27th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY2019) May 20 - 24, 2019

Ultra-High-Energy Neutrinos

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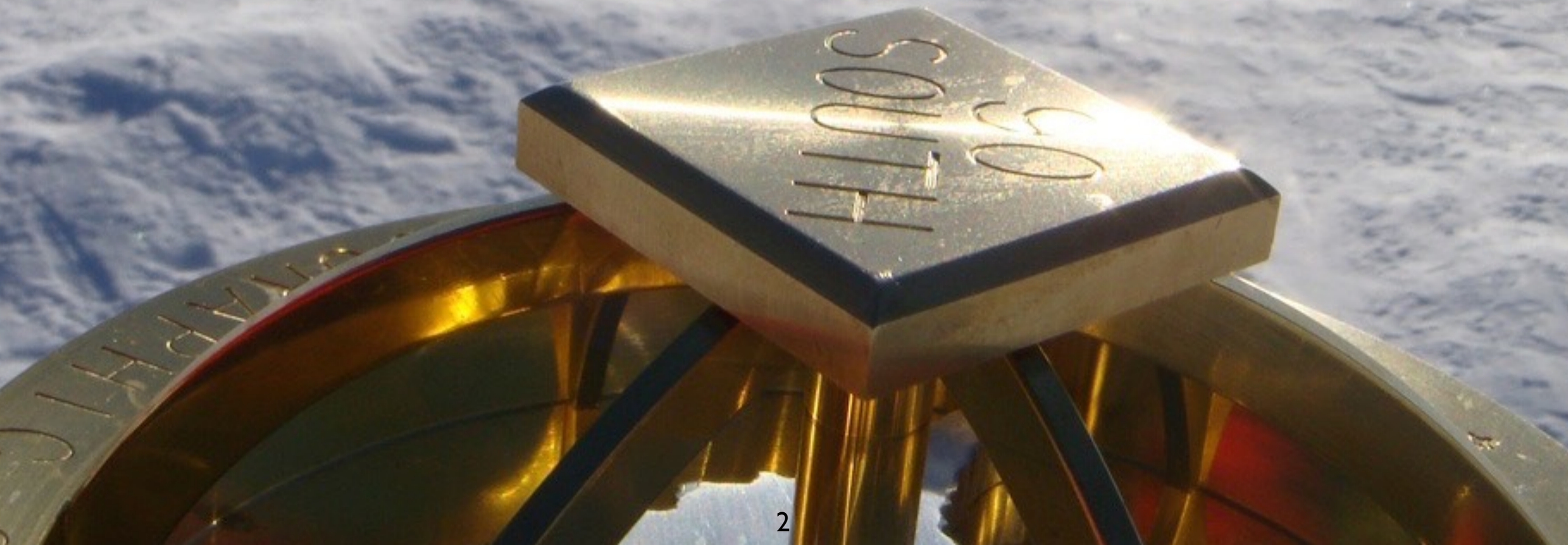
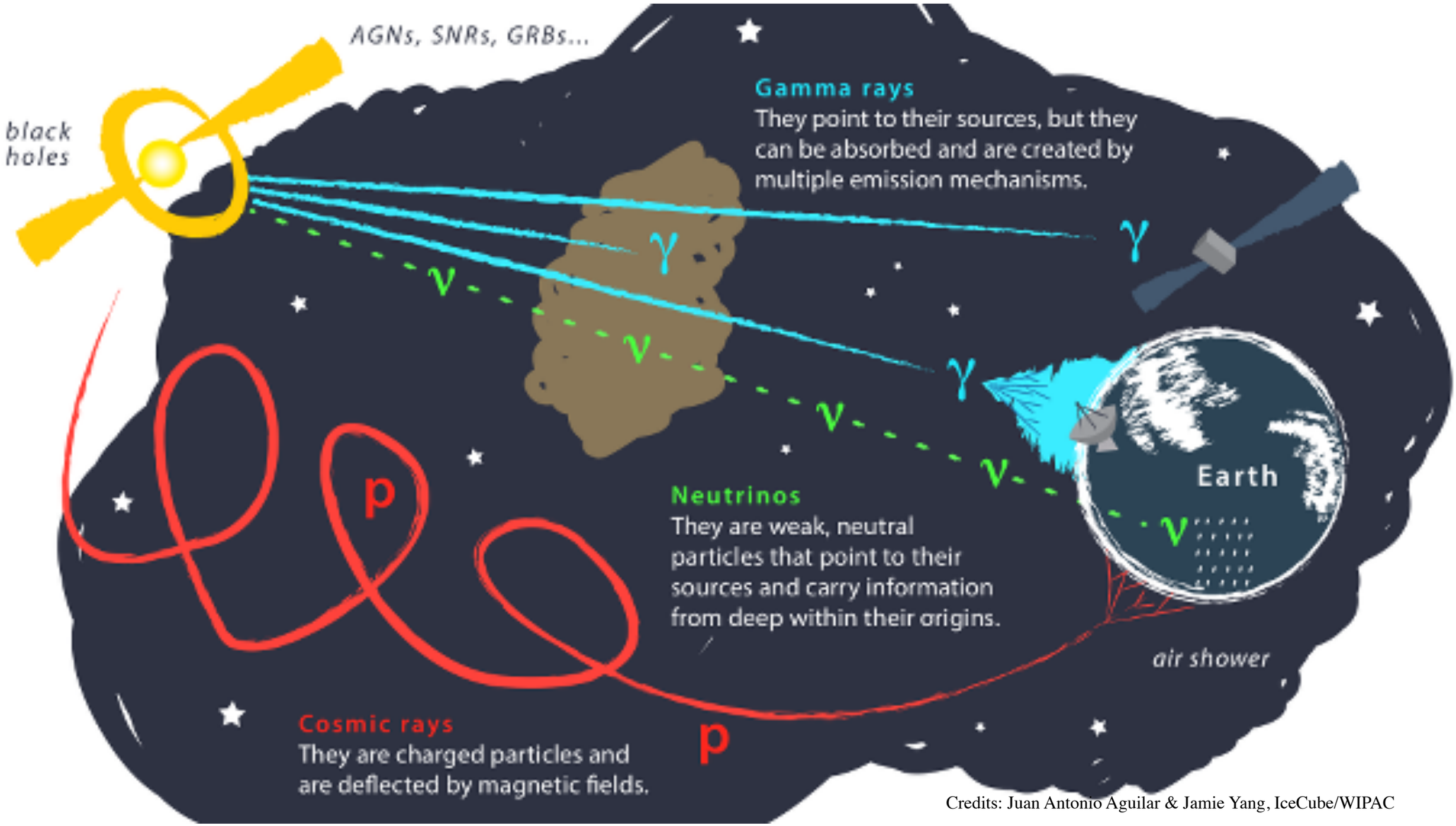
Outline

- Motivation
- Anomalous ANITA events
- Astrophysical Neutrinos
- Multi-messenger Neutrino Astroparticle physics
- Search for Physics Beyond the Standard Model
- Outlook and Conclusions



Motivation

Motivation

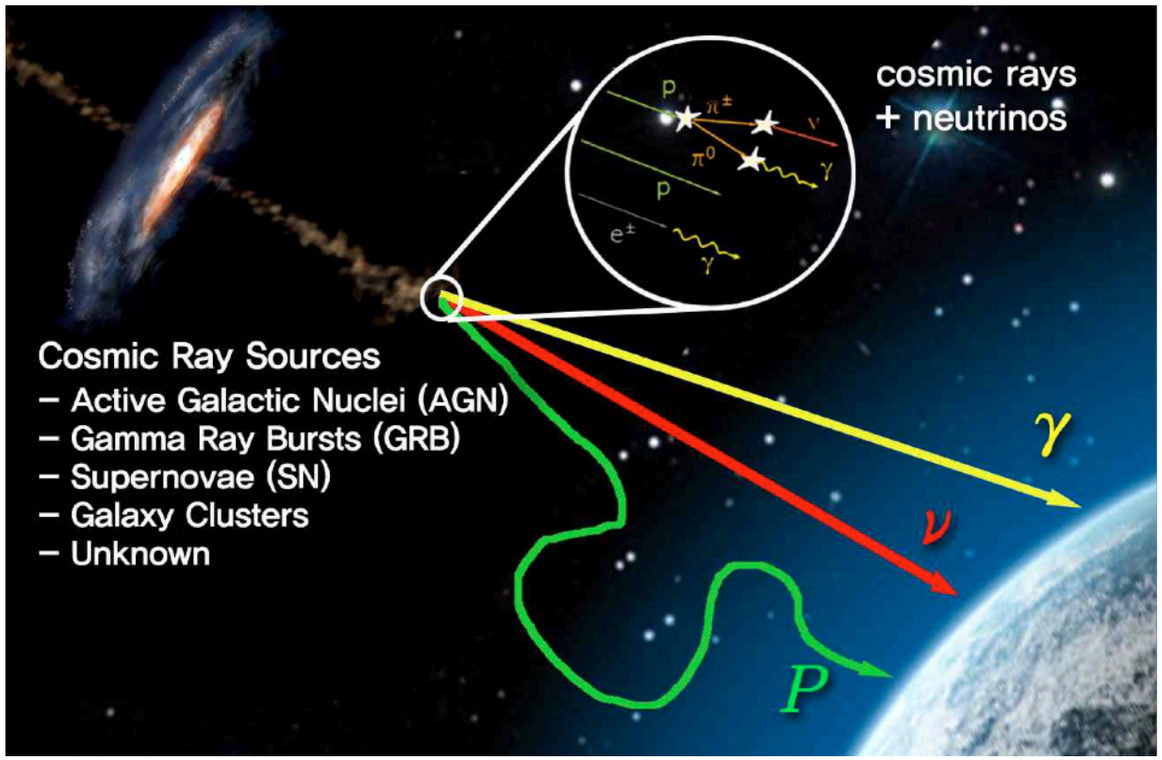


Credits: Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

- Identify the origin of the high-energy cosmic rays
- Open a new window to the Universe

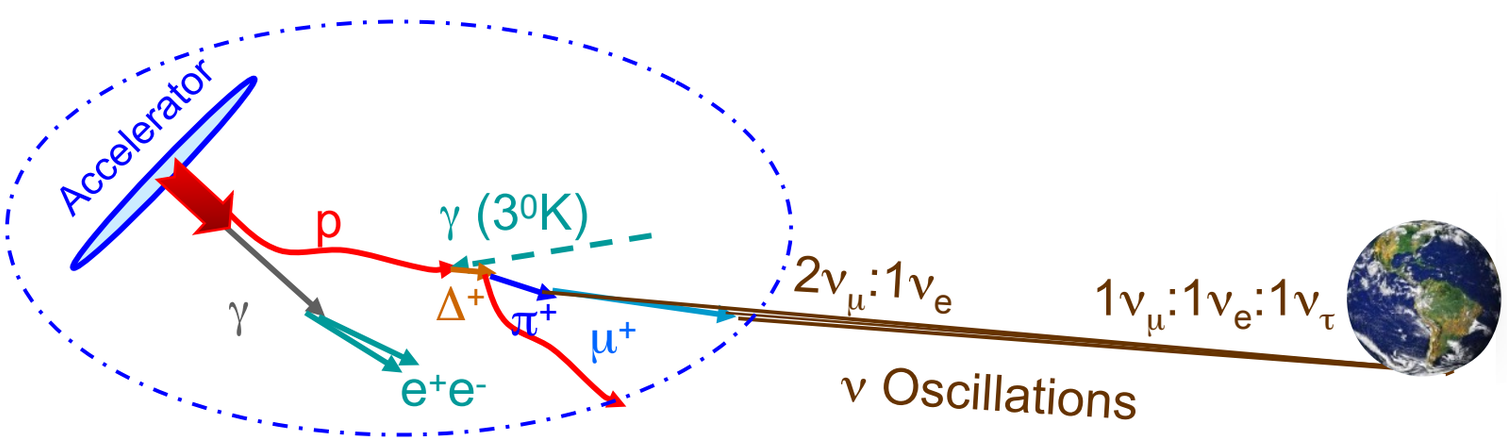
Sources of High Energy Neutrinos

Astrophysical Neutrinos

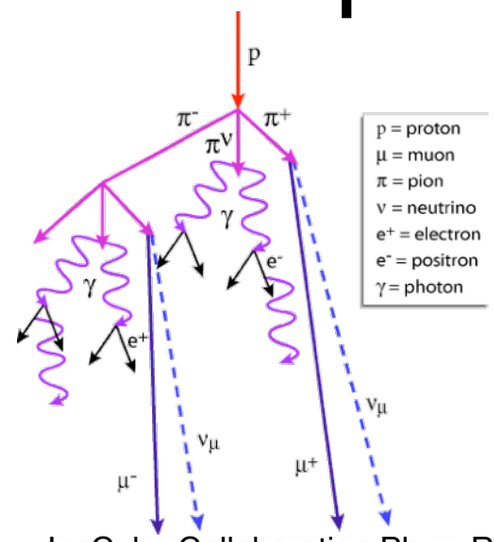


Greisen-Zatsepin-Kuzmin (GZK) - neutrinos

At energies above 4×10^{19}eV, protons interact with CMB to produce delta resonance and in sequential decays (p + γ3°K -> Δ+ –> nπ+, π+–> νμ, μ–>evv) neutrinos of 10^{17} - 10^{20} eV



Atmospheric Neutrinos

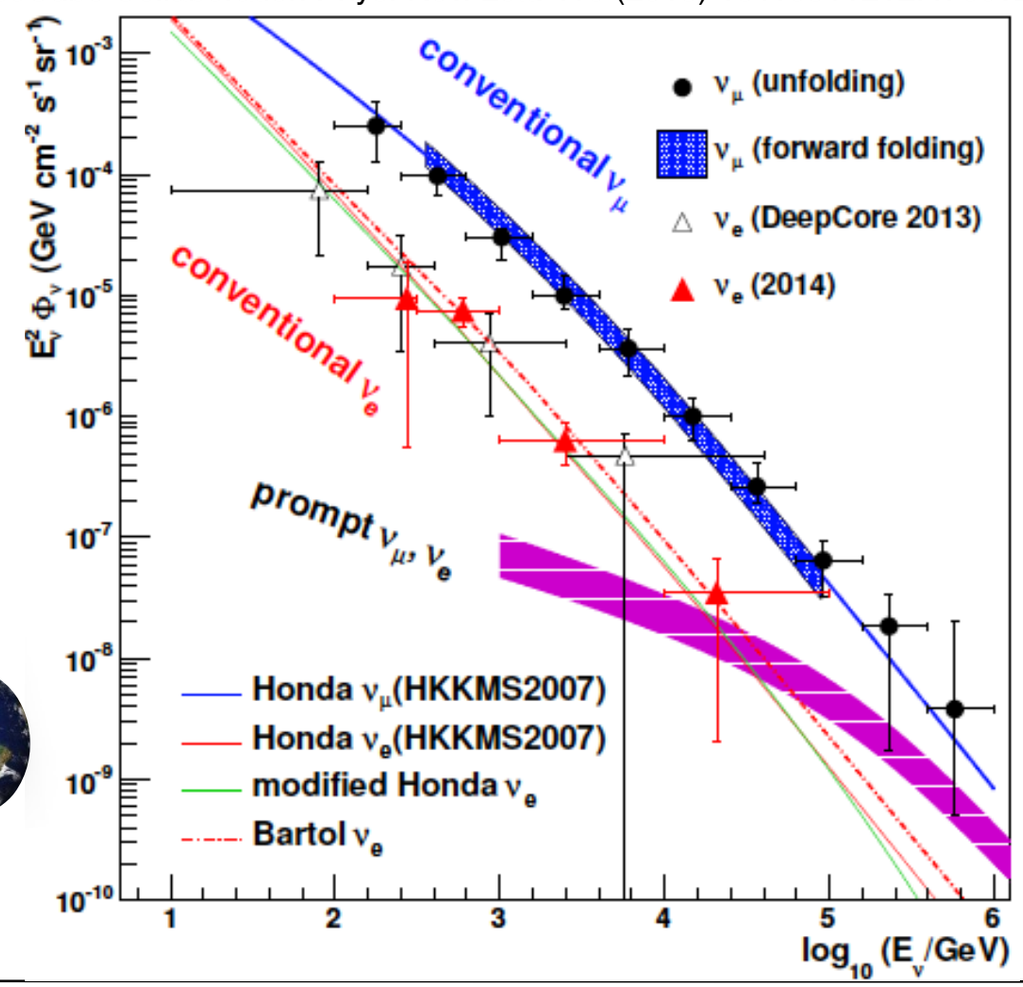


Cosmic rays interact in the upper atmosphere:

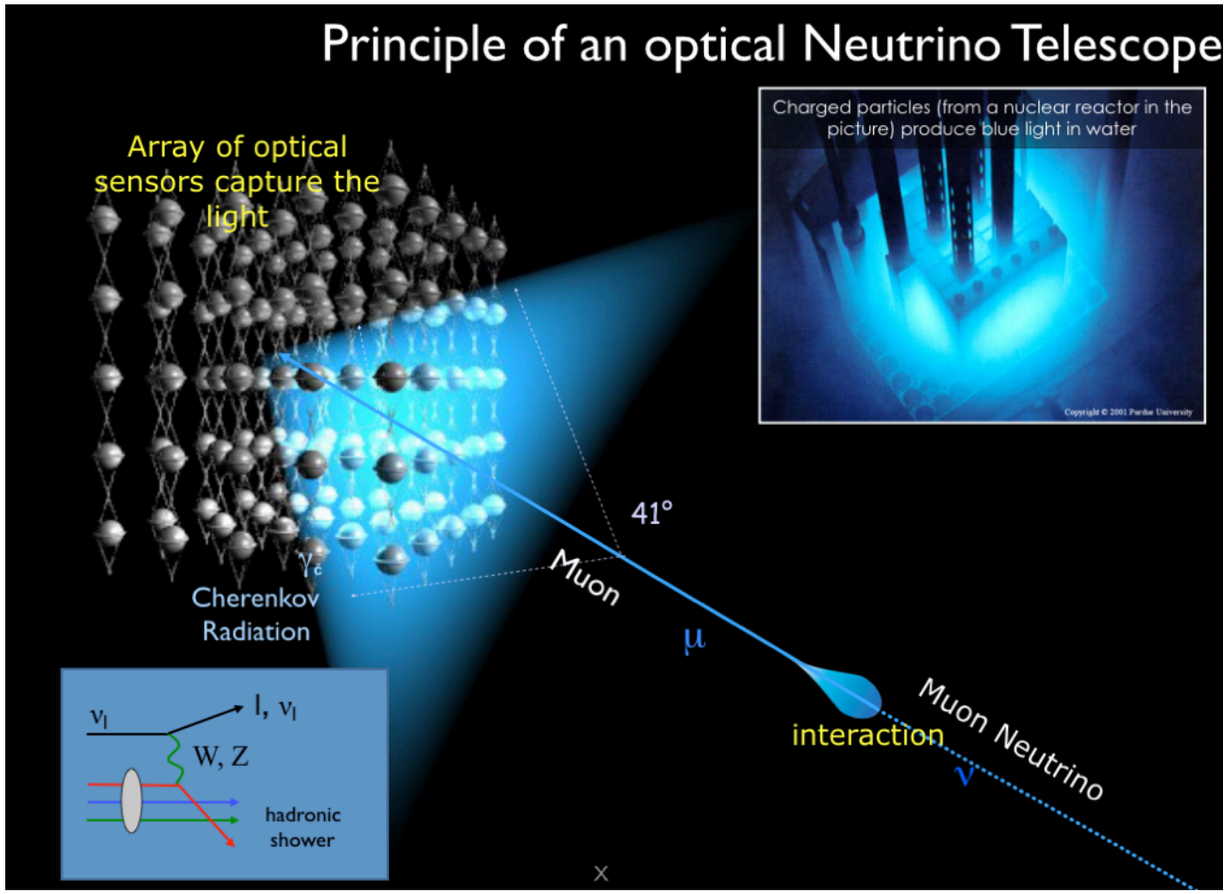
$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons ...

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

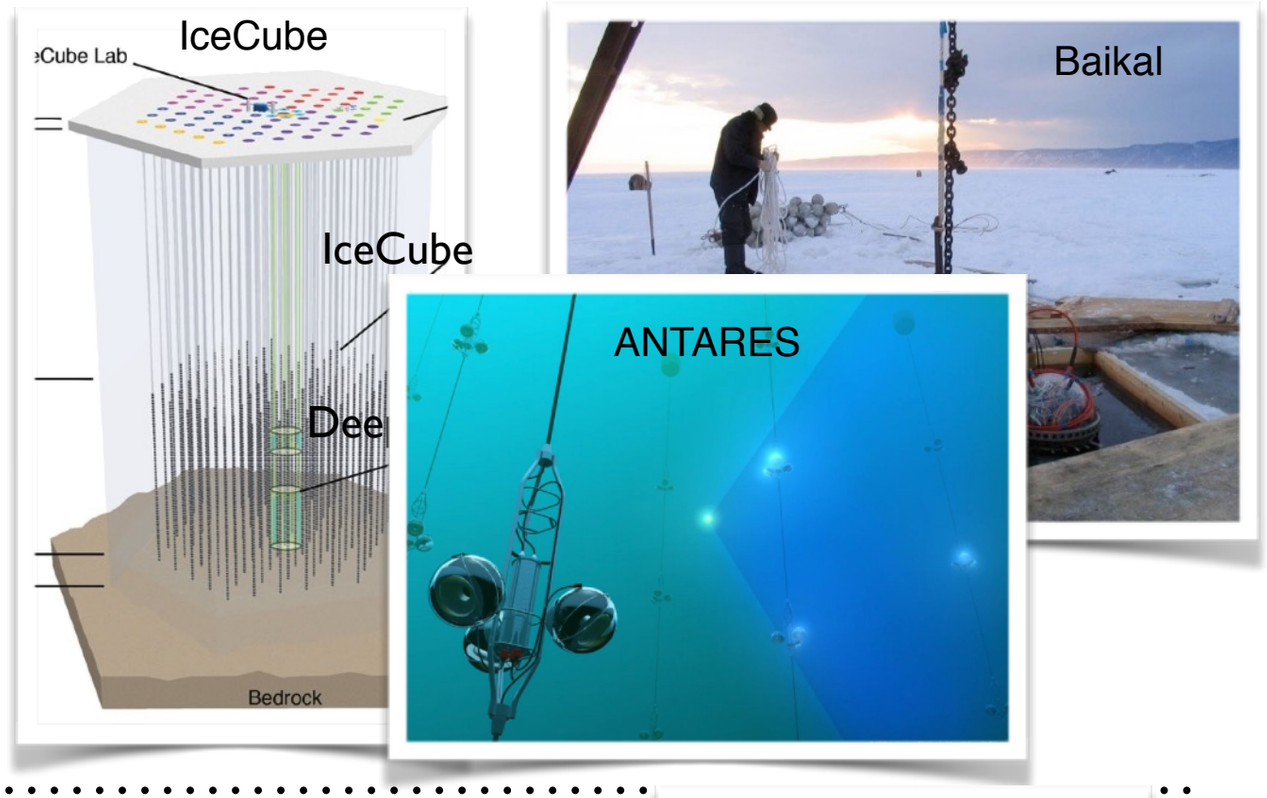
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2

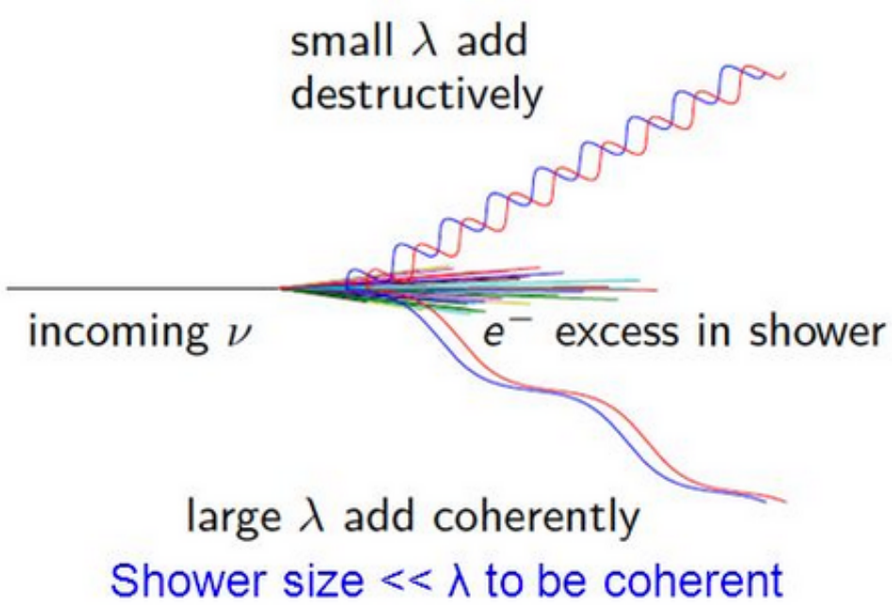


Detection



Neutrino detection via water/ice **Cherenkov light**





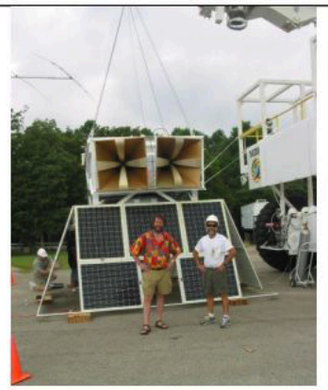
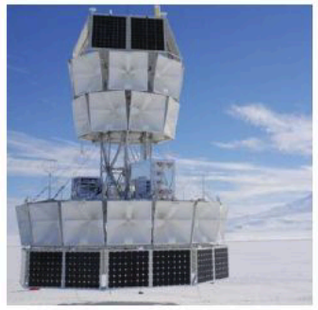
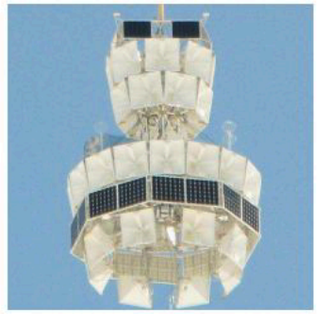
Neutrino detection via **Askaryan effect** :
Coherent radio emission from excess negative charge in an electromagnetic shower (positron annihilation and Compton scattering)
Threshold ~10PeV

Askaryan effect confirmed in beam dump experiment:
SLAC data:D. Saltzberg *et al.,* PRL **86**, 2802 (2001)
Angles: O. Scholten et al. J.Phys.Conf.Ser. **81**, 012004 (2007)

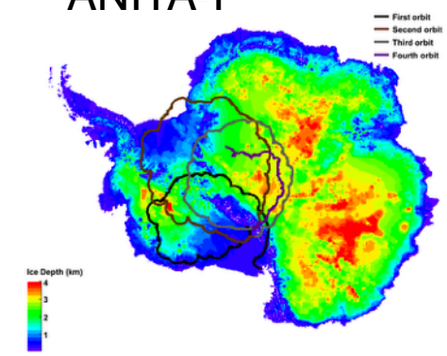
ANITA - ANtarctic Impulsive Transient Antenna

ANITA

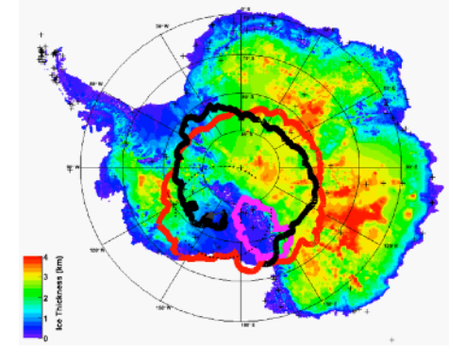
- ANtarctic Impulsive Transient Antenna
  - NASA ultralong duration balloon experiment
- Seeking radio signals from earth-skimming UHE neutrinos
- To this date, 4 flights

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger
Analyzed	Analyzed	Analyzed	**Recently analyzed**	Analysis Ongoing

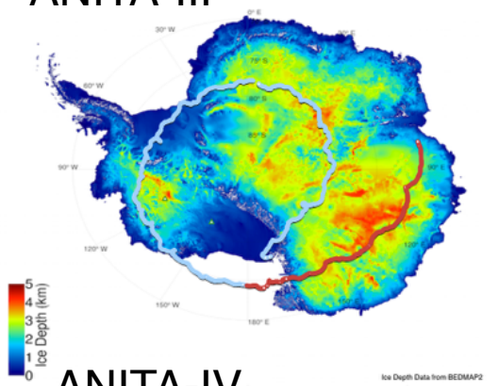
ANITA-I



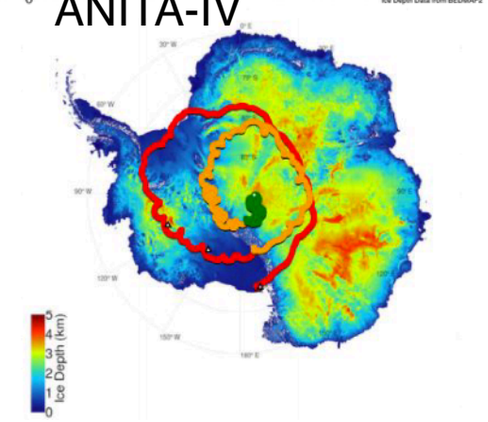
ANITA-II



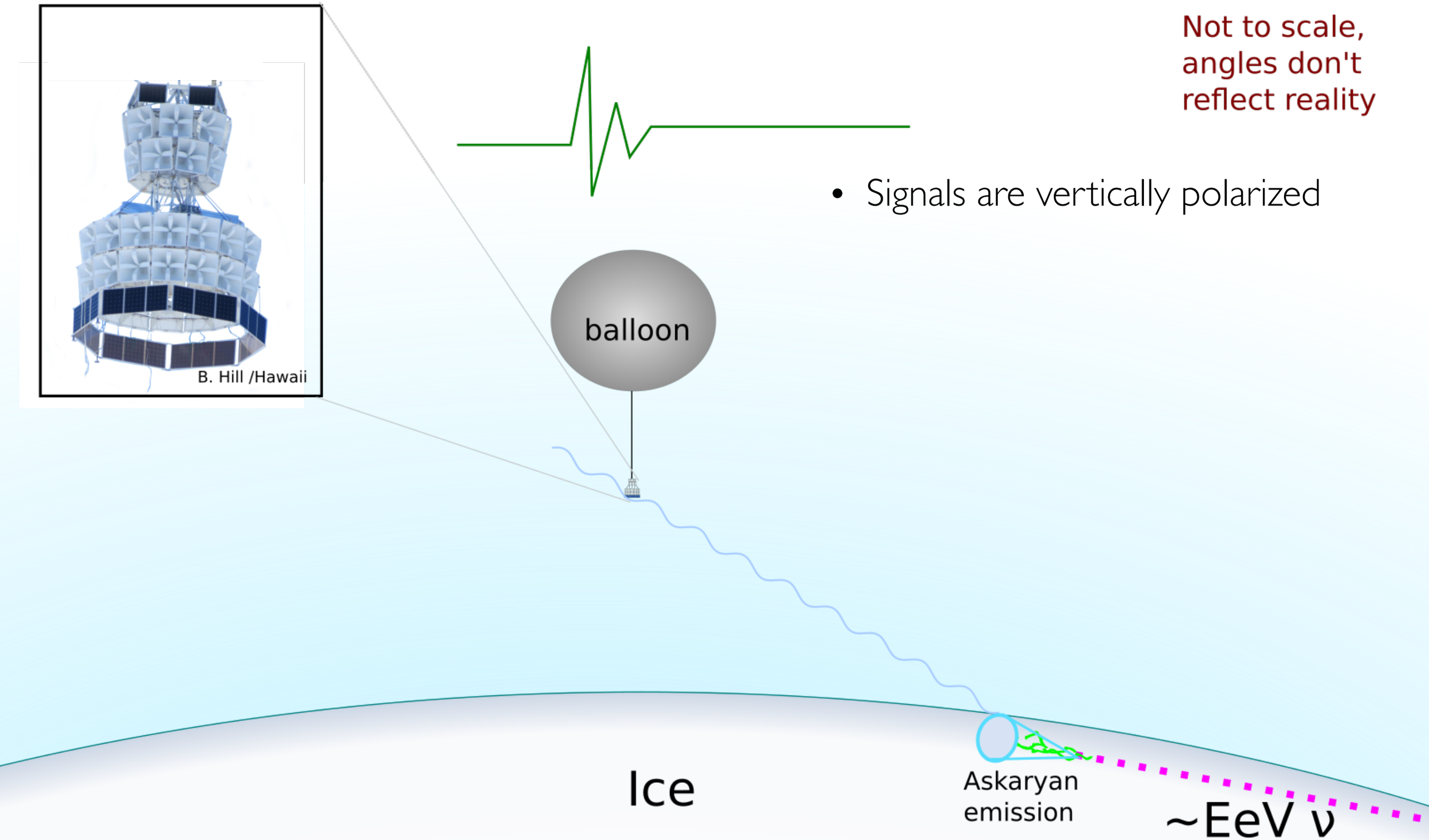
ANITA-III



ANITA-IV



1) Neutrino-Induced Askaryan Emission in Ice

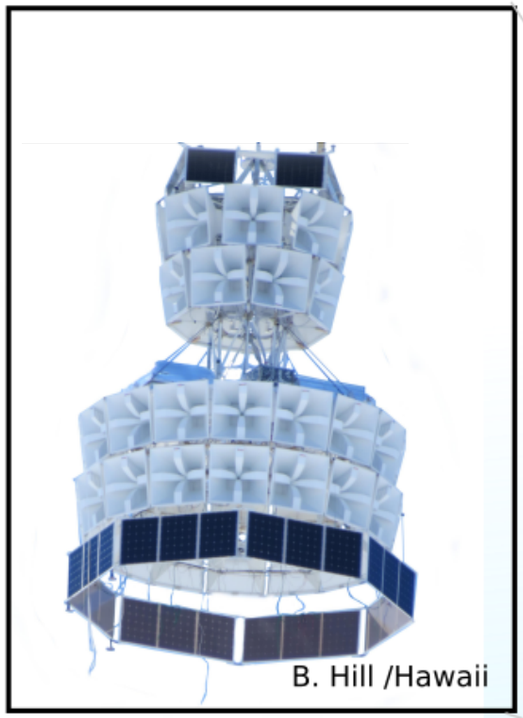


Not to scale, angles don't reflect reality

- Signals are vertically polarized

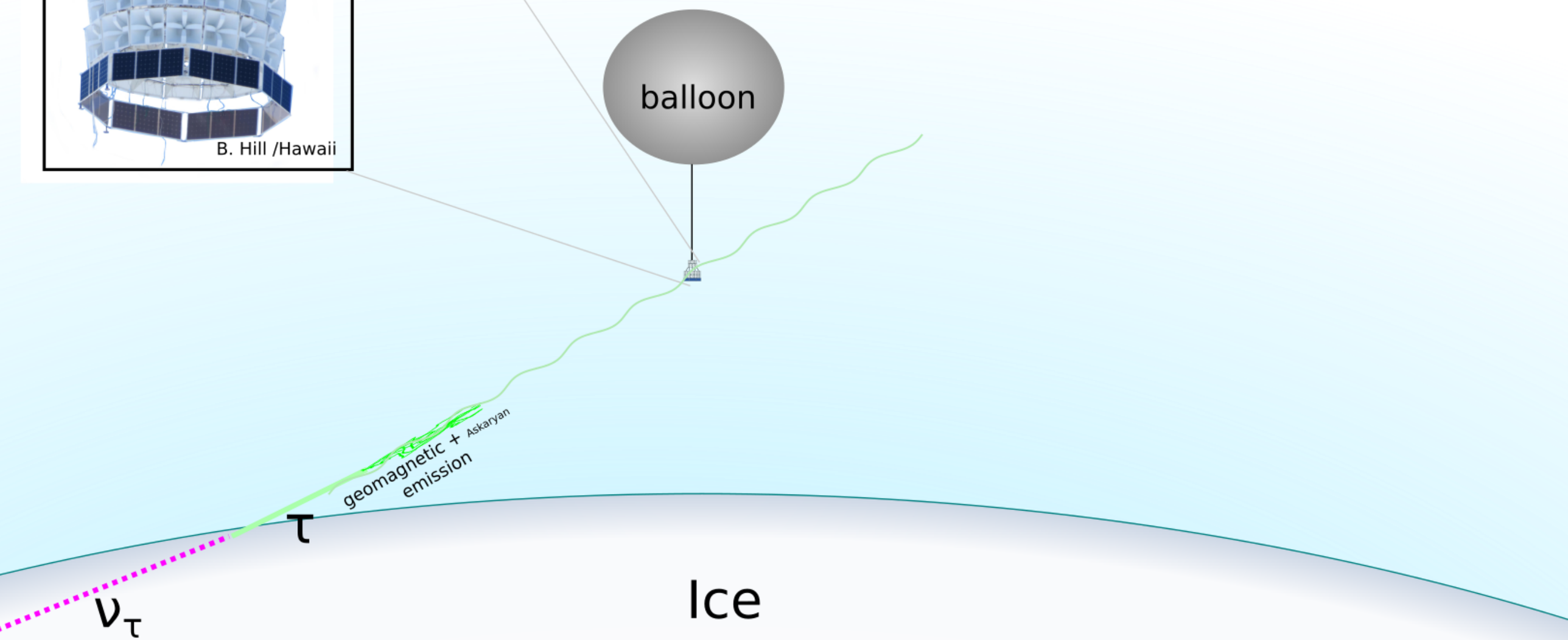
Askaryan effect confirmed in beam dump experiment:
SLAC data:D. Saltzberg *et al.,* PRL **86**, 2802 (2001)
Angles: O. Scholten et al. J.Phys.Conf.Ser. **81**, 012004 (2007)

2) Radio Emission from Tau-Neutrino-Induced EAS

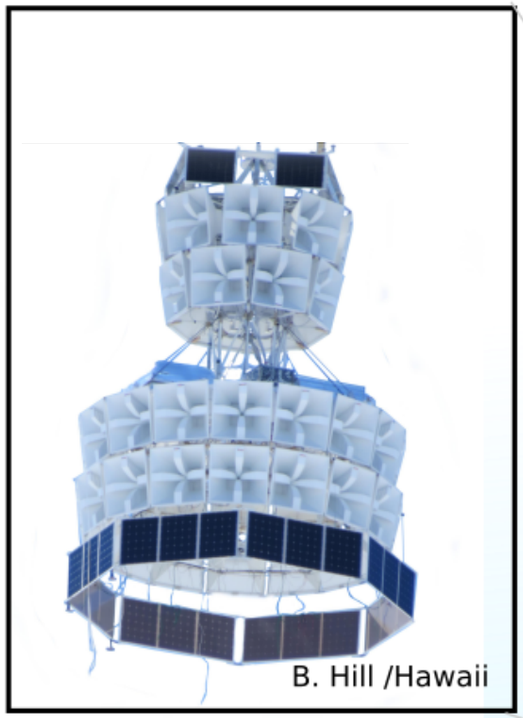


Not to scale, angles don't reflect reality

- Signals are horizontally polarized
- Comes from below the horizon

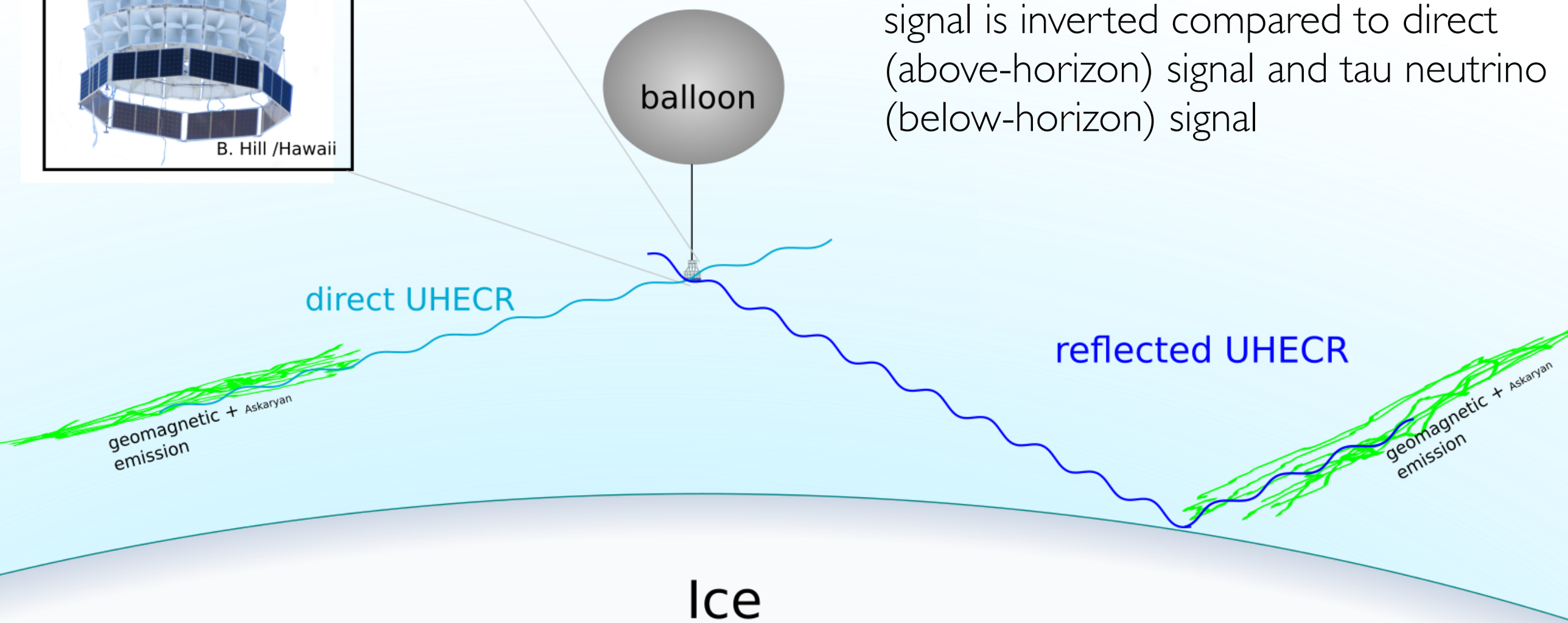


3/4) Radio Emission from Cosmic-Ray-Induced EAS



Not to scale, angles don't reflect reality

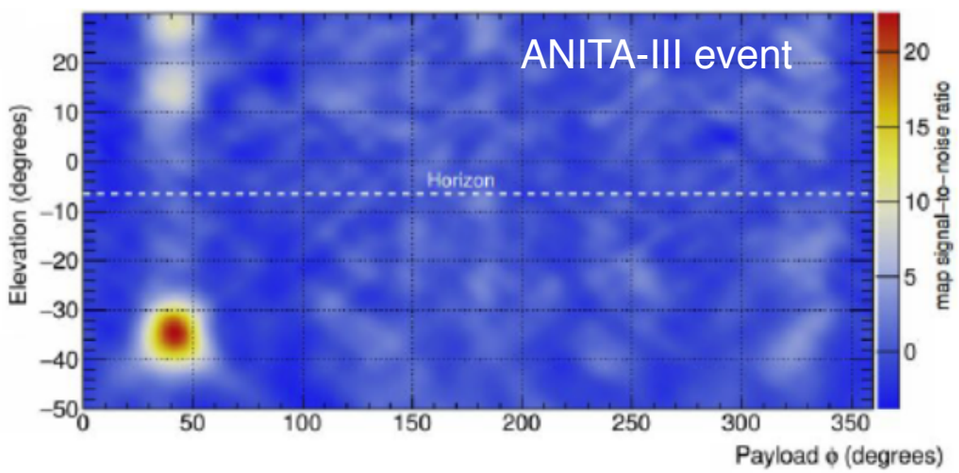
- Signals are horizontally polarized
- Polarity of reflected (below-horizon) signal is inverted compared to direct (above-horizon) signal and tau neutrino (below-horizon) signal

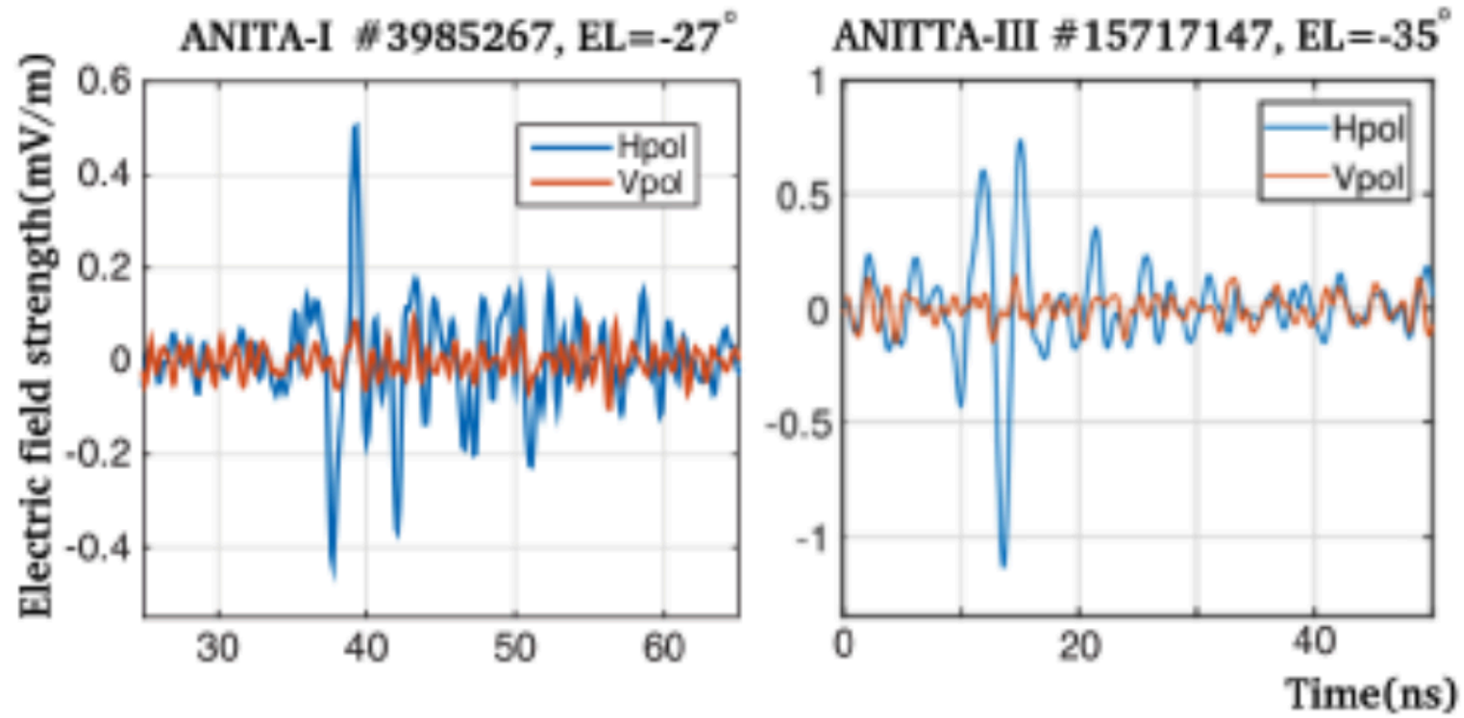


Romero-Wolf et al Phys.Rev. D99 (2019) no.6, 063011 (arXiv:1811.07261)

ANITA Anomalous Events

- ANITA-I event reported in P. Gorham et al. [ANITA Collaboration], Phys. Rev. Lett. 117, 071101 (2016).
- ANITA-III event reported in P. Gorham et al. [ANITA Collaboration], Phys. Rev. Lett. 121, 161102 (2018).





	ANITA-I: Event 3,985,267	ANITA-III: Event 15,717,147
Payload Elevation Angle	-27.4° ± 0.3°	-35.0° ± 0.3°
Payload Azimuth Angle	159.6° ± 0.7°	61.4° ± 0.7°
Payload Altitude	35.029 km	35.861 km
Ice Thickness	3.53 km	3.22 km
Magnetic Field Strength at 0-km	49.9892 μT	60.0783 μT
Magnetic Field I	-68.24265°	-77.4927°
Magnetic Field D	-38.5059°	-155.6842°
Peak Hpol Electric Field Strength	0.77 mV/m	1.1 mV/m
Air shower energy	0.6 ± 0.4 EeV	$0.6^{+0.3}_{-0.2}$ EeV

- Two anomalous events observed
- Mostly H-pol
- Consistent with UHECR signature but clearly up-going (emerging from ice)

ANITA Anomalous Events

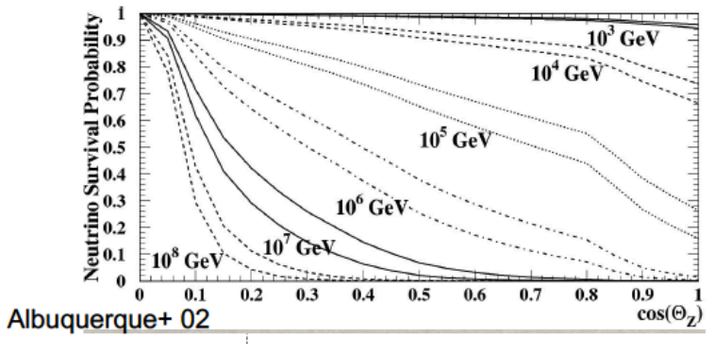
Fox et al (2019)

TABLE I. Properties of the ANITA Anomalous Events

Property	AAE 061228	AAE 141220
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. 282°.14064, Dec. +20°.33043	R.A. 50°.78203, Dec. +38°.65498
Energy ε_{cr}	0.6 ± 0.4 EeV	$0.56^{+0.30}_{-0.20}$ EeV
Zenith angle z'/z	117°.4 / 116°.8 ± 0°.3	125°.0 / 124°.5 ± 0°.3
Earth chord length ℓ	5740 ± 60 km	7210 ± 55 km
Mean interaction length for $\varepsilon_\nu = 1$ EeV	290 km	265 km
$p_{SM}(\varepsilon_\tau > 0.1\,\text{EeV})$ for $\varepsilon_\nu = 1$ EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{SM}(z > z_{obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > 0.1$ EeV	6.7×10^{-5}	3.8×10^{-6}
n_τ(1–10 PeV) : n_τ(10–100 PeV) : n_τ(> 0.1 EeV)	34 : 35 : 1	270 : 120 : 1

- Emerged from the Earth at ~27 degrees below the horizon
- Earth chord length 5740 km (~15 interaction lengths for incoming EeV neutrino)

- Emerged from the Earth at ~35 degrees below the horizon
- Earth chord length 7210 km (~27 interaction lengths for incoming EeV neutrino)



Albuquerque+ 02

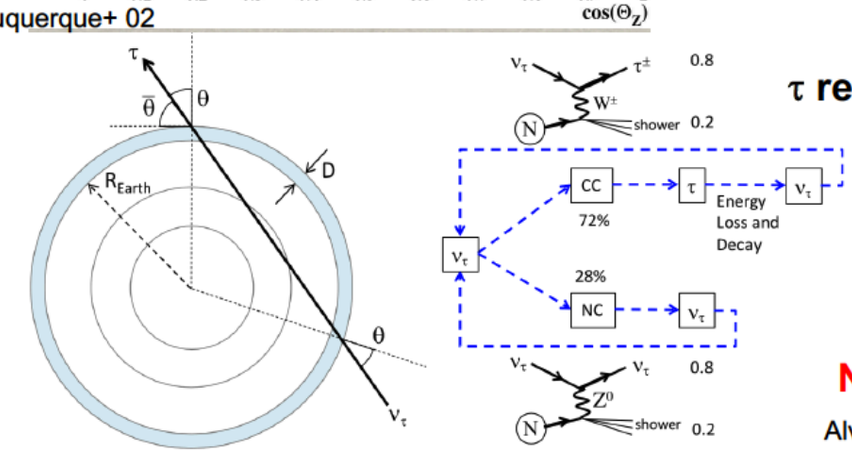
K. Murase LHC-Results Forum 2019

$\sigma_{\nu N}$~10^{-32} cm2 @ EeV

ρ_{Earth}~5.5 g cm-3

chord length~7300km

-> $\tau_{\nu N}$~60 >> 1



τ regeneration

NuTauSim

Alvarez-Muniz+ 08

New Physics Implications

Standard model explanation can be excluded (if we consider the ANITA signals as real)

- Inconsistency with energy and zenith angle of events
- Inconsistency with observed astrophysical neutrino flux by IceCube

- SUSY (Long-lived particles) - NLSP stau / NLSP bino / CHAMPS / sphaleron configurations
  - Long-lived stau (Fox et al 2018, Collins et al 2018, Anchordoqui & Antoniadis 2018, … Albuquerque 2004/2007)
- Leptoquarks
  - Chauhan & Mohanty 2018
- Dark matter related models
  - Heurtier et al 2019, Anchordoqui et al. 2018
- Sterile neutrinos
  - Cherry & Shoemaker 2018, Huang 2018

Connolly et al
arXiv:1807.08892

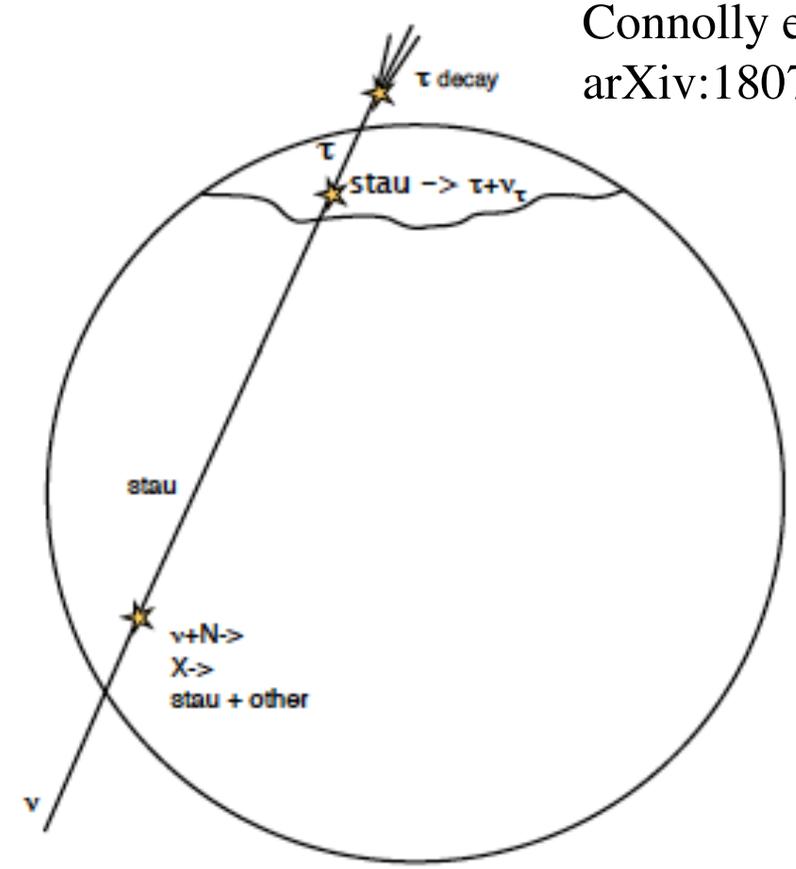
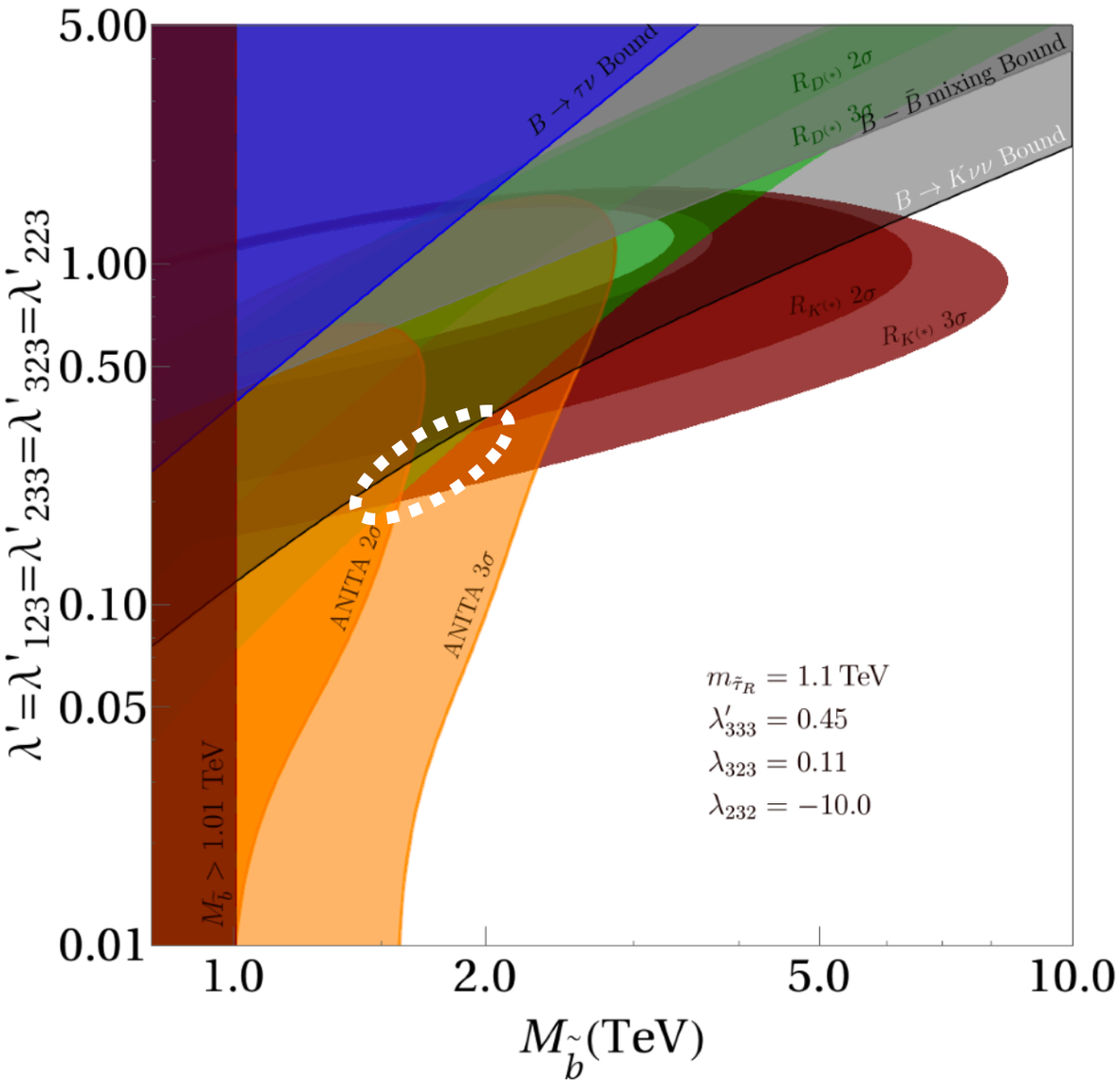


Figure 2: Sketch of the signature being considered here. Although the figure shows one stau being produced in the νN interaction, a stau pair could be produced instead, doubling the probability of detection.

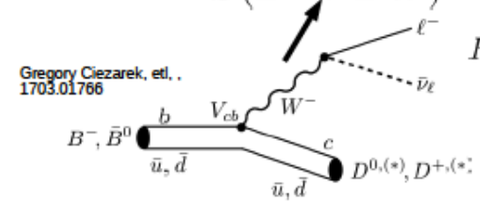
Yicong Sui, Wolfgang Altmannshofer,
Bhupal Dev, Amarjit Soni
(See talk Monday afternoon session)



B Anomaly

$$R_D = \frac{\mathcal{B}(B \to D\tau\bar{\nu})}{\mathcal{B}(B \to D\ell\bar{\nu})} \qquad R_{D^*} = \frac{\mathcal{B}(B \to D^*\tau\bar{\nu})}{\mathcal{B}(B \to D^*\ell\bar{\nu})}$$

BaBar, Belle : $\ell = e, \mu$
LHCb : $\ell = \mu$

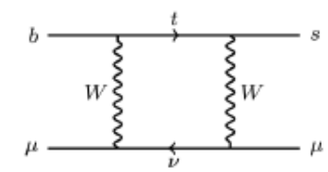


$R_D^{\rm exp}|_{\rm means} = 0.407 \pm 0.039 \pm 0.024$ $\quad R_{D^*}^{\rm exp}|_{\rm means} = 0.304 \pm 0.013 \pm 0.007$ PDG2018

$R_D^{\rm SM} = 0.299 \pm 0.003$ $\quad R_{D^*}^{\rm SM} = 0.257 \pm 0.003$ Florian U. Bernlochner, etl, 1703.05330

2.4σ

$$R_K = \frac{\mathcal{B}(B \to K\mu\bar{\mu})}{\mathcal{B}(B \to Ke\bar{e})} \qquad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu\bar{\mu})}{\mathcal{B}(B \to K^*e\bar{e})}$$



$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$, for $1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$ LHCb collaboration, 1903.09252

2.5σ

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03\,, & \text{for } 0.045\,\text{GeV}^2 < q^2 < 1.1\,\text{GeV}^2\,, \\ 0.69^{+0.11}_{-0.07} \pm 0.05\,, & \text{for } 1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2\,, \end{cases}$$

LHCb collaboration, 1705.05802

$R_{K^*}^{\rm SM}|_{q^2 \in [0.045, 1.1]\ \rm GeV} = 0.906 \pm 0.028.$ $\quad R_{K^*}^{\rm SM}|_{q^2 \in [1.1, 6]\ \rm GeV} = R_K^{\rm SM} = 1.00 \pm 0.01.$

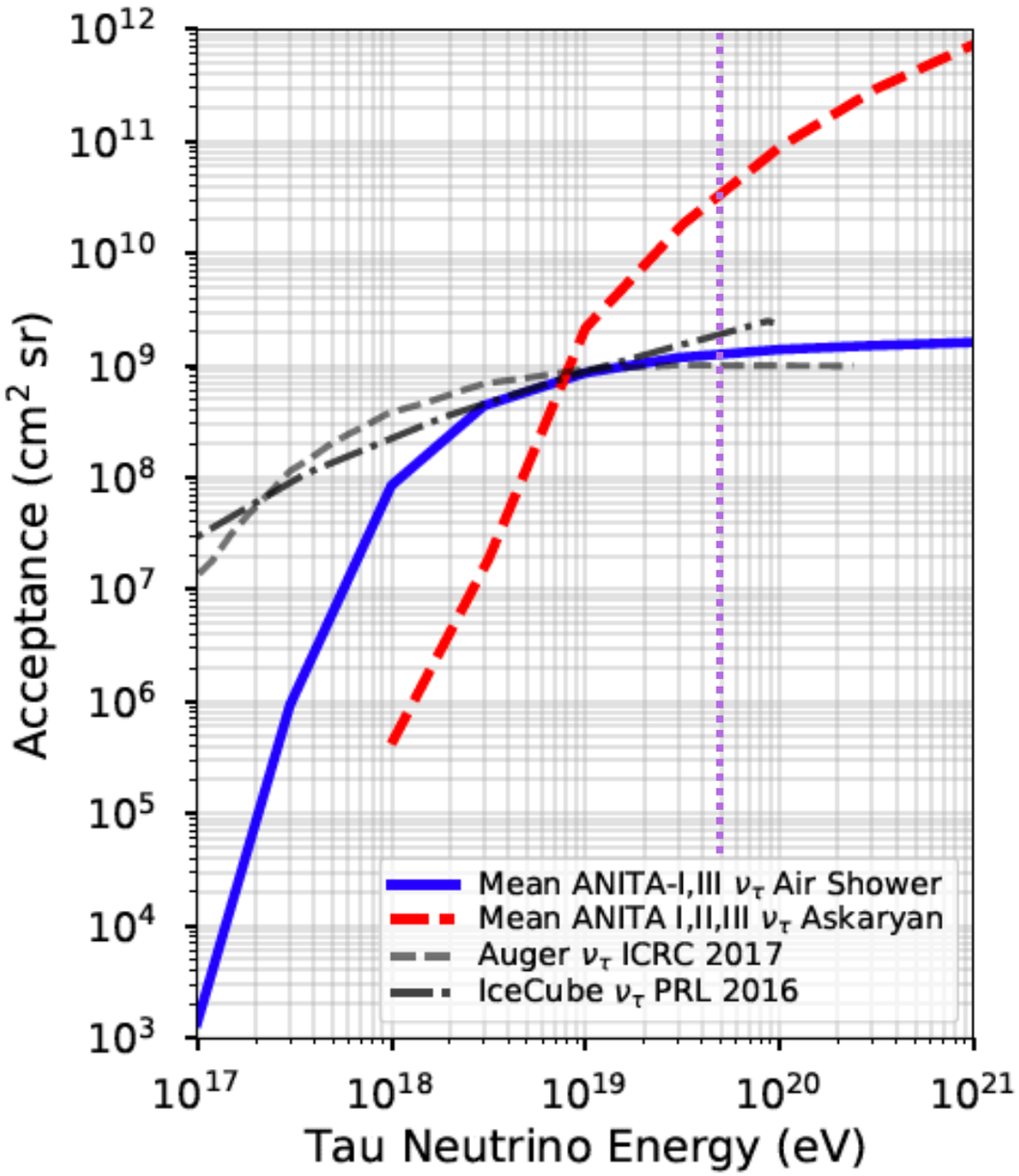
Marzia Bordone, Gino Isidori, Andrea Pattori, 1605.07633

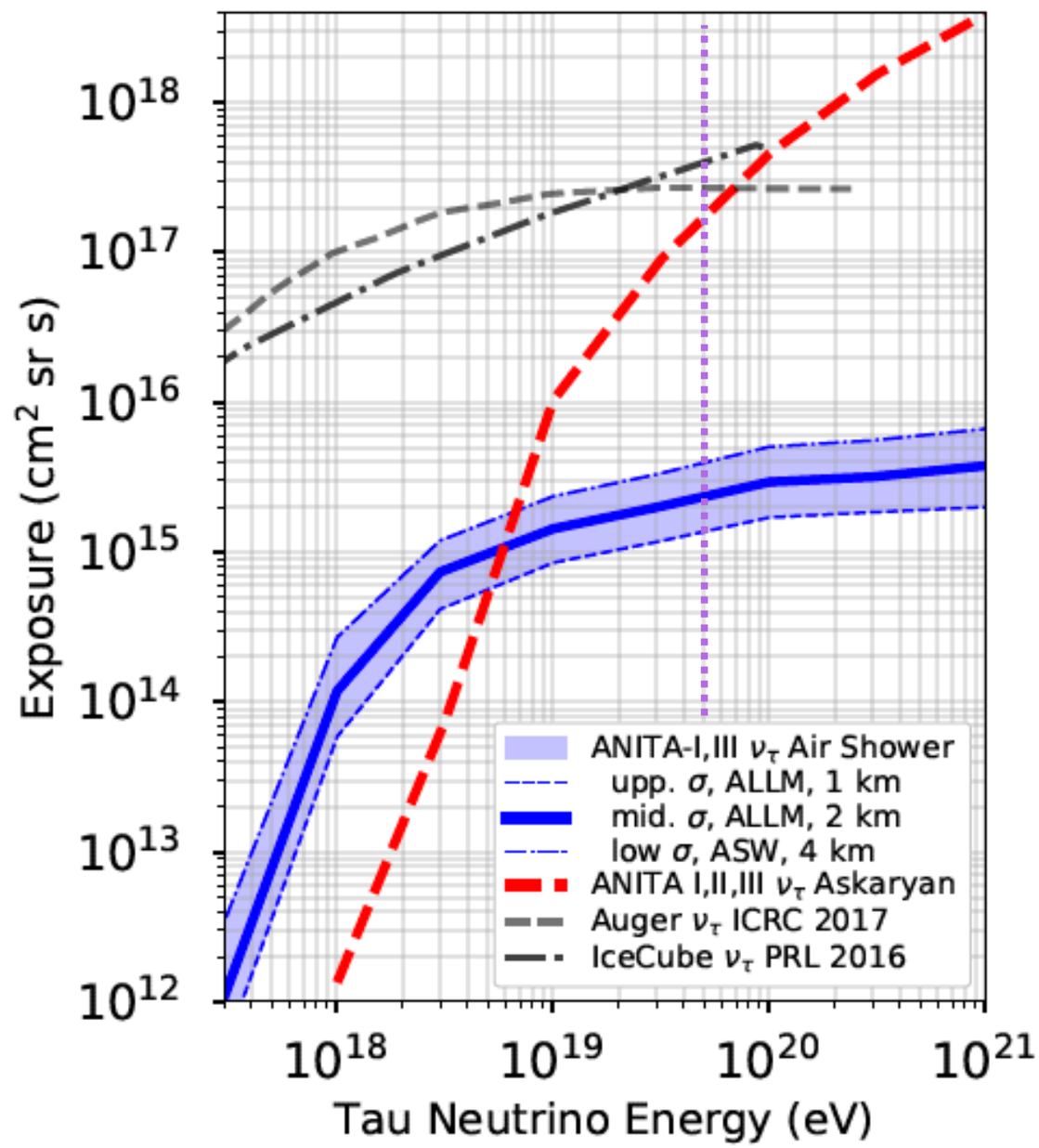
- Under the framework of RPV-SUSY, ANITA anomaly has quite large parameter space, which is in the similar range demanded by RD and RK.
- Rk Rk* and RD RD* anomalies could be explained simultaneously after a "fourth term" is included in the traditional RPV-SUSY Rk Rk* expression.
- Under the simplified parameter setup, we find that there exist parameter spaces that could satisfy RK-RD-ANITA altogether.

Romero-Wolf et al Phys.Rev. D99 (2019) no.6, 063011
(arXiv:1811.07261)

Consistency among experiments

Romero-Wolf et al. (2018)

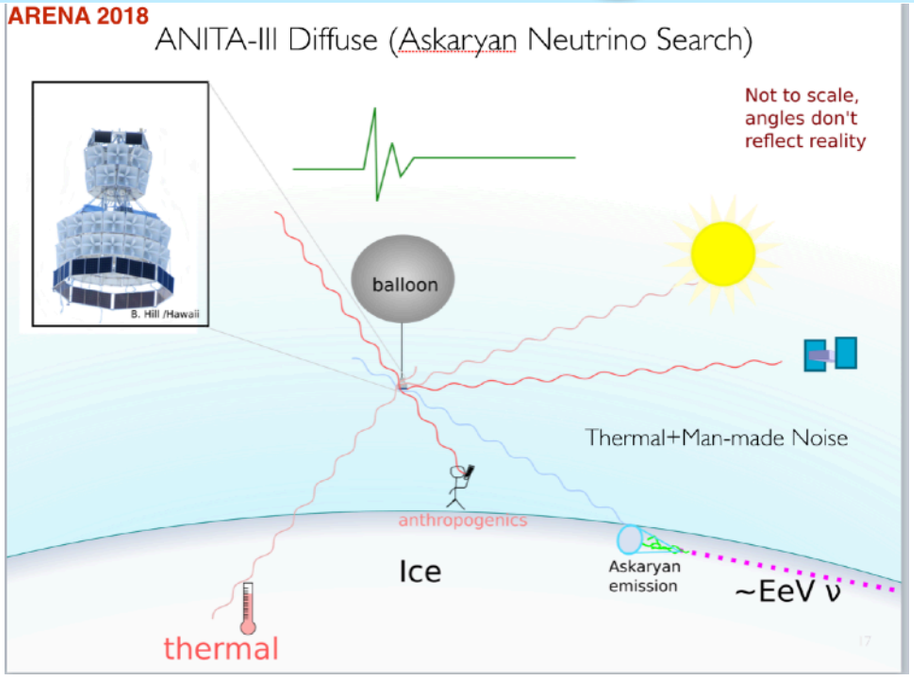


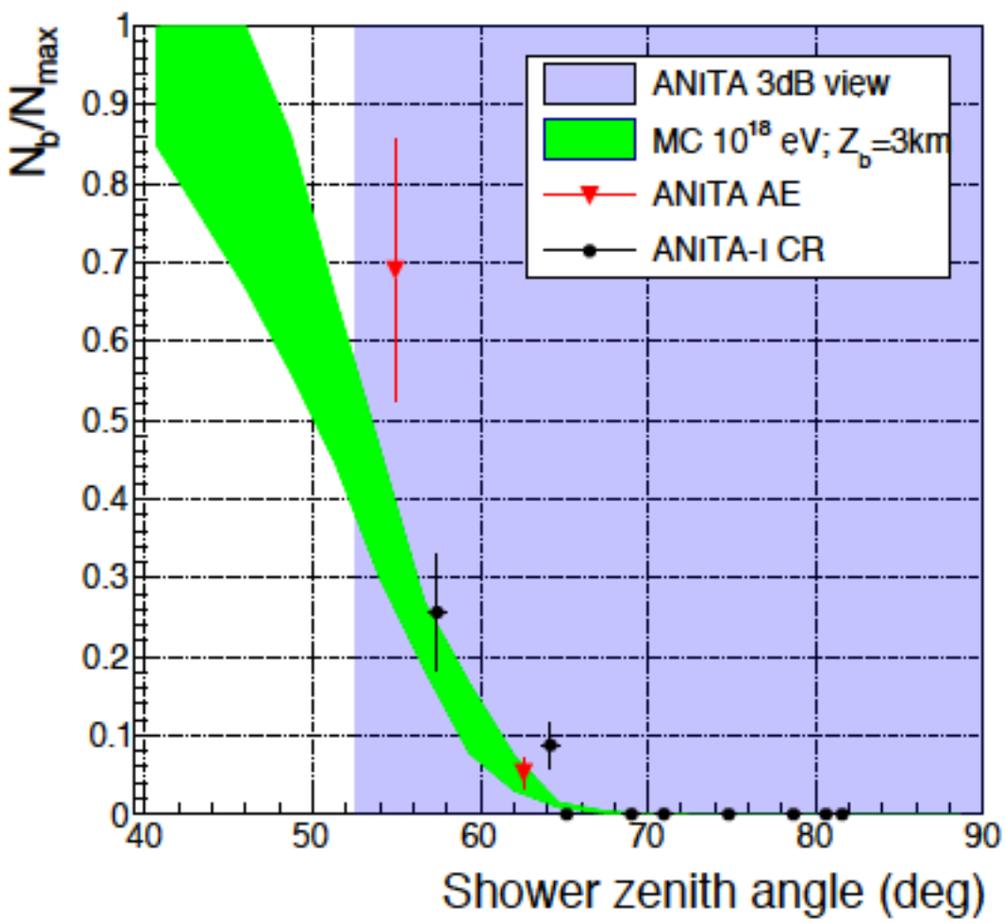


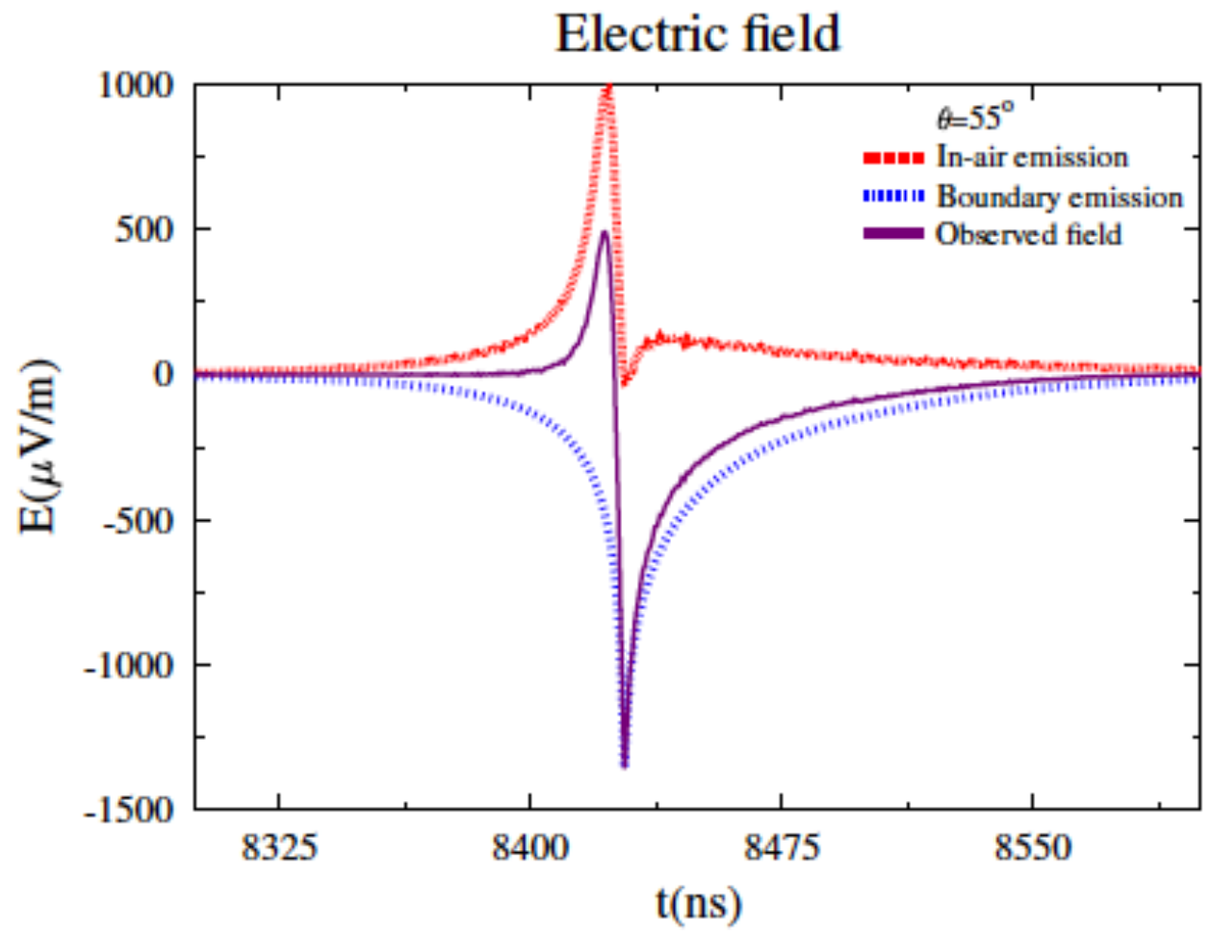
Many more events in IceCube & Auger data expected for $E<10^{19.5}$ eV
… but not reported
(Kistler & Laha PRL 120 (2018) no.24, 241105 - very high-energy tau tracks)

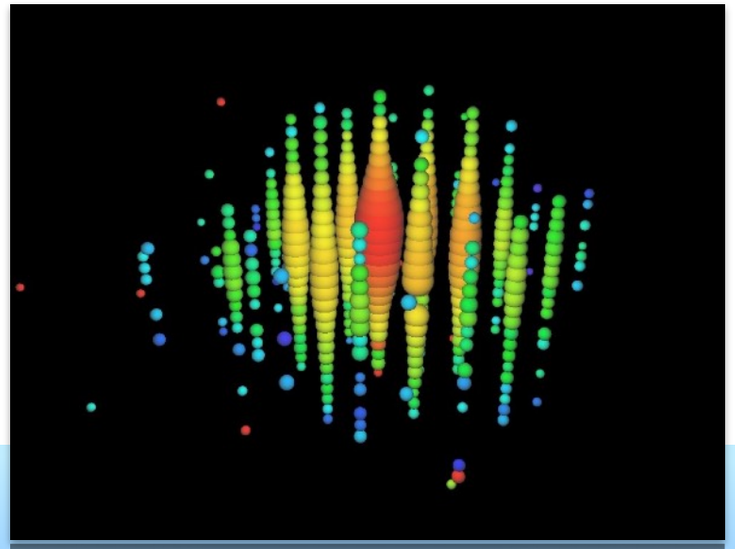
Unexpected Backgrounds

- Double reflection by crevasses?
- Anthropogenic backgrounds
- Other unknown backgrounds ?
- Coherent transition radiation (de Vries & Prohira 2019)





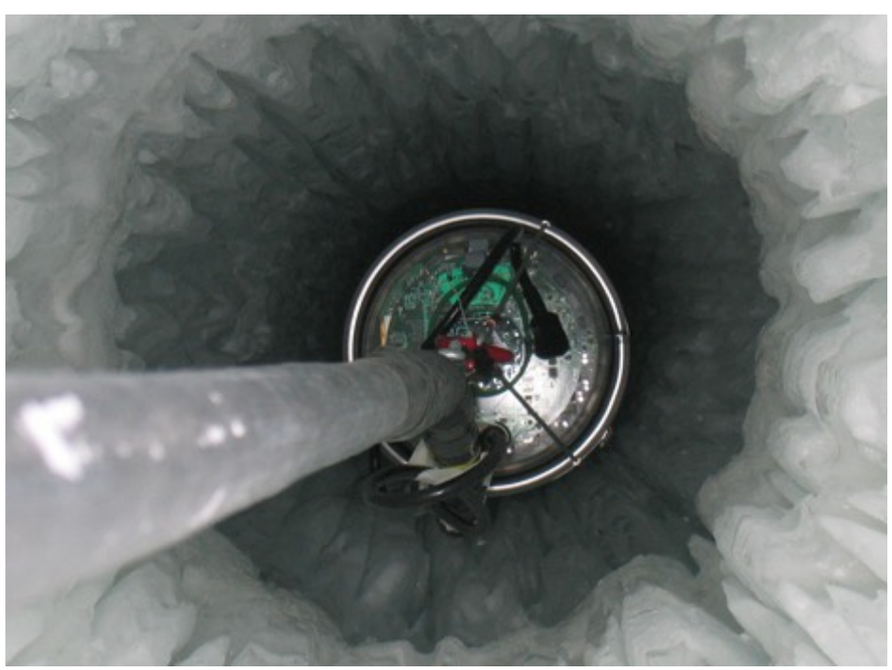


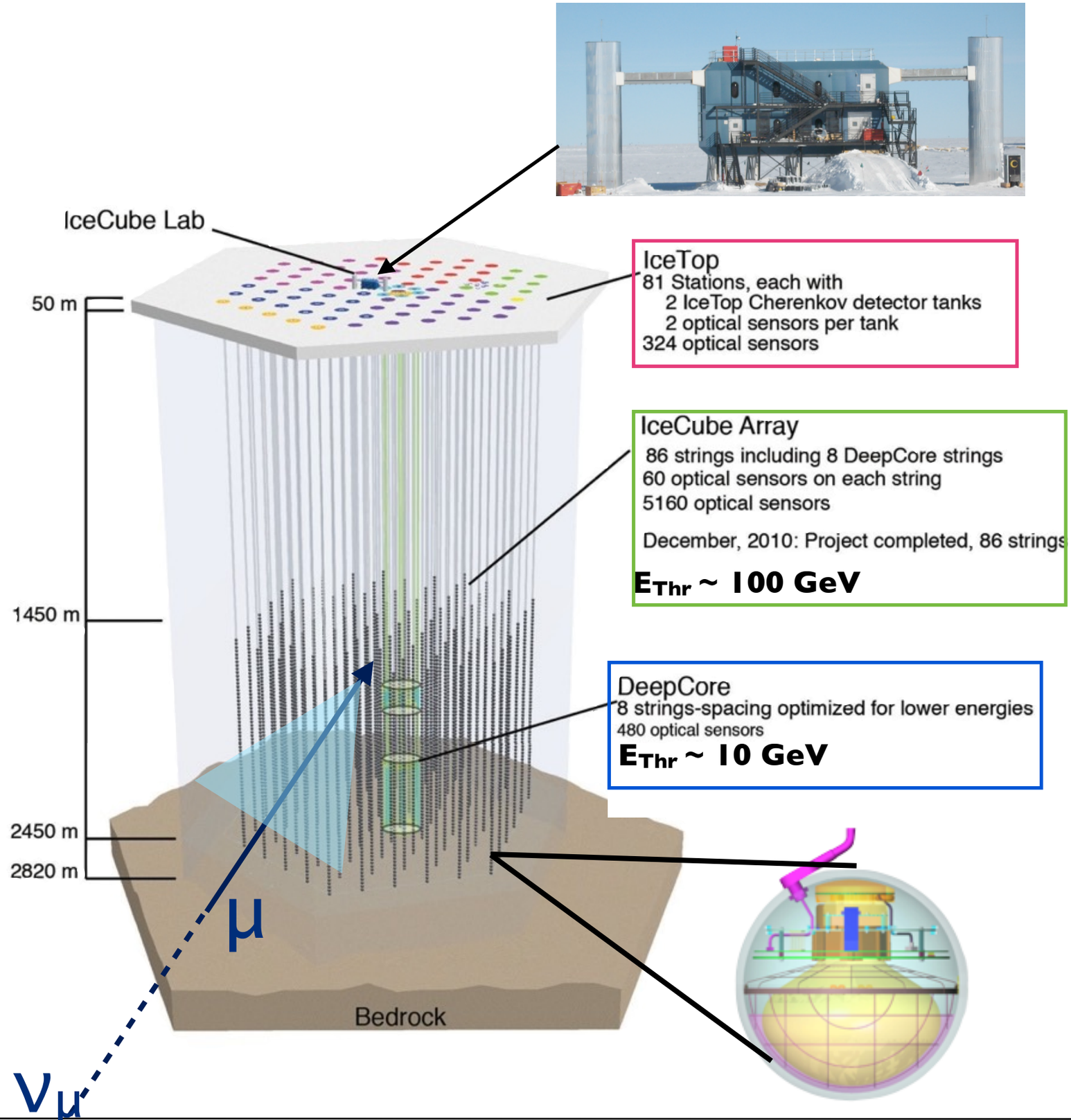


Astro-physical Neutrino Search

The IceCube Neutrino Telescope

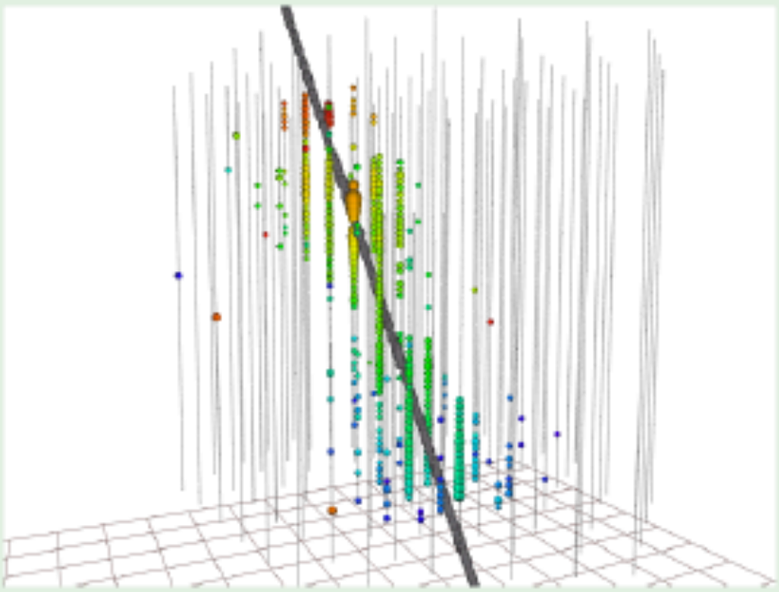
- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice





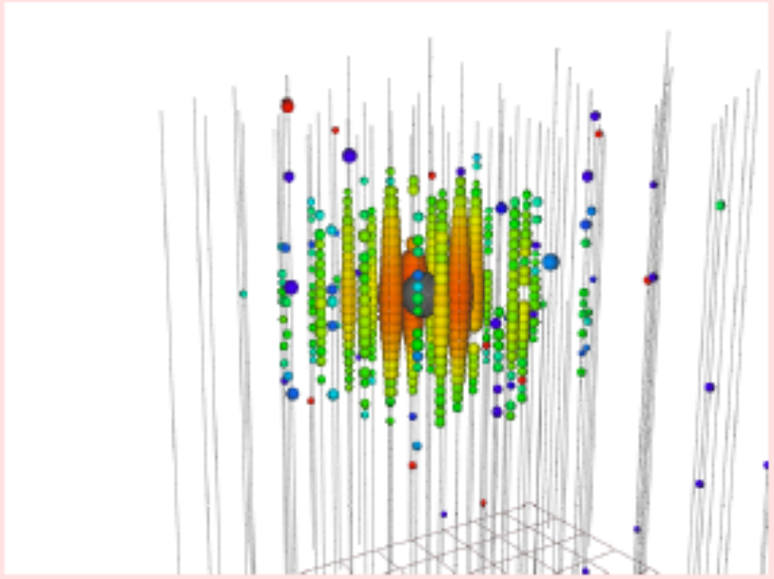
Event topologies in IceCube

Track



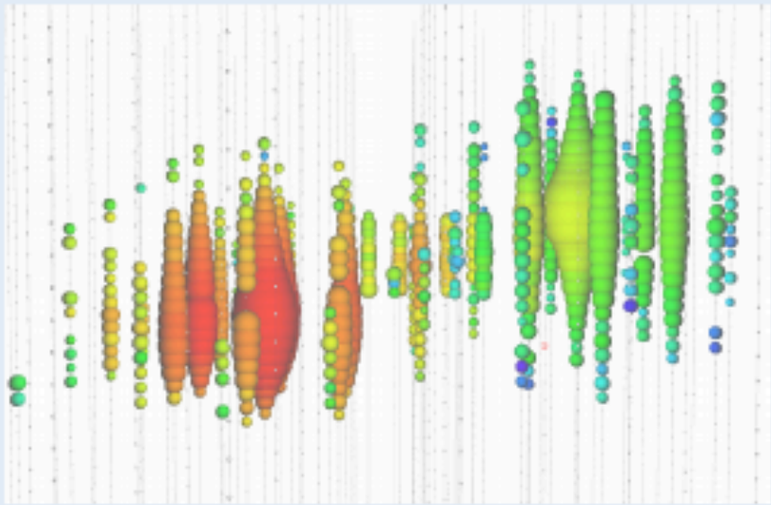
- Muon tracks (CC ν_μ)
- Resolution $< 1^\circ$
- Large energy uncertainties

Cascade

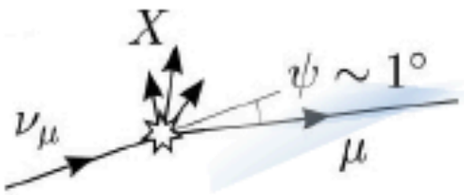


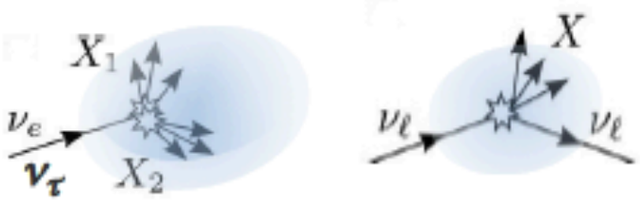
- NC or ν_e/ν_τ
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$

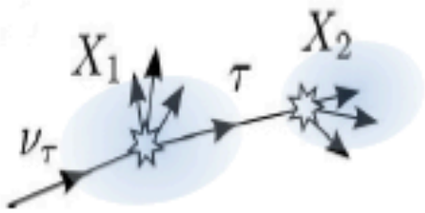
Double-bang



- High energy ν_τ (>100 TeV)
- Not observed yet







early  late

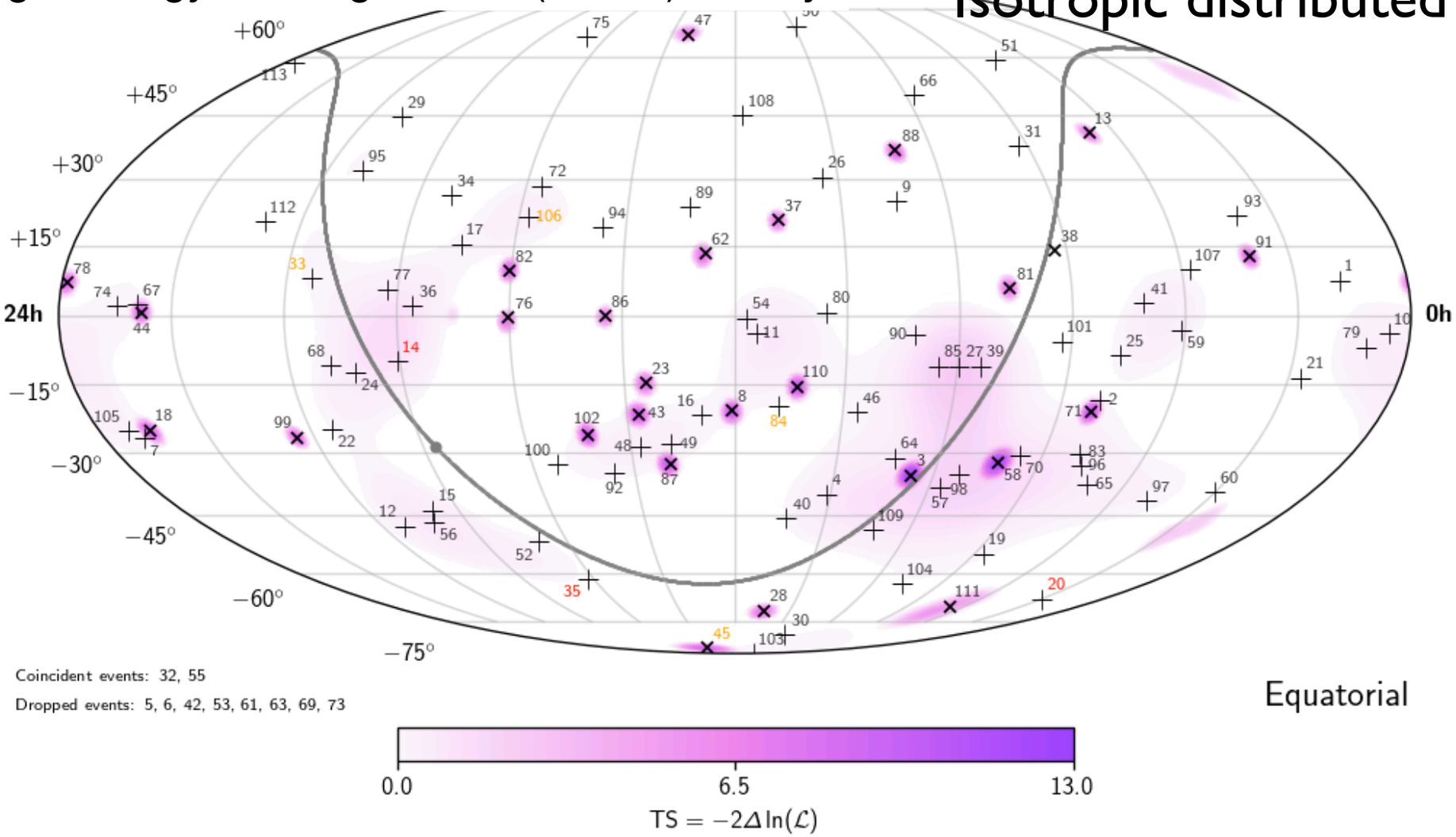
amount of light in detector $\propto$ ν energy

Arrival directions (highest energy events)

IceCube Collaboration, *Science* 342, 1242856 (2013)

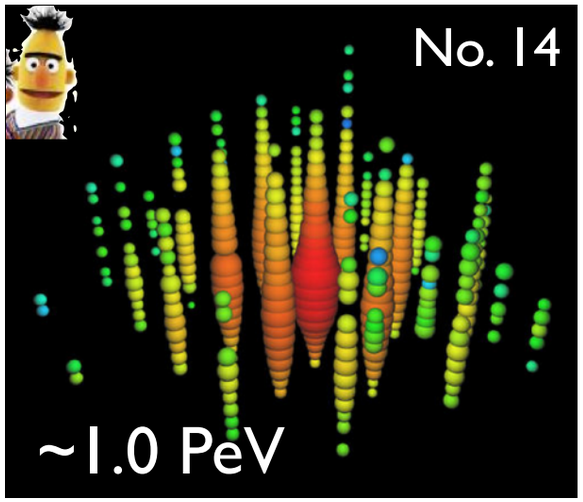
High-Energy Starting Events (HESE) – 7.5 yr

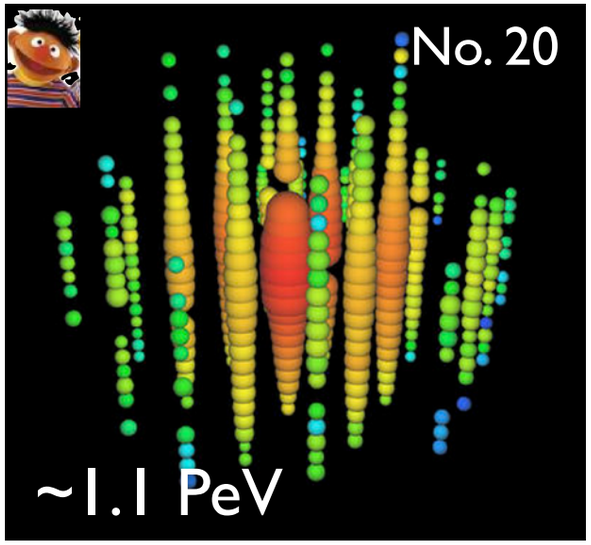
Isotropic distributed

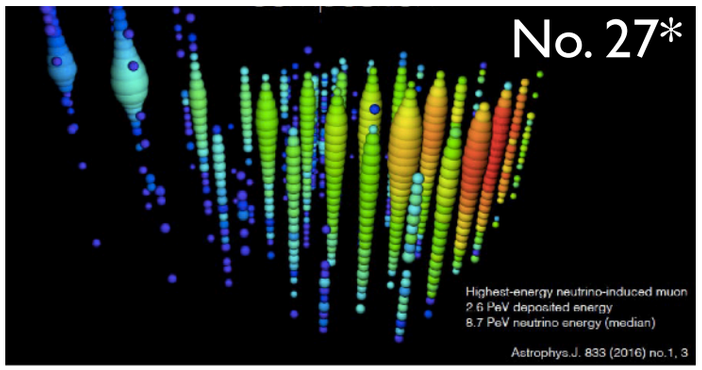


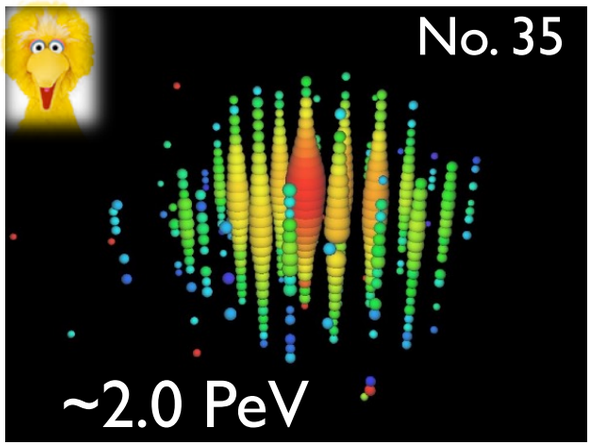
Equatorial

$E < 300$ TeV 300 TeV $< E <$ 1 PeV 1 PeV $< E$





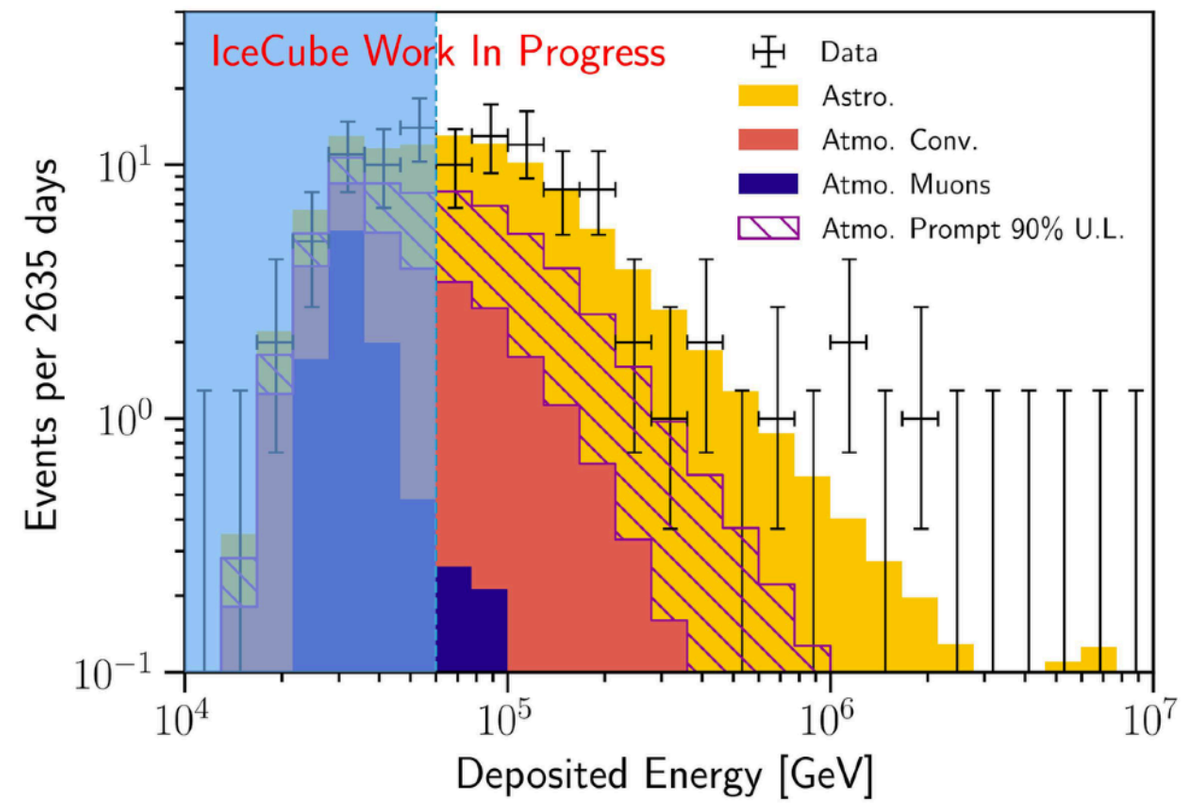




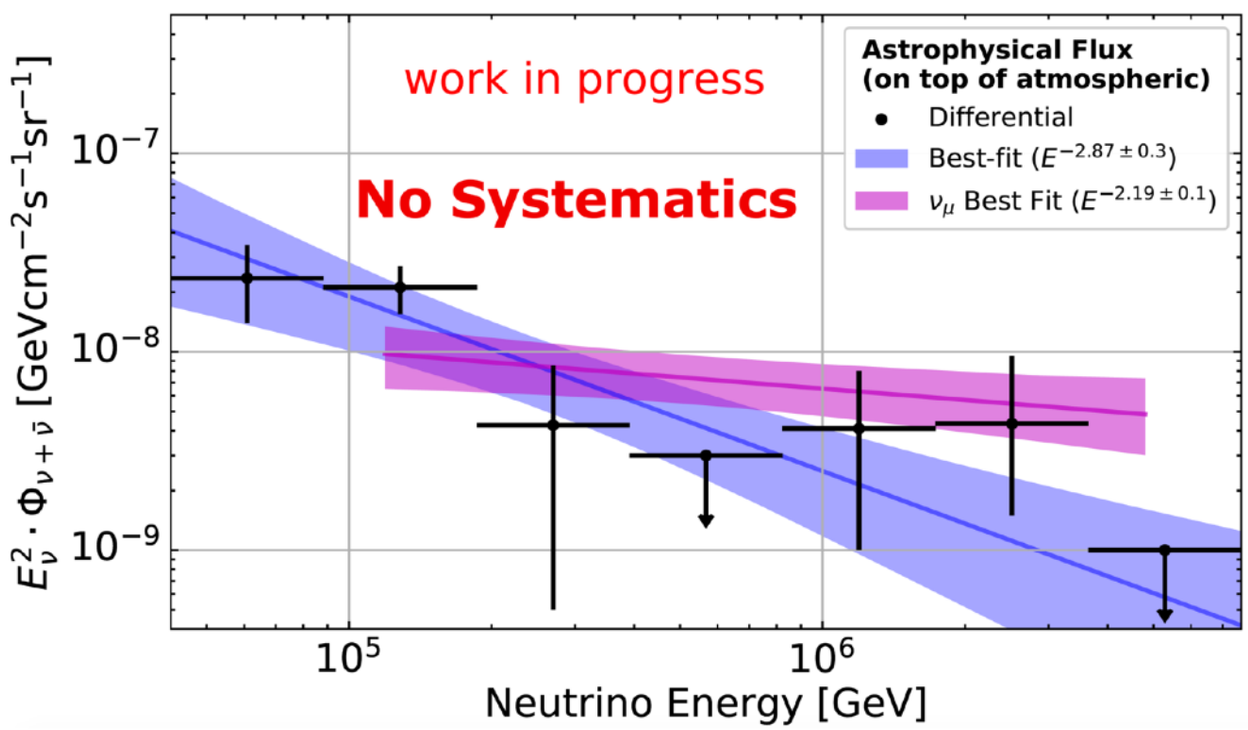
No evidence for point sources, nor a correlation with the galactic plane

Neutrino energy spectrum

High-Energy Starting Events (HESE) - 7.5years



HESE 7.5 year
103 events
(60 events > 60 TeV)
Best-fit: γ=2.87+/-0.3

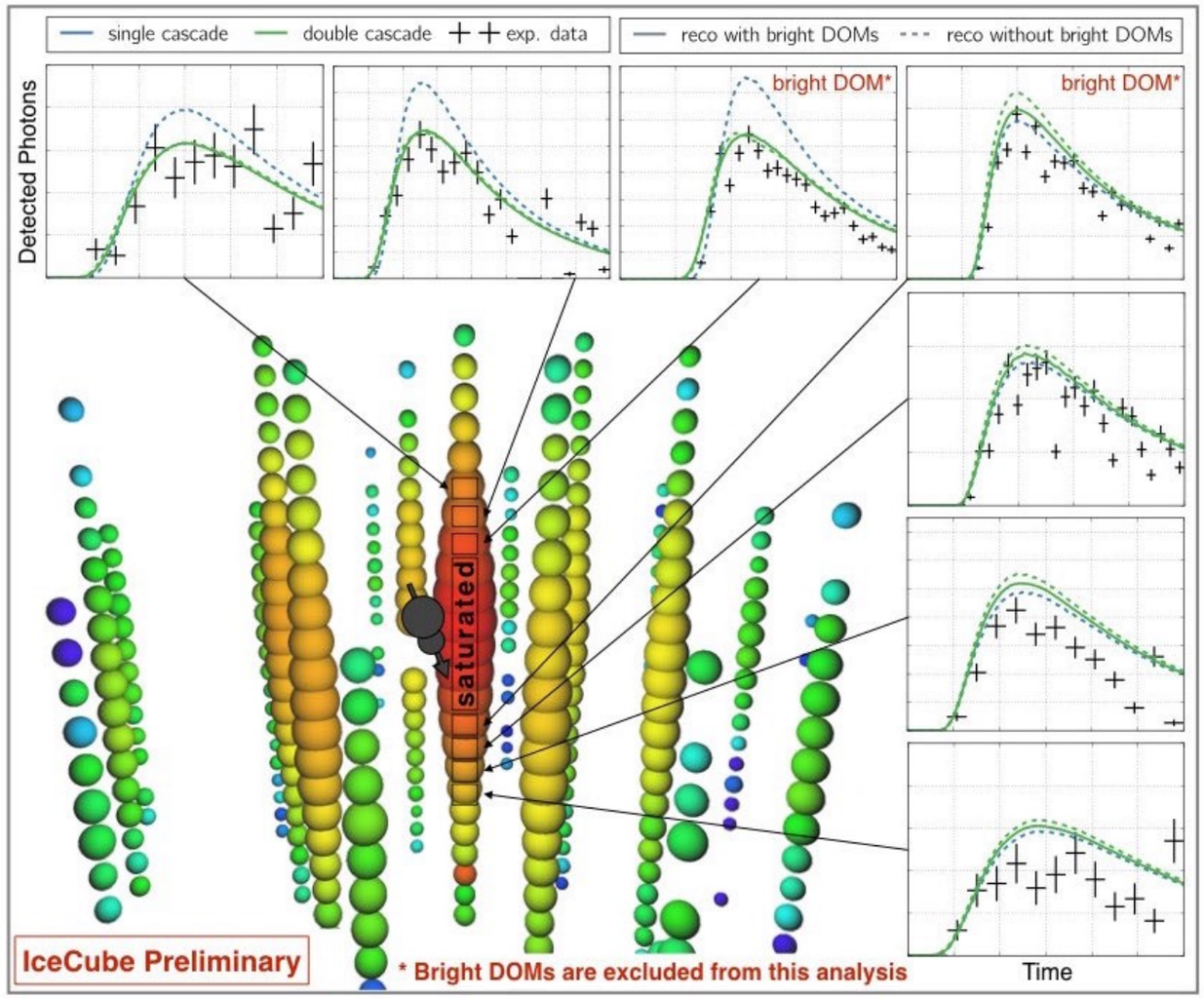


8-yr upgoing ν_μ "track"
36 events at >200 TeV (6.7σ)
- Best-fit: γ=2.19+/-0.10
- ν_μ flux above 100 TeV:

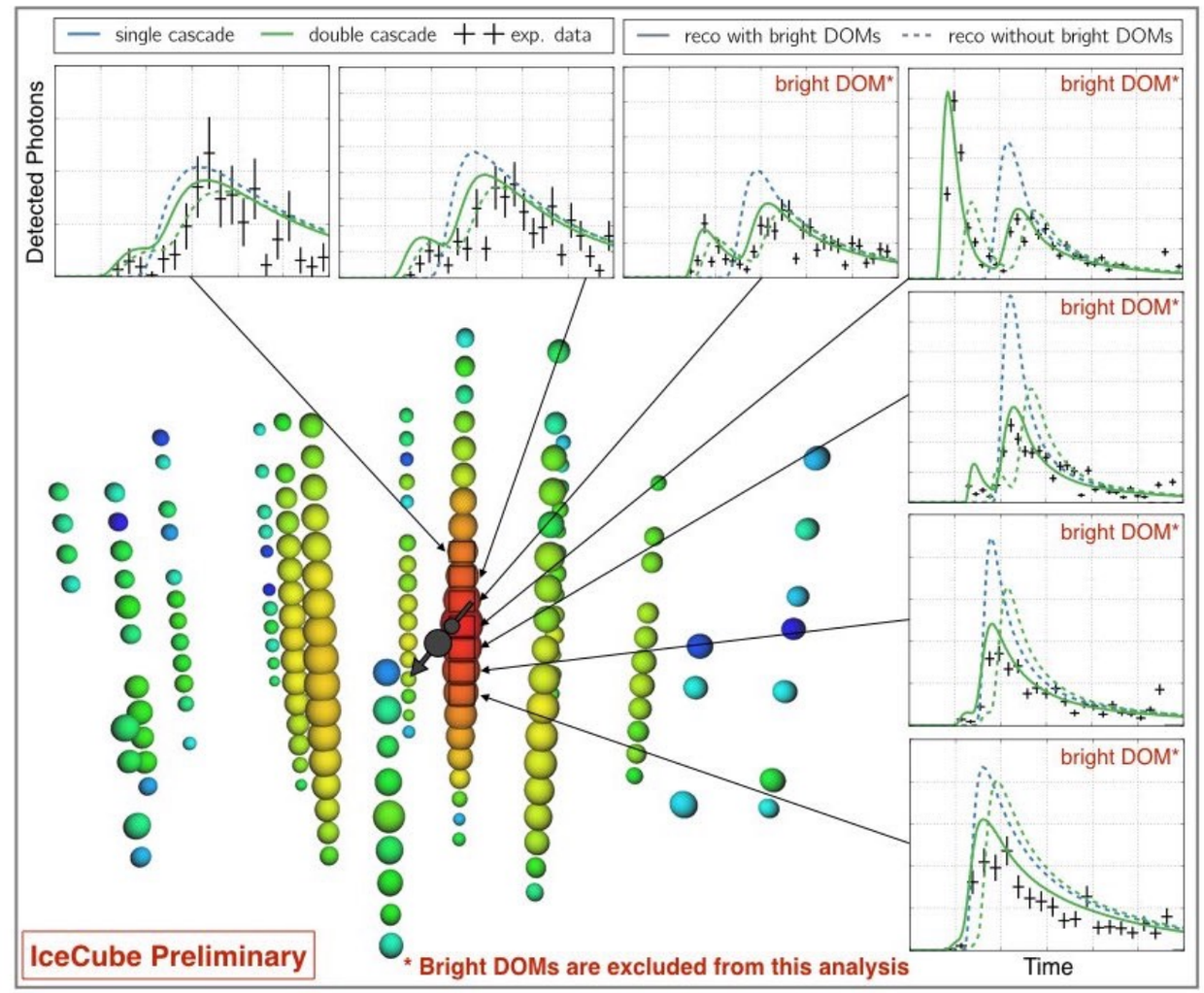
$E_\nu^2\Phi_\nu=(1.01^{+0.26}_{-0.23})\times10^{-8}$ GeV cm^{-2} s^{-1} sr-1

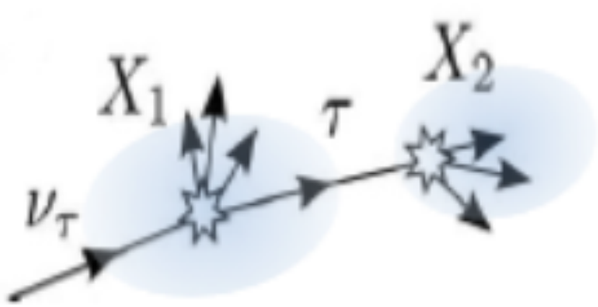
HESE 7.5yrs Tau Search

Double cascade Event #1



Double cascade Event #2



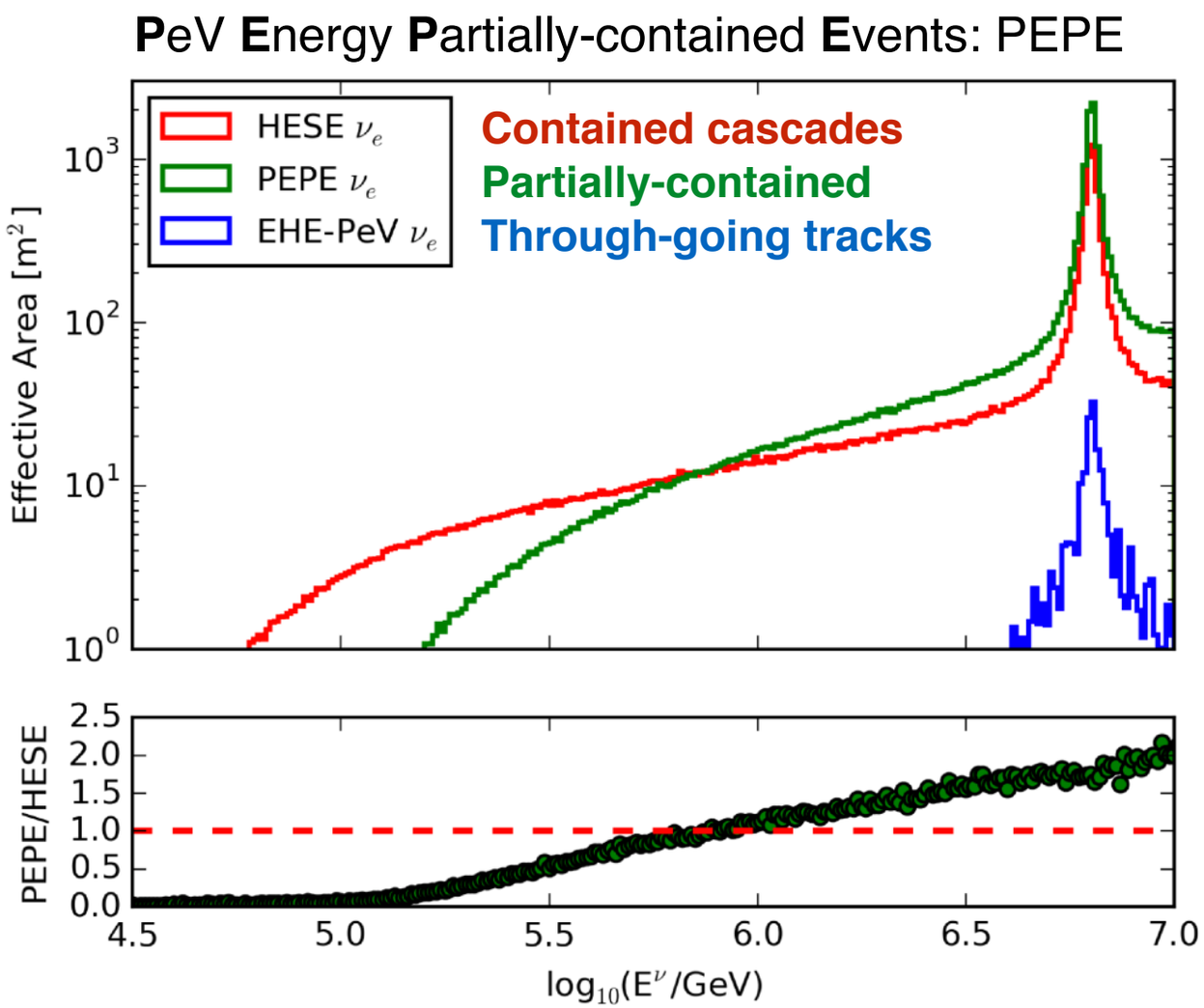


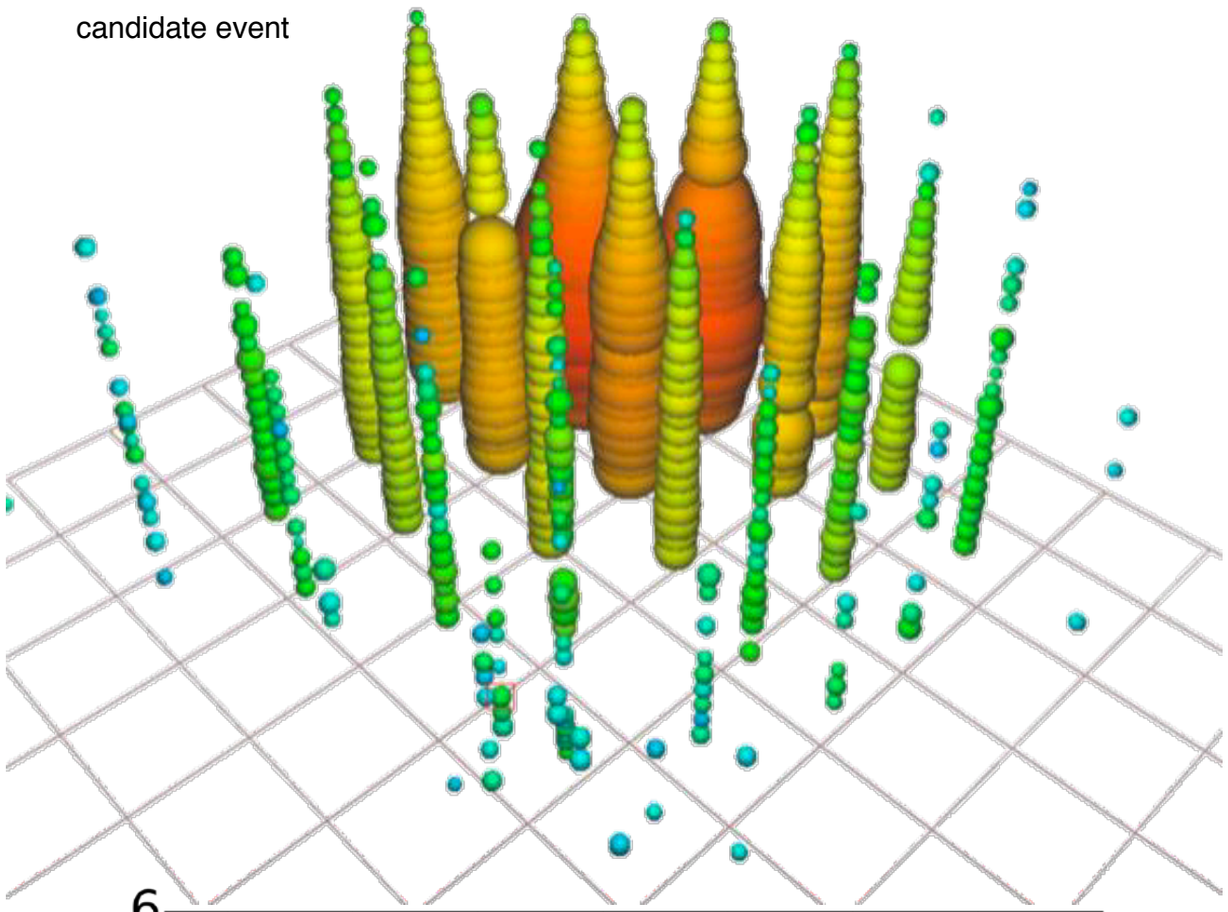
Two double cascades candidate events have been identified

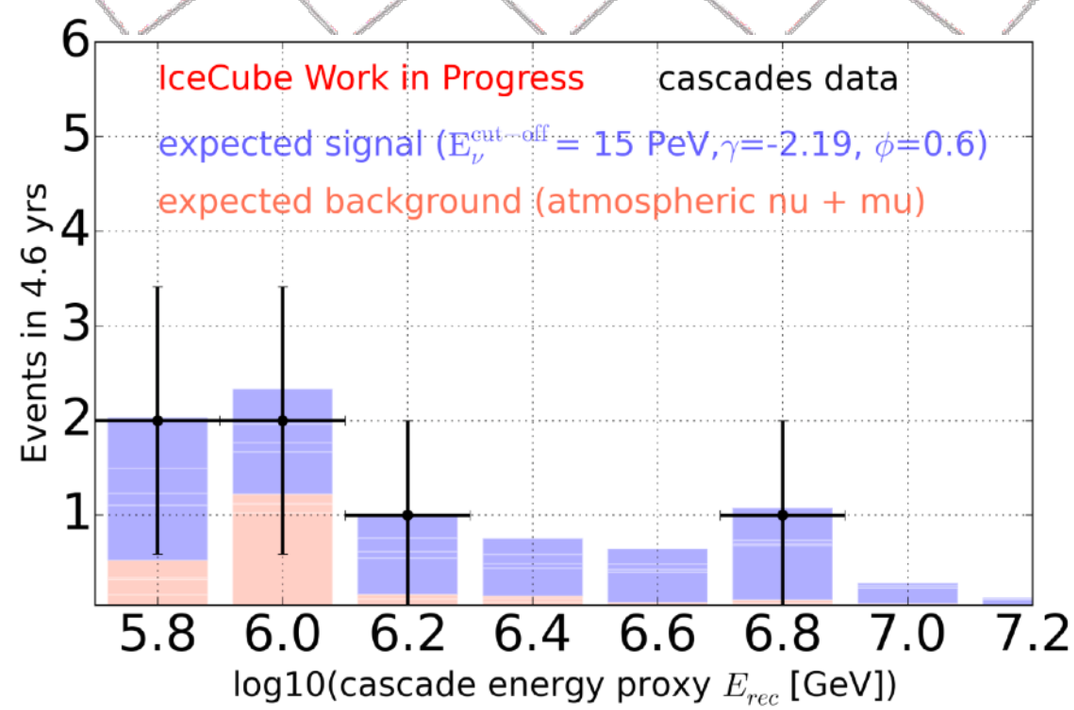
Double cascades arise from ν_τ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

Separate study of taus of the double cascade events on-going

The global high-energy picture



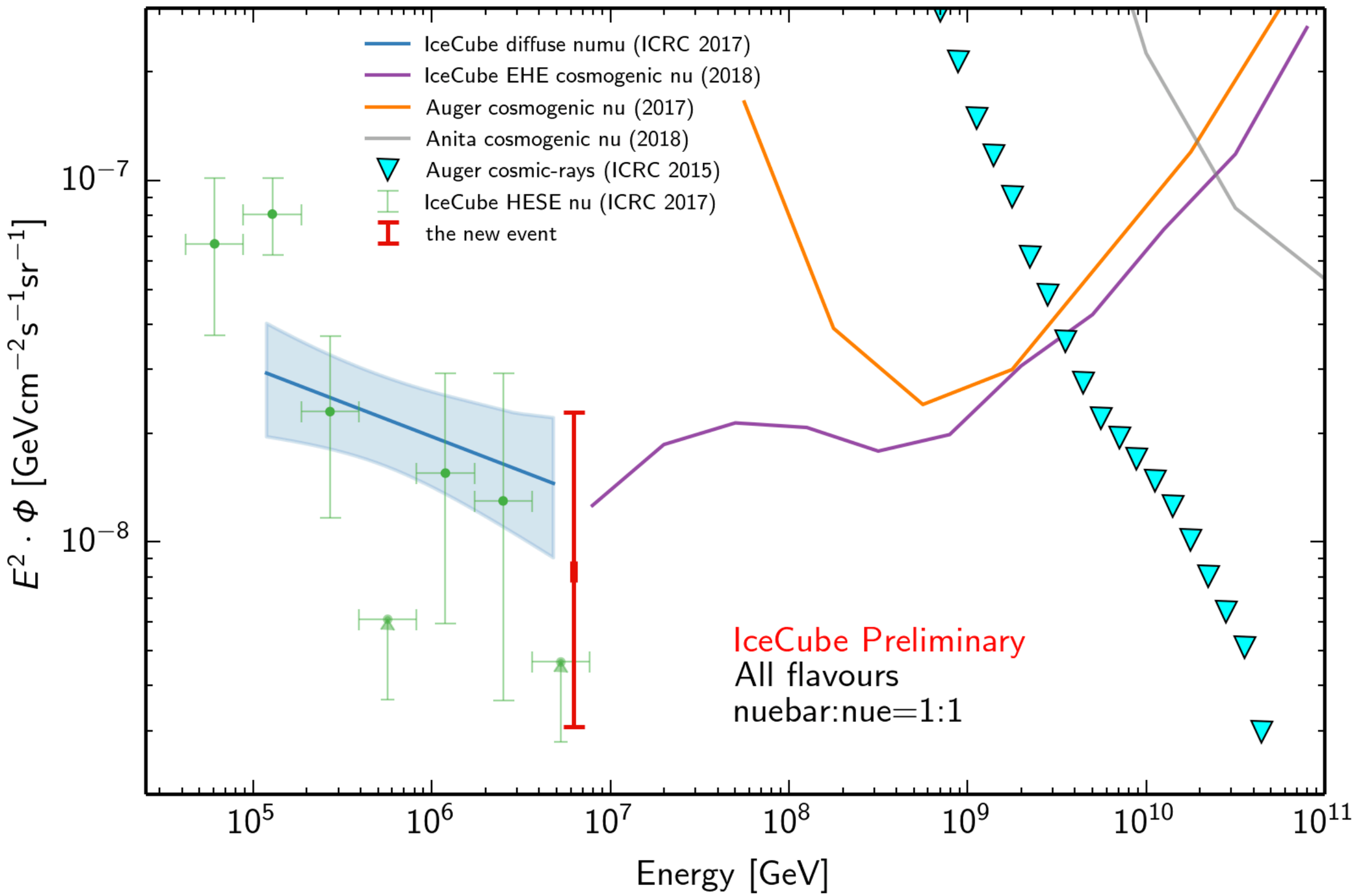




4.6 years (2012-2016) of data. **One event is at Glashow** bin

Brightest of all IceCube PeV events in the dataset even though only partially-contained

The global high-energy picture



Multi-messenger Neutrino Astronomy and IceCube-170922A

Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17
FROM: E

Claudio Ko
report on I

On 22 Sep,
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ra
TXS 0506+056, located inside the IceCube
error region.

ATel #10791; Y
K
Crede
Subjects: Gamma
Referred to by AT
10844, 10845, 10

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

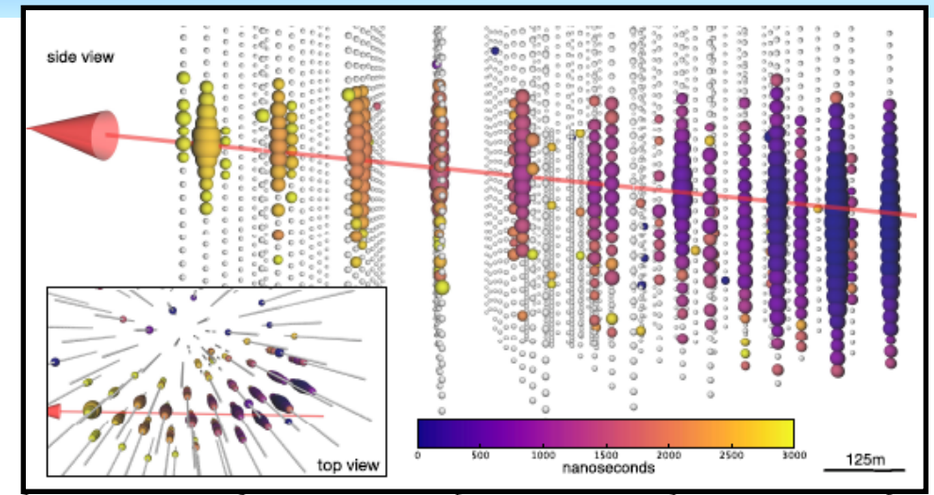
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

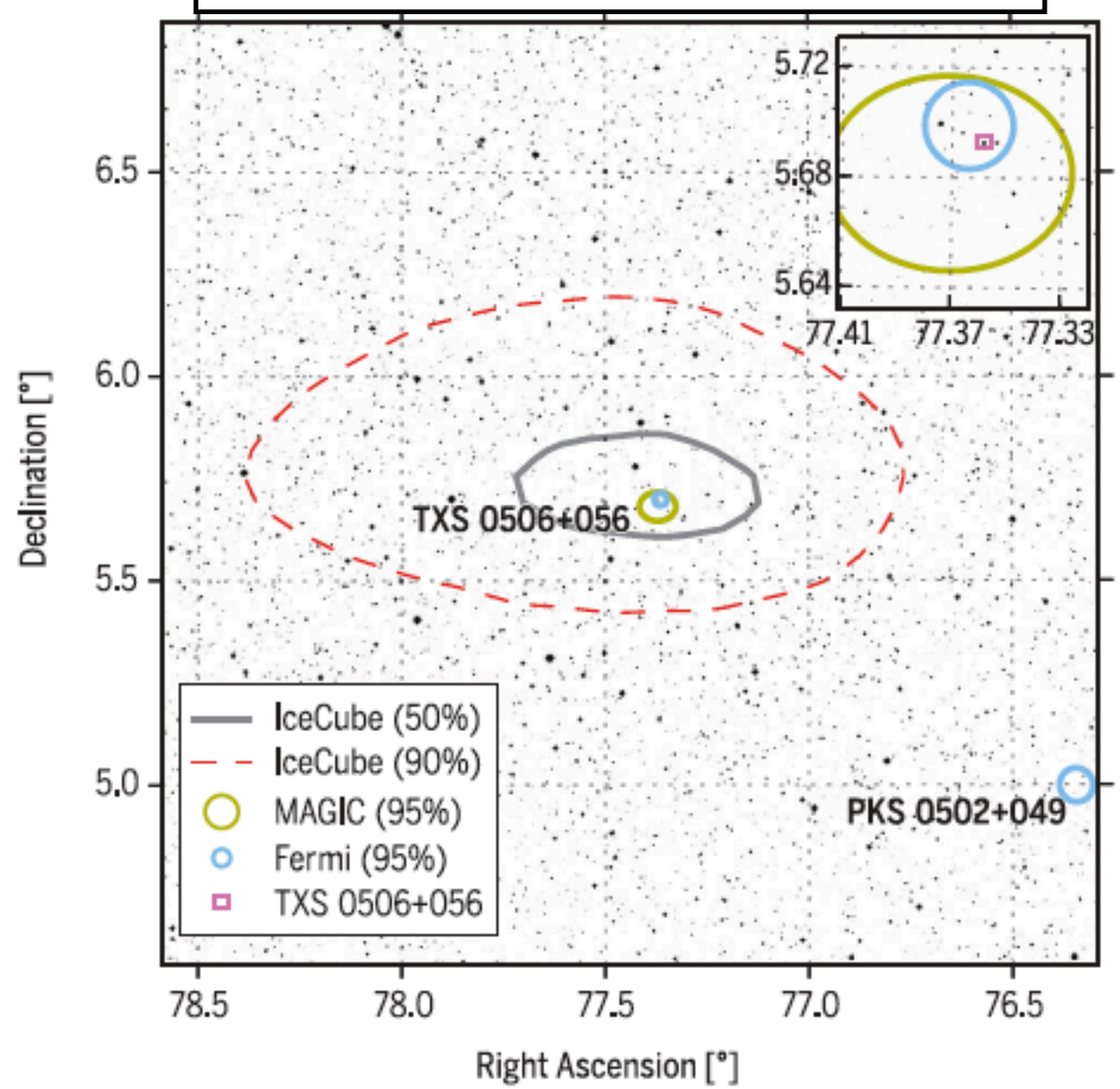
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916 Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 0 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this sourc under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h c





- September 22, 2017: a neutrino alert issued by IceCube
- Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
- Very active multi-messenger follow-up from radio to γ-rays

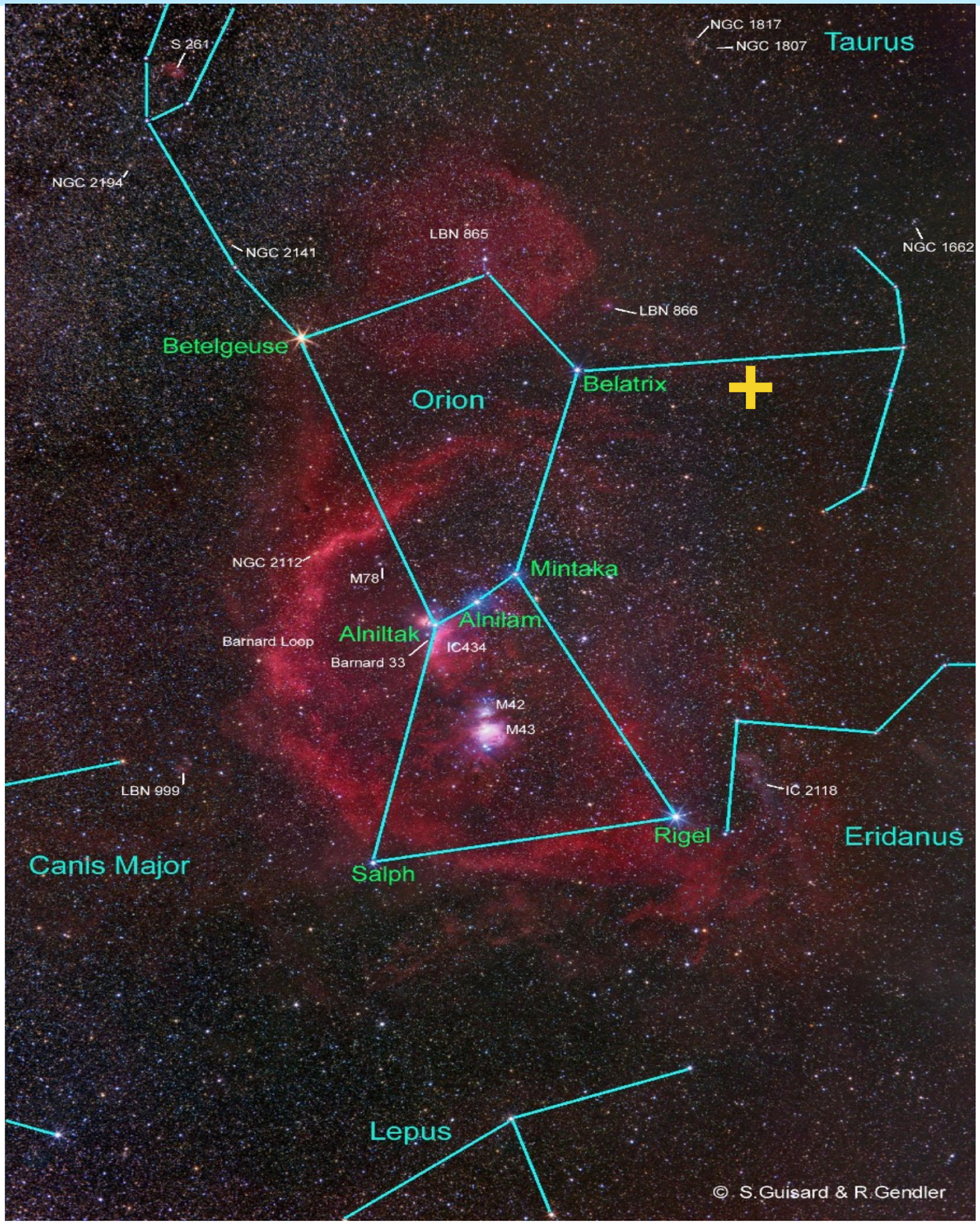
(Science 361, eaat1378 (2018)

IceCube-170922A

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

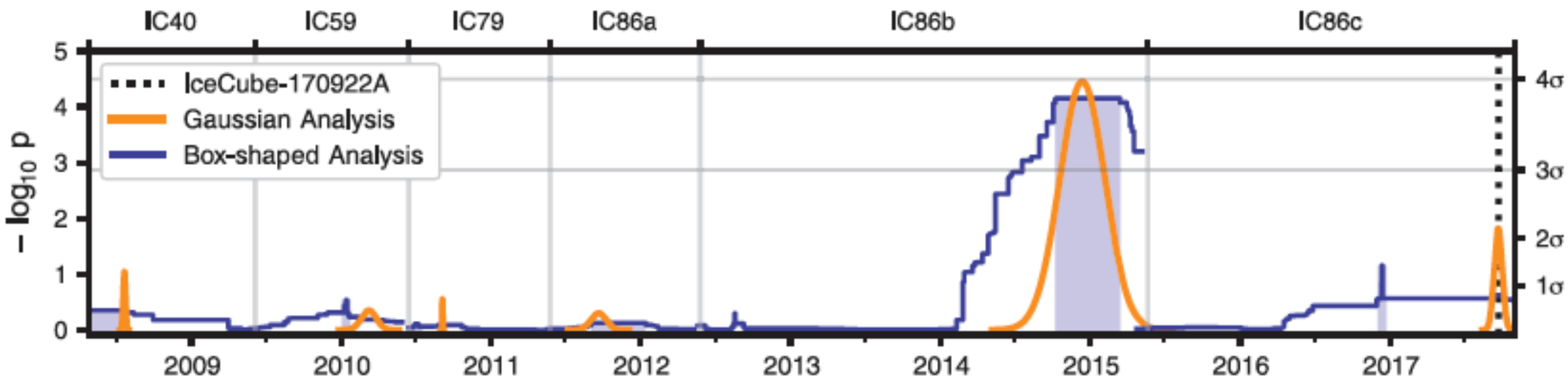
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: **~3σ** (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- **TXS 0506+056 redshift determined to be z=0.3365** (S. Paiano et al. ApJL 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605

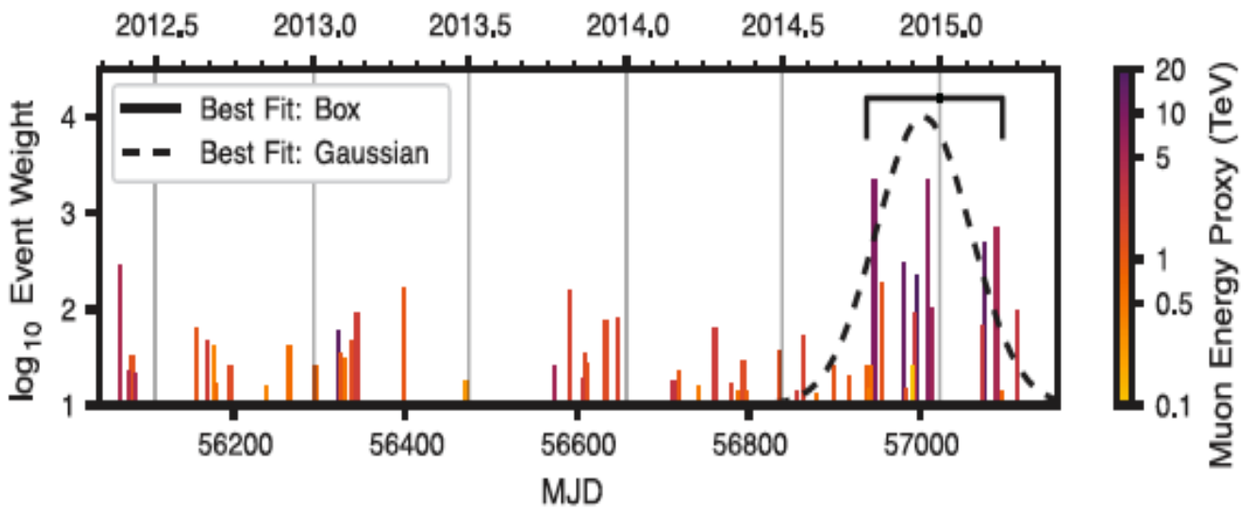


Science 361 (6398), 147-151.

IceCube-170922A



- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)

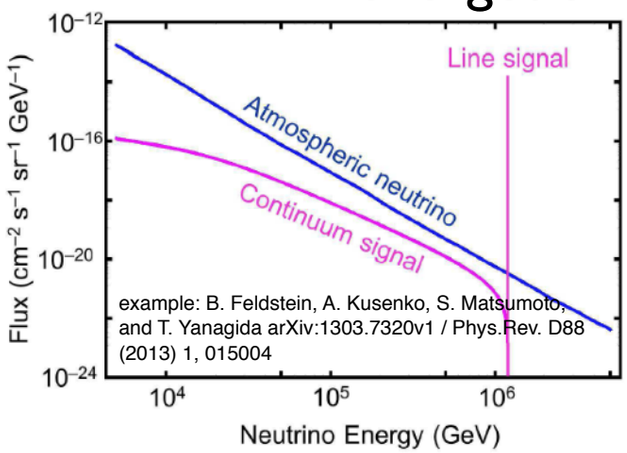


Time-independent weight of individual events during the IC86b period.

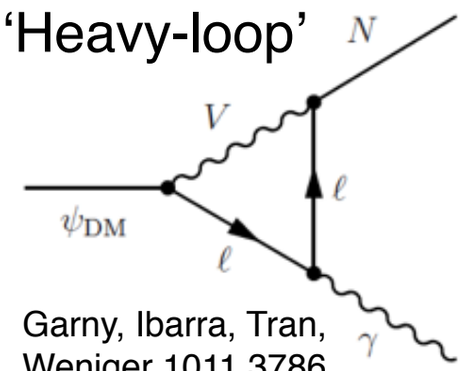
Search for Physics Beyond the Standard Model

Heavy Dark Matter Decay

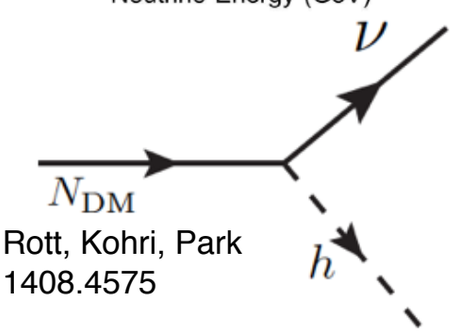
Decay process might produce mono-energetic neutrinos



'Heavy-loop'

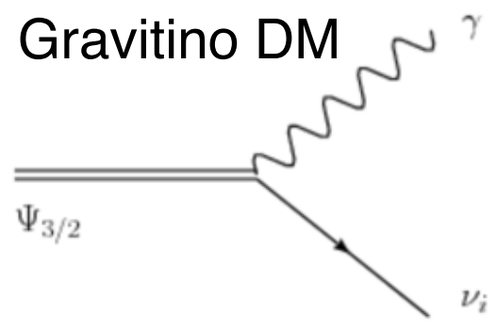


Garny, Ibarra, Tran, Weniger 1011.3786

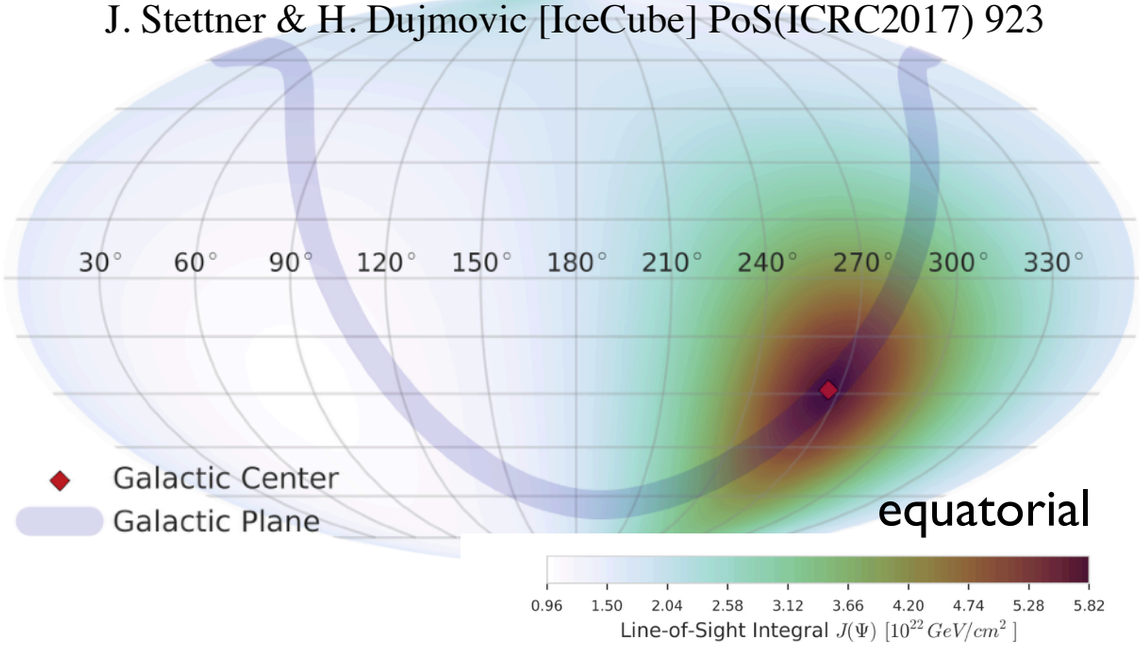


Rott, Kohri, Park 1408.4575

Gravitino DM



J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



Two flux contributions: Galactic and Extra galactic

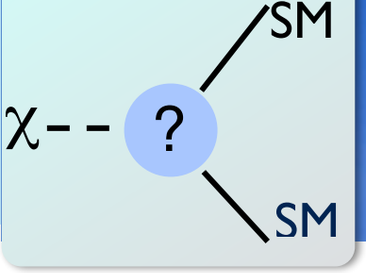
$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_{\mathrm{c}}}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$



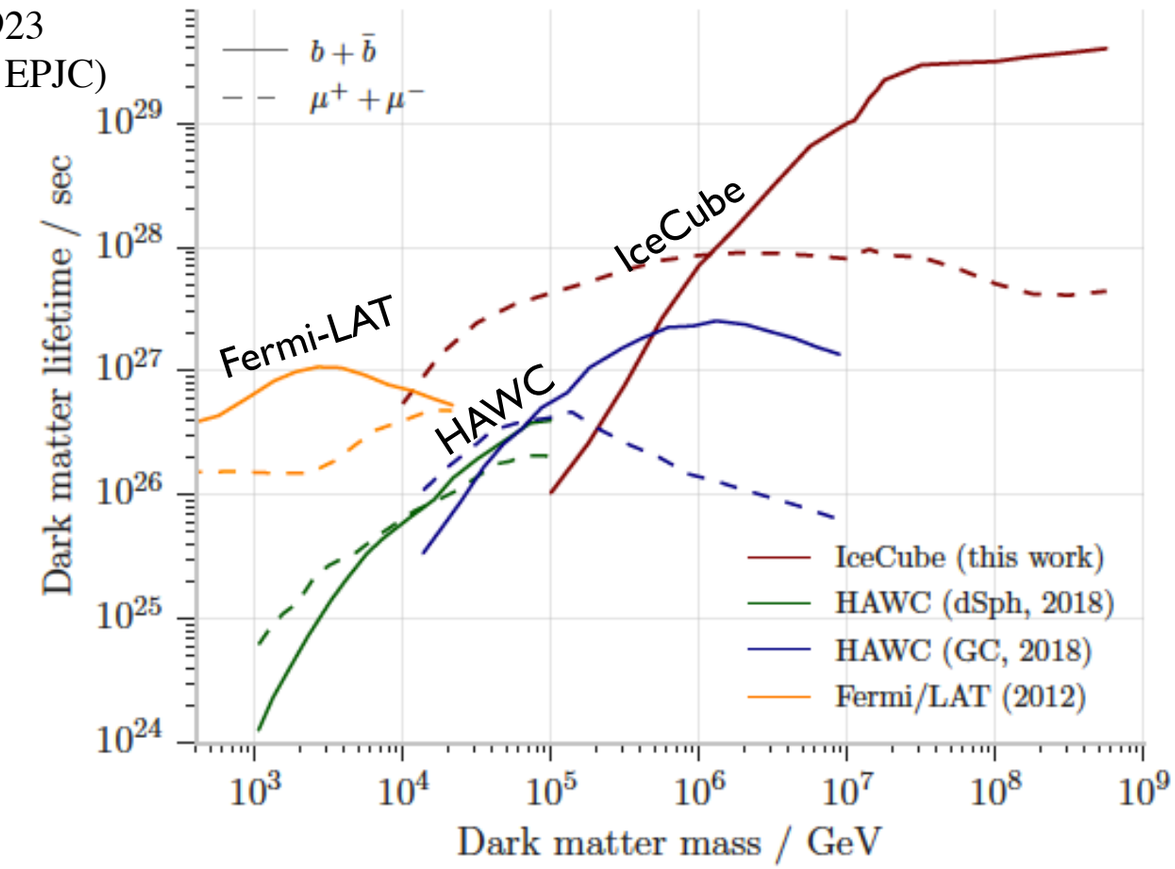
Dark Matter Decay with IceCube

J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923
IceCube Collaboration arXiv:1804.03848v1 (published EPJC)

- Two IceCube analyses have been performed on independent data samples
  - Track-like with six years of data
  - Cascade-like with two years of data

	Track-like	Cascade-like
Number of events	352,294	278
Livetime	2060 days	641 days
Sky coverage	North (zenith > 85°)	Full Sky
Atm. muon background	0.3%	10%
Median reconstr. error	$< 0.5°$ ($E_\nu > 100$ TeV)	$\sim 10°$
Energy uncertainty	$\sim 100\%$	$\sim 10\%$

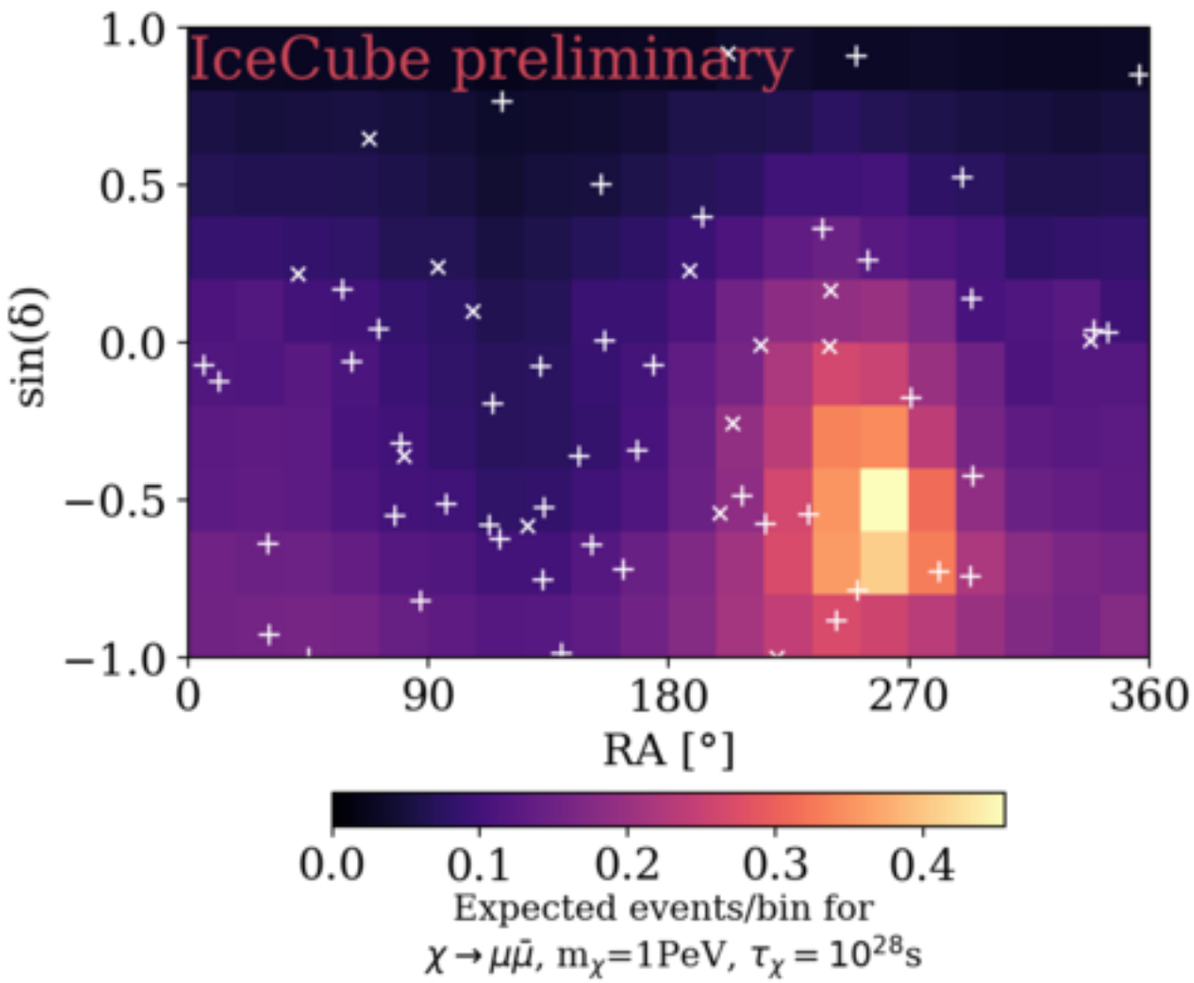
Test-Statistic: $$TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$$

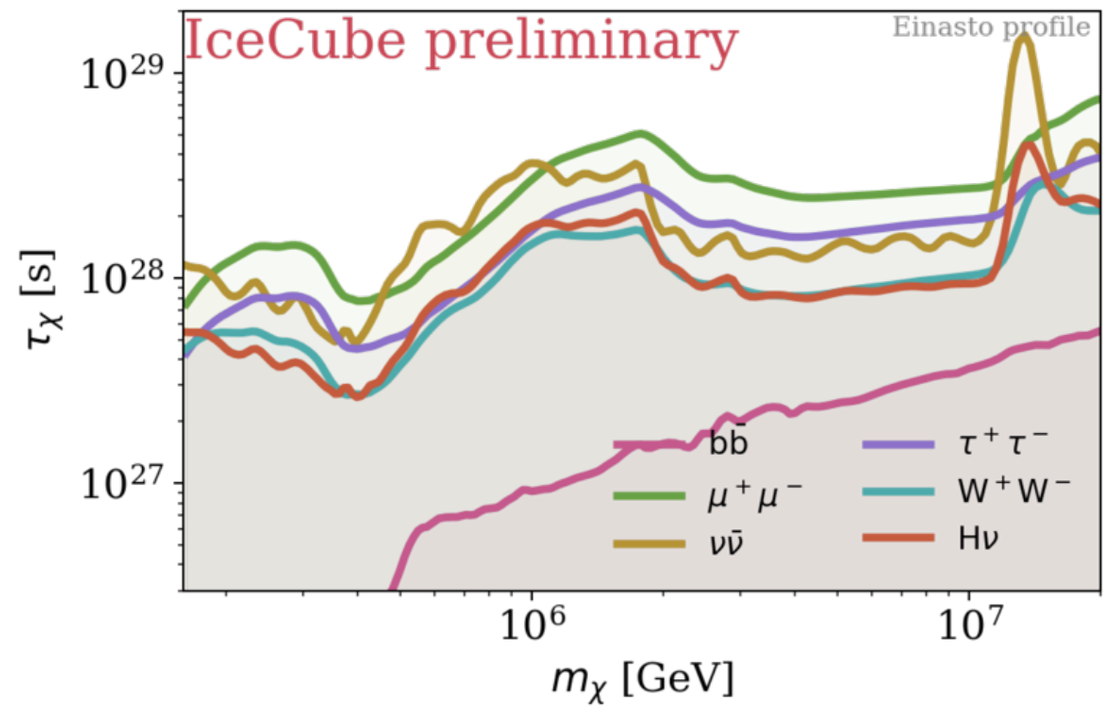


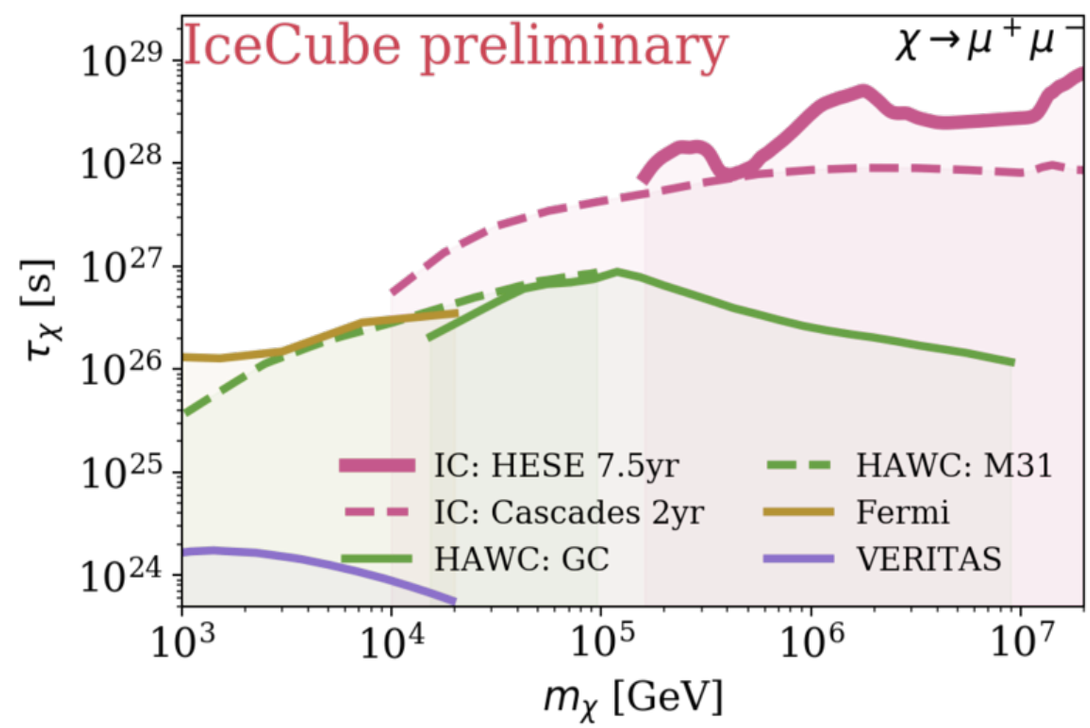
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

- Dark matter alone cannot explain the observed astrophysical neutrino flux in IceCube
- Scenarios with a PeV neutrino line became less attractive with IceCube's observation of neutrino events well above this energy

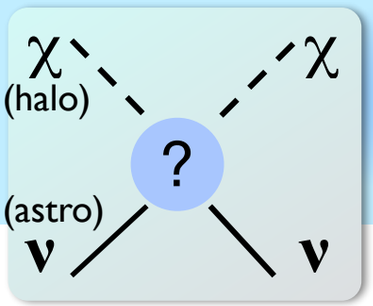
Search DM Decay with IceCube's 7years HESE Sample







- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Most competitive limits above 100TeV for a large number of channel



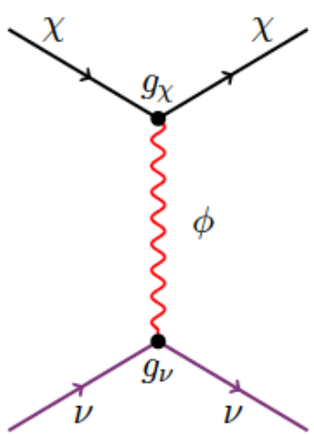
Probing dark matter neutrino interactions with HESE 7.5yrs and based on TXS0506

[C. A. Argüelles, A. Kheirandish A. C. Vincent Phys.Rev.Lett. 119 (2017) no. 20, 201801 (arXiv:1703.00451)]

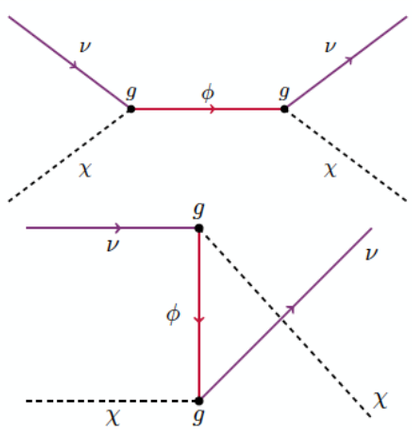
Dark Matter - Neutrino Interaction

- Scattering of high energy astrophysical neutrinos on DM in the Galactic halo can lead to a deficit of high energy neutrinos
  - Neutrino-DM interactions mediated by a scalar or vector mediator f.
  - Limits on coupling constant, g, possible by measuring the isotropy of the HE neutrino flux

(1) Fermionic DM, vector mediator

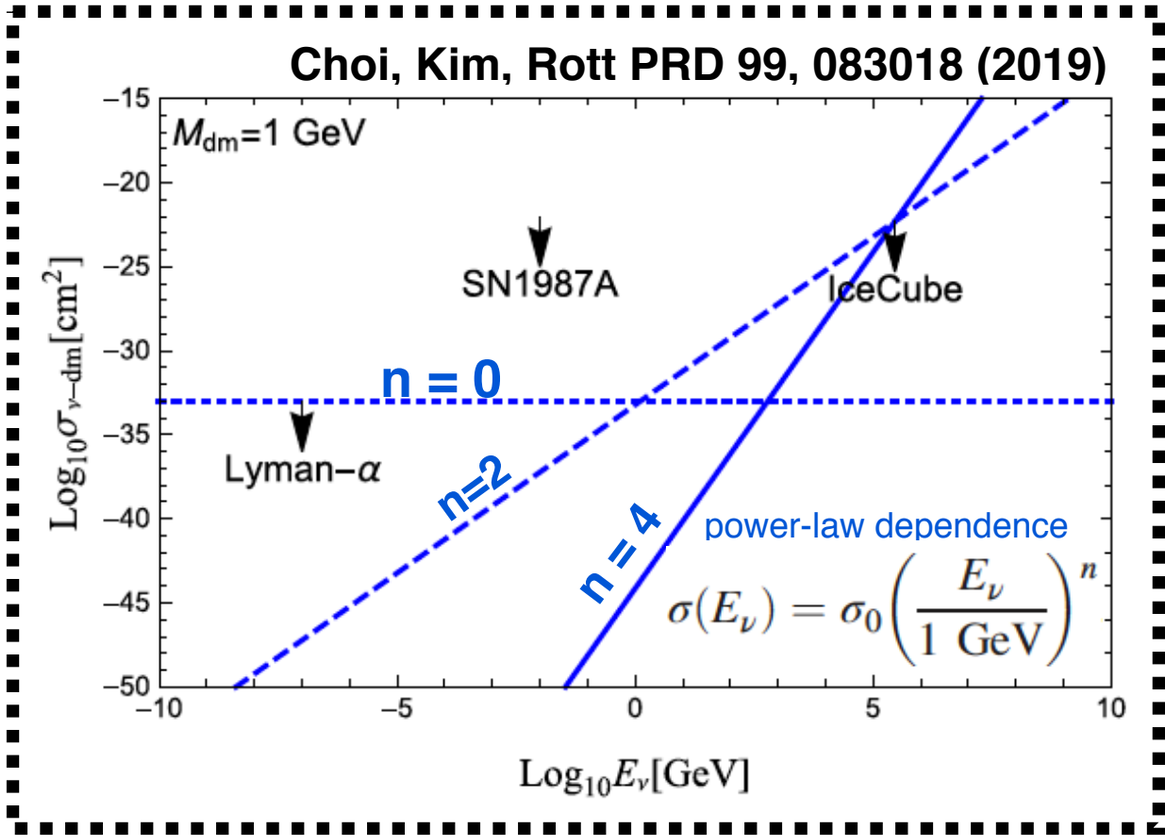


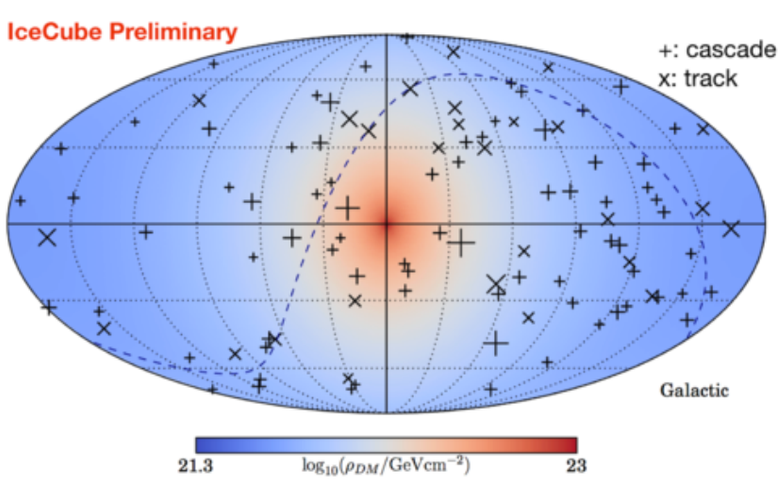
(2) Scalar DM, ferminonic mediator



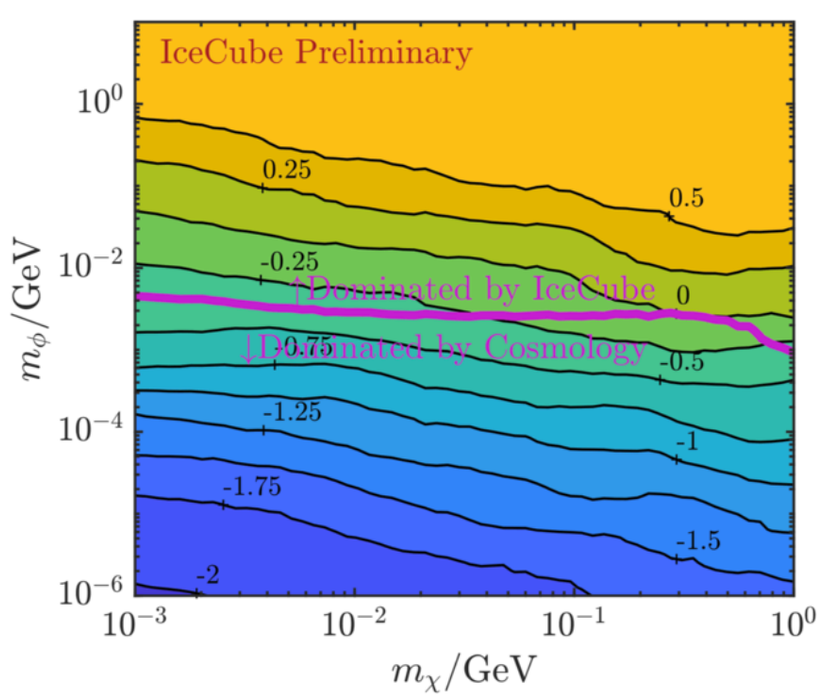
Assume:

$$\sigma_{DM-\nu} \propto E_\nu^2$$

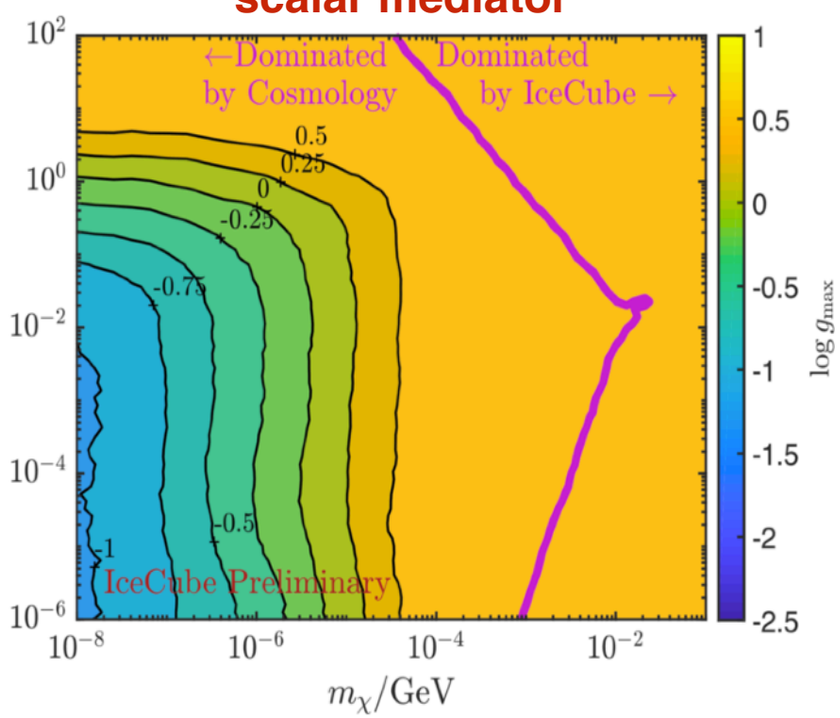




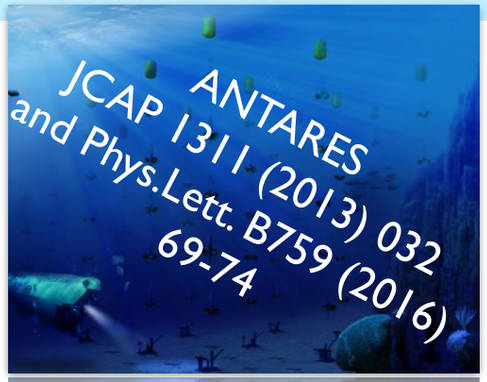
vector mediator

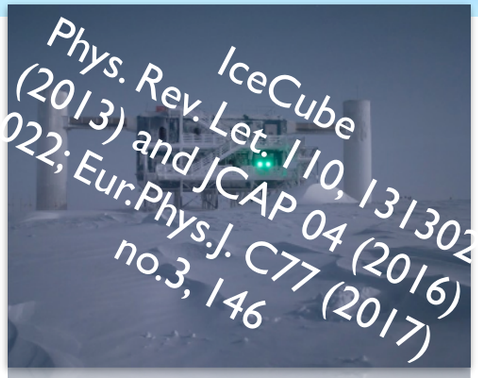


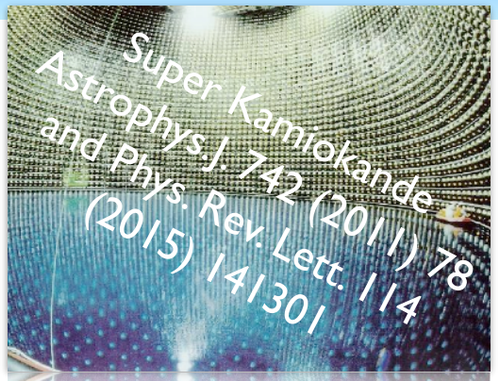
scalar mediator

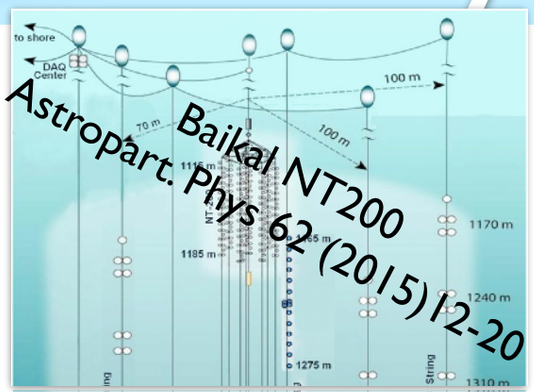


Solar Dark Matter Summary

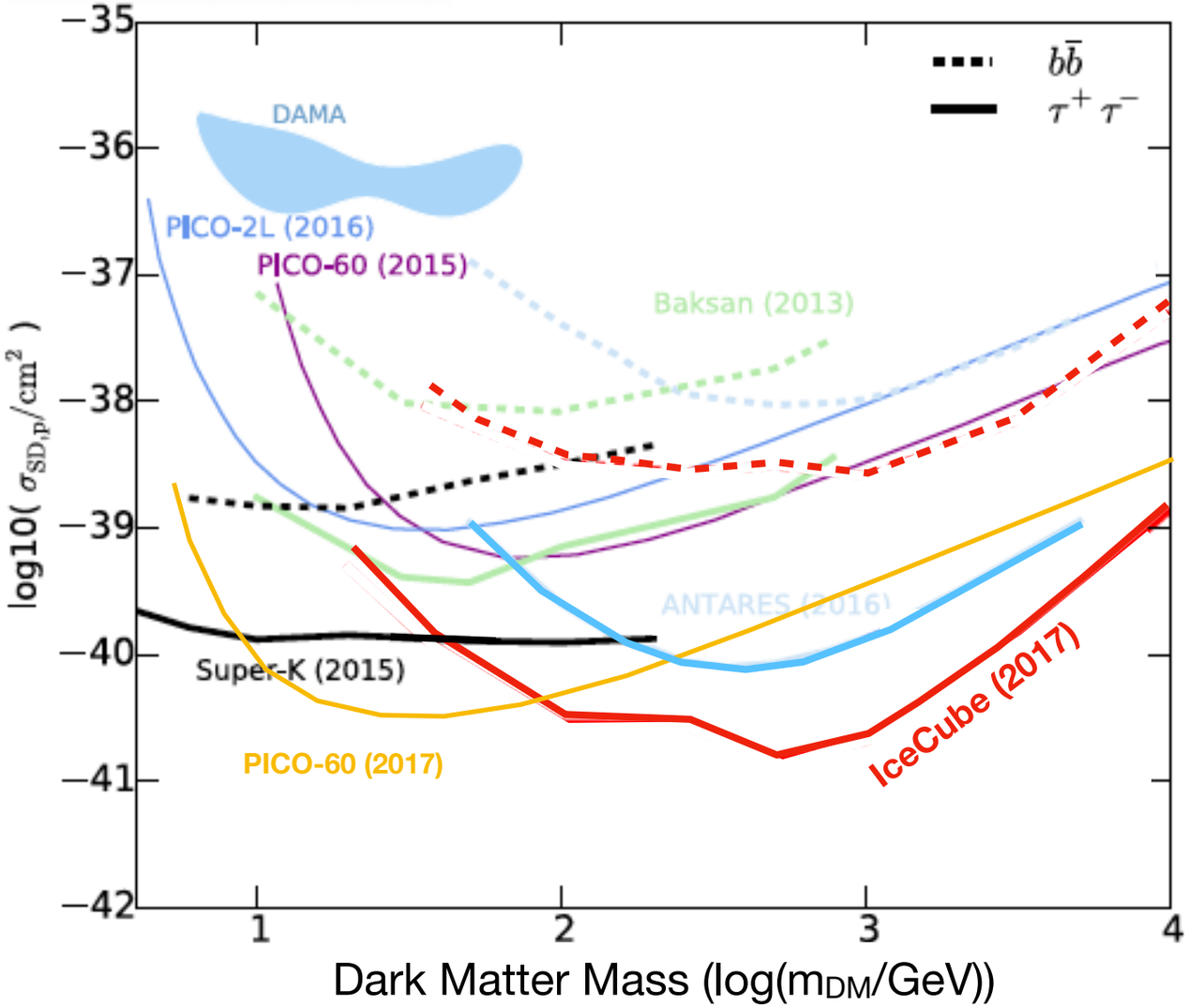




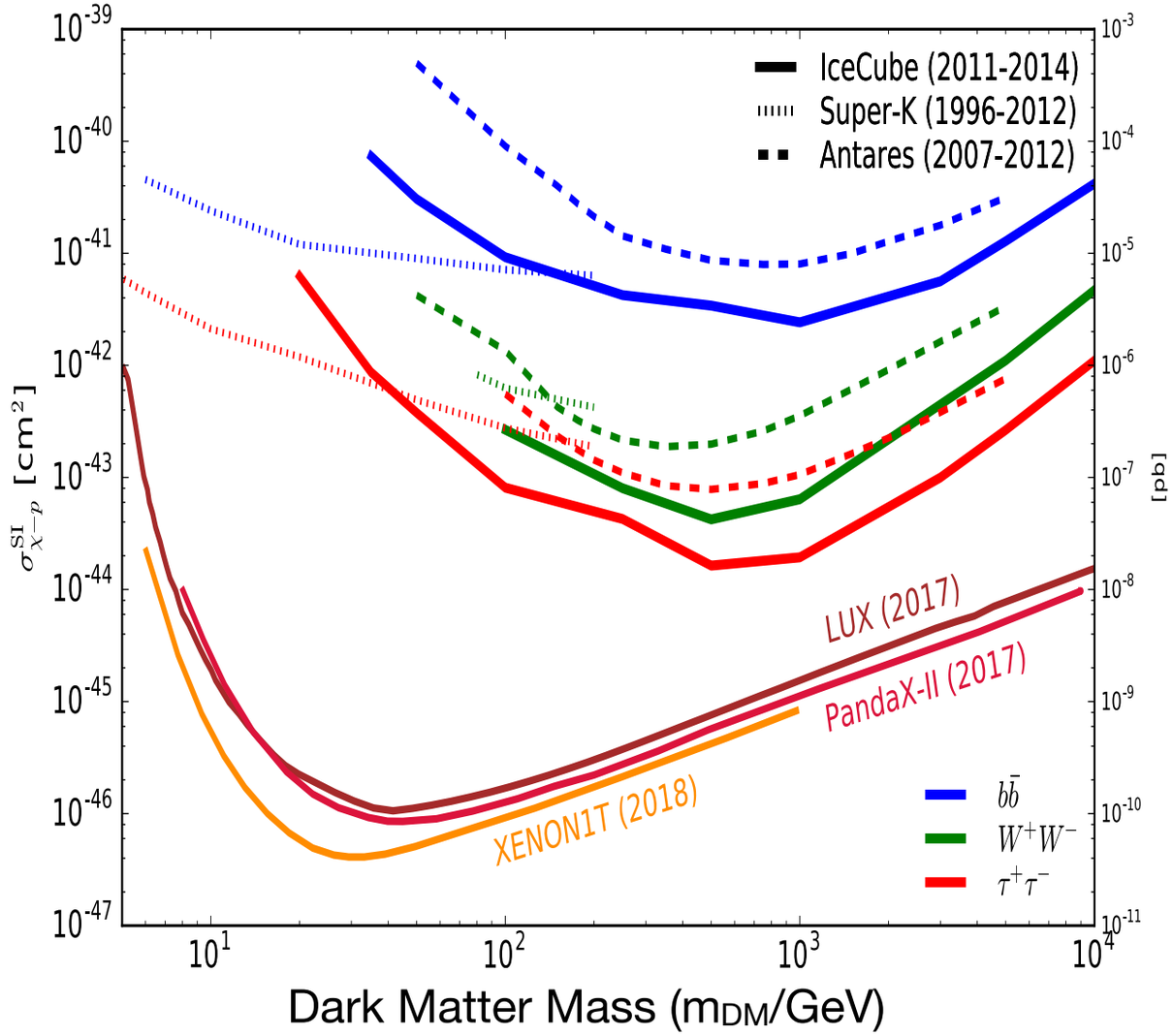




Spin-dependent scattering

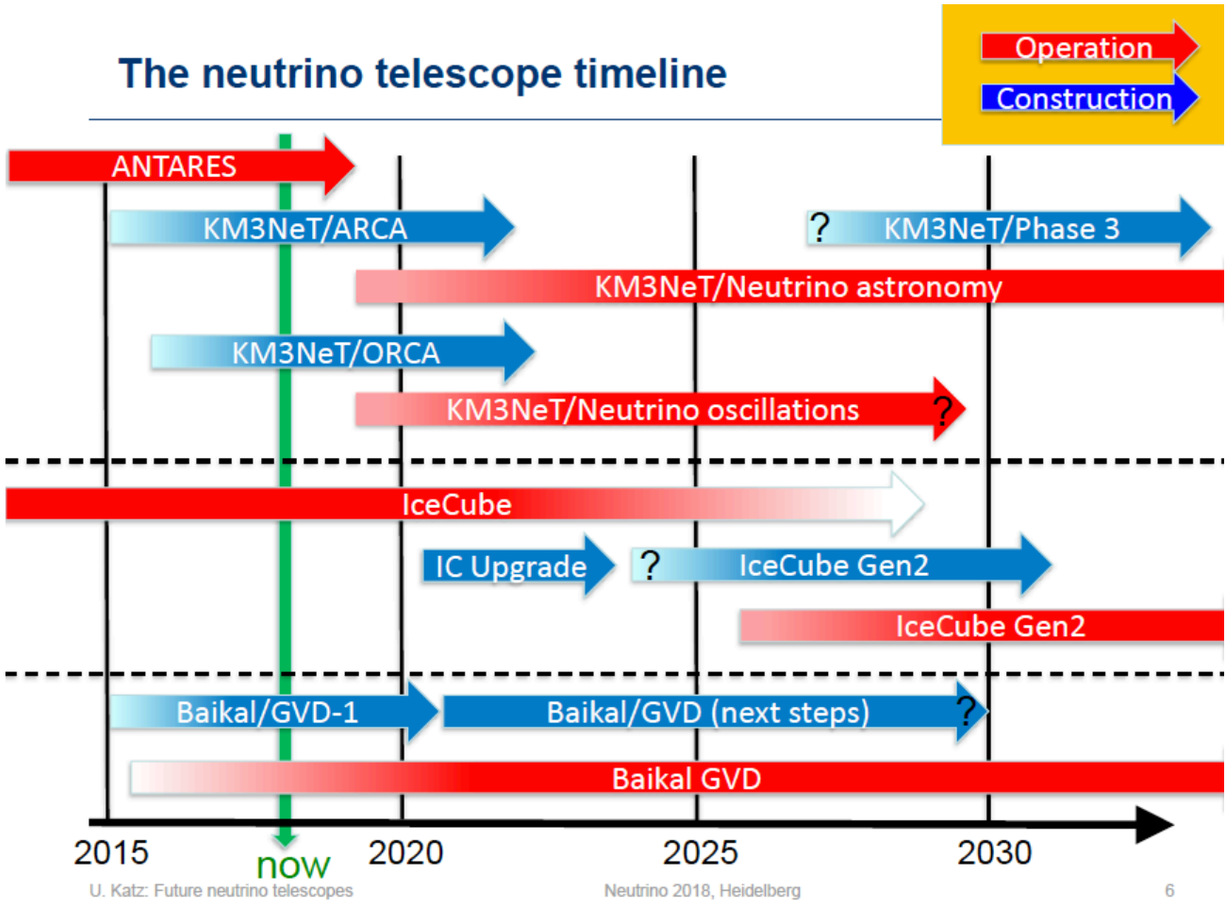


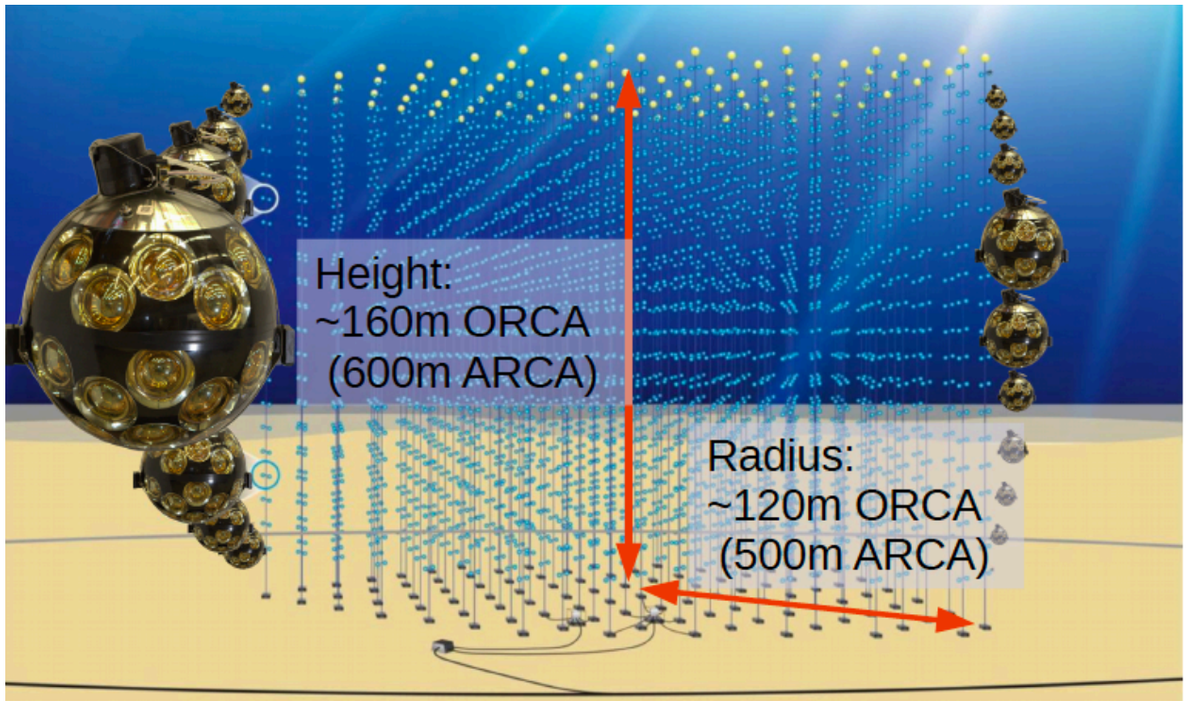
Spin-independent scattering

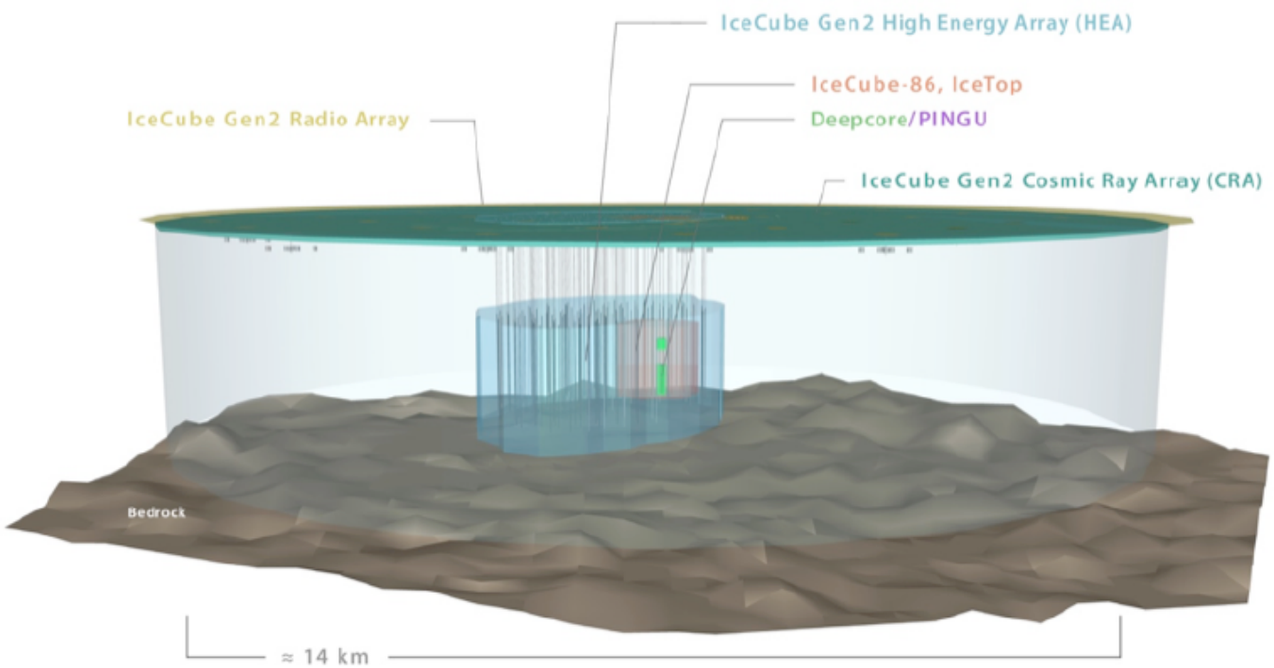


Next generation neutrino telescopes

Neutrino telescope landscape expanding quickly

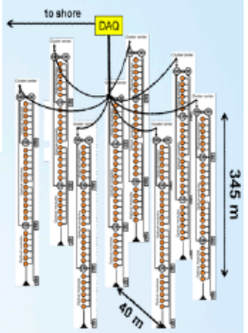




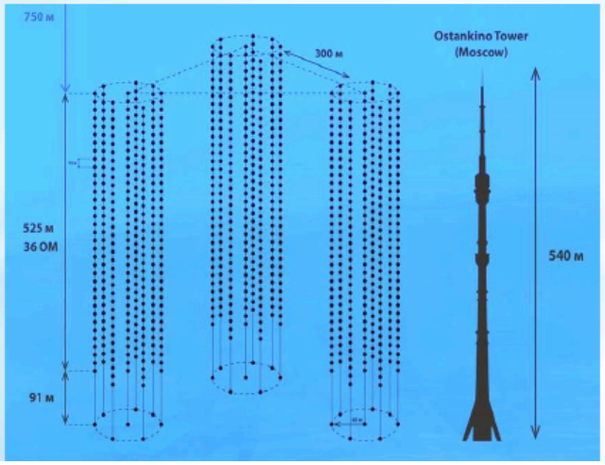


BAIKAL-GVD

hern latitudes
2015: «Dubna»
strings (192 OMs)



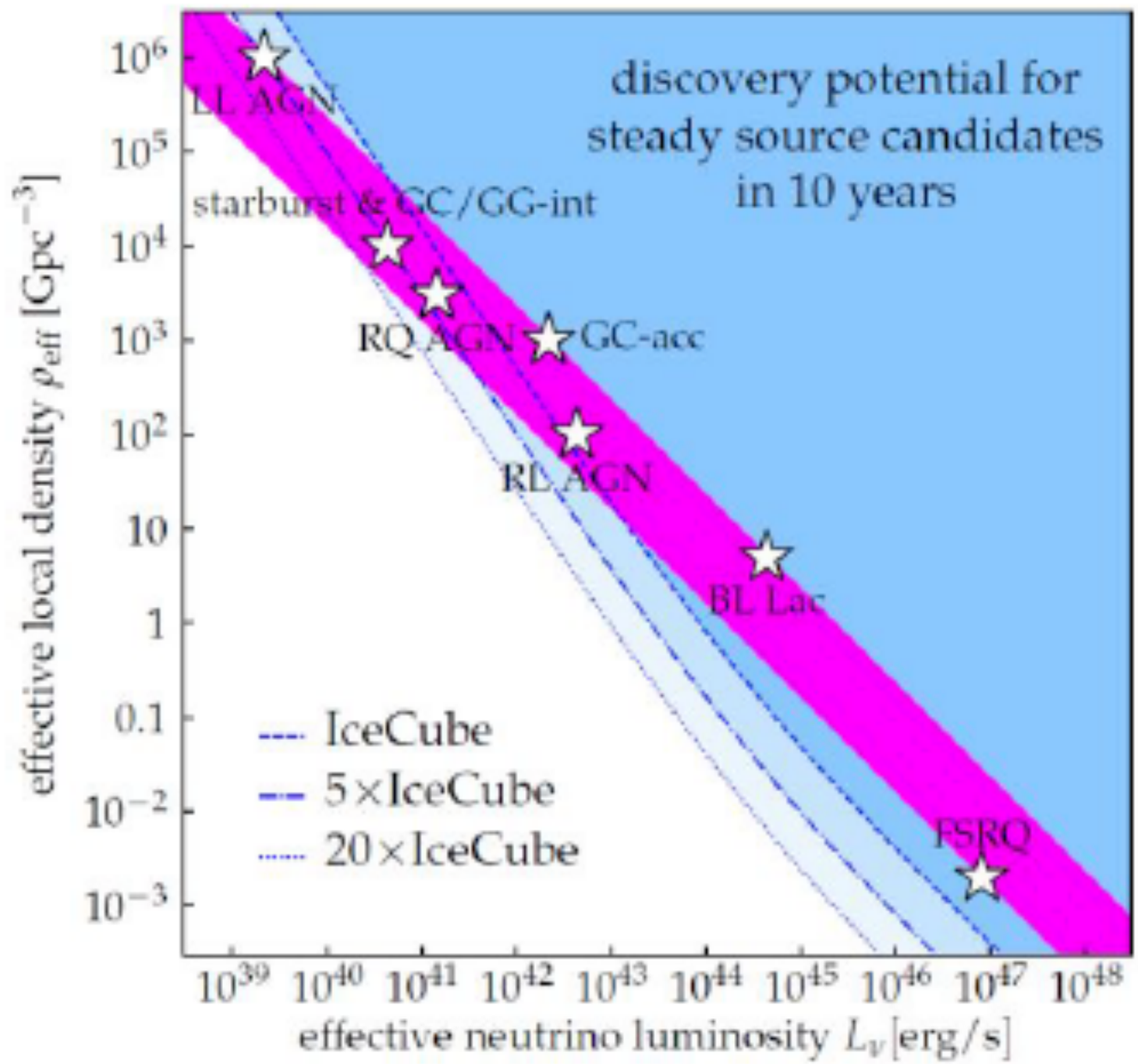
2018: Data taken with three Baikal-GVD clusters



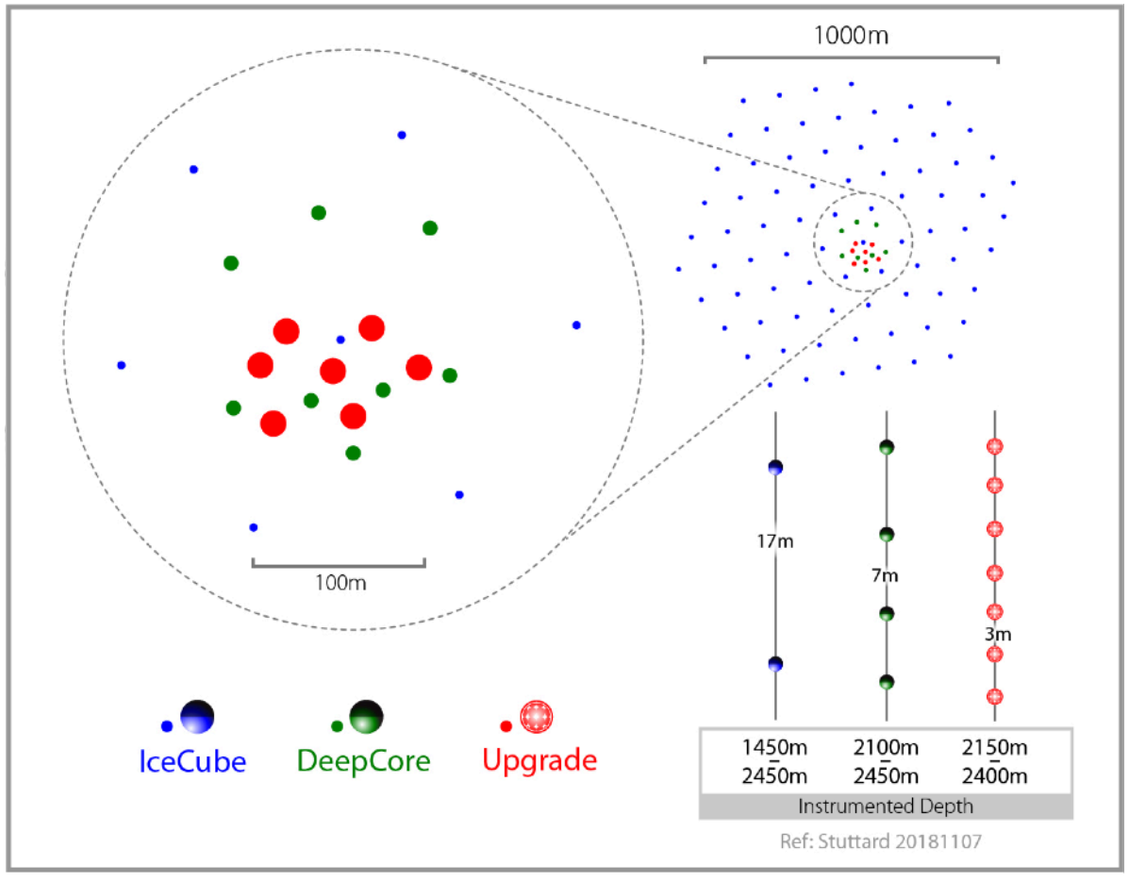
Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

IceCube-Gen2

- IceCube has provided an amazing sample of events, but is still statistics limited
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
- Gen2 objectives
  - High precision flavor composition studies
  - Detailed measurement of features / cut-off in neutrino spectrum
  - Transients sources and multi-messenger astrophysics
  - Identify astrophysical neutrino sources
  - GZK neutrinos
  - New physics or something unexpected



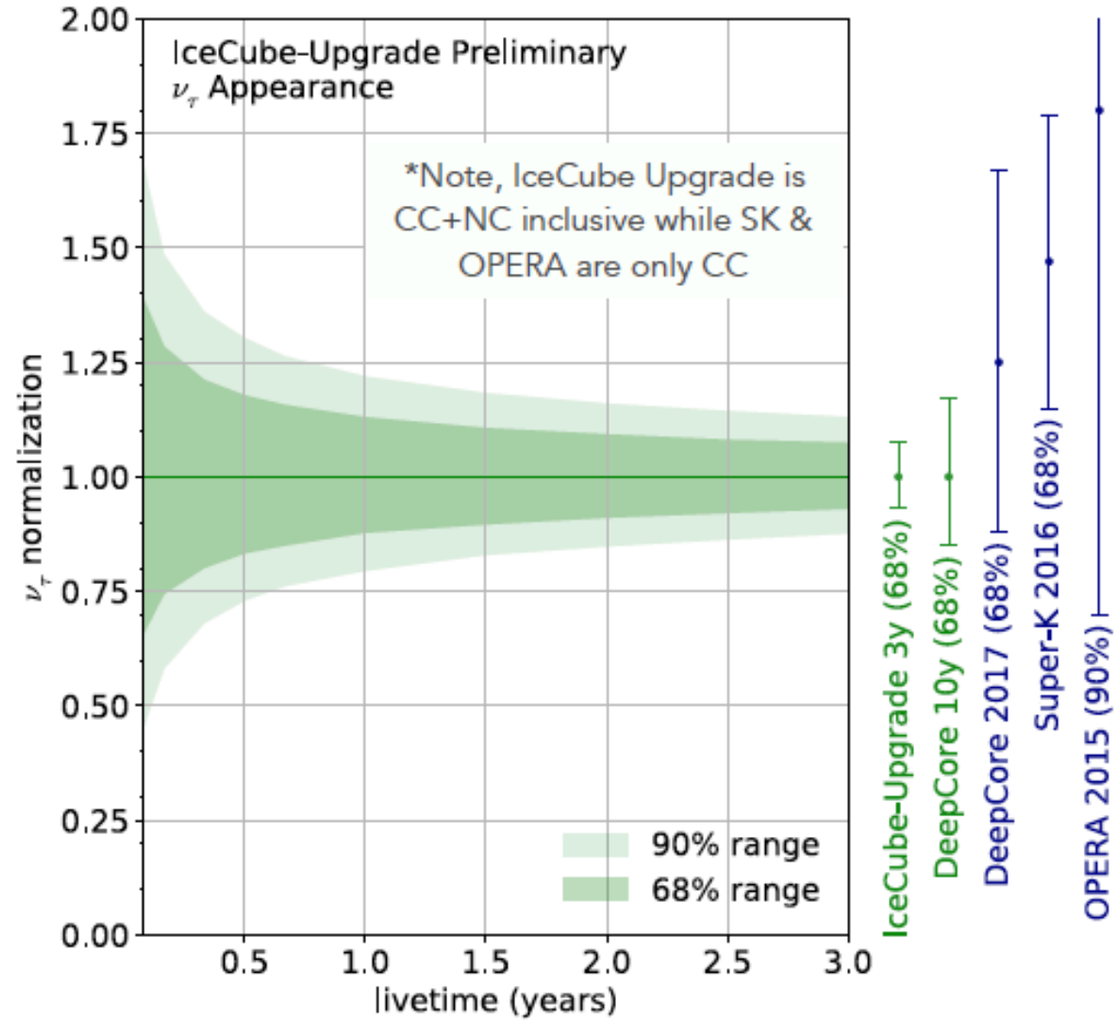
The IceCube Upgrade

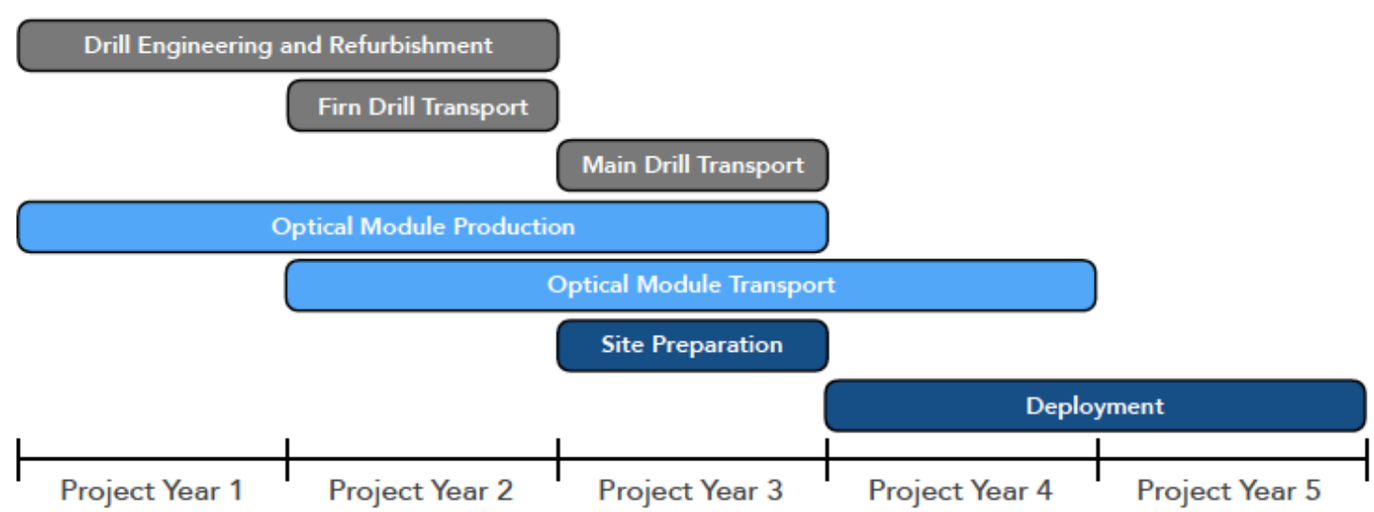


Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

Science goals

- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Recalibration campaign - Retroactively apply improved ice-model to archival data ()





- Anomalous ANITA events imply new physics (clarity from ANITA-IV and PUEO)
- High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What's the origin of the high-energy neutrinos ?
- First compelling evidence of high-energy neutrinos with electromagnetic counterparts (TXS 0506+056)
- Neutrino astronomy is a central part of the multi messenger astroparticle physics field
- First hint of a Glashow resonance event
- Very strong bounds on dark matter scattering with nucleons and decaying dark matter
- Funding for IceCube Upgrade approved

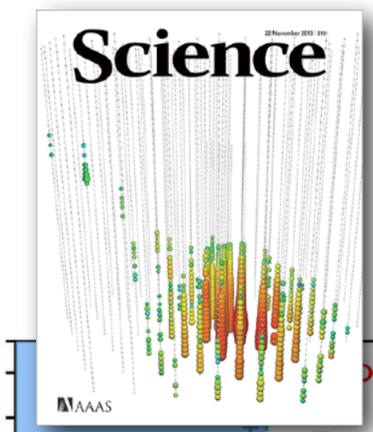
Image:Stephan Richter, IceCube/NSF

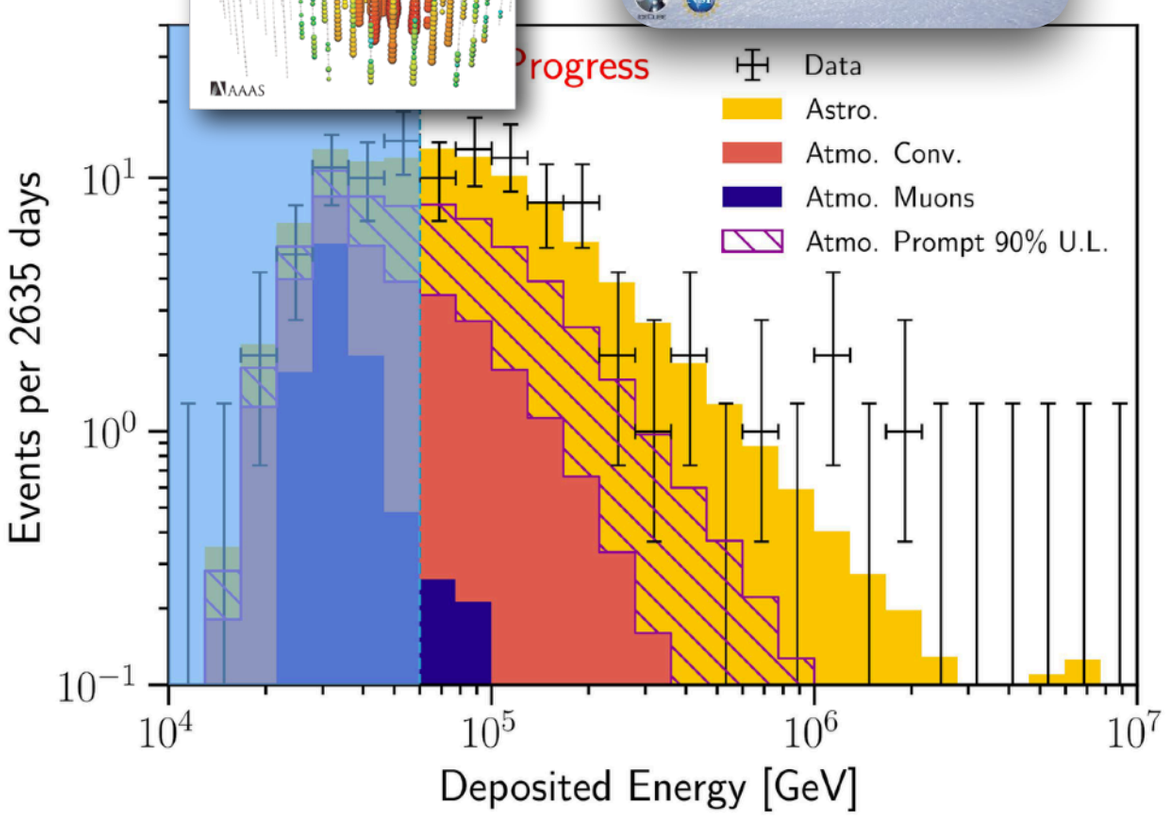
New Window to the Universe !

2002

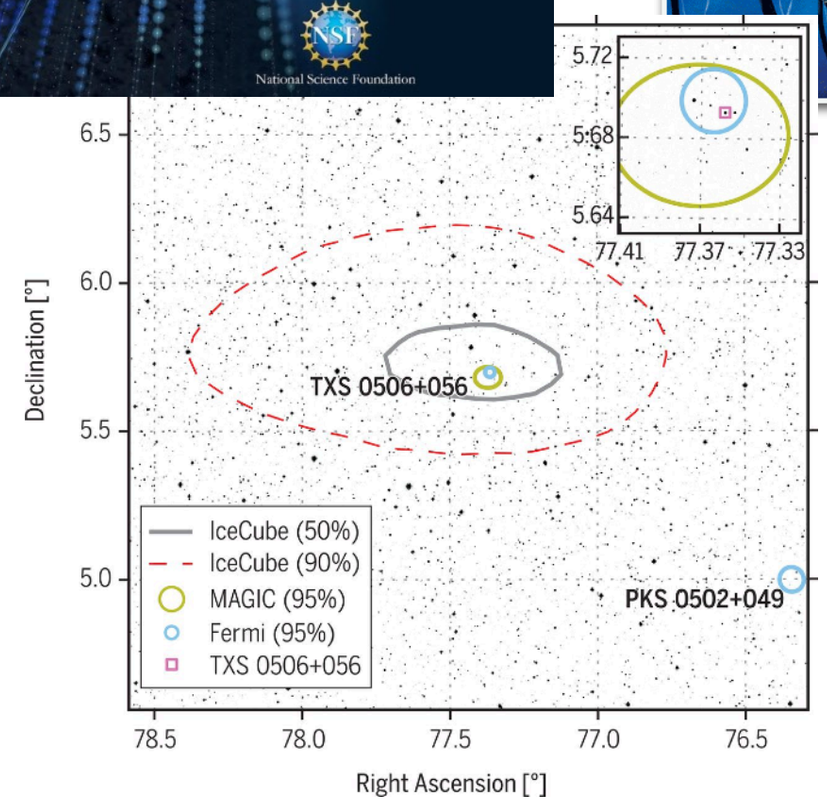
Following the observation of supernova burst neutrinos in 1987*, neutrino astronomy is becoming a reality quickly now …*

2013 Discovery of diffuse astrophysical neutrino flux

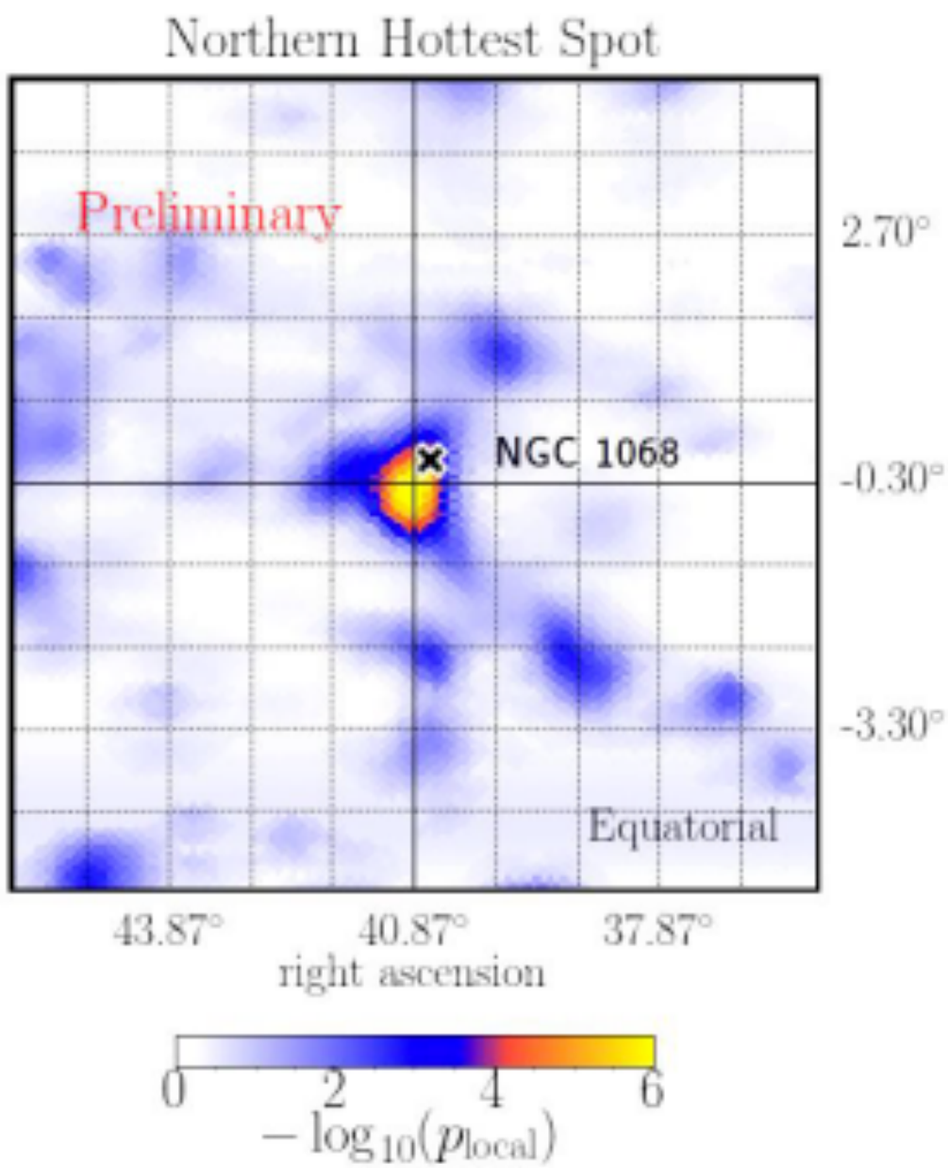




2018 Neutrino multi-messenger astroparticle physics

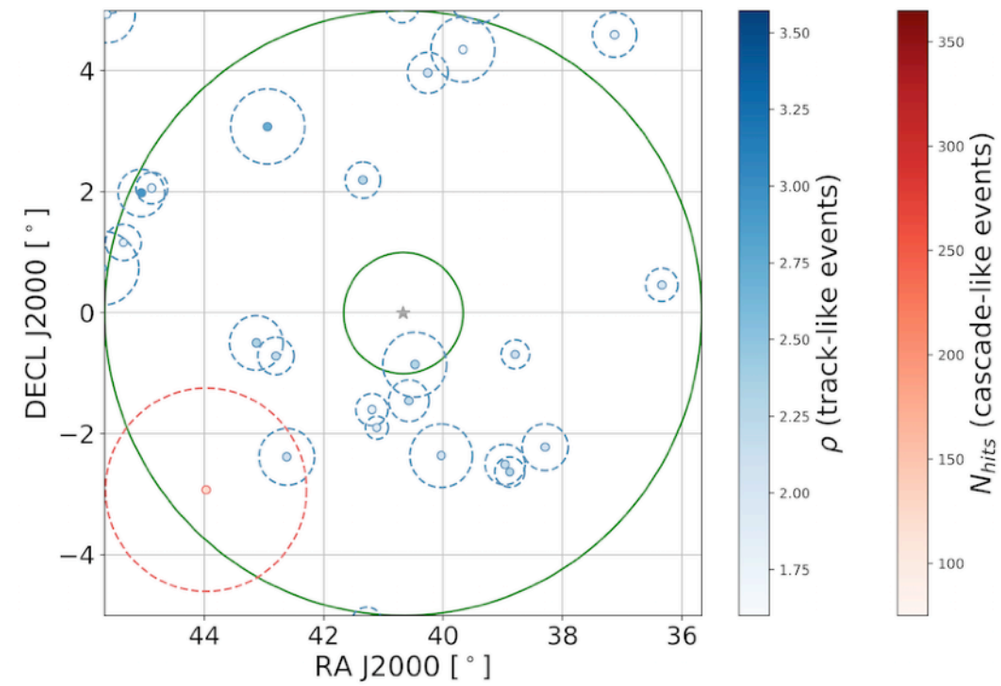


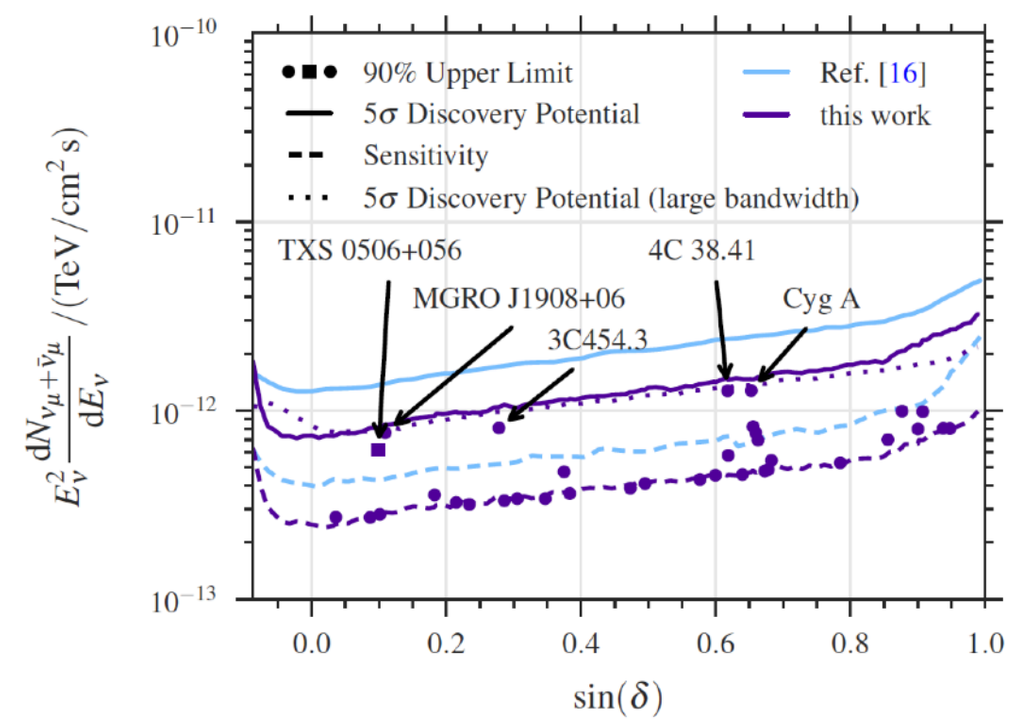
More sources in the future ?



ANTARES NGC 1068 10 years of data

http://antares.in2p3.fr/News/





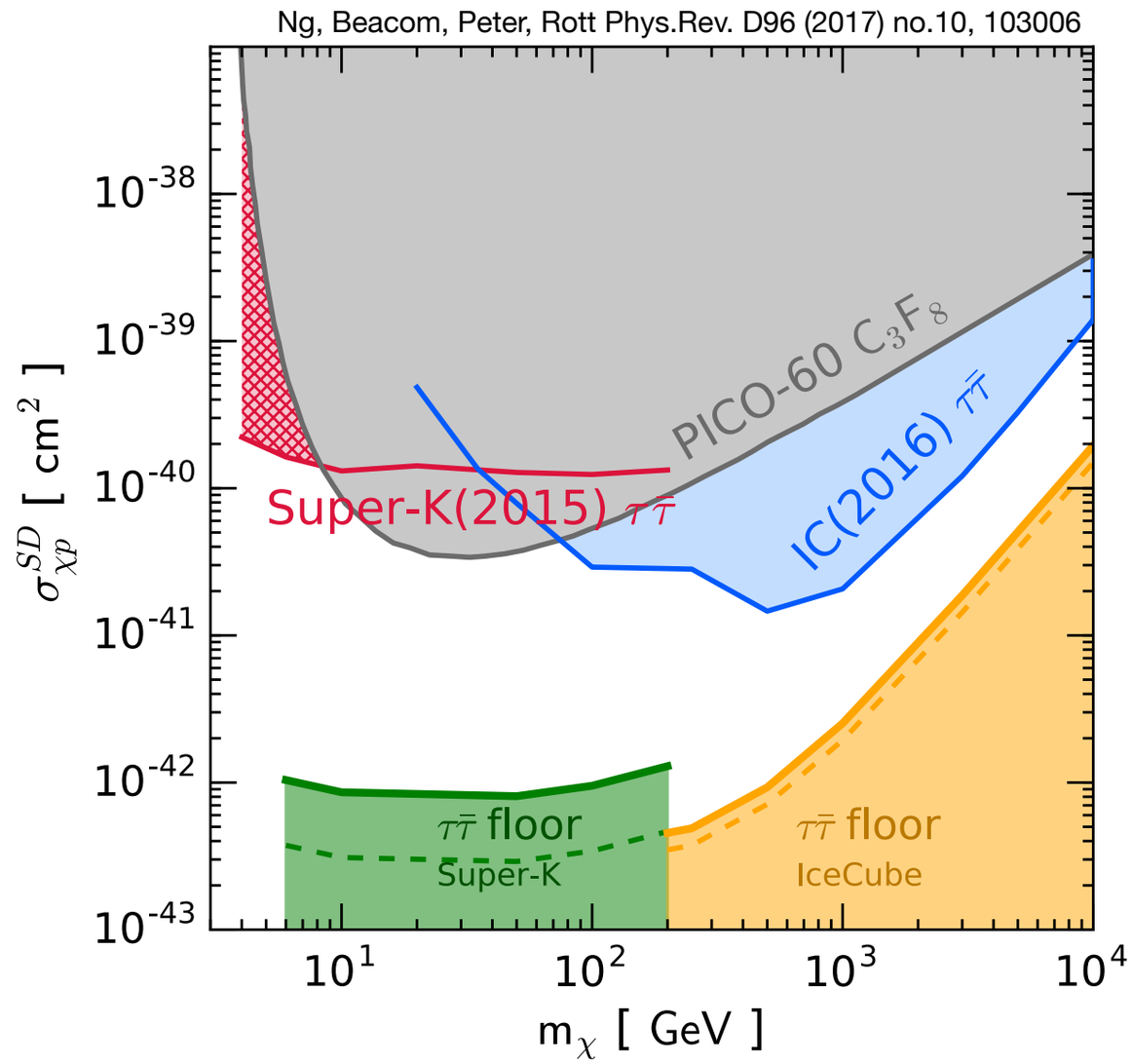
10 years of IceCube data which recently have been unblinded, unifying the muon diffuse and point source streams

Most significant excess was found 0.3° away from M77 (NGC1068) (RA 40.667°, Dec -0.0069°) with a significance of 2.9σ (post-trial)

Cosmic background from the Sun

Ng, Beacom, Peter, Rott Phys.Rev. D96 (2017) no.10, 103006

(cubic kilometer detector)

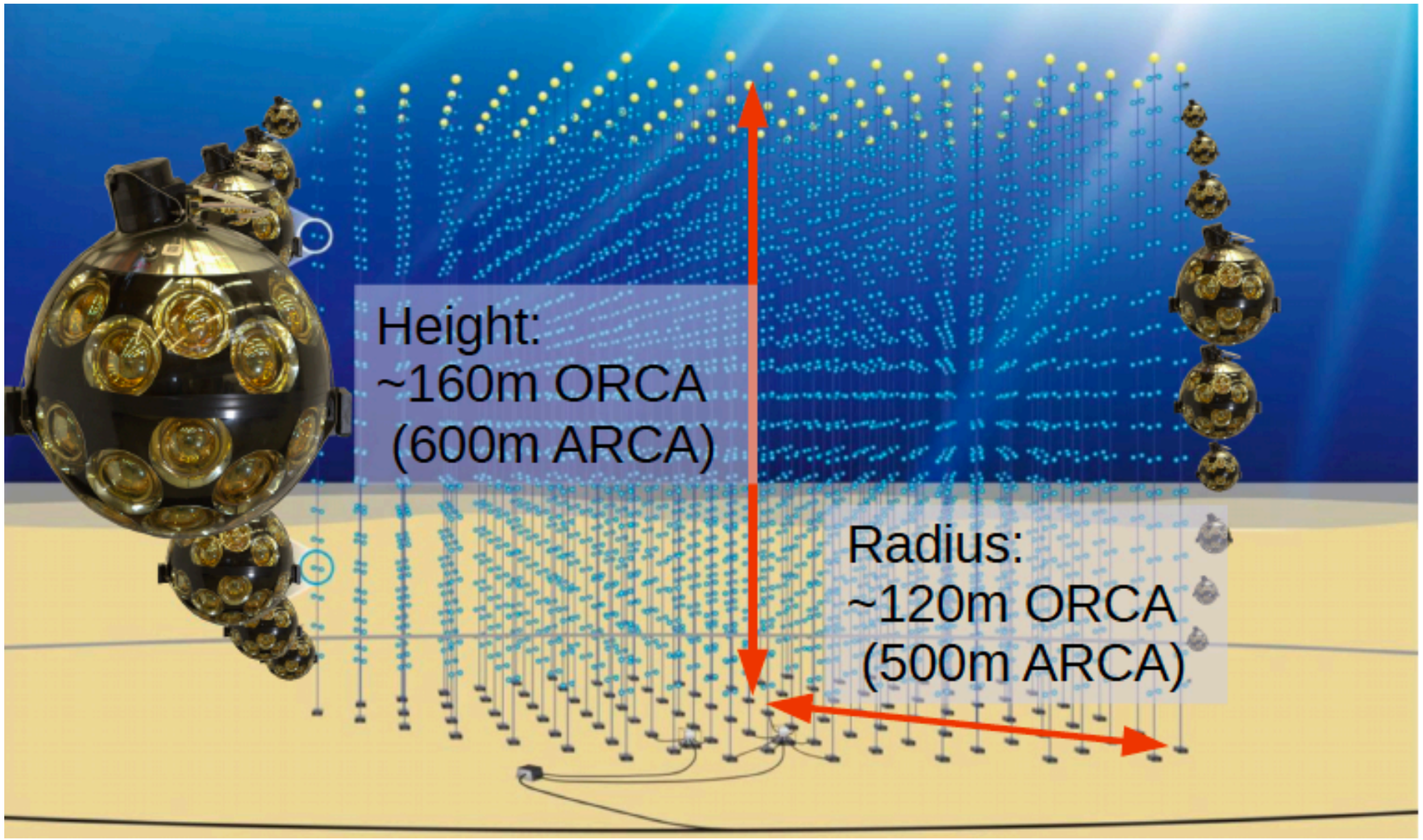


- Solar Atmospheric neutrinos give a new background to solar dark matter searches
  - However, energy spectrum expected to be different
  - In DM annihilation neutrinos significantly attenuated above a few 100GeV

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no. 10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 . 06 (2017), p. 033**, arXiv: 1704.02892 [astro-ph.HE]
- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]

ORCA / KM3NeT



	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton

ORCA will consist of one dense KM3NeT Building Block

115 detection lines

Total: 64K * 3" PMTs

ARCA/ORCA construction on-going

Baikal-GVD: first clusters

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March. 2019

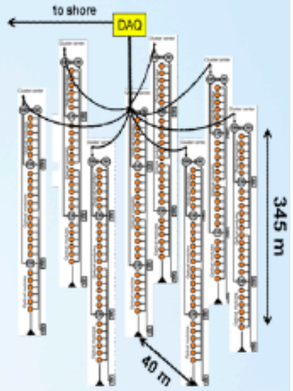
- GVD detector construction underway in Lake Baikal
- Currently clusters #2 and #3 are in operation while cluster #1 is subject to maintenance works
- Baikal-GVD expedition on-going (deployments until April 11th) Plan was to deploy and commission two new GVD-clusters (clusters 4 and 5), well underway (and **completed on April 7**)
  - Now reached 0.25 km³ effective volume

Optical module
PMT: R7081-100

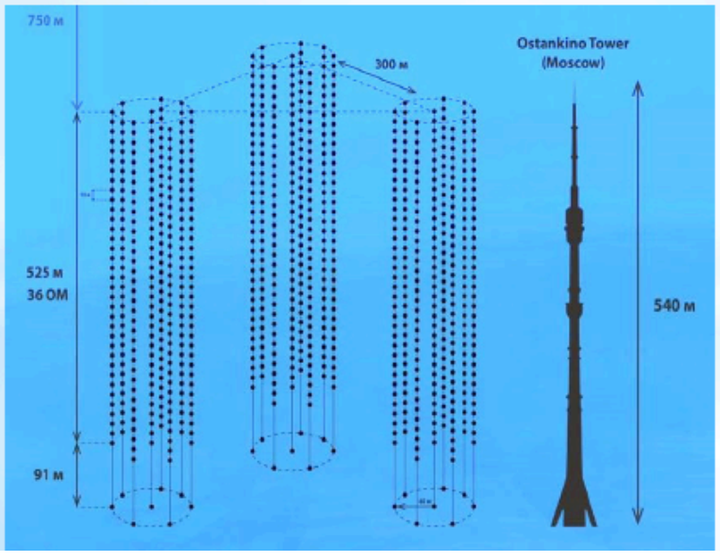
2018: 24 strings (864 OMs) – largest NT in the northern latitudes

Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	∅80×345	∅120×525	2×∅120×525	3×∅120×525
Eff. Vol	0.03 km³	0.05 km³	0.1 km³	0.15 km³

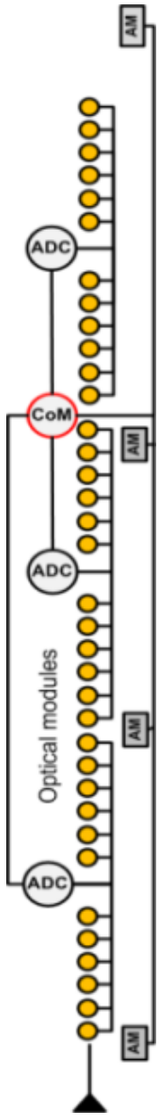
2015: «Dubna»
8 strings (192 OMs)

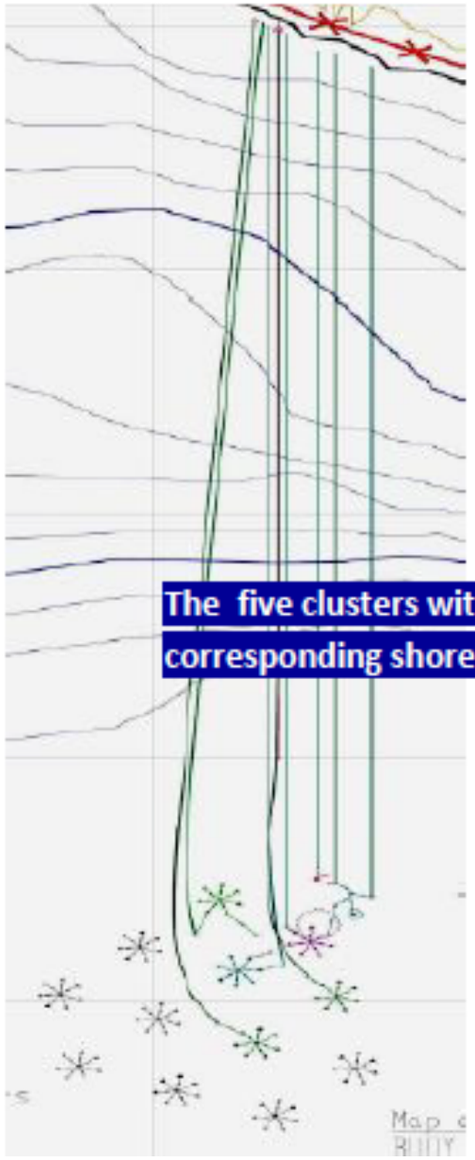


2018: Data taken with three Baikal-GVD clusters



Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

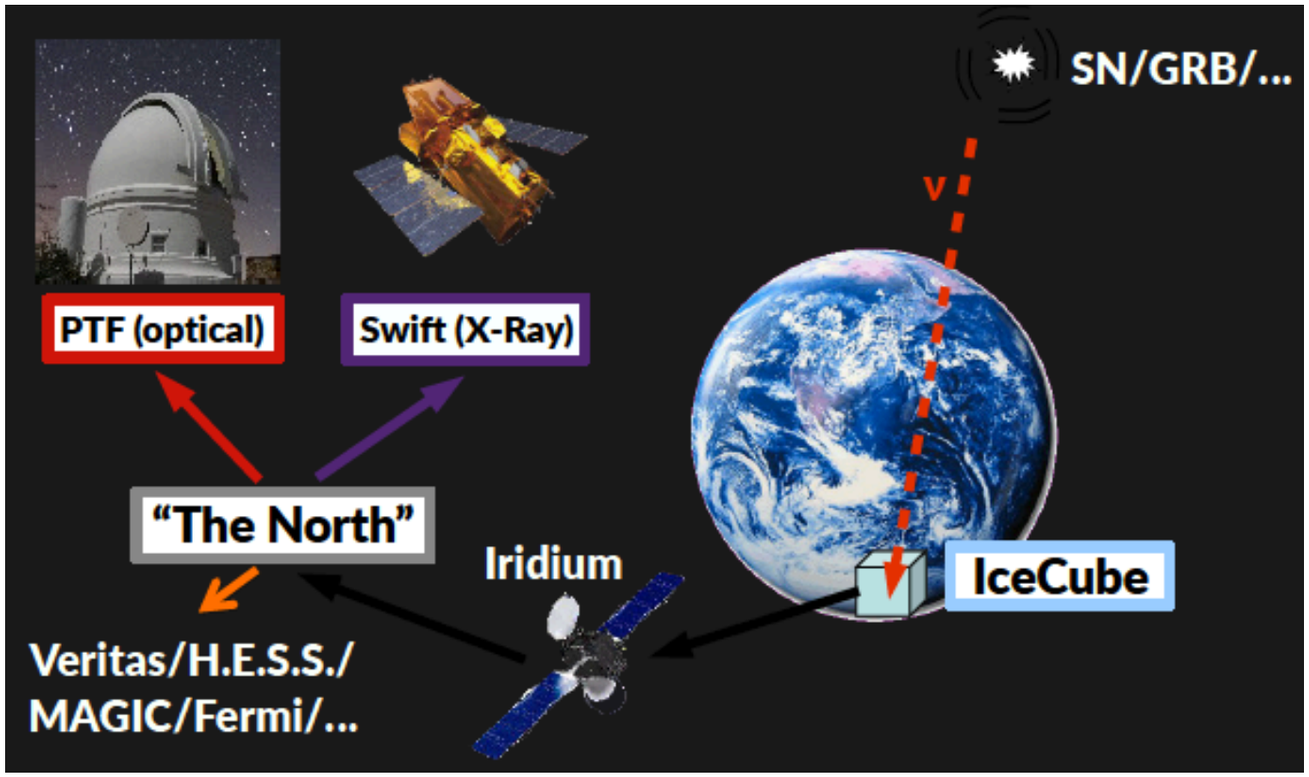


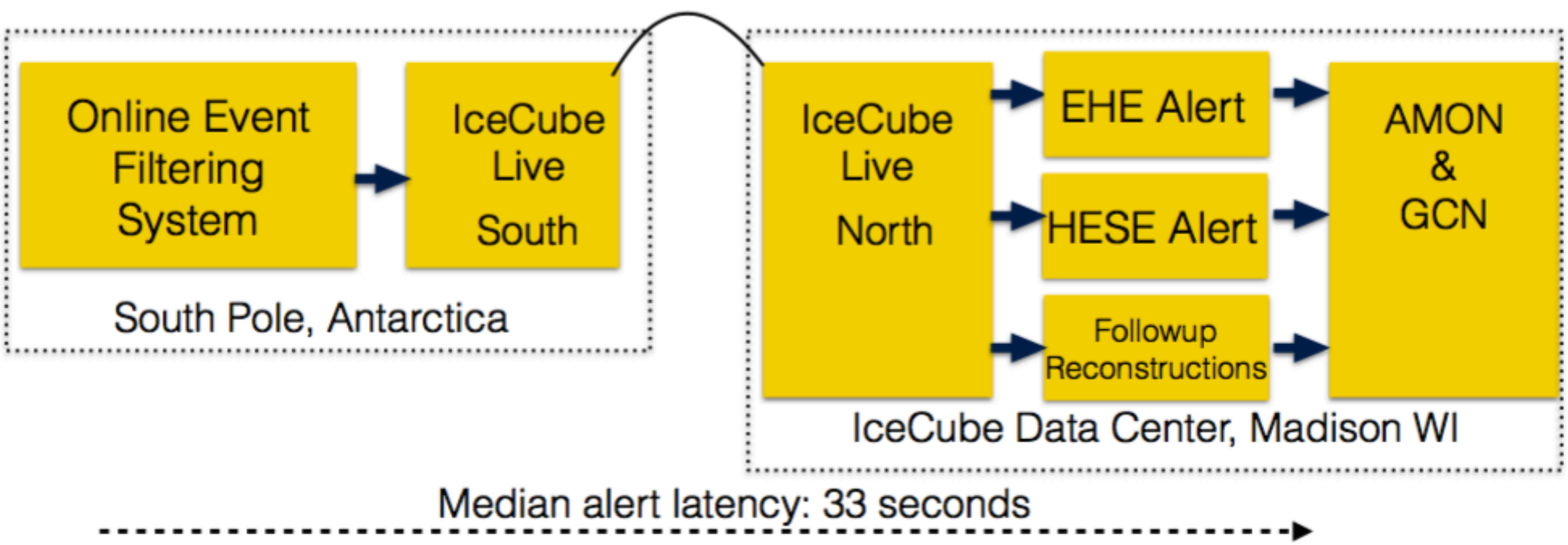


Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

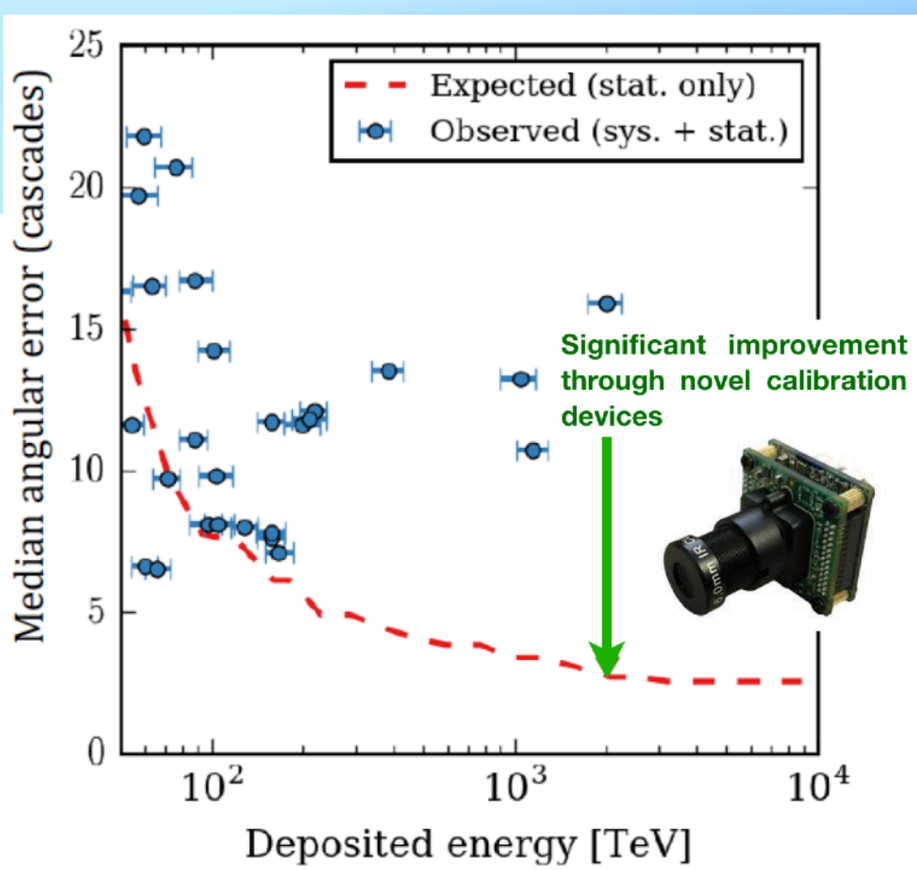
IceCube-170922A & TXS 0506+056

- Real-time alerts. Since 04/2016, ≈6-8/yr
  - Improved selection summer 2018
    - Good angular resolution (0.5° - 2° 90% of events)
    - 50% astrophysical fraction



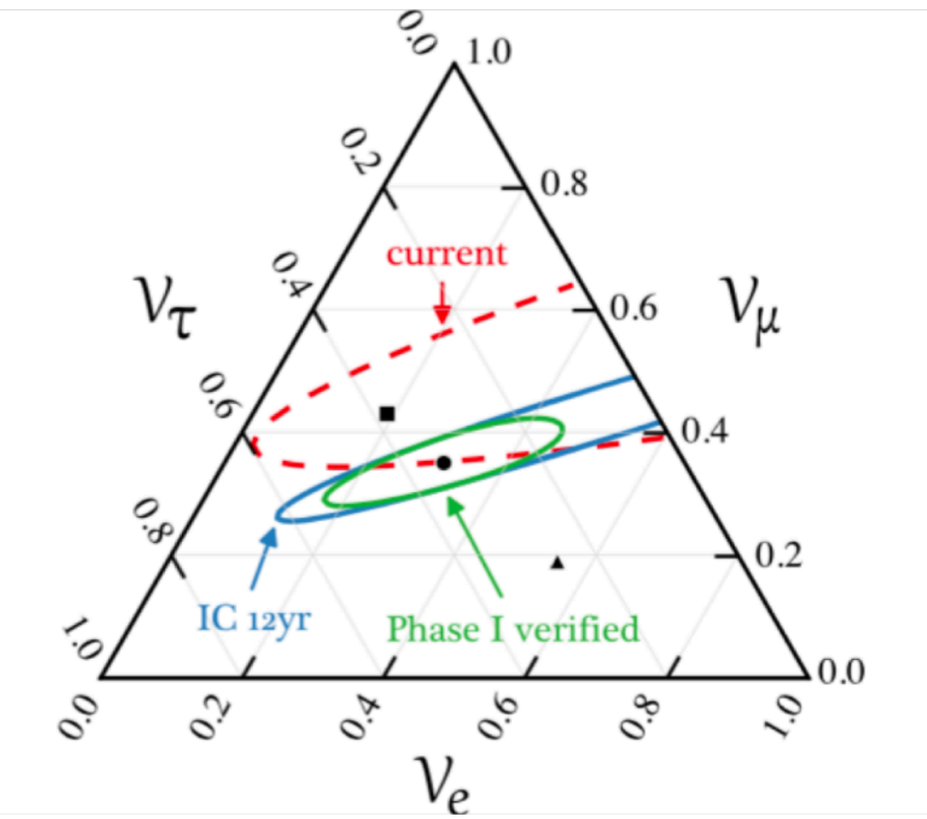


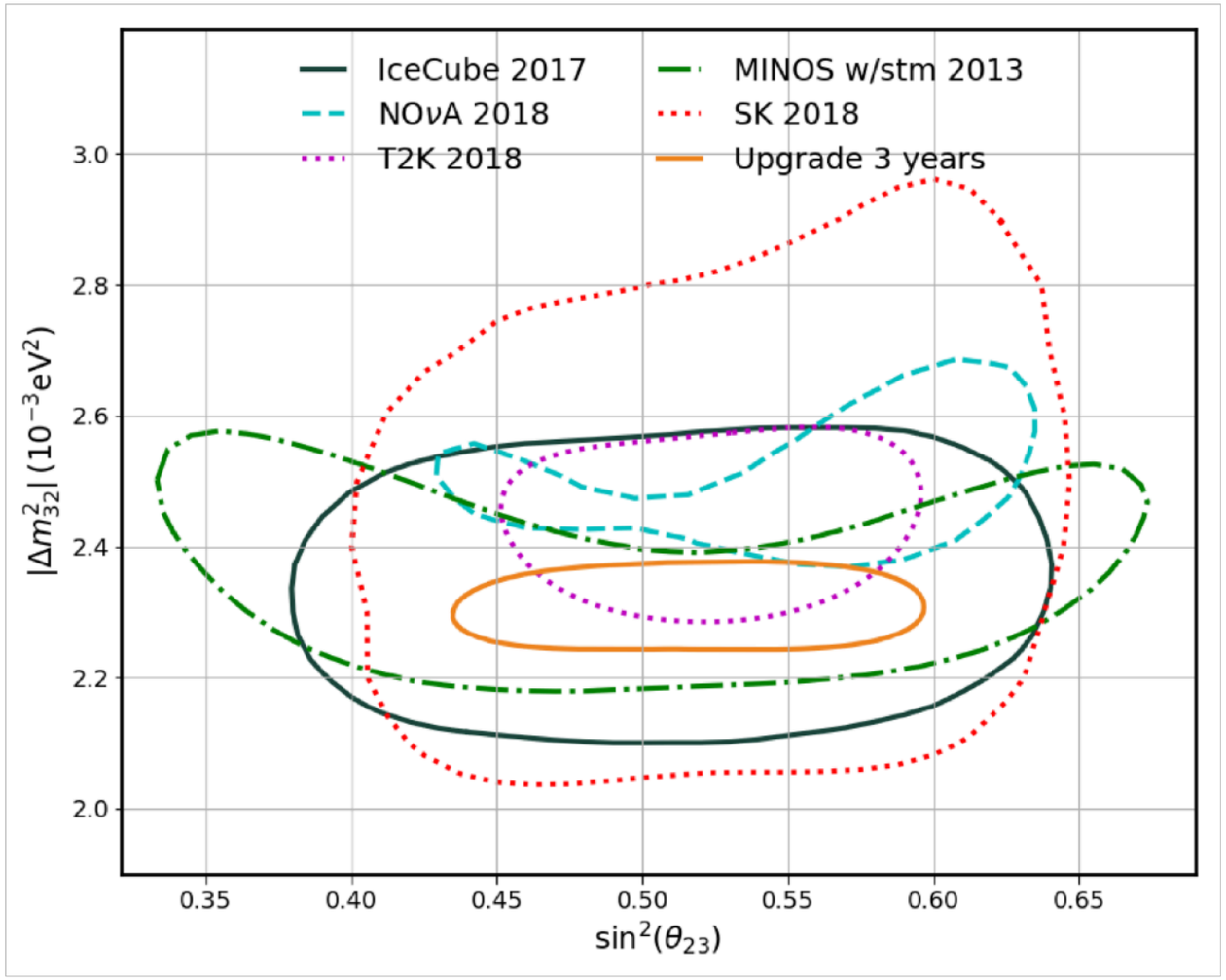
The IceCube Upgrade



Recalibration campaign

- Improved ice model
- Retroactively apply improved ice-model to archival data
- Precision neutrino physics
- Multi-messenger science with improve pointing





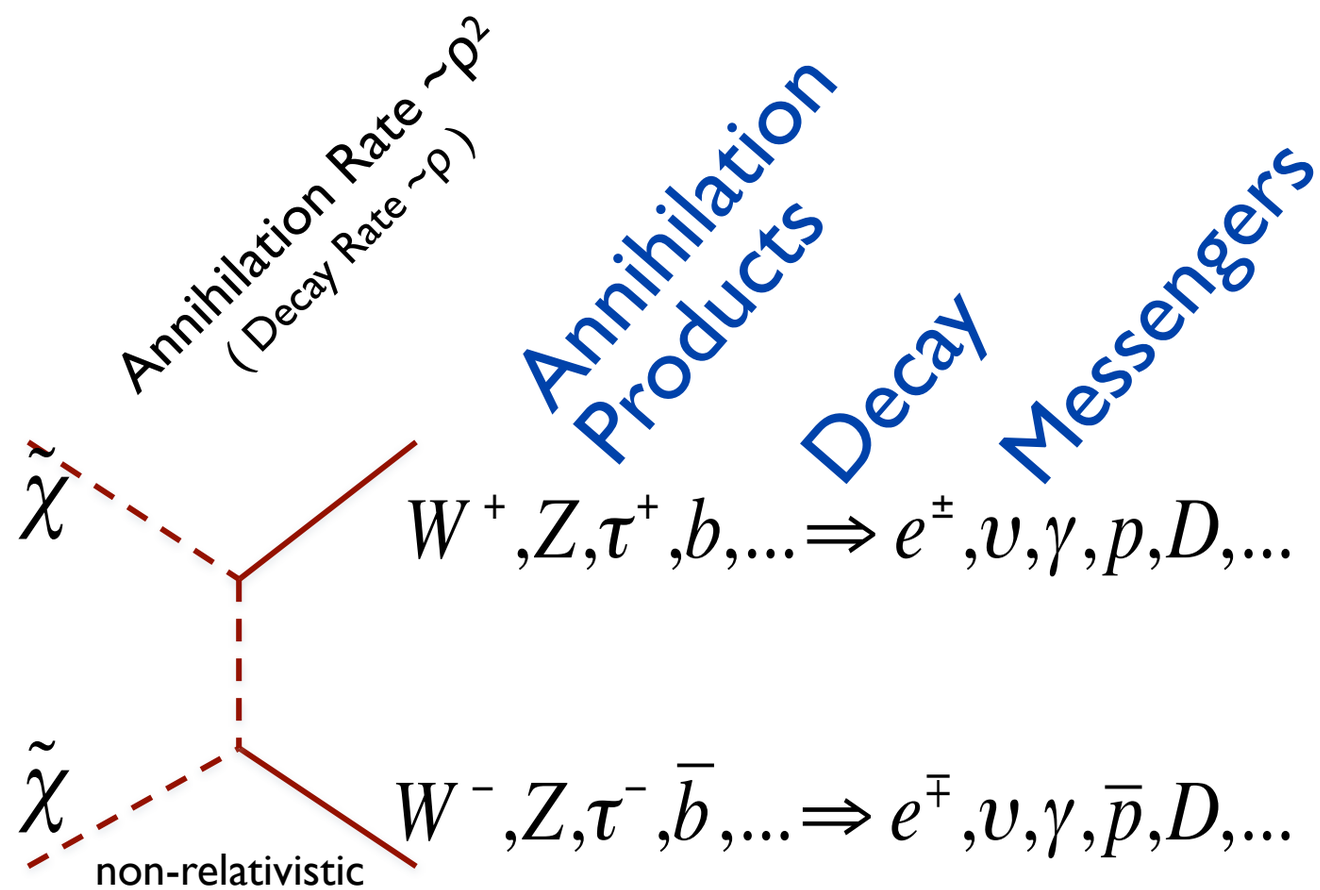
3σ discovery of cosmic tau neutrinos in 12 years of IceCube data, using the new calibration devices

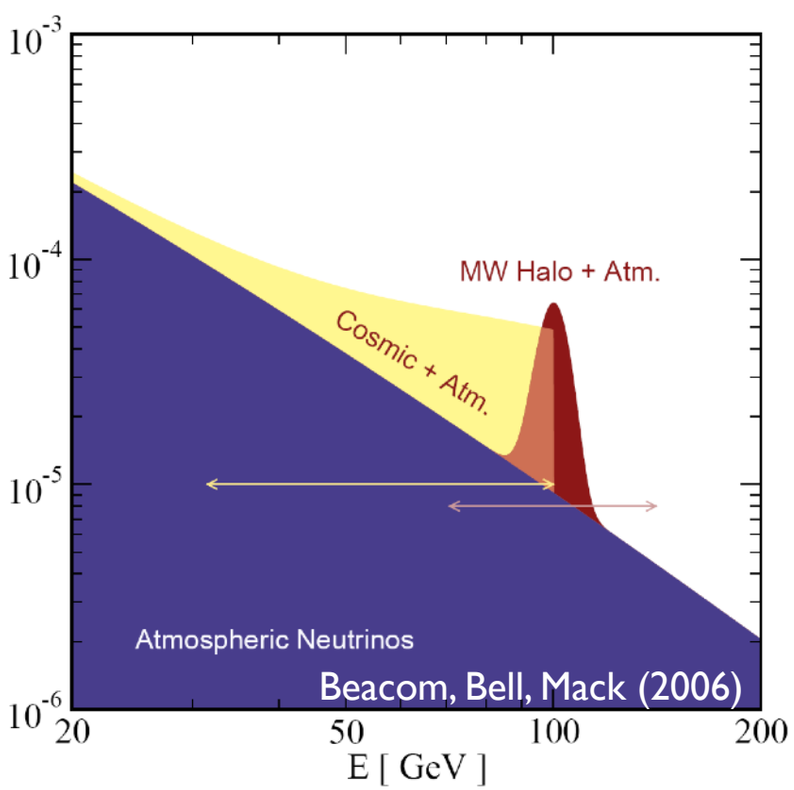
Dark Matter Signals

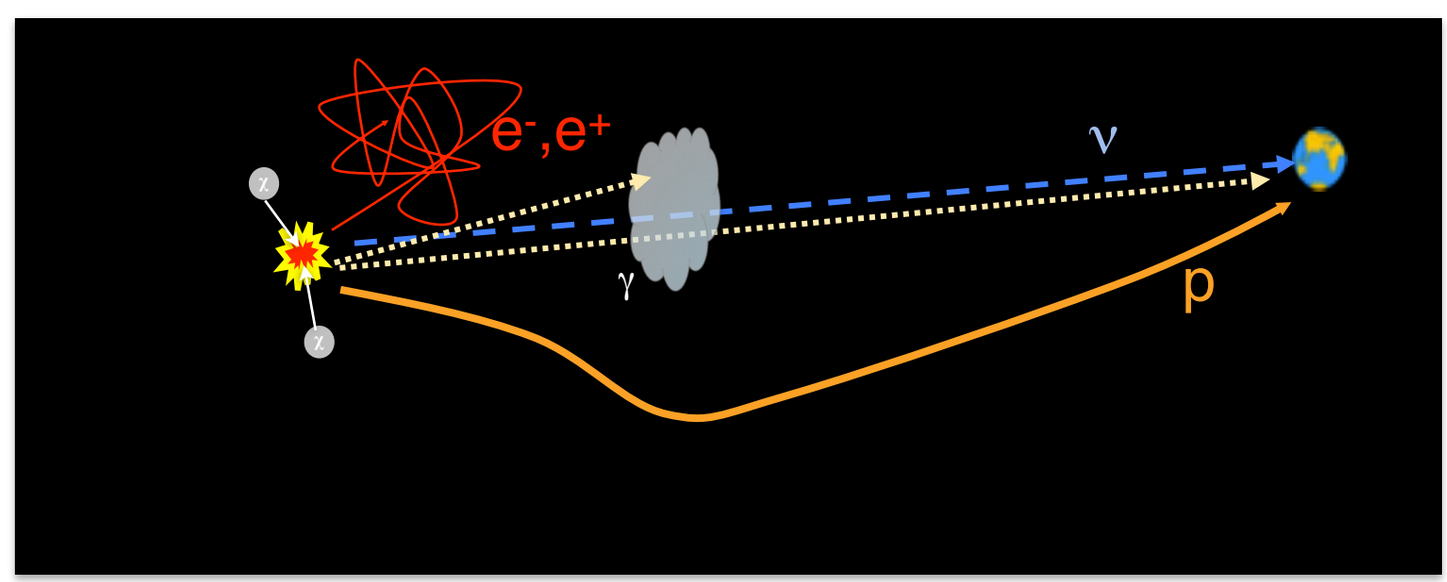
- Identify overdense regions of dark matter

  ⇒self-annihilation can occur at significant rates

- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds



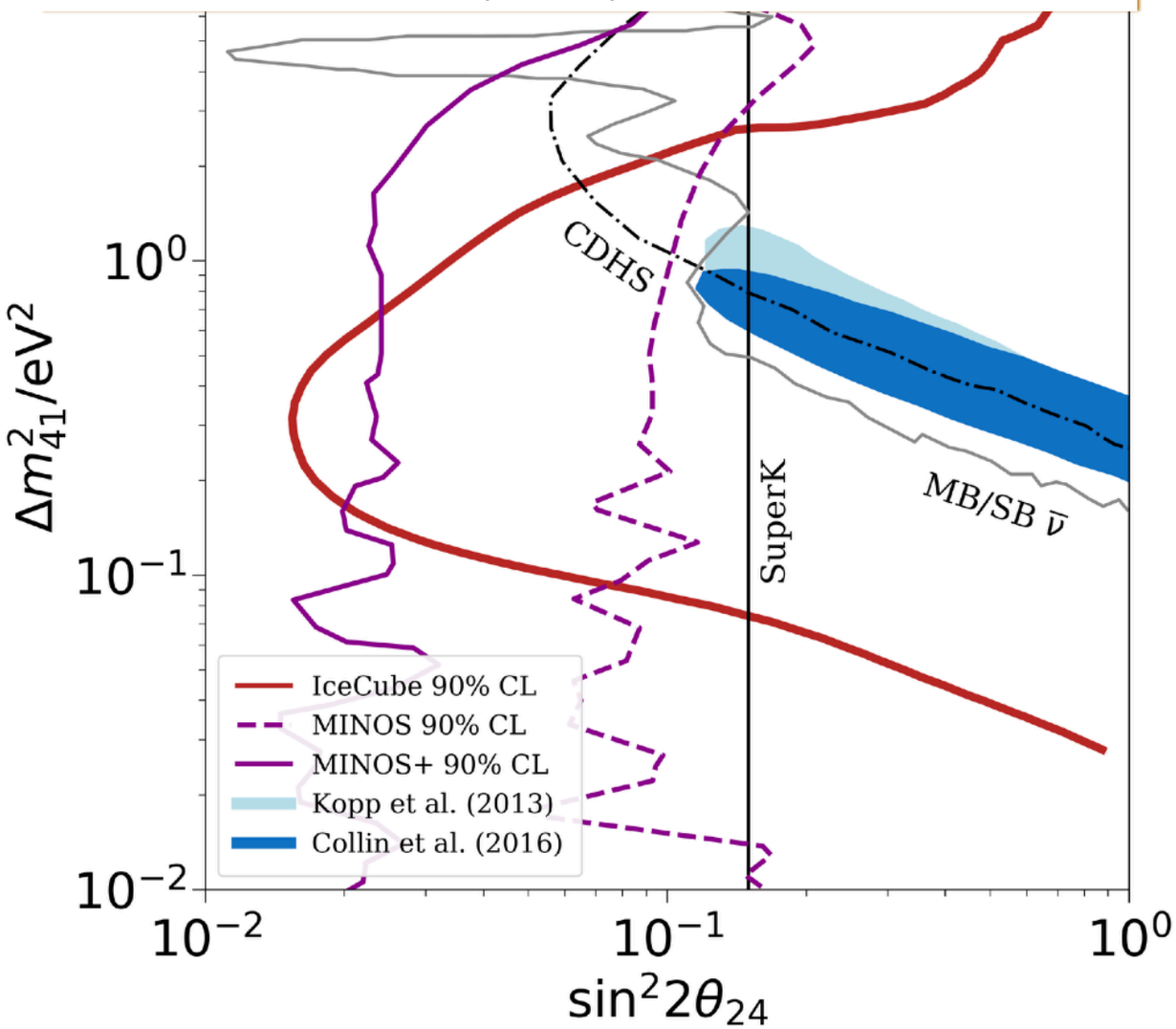




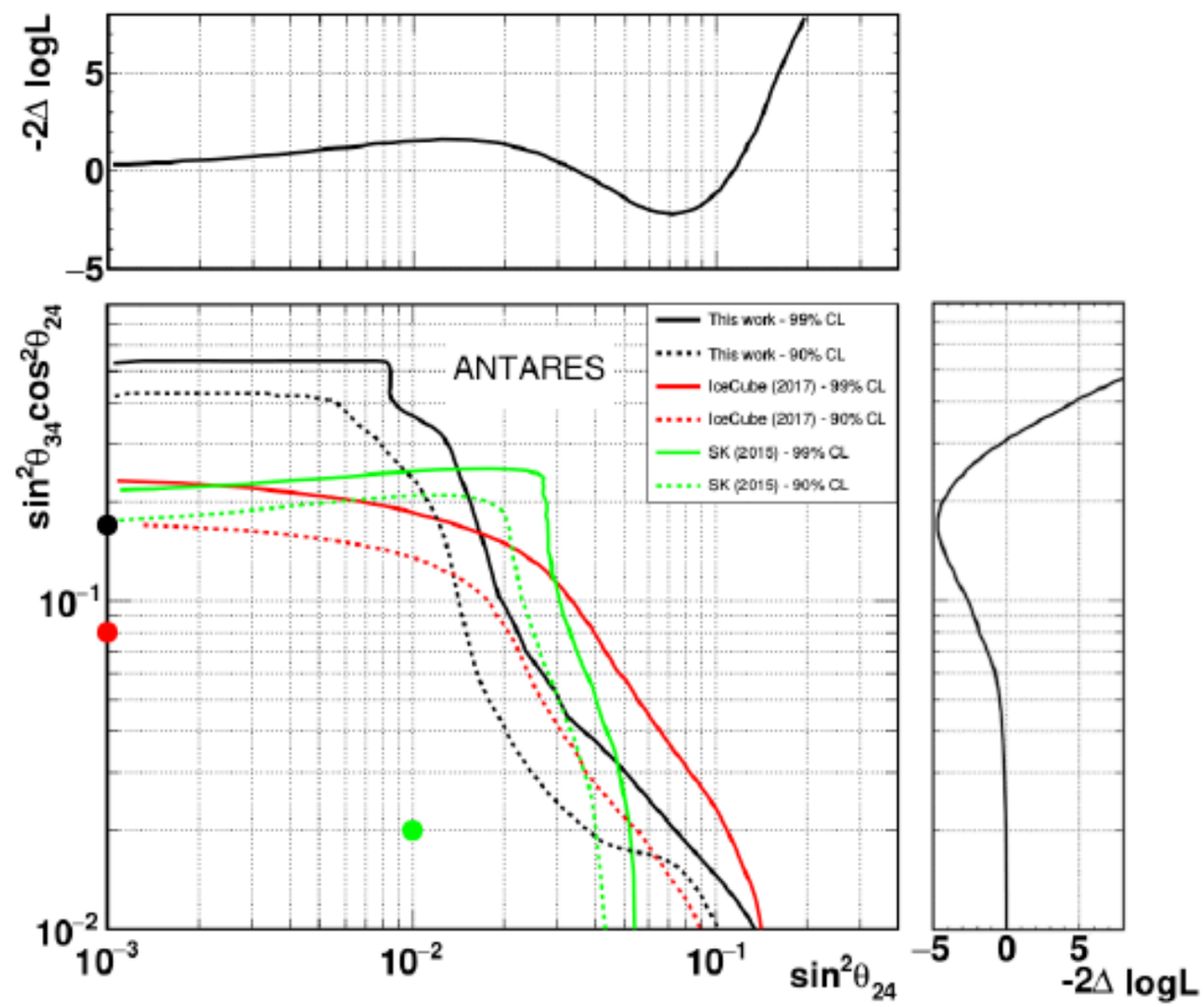
BSM Physics Searches

Sterile Neutrinos

M.G. Aartsen et al. (IceCube), Phys. Rev. Lett. 117, 071801 (2016), 1605.01990



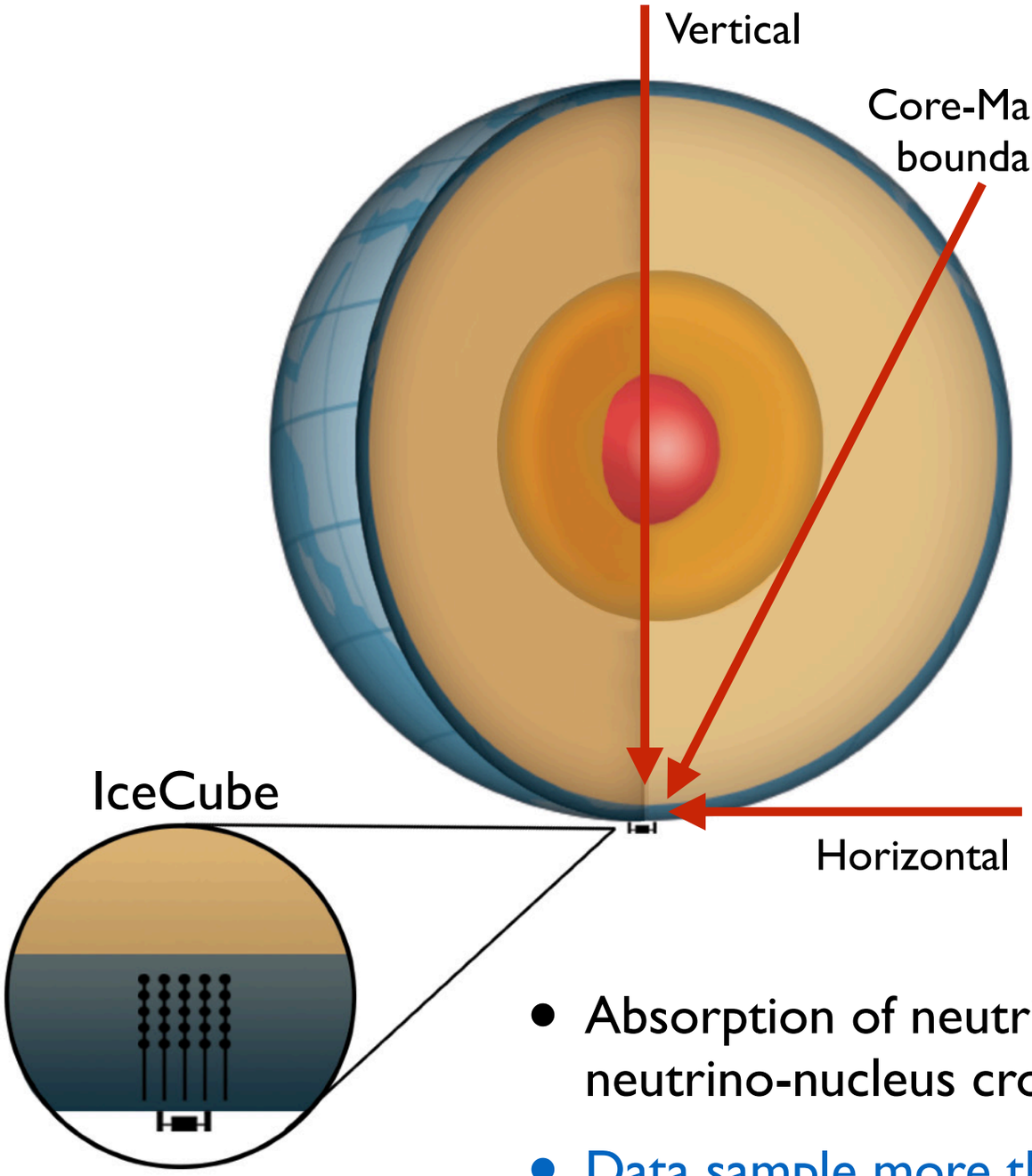
ANTARES arXiv:1812.08650v1



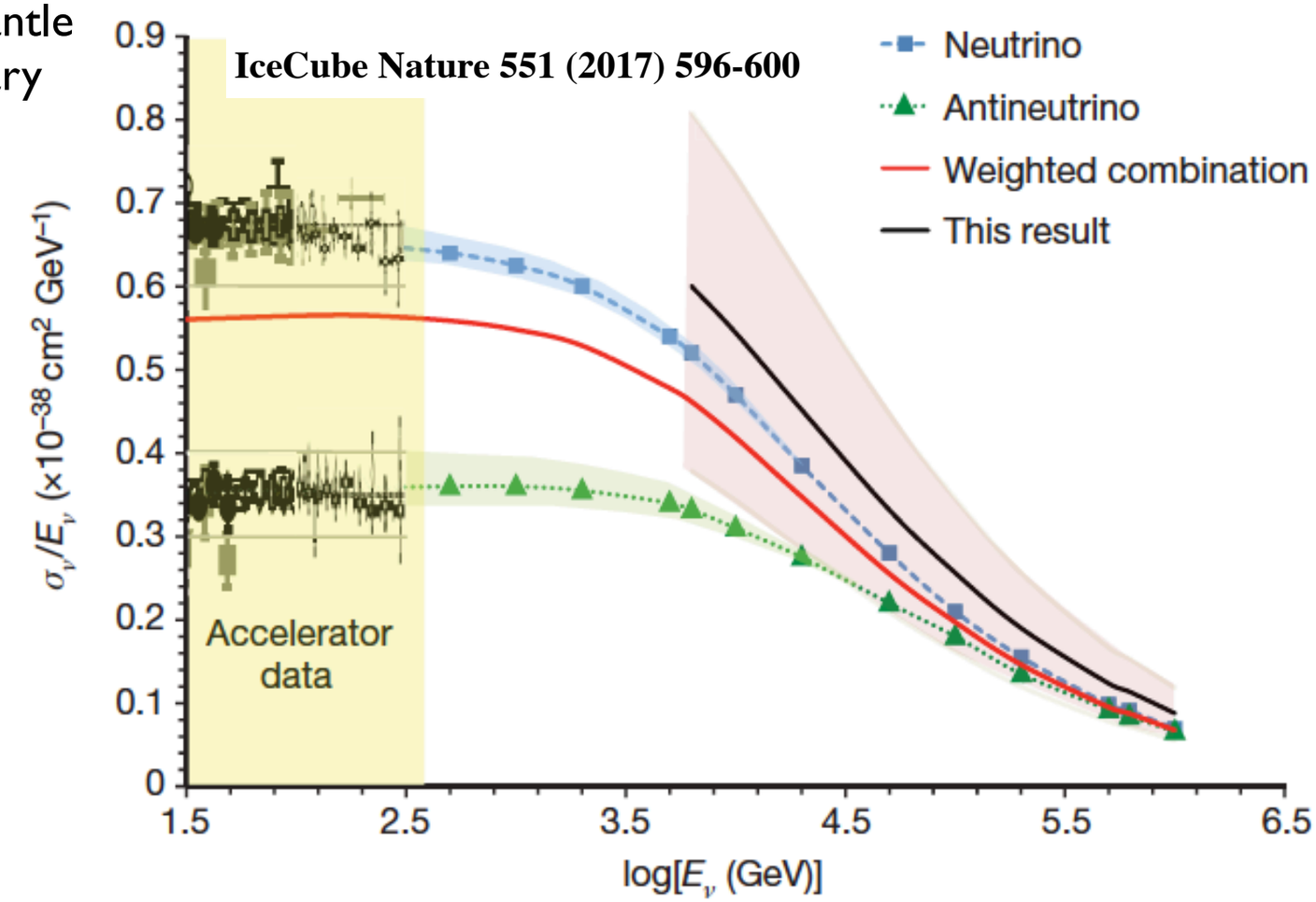
- Anomalies in short baseline experiments have been interpreted as evidence for additional neutrino mass states with large mass splittings
- No evidence for sterile neutrinos observed. Data consistent with 3 active neutrinos

IceCube Nature 551 (2017) 596-600

Neutrino Absorption in the Earth



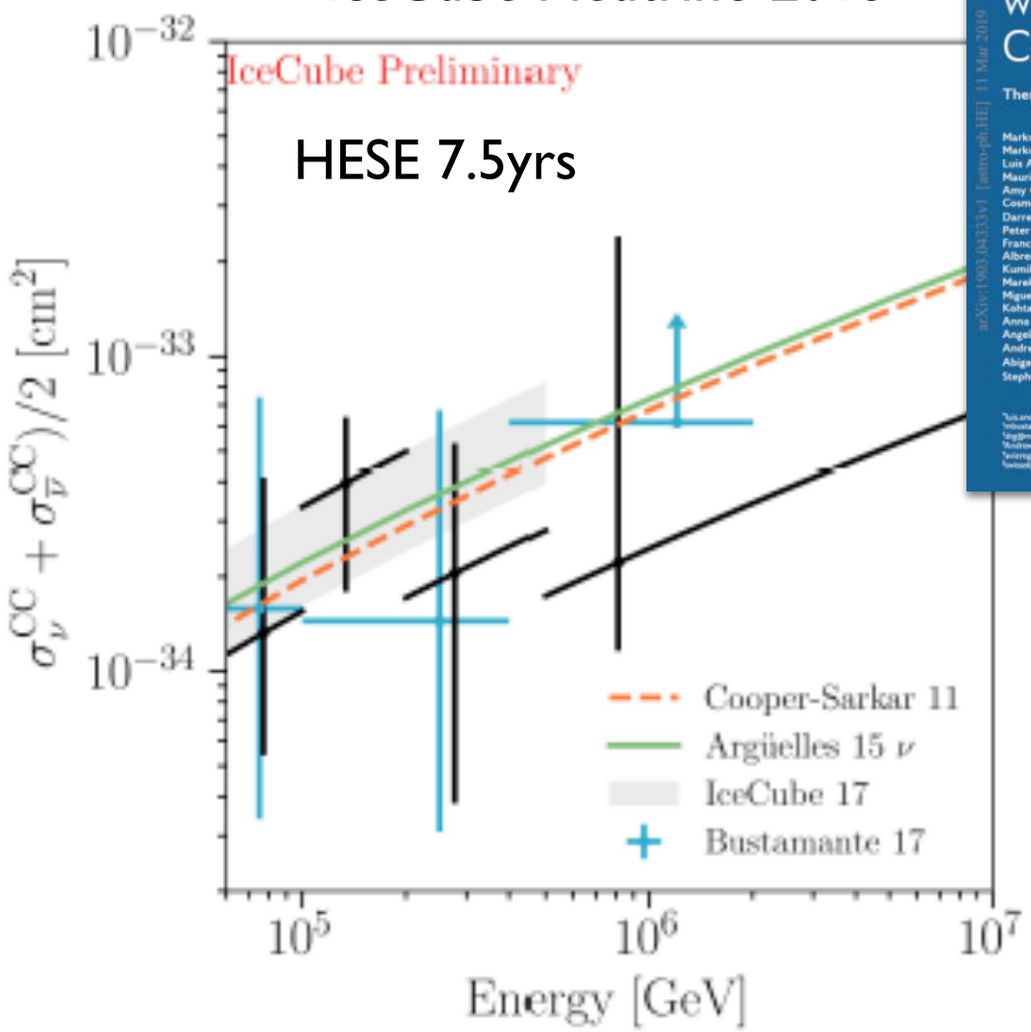
Neutrino-Nucleus Cross Section

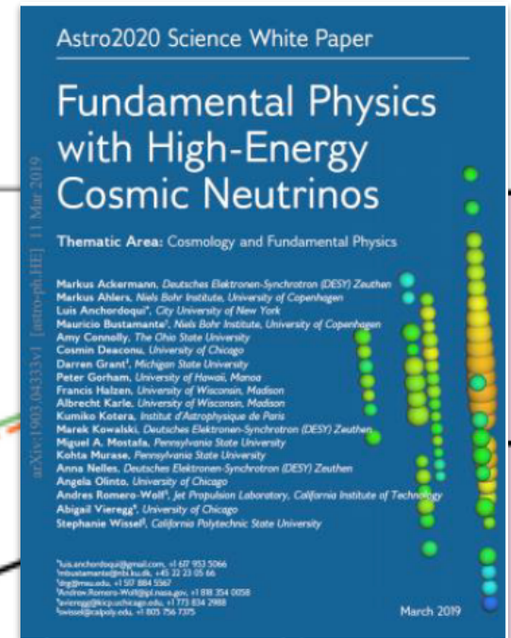


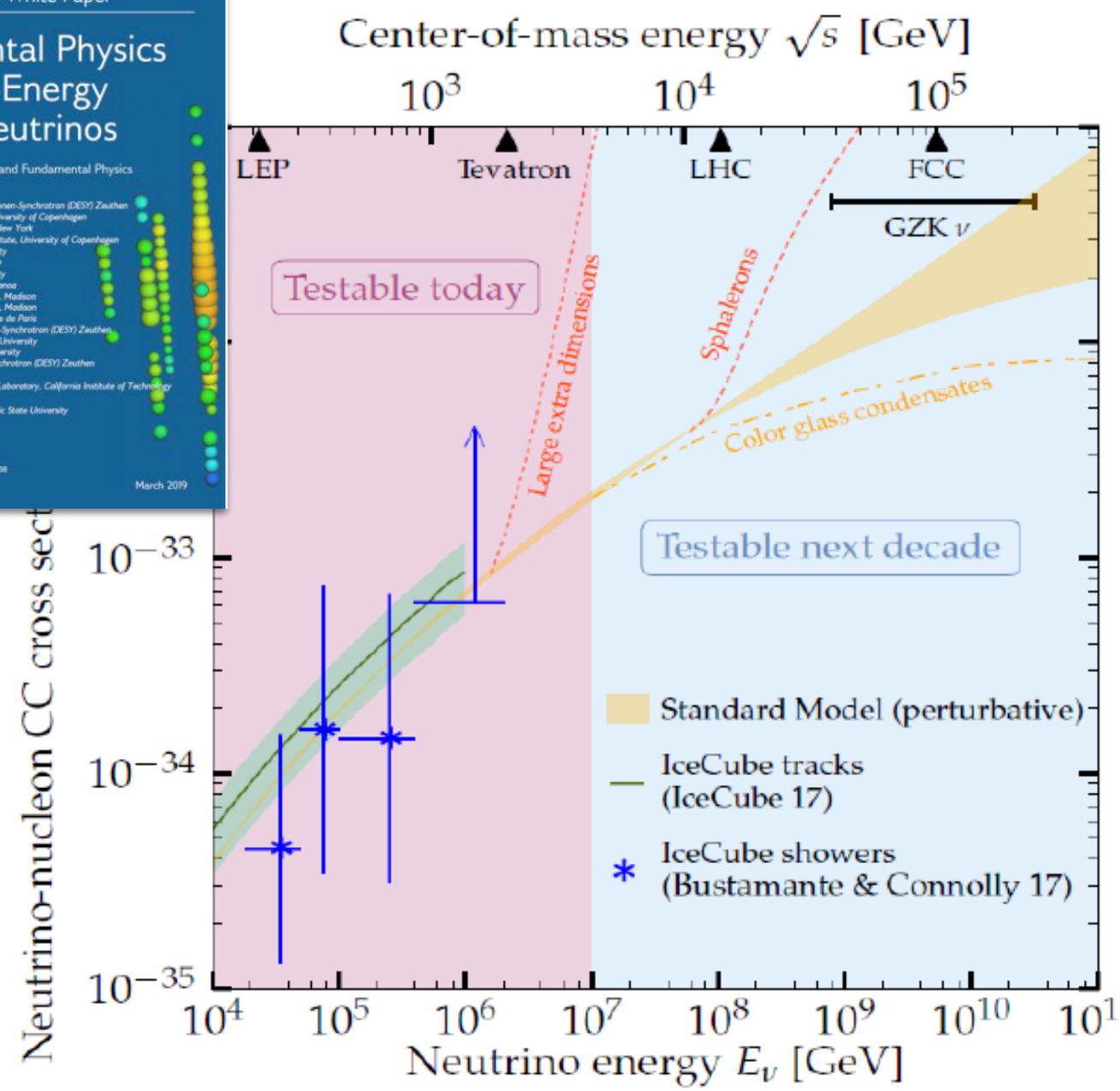
- Absorption of neutrinos in the Earth can be a powerful tool to measure neutrino-nucleus cross section
- Data sample more than 10,000 muon neutrino in one year of data
- Measured cross section between 6.3-980 TeV (extents previous measurements by more than an order of magnitude

Neutrino Absorption in the Earth

IceCube Neutrino 2018





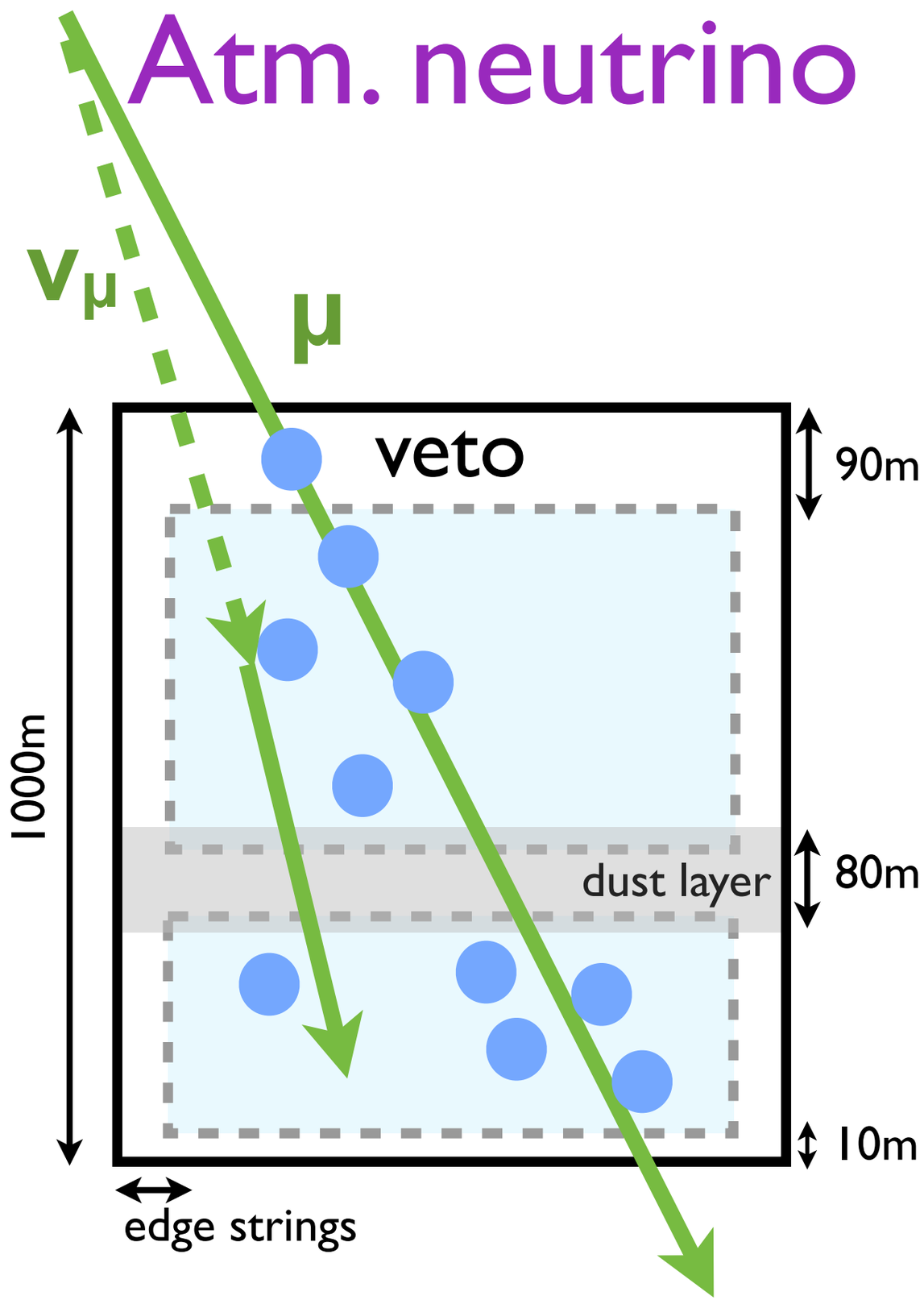


See also tomography:

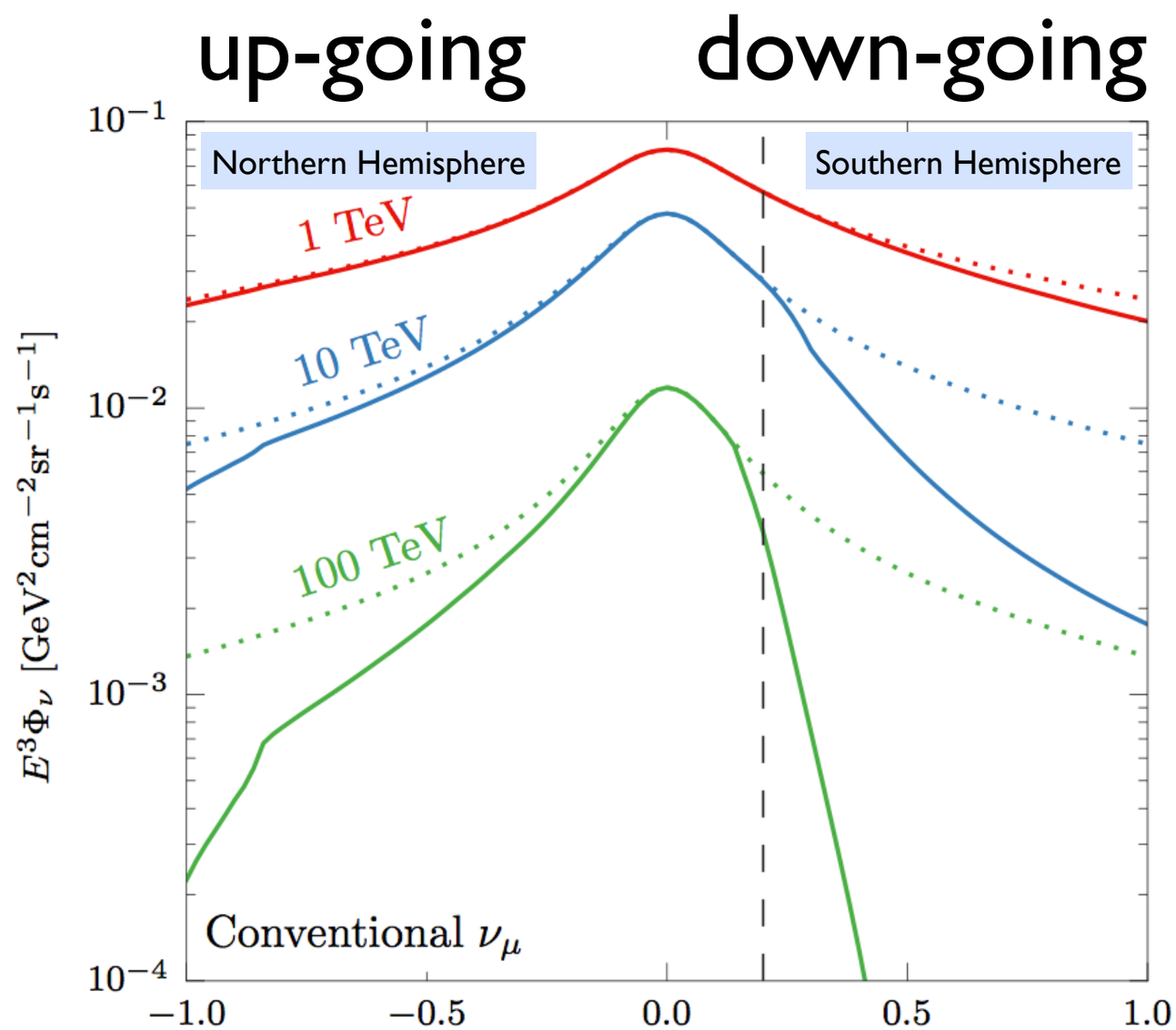
- Gonzalez−Garcia, Halzen, Maltoni, Tanaka, Phys. Rev. Let. 100 (2008)
- Rott, Taketa, Bose, 2015; Winter, 2016; Bourret, Coelho, van Elewyck, 2017
- A. Donini, S. Palomares-Ruiz, and J. Salvado, Nature Phys. 15, 37 (2019)

IceCube Collaboration **Phys.Rev. D91 (2015) no.2, 022001** (arxiv:1410.1749)

Veto and Self-veto

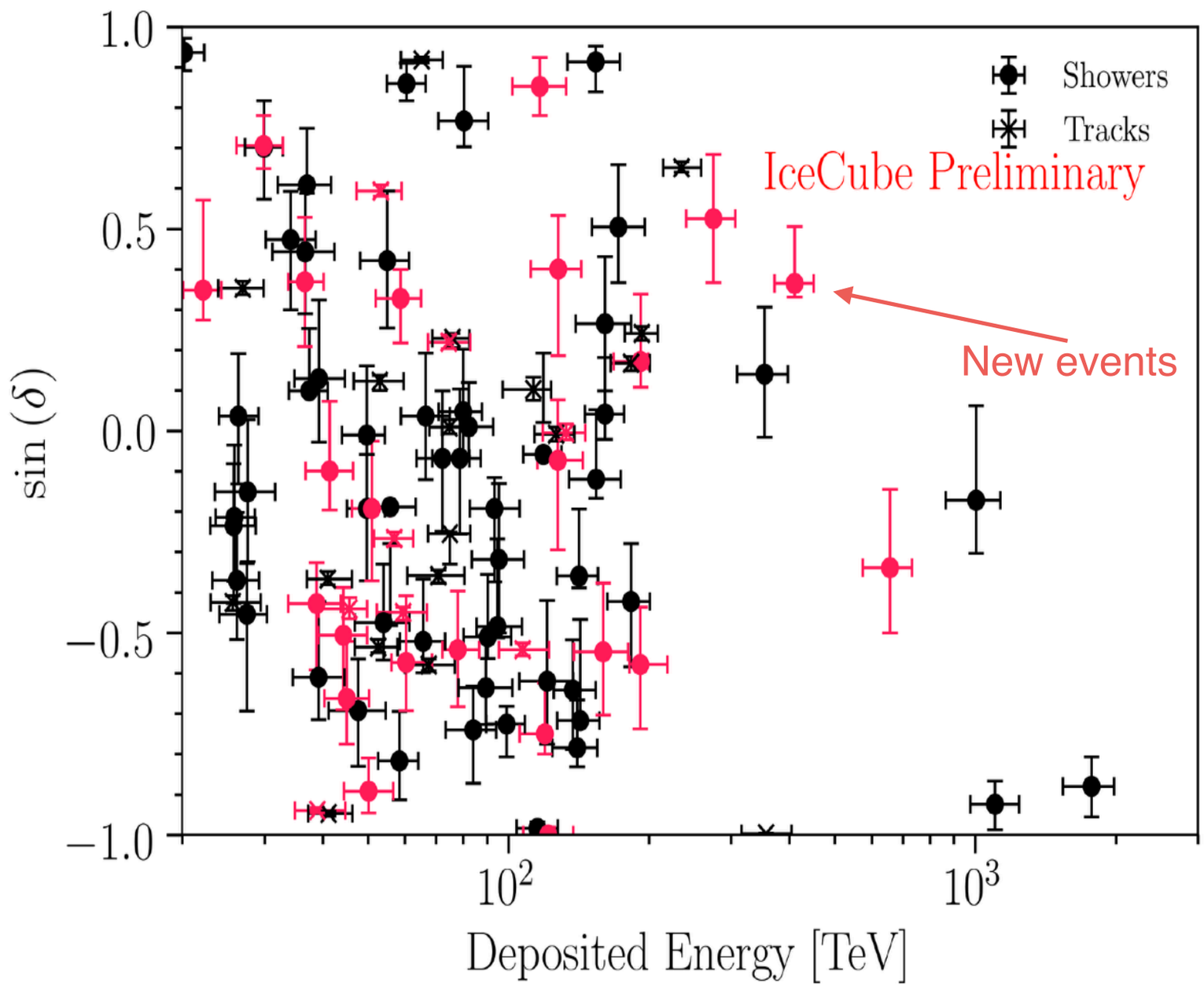


Down-going high-energy neutrinos can be nearly background free identified as astro-physical neutrinos

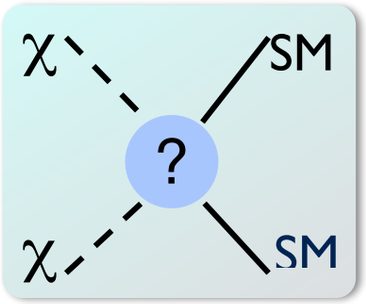


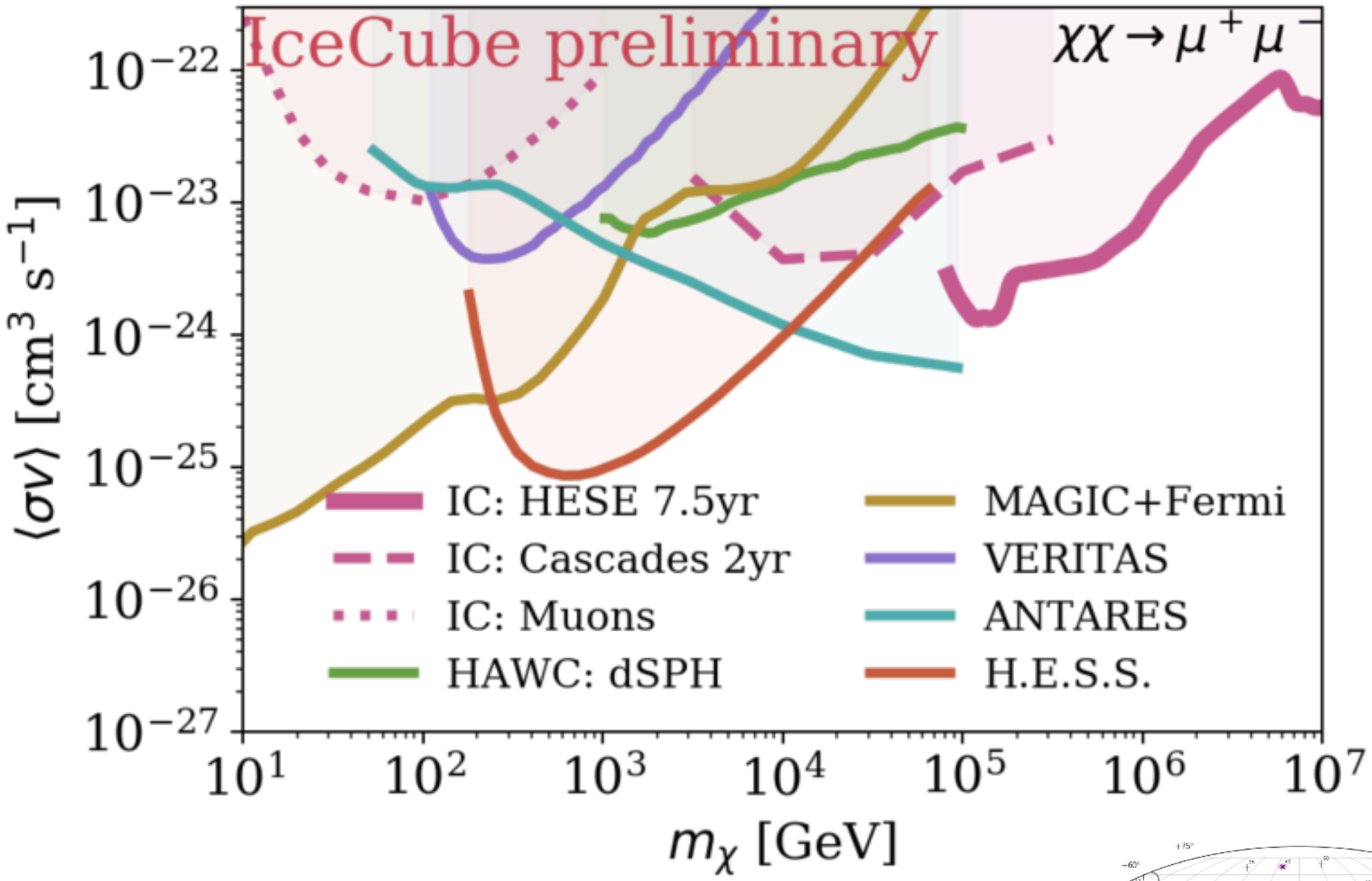
High-energy neutrino search 7.5years

- Recently unblinded 1.5 additional years of data (new calibration)
- Ternary topology ID added (Cascades, Tracks, Double Cascades)
- Above 60TeV: 60 events
  - 12 new events in 2016 season
  - 5 new events in 2017 season
- All energies: 102 events
  - 22 new events in 2016 season
  - 9 new events in 2017 season

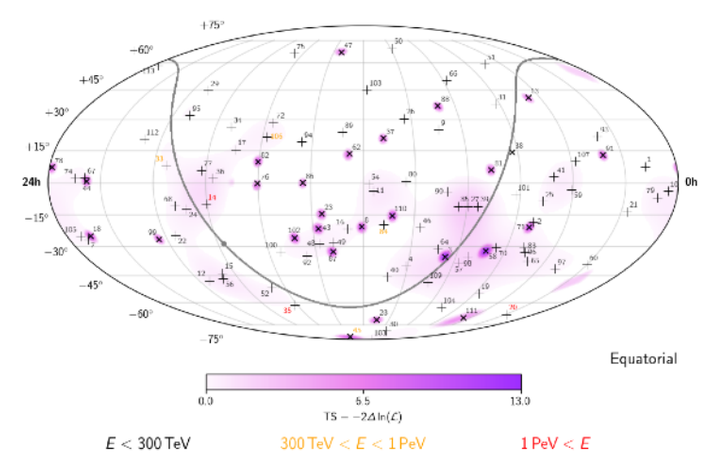


Search DM Annihilation with IceCube's 7years HESE Sample



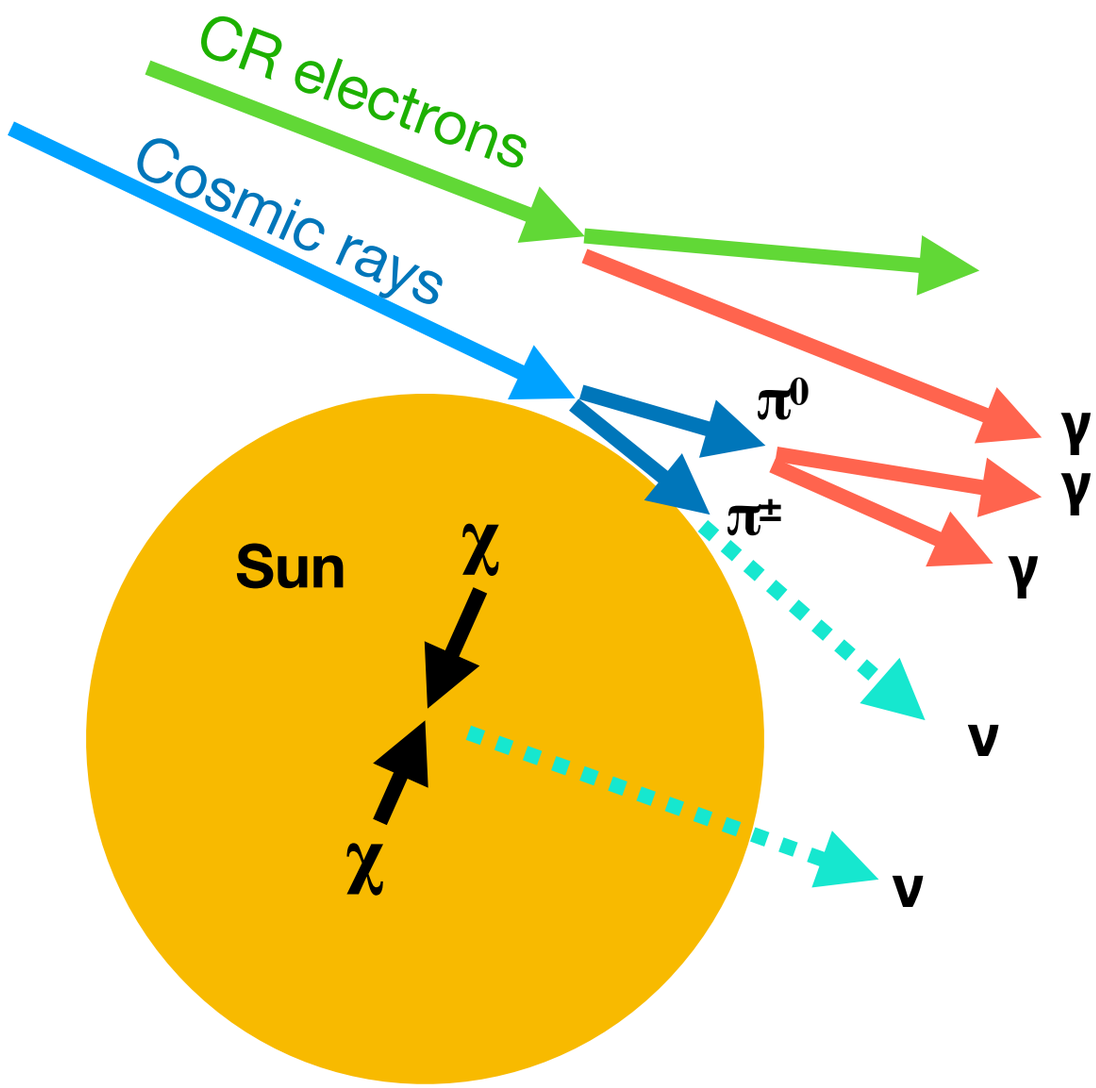


- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Improve neutrino bounds above 100TeV and extend to high masses

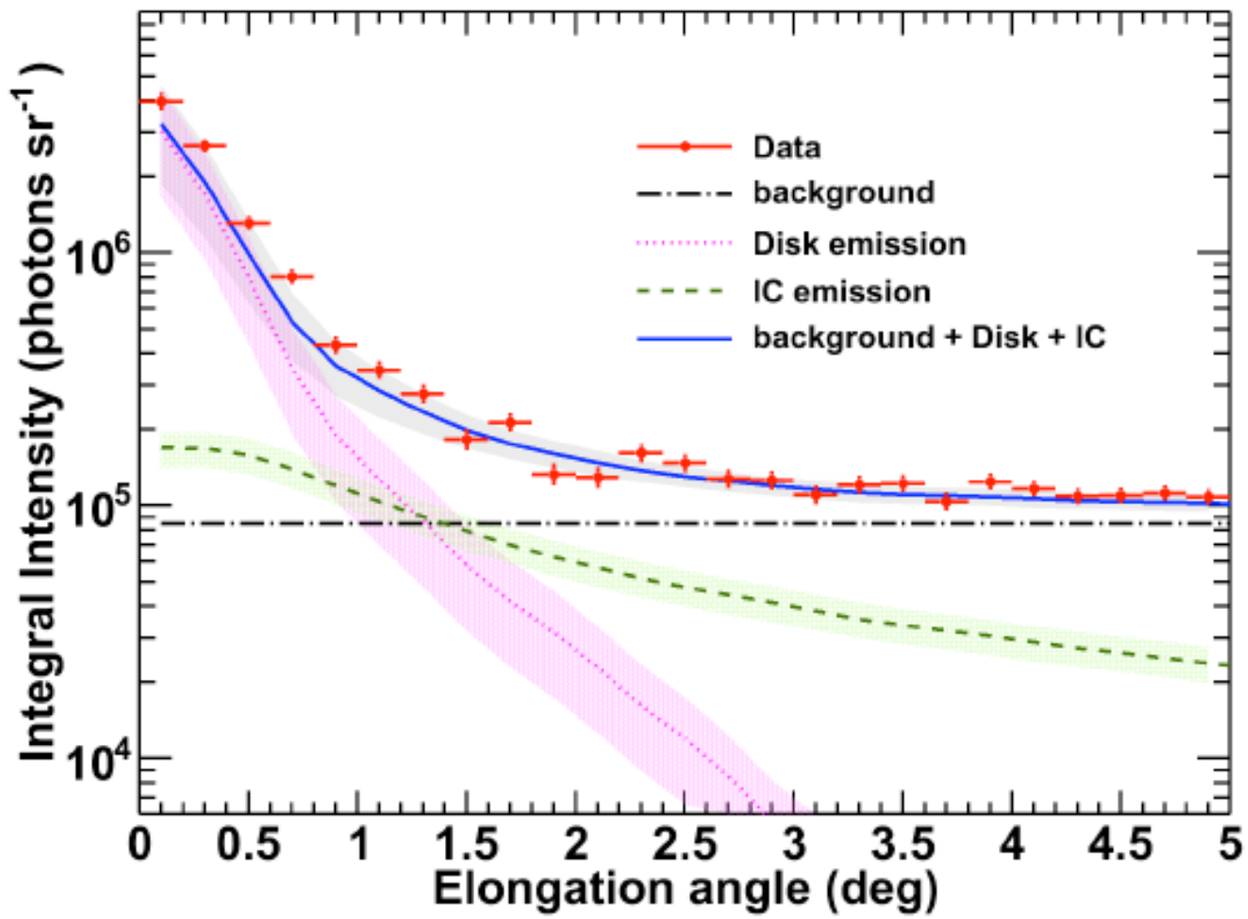


Solar Atmospheric Neutrinos

Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: The Astrophysical Journal 734 (2011) 116 (arxiv:1104.2093)



- Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos
- Background to dark matter searches from the Sun, that soon will be relevant (and could result in the first high-energy neutrino point source)

Leptonic

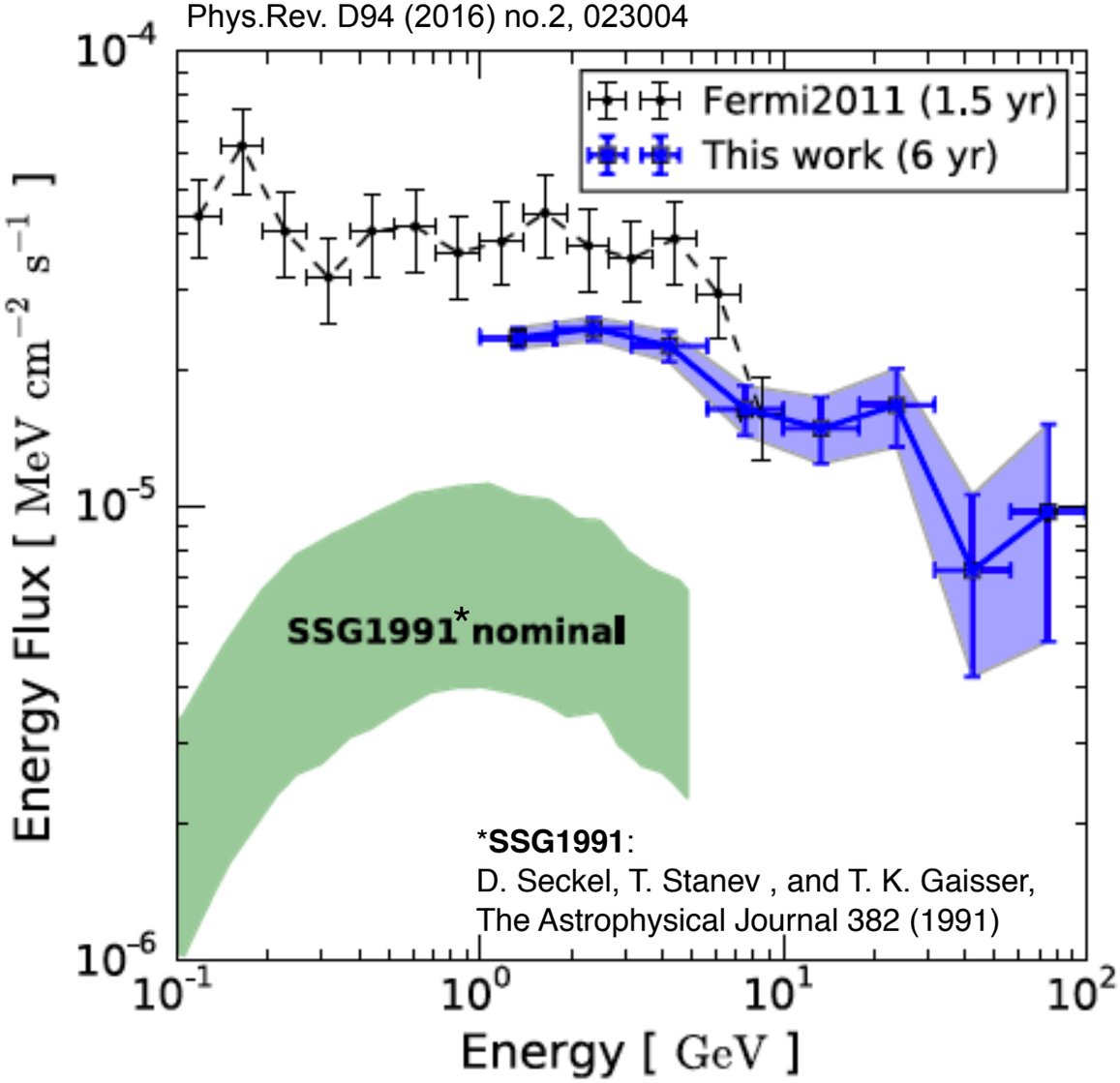
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

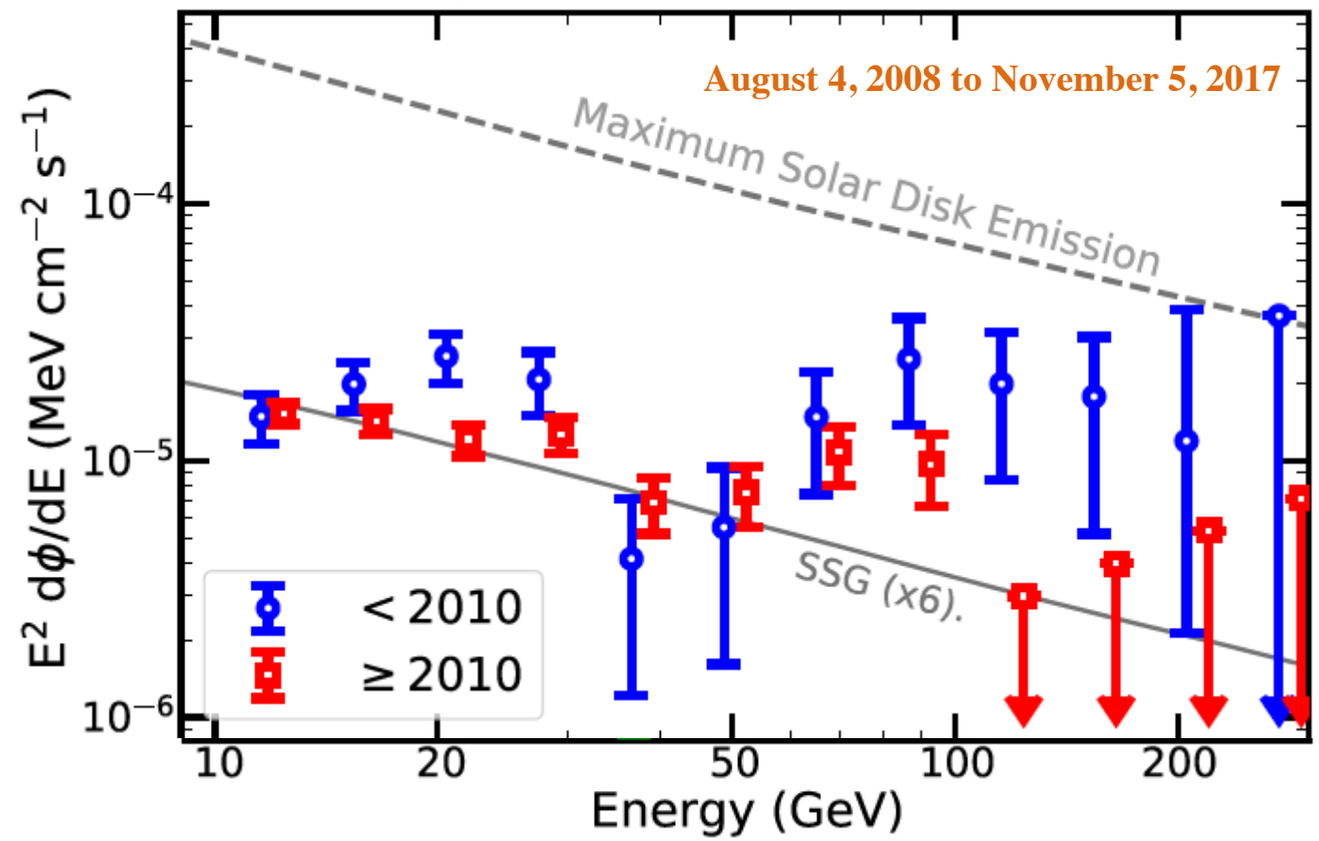
Cosmic ray interactions with the Sun

Kenny C.Y. Ng, John F. Beacom, Annika H.G. Peter, Carsten Rott
Phys.Rev. D94 (2016) no.2, 023004



- Gamma-ray flux extends to 100GeV and beyond
- Gamma-rays below 10GeV anti-correlations with solar activity
- Observed flux factor 5 larger compared to central prediction of SSG1991
- Spectrum could be fit by single power law (γ~2.3)

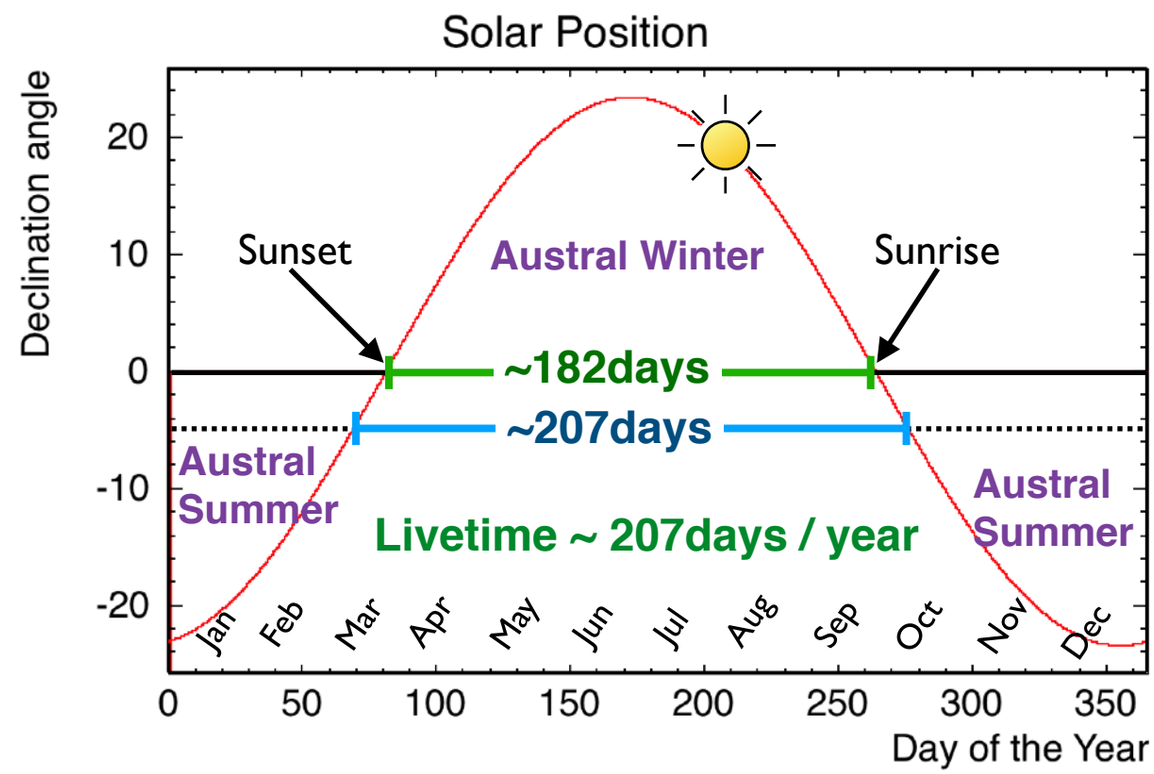
Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C. Y. Ng, and Qing-Wen Tang arXiv:1803.05436

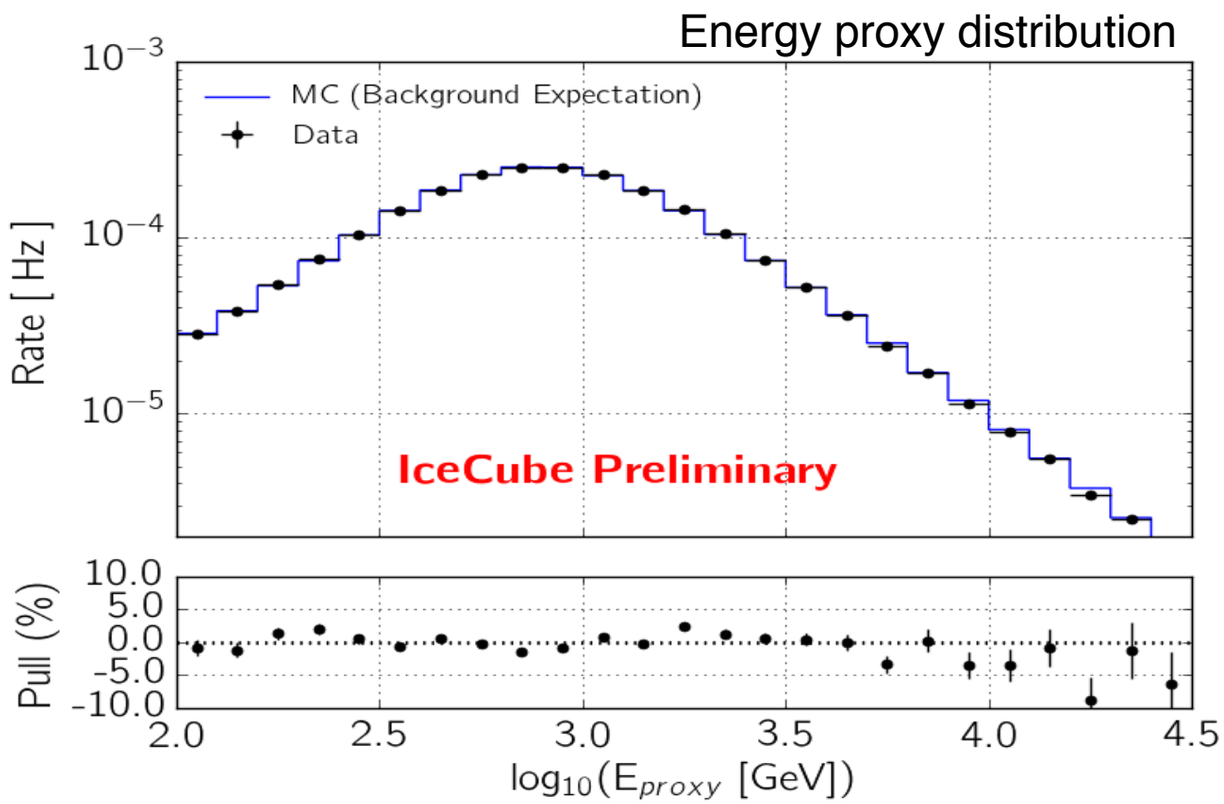


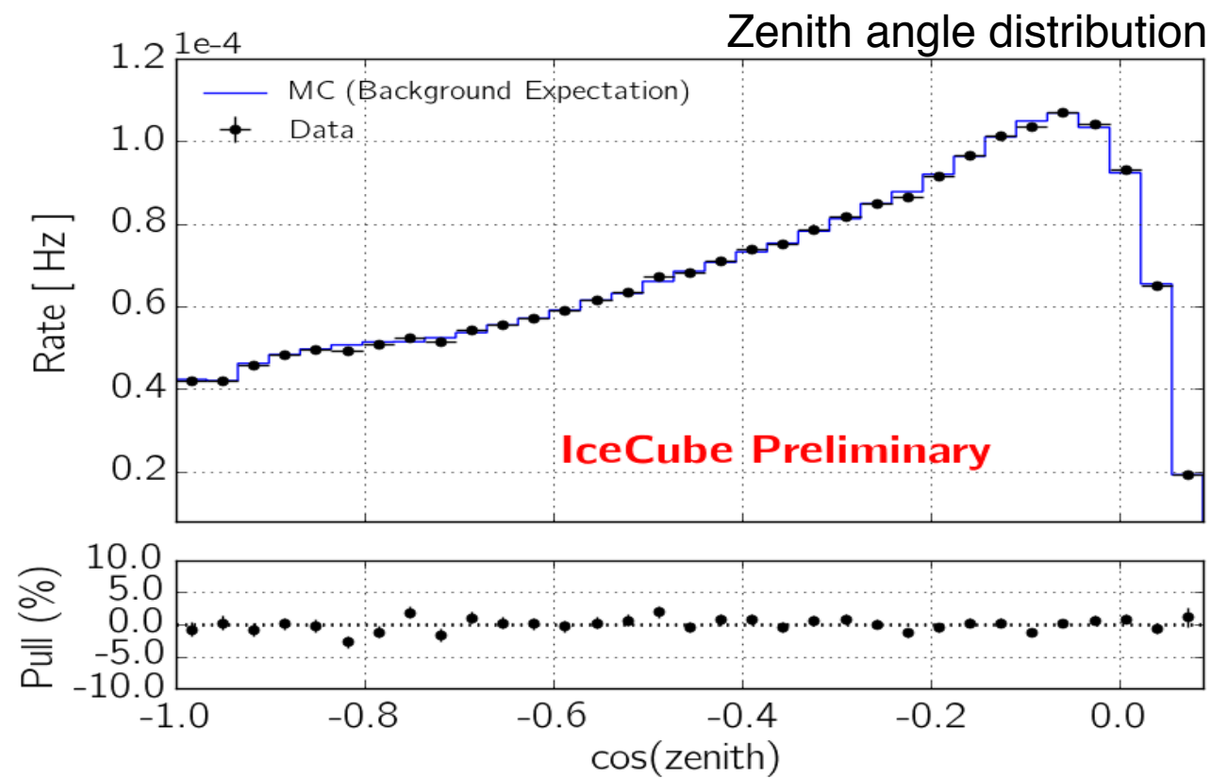
- Six gamma rays above 100 GeV are observed during the 1.4 years of solar minimum, none are observed during the next 7.8 year
- From morphology: Evidence that emission is produced by two separate mechanisms
- To understand the underlying physics, gamma-ray (HAWC, Fermi, ...) and neutrino (IceCube) observation of the imminent Cycle 25 solar minimum are crucial

Data sample

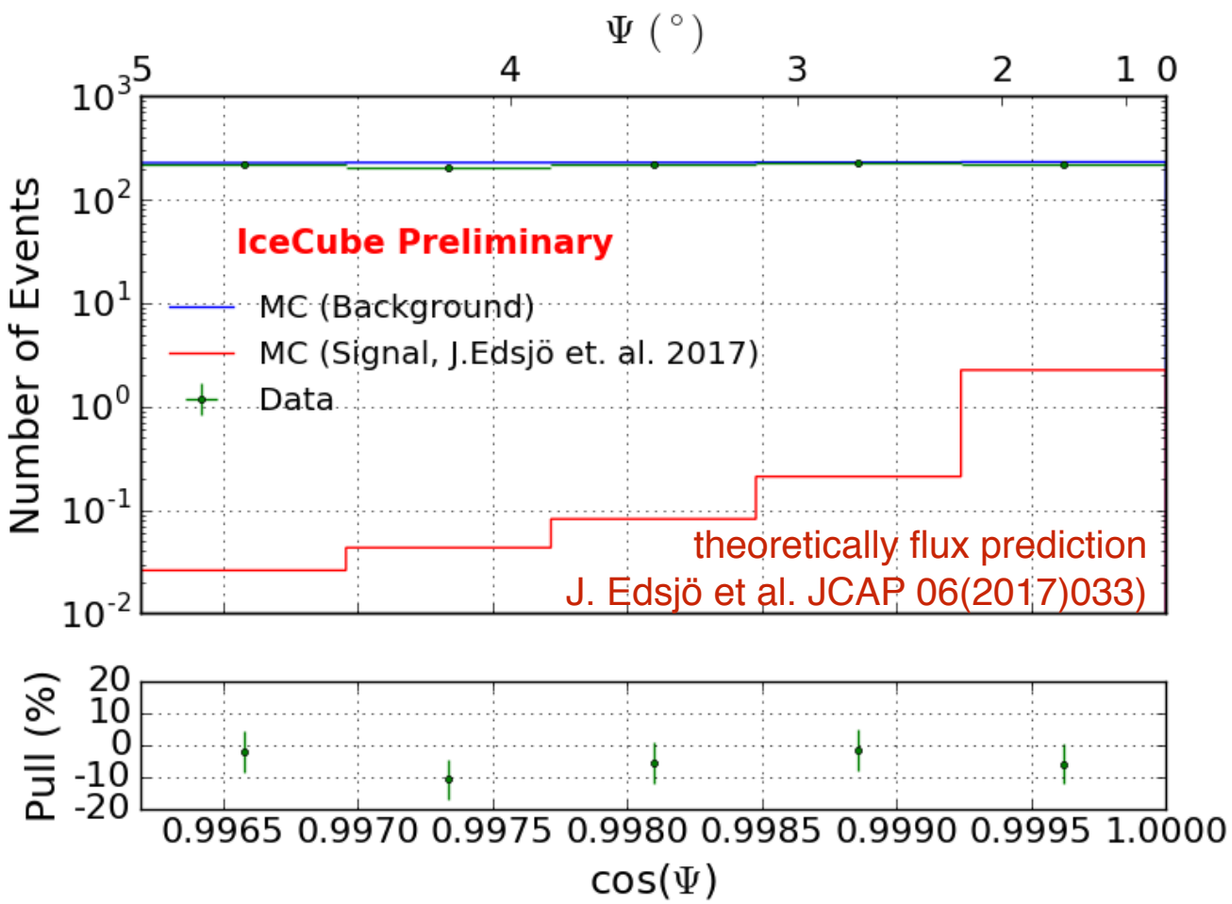
- The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)
  - Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
  - We only consider events from the winter season when the Sun is below the horizon (δ=[-5°,23°]). This results in a total analysis livetime of 1420.73 days.

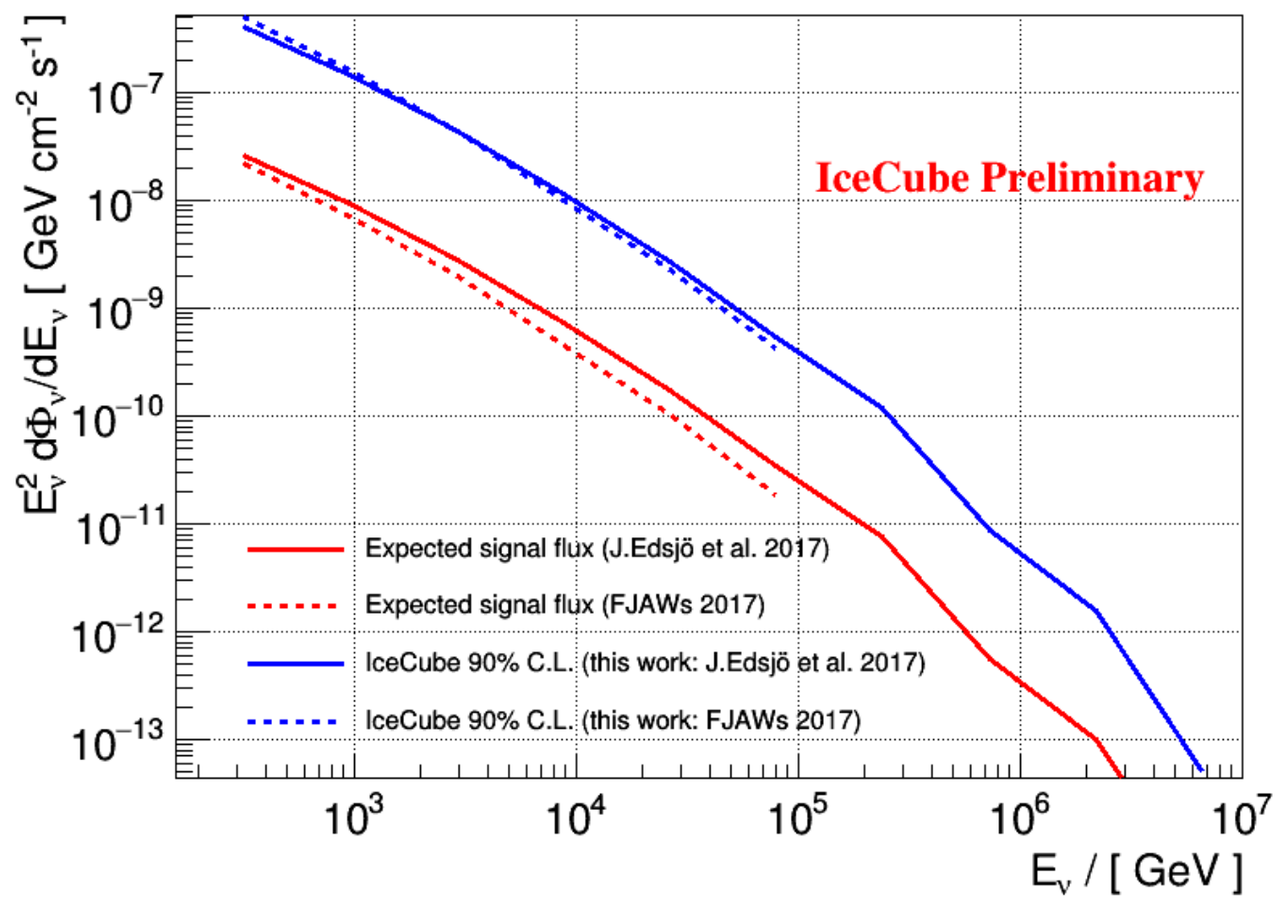






IceCube Solar Atmospheric Neutrinos



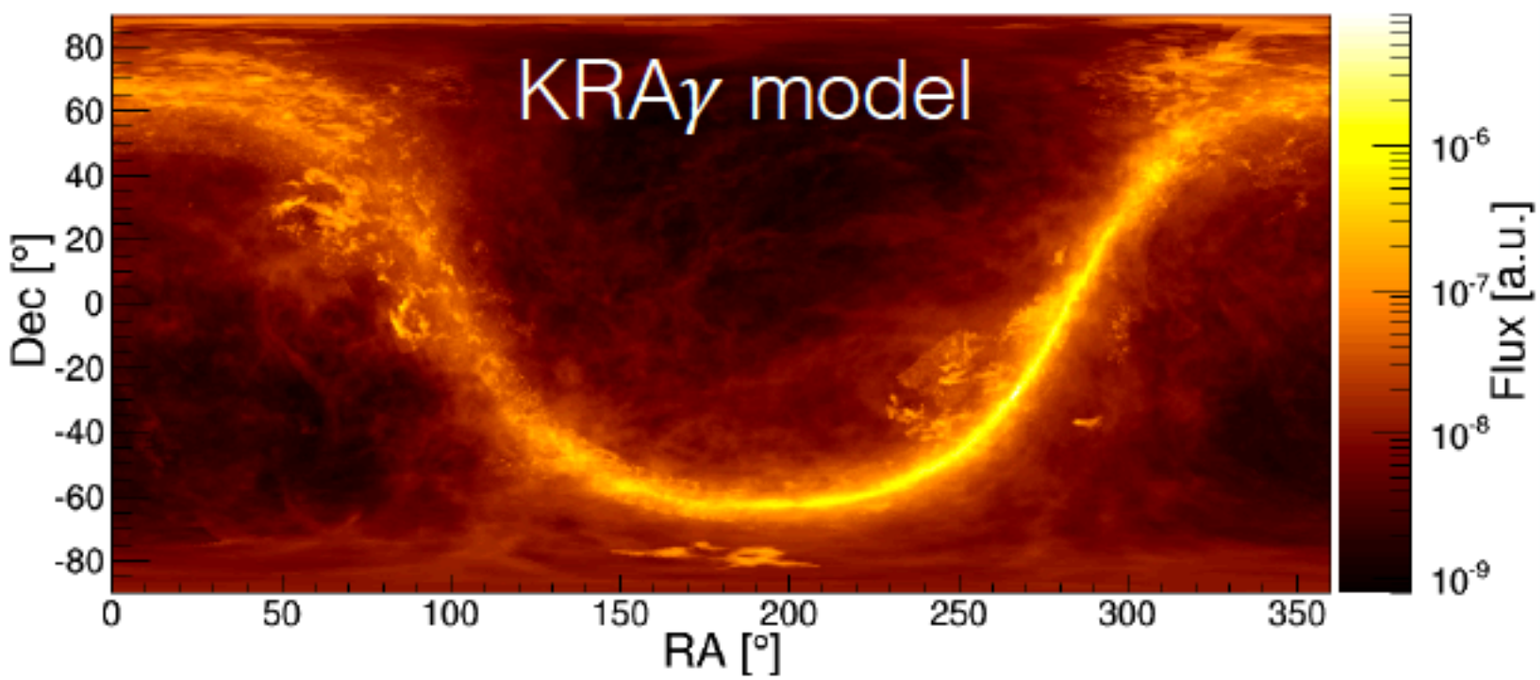


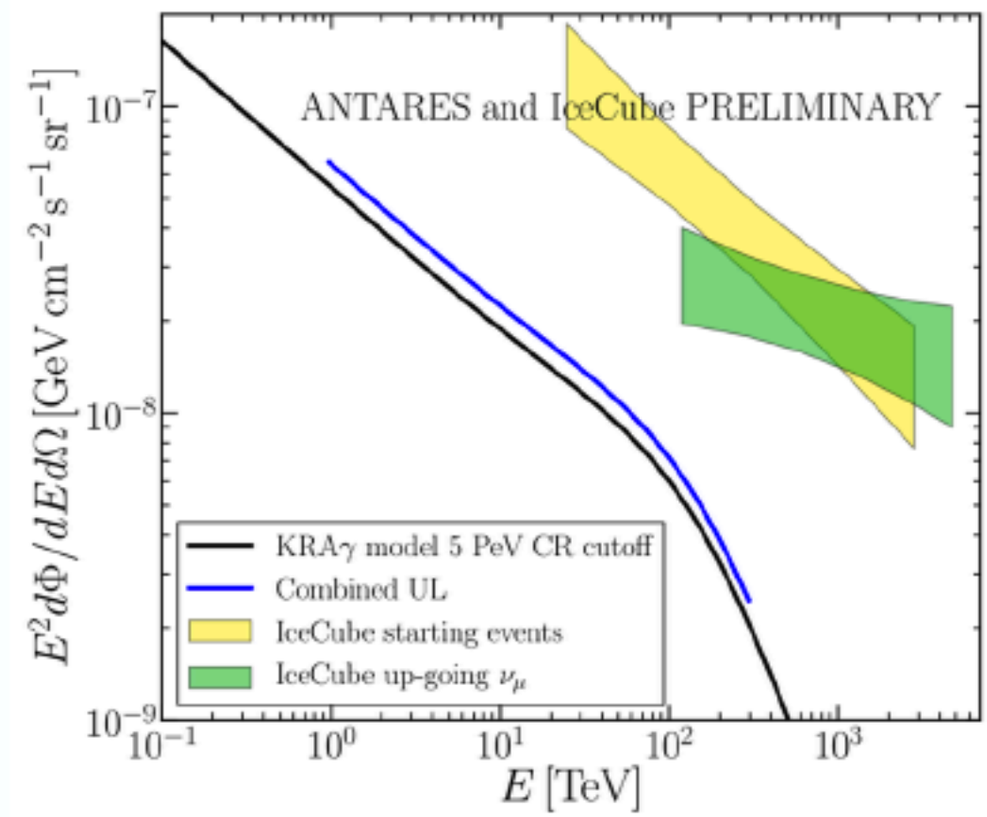
- Maximum log likelihood method is used to calculate significance with a test statistic (TS) distribution
  - Observation in data consistent with background only hypothesis

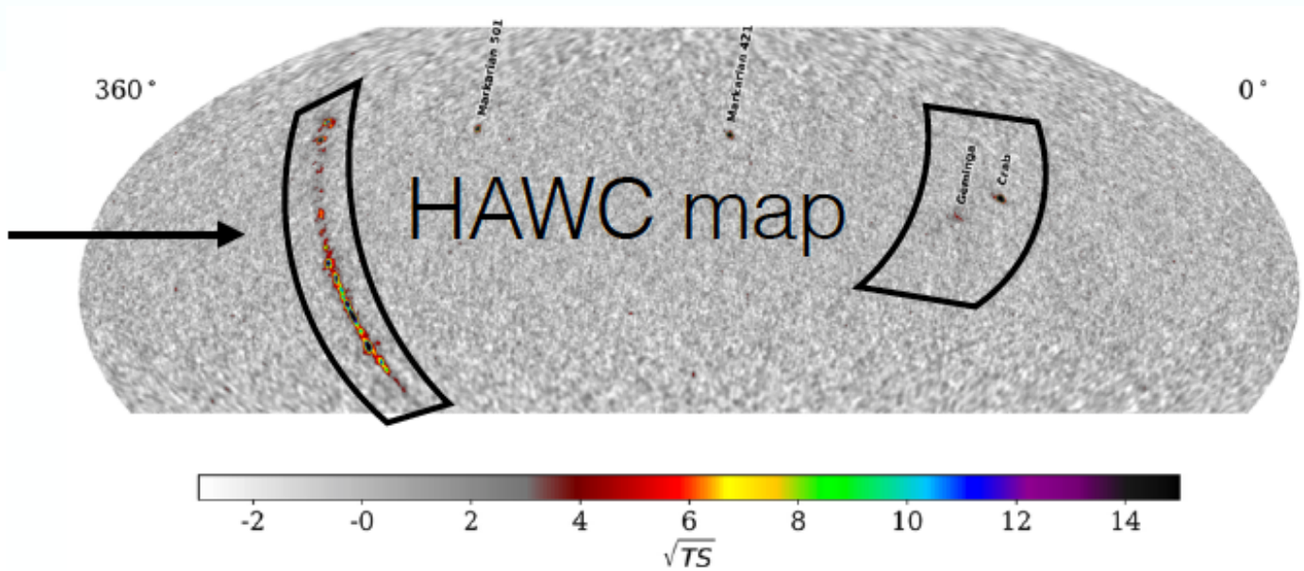
Feldman-Cousins Upper limit at 90% C.L.
- preliminary systematic uncertainties are included by worsening the limit by 13%

Galactic Neutrino Searches

- Combined ANTARES and IceCube search for diffuse ν emission from Galactic plane



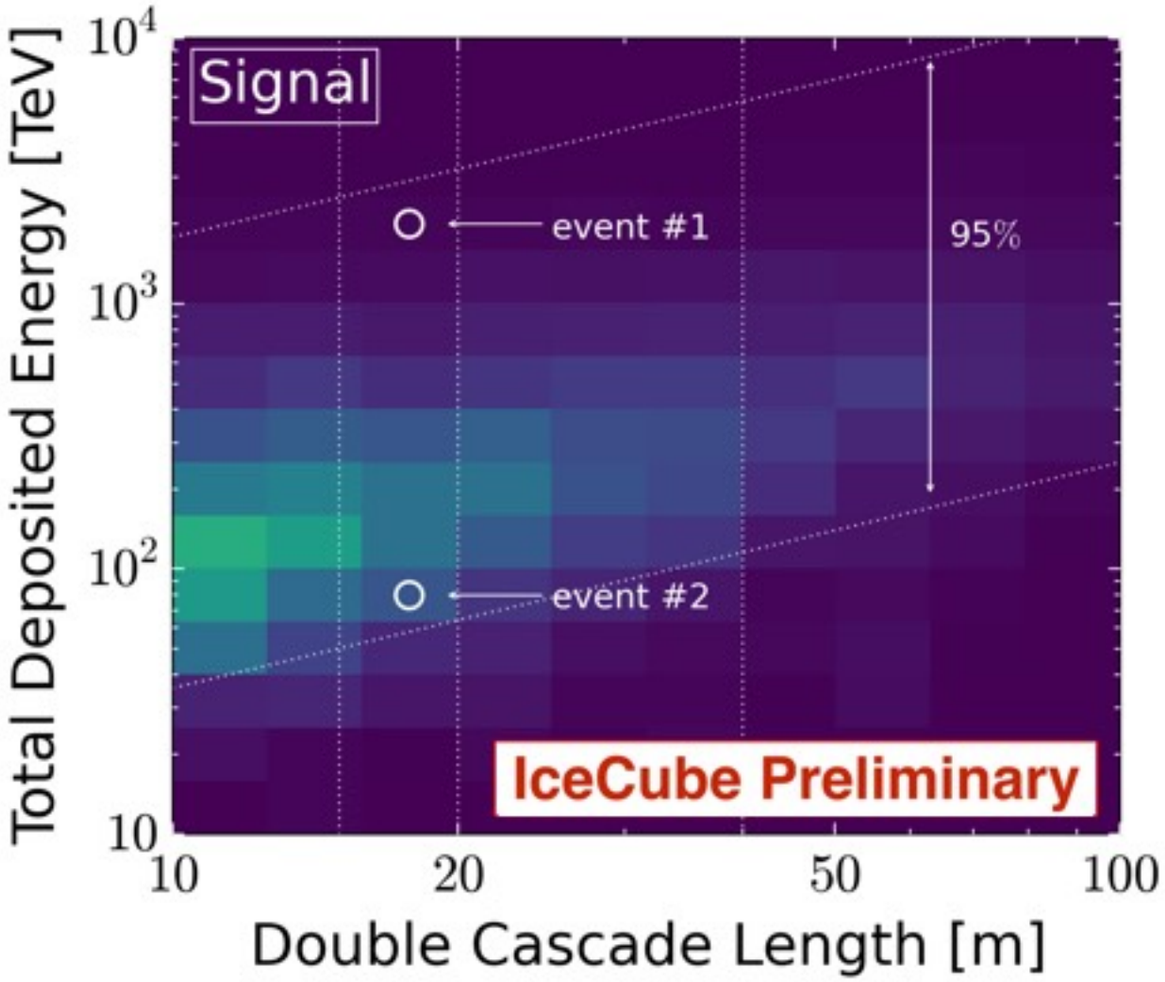


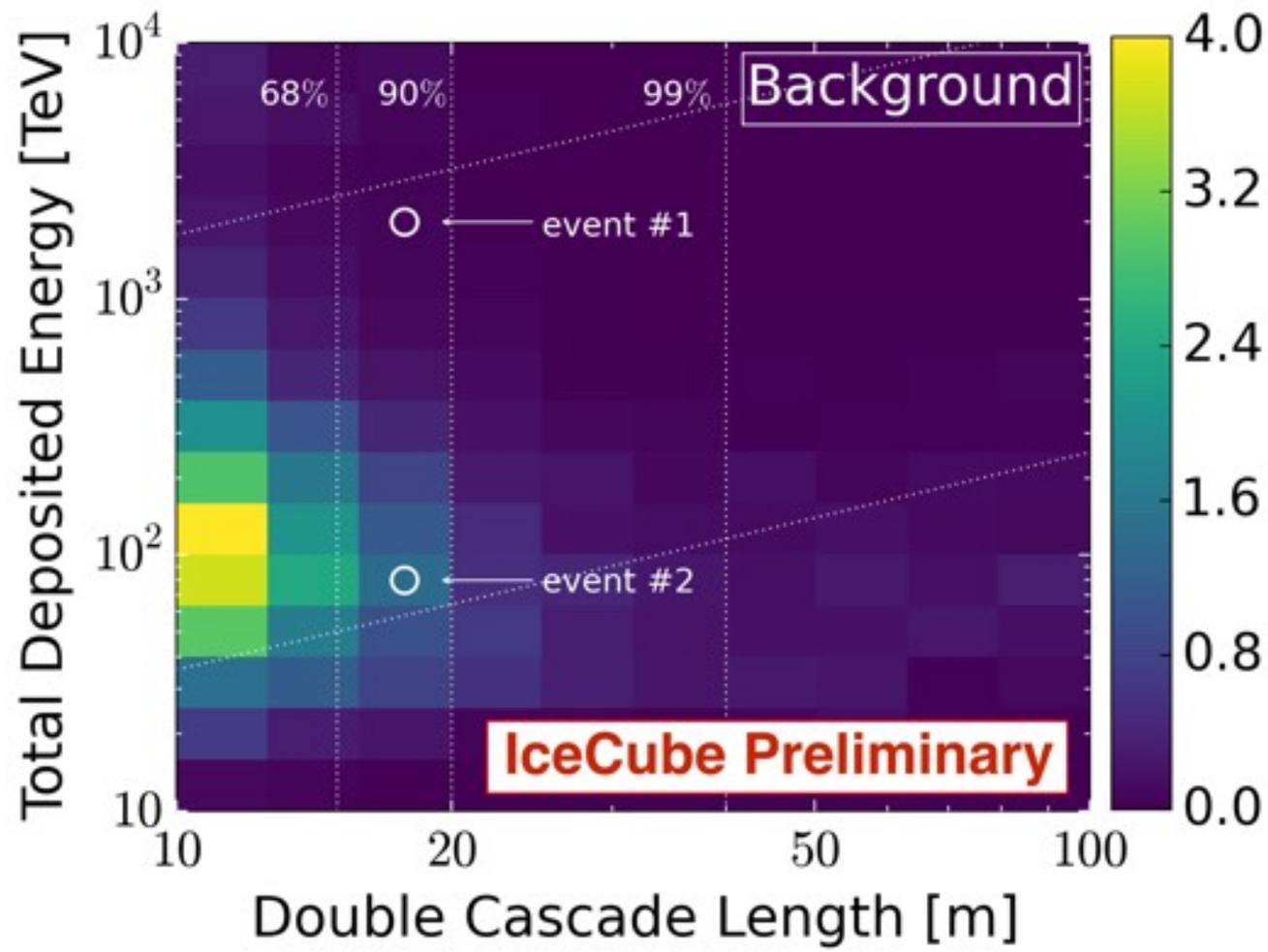


Diffuse astrophysical neutrino flux cannot be attributed to Galactic sources / Galactic plane

IceCube tested HAWC sources … no significant excess observed

High-Energy Starting Events





Two double cascades have been identified

Double cascades arise from ν_τ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

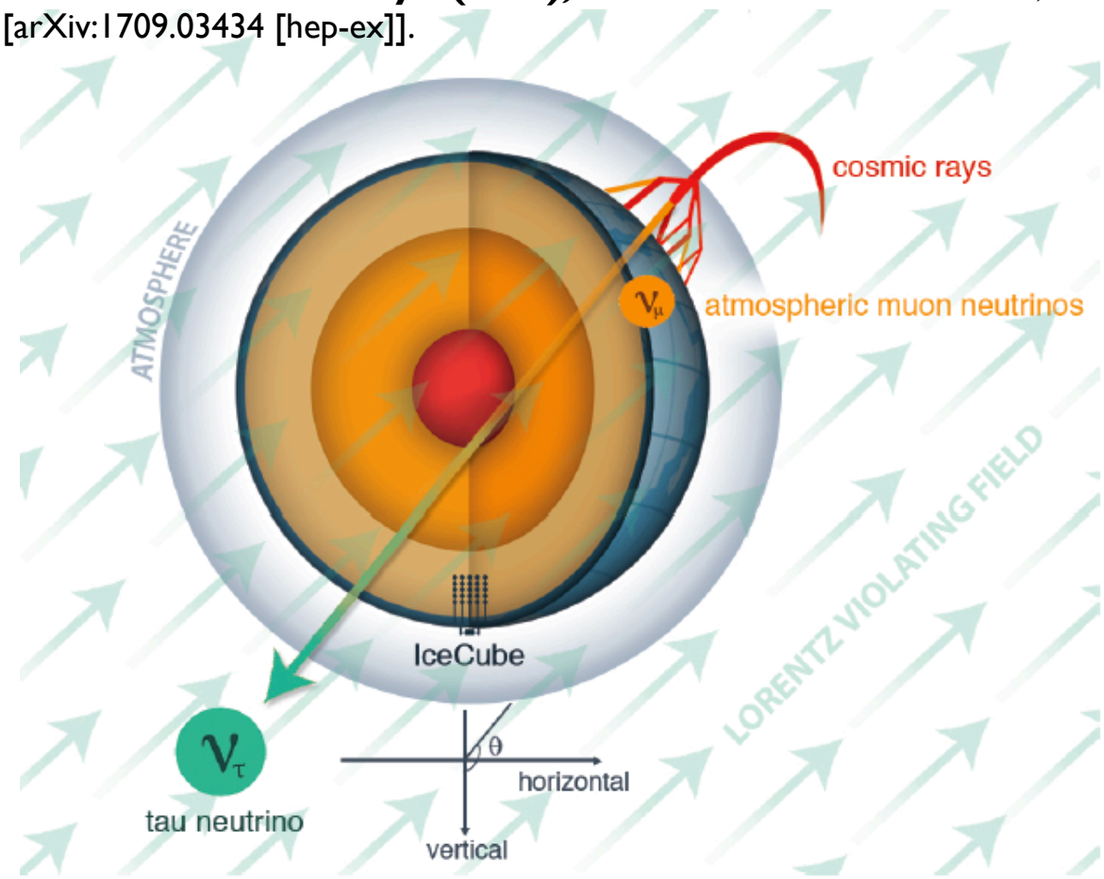
Separate study of taunts of the double cascade events on-going

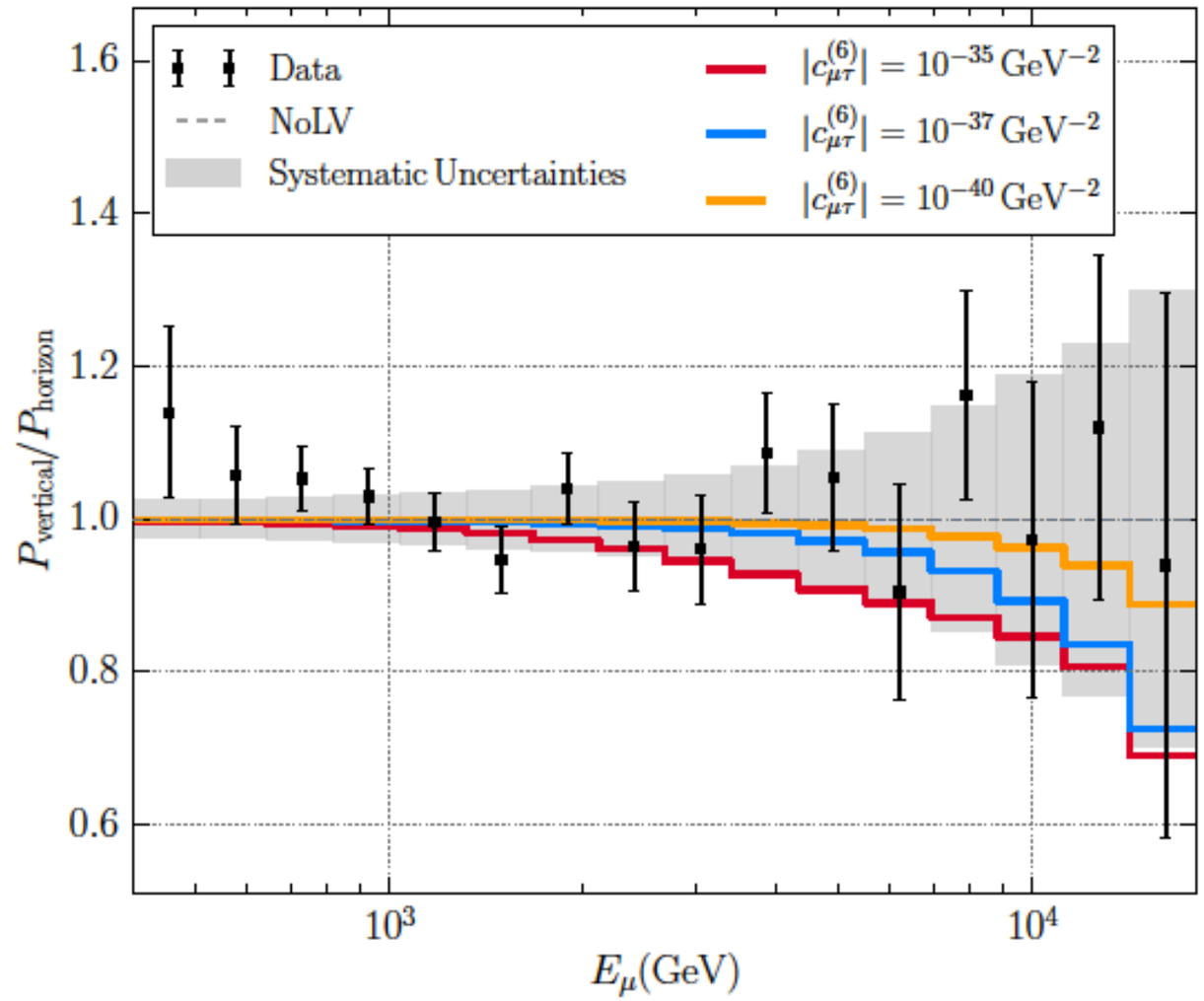
IceCube Coll. **Nature Phys. (2018),** doi:10.1038/s41567-018-0172-2,
[arXiv:1709.03434 [hep-ex]].

Tests of Lorentz Symmetry

Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

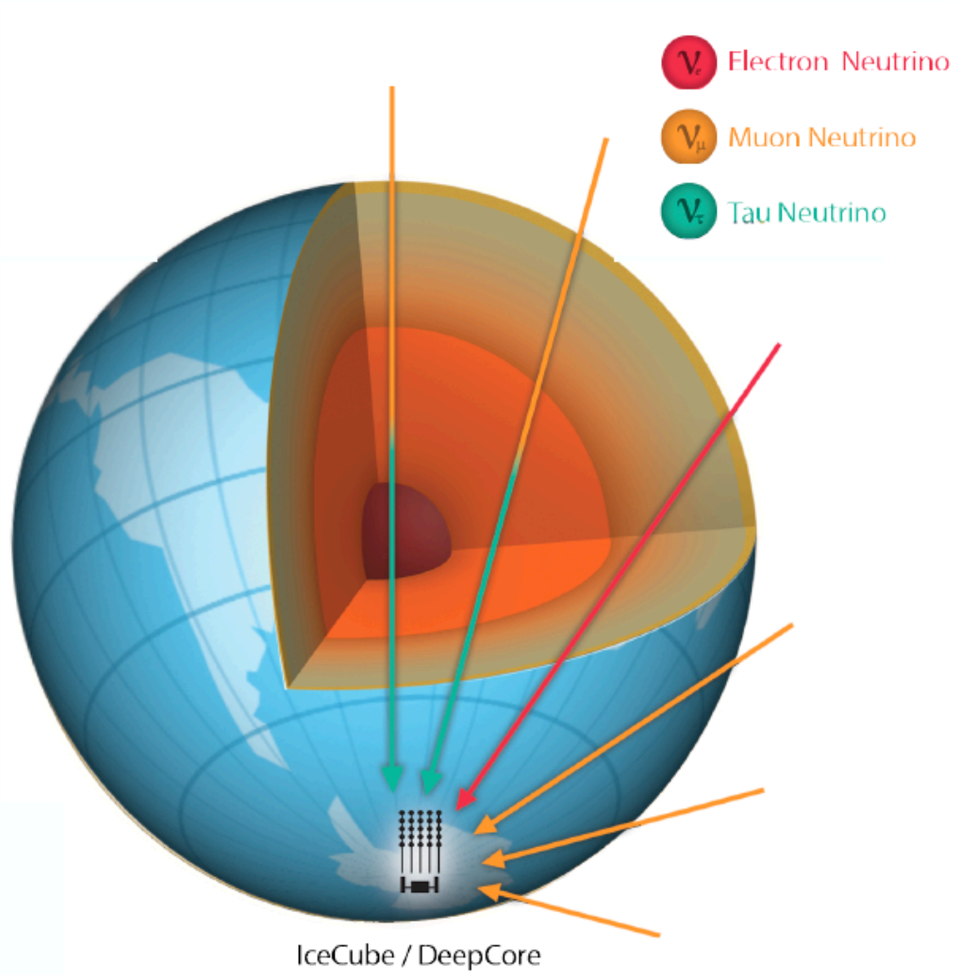
IceCube Coll. **Nature Phys. (2018),** doi:10.1038/s41567-018-0172-2,
[arXiv:1709.03434 [hep-ex]].

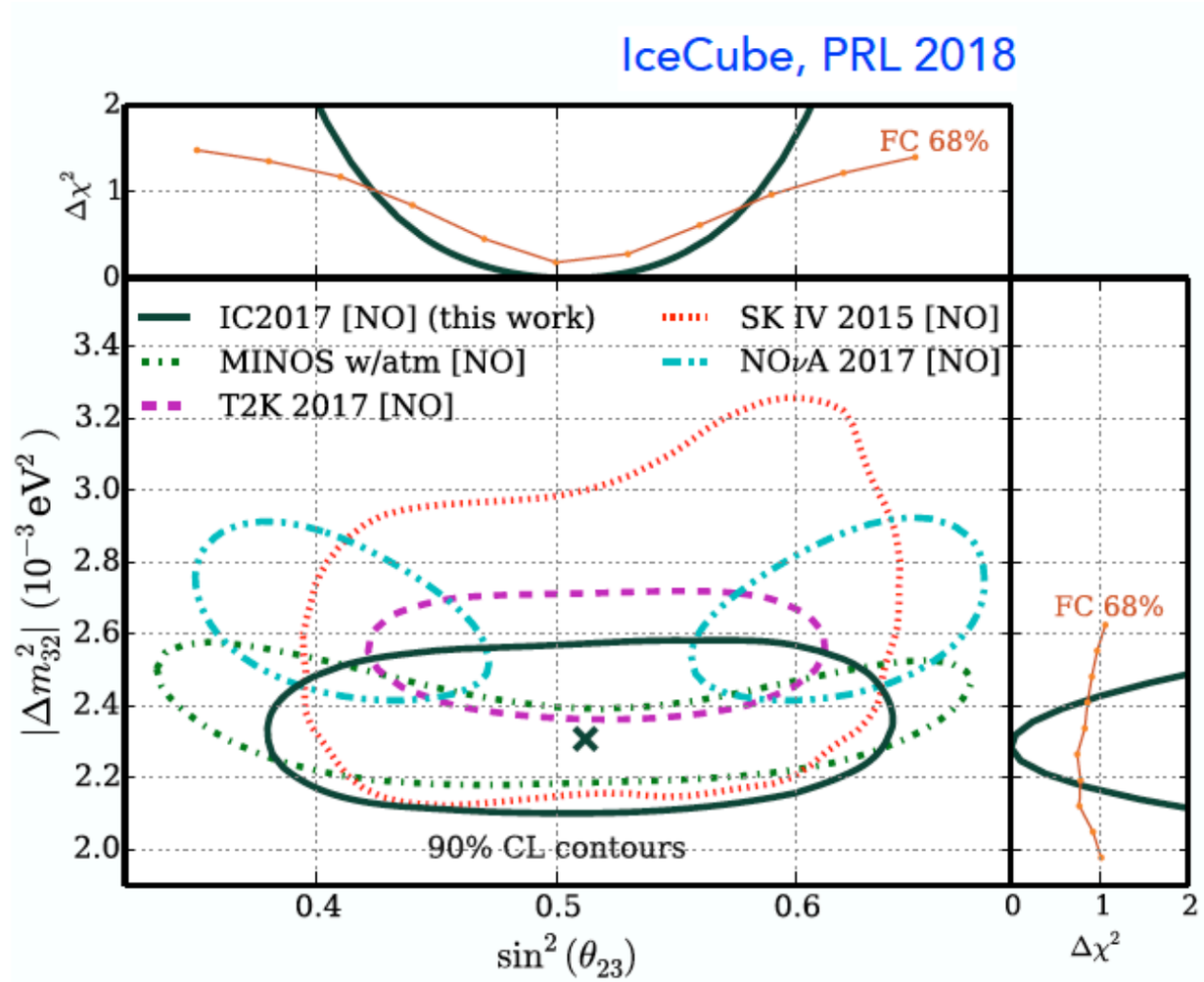




- Most precise test of space-time symmetry in the neutrino sector to date
- Search for anomalous neutrino oscillations in IceCube's high energy neutrino sample
  - No evidence for such phenomena

Neutrino Oscillations





- 3 years of IceCube Deep Core data
- Measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

Normal ordering best fits

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$