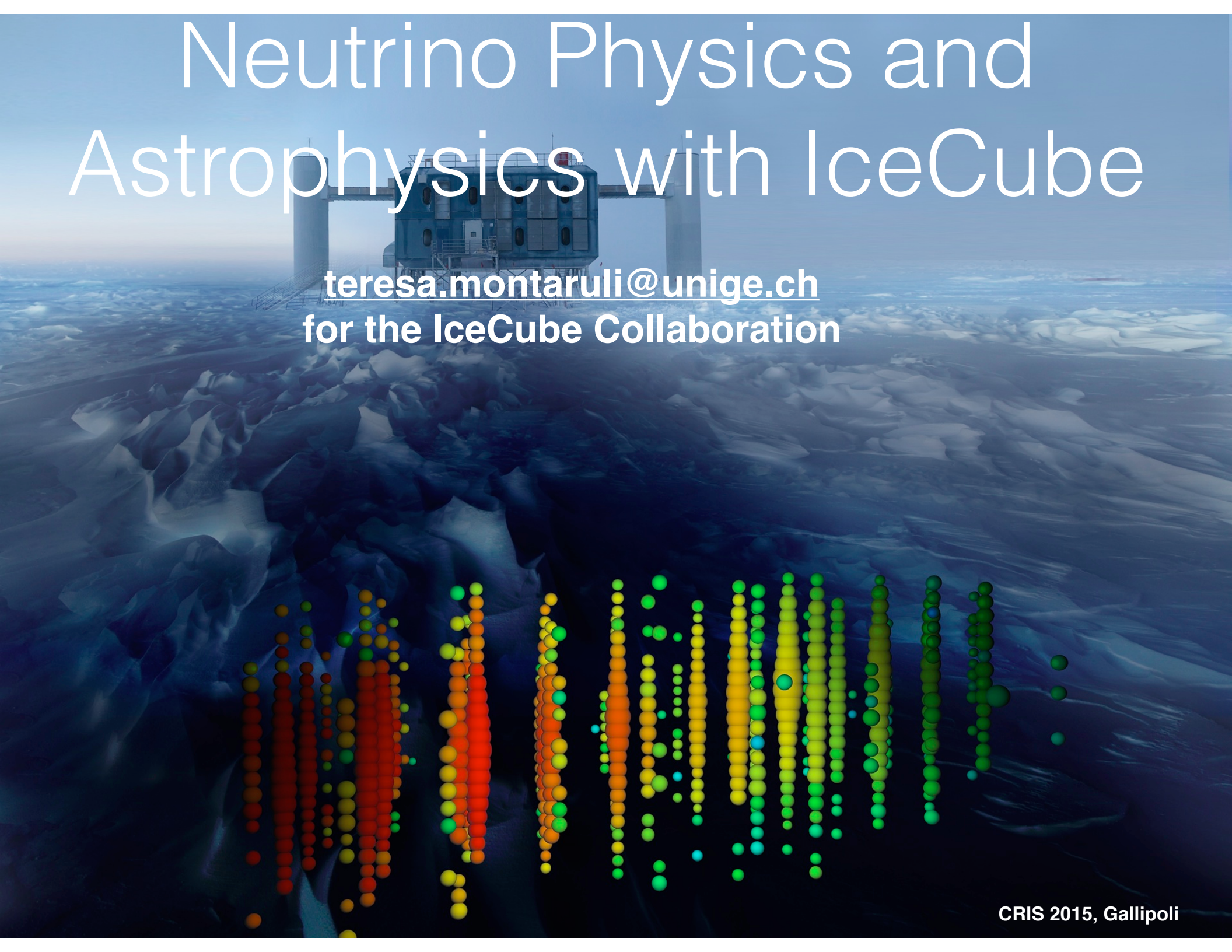
Neutrino Physics and Astrophysics with IceCube

teresa.montaruli@unige.ch
for the IceCube Collaboration

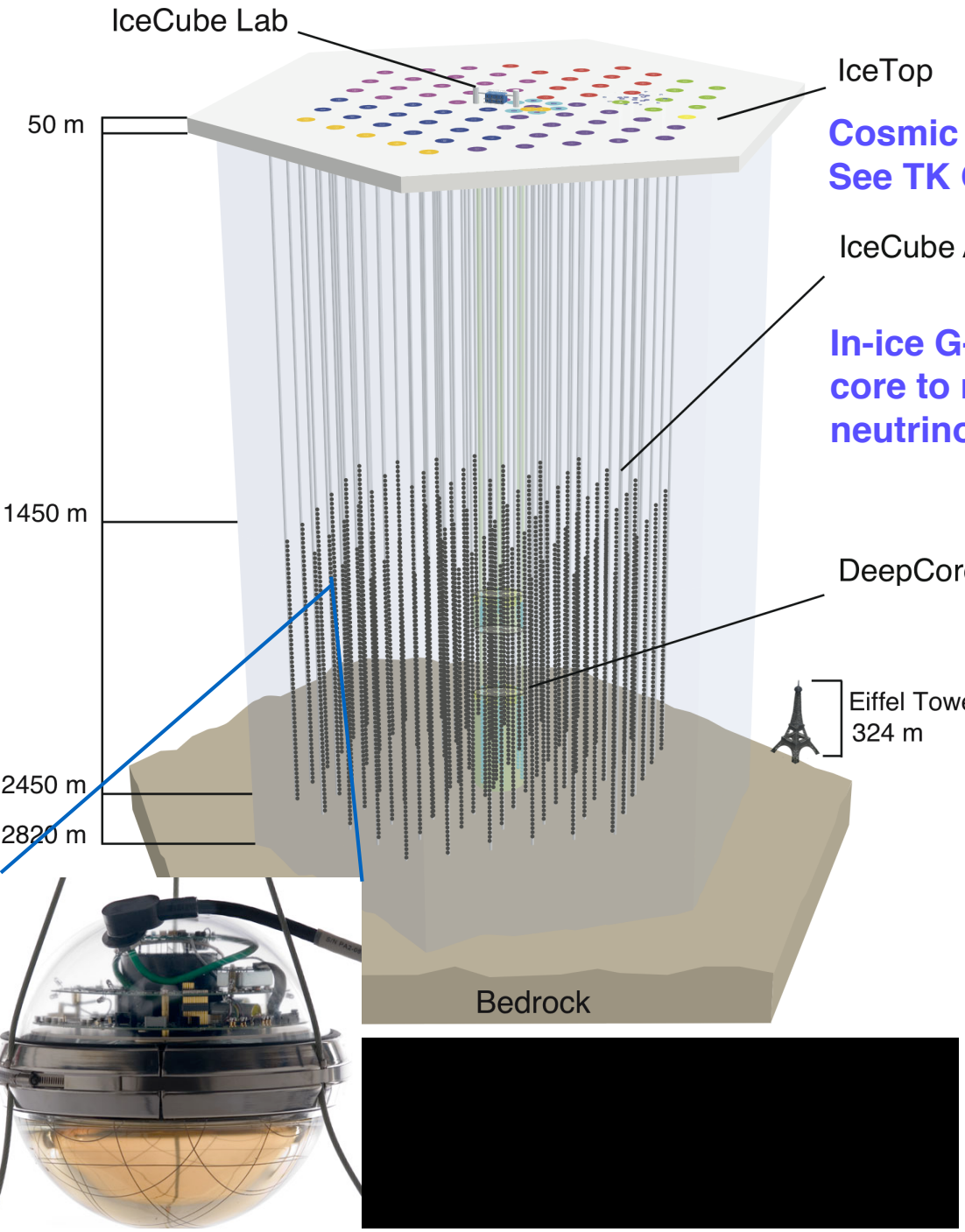


CRIS 2015, Gallipoli

The IceCube-PINGU Collaboration

Collaboration of about 300 members at 45 international institutions

IceCube Detector



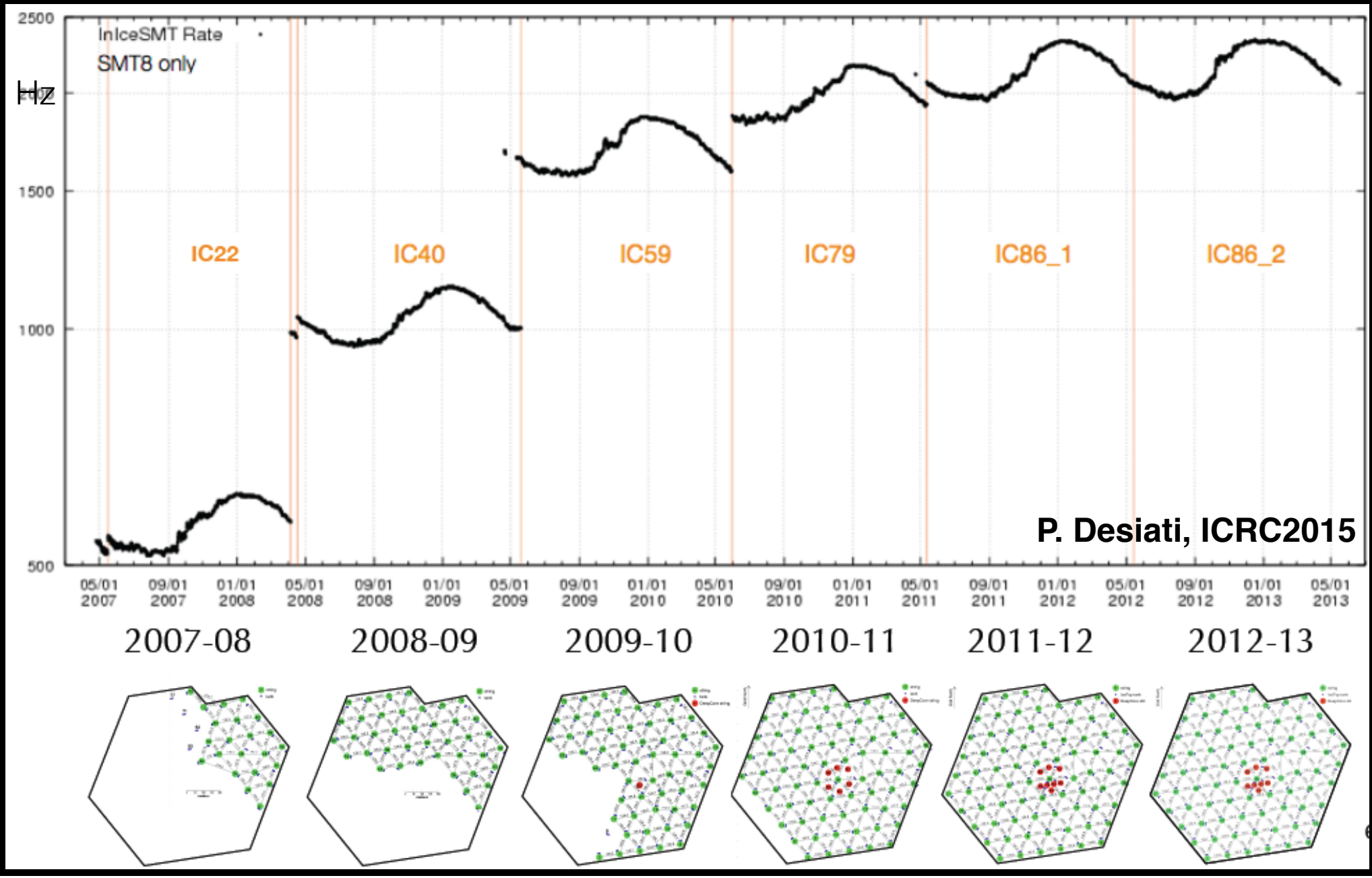
Cosmic ray surface detector and veto
See TK Gaisser talk

In-ice G-ton neutrino detector with inner core to reach down to about 10 GeV neutrinos

- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase
  (2004-2011)

The IceCube seasons

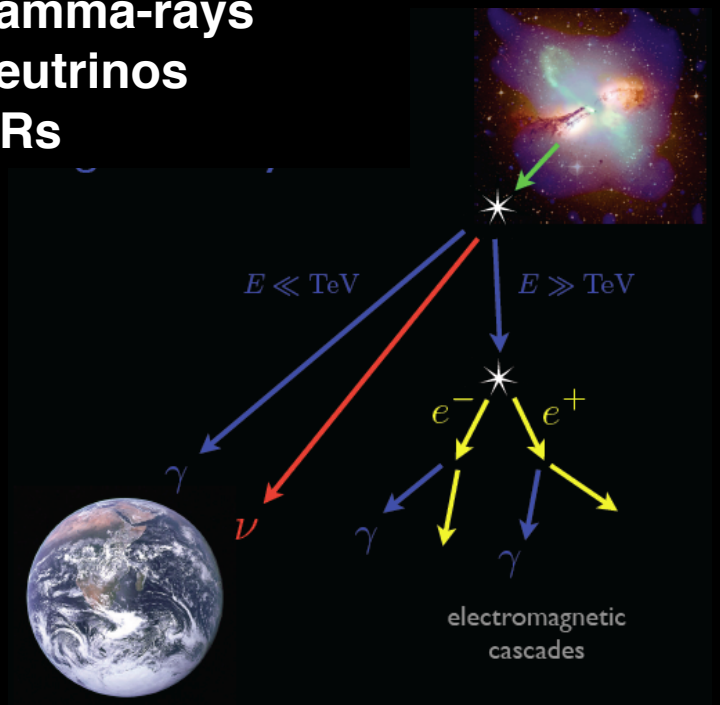
Now, 5th yr of full detector stable operation since May 2011



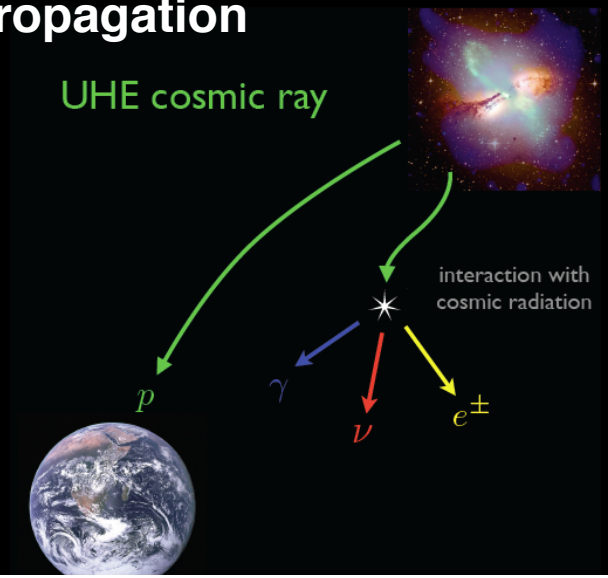
Multi-messengers

Products of cosmic accelerators

gamma-rays
neutrinos
CRs



Products of interactions during propagation



$p + \gamma \rightarrow \pi^0 + p$
or p...
$\gamma + \gamma + p$
$\rightarrow \pi^+ + n$
$\rightarrow \mu^+ + \nu_\mu + n$
$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$

Neutrinos

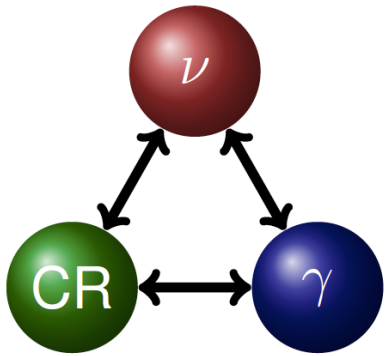
Photons

UHECRs

Neutrino

10^9 10^{12} 10^{15} 10^{18} 10^{21}

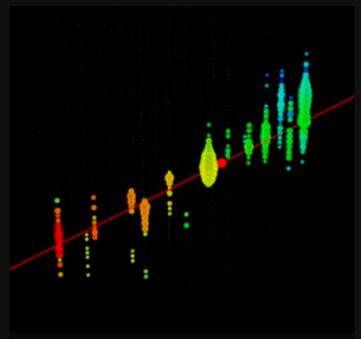
Energy (eV)



1 PeV neutrinos correspond to
20 PeV CR nucleons and
2 PeV γ-rays

Neutrino events

CC Muon Neutrino

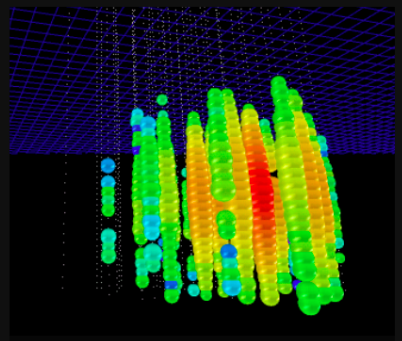


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current /Electron Neutrino



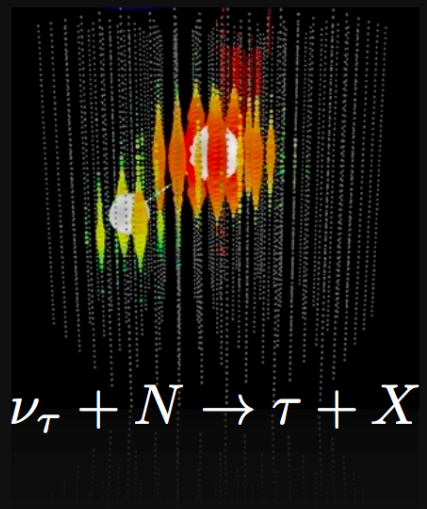
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

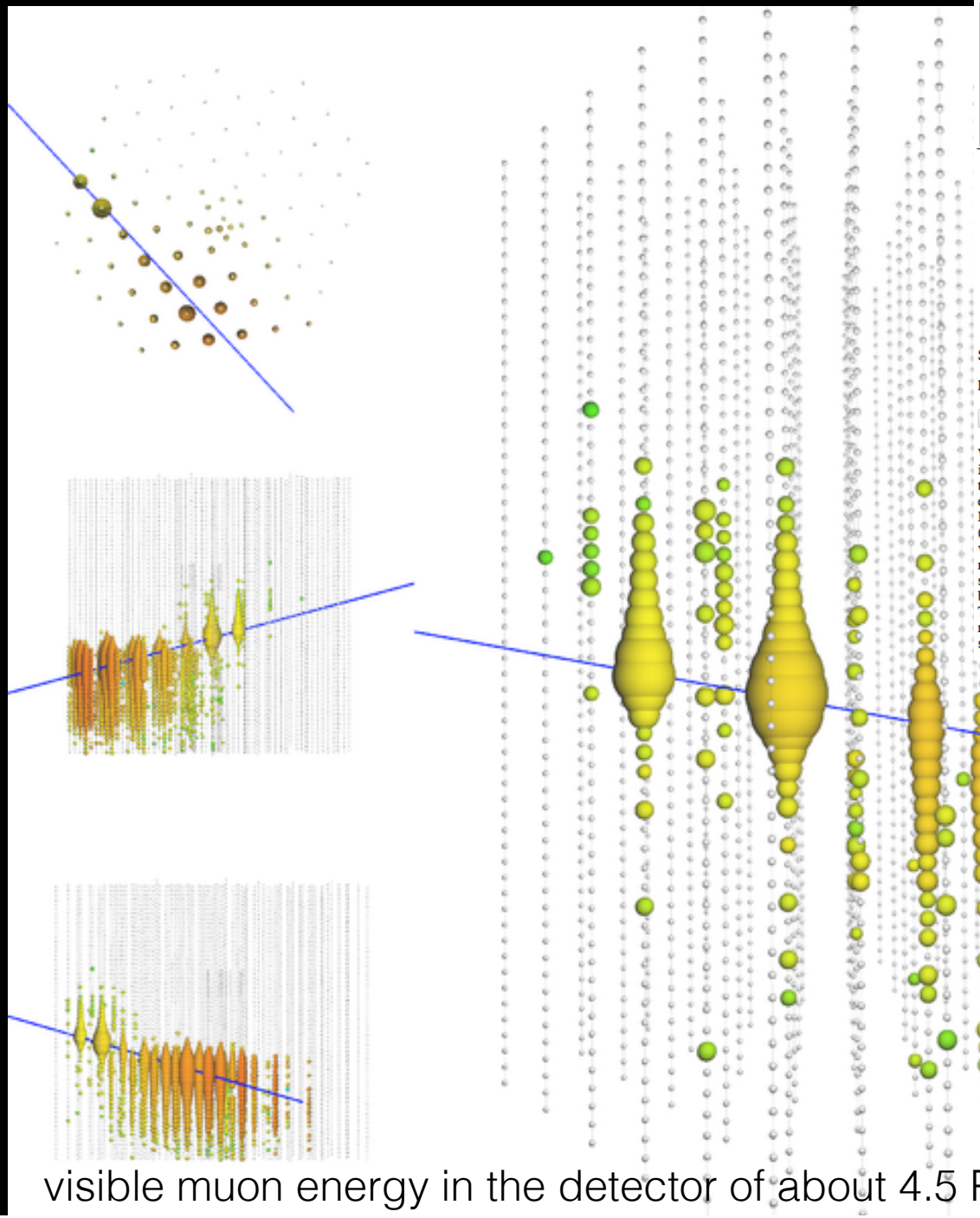


$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

(not observed yet)

Multi-PeV neutrino events



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28 Aug 2015; 13:40 UT

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Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
on 29 Jul 2015; 20:47 UT
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

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Related
7868 HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event
7856 Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

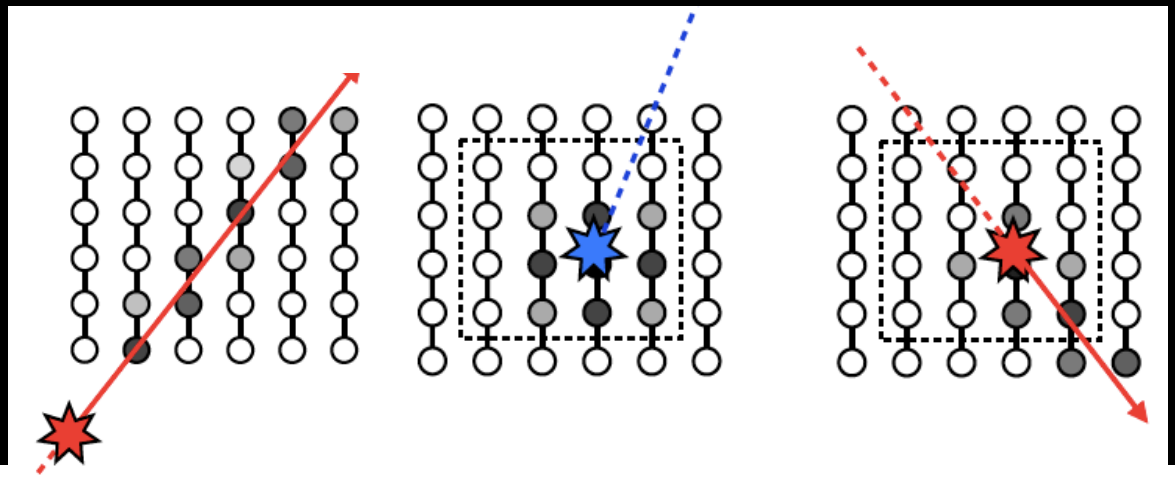
Followed up by HAWC

We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)

visible muon energy in the detector of about 4.5 PeV

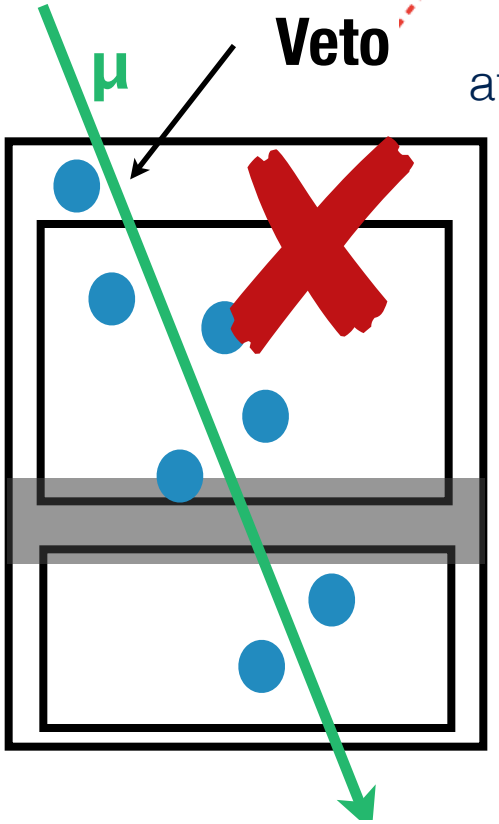
Neutrino selection & background rejection

Upgoing thoroughgoing neutrino induced muons - Earth is a filter - or vertex identification of 'starting events' (tracks and cascades)



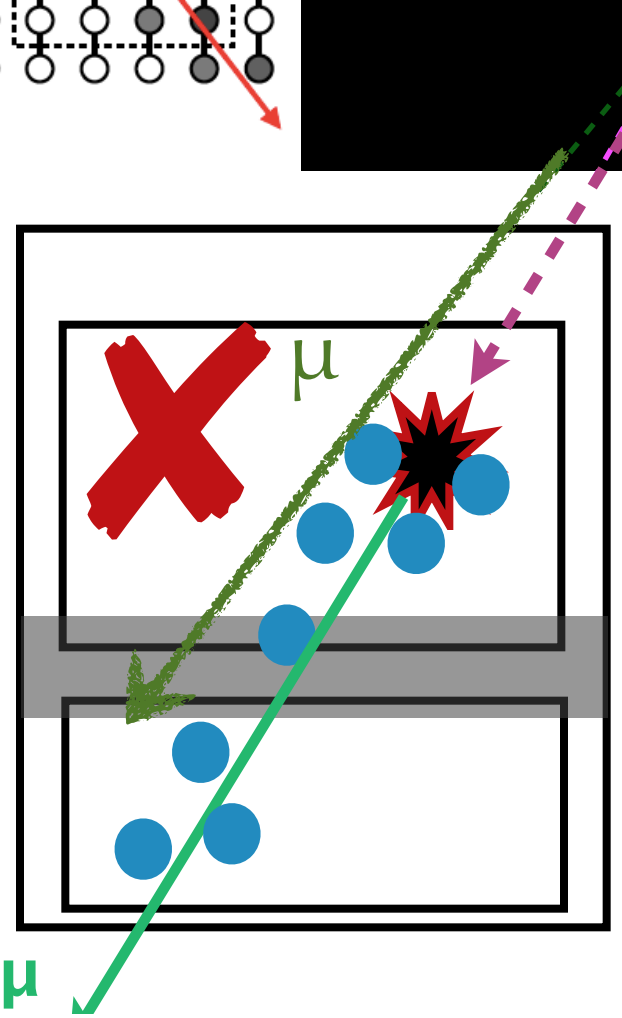
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

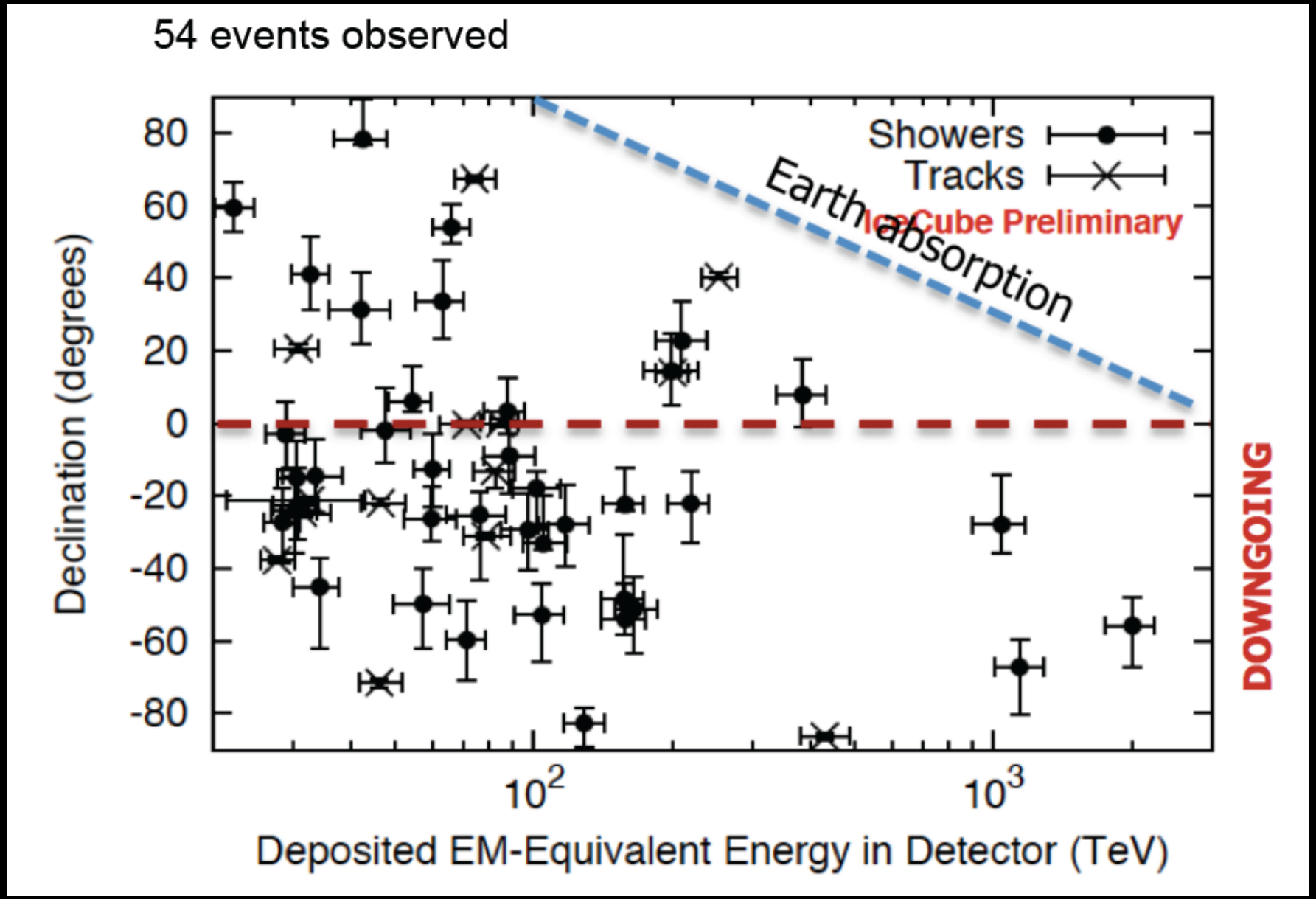


atmospheric muon tag

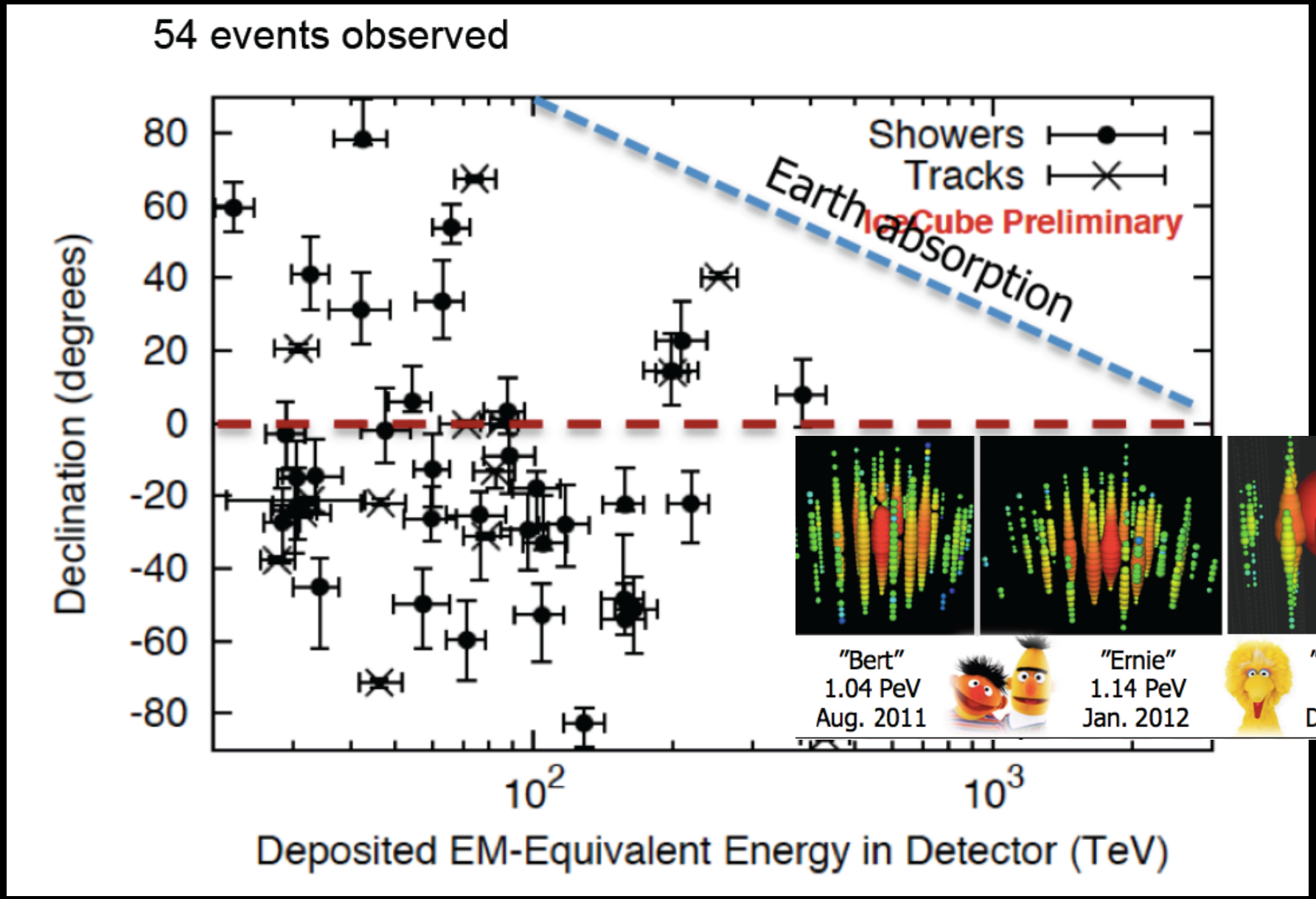
atmospheric neutrino tag



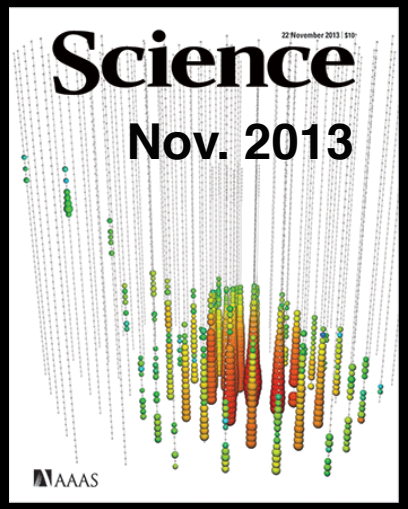
High Energy Starting Events (4 yr)



High Energy Starting Events (4 yr)

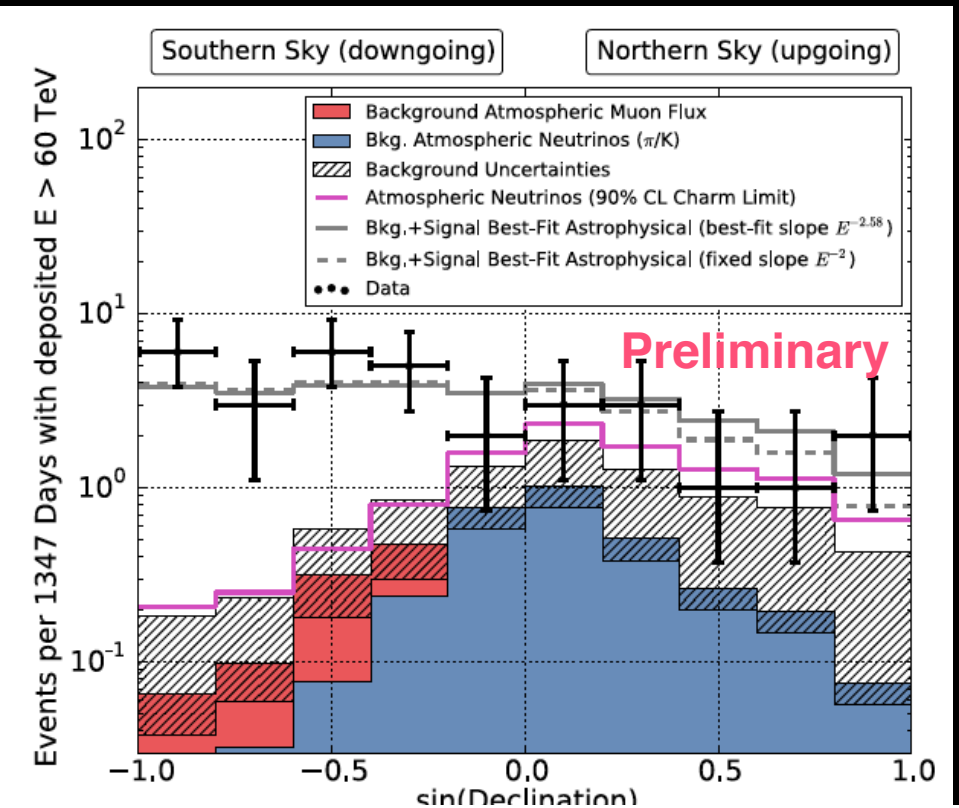


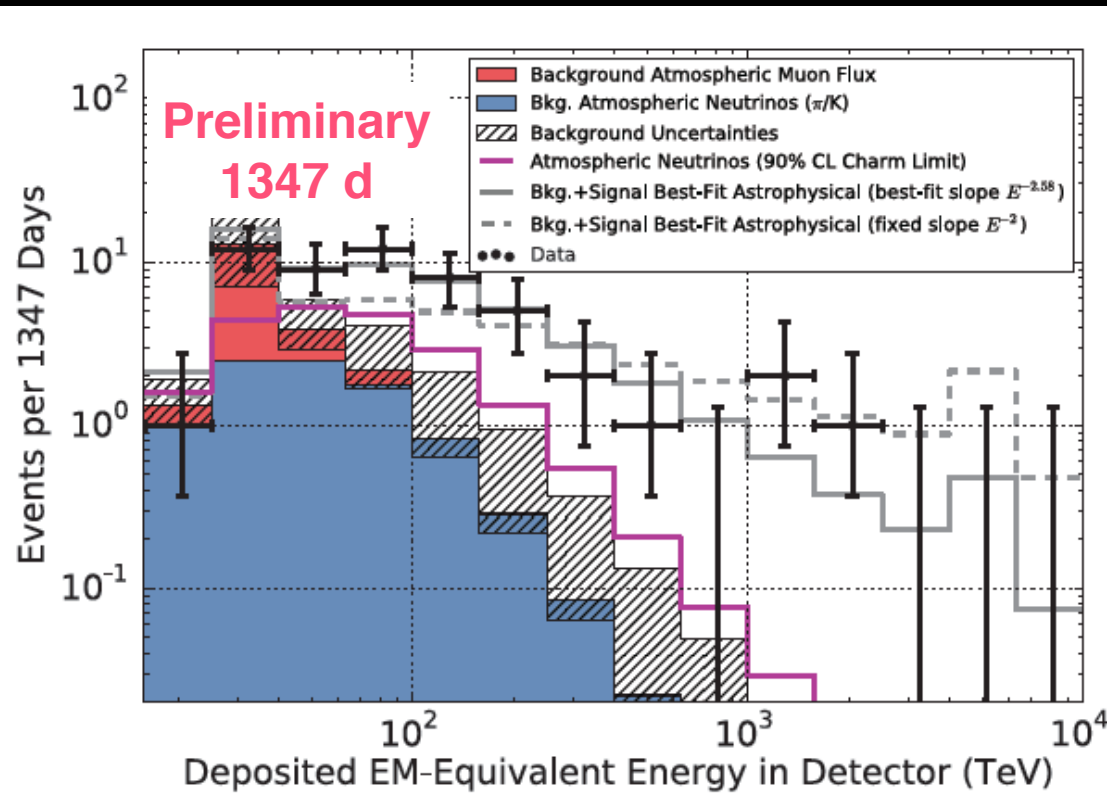
4 yr (2010-14) of HESE



Anti-coincidence veto + >6000 p.e. (>30 TeV)
54 events (17+events in PRL 113 (2014) 101101).
2 are evident background events.
Background:
Measured: 12.6 ± 5.1 atmospheric muon events
Atmospheric prompt component estimated using a previously set limit on atmospheric neutrinos with 59 strings: $9.0^{+8.0}_{-2.2}$

Kopper, Giang, Kurahashi, ICRC 2015, POS 1081, PRL 113 (2014) 101101





Neutrino diffuse astrophysical flux

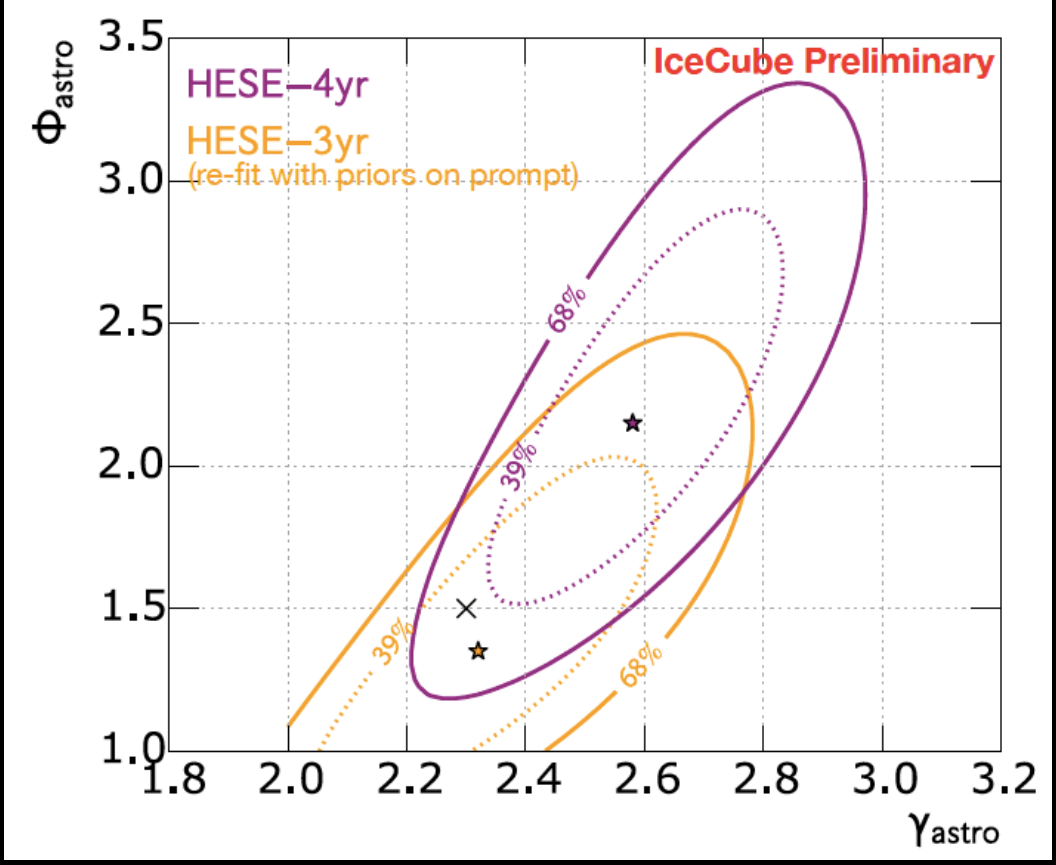
Likelihood fit of all components between 60 TeV-3PeV (atmospheric muons, atmospheric neutrinos from π/K decay, atmospheric neutrinos from charm decay and an astrophysical flux assuming a 1:1:1 flavor ratio).

Rejection of purely atmospheric component at **6.5σ significance**.

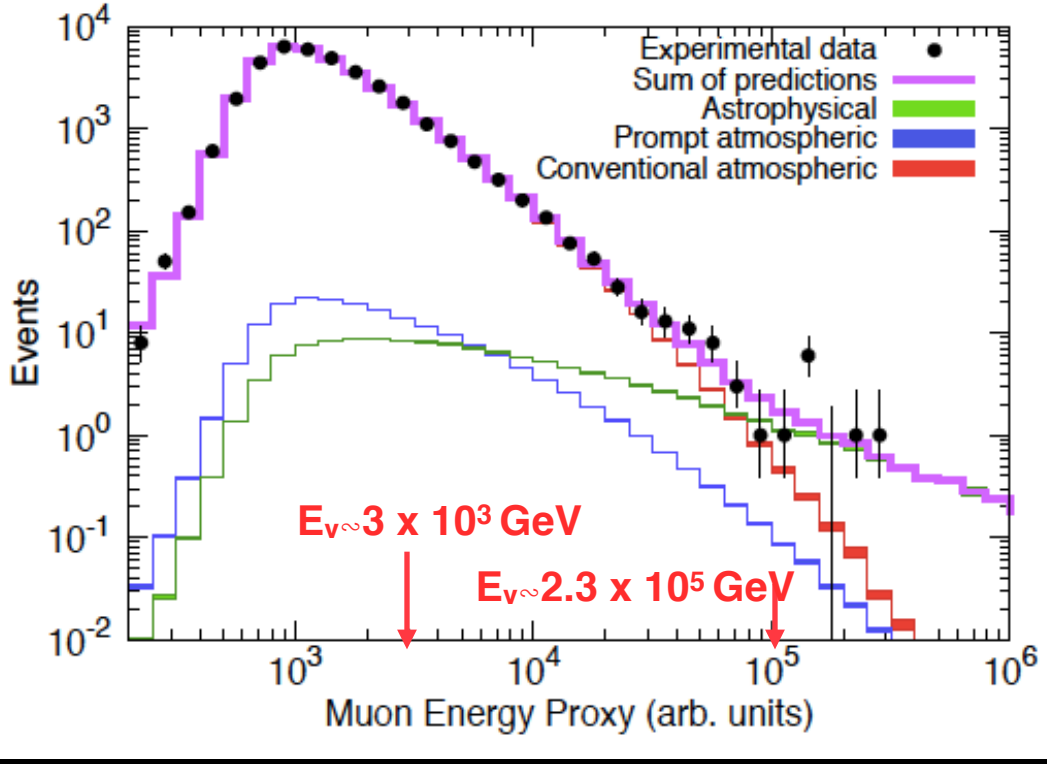
For E^{-2} the normalization is:

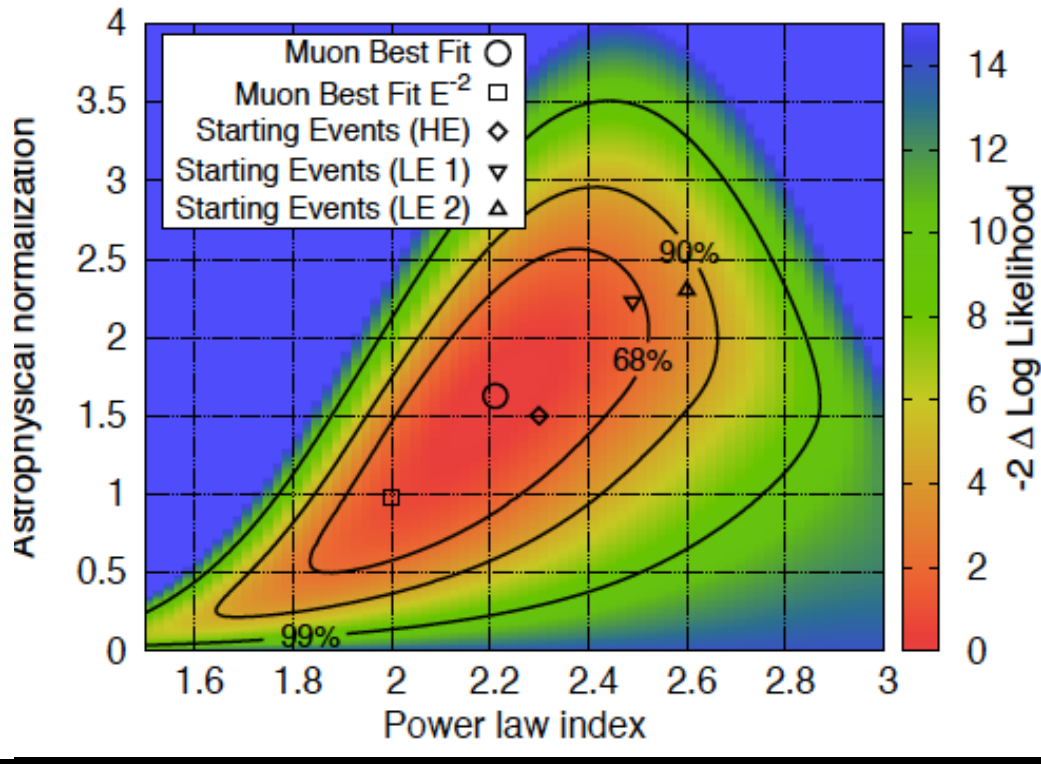
$$E^2 \phi(E) = \mathbf{0.84 \pm 0.3} \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Best fit astrophysical spectral index: -2.58 ± 0.25 (2.3 ± 0.3 for 3 yr)



Diffuse ν_μ induced upgoing events





659.5 yr (May 2010-May 2012)

PRL 115 (2015) 081102

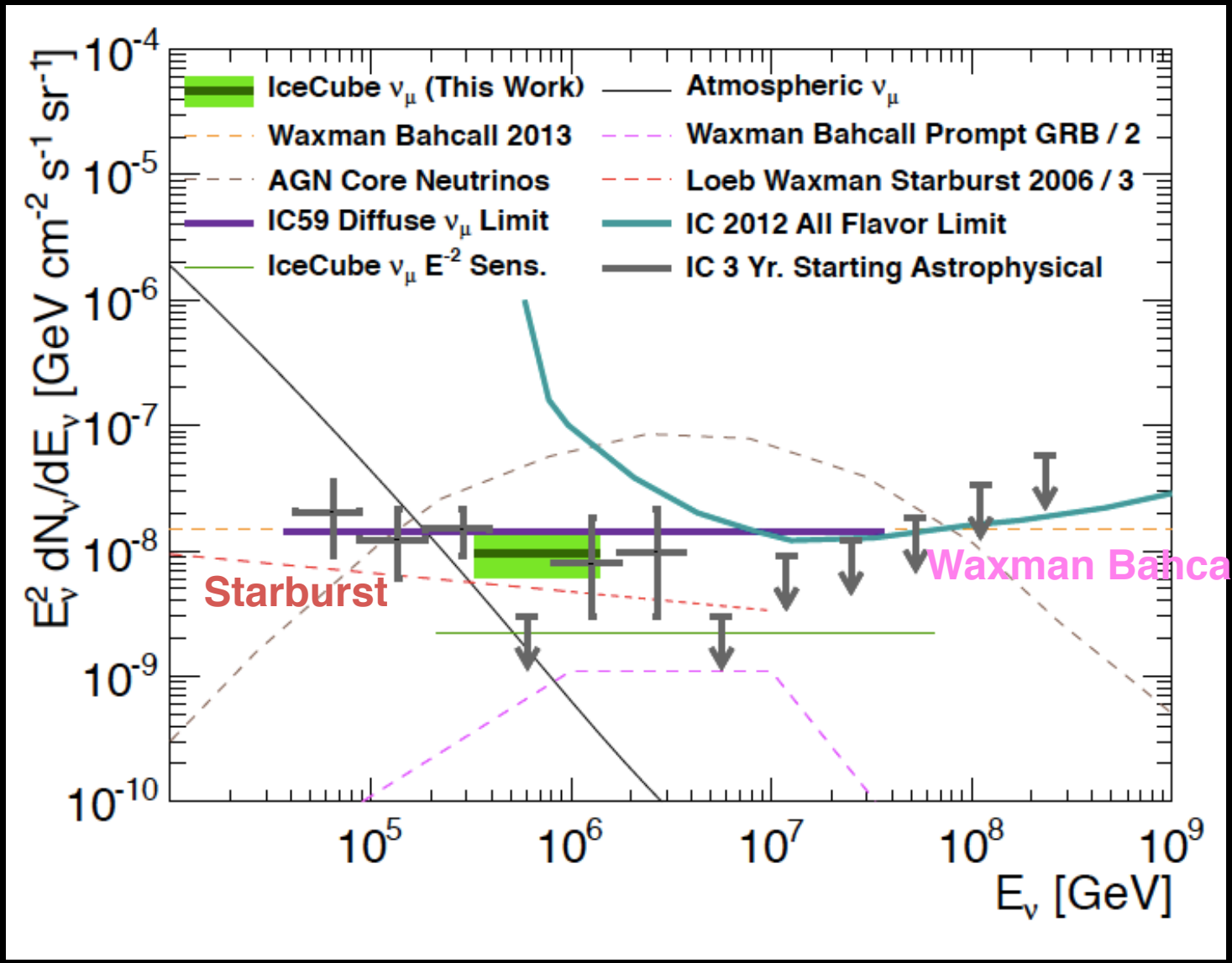
The highest energy events are inconsistent with a hypothesis of solely terrestrial origin at 3.7σ significance and can be explained by an astrophysical flux (consistent with HESE):

$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-2}$$

Best fit spectral index: 2.2 ± 0.2.

The result is compatible with HESE, and all flavor samples with energies 1TeV-1PeV (LE1- (PRD91(2015) 022001) and > 35 TeV (LE2 - PRL 114(2015)171102)

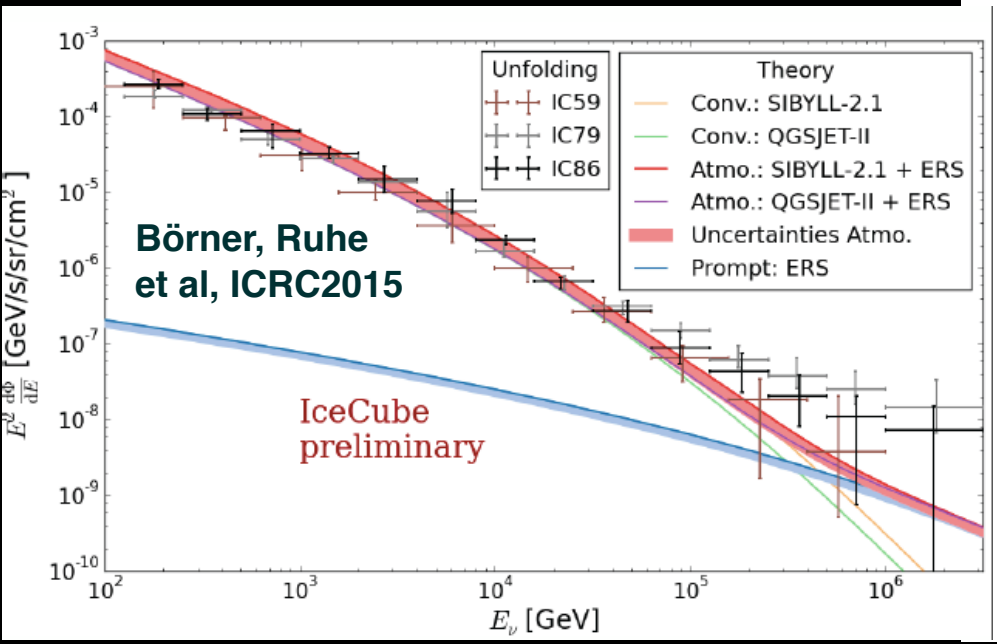
HESE-Diffuse ν_μ events

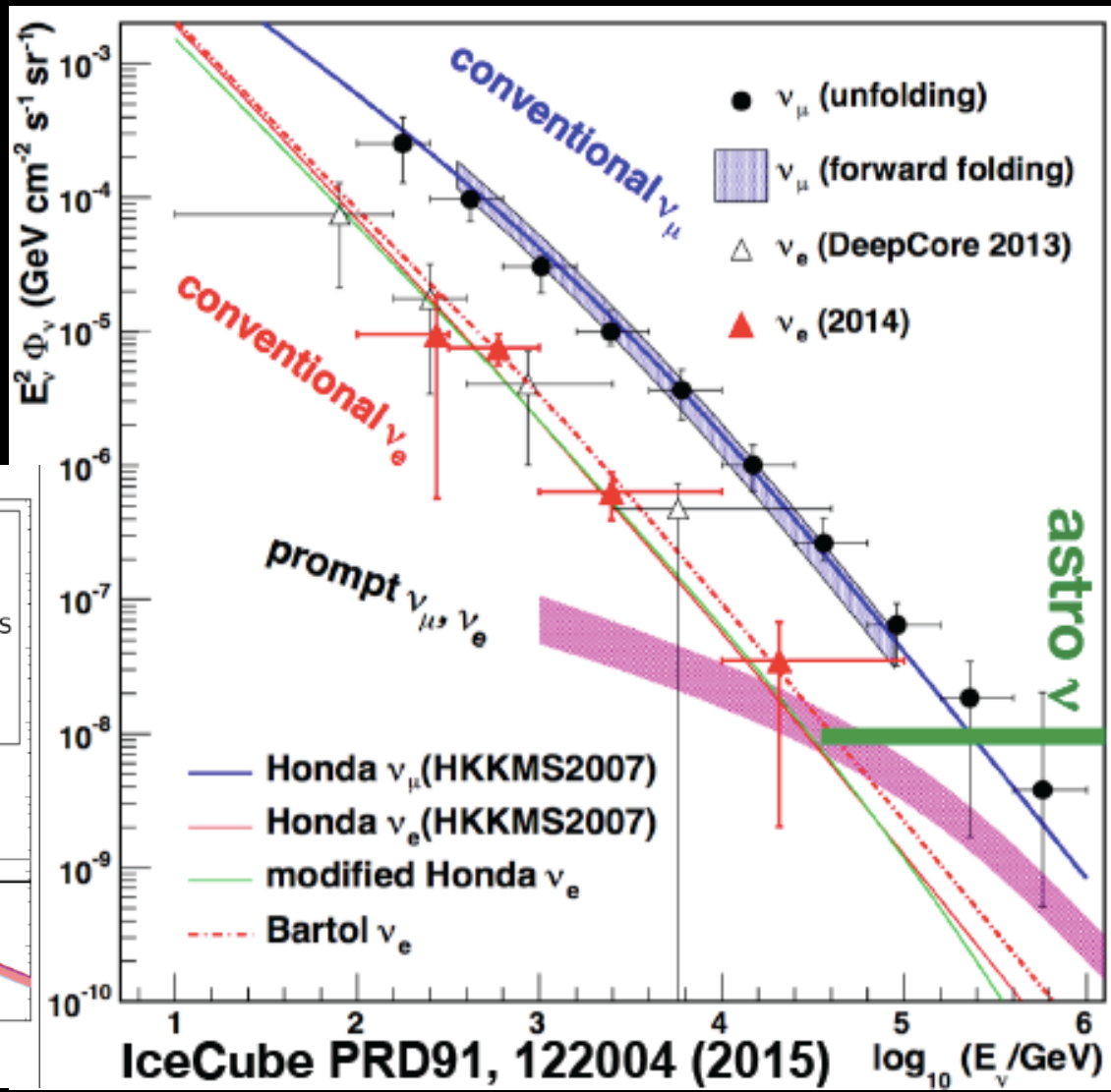


Atmospheric neutrino measurement

More statistic is needed to:

- Where is the transition between the astrophysics and neutrino prompt component;
- understand the prompt component reaching higher energies in the electron neutrino diffuse flux measurement as well as with muons.





2013: Phys. Rev. Lett. 110, 151105

Global fit of IceCube analyses

8 samples from different searches from 2008 to 2014 are fit at TeV-PeV energies in 3 observables between : energy, zenith angle and event topology; assume isotropic astrophysical flux with equal flavors at Earth.

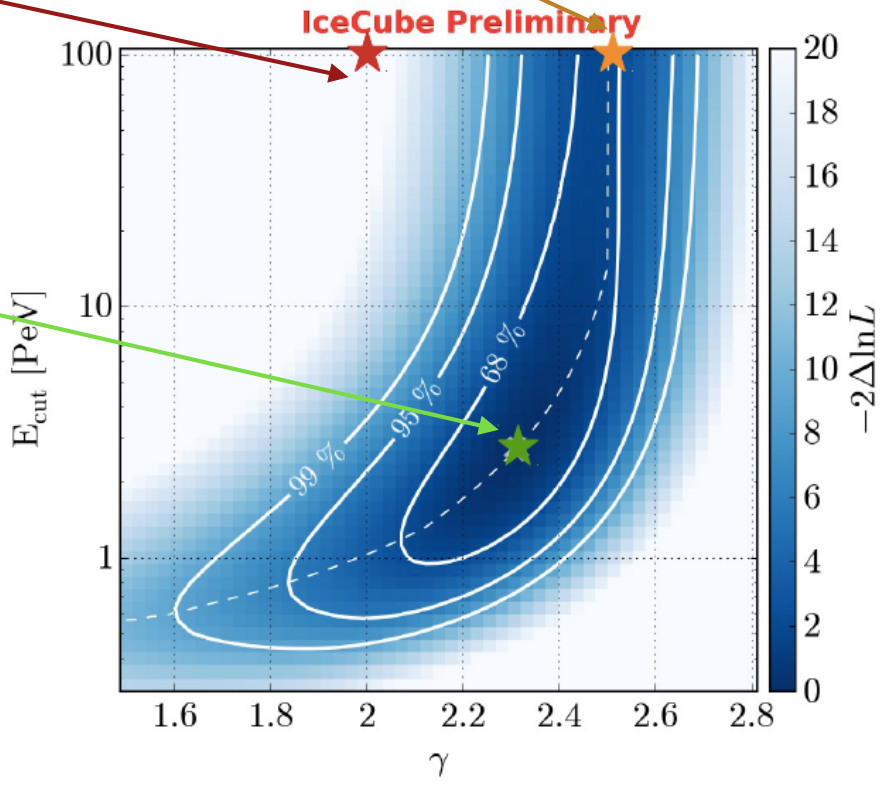
> **Best fit hypothesis A: unbroken spectrum**

- $\Phi_\nu = (7.0^{+1.0}_{-1.0}) \times 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.49\pm0.08}$ (all-flavor!)
- E^{-2} excluded at $4.6\,\sigma$

> **Best fit hypothesis B: with cut-off**

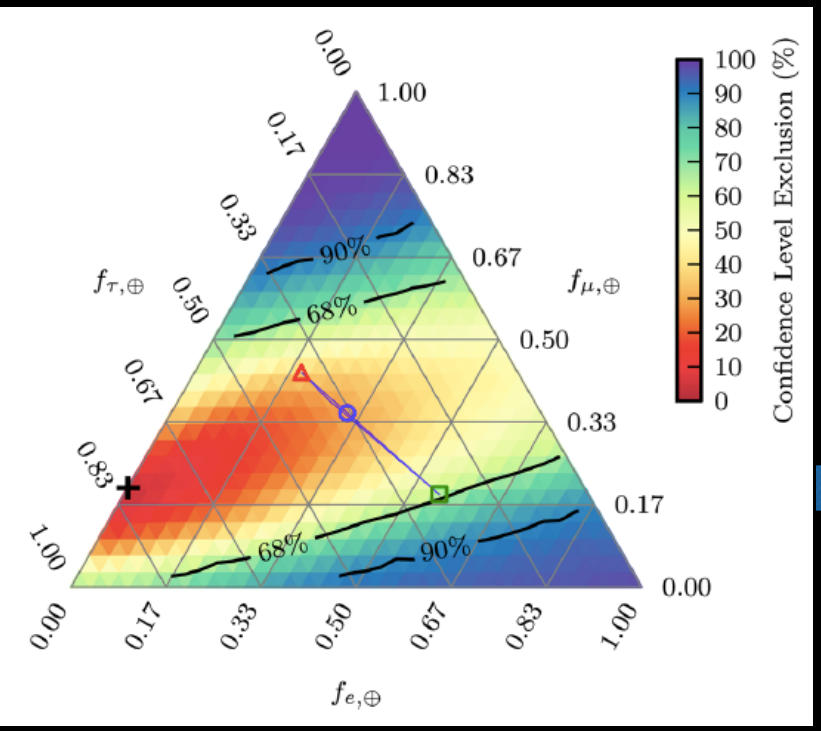
- $\Phi_\nu = (8.0^{+1.3}_{-1.2}) \times 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.31\pm0.15} \times \exp\left(-E/(2.7^{+7.7}_{-1.4})\,\mathrm{PeV}\right)$. (all-flavor!)
- preferred over hypothesis A by $1.2\,\sigma$

L. Mohrmann et al, ICRC2015 and arXiv:1507.03991



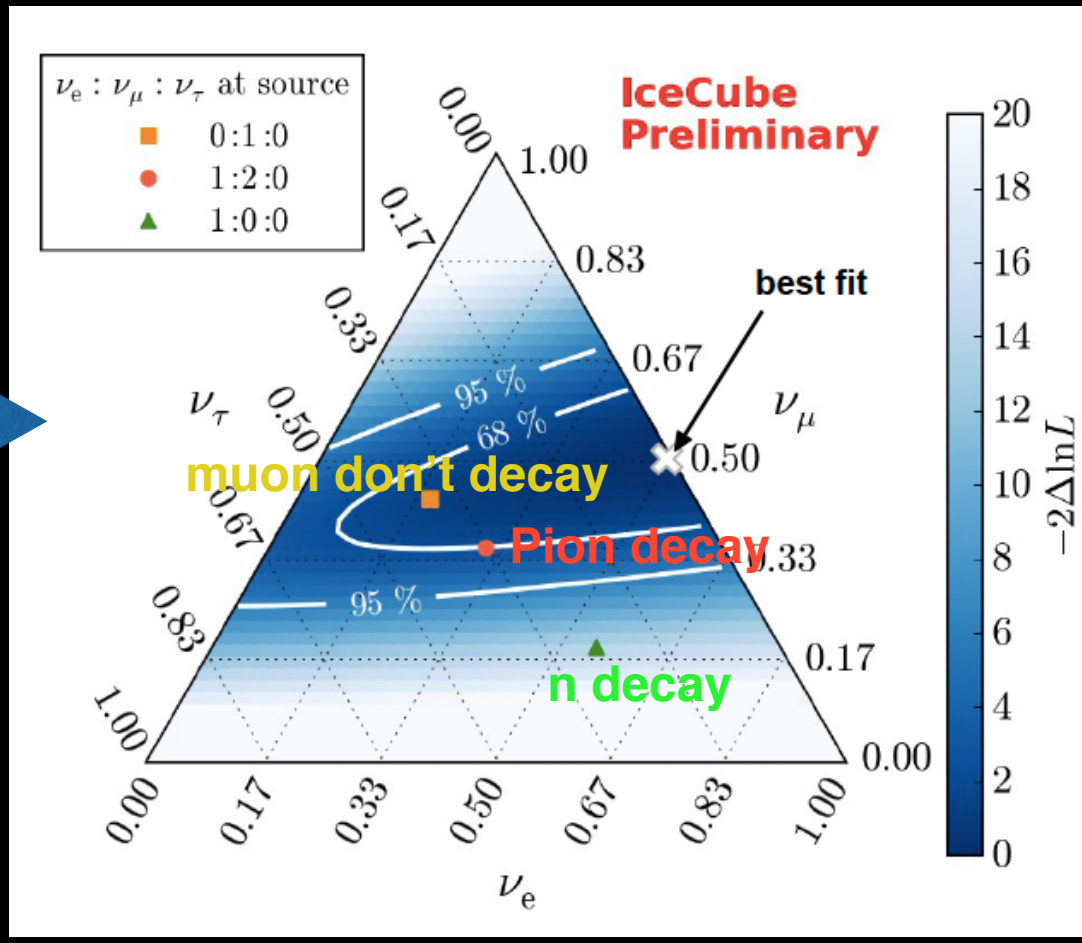
Digging in the flavor

So far, observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors.



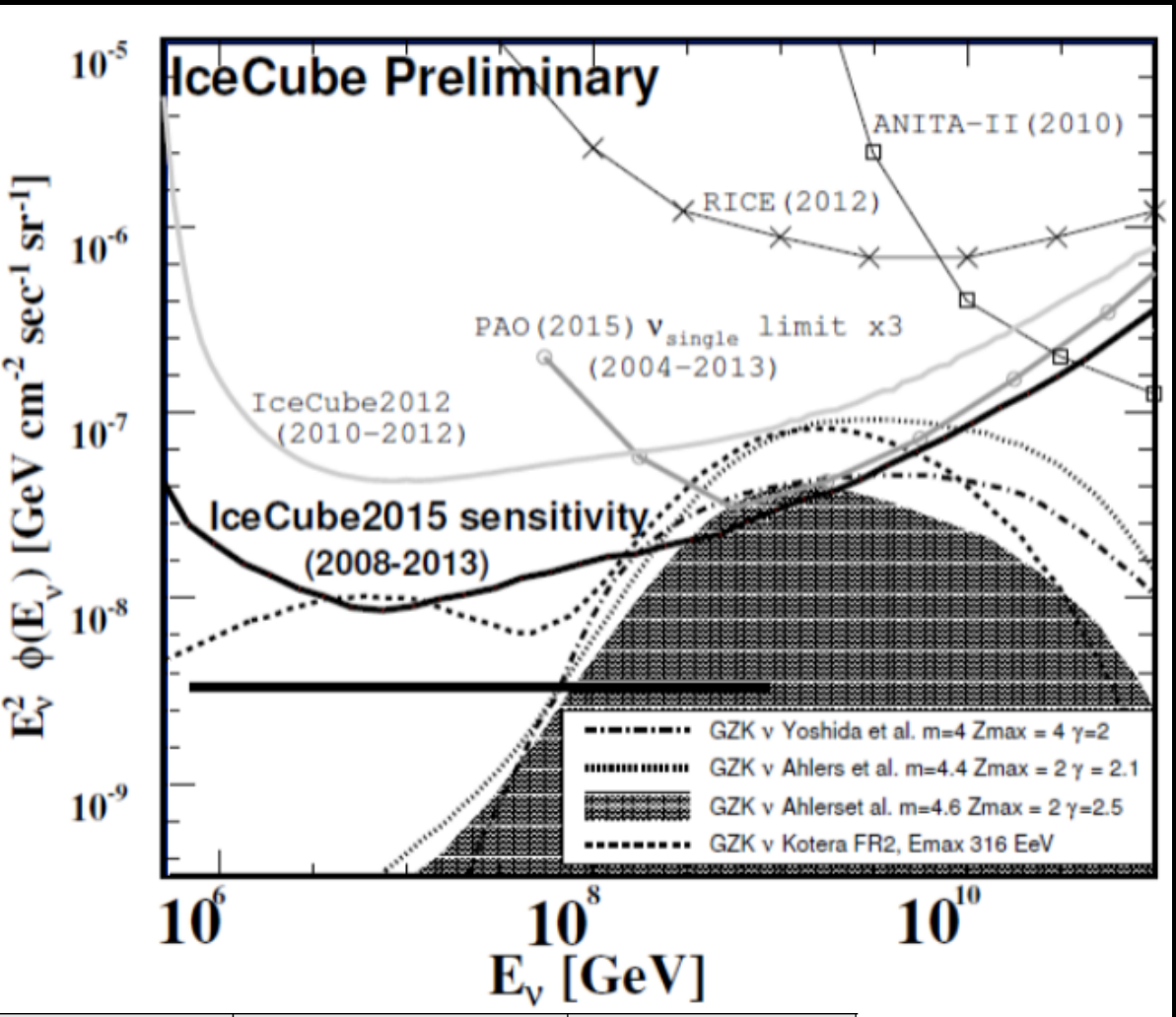
PRL 114(2015)171102

Using hypothesis B with cut-off: compatible with pion decay at the source (tricky diagram which can be read on 2 sides…)

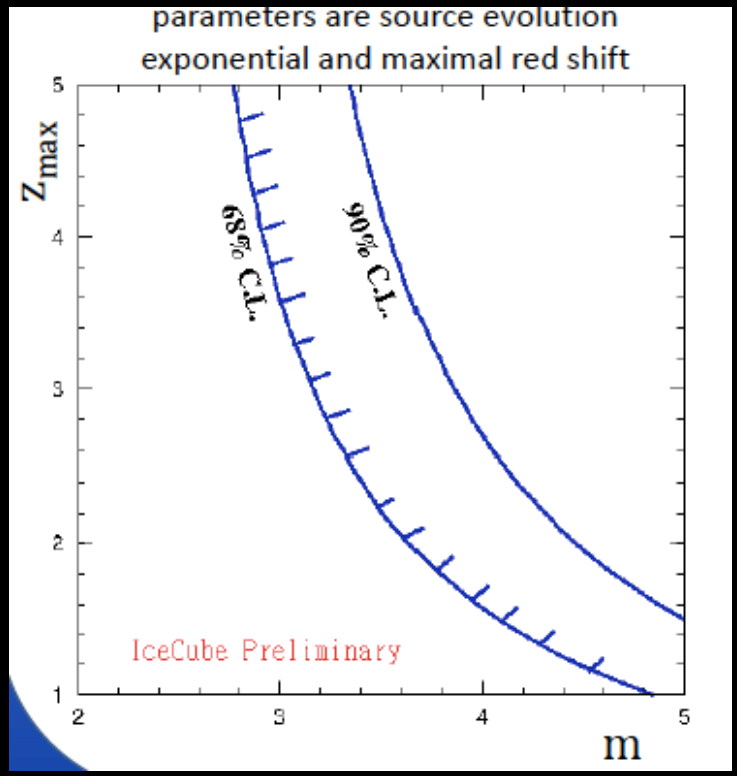


L. Mohrmann et al, ICRC2015 and arXiv:1507.03991

Diffuse cosmic neutrino fluxes



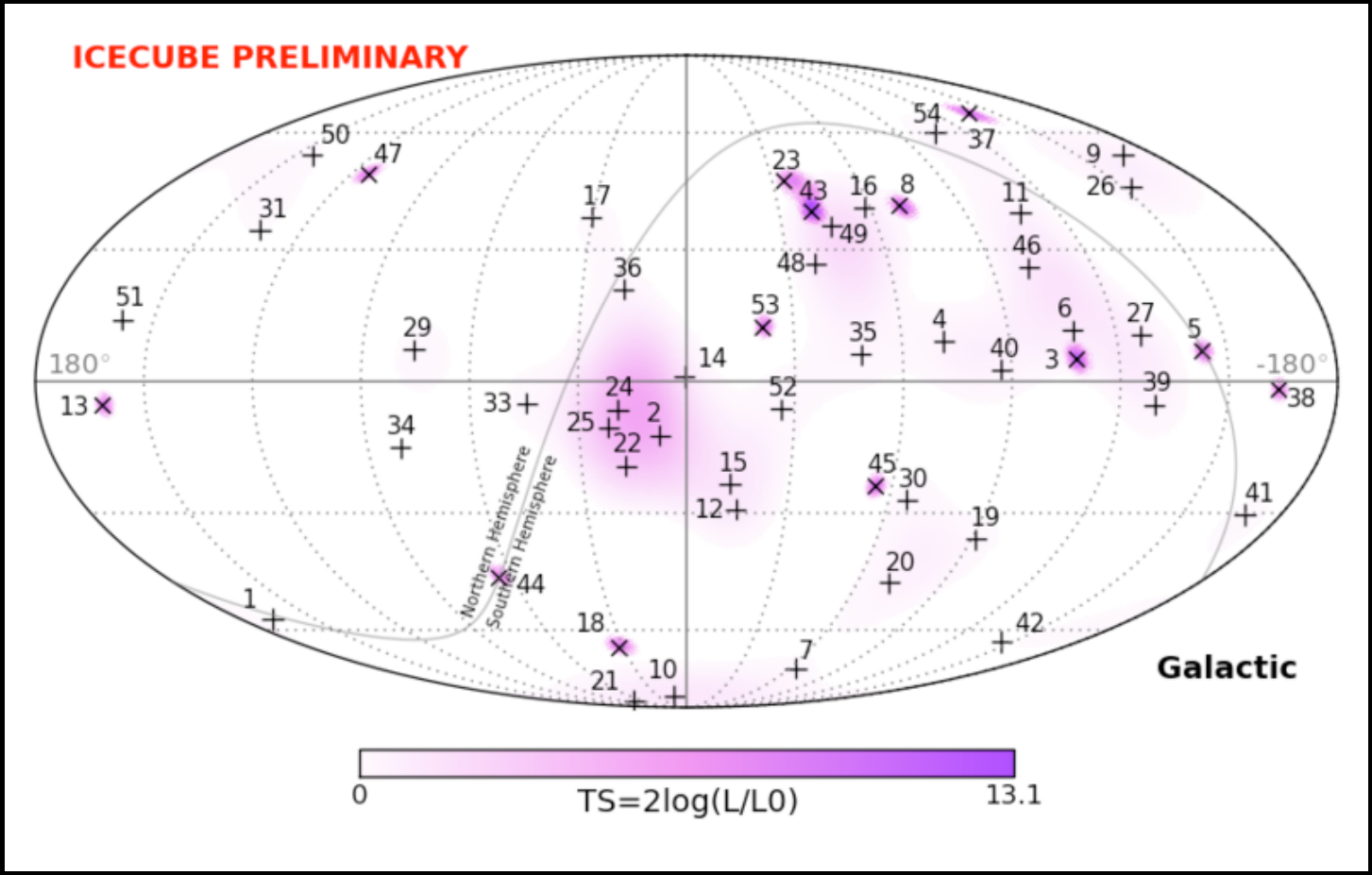
Aloisio et al: arXiv:1505.04020 IceCube and Pierre Auger limits on PeV to EeV neutrinos constrain models with strong evolution m>3.5 (such as for AGNs)



Cosmogenic n models	Model parameters				Event rates in IceCube 2008-2013
	m	z_{max}	γ	E_{max}(eV)	
Ahers-Max [2]	4.4	2	2.1	10^{21}	7.8 ± 0.1
Ahers-Best [2]	4.6	2	2.5	10^{21}	3.9 ± 0.1
Yoshida-(4,4) [3]	4	4	2.0	10^{22}	5.1 ± 0.1
Yoshida-(2,4) [3]	2	4	2.0	10^{22}	0.8 ± 0.1
Kotera-GRB [4]	GRB	GRB	2.0	3×10^{20}	2.0 ± 0.1
Kotera-SFR [4]	SFR	SFR	2.0	3×10^{20}	2.6 ± 0.1

A. Ishihara et al, ICRC2015, updates at TAUP

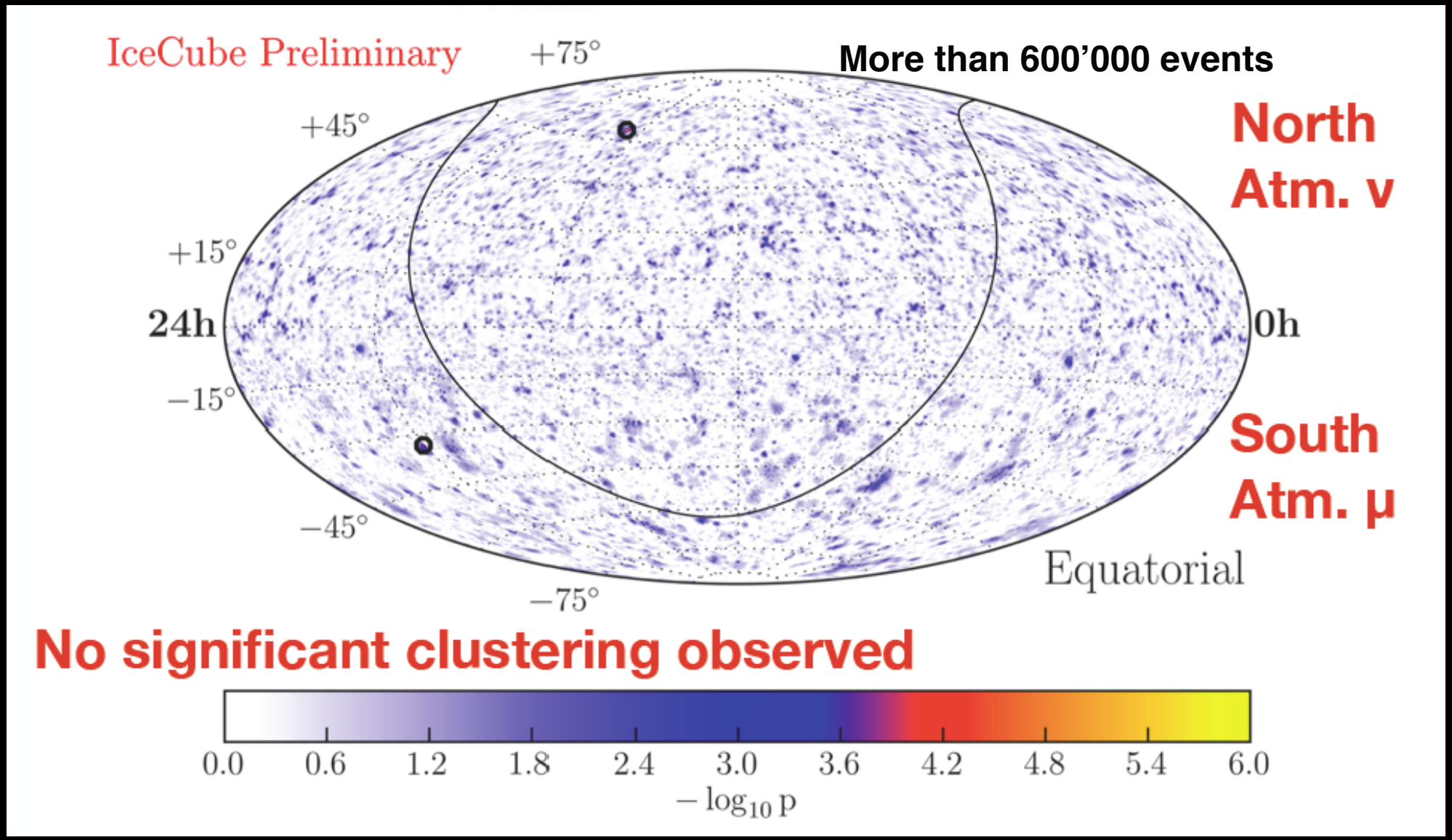
Clustering tests



Clustering of events has been tested and did not yield significant evidence with post trial p-values of 44% and 58% for the shower-only and all-events, respectively.

A galactic plane clustering test using a fixed width of 2.5° around the plane (post trial p-value 7%) and using a variable-width scan (post trial p-value 2.5%).

6 yr (1700 d) of point source searches



S. Coenders, E. Resconi et al, ICRC2015, ApJ 796 (2014) 109

UHECR-neutrinos

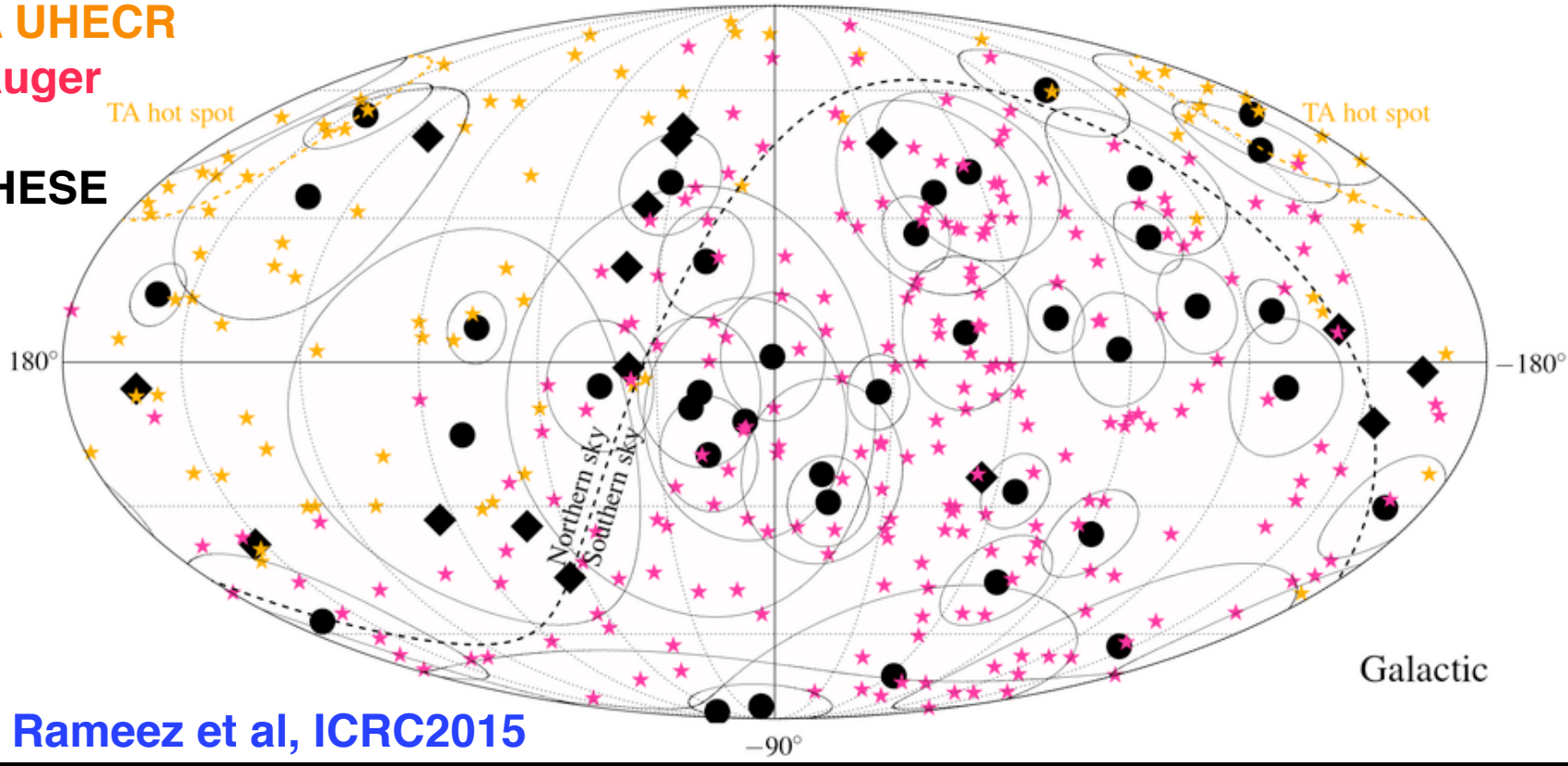
231 events (E>52 EeV, zenith angle <80°, ang. res. ≤0.9°) between 01/01/2004 to 31/03/2014°

87 events (E>57 EeV, zenith angle <55°, ang. res. ≤1.5°) between 11/05/2008 to 01/05/2014°

The Pierre Auger Collaboration, Astrophys. J. 804 (2015) 1 and PoS(ICRC2015)310.
The Telescope Array Collaboration, Astrophys. J. Lett. 790 (2014) L21.

Orange stars: TA UHECR
Magenta stars: Auger

Black symbols: HESE
Blue: diffuse ν_μ - induced tracks



Christov, Golup, Rameez et al, ICRC2015

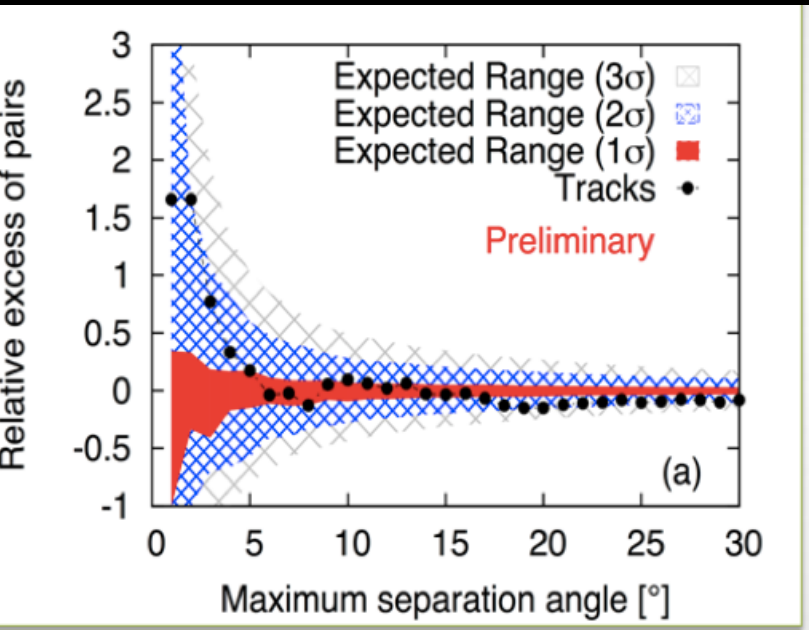
HESE 4 yr (> 30 TeV): 39 cascades (ang. res. ~20°) + 7 tracks (ang. res. ~1°)

ICRC 2015, POS 1081, PRL 113 (2014) 101101

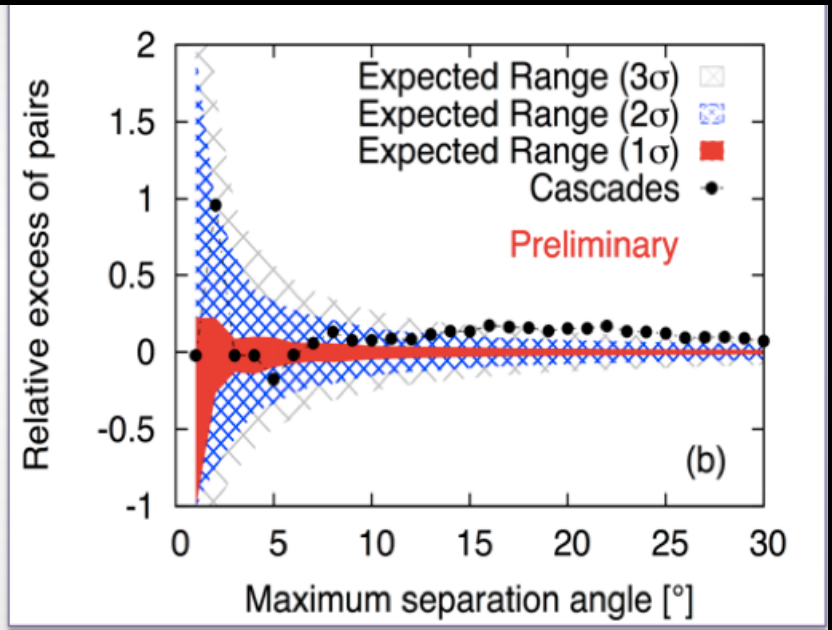
9 ν_μ induced upgoing muons with E> 100 TeV (PRL 115 (2015) 081102)

Cross Correlation and LH stacking

Relative excess of pairs: $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$



Tracks
minimum at 2^0, n_p=4, $\langle n_p^{iso}\rangle$= 1.5,
post-trial p-value=0.34
with respect to an isotropic flux of CRs.



Cascades
minimum at 22^0, n_p=575, $\langle n_p^{iso}\rangle$= 490.3,
post-trial p-value=5 x 10^{-4}
with respect to an isotropic flux of CRs.

Compute the significance of UHECR-neutrino pair angular separation with respect to an isotropic distribution of UHECRs

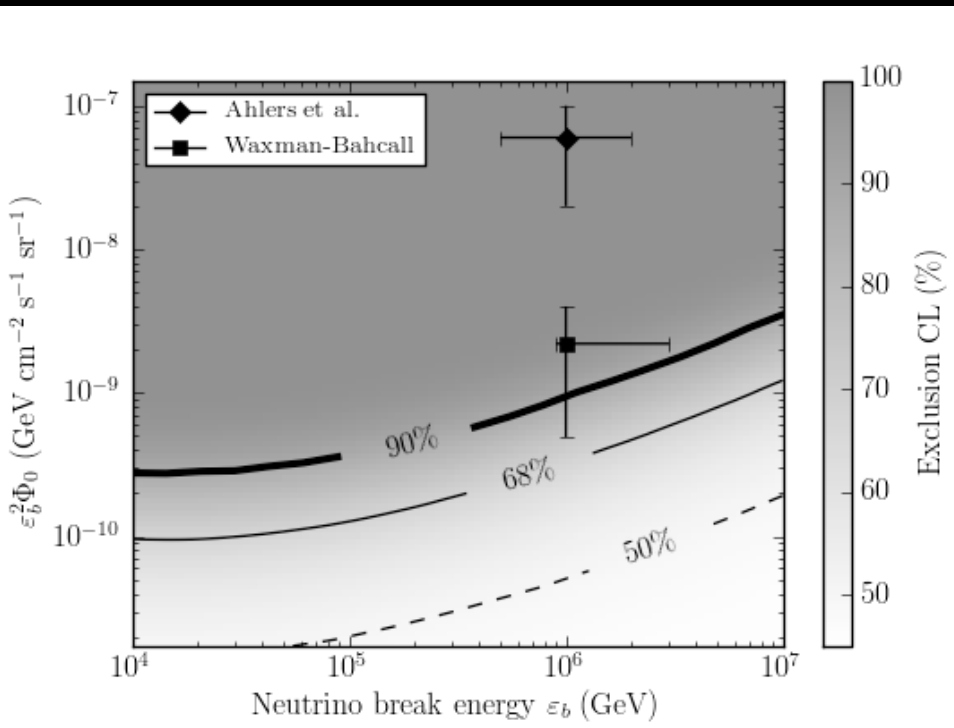
D	Tracks		Cascades	
	n_{sCR}	pre-trial p-value	n_{sCR}	pre-trial p-value
3°	4.3	0.22	53.7	2.1×10^{-3}
6°	0.5	0.48	85.7	2.7×10^{-4}
9°	-	under-fluctuation	106.1	3.8×10^{-4}

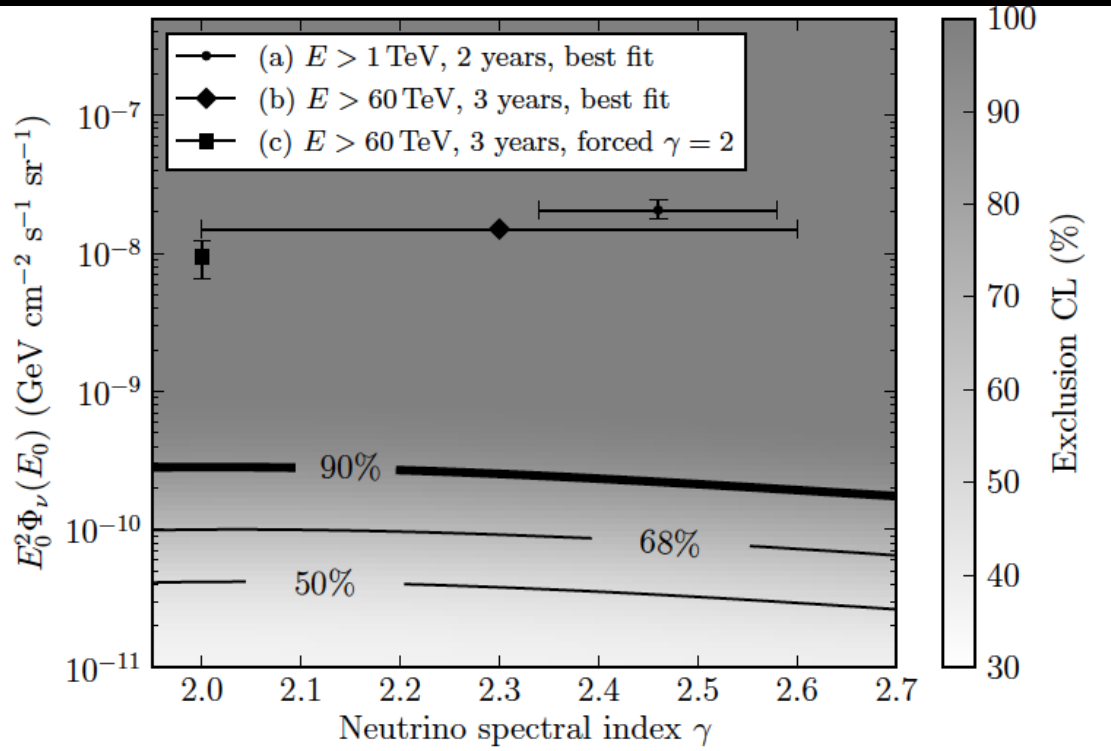
post-trial p-value = 8 x 10^{-4}

Compute the significance with respect to an UHECR isotropic distribution considering the neutrinos as the UHECR 'stacked' sources

Gamma-ray bursts

Stringent limits on both CR-normalized and burst-physics-normalized models (Ahlers et al, 2011 - n escape; WB 1997, Katz et al 2009 - p escape).



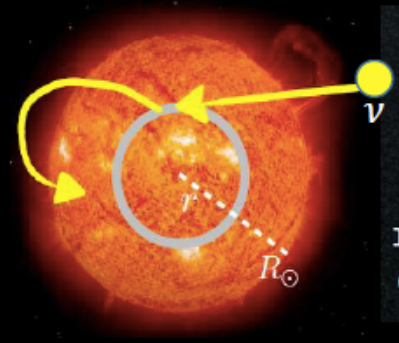


If the observed astrophysical signal in HESE and TeV all flavor starting events analysis is parametrized as a power law, the possible contribution to the observed quasi-diffuse nu flux would be only ~1%.

M. Richman et al.
M. G. Aartsen et al., ApJ 805 (2015) L5

3yrs of WIMP search from the Sun

WIMP Capture and Annihilation in the Sun



$$\Gamma_{\text{capt}} = \frac{\rho_{\text{DM}}}{M_{\text{DM}}} \sum_i \sigma_i \int_0^{R_\odot} dr\, 4\pi r^2\, n_i(r) \int_0^{\infty} dv\, 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot\text{esc}}^2}{v} \varphi_i(v, v_{\odot\text{esc}})$$

DM number density

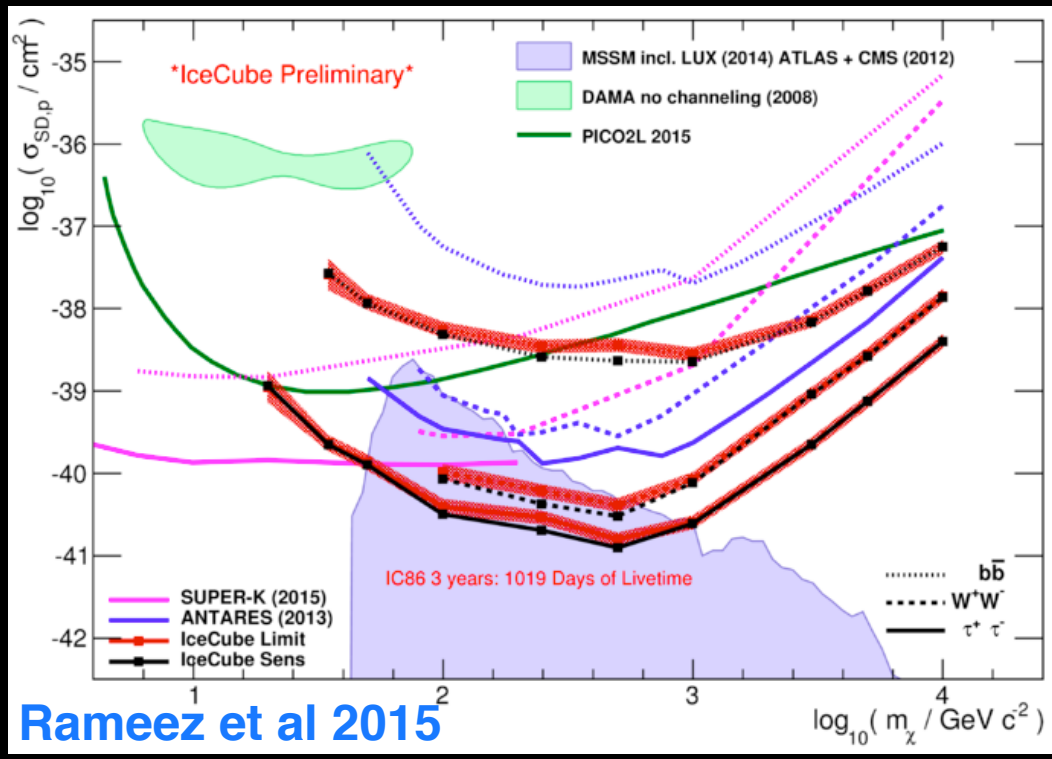
Scattering Cross Section
$\sigma_{SD} \propto J(J+1)$
$\sigma_{SI} \propto A^2$

Number density of element i -> Solar Model

velocity distribution (in solar frame, without Sun's gravity)

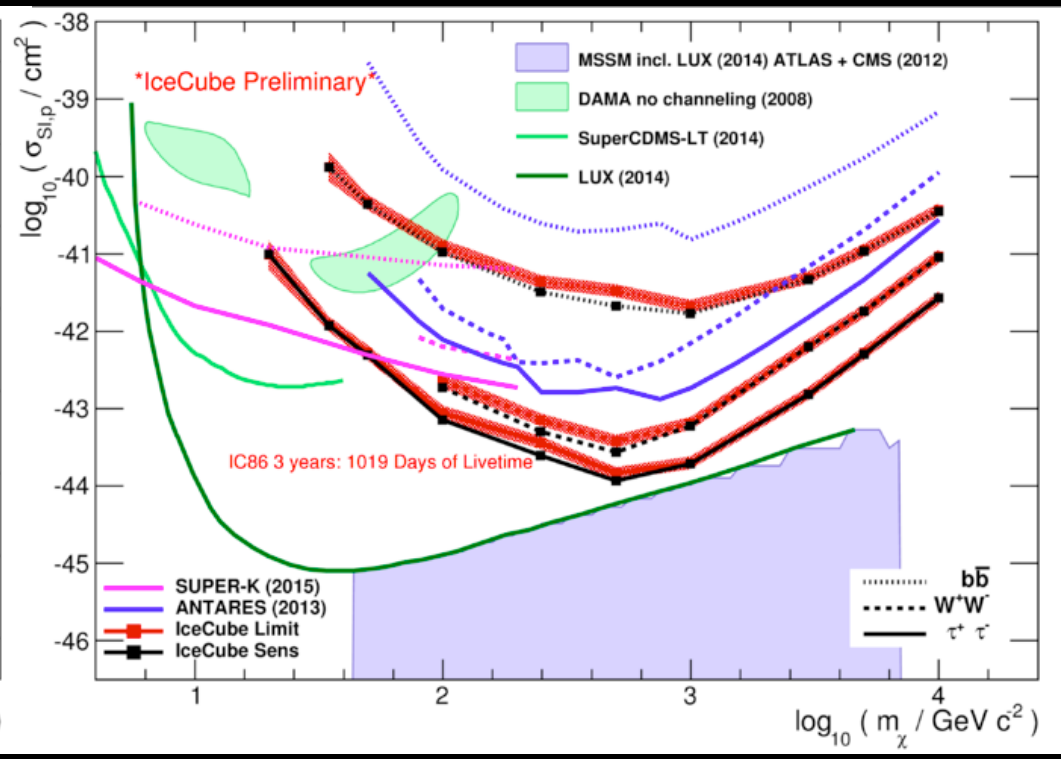
effect of solar gravity

Spin dependent



Rameez et al 2015

Spin independent

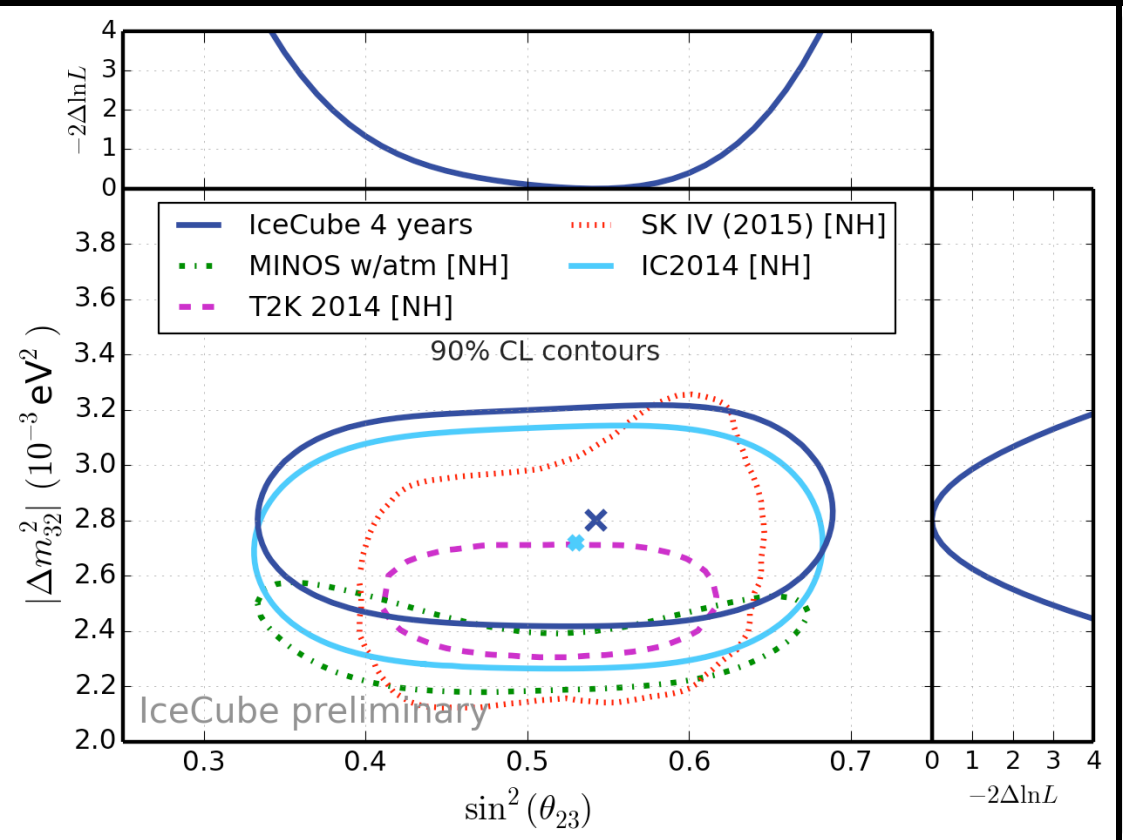


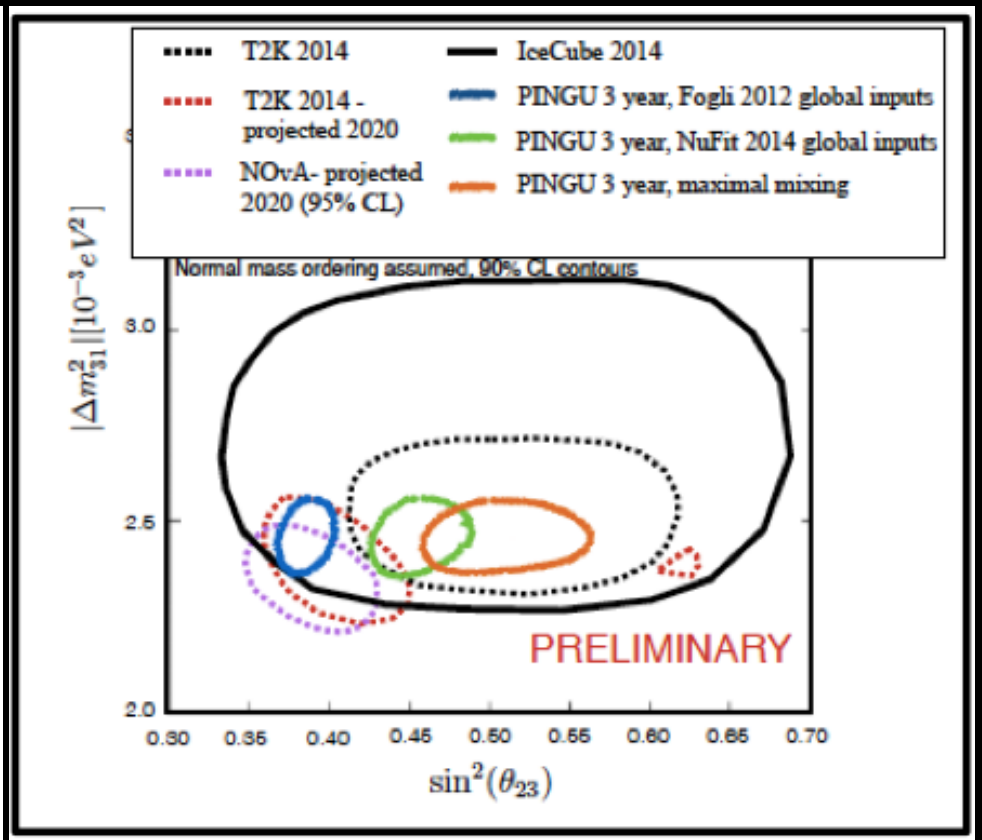
IceCube/DeepCore ⇒ PINGU

- IceCube/IceCube-Gen2 has great potential in neutrino physics:
  1. *coming results on sterile neutrinos*
  2. *about 6400 events (4 yr) for standard oscillation at 10 GeV contour approaching T2K one.*
  3. *PINGU (add 40 strings with 22 m string spacing and 2 m DOM spacing will reach 1 GeV*

$\Delta m^2 = 2.80_{-0.16}^{+0.20} \times 10^{-3}$ eV^2

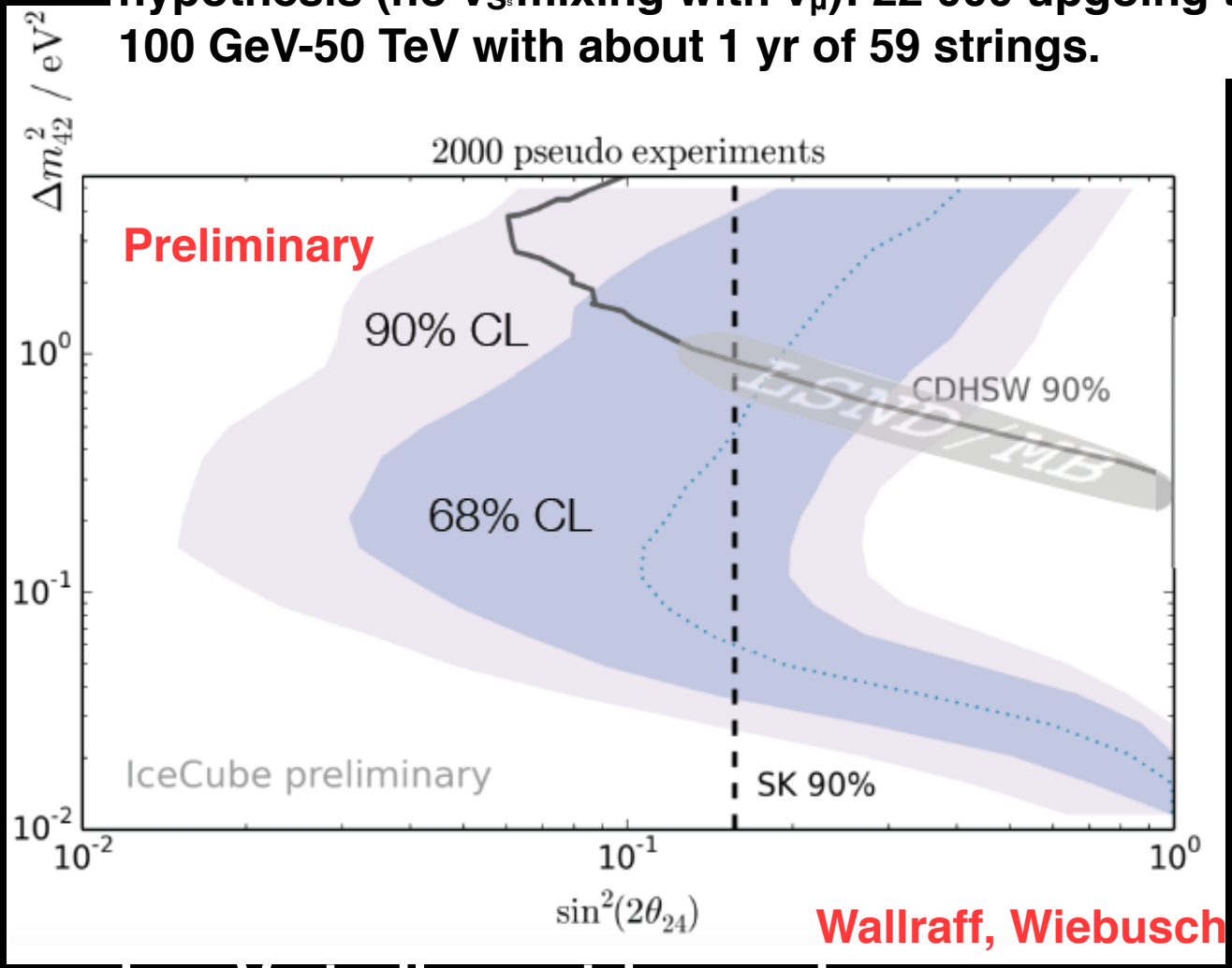
PRD91 (2015) 072004 (3 yr) $\sin^2(\text{theta}) = 0.54_{-0.13}^{+0.08}$





Sterile neutrino sensitivity

Expected region for 90% C.L. exclusion sensitivity for the null hypothesis (no ν_{s} mixing with ν_{μ}): 22'000 upgoing tracks between 100 GeV-50 TeV with about 1 yr of 59 strings.



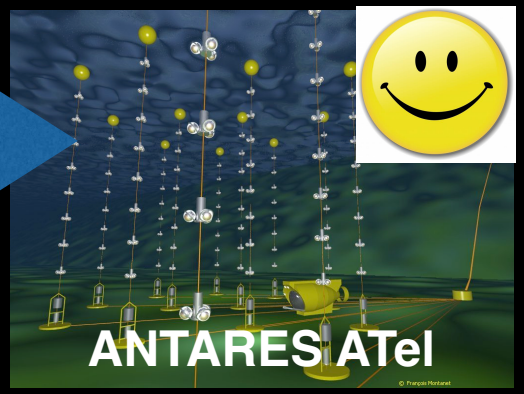
Wallraff, Wiebusch et al. ICRC2015

IceCube can probe eV sterile neutrino region

systematic uncertainties included in the LH function under study as nuisance parameters

ApP-conclusions: a lot of open questions

- Where are the point sources?
- Are transient sources accessible?
- What are the spectra? Cutoffs?
- What is the flavor composition?
- Multi-messenger physics is possible?
- GZK neutrinos start to be at reach?
- WIMP miracle?



PP-conclusions: a lot of open questions

- Where are the prompt? muons and neutrinos
- eV sterile neutrino can be severely constrained
- Hierarchy determination depends on ability to calibrate the GeV ice

Most probable answer: a larger detector with a dense inner core

IceCube-Gen2

Add ~120 strings to IceCube

Spacing: 240 m

Volume: 8.0 km^3