Latest Results from IceCube and Searches Dark Matter

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NDM 2018

6th Symposium on Neutrinos and Dark Matter in Nuclear Physics 2018

2018.6.29(Fri)~7.4(Wed)

Institute for Basic Science HQ, Daejeon, Korea

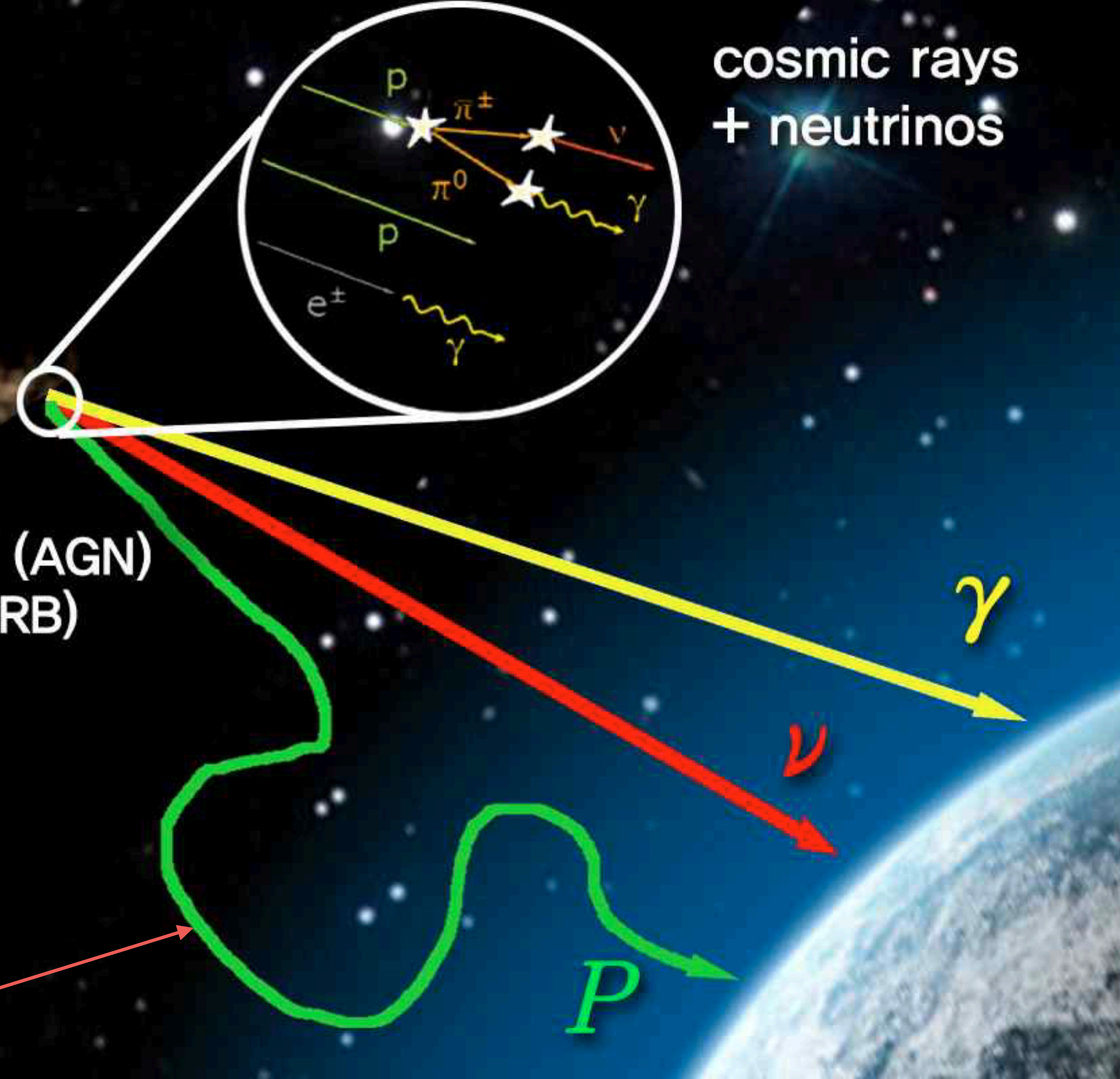
Image Credits:
ESA/Hubble Galaxy Cluster Abell 1689
ESO/Digitized Sky Survey 2 - Fornax dSph
M31 Andromeda

Outline

- Motivation
- The IceCube Neutrino Telescope
- IceCube Science Program and Selected Results
  - Search for Astrophysical Neutrinos
  - Search for Dark Matter
- Outlook & Conclusions

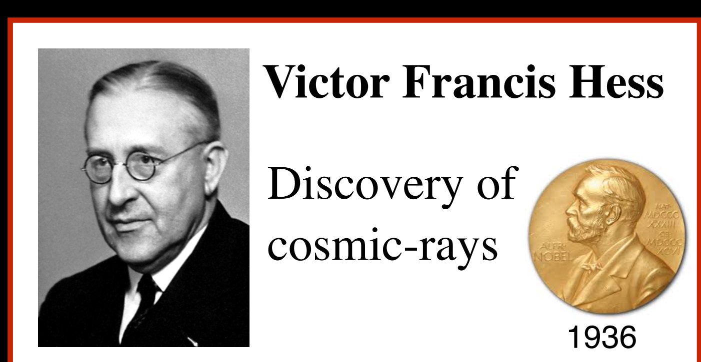
Astrophysical Messengers

cosmic rays + neutrinos



Cosmic Ray Sources

- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)
- Supernovae (SN)
- Galaxy Clusters
- Unknown

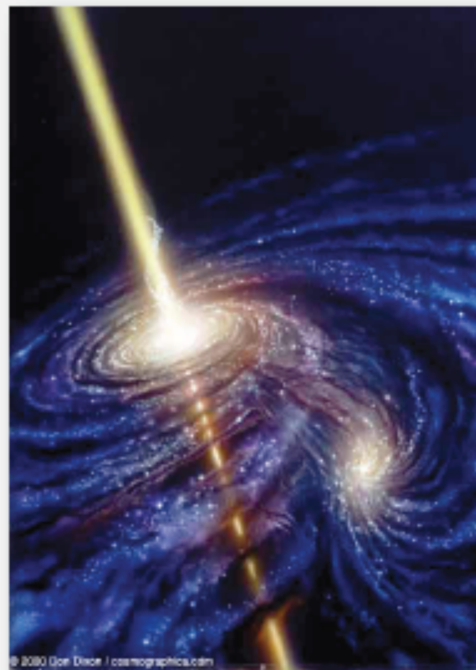


Sources of High Energy Neutrinos

Astrophysical

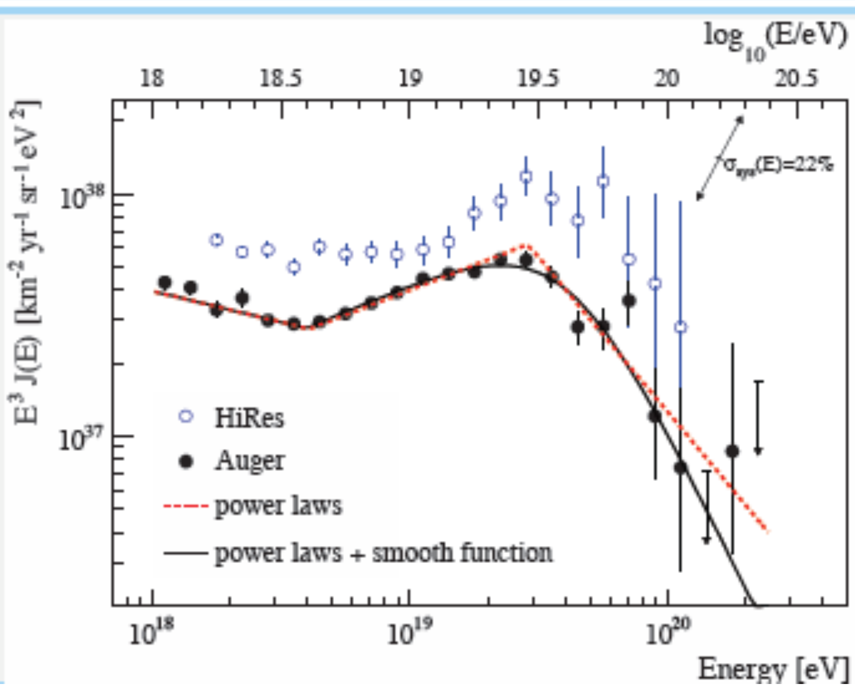
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Active Galactic Nuclei



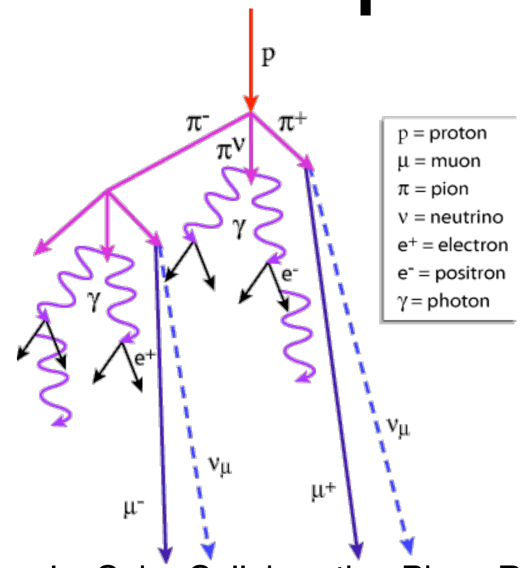
Gamma-ray Bursts

$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)



Auger Collab, arxiv:1002.1975v1

Atmospheric Neutrinos

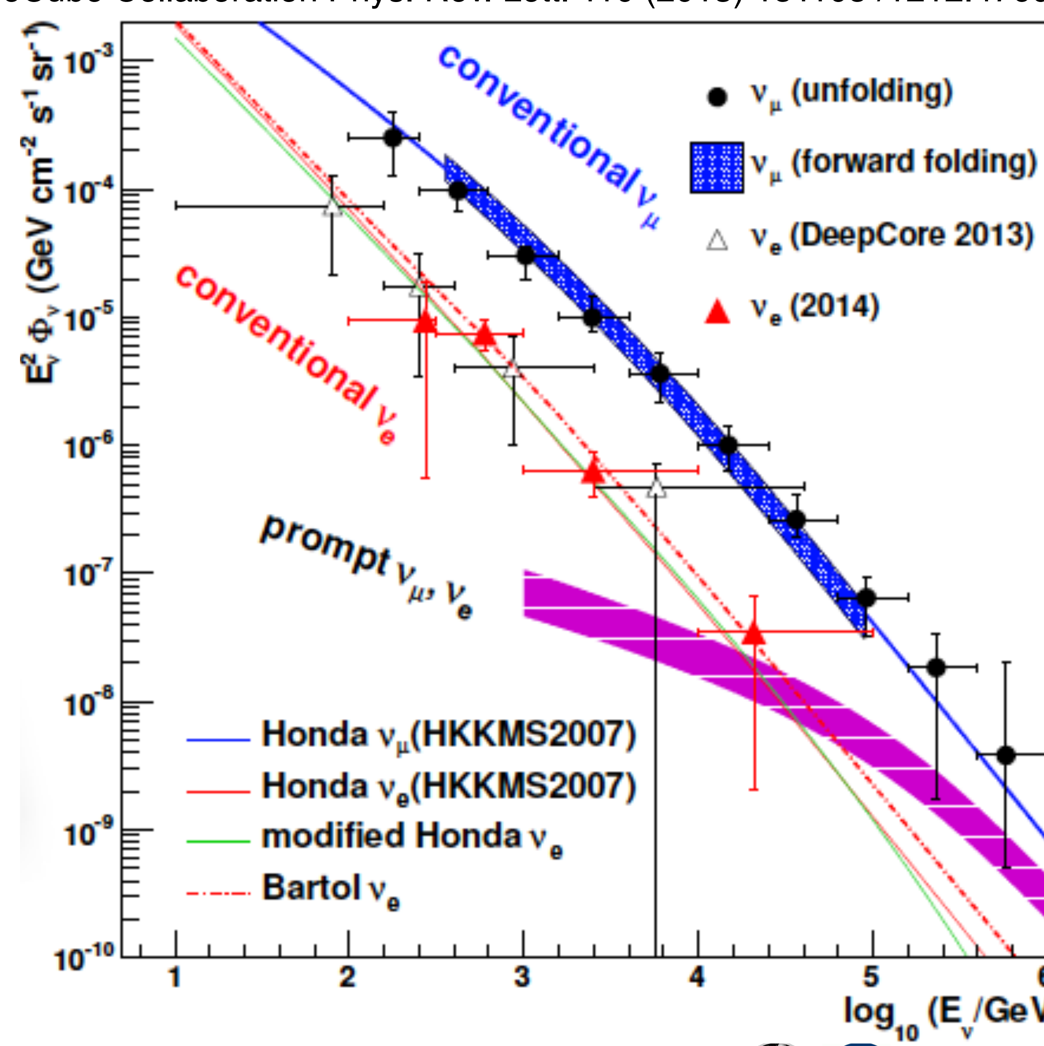


Cosmic rays interact in the upper atmosphere:

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

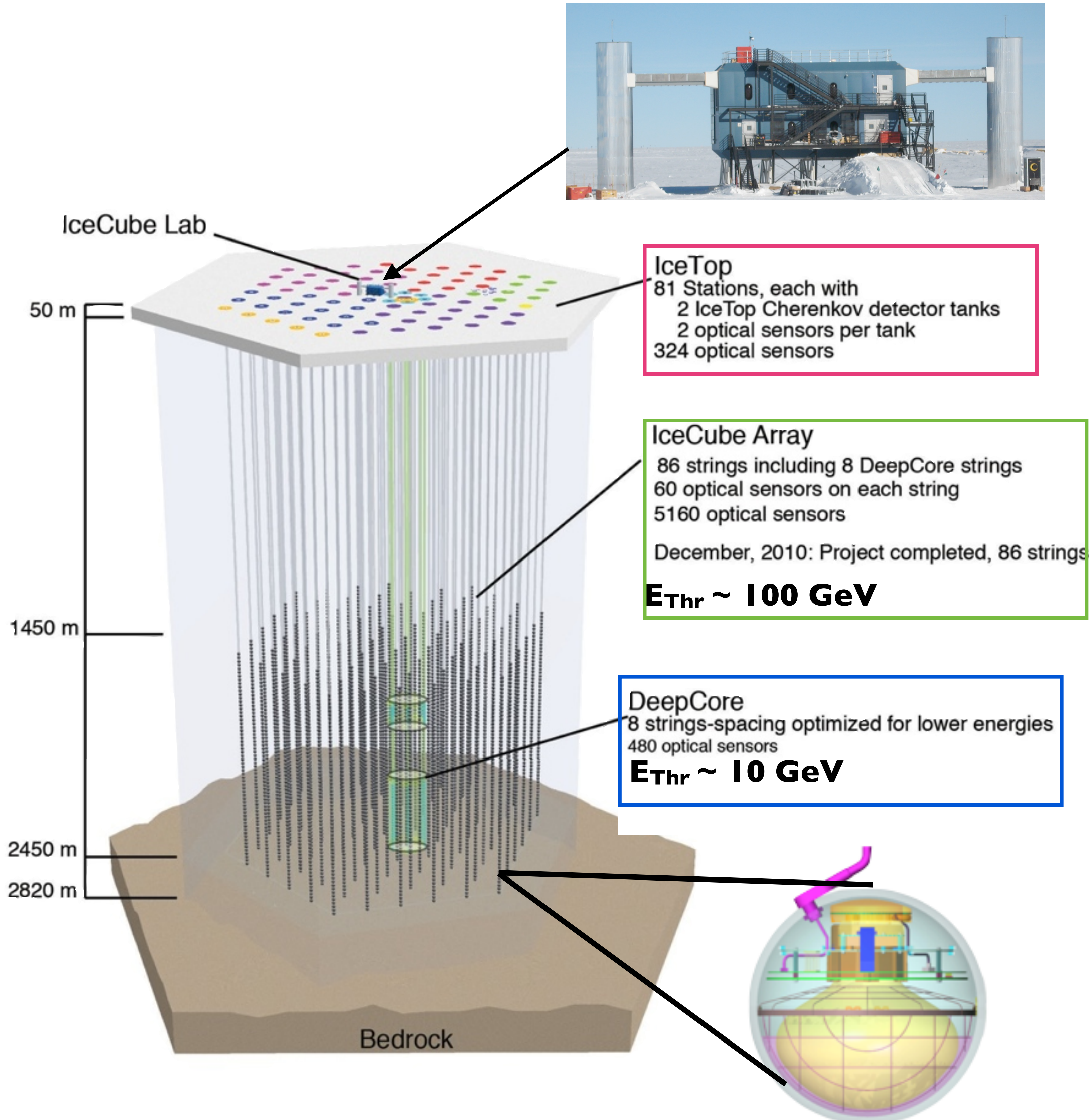


The IceCube Neutrino Telescope


In Korea: Sungkyunkwan University since 2013
THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
JAPAN
Chiba University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Sungkyunkwan University
SWEDEN
Stockholms universitet
Uppsala universitet
SWITZERLAND
Université de Genève
UNITED KINGDOM
University of Oxford
UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

The IceCube Neutrino Telescope

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



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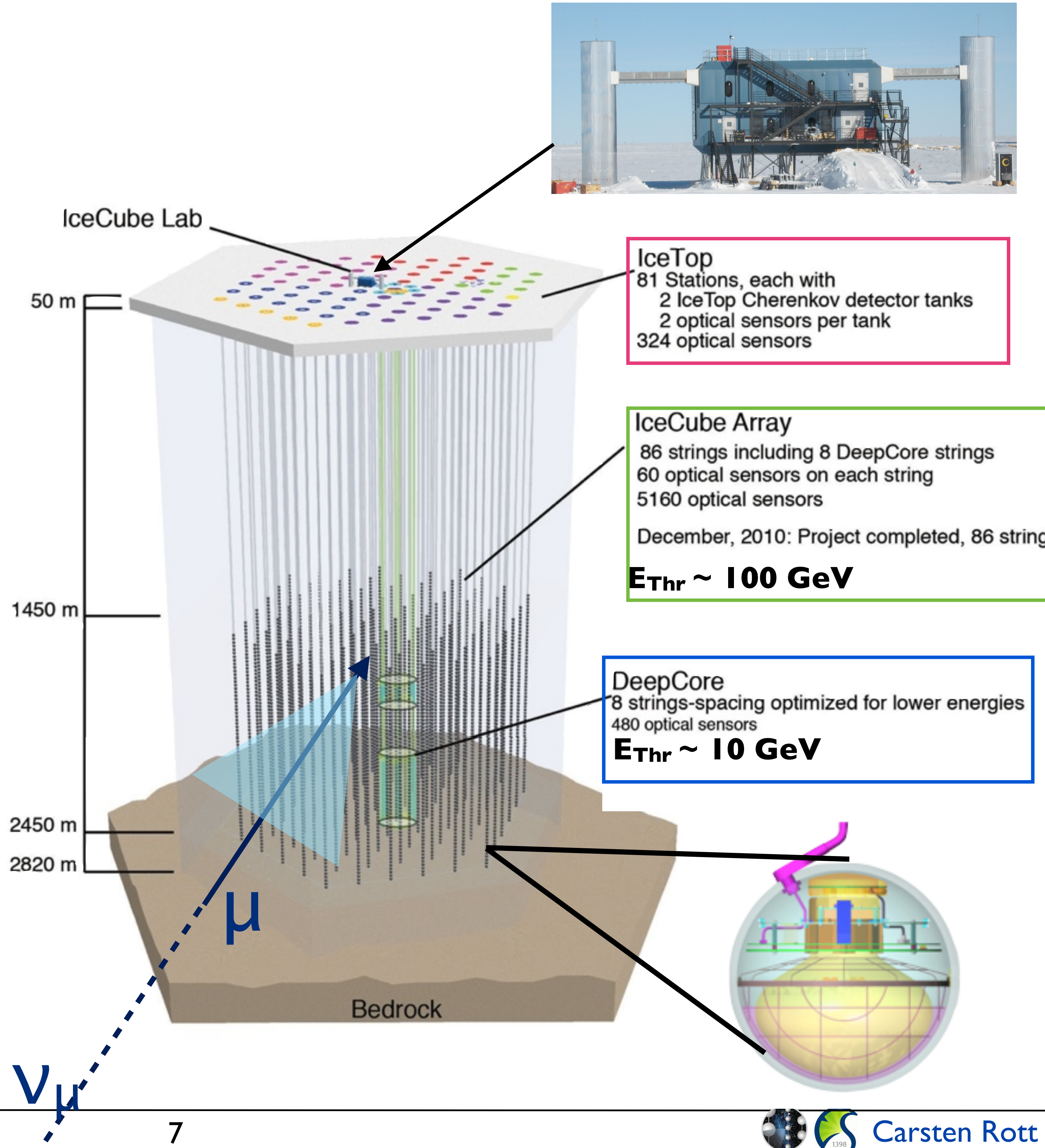


Signals in IceCube

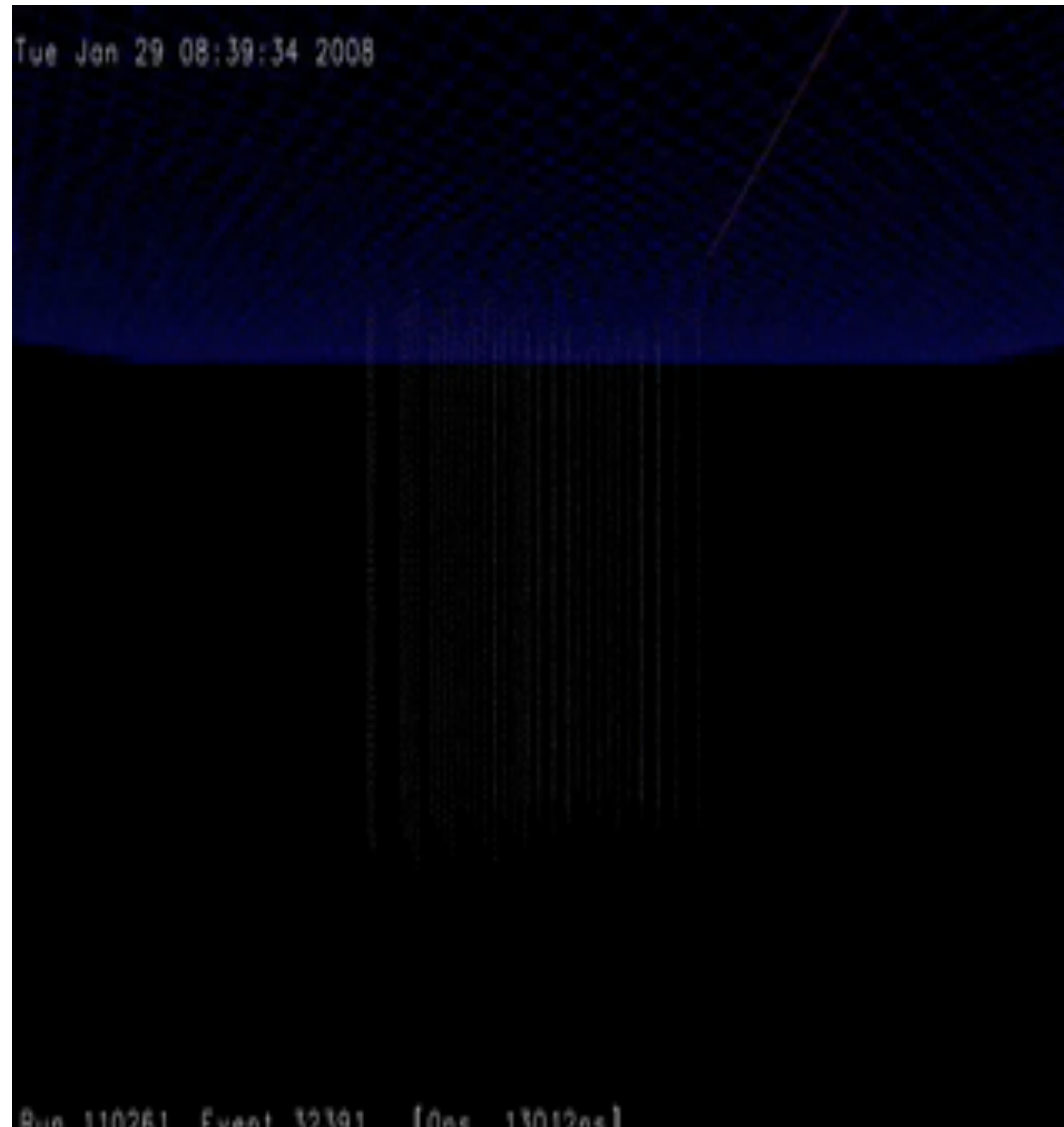
South Pole

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

IceCube Depth: 1.5-2.5 km

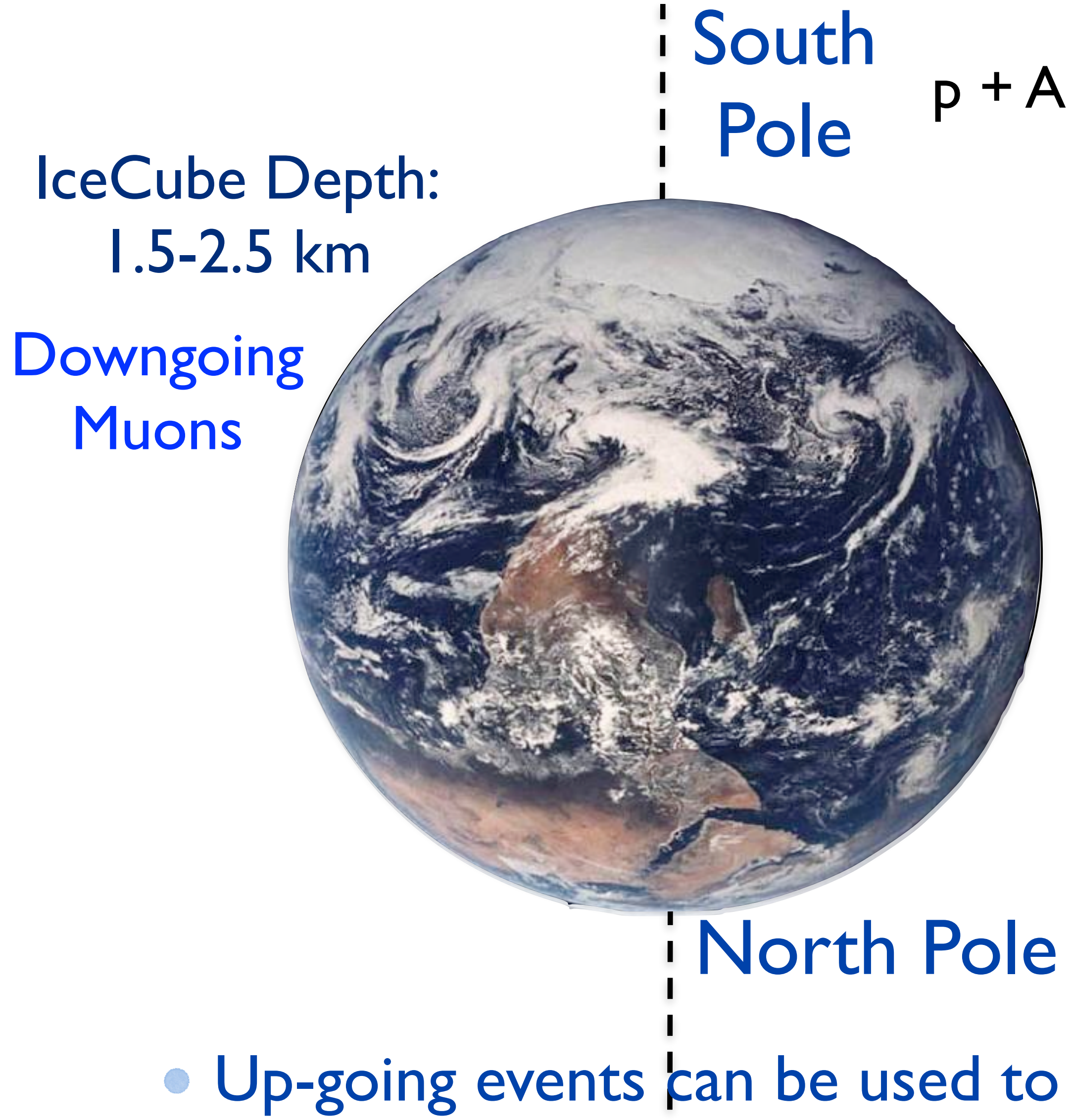
Downgoing Muons

North Pole



- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

Signals in IceCube



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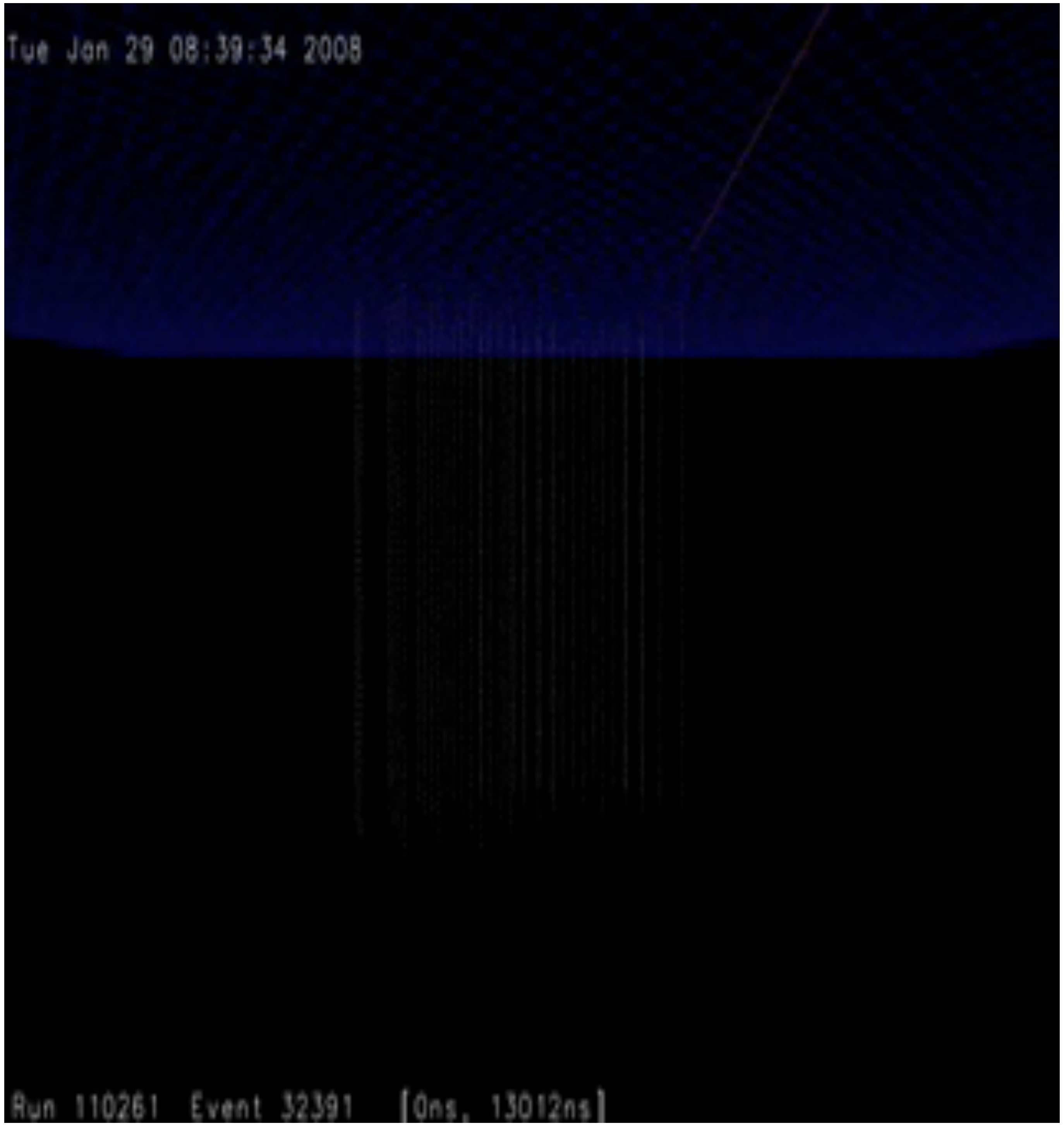

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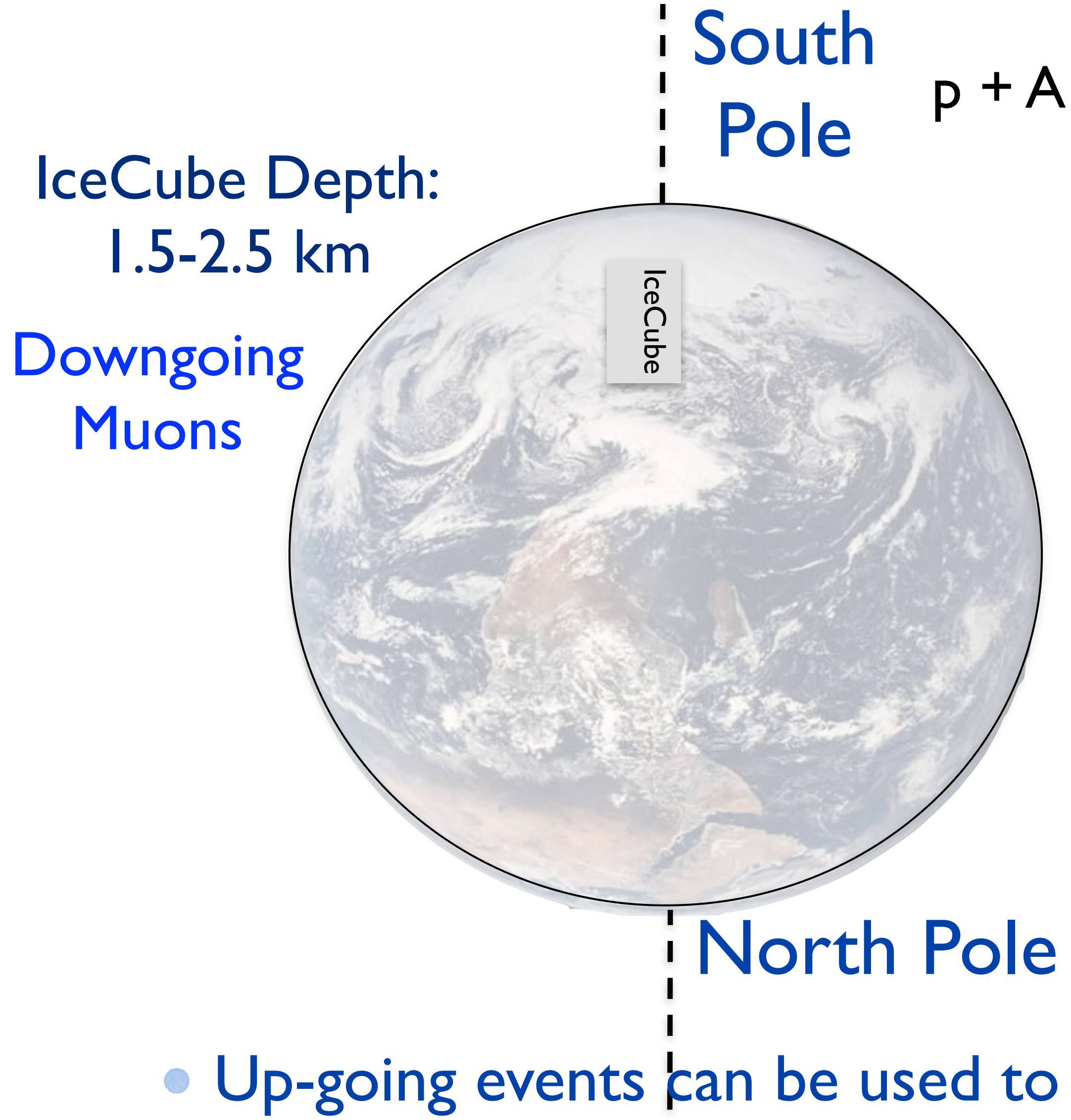

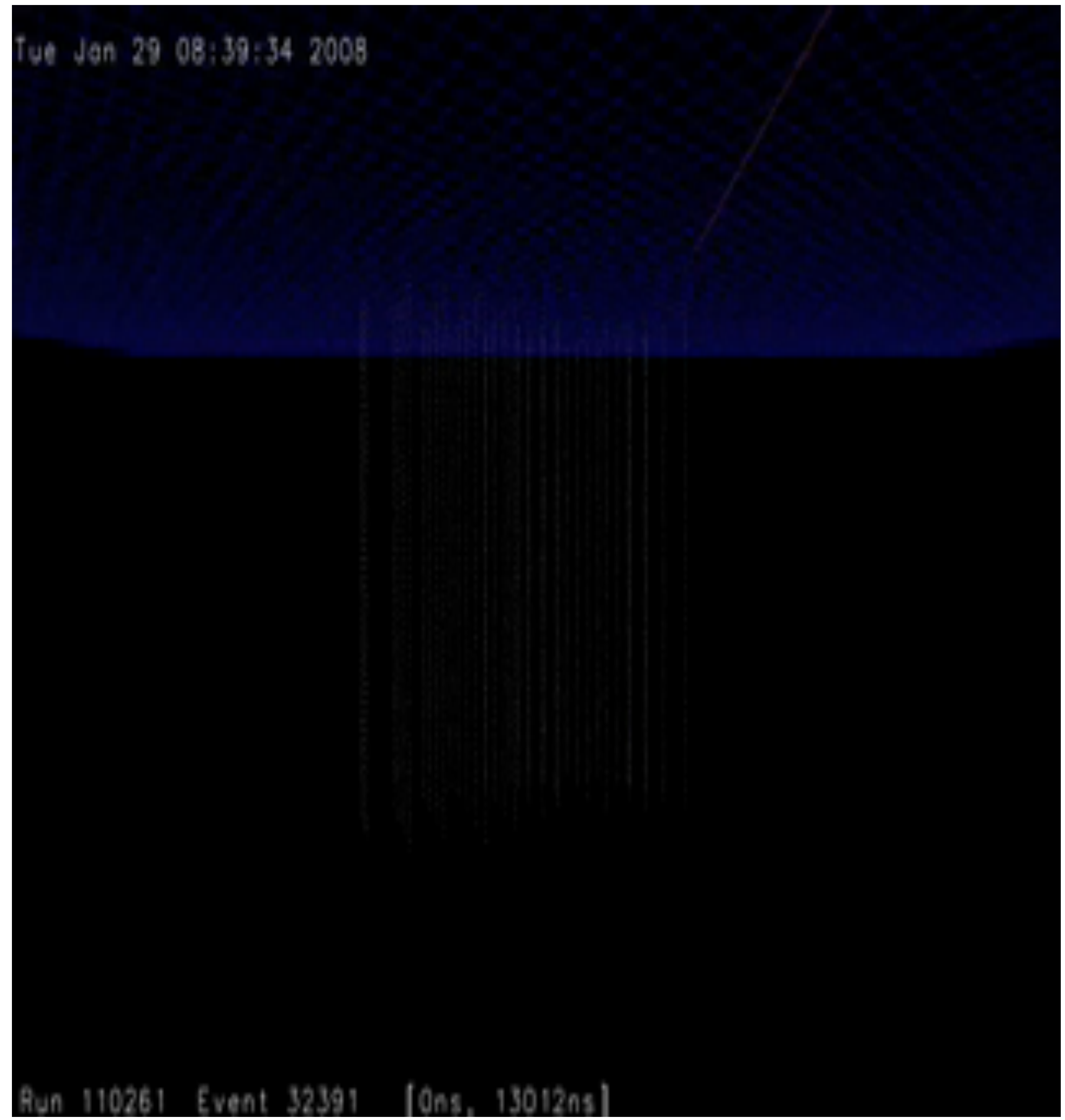

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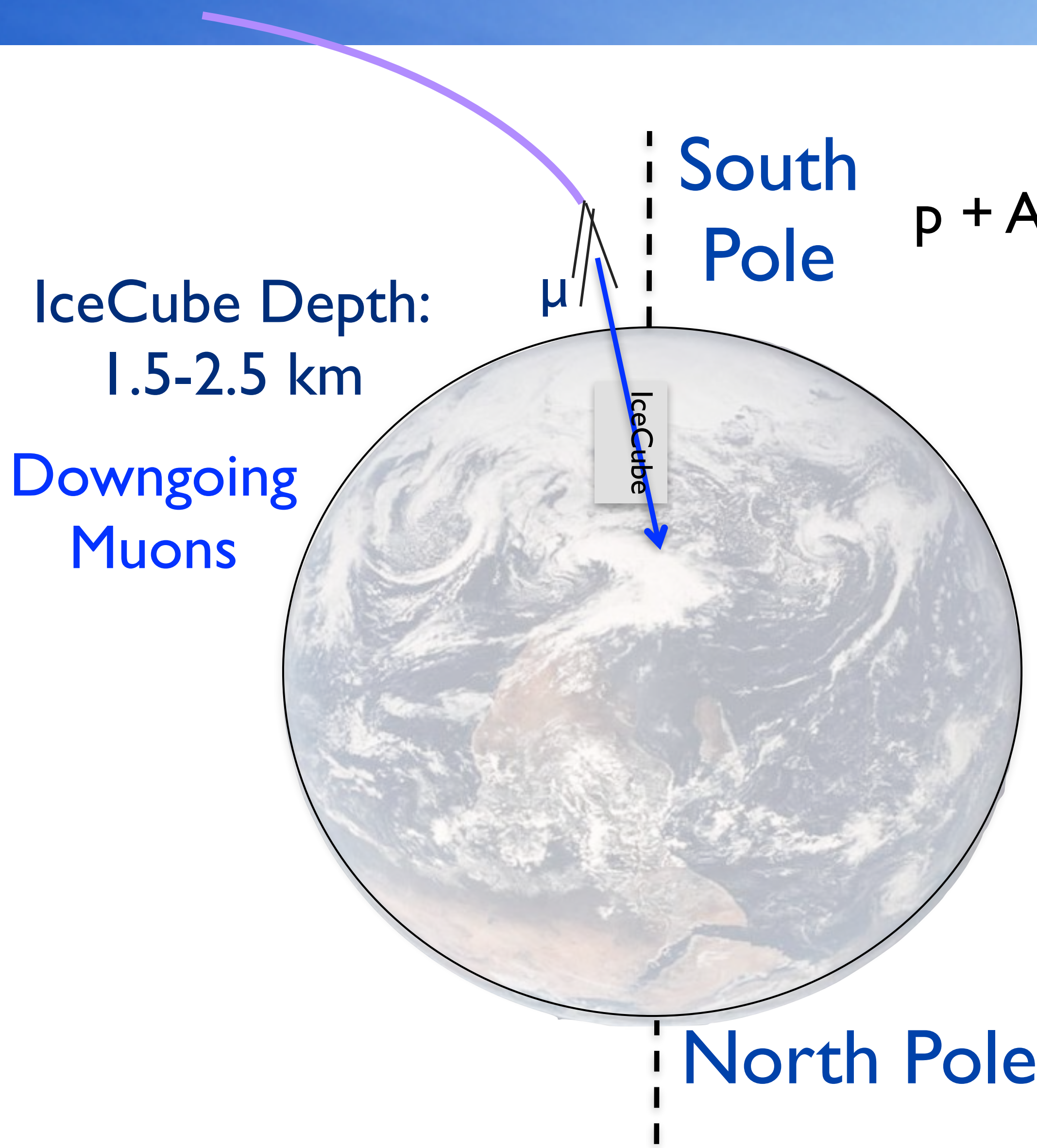

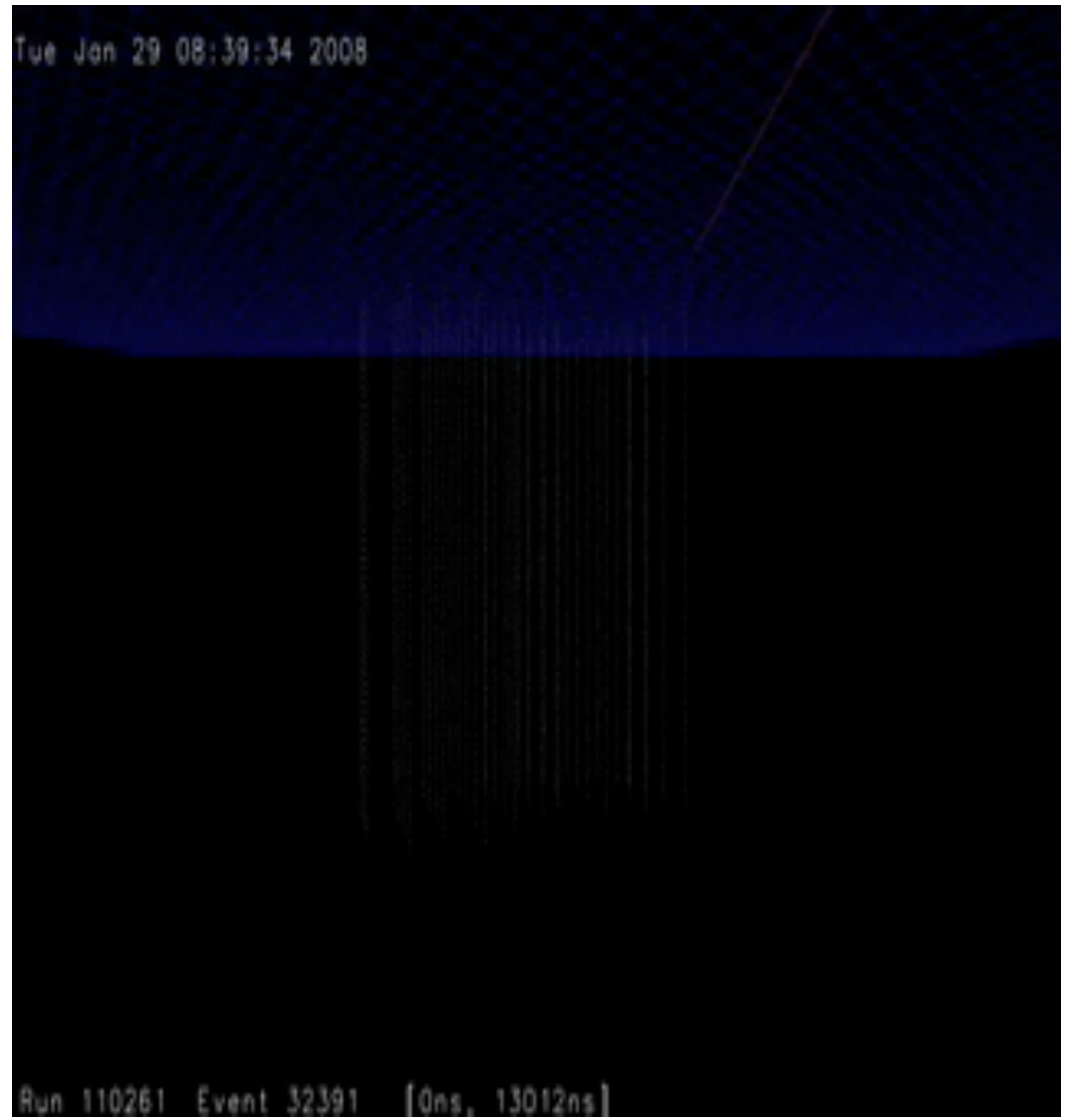

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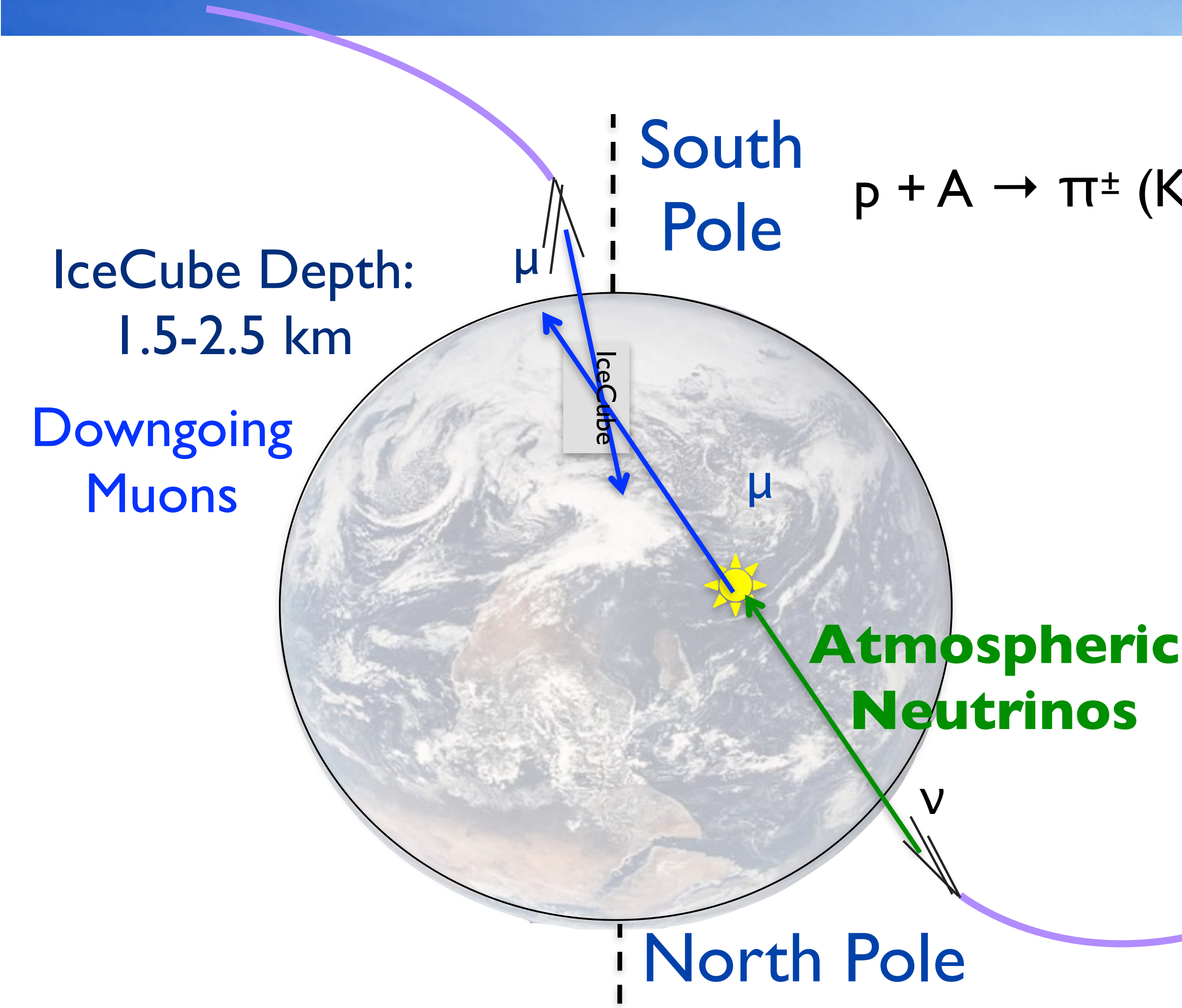

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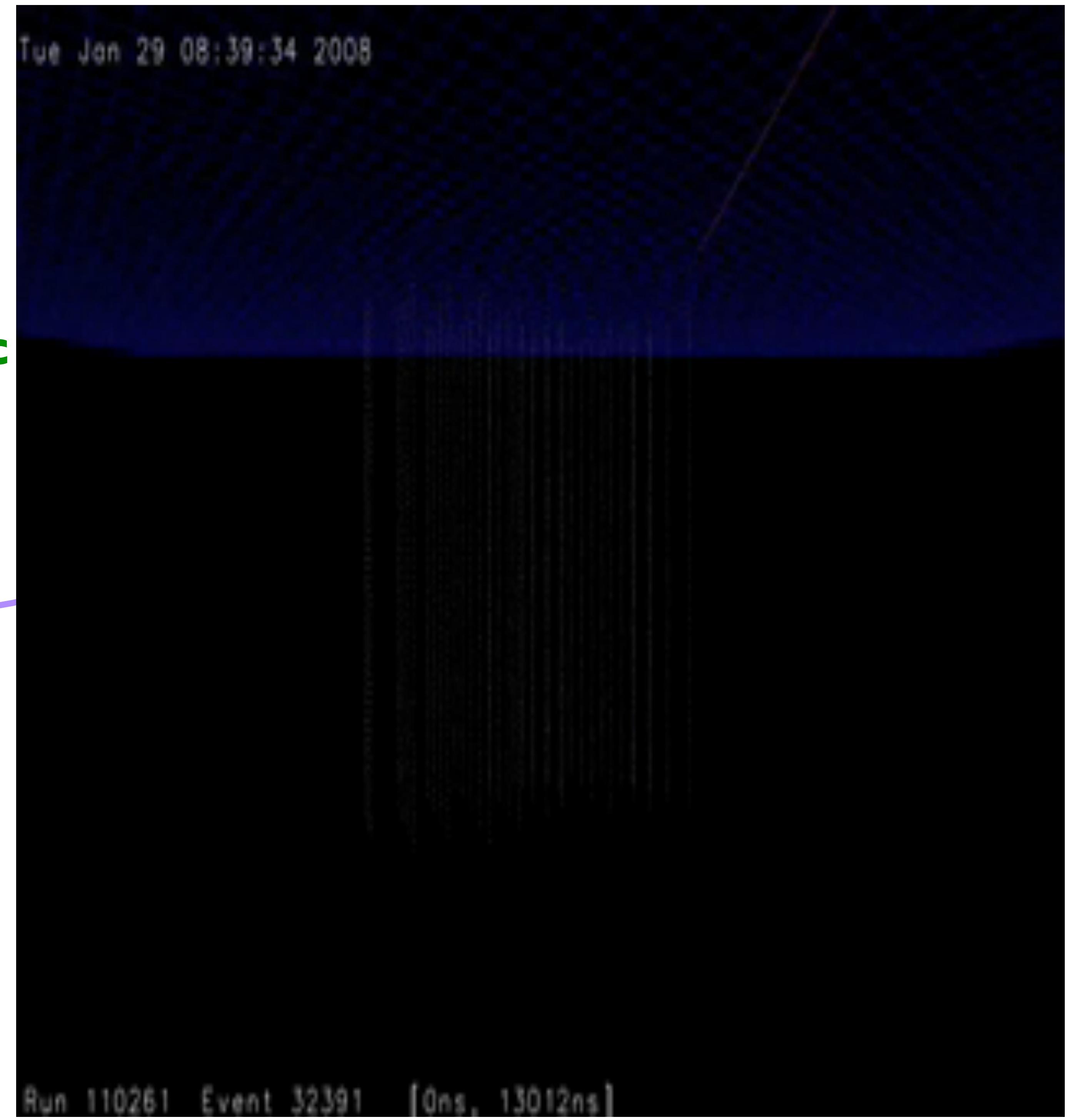

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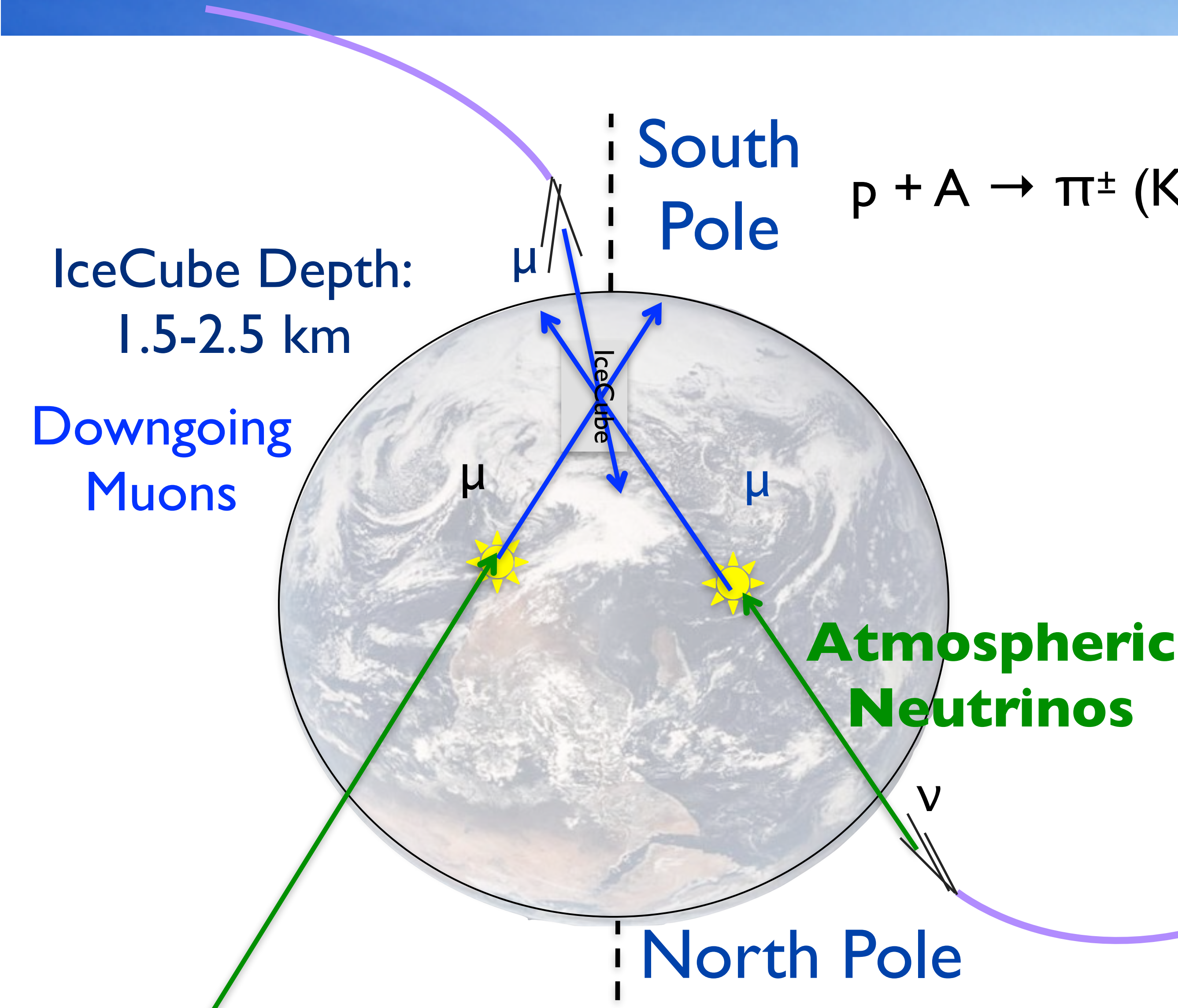

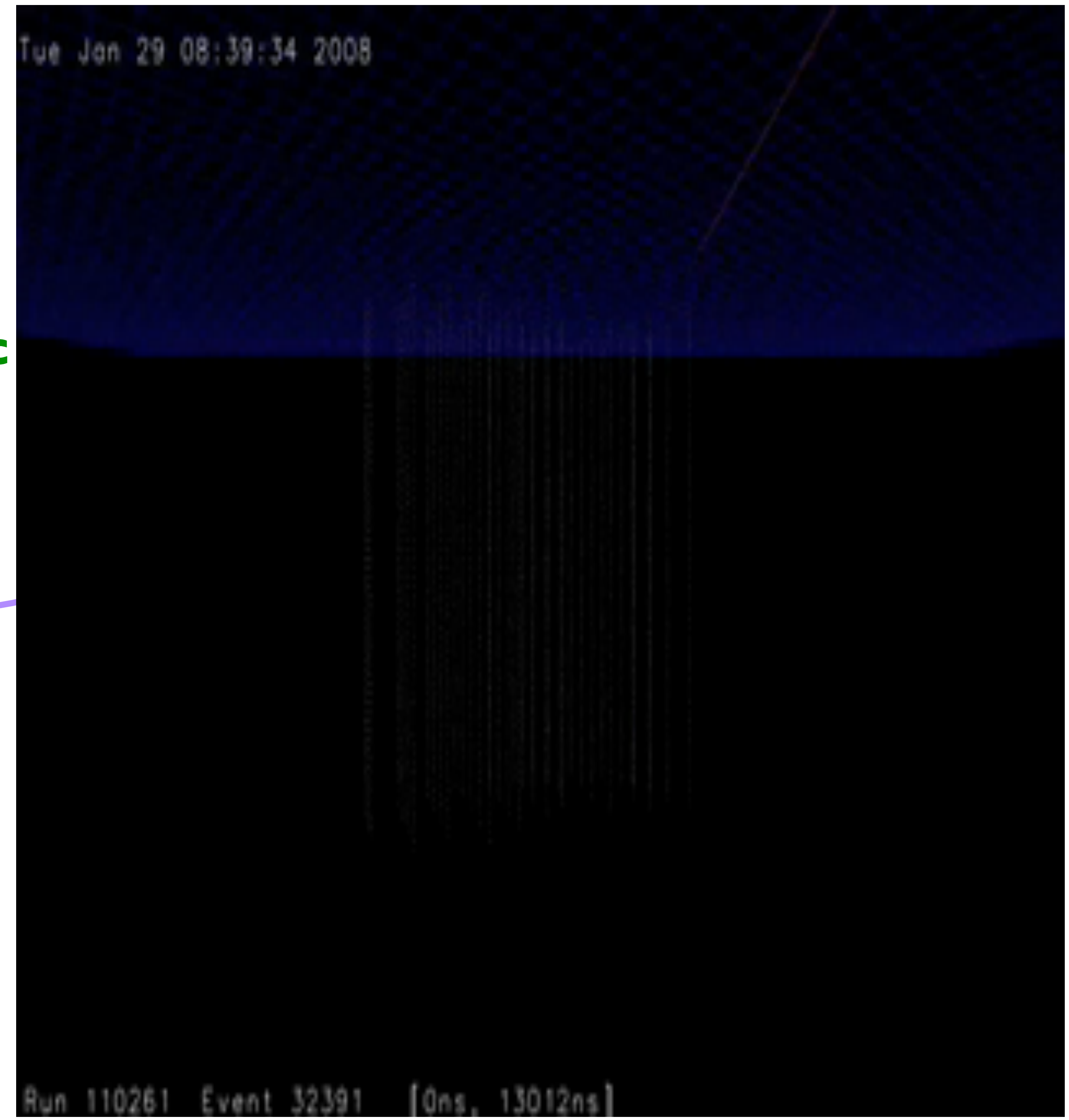

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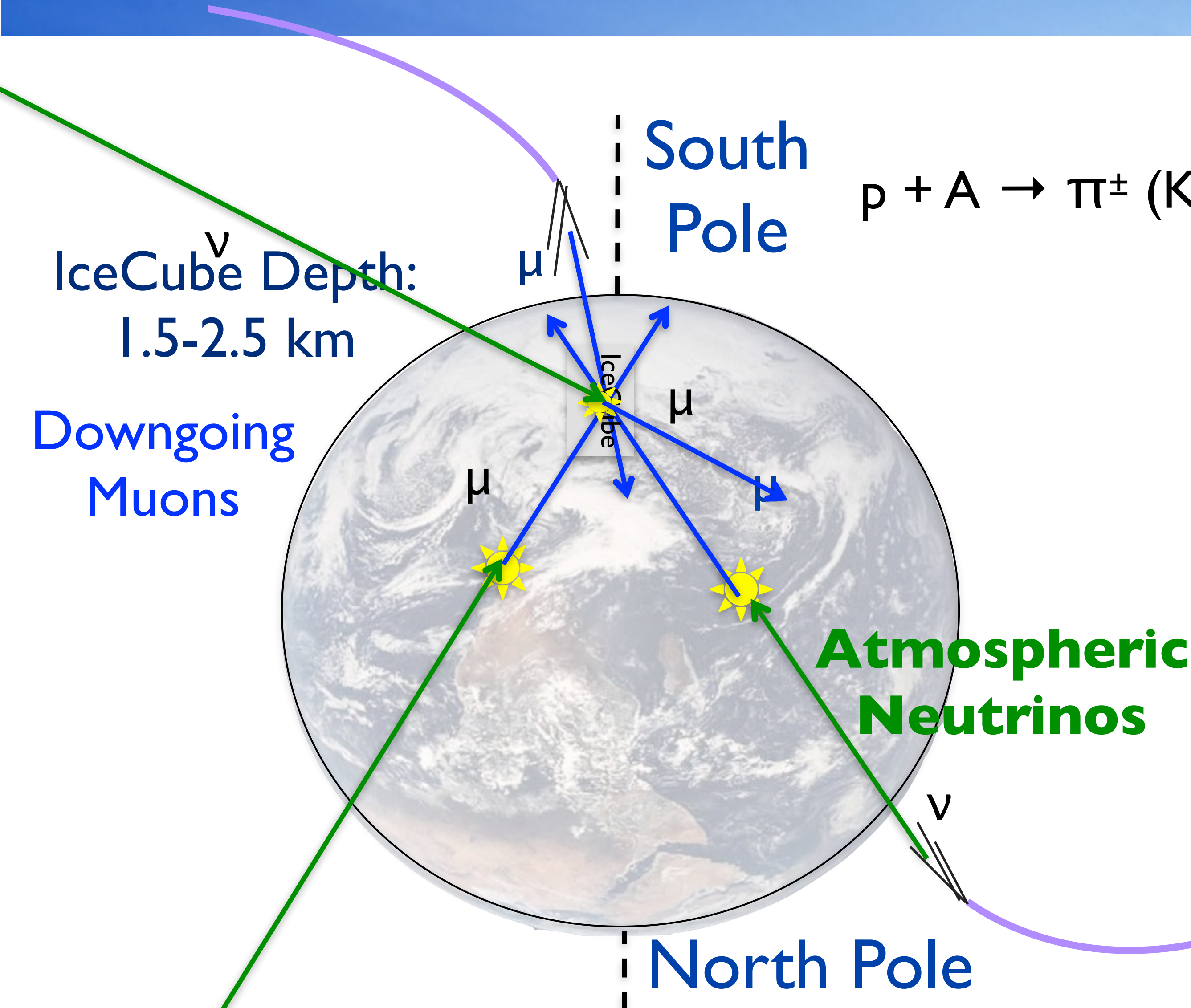

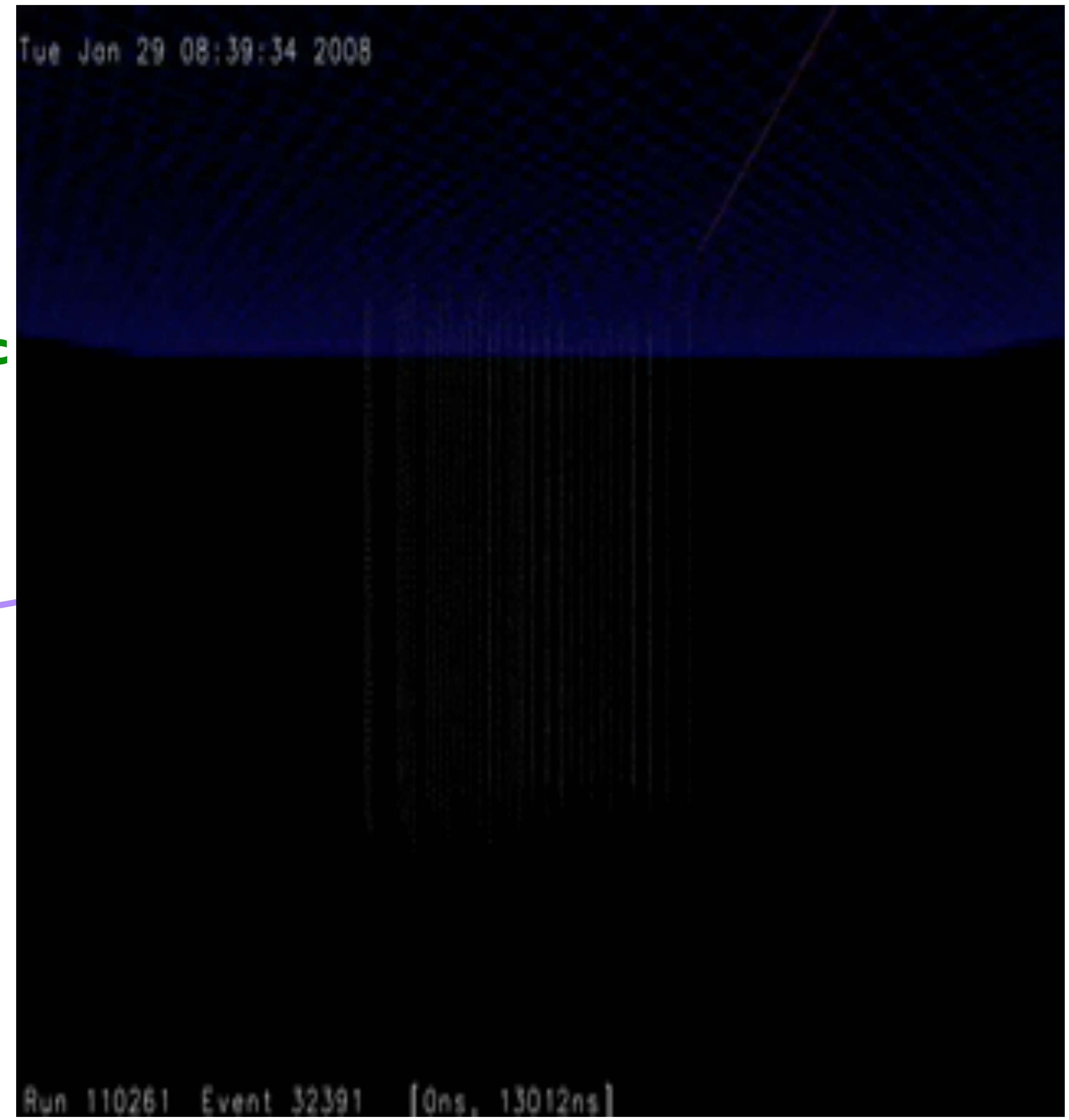

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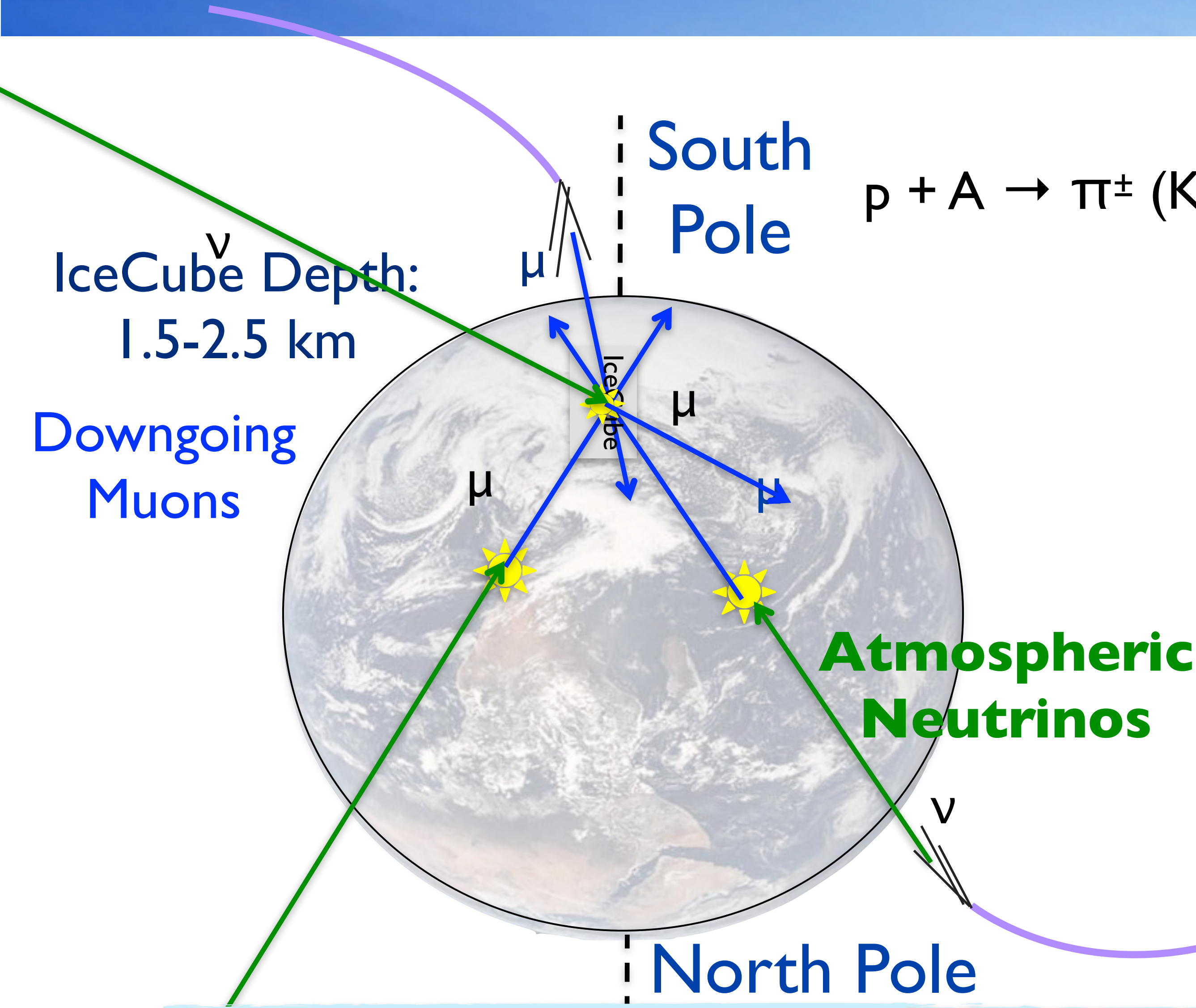
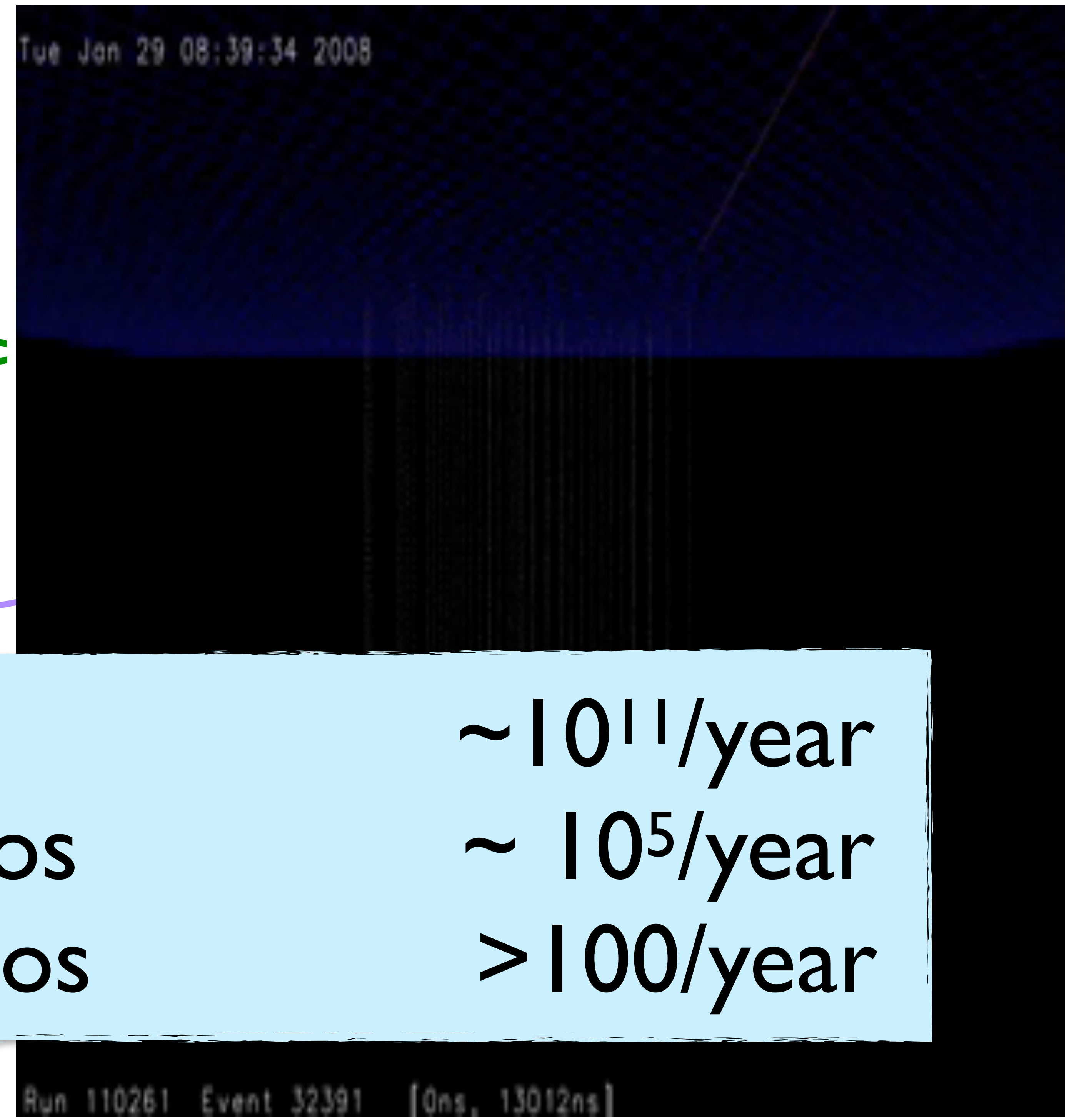




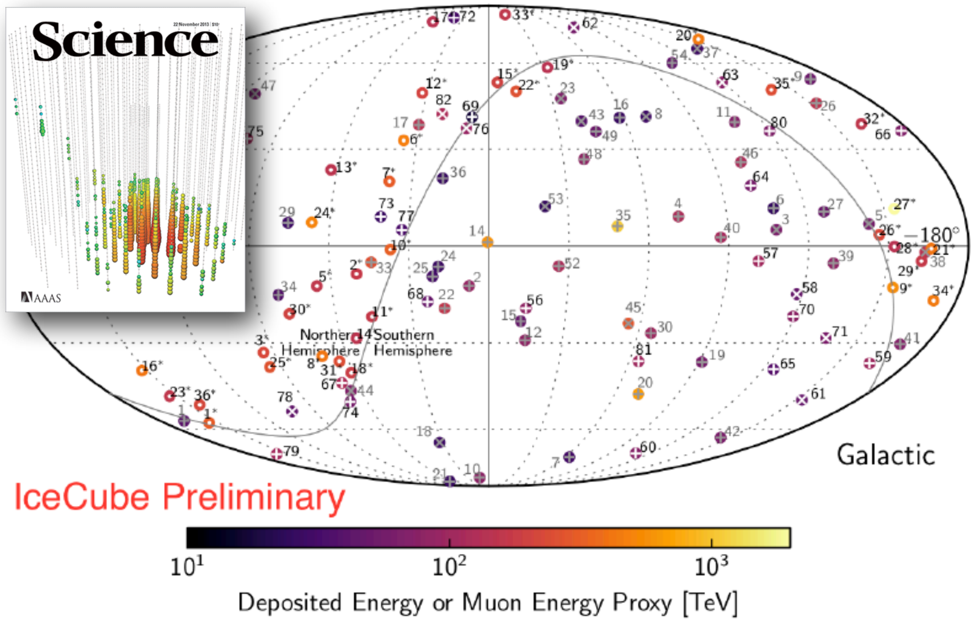
Atmospheric muons	~10^{11}/year
Atmospheric neutrinos	~ 10^{5}/year
Astrophysical neutrinos	>100/year

extra terrestrial neutrino fluxes

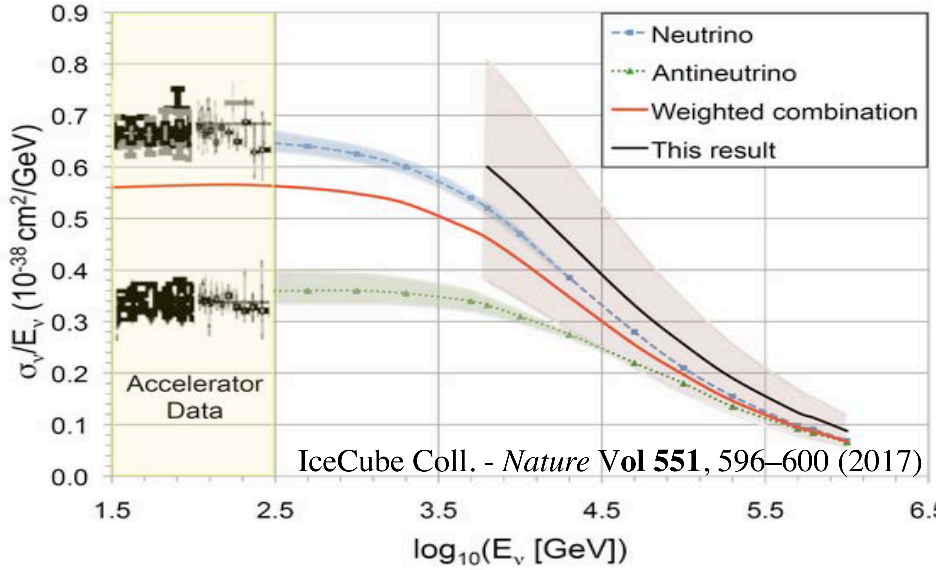
IceCube Science and Selected Results

IceCube Science

Astrophysical Neutrino Searches

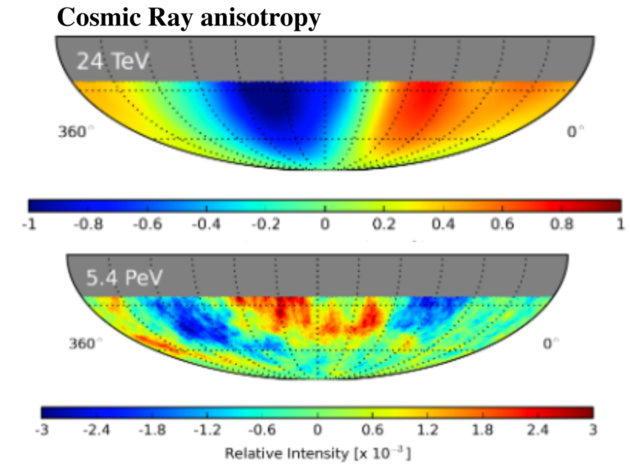


Neutrino Tomography / Neutrino Cross Section Measurements



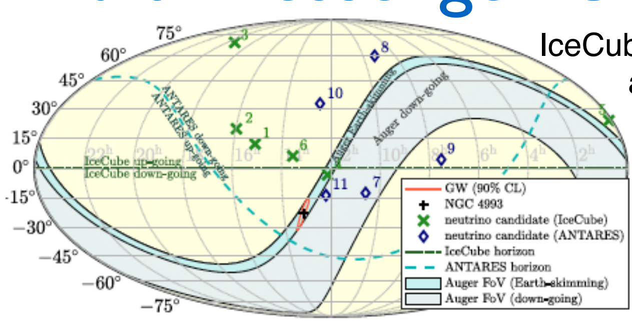
IceCube Coll. - *Nature* Vol **551**, 596–600 (2017)

Cosmic Rays

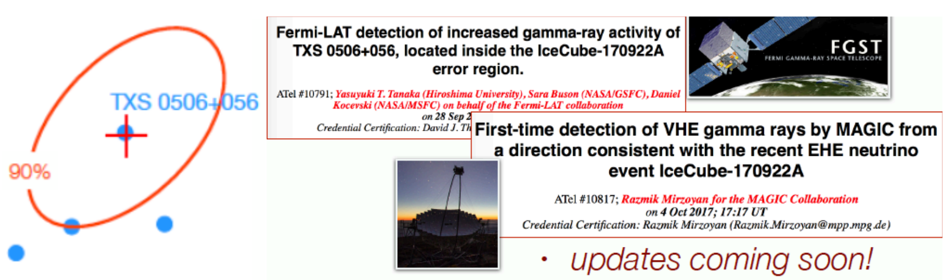


IceCube Coll. Astrophys.J. 826 (2016) no.2, 220

Multi-messenger Observations

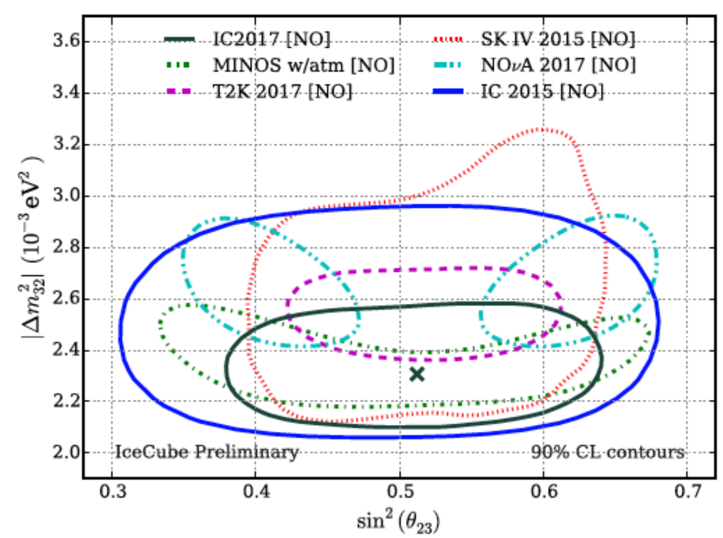


IceCube/ANTARES/Auger/LIGO
arXiv:1710.05839



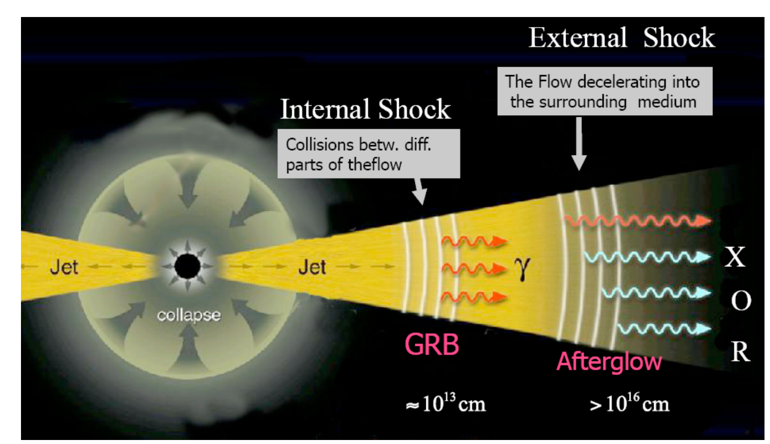
- *updates coming soon!*

Neutrino Oscillations



IceCube Coll. - Phys. Rev. Lett. 120, 071801 (2018)

Transient Source Searches - Gamma ray bursts



IceCube Coll. - Nature Vol **484**, 351 (2012)

… and many more exciting results and topics …

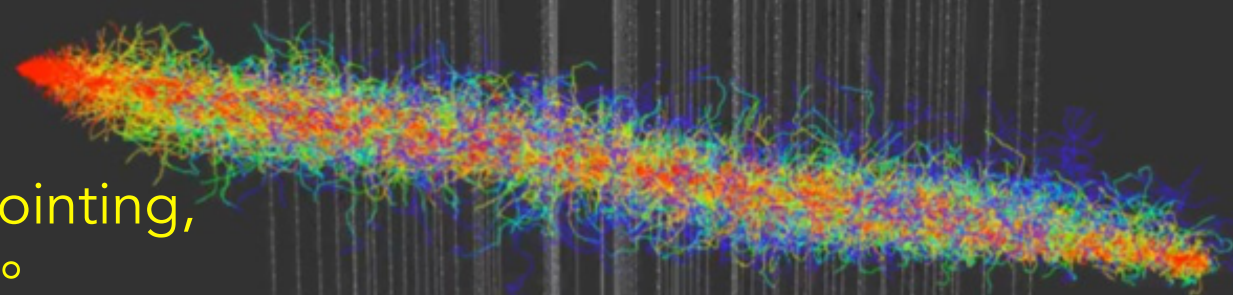
Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

Event Topologies in IceCube

Track topology

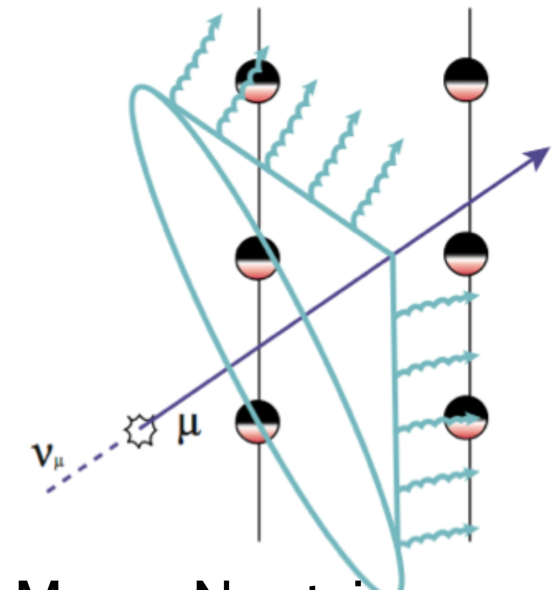
(e.g. induced by muon neutrino)

CC: ν_μ



Good pointing,
0.2° - 1°

Lower bound on energy for through-going events

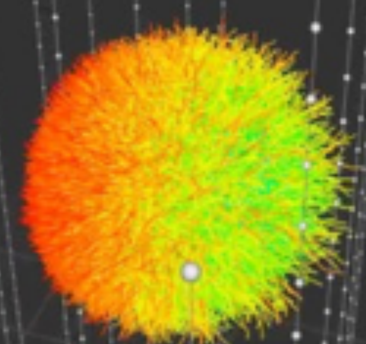


Muon Neutrino ν_μ
(ν_μ CC–int)

CC: ν_e ν_τ
NC: ν_e ν_μ ν_τ

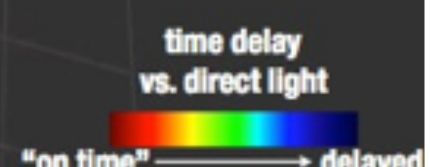
Cascade topology

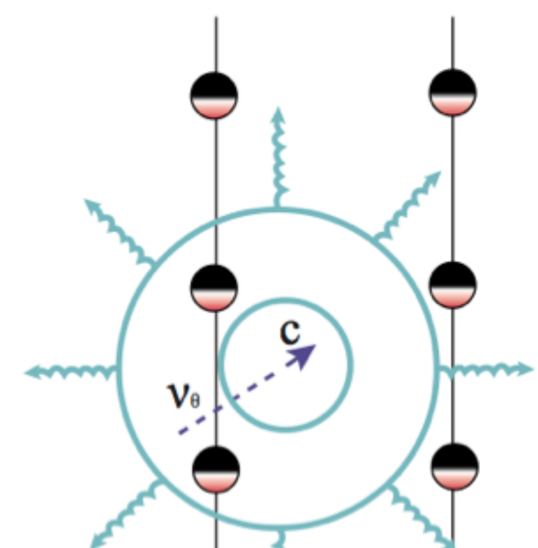
(e.g. induced by electron neutrino)



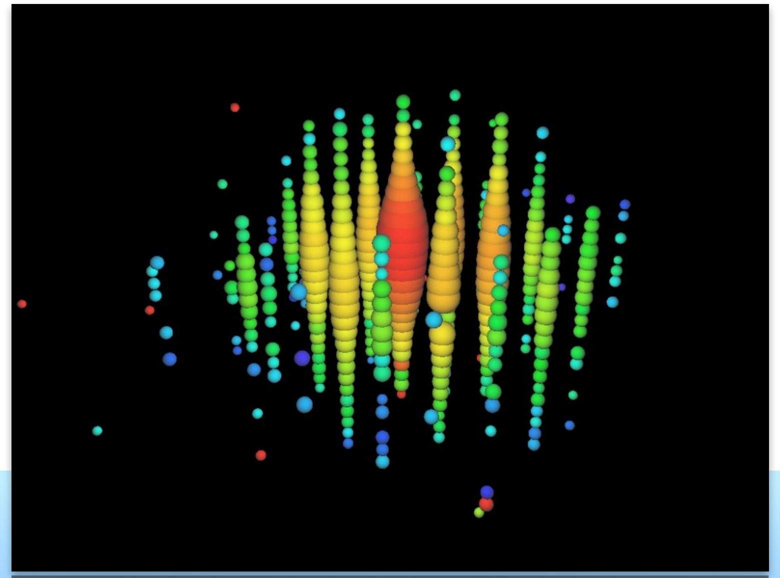
Good energy resolution, 15%

Some pointing,
10° - 15°





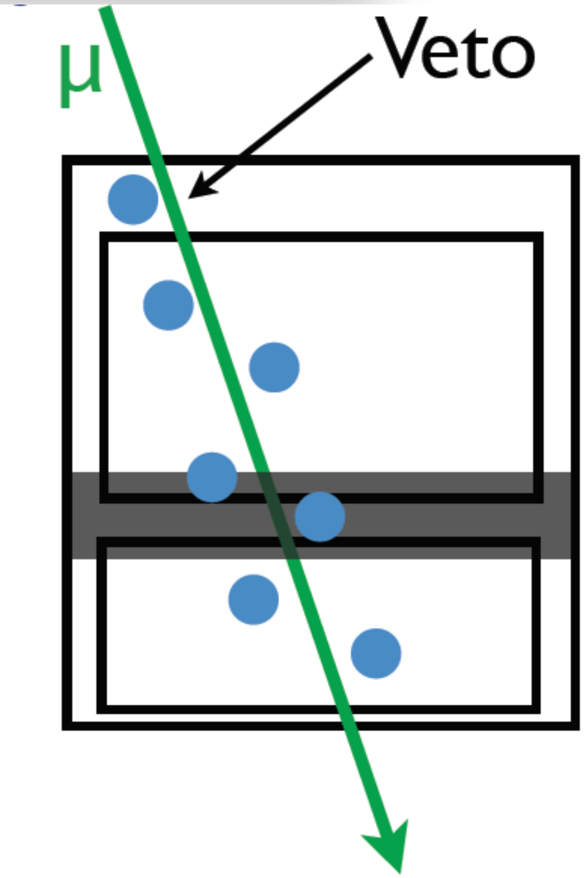
Electron Neutrino ν_e
or Tau Neutrino ν_τ
(ν_e ν_τ CC–int & ν_i NC–int)



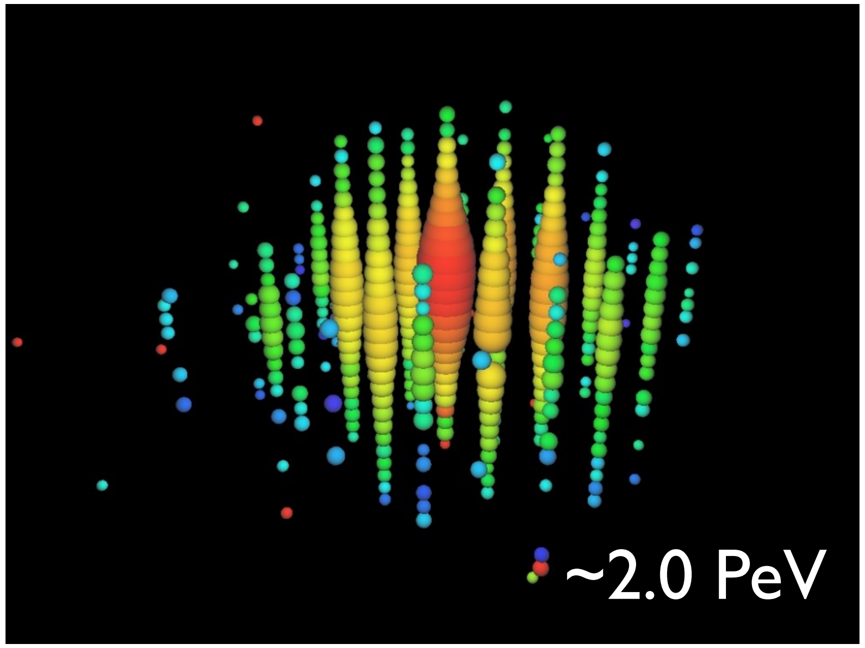
Astro-physical Neutrino Search

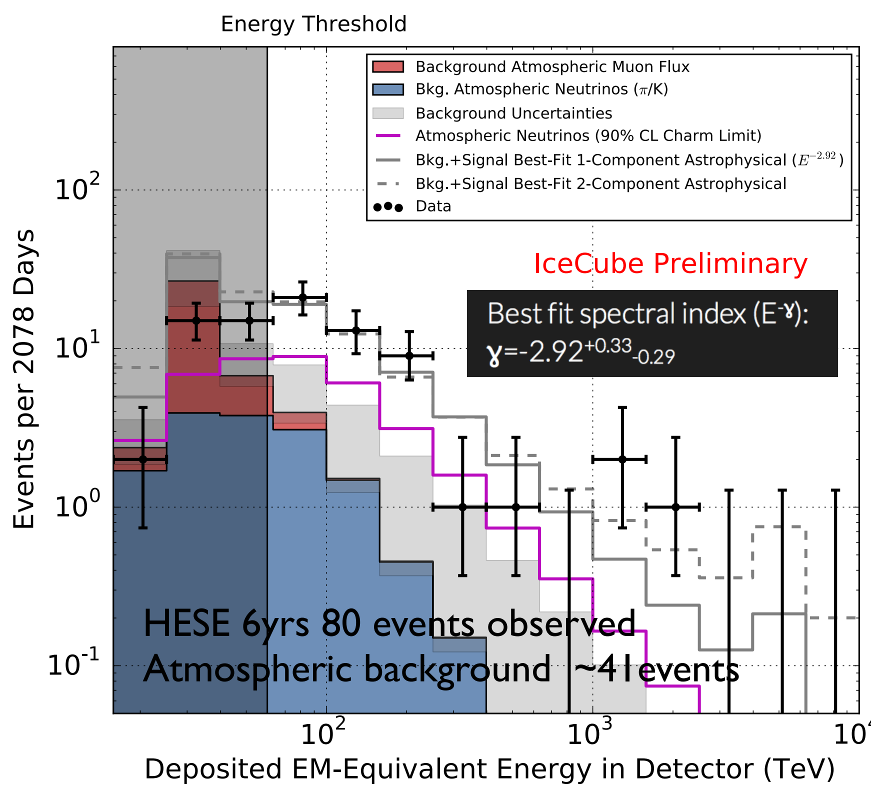
Observation of high-energy astrophysical neutrinos

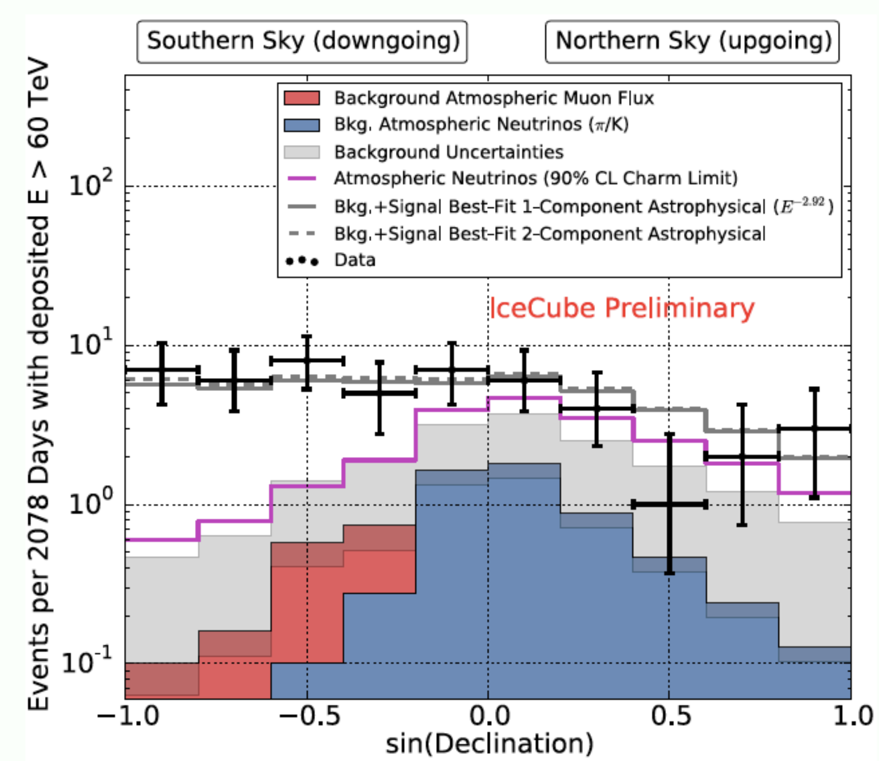
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*



- Search for High-Energy Starting Events (HESE)
  - Efficient reject atmospheric backgrounds
  - Discovery of astrophysical neutrinos



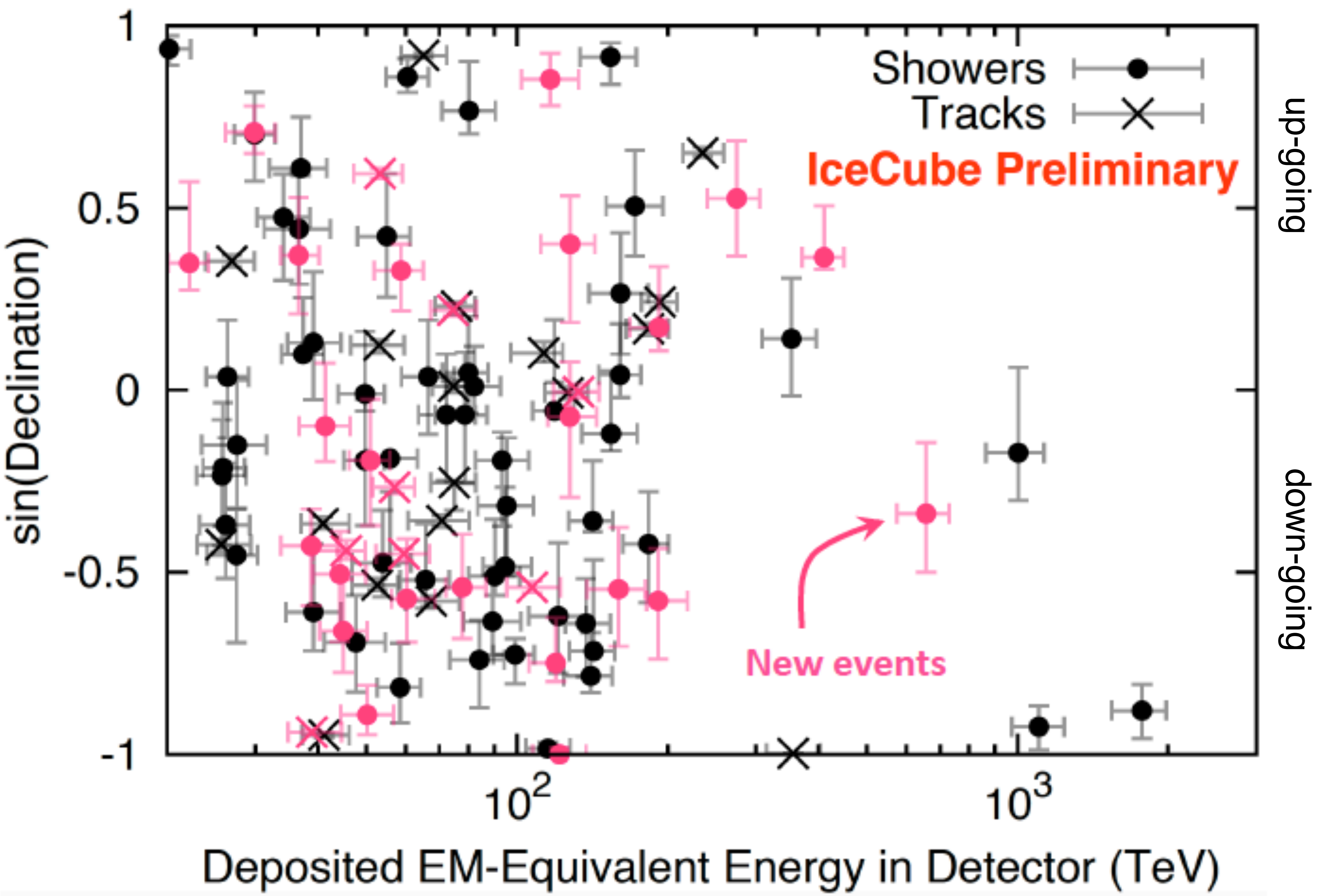




HESE7.5yrs results

High-Energy Starting Events (HESE) – 7.5 yr

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



Prior result 6 years ICRC 2017 arXiv:1710.01191

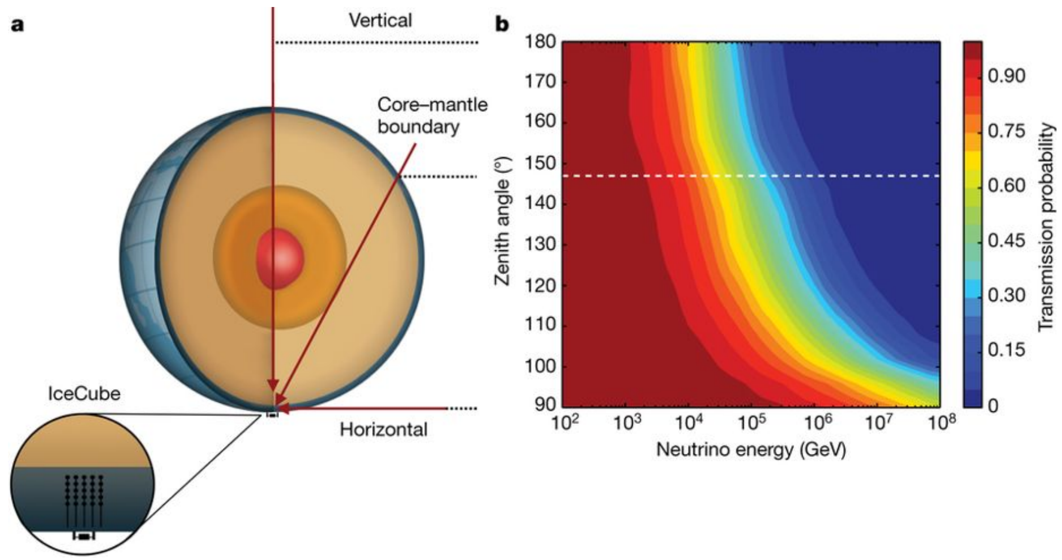
Updates to calibration and ice optical properties

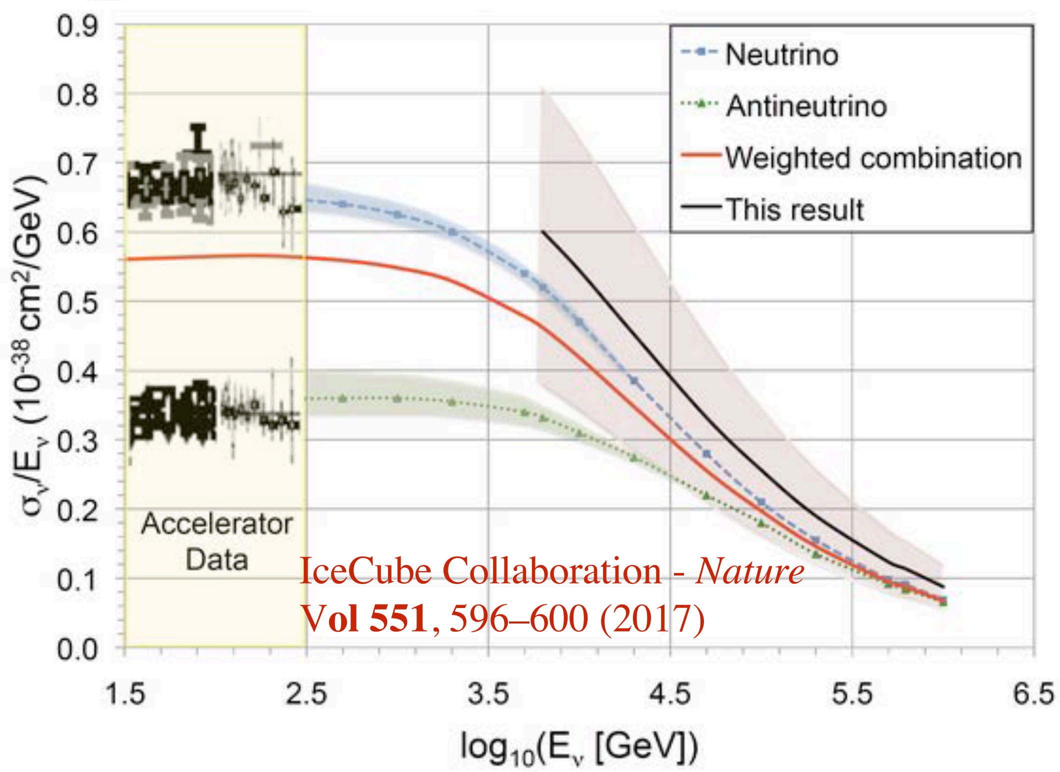
103 events, with 60 events >60 TeV

→Changes to RA, Dec, energy

Neutrino absorption in the Earth / Neutrino Cross section measurement

Neutrino Tomography / Neutrino Cross Section Measurements

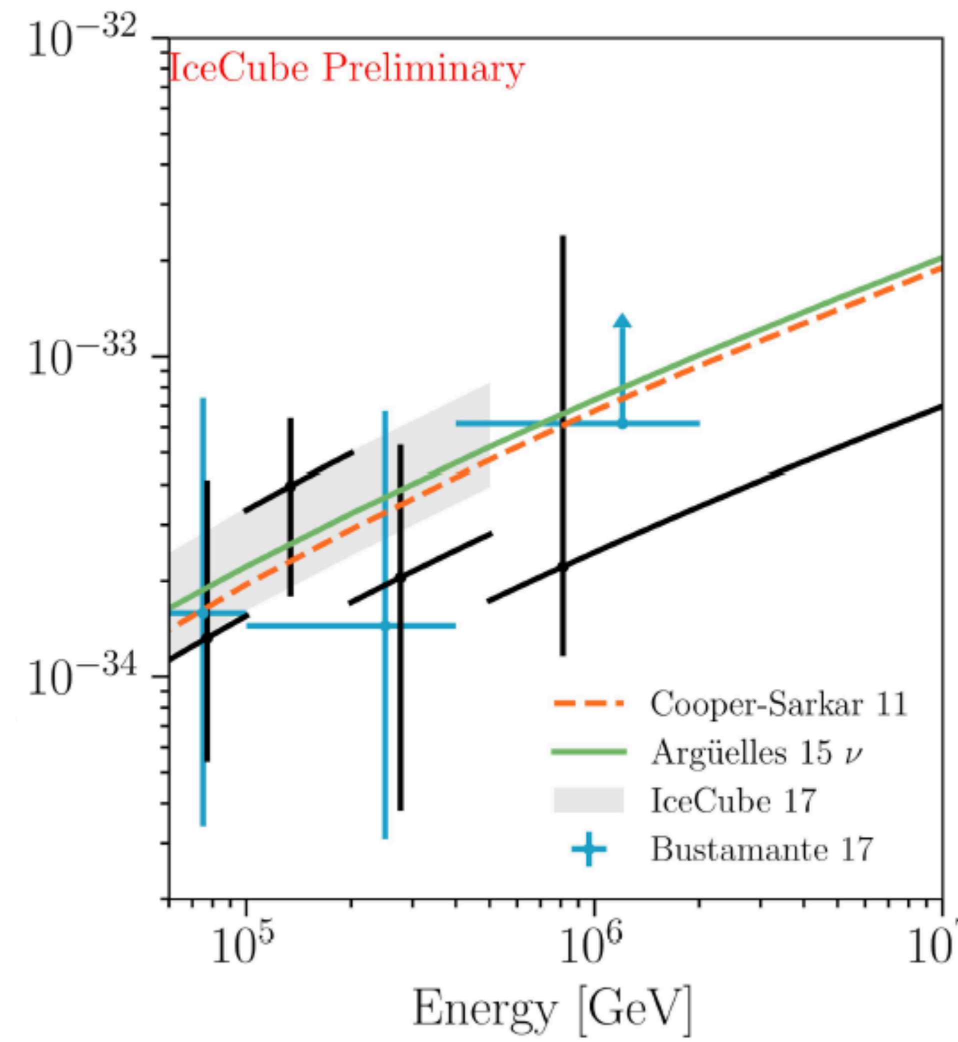




IceCube Collaboration - *Nature* **Vol 551**, 596–600 (2017)

Only one year of data (2009-2010)

- For charge-current interactions, neutrinos are either lost or regenerated via tau decay
- For neutral-current interactions, neutrinos are not destroyed but cascade down in energy



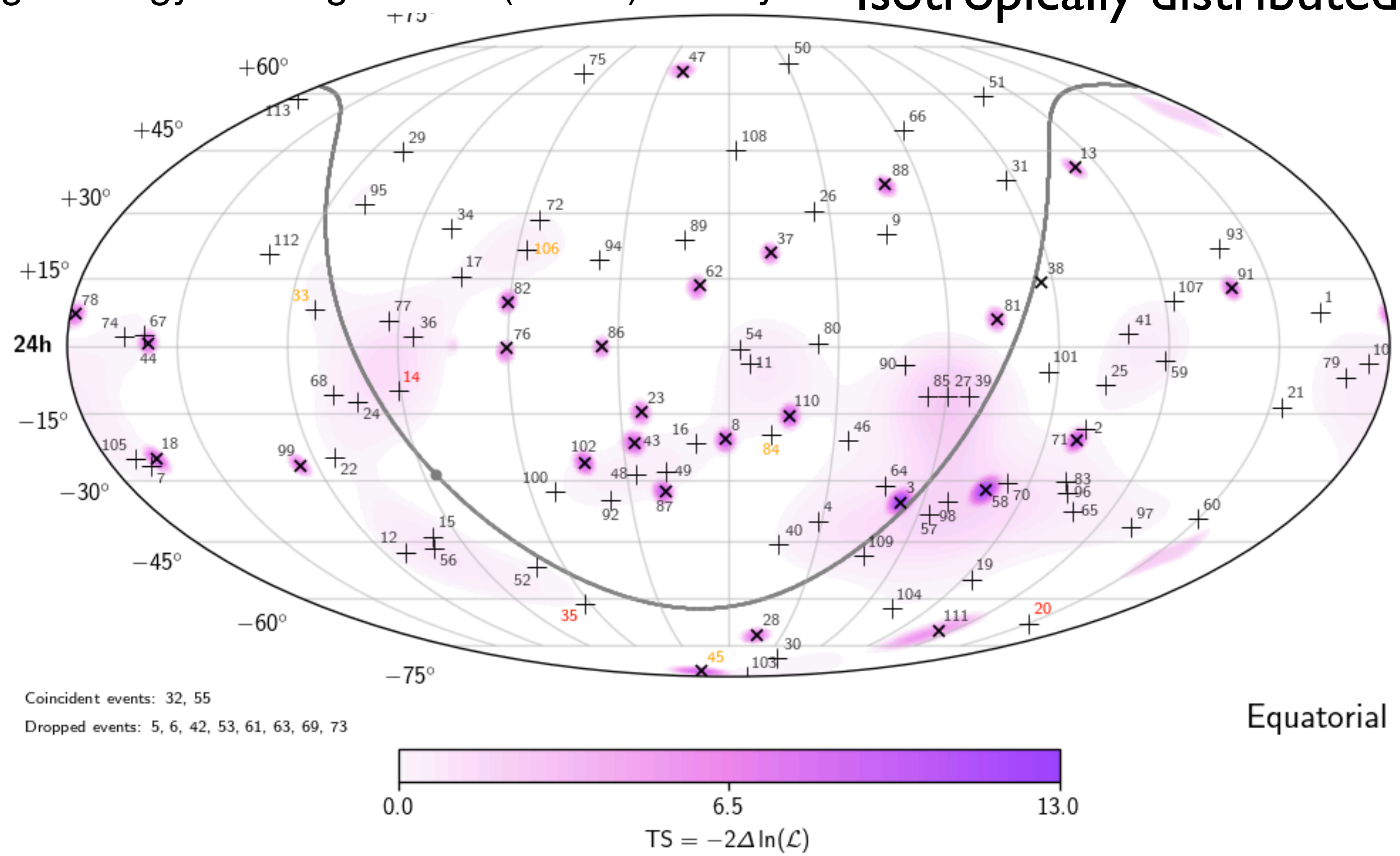
- 7.5yrs of HESE data
- Forward-folded fit in energy and zenith

Arrival directions (highest energy events)

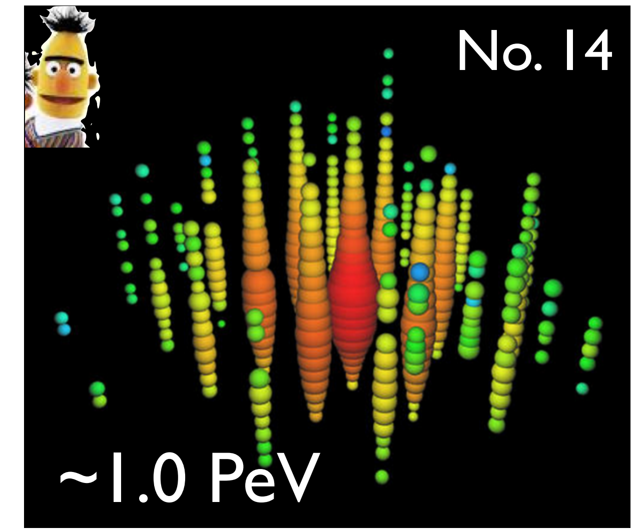
IceCube Collaboration, *Science* 342, 1242856 (2013)

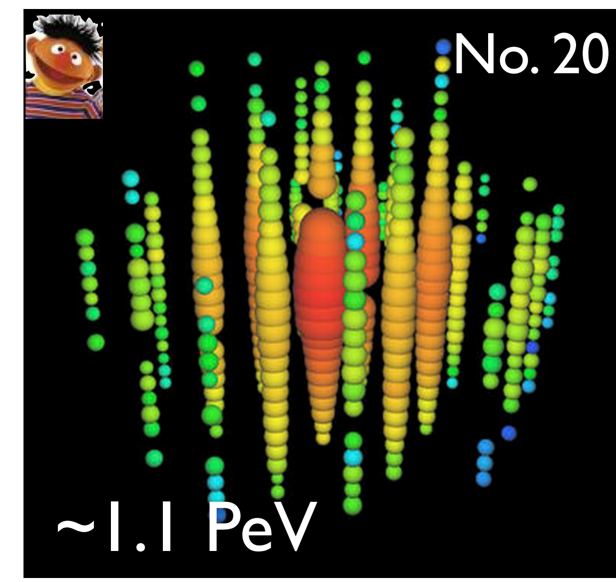
High-Energy Starting Events (HESE) – 7.5 yr

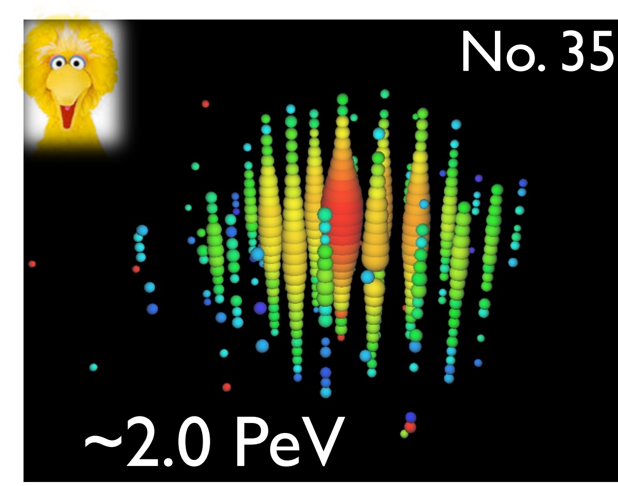
Isotropically distributed



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



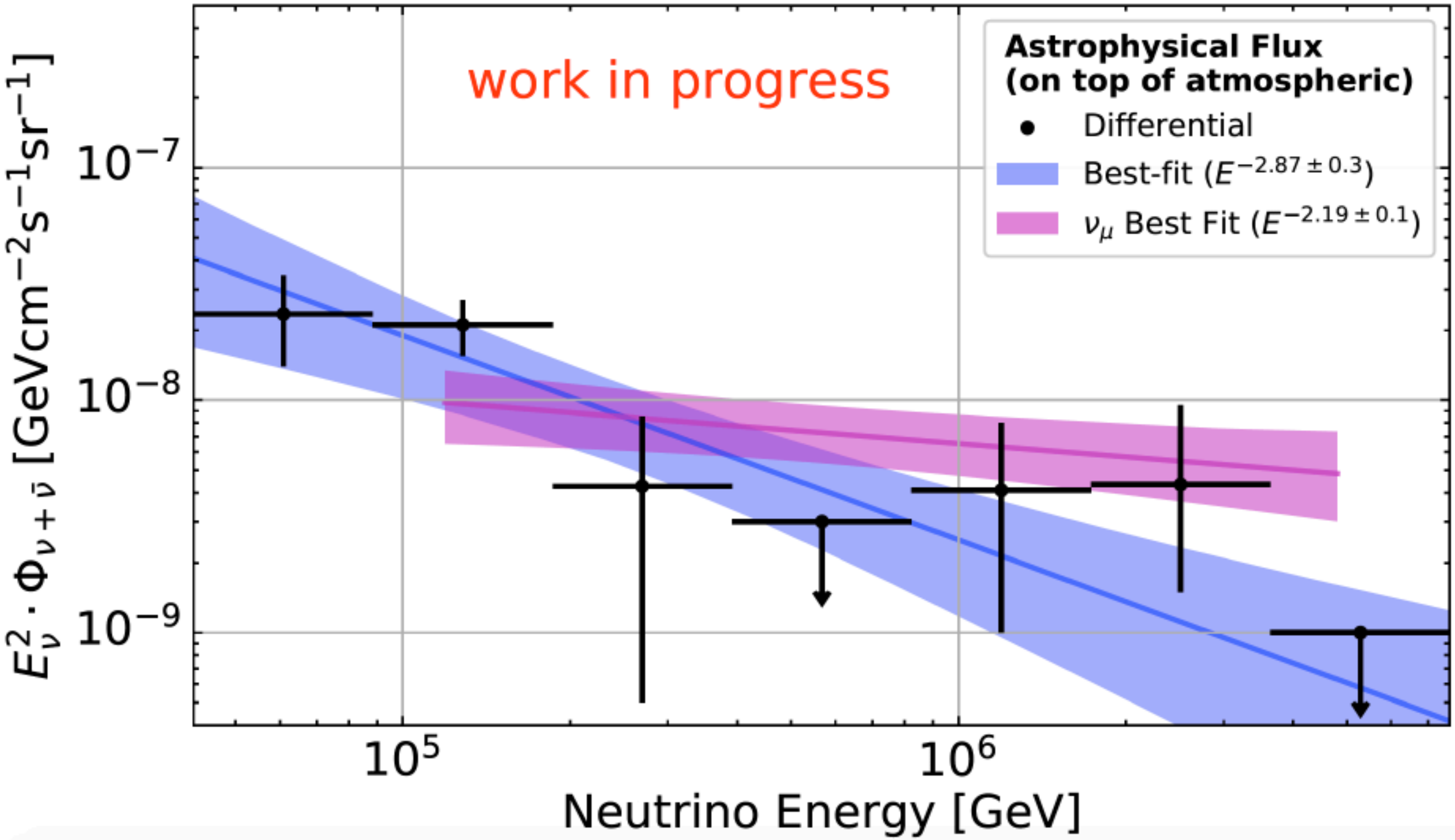




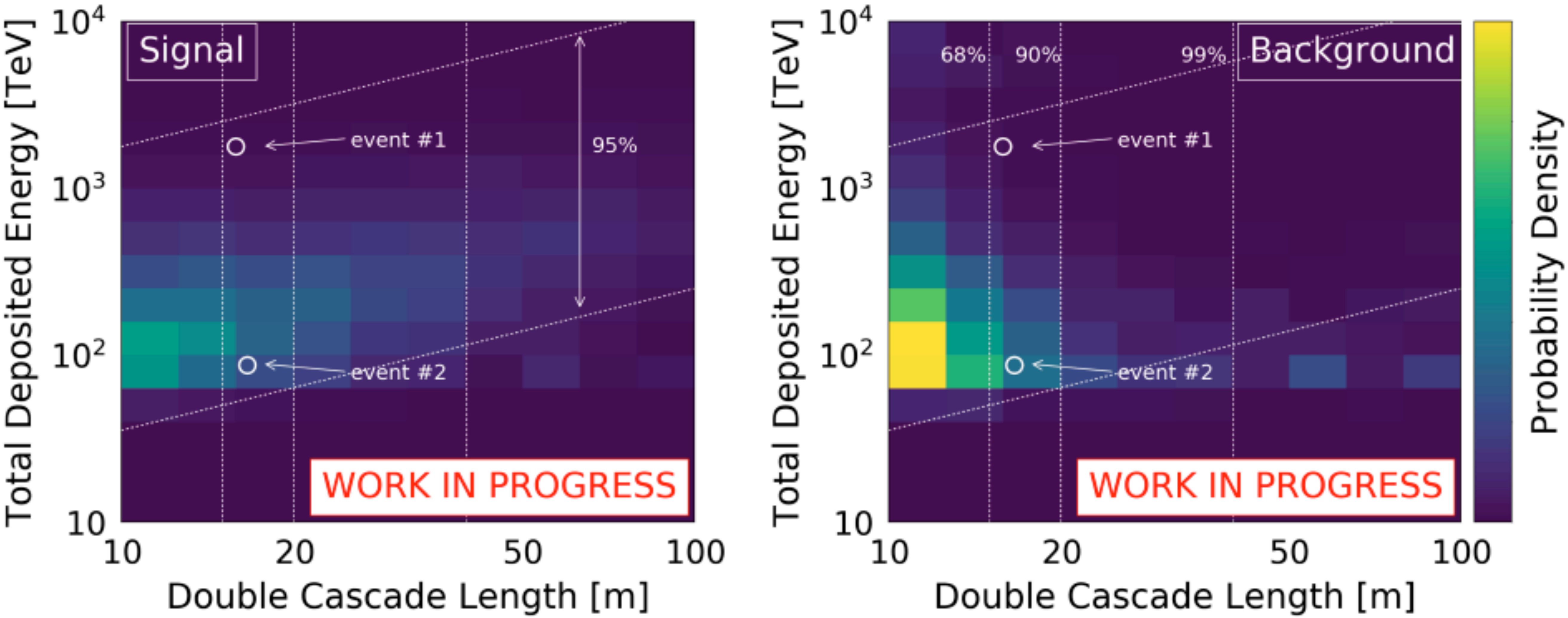
No evidence for point sources, nor a correlation with the galactic plane

Neutrino energy spectrum

High-Energy Starting Events (HESE) – 7.5 yr



High-Energy Starting Events

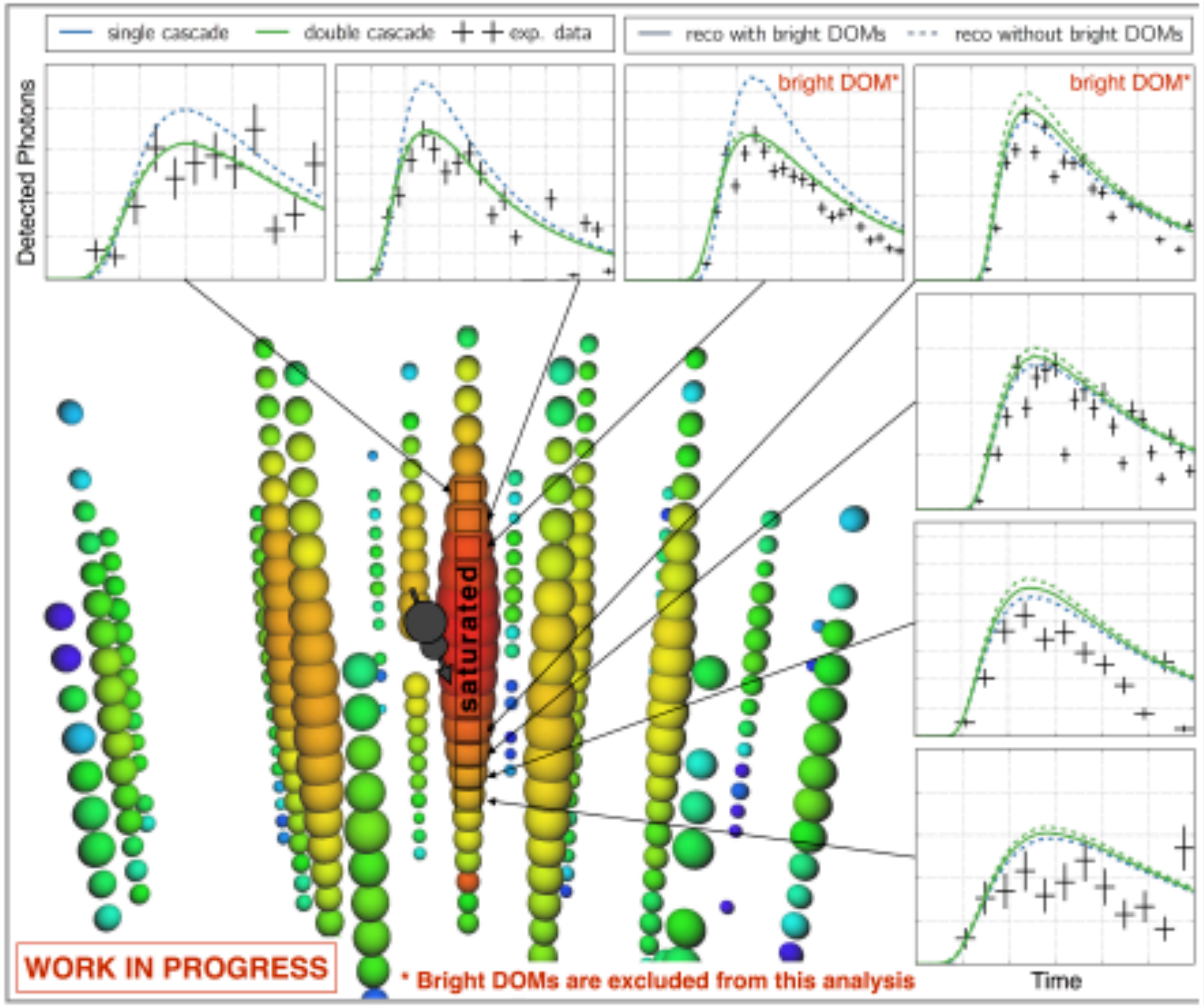


Two double cascades have been identified

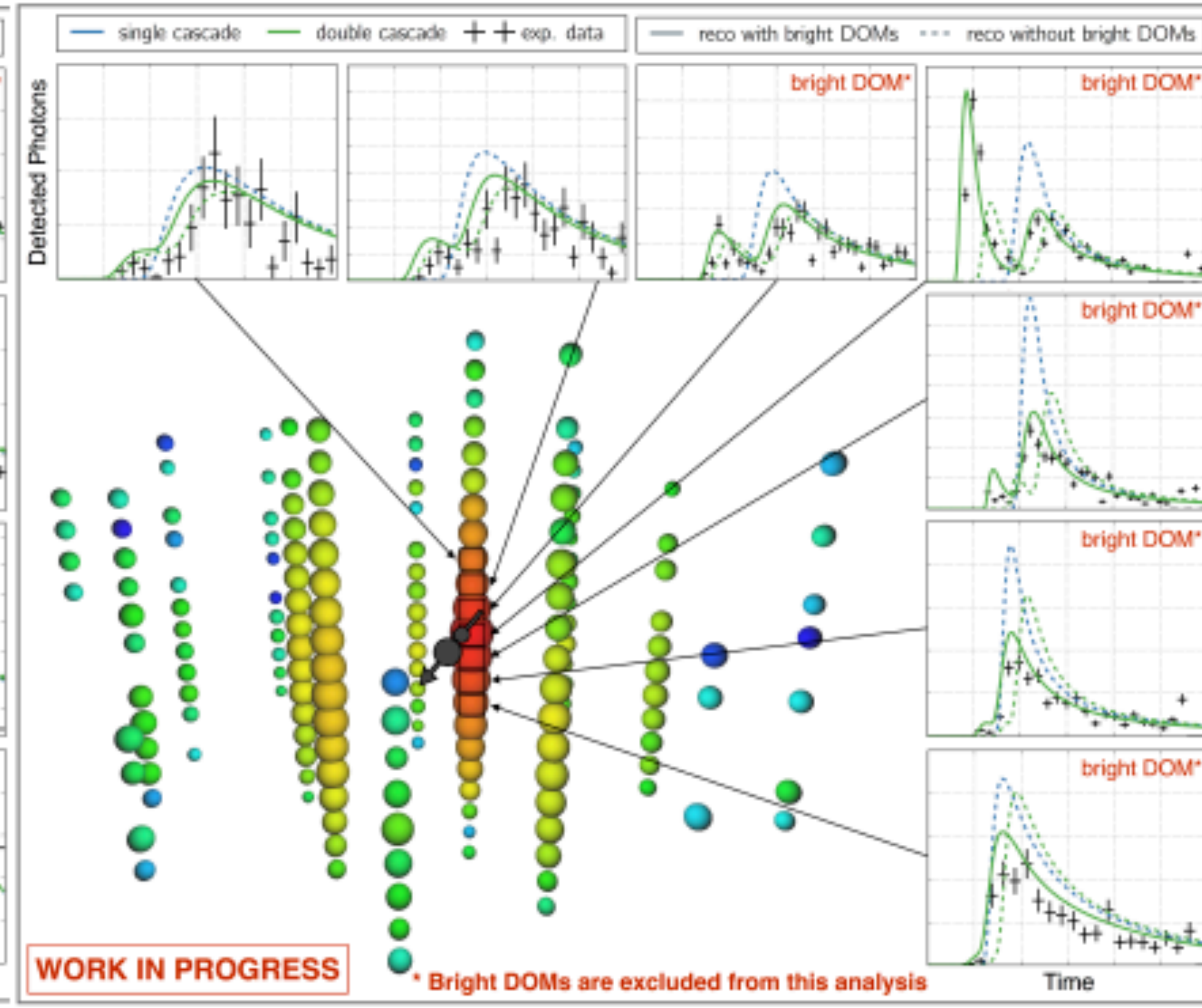
Double cascades can arise from ν_τ or mis-identified bckg (astro ν/ atm).

Separate study of tauness of the double cascade events ongoing

HESE 7.5yrs Tau Search



Double cascade Event #1



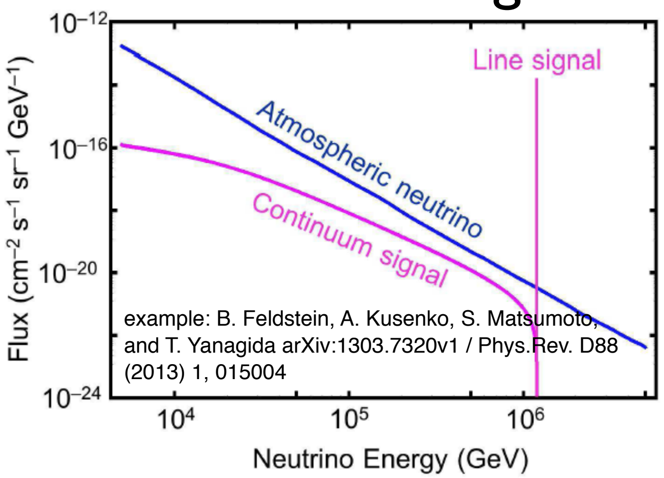
Double cascade Event #2

The two reconstructed cascades per event are shown in gray.
The direction is indicated by the arrow
Bright DOMs not used in the reconstruction

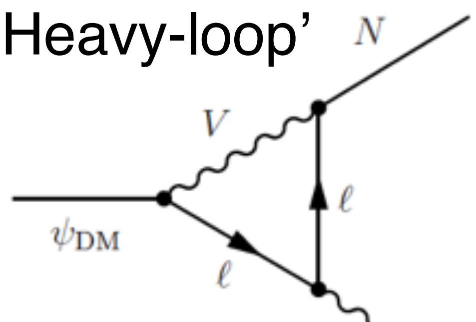
Dark Matter Decay

Heavy Dark Matter Decay

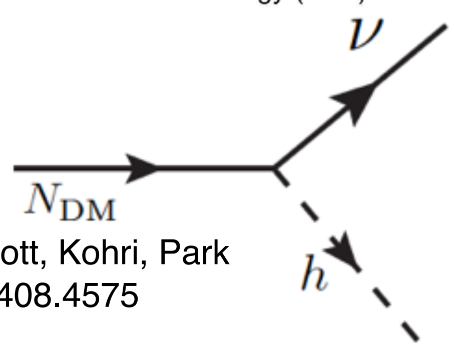
Decay process might produce mono-energetic neutrinos



'Heavy-loop'

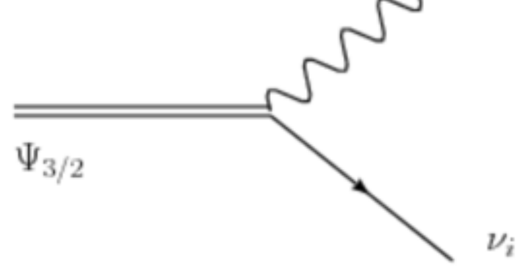


Garny, Ibarra, Tran, Weniger 1011.3786

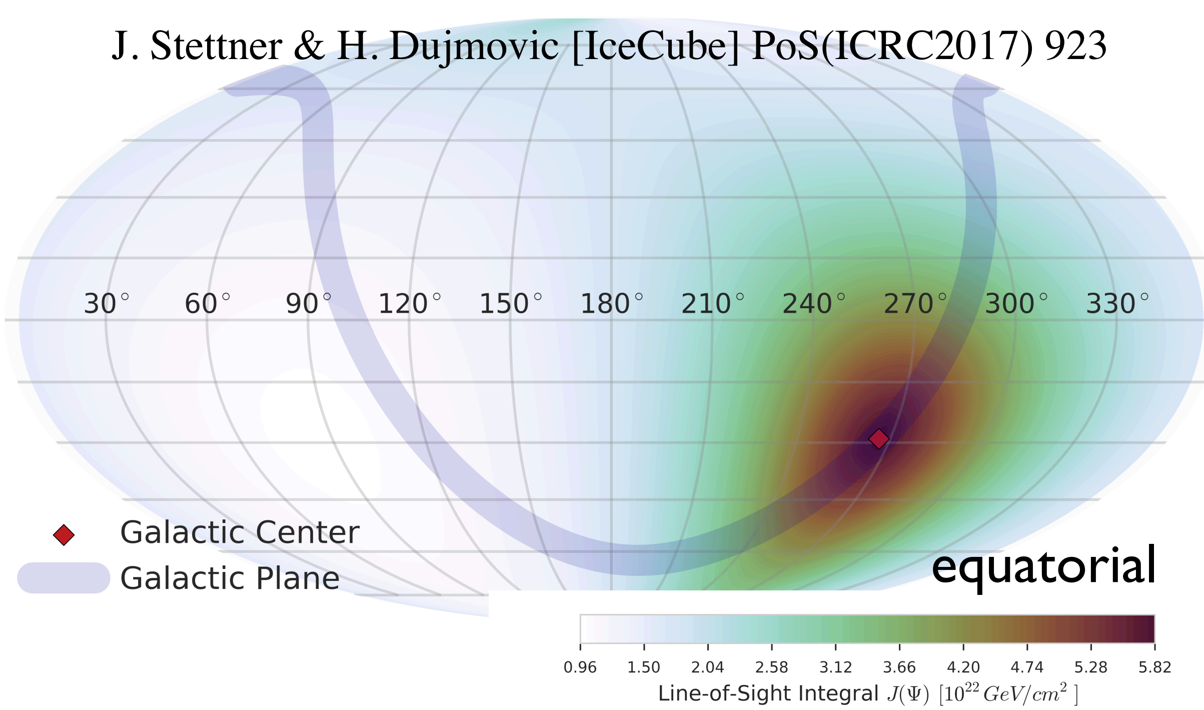


Rott, Kohri, Park 1408.4575

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)

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

Dark Matter Decay with IceCube

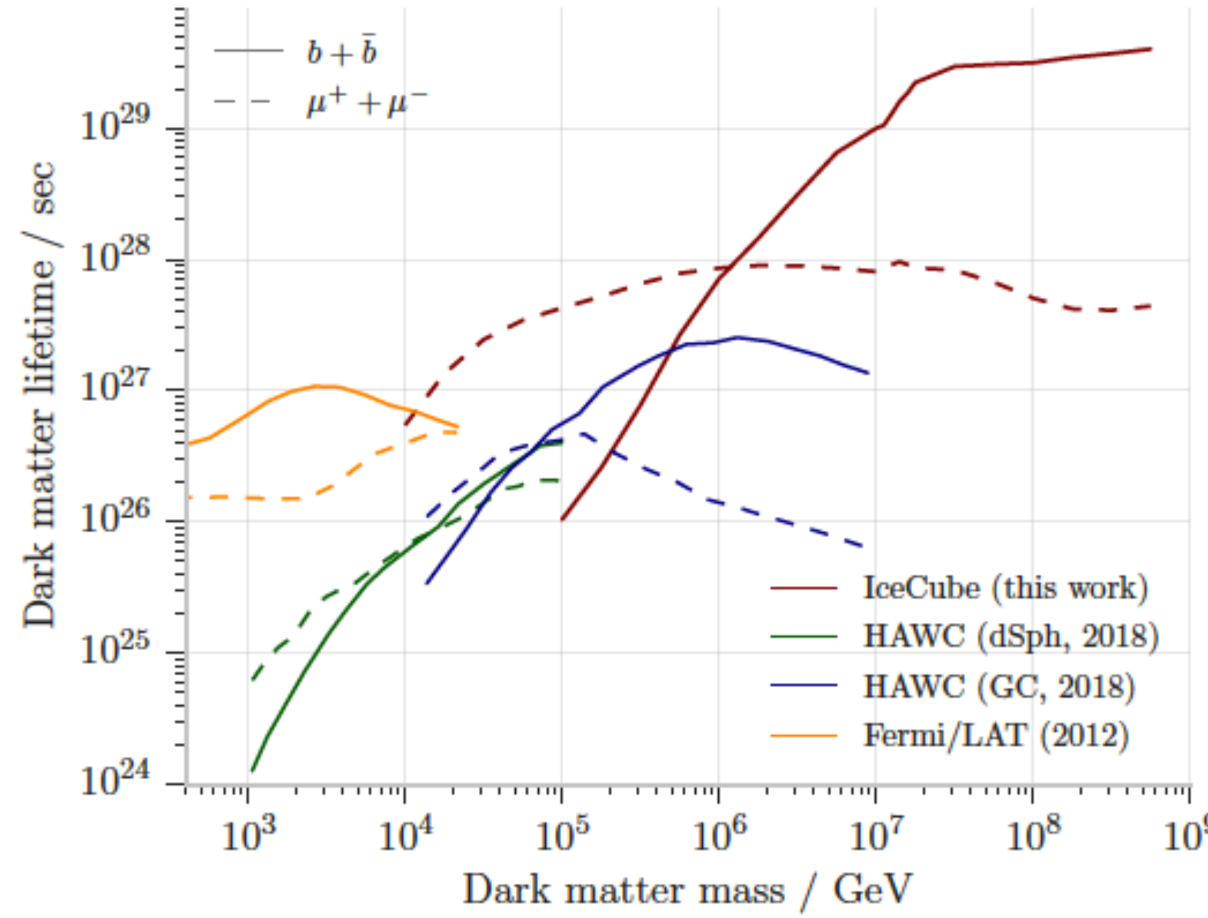
see also HAWC arXiv:1710.10288

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

- 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

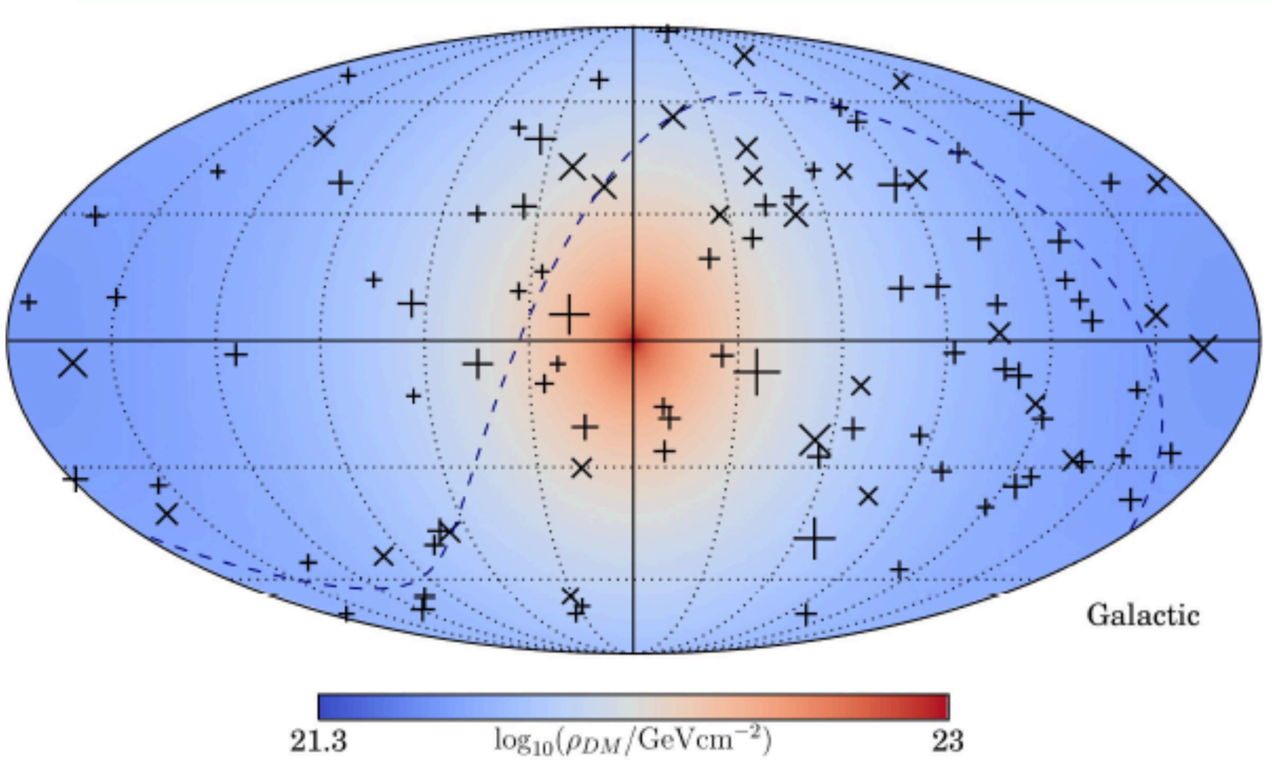
- Models in which the astrophysical neutrino flux arises entirely from dark matter decay are disfavoured
- Scenarios with a PeV neutrino line became less attractive with IceCube's observation of neutrino events well above this energy.

Sensitivity further improved for high masses using the HESE 7.5yrs sample

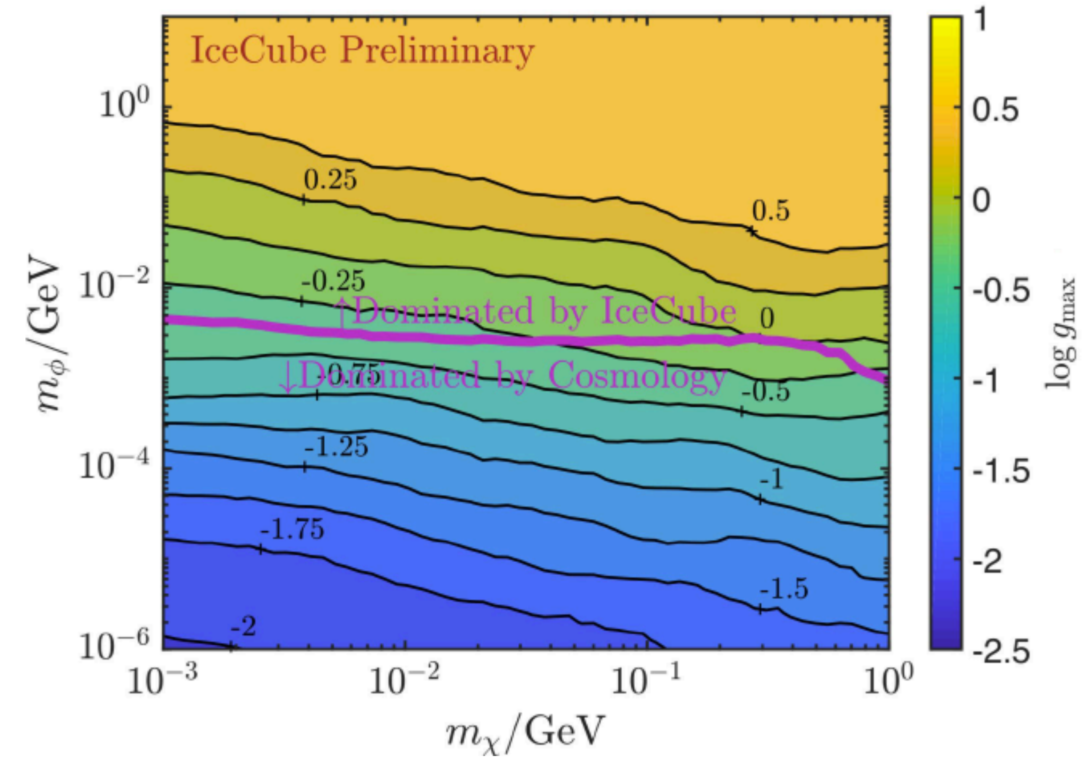
Imaging Galactic Dark Matter with IceCube's High-Energy Cosmic Neutrinos

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

Dark Matter Column Density* as seen from Earth



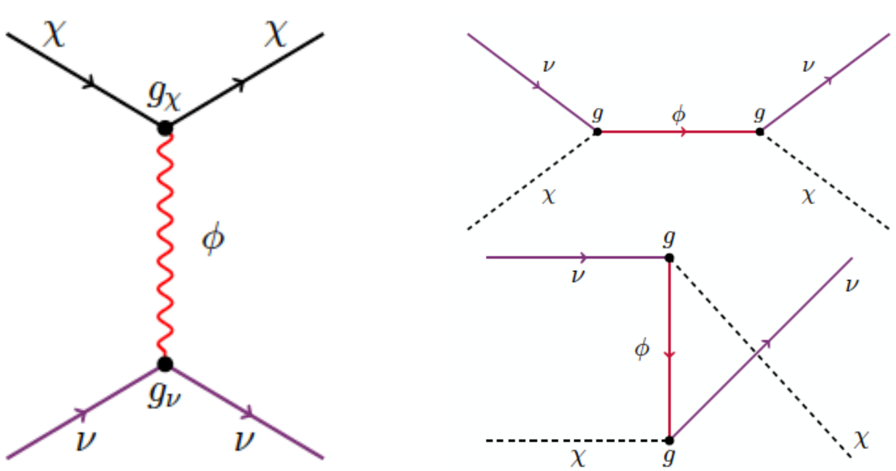
Fermion DM - Vector Mediator



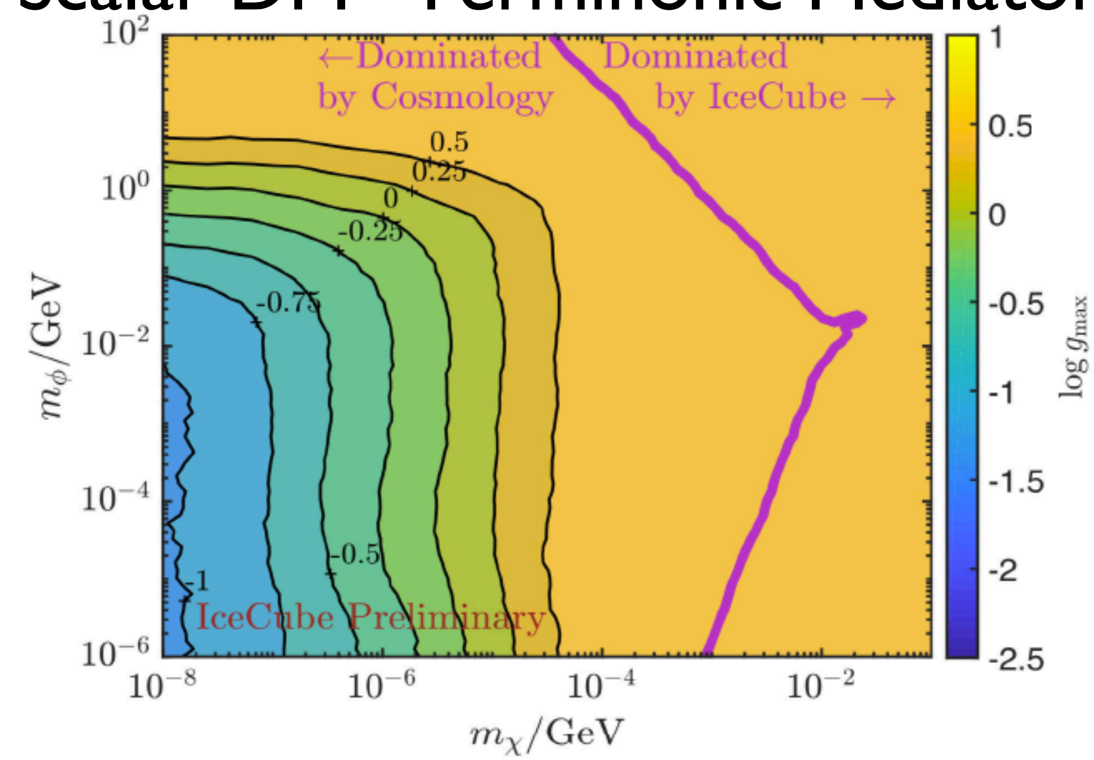
Dark Matter - Neutrino Interaction

(1) Fermion DM, vector mediator

(2) Scale DM, ferminonic mediator

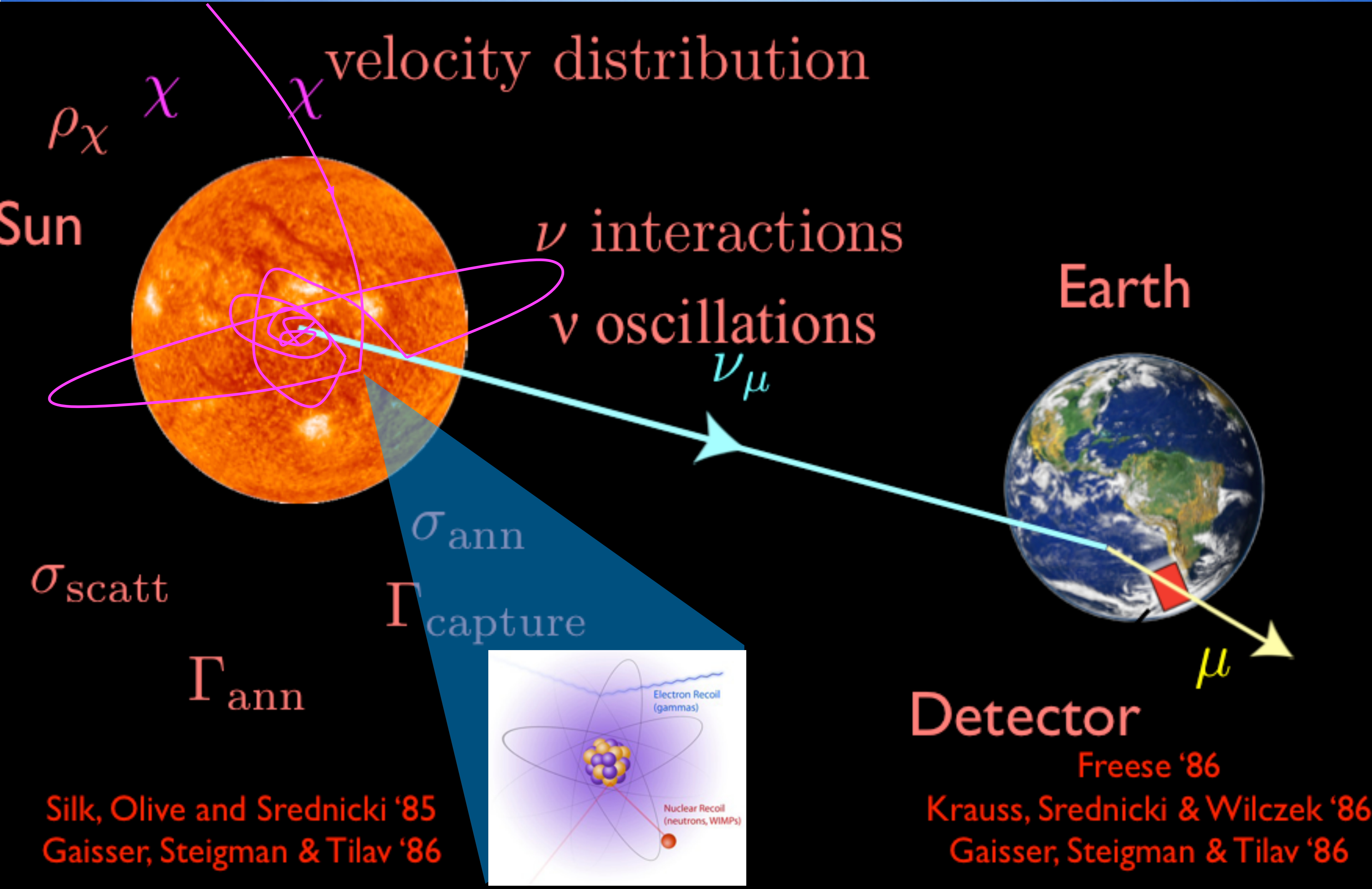


Scalar DM - Ferminonic Mediator



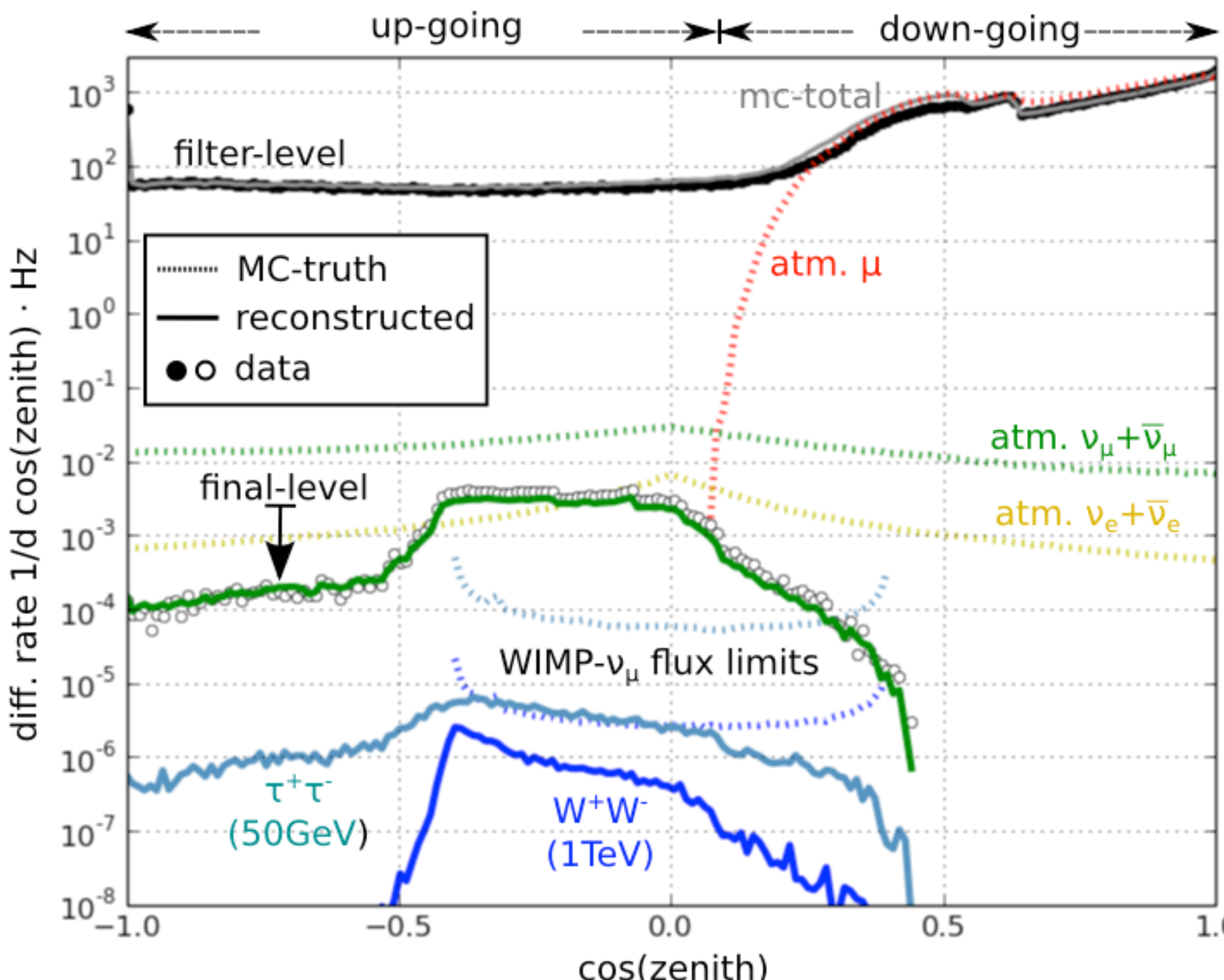
Dark Matter Capture in the Sun

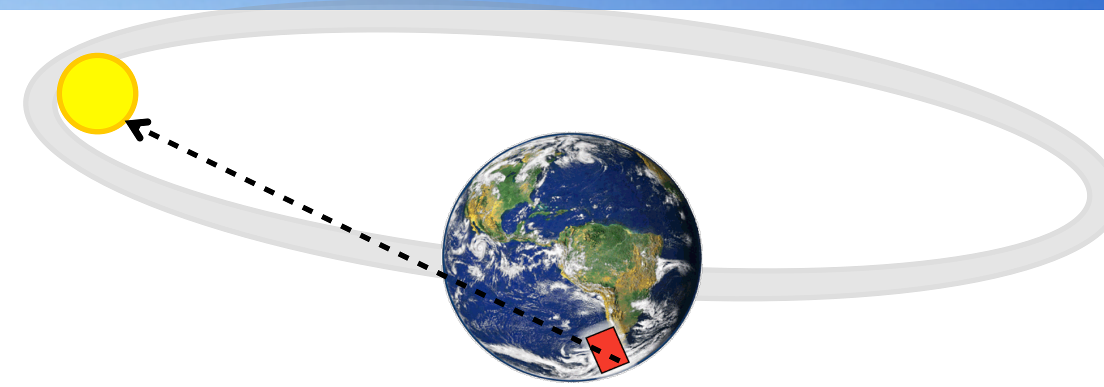
Solar Dark Matter



3yrs IceCube Solar WIMP Analysis

IceCube arXiv:1612.05949

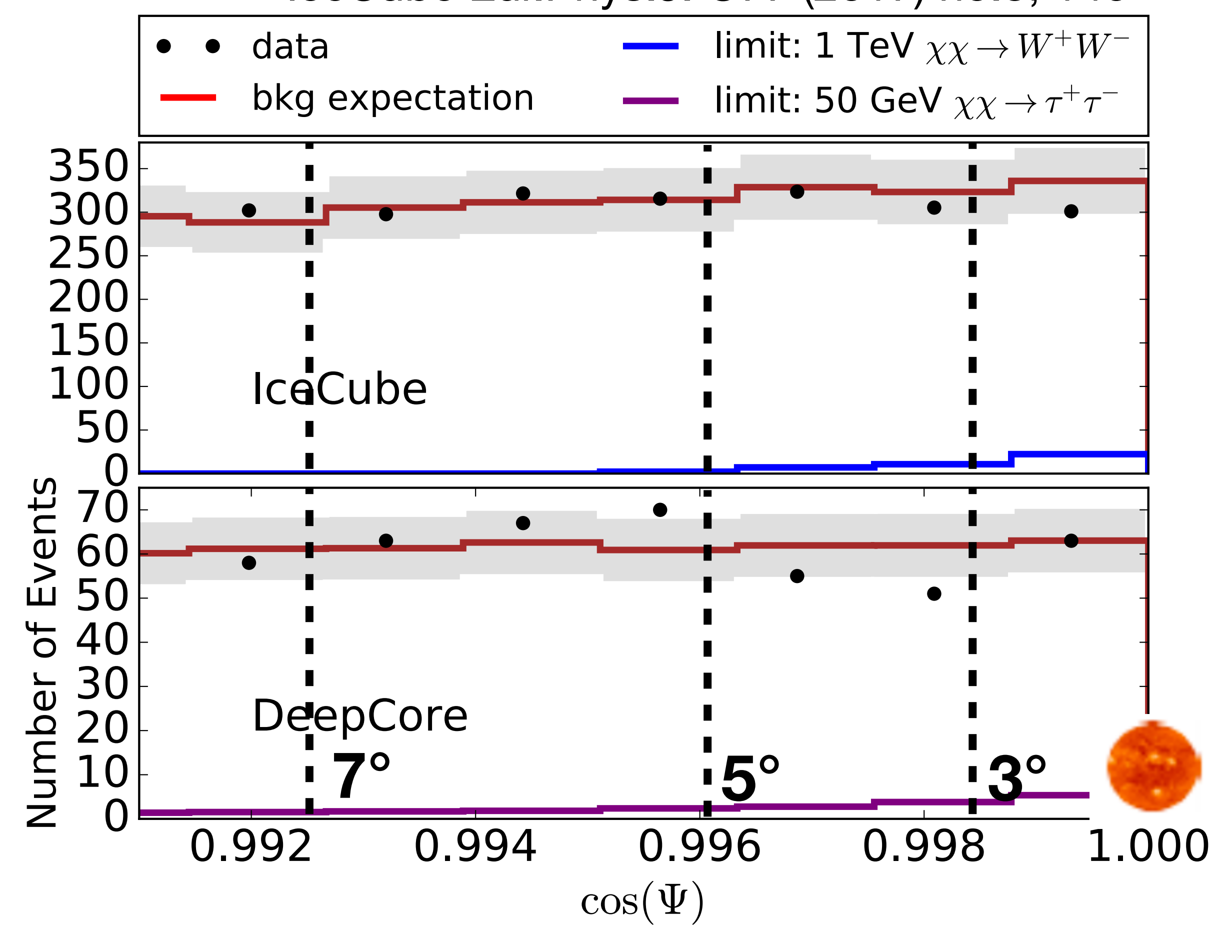




- Use track events for better pointing
- Search for an excess of events from the direction of the Sun
- Observed events consistent with background only expectations

Observed events

IceCube Eur.Phys.J. C77 (2017) no.3, 146



Signal pdf:

$$S_i(|\vec{x}_i - \vec{x}_{\text{sun}}(t_i)|, E_i, m_\chi, c_{\text{ann}})$$

$$= \mathscr{K}(|\vec{x}_i - \vec{x}_{\text{sun}}(t_i)|, \kappa_i) \times \mathscr{E}_{m_\chi, c_{\text{ann}}}(E_i)$$

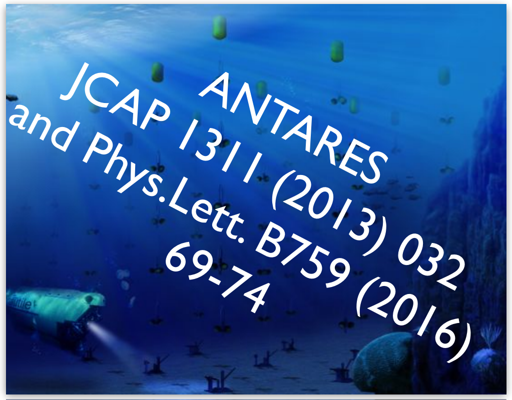
Spectral part

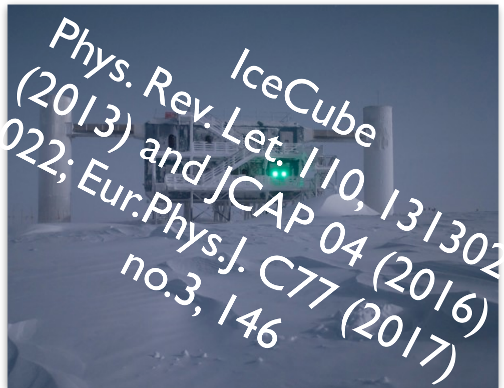
Monovariate Fisher Bingham distribution from directional statistics

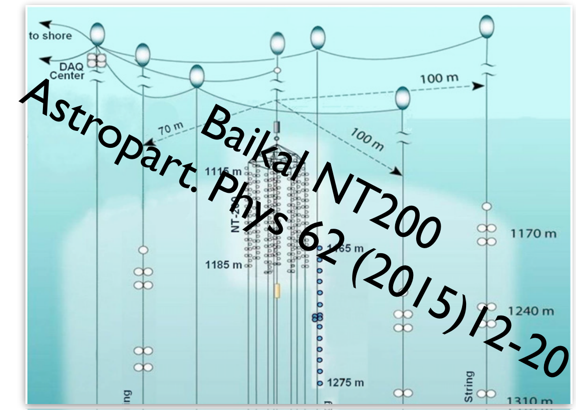
Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\text{atm}})$

Likelihood: $\mathscr{L}(n_s) = \prod_N \left(\frac{n_s}{N} S_i + (1 - \frac{n_s}{N})\mathscr{B}_i\right)$

Solar Dark Matter Summary

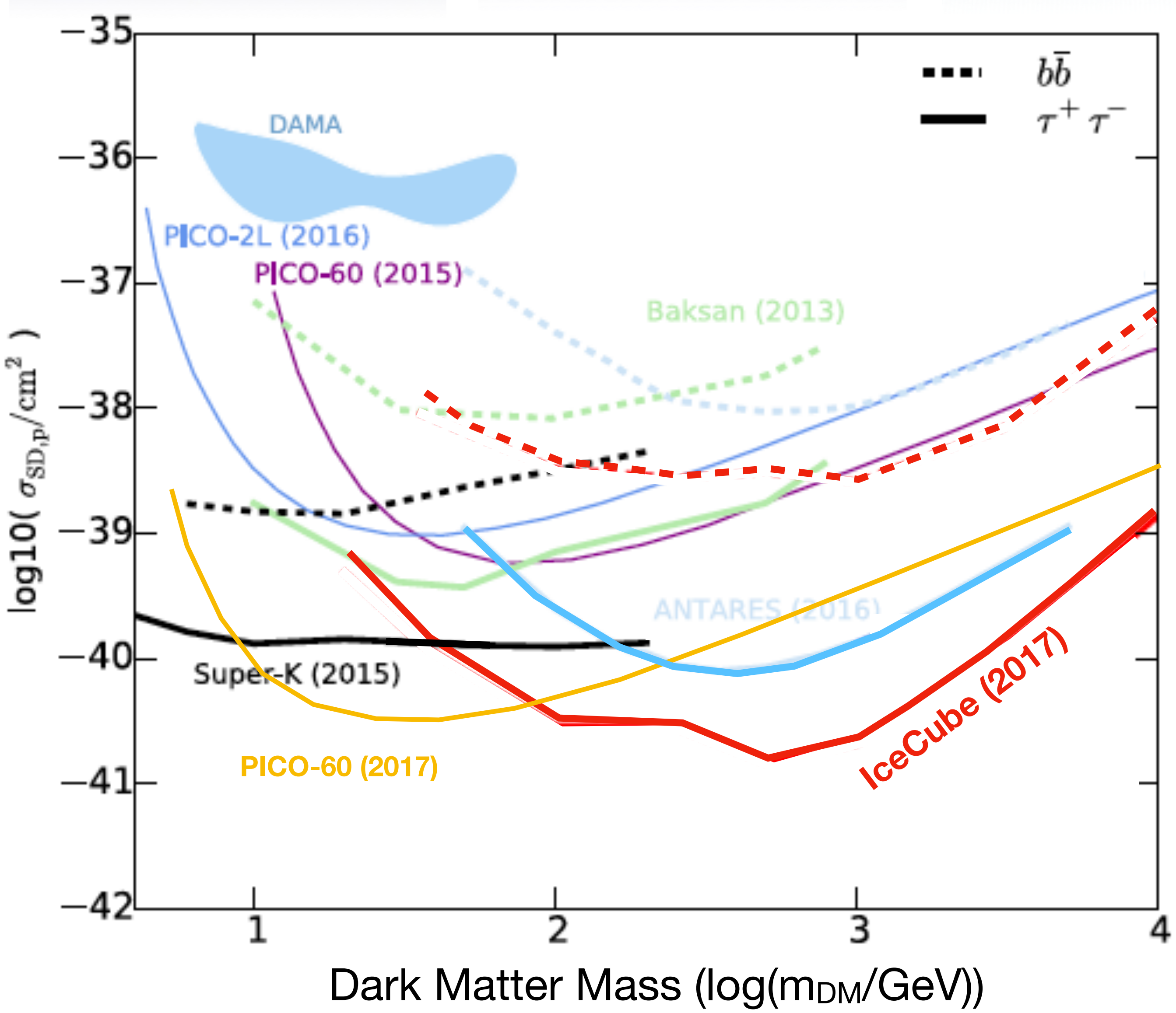


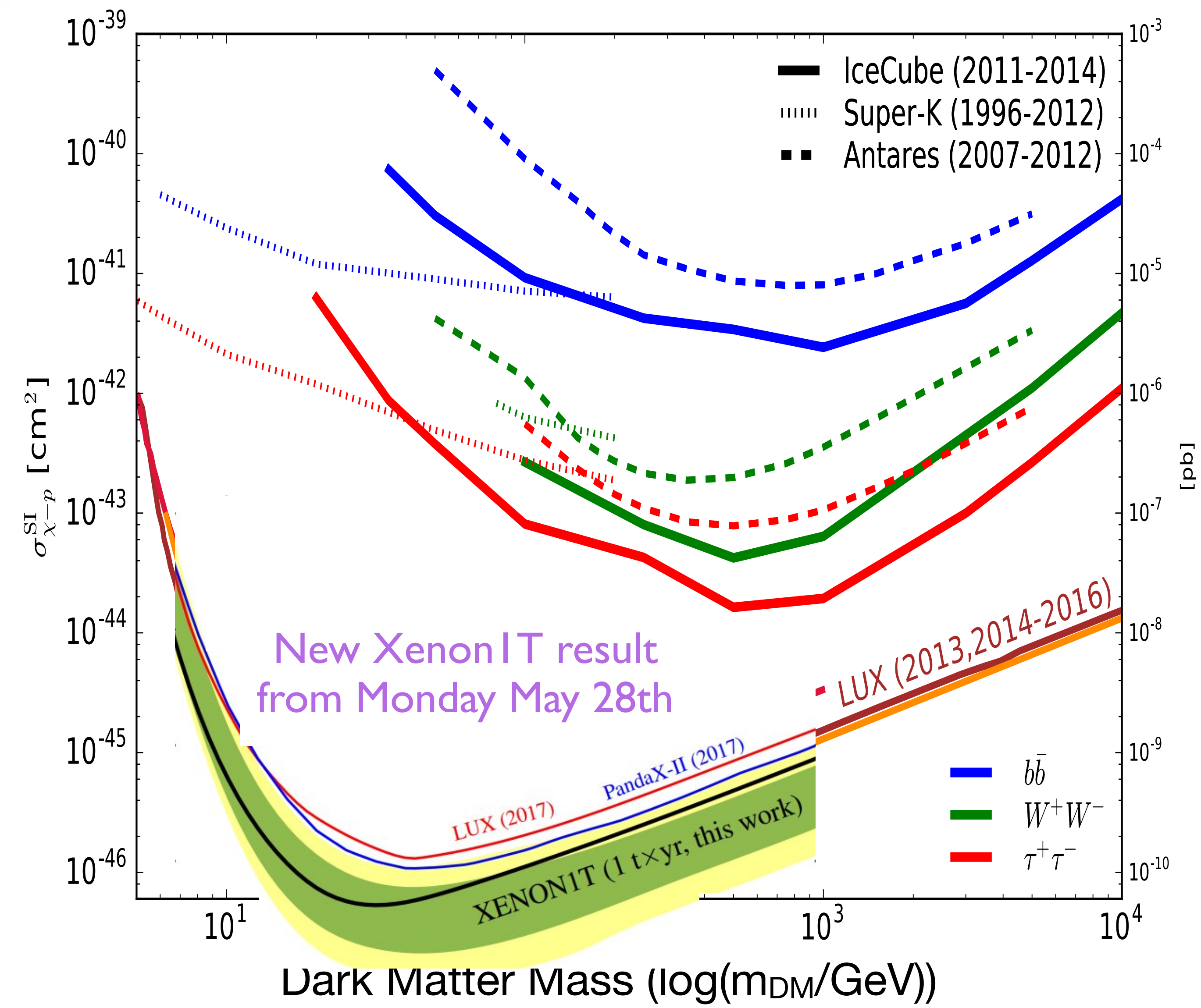




Spin-dependent scattering

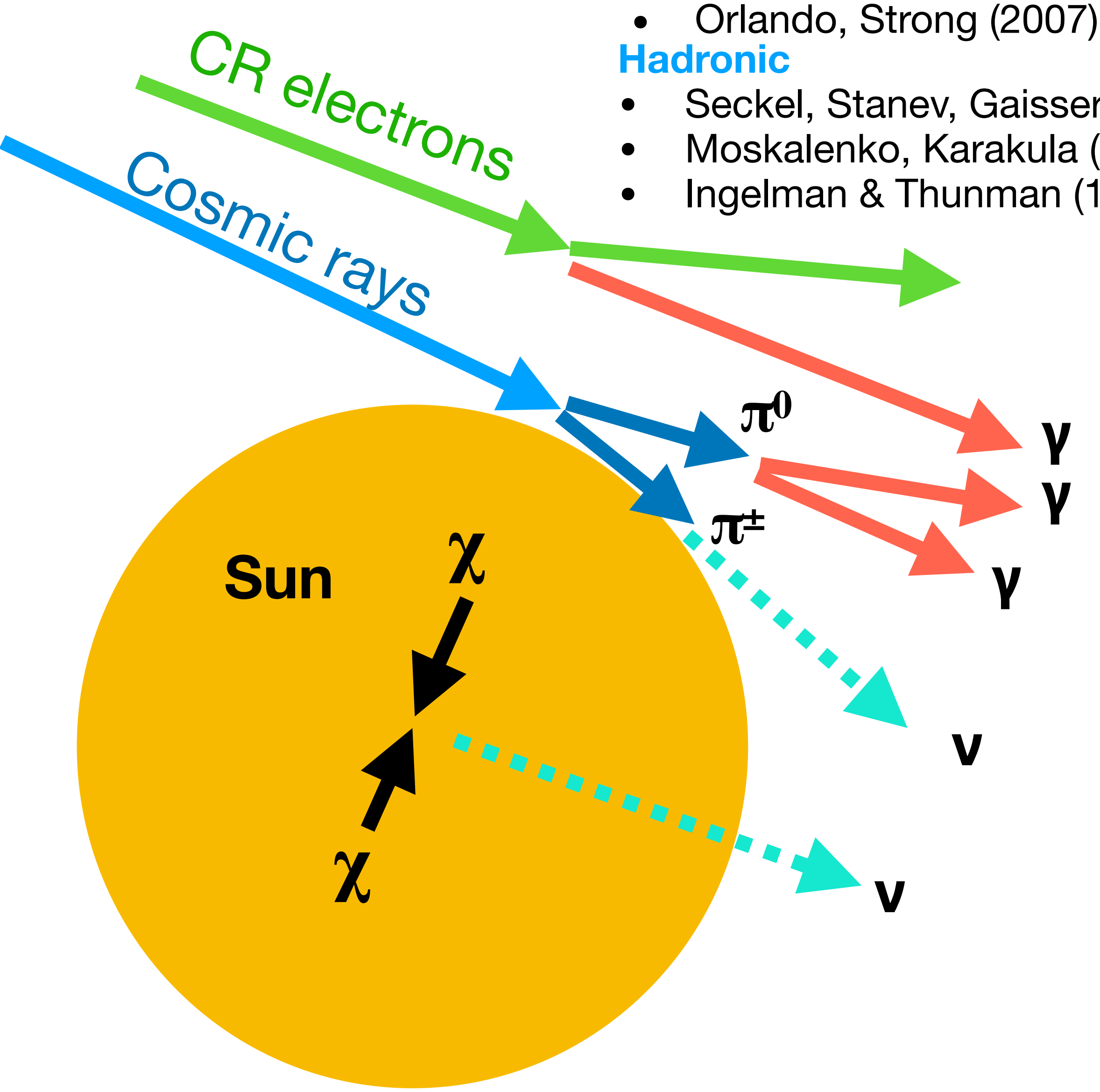
Spin-independent scattering





Solar Atmospheric Neutrinos / Solar Atmospheric Neutrino Floor

Cosmic ray interactions with the Sun



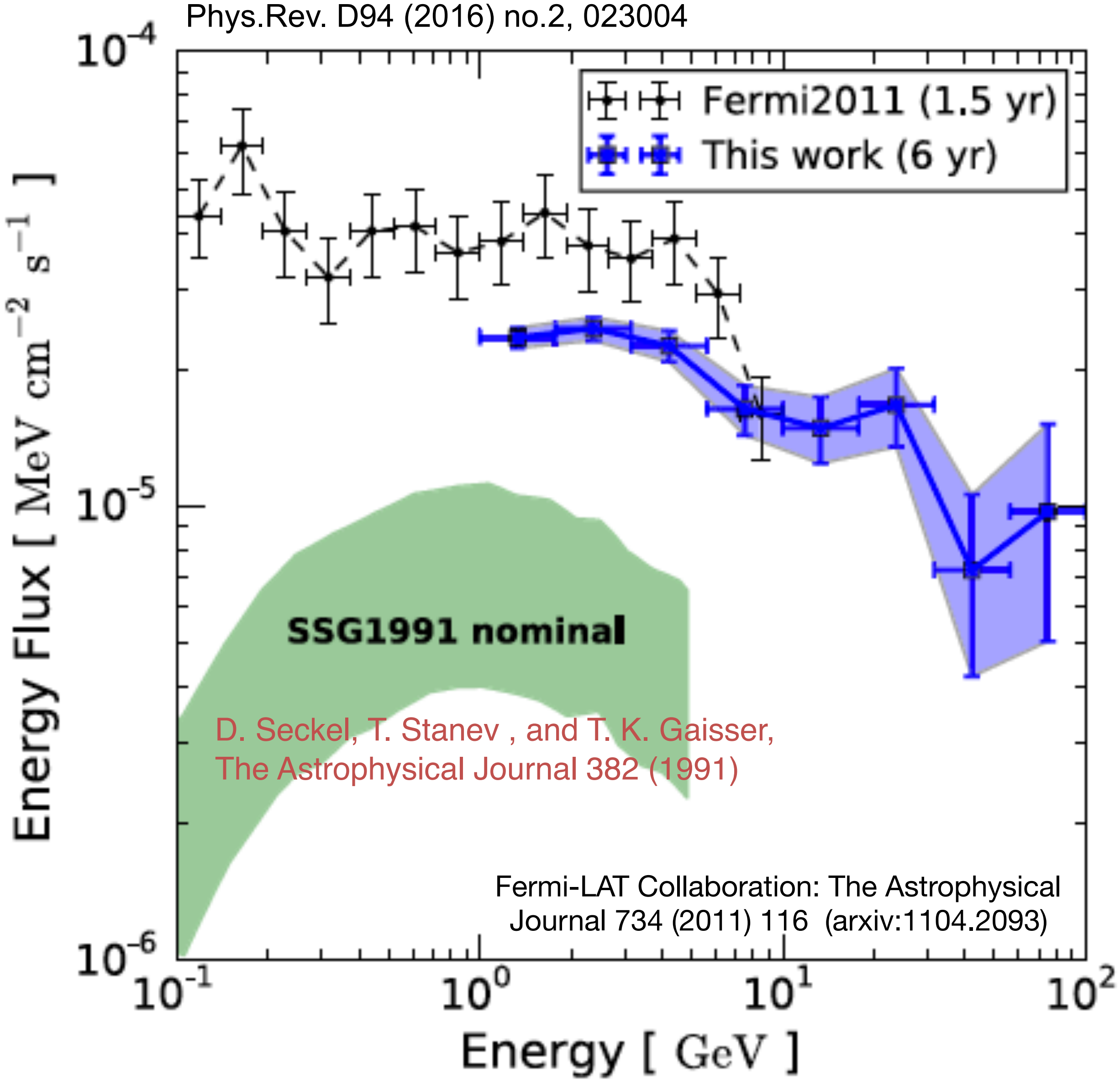
Leptonic

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

Hadronic

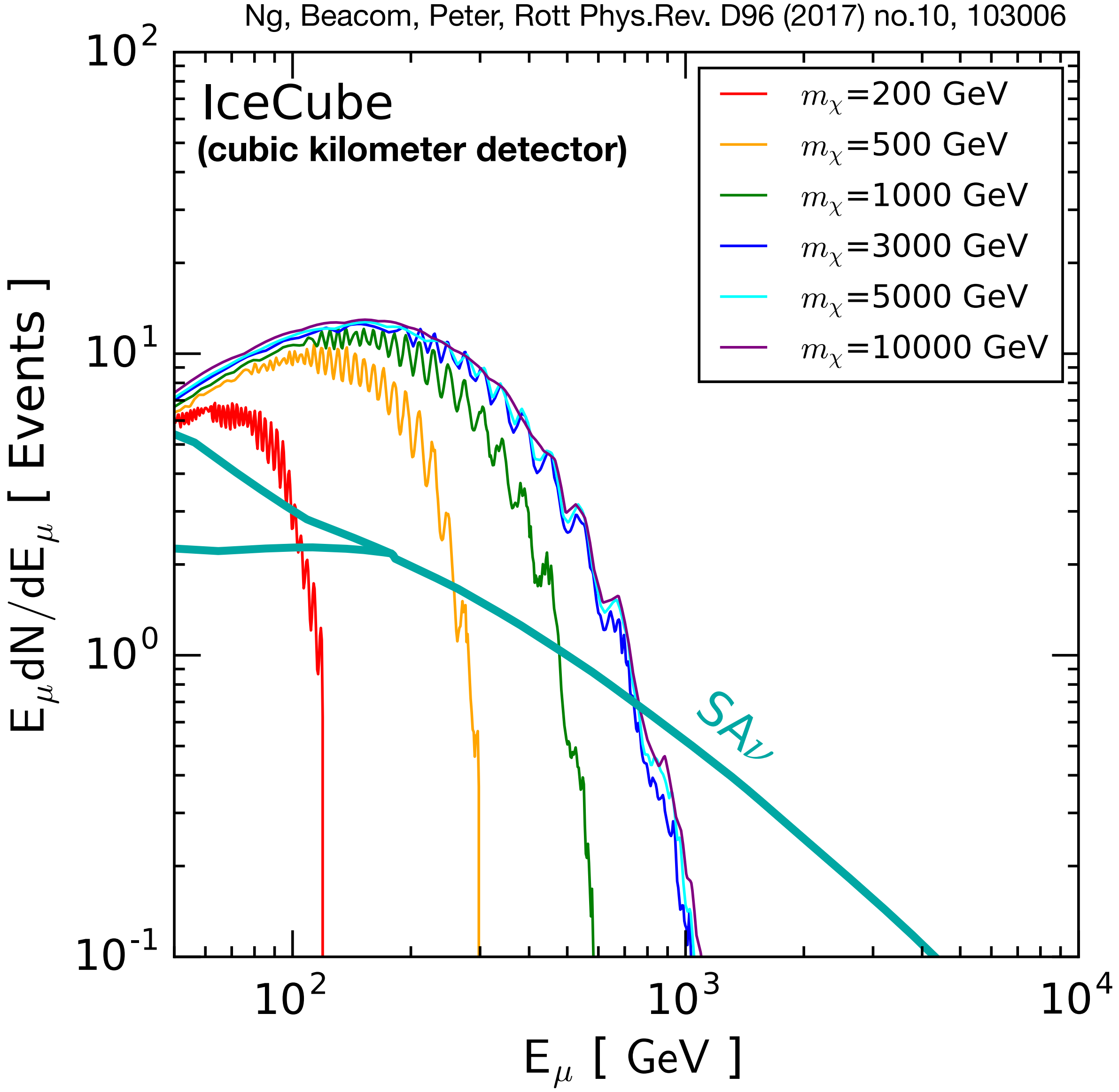
- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

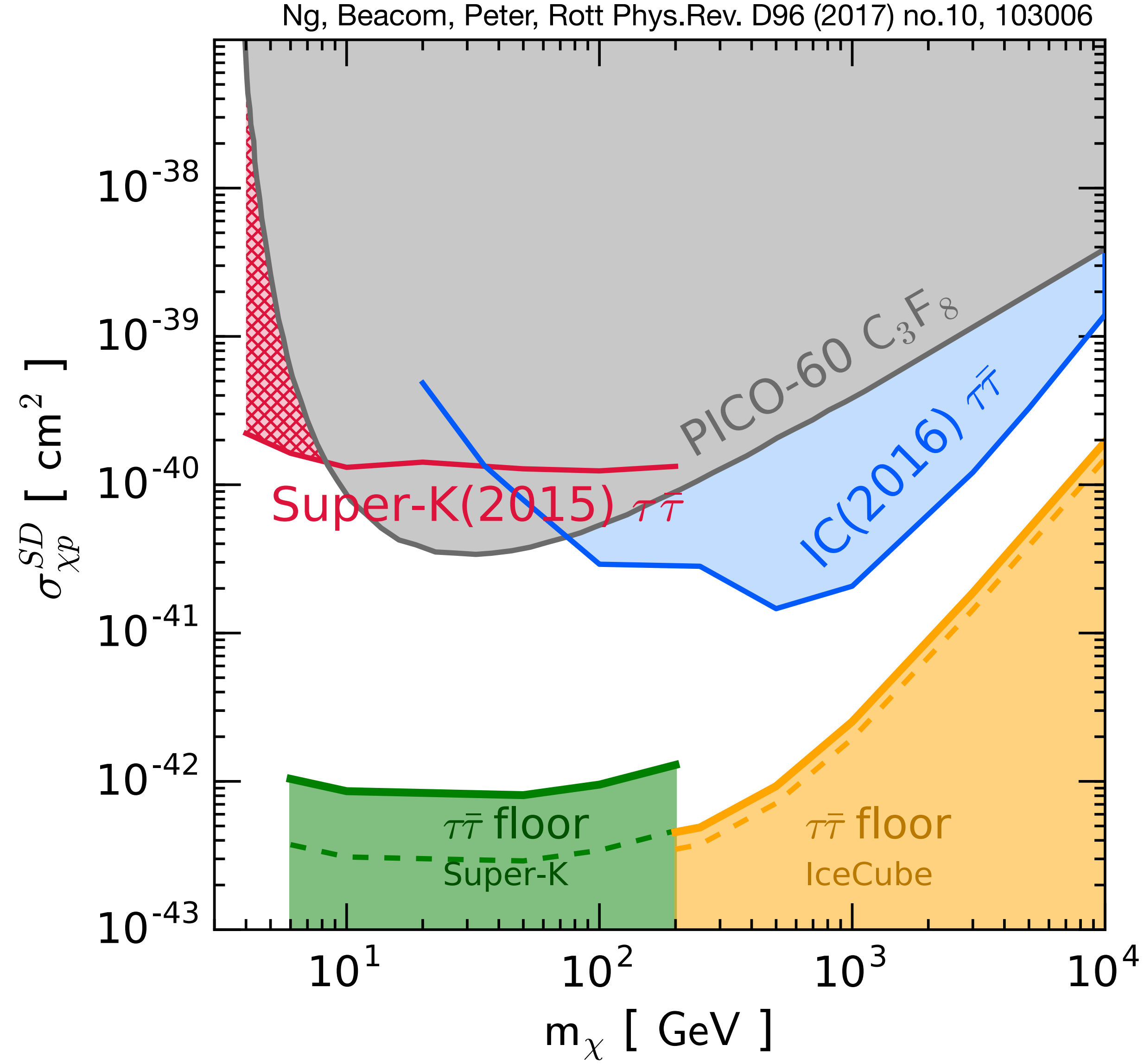
Kenny C.Y. Ng, John F. Beacom, Annika H.G. Peter, Carsten Rott
Phys.Rev. D94 (2016) no.2, 023004



- **Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos**
  - **Gamma-ray flux extends to 100GeV and beyond** (see Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C.Y. Ng, and Qing-Wen Tang arXiv:1803.05436 / Kenny C.Y. Ng, John F. Beacom, Annika H.G. Peter, Carsten Rott Phys.Rev. D94 (2016) no.2, 023004)
- **Background to dark matter searches from the Sun and potential signal for IceCube**

Cosmic background from the Sun





- 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

Expect ~2events per year at cubic kilometer detector

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]

See also S. In & C. Rott [IceCube] ICRC2017 (965)

Solar Atmospheric Neutrino Search

- Experimental search on-going
  - Off-source data for background prediction
  - Cosmic-ray Sun shadow needs to be included as systematic uncertainty

- Region of interest = $\theta < 5°$ from the Sun, E = $[10^{2.2}, 10^{7.2}]$ GeV (IC79-2010/2011)
  = $[10^{2}, 10^{7}]$ GeV (IC86-2011/2016)
- We estimated the sensitivity as using maximum LLH method

Likelihood function ($L(E,\theta|\mu)$) is defined as a function of energy(E) and angular distance(θ) from the Sun

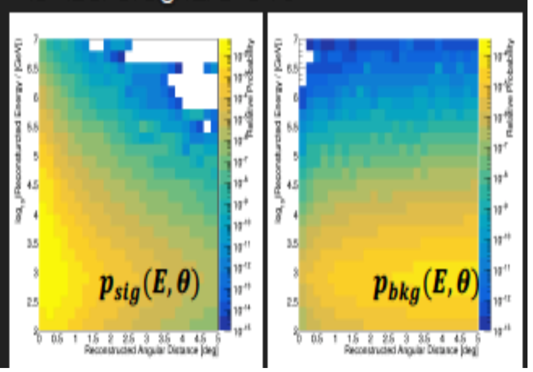
$$L(E,\theta|\mu) = (\mu/N) * p_{sig}(E,\theta) + (1 - \mu/N) * p_{bkg}(E,\theta))$$

where N = total number of events in pseudo experiment, μ = number of signal events

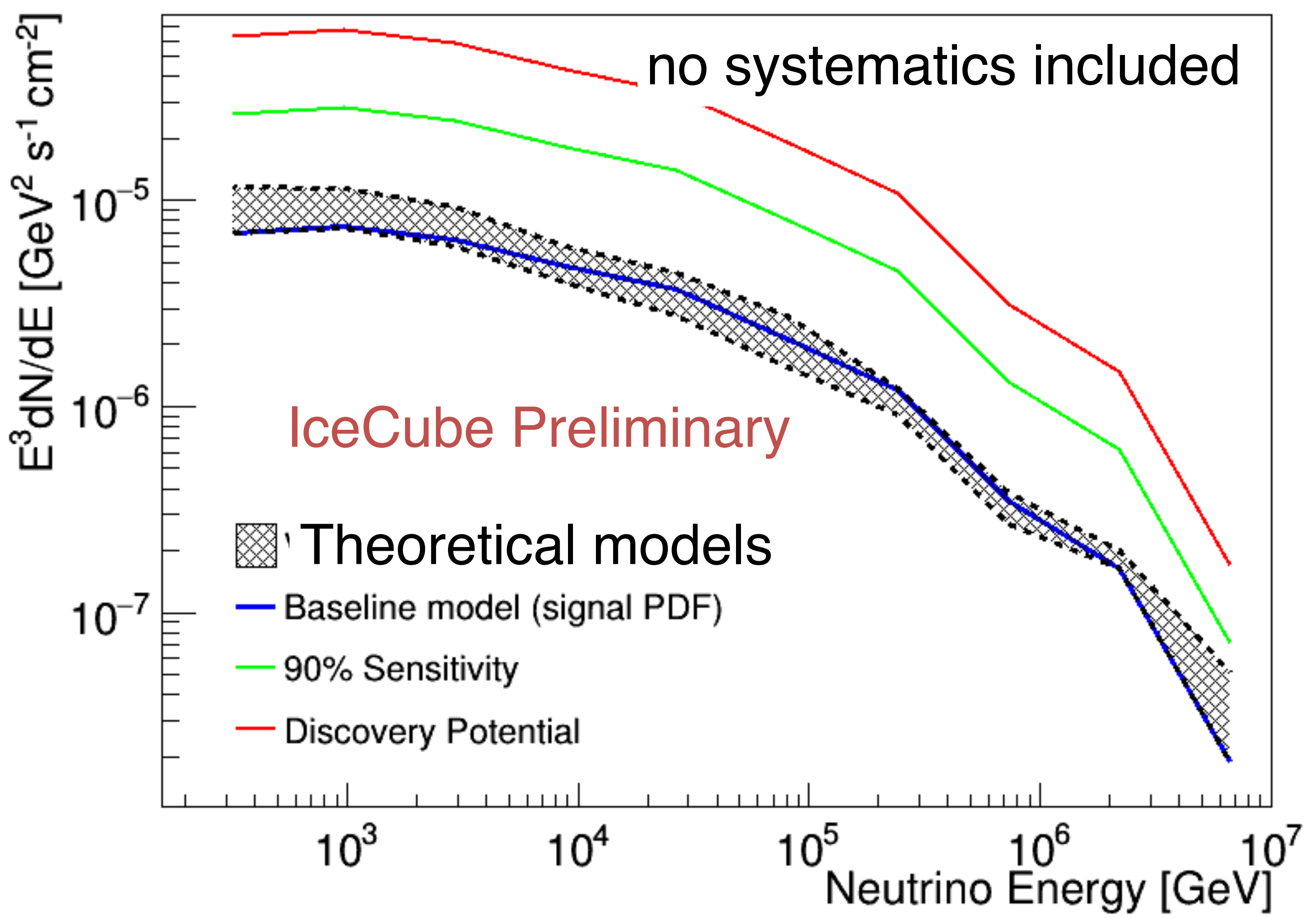
$$p_{sig}(E,\theta) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{\theta^2}{2\sigma^2}\right)\cdot p_{sig}^{E}(E,\theta)$$

$$p_{bkg}(E,\theta) = \frac{n_a}{N}\cdot p_{astro}(E,\theta) + \left(1-\frac{n_a}{N}\right)\cdot p_{atmo}(E,\theta)$$

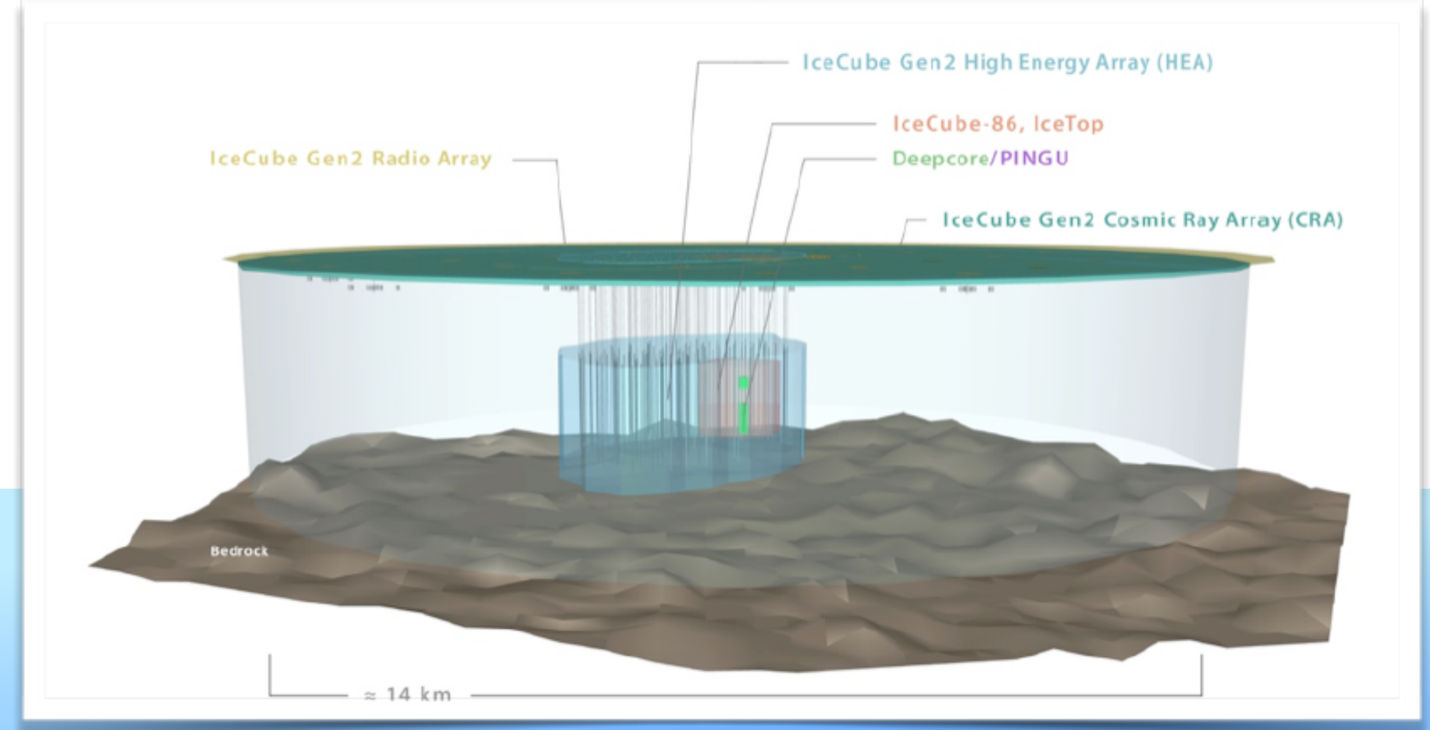
- Position of the Sun is homogeneously randomized within solar radius from the events → called circle distribution
- $p_{sig}^{E}(E,\theta)$ is obtained by re-weighting the Sample to the baseline model



Sensitivity Solar Atm. Neutrinos



- Solar Atmospheric neutrinos might be observable with IceCube
- Observing solar atmospheric neutrinos is important for:
  - Understanding solar magnetic fields;
  - Cosmic ray propagation in the inner solar system;
  - Improving models of cosmic ray interactions in the solar atmosphere;
  - Finding a high-energy neutrino point source
  - Better understand the background for dark matter searches

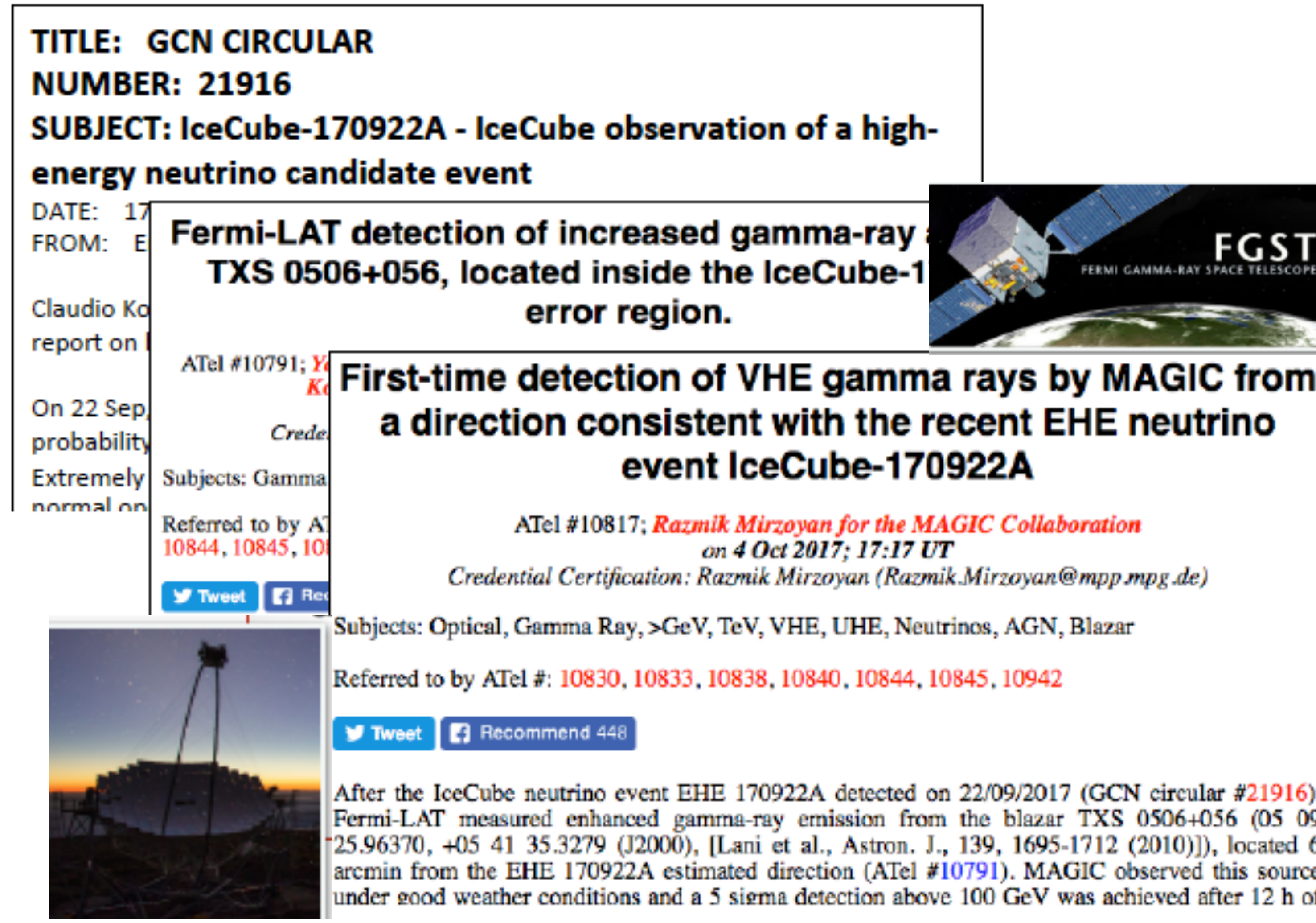

IceCube Gen2 High Energy Array (HEA)
IceCube-86, IceTop
IceCube Gen2 Radio Array
Deepcore/PINGU
IceCube Gen2 Cosmic Ray Array (CRA)
Bedrock
≈ 14 km

Outlook

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

IceCube-170922A & TXS 0506+056

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



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

On 22 Sep,
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ray
TXS 0506+056, located inside the IceCube-1
error region.

ATel #10791; Y
K

Crede

Subjects: Gamma

Referred to by A
10844, 10845, 10

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

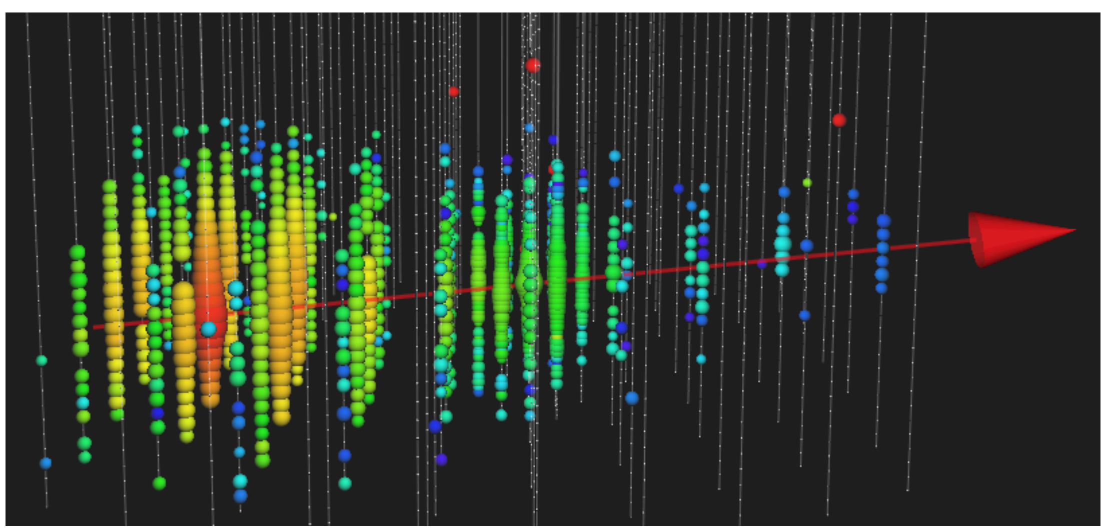
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

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 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of



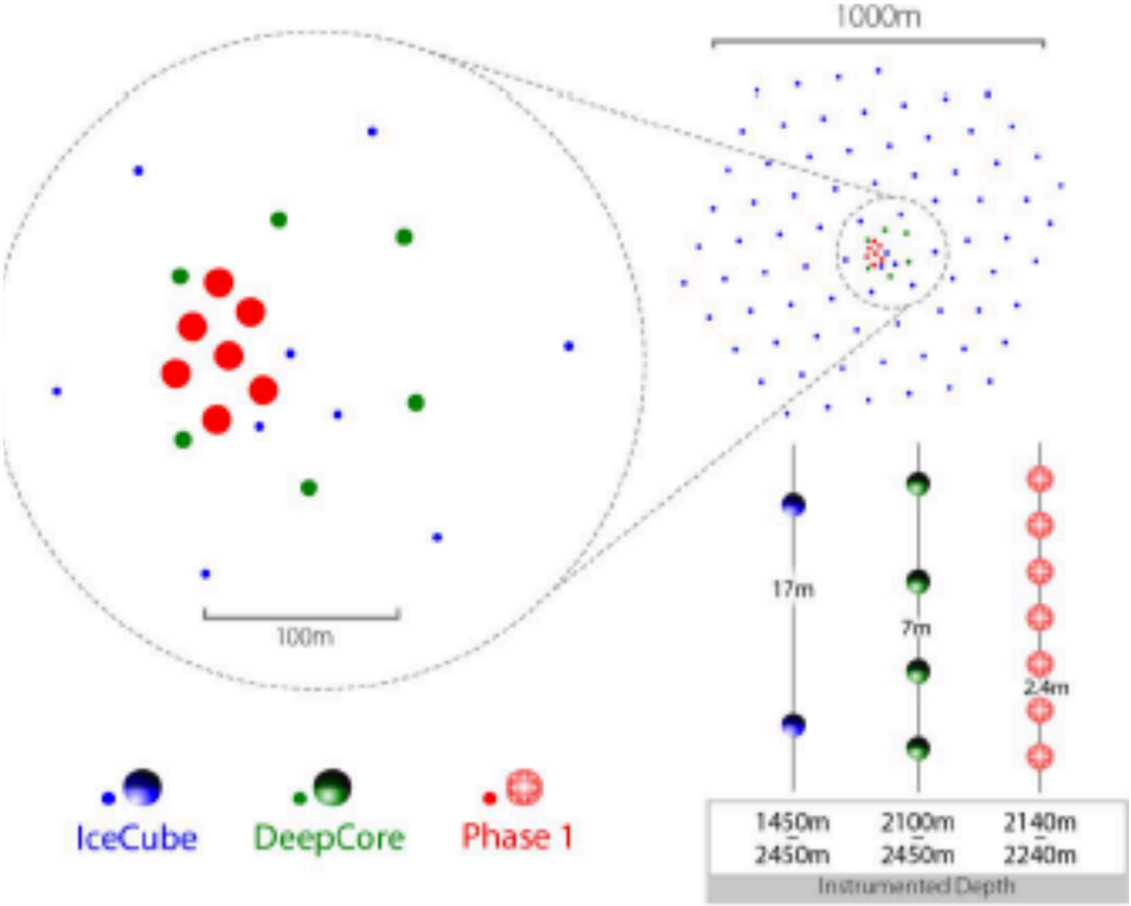
First public ν Alert: IceCube-160427

- 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

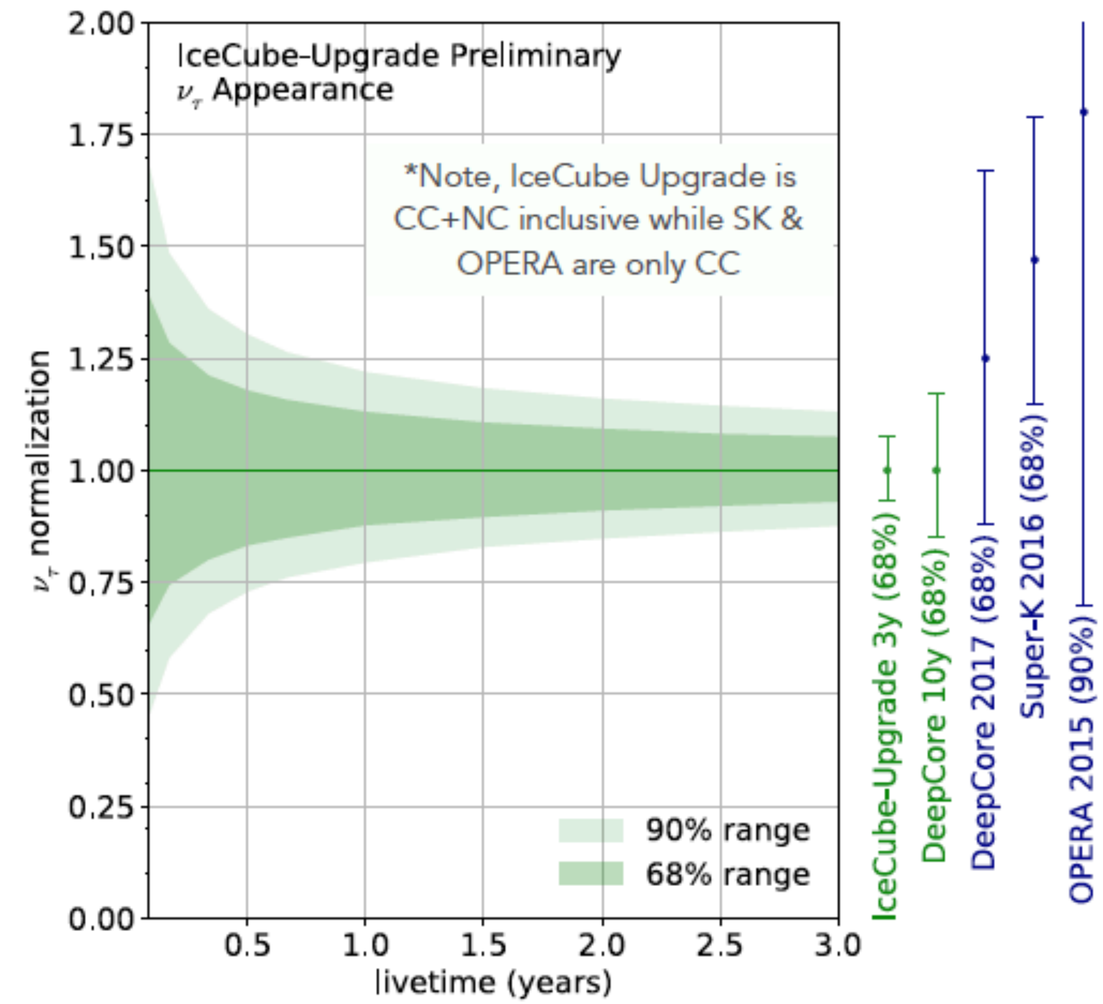
Work in progress … more information soon

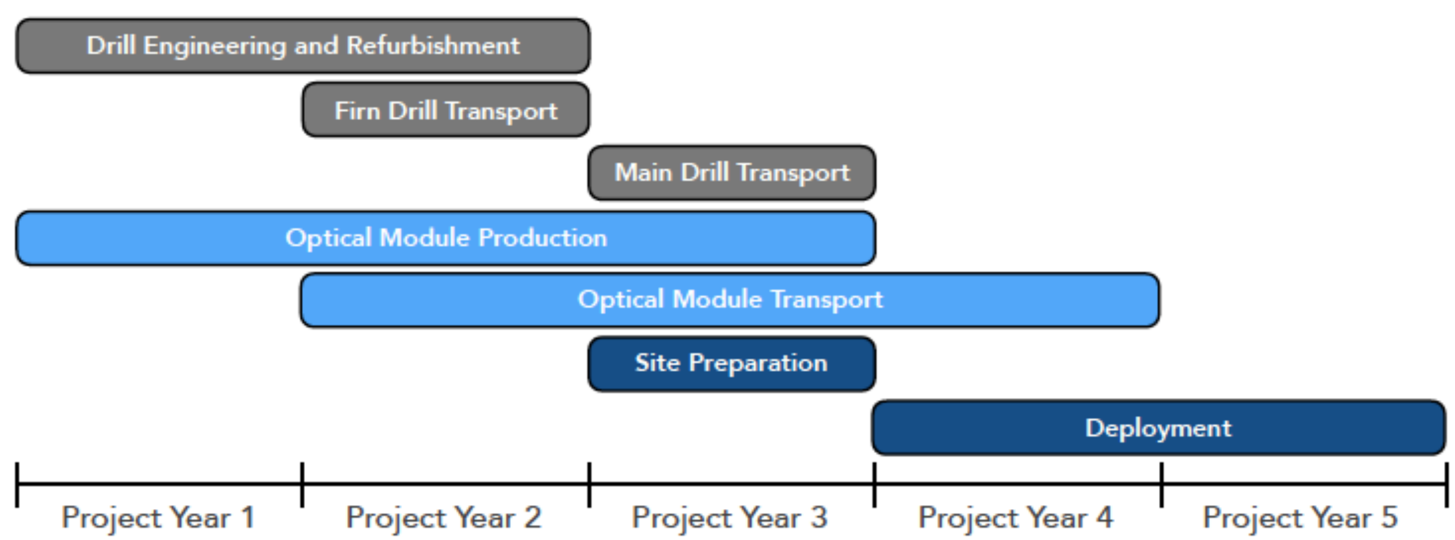
see also:
- PINGU LOI arXiv:1412.5106

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





Goals of the IceCube Upgrade

- Tau neutrino appearance - Unitarity of the PMNS matrix
- Calibration effort - reanalyze existing IceCube data with reduced systematics
- It can also be a platform to test new technologies

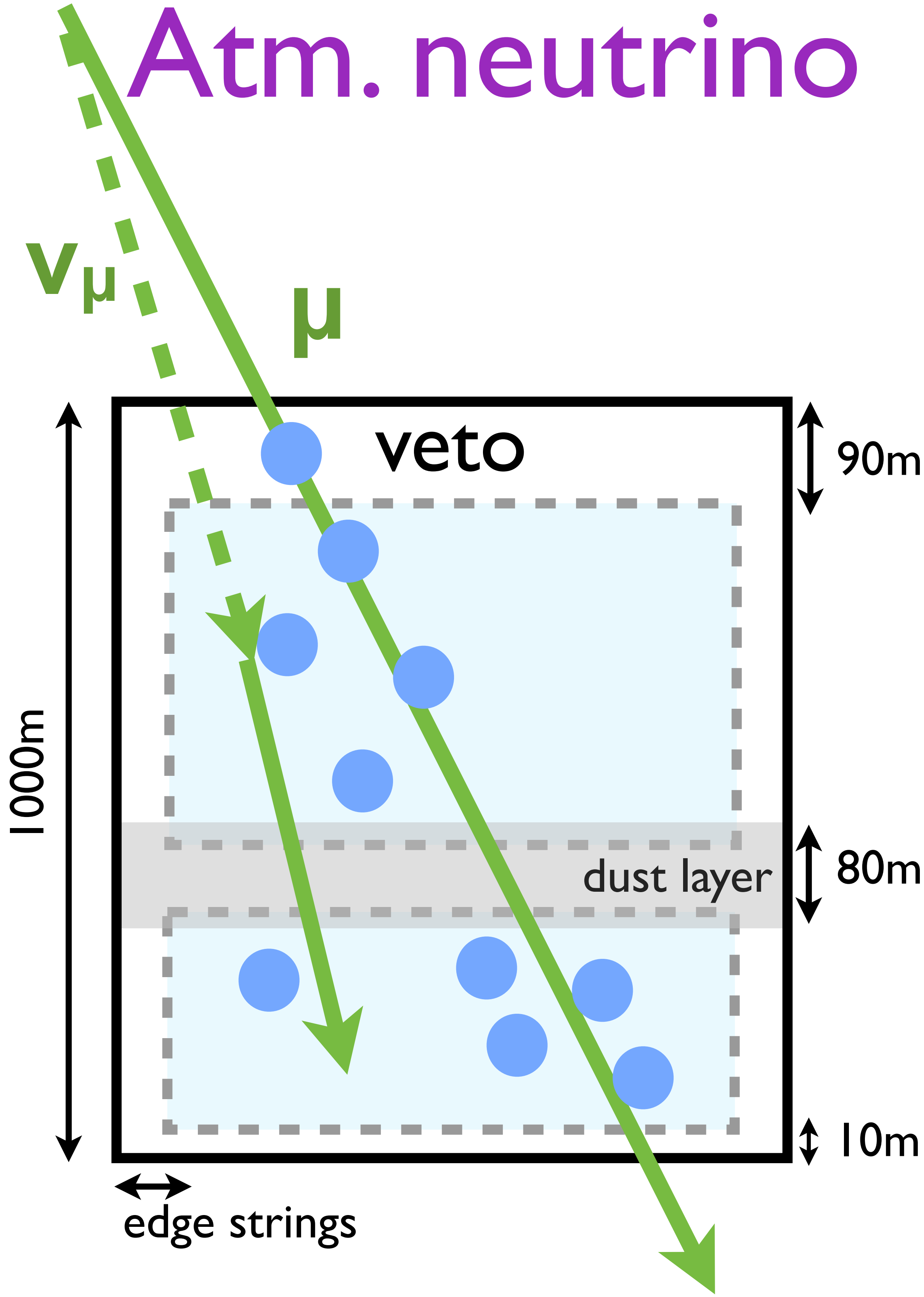
- High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What's the origin of the high-energy neutrino
- Very strong bounds on dark matter scattering with nucleons
- Lifetimes of heavy decaying dark matter can be constrained to 10^{28}s using neutrino signals
- Very diverse science program, IceCube turns out to be a treasure throve
- Neutrino astronomy is a central part of the multi messenger astroparticle physics field

Image:Stephan Richter, IceCube/NSF

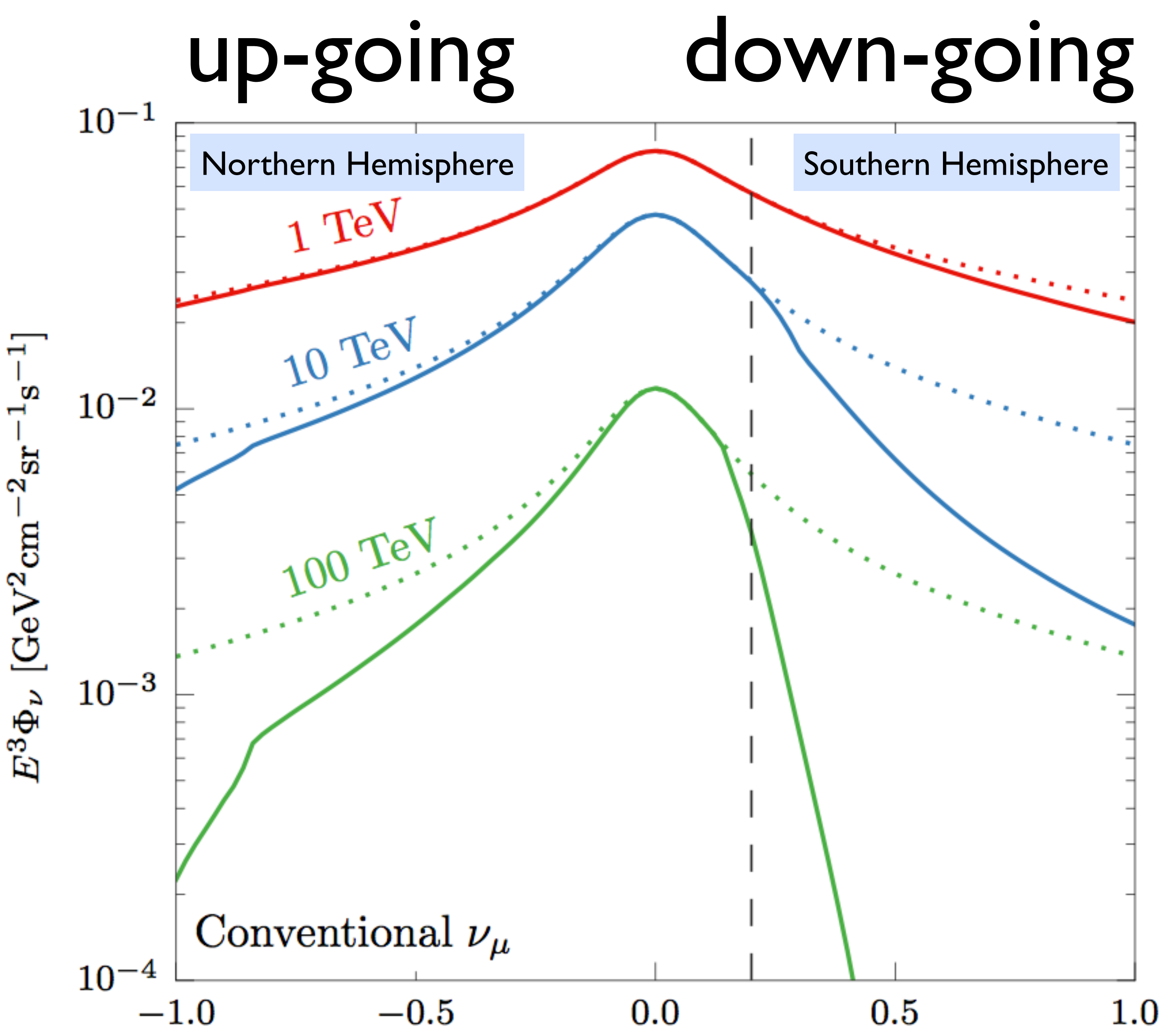
Thanks !

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

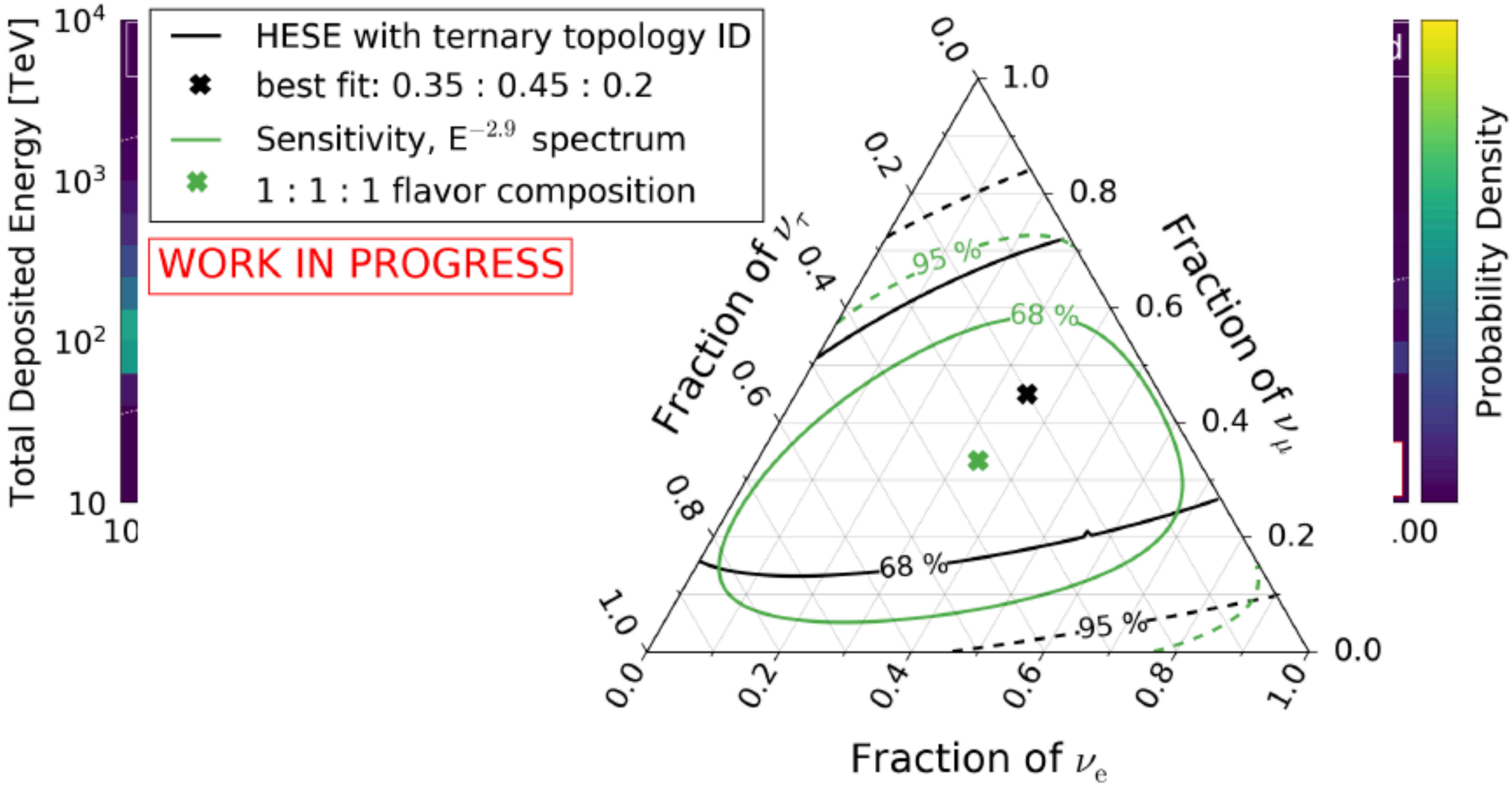
Veto and Self-veto



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



High-Energy Starting Events (HESE) – 7.5 yr



Solar Atmospheric Neutrino flux predictions

FJAWs (C. Argüelles et al. [astro-ph/1703.07798])

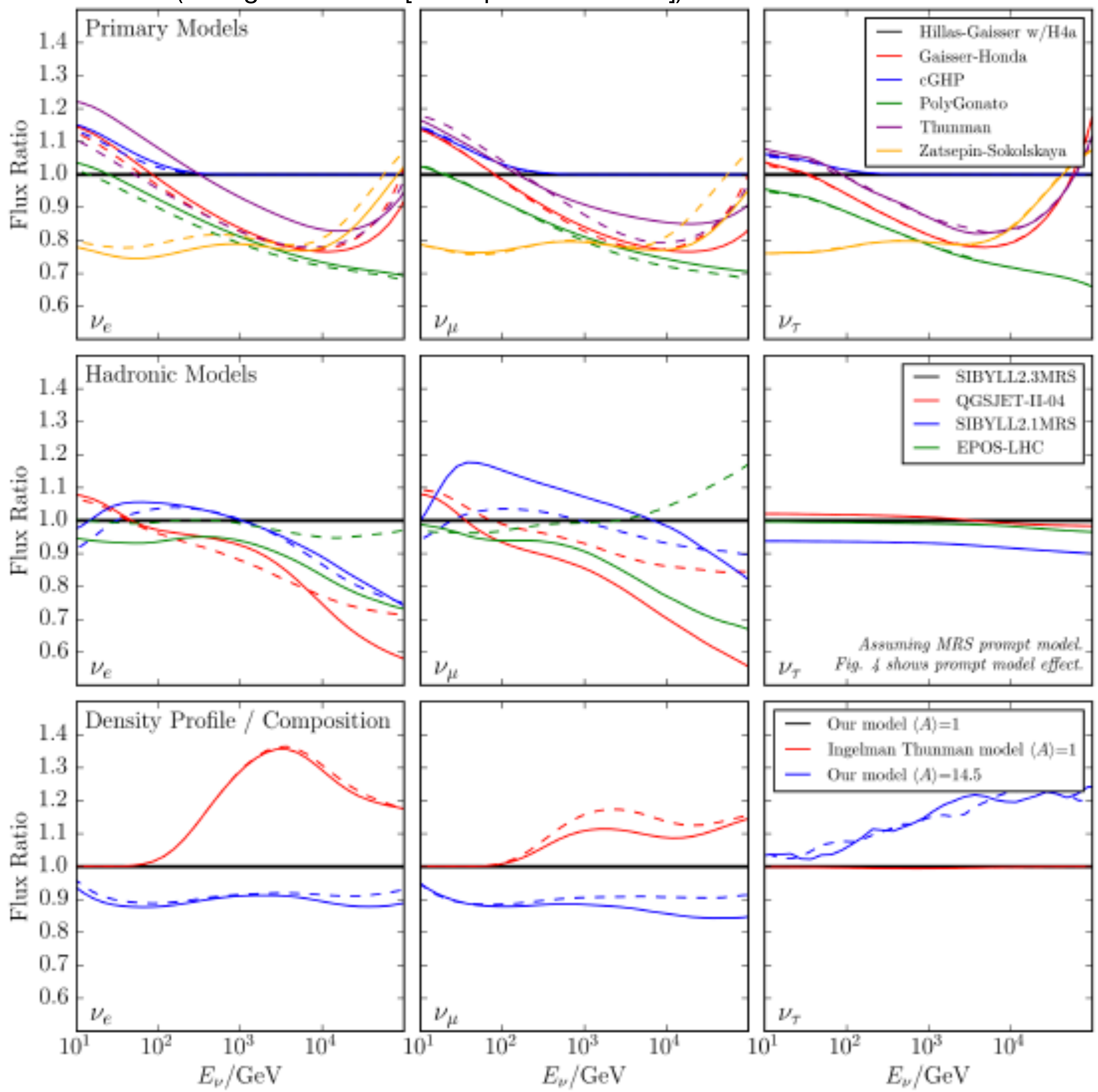
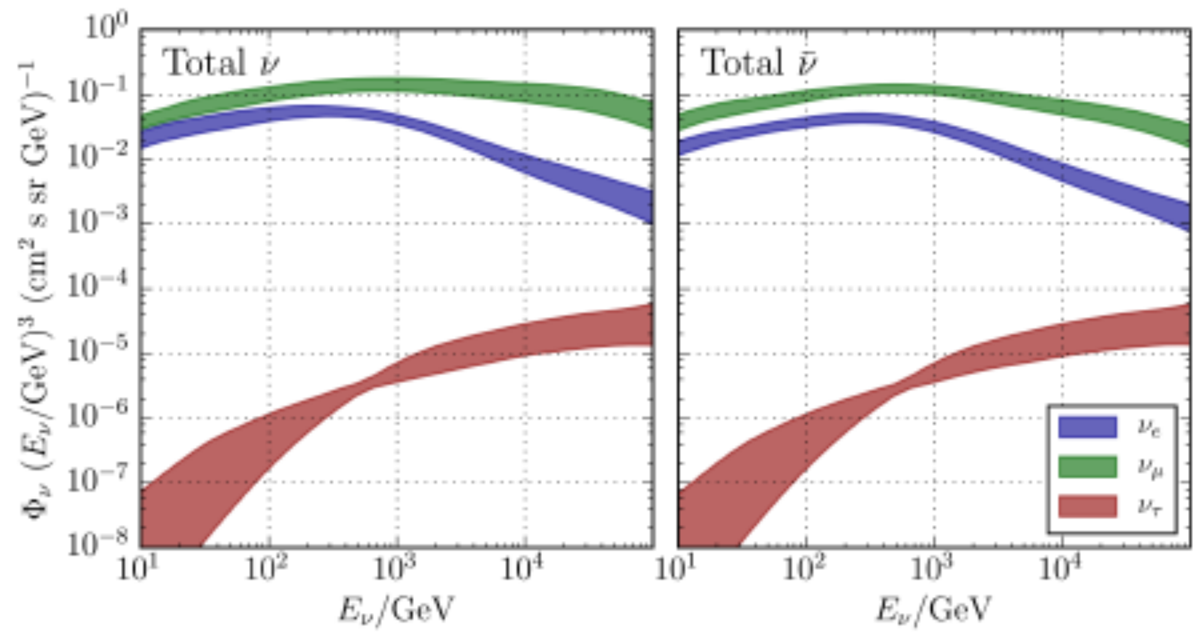


Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.



- Flux predictions vary by <30%, based on
  - primary models
  - hadronic models
  - extremal solar density and composition models

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]