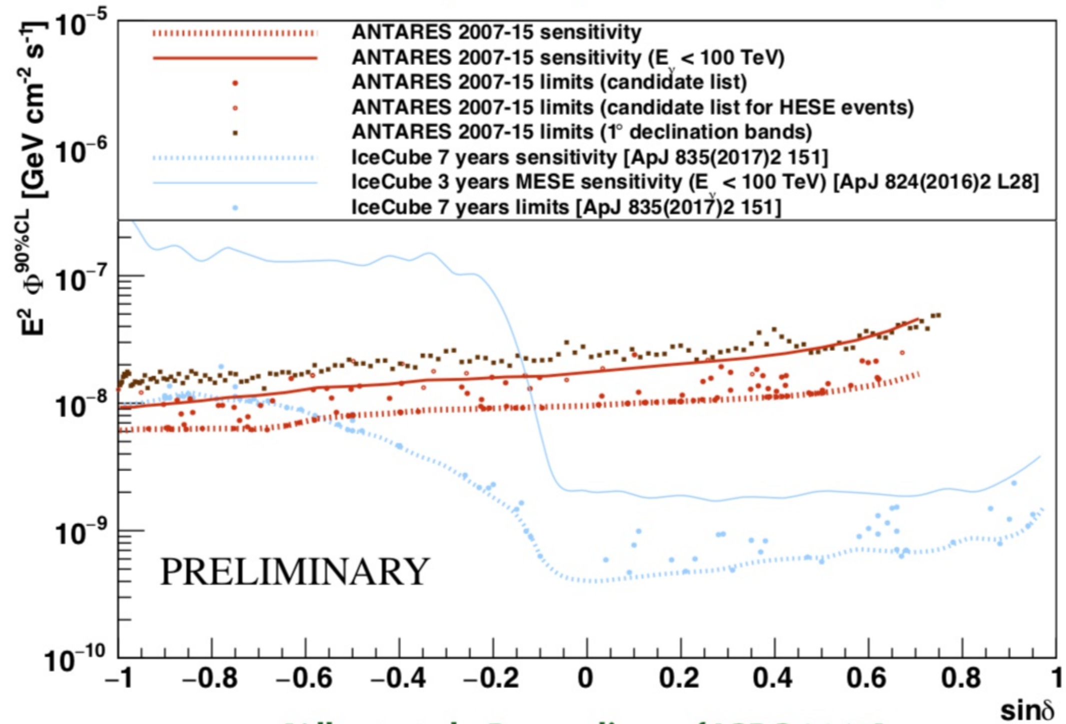
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere



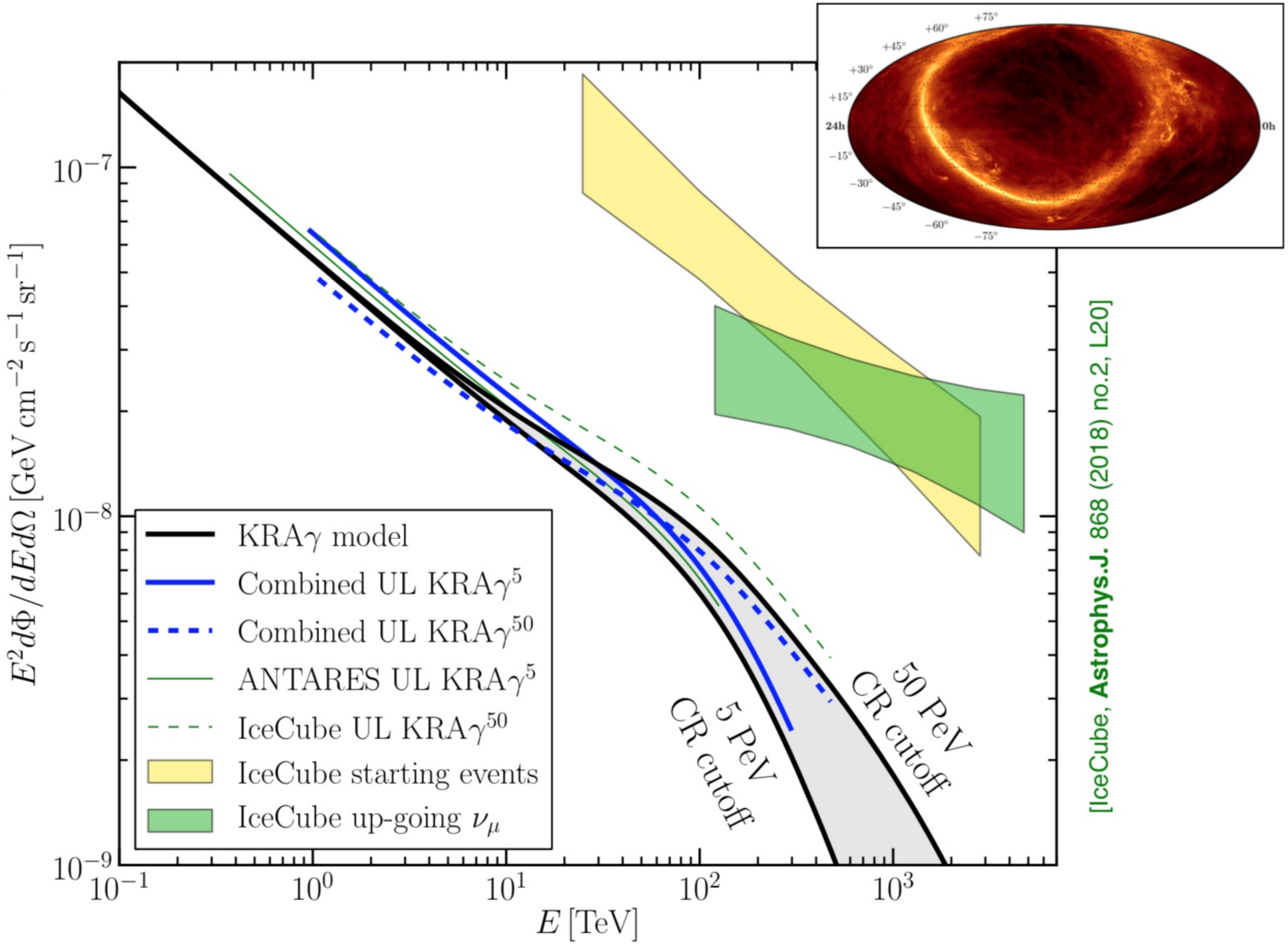
[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]



[Albert et al., Proceedings of ICRC 2017]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

Galactic Neutrino Emission

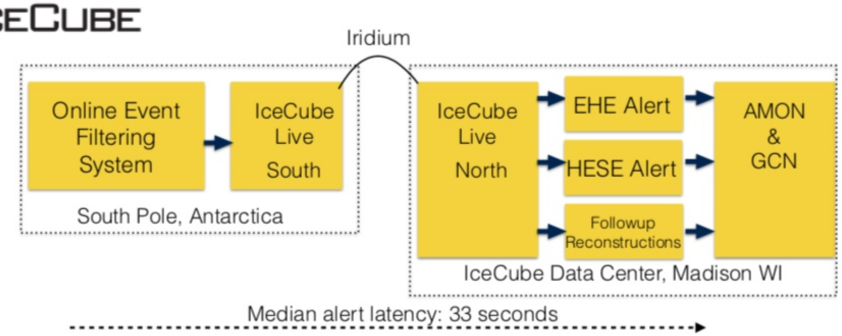


[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Realtime Neutrino Alerts

IceCube and ANTARES issue realtime neutrino alerts to multi-messenger partners for rapid follow-up.



- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- **high-energy starting tracks** (>60TeV)
  - 4.8 alerts/year (1.1 signal/year)
- **through-going muons** (>100TeV)
  - 4-5 alerts/year (2.5-4 signal/year)

[Blaufuss et al., Proceedings of ICRC 2017]

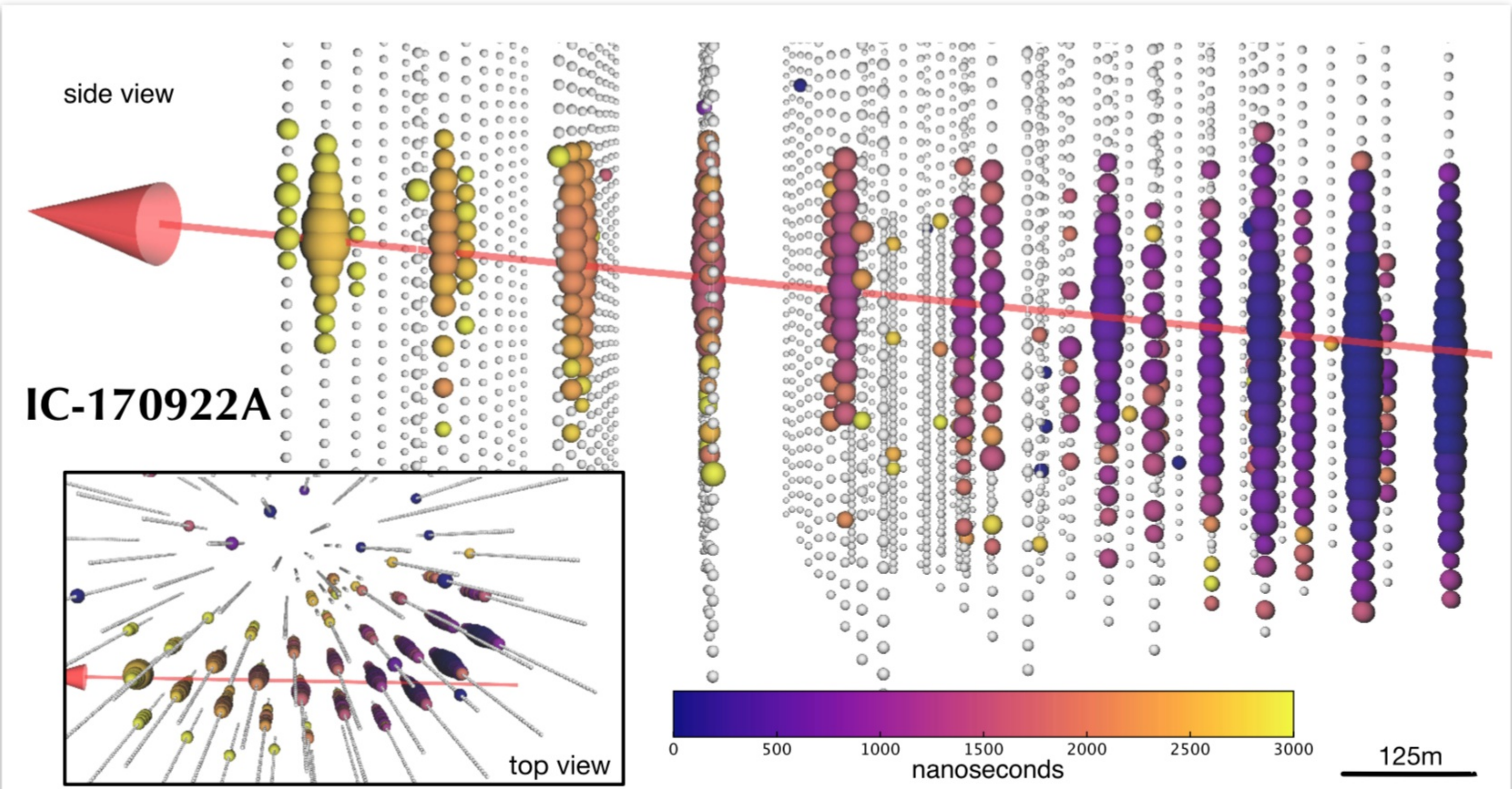
- time to issue alert: 5s
- median angular resolution 0.5deg
- **neutrino doublets**
  - 0.04 alerts/year
- **neutrinos from local galaxies** (>1TeV)
  - 10 alerts/year
- **high-energy neutrinos** (>5TeV)
  - 20 alerts/year
- **very high-energy neutrinos** (>30TeV)
  - 3-4 alerts/year

[Dornic et al., Proceedings of ICRC 2017]

Realtime Neutrino Alerts

IceCube issues realtime neutrino alerts* to multi-messenger partner for rapid follow-up.

[* high-energy muon tracks (likely astrophysical) with good angular resolution (0.5-2deg)]



up-going muon track (5.7° below horizon) observed September 22, 2017

best-fit neutrino energy is about 300 TeV

IceCube GCN 21916 17/09/23

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

“ We encourage follow-up by ground and space-based instruments”

~~A~~ The neutrino event in IceCube

TXS 0506+56

High-energy, through going track

Event 130033/50579430-0
Time 2017-09-22 20:54:30 UTC
Duration 22468.0 ns

IC170922A
Alert sent
Sep 22, 2017
via *Realtime* stream

Coincident observations by Fermi-LAT and MAGIC

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka* ... *Daniel Kocevski (NASA/M...*

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B.* ... *cester), and F. E. Marshall* ... *e collaboration:*

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DE... (OSU), T. W.-S. Holoien, B. J... (Diego Portale...*

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.* ... *AR), M. Tavani (INAF/IAPS, and Univ.* ... *-Bo), P. Munar-Adrover, G. Minervini,* ... *A-Brera), I. Donnarumma (ASI), V.* ... *(CIFS and INAF/IAPS), M. Cardillo* ... *tti, M. Trifoglio (INAF/IASF-Bo), A.* ... *tti (INAF/IASF-Mi), A. Chen (Wits* ... *onte, Y. Evangelista, M. Feroci, F.* ... *Soffitta, S. Sabatini, V. Vittorini* ... *ENEA-Frascati), G. Di Cocco, F.* ... *(INAF/IASF-Bo), A. Pellizzoni, M.* ... *llini, E. Vallazza (INFN Trieste), F.* ... *orselli, P. Picozza (INFN and Univ.* ... *ia), P. Lipari, D. Zanello (INFN and* ...

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; *D. B. Fox (PSU), J. J... (U. Leicester), C. F. Turley (PSU... Osborne (U. Leicester), M....*

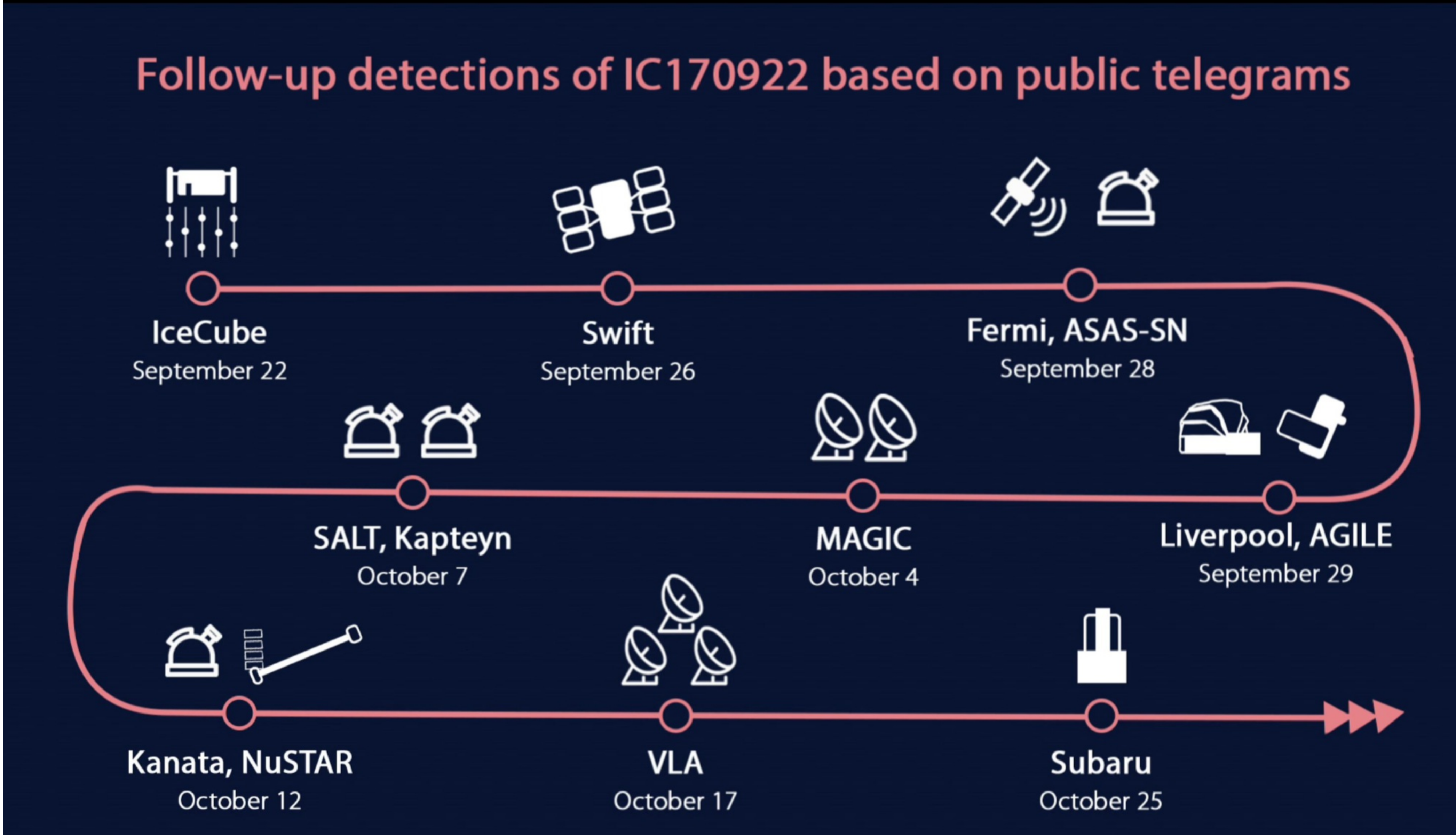
MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara,* ... *ki, S. Nakahira, W. Iwakiri,* ... *N), N. Kawai, S. Sugita, T.* ... *), A. Yoshida, T. Sakamoto,* ... *U), H. Tsunemi, T. Yoneyama* ... *on U.), Y. Ueda, T. Hori, A.*

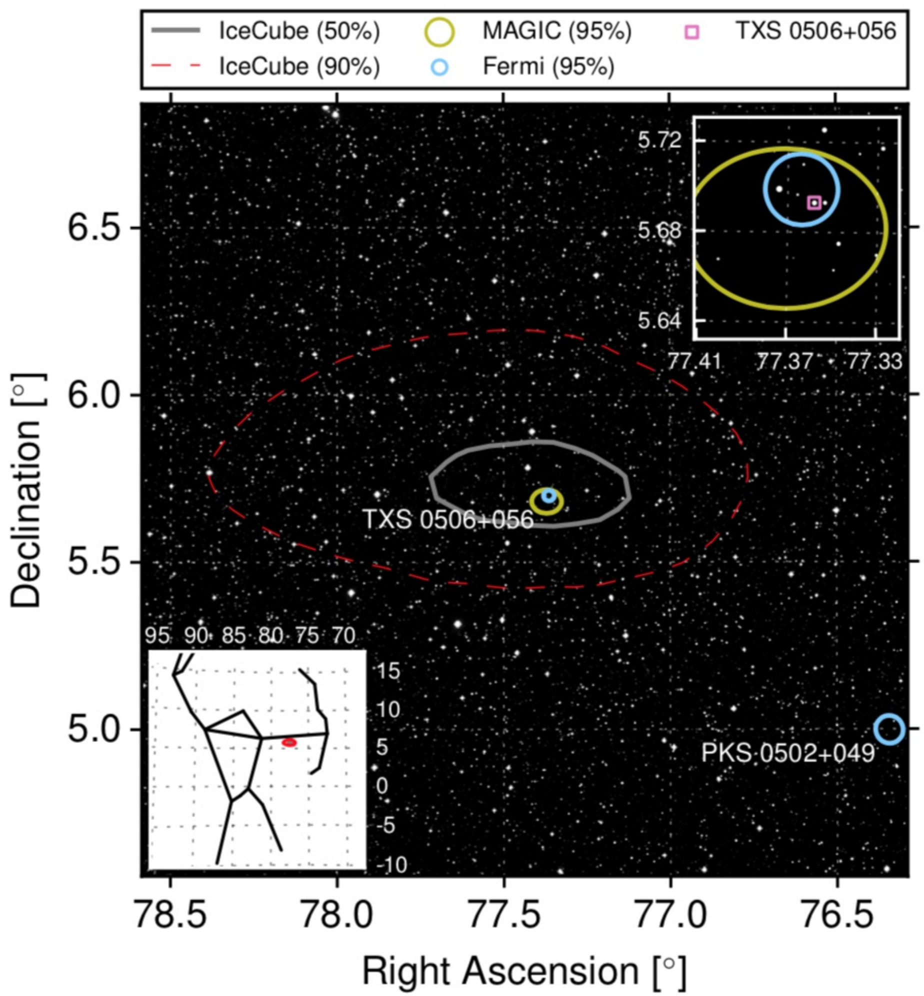
VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

Science 361 (2018) no.6398, eaat1378

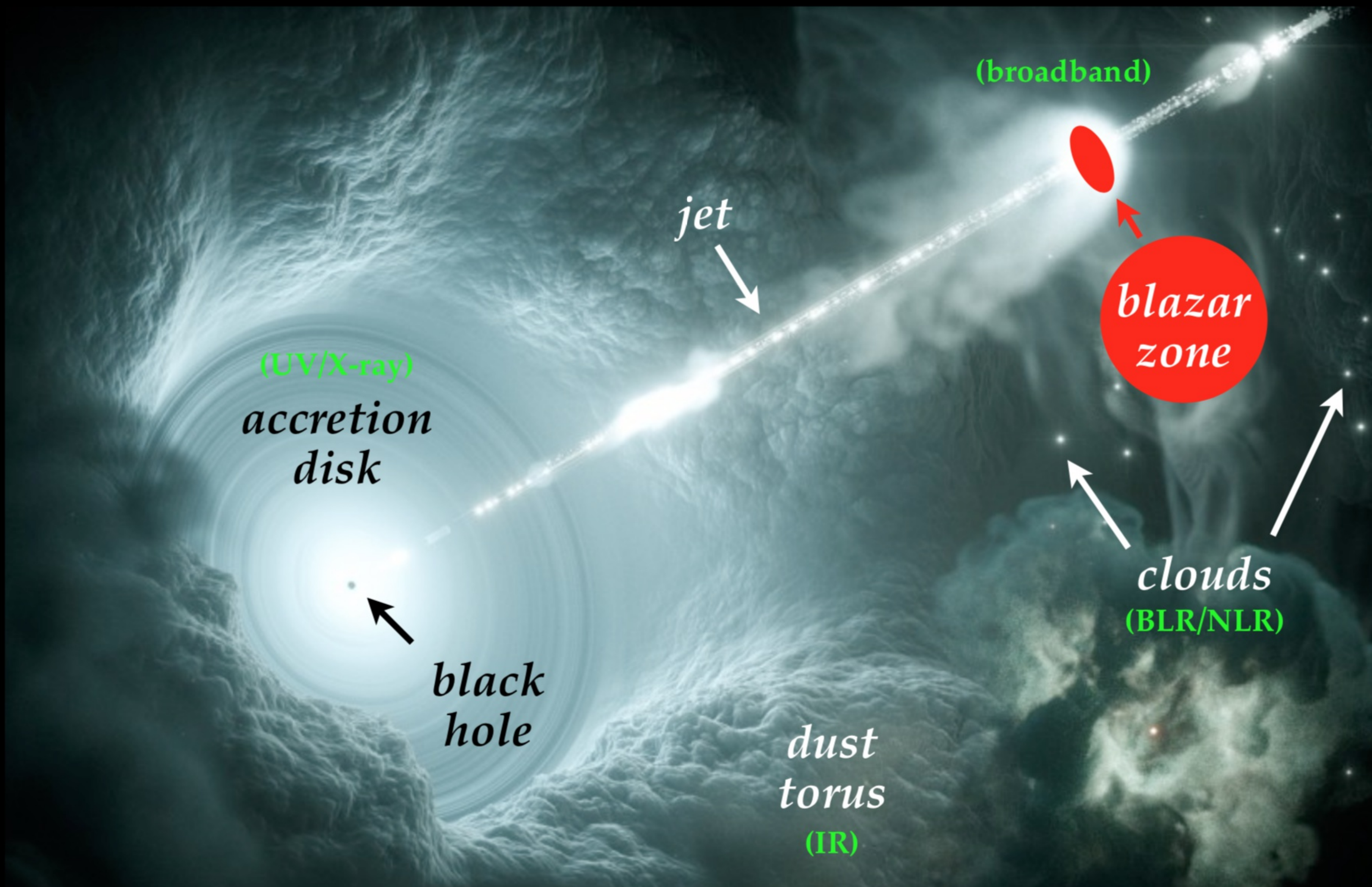

Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
SALT, Kapteyn
October 7
MAGIC
October 4
Liverpool, AGILE
September 29
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25

TXS 0506+056

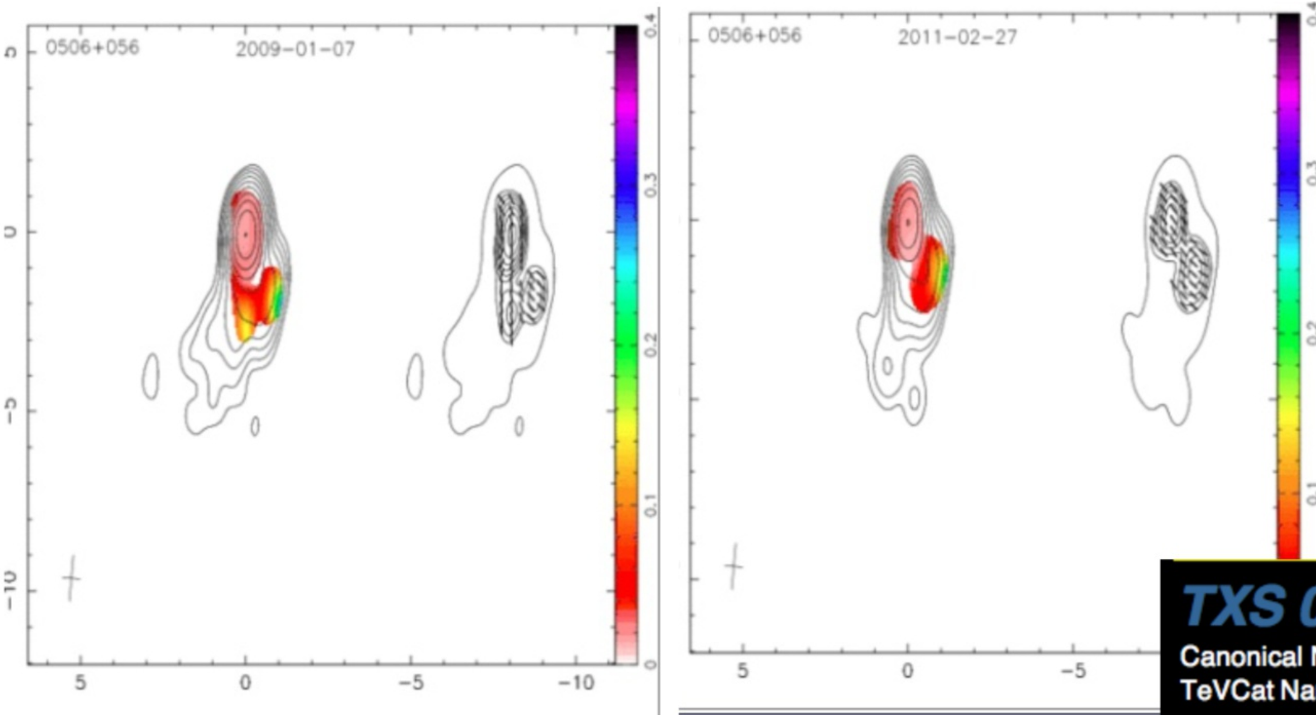


- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Blazars as Neutrino Factories



Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.



TXS 0506+056

$$z = 0.3365 \pm 0.0010$$

$$\dot{\Omega} = 332 \pm 82 \ \mu\text{as/year}$$

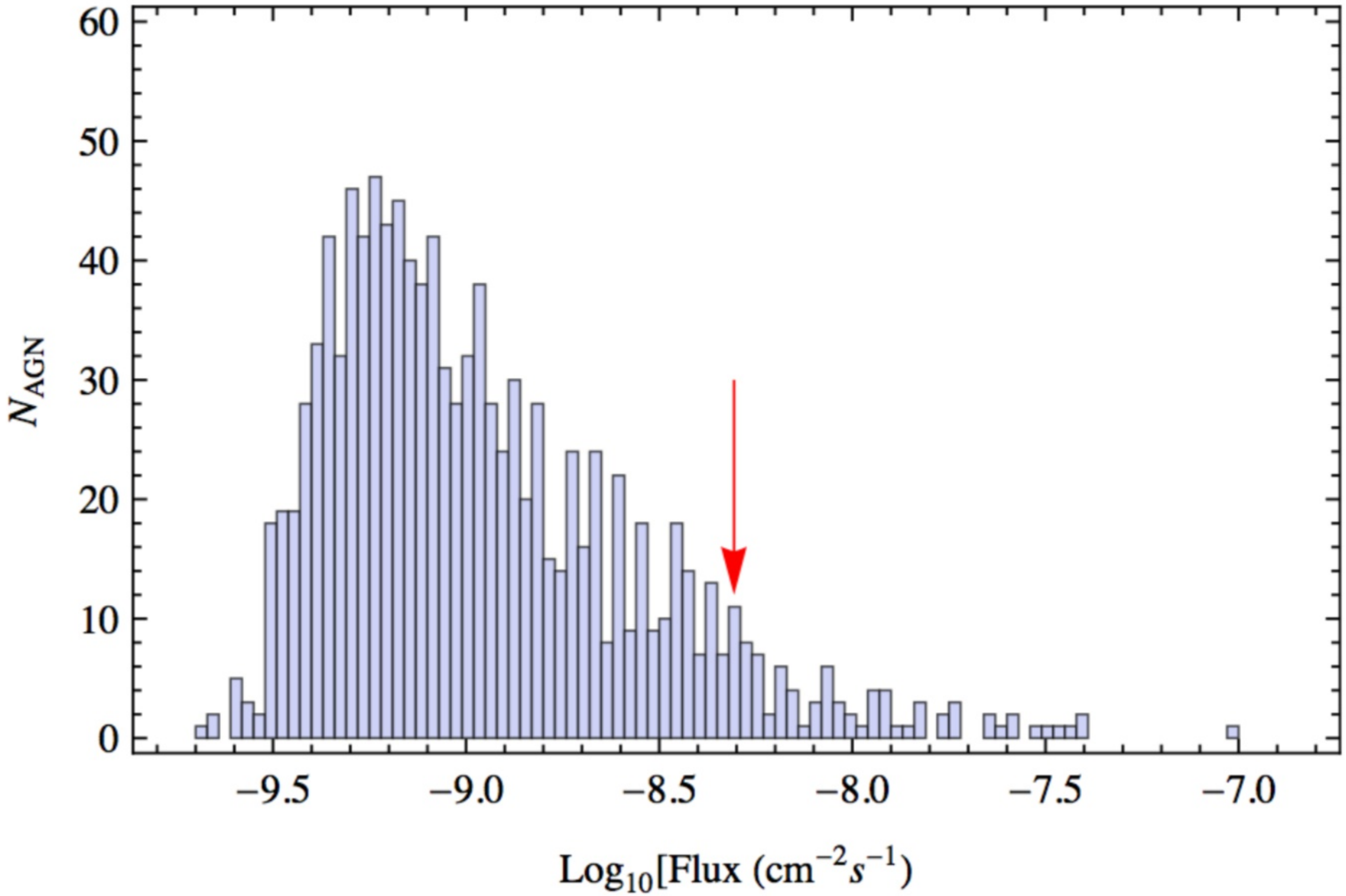
$$d = 706 \ \text{Mpc}$$

$$\beta_{\text{app}} = \frac{\dot{\Omega}\, d}{c} = 3.7 \pm 0.9$$

TXS 0506+056

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 3FGL J0509.4+0541 3FHL J0509.4+0542
Source Type:	Blazar
R.A.:	05 09 25.96370 (hh mm ss)
Dec.:	+05 41 35.3279 (dd mm ss)
Gal Long:	195.41 (deg)
Gal Lat:	-19.64 (deg)
Distance:	z=0.3365
Flux:	(Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced
Source Notes:	

The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916.
Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for gamma-ray emission from positions consistent with the IceCube neutrino error circle which they thus associate with the blazar TXS 0506+056.
Upper limits on the gamma-ray emission from the region were reported by H.E.S.S, HAWC and VERITAS.



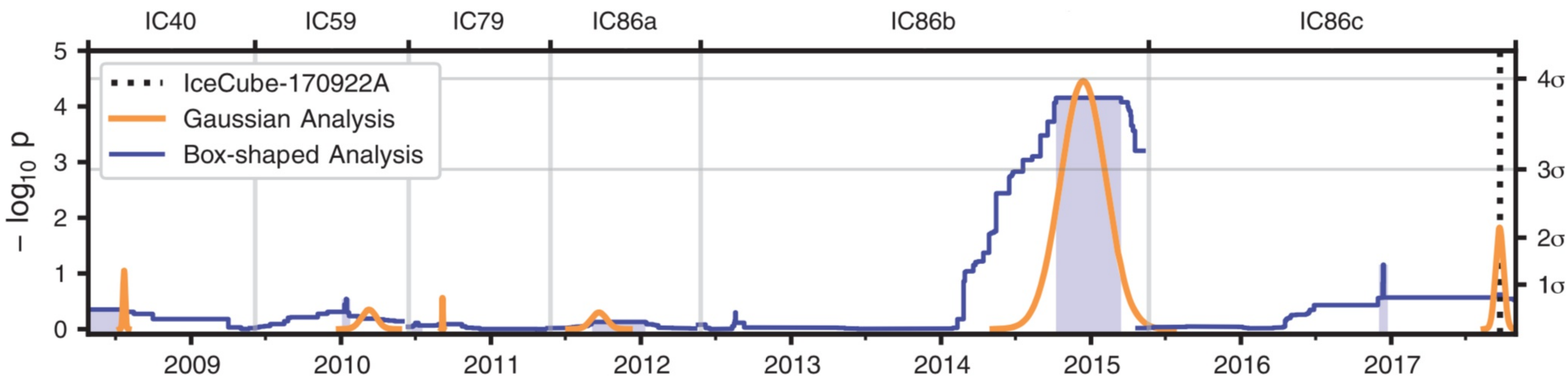
Ranking all
Fermi Blazars
TXS 0506+056 = 80[th]

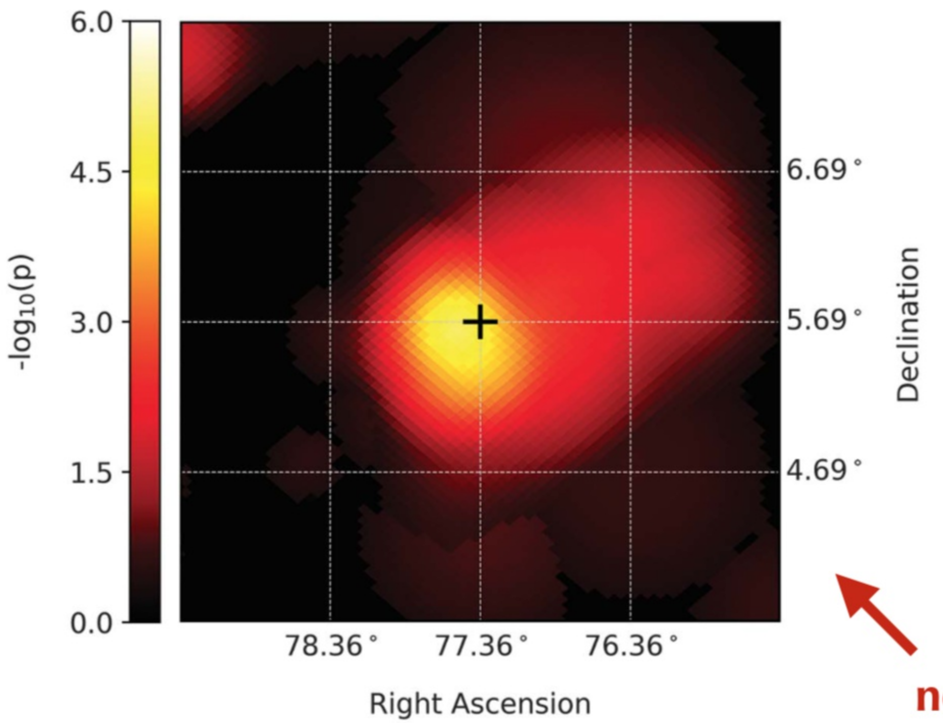
$$\alpha = 2.059 \pm 0.042$$

$$\Phi_\gamma[1 \div 100 \text{ GeV}] = 4.94 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$$

$$L(E) = \phi_\gamma(E) \times E^2 \simeq 4.5 \times 10^{45} \ \frac{\text{erg}}{\text{s}}$$

Neutrino Flare in 2014/15

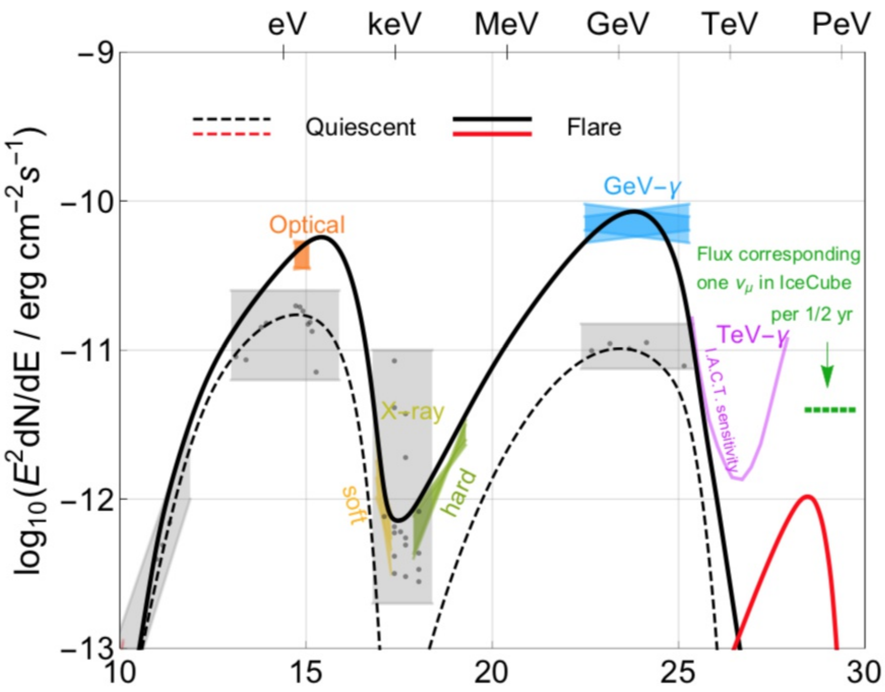




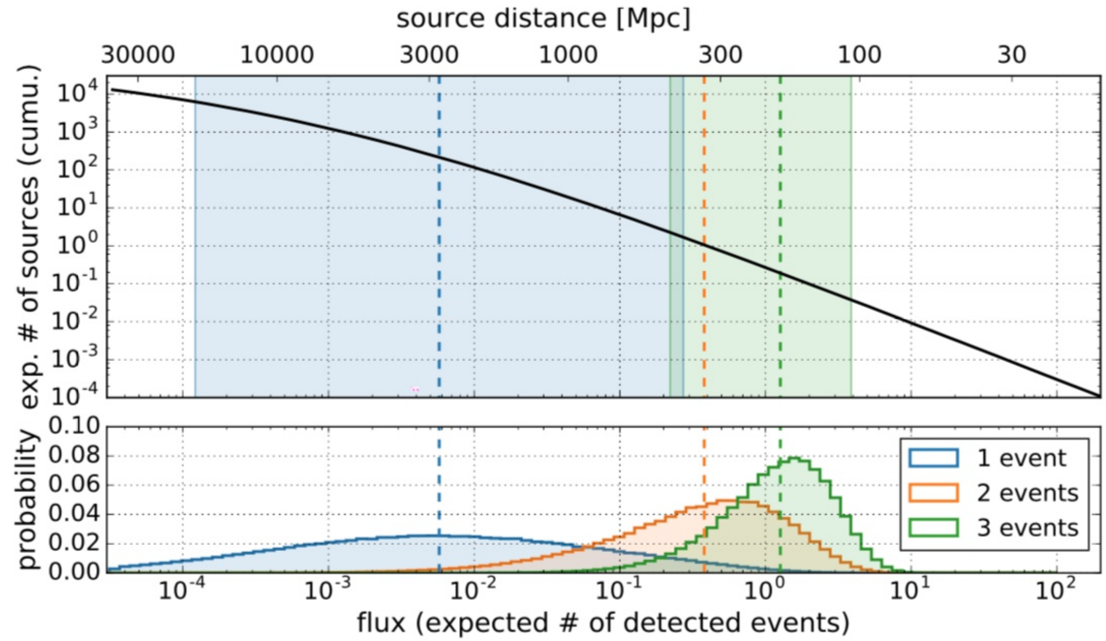
- Independent 3.5σ evidence for a **neutrino flare** (13±5 events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of gamma-rays** (Fermi-LAT).

neutrino "morphology" of flare

Neutrino Flare in 2017



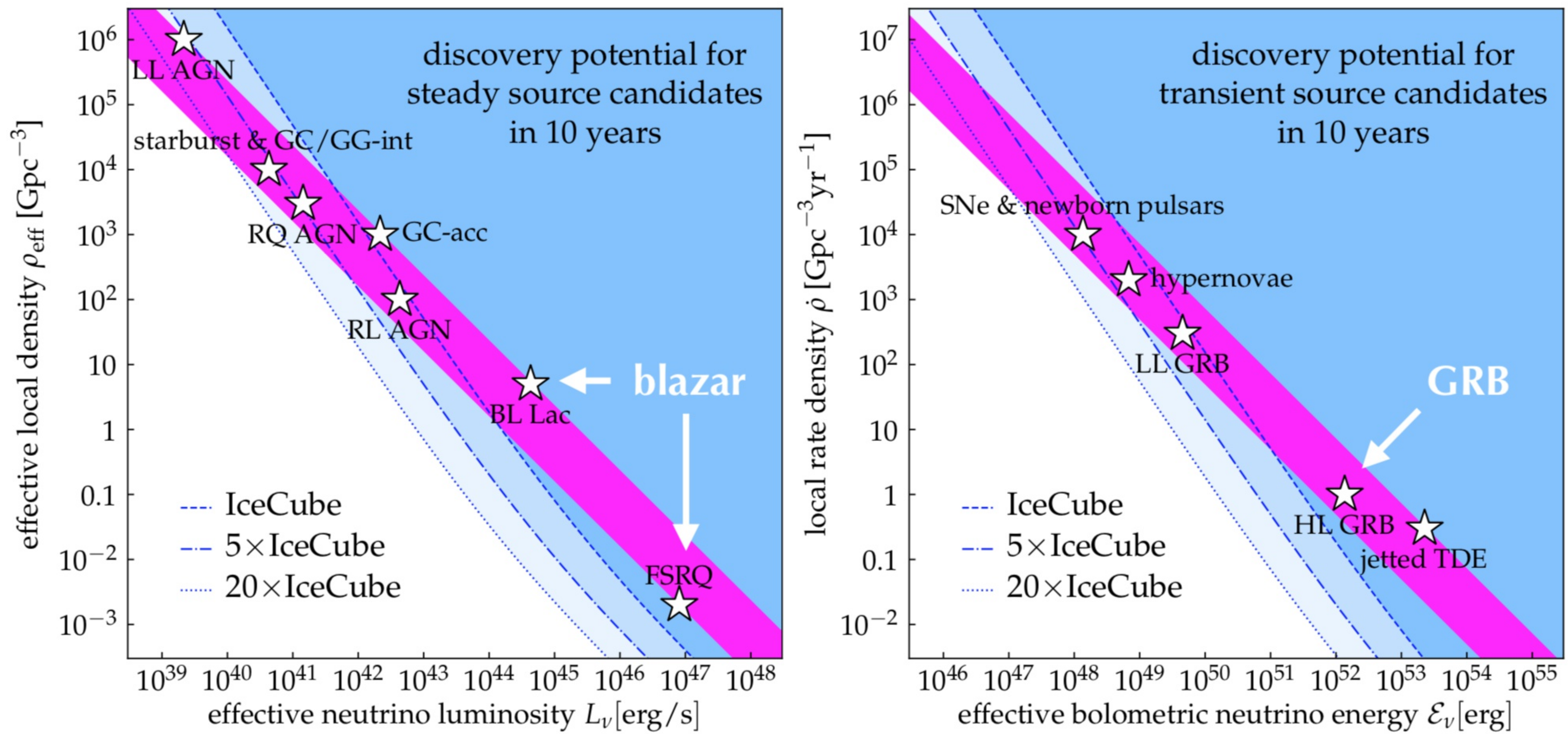
[Gao *et al.*'18]



[Strotjohann, Kowalski & Franckowiak'18]

- Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.
  [Keivani *et al.*'18.; Gao *et al.*'18; Cerruti *et al.*'18; Zhang, Fang & Li'18; Gokus *et al.*'18; Sahakyan'18]
- Neutrino flux limited to **less than one event** by theoretically feasible cosmic ray luminosity and X-ray data. [Murase, Oikonomo & Petropoulou'18]
- **Eddington bias**: expected number of events expected from BL Lacs observed by one event in the range **0.006 - 0.03** [Strotjohann, Kowalski & Franckowiak'18]

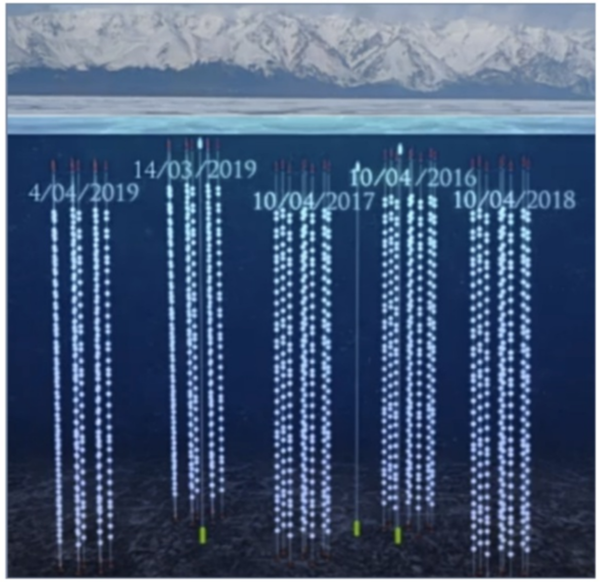
Are Blazars the only Sources?



[Ackermann, MA, Anchordoqui, Bustamante et al., arXiv:1903.04333]

Rare sources, like blazars or gamma-ray bursts, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).

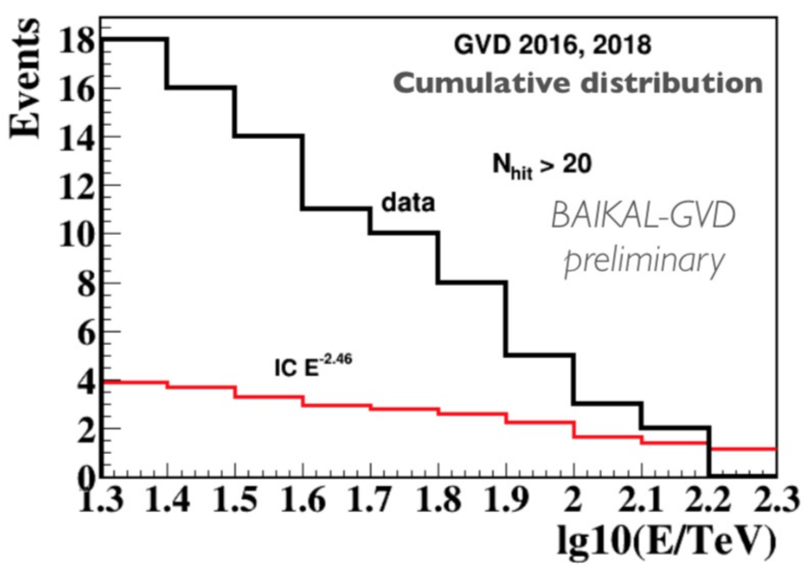
Outlook: Baikal-GVD

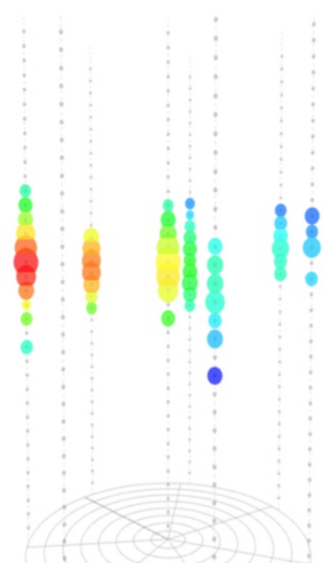


present detector outline (2019)

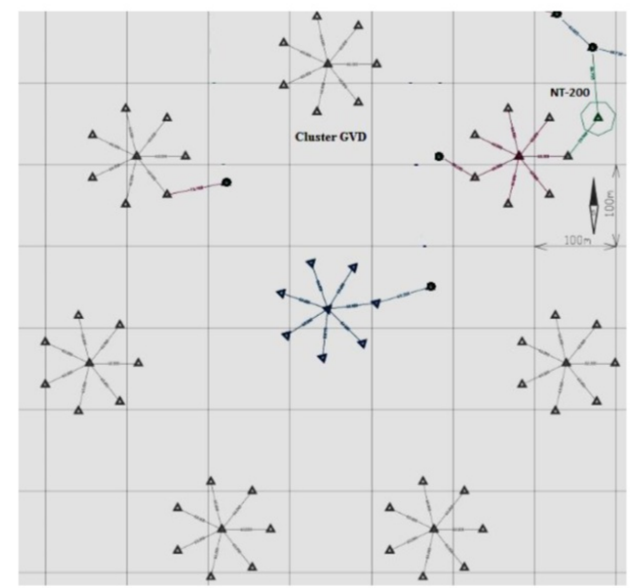
- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- since April 2019: 5 clusters
- **final goal**: 27 clusters (~1.4 km³)

BAIKAL-GVD





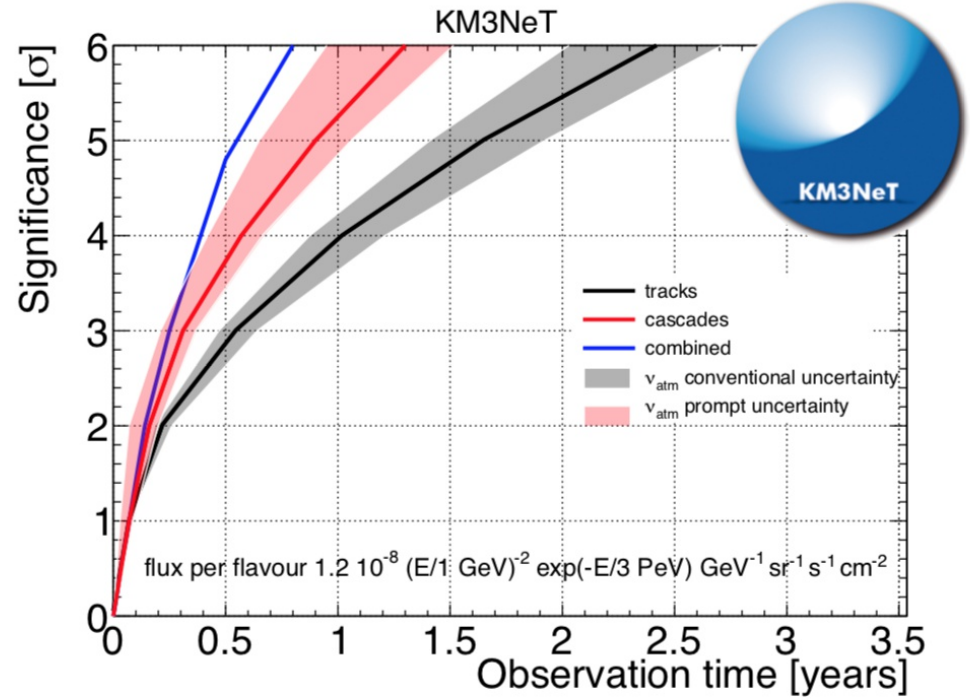
~157 TeV cascade event



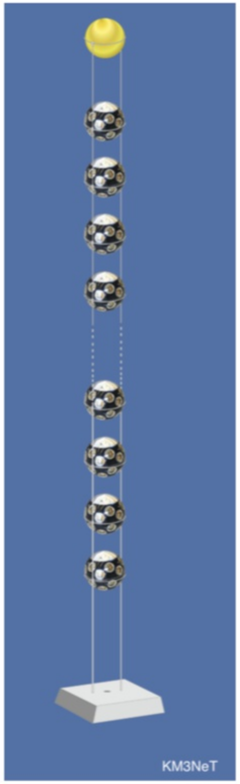
GVD-Phase 1

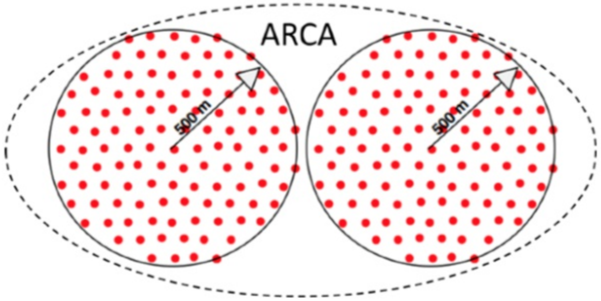
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km^3)
- 3 DU deployed off the coast of Italy (1 DU recovered after shortage)
- 2 DUs operated until March 2017



detection unit with multi-PMT DOMs

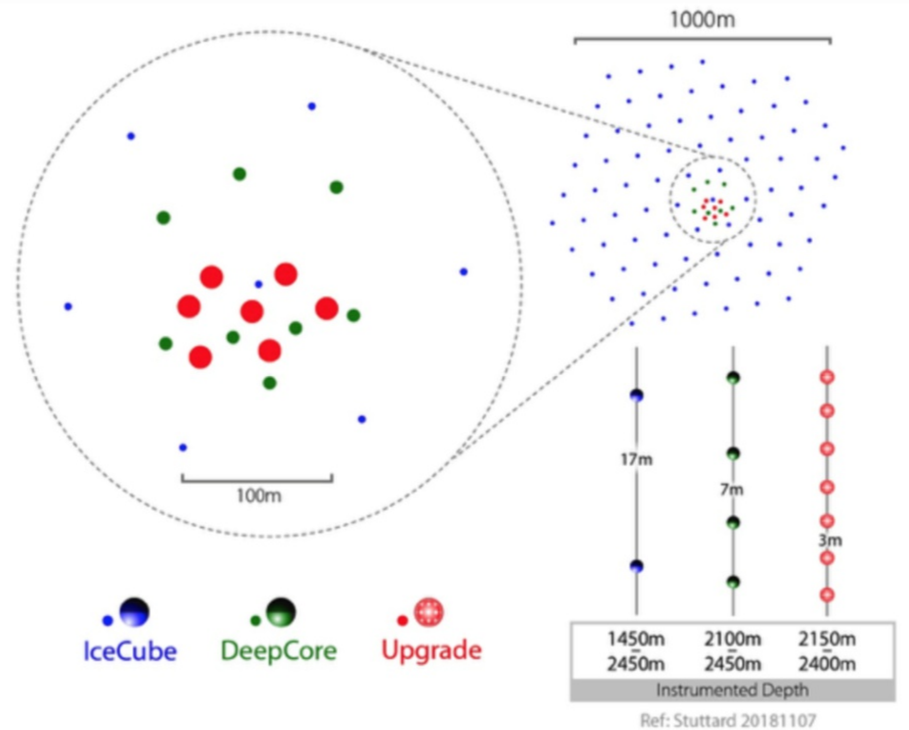


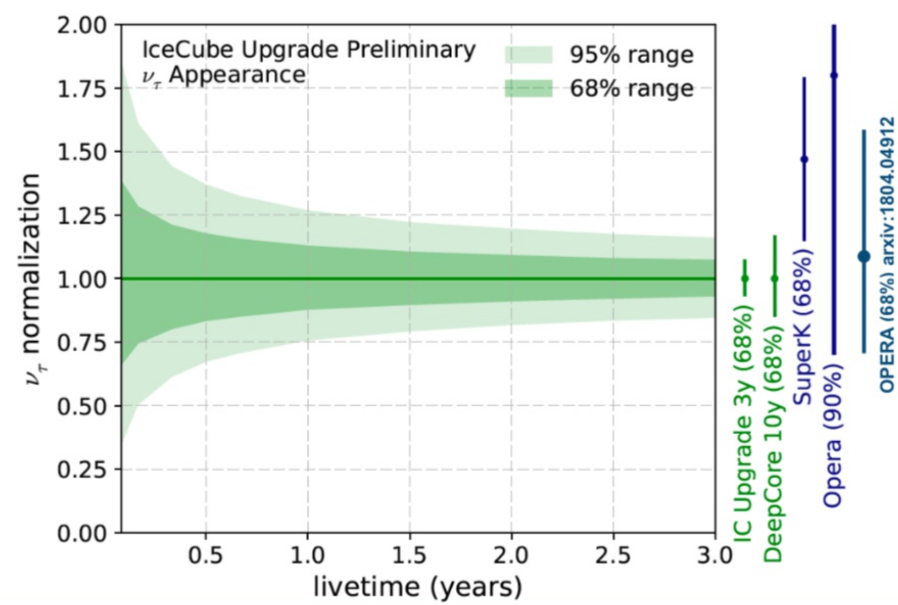


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Outlook: IceCube Upgrade

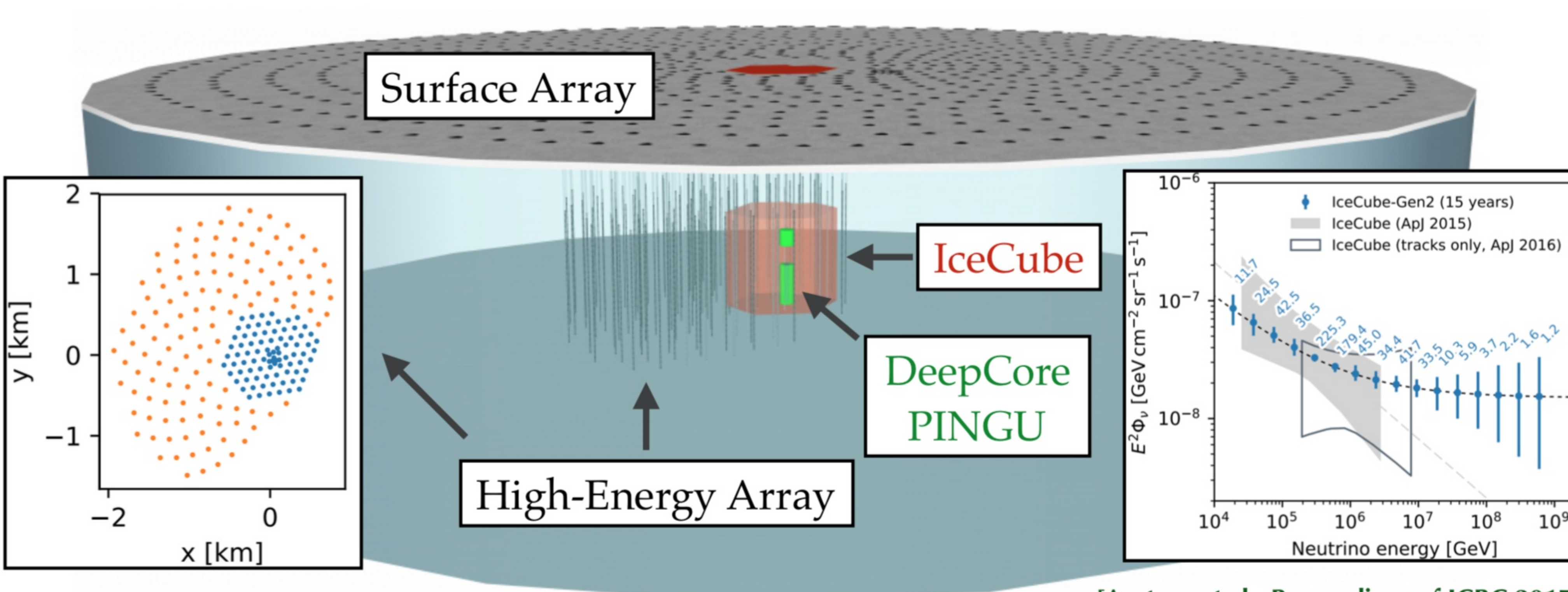
- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.
- **Precision measurement** of atmospheric neutrino oscillation.
- Midscale NSF project with an estimated total cost of $23M.
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2022/23**





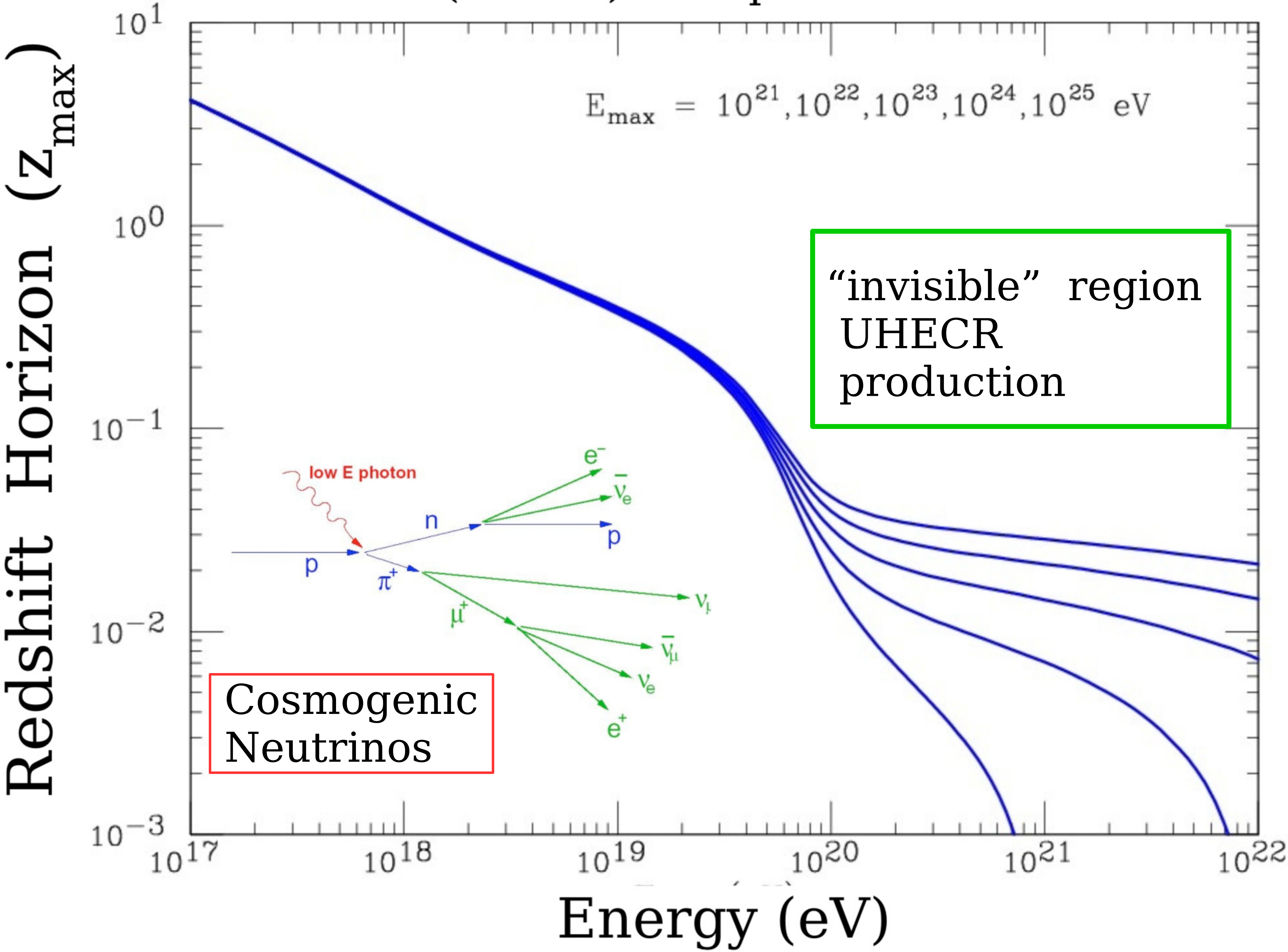
Vision: IceCube-Gen2

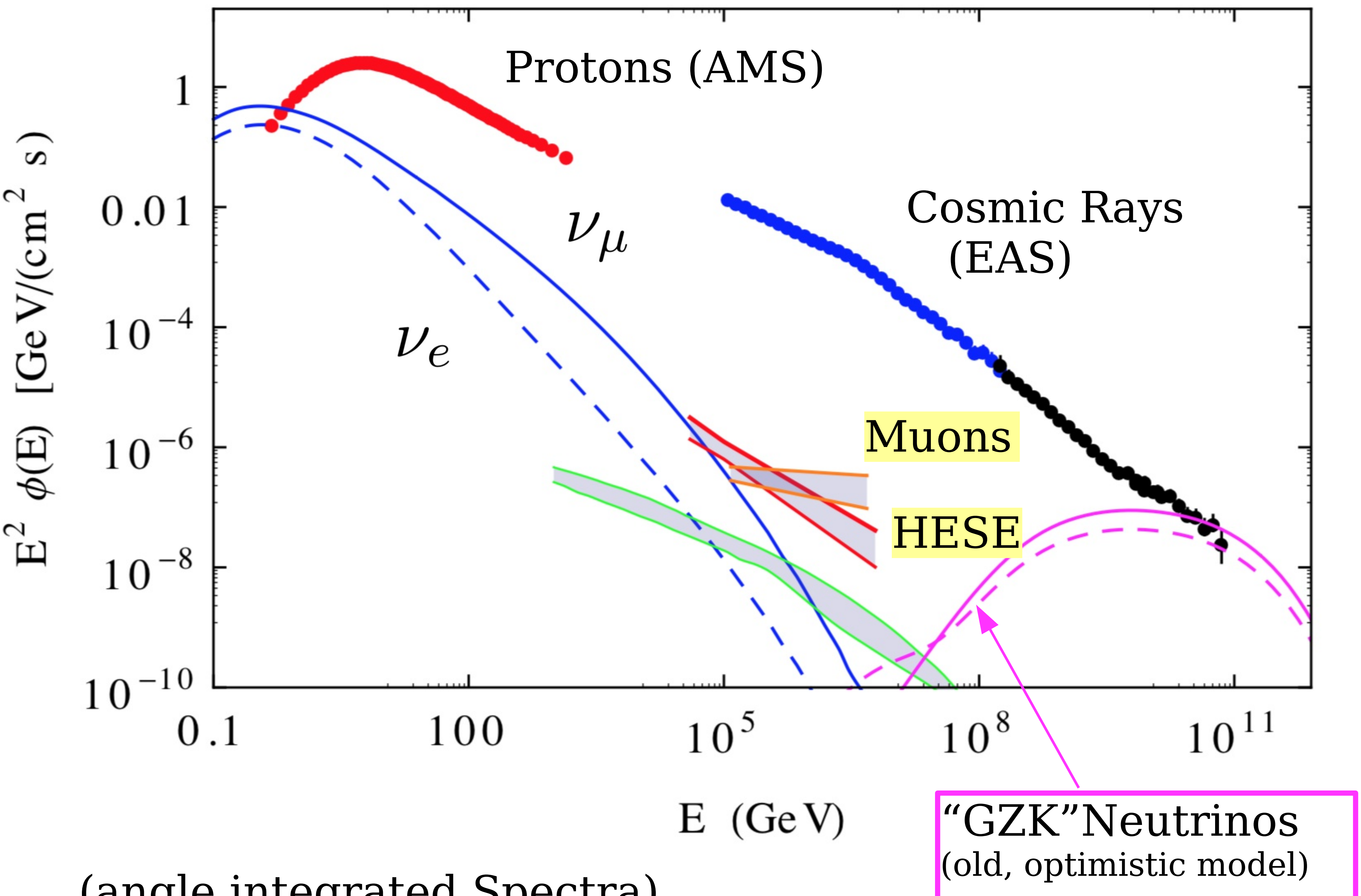
- **Multi-component facility** (low- and high-energy & multi-messenger).
- In-ice **high-energy Cherenkov array** with 6-10 km³ volume.
- **Under investigation:** Surface arrays for in-ice radio Askarayan and cosmic ray veto (air Cherenkov and/or scintillator panels).



[Aartsen et al., Proceedings of ICRC 2017]

"Horizon" (in time) for protons

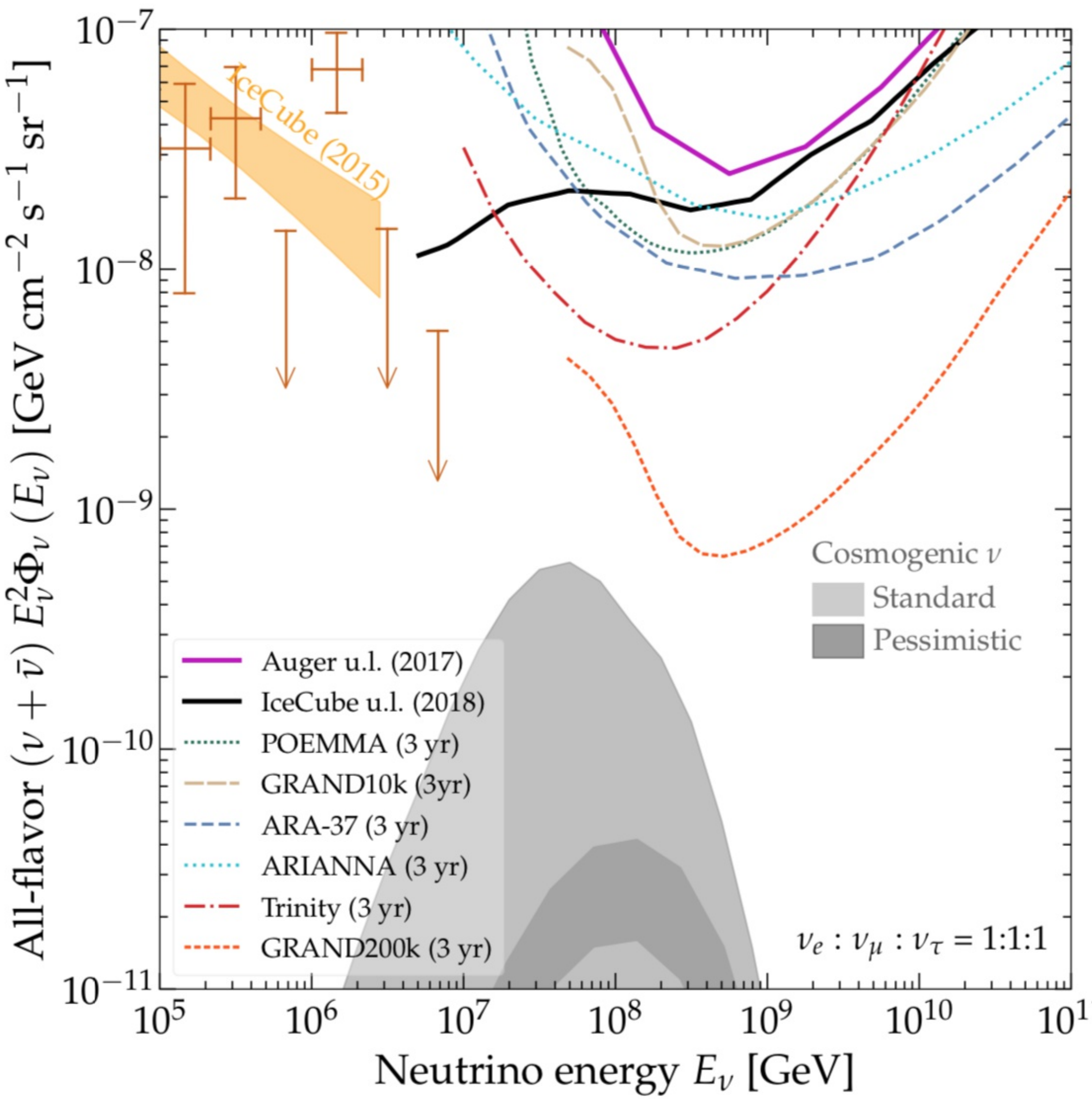




(angle integrated Spectra)

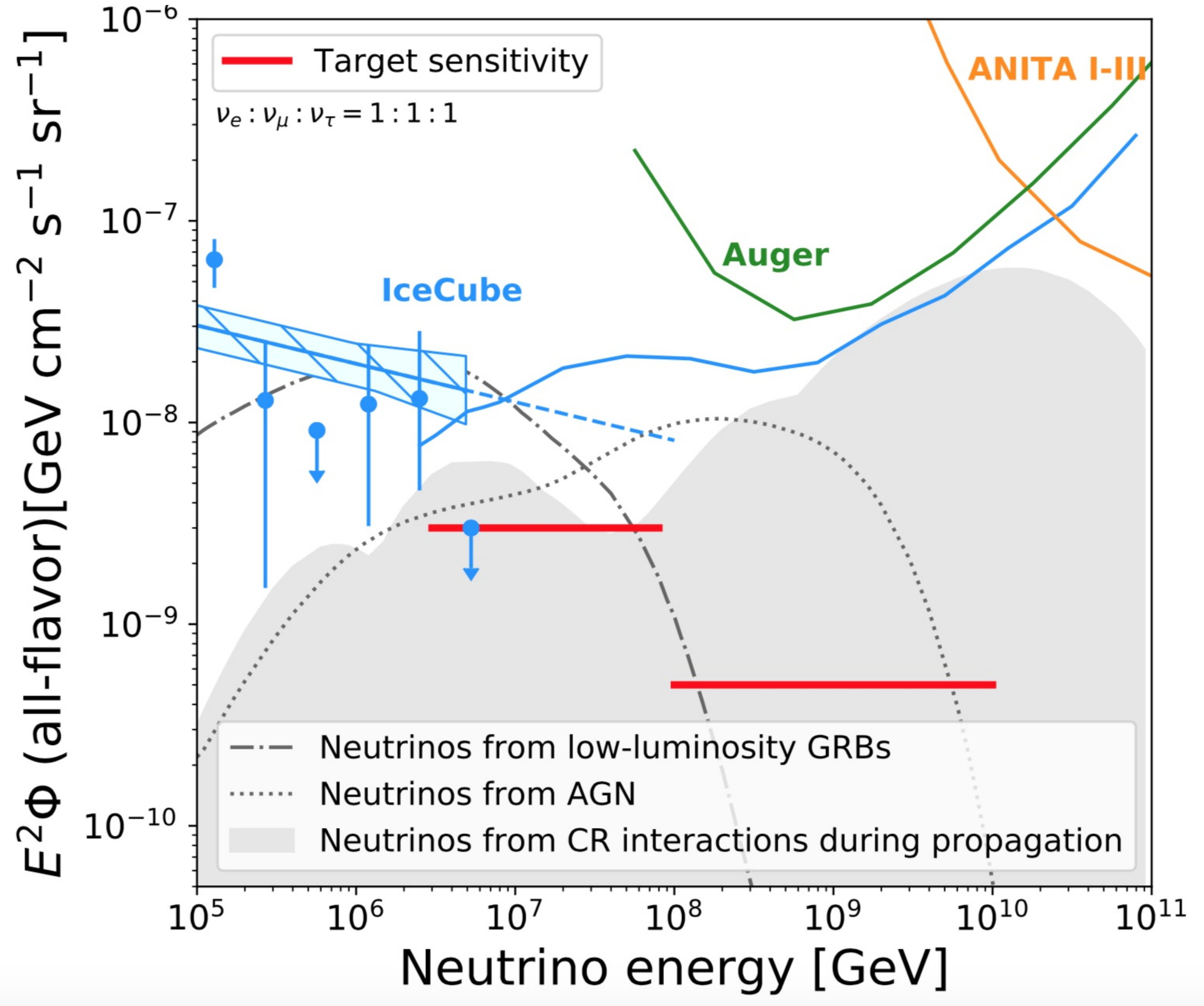
Vision: EHE Neutrino Observatory

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
  [Berezinsky&Zatsepin'70]
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal energies.
  [e.g. MA *et al.*'10; MA & Halzen'12]
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.



[Alves Batista *et al.*'19]

Very strong case to develop Neutrino telescopes beyond the "beaded string - km3 concept" aiming at the EeV range [Radio attractive technique with this potential]



Summary

- The future of neutrino astronomy is bright:
  - Diffuse TeV-PeV neutrino flux of unknown origin.
  - Intensity comparable to cosmic-ray and gamma-ray observations.
  - First compelling evidence of neutrino emission from blazars.
- With next-generation telescopes we will go from discovery to astronomy!
- Many more avenues of neutrino astronomy, that could not be covered:

  supernova neutrinos, GZK neutrinos, BSM physics, neutrino-nucleon cross-section measurements, dark matter indirect signals, …

Happy 20th Anniversary!