IceCube-Gen2 and Future Astronomy

Xinhua Bai, SDSMT

on behalf of the IceCube Collaboration
http://icecube.wisc.edu

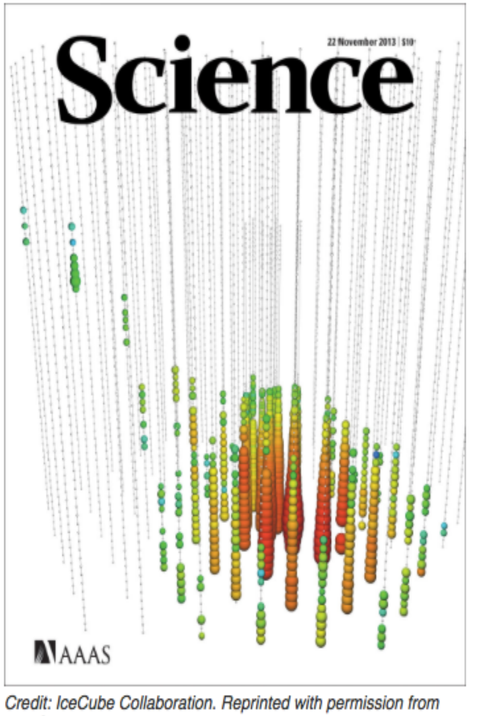
Sept. 28-29, 2015, KIAA at Peking University, Beijing, P. R. China

An Older News

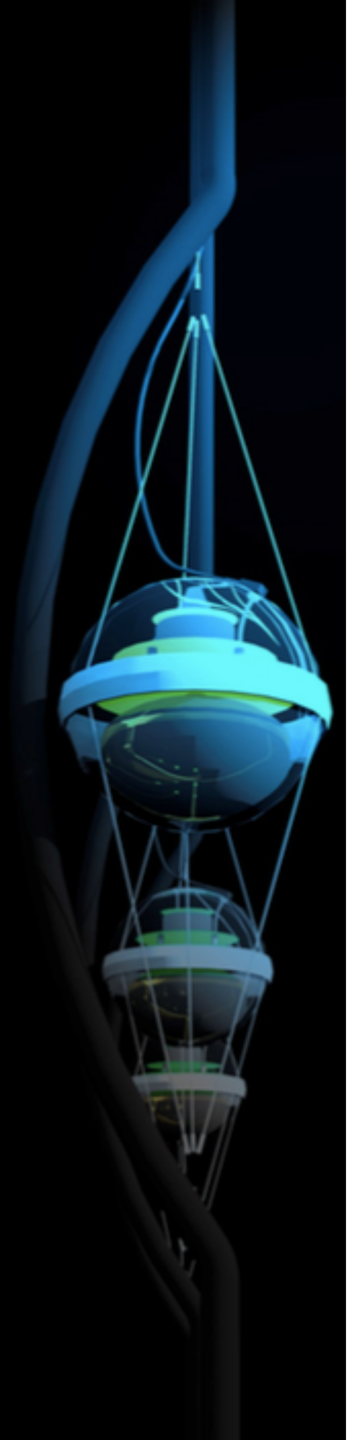
(Two years ago) "This is the first indication of very high-energy neutrinos coming from outside our solar system, with energies more than one million times those observed in 1987 in connection with a supernova seen in the Large Magellanic Cloud,"
- Francis Halzen

IceCube pushes neutrinos to the forefront of astronomy

By the IceCube Collaboration, 21 Nov 2013 13:00 PM



Credit: IceCube Collaboration. Reprinted with permission from AAAS.



Outline

1. Neutrino Astronomy: What & Why
2. The IceCube Neutrino Observatory
3. Some science results from IceCube

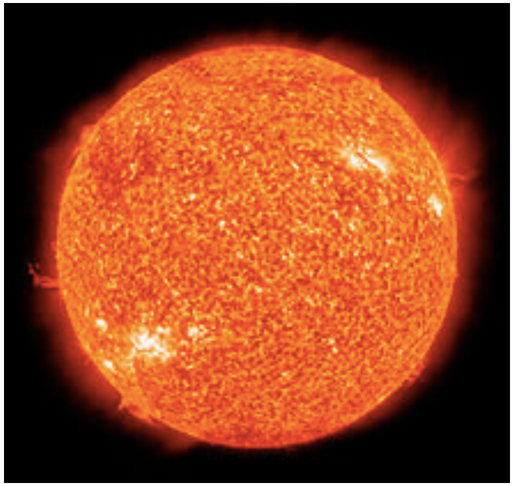
   3.1 High-energy astrophysical neutrinos: Evidence, spectrum, source, correlations with HE events, & flavor.

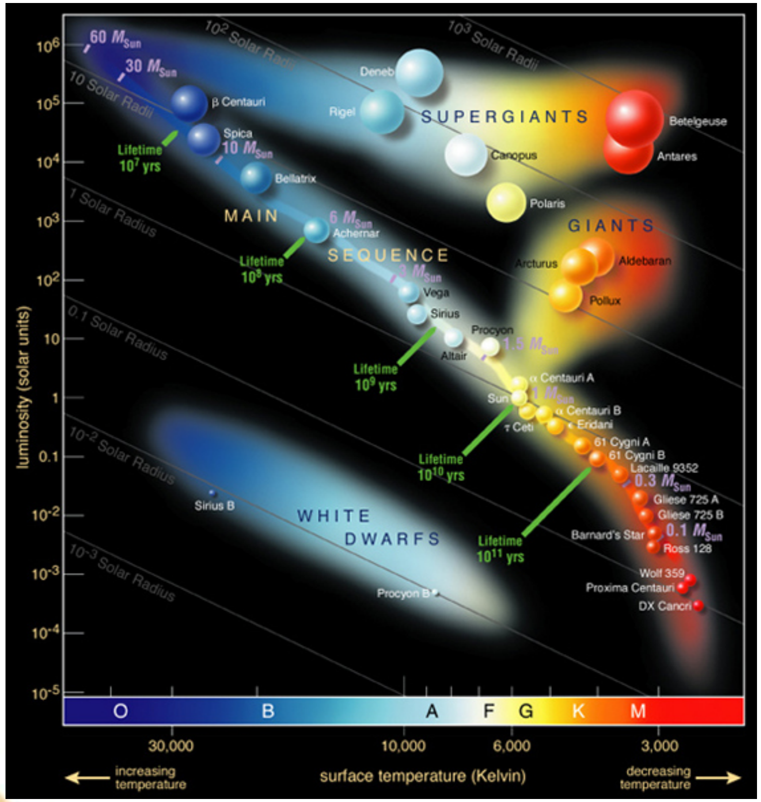
   3.2 Indirect search for dark matter annihilations
4. Upgrade of IceCube & What to Expect

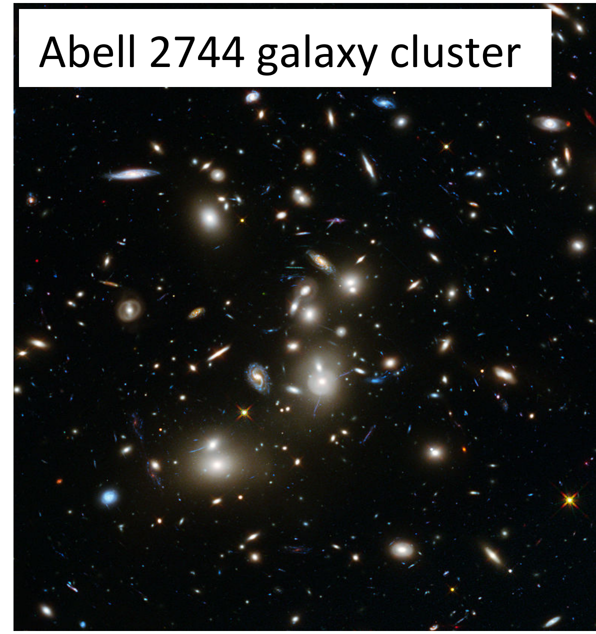
   4.1 Where we stand & Open questions

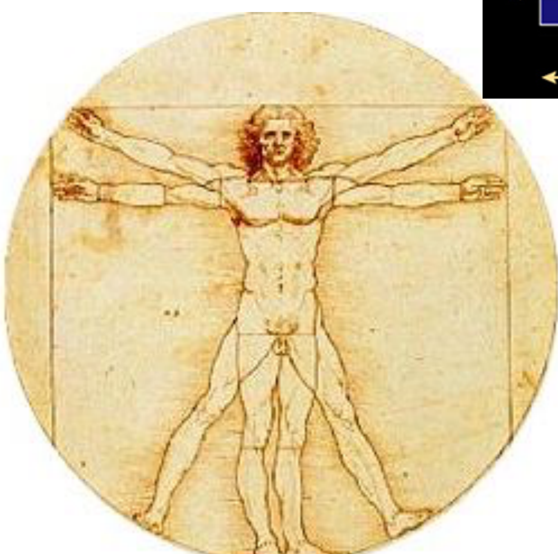
   4.2 High & Low energy extensions
5. Summary

Radiations & Astronomy: Thermal



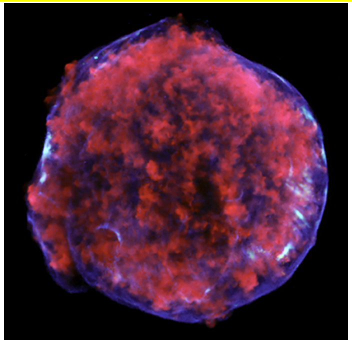






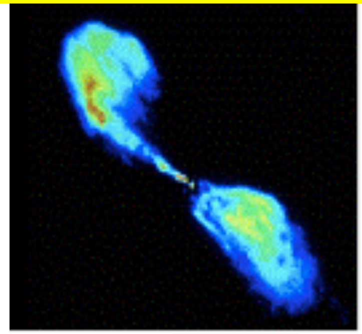
More violent/large scale phenomena & processes

Supernova

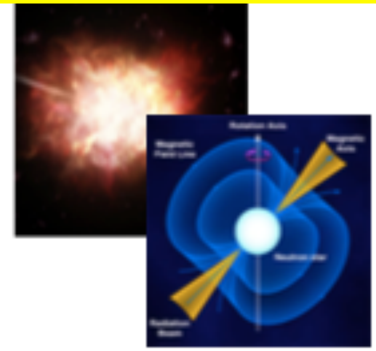


Blazars

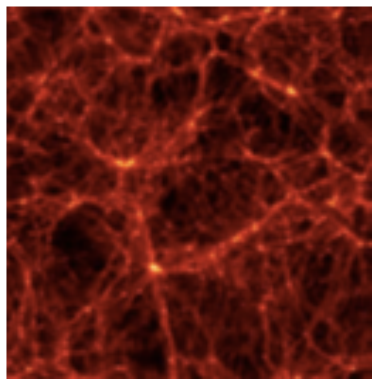
Radio Galaxies



GRBs, Pulsars



Intergalactic Shocks



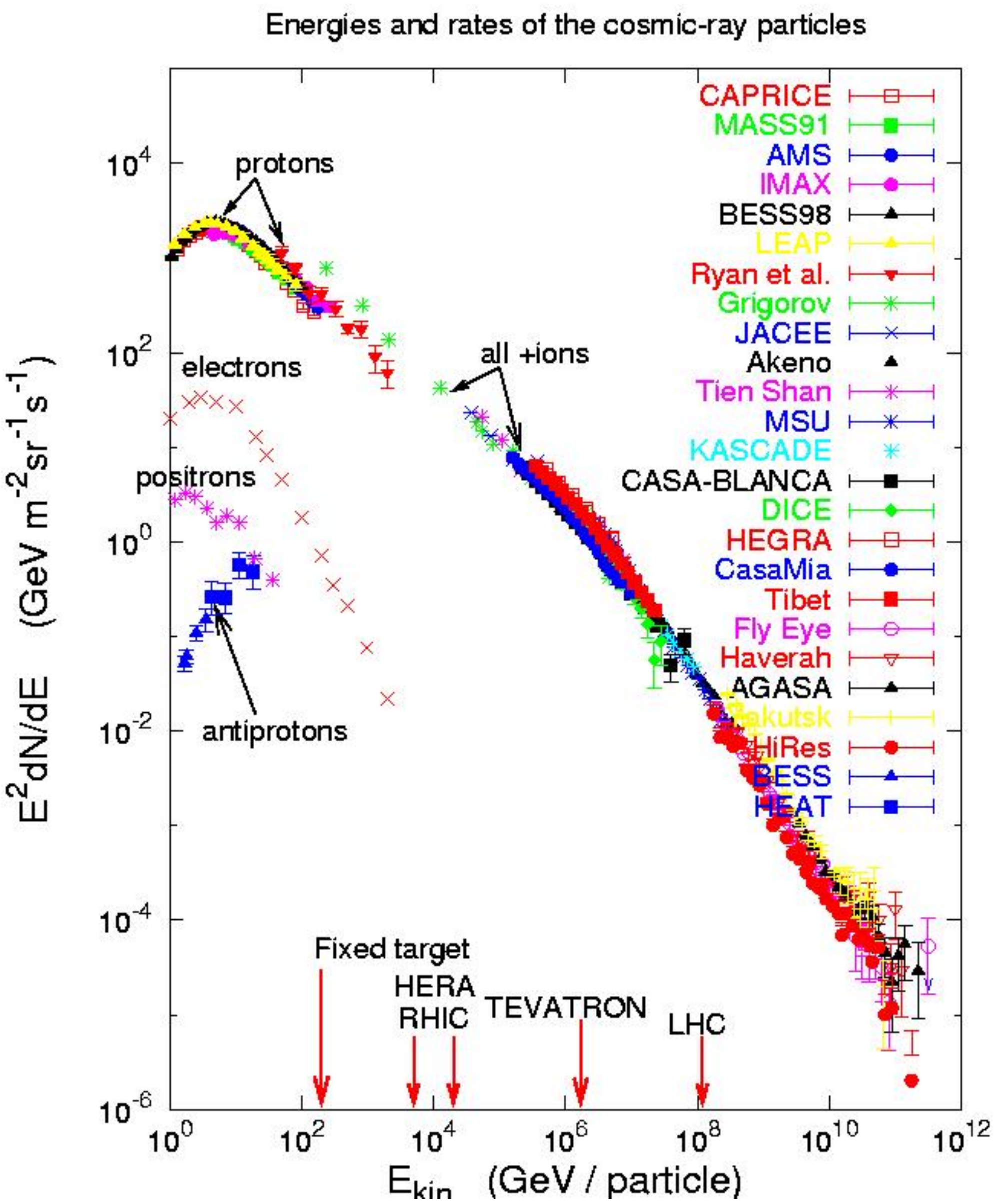
Dark Matter Annihilation

Something else

FNAL

CERN

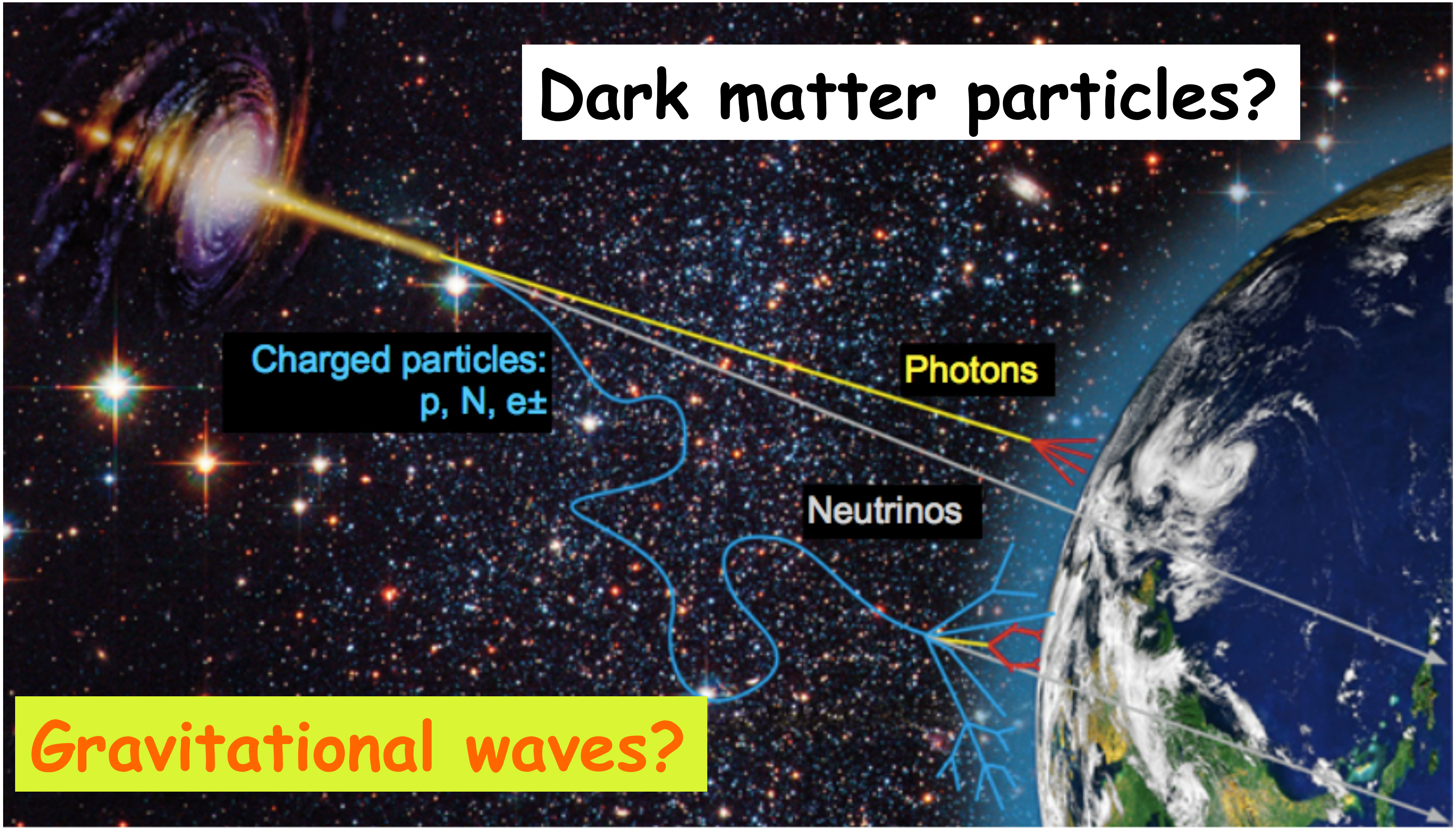
Puzzle of high energy cosmic rays



- ✓ **Cosmic ray particles are mainly ions.**
- ✓ **Cover huge energy range.**
- ✓ **Power law spectrum, more or less**
- ✓ **Structure: Knee, Ankle, cut-off at the highest energy**

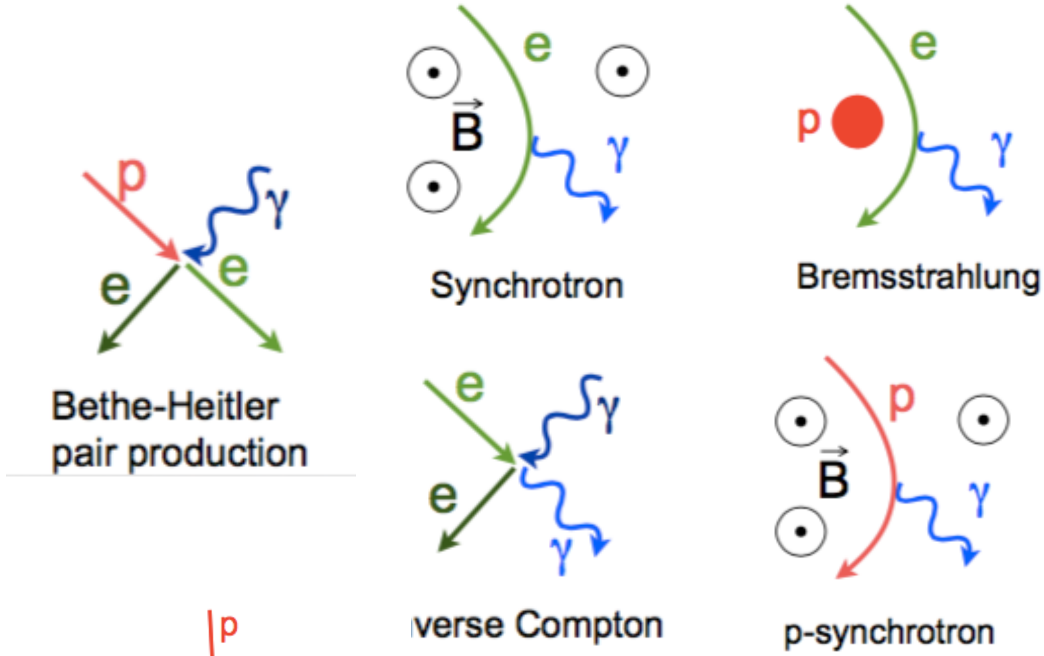
- ➢ The origin (source/mechanism) of high energy CRs: Where do they come from and how they obtain such high energies?
- ➢ Composition at high energies?
- ➢ Propagation in space
- ➢ Long term correlation with astrophysical phenomena?

Three++ messengers

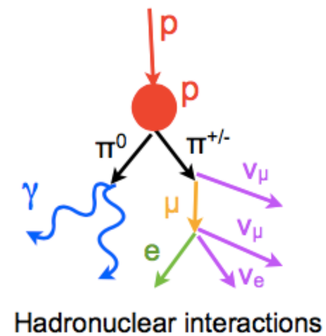


Interactions

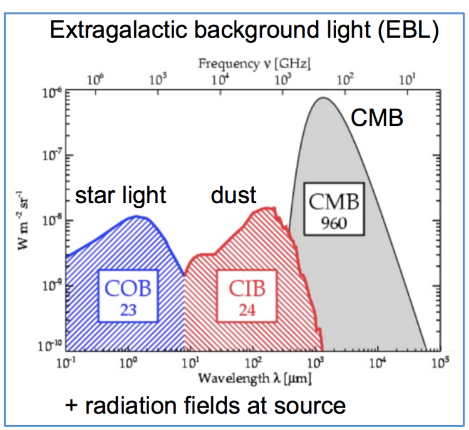
Gamma/electrons **without** neutrino production



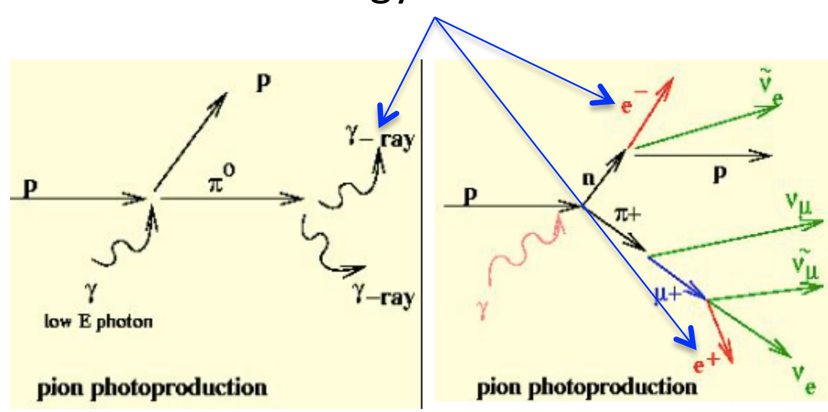
Neutrinos are a **diagnostic** for hadronic interactions



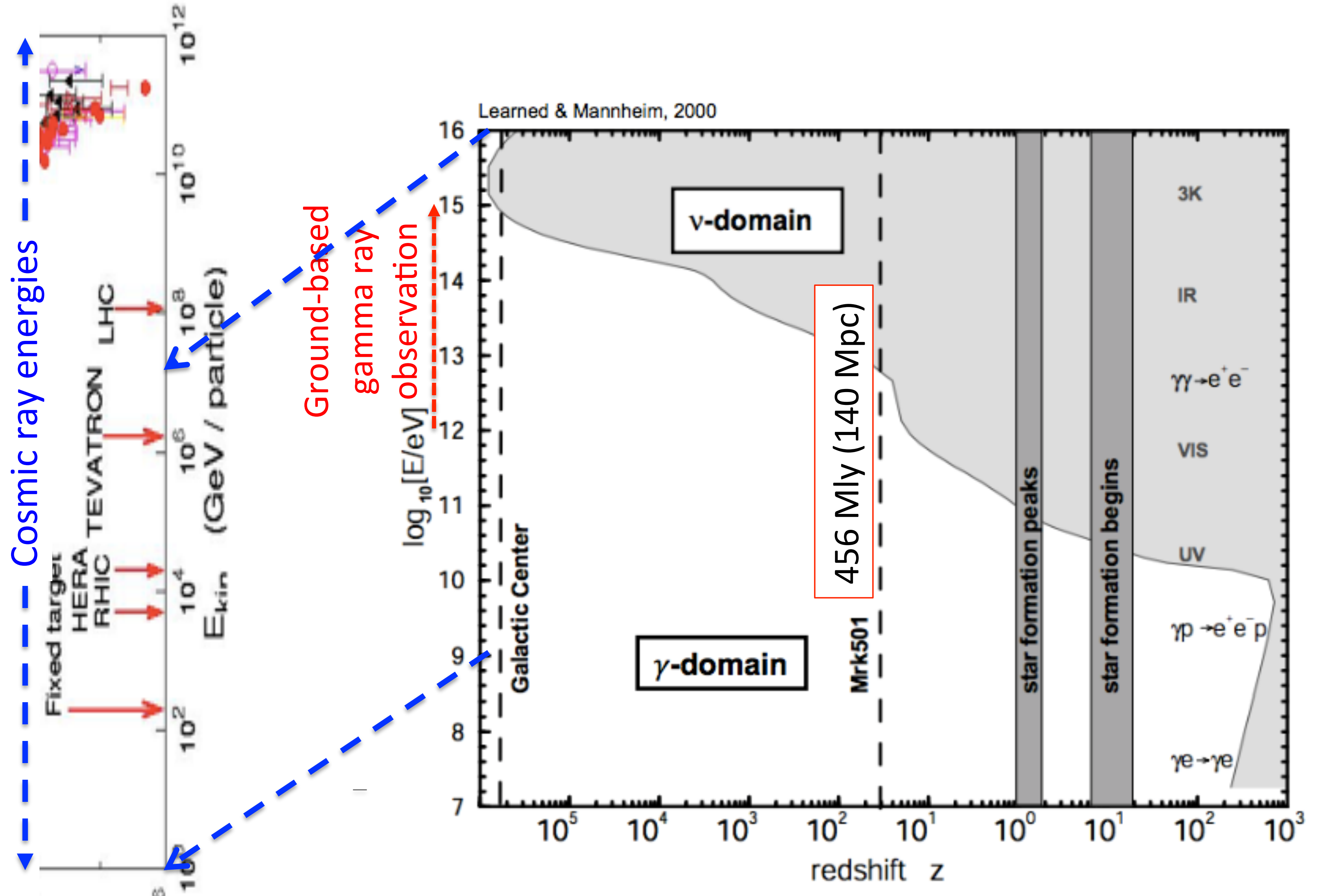
CRs propagation through radiations



Gamma/electrons soon become low energy EM cascades

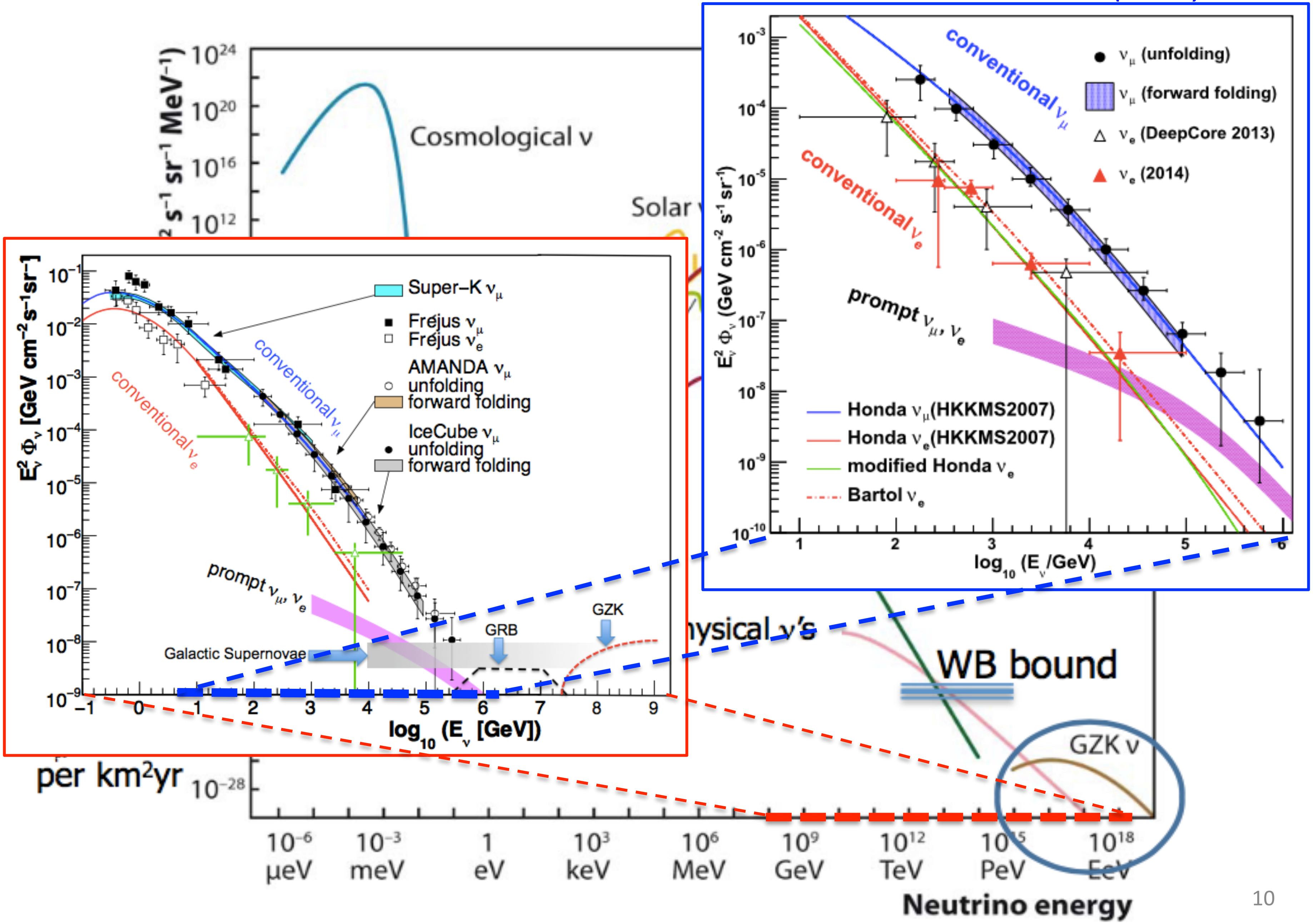


High energy neutrino astronomy

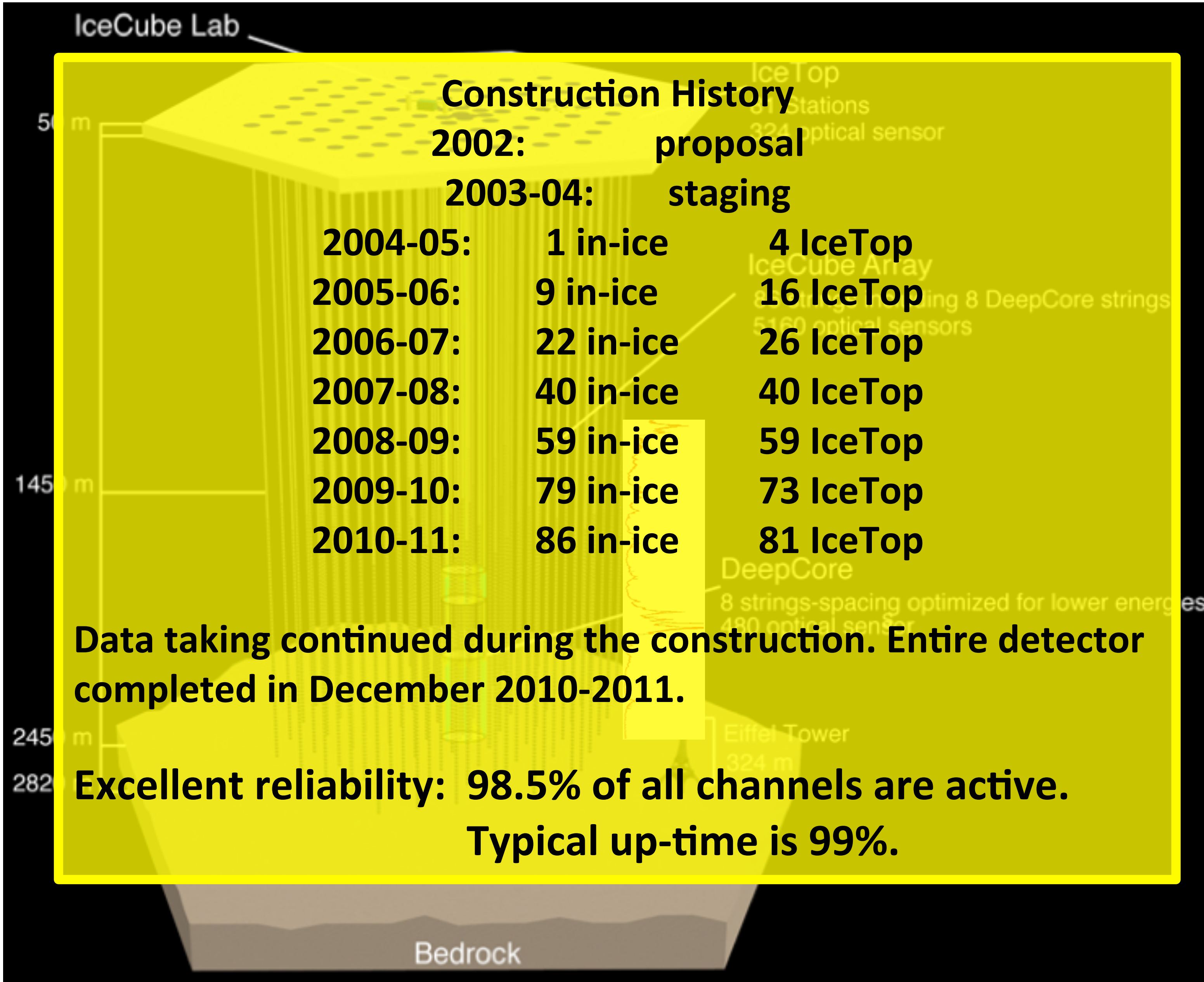


Neutrino sky is complicated and rich

PRD 91(2015)122004



The IceCube Neutrino Observatory



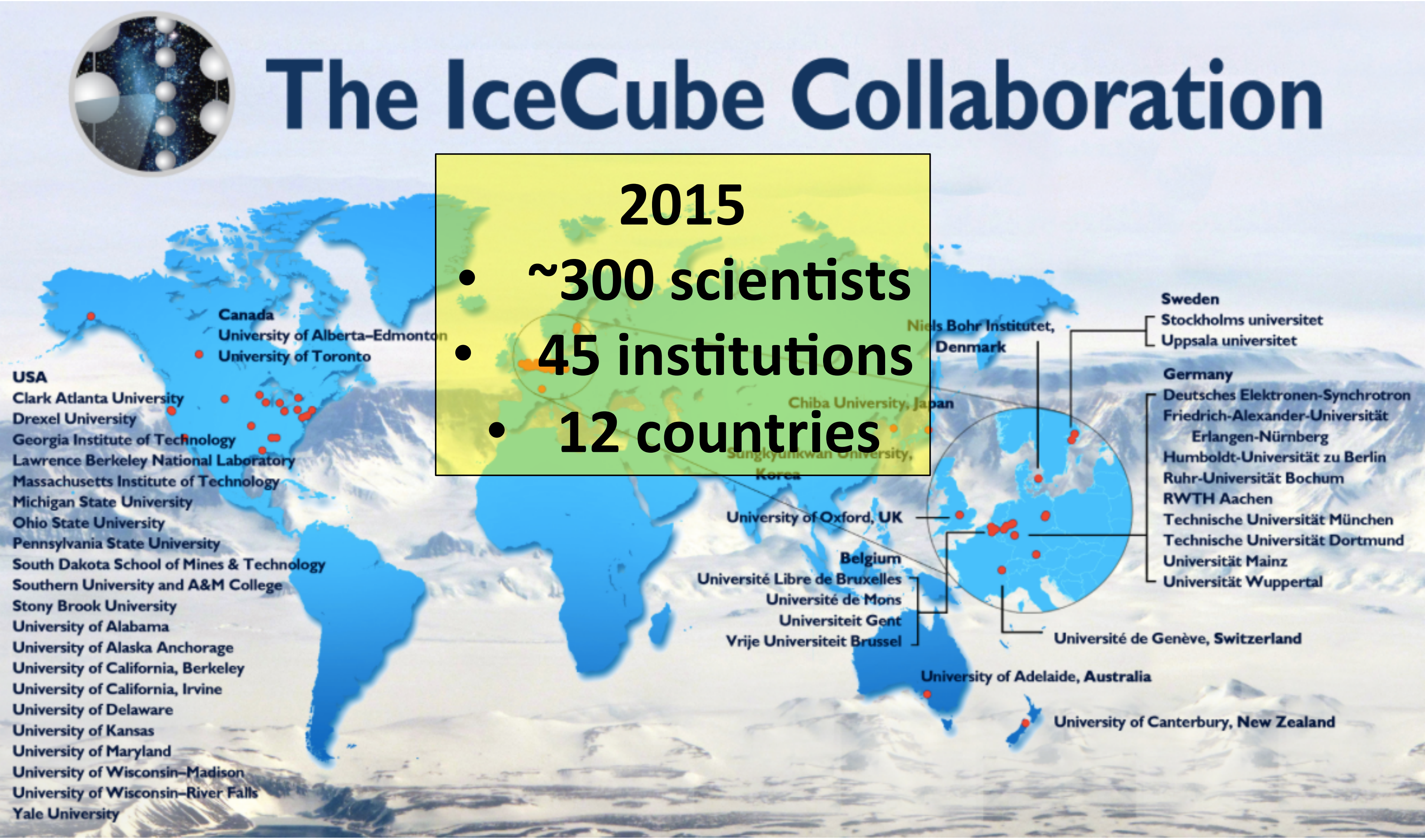
Construction History

2002:	**proposal**	
2003-04:	**staging**	
2004-05:	**1 in-ice**	**4 IceTop**
2005-06:	**9 in-ice**	**16 IceTop**
2006-07:	**22 in-ice**	**26 IceTop**
2007-08:	**40 in-ice**	**40 IceTop**
2008-09:	**59 in-ice**	**59 IceTop**
2009-10:	**79 in-ice**	**73 IceTop**
2010-11:	**86 in-ice**	**81 IceTop**

Data taking continued during the construction. Entire detector completed in December 2010-2011.

Excellent reliability: 98.5% of all channels are active.
Typical up-time is 99%.

Collaboration



2015

- **~300 scientists**
- **45 institutions**
- **12 countries**

IceCube data

- ~280 … even…
  - En… eV up to about one EeV
- ~500 n… ay
  - Ener… GeV (D… GeV (upper strings) to PeV.
  - … sph…
- About 1 TB of un… raw data per day
- About 100 … e sent out from the South Pole o… analysis every day.

Cosmic rays

H.E. Neutrino astronomy

Dark matter

Neutrino physics

Muon physics

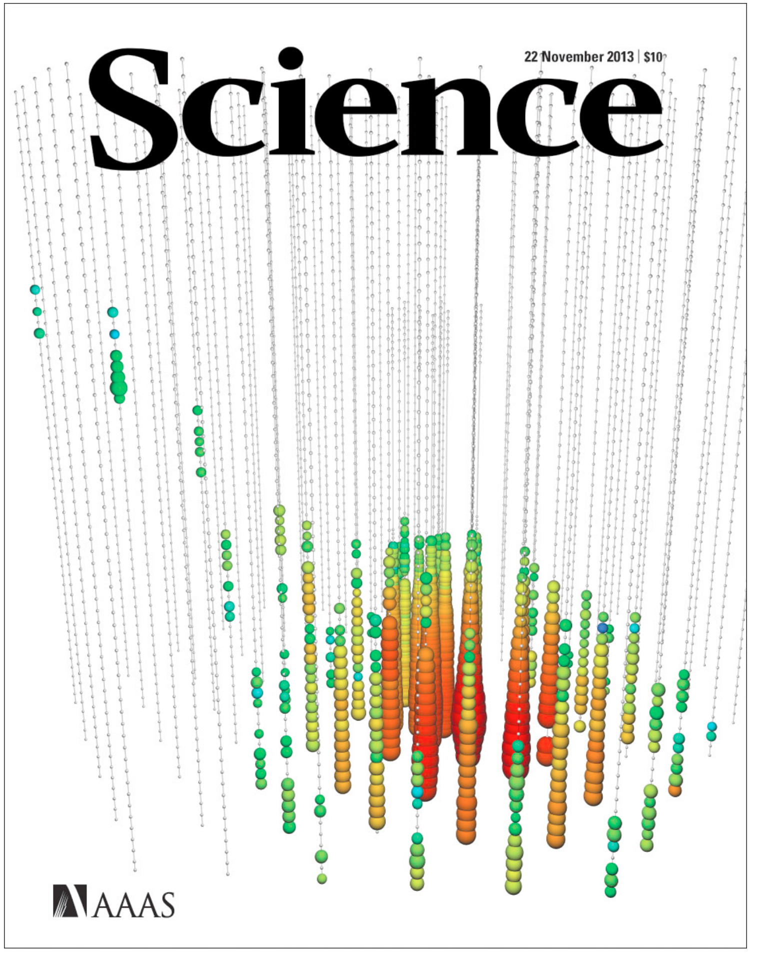
Interactions At H.E.s

Atmosphere science

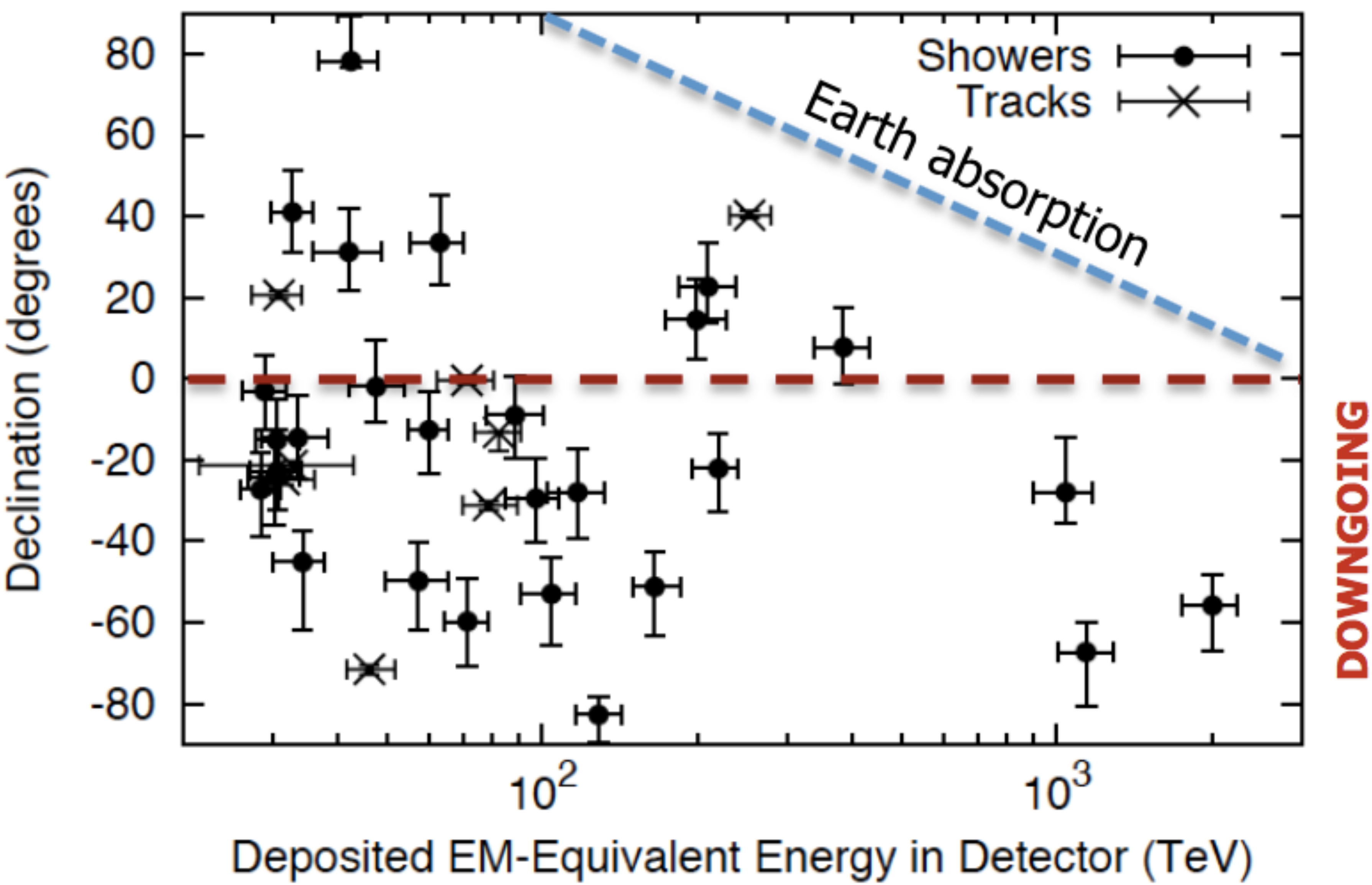
…

Neutrinos in IceCube: New cosmic component

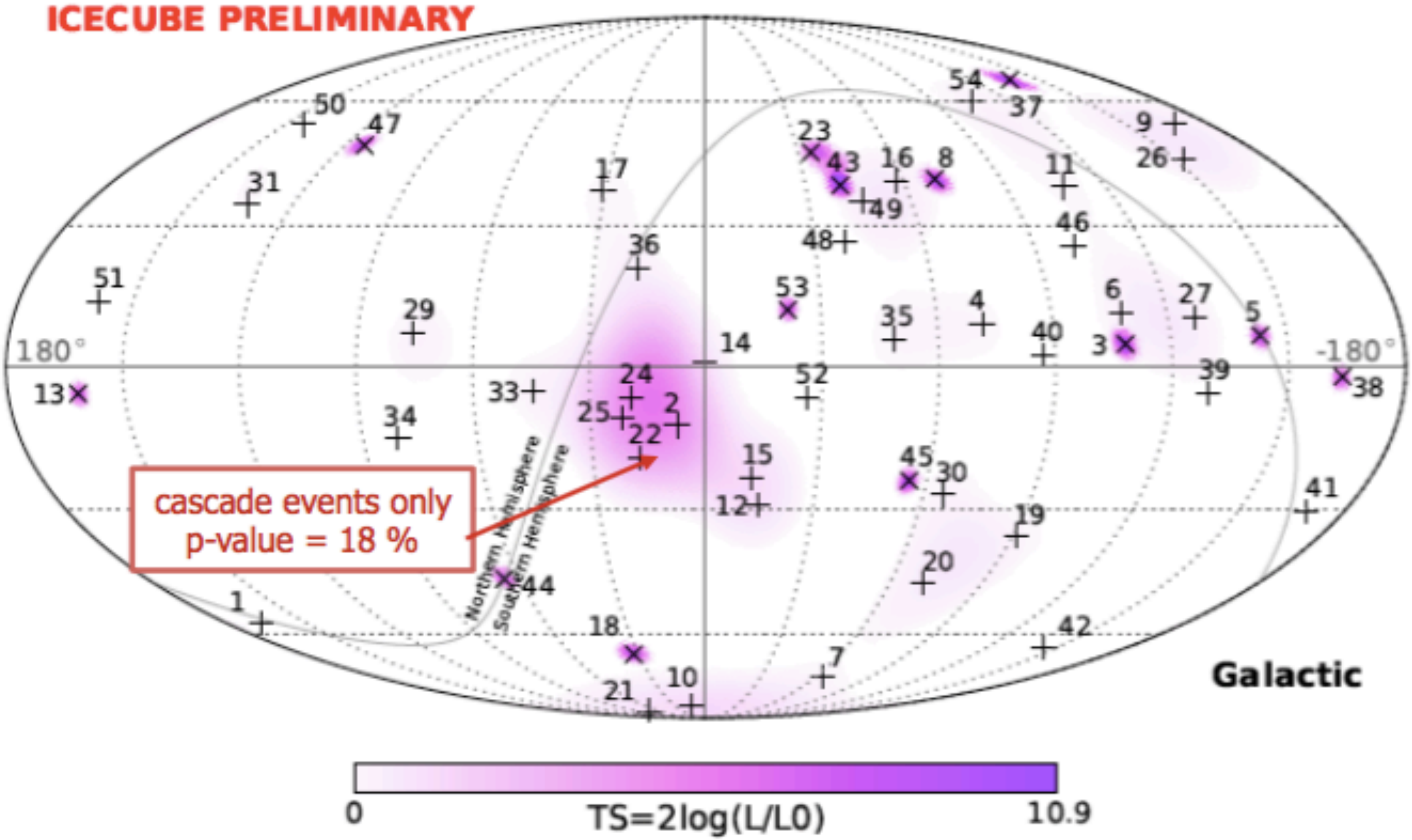
- First evidence for an extra-terrestrial flux: 28 events, *Science 342 (2013)*
- 3 yrs: 37 events in 988 days, with expected bkg. 8.4±4.2 atm. μ & 6.6+5.9 atm. ν. *Phys. Rev. Lett. 113:101101 (2014)* → *5.7σ*
- 4 yrs: 54 events → ~7σ, all flavor (two more plots)



Flavor and declination vs energy

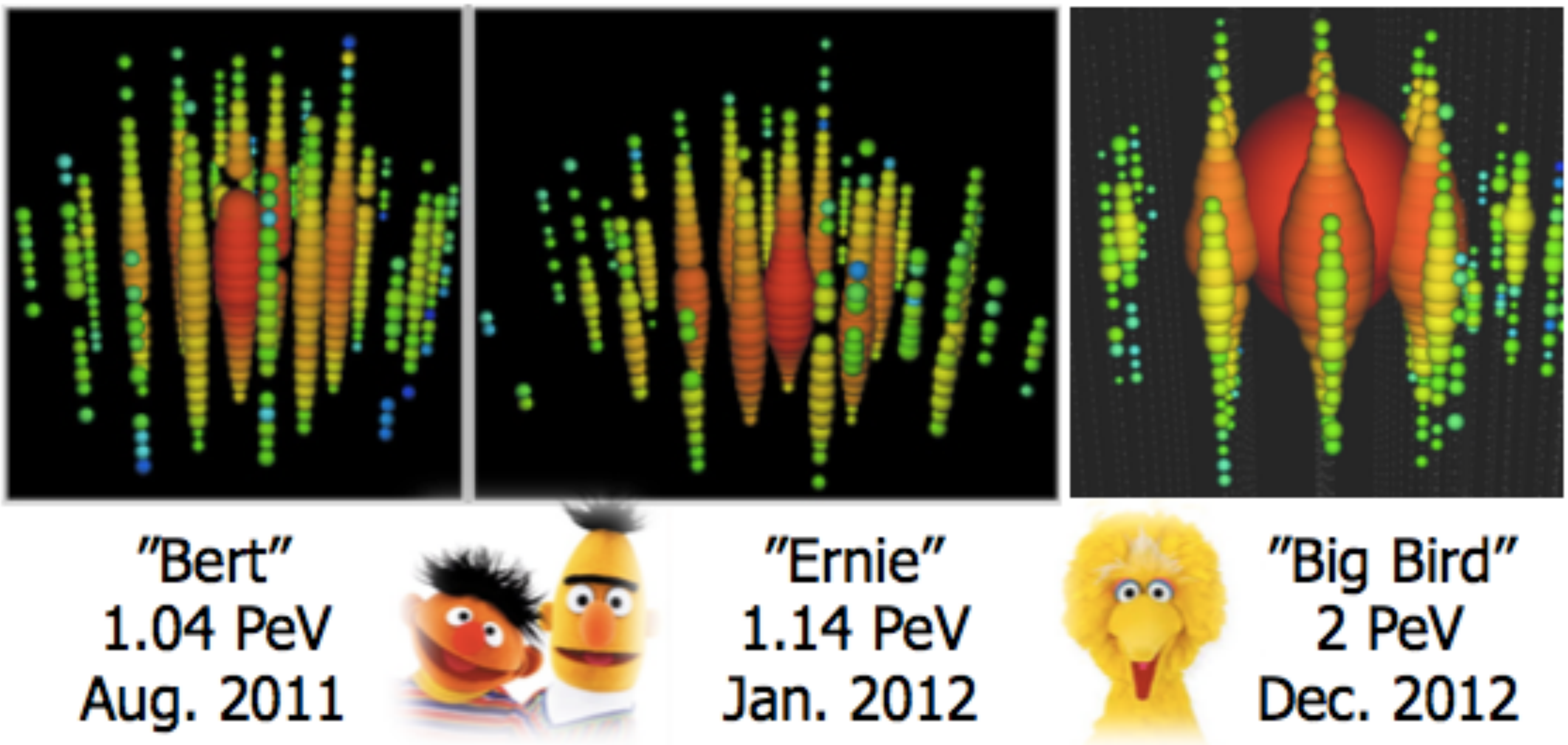


Arrival directions



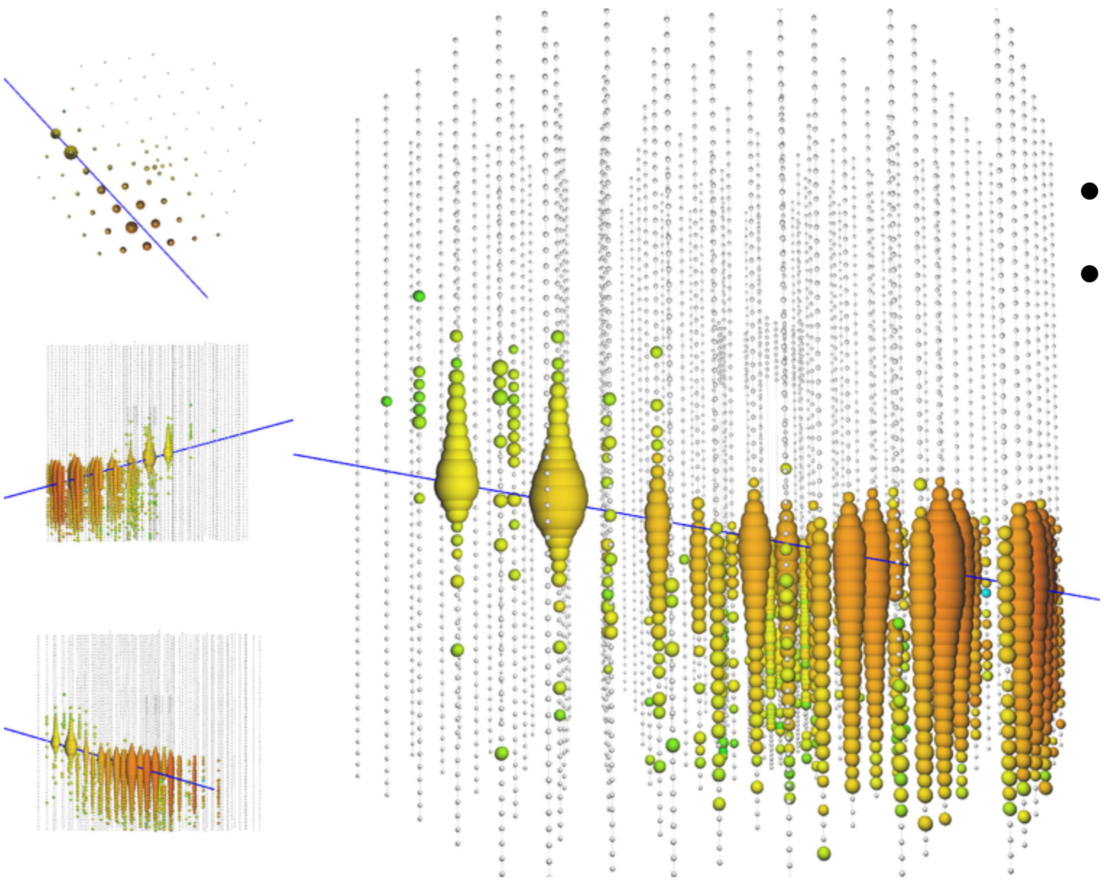
No significant correlations – spatial or temporal

High energy events



The most recent high energy ν_μ event

https://wiki.icecube.wisc.edu/index.php/Multi_PeV_Track_IC2014_Plots



06/11/2014

- Up-going (Decl= 11.5°) ν_μ
- $E_\nu > E_\mu \sim 2.6\times10^{15}$ eV

1. No hot spot in published 4-year point source map within 0.5°
2. Closest object in TeVCat ~8° away
3. Closest object in Fermi's 2FGL & 3FGL is 3° away
4. ~11° off the Galactic plane
5. No coincident GRB

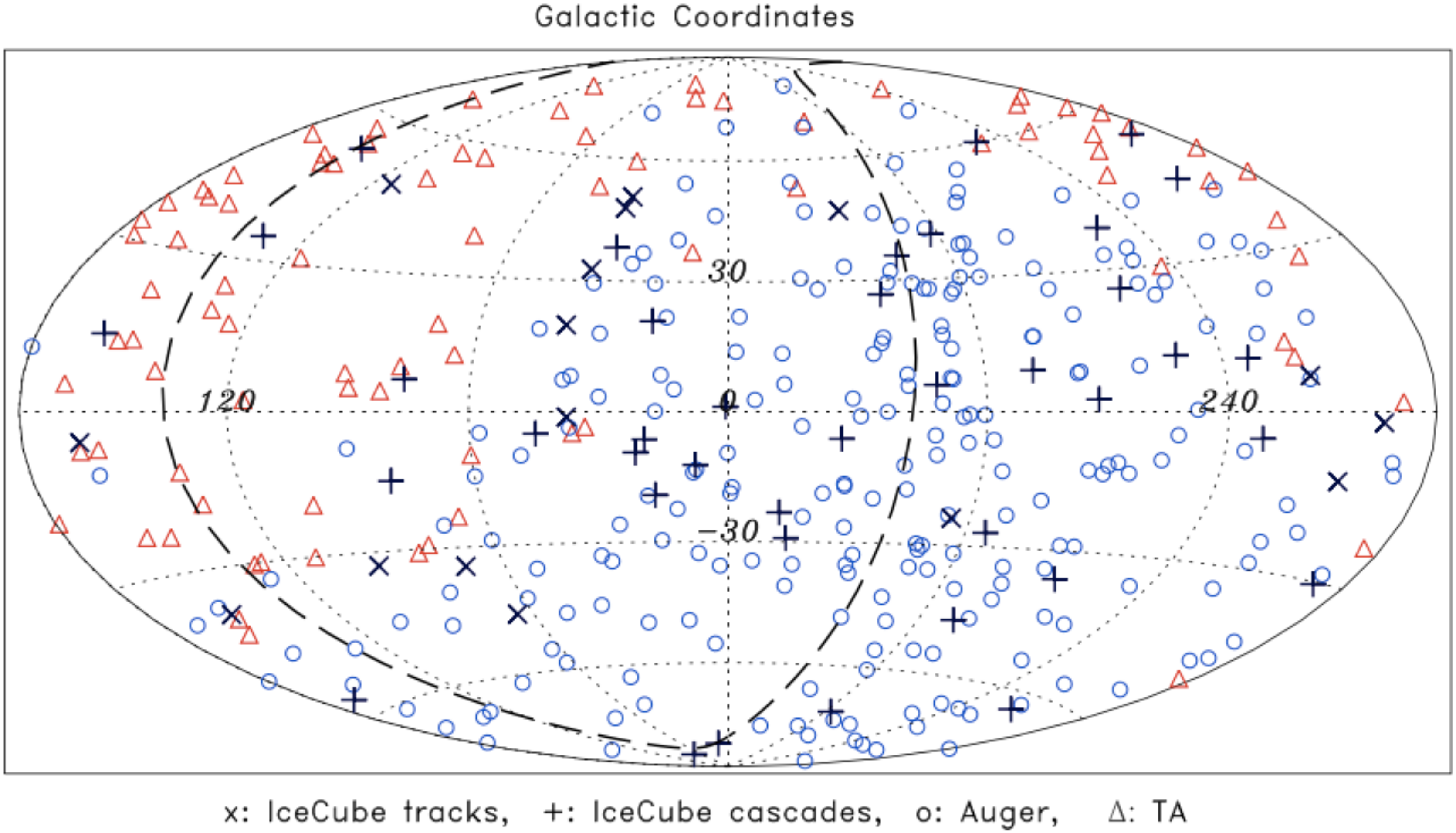
stay tuned for new surprise.

Correlation with other UHECR events

- Pierre Auger: 231 events, E>52 EeV, zenith <80°, ang. res. ≤0.9°.
  - *ICRC2015-310, APJ 804(2015) 1*
- Telescope Array: 87 events (E>57 EeV, zenith <55°, ang. res. ≤1.5°) between 11/05/2008 to 01/05/2014.
  - *APJL 790(2014)L21*
- IceCube: 4 yr (> 30 TeV): 39 cascades (ang. res. ~20°) + 7 tracks (ang. res. ~1°). 9 ν_μ induced upgoing muons with E> 100 TeV.
  - *ICRC2015-1081, PRL 113 (2014) 101101, PRL 115 (2015) 081102*

Correlation with other UHECR events

A. Christov, et al., ICRC2015_1082.pdf



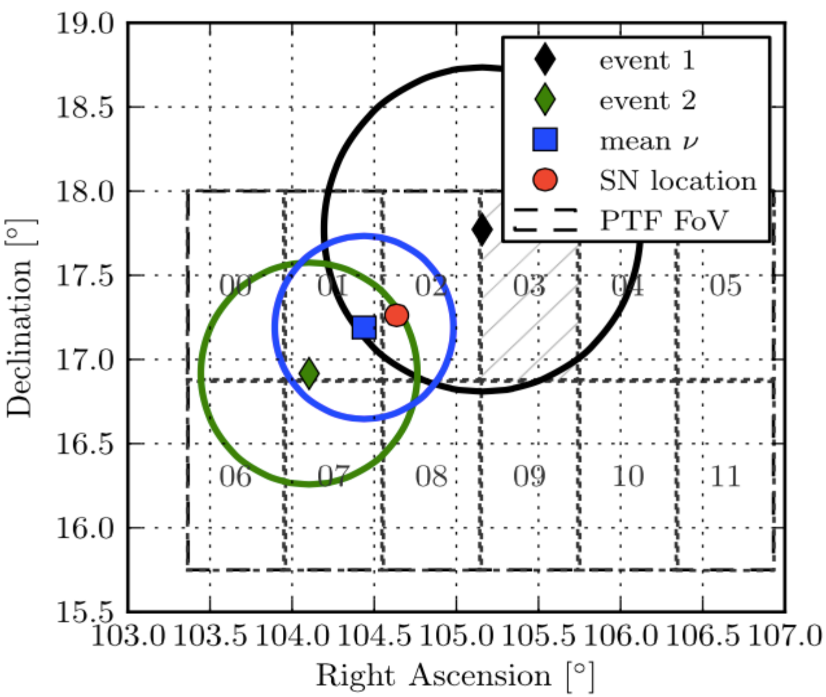
No significant correlation has been found in any of the analyses.

Optical follow-up observations of IceCube neutrino events.

A coincidental discovery of SN IIn PTF12csy: Palomar Transient Factory (PTF)

- 0.2° away from the neutrino direction
- z = 0.0684
- $D_{luminosity}$ ~300 Mpc

M. G. Aartsen, et al. The Astrophysical Journal, 811:52 (17pp), 2015 September 20.



- SN explosion was ≥169 days (in O.F.) before the neutrinos. (by Pan-STARRS1 survey)
- The posteriori significance of the neutrino doublet & the SN coincident is 2.2σ for the 2011/12 IceCube data.

Conclusion:

The connection between the SN and the ν-doublet is unlikely causal.

Table 1
Properties of the Neutrino Alert Events

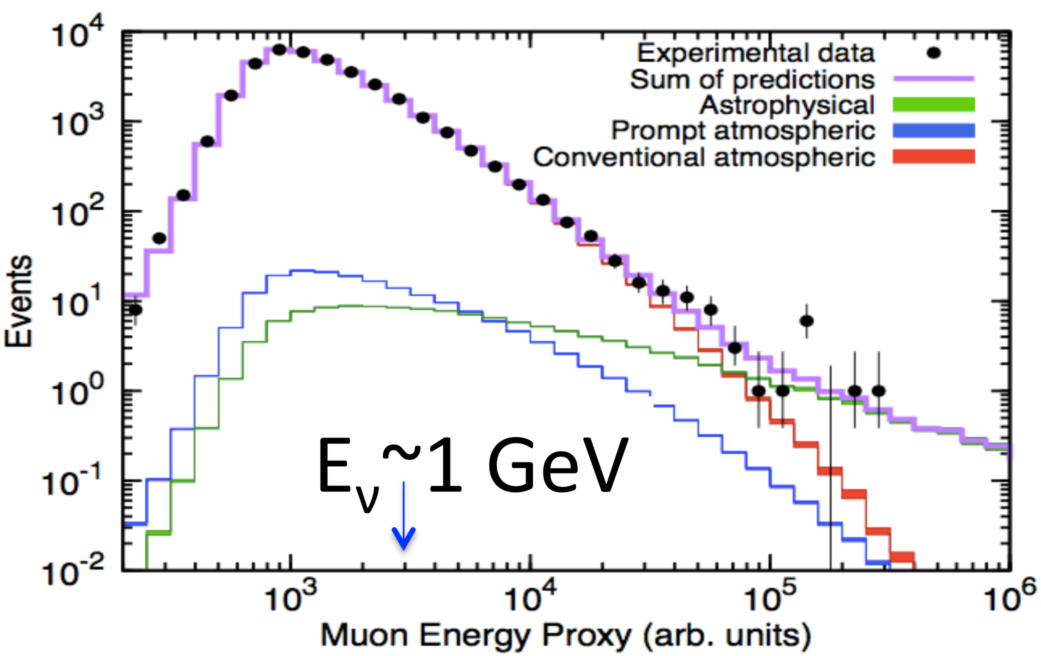
Time (UT)	σ_Ψ (°)	$\hat{E}_\mu$ [a] (GeV)	E_ν [b] (Atm.) (TeV)	E_ν [b] (E^{-3}) (TeV)	E_ν [b] (E^{-2}) (TeV)
01:06:58	0.96	1155	$0.5^{+2.9}_{-0.4}$	$0.7^{+5.6}_{-0.5}$	$5.4^{+292.0}_{-5.0}$
01:07:00	0.66	3345	$0.9^{+6.7}_{-0.7}$	$1.5^{+14.8}_{-1.3}$	$15.7^{+611.5}_{-14.5}$

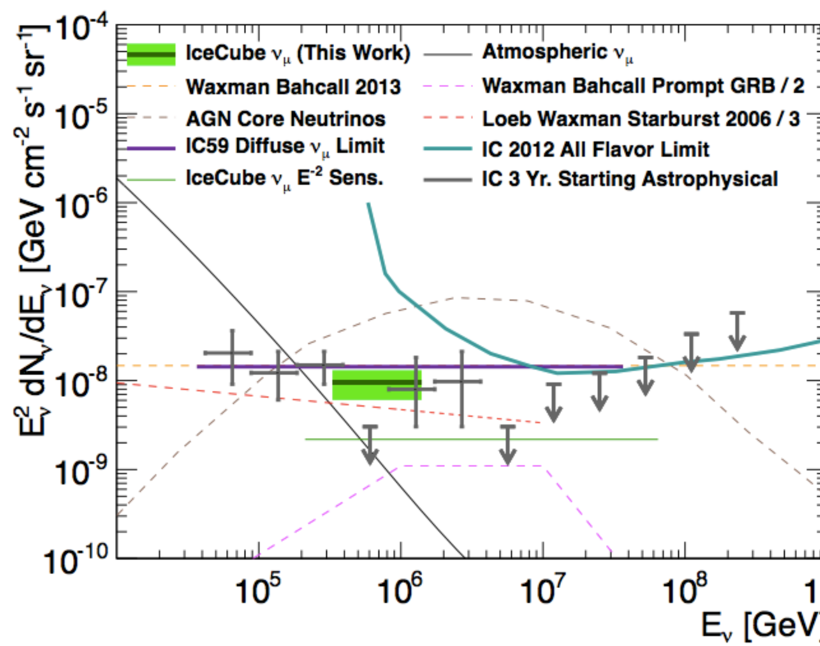
Astrophysical Muon Neutrinos from the Northern Sky

659.5 days of livetime, 05/ 2010 – 05/2012, ~ 35,000 muon neutrinos from the Northern sky: Reconstructed θ>85°, ~ an overburden > 12 km of water.

Conclusions:

- An astrophysical flux per neutrino flavor is $\Phi(E_\nu)= 9.9^{+3.9}_{-3.4}\times10^{-19}$ $GeV^{-1}\ cm^{-2}\ sr^{-1}\ s^{-1}\ (E_\nu/100TeV)^{-2}$.
- Consistent with IceCube's Southern hemisphere result.





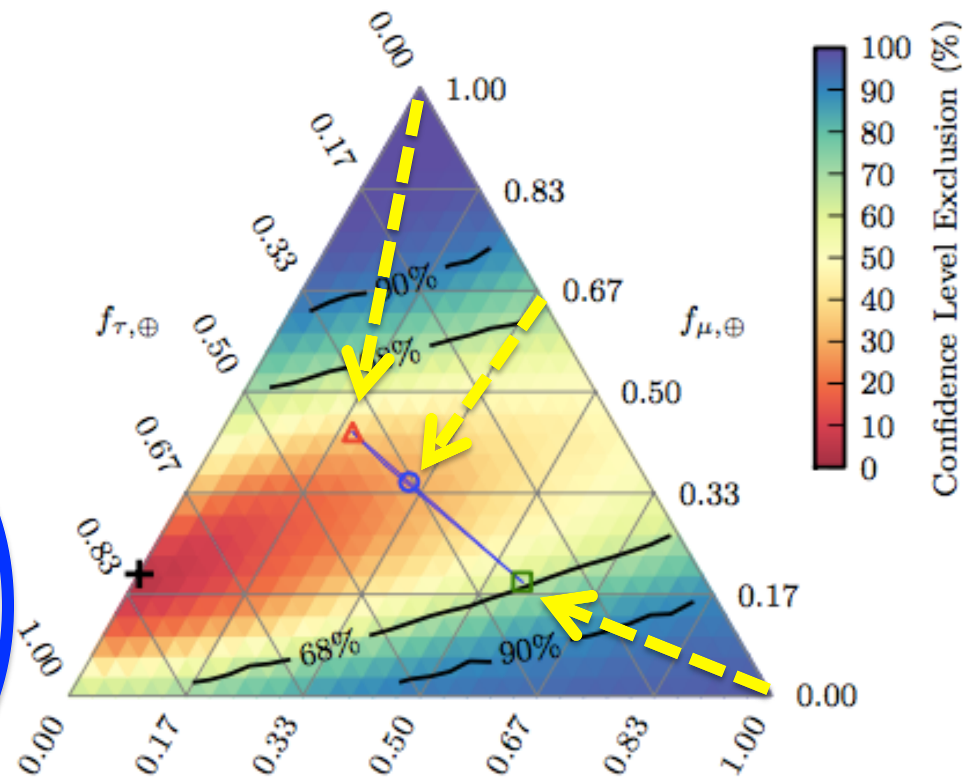
(to be published PRL, arXiv:1507.04005)

Flavor ratio of astrophysical neutrinos

- Data collected in three years from 2010 to 2013
- (129 shower-like ν events) + (8 track-like ν events) for flavor composition analysis > 35TeV

PRL 114 (2015) 171102

- $(1:2:0)_S$: π & μ decay
- $(0:1:0)_S$: μ-suppressed π decay
- $(1:0:0)_S$: n decay
- $(0:0.2:0.8)_E$ at Earth, the best-fit



Conclusions

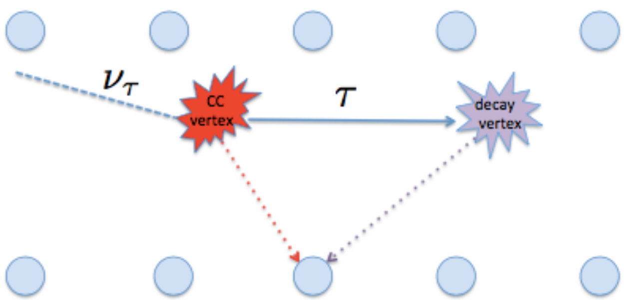
- Consistent with the $(1:1:1)_{earth}$ flavor ratio at the Earth.
- A track-like composition of $(0:1:0)_{earth}$ is excluded at 3.3σ.
- A shower-like composition of $(1:0:0)_{earth}$ is excluded at 2.3σ.

stay tuned for improvements.

ν_τ flux upper limits and comparisons

Detection of ν_τ at high energies

- ✓ (a:b:c≈0) at sources → (a’:b’:c’>0) at the Earth after enough oscillation over large propagation lengths.
- ✓ An **additional confirmation** of the astrophysical origin of the high energy diffuse neutrino signal



The characteristic high energy ν_τ signal in IceCube

- 914.1 live days of data from the full detector between May 13, 2011 and May 6, 2014.
- Using signals from individual IceCube sensors to resolve the double-bang for ν_τ in 214 TeV - 72 PeV energy range.

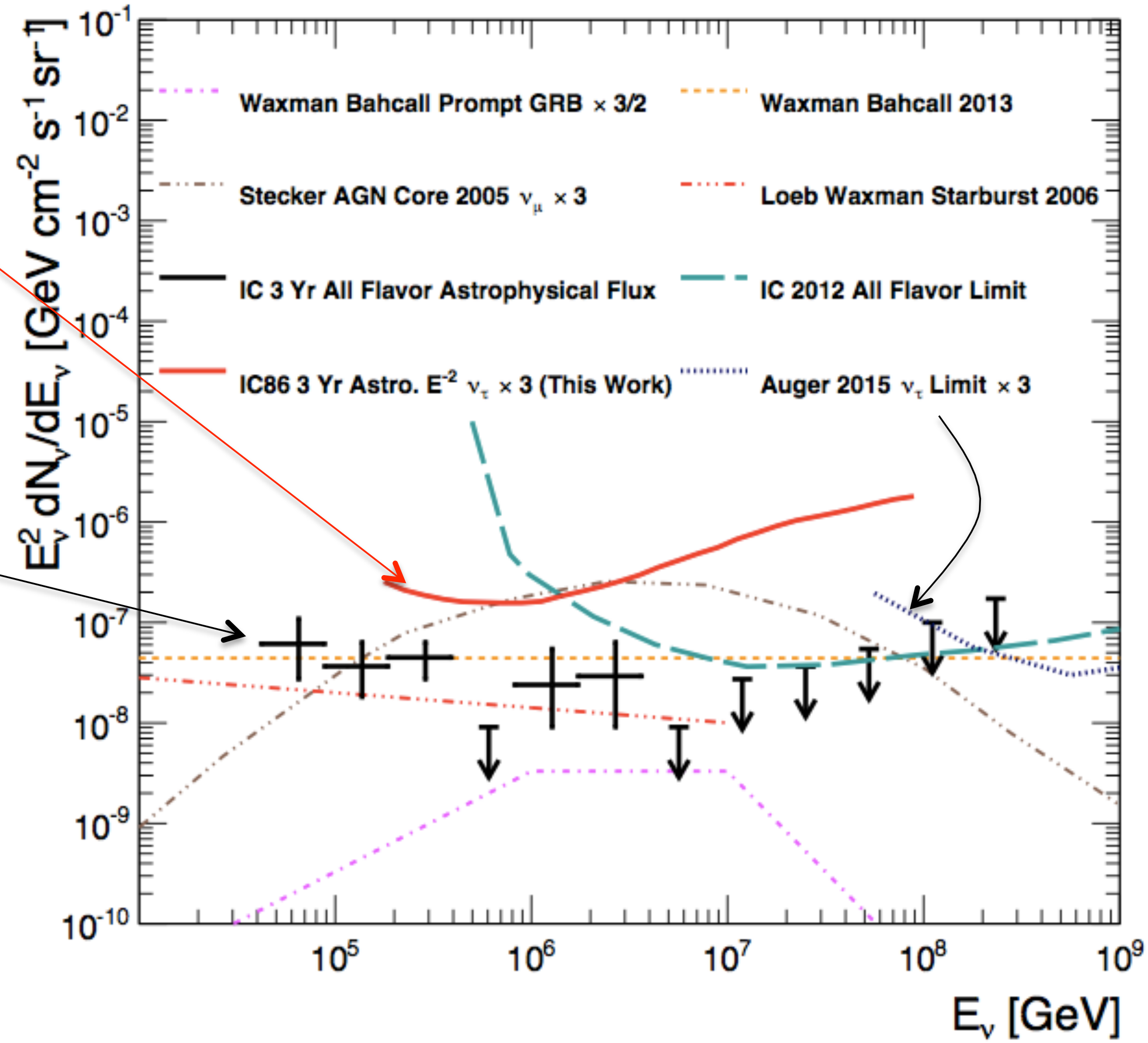
Result

- No candidate events were observed; Much improved upper limit on astrophysical ν_τ flux between 214 TeV - 72 PeV.

ν_τ flux upper limits and comparisons

ν_τ differential upper limit derived from this analysis. *Submitted to PRD, arxiv: 1509.06212*

All-flavor astrophysical neutrino flux *PRL. 113(2014) 101101*



Neutrino flux upper limits and models as a function of the primary neutrino energy.

Indirect search for DM in IceCube

Multipole Analysis of IceCube Data to Search for Dark Matter Accumulated in the Galactic Halo
IceCube Collaboration: M. G. Aartsen et al
(Journal) The European Physical Journal C75; e-print archive arXiv:1406.6868 [astro-ph.HE]

Search for Dark Matter Annihilations in the Sun with the 79-string IceCube Detector
IceCube Collaboration: M. G. Aartsen et al
(Journal) Physical Review Letters 110 (2013) 131302; e-print archive arXiv:1212.4097 [astro-ph.HE], 17 December 2012

Multiyear Search for Dark Matter Annihilations in the Sun with the AMANDA-II and IceCube Detectors
IceCube Collaboration: R. Abbasi et al
(Journal) Physical Review **D85** (2012) 042002, 22 February 2012

Search for Neutrinos from Annihilating Dark Matter in the Direction of the Galactic Center with the 40-String IceCube Neutrino Observatory
IceCube Collaboration: R. Abbasi et al
(Journal) e-print archive arXiv:1210.3557 [astro-ph.HE], 12 October 2012

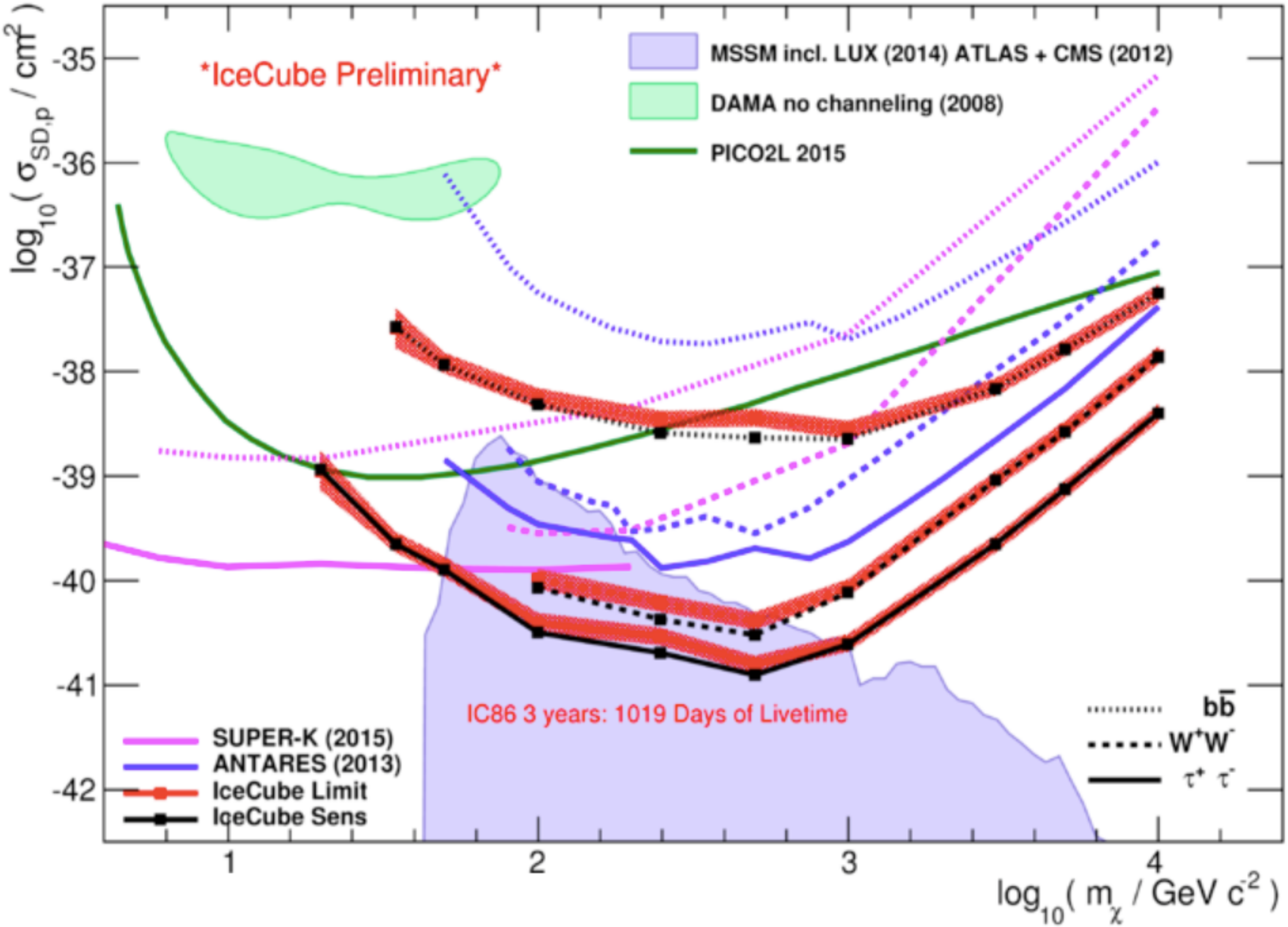
Search for Dark Matter from the Galactic Halo with the IceCube Neutrino Telescope
IceCube Collaboration: R. Abbasi et al
(Journal) Physical Review **D84** (2011) 022004, 29 July 2011

Limits on a Muon Flux from Kaluza-Klein Dark Matter Annihilations in the Sun from the IceCube 22-string Detector
IceCube Collaboration: R. Abbasi et al
(Journal) Physical Review **D81** (2010) 057101, 29 March 2010

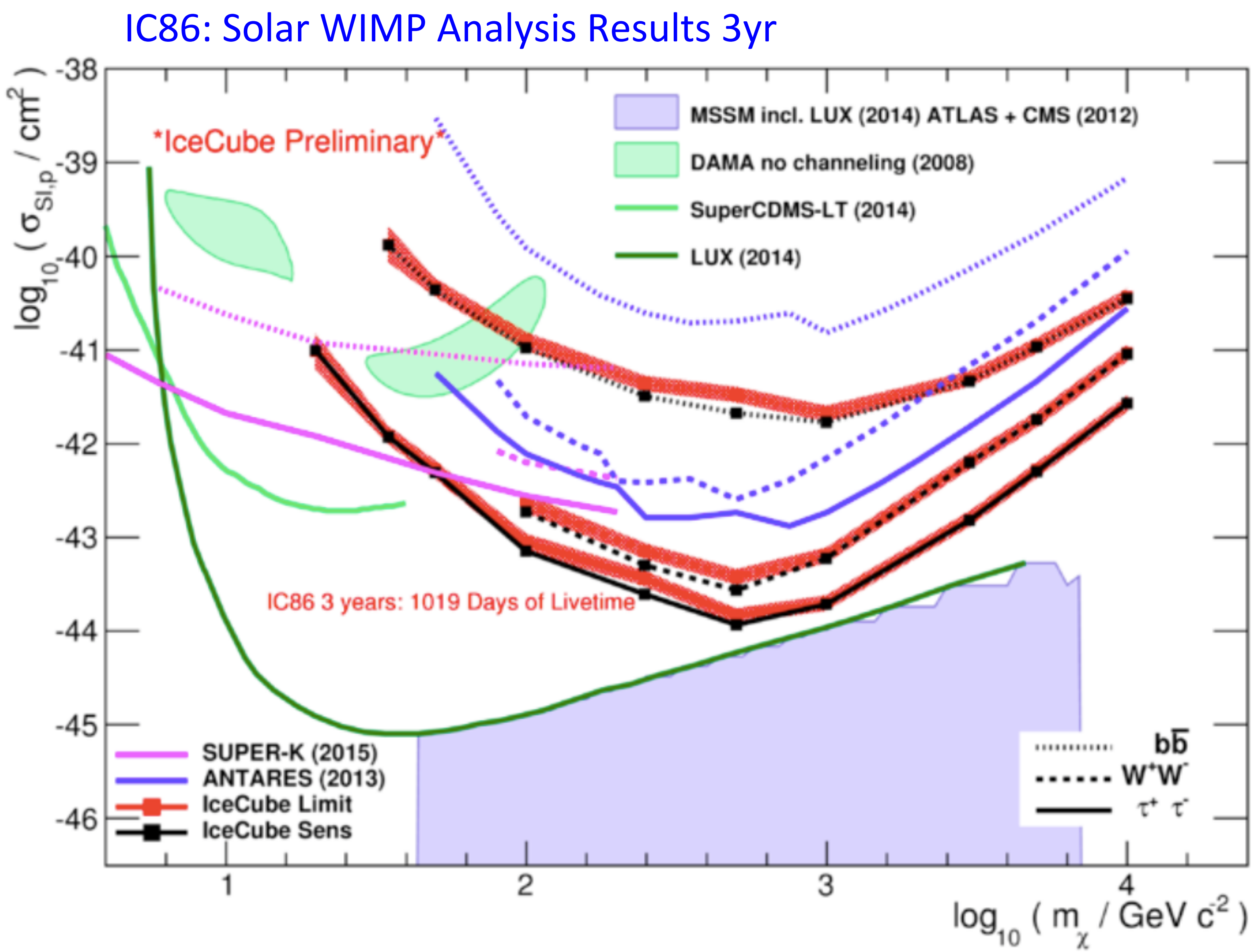
The Indirect Search for Dark Matter with IceCube
Francis Halzen and Dan Hooper
(Journal) New Journal of Physics **11** (2009) 105019, October 2010

Indirect search for DM in IceCube: σ_{SD}

IC86: Solar WIMP Analysis Results 3yr



Indirect search for DM in IceCube: σ_{SI}



Where we stand

IceCube has

1. Discovered the hypothesized flux of high-energy cosmic neutrinos
2. Provided compelling sensitivity to dark matter annihilations
3. New results about cosmic rays, GRBs, neutrino physics, …
4. **Demonstrated that an ice-based detector can pursue**
   - neutrino astronomy
   - cosmic ray physics
   - neutrino physics
   - dark matter
   - …

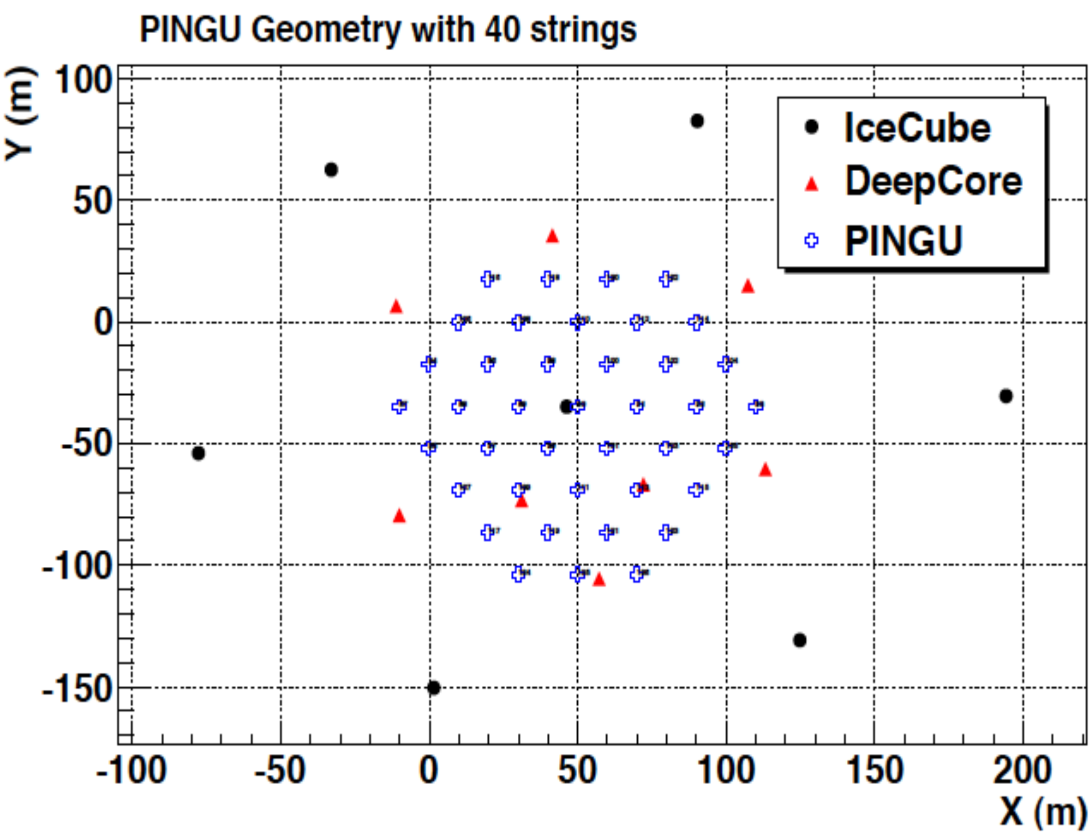
Improvements & Open Questions

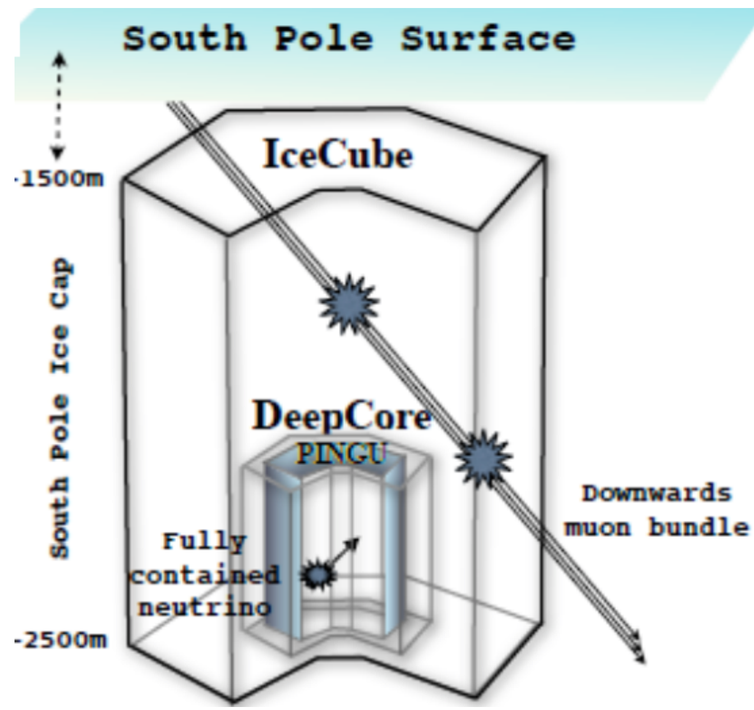
1. HECR origin puzzle remains unsolved
   - Neutrino point source versus diffuse
   - Mechanism of UHECR production: Bottom-up versus top-down, and how?
   - UHE particle propagation
2. Uncertainties in astrophysical calculations and modeling
3. Precise spectrum of astrophysical and cosmogenic neutrinos
4. Lepton flavor & astrophysical processes
5. Details of high energy astrophysical objects and processes
6. "3M" observations: What to look for?
7. Dark matter
8. Universe at ultra high energies
9. Universe at ultra large distances
10. …

IceCube-Gen2: Low energy extension

Current experimental uncertainties:
- Ice calibration and model (5% - 15%)
- Absolute DOM efficiency (15% - 50%)

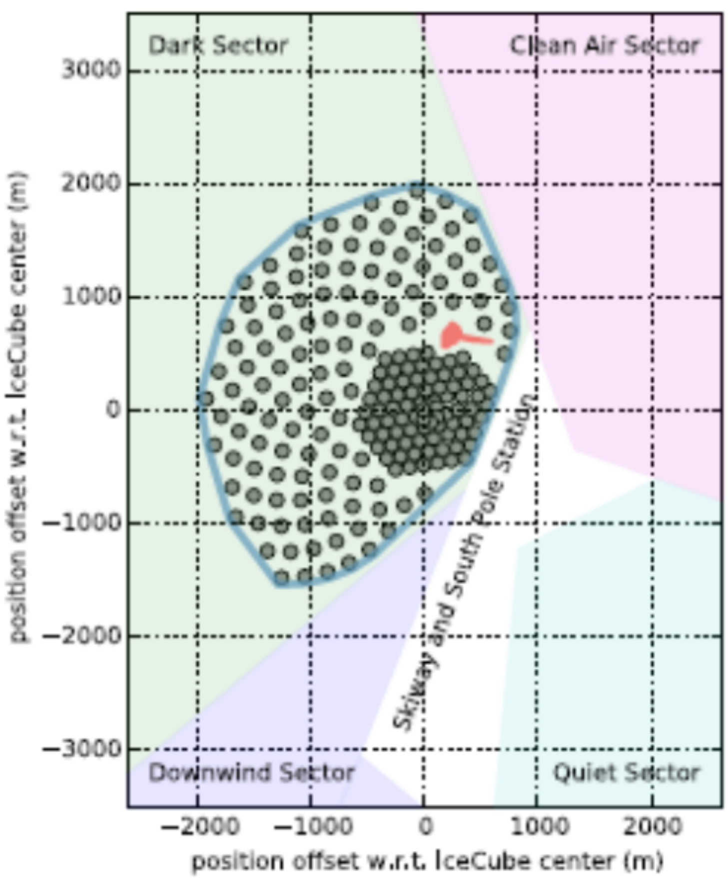
Proposed solutions:
- More precise & finer ice property calibration
- Higher QE PMTs: 25%→40%→~45%?
- Denser strings: 125m→75m→~25m
- Denser DOMs: 17m→7m→~5m

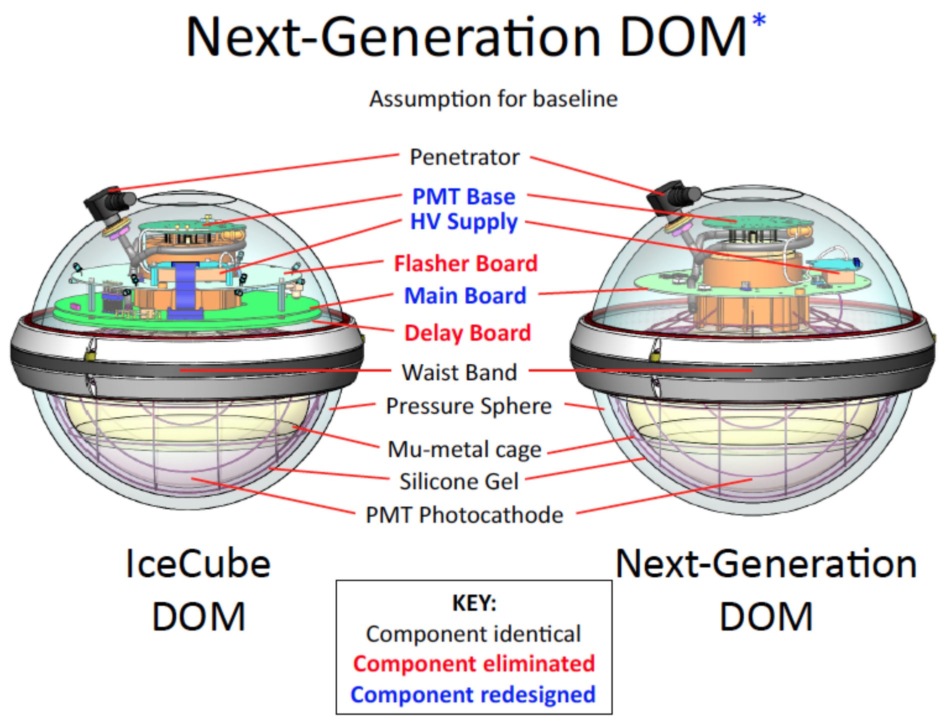




IceCube-Gen2: High energy extension

- 120 additional strings
- Average spacing 240 m
- Total volume ~10 km^3

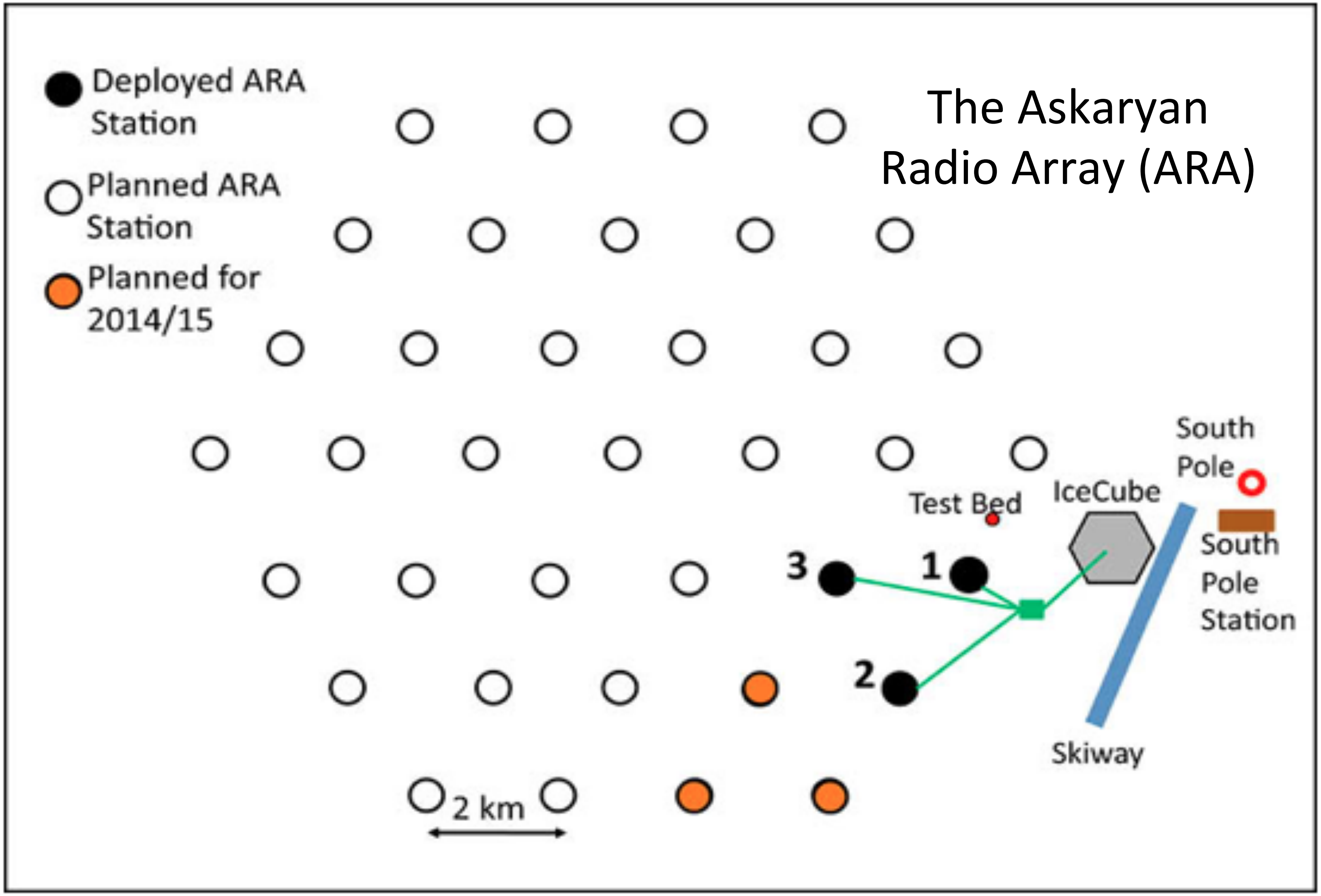


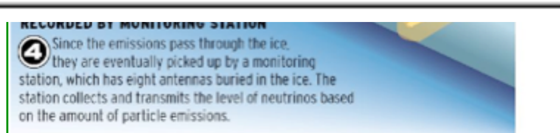


*P. Sandstrom *et al.*, VLVnT13 (Stockholm)

High energy option-2

Ask





From OC Register 2012

More details

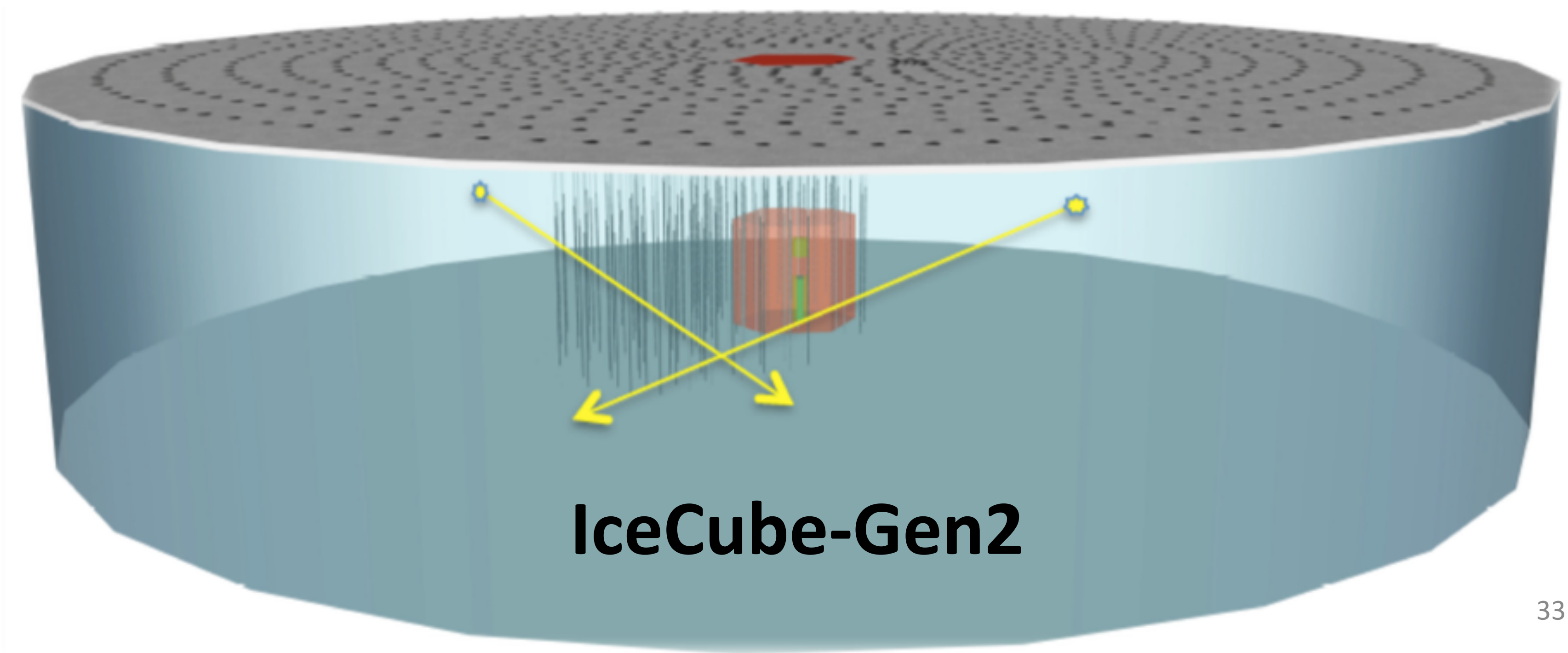
arXiv.org > astro-ph > arXiv:1412.5106

Search or A

Astrophysics > High Energy Astrophysical Phenomena

IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica

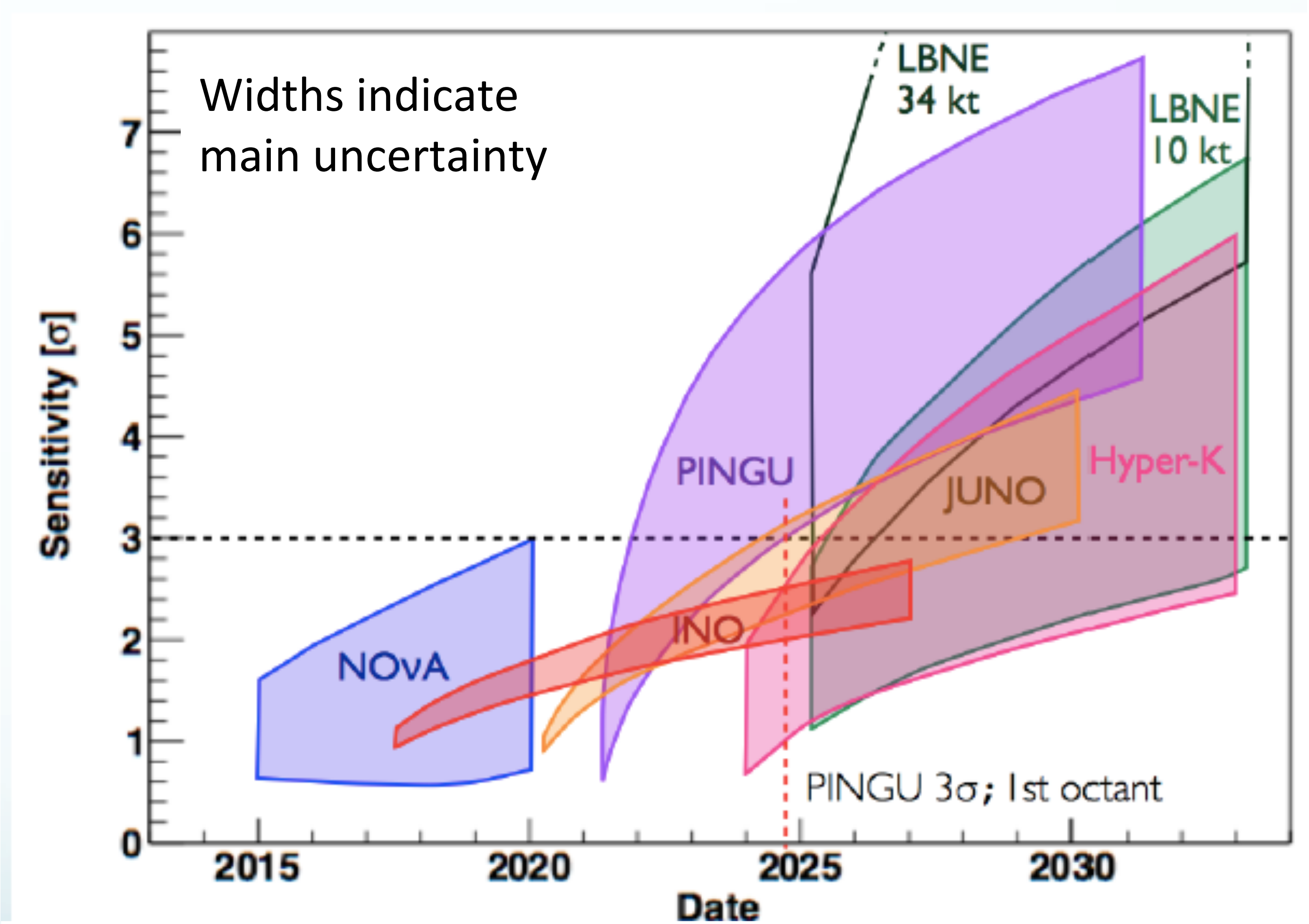
IceCube-Gen2 Collaboration: M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D. Altmann, T. Anderson, G. Anton, C. Arguelles, T. C. Arlen, J. Auffenberg, S. Axani, X. Bai, I. Bartos, S. W. Barwick, V. Baum, R. Bay, J. J. Beatty, J. Becker Tjus, K.-H. Becker, S. BenZvi, P. Berghaus, D. Berley, E. Bernardini, A. Bernhard, D. Z. Besson, G. Binder, D. Bindig, M. Bissok, E. Blaufuss, J. Blumenthal, D. J. Boersma, C. Bohm, F. Bos, D. Bose, S. Böser, O. Botner, L. Brayeur, H.-P. Bretz, A. M. Brown, N. Buzinsky, J. Casey, M. Casier, E. Cheung, D. Chirkin, A. Christov, B. Christy, K. Clark, L. Classen, F. Clevermann, S. Coenders, G. H. Collin, J. M. Conrad, D. F. Cowen, A. H. Cruz Silva, J. Daughhetee, J. C. Davis, M. Day, J. P. A. M. de André, C. De Clercq, S. De Ridder, et al. (265 additional authors not shown)



IceCube-Gen2

IceCube-Gen2: What to expect, mass hierachy

Neutrino physics

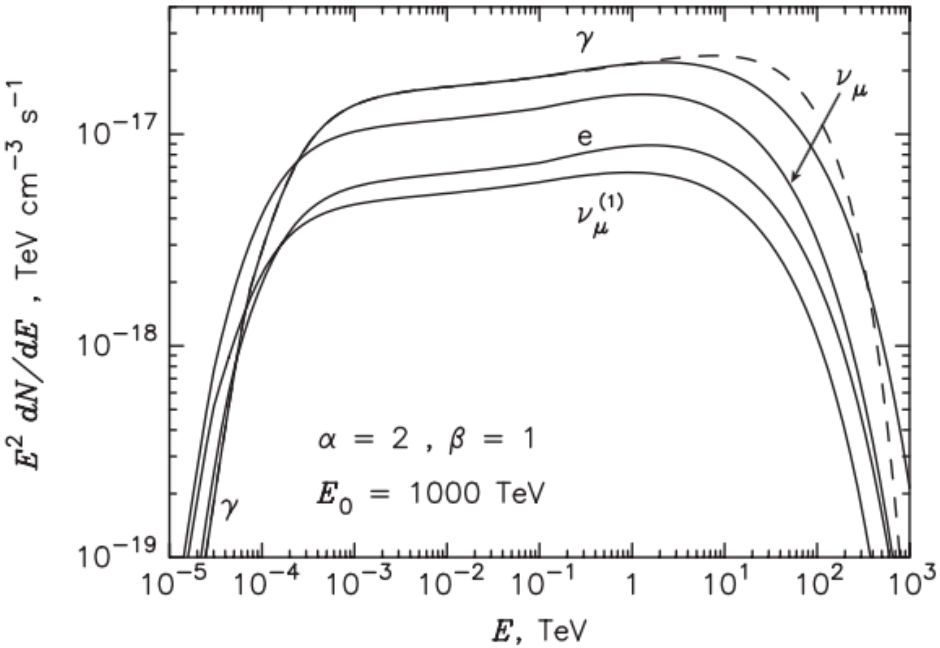


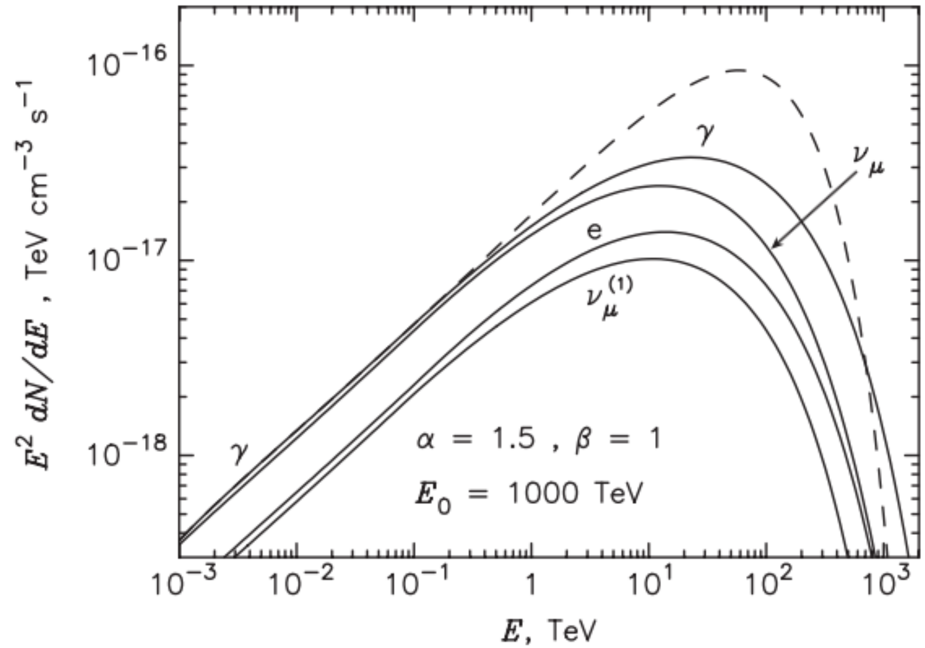
Blennow et al., arxiv:1311.1822, LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011)

Spectrum and source flux

Hadron-nuclear interactions: proton energy spectrum

Kelner, Aharonian & Bugayov, 2006



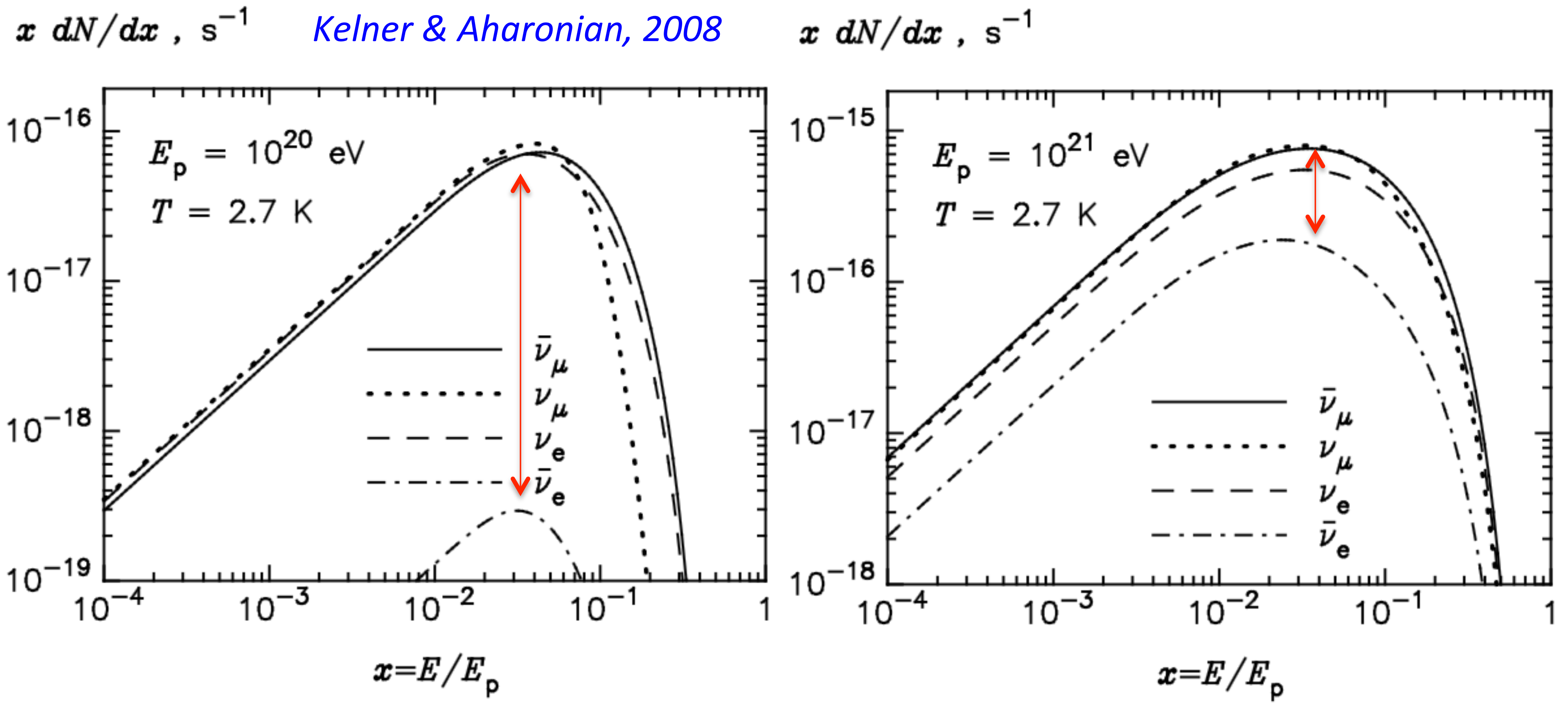


Energy spectra of gamma rays and leptons from p-p interactions calculated for the distribution of protons

$$J_p(E_p) = \frac{A}{E_p^\alpha} \exp\left[-\left(\frac{E_p}{E_0}\right)^\beta\right], \qquad (74)$$

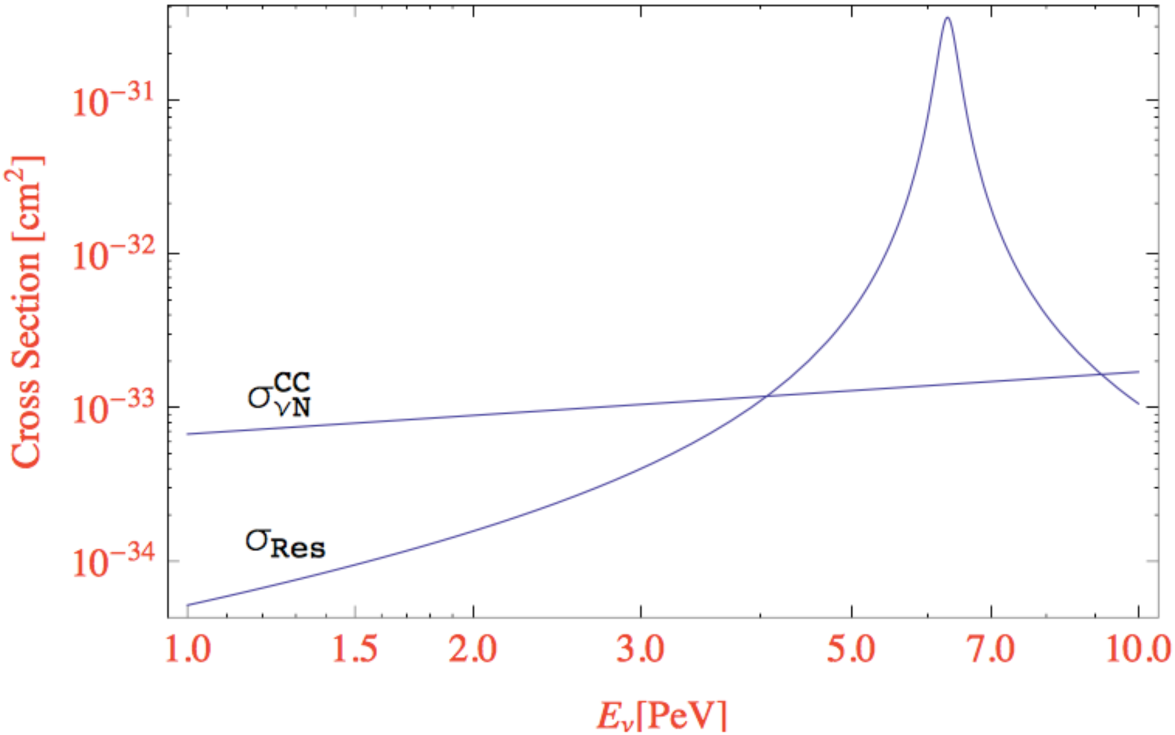
$\nu_\mu^{(1)}$ neutrinos from the direct decay $\pi \rightarrow \mu\nu_\mu$

CR at GZK energy and flavor



Cosmic neutrinos

The Glashow resonance: flavor filter



- The W-resonance: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ anything, at $E_\nu \simeq 6.3$ PeV, the Glashow resonance. (ν_e, ν_μ, ν_τ , $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ + electron ~ negligible). *S. L. Glashow, 1960*

Signal for $\bar{\nu}_e$ at the Glashow resonance can be used to differentiate among the main primary mechanisms for neutrino-producing interactions in sources of cosmic rays. *V. Barger, et al. 2013, 2014.*

- Sub-PeV neutrinos of other flavors may have resonance in the Coulomb field of a nucleus. *I. Alikhanov, 2015.*

The Glashow resonance& Lepton flavor and sources

TABLE I: Neutrino flavor ratios at source, component of $\bar{\nu}_e$ in total neutrino flux at Earth after mixing and decohering, and consequent relative strength of Glashow resonance, for six astrophysical models. (Neutrinos and antineutrinos are shown separately, when they differ.)

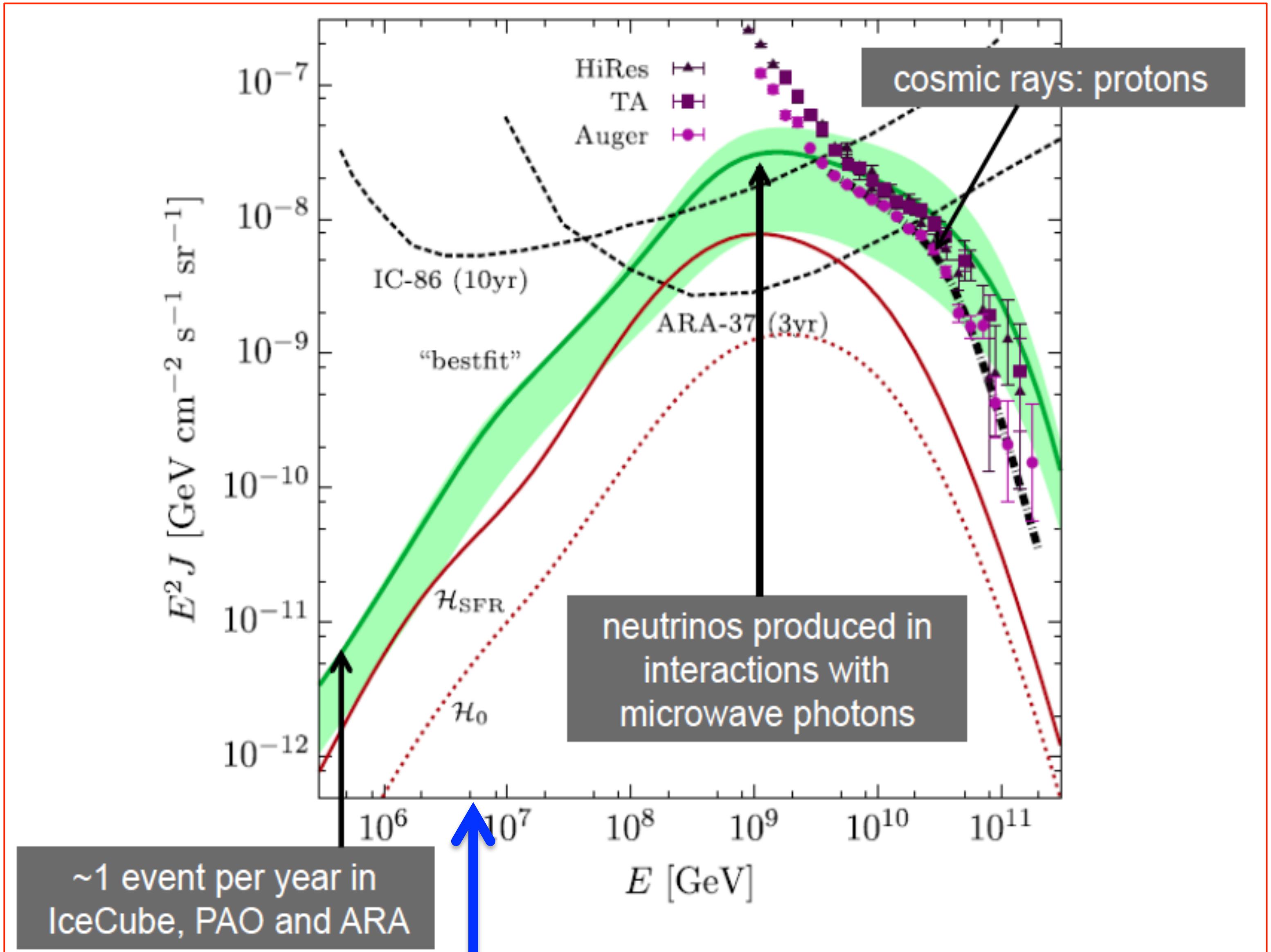
	Source flavor ratio		Earthly flavor ratio		$\bar{\nu}_e$ fraction in flux ($\mathcal{R}$)
$pp \to \pi^{\pm}$ pairs	(1:2:0)		(1:1:1)		$18/108 = 0.17$
w/ damped $\mu^{\pm}$	(0:1:0)		(4:7:7)		$12/108 = 0.11$
$p\gamma \to \pi^{+}$ only	(1:1:0)	(0:1:0)	(14:11:11)	(4:7:7)	$8/108 = 0.074$
w/ damped μ^{+}	(0:1:0)	(0:0:0)	(4:7:7)	(0:0:0)	0
charm decay	(1:1:0)		(14:11:11)		$21/108 = 0.19$
neutron decay	(0:0:0)	(1:0:0)	(0:0:0)	(5:2:2)	$60/108 = 0.56$

Small difference

V. Barger, et al., 2014

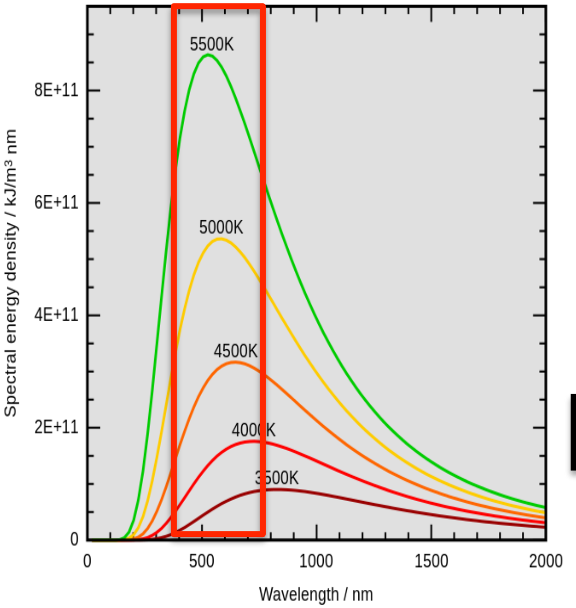
Flavor astrophysics?

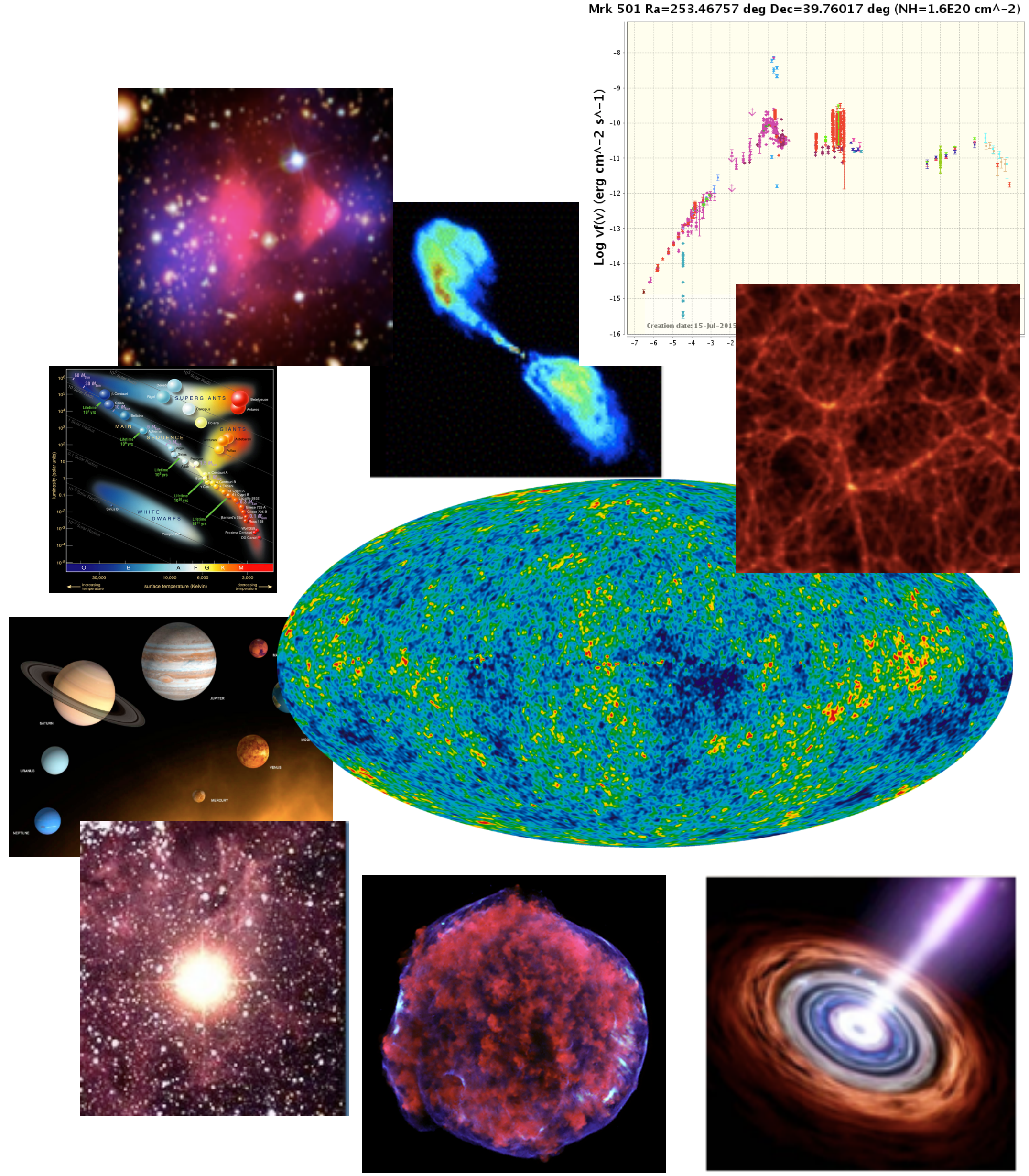
At the cosmic energy frontier



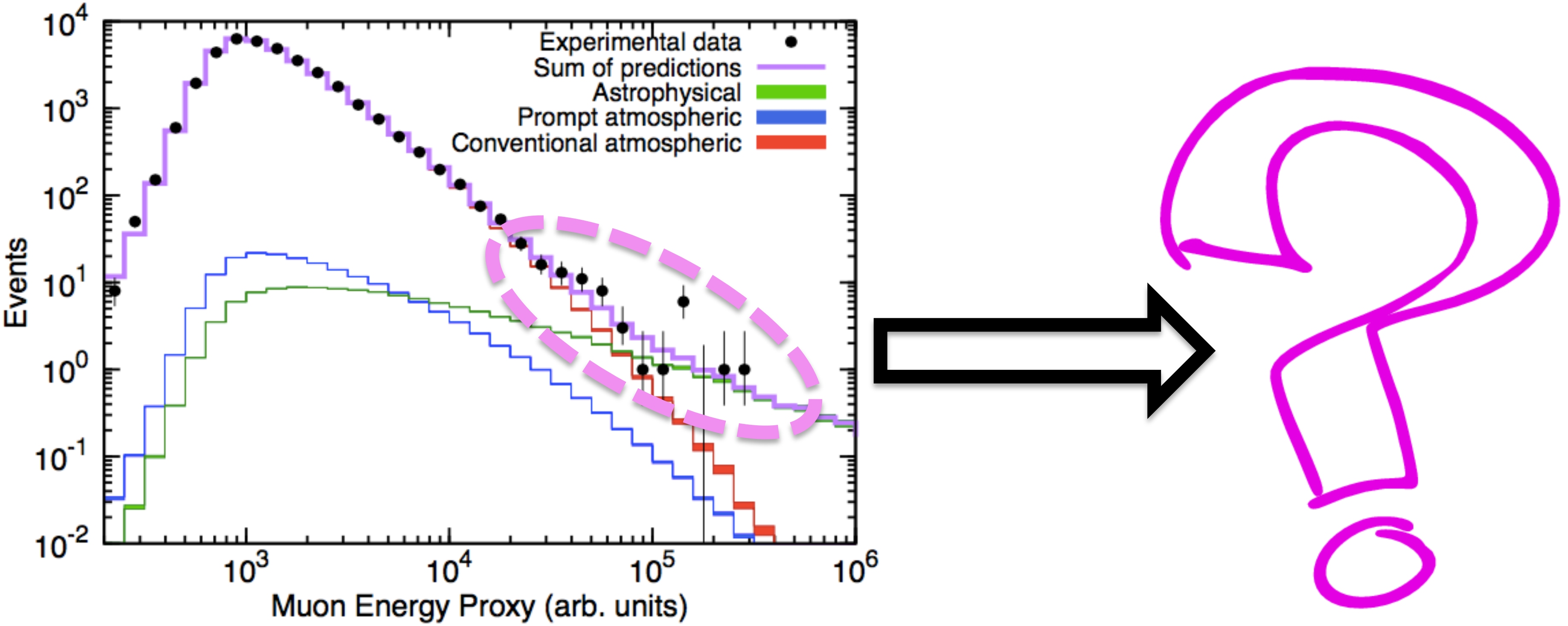
$E_\nu \simeq$ 6.3 PeV, G.R. peak

IceCube-Gen2: What really to expect





IceCube-Gen2: What really to expect



IceCube-Gen2 matters for us

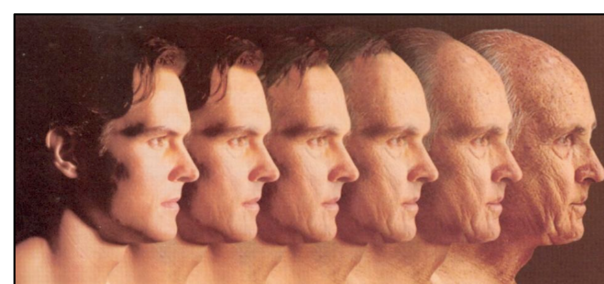
IceCube-Gen2

Data rate ≈ 10 ×

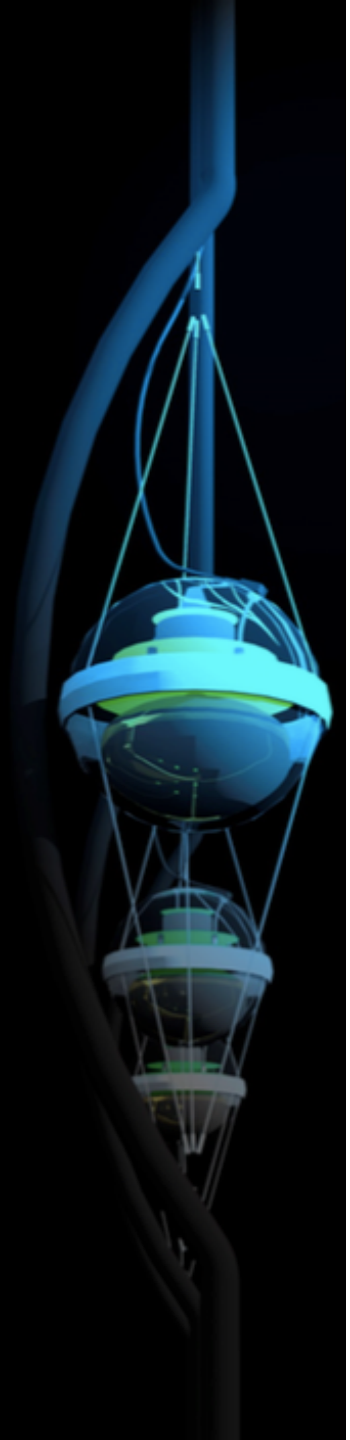
IceCube

- ~280 million cosmic rays events per day
- ~500 neutrinos per day
- About 1 TB of unfiltered raw data per day
- About 100 GB filtered data are sent out from the South Pole over satellite for analysis every day.

$T_{resolving}$ ≈ **/10**



Summary



High energy astrophysical neutrinos are discovered by IceCube.

Long-standing high energy CR origin puzzle remains unsolved.

Scientifically, IceCube-Gen2 is highly needed; Technically, IceCube-Gen2 can be built.

IceCube-Gen2 data means new observational astronomy & astrophysics in energy and cosmic frontiers.

Questions

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