New results from IceCube

Tomasz Palczewski
University of California, Berkeley (UCB)
Lawrence Berkeley National Laboratory (LBNL)

Aspen 2017 Winter Conference
“From the LHC to Dark Matter and Beyond”
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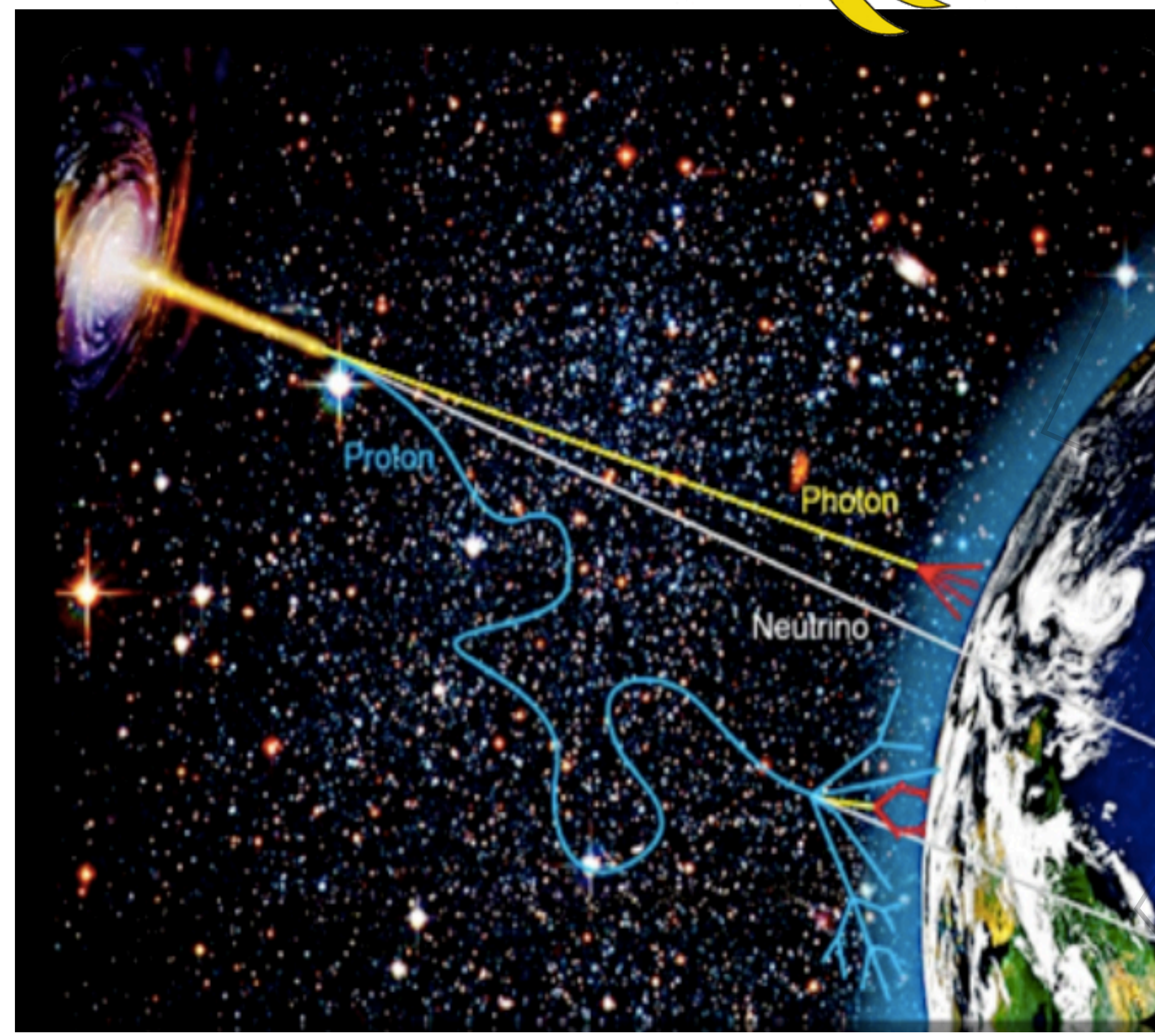
Aspen, Colorado, USA

Outline

- IceCube detector
- Detection principle
- Astrophysical Neutrinos
    - High-energy starting events (HESE) 4-year analysis
    - Through-going muons
- Searches for neutrino sources
- Dark Matter
- Summary

Neutrinos as ideal astronomical messengers

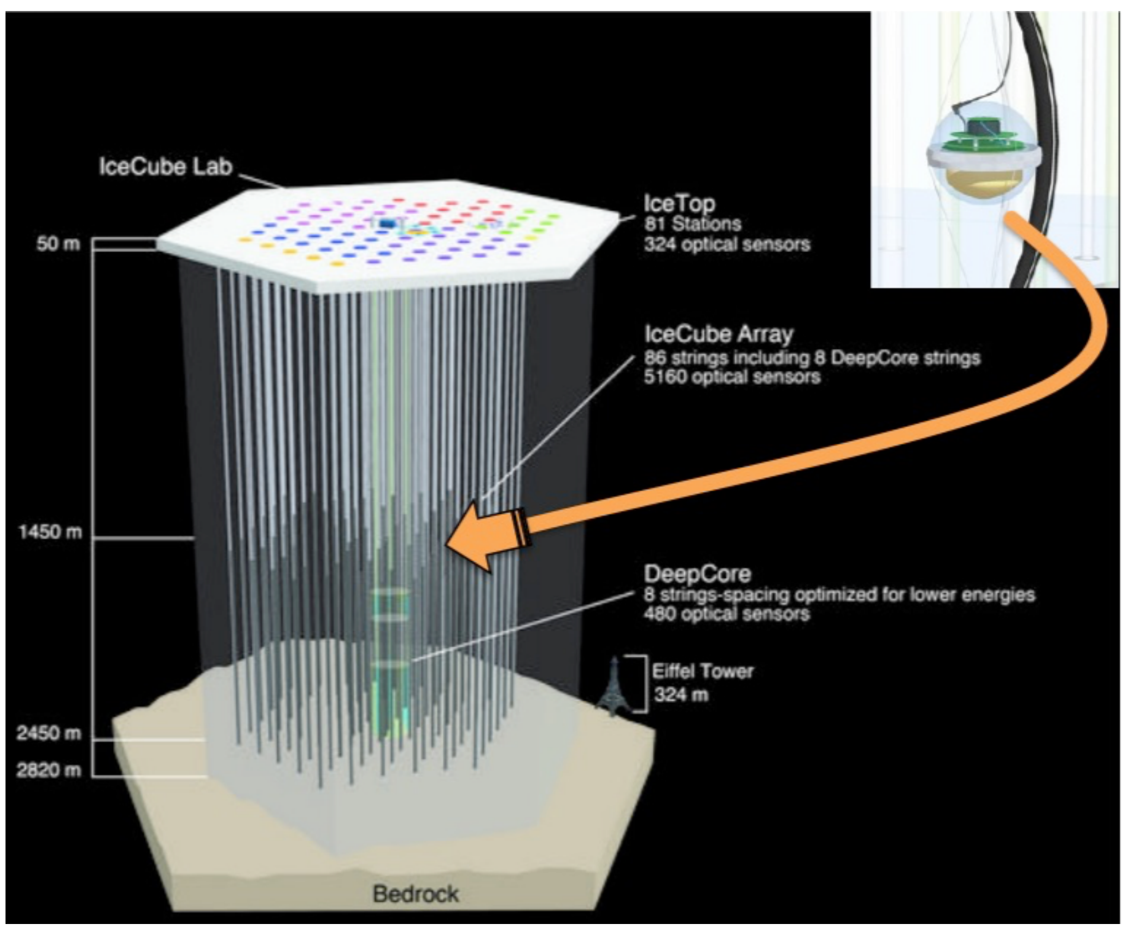
- Neutrinos travel from the edge of the Universe
  - **with no deflection by magnetic fields**
  - **essentially without absorption**
- no charge and essentially no mass
  - similar to the photon **but interactions with matter are extremely weak.**



Direct information about cosmological objects of the high redshift universe like gamma-ray bursts and active galactic nuclei.

IceCube detector

- IceCube detects neutrinos of all flavors by observing the end products of charged- or neutral-current deep-inelastic neutrino-nucleon interaction in the glacial ice



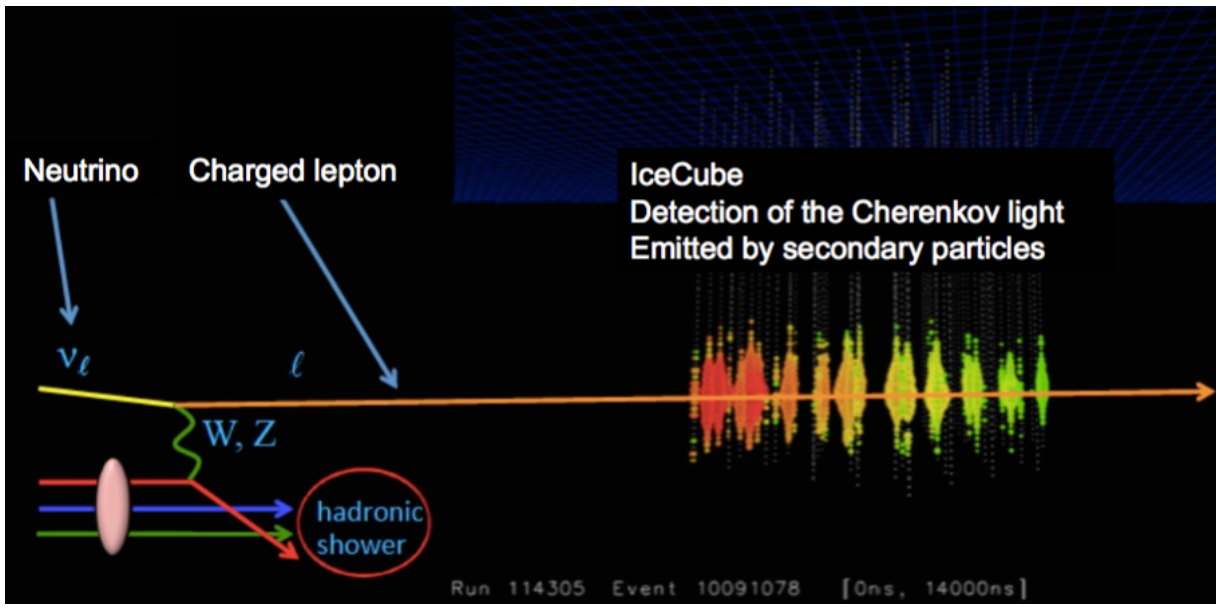
86 strings with 60 Digital Optical Modules (DOMs) (IceCube + DeepCore)

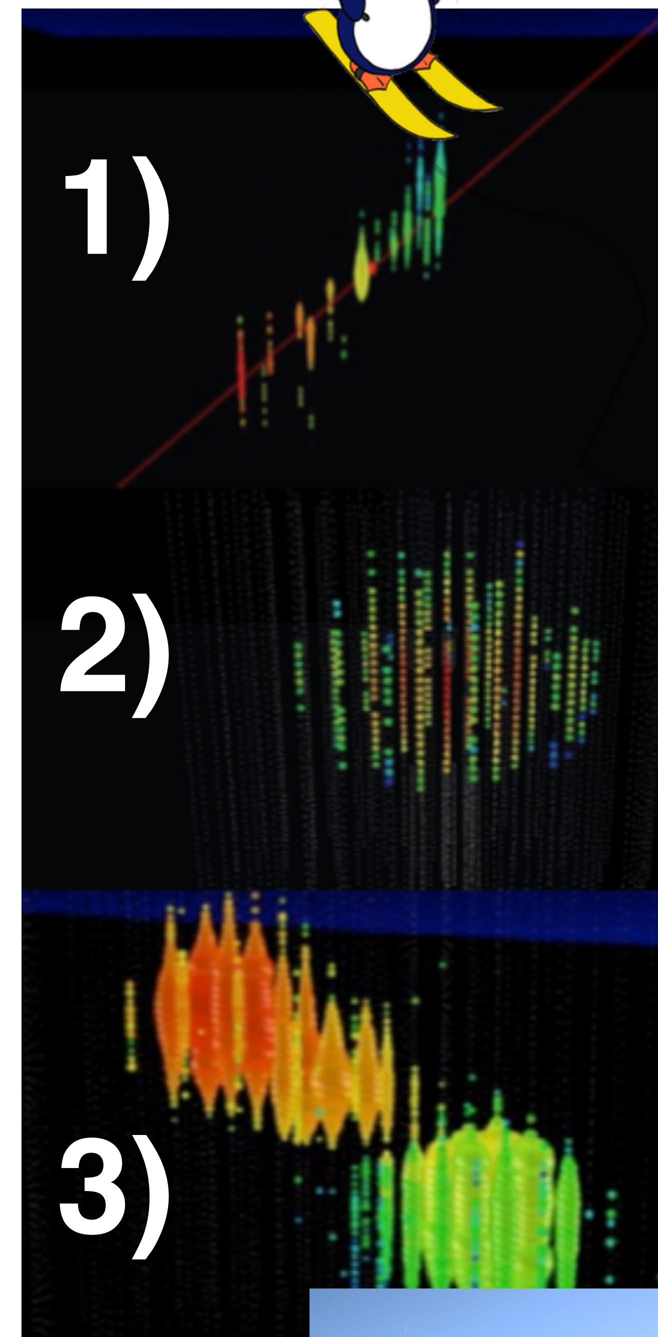
Optical sensor
10” photomultiplier (PMT) + in situ signal digitization in pressure glass sphere

Deployed between 1450 and 2450 m depth

81 IceTop surface stations

Detection principle





The characteristic pattern (topology) of the Cherenkov light provides information about the energy, direction, and flavor of the parent neutrino

1) Track-like events

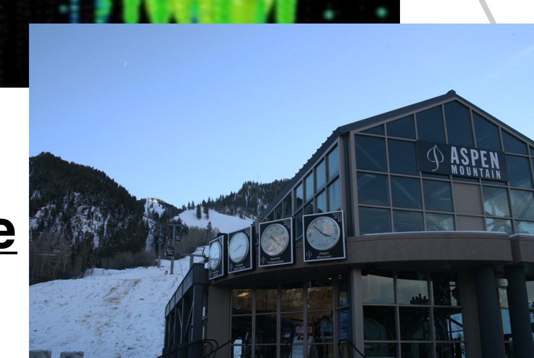
good angular resolution (<1°), limited energy resolution when not fully contained in the detector volume; source - ν_μ CC interactions

2) Cascade-like event

good energy resolution (~10% at high energies), limited angular resolution (>10°); source - ν_e, ν_μ, ν_τ NC + ν_e, ν_τ CC interactions

3) Composite events

mixture of track-like and cascade-like events or multiple cascade events; high-energy ν_τ CC as a possible source

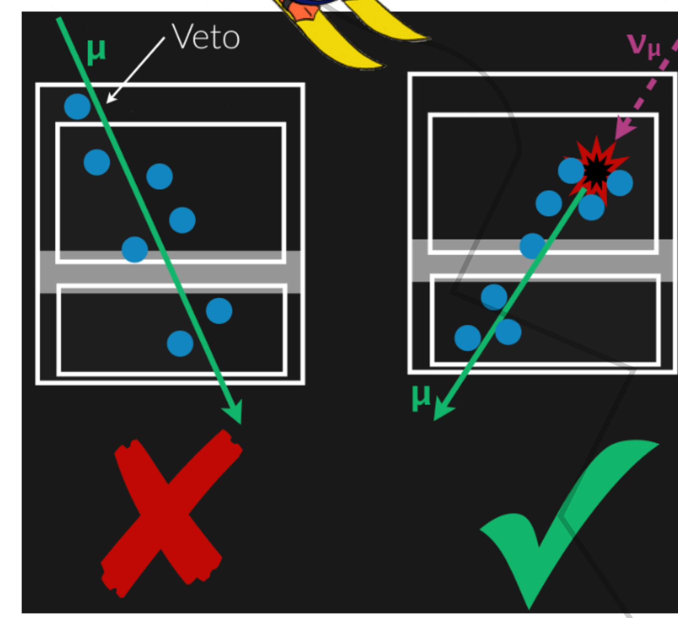


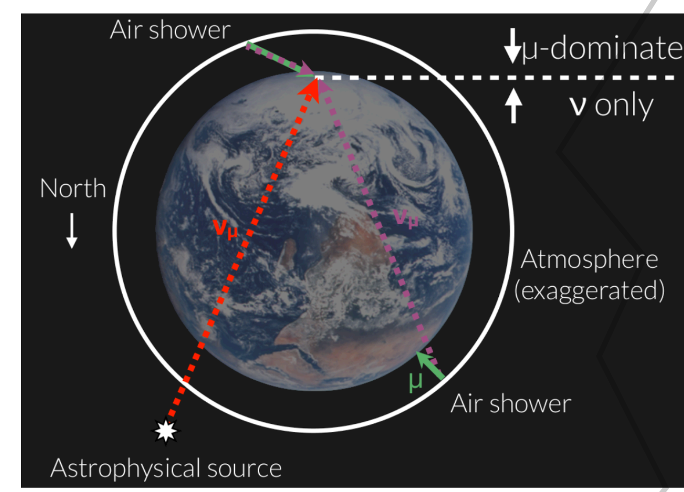
Astrophysical Neutrinos

- The IceCube detector is triggered by down-going atmospheric muons at a rate of ~**3 kHz**.
    - There is roughly **one atmospheric neutrino in a million cosmic-ray induced muons (**rate of **~5 mHz)**, while this number for astrophysical neutrinos is one in a billion (rate of **~μHz**)
- Thus, it is challenging to separate the astrophysical neutrinos from the enormous atmospheric backgrounds

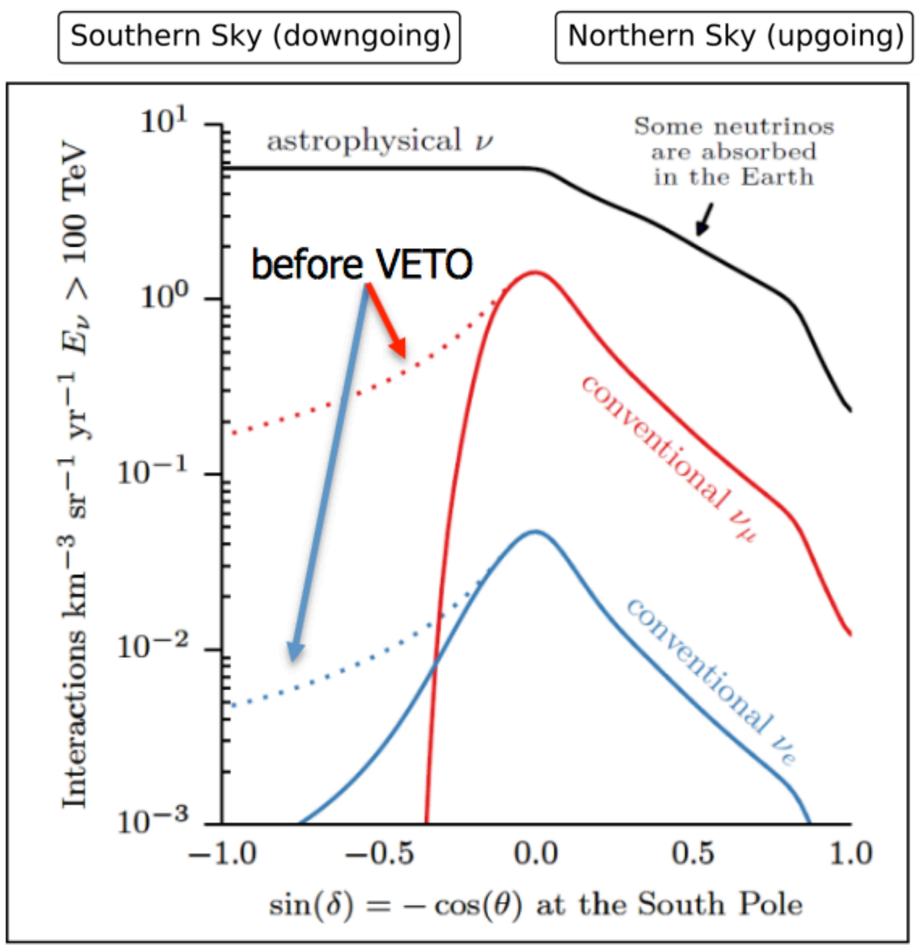
Astrophysical Neutrinos

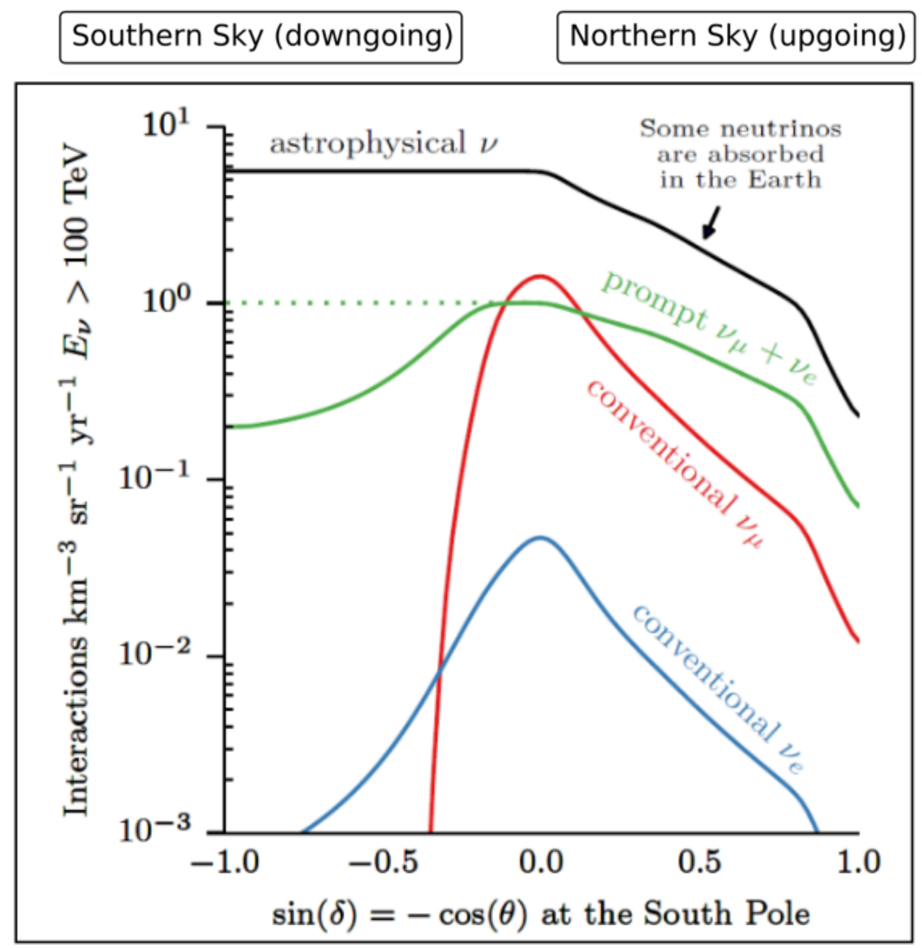
- Currently, two general-purpose strategies are used:
  - **Veto**: using a thin **outer layer of the detector** as an active veto; events starting within the detector fiducial volume (**HESE**) -> <u>sensitive to neutrinos of all flavors from the whole sky</u>
  - Use the **Earth as a filter** for atmospheric muons; only up-going track-like events -> <u>North sky and ν_μ only</u>

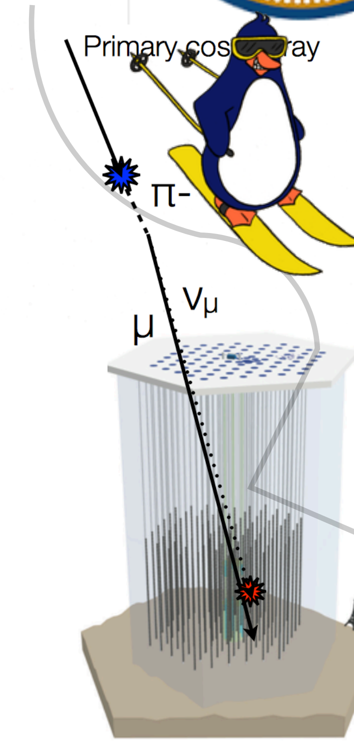




Atmospheric Neutrino Veto







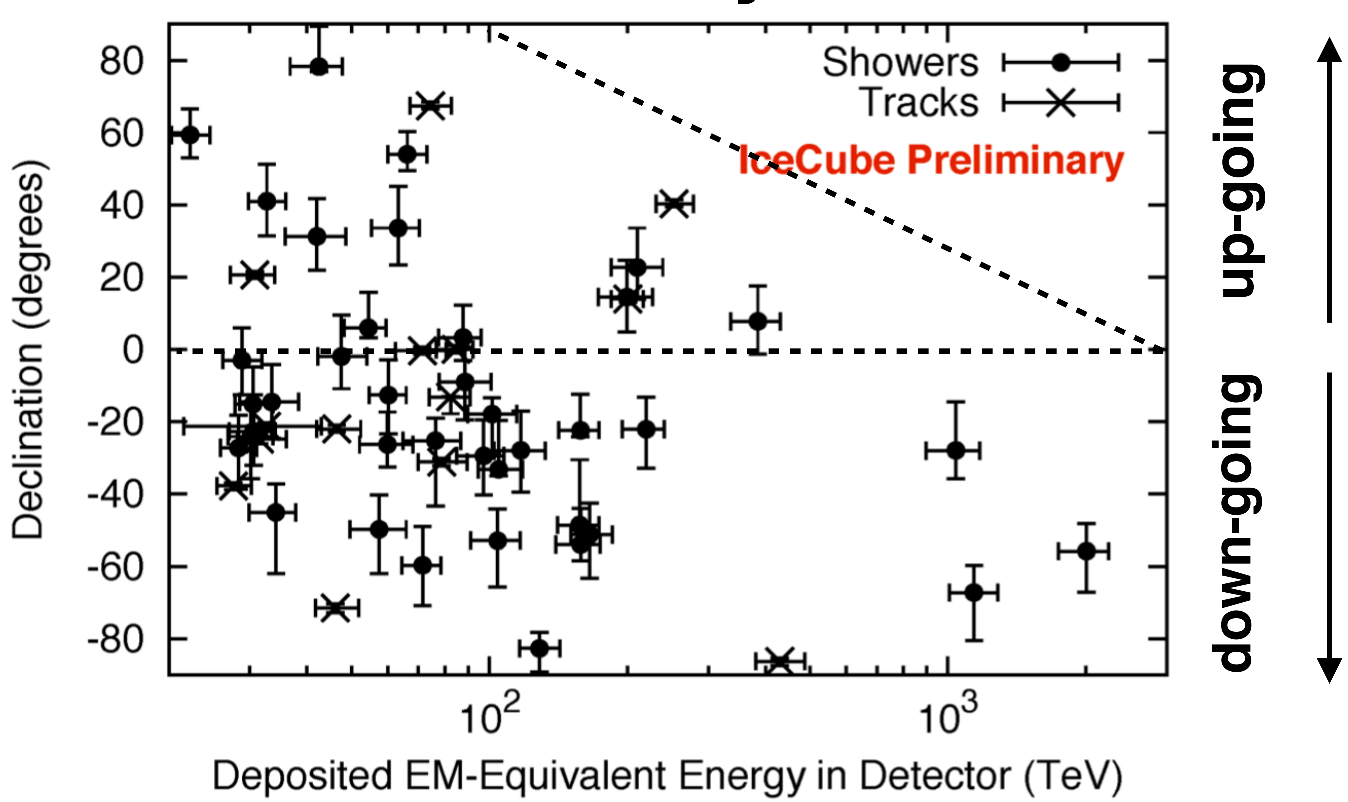
Sufficiently vertical/high-energy atmospheric neutrinos come with accompanying muons

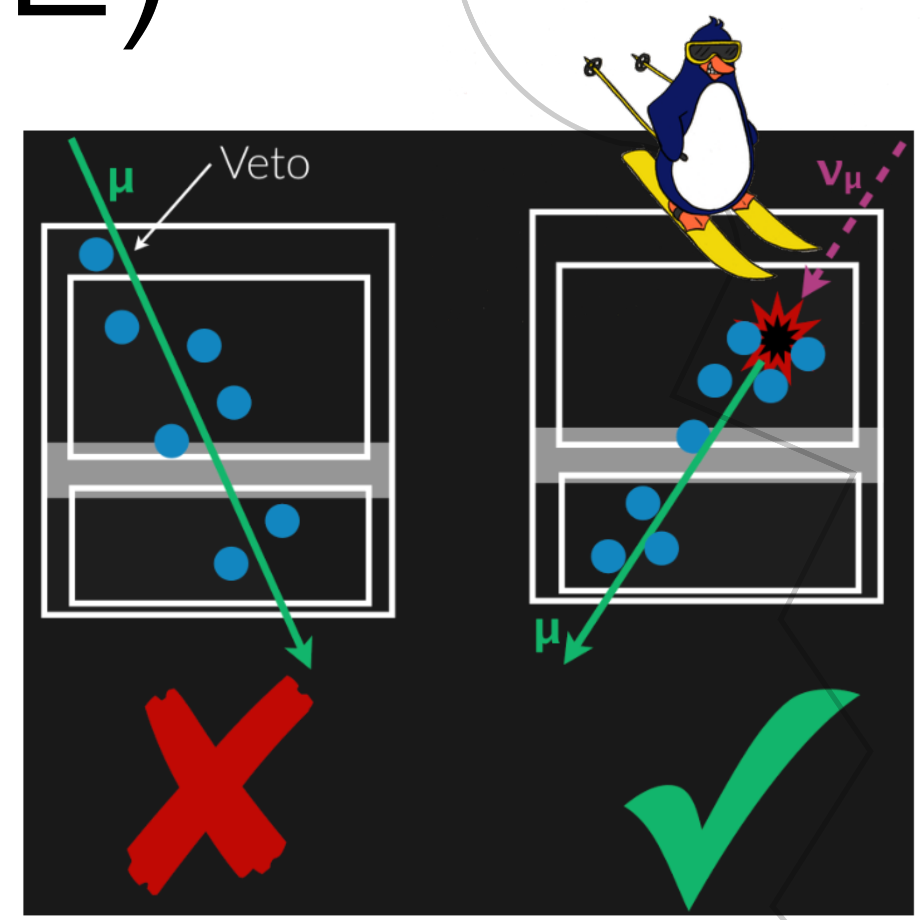
Up-down asymmetry due to veto

Phys. Rev. D79, 043009 (2009)
Phys. Rev. D90, 023009 (2014)

High Energy Starting Events (HESE)

- Search for contained, very bright events
- Sensitive to all flavors above ~ 60 TeV
- **53 events in four years**





Tomasz Palczewski - UCB/LBNL - Aspen 2017 Winter Conference

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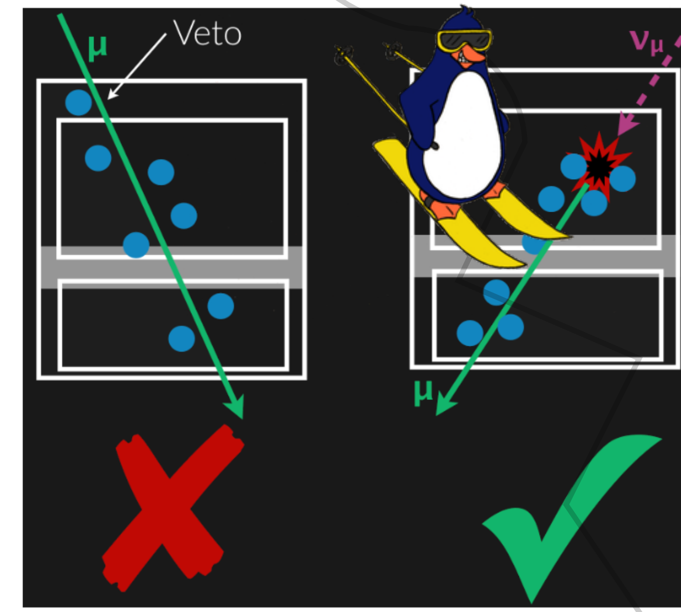
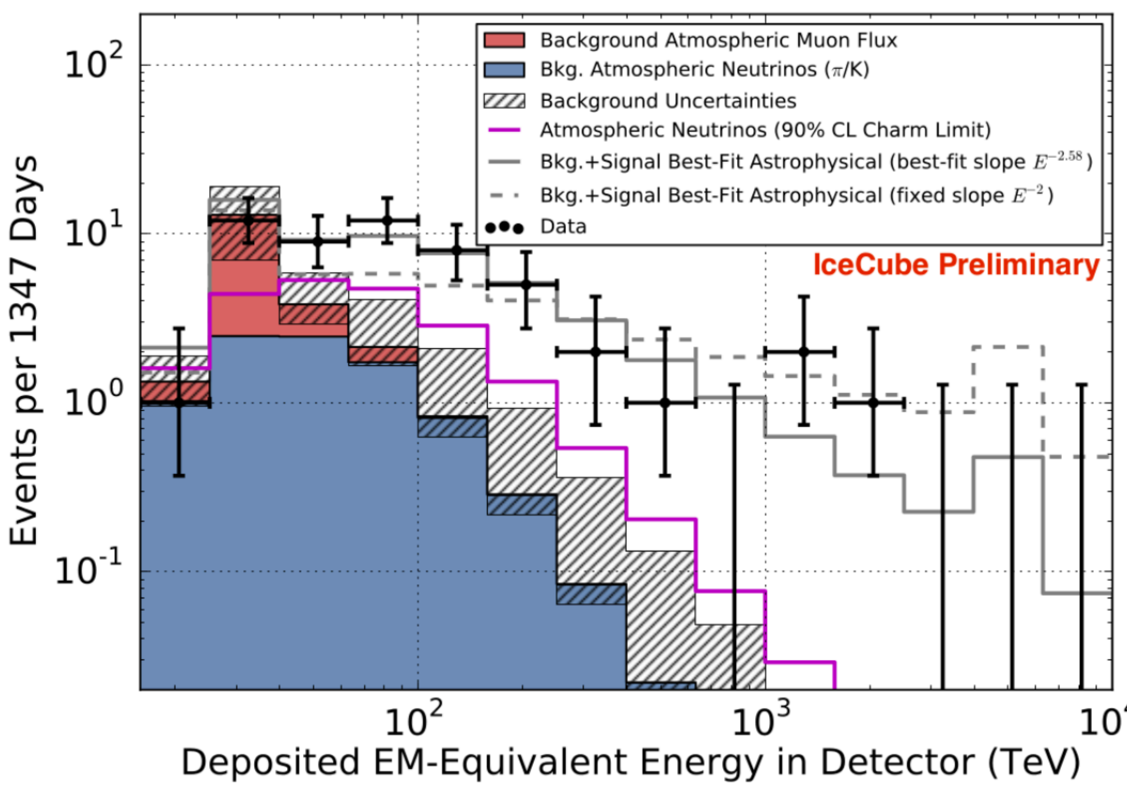


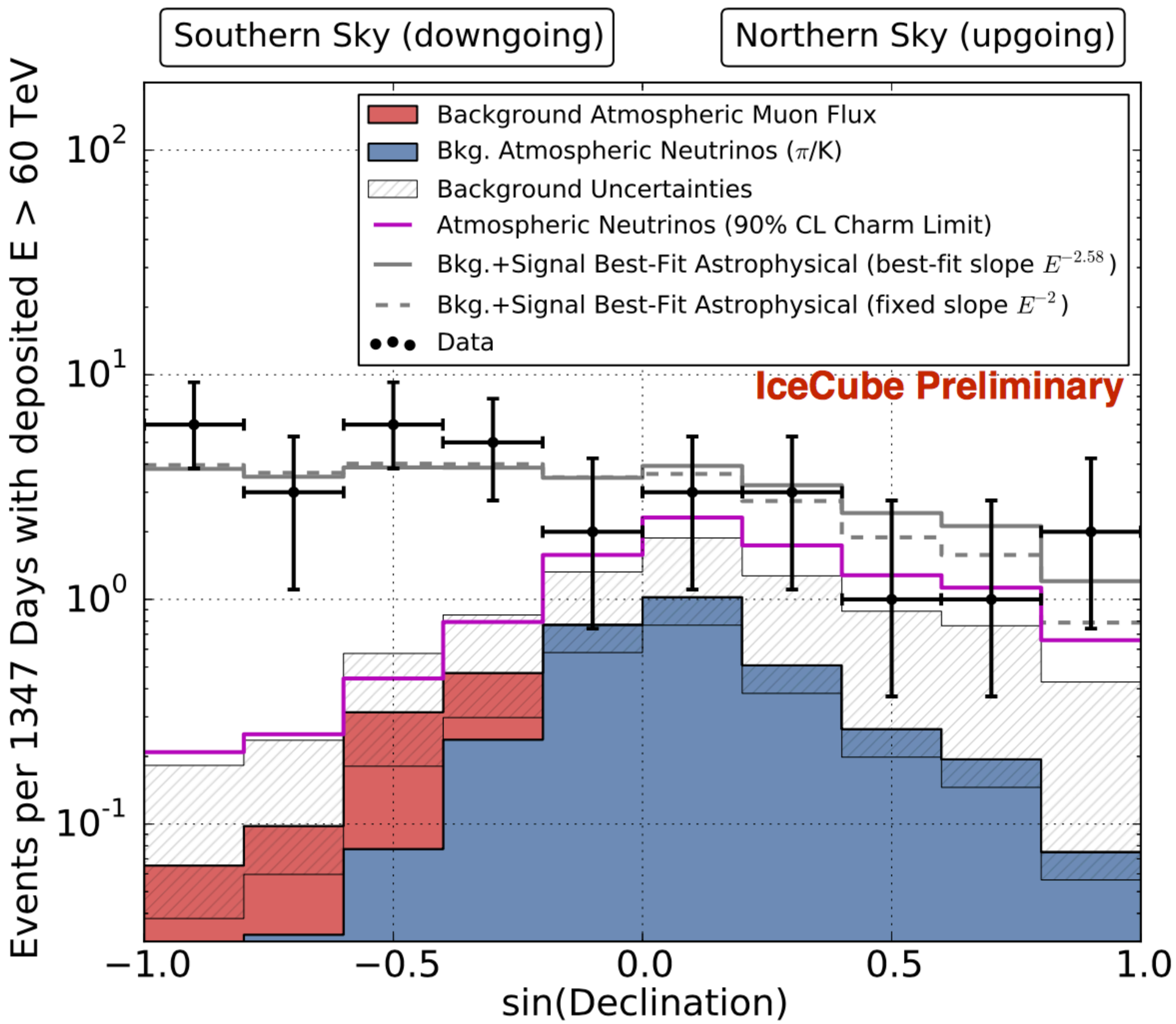


6.5σ above background from maximum likelihood forward-folding

$$\Phi_\nu(E) = \Phi_0 \cdot (E/100\,\mathrm{TeV})^{-2.58\pm0.25}$$

$$\Phi_0 \simeq 2.2\times10^{-18}/\mathrm{GeV/cm^2/s/sr}$$

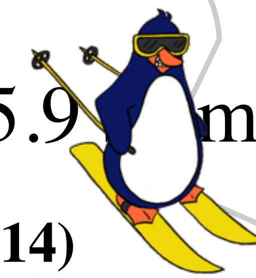
HESE - 4 years



2 yrs data, 28 events; 4.1 sigma

Science 342 (2013)

3 yrs data, 37 events; 5.9 ma



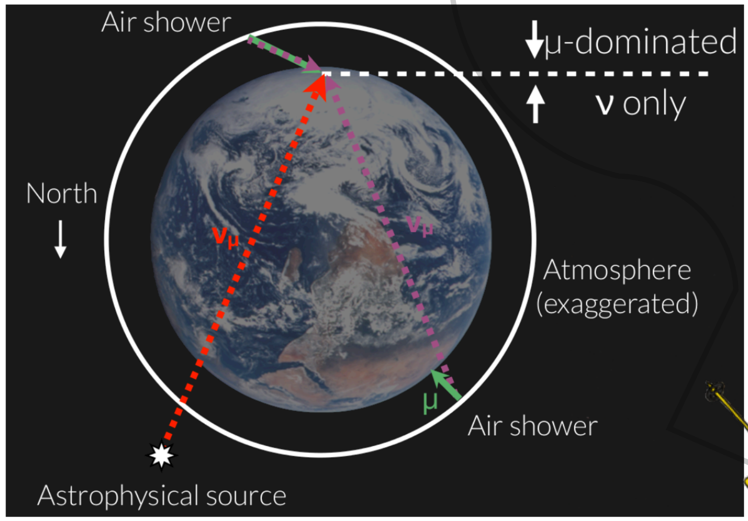
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 53 events; 6.5 sigma

Proceedings of Science (ICRC2015)1081

since April 2016 : Online Starting Event Alerts
to GCN/AMON network (track-like)
~1 min from event to alert

Through-going muons

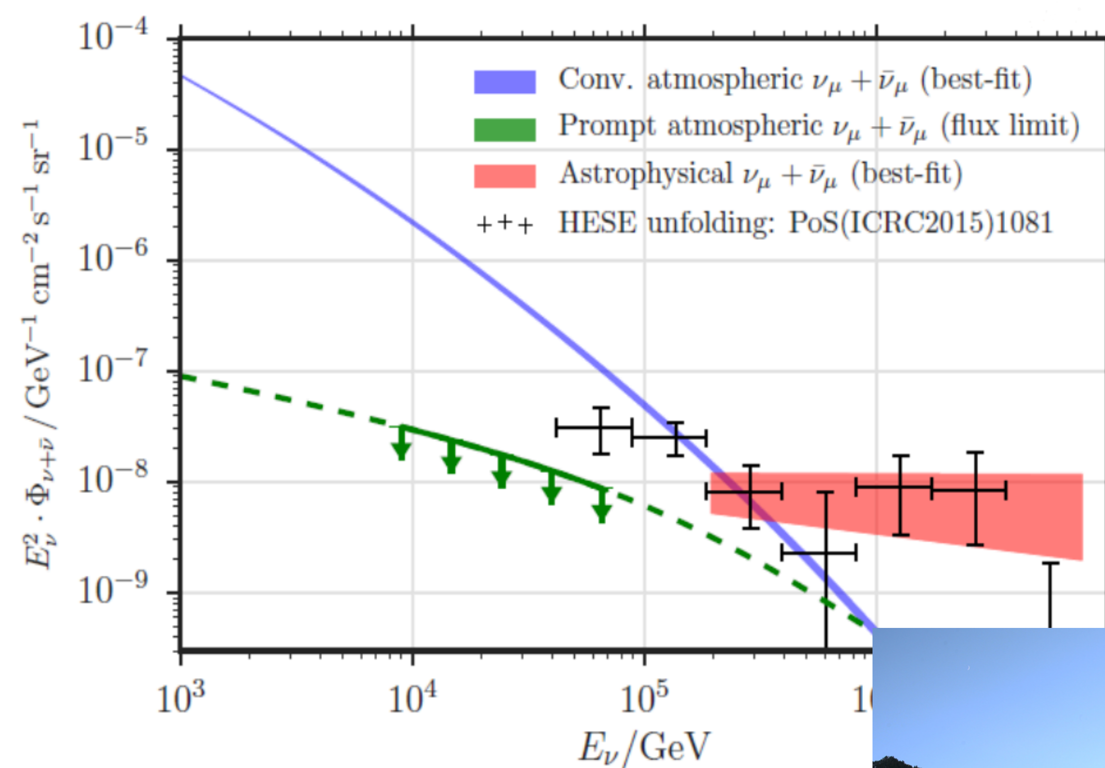


- **Six years (2009-15) of data.**
- Independent to HESE data set
- Similar flux level, but best-fit spectrum somewhat harder

$$\Phi_{\nu+\bar{\nu}} = (0.90^{+0.30}_{-0.27}) \cdot (E_\nu/100\,\mathrm{TeV})^{-(2.13\pm0.13)}$$

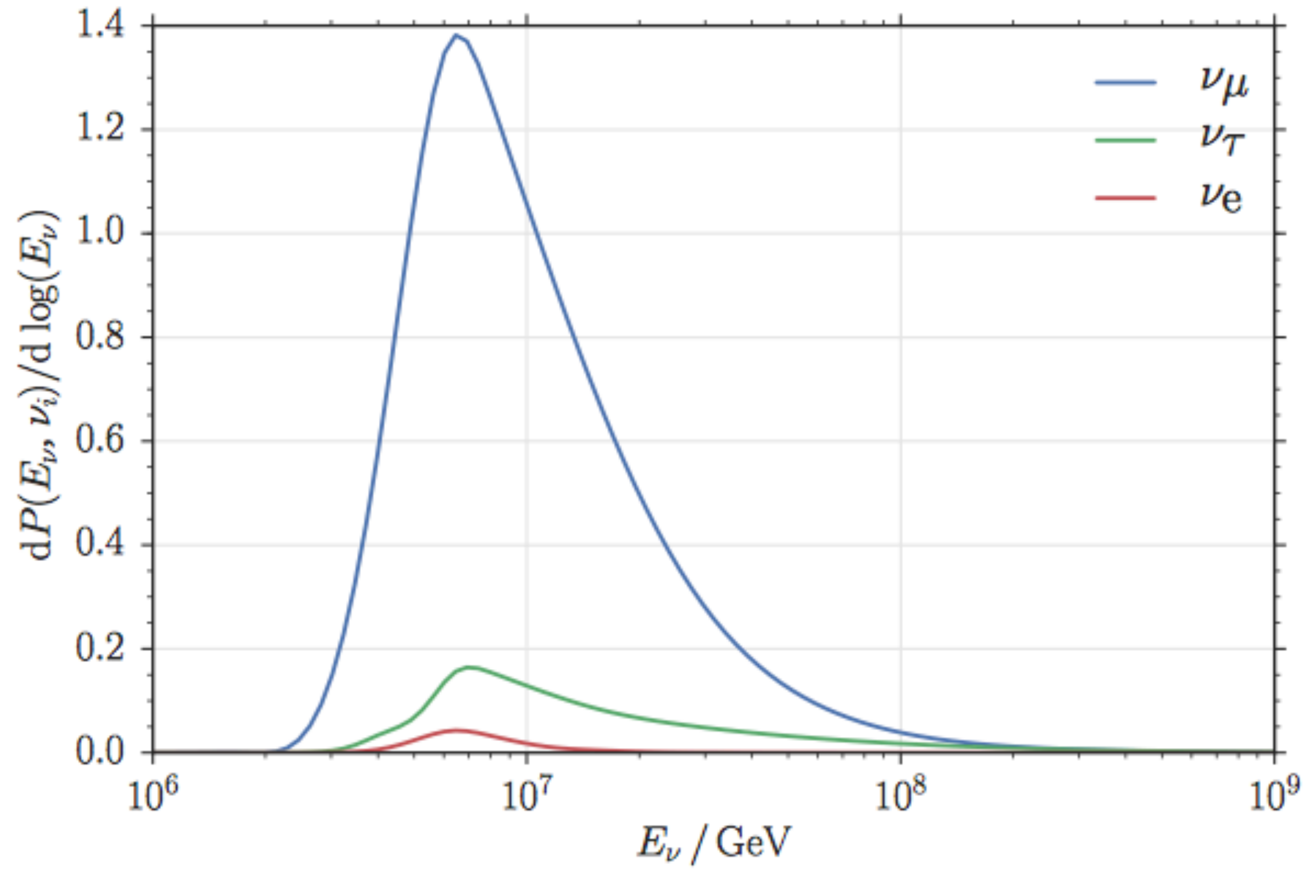
5.6 σ

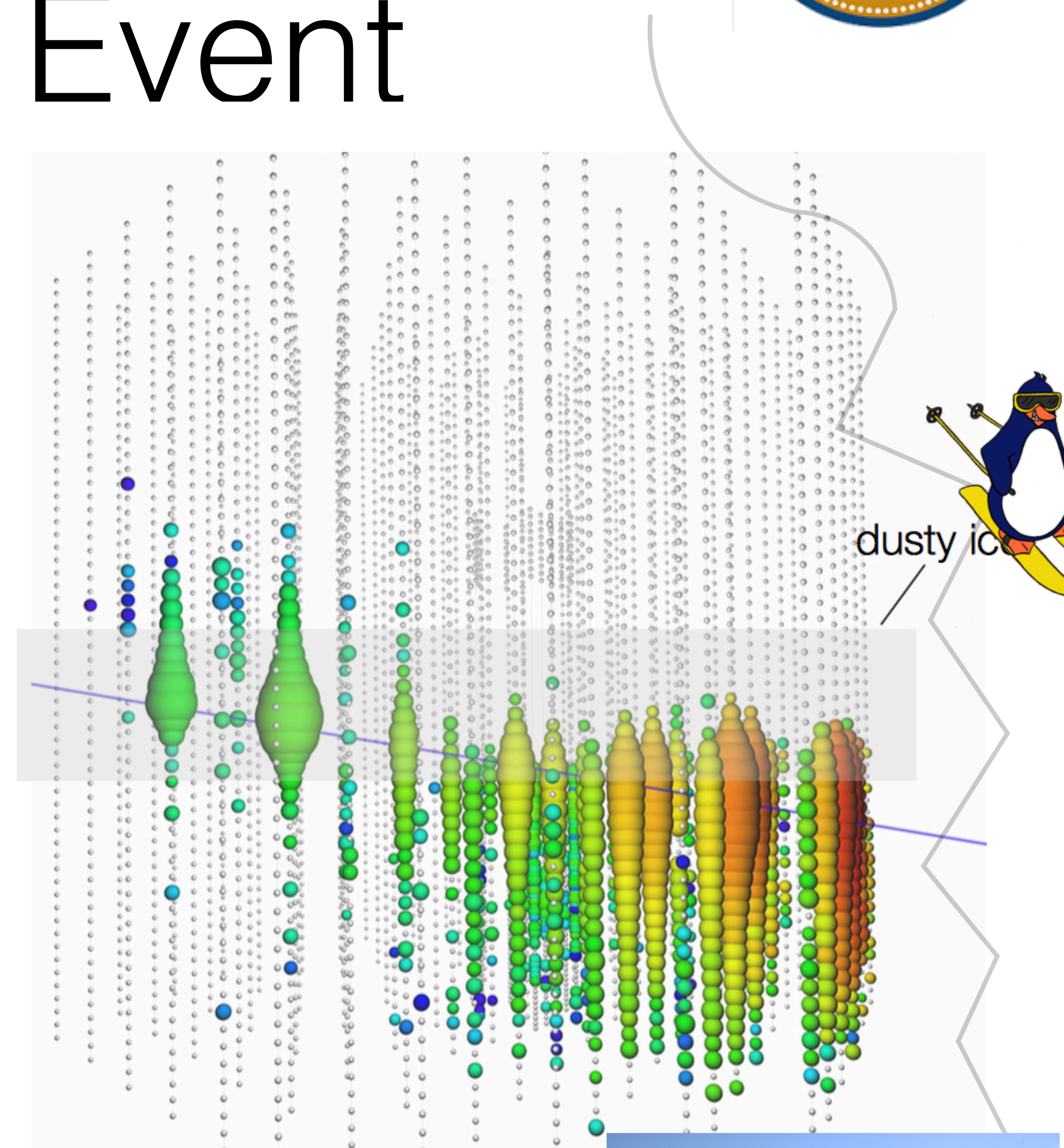
Energy range > 200 TeV



Phys. Rev. Lett. 115, 081102 (2015),
Astrophys. J. 833, 3 (2016)

Highest Energy Neutrino Event



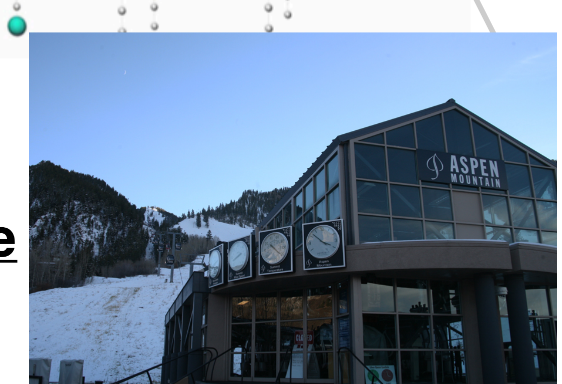


Track deposited

2.6 ± 0.3 PeV in detector

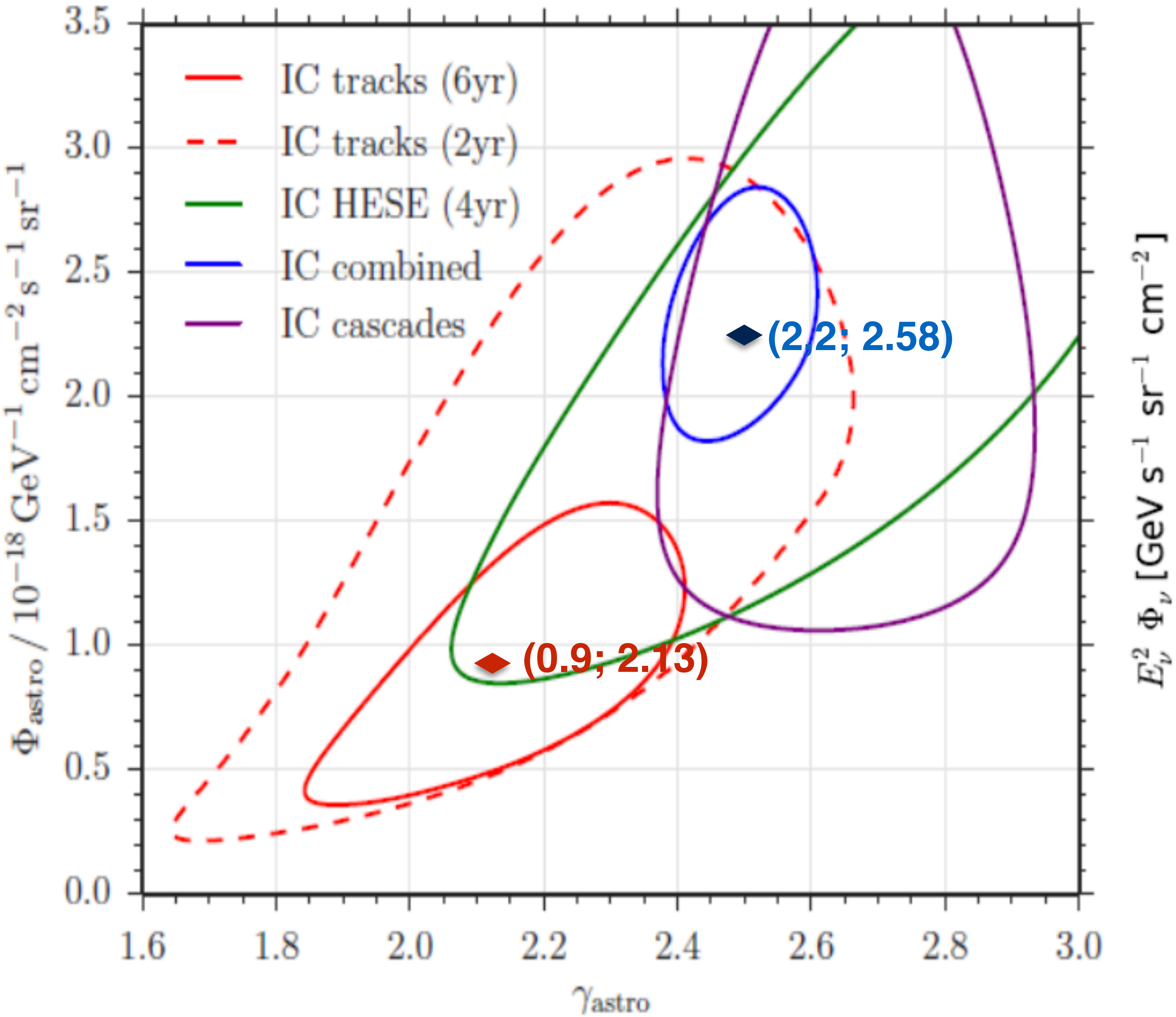
~7 PeV (under

E^{-2} spectral assumption)



Astrophys. J. 833, 3 (2016)

Broken spectrum?

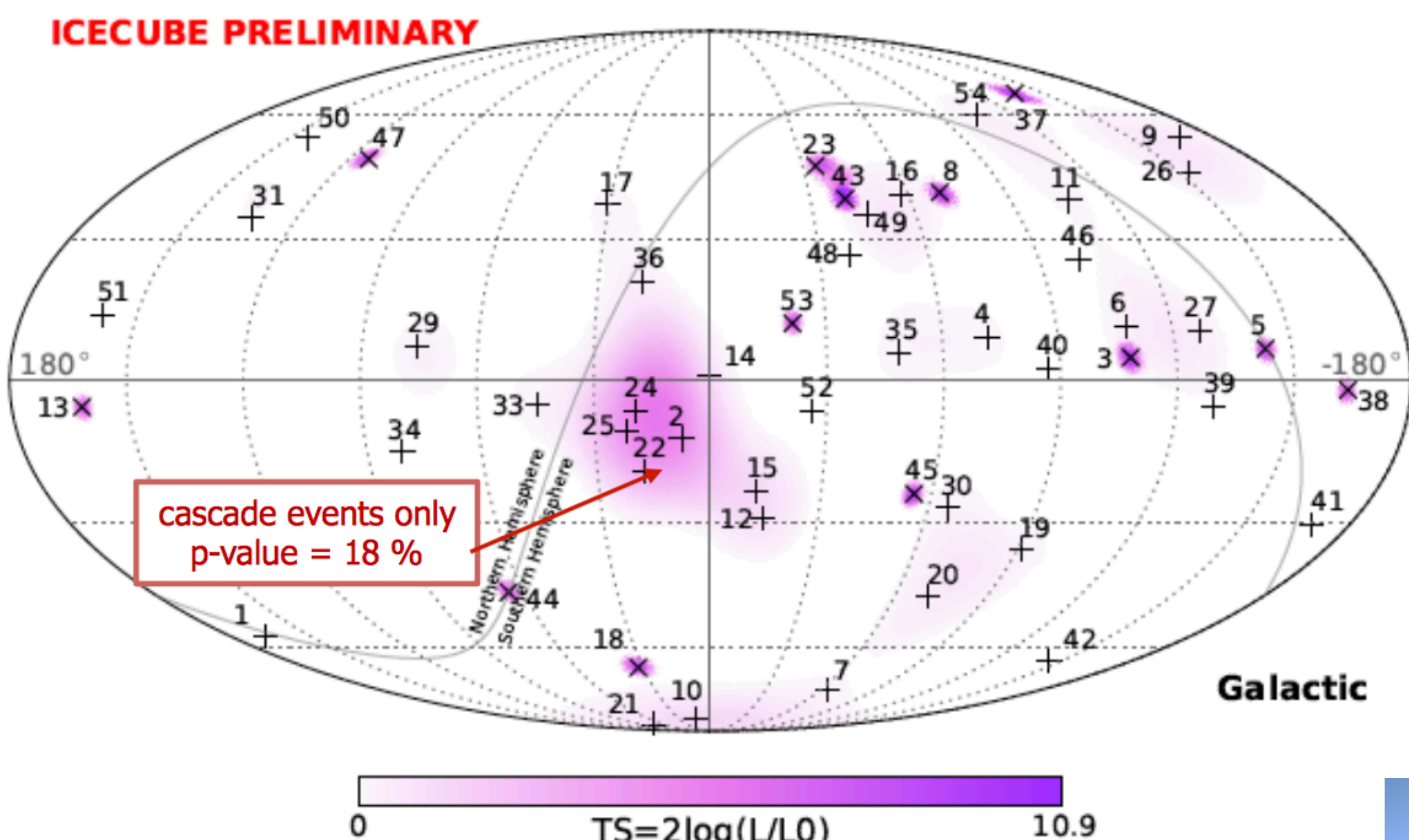


Are we seeing a spectral break, anisotropy, multiple components,...?

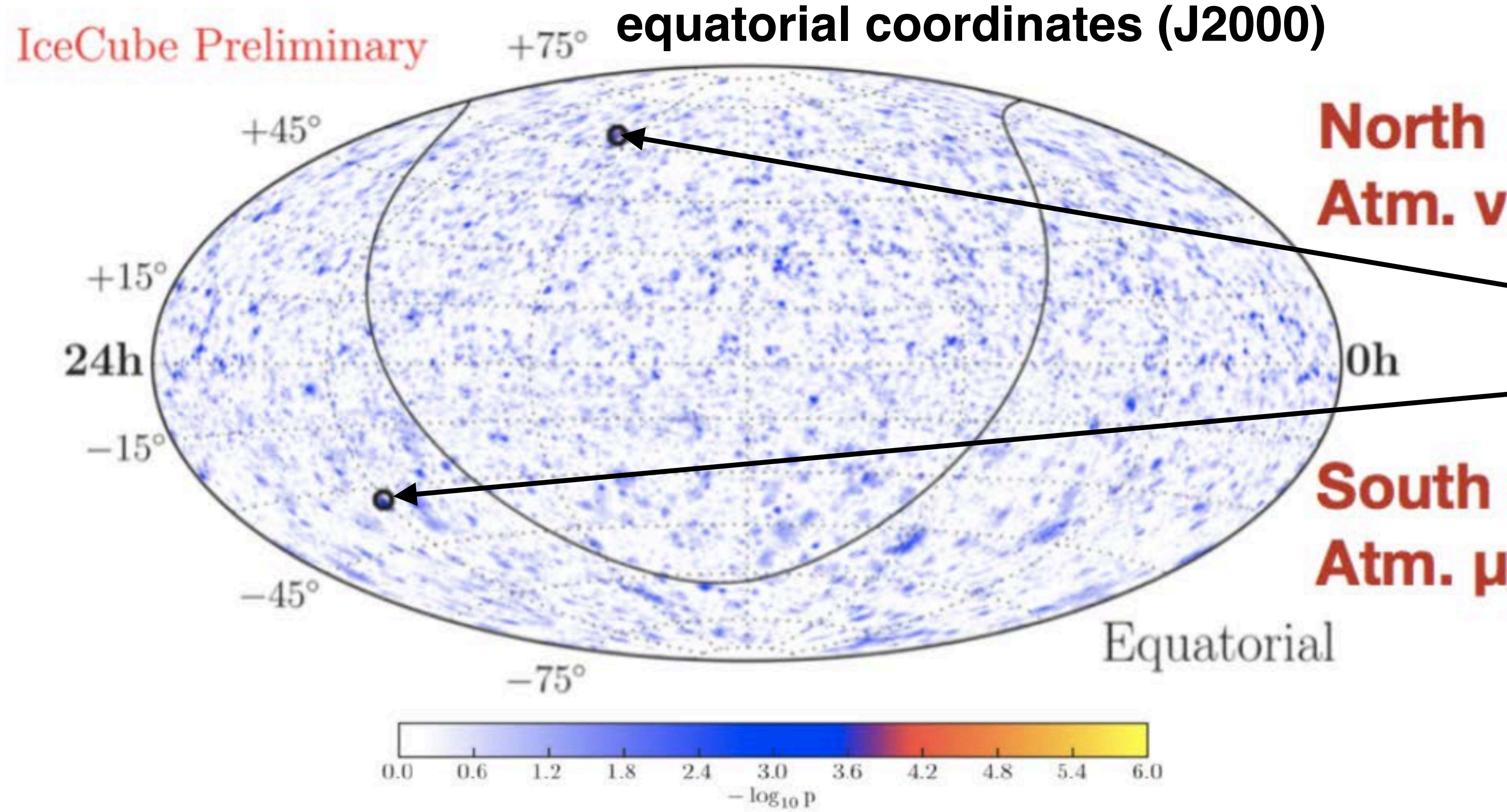
Searches for neutrino sources

- No sources in 4 y HESE

Arrival directions of the events in galactic coordinates



Search for point sources in 7 years of data



Hottest spots not significant

post-trial **p**-values of **29%** and **17%** for northern and southern sky, respectively.

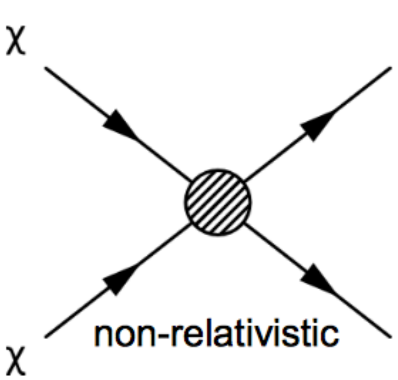
No significant excesses

Astrophys. J., 835 (2017) no. 2, 151

Indirect Dark Matter Search principle

- Look at **dense regions of DM where self-annihilation may occur at significant rate**:
  - Sun/Earth
  - The Milky Way
  - Galactic Dark Matter Halo
  - Nearby galaxies and galaxy clusters
- Annihilation products may decay producing **neutrinos**

Sensitive DM mass range for IceCube:
~10 GeV - ~100 TeV



$\nu, e^+, \mu^+, \tau^+, W^+, Z, b, t \Rightarrow e\pm, \upsilon, \gamma, p, D, \ldots$

$\bar{\nu}, e^-, \mu^-, \tau^-, W^-, Z, \bar{b}, \bar{t} \Rightarrow e\pm, \upsilon, \gamma, p, D, \ldots$

Search for dark matter annihilations in the **Sun**

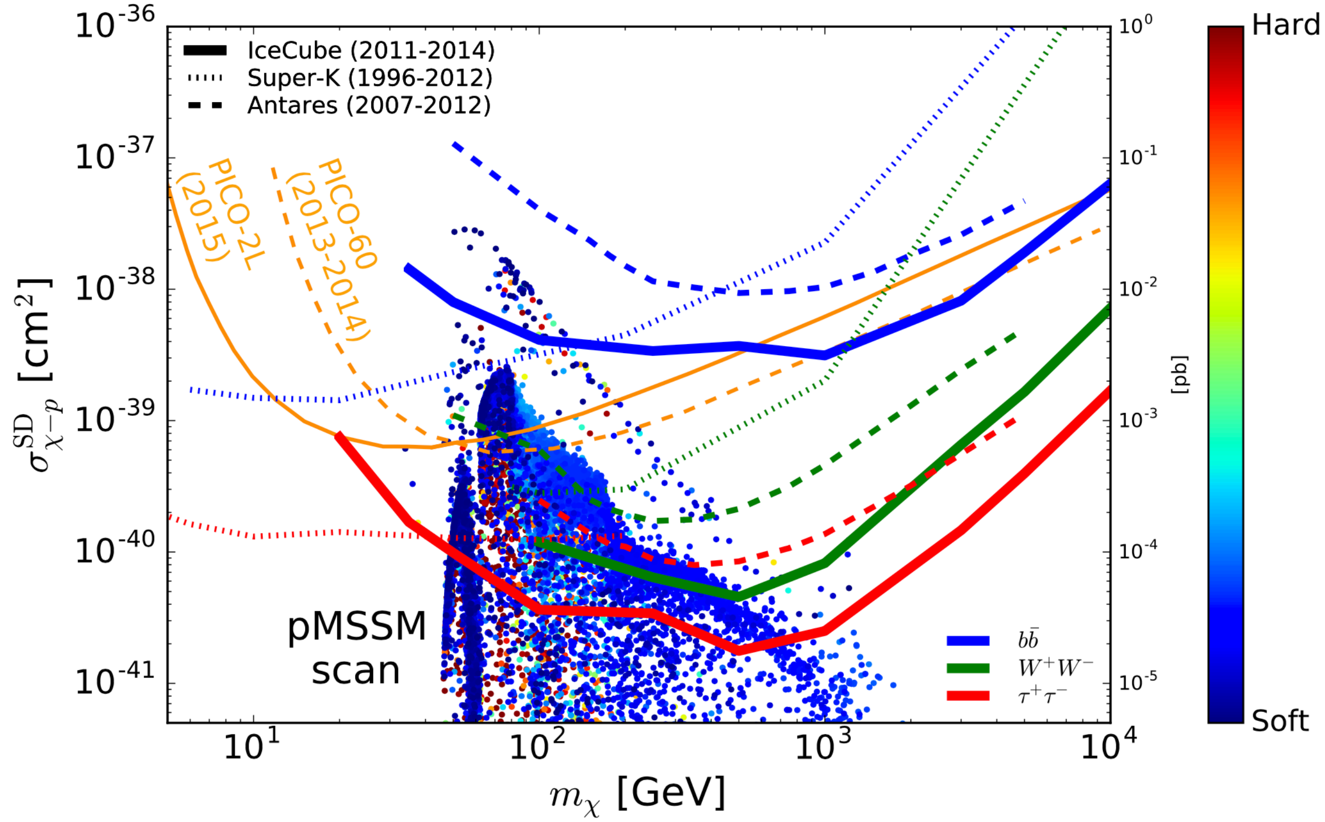
- WIMPs could be captured by the Sun through WIMP-nucleon scattering
- Search for **muon neutrinos** from dark matter annihilation
- **DeepCore** sub-array was included in the analysis, **lowering the energy threshold**
- Data gathered in the austral winters between May 2011 and May 2014, corresponding to **532 days of livetime** when the Sun, being below the horizon, is a source of up-going neutrino events, easiest to discriminate against the dominant background of atmospheric muons
- Dependent on WIMP mass & annihilation channel
- This search is sensitive to the **spin-dependent WIMP-nucleon cross section**
    - The cross section depends on the nature of the couplings. For non-relativistic WIMPs, one in general has to distinguish spin-independent (Scalar, Vector) and spin-dependent (Axial-Vector) couplings. Due to coherence effects, the spin-independent cross section scales approximately as the square of the mass of the nucleus.

Search for dark matter annihilations in the **Sun**

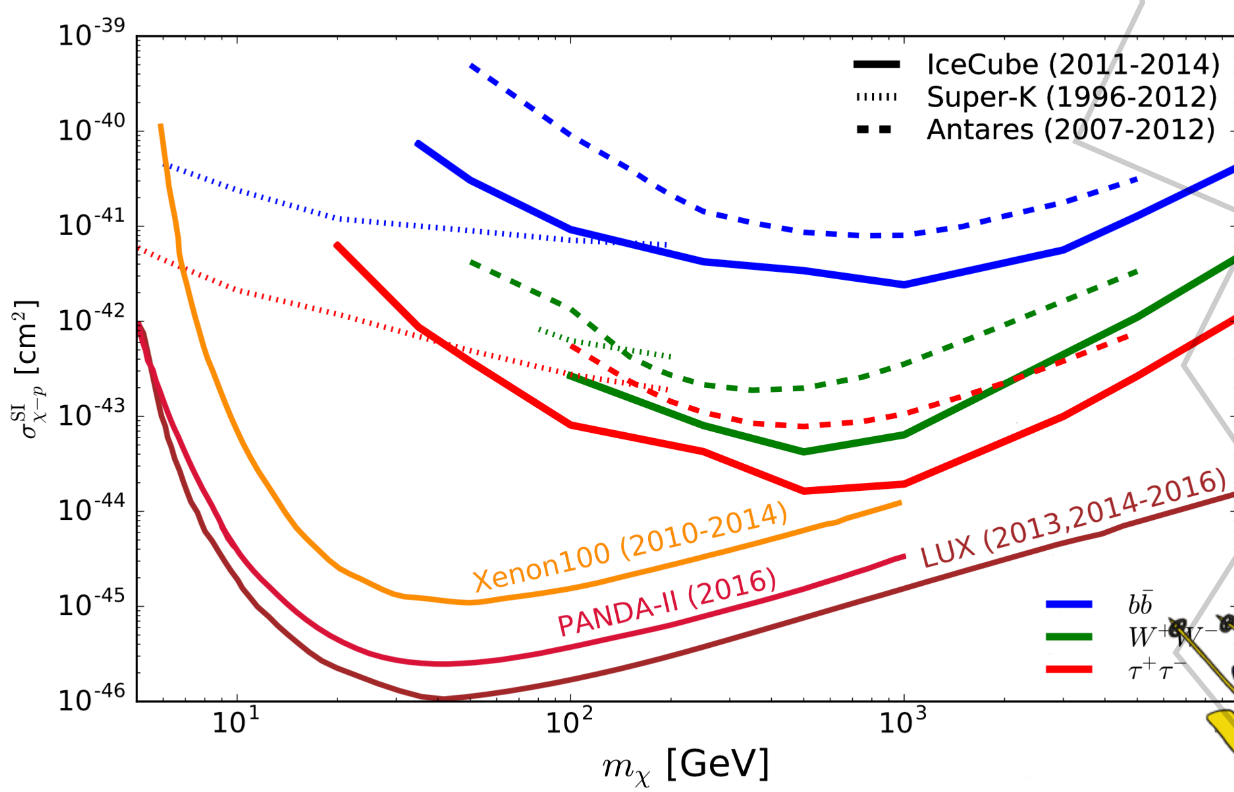
IceCube detector with 86 strings; 3 years of data

Eur. Phys. J. C (2017) 77

spin-dependent WIMP-nucleon cross section



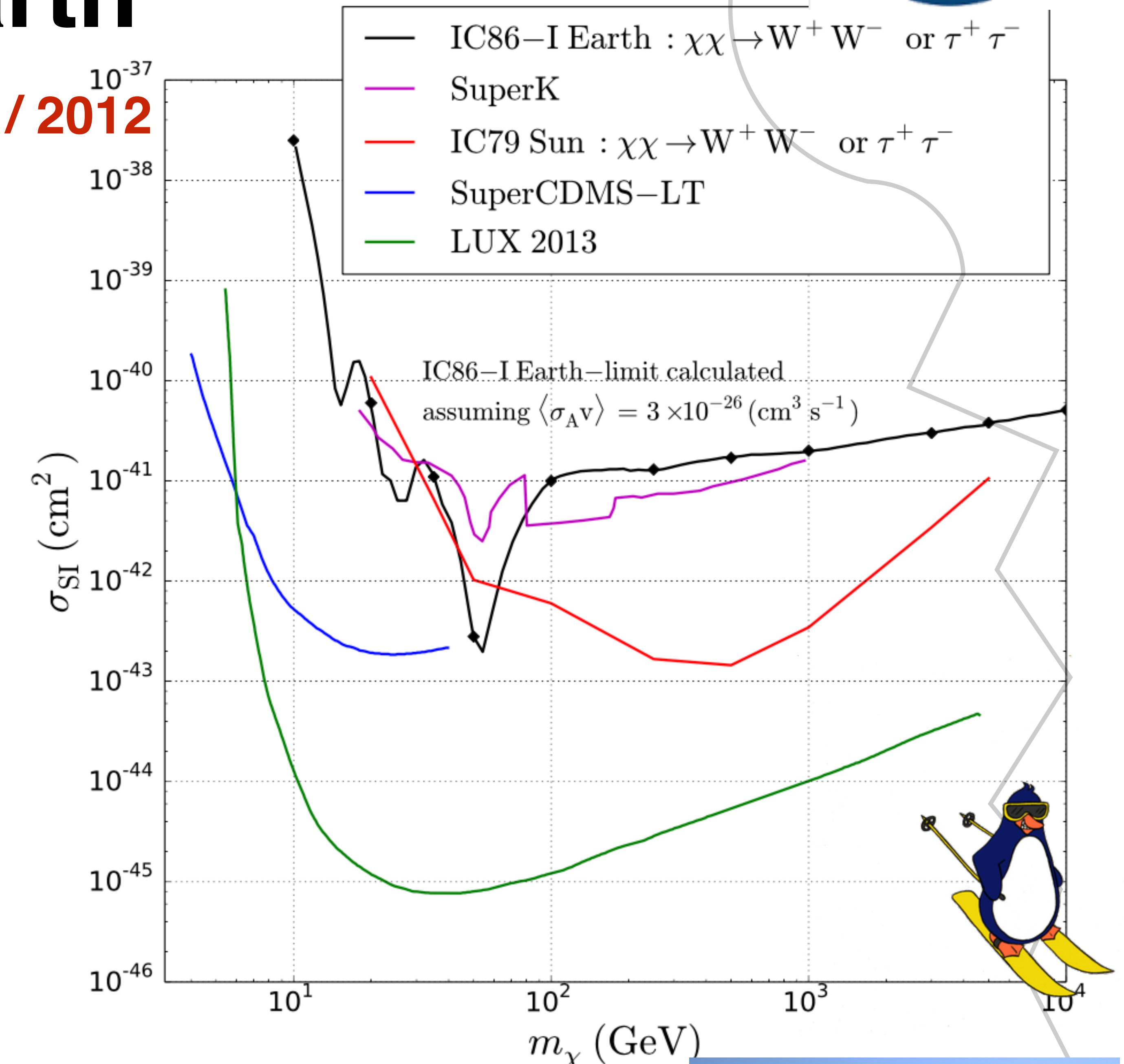
spin-independent WIMP-nucleon cross section



The IceCube limits have been scaled up to the upper edge of the total systematic uncertainty band. The colored points correspond to models from a scan of the pMSSM and are shown color coded by the 'hardness' of the resultant neutrino spectrum.

Search for dark matter annihilations in the center of the **Earth**

IceCube detector with 86 strings;
327 days of detector livetime during 2011/ 2012
Eur. Phys. J. C77, 82 (2017).



The same WIMP collection mechanism applies for the Earth as in the Sun

WIMPs annihilating in the center of the Earth will produce a unique signature in IceCube as **vertically up-going muons**

No excess beyond the expected background from atmospheric neutrinos was detected

Assumed: $\langle\sigma_A v\rangle = 3 \cdot 10^{-26} cm^3 s^{-1}$
$\rho_\chi = 0.3$ GeV cm^{-3} (displayed limits)

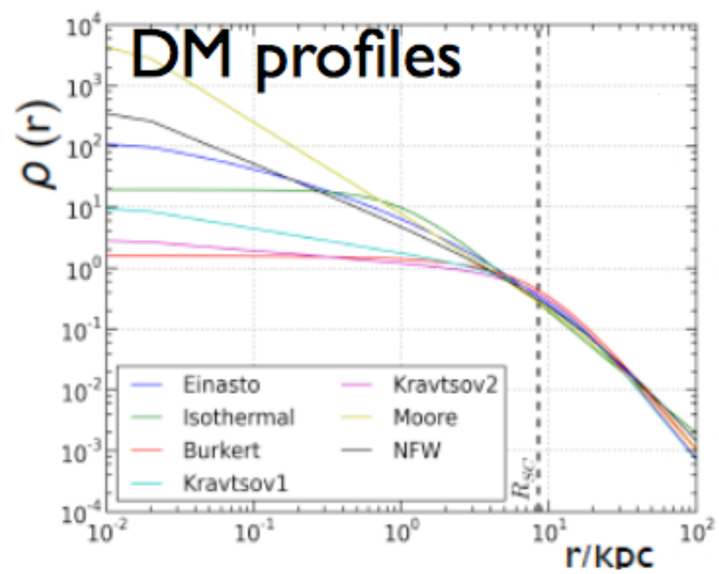
Search for Neutrinos from Dark Matter Annihilations in the **Milky Way**

- The Milky Way is expected to be embedded in a halo of WIMPs, which can annihilate and produce a flux of neutrinos possibly detectable at Earth.

- The expected signal is particularly **sensitive to the chosen density profile** of the dark matter halo

- Two profiles used: Navvarro-Frenk-White (NFW) [APJ 462, 563 (1996)] and Burkert [APJ 447, L25 (1995)]

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\nu^2} J_a(\psi) \frac{dN_\nu}{dE}$$



Search for Neutrinos from Dark Matter Annihilations in the **Milky Way**

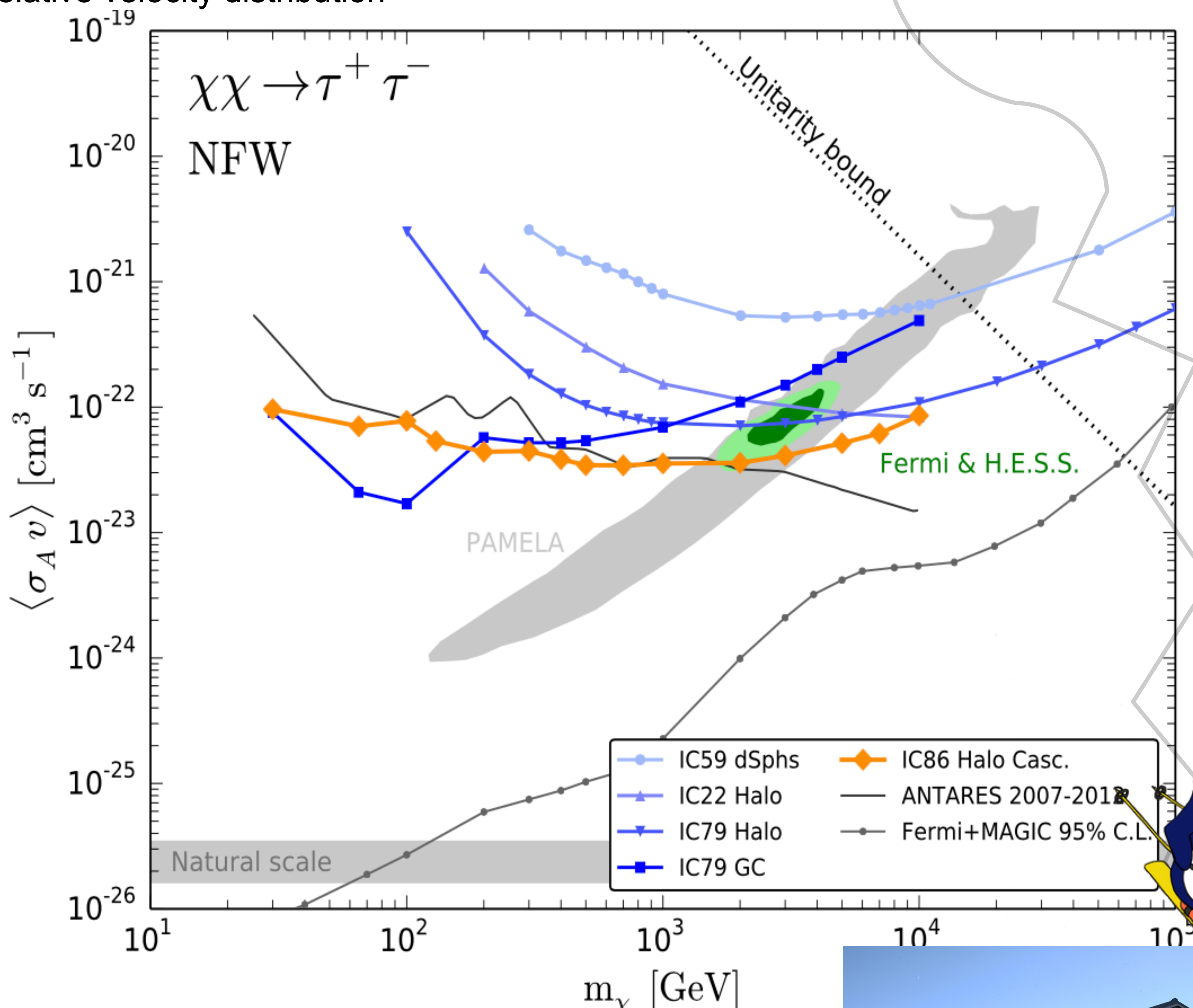
Eur. Phys. J. C76, 531 (2016)

329.1 live-days of detector operation between May 2011 and March 2012

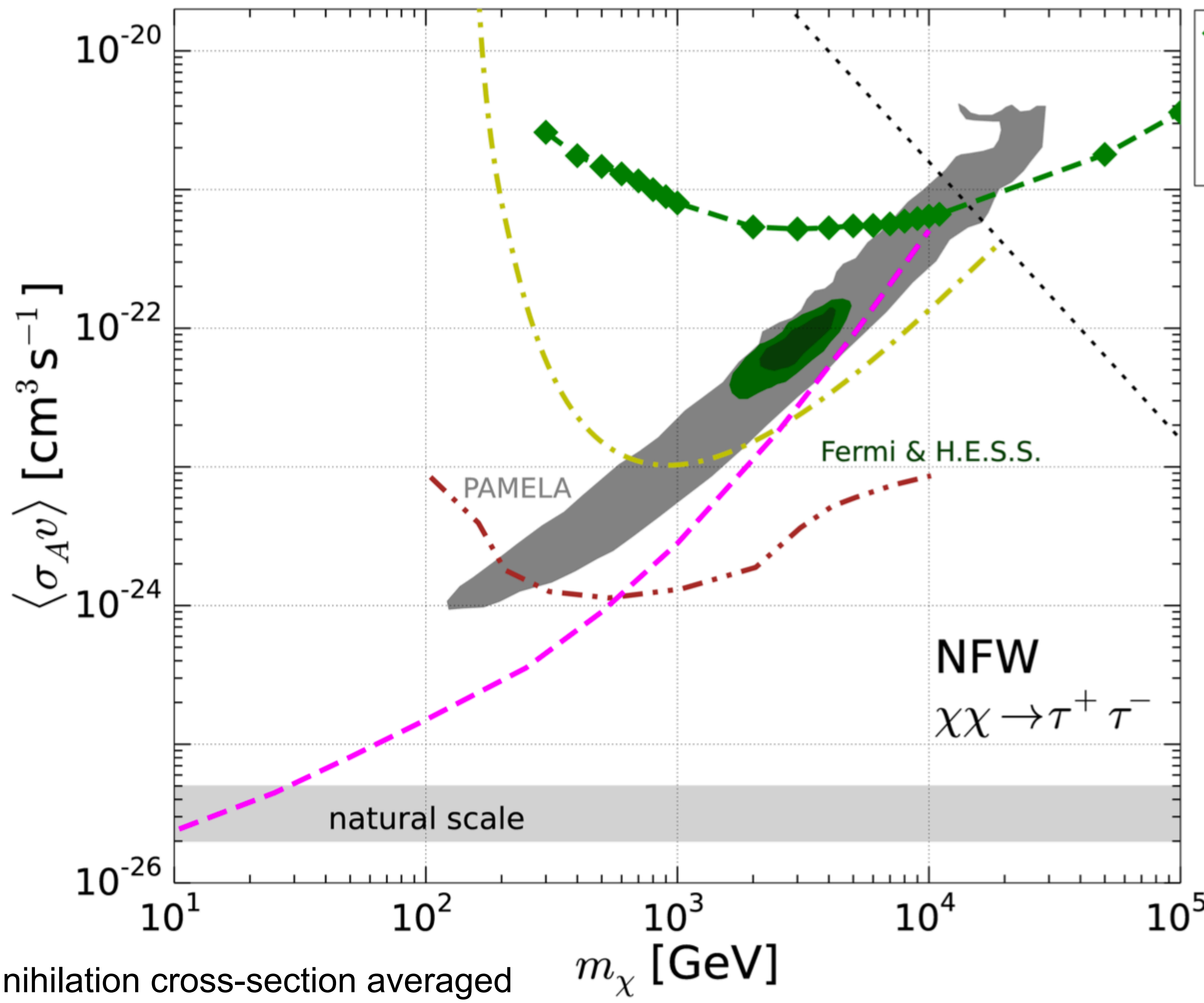
focus on **cascades** produced by neutral or charged current neutrino interactions occurring inside the DeepCore

event selection has been optimized to identify and select the more spherical light pattern

self-annihilation cross-section averaged over the relative velocity distribution



Dark matter annihilation in **nearby galaxies and galaxy clusters**



self-annihilation cross-section averaged over the relative velocity distribution

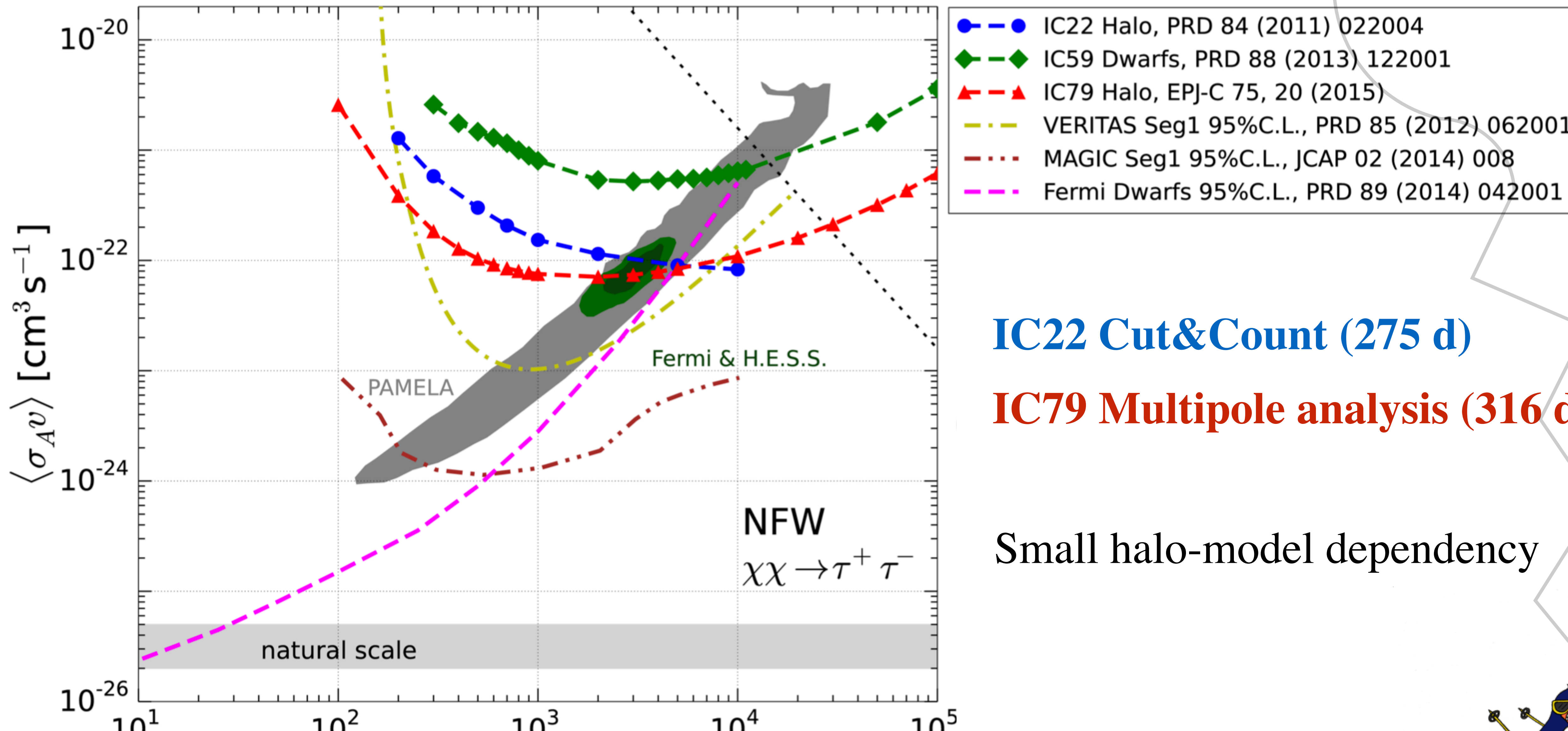
Dwarf Galaxies & Clusters of Galaxies analysis

IC59

Source stacking analysis (340 d)

Optimized cuts & size of search window for 5 TeV WIMPs

Search for dark matter accumulated in the **Galactic halo**



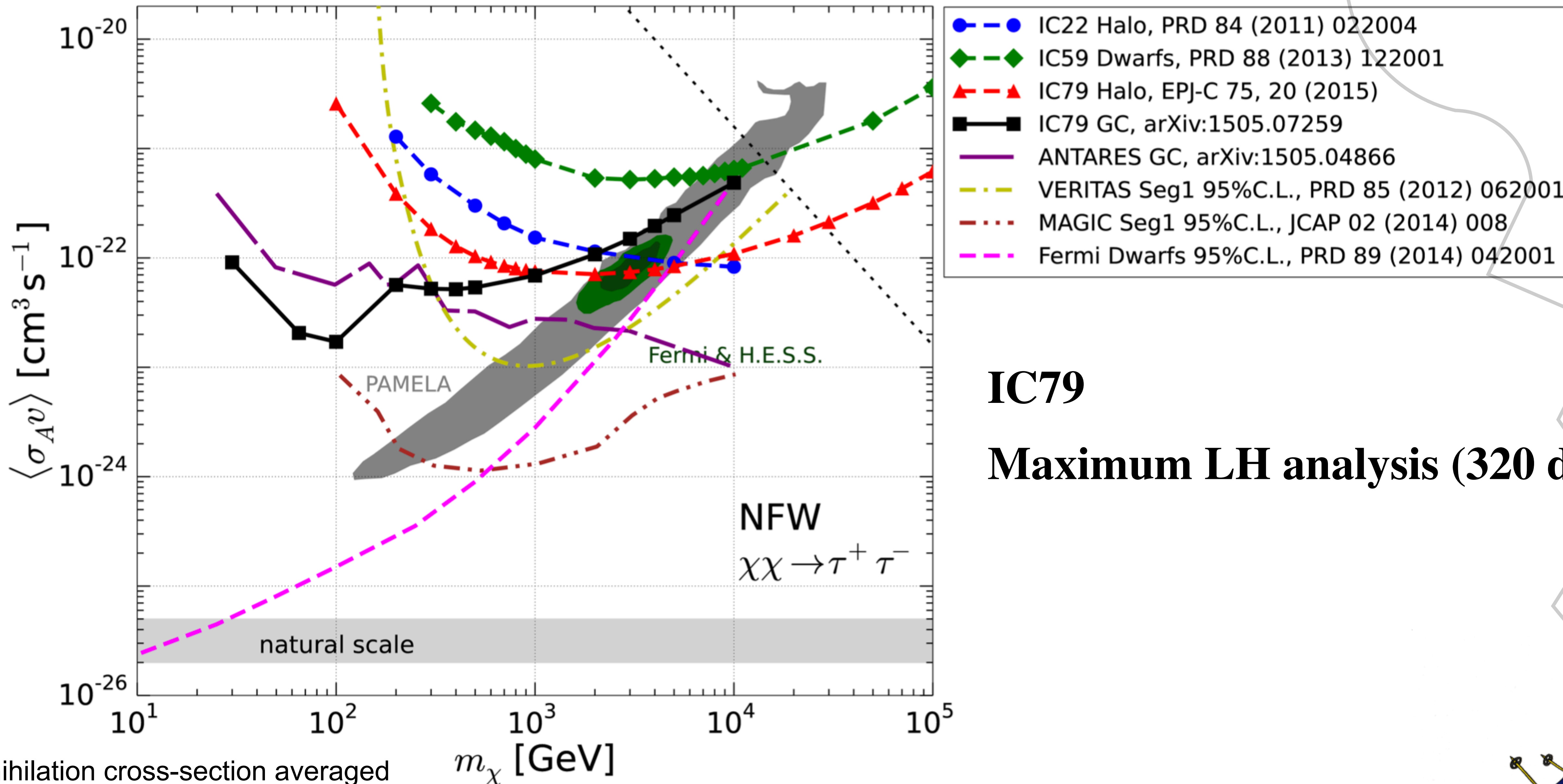
self-annihilation cross-section averaged over the relative velocity distribution

IC22 Cut&Count (275 d)

IC79 Multipole analysis (316 d)

Small halo-model dependency

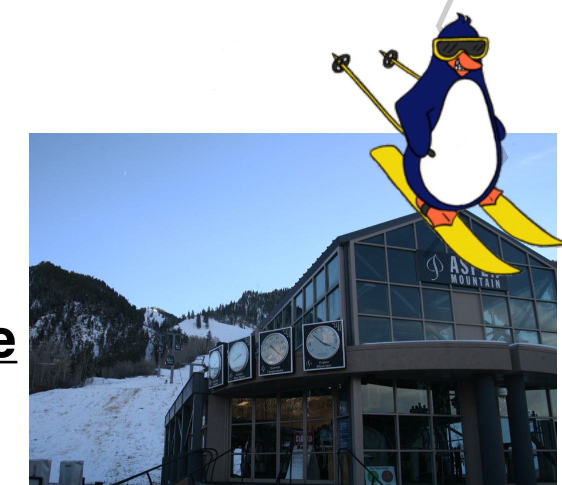
Search for dark matter accumulated in the **Galactic center**



self-annihilation cross-section averaged over the relative velocity distribution

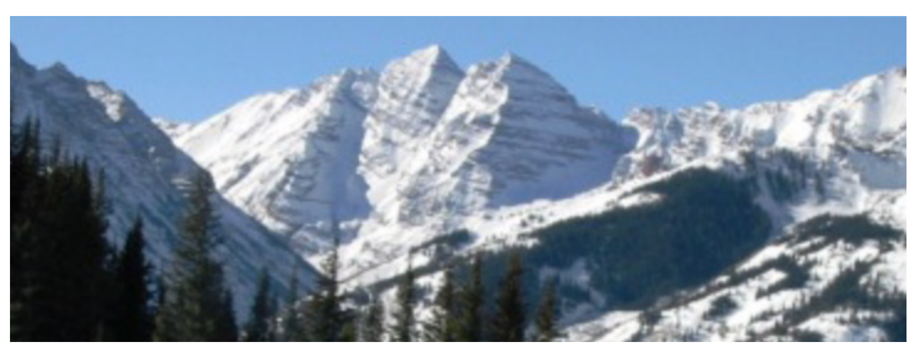
IC79

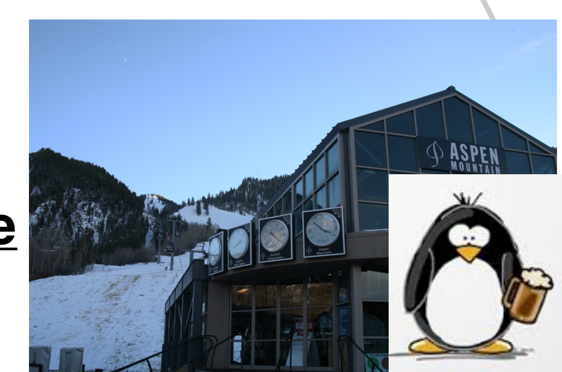
Maximum LH analysis (320 d)



Conclusions

- Selected IceCube results were presented
  - IceCube reported significant detection of high-energy astrophysical neutrinos in three channels (HESE, Through-going muons, cascades)
    - The source of this flux has not yet been found
  - Neutrinos provide high discovery potential for indirect Dark Matter searches
  - The proposed Gen2 array will play the leading role, with its rich physics program, in the future multi-messenger astronomy programs and DM searches!

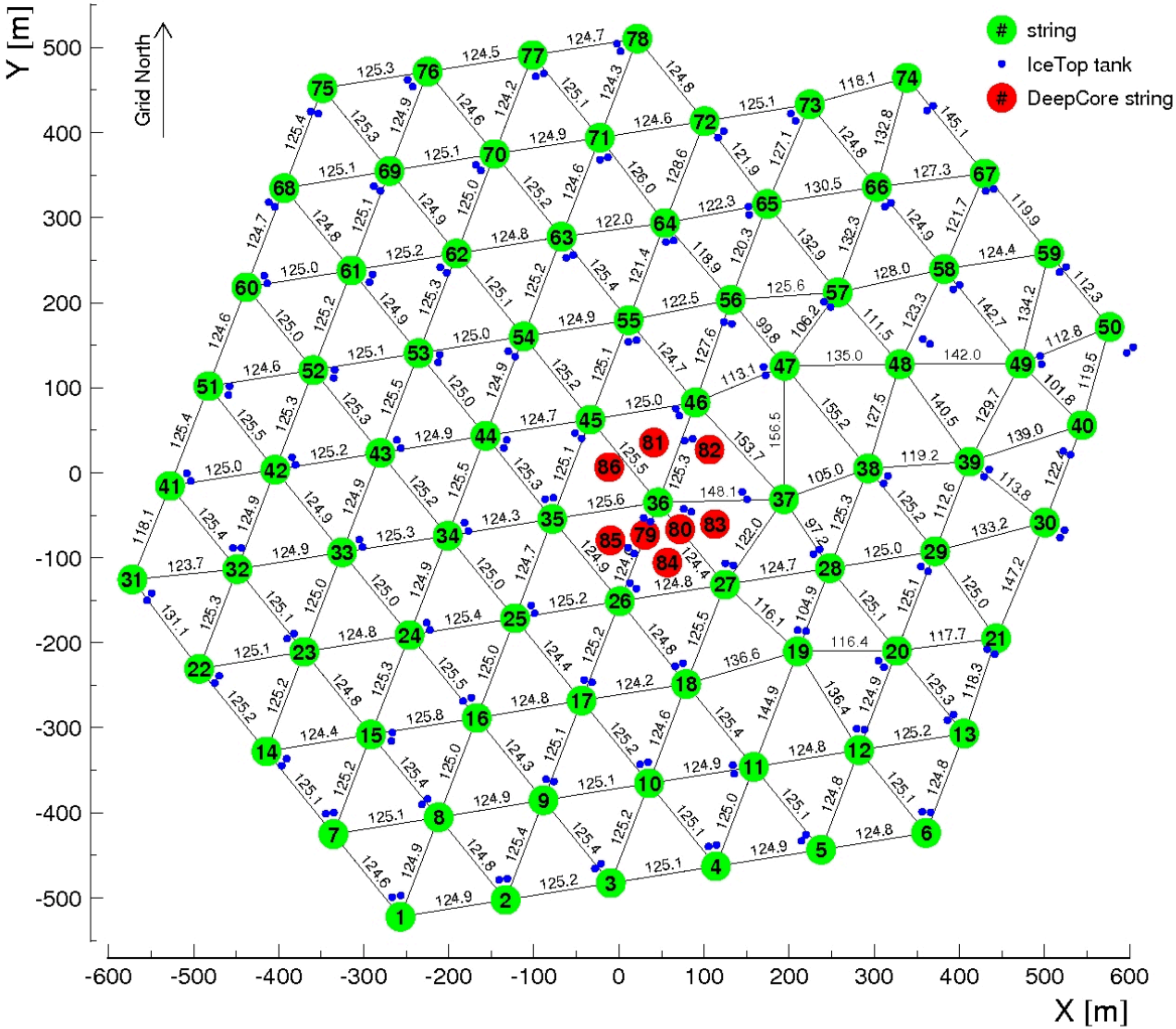




The IceCube–PINGU Collaboration

Backup slides

IceCube-86 (78+8) interstring (surface) distances

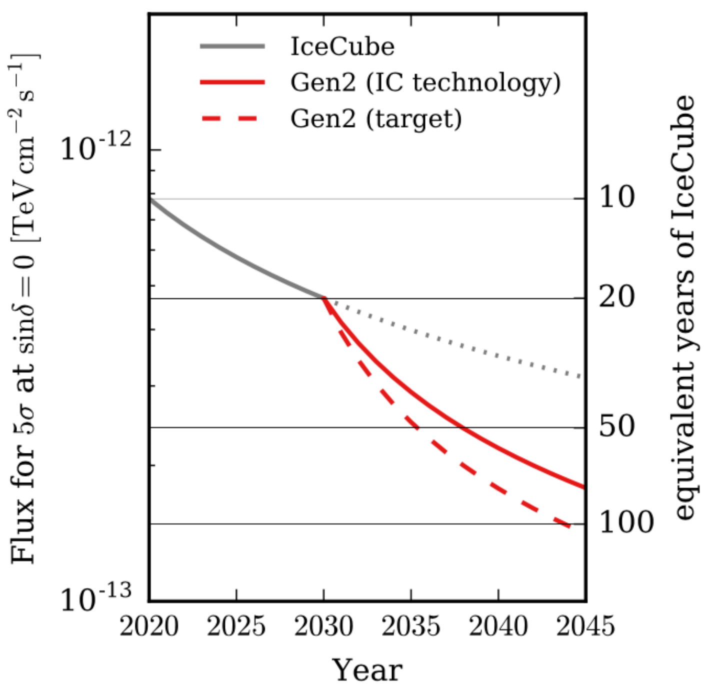


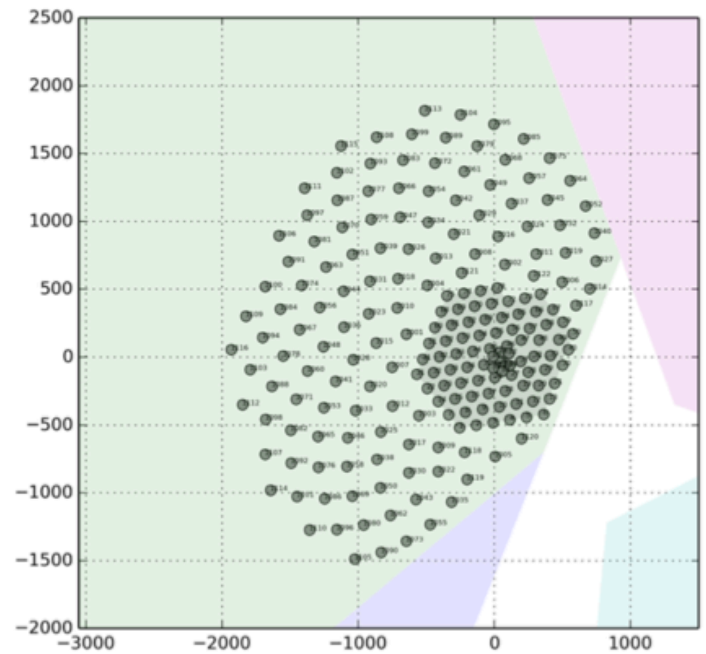
Gen2 array

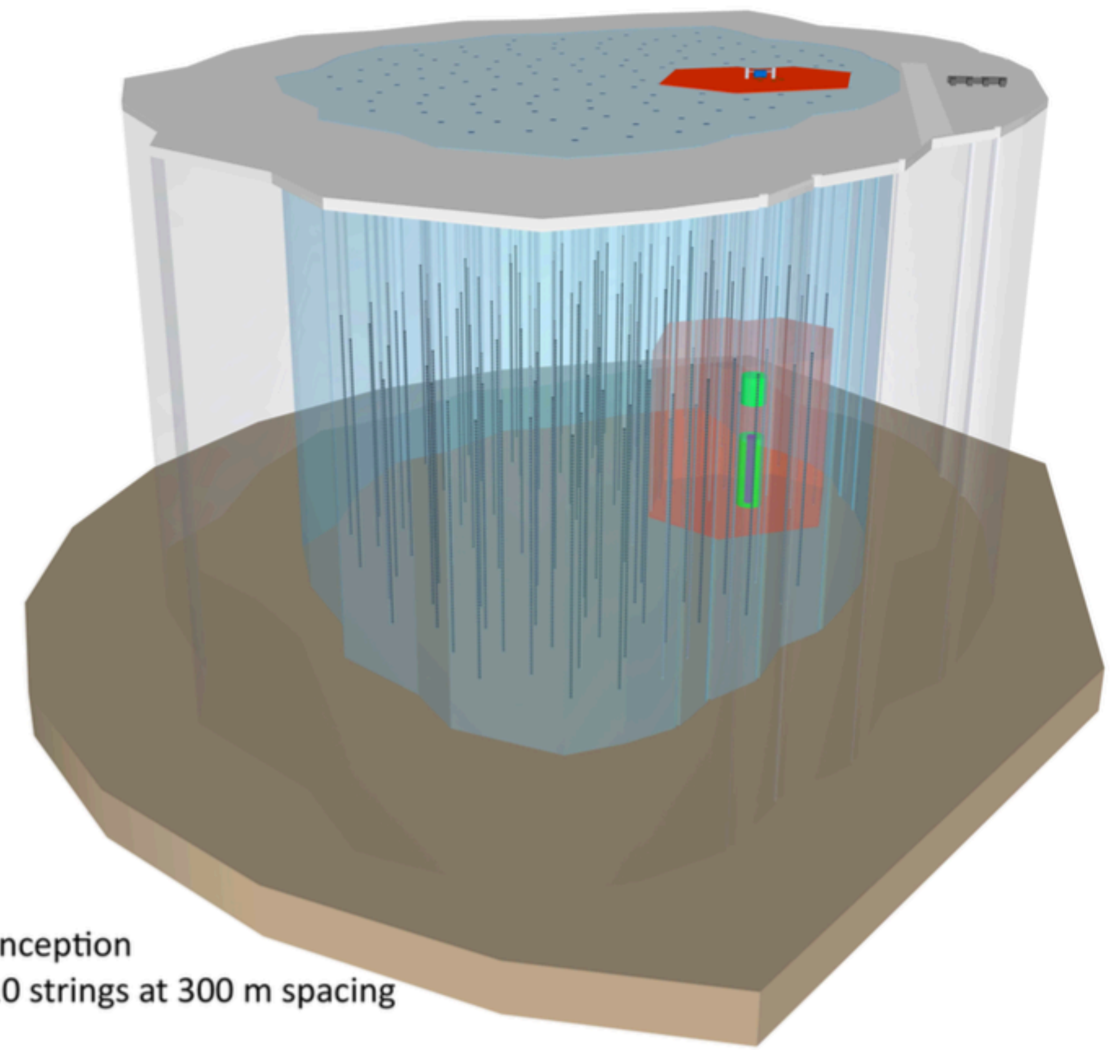
High Energy Extension will improve sensitivity to astrophysical sources by an order of magnitude

Gen2 would instrument $\sim$ **10 km^3**

Layout optimization still in progress







Artist conception
Here: 120 strings at 300 m spacing

DeepCore Physics

- Dark matter searches
  - Solar WIMP annihilation: *Phys. Rev. Lett.* 110, 131302 (2013), three-year update coming very shortly
  - Galactic Center: *Eur. Phys. J.* C75. 492 (2015), *Eur. Phys. J.* C76. 531 (2016)
  - Galactic Halo: *Eur. Phys. J.* C75. 20 (2015)
  - Dwarf galaxies: *Phys. Rev.* D88, 122001 (2013)
- Direct searches for exotic particles
  - E.g. slow monopoles: *Eur. Phys. J.* C74, 2938 (2014)
- Neutrino astronomy
  - Transient bursts of low energy neutrinos, e.g. choked GRBs: *Astrophys. J.* 816, 75 (2016)
- Measurement of atmospheric neutrino spectrum
  - First measurement of electron neutrinos above 50 GeV: *Phys. Rev. Lett.* 110, 151105 (2013)
- Measurements of atmospheric neutrino oscillations
  - First IceCube observation: *Phys Rev. Lett.* 111, 081801 (2013)
  - Improved analysis, reduced energy threshold and 2D data fit: *Phys. Rev.* D91, 072004 (2015)

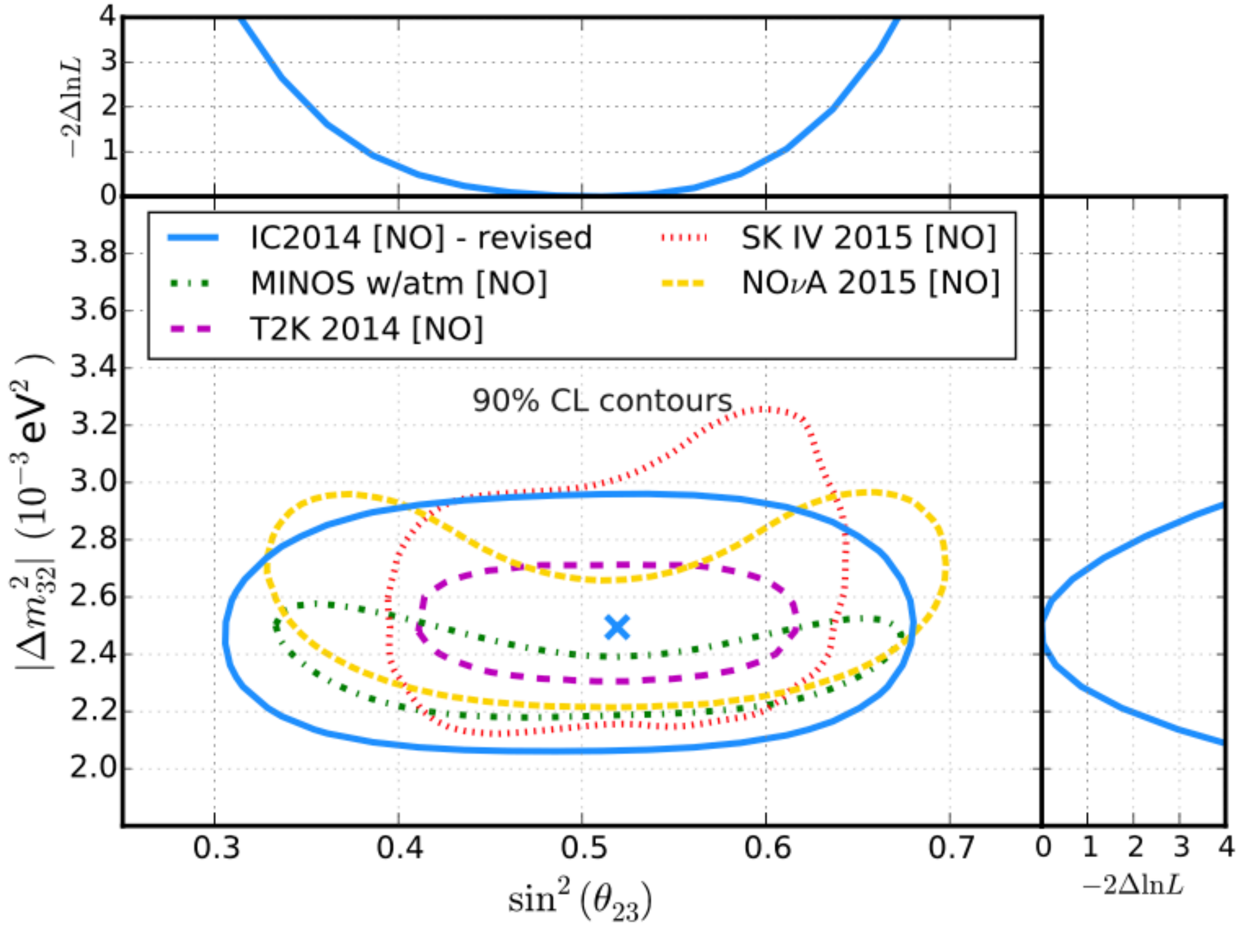
Neutrino Oscillations

The deposited energy and path length through Earth to constrain neutrino oscillations

Best measurement so far is for ν_μ disappearance, using 3 years of data

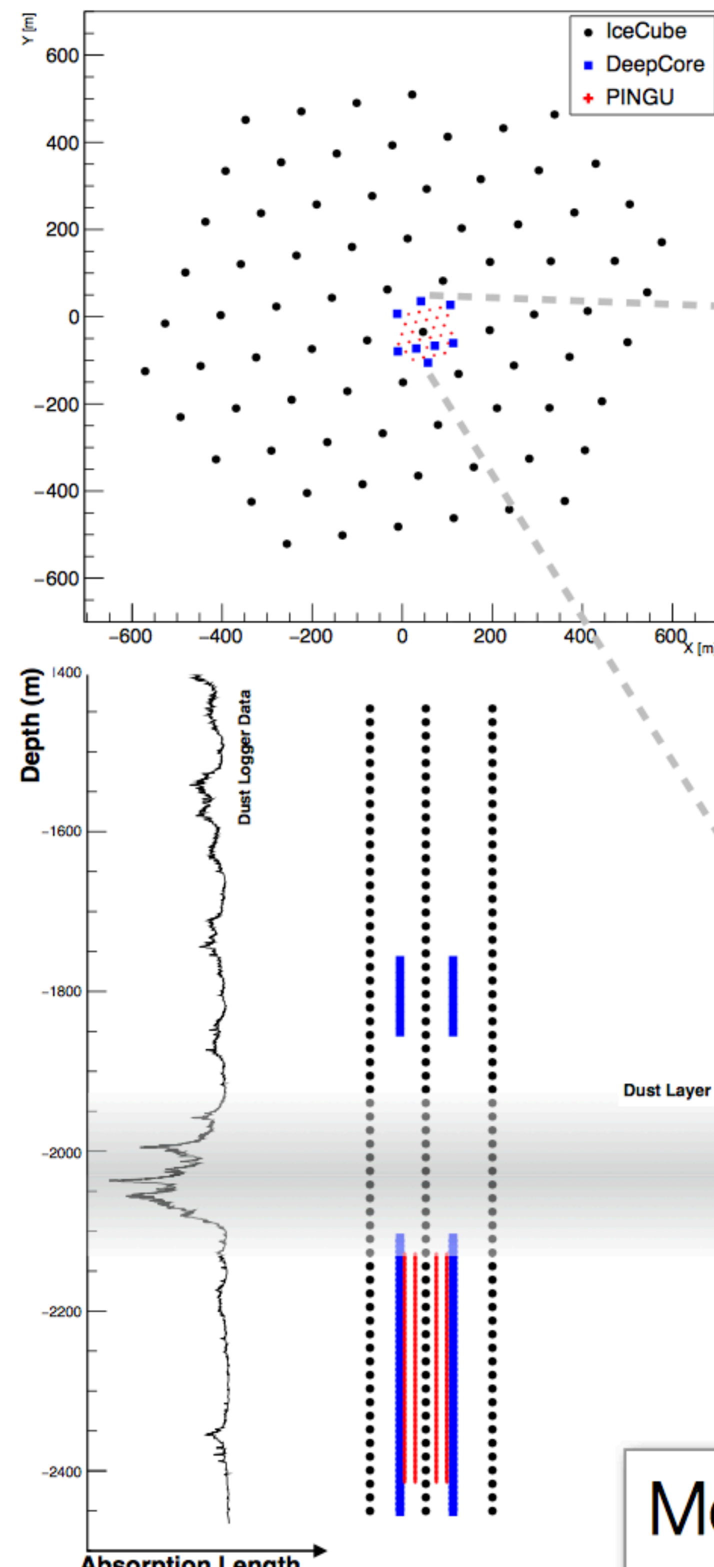
$\sin^2(\theta_{23})$ vs. $|\Delta m^2_{32}|$ fit consistent with other experiments

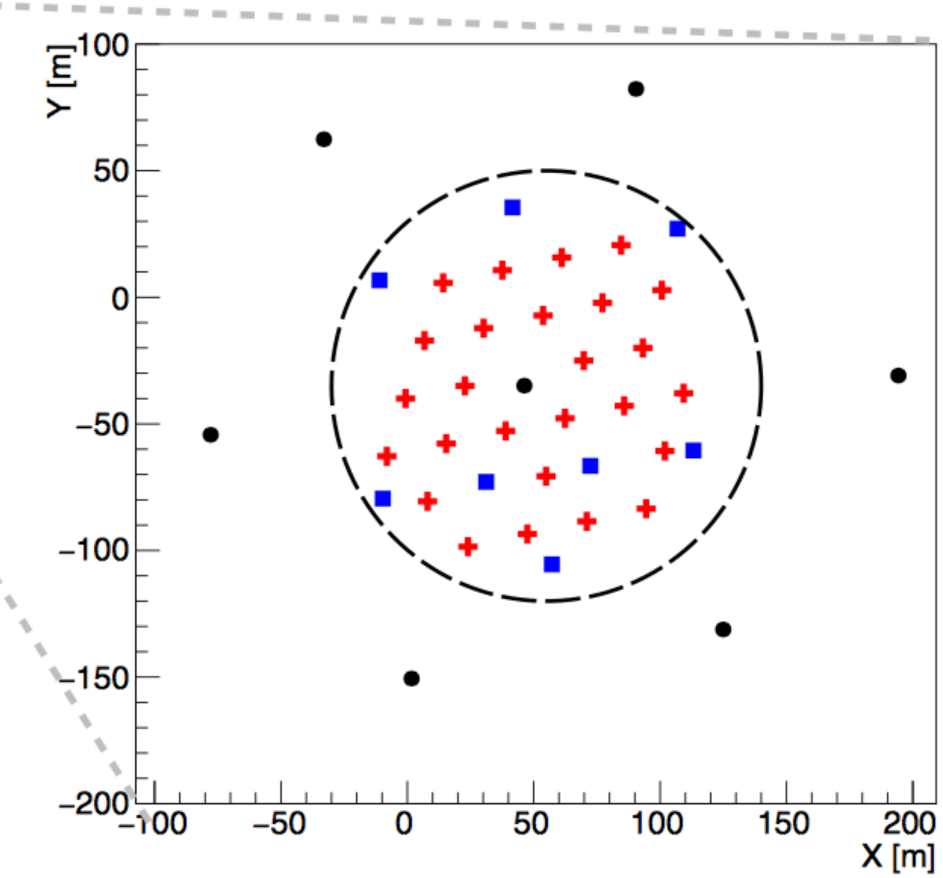
See Phys. Rev. D 91, 072004 (2015)



PINGU

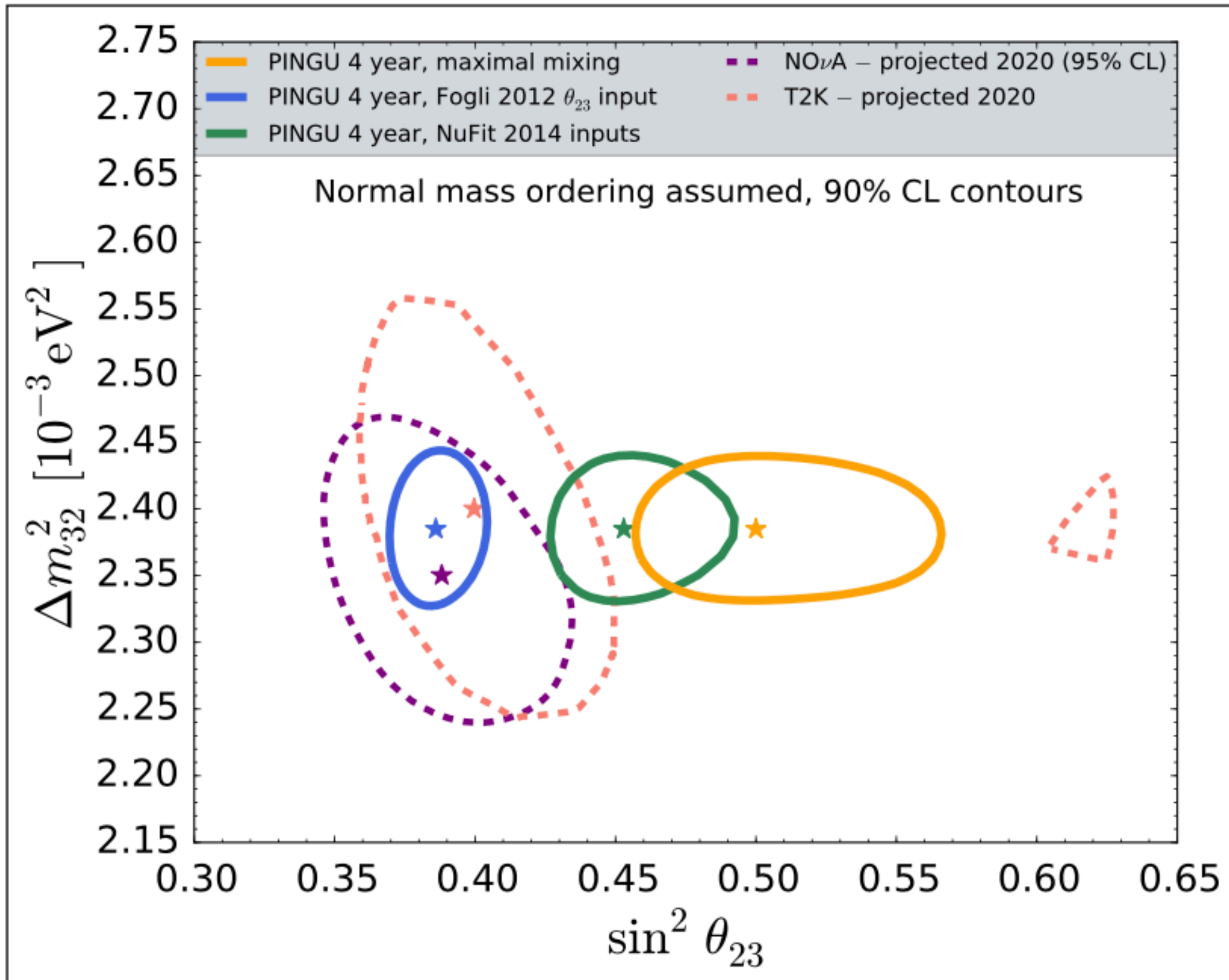
- 26 additional, very densely instrumented strings embedded in DeepCore
  - Additional calibration devices to better control detector systematics
- 6 MTon fiducial volume with few GeV energy threshold



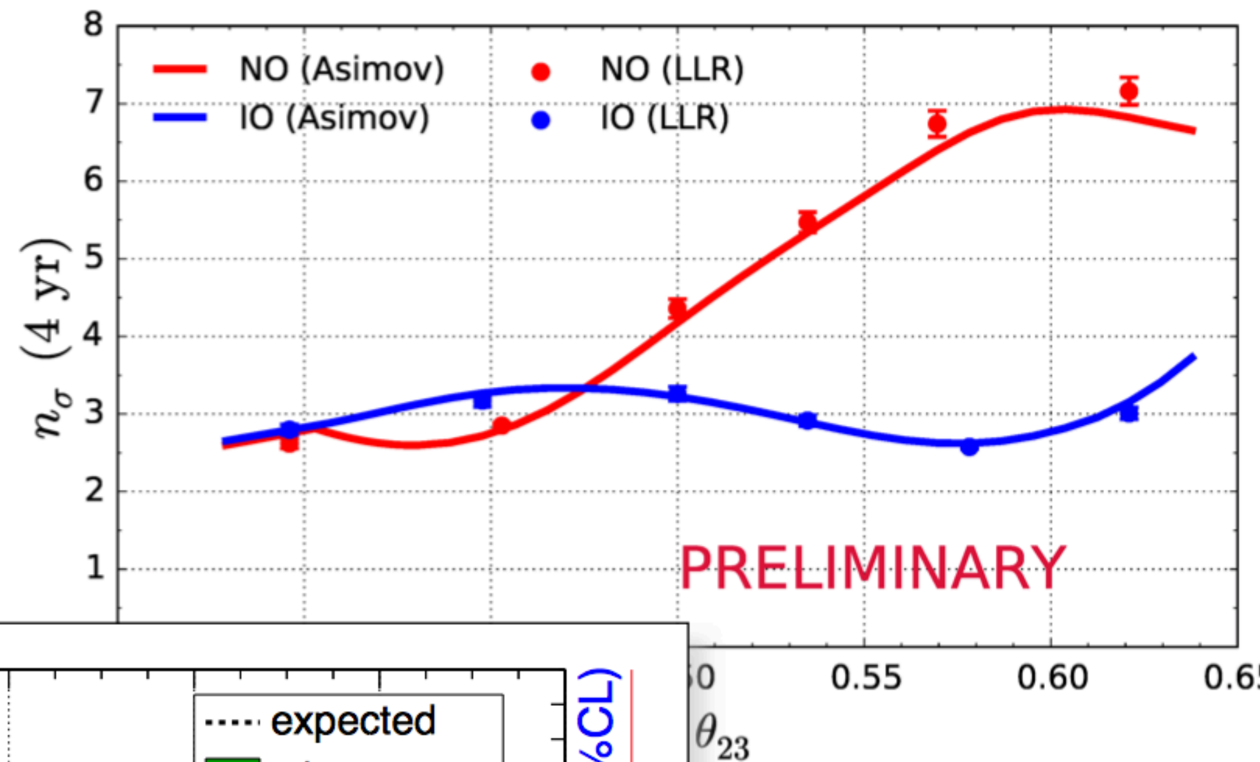


More information, performance estimates in updated Letter of Intent, arXiv:1607.02671

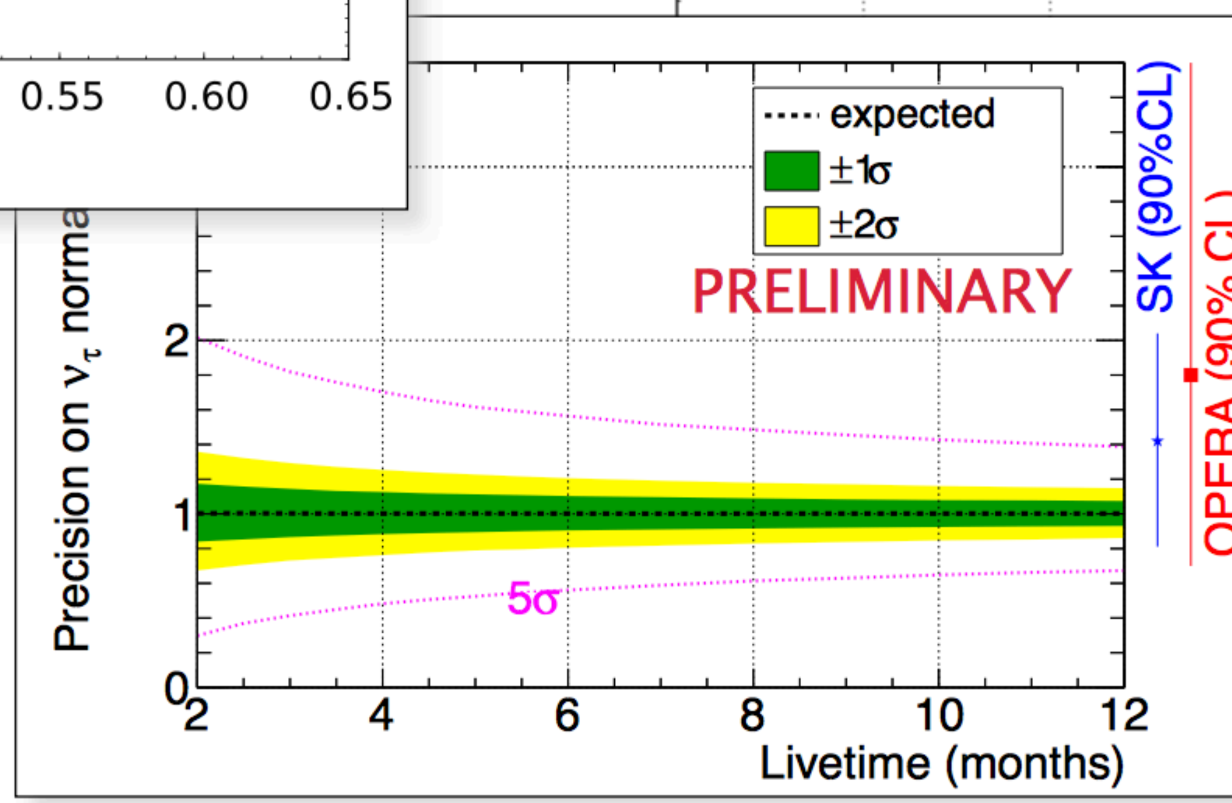
Neutrino Physics with PINGU



Determination of the neutrino mass ordering



Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}



Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

Possible Source Classes

✗ Gamma Ray Bursts

- No more than 1% of the observed HE neutrino flux is associated with GRBs
- However, limits on UHECR-GRB models are constraining but not definitive

? Active Galactic Nuclei

- No correlation found: < 30% of astrophysical neutrino flux is correlated with 2LAC blazar catalog (even less if weighted by gamma ray emission)
- Possible to evade limits if production is from special sub-populations

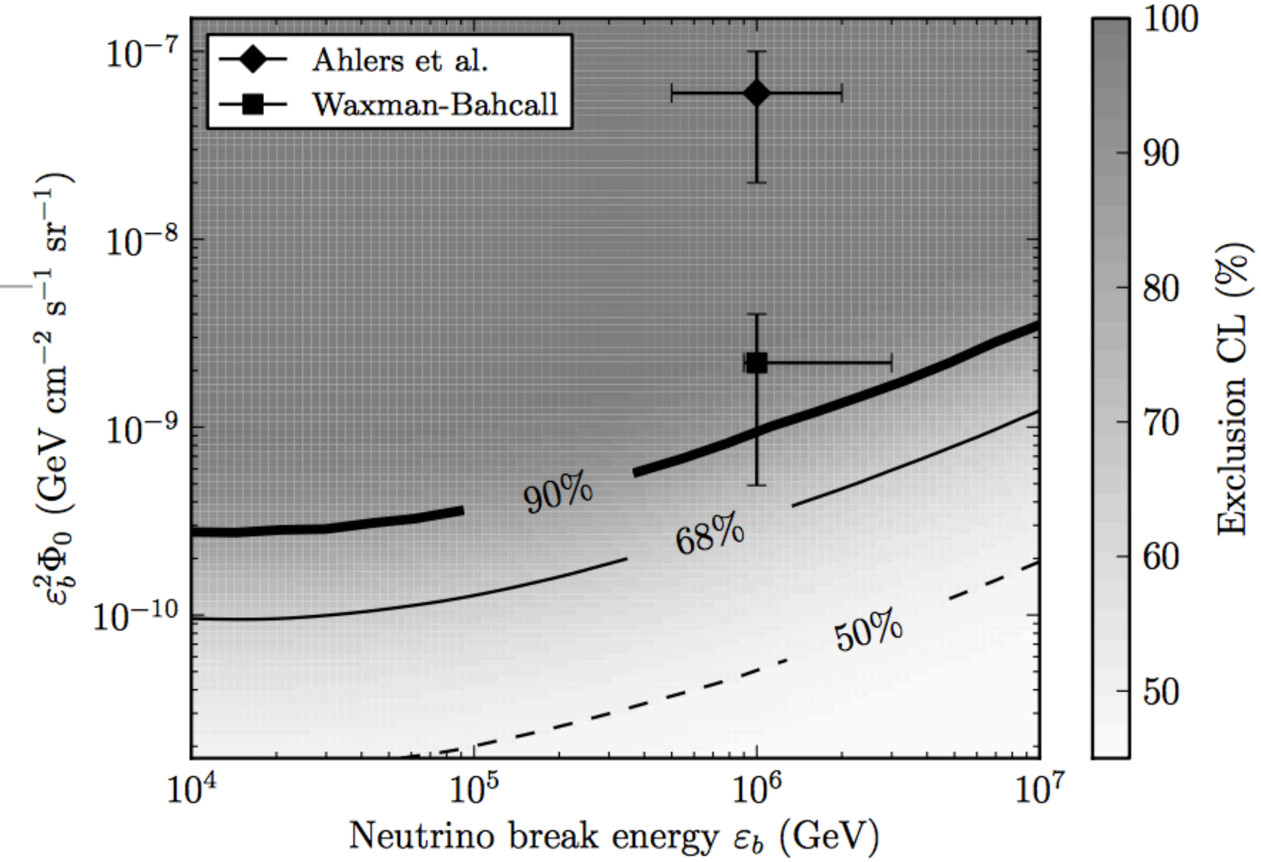
? Starburst Galaxies

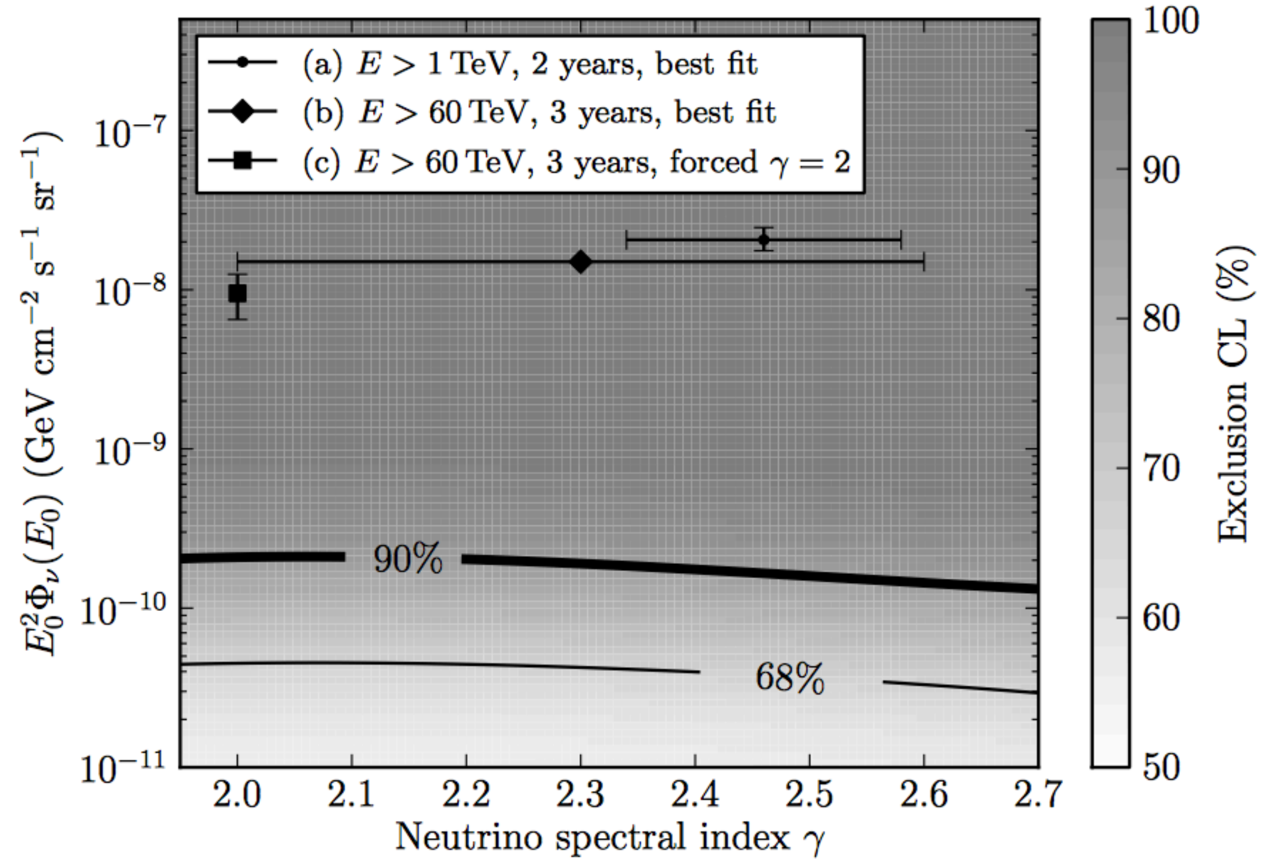
- Gamma rays should be produced along with neutrinos – would exceed residual Fermi-LAT diffuse gamma ray flux not associated with blazars *(Bechtol et al. 2015)*

Gamma Ray Bursts

- Energetically attractive UHECR source candidates
- Good information from Swift, Fermi – very low background
  - Up-going ν_μ track search: 506 northern bursts (4 years)
  - All-flavor cascade search: 257 bursts (1 year)
- Current UHECR-GRB models constrained but not ruled out – but only ~1% of the HE ν flux can come from GRBs

Astrophys. J. 805, L5 (2015)





Candidate Neutrino Sources

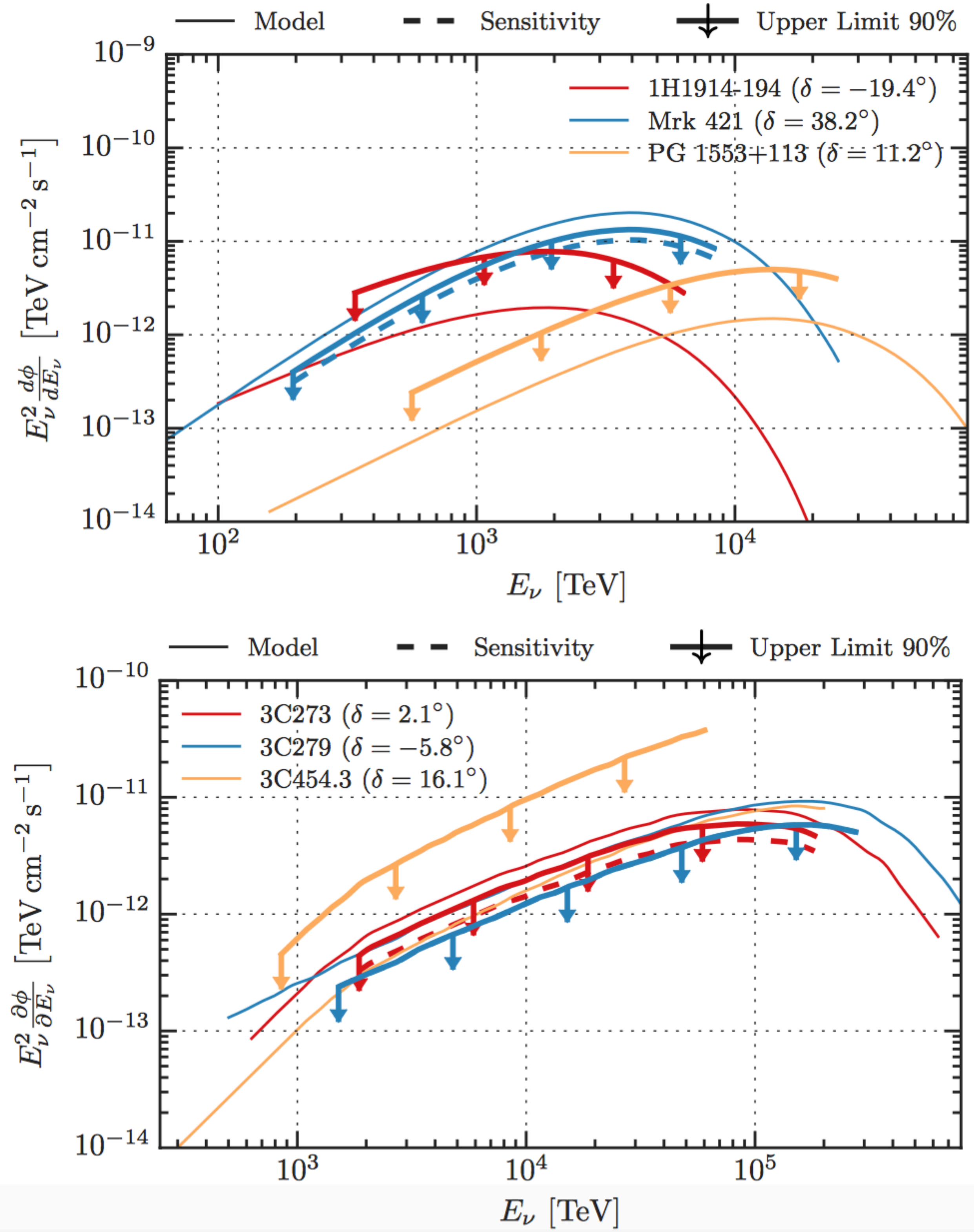
Astrophys. J. 835, 151 (2017)

- No significant detections among 74 candidate neutrino sources, selected *a priori*

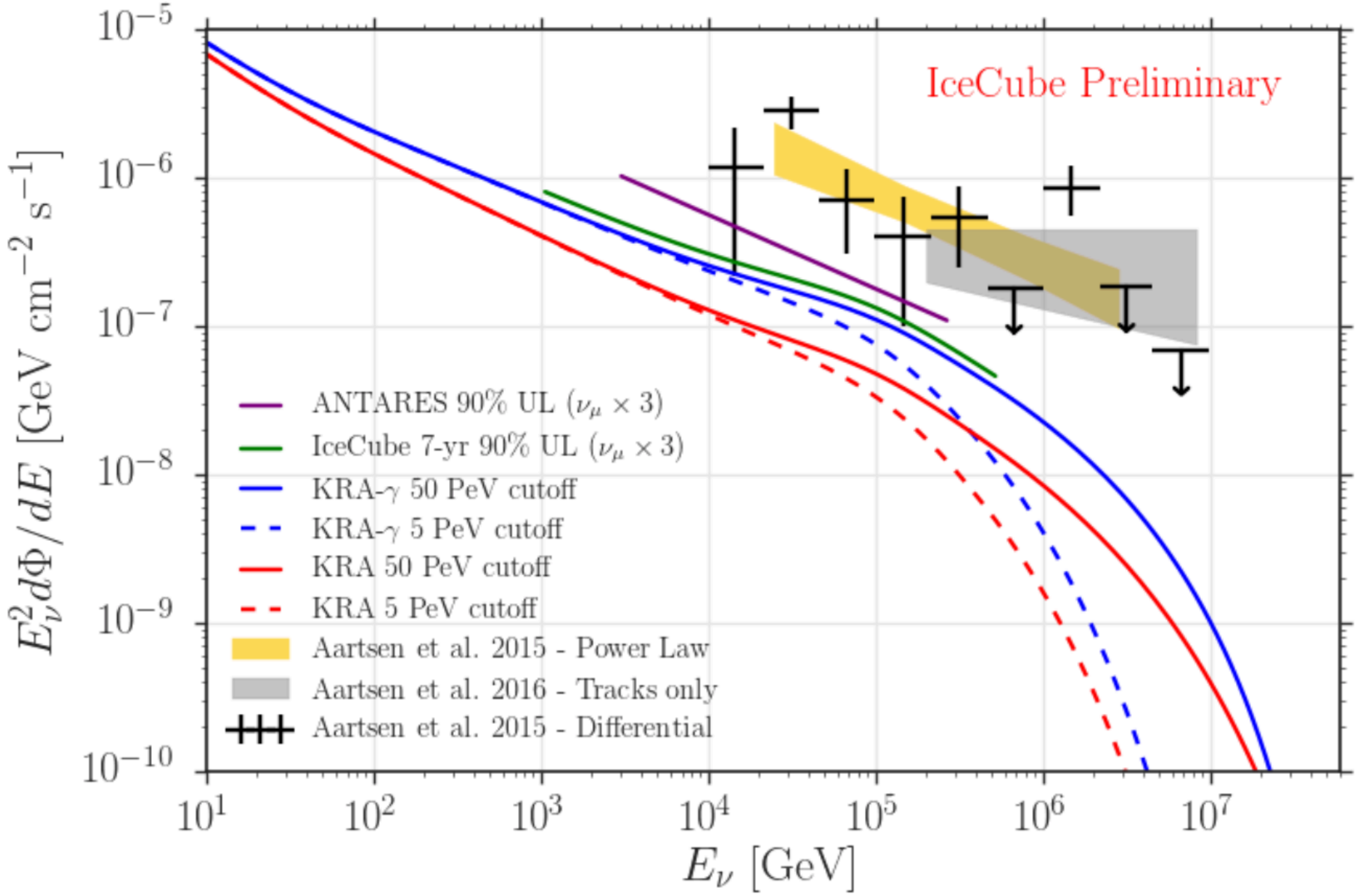
- Limits on several sources now constraining hadronic models of multiwavelength emission

  - Top: BL Lacs (Petropoulou *et al.* 2015)

  - Bottom: FSRQs (Reimer 2015)

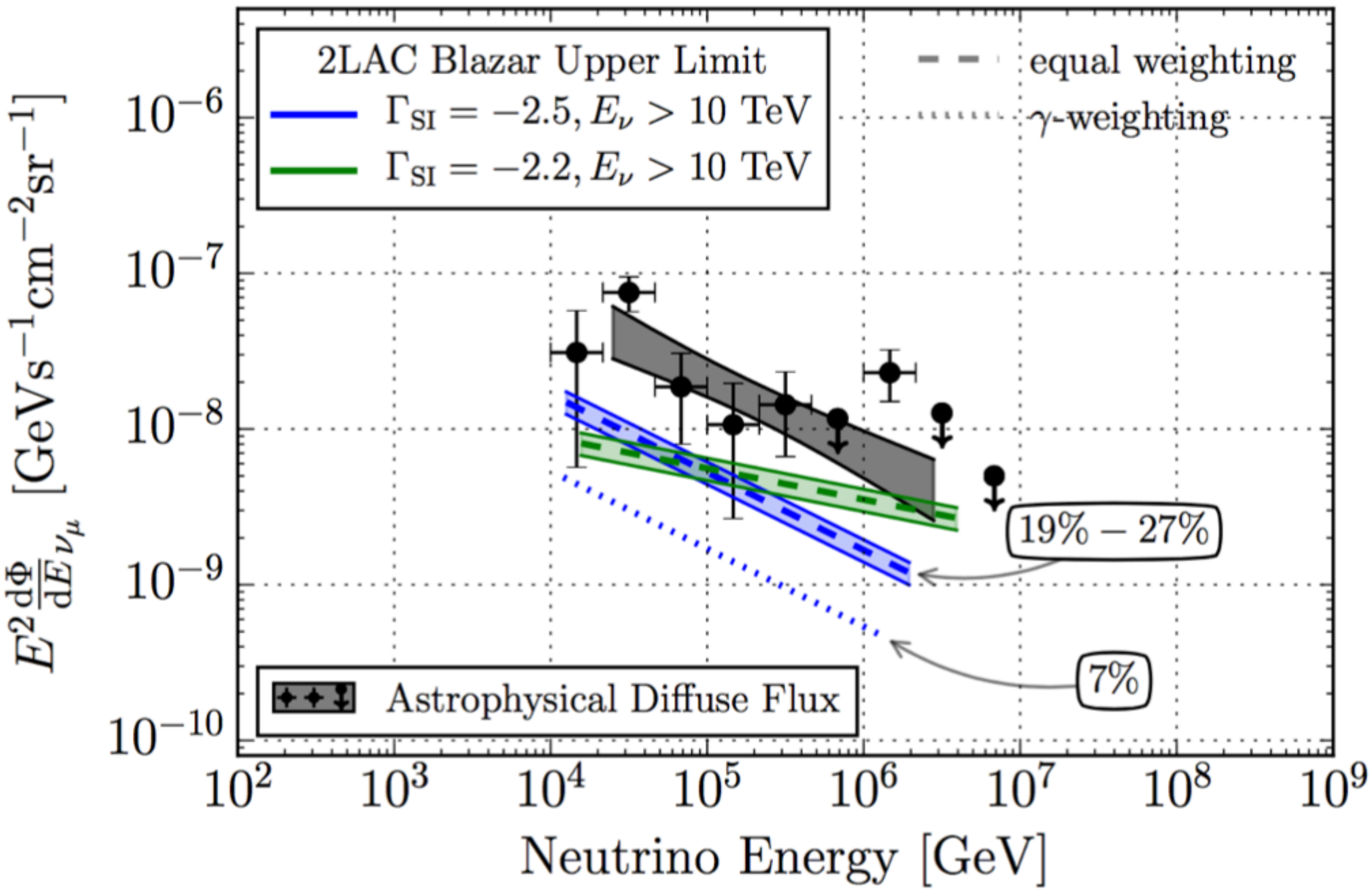


A Galactic Component?



- No significant evidence for emission from Galactic plane (p = 4.3%)
    - Upper limit is a factor of ~5 below the observed high energy neutrino flux

Active Galactic Nuclei/Blazars



- Stacking limit on Fermi-LAT blazars suggests less than 30% of observed HE astrophysical neutrino flux comes from these sources
  - But much more model dependence than for GRBs – time dependence, correlation between neutrinos and gamma rays, etc.