Understanding IceCube's astrophysical neutrino observations

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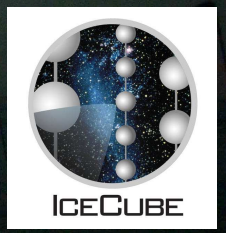
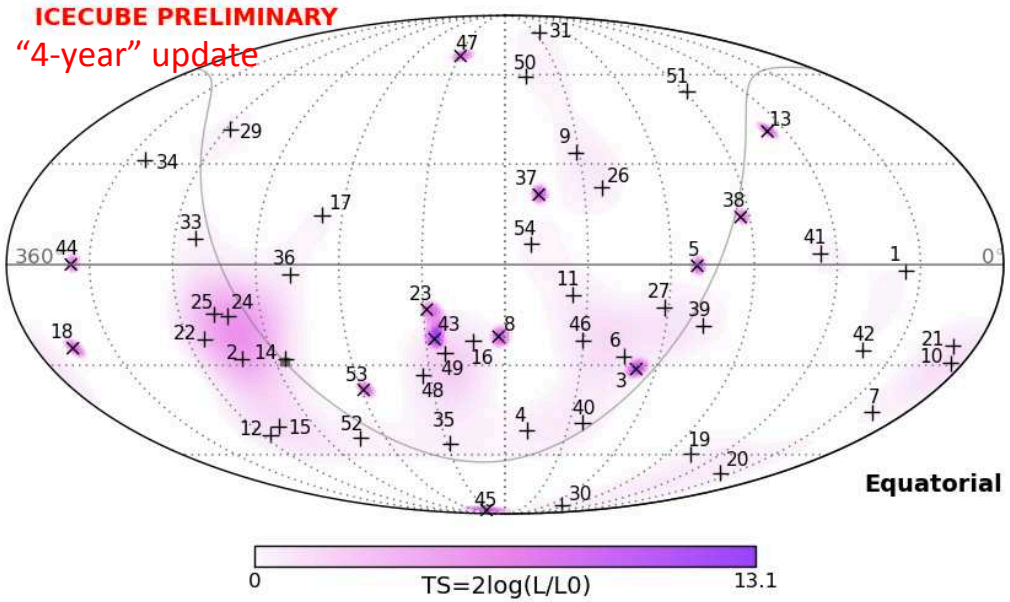


Astrophysical neutrinos observed: What are the sources?



Consistent with an isotropic diffuse flux (>100 sources)

Event flavor consistent with standard neutrino oscillations

Point source: No (p-value 0.44 cascades / 0.58 all)

Galactic plane: No (p-value 0.025; 7.5^{o} band)

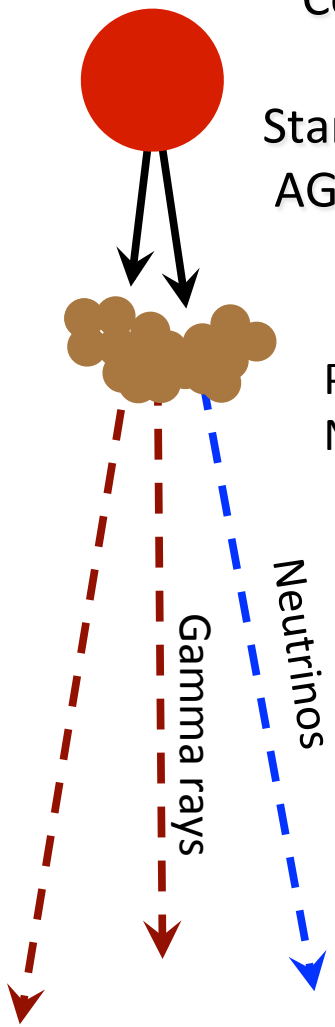
Follow up by multiple instruments (e.g. VERITAS, HAWC): No obvious counterpart

GRBs (prompt < 0.5%, ±20h <12%): No

Blazars < 20%

Star Burst galaxies disfavored by Fermi

Cosmic ray – γ-ray – neutrino connection



Cosmic particle accelerator:
Star burst galaxies, AGNs, SNRs, etc ..

Photon field or matter
Near/at the accelerator

Cosmic ray – matter / photon interaction:

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$p + p \rightarrow A\pi^+ + B\pi^- + C\pi^0 + X$$

Collision results in photons & neutrinos

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

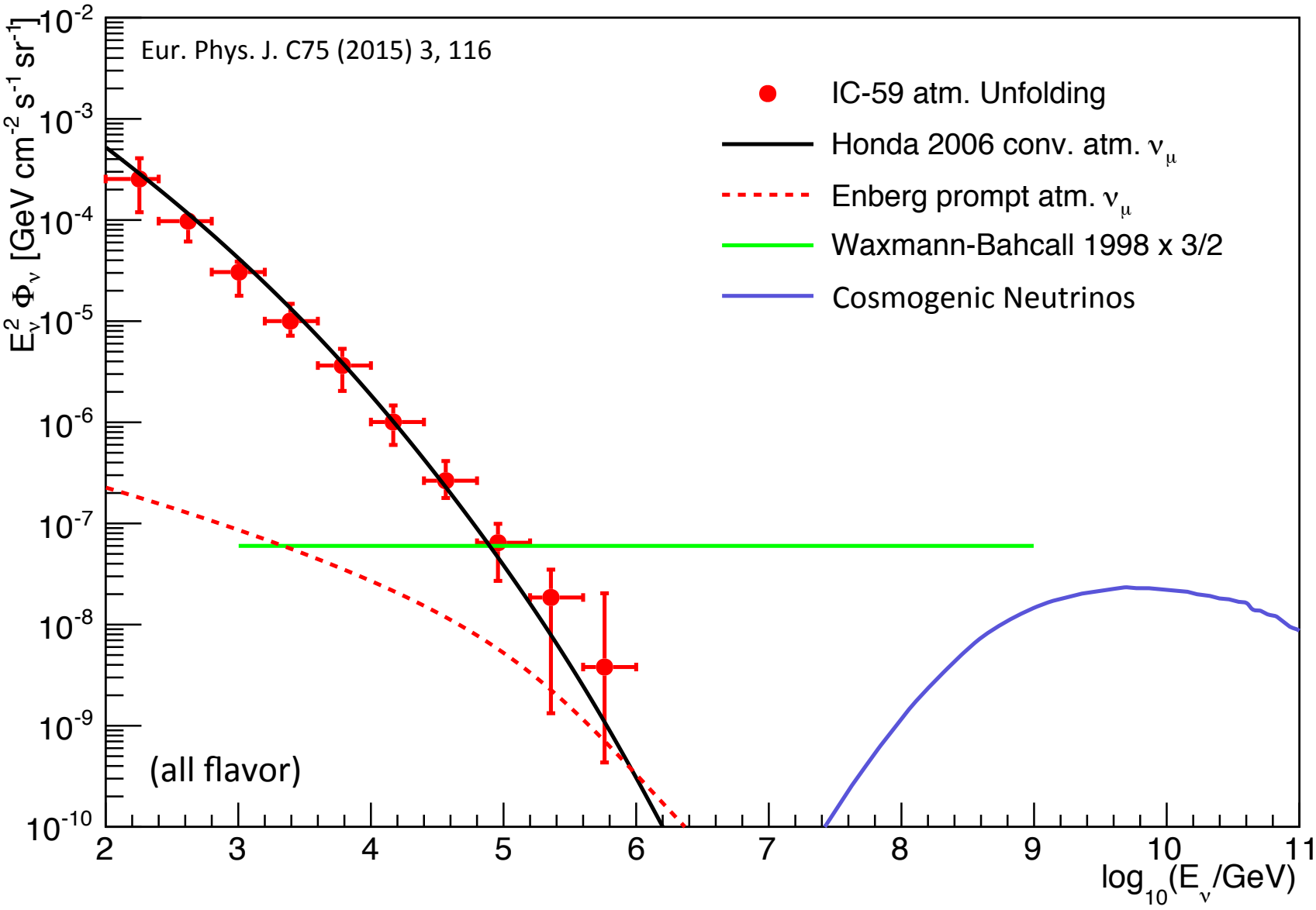
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$

$$\pi^0 \rightarrow \gamma + \gamma$$

2:1:0 | 0:1:0

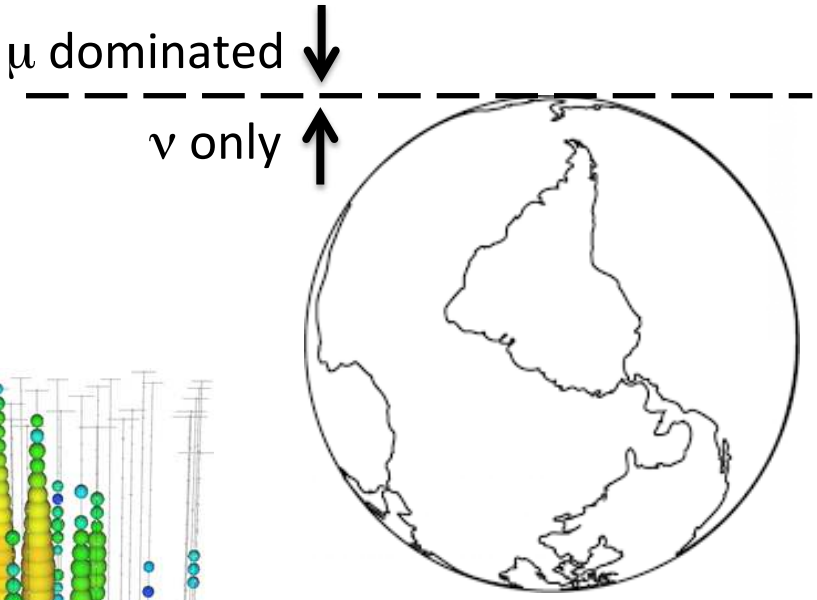
Cosmic ray sources produce neutrinos and γ-rays
γ-rays may also have leptonic origin.

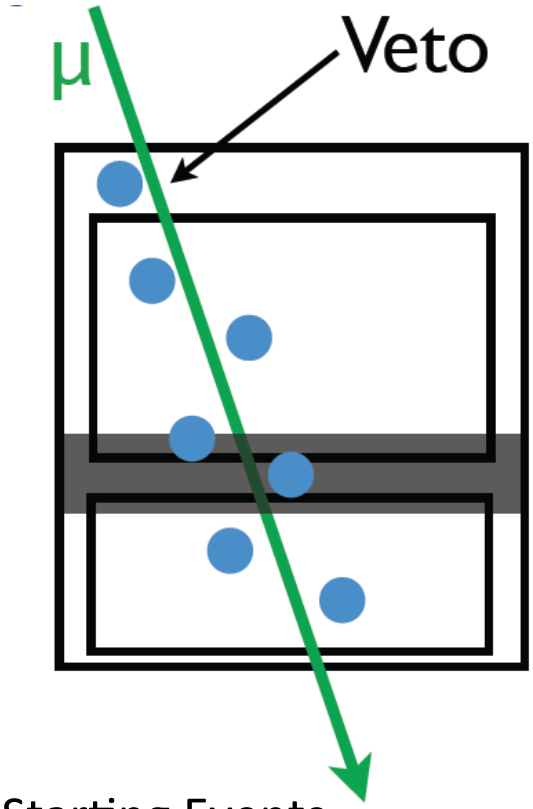
High-energy neutrinos

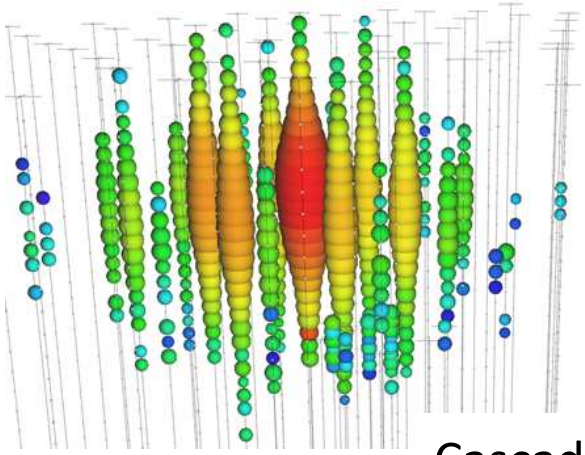


Detection methods

<u>Tracks</u> – Traditional ν astronomy
Earth as a filter
~2 π sr. ν_μ mostly.





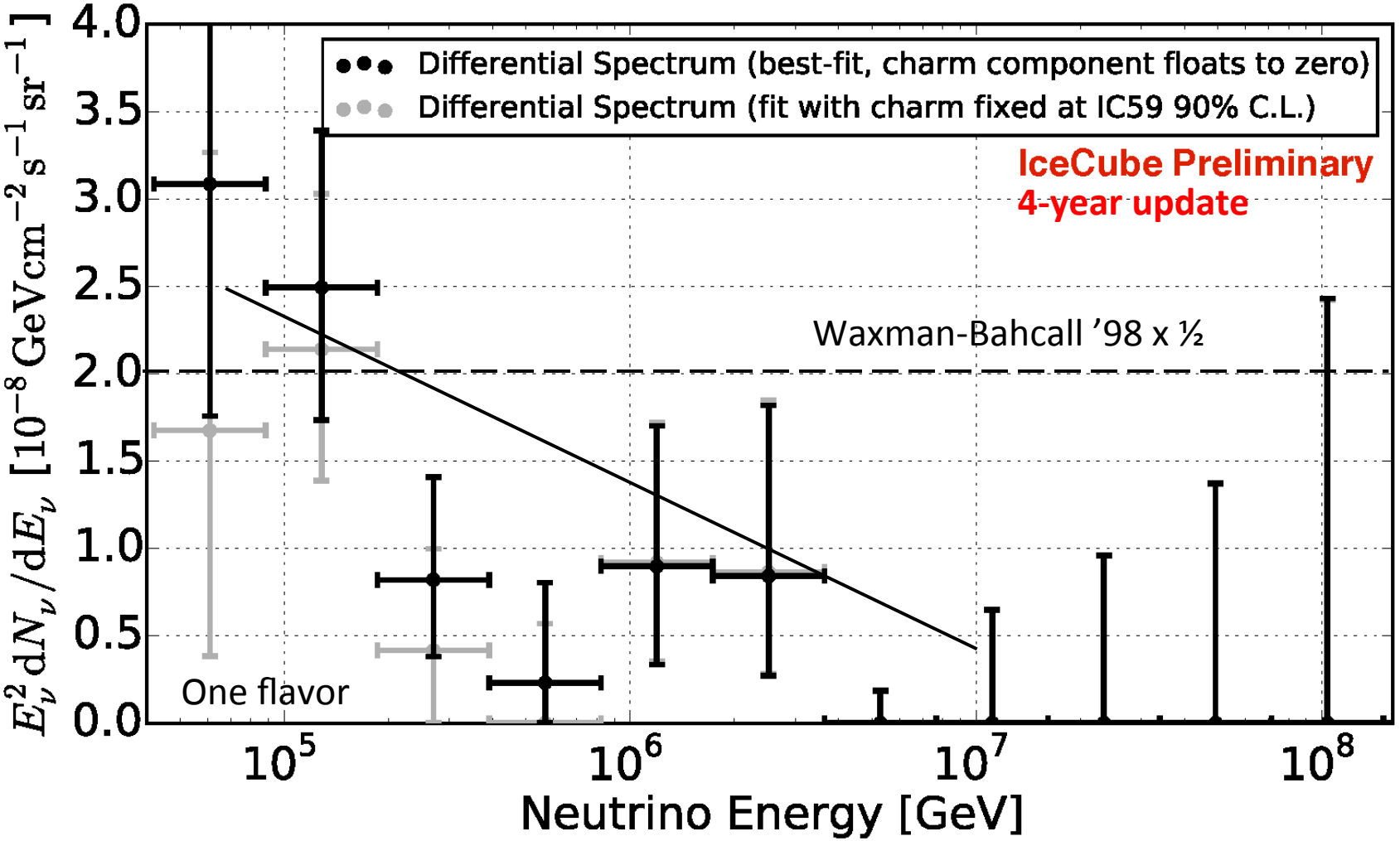


<u>Starting Events</u>
Veto and energy proxy
4 π sr. All flavor. Shower-rich.

- High-Energy Starting Event
- Medium-Energy Starting Event

<u>Cascades</u>
Event reconstruction
4 π sr. All flavor. Shower-rich.

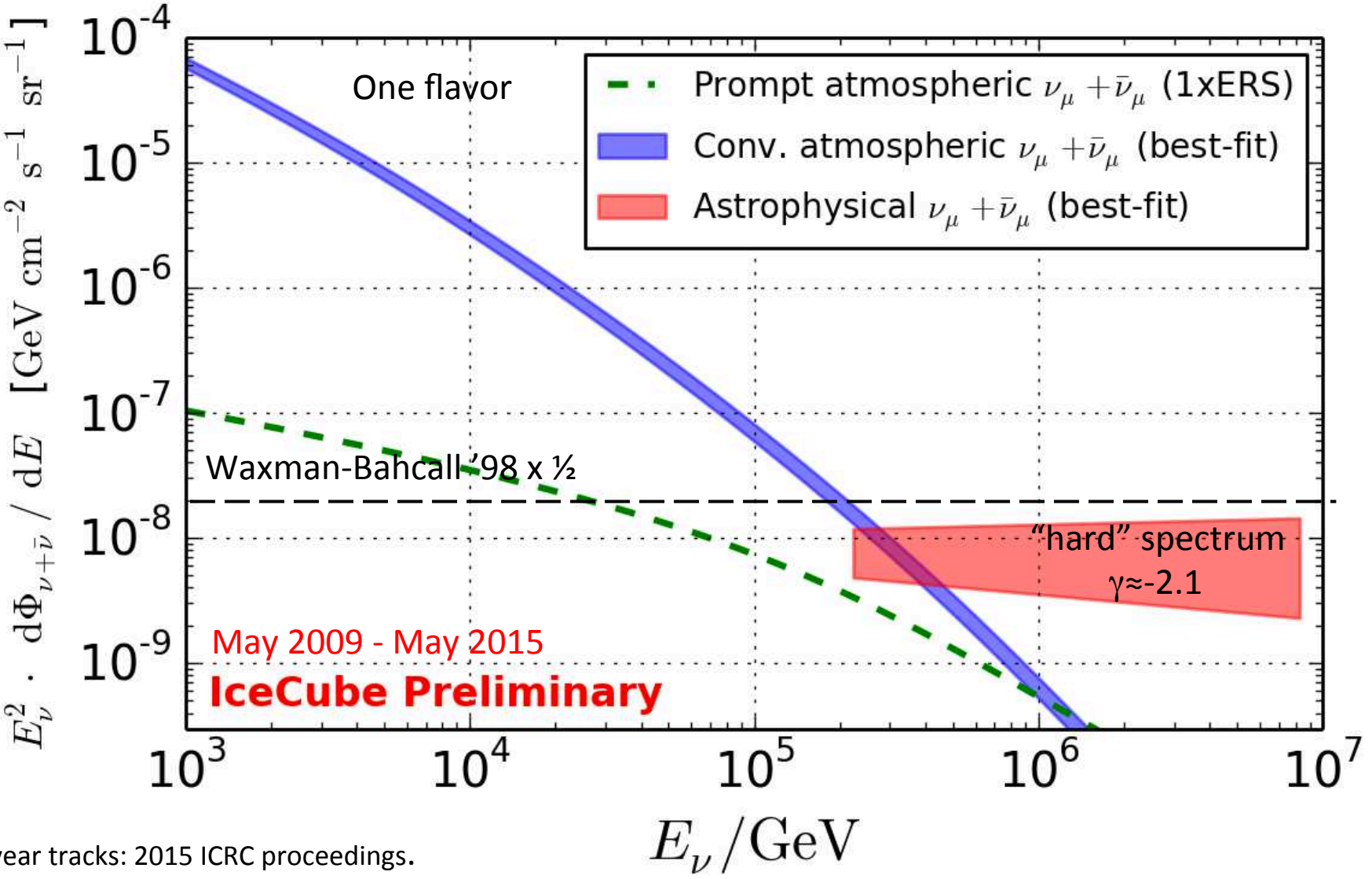
High-Energy Starting Events: spectrum



"Soft": $\gamma \approx -2.6$

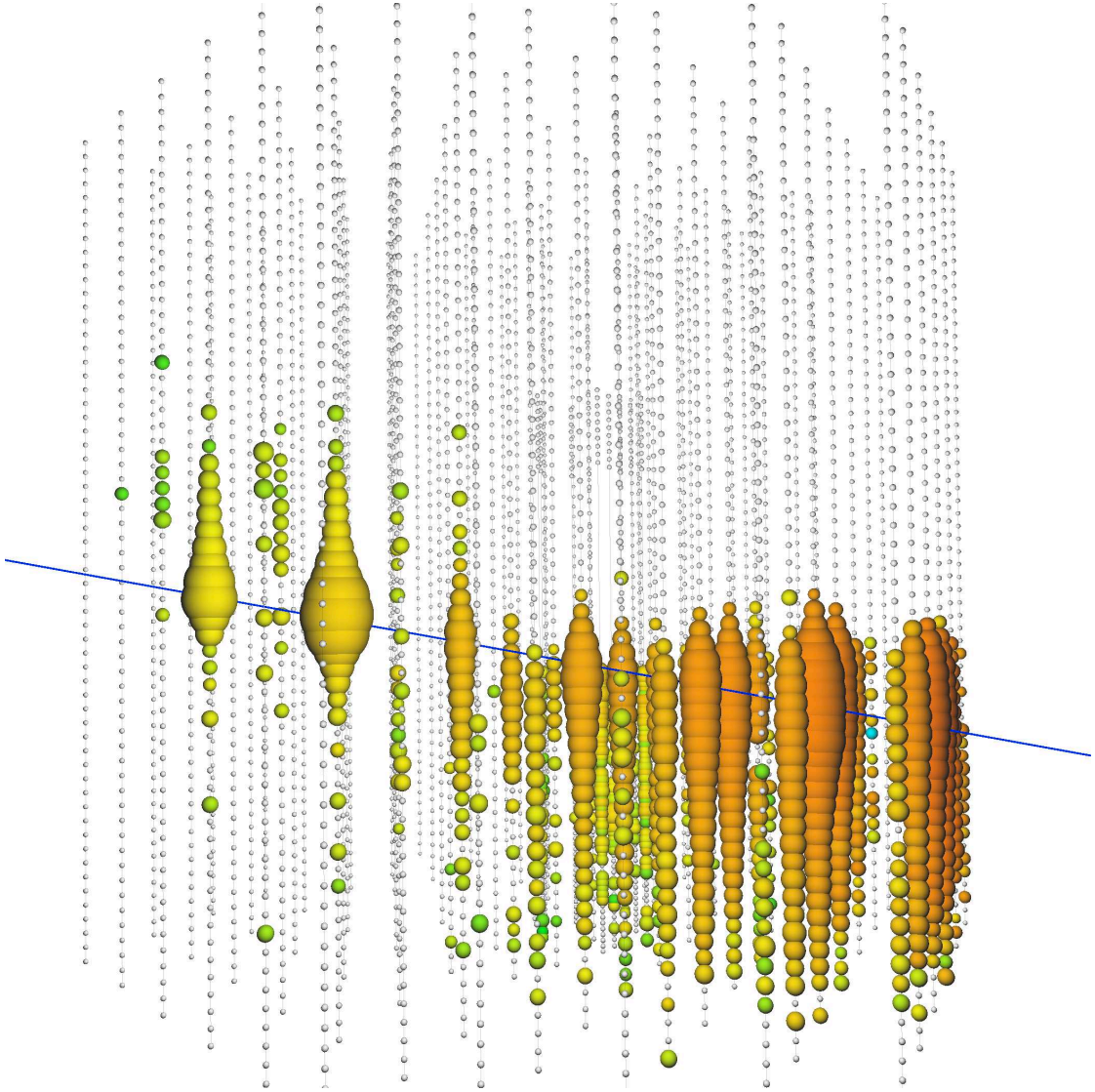
"4-year" 2015 ICRC proceedings. arXiv:1510:05223
"3-year" PRL **113** (2014) 101101
"2-year" Science **342** (2013) 6161

Through-going tracks: spectrum



6-year tracks: 2015 ICRC proceedings.
arXiv:1510:05223

Highest energy neutrino in 6 years (ν_μ search)



Several PeV track

Schoenen & Raedel et al. ATel # 7856

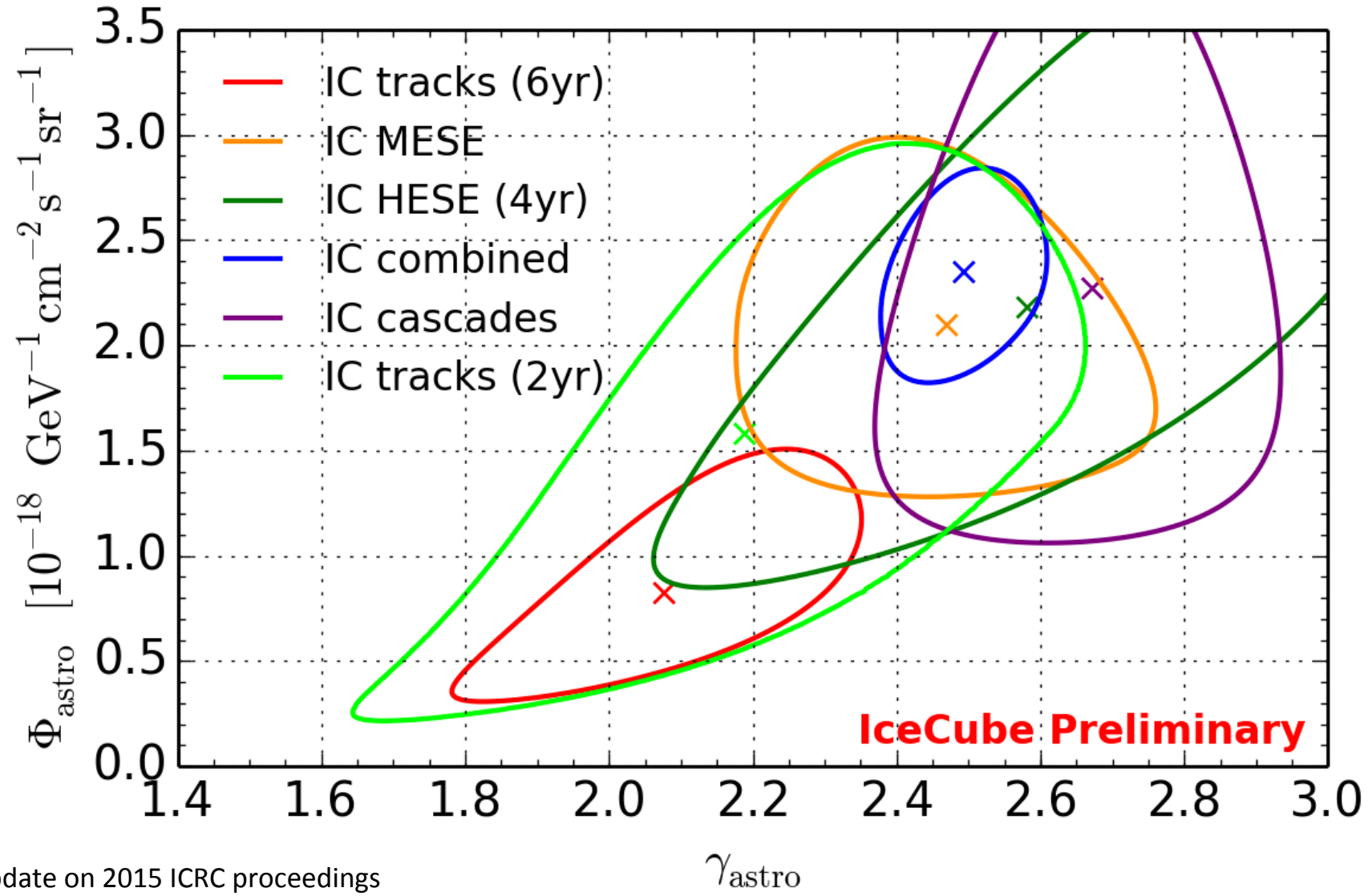
RA: 110.34^o

Dec: 11.48^o

PSF 99%: 1^o

June 11, 2014
(56819.20444852863 MJD)

Spectral index: Evidence for 2 components / populations?

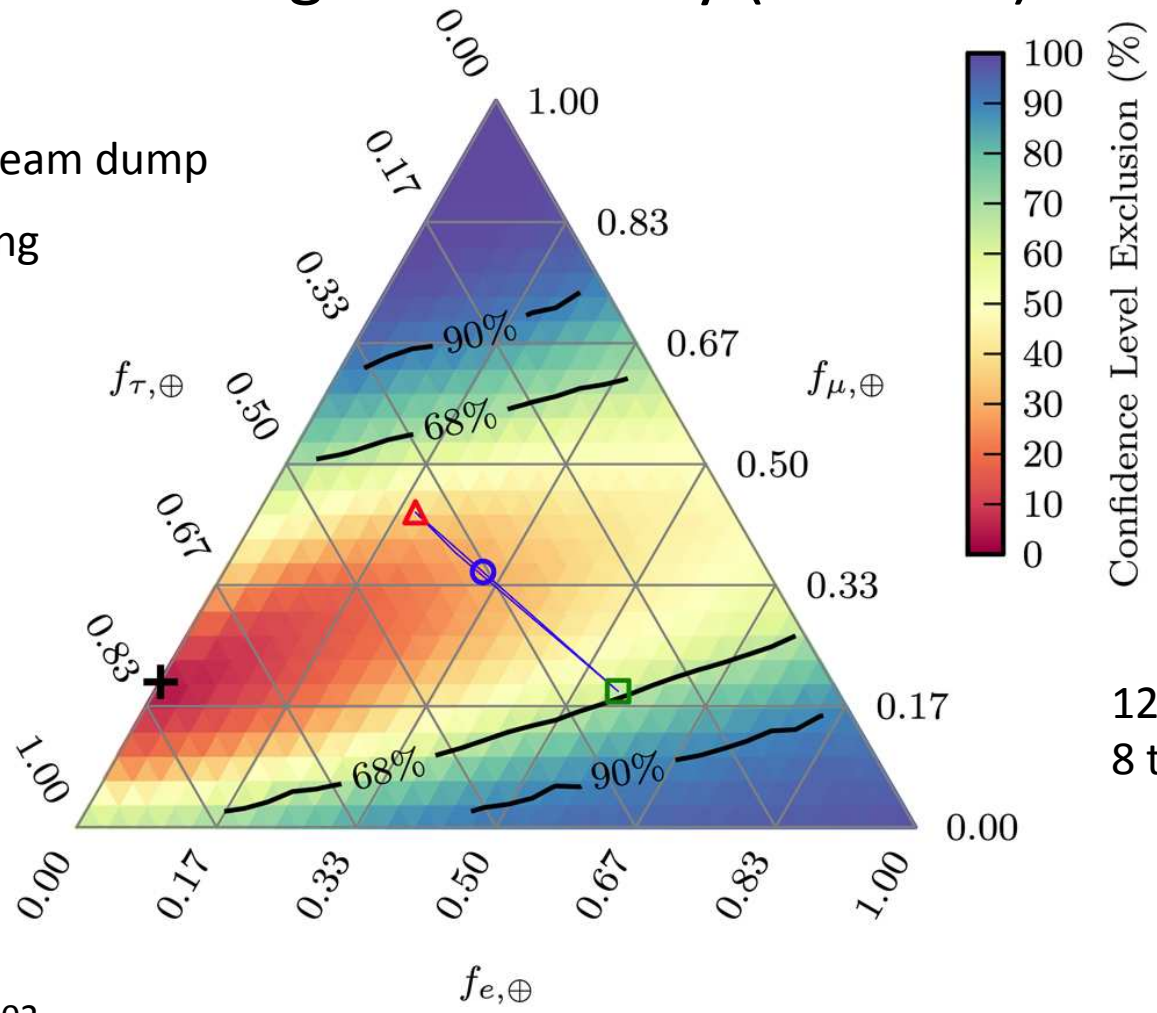


Update on 2015 ICRC proceedings
arXiv:1510:05223

Compatibility with neutrino oscillations

Variable veto starting events study (>35 TeV)

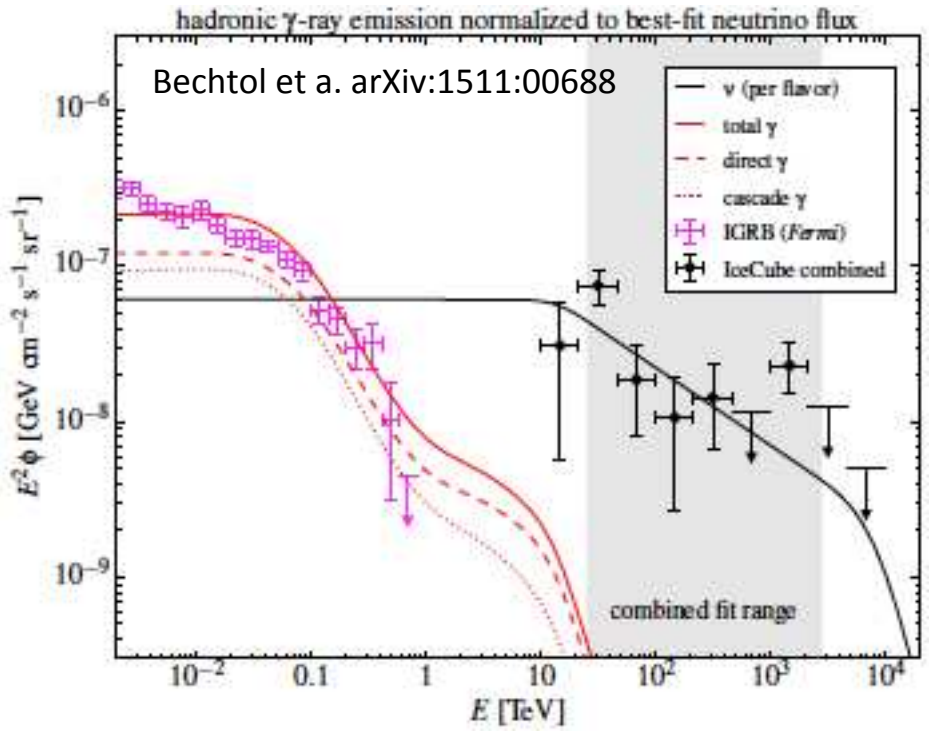
- ○ Canonical beam dump
- △ Muon cooling
- □ $\bar{\nu}_e$ source



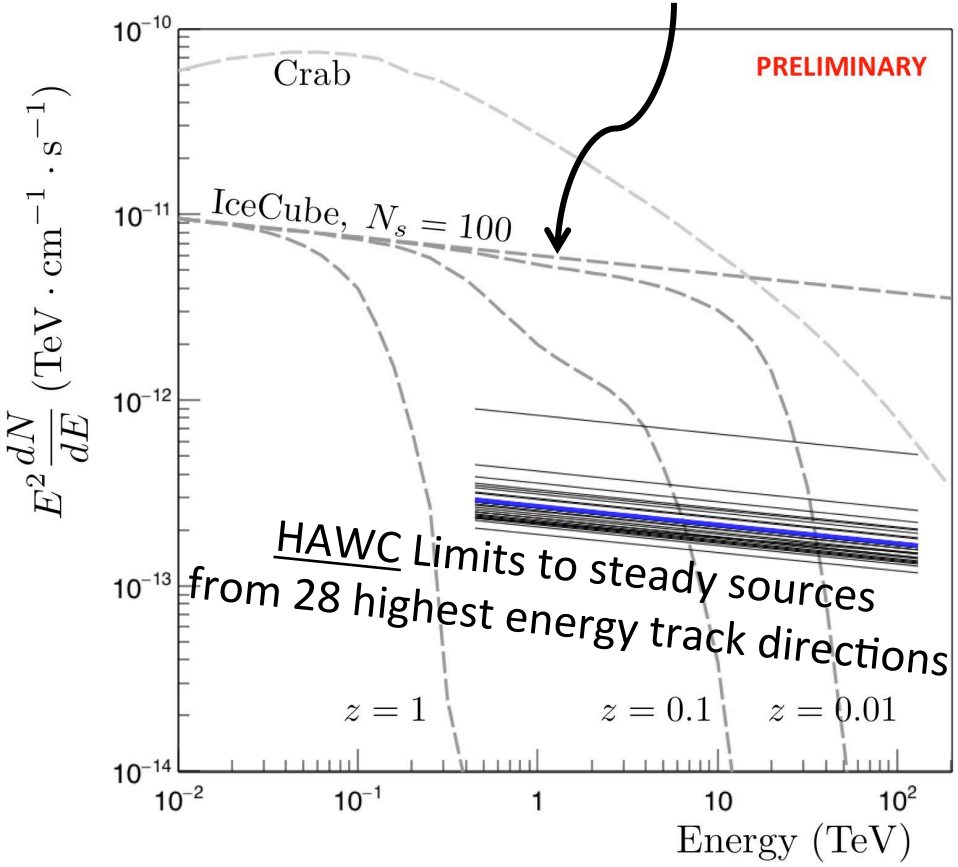
129 showers
8 tracks

PRL **114** (2015) 171102

Gamma ray counterparts



IceCube flux distributed into 100 sources

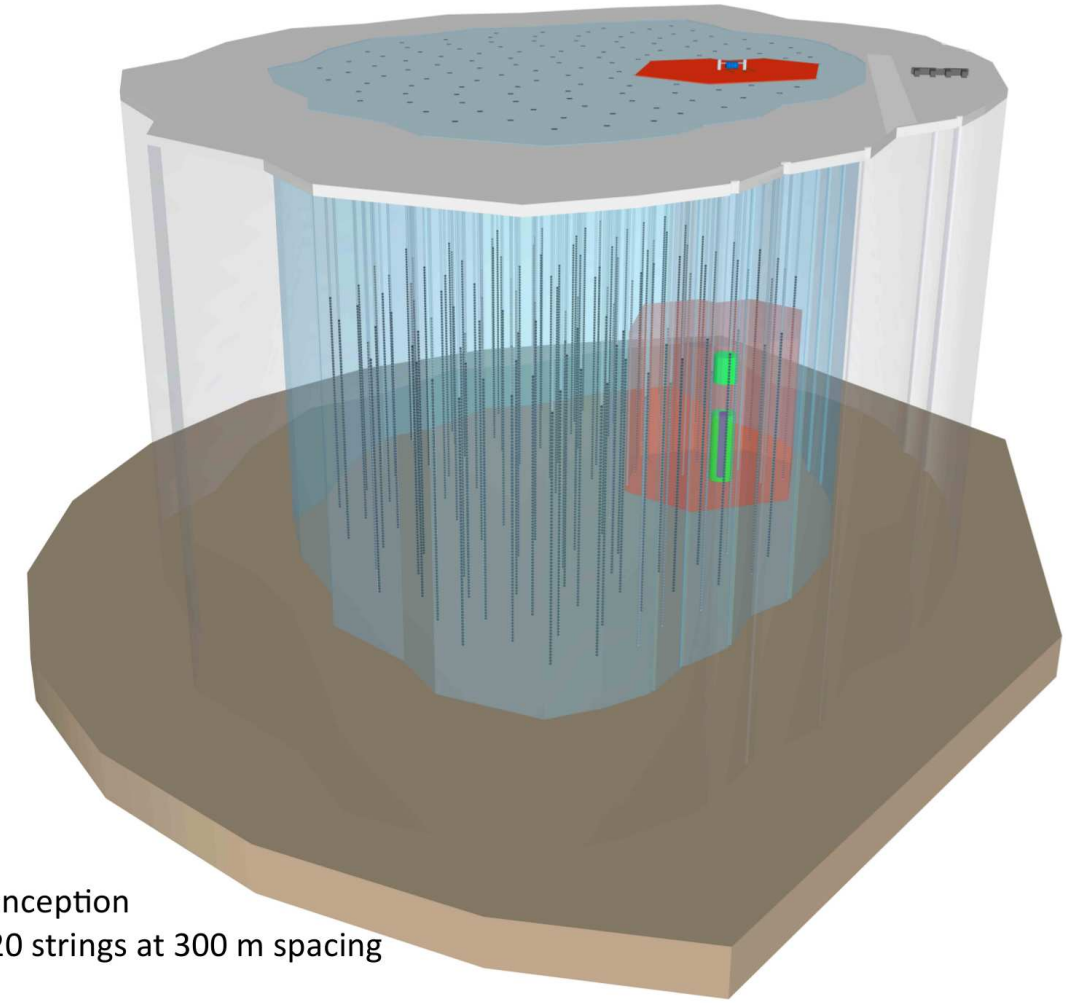


"Too many" neutrinos to match Fermi – in particular SFGs

No evidence for steady gamma-ray TeV counterparts.

Sources opaque to CR/γ? Many sources? Very distant sources?

Outlook: IceCube-Gen2



Artist conception
Here: 120 strings at 300 m spacing

The IceCube Collaboration

April 2015

Canada
University of Alberta–Edmonton
University of Toronto

USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

Niels Bohr Institutet, Denmark

Sweden
Stockholms universitet
Uppsala universitet

Chiba University, Japan

Sungkyunkwan University, Korea

University of Oxford, UK

Germany
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
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RWTH Aachen
Technische Universität München
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal

Belgium
Université Libre de Bruxelles
Université de Mons
Universiteit Gent
Vrije Universiteit Brussel

Université de Genève, Switzerland

University of Adelaide, Australia

University of Canterbury, New Zealand

44 institutions/ 12 countries / ~ 310 authors

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Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Conclusion

IceCube has observed a non-terrestrial neutrino flux in the ~15 TeV to ~8 PeV energy range.

The sources of these neutrinos are not known.

Flux is consistent with isotropy and standard oscillations.

Evidence for 2 source populations?

Are the sources opaque? How many sources are there? How far away?

Back Up

Neutrino Oscillations & IceCube

Astrophysical beam dump

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$$

Results in a 1:2:0 flavor flux ratio (at the source)

With muon cooling (e.g. Synchrotron) 0:1:0

$\bar{\nu}_e$ source (neutron decay): 1:0:0

After oscillations this results in:

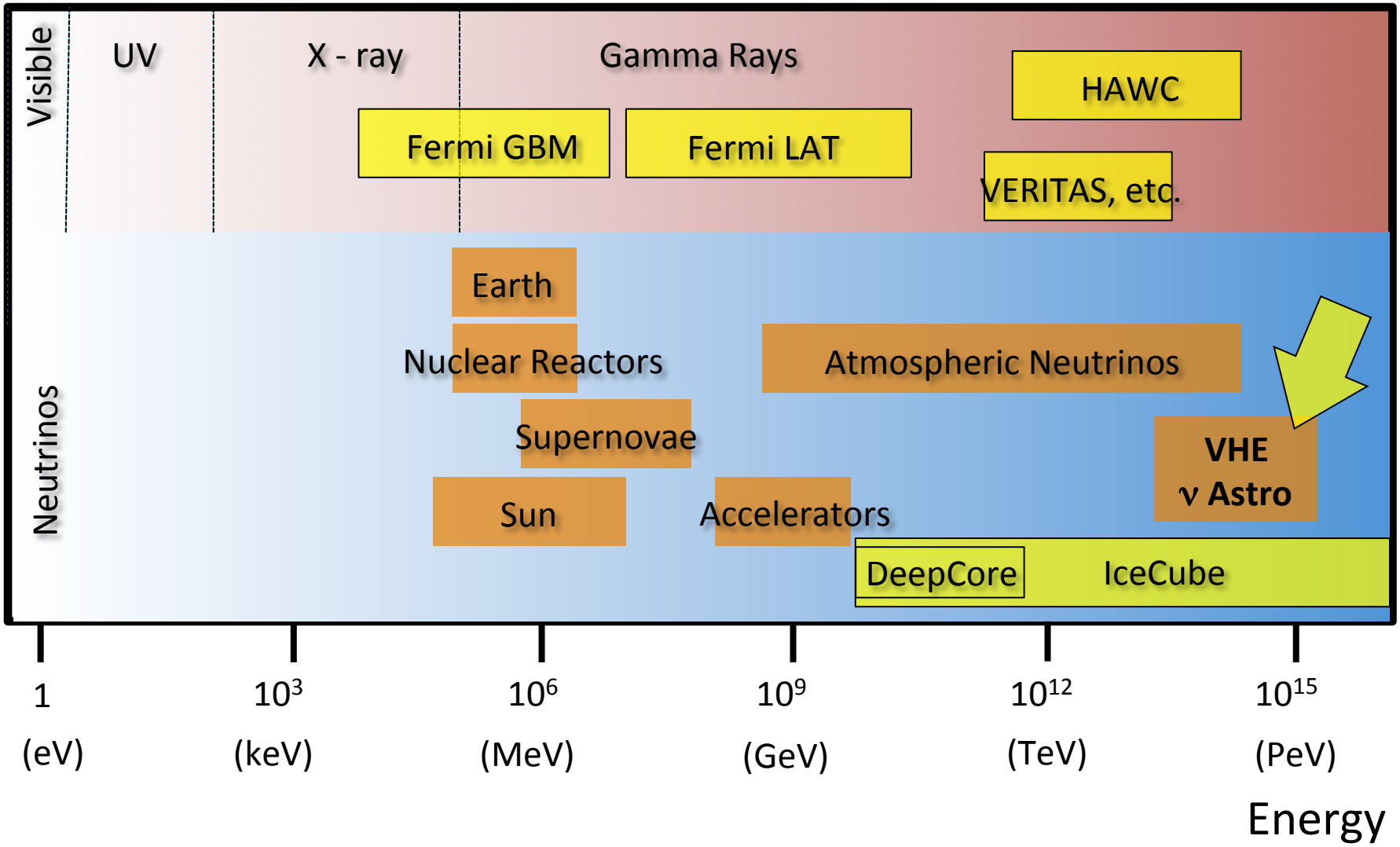
1:1:1 (no muon cooling)

0.2:0.4:0.4 (with cooling)

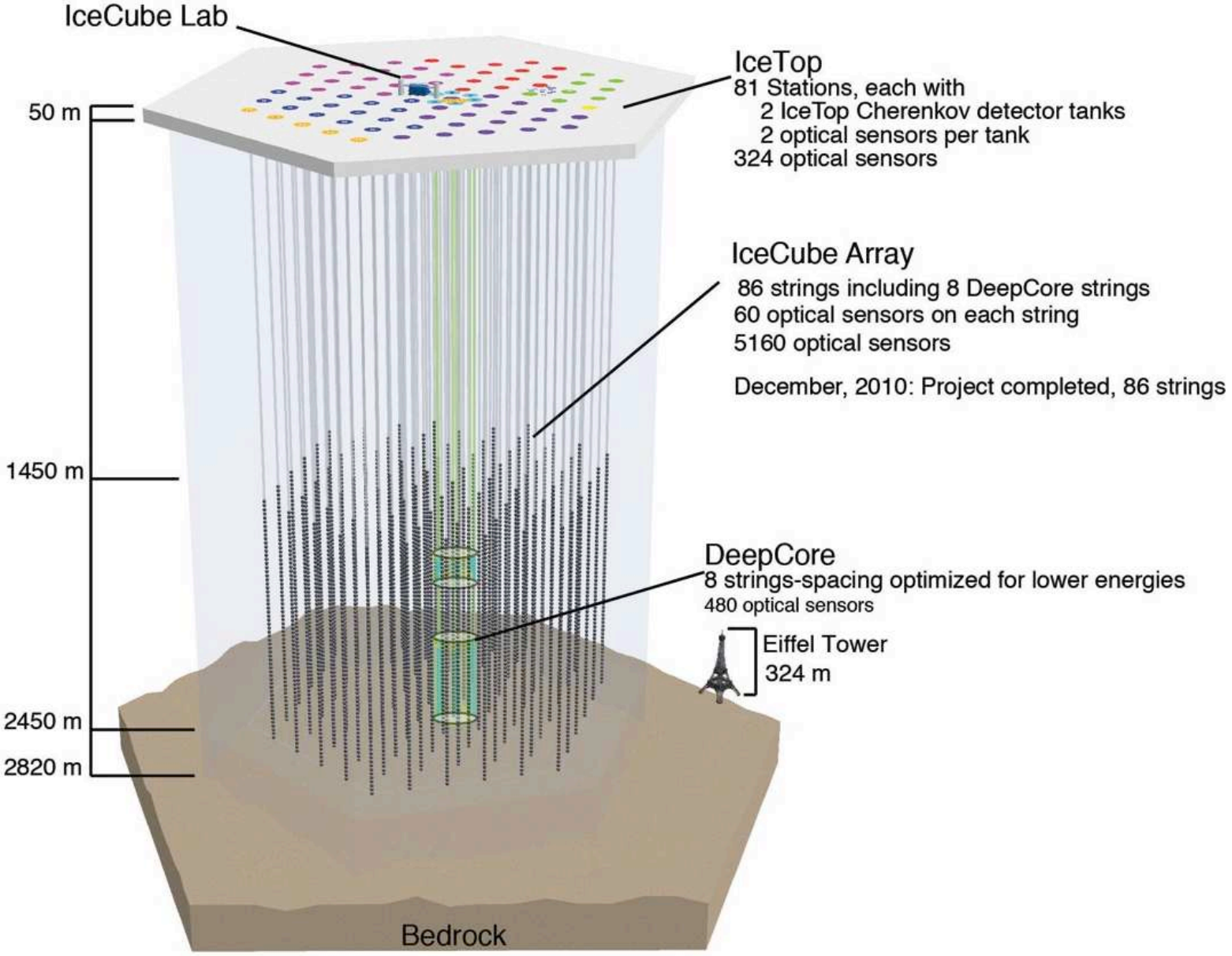
0.5:0.2:0.3 ($\bar{\nu}_e$ source)

No distinction between ν and $\bar{\nu}$ in IceCube

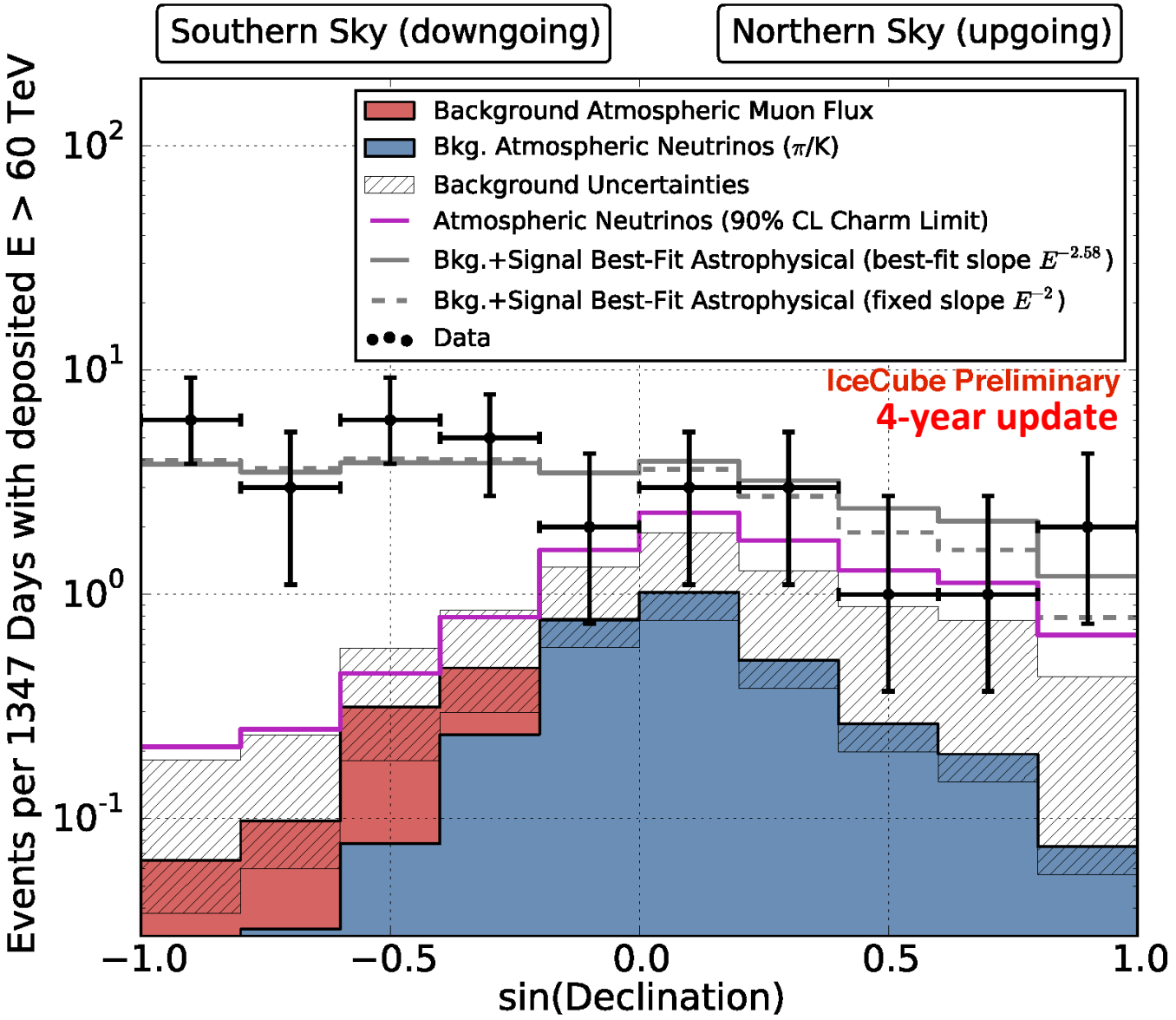
Neutrinos and electromagnetic radiation



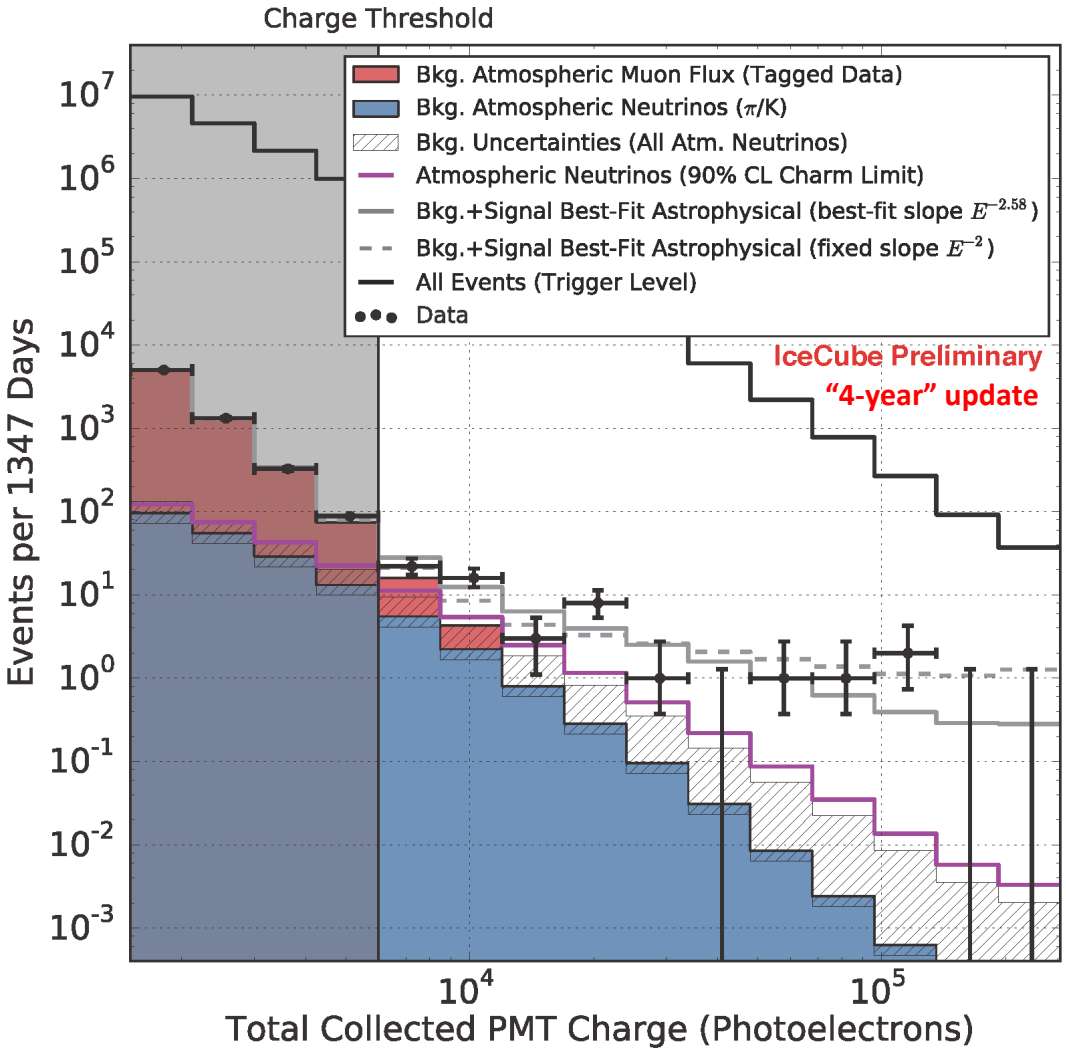
IceCube


IceCube Lab
50 m
1450 m
2450 m
2820 m
Bedrock
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m

HESE: deposited energy vs. declination



HESE method



54 events between 60 TeV and 2.1 PeV.

- 39 cascades
- 13 tracks
- 2 "background"

Background Expectation:

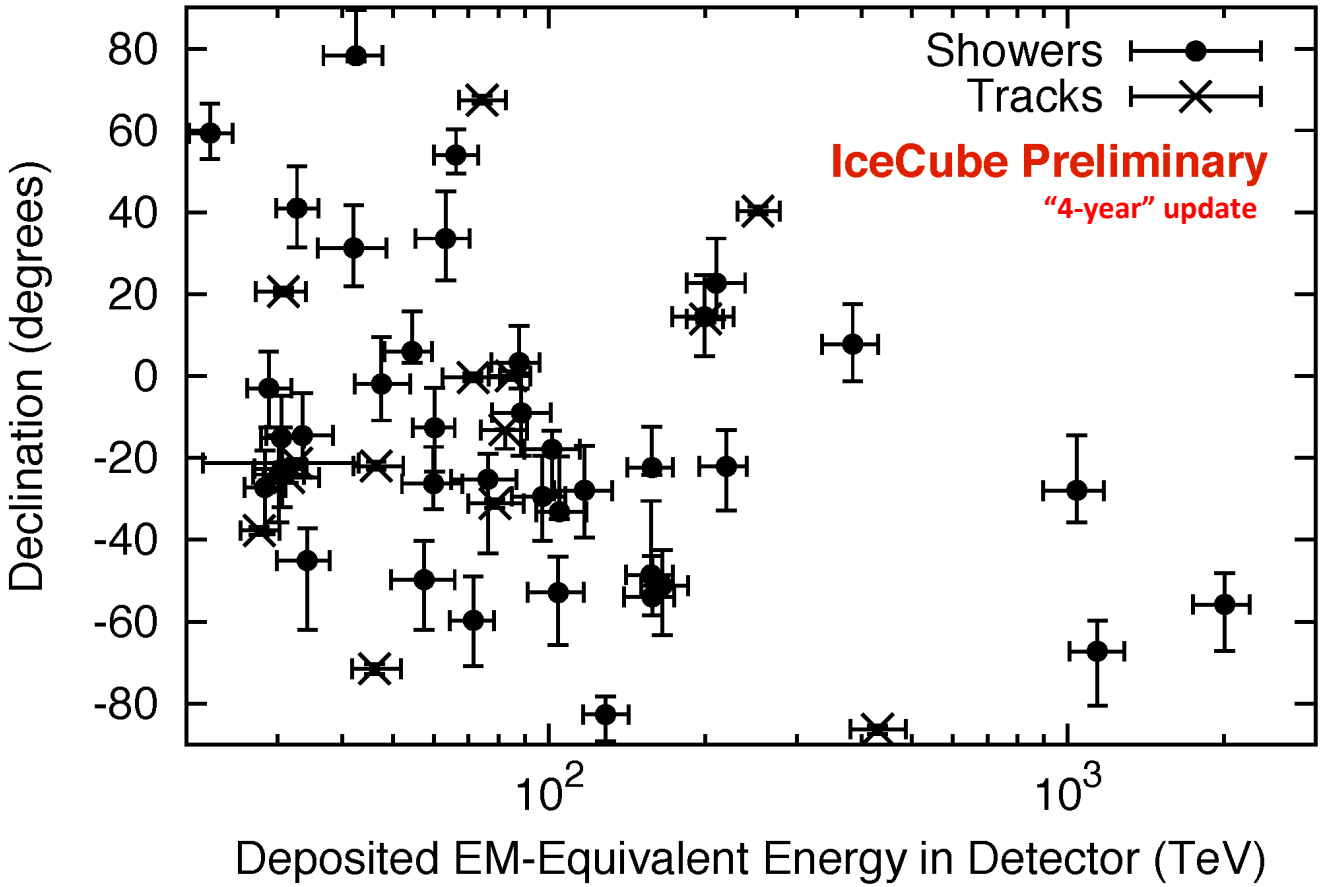
atm μ:

- 12.6 ± 5.1 (from data)

atm ν (π, K + prompt):

- $9.0^{+8.0}_{-2.2}$

HESE: Visible energy, direction & event type



13 track-like events

0.4 – 1.5° ang. resolution

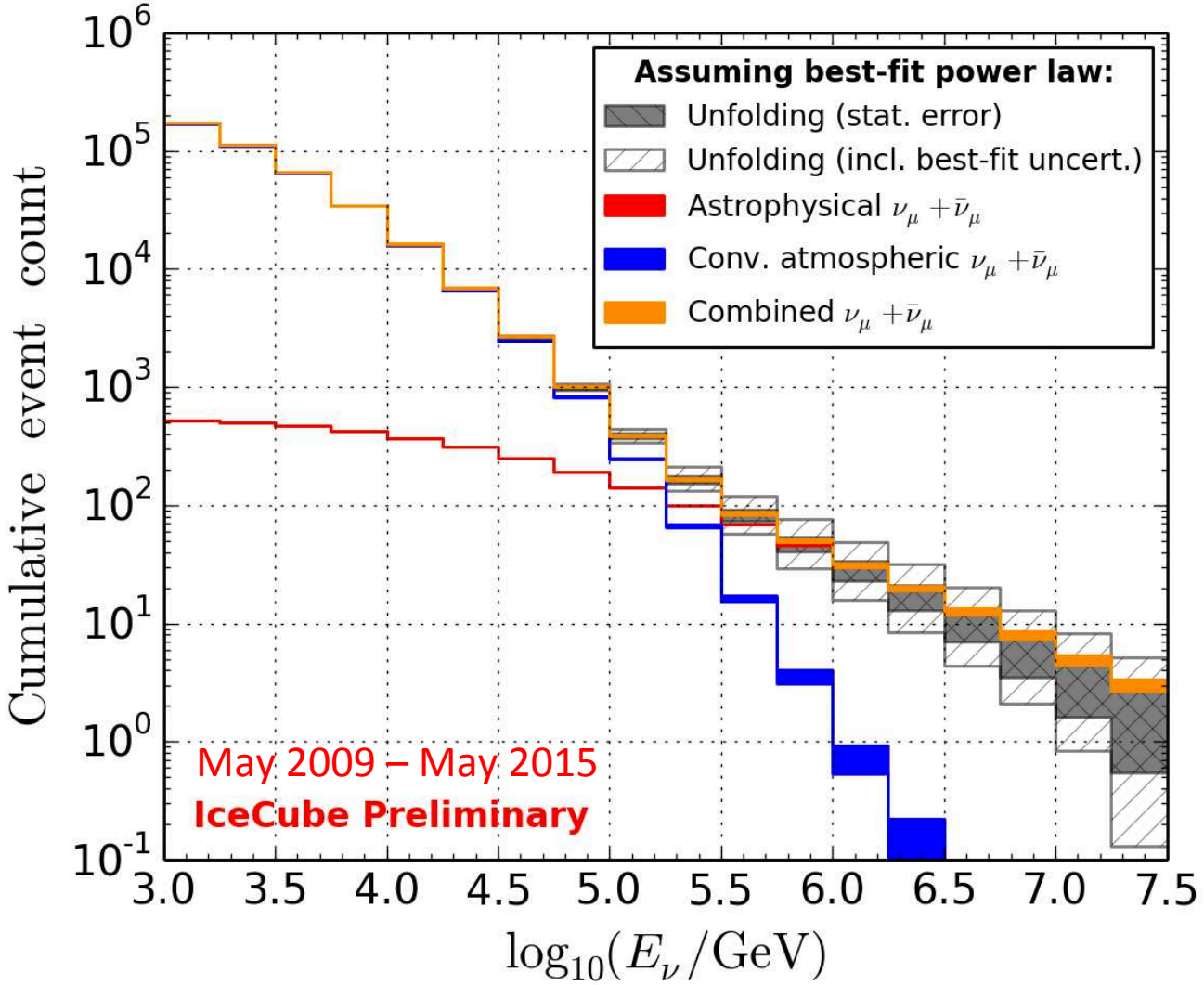
Muon takes some energy away

39 cascade-like events

10-25° ang. resolution

15% visible energy resolution

Tracks: "Standard" neutrino astronomy



Use Earth as a filter for muons – northern hemisphere only

Sensitive to muon neutrinos