High-energy Neutrinos and Multi-messenger Astroparticle Physics

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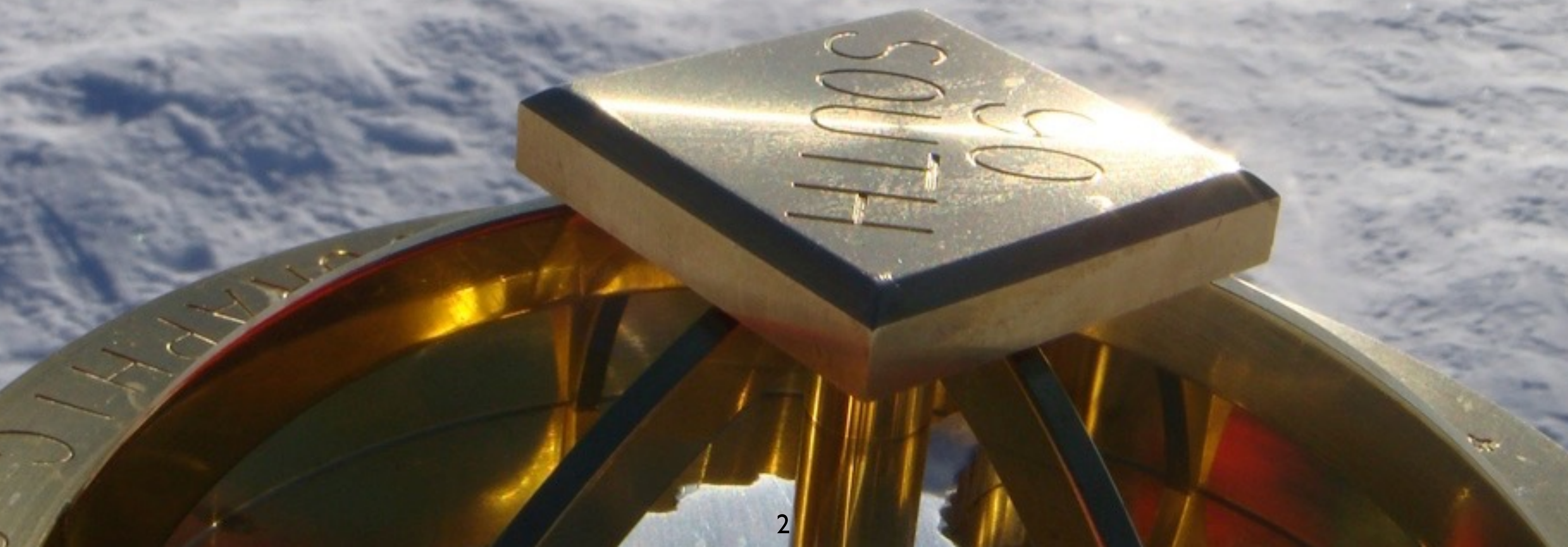
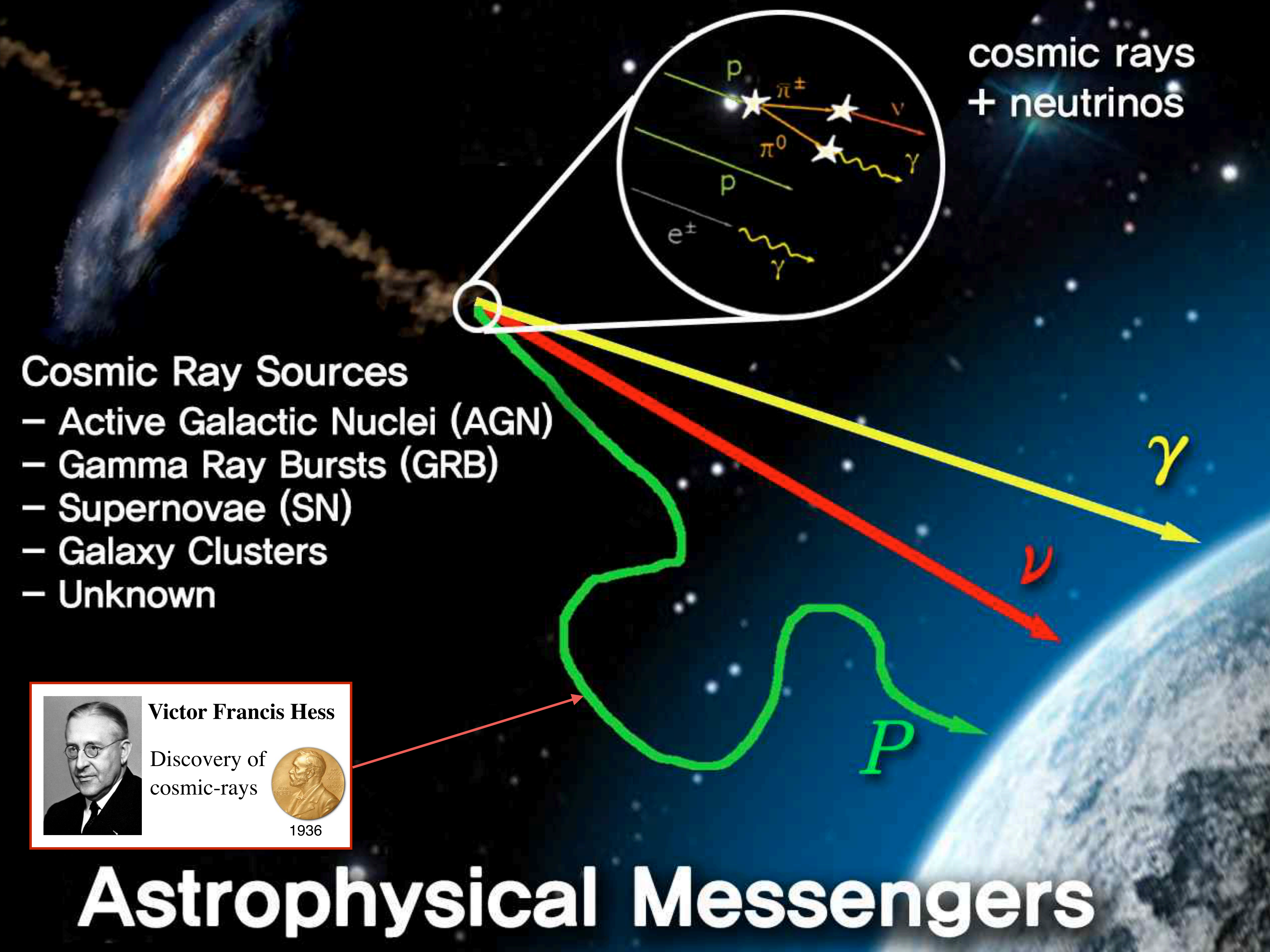
Outline

- Motivation
- Neutrino Telescopes and IceCube
- Search for Astrophysical Neutrinos
- Search for Physics Beyond the Standard Model
- Search for Solar Atmospheric Neutrinos
- Outlook and Conclusions

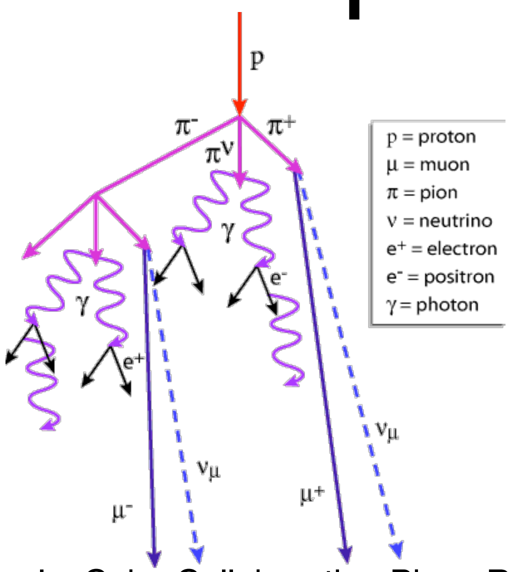


Motivation


cosmic rays
+ neutrinos
p
$\pi^\pm$
ν
π^0
γ
p
$e^\pm$
γ
Cosmic Ray Sources
– Active Galactic Nuclei (AGN)
– Gamma Ray Bursts (GRB)
– Supernovae (SN)
– Galaxy Clusters
– Unknown
γ
ν
P
Victor Francis Hess
Discovery of cosmic-rays
1936
Astrophysical Messengers

Sources of High Energy Neutrinos

Atmospheric Neutrinos

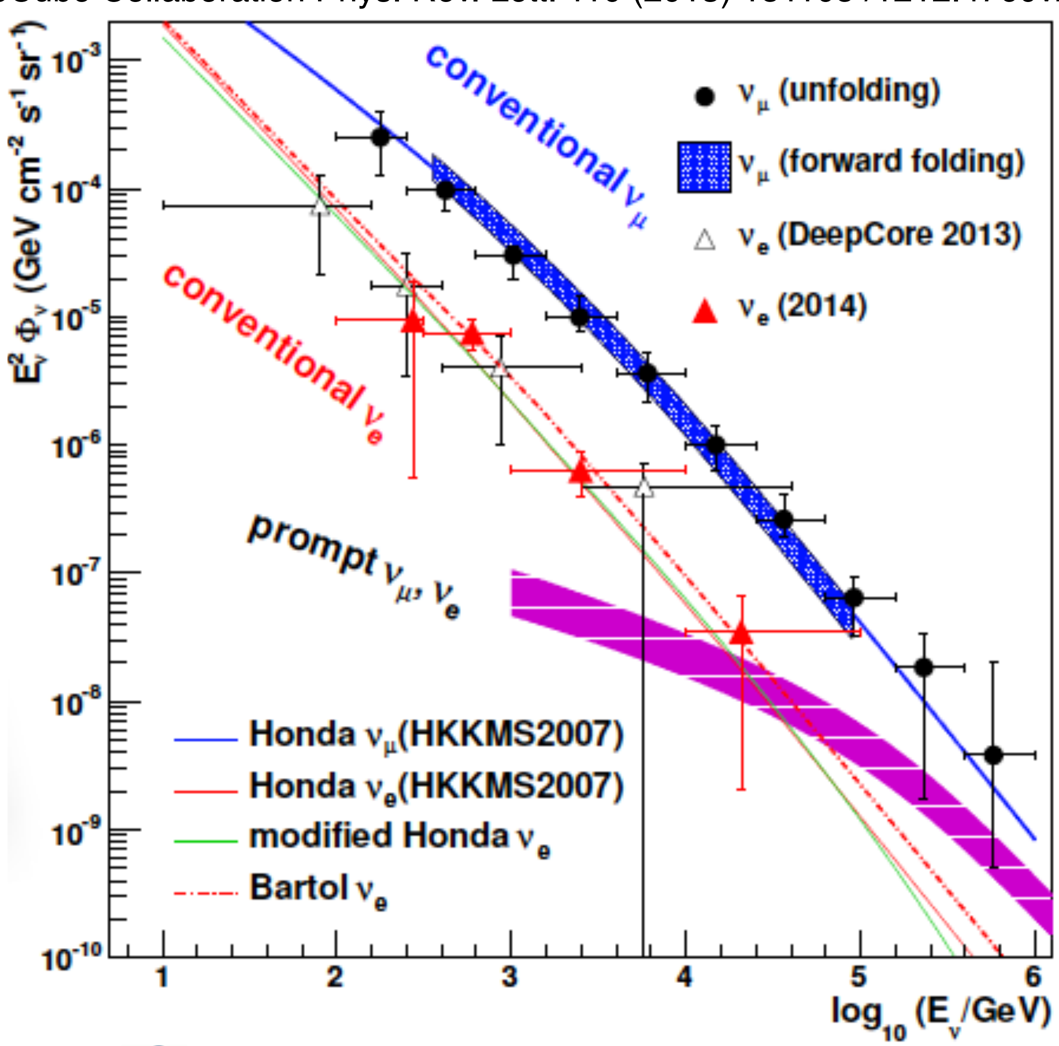


Cosmic rays interact in the upper atmosphere:

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

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

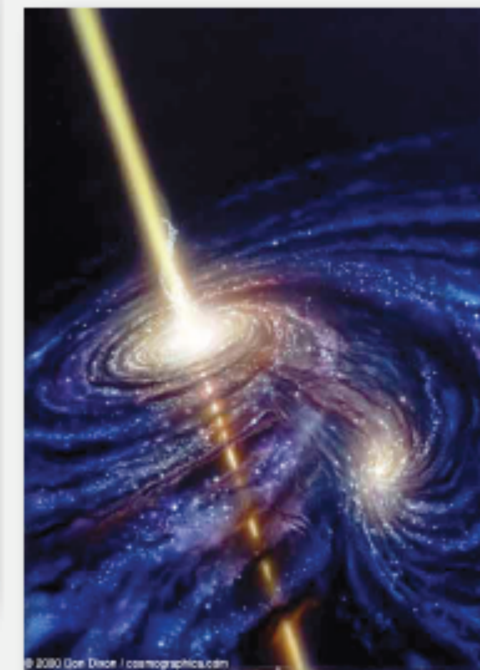
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



Astrophysical

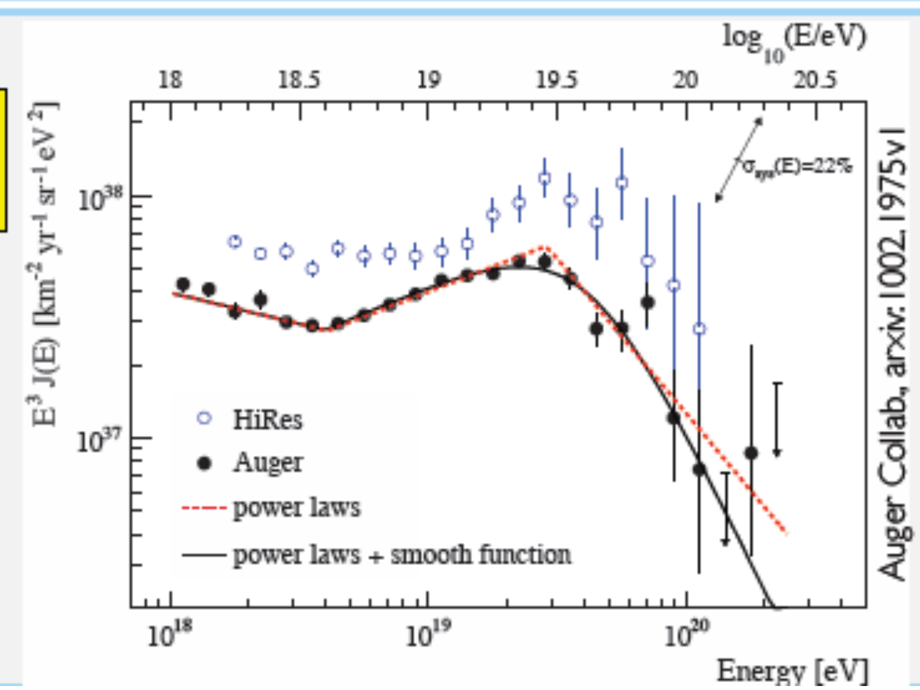
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Active Galactic Nuclei

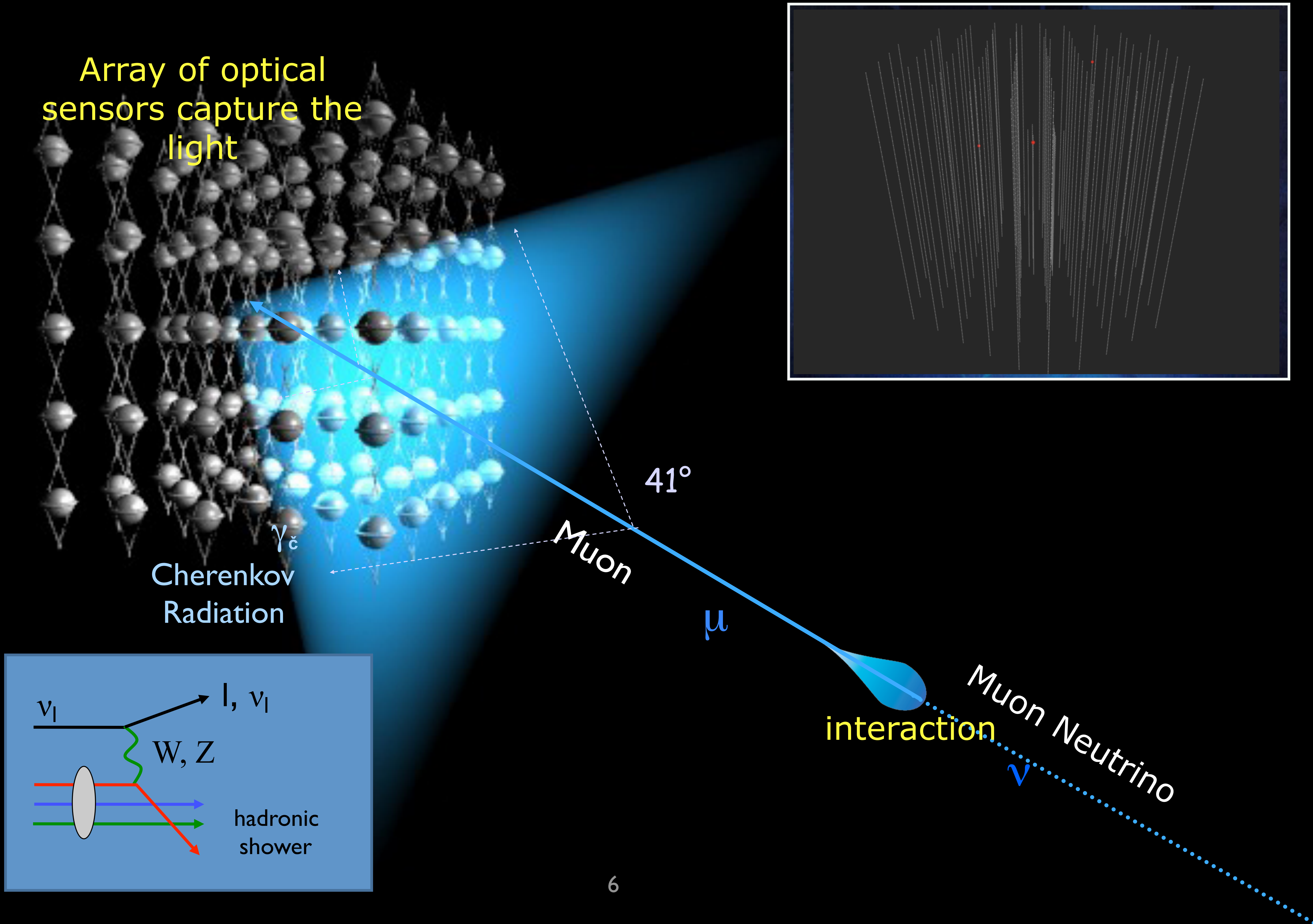


Gamma-ray Bursts

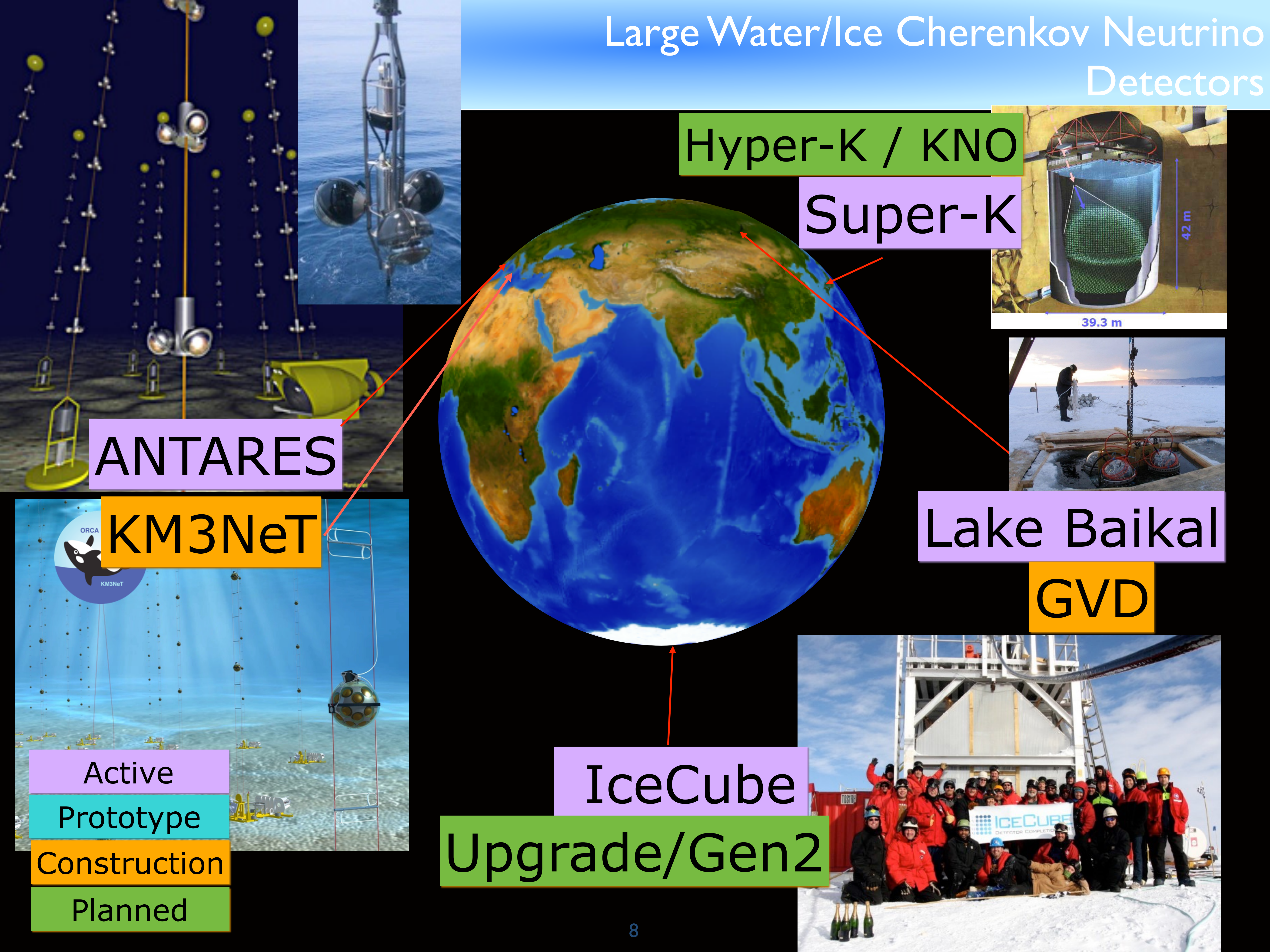
$p + \gamma_{3K} \rightarrow \Delta^+$ (GZK)



Principle of an optical Neutrino Telescope

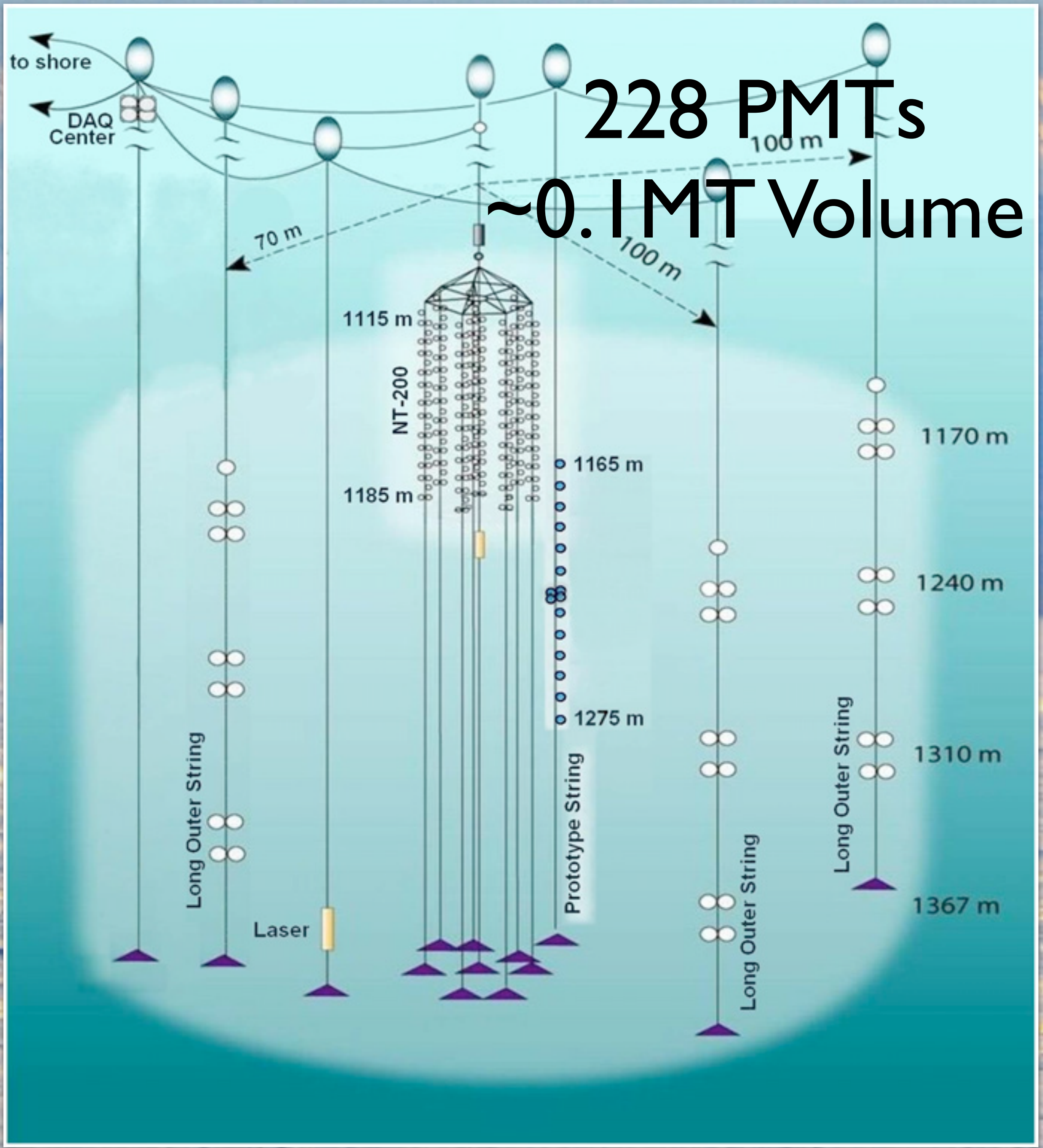


Neutrino Telescopes and IceCube


Large Water/Ice Cherenkov Neutrino Detectors
Hyper-K / KNO
Super-K
42 m
39.3 m
ANTARES
ORCA
KM3NeT
KM3NeT
Lake Baikal
GVD
IceCube
Upgrade/Gen2
ICECUBE
Active
Prototype
Construction
Planned

Lake Baikal

arXiv:astro-ph/0609743

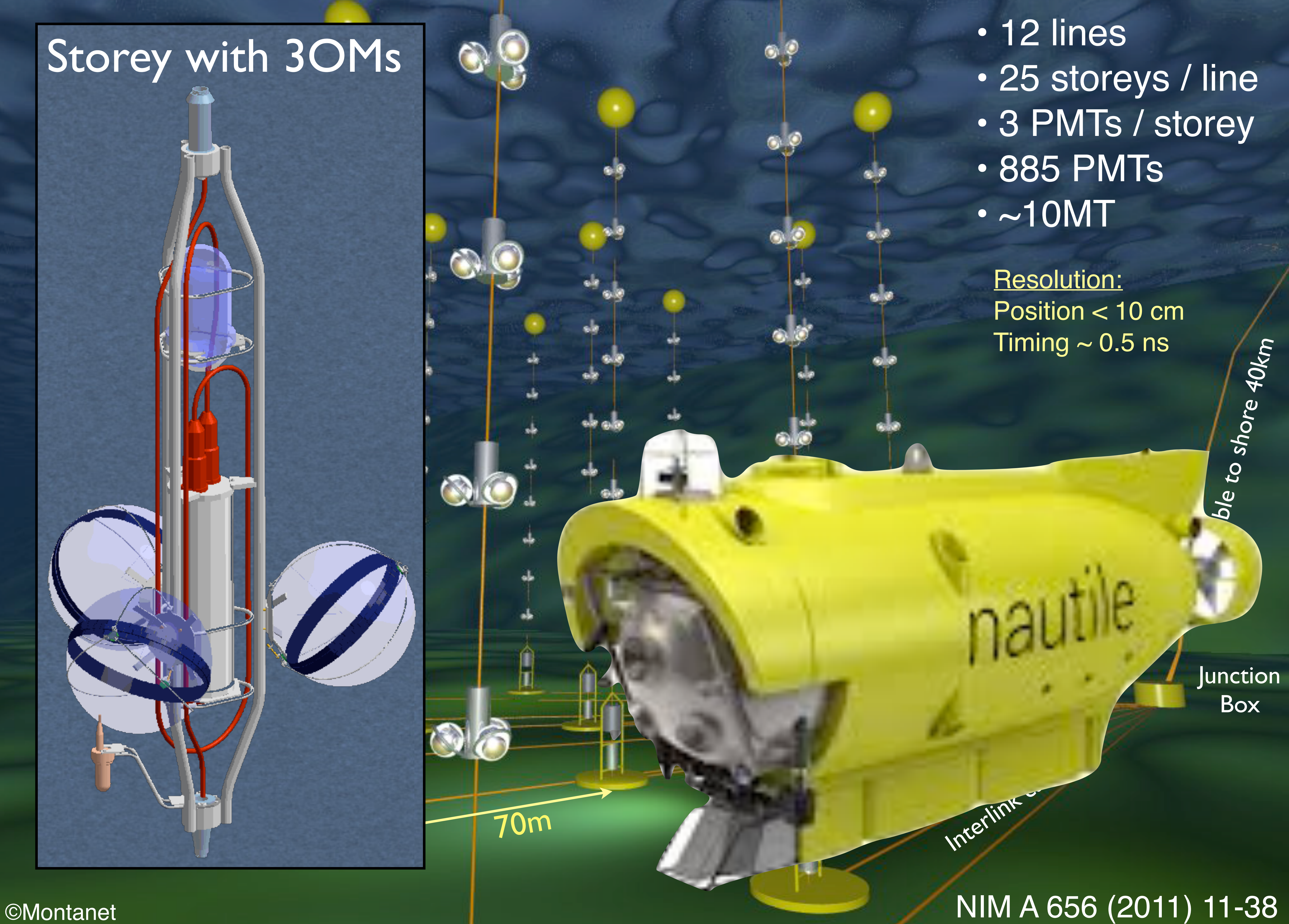


228 PMTs
~0.1MT Volume

Baikal-GVD
First cluster deployed in April 2015
Plan: 8-12 such arrays

Storey with 3OMs

- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs
- ~10MT



NIM A 656 (2011) 11-38

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since 2013
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Universiteit Gent
Vrije Universiteit Brussel
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SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität
Erlangen-Nürnberg
Humboldt–Universität zu Berlin
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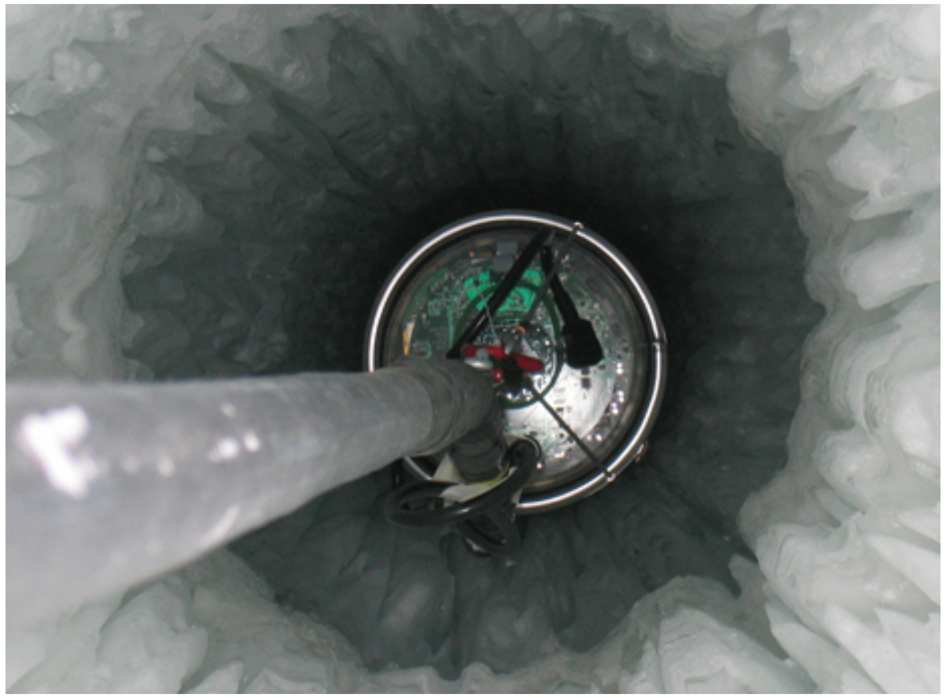
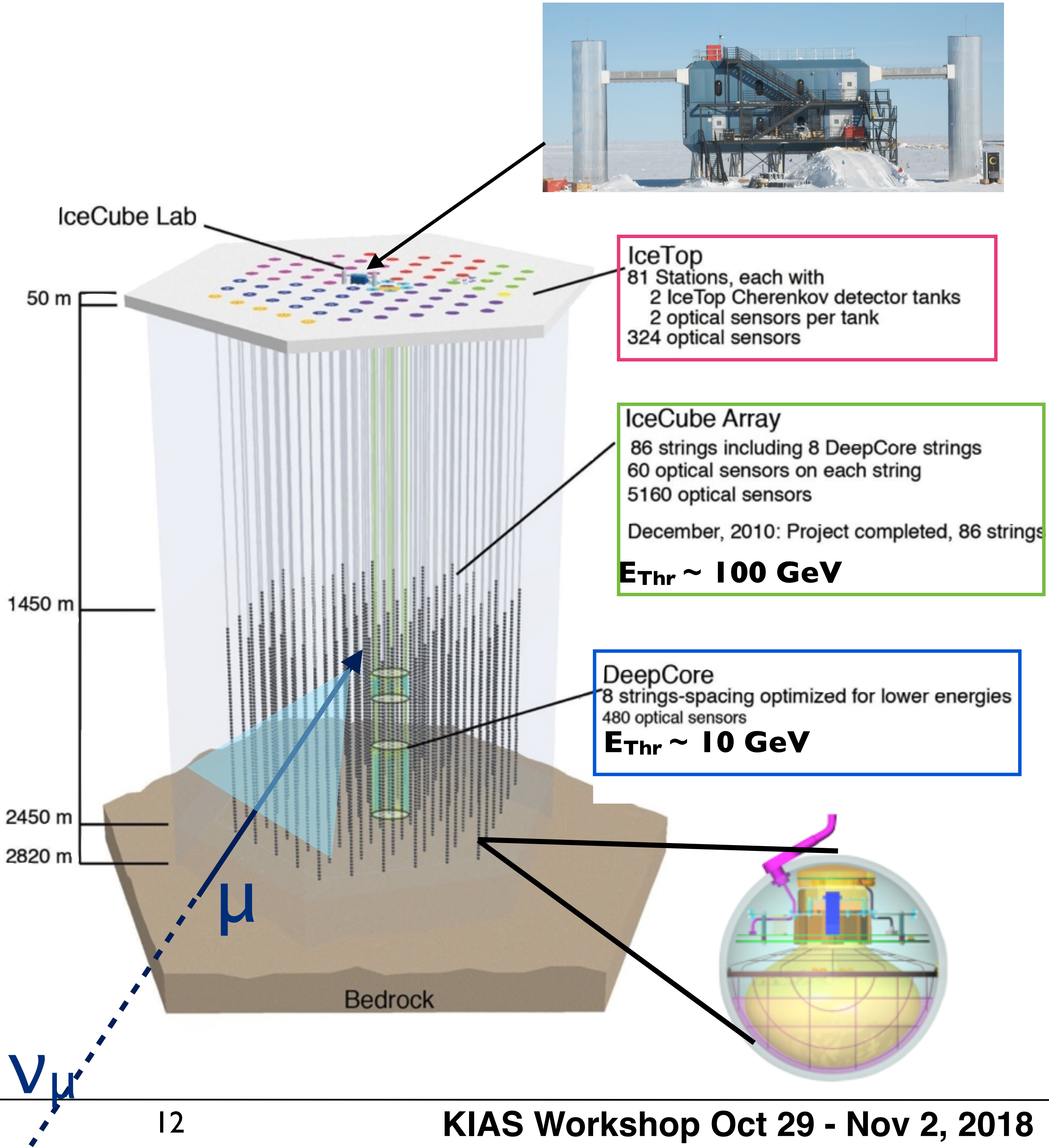
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

The IceCube Neutrino Telescope

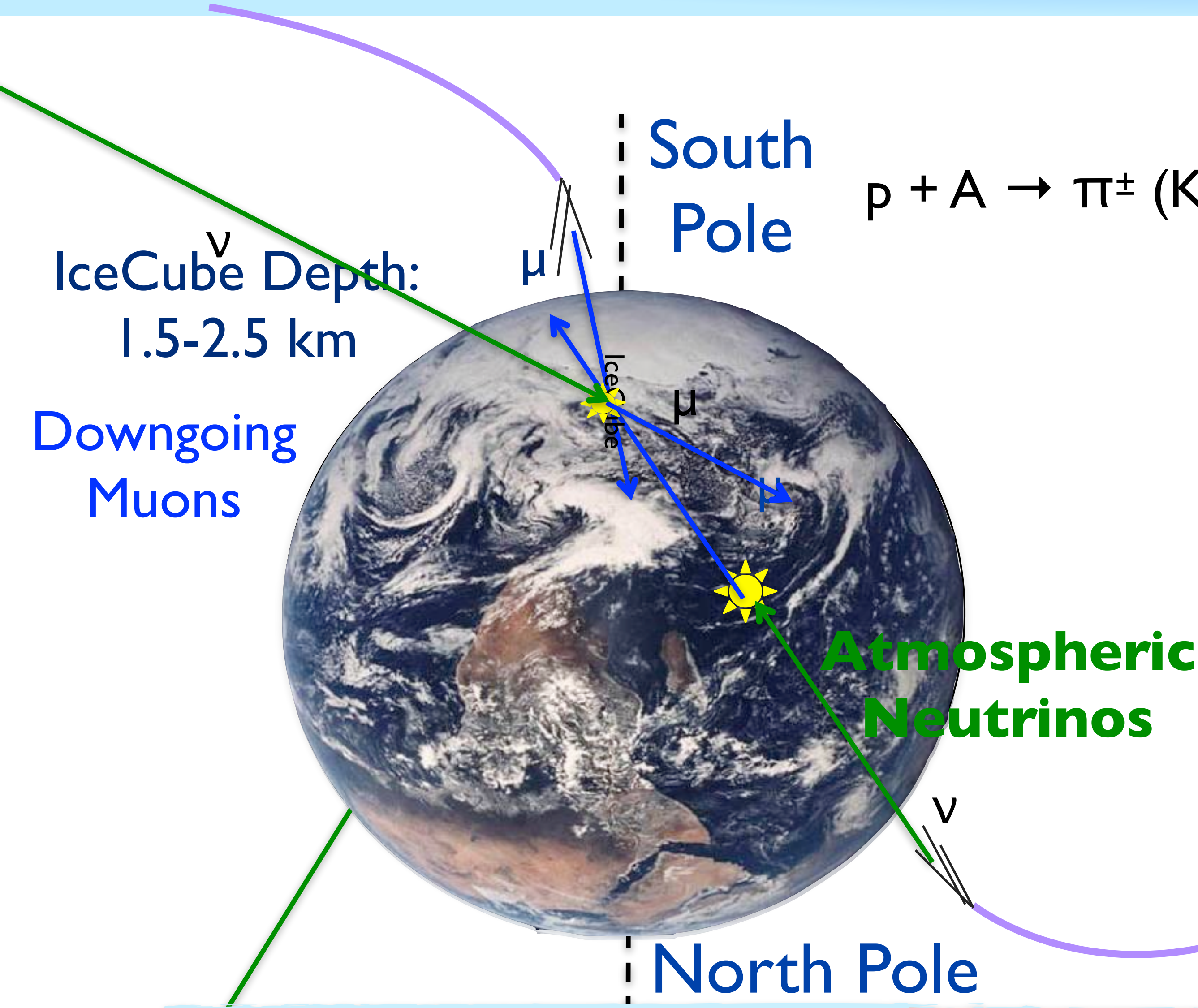
- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction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

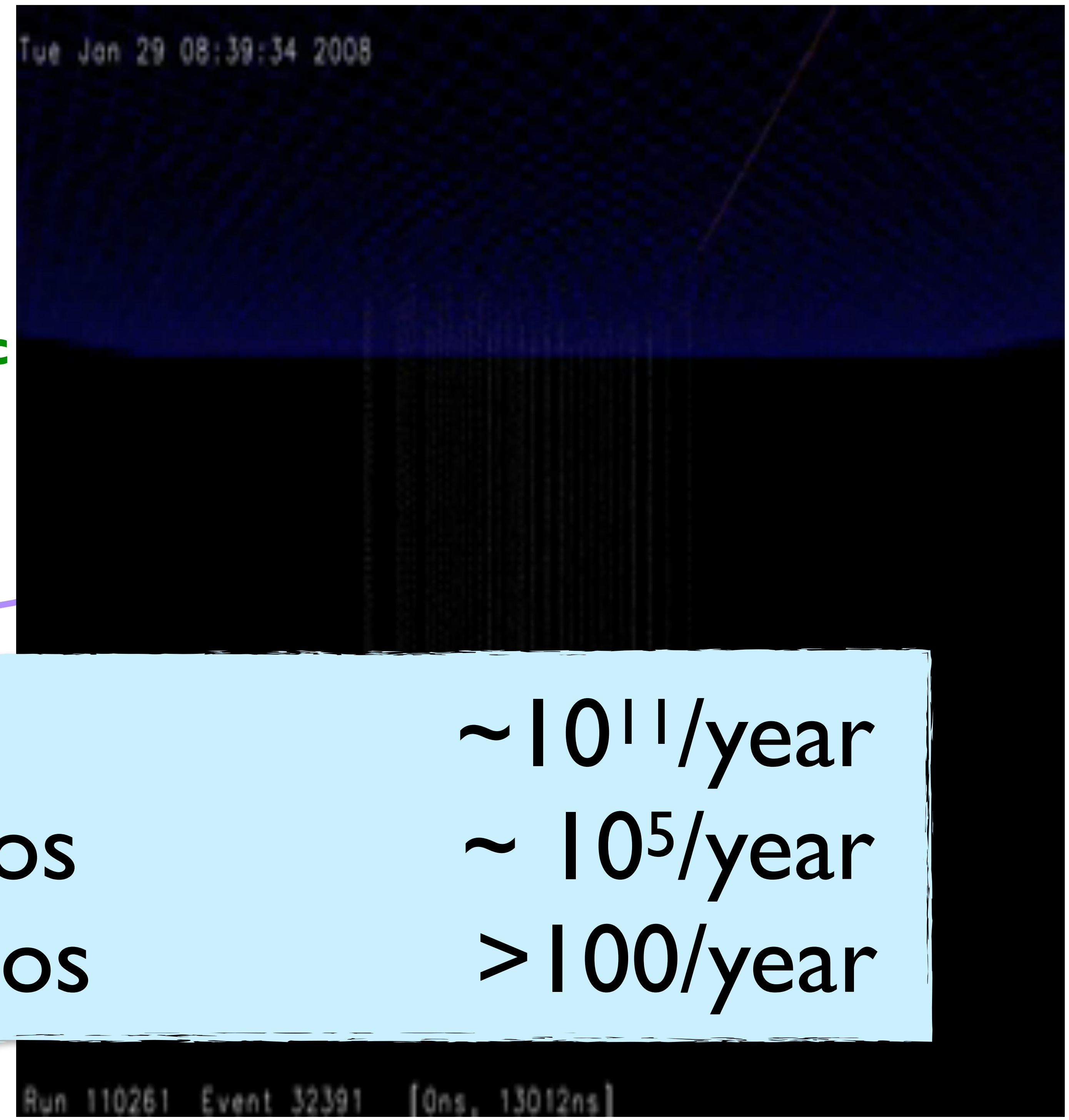




Signals in IceCube

p + A → π± (K±) + other hadrons ... $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$



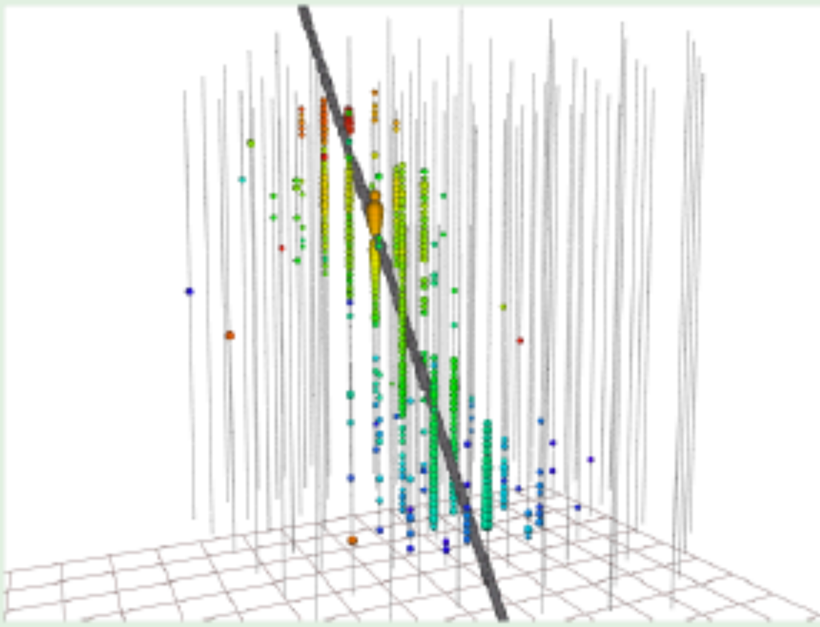


Atmospheric muons	~10^{11}/year
Atmospheric neutrinos	~ 10^5/year
Astrophysical neutrinos	>100/year

irreducible neutrino background to extra terrestrial neutrino fluxes

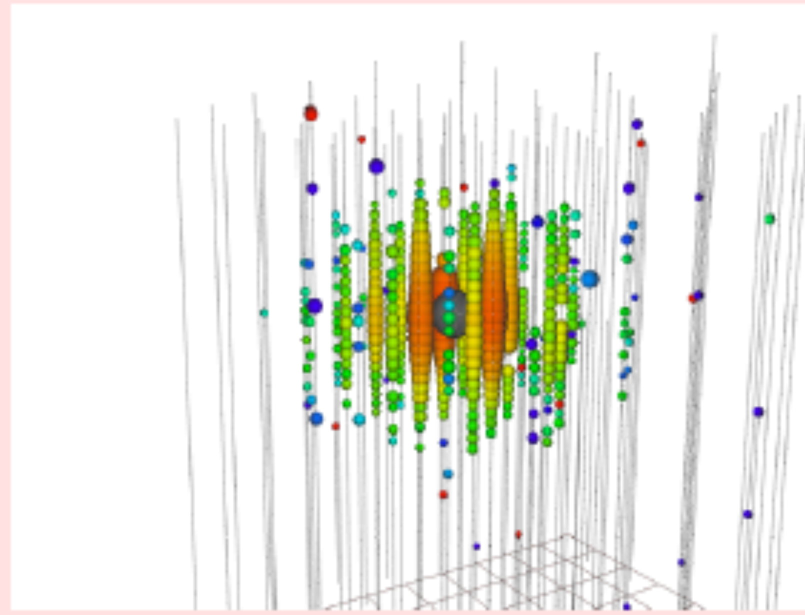
Event topologies in IceCube

Track



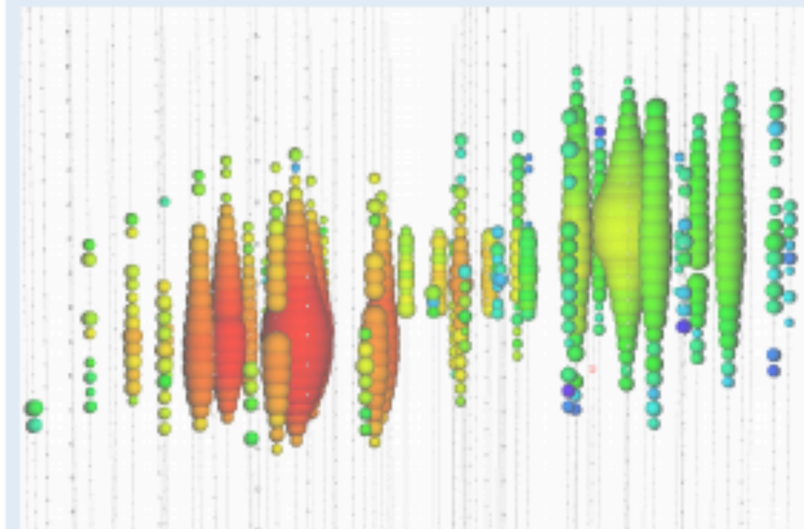
- Muon tracks (CC ν_μ)
- Resolution $< 1^\circ$
- Large energy uncertainties

Cascade

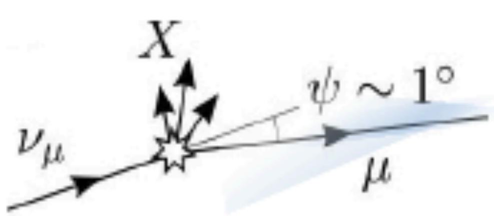


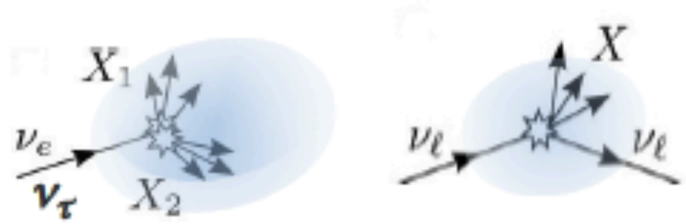
- NC or ν_e/ν_τ
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$

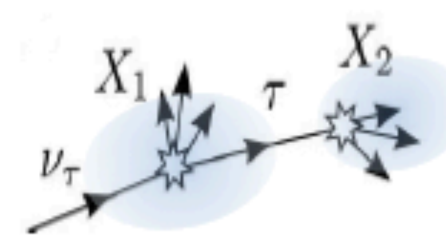
Double-bang



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

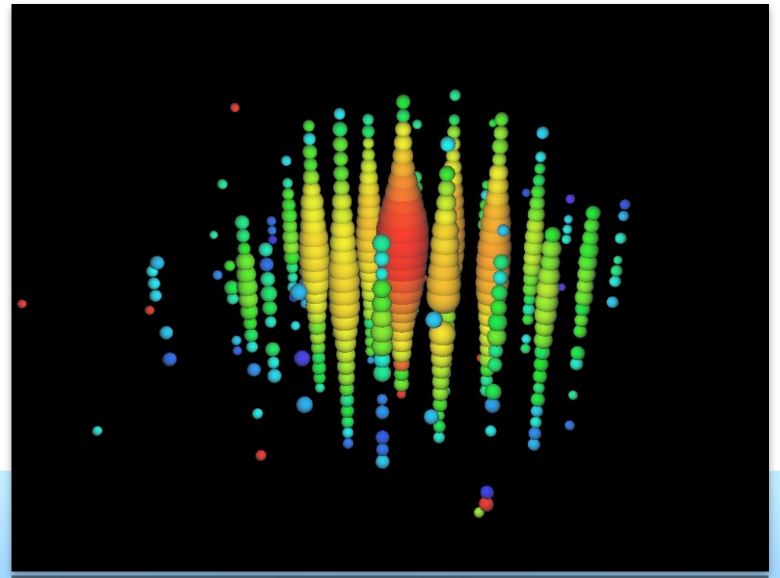






early  late

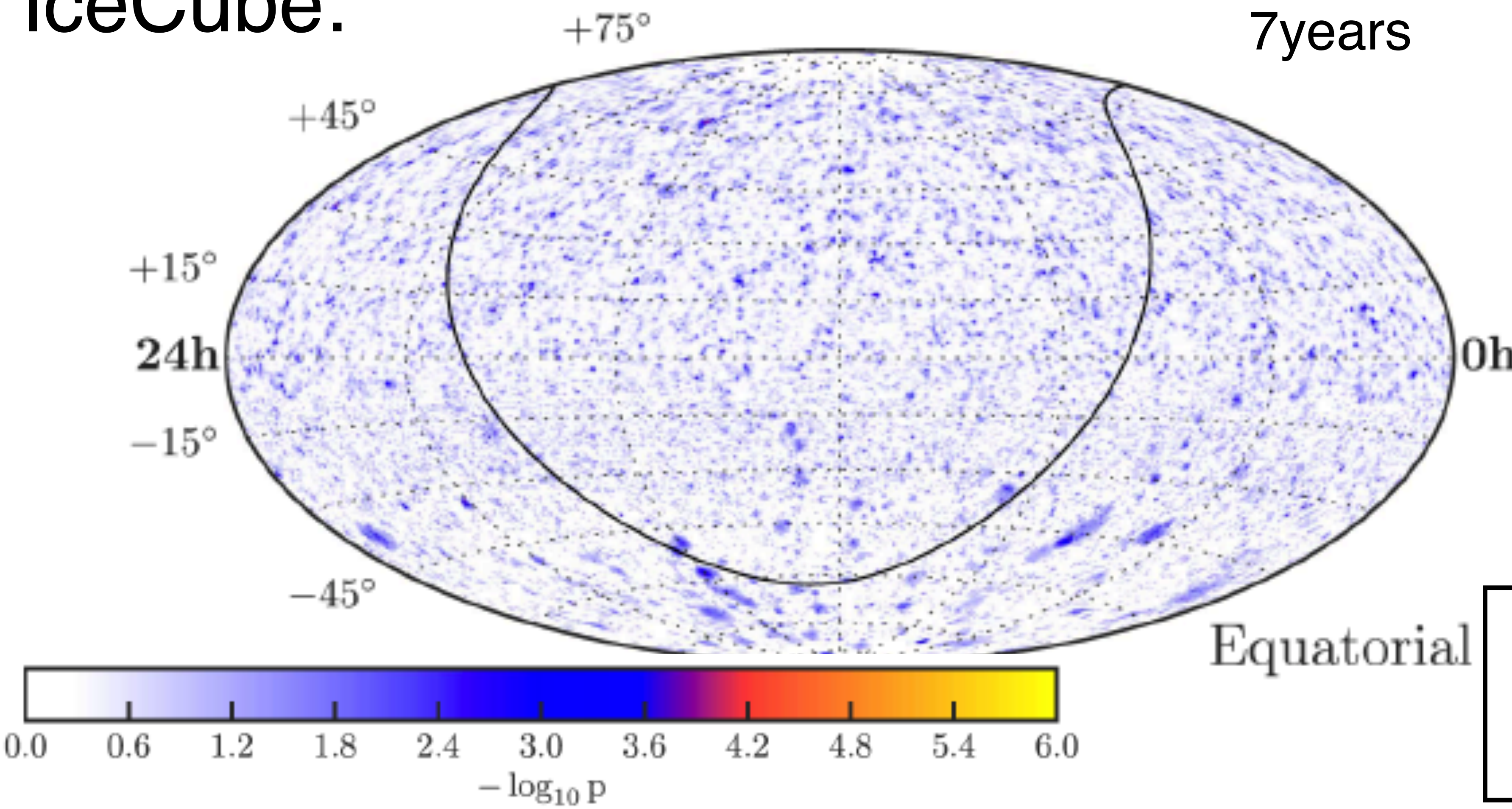
amount of light in detector ∝ ν energy



Astro-physical Neutrino Search

IceCube:

7years



No significant PS reported

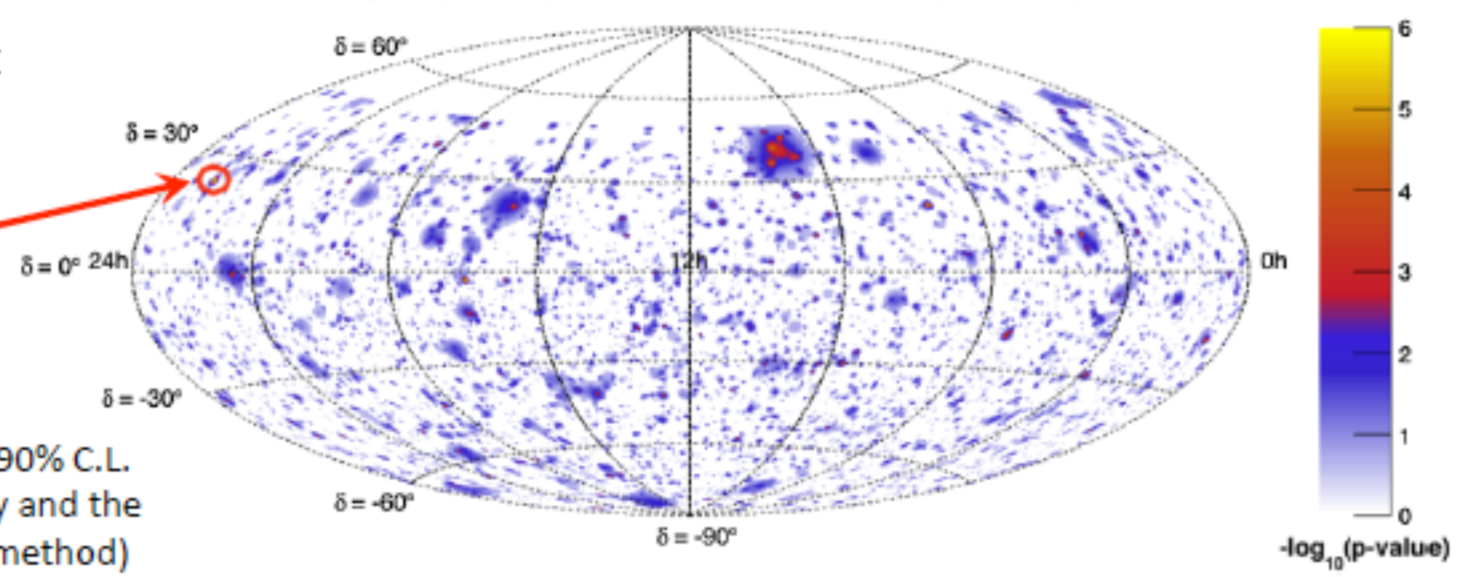
No correlation with list of 74 sources in both hemispheres. Galactic & Extragalactic

Most recent data periods:
~80k nothern hemisephere evt/yr (atm ν)
~35k southern hemisepher evt/yr (atm μ)
~200 starting tracks. Southern sky

ANTARES:

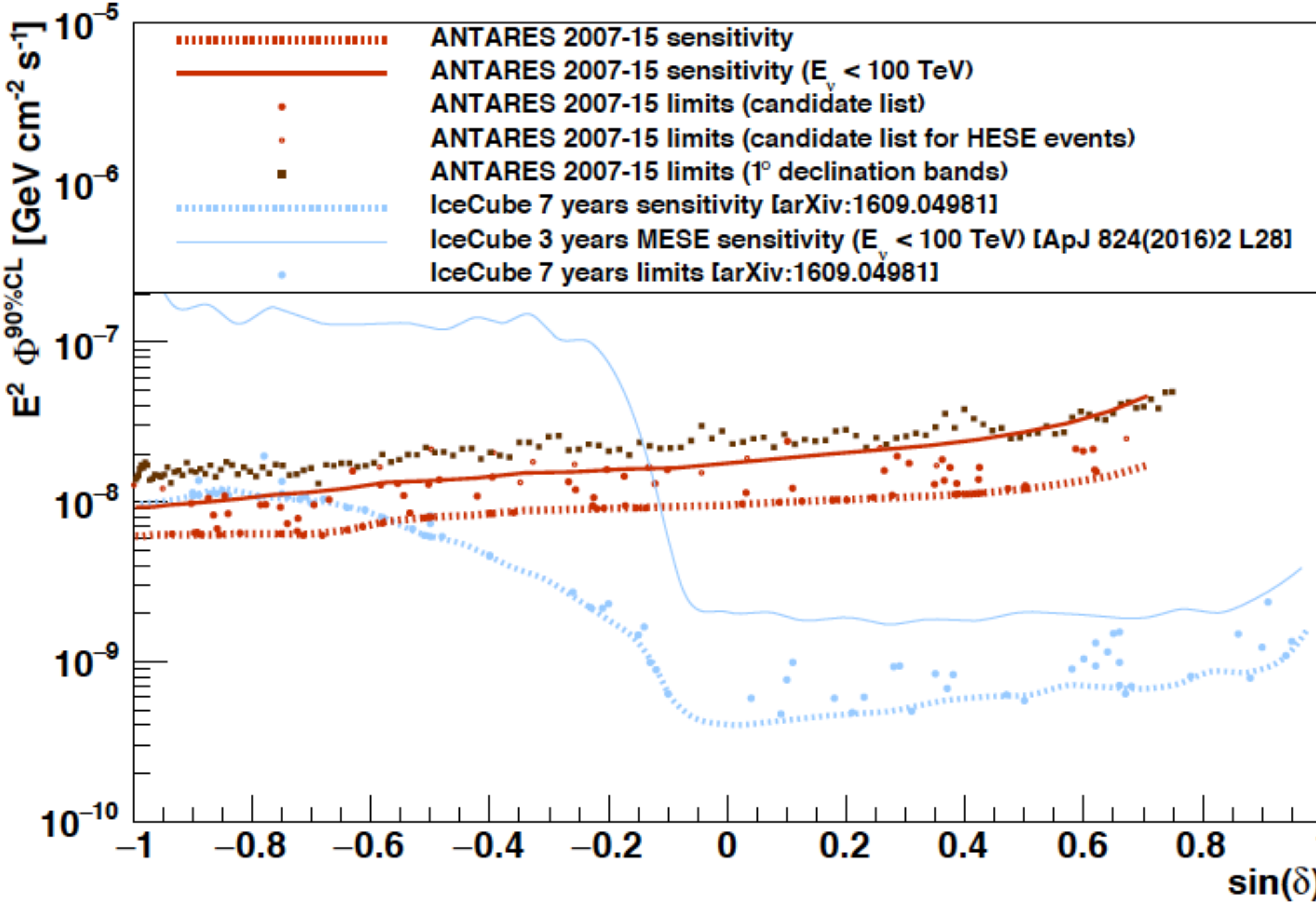
Most significant cluster c
the full-sky search (1.9σ
post-trial significance)
$\alpha = 343.8°$ $\delta = 23.5°$

Sky map in equatorial coordinates of pre-trial p-values

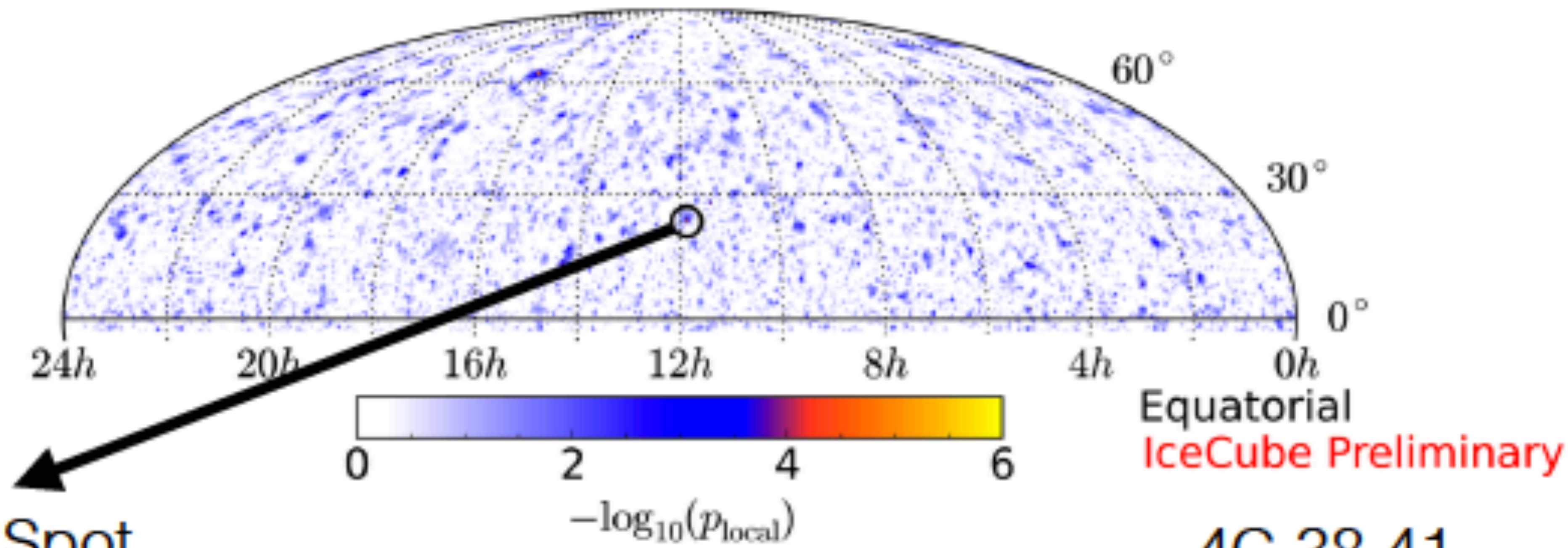


Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

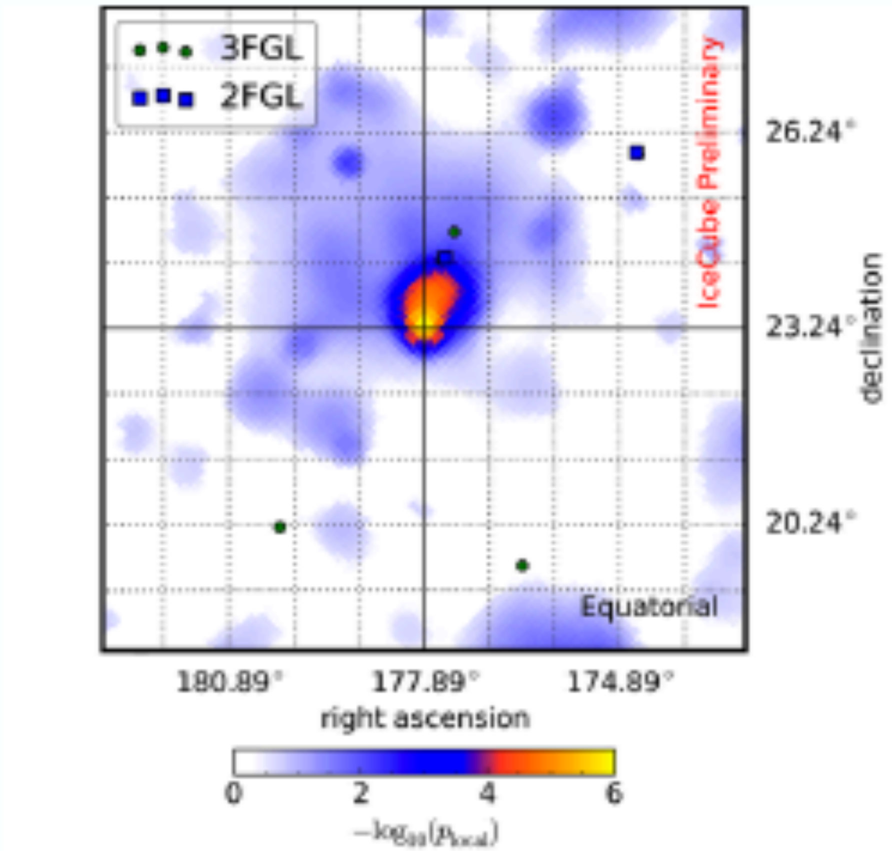
Constraints on point sources



IceCube 8-years Point Source Search - Northern Sky (steady state)



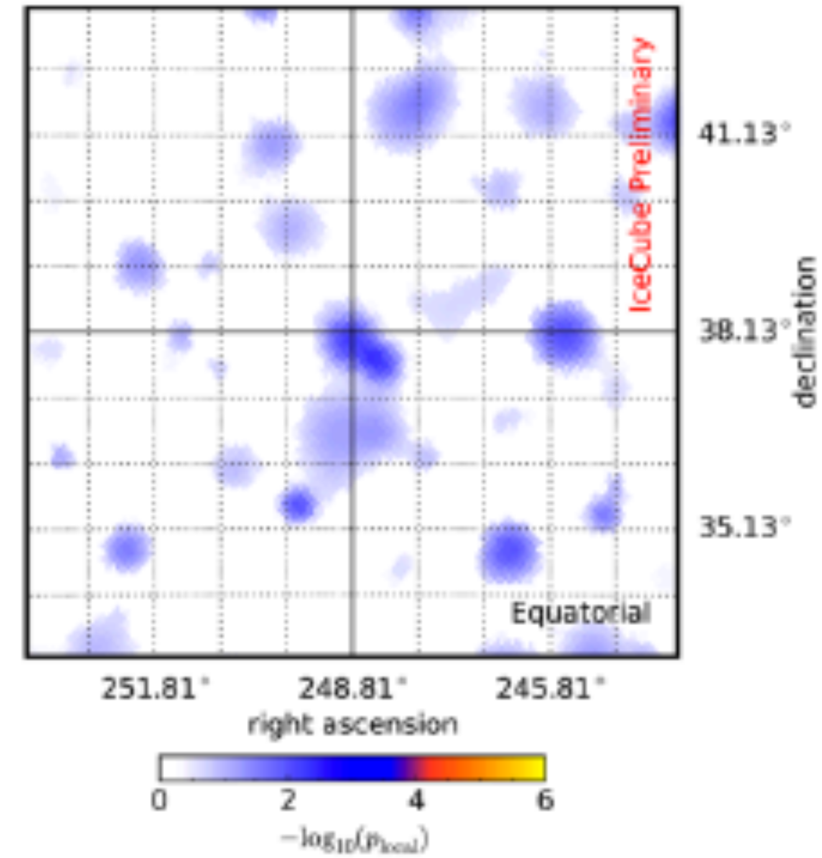
Hottest Spot



$p_{\text{post-trial}}$ = 26%

Best candidate from catalog search of 34 sources

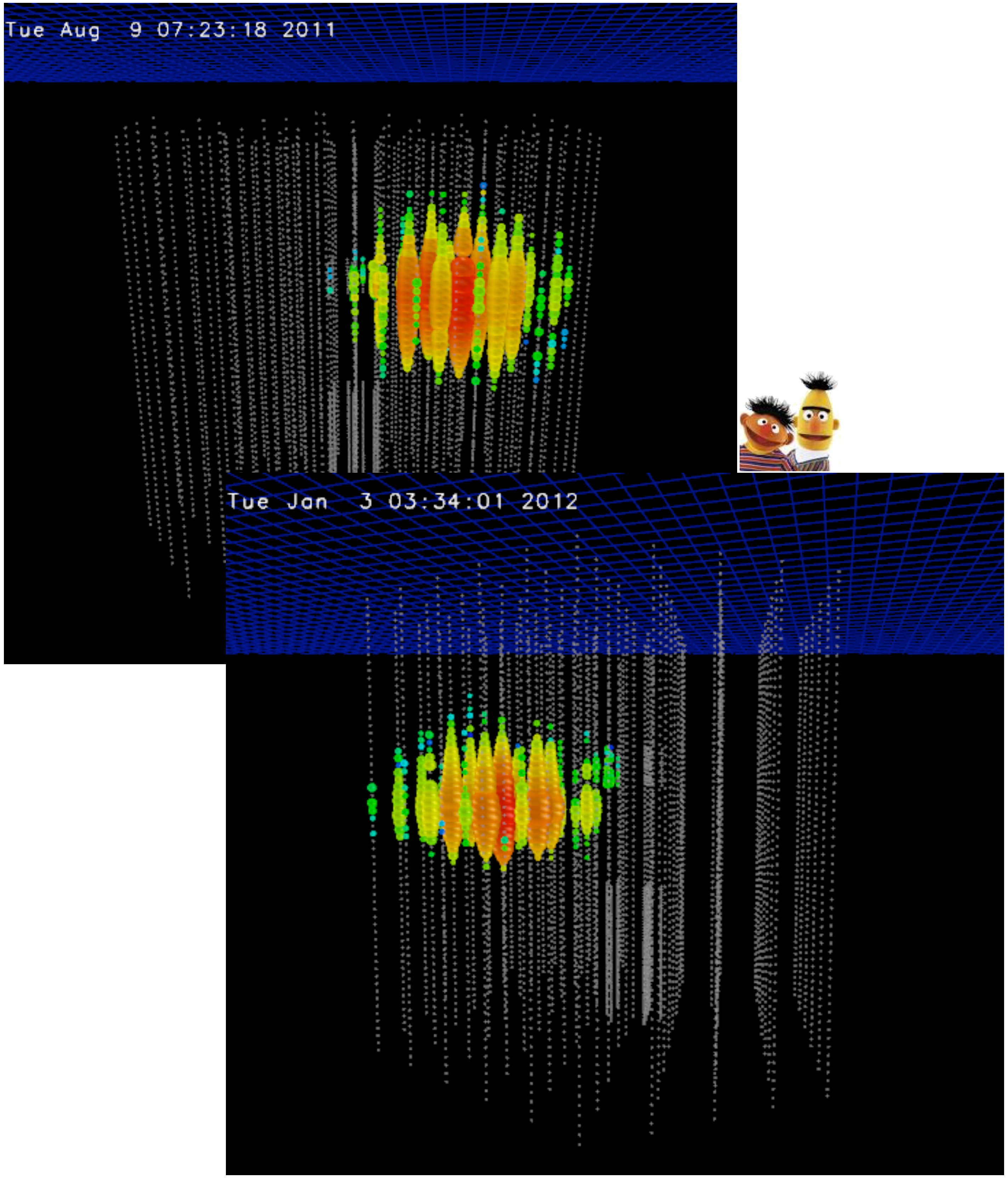
4C 38.41



$p_{\text{post-trial}}$ = 20%

Search for highest energy neutrinos

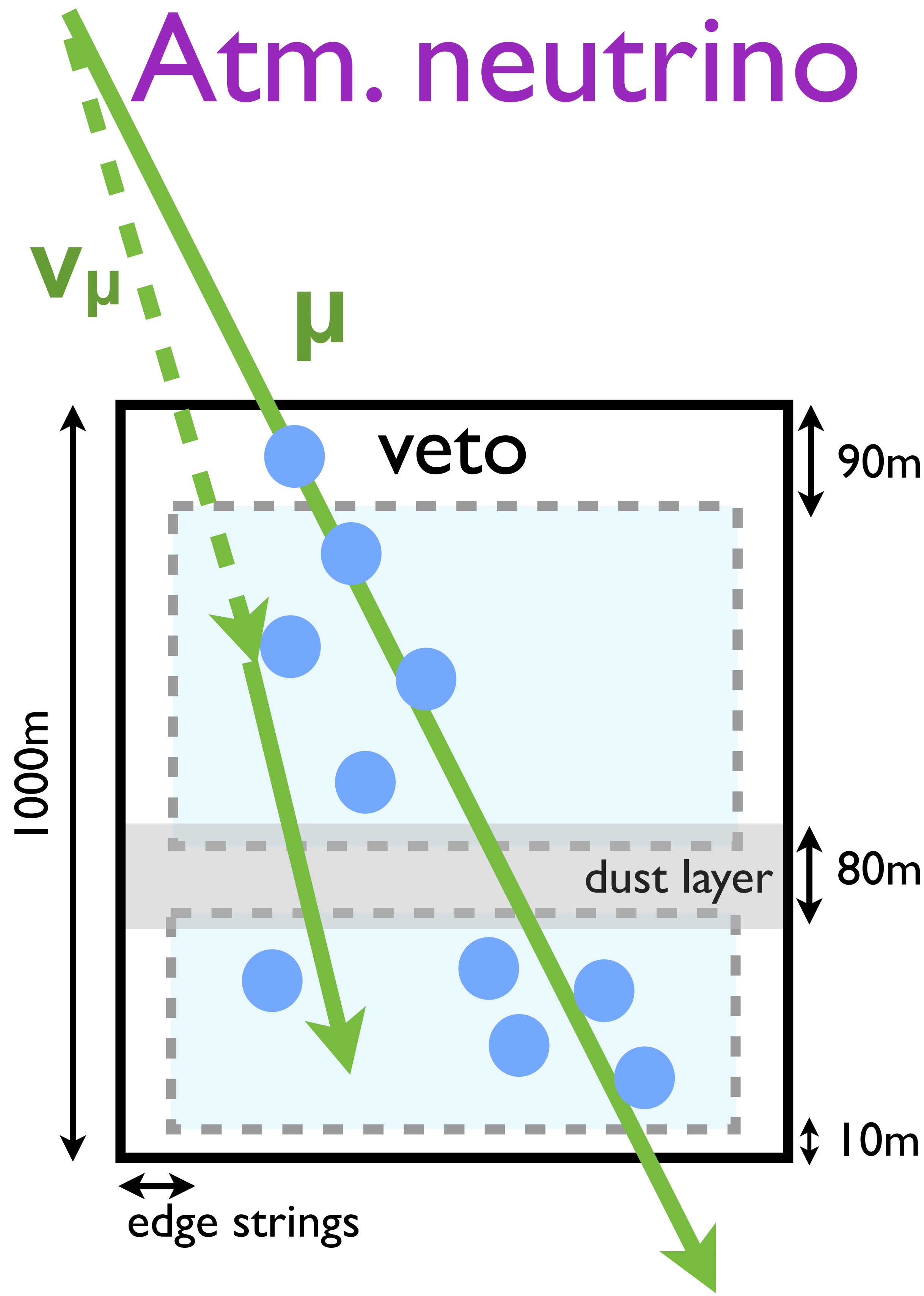
IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



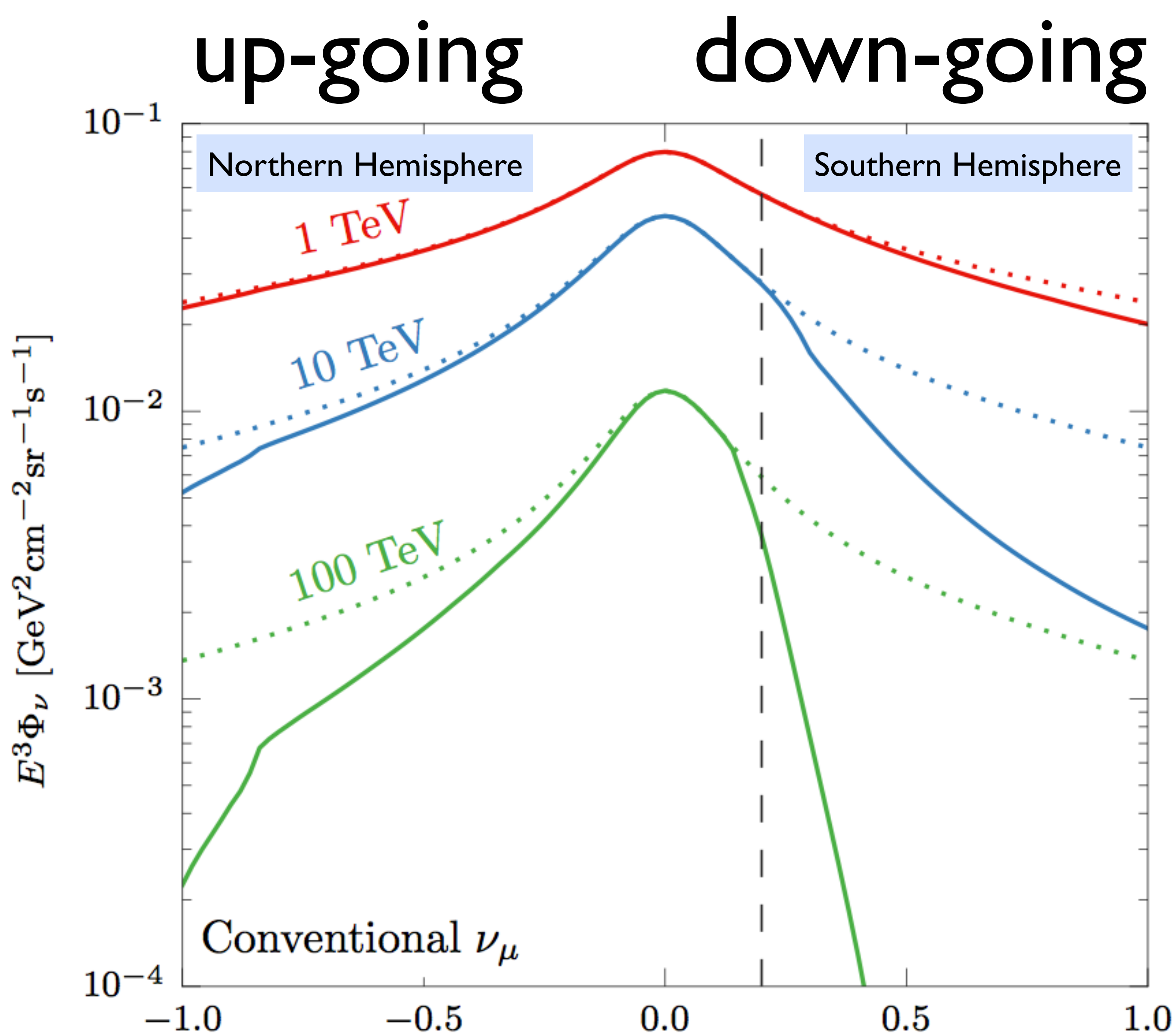
In two years of data expect 0.08 events at high energies, but observed 2 events !!

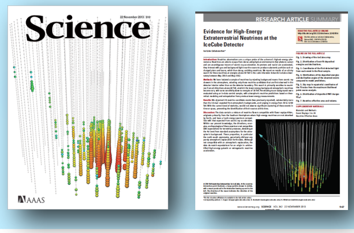
- Ernie ~1.15 PeV (~1.9 $\cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~1.7 $\cdot 10^{-4}$J)
- Topology of the events - cascades
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

Veto and Self-veto



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

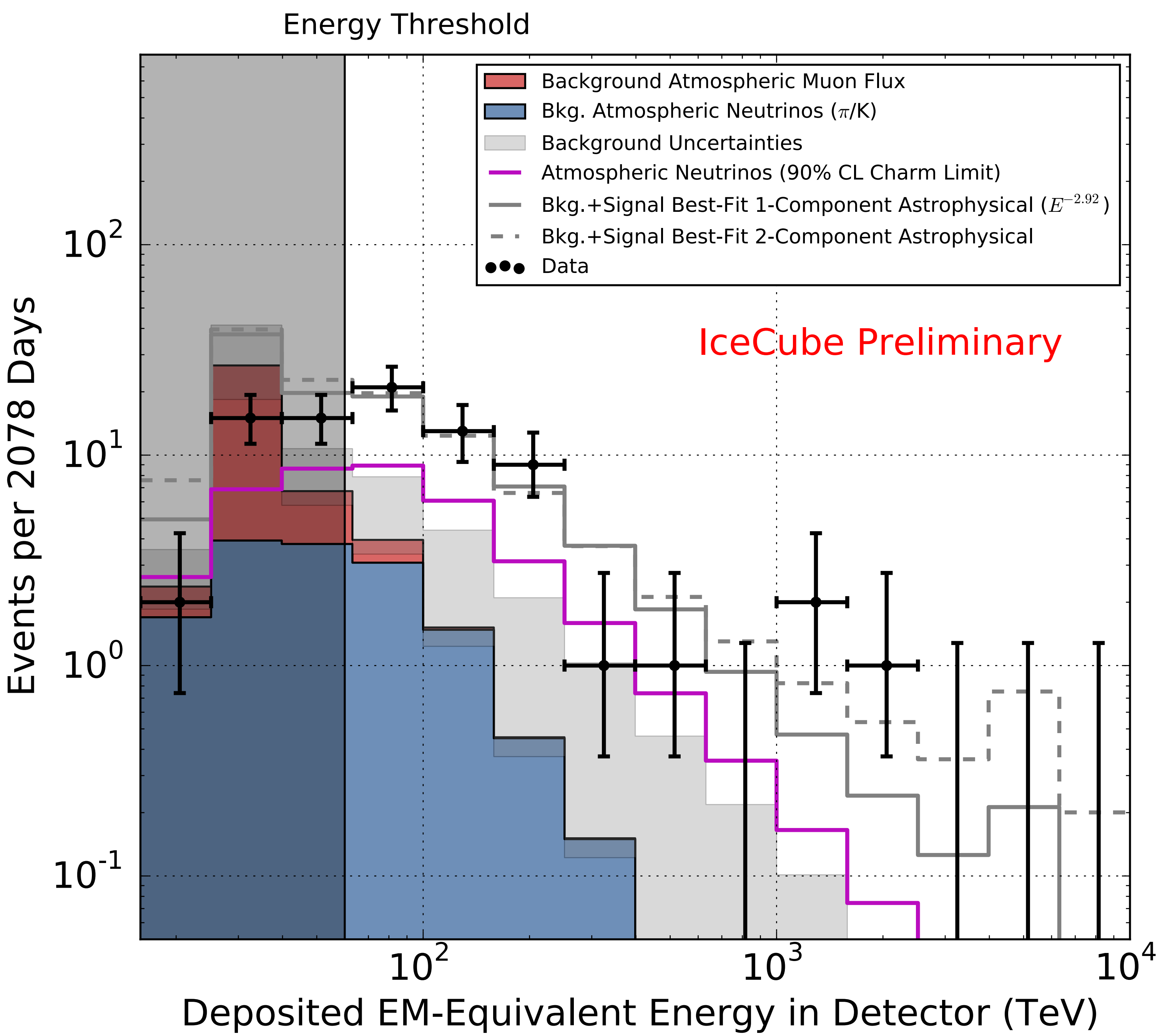


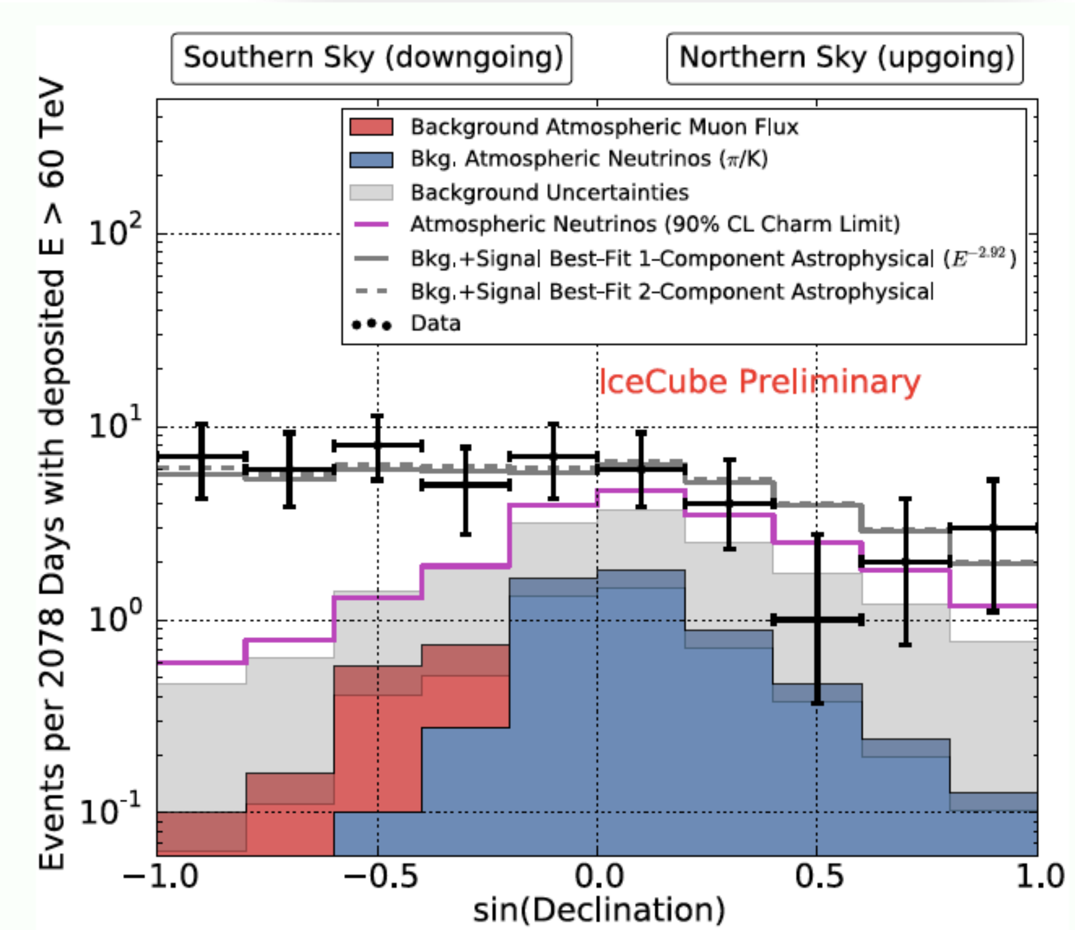


High-energy neutrino search 6years

HESE 6yrs 80 events (track-like & showers) observed

Expected from the Earth atmosphere ~41events

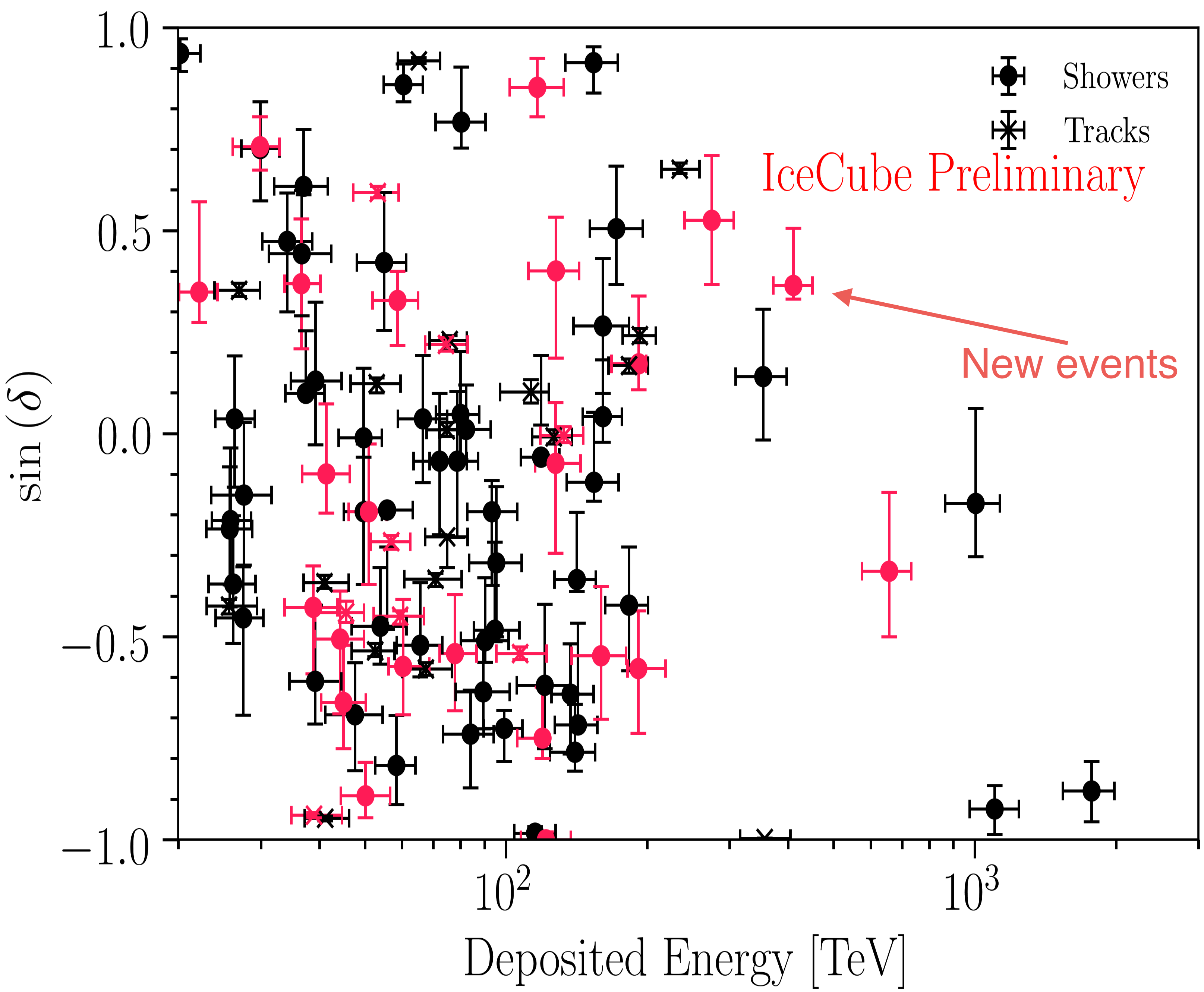




Best fit spectral index ($E^{-\gamma}$):
$\gamma=-2.92^{+0.33}_{-0.29}$

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

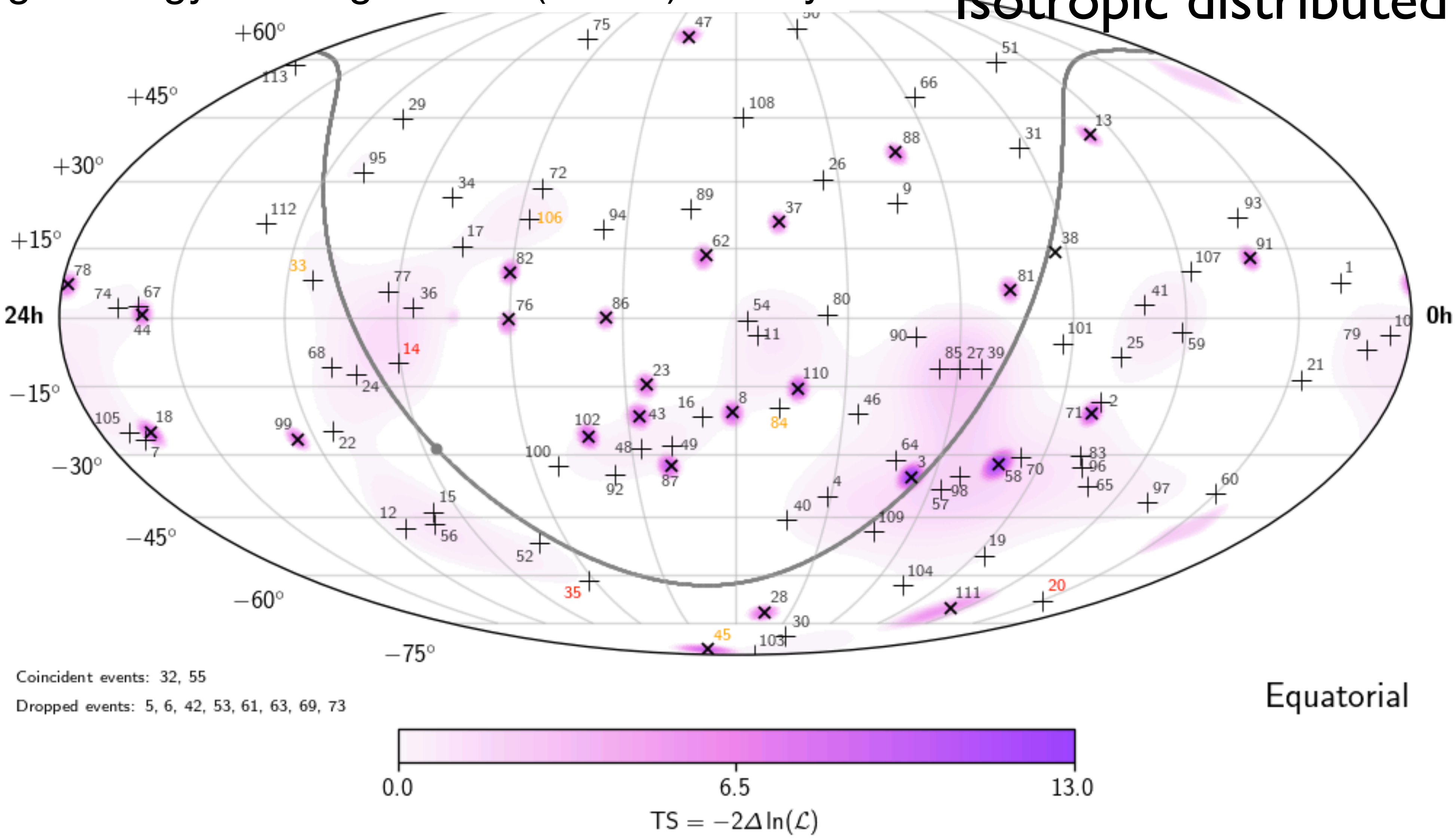


Arrival directions (highest energy events)

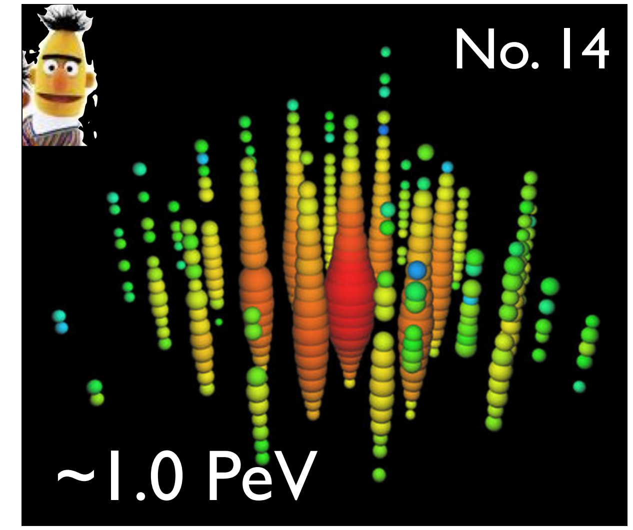
IceCube Collaboration, *Science* 342, 1242856 (2013)

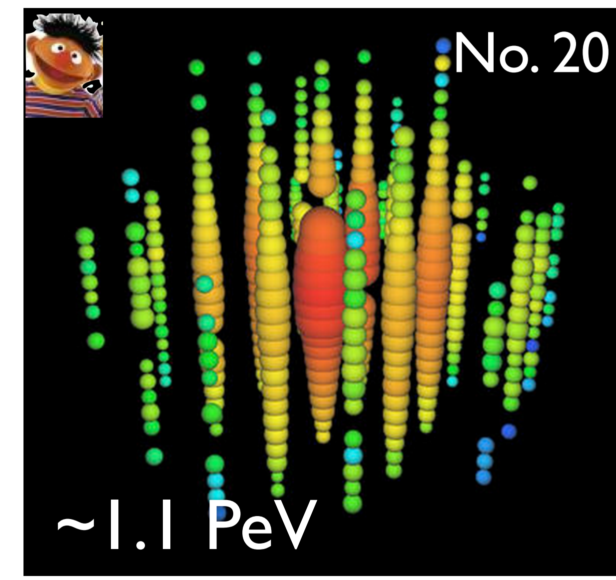
High-Energy Starting Events (HESE) – 7.5 yr

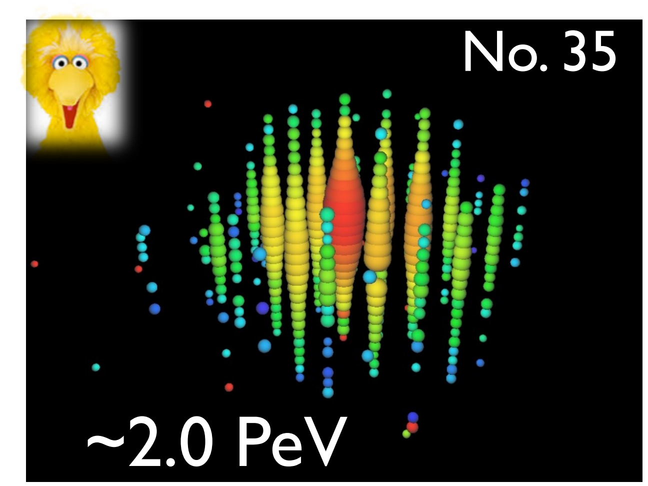
Isotropic distributed

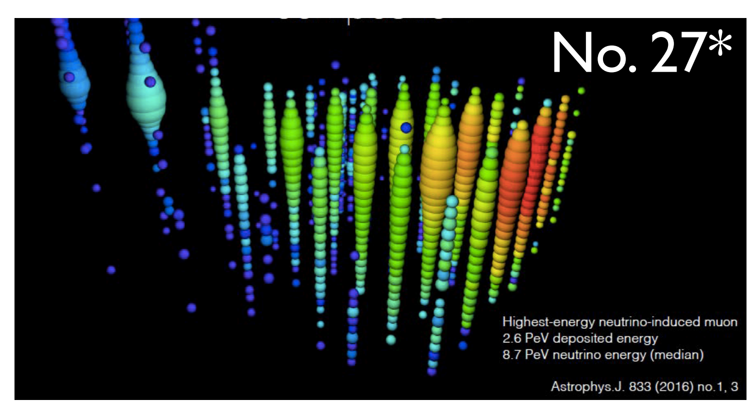


$E < 300$ TeV   300 TeV $< E <$ 1 PeV   1 PeV $< E$



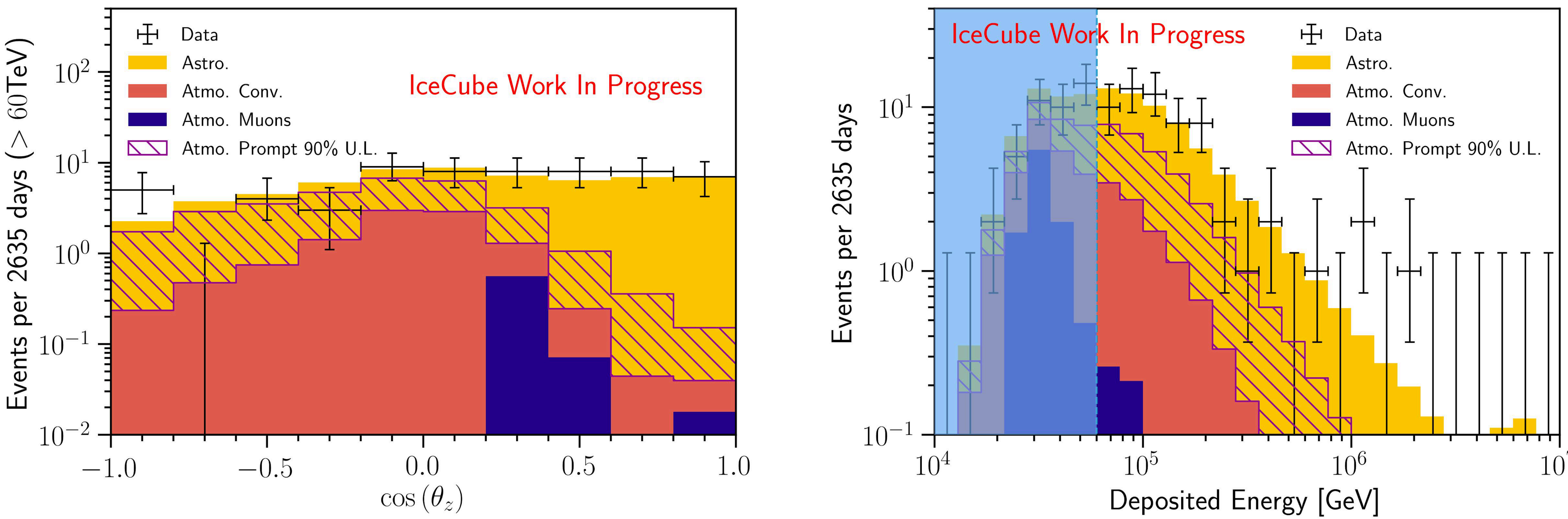






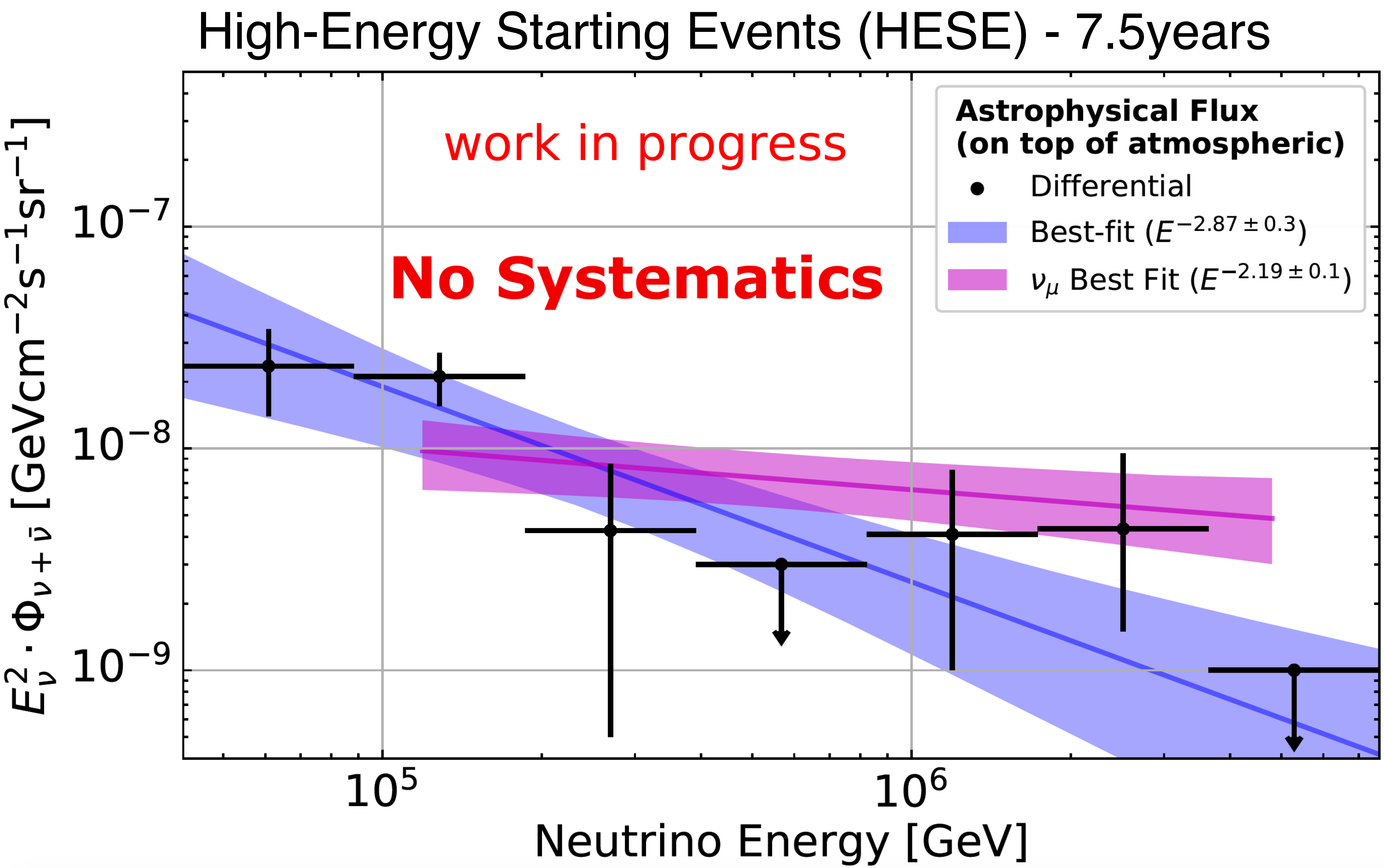
No evidence for point sources, nor a correlation with the galactic plane

HESE 7.5yrs Zenith angle and Energy distribution



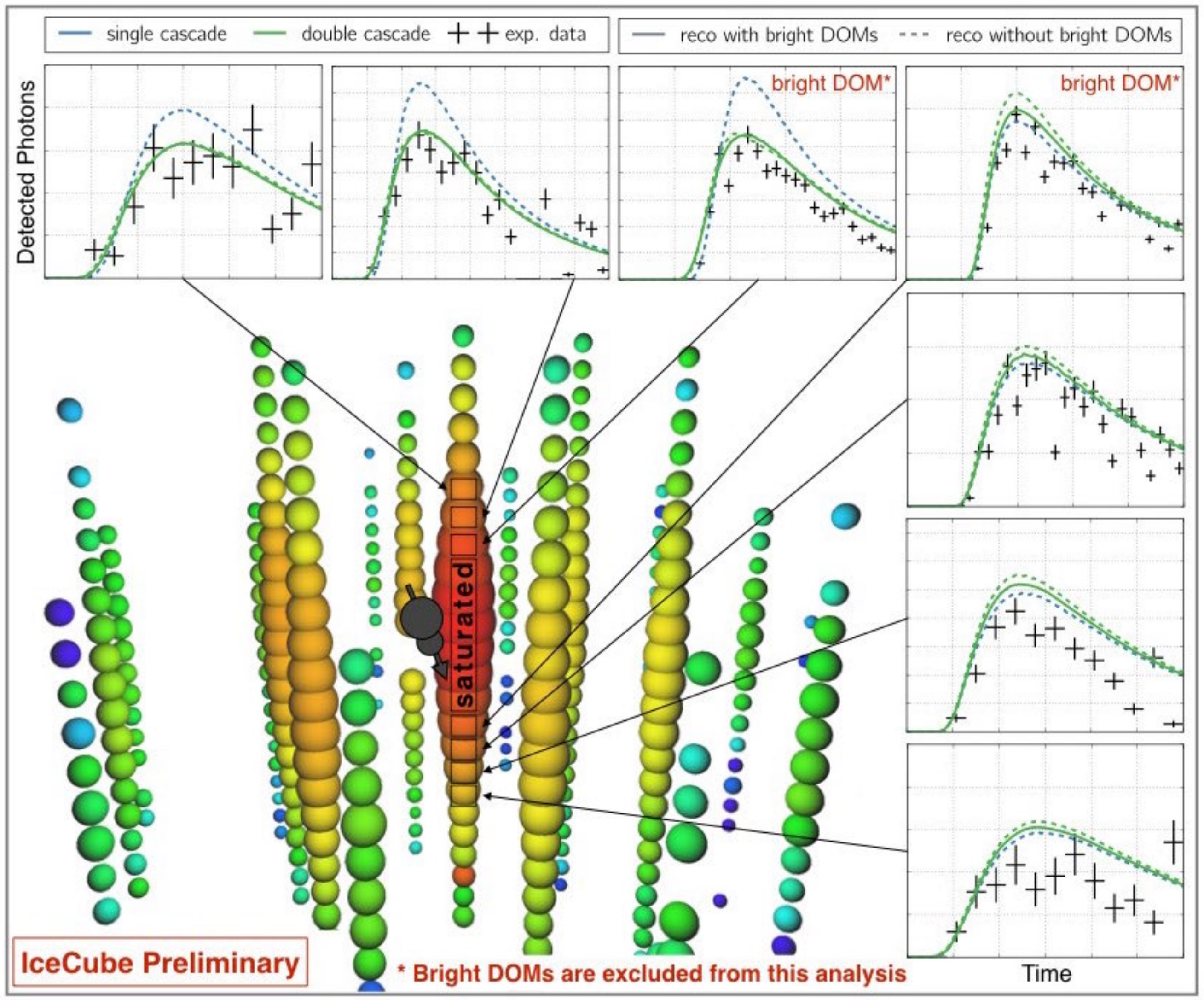
- Compatible with benchmark single power-law model.
- Best fit spectral index ($E^{-\gamma}$): $\gamma=2.91^{+0.33}_{-0.22}$
- $E^2\phi = 2.19^{+1.10}_{-0.55} \times 10^{-8} \times (E / 100\text{TeV})^{-0.91}$ GeV cm^{-2} s^{-1} sr^{-1}

Neutrino energy spectrum

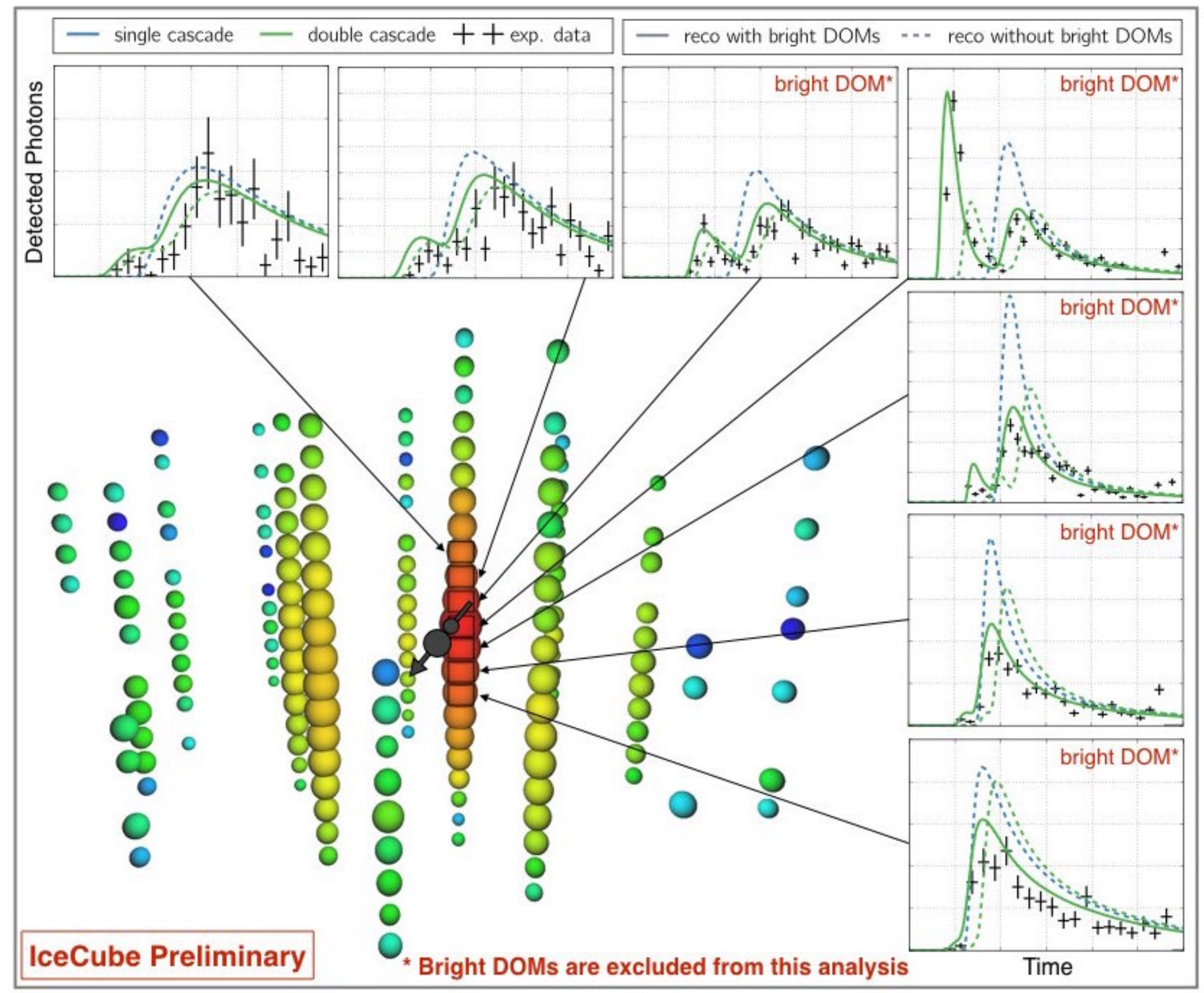


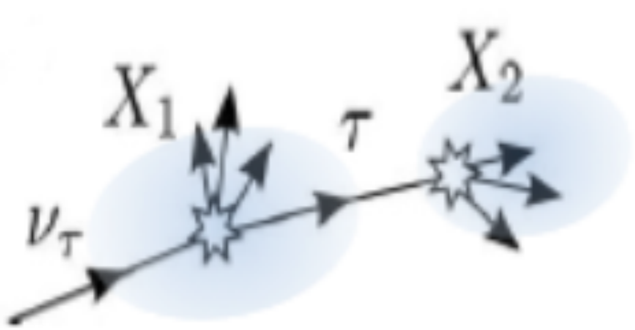
HESE 7.5yrs Tau Search

Double cascade Event #1



Double cascade Event #2





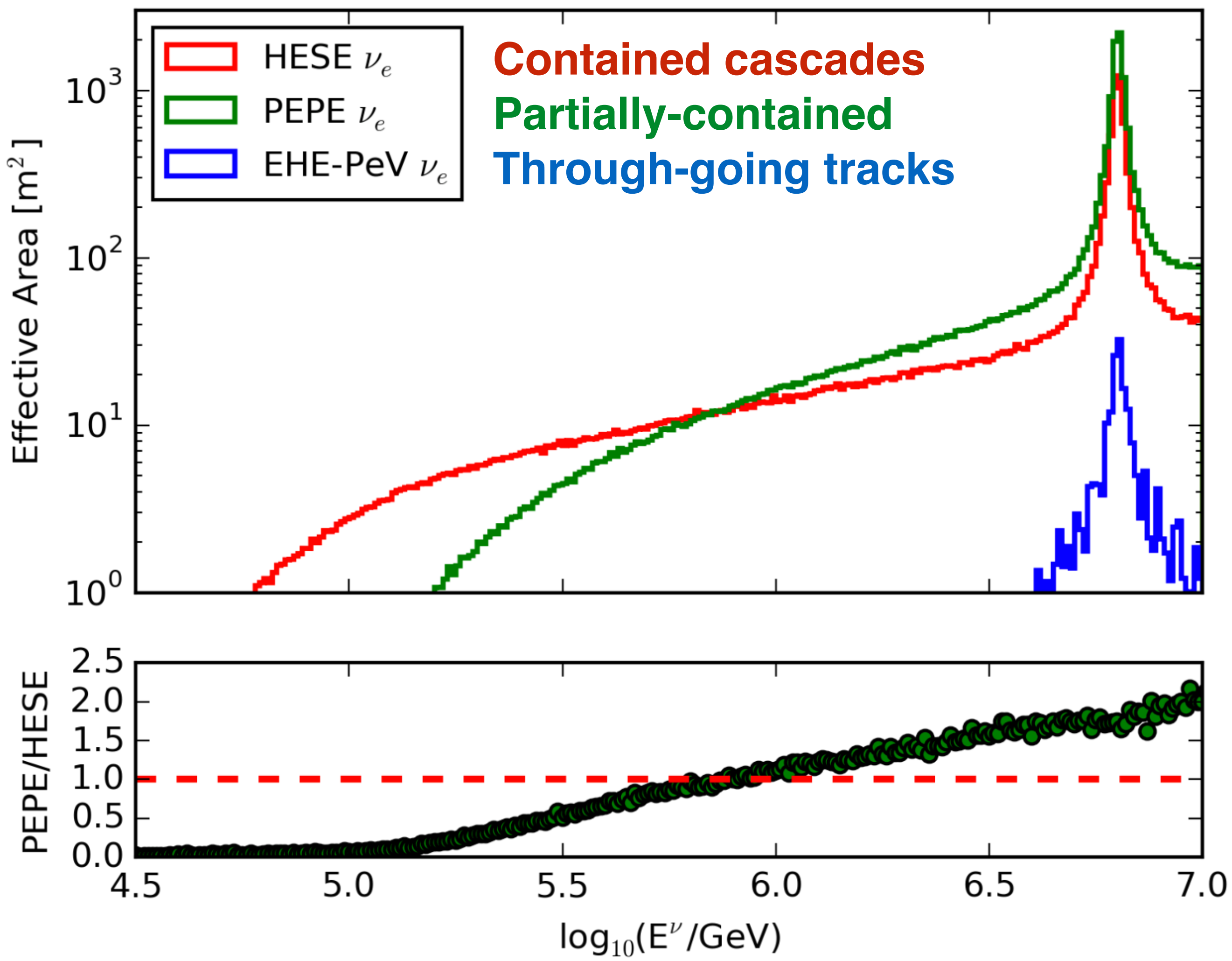
Two double cascades have been identified

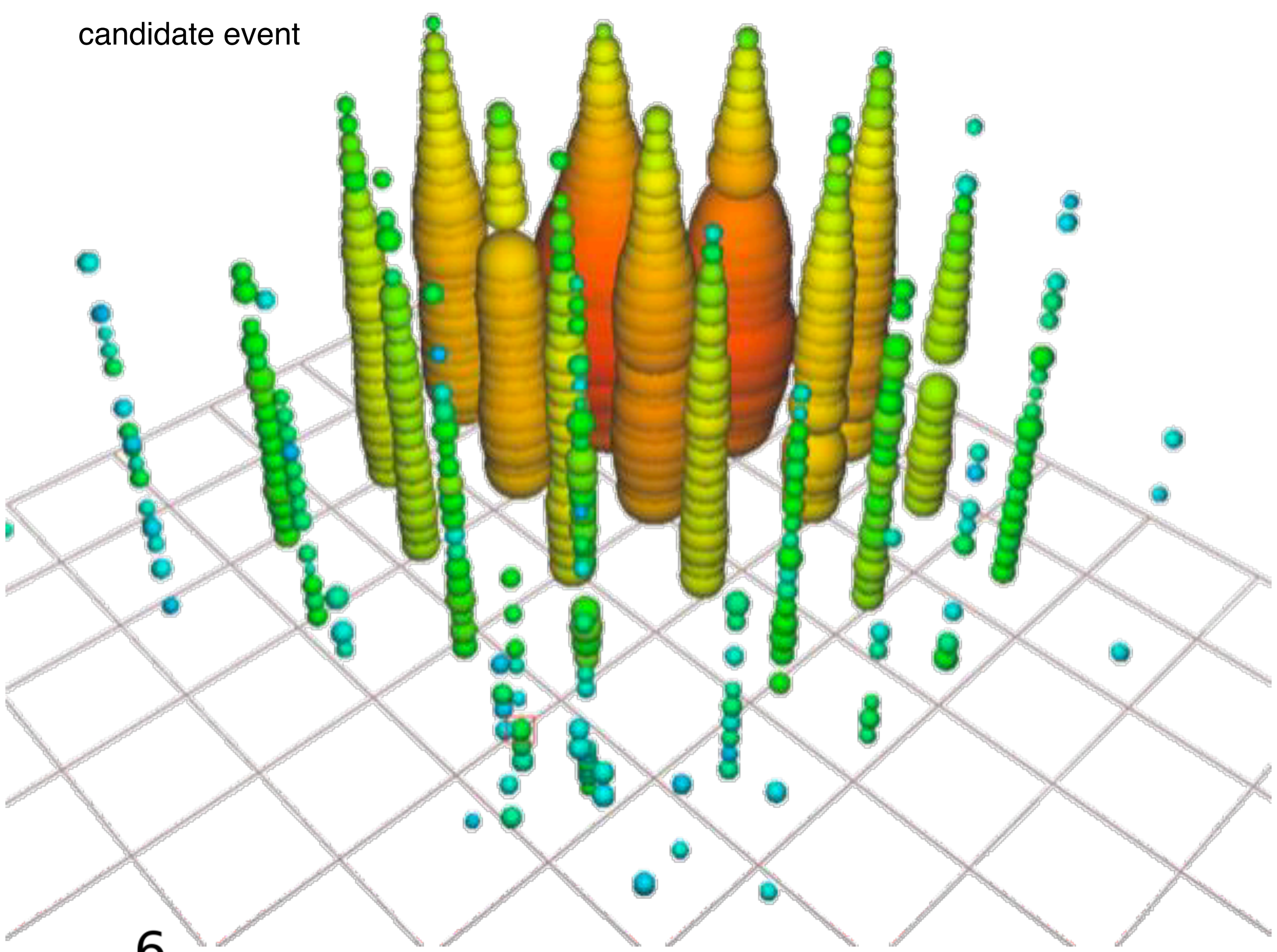
Double cascades arise from ν_τ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

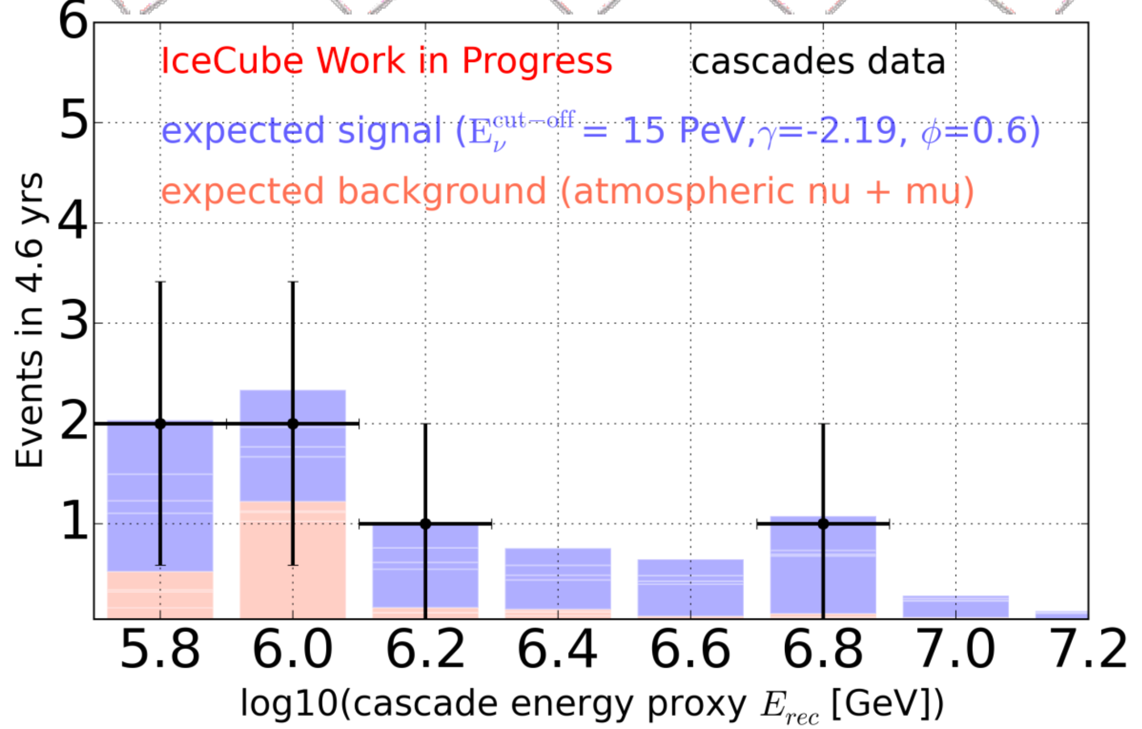
Separate study of taunts of the double cascade events on-going

The global high-energy picture

PeV Energy Partially-contained Events: PEPE



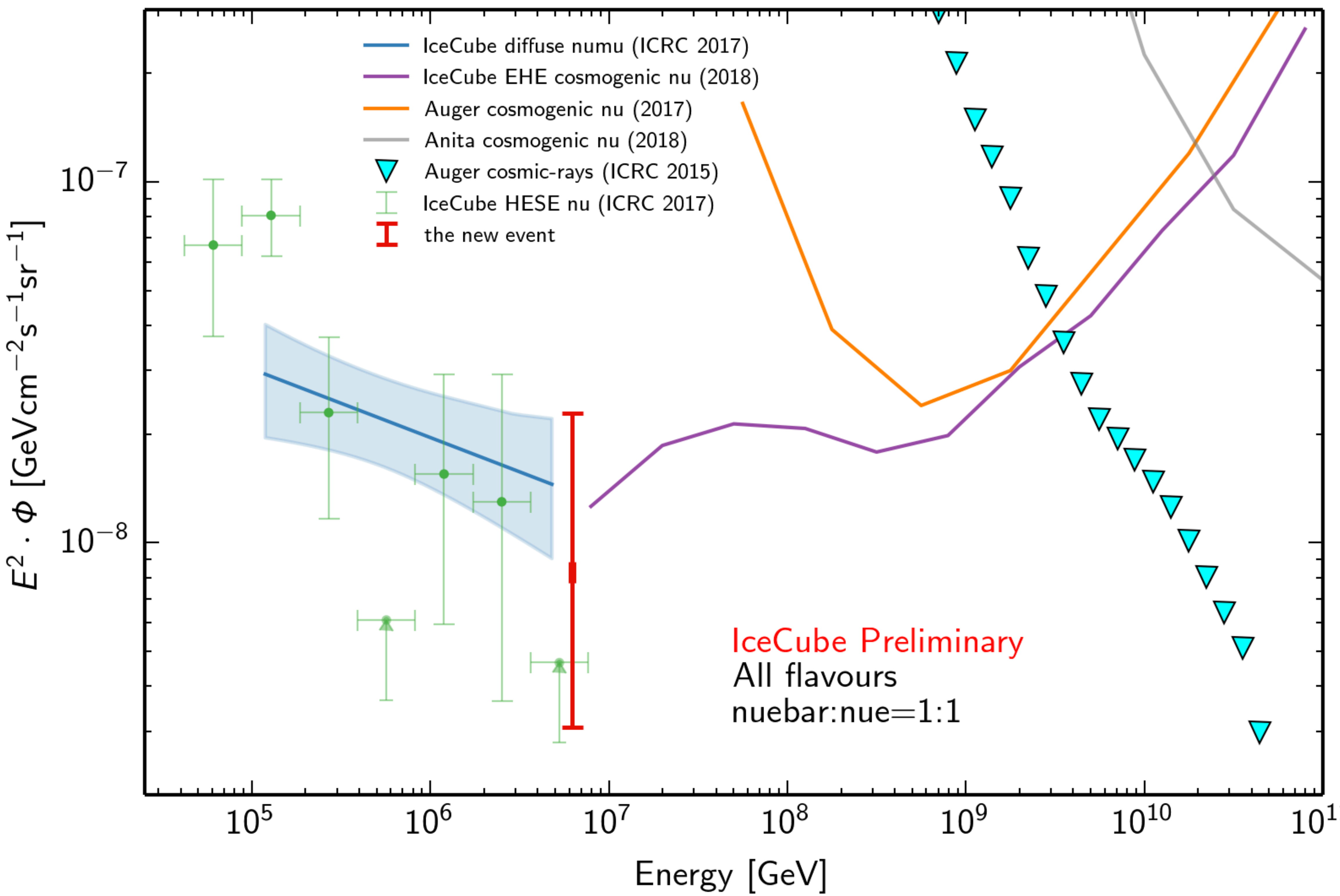


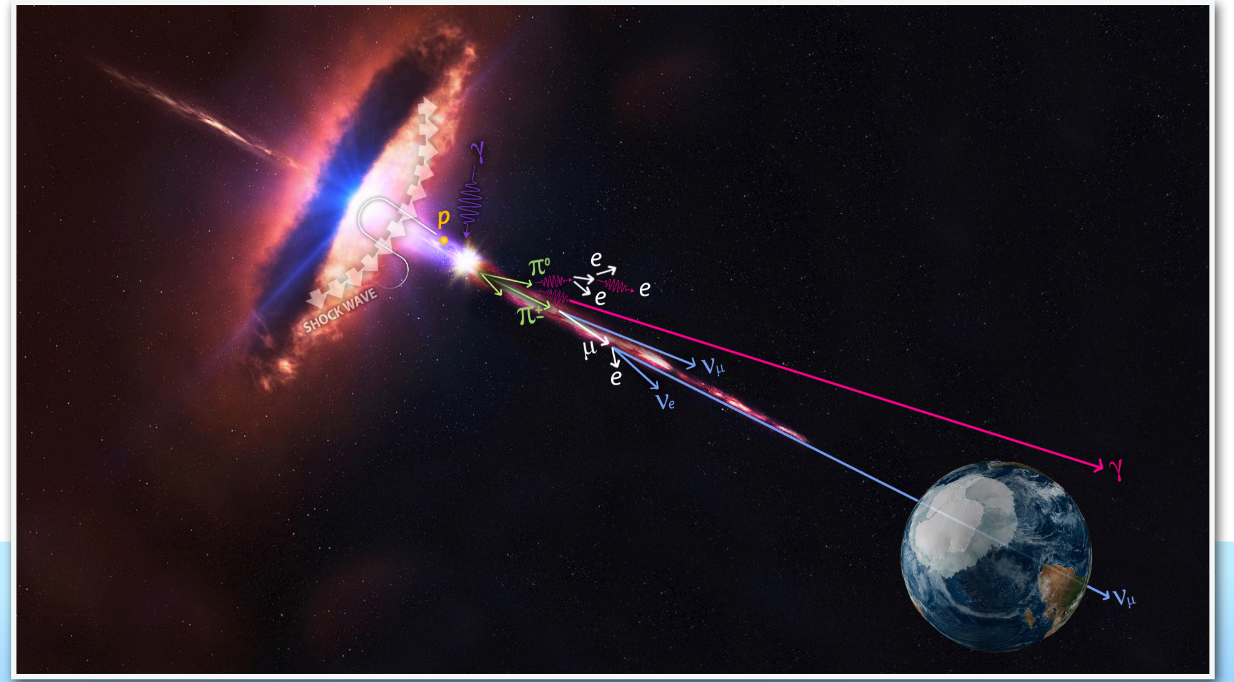


4.6 years (2012-2016) of data. **One event is at Glashow** bin

It is **brighter than all IceCube PeV events** even only partially-contained

The global high-energy picture



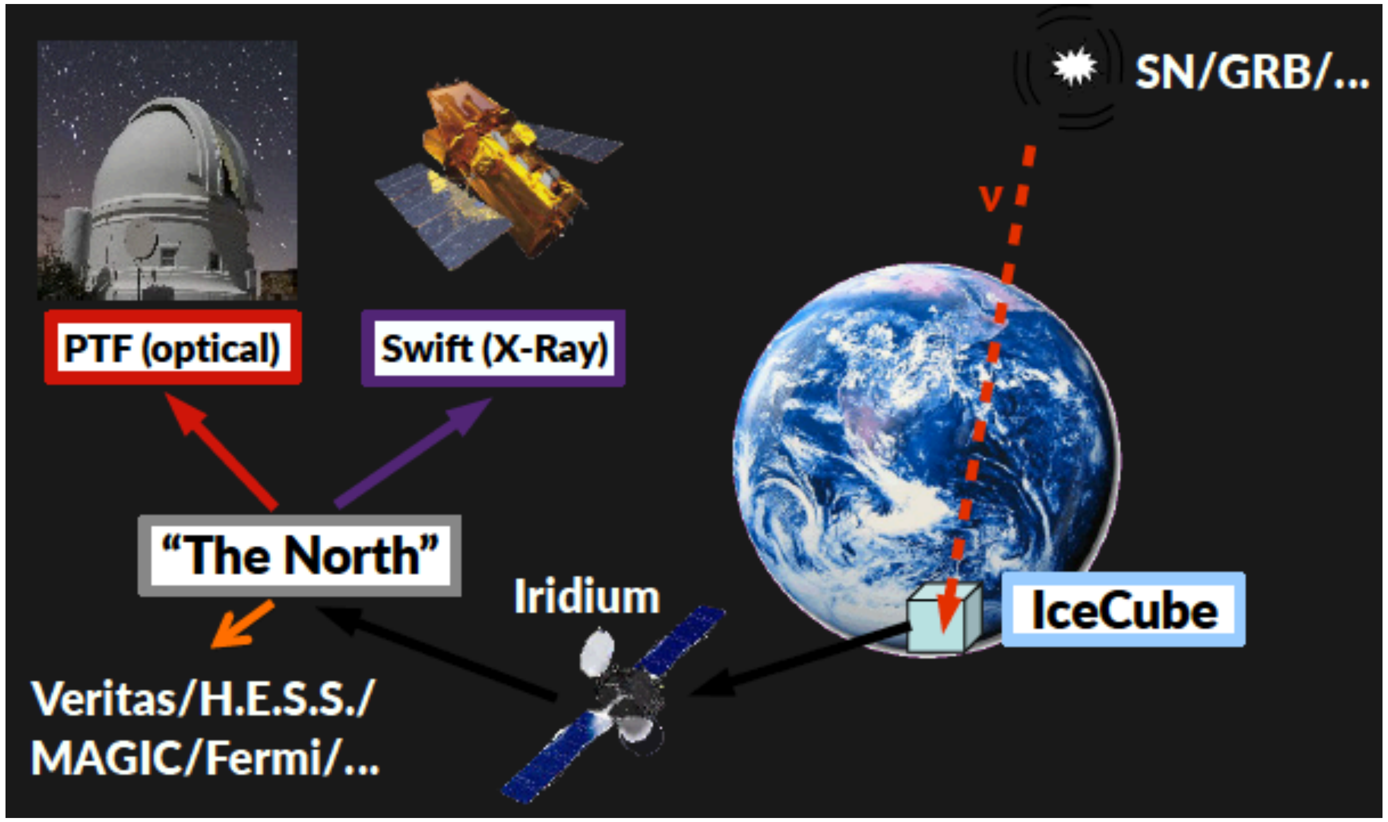


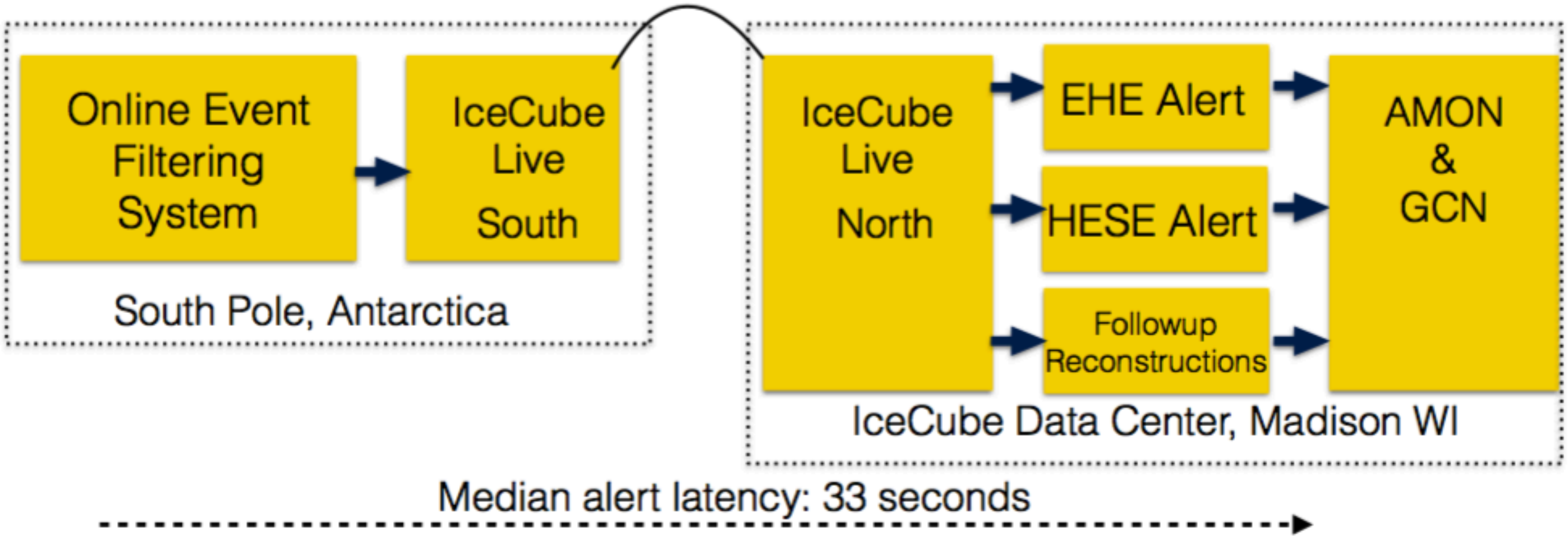
Multi-messenger Neutrino Astronomy and IceCube-170922A

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

IceCube-170922A & TXS 0506+056

- 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





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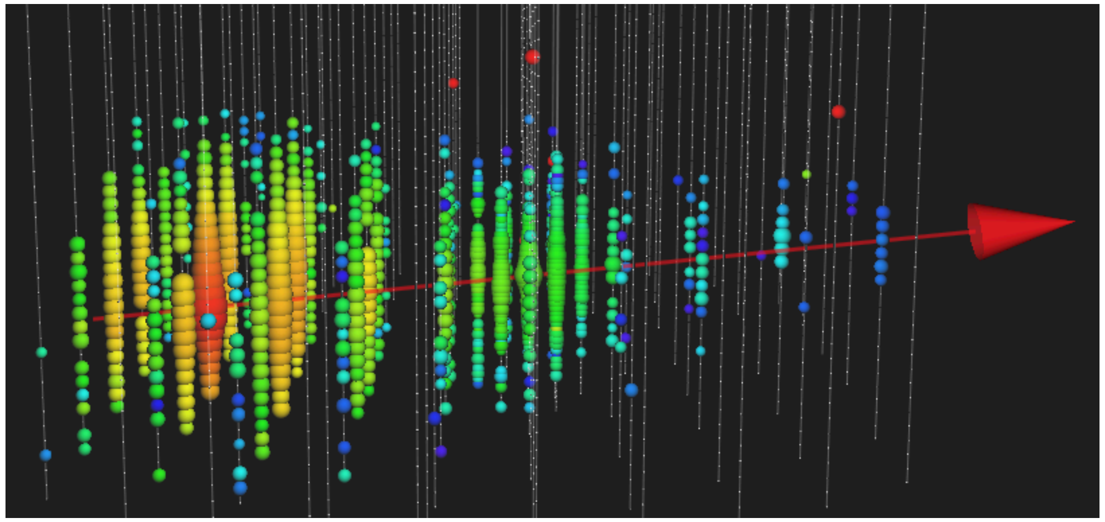
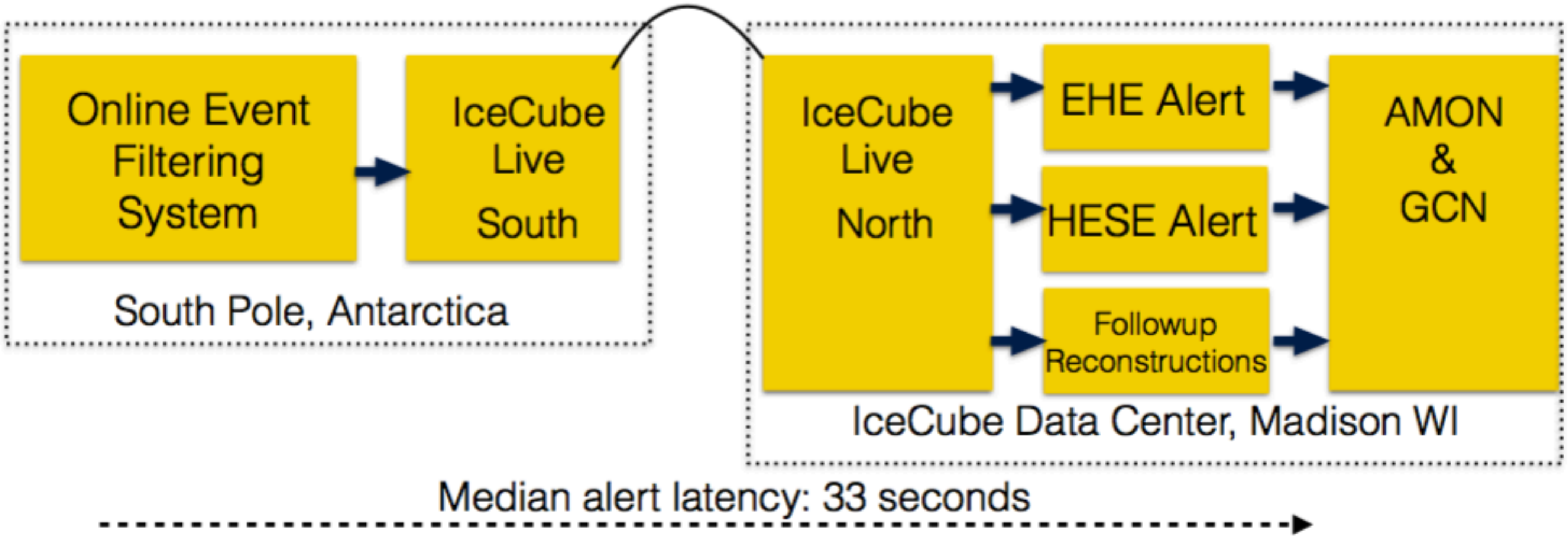
    - Good angular resolution (0.5° - 2° 90% of events)
    - 50% astrophysical fraction

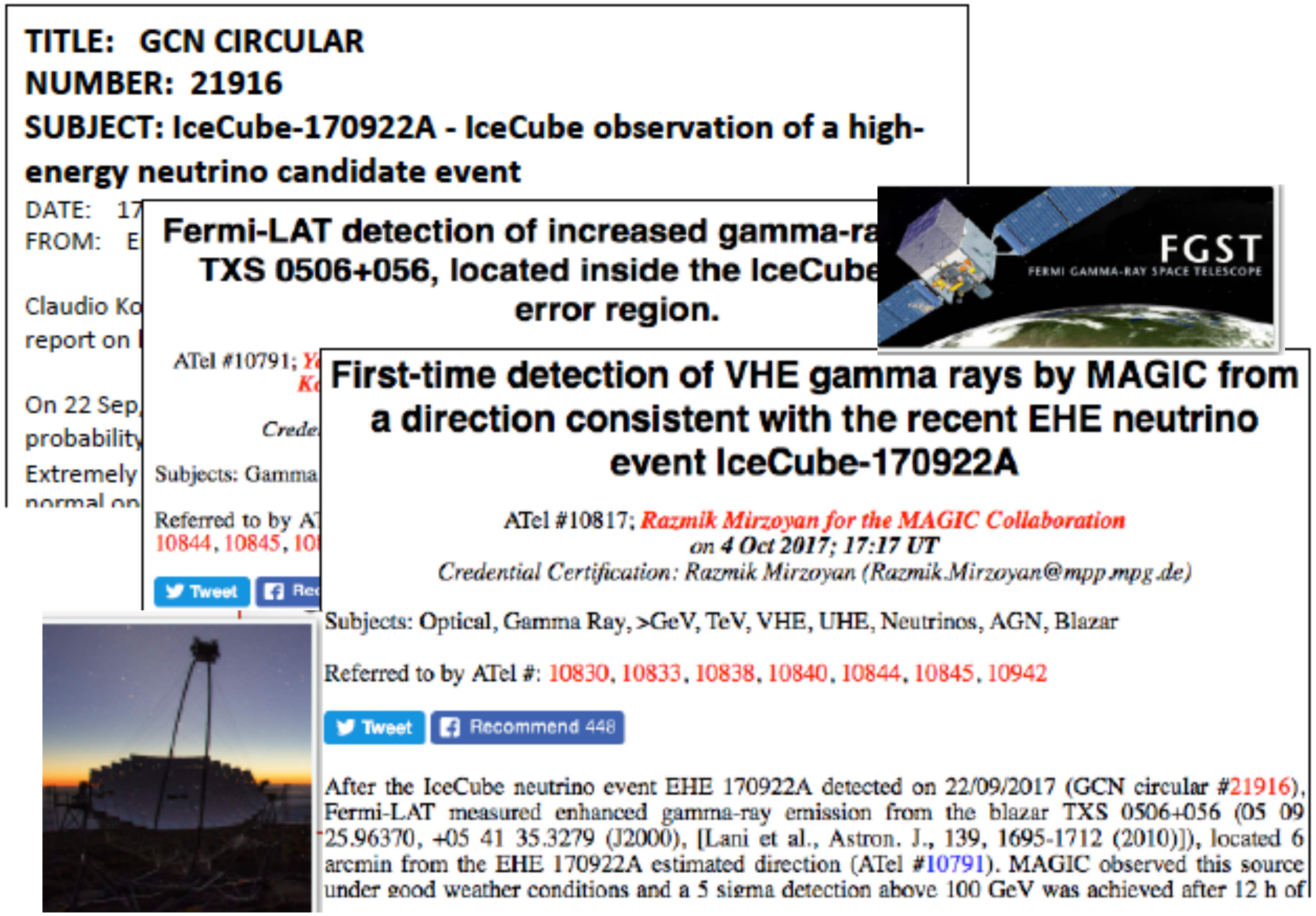


First public ν Alert: IceCube-160427

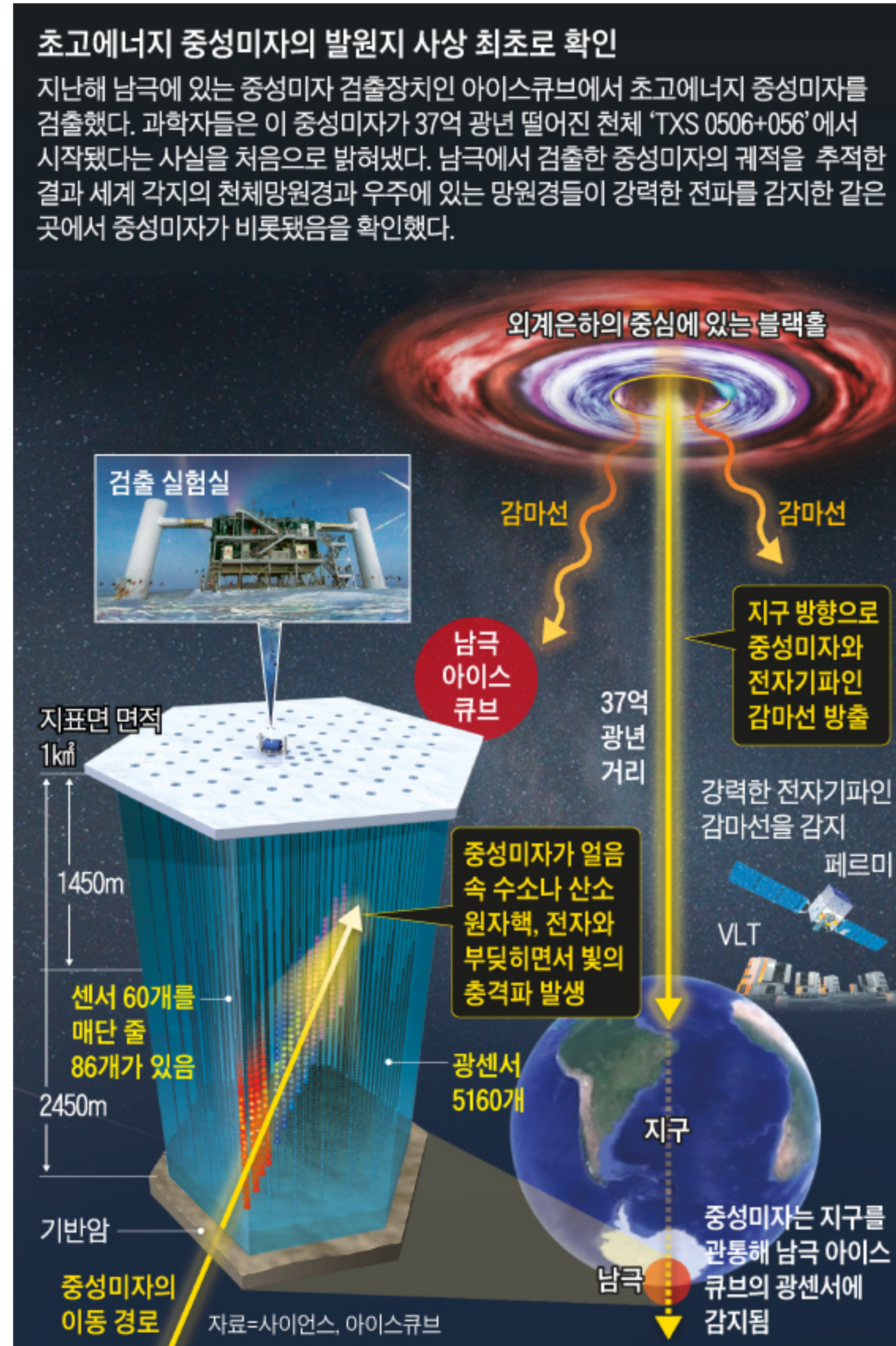


Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056



- 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

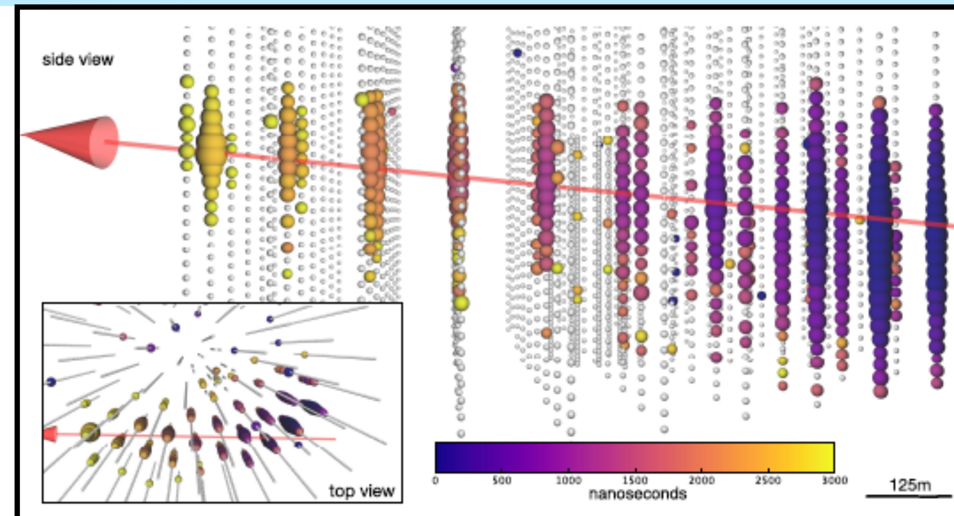


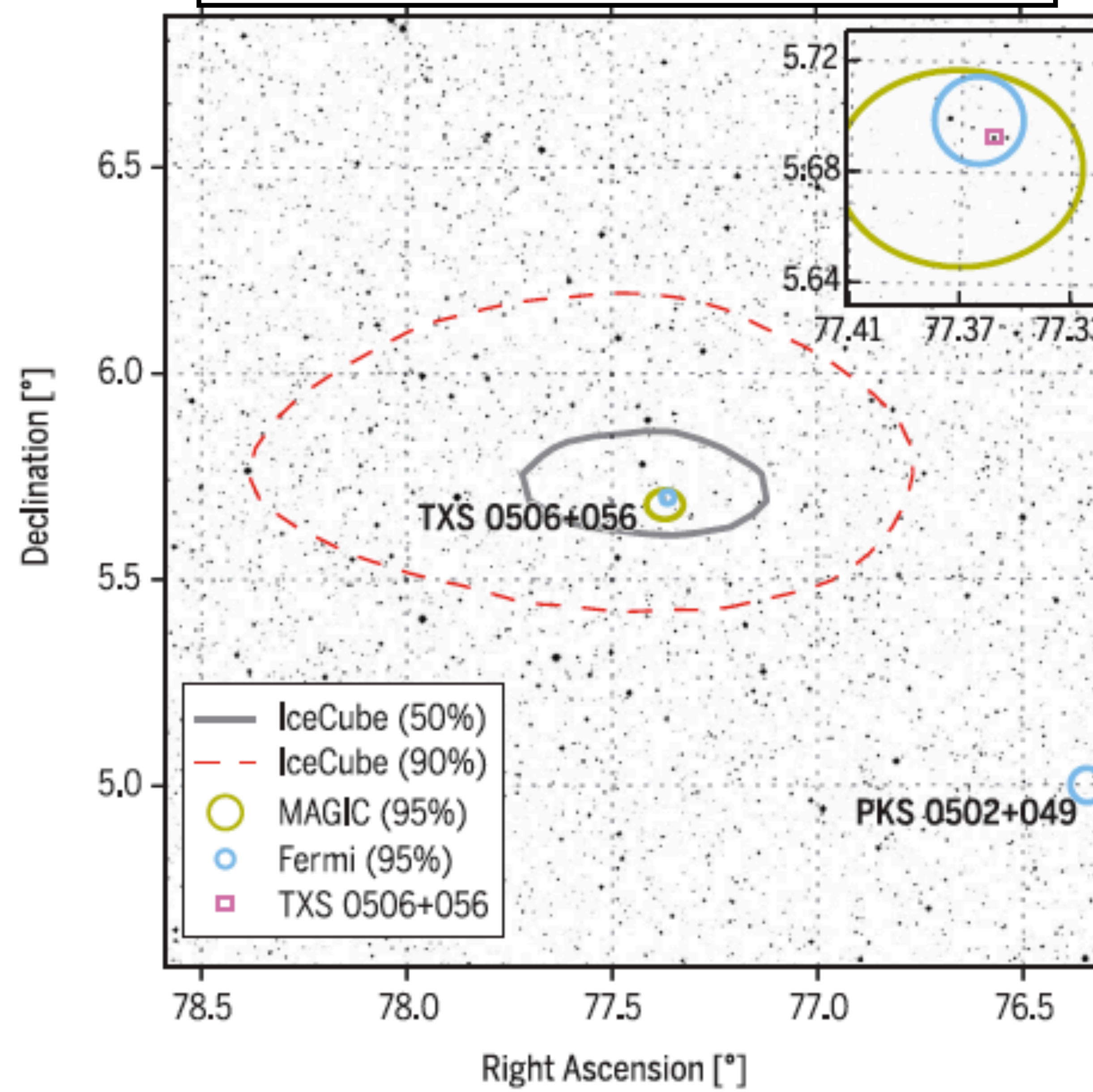
IceCube-170922A

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*†

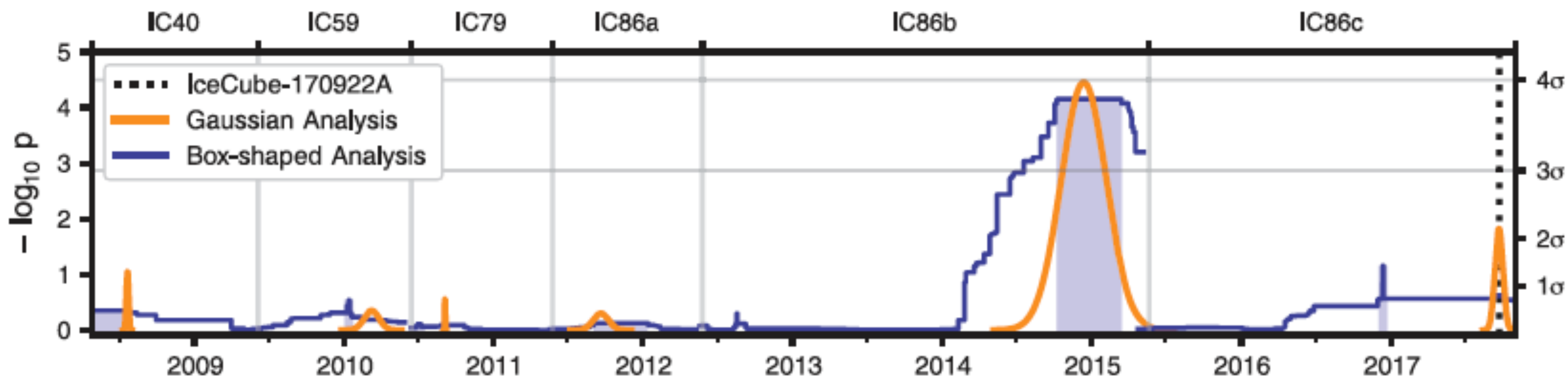
- Chance probability of a Fermi-IceCube coincident observation: ~**3σ** (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- **TXS 0506+056 redshift determined to be z=0.3365** (S. Paiano et al. ApJL 854.L32(2018))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



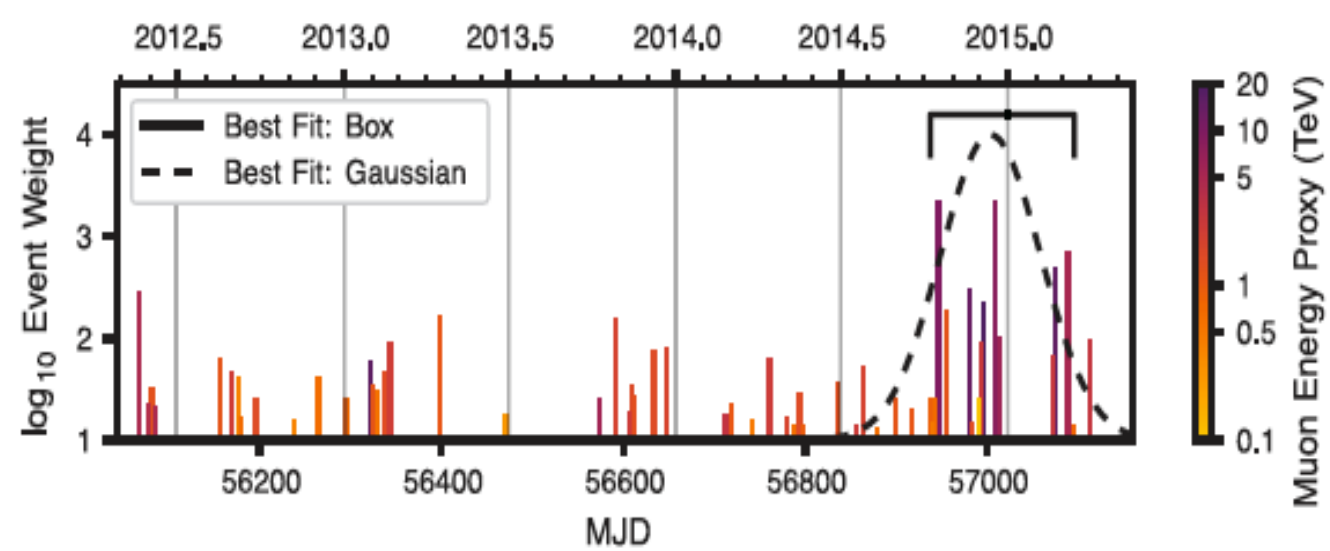


Science 361 (6398), 147-151.

IceCube-170922A



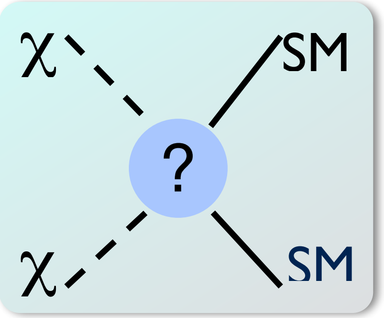
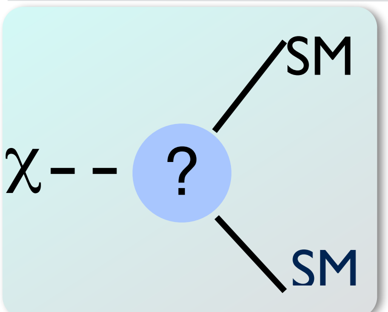
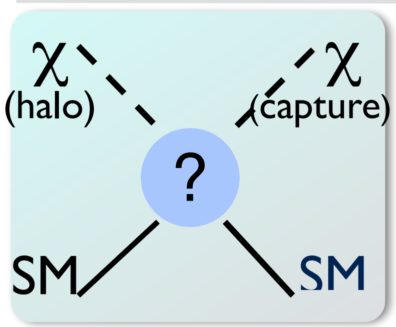
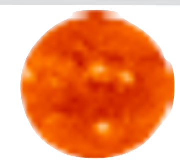
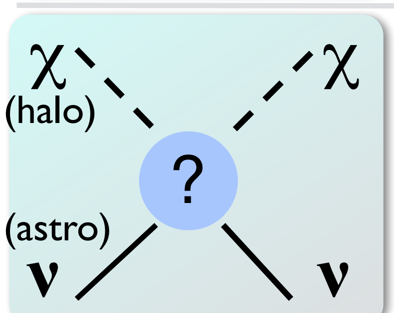
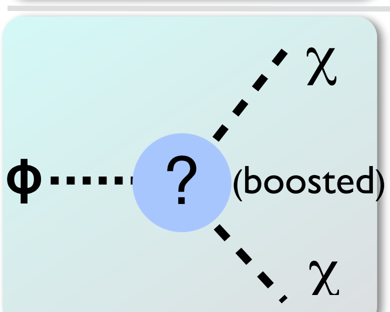
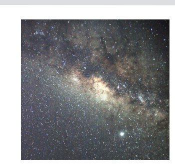
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)



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

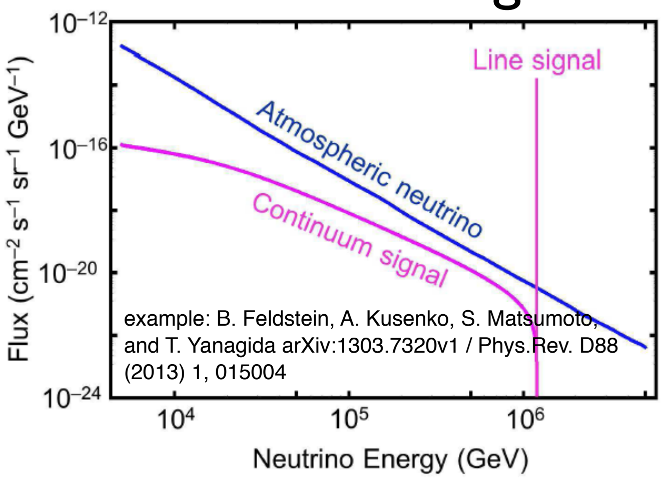
Search for Physics Beyond the Standard Model

Signatures of Dark Matter in Neutrino Detectors

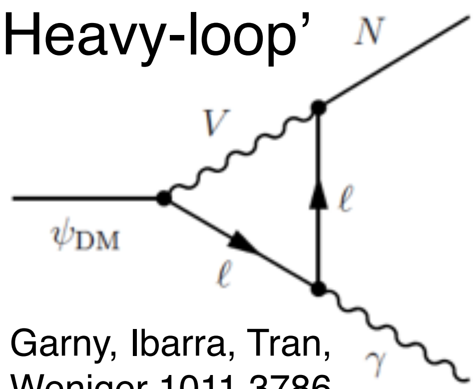
Channel	Type of Search	Typical Sources		Measures
	**DM Annihilation searches** ν from SM particle decay, direct neutrinos helicity suppressed	• Galactic Center • Galactic Halo • Dwarf Spheroidals • Galaxy clusters • …		Self-annihilation cross section $\langle\sigma v\rangle$ DM Mass m_χ (Branching fractions)
	**DM Decay searches** ν from SM particle decay or directly produced	• Extragalactic • Galactic Halo • Galaxy clusters • …		DM Lifetime τ_χ DM Mass m_χ (Branching fractions)
	**DM Nucleon scattering** Following χ capture, annihilation. Once annihilation and capture in balance (equilibrium) - no dependence on $\langle\sigma v\rangle$	• Sun • Earth	 	DM-Nucleon scattering cross section σ^{SD} / σ^{SI} DM Mass m_χ (Branching fractions)
	**Neutrino DM scattering** Astrophysical ν scatter off χ from Galactic halo - resulting in anisotropy	• Milky Way Halo		Combination of coupling strength **g** and masses m_ϕ m_χ
	**Boosted DM** Highly boosted χ from the decay or annihilation of a heavy DM particle m_ϕ interacts directly in the detector	• Galactic Center • Sun • …	 	DM Lifetime τ_χ … or self-annihilation cross section $\langle\sigma v\rangle$ DM mass m_ϕ

Heavy Dark Matter Decay

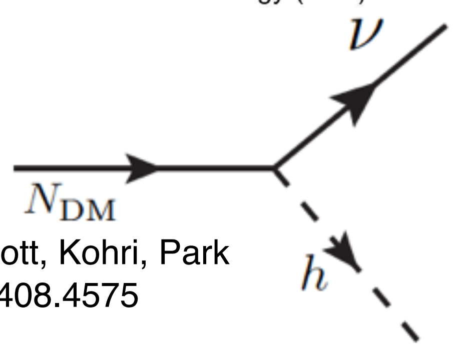
Decay process might produce mono-energetic neutrinos



‘Heavy-loop’

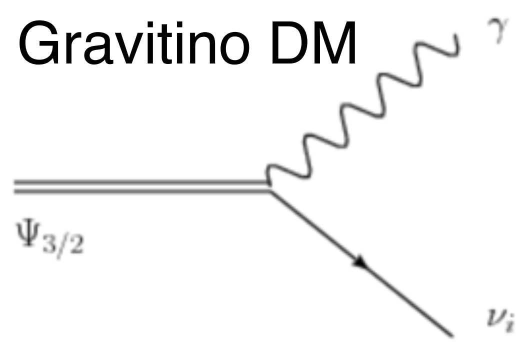


Garny, Ibarra, Tran, Weniger 1011.3786

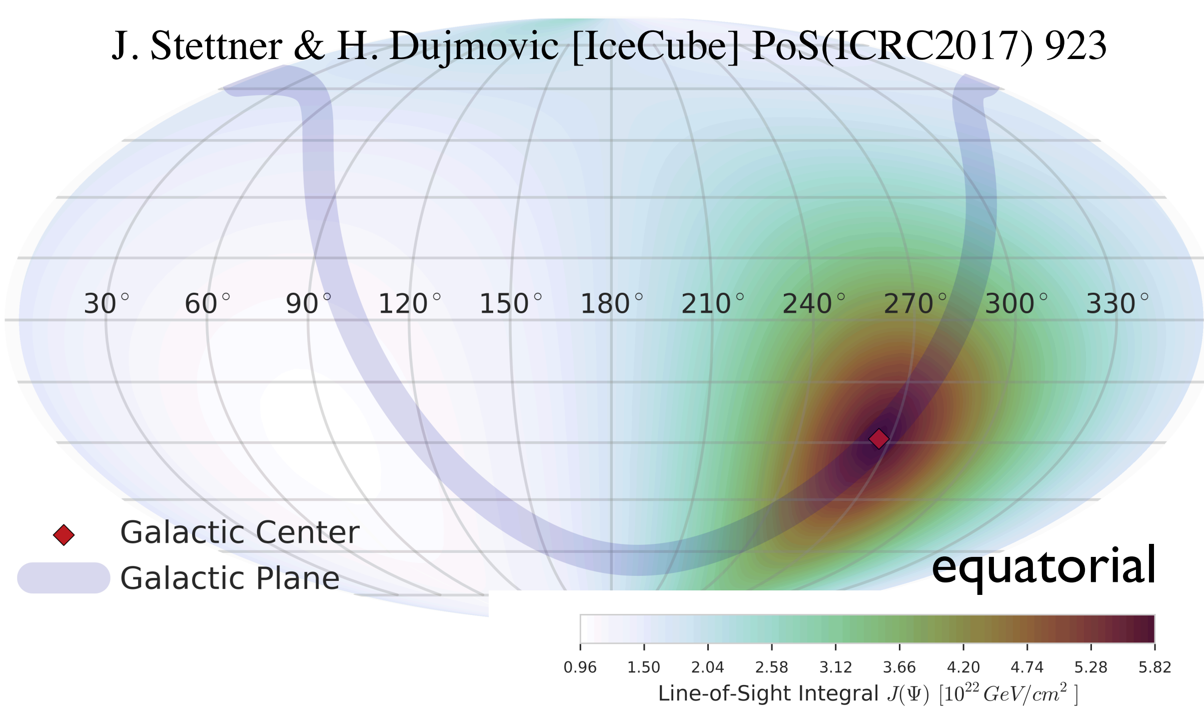


Rott, Kohri, Park 1408.4575

Gravitino DM



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



Two flux contributions:
Galactic and Extra galactic

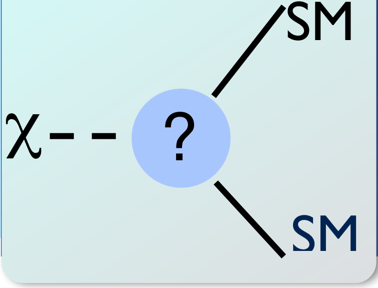
$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- 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)

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



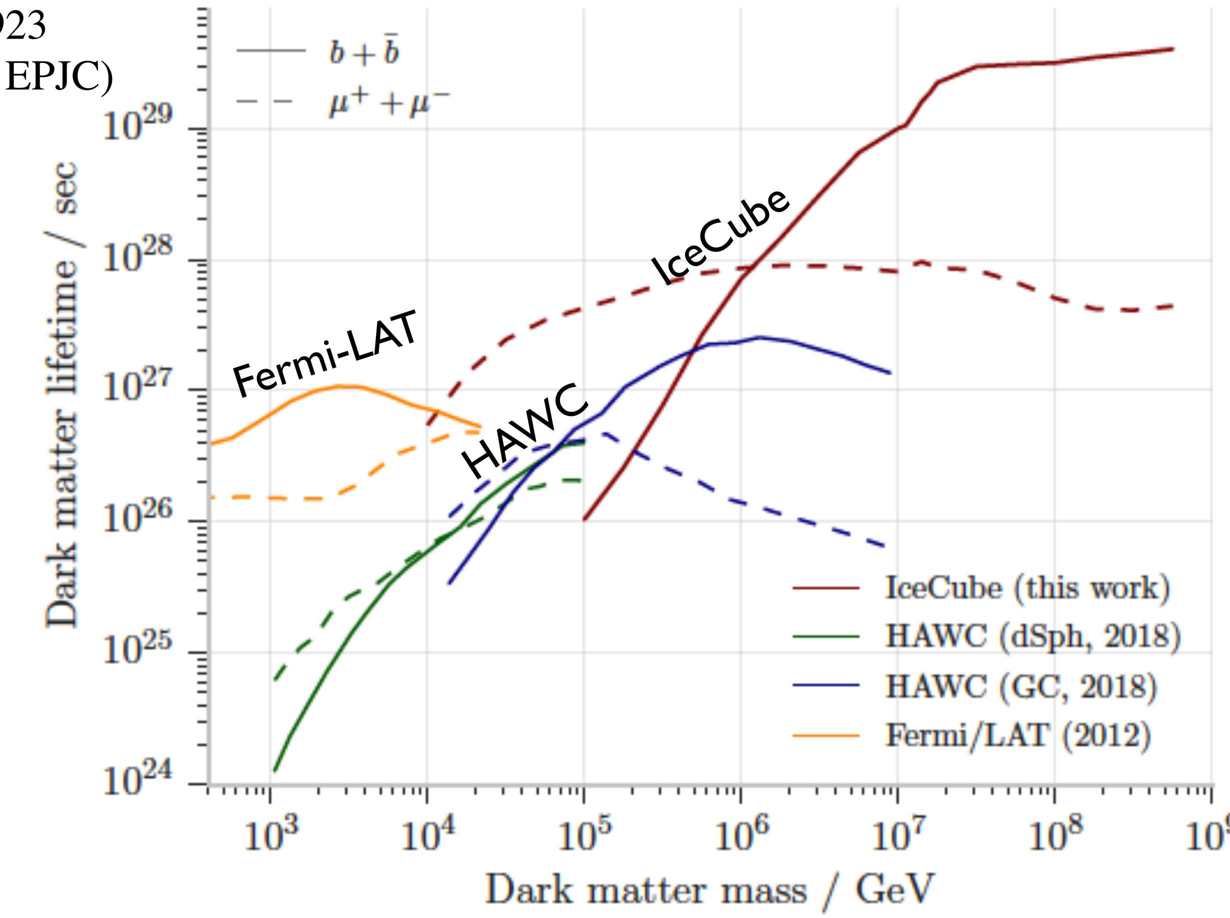
Dark Matter Decay with IceCube

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	$\sim 100\%$	$\sim 10\%$

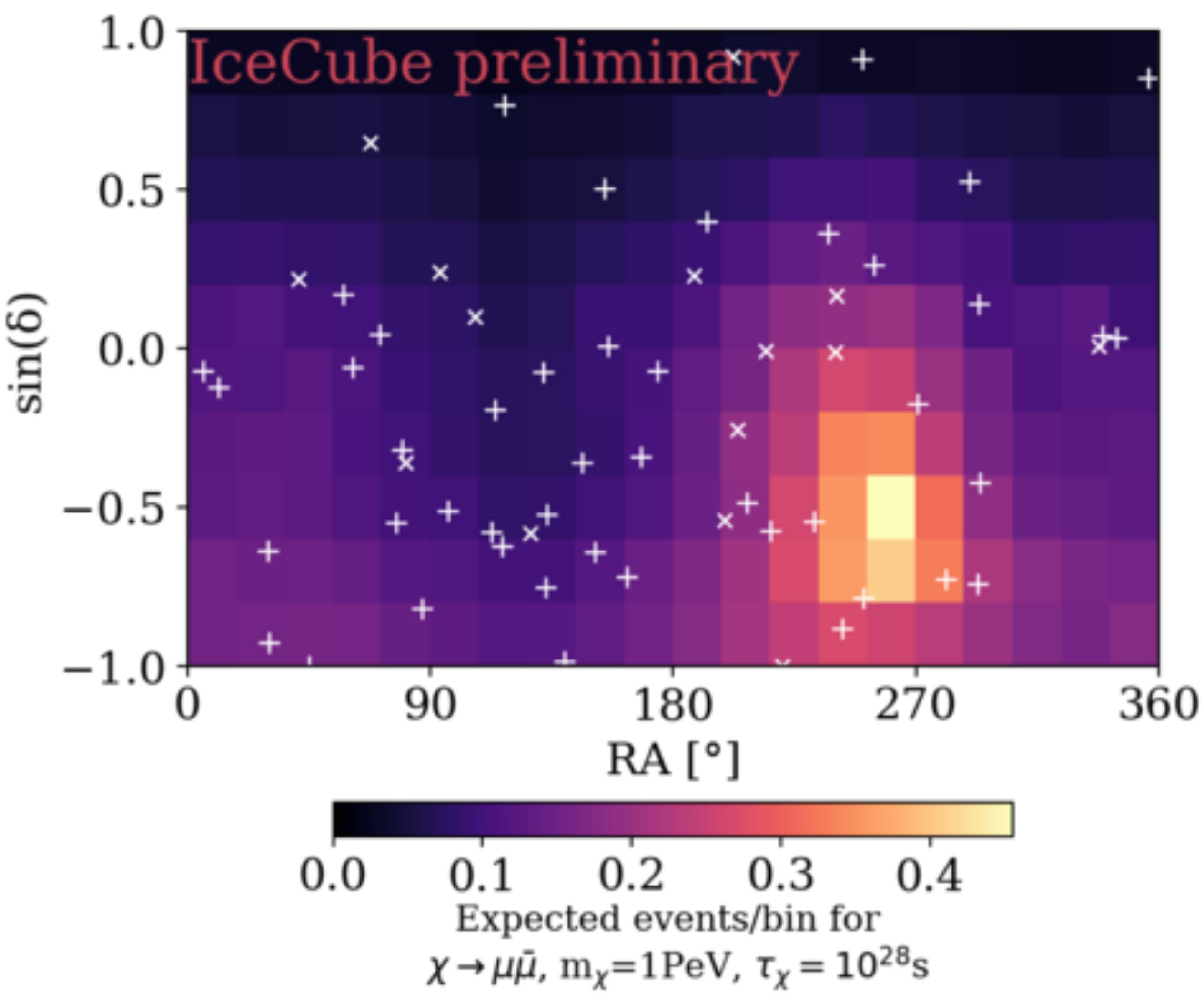
Test-Statistic: $TS = 2 \times \log \dfrac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$

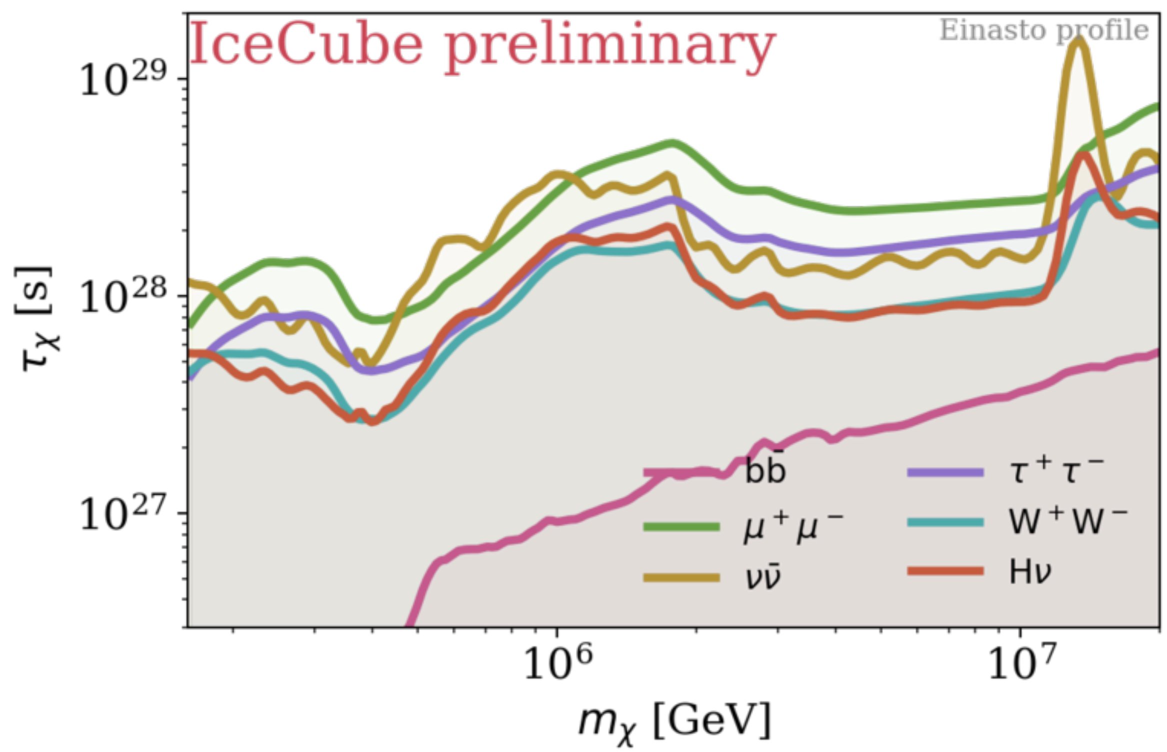


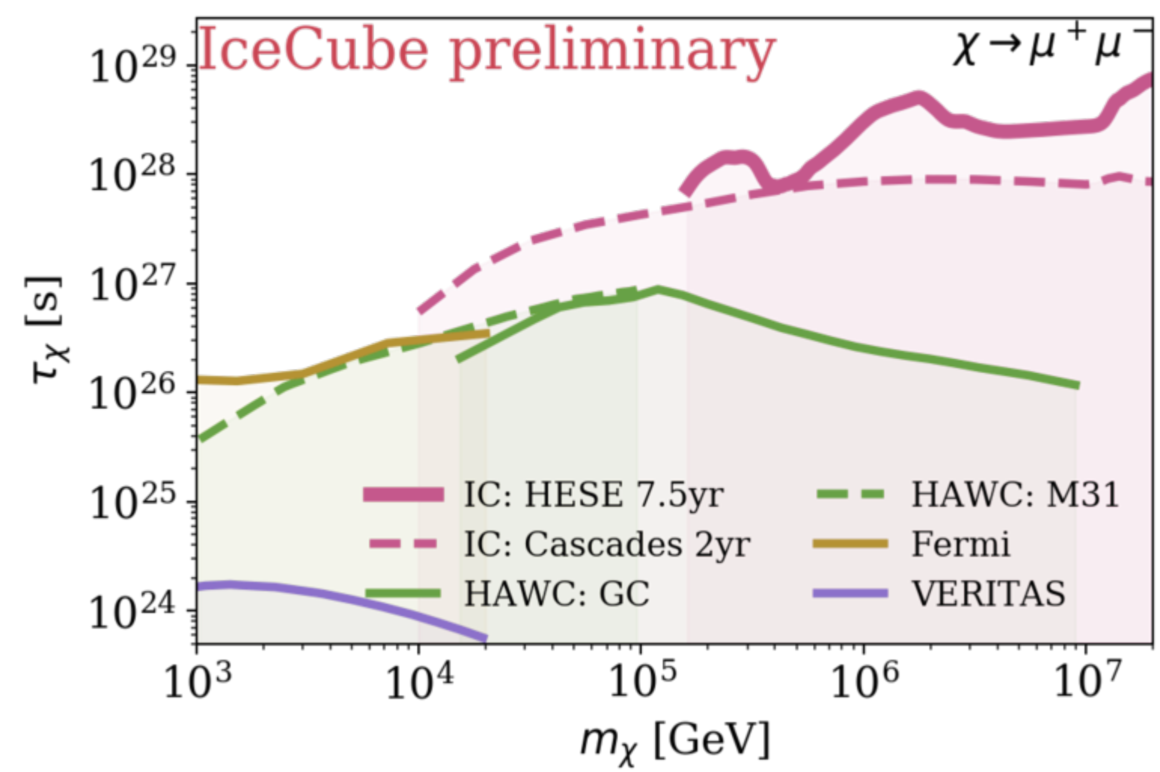
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

- 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

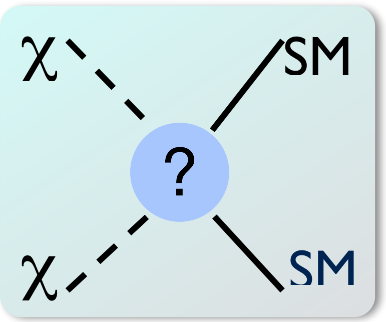


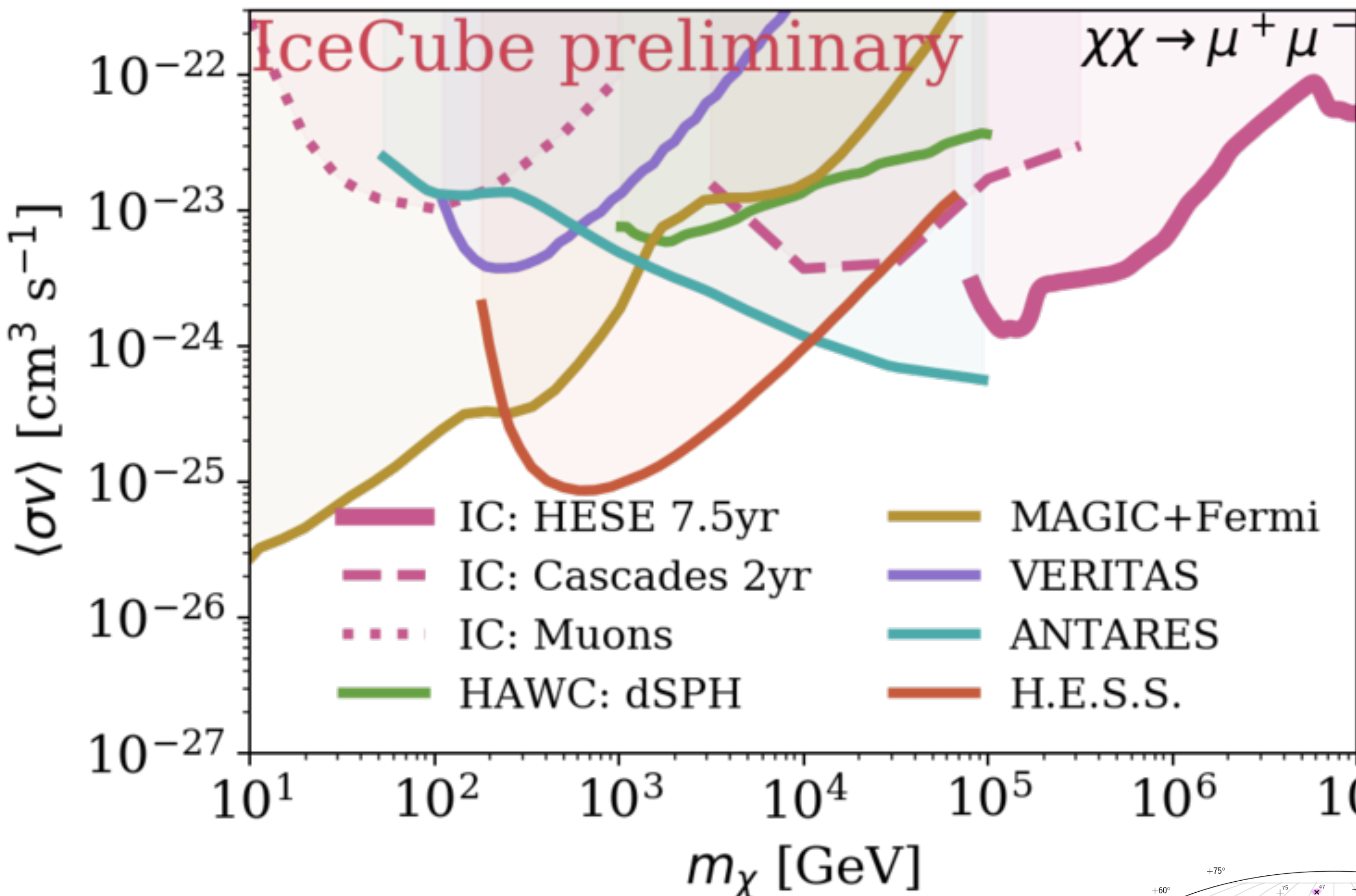


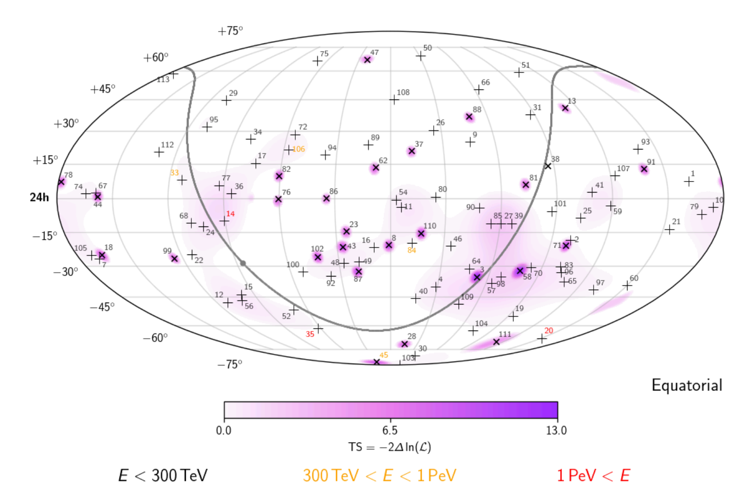


- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Most competitive limits above 100TeV for a large number of channel

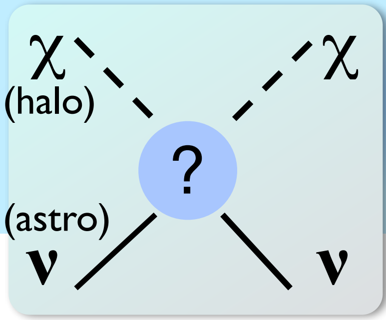
Search DM Annihilation with IceCube's 7years HESE Sample







- 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



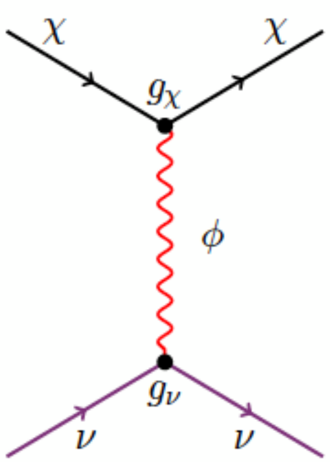
Imaging Galactic Dark Matter with IceCube's High-Energy Cosmic Neutrinos using HESE data

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

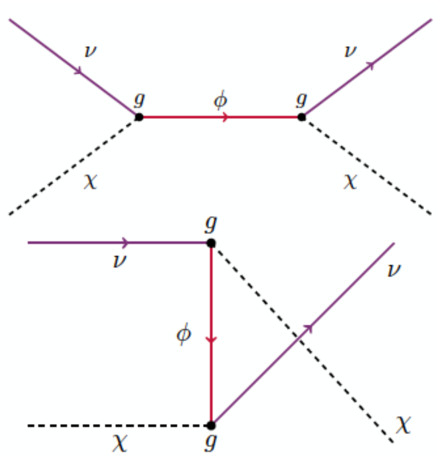
Dark Matter - Neutrino Interaction

- 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

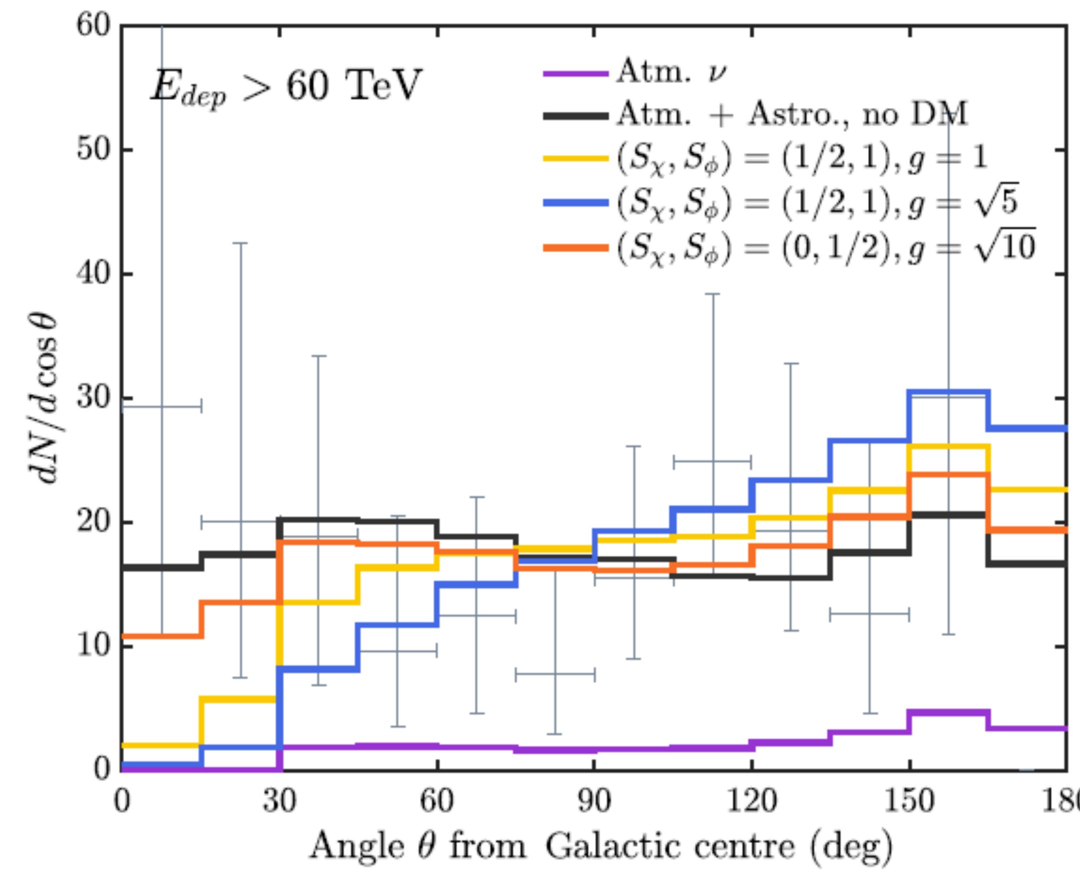


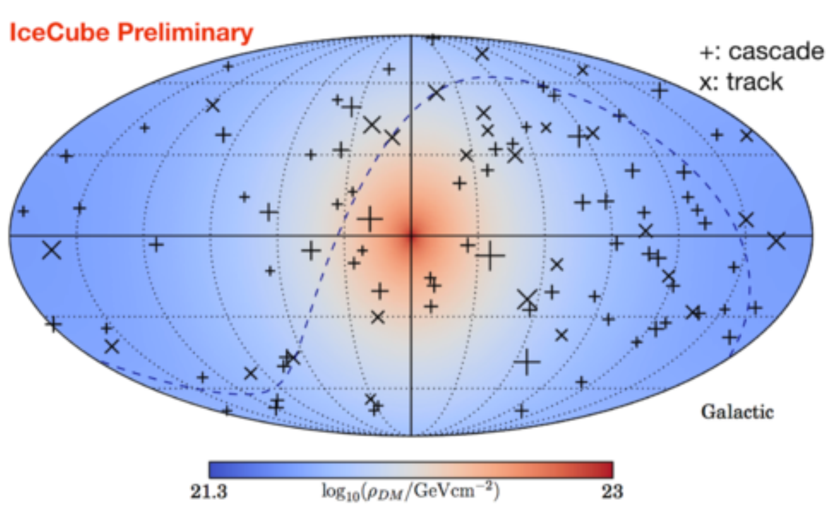
(2) Scalar DM, ferminonic mediator



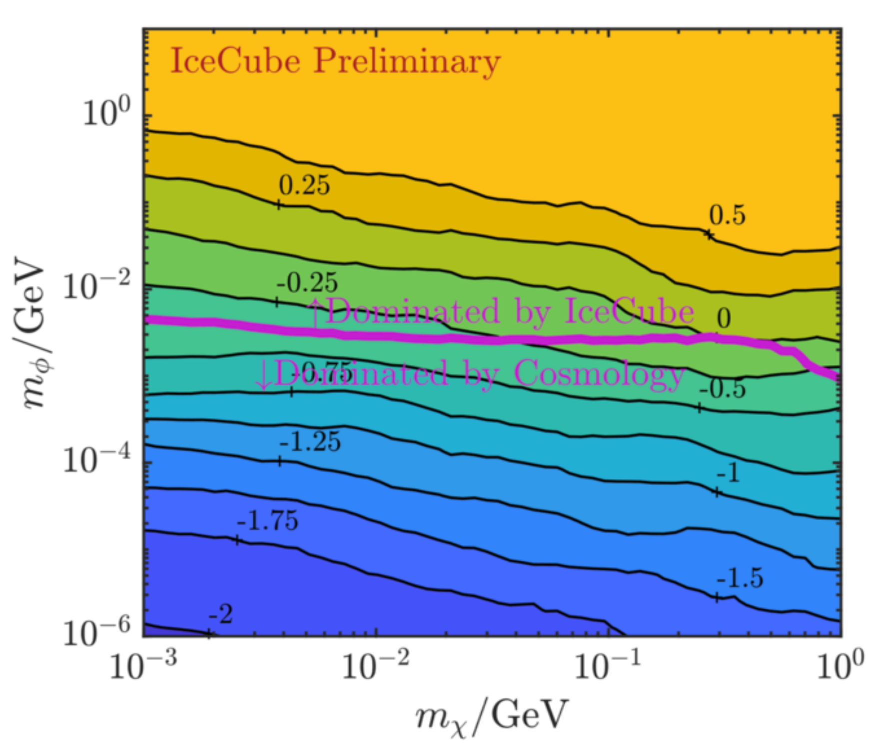
Assume:

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

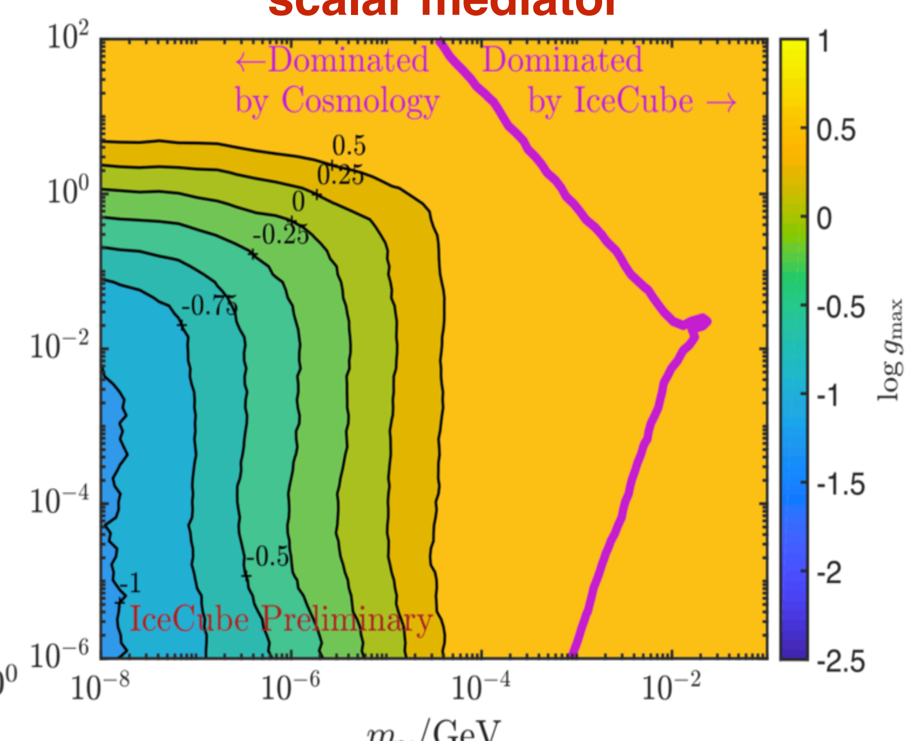




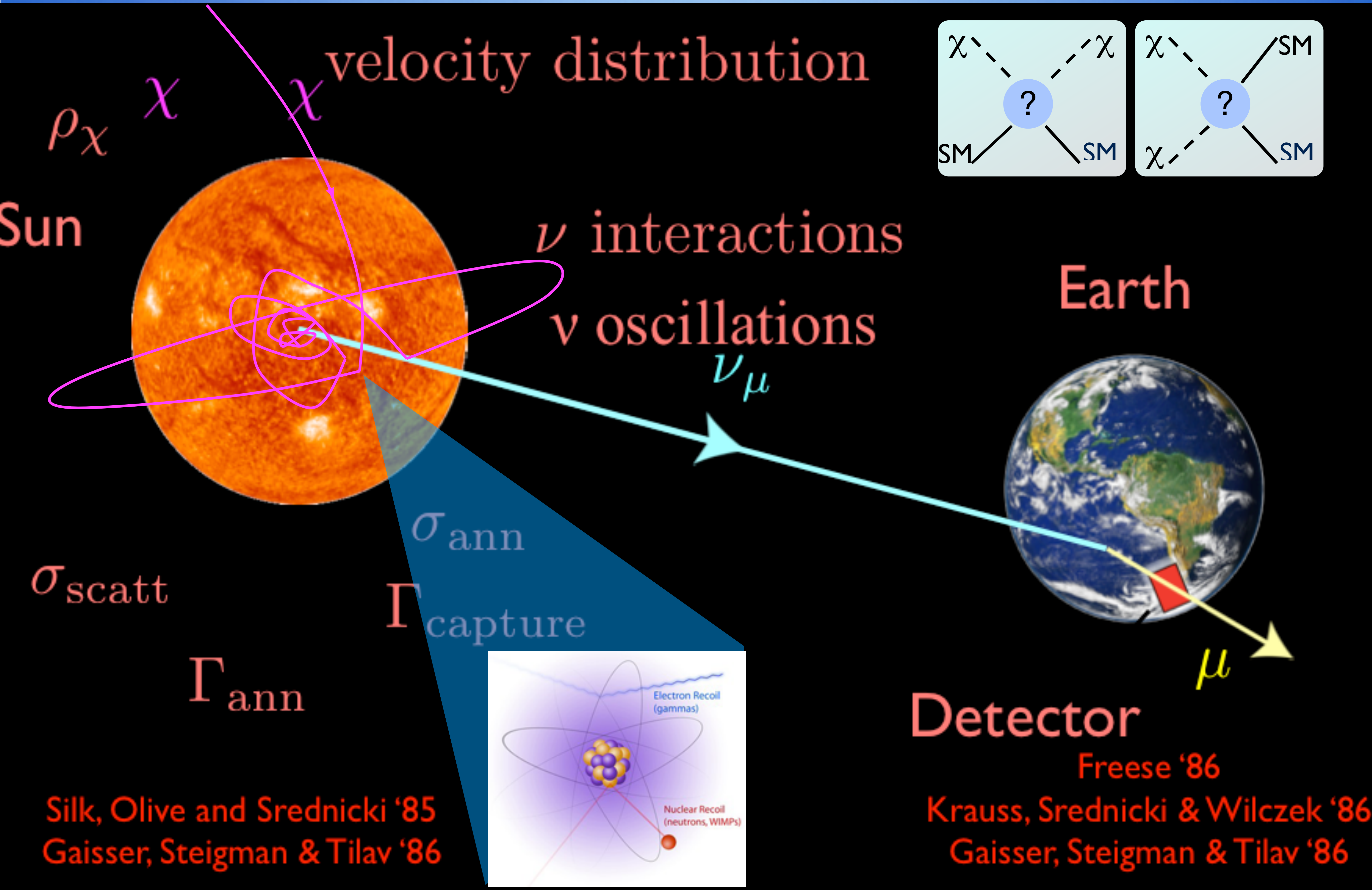
vector mediator



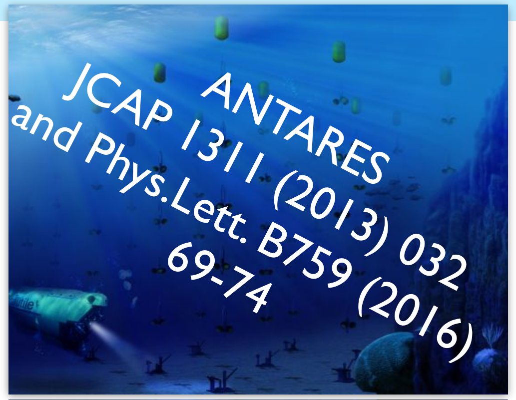
scalar mediator

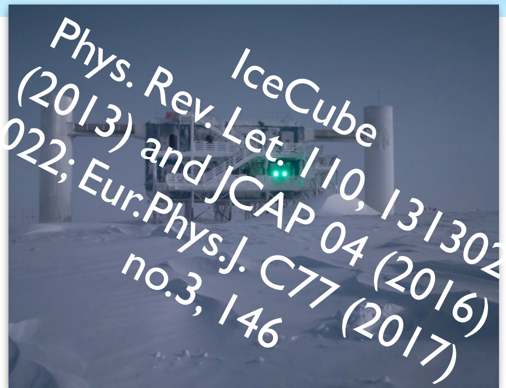


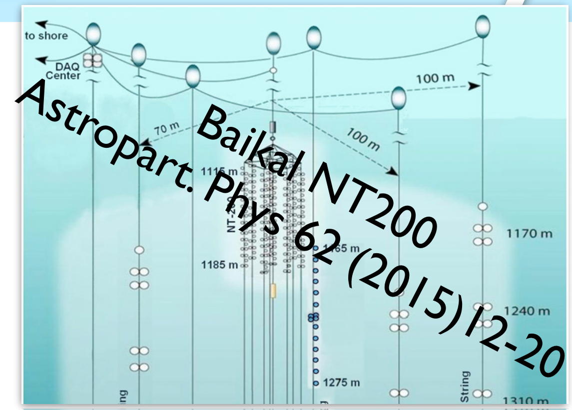
Solar Dark Matter



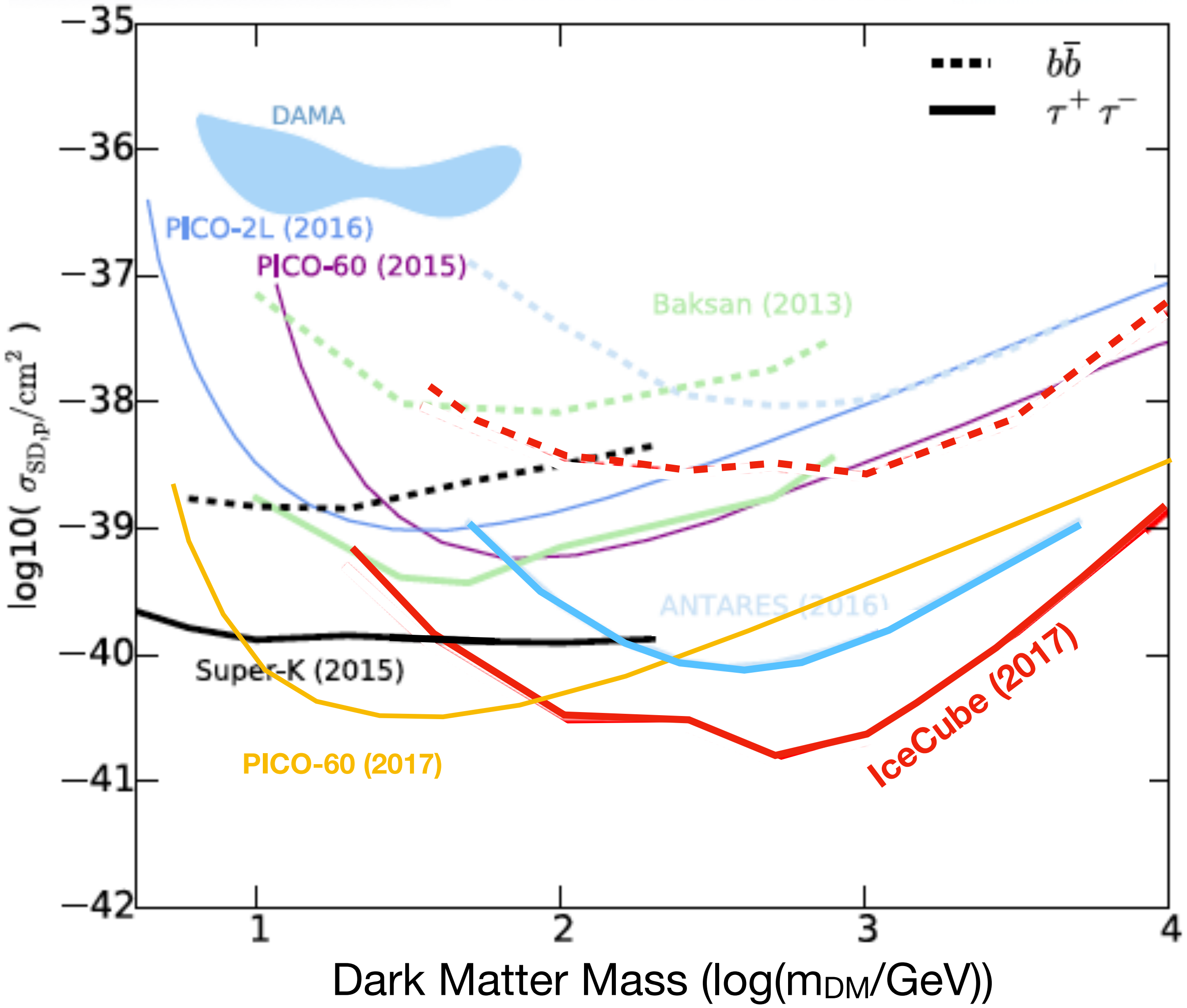
Solar Dark Matter Summary



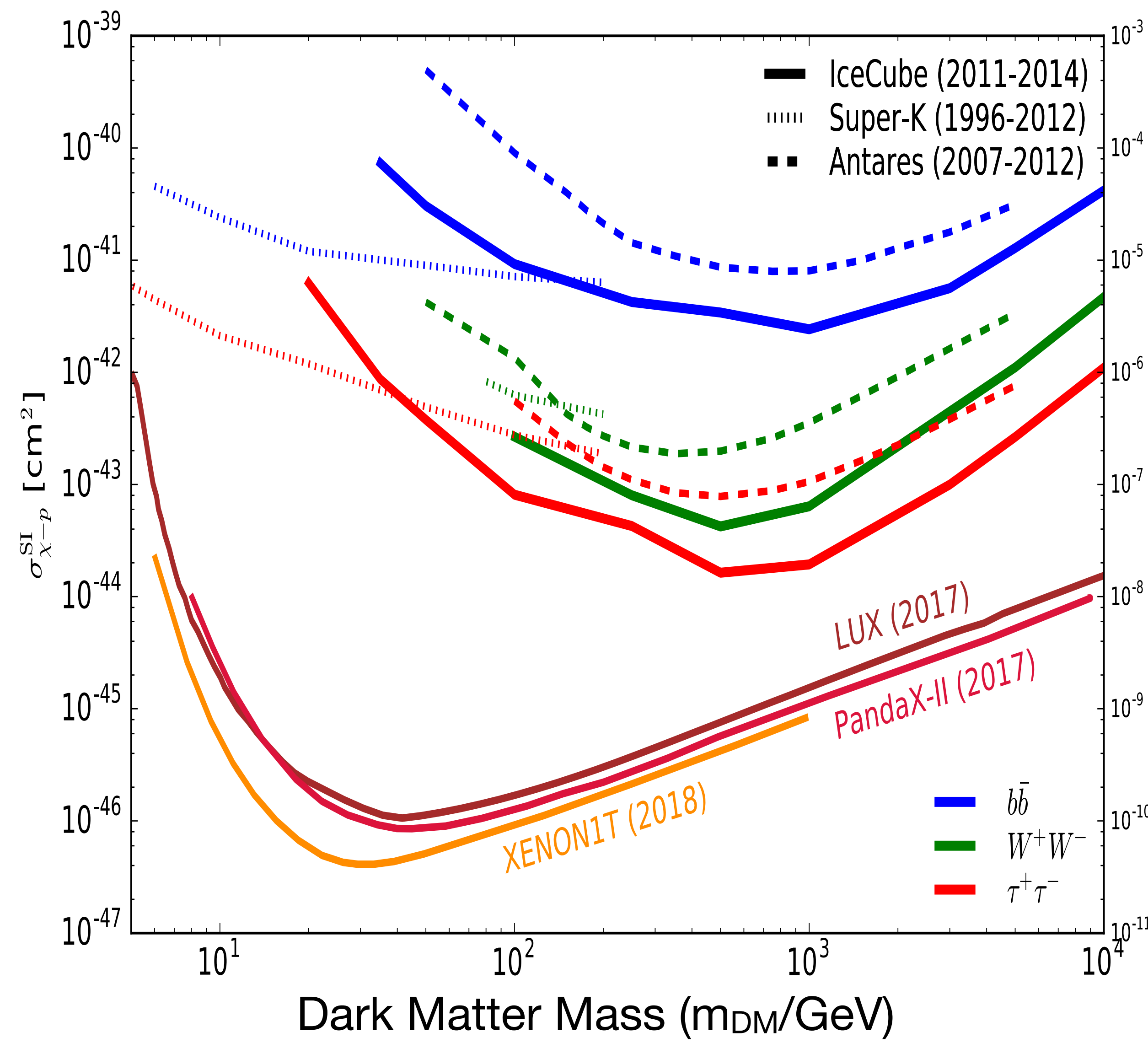




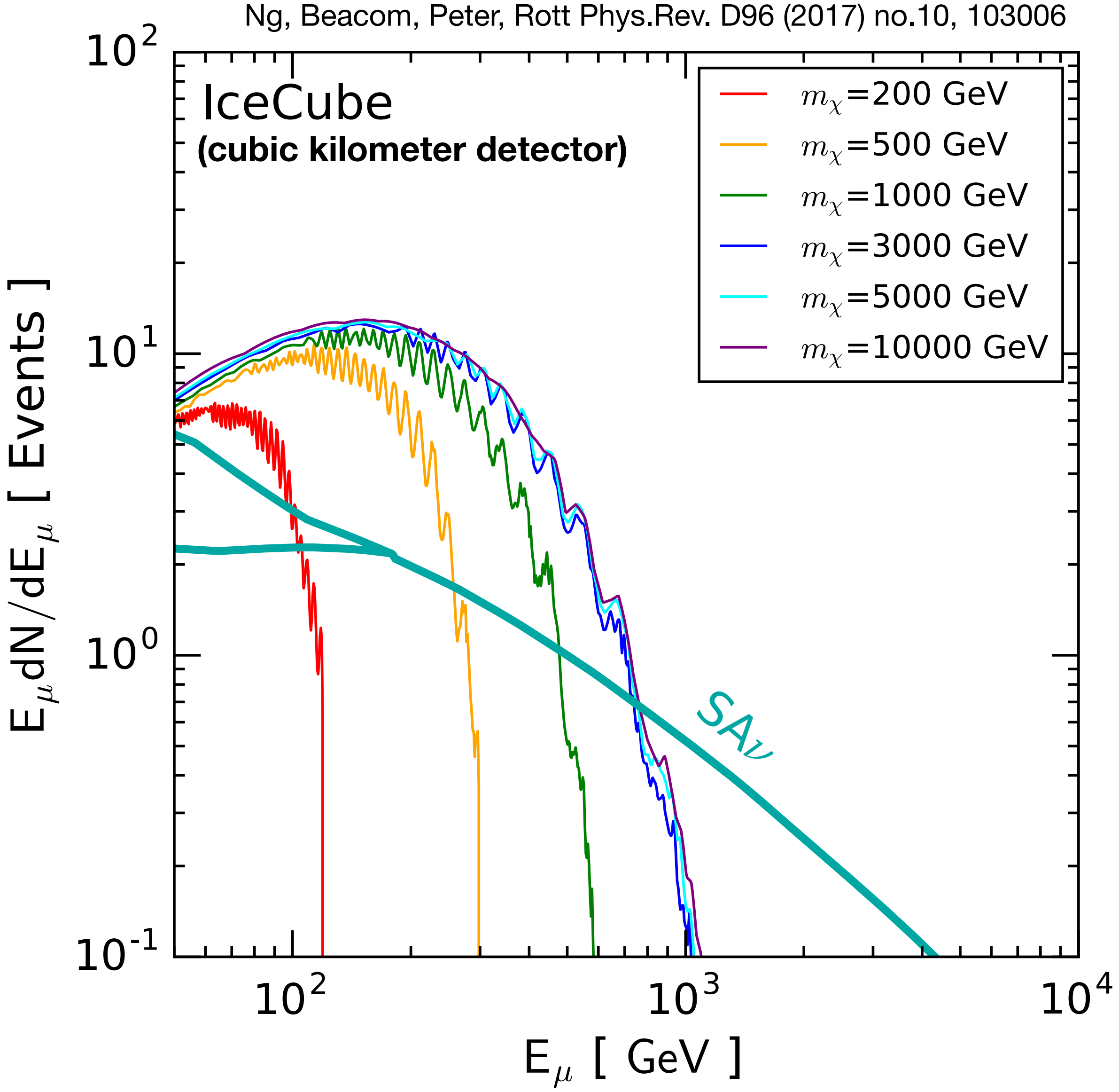
Spin-dependent scattering

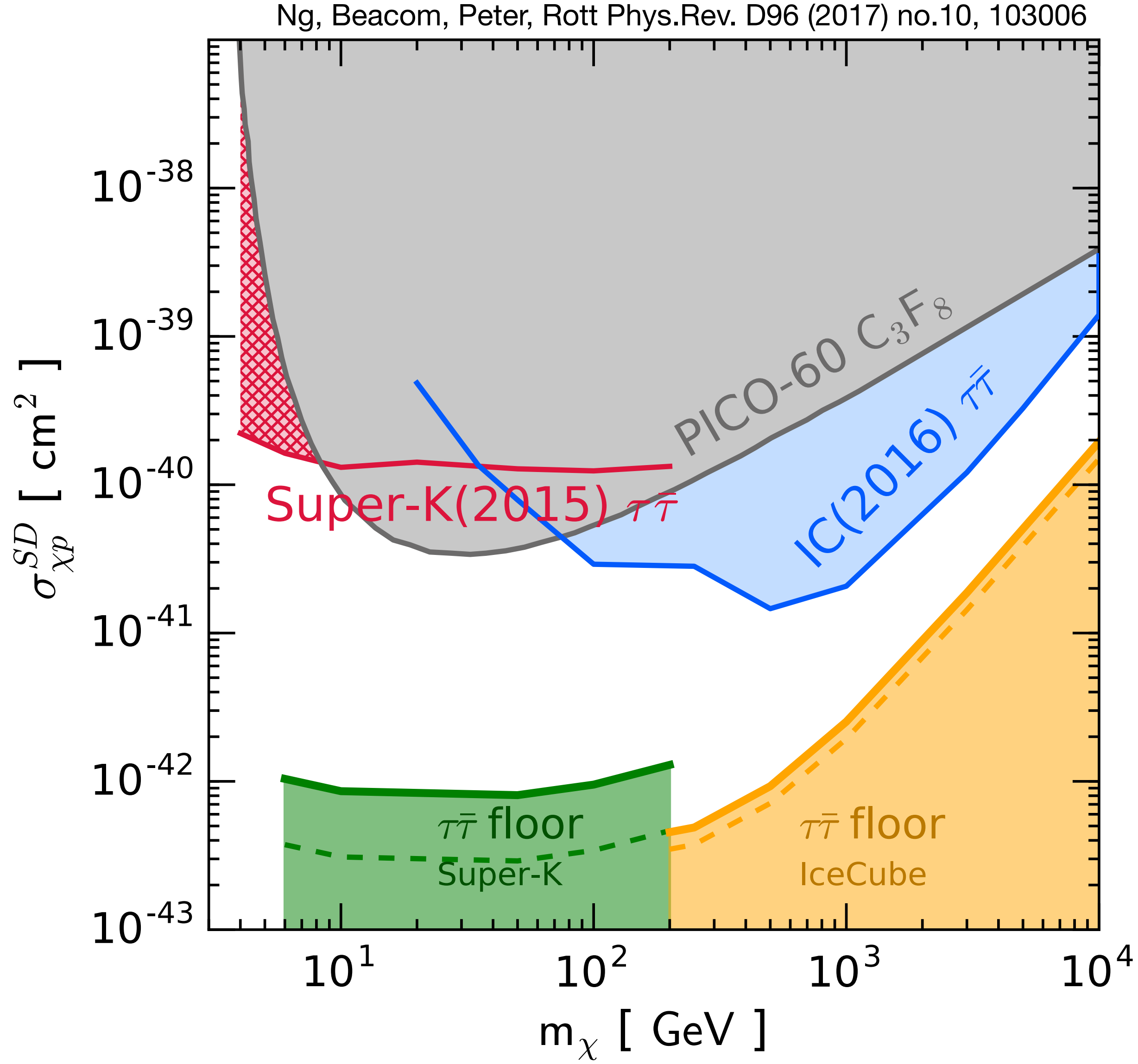


Spin-independent scattering



Cosmic background from the Sun





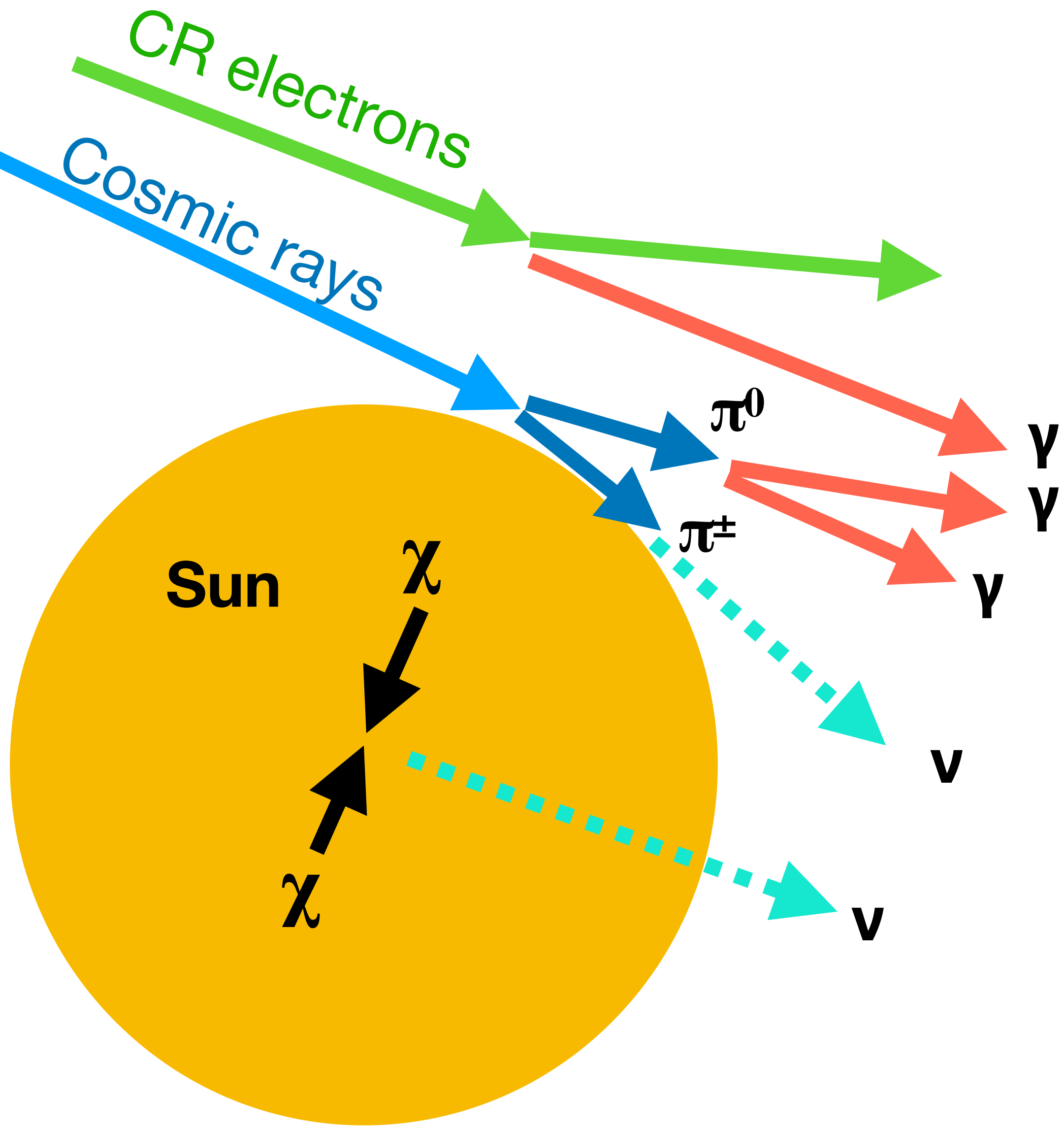
- Solar Atmospheric neutrinos give a new background to solar dark matter searches
  - However, energy spectrum expected to be different
  - In DM annihilation neutrinos significantly attenuated above a few 100GeV

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

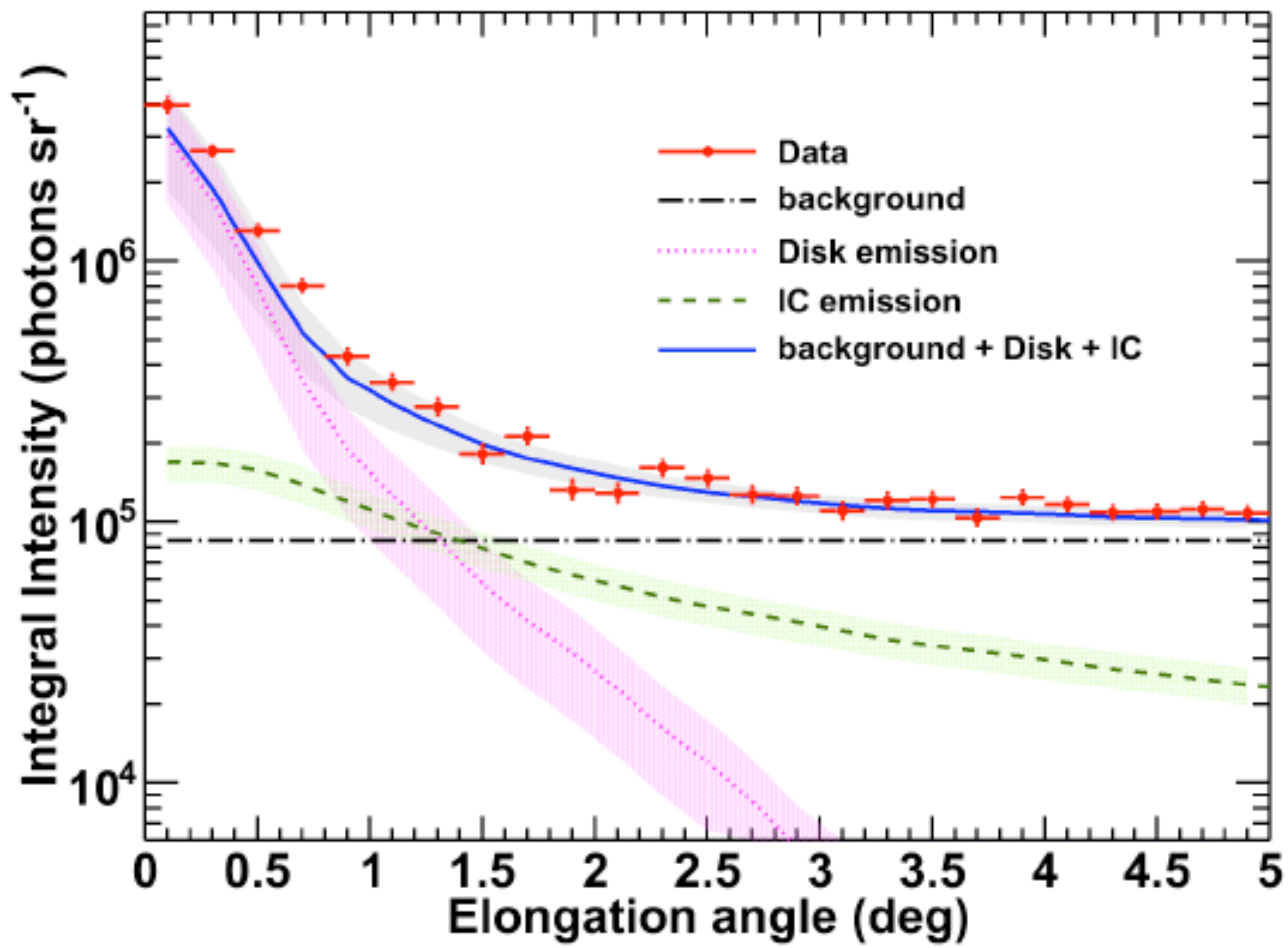
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no. 10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 . 06 (2017), p. 033**, arXiv: 1704.02892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

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

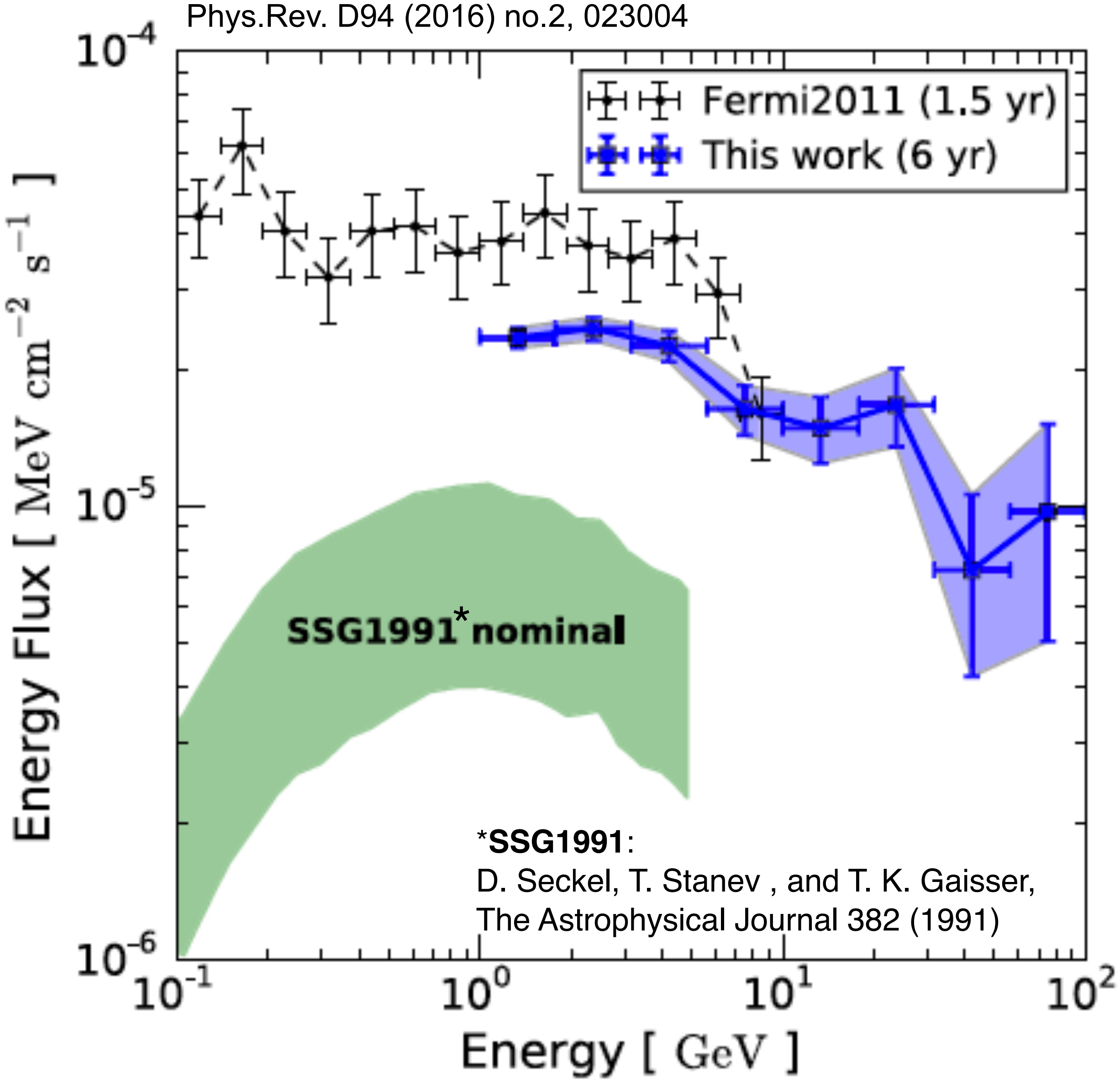
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

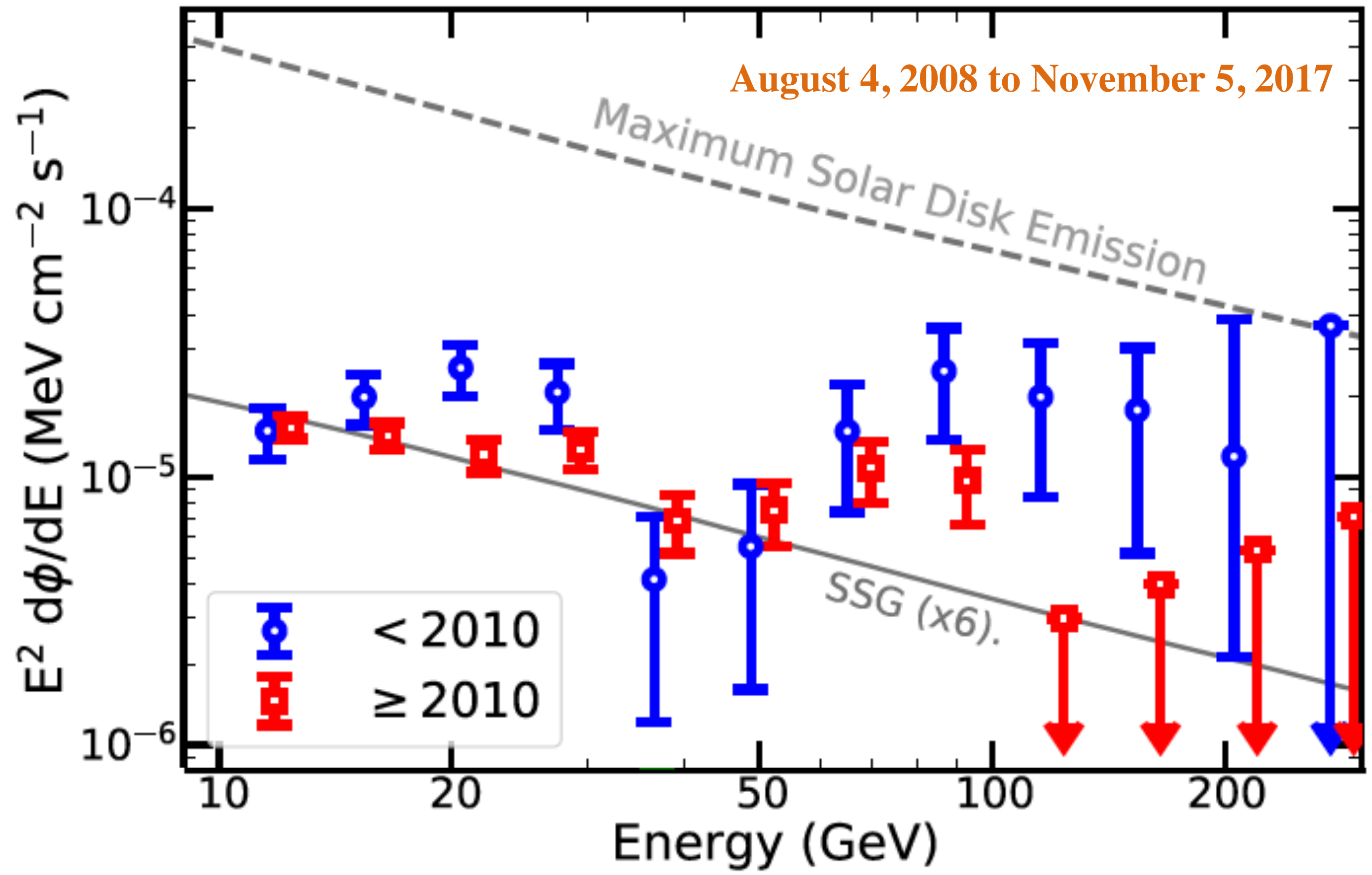
- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

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



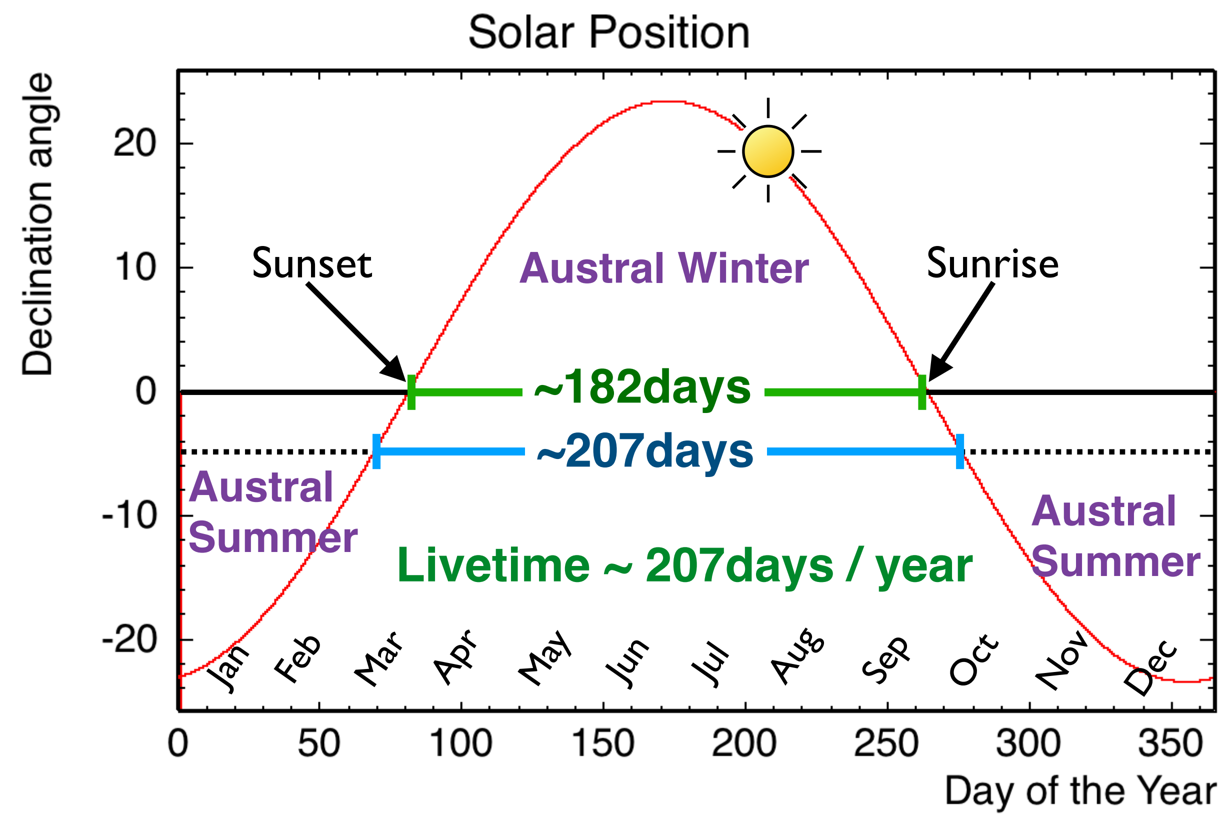
Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C. Y. Ng, and Qing-Wen Tang arXiv:1803.05436

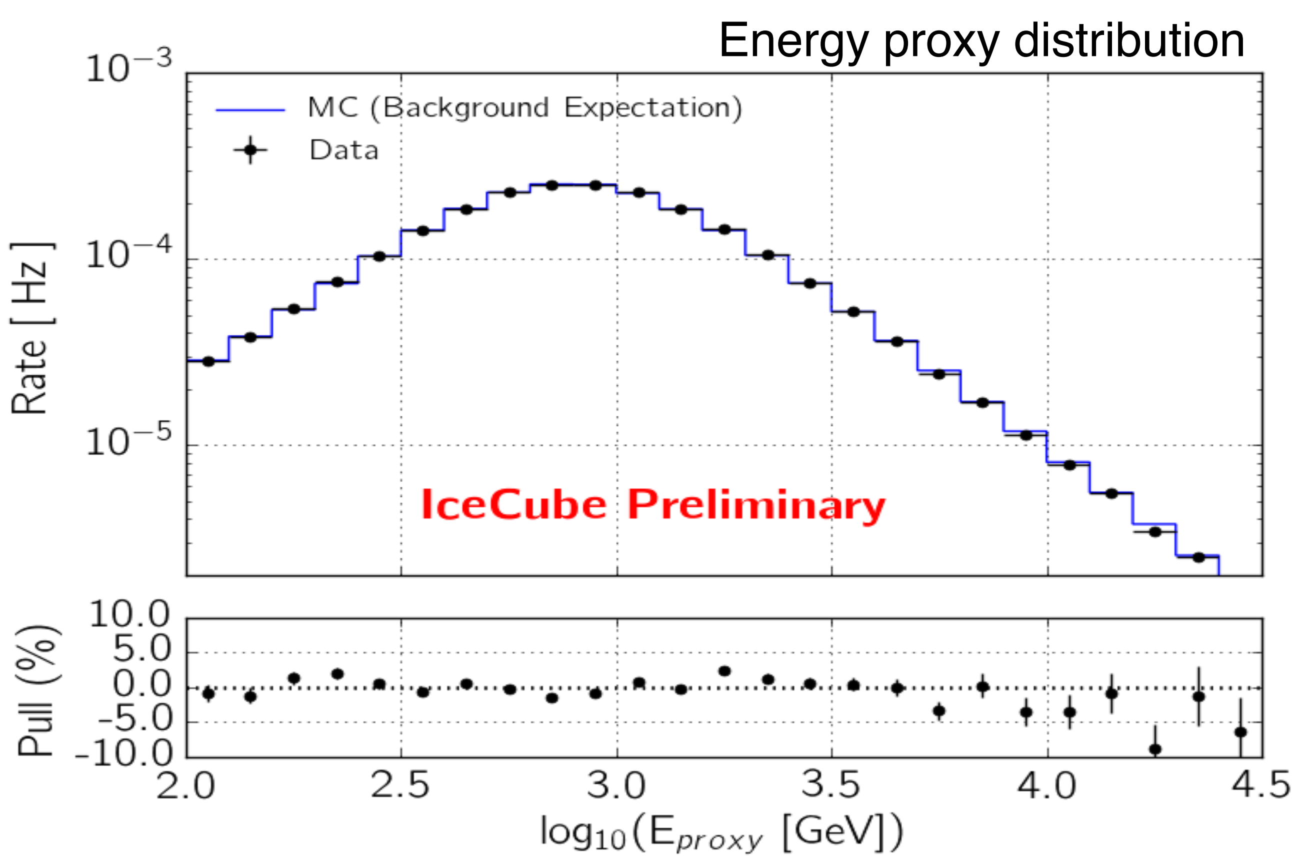


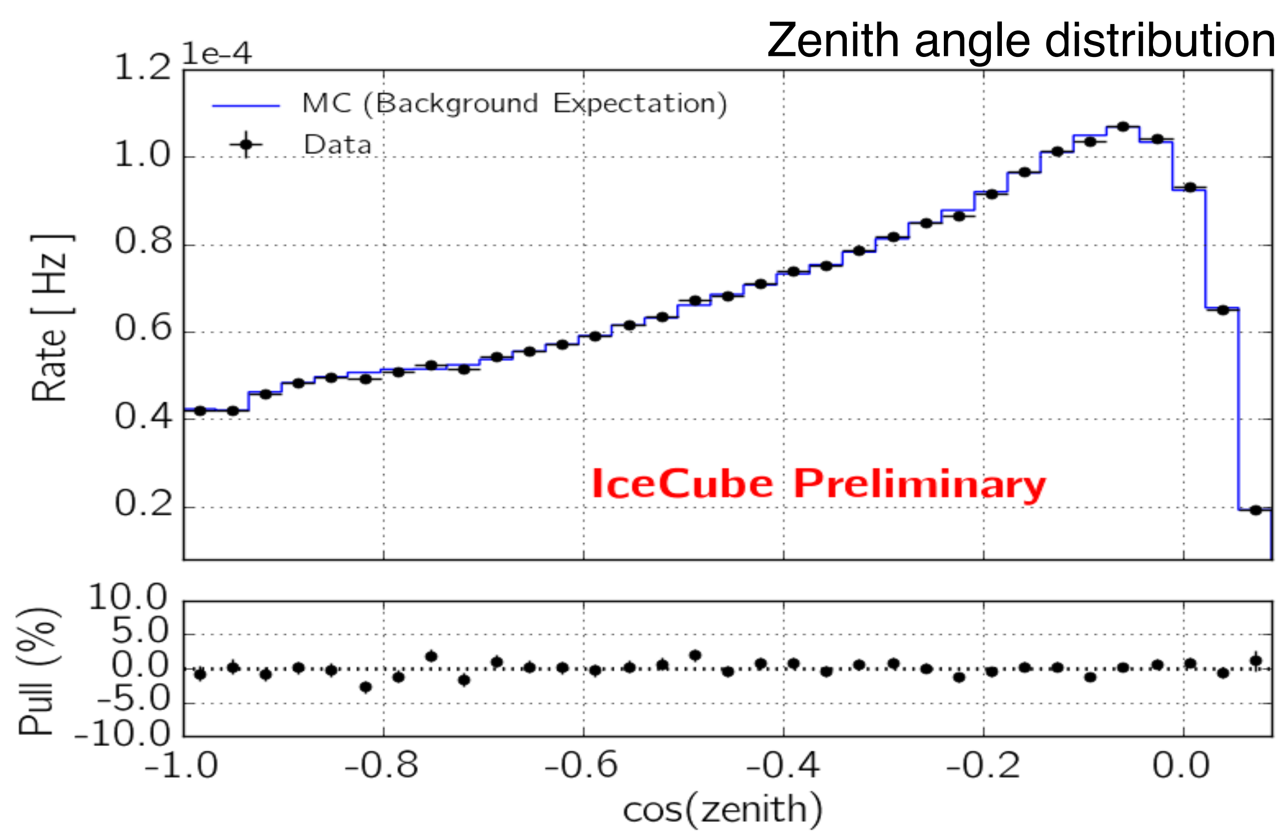
- Gamma-ray flux extends to 100GeV and beyond
- Gamma-rays below 10GeV anti-correlations with solar activity
- Observed flux factor 5 larger compared to central prediction of SSG1991
- Spectrum could be fit by single power law (γ~2.3)

- 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

- 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.







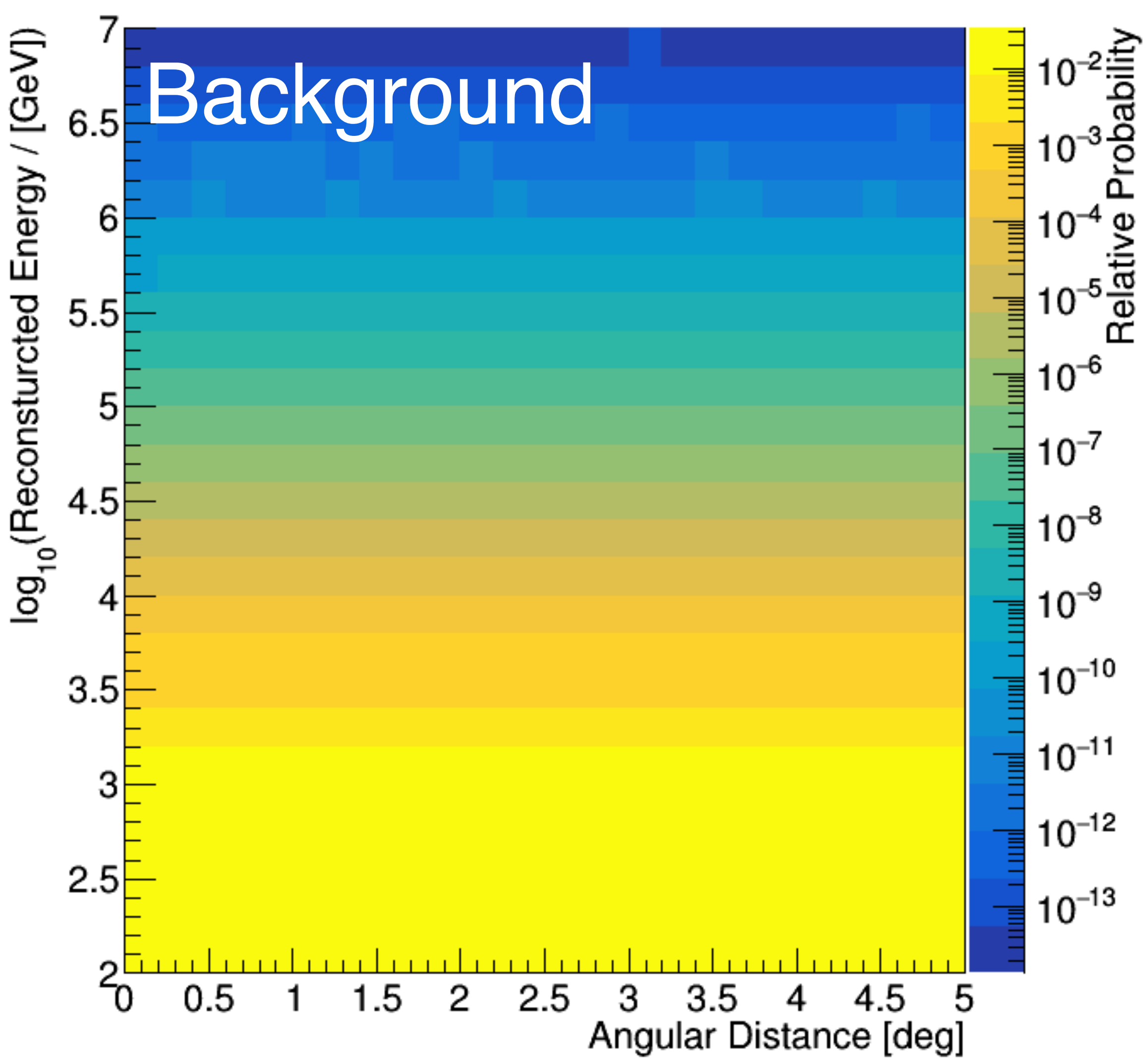
Likelihood

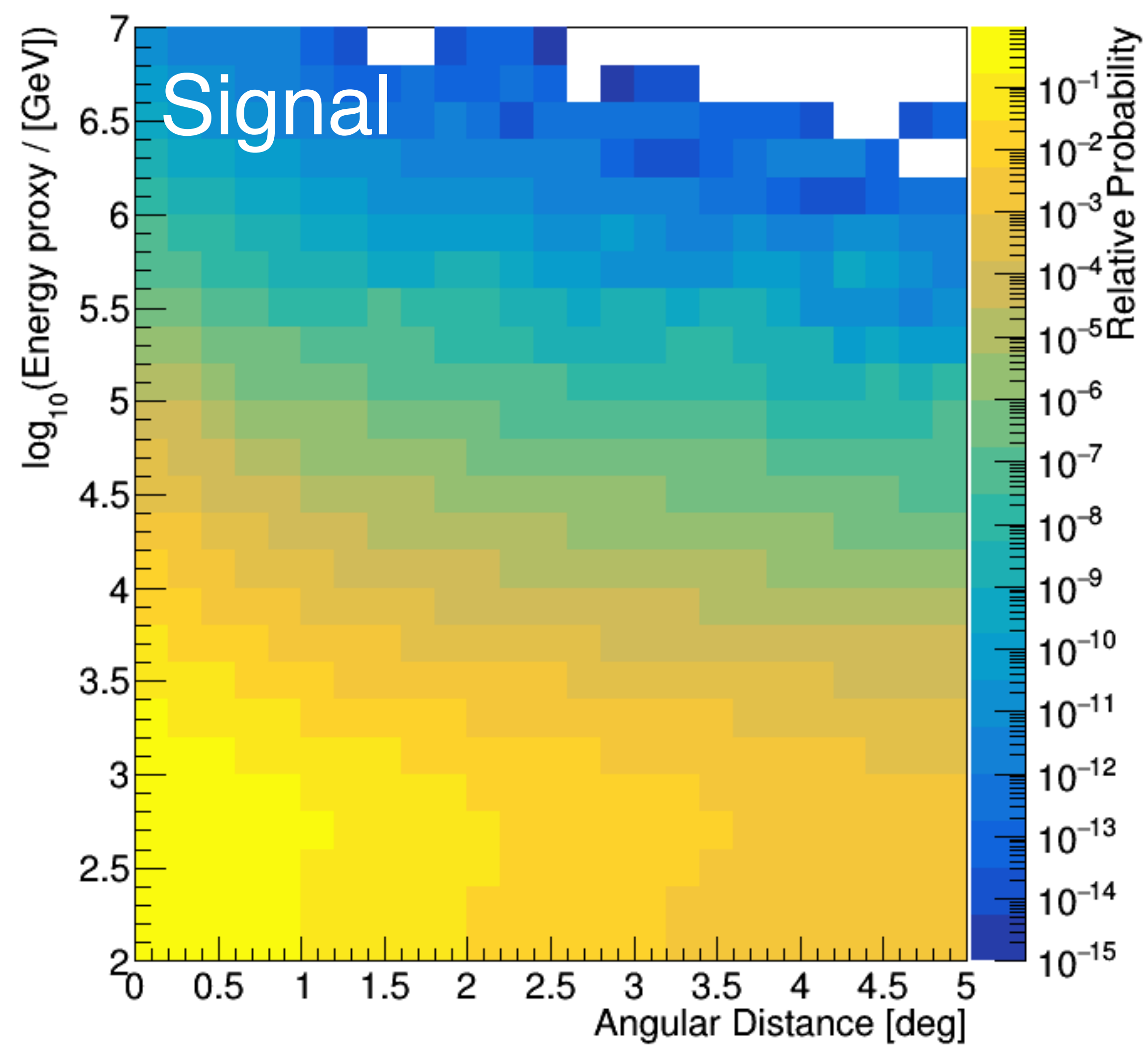
- Maximum log likelihood method is used to calculate significant with a test statistic (TS) distribution
  - The likelihood function is defined by

$$L(E,\Theta) = \Pi\left(\frac{\mu}{N}\times p_{sig}(E,\Psi\,|\,\mu) + (1-\frac{\mu}{N})\times p_{bkg}(E,\Psi)\right)$$

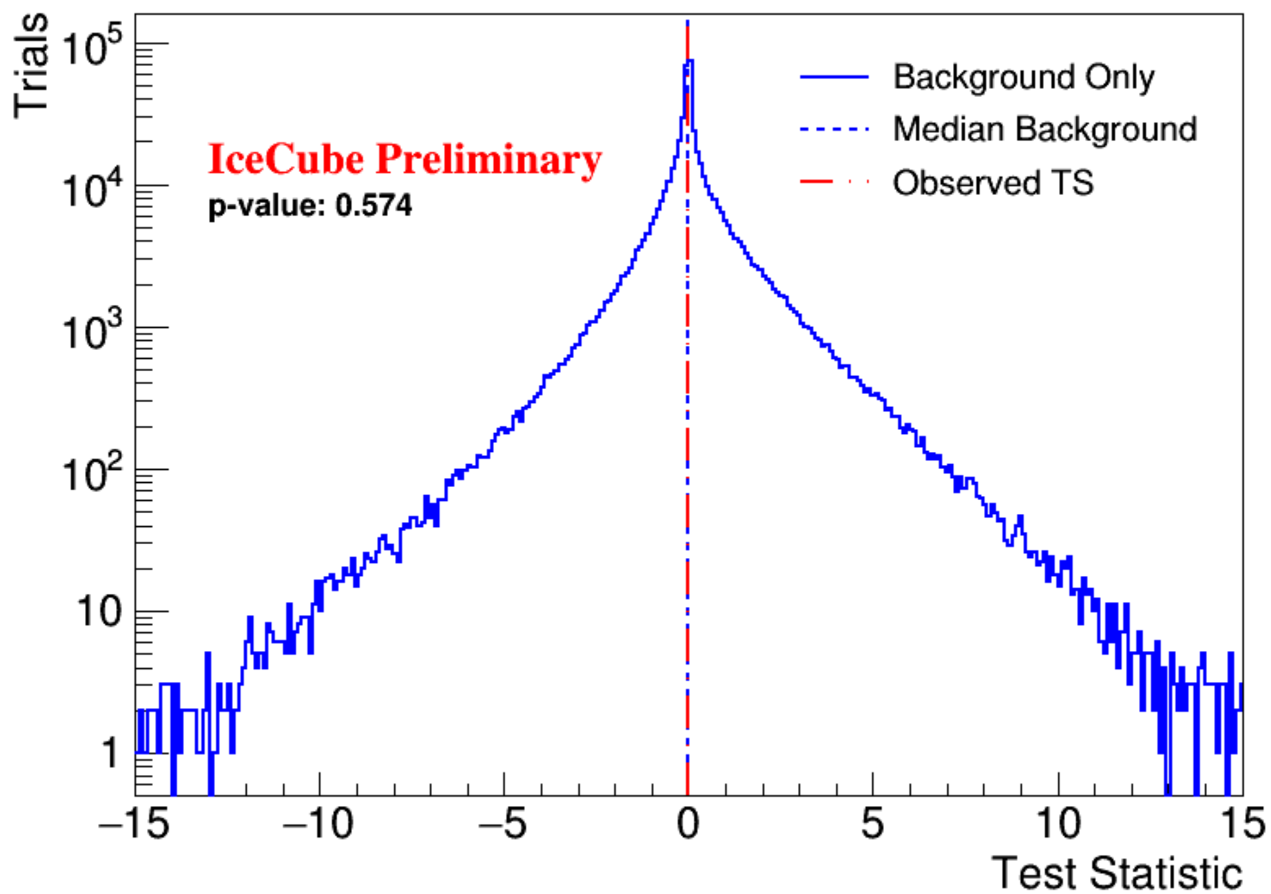
N = total number of events,
μ = number of signal events
E = neutrino energy proxy
Ψ= angular distance to the Sun's center

Signal and background pdfs





Test Statistics

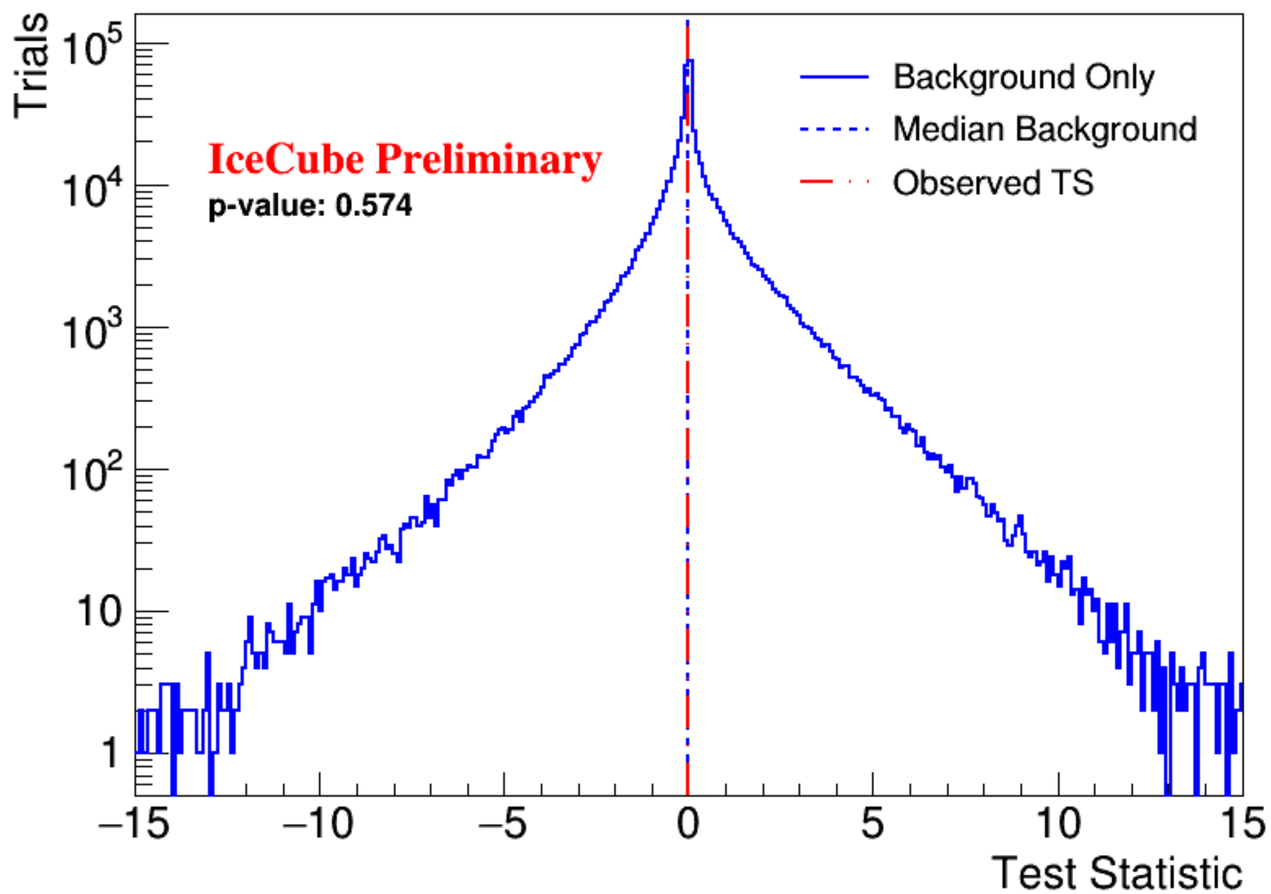


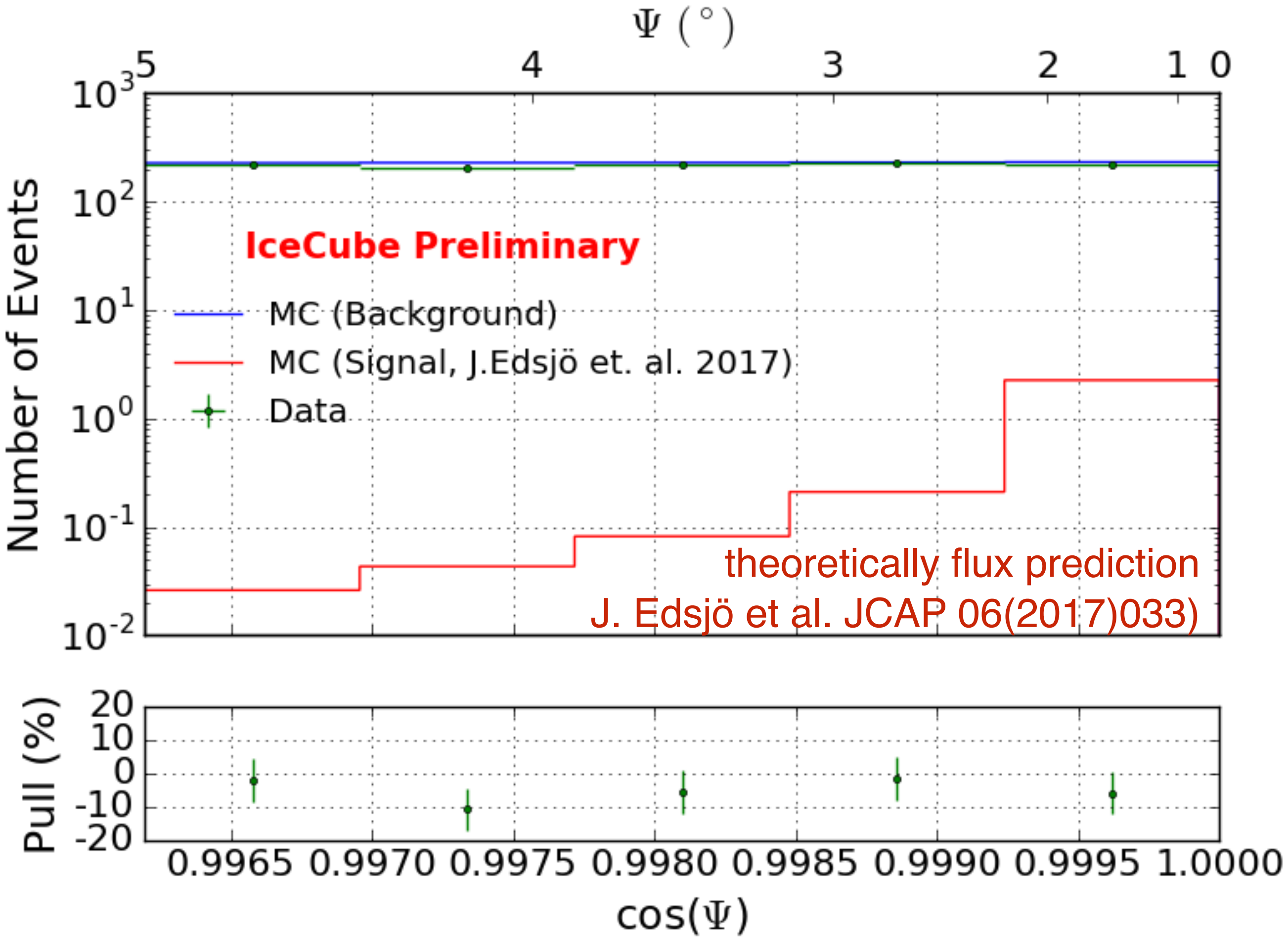
- Test statistics (TS) is defined as a ratio of likelihood function

$$TS = -2\ln(L(0)/L(\hat{\mu})) \qquad \hat{\mu} > 0$$
$$= -\left(\frac{d}{d\mu}L(\mu)|_0\right)^2 / \left(2\frac{d^2}{d\mu^2}L(\mu)\right) \qquad \hat{\mu} = 0$$

- The p-value calculate based on a background only assumption is 0.57. Hence, no excess of solar atmospheric neutrinos is seen.

Test Statistics





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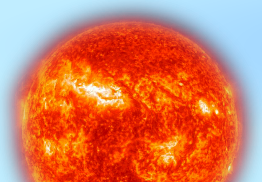


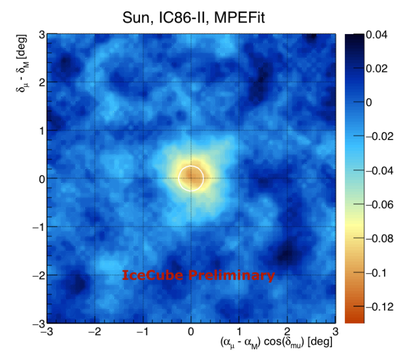
Systematic uncertainties

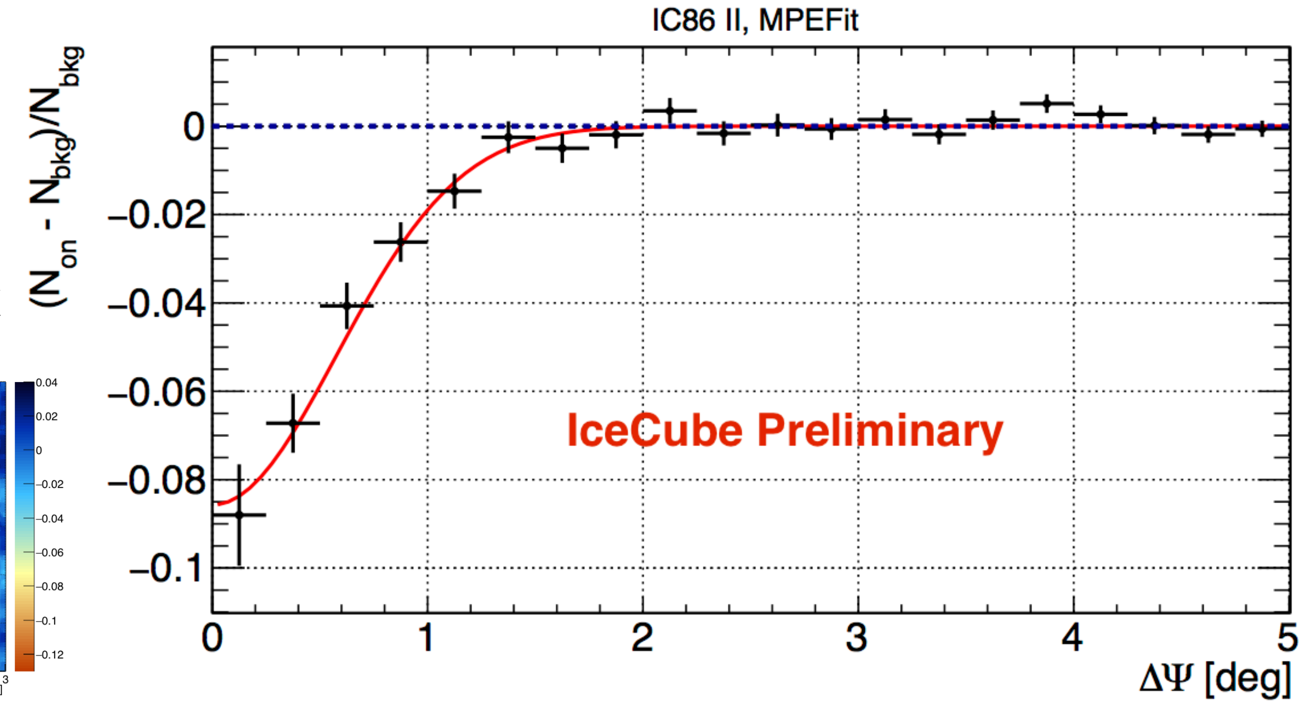
Cosmic ray Sun shadow

Cosmic rays are absorbed by the Sun, resulting in a deficit in muon and neutrino flux. Two extreme cases were compared:

- no absorption
- neutrino flux deficit as measured for muon flux

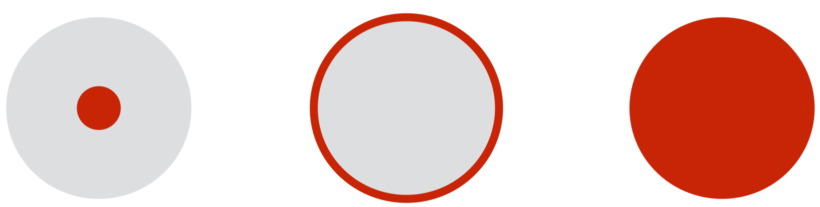
Systematic effect~ 2%





Source distribution

Three extreme cases are considered to derive a sys. uncertainty



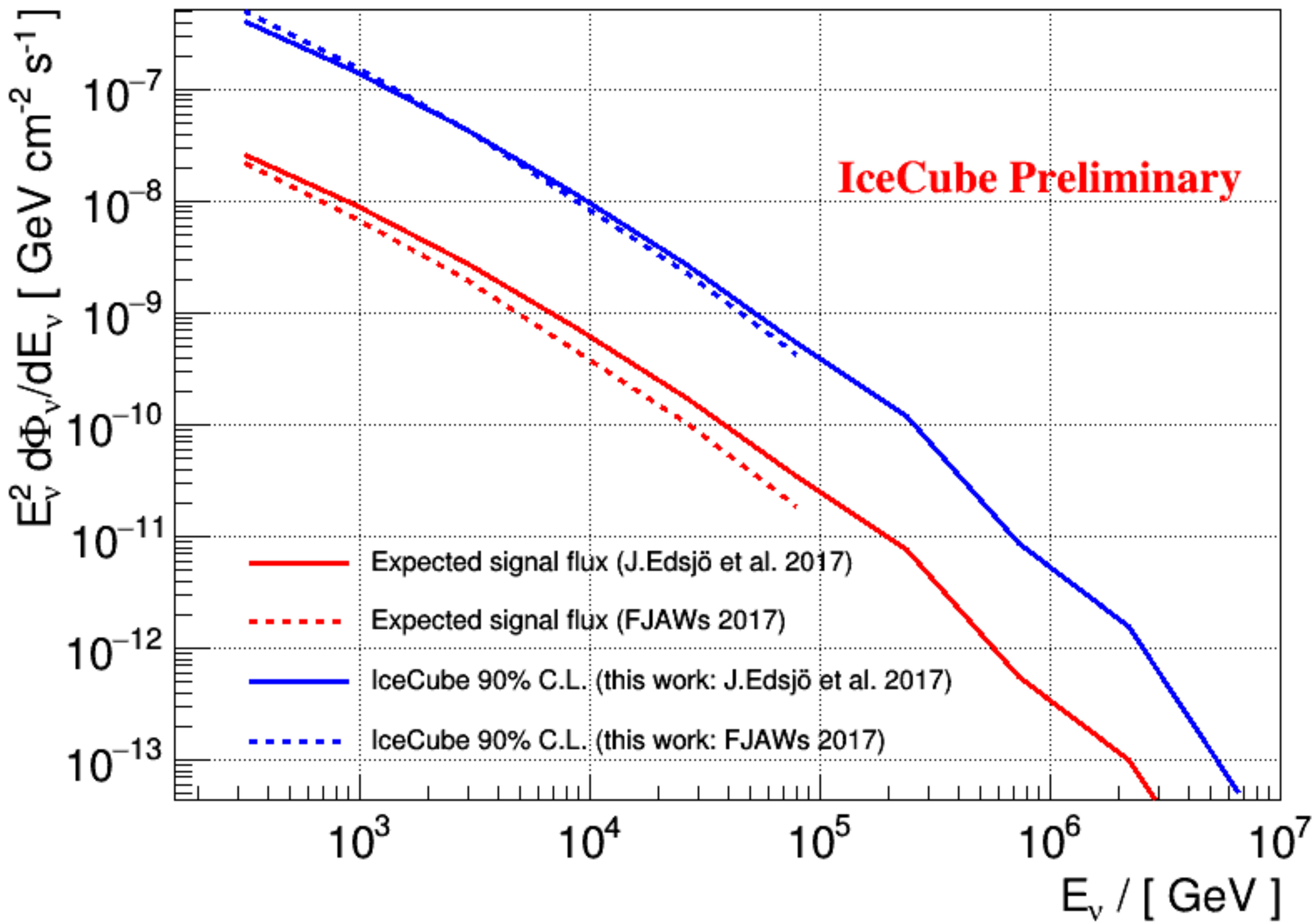
Point Source | Ring | Uniform disk

Systematic effect~ 4%

Systematic	Size
DOM efficiency	12%
Ice properties	4%
Source distribution	4%
Cosmic ray shadow	2%
Total	**13%**

Preliminary systematic study completed
Full study on-going

Upper limit



Feldman-Cousins Upper limit at 90% C.L.

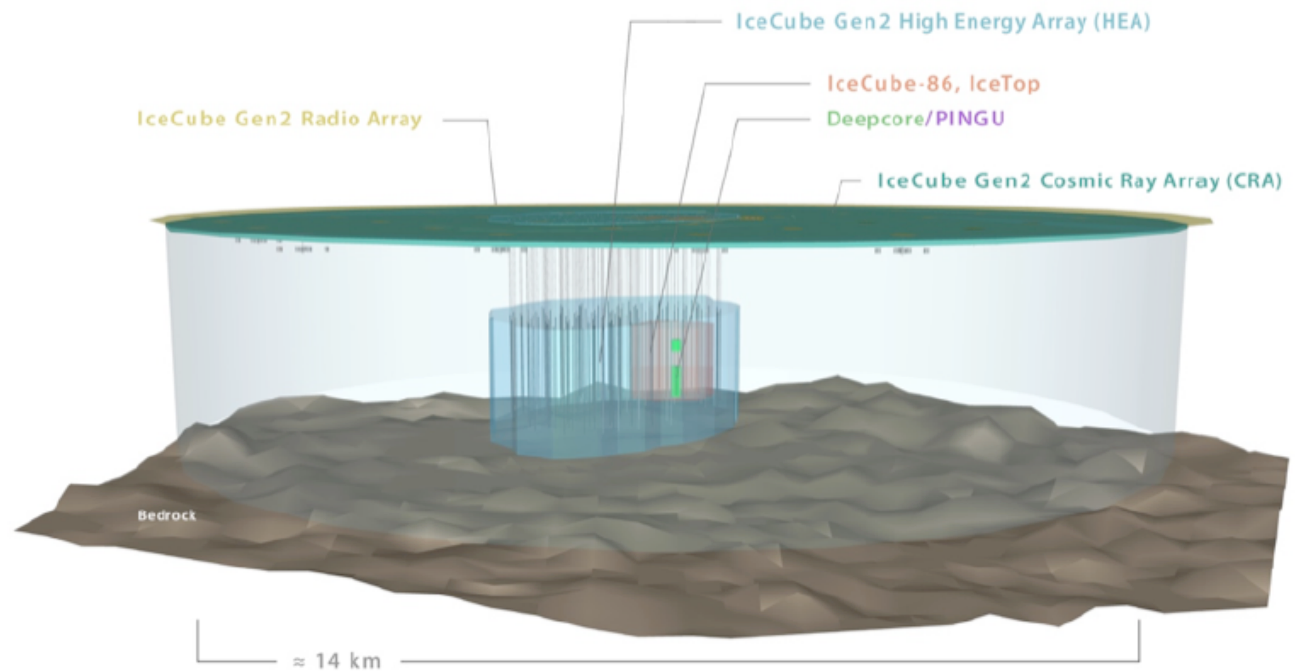
- preliminary systematic uncertainties are included by worsening the limit by 13%

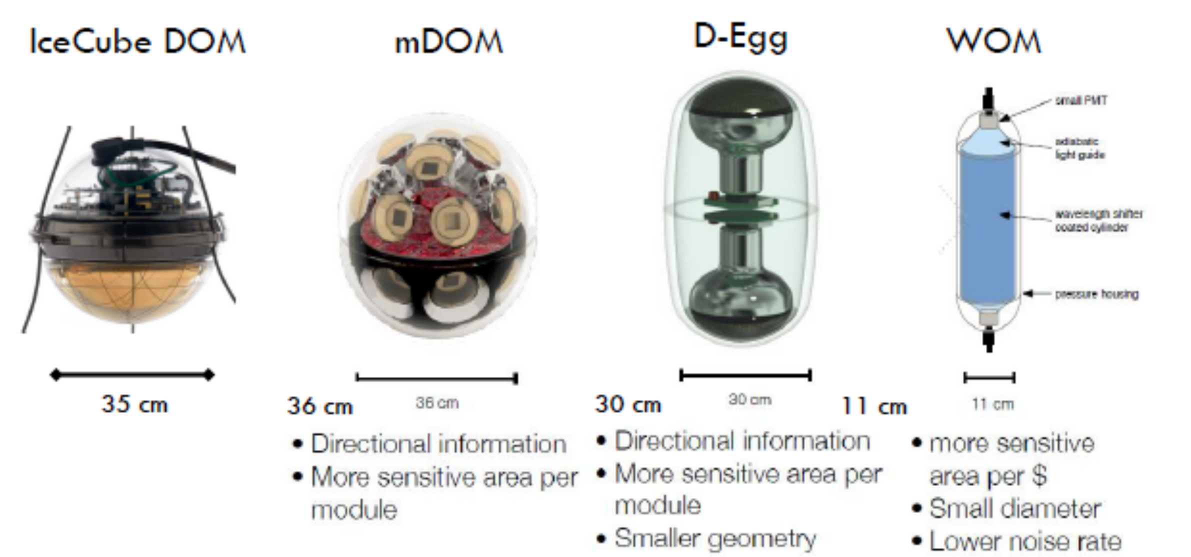
Future Plans

Next generation

- 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
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- New physics or something unexpected ?
- …

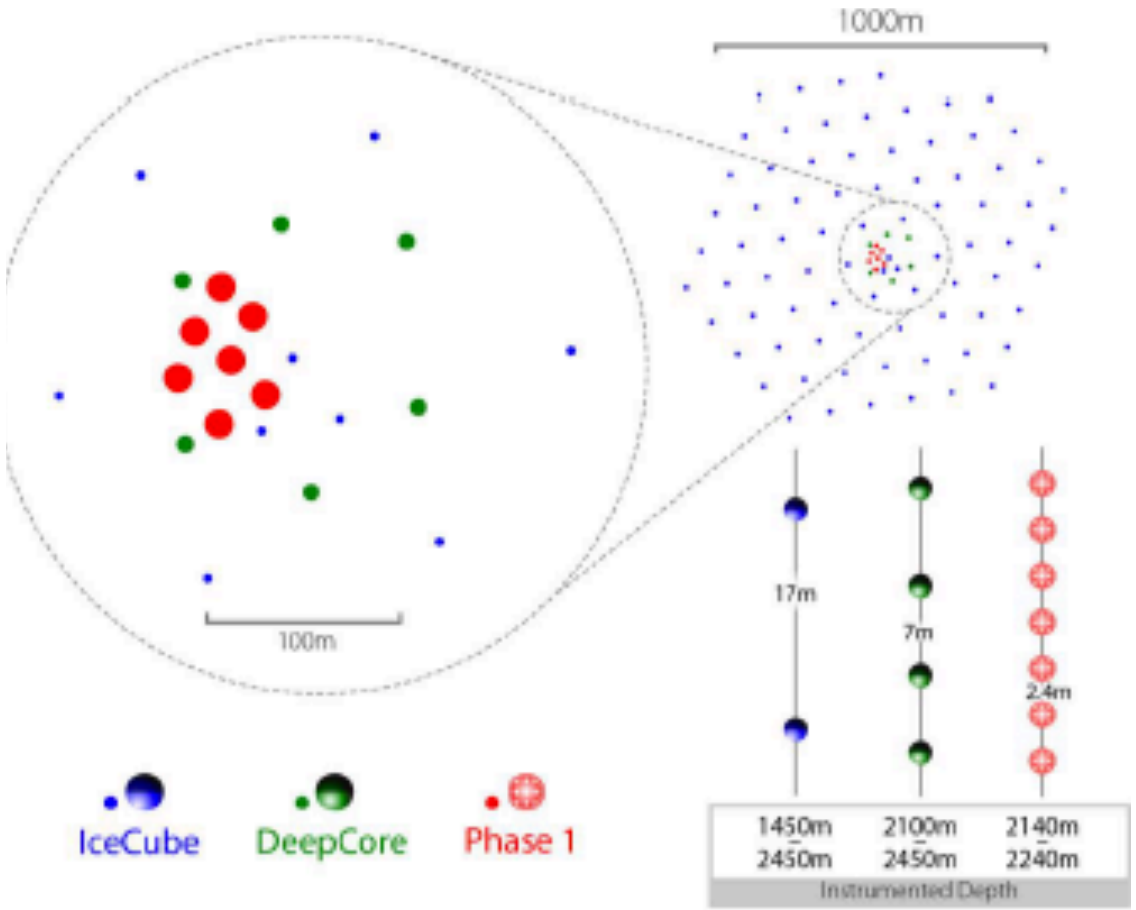
IceCube Gen2 Facility



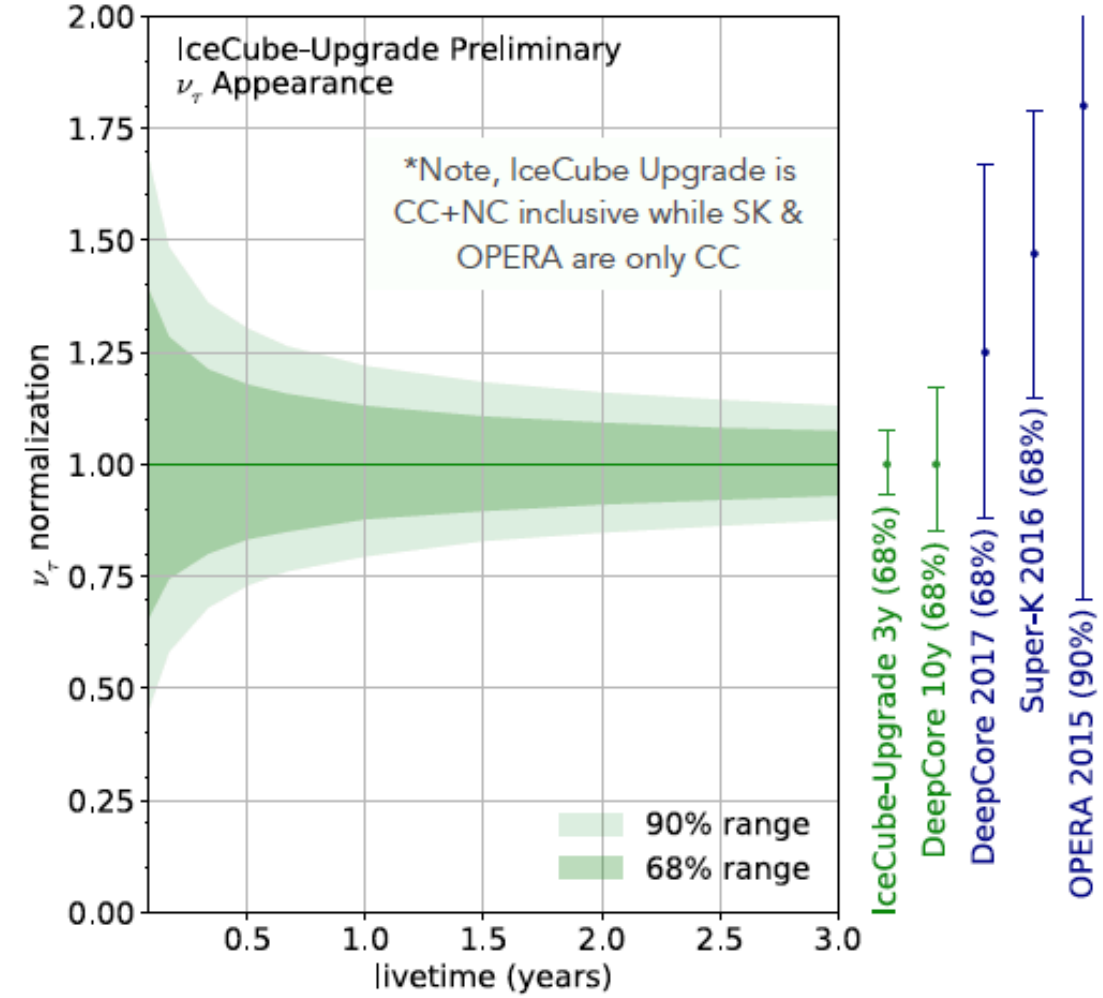


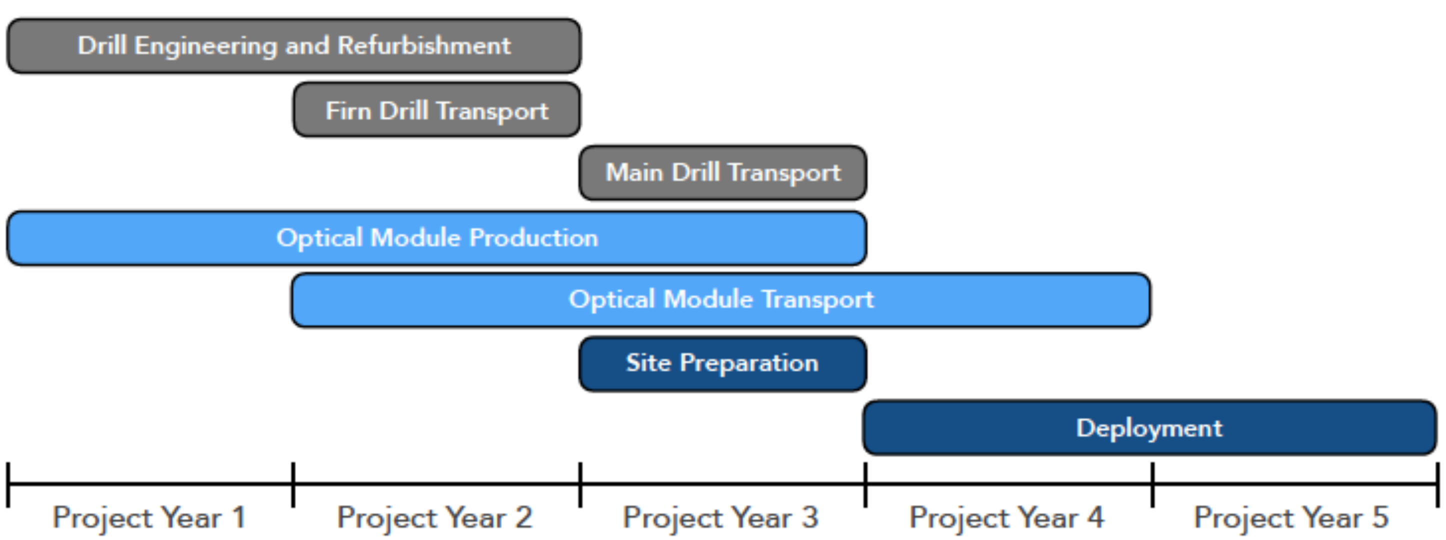
see also:
- PINGU LOI arXiv:1412.5106

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

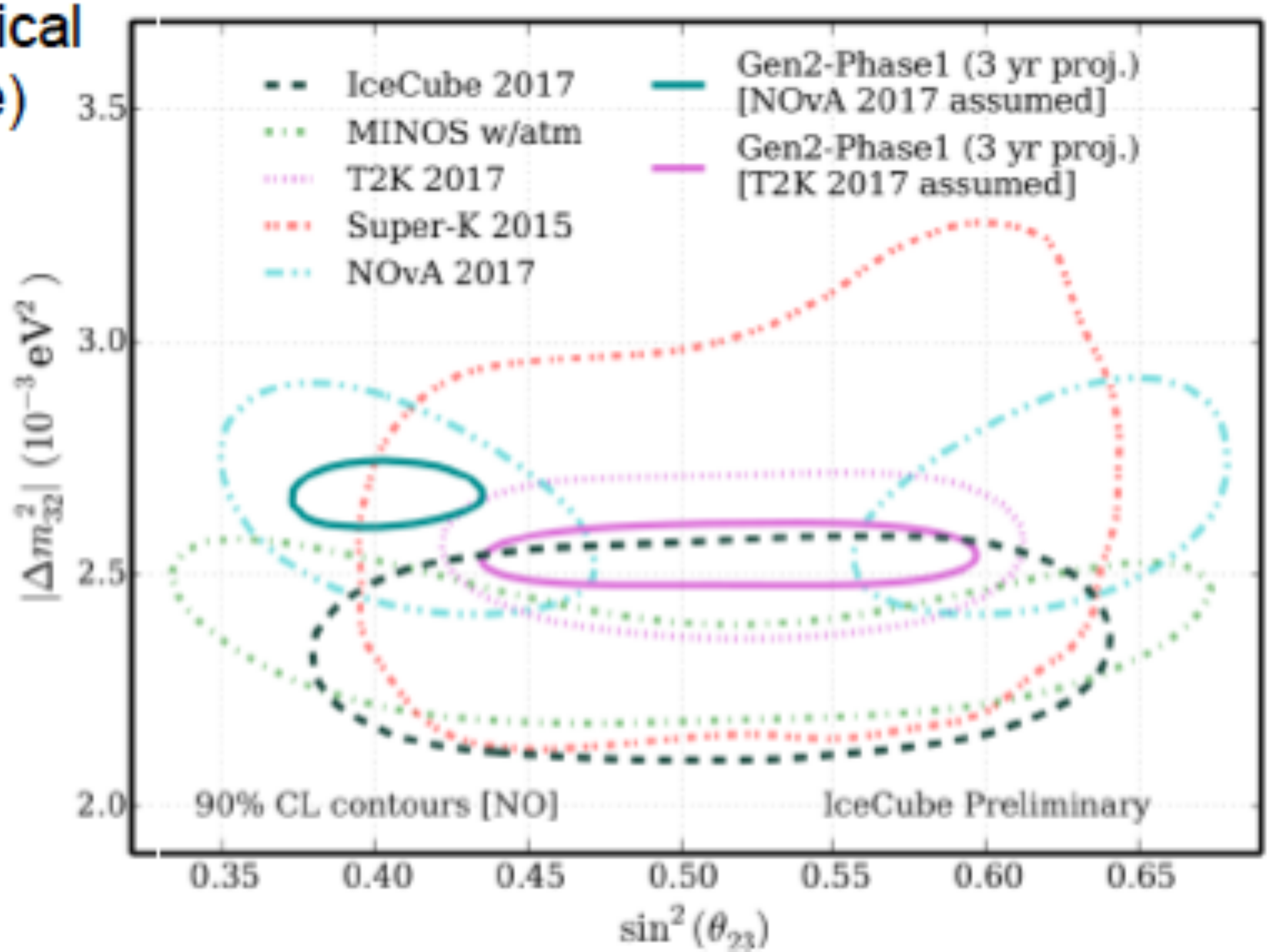




First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies

The IceCube Upgrade

- Target $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Detect ν_τ events on a statistical basis (up-going, shower-like)
- Case study for IceCube Upgrade:
  - ~2500 ν_τ events / year
  - Drastically improve measurement of atmospheric mixing parameters
  - Chance to determine octant of θ_{23}
- Also possible with ORCA



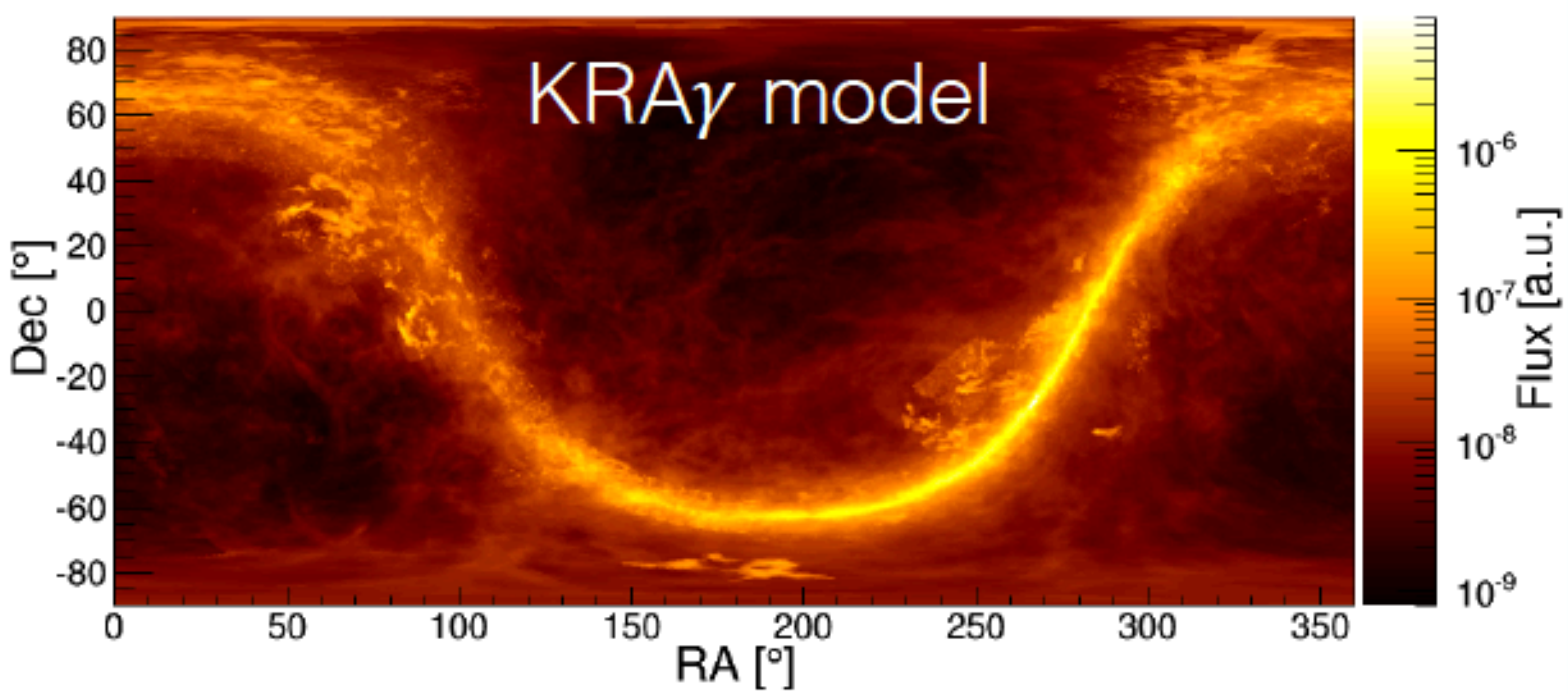
IceCube extremely competitive for neutrino oscillation parameter measurements using atmospheric neutrinos

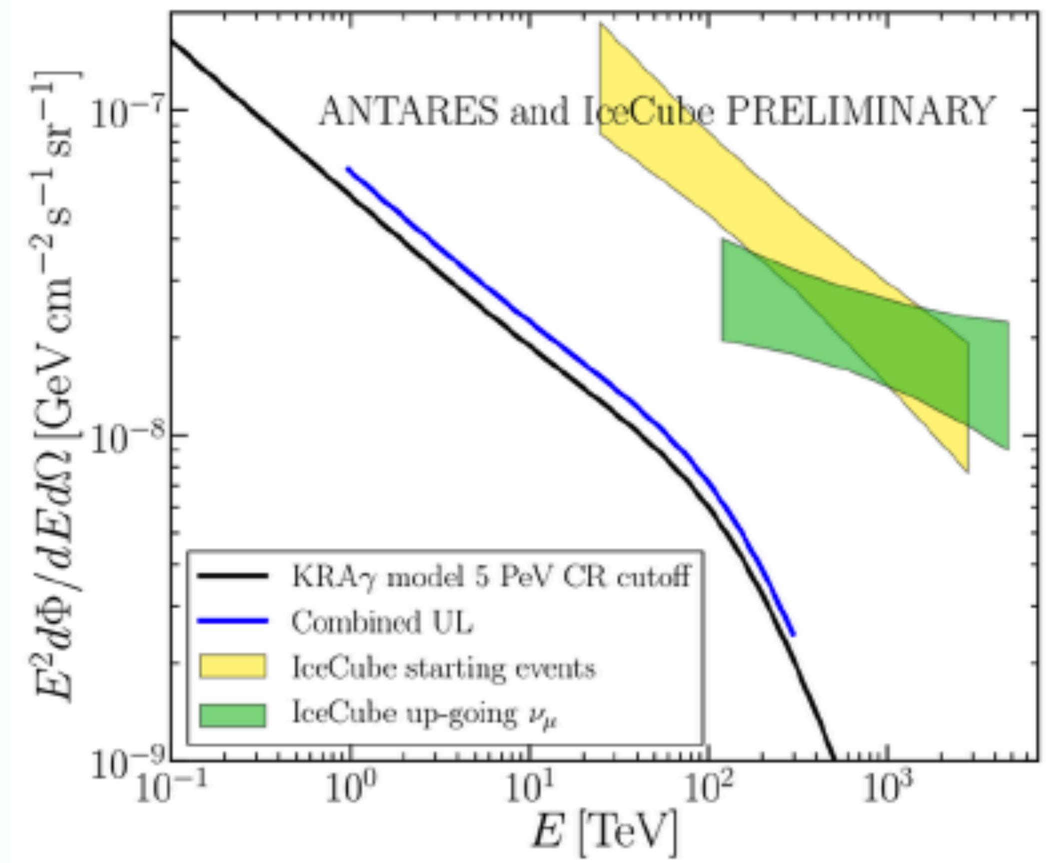
- High-energy astrophysical neutrinos have opened up a new window to the Universe
    - What’s the origin of the high-energy neutrinos ?
- First compelling evidence of high-energy neutrinos with electromagnetic counterparts (TXS 0506+056)
- Neutrino astronomy is a central part of the multi messenger astroparticle physics field
- First hint of a Glashow resonance ?
- Very strong bounds on dark matter scattering with nucleons and decaying dark matter
- First search for solar atmospheric neutrinos was able to place a stringent limit on the neutrino flux from the Sun
- The IceCube Upgrade has just been approved and we can look forward to many exciting discoveries in the near future

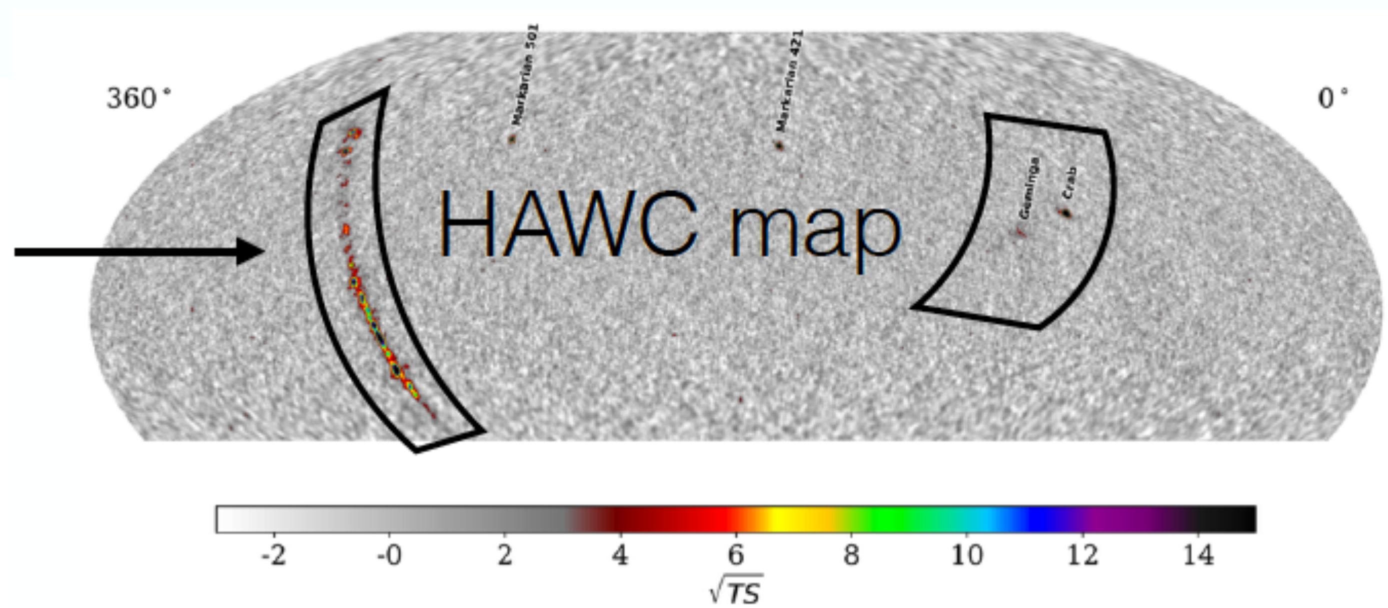
Image:Stephan Richter, IceCube/NSF

Galactic Neutrino Searches

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





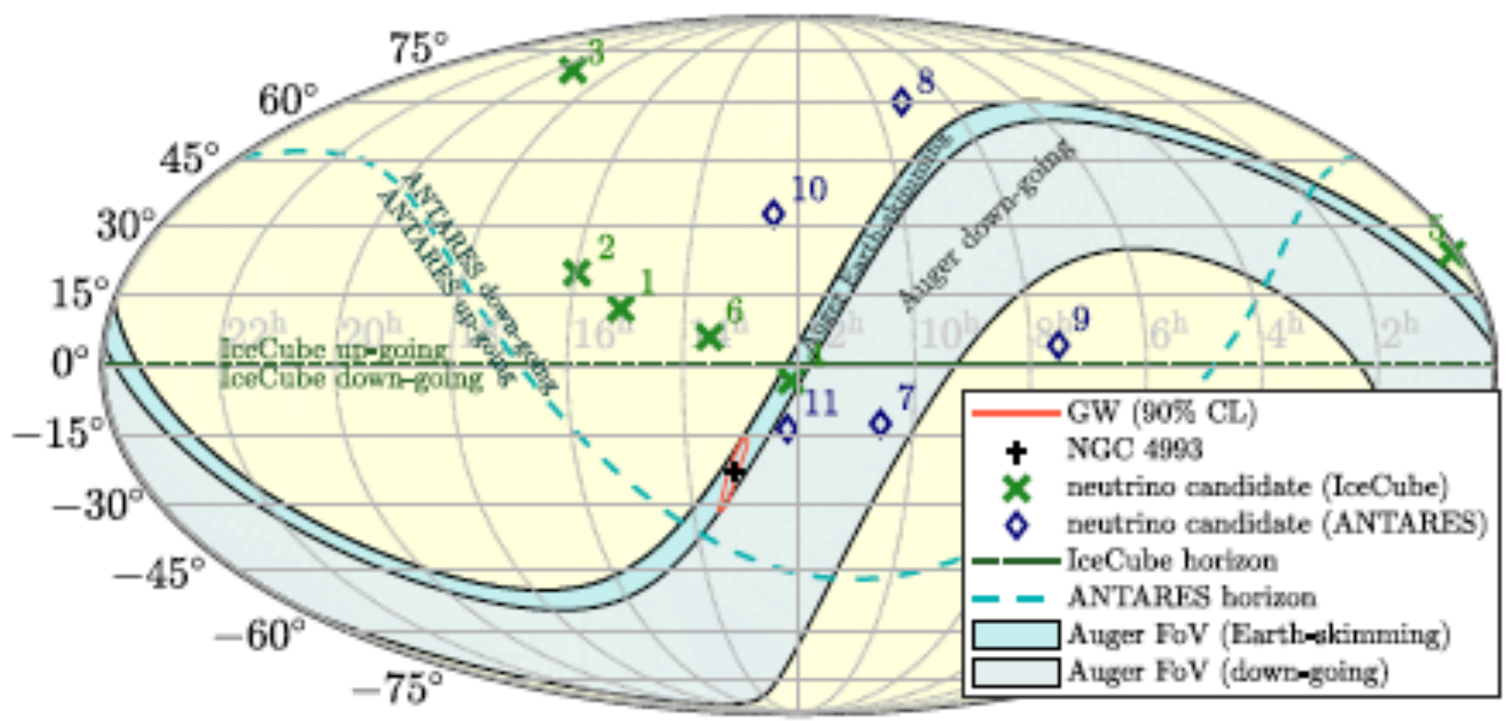


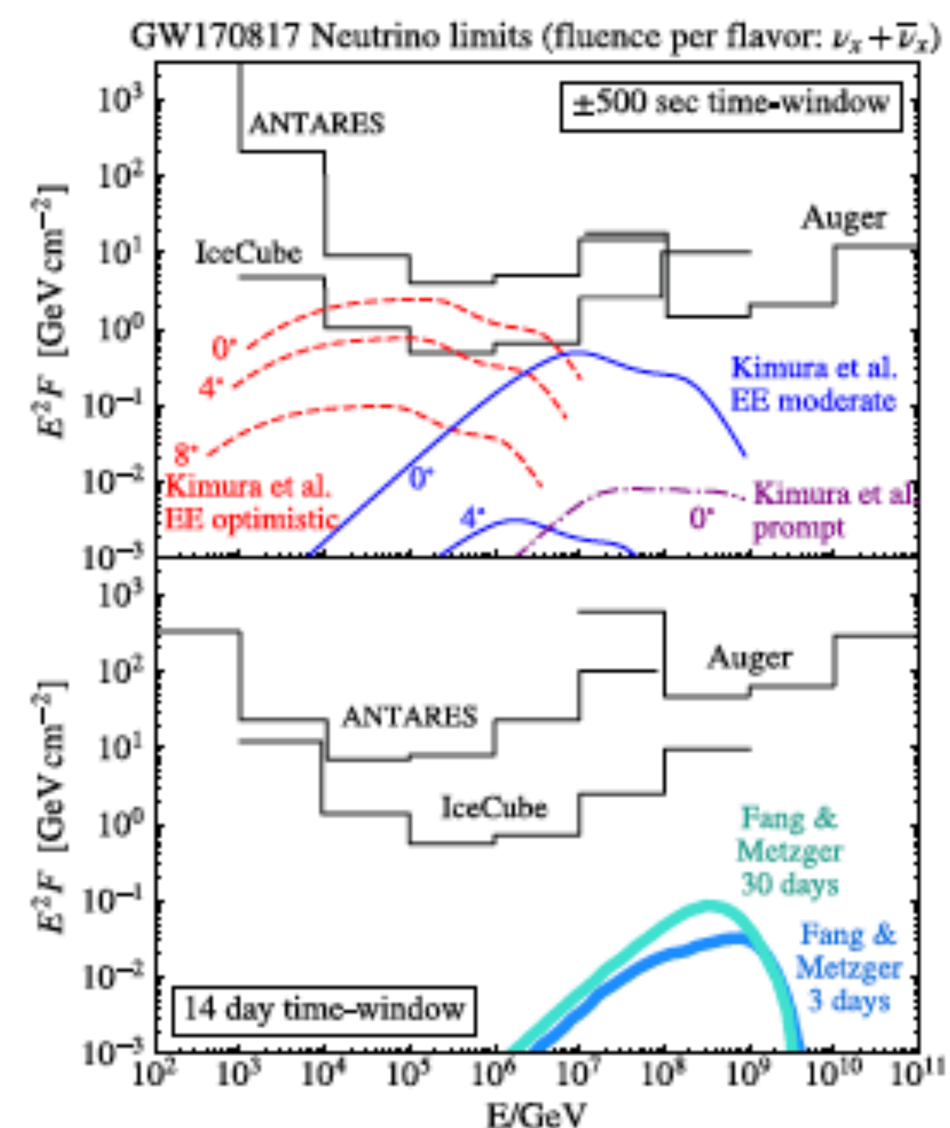
Diffuse astrophysical neutrino flux cannot be attributed to Galactic sources / Galactic plane

IceCube tested HAWC sources … no significant excess observed

Gravitational Waves

Imre Bartos Neutrino 2018

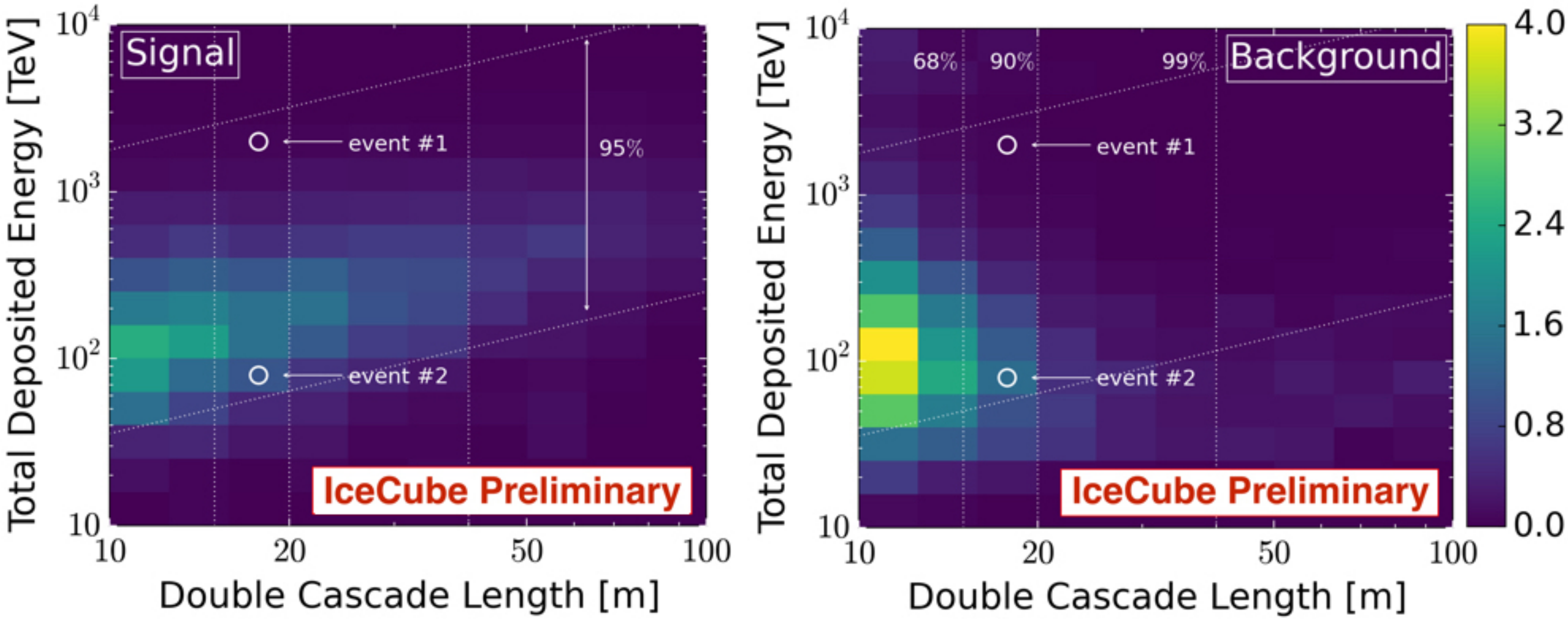




- Search within 1000 s and 2-week time windows (model motivated).
- Complementary sensitivity from the three detectors.
- No significant coincident detection.
- On-axis emission could have produced detectable emission in some models.

ANTARES, IceCube, Auger, LIGO, Virgo 2017

High-Energy Starting Events



Two double cascades have been identified

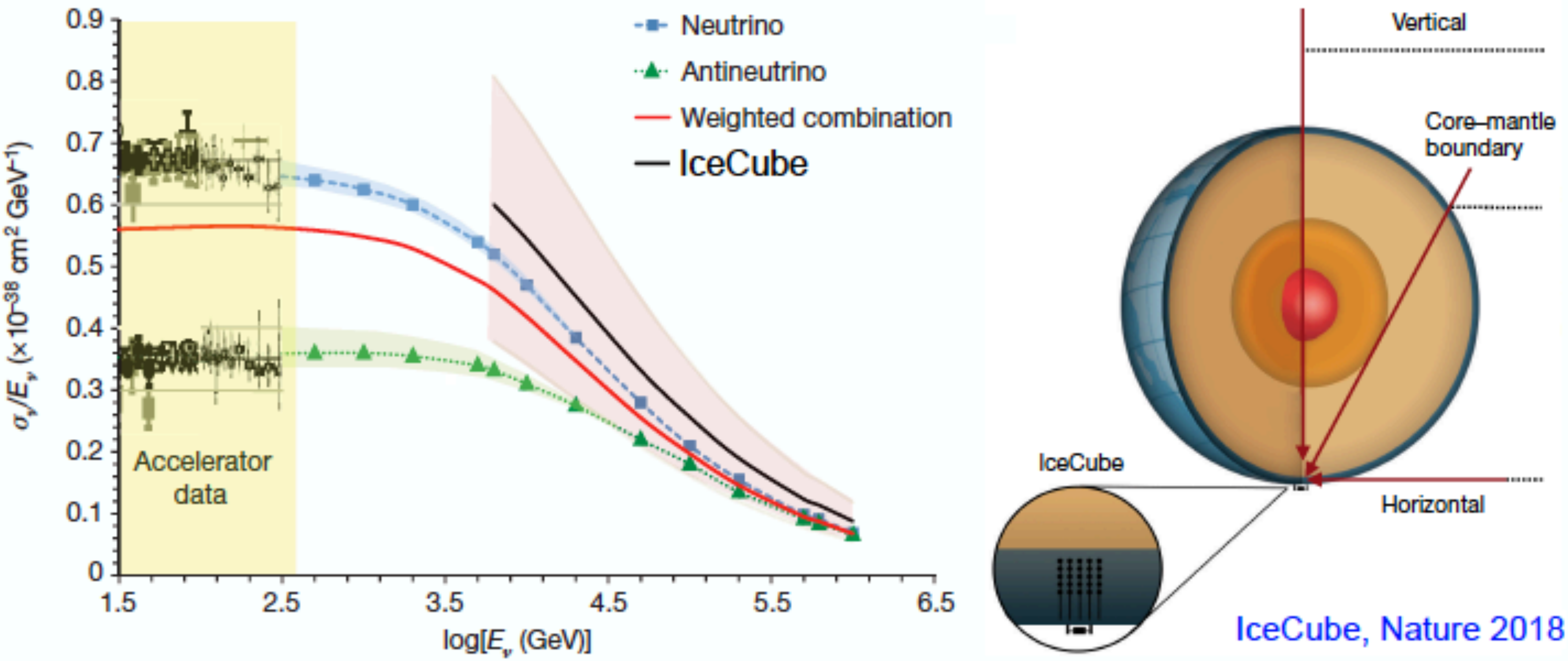
Double cascades arise from ν_τ or mis-identified backgrounds (astrophysical neutrinos / atmospheric backgrounds)

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

Published in Nature 2018

Neutrino Absorption

Neutrino-Nucleus Cross Section



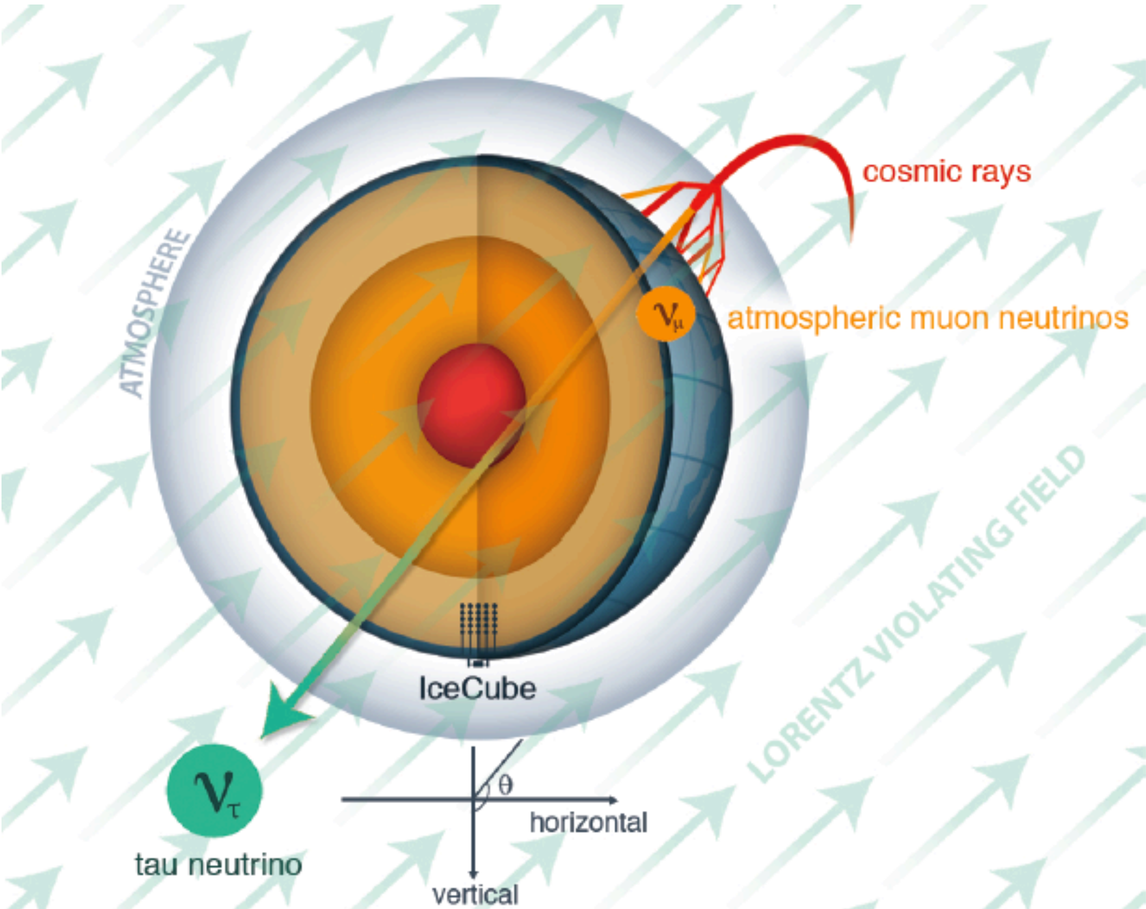
IceCube, Nature 2018

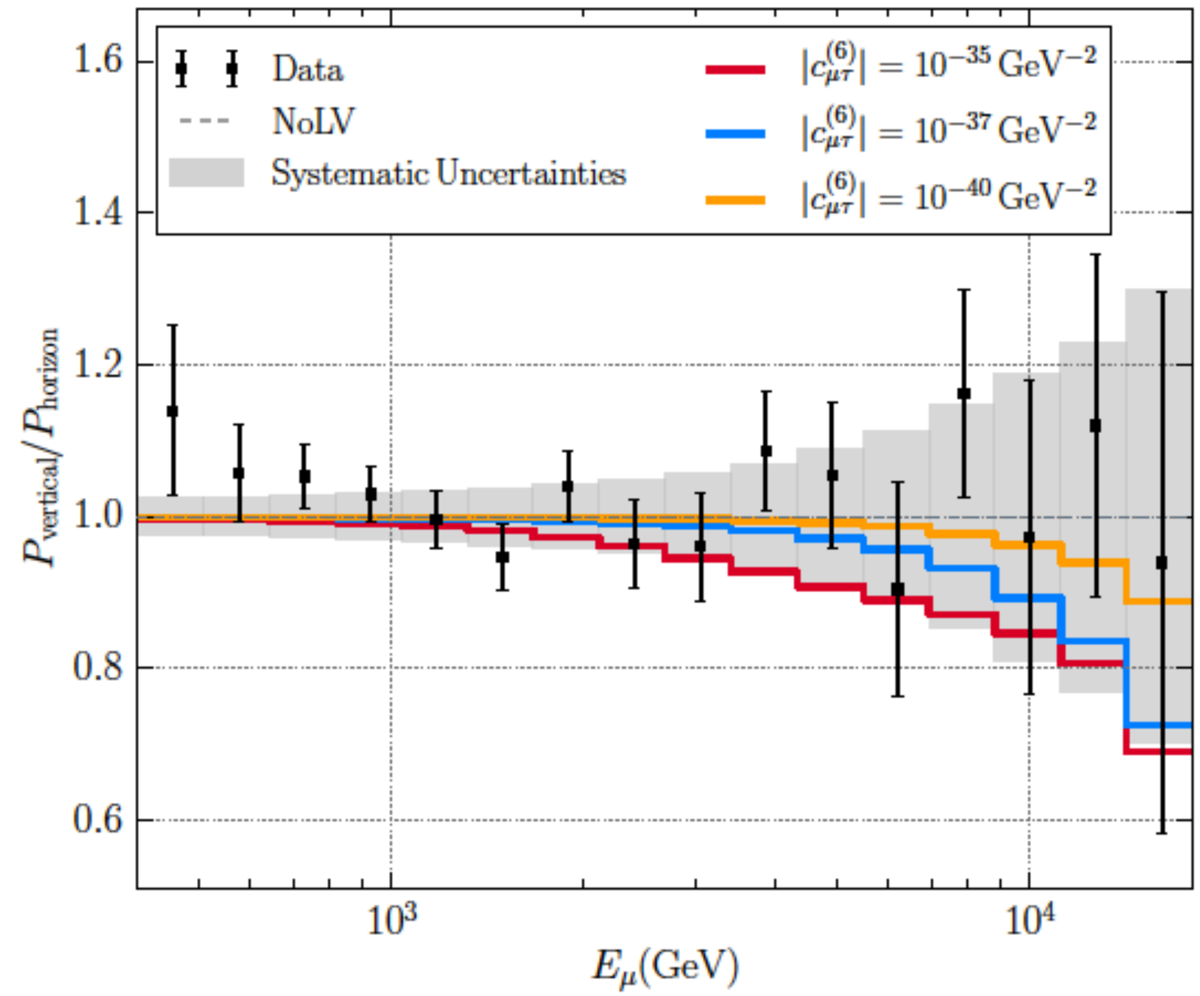
- **Absorption of neutrinos** in the earth a powerful tool to measure neutrino-nucleus cross section
- > 10000 high-energy muon neutrinos used in this analysis
- measuring the cross section between 6.3-980 TeV
- More than an order of magnitude higher than previous measurements

Published in Nature Physics 2018

Tests of Lorentz Symmetry

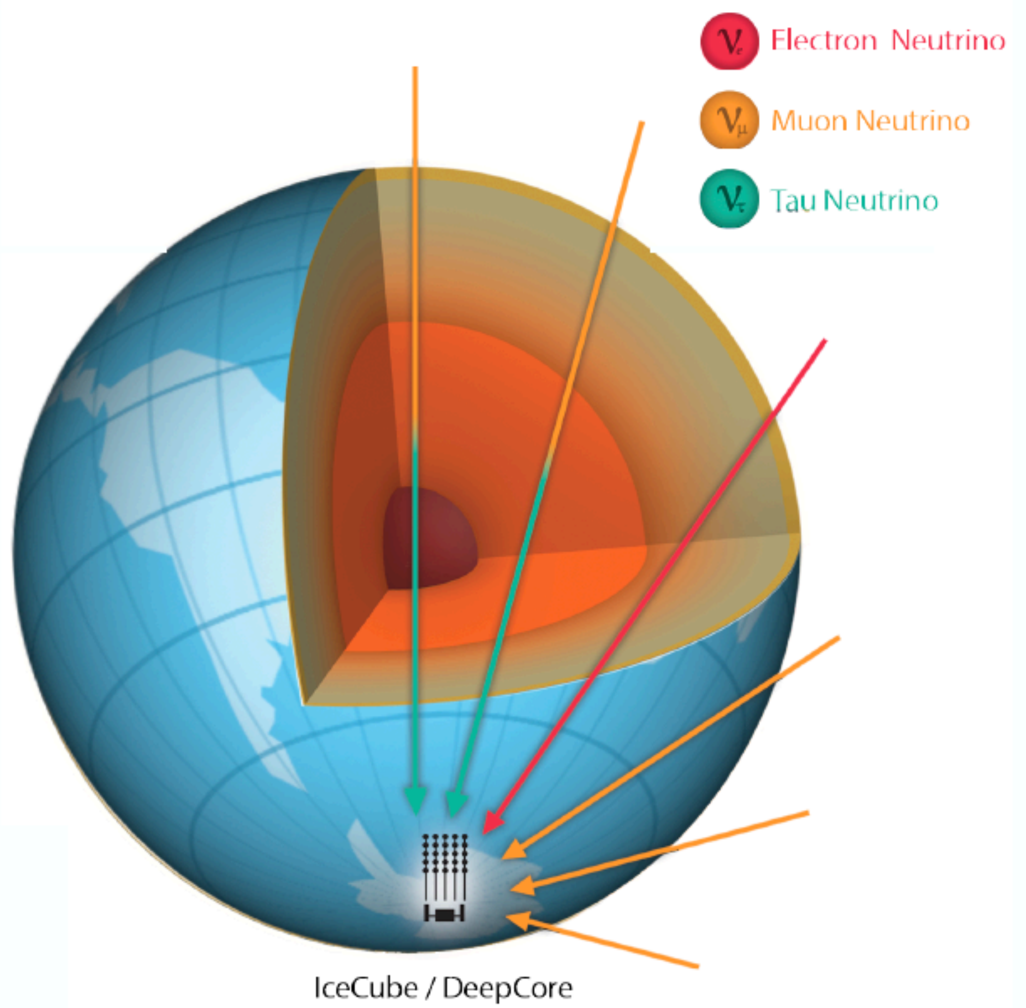
Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

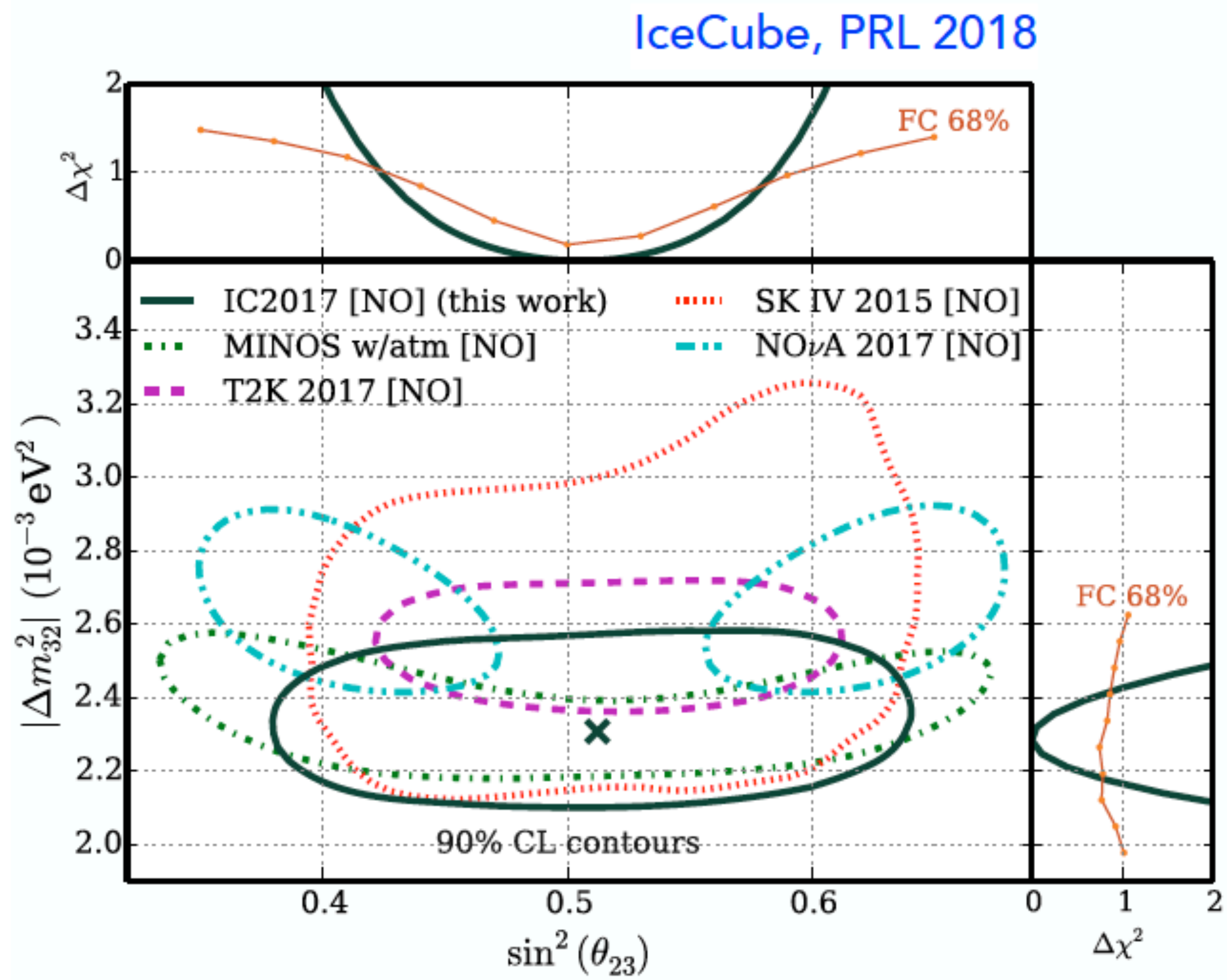




- Most precise test of space-time symmetry in the neutrino sector to date
- Search for anomalous neutrino oscillations in IceCube's high energy neutrino sample
  - no evidence for such phenomena

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

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

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

Solar Atm. Neutrino flux predictions

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

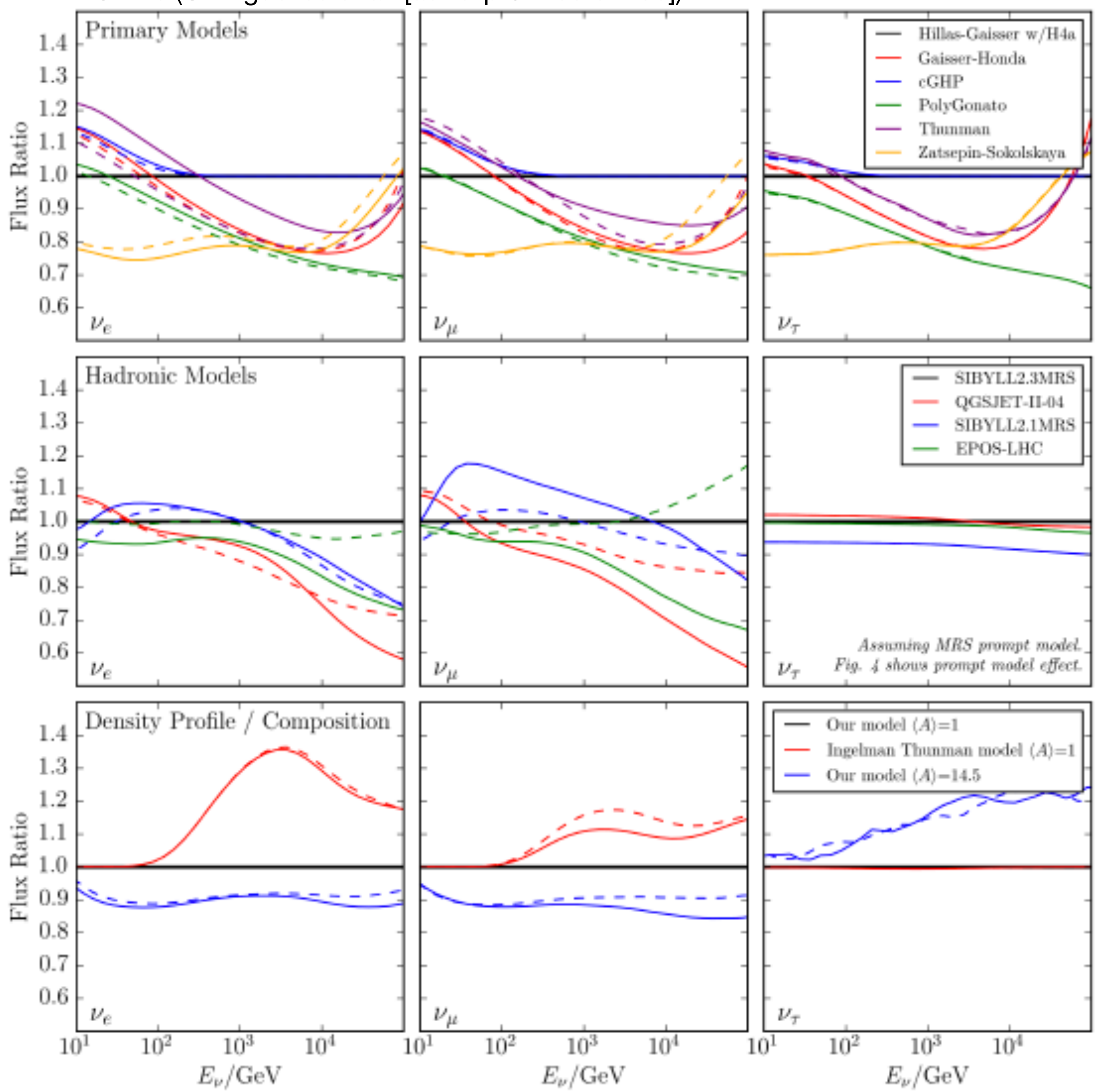
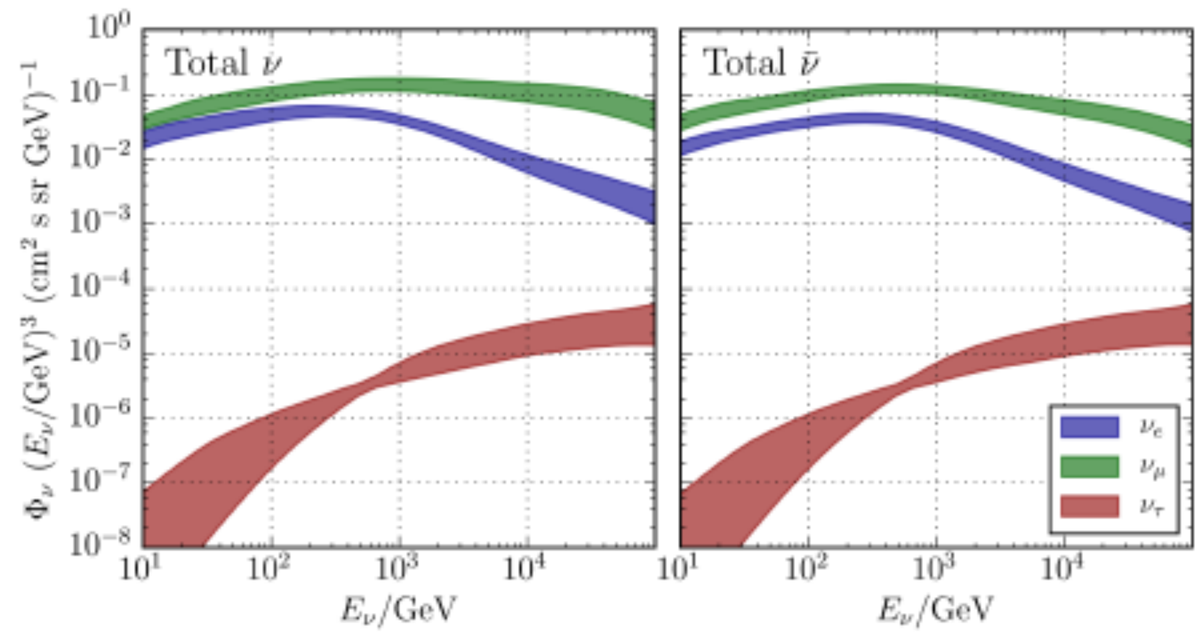


Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.

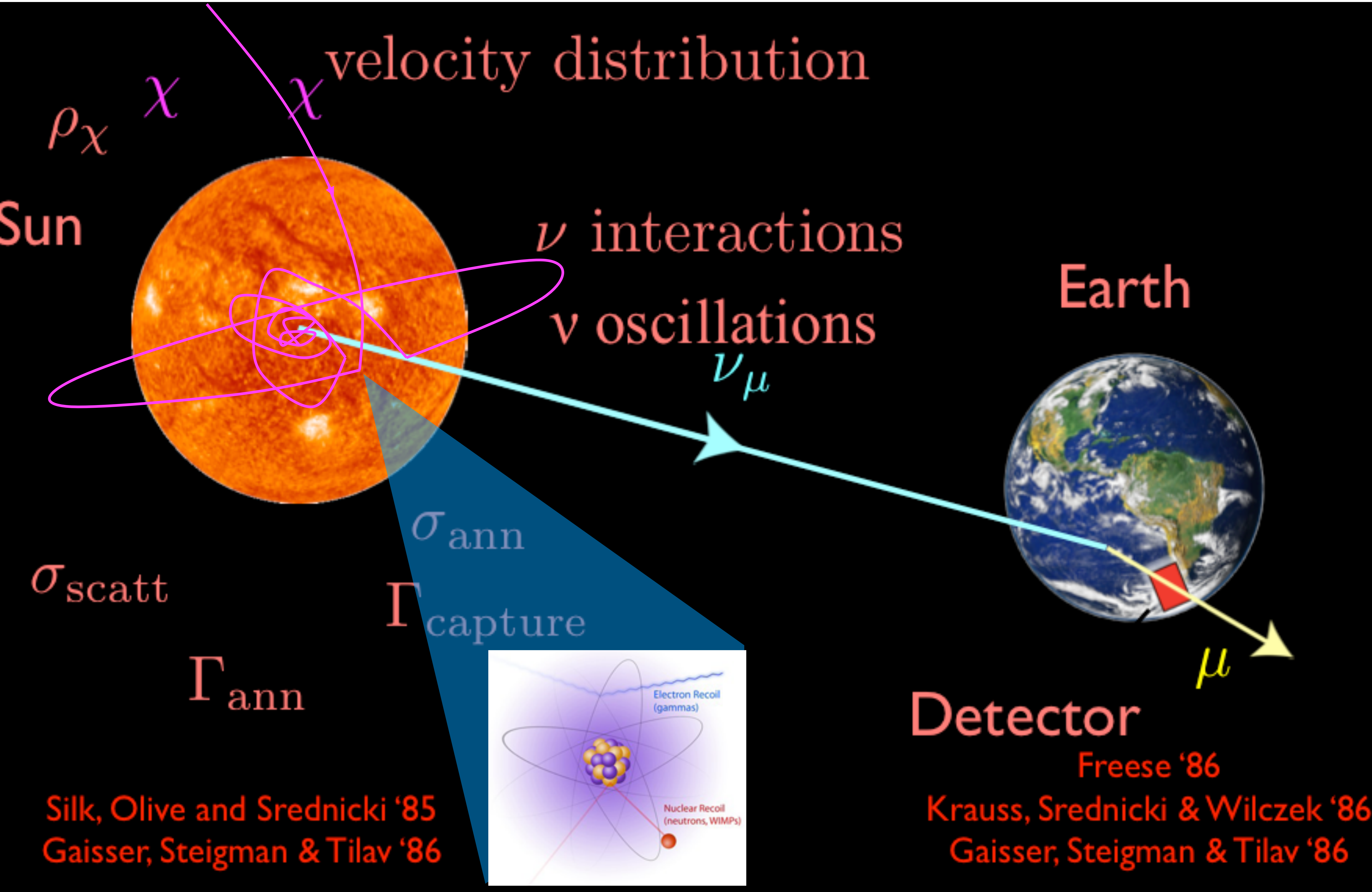


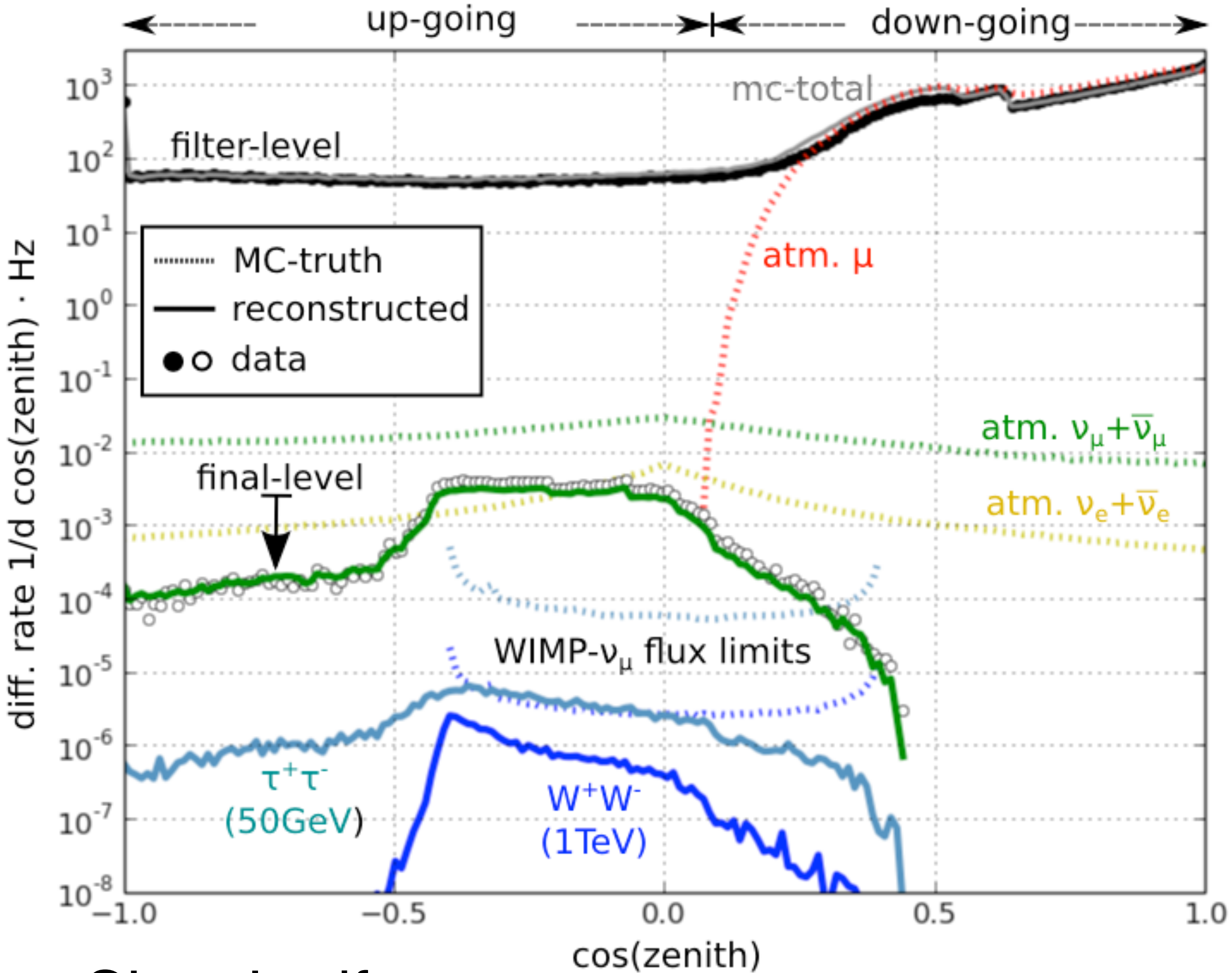
- Flux predictions vary by <30%, based on
  - primary models
  - hadronic models
  - extremal solar density and composition models

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

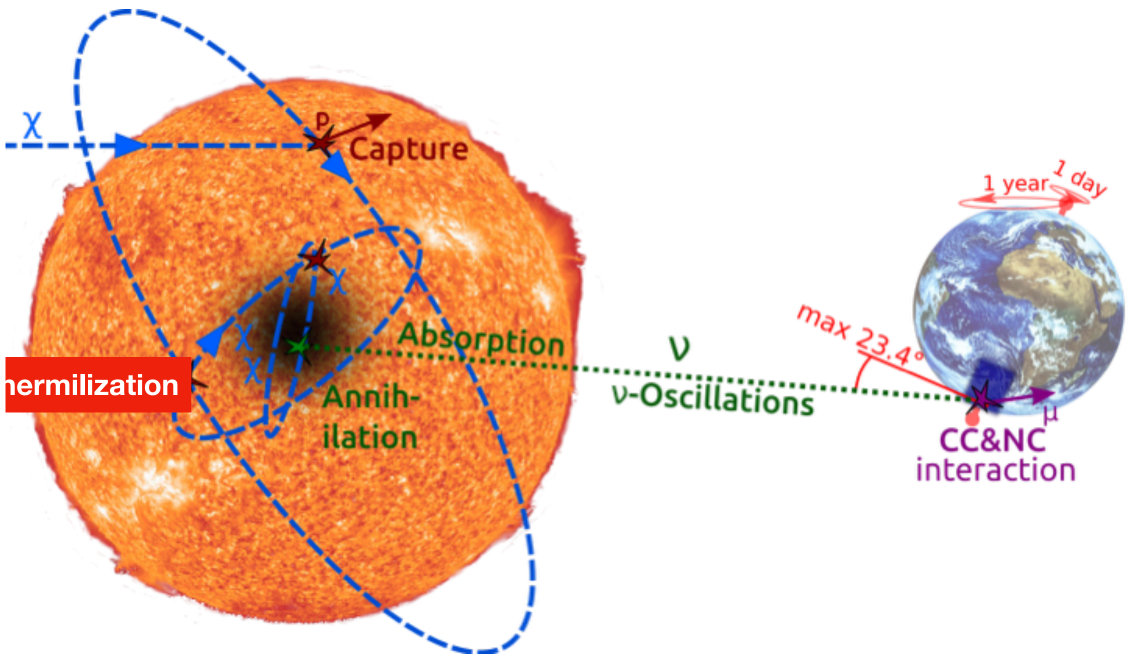
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no. 10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 . 06 (2017), p. 033**, arXiv: 1704.02892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

Solar Dark Matter





Search for Dark Matter in the Sun



Signal pdf:

Spectral part

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

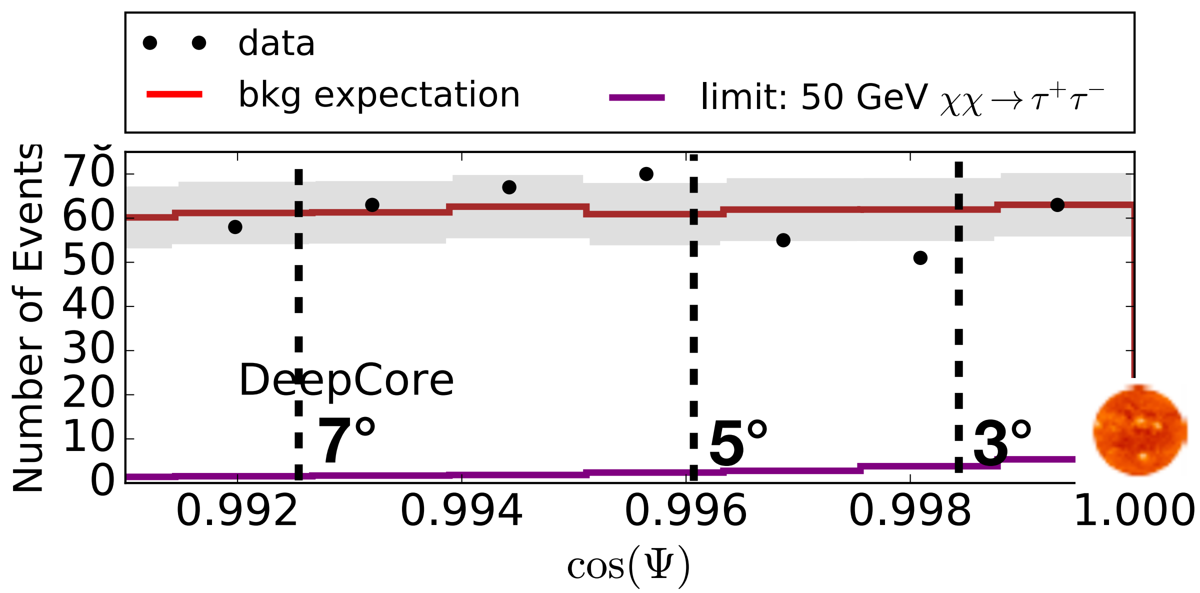
Monovariate Fisher Bingham distribution from directional statistics

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

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

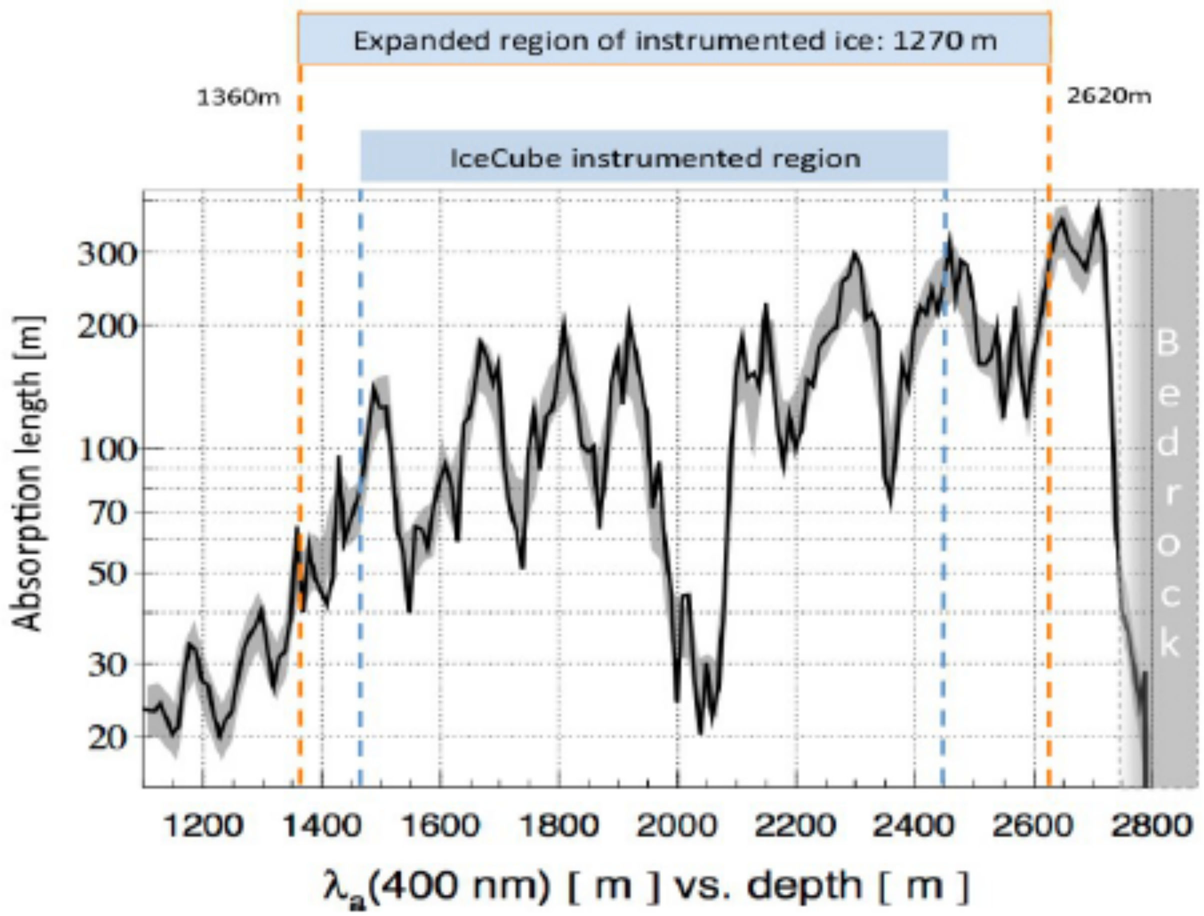
Observed events

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

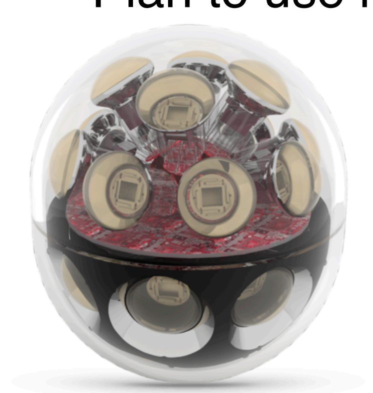


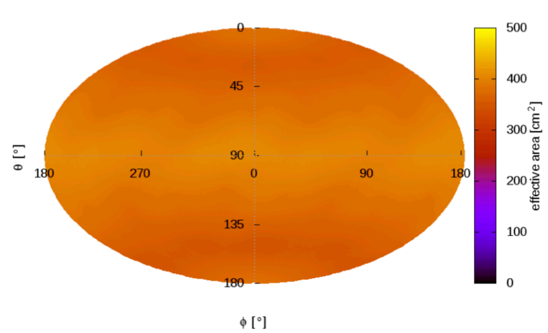
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Observed events consistent with background only expectations

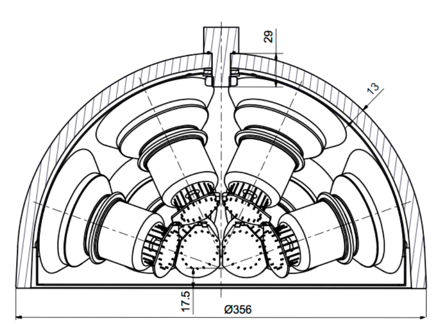
IceCube Gen2



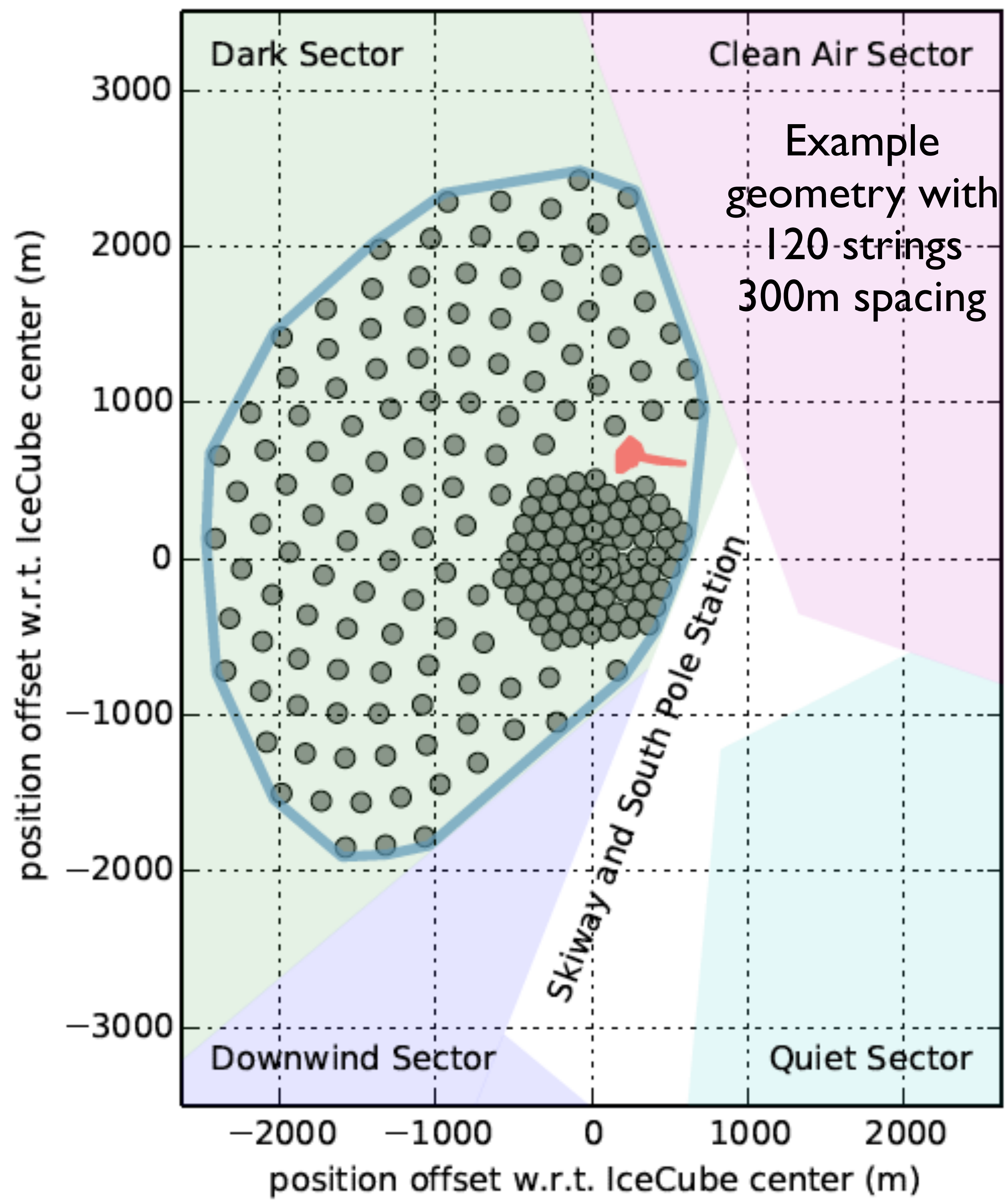
Plan to use new sensor modules







IceCube Coll. Gen2 LOI [arXiv:1412.5106]



High Energy Starting Events (HESE) Analysis

required that each event have fewer than three of its first 250 observed photoelectrons detected in the veto region. In addition, we required that the event produce at least 6000 photoelectrons overall