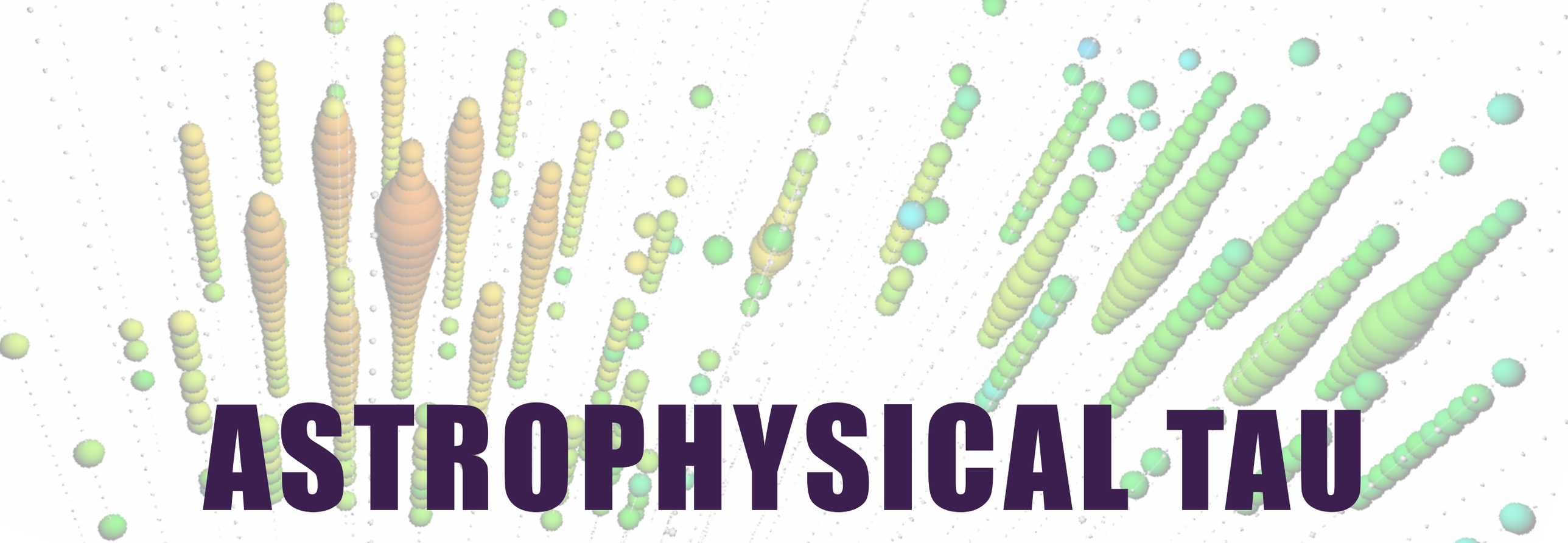

ASTROPHYSICAL TAU NEUTRINOS IN ICECUBE

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for the IceCube Collaboration

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Email: dxu@icecube.wisc.edu

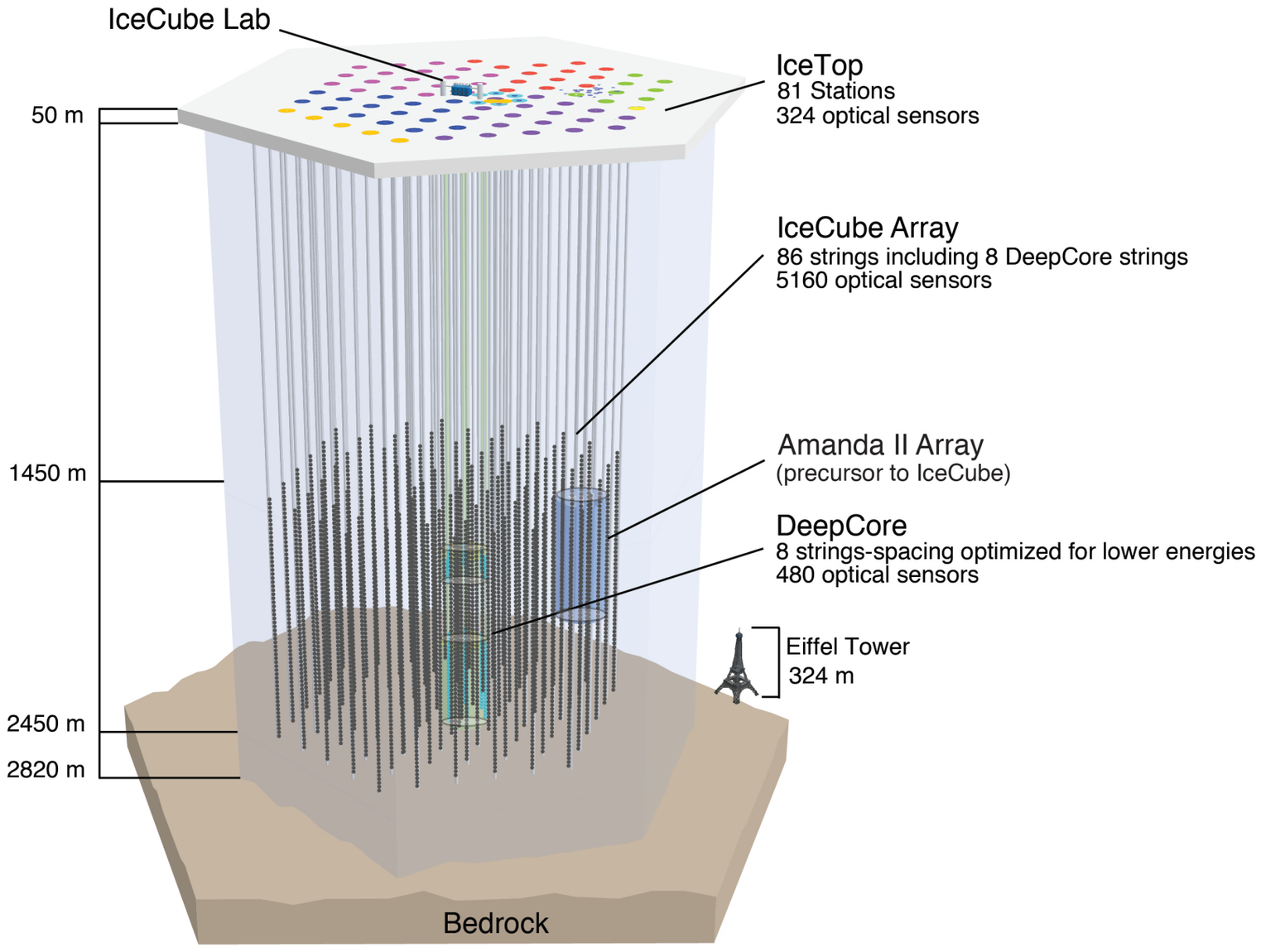
May 9th, 2017
IPA 2017, Madison

IceCube Detector

Goal: detecting TeV-PeV astrophysical neutrinos

Construction completed in December 2010

Inter-string spacing ~125 m
Vertical DOM spacing ~17m



- Cubic-kilometer, high energy neutrino telescope located at geographic South Pole
- 86 in-ice strings
  - 60 Digital Optical Modules (**DOM**) per string
  - DOMs are deployed between 1450m to 2450m in depth
  - Densely instrumented sub-array "DeepCore" at center bottom of detector
- 81 IceTop surface stations
  - 2 tanks per station

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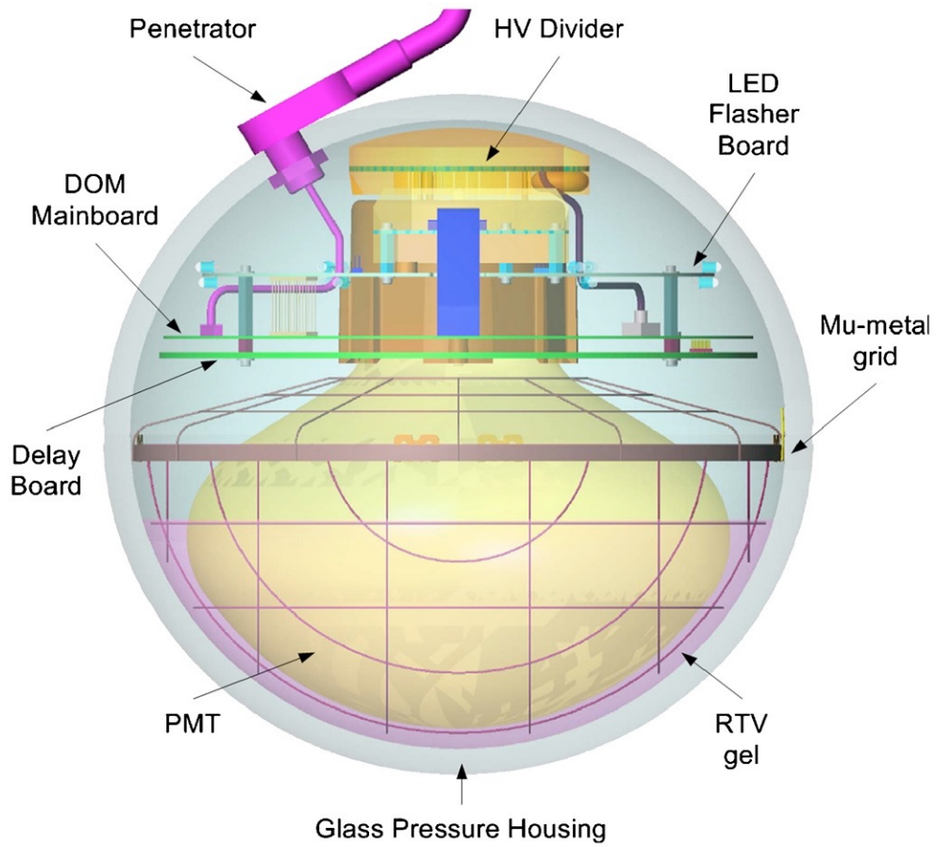
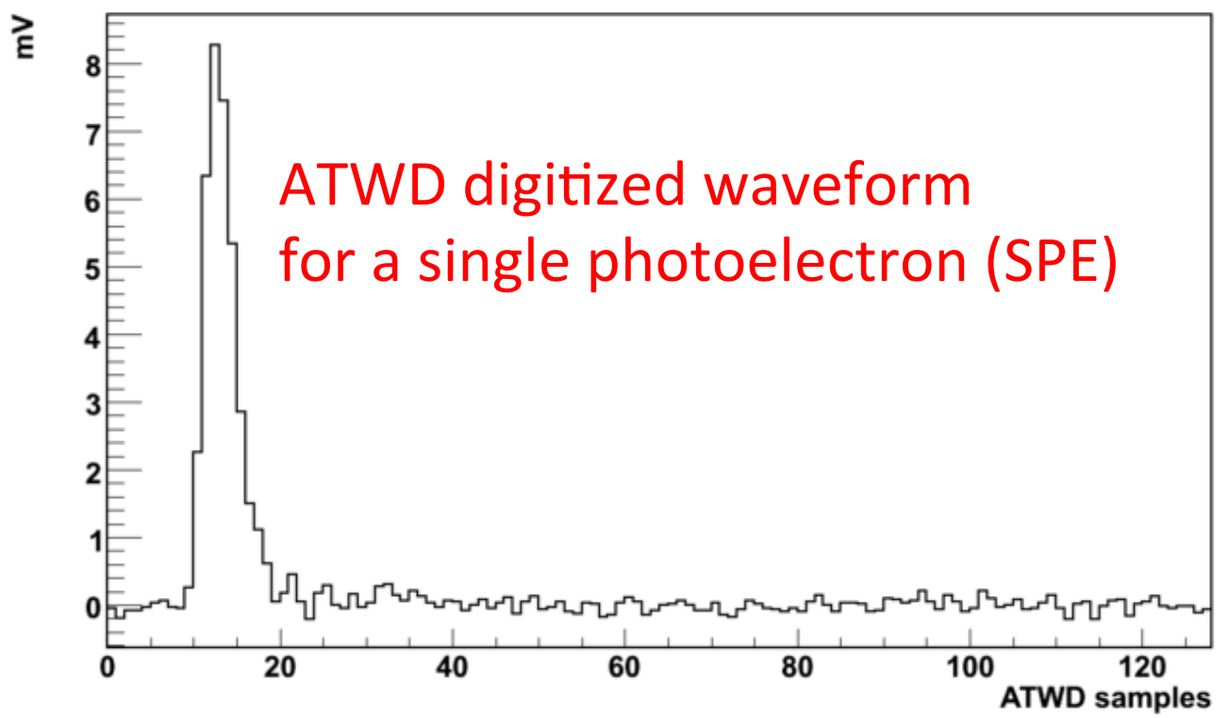
IceCube DOMs and Waveforms

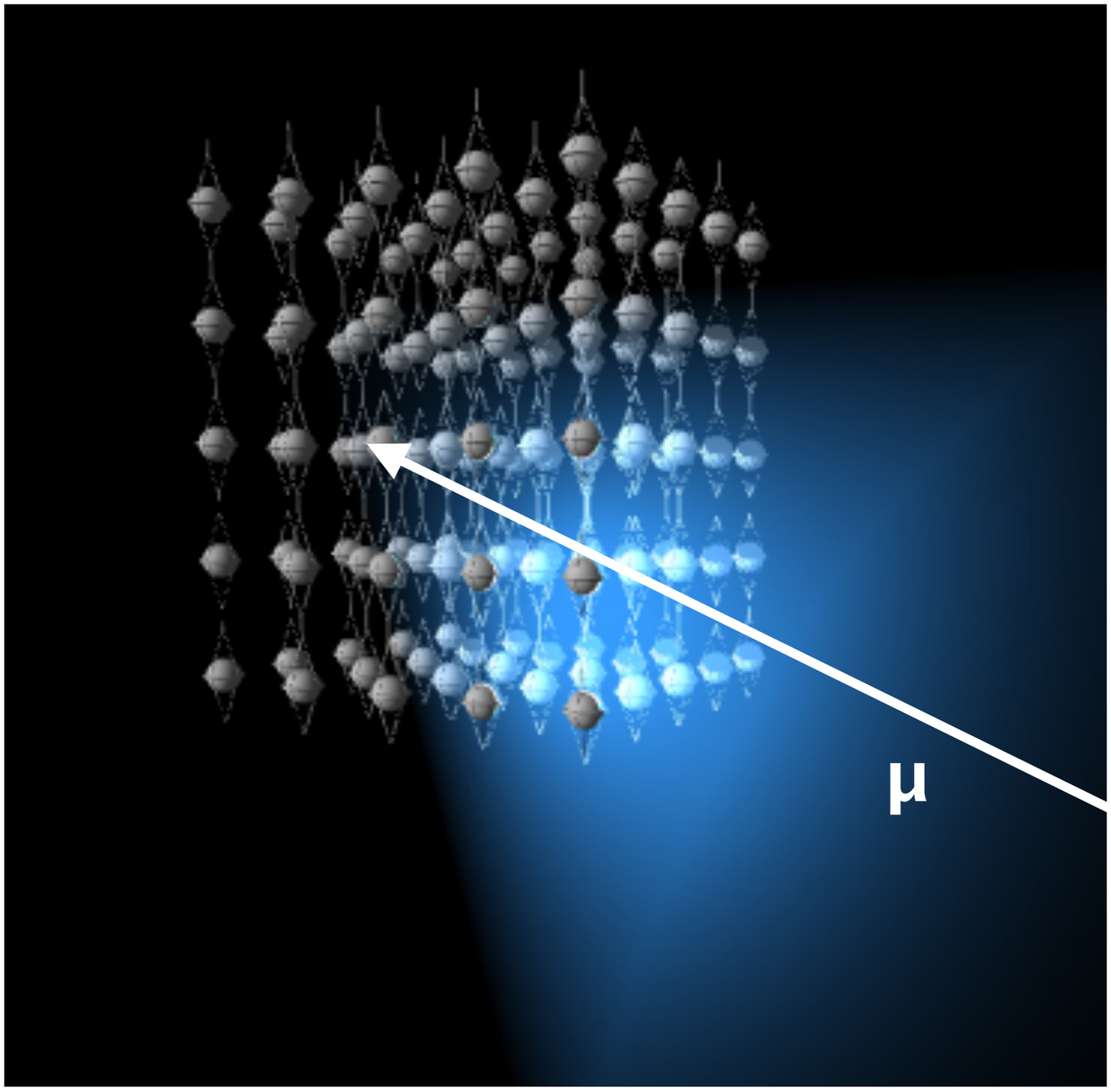




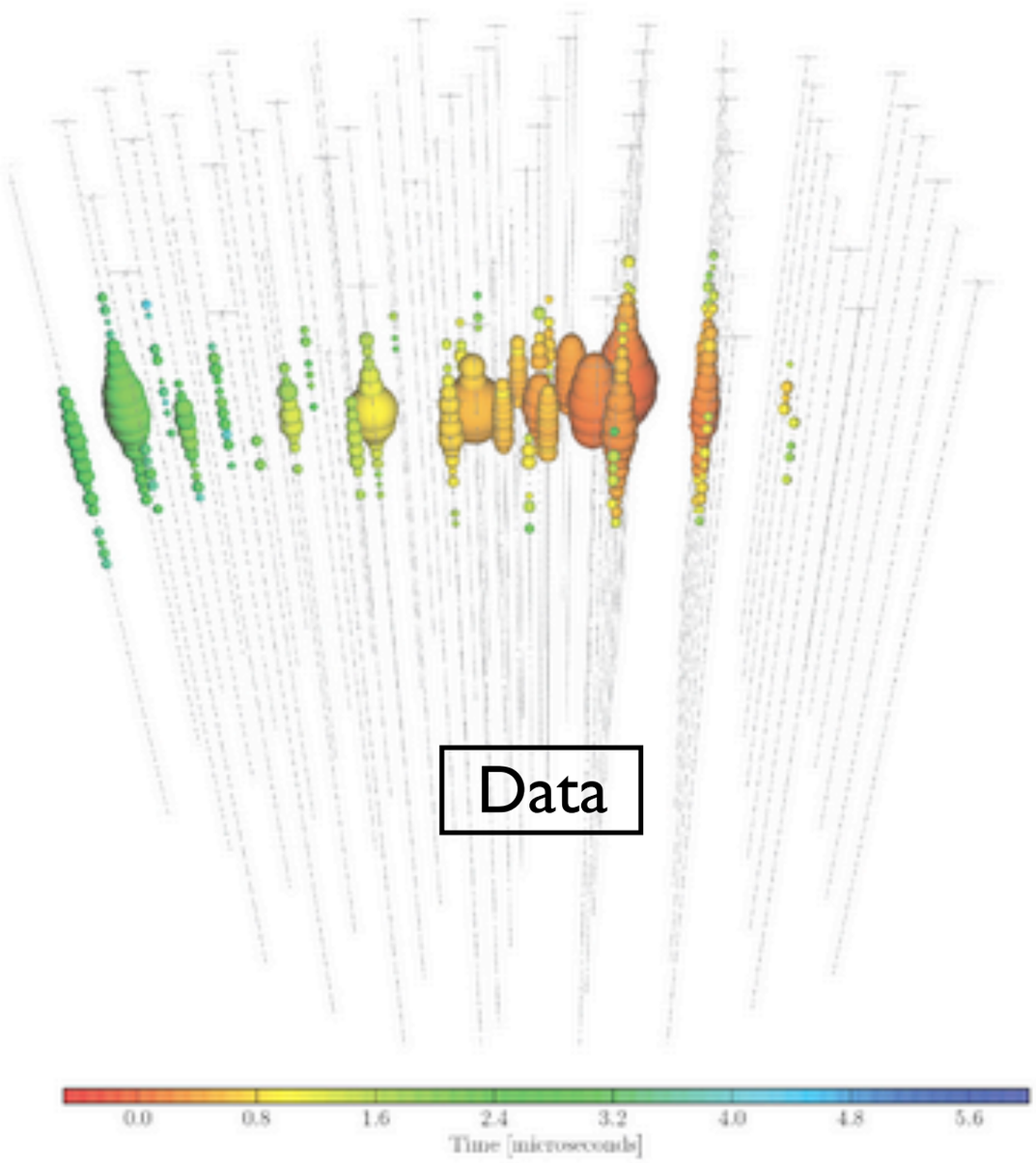
- Digitization of Photomultiplier Tube (PMT) waveforms in ice

- Analog Transient Waveform Digitizer (ATWD) waveform:
  - Three channels with (16x, 2x, 0.25x) of nominal gain 10^7
  - Time window: 422.3 ns, 128 samples with 3.3ns/sample

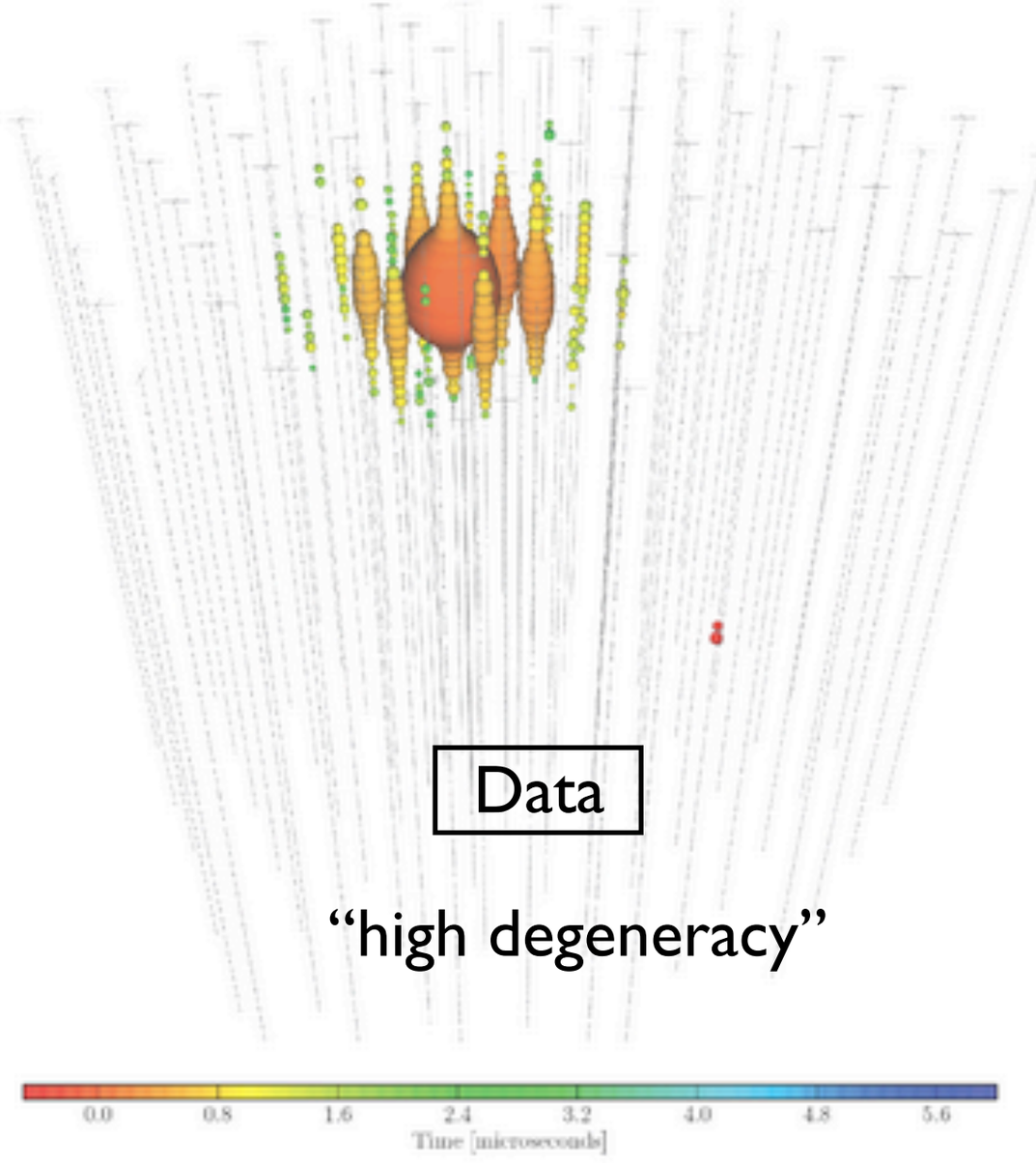
Detection Principle - Cherenkov Radiation



- Neutrinos cannot be detected directly
- Detecting light from neutrino interactions with the ice nuclei
- Sensitive to single photons



(1) Track: ν_μ CC



"high degeneracy"

(2) Cascade: ν_e CC, all-flavor NC, low-E ν_T

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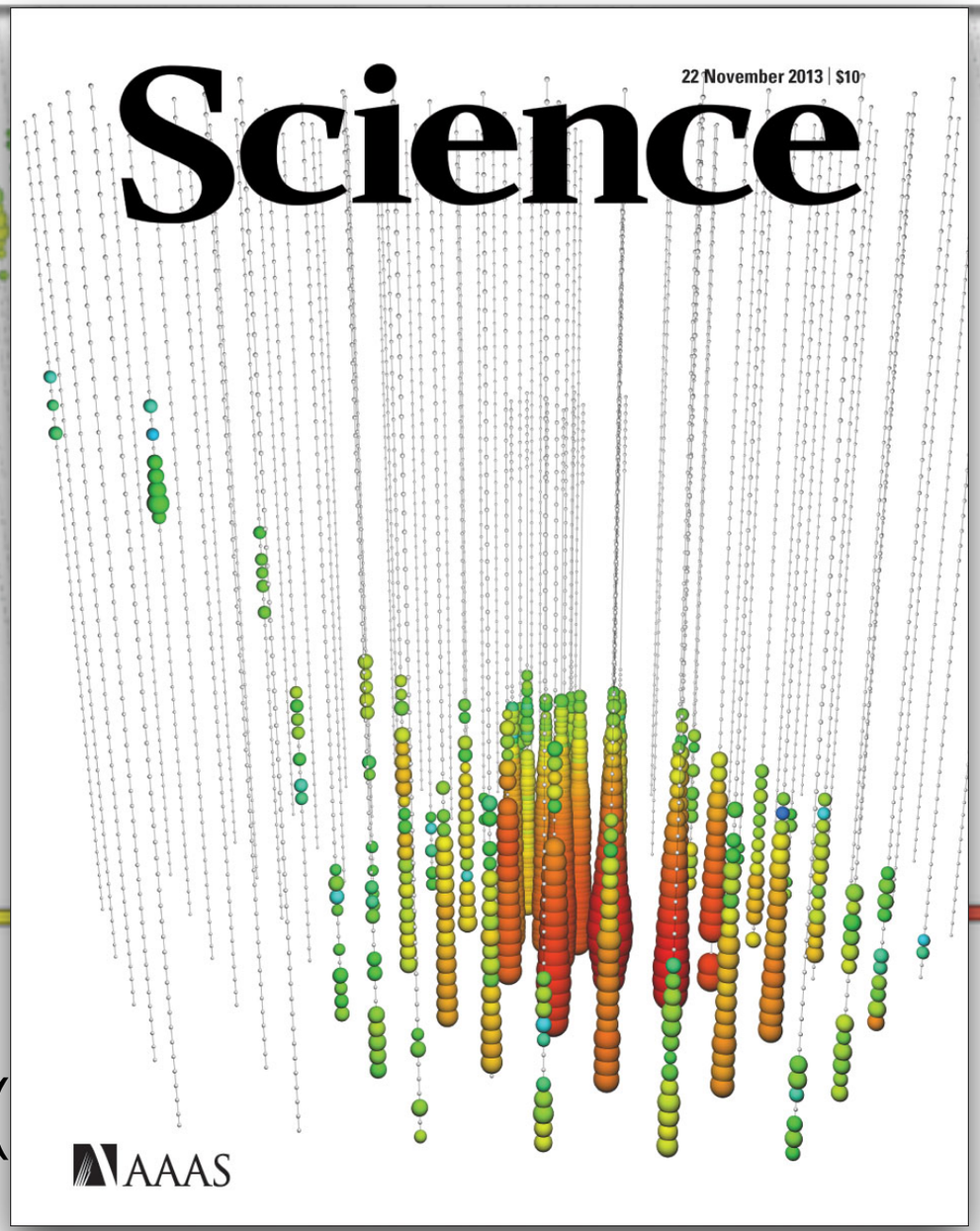
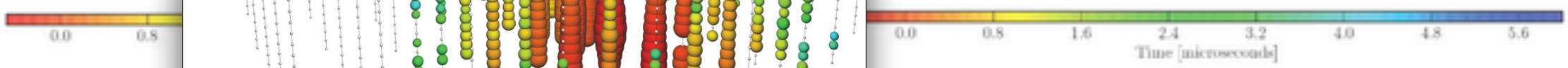
“Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector”



No dedicated identification for tau neutrinos

.. but essential in astro. nu flavor ratio measurement

“high degeneracy”



(2) Cascade: ν_e CC, all-flavor NC, low-E ν_T

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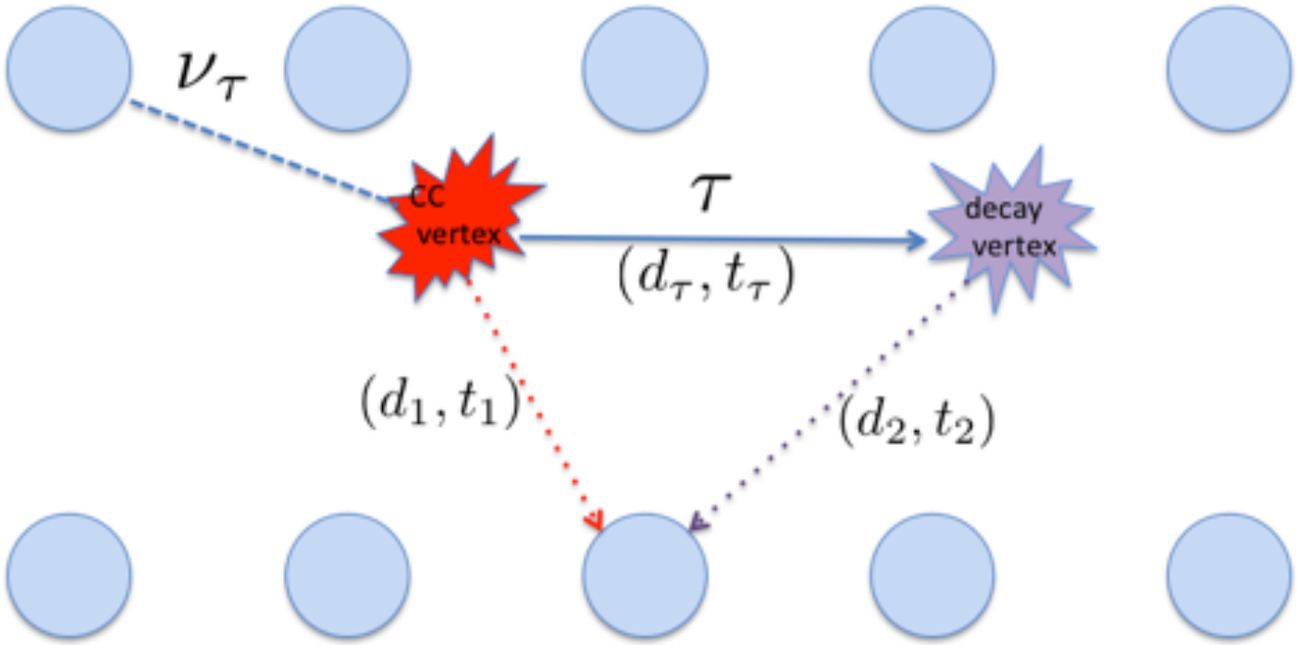
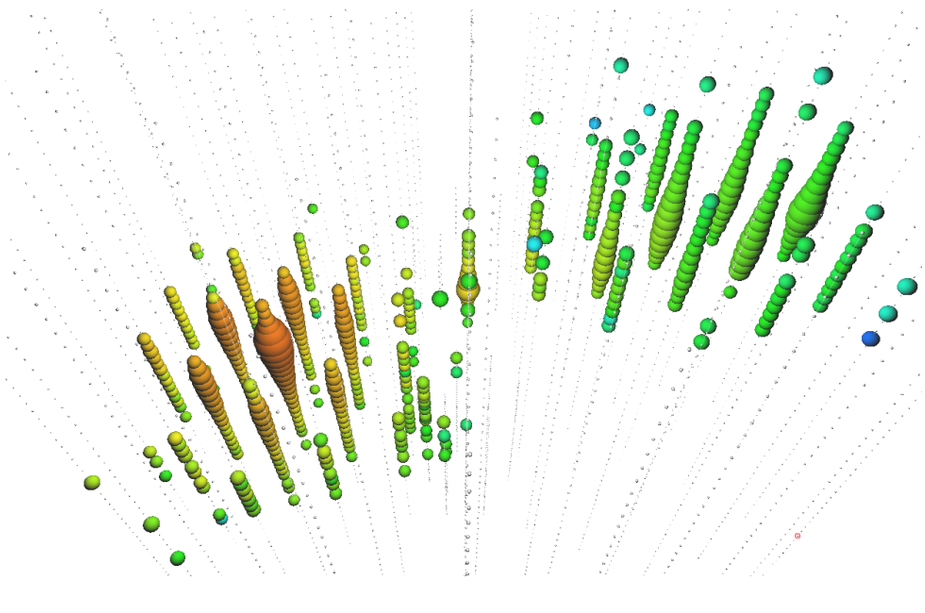
Neutrino Signatures in IceCube - Not Yet Detected

$$l_\tau \sim 1\,\mathrm{PeV}/50\,\mathrm{m}$$



Simulation

E ν_τ = 300 PeV



(3) Double Cascades: High-E ν_τ CC

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

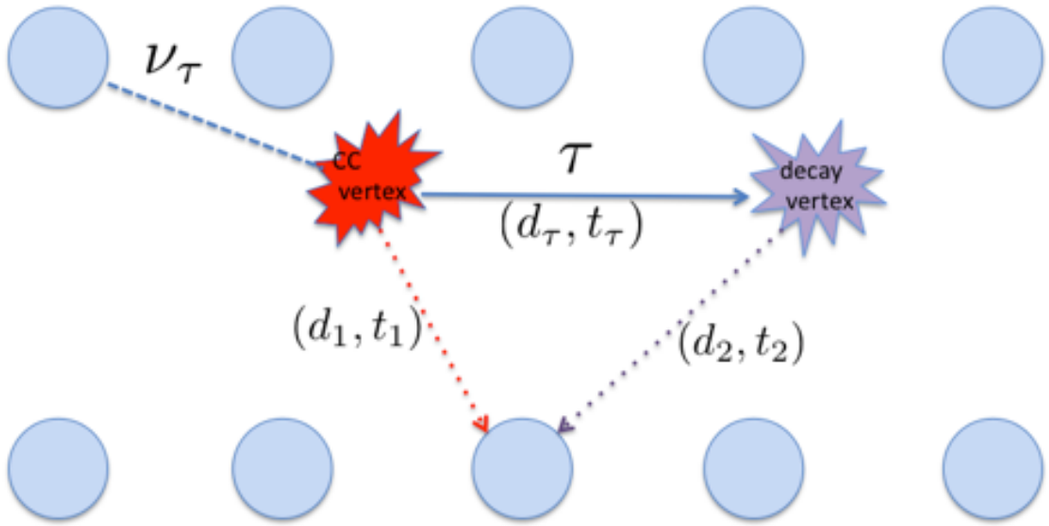
$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$

Tau Neutrino Charged-Current Double Pulse Events

Schematic ν_τ CC interaction in IceCube

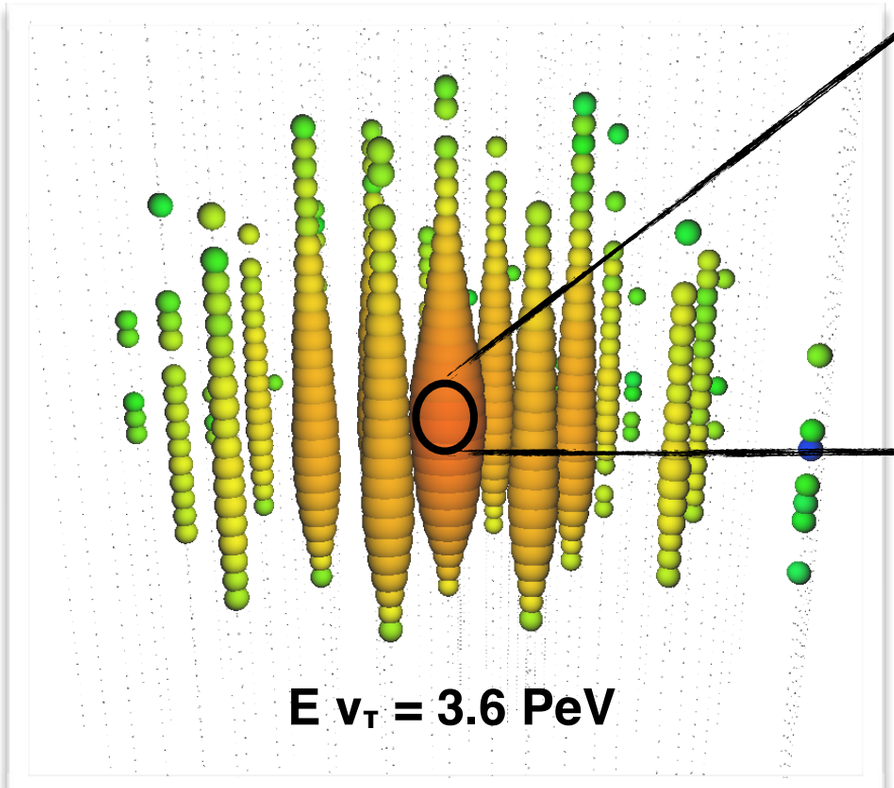


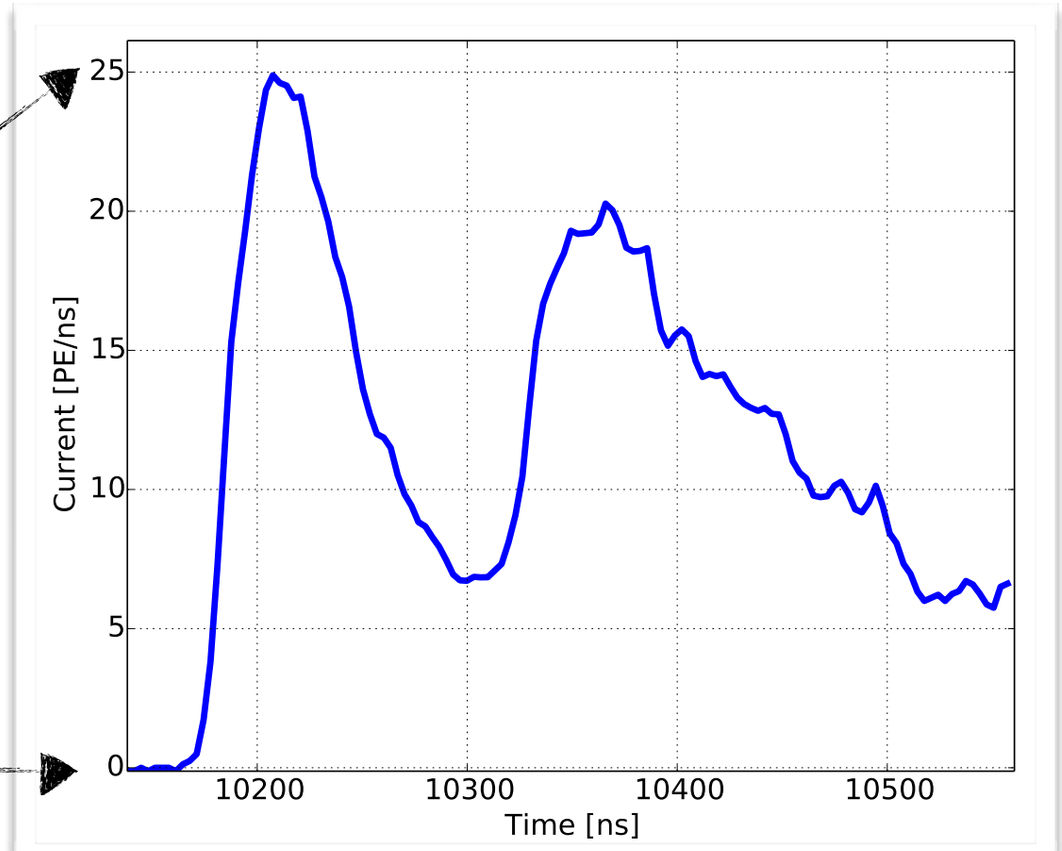
$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$





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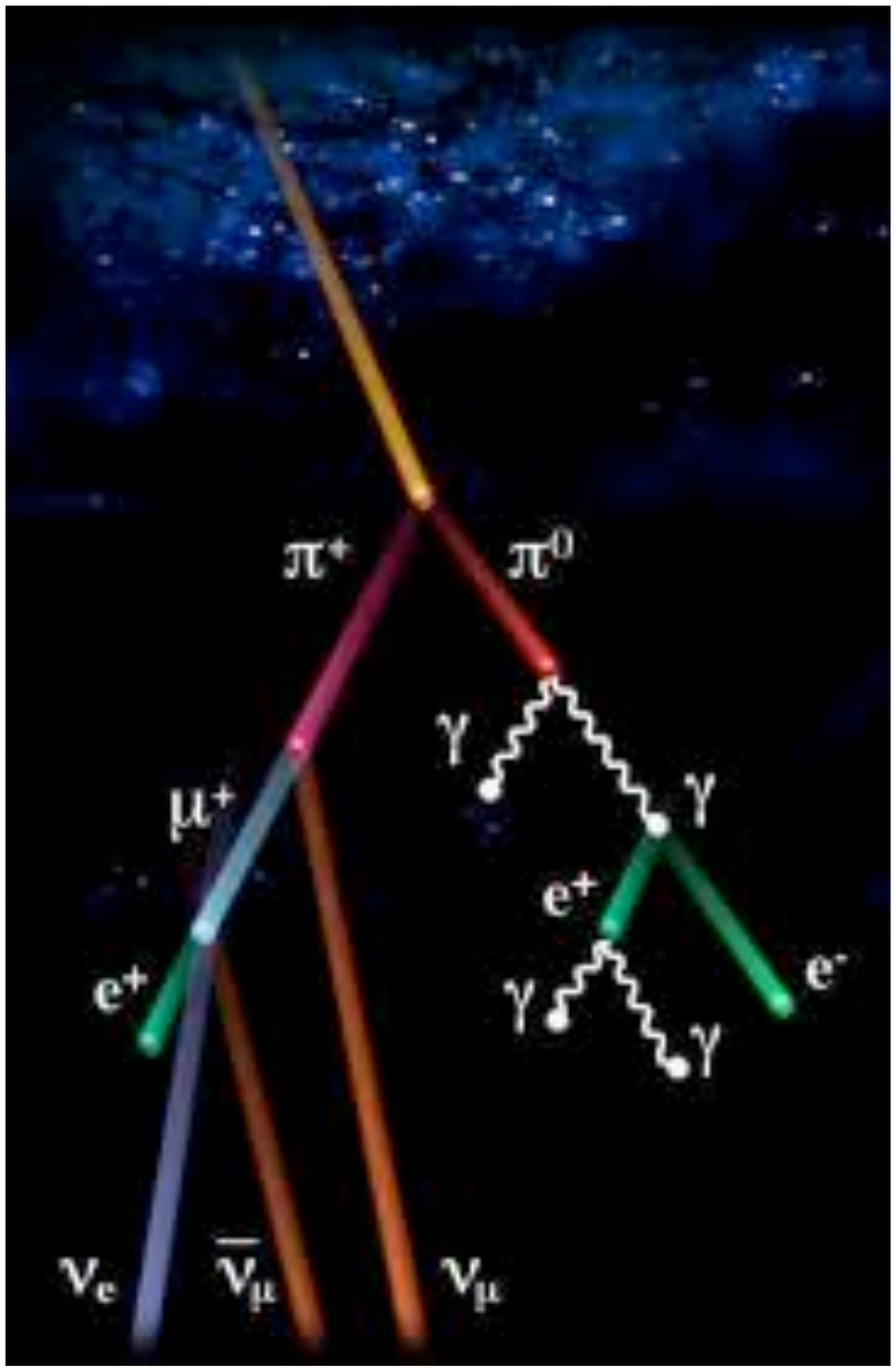
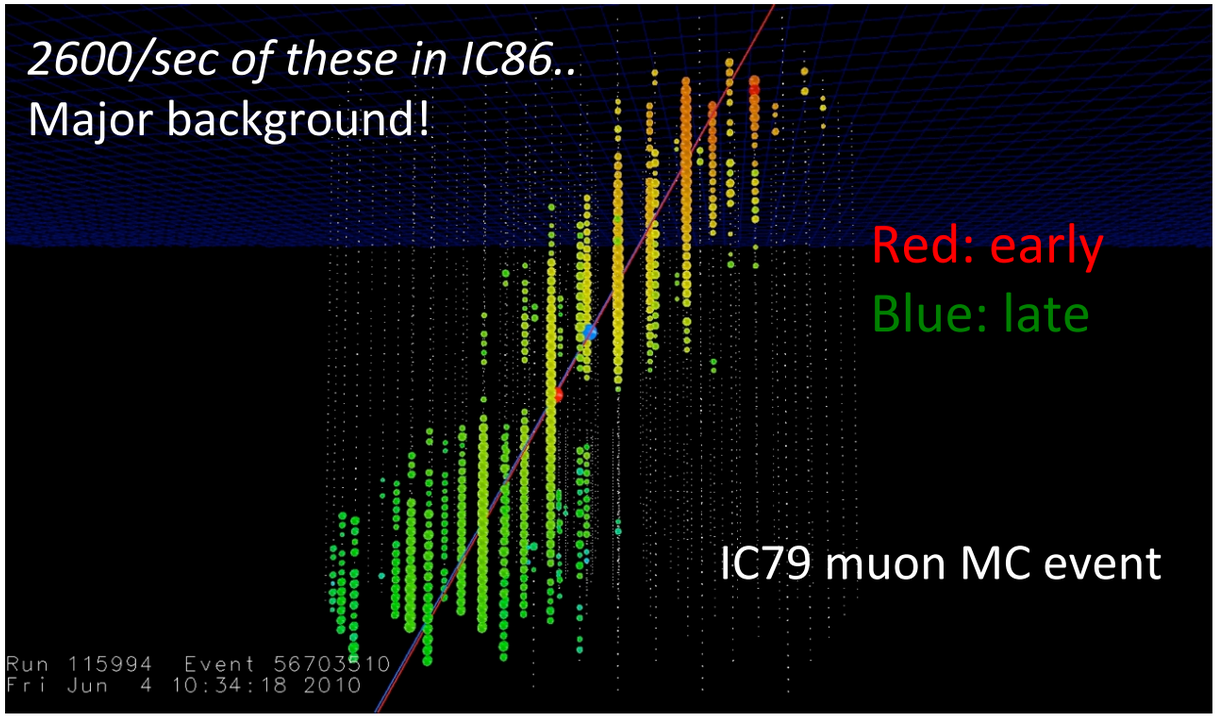
Background — Atmospheric Muons & Neutrinos



neutrino : muon ~ 1 : 10^6



- Conventional: $\frac{dN}{dE_\nu} \sim E_\nu^{-3.7}$

  $\nu_e : \nu_\mu \simeq 1 : 2$

- Prompt: $\frac{dN}{dE_\nu} \sim E_\nu^{-2.7}$ $\quad \nu_e : \nu_\mu \simeq 1 : 1$

Atmospheric prompt ν_τ is ~10 times lower than ν_μ and ν_e

Double Pulse Event Candidates

Signal

ν_τ

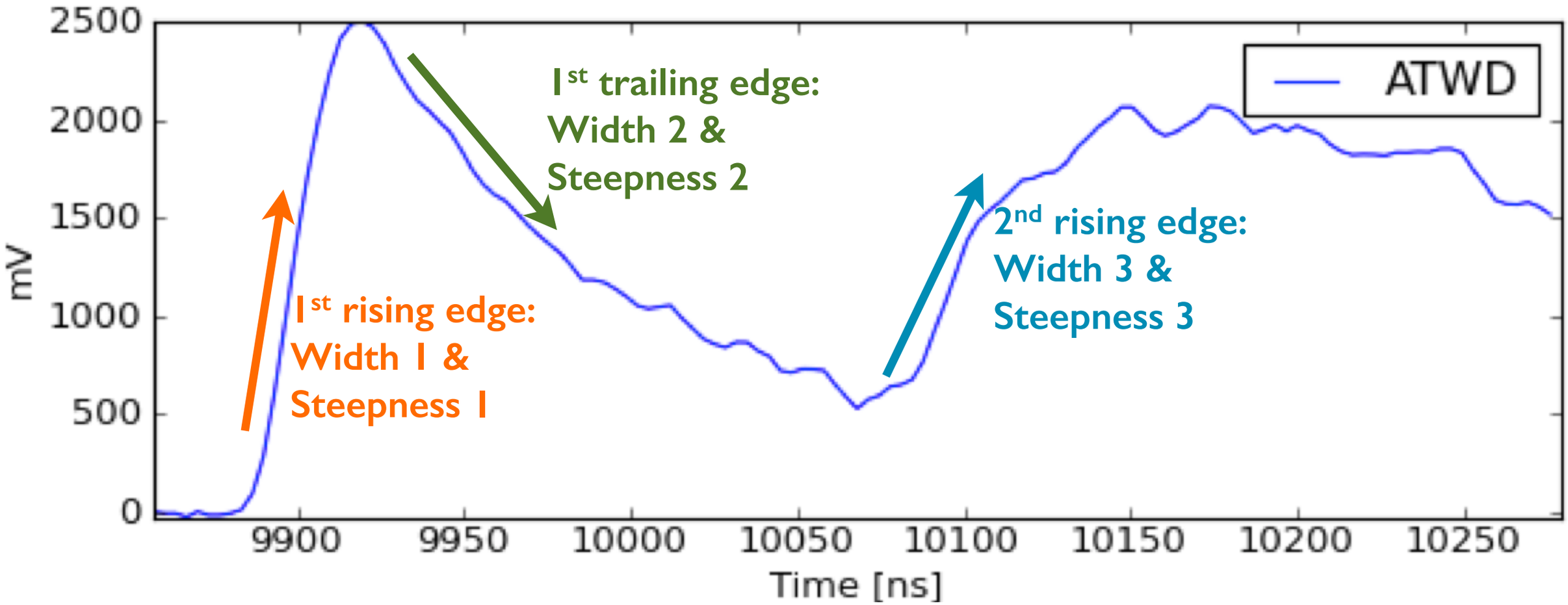
Backgrounds

Muons

ν_μ

TeV-scale stochastic losses ~O(10) meters near some DOM

Double Pulse Algorithm (DPA)

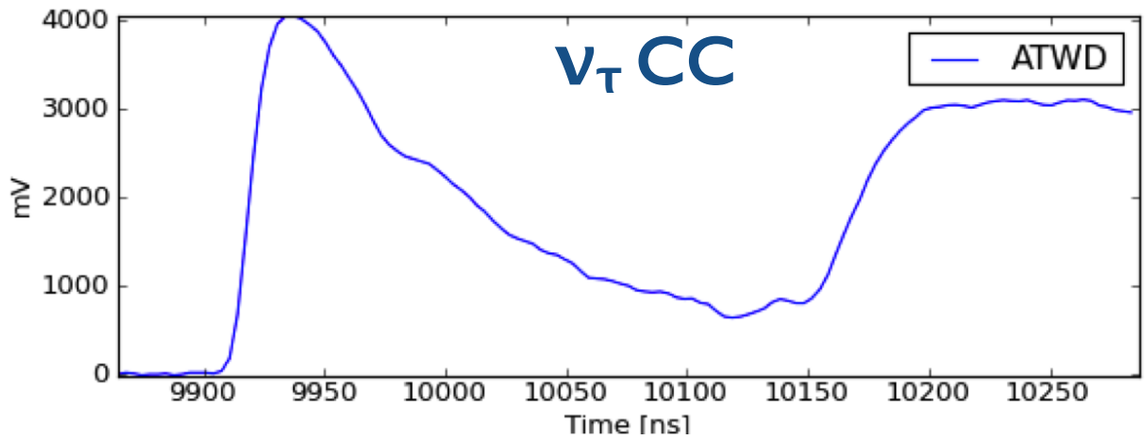


Note: DPA only runs on ATWD waveforms with accumulated charge > 432 PE

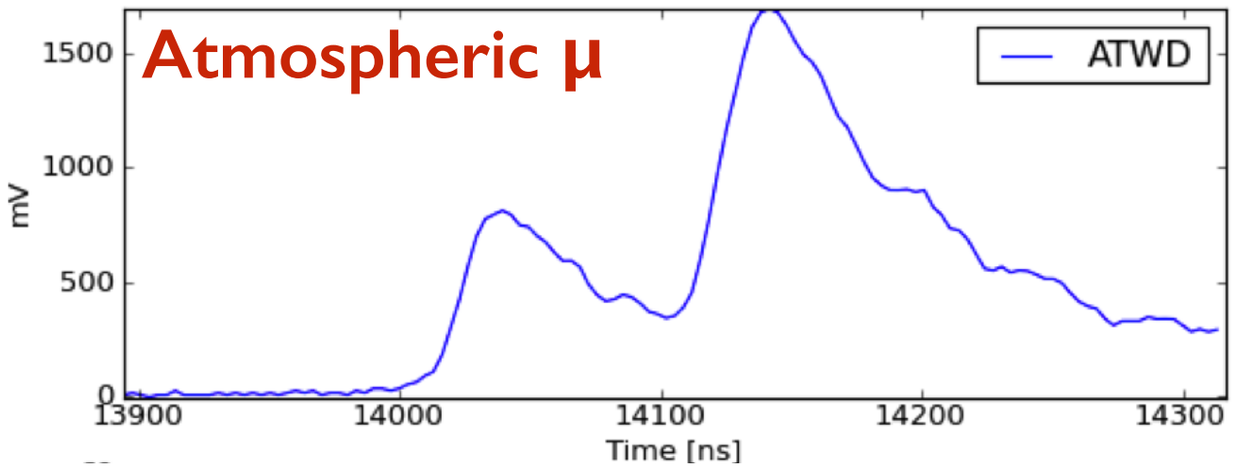
ICRC2013 poster: "Detecting Tau Neutrinos in IceCube with Double Pulses"
[arXiv:1309.7003]

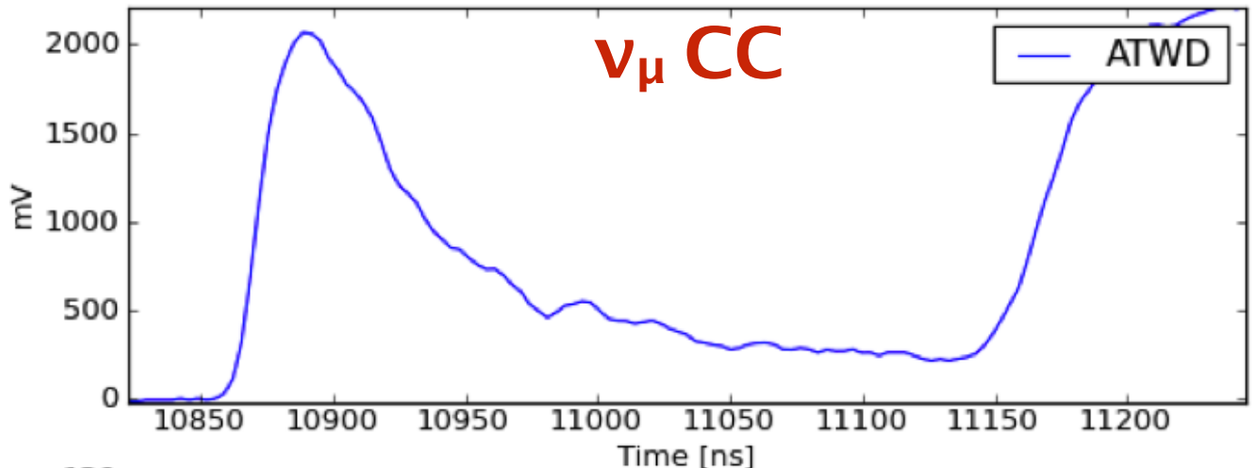
Identified Double Pulse Waveforms

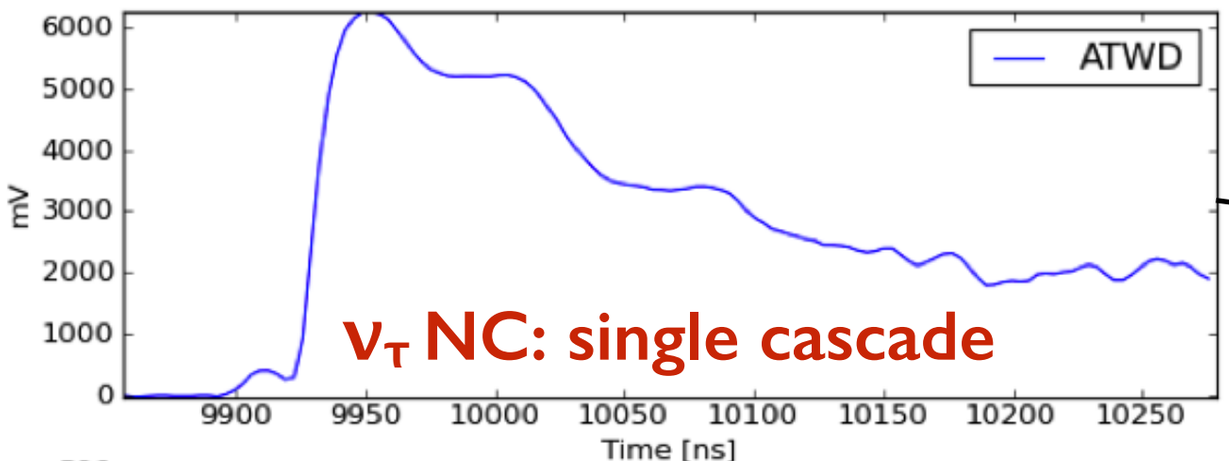
Signal:



Background:

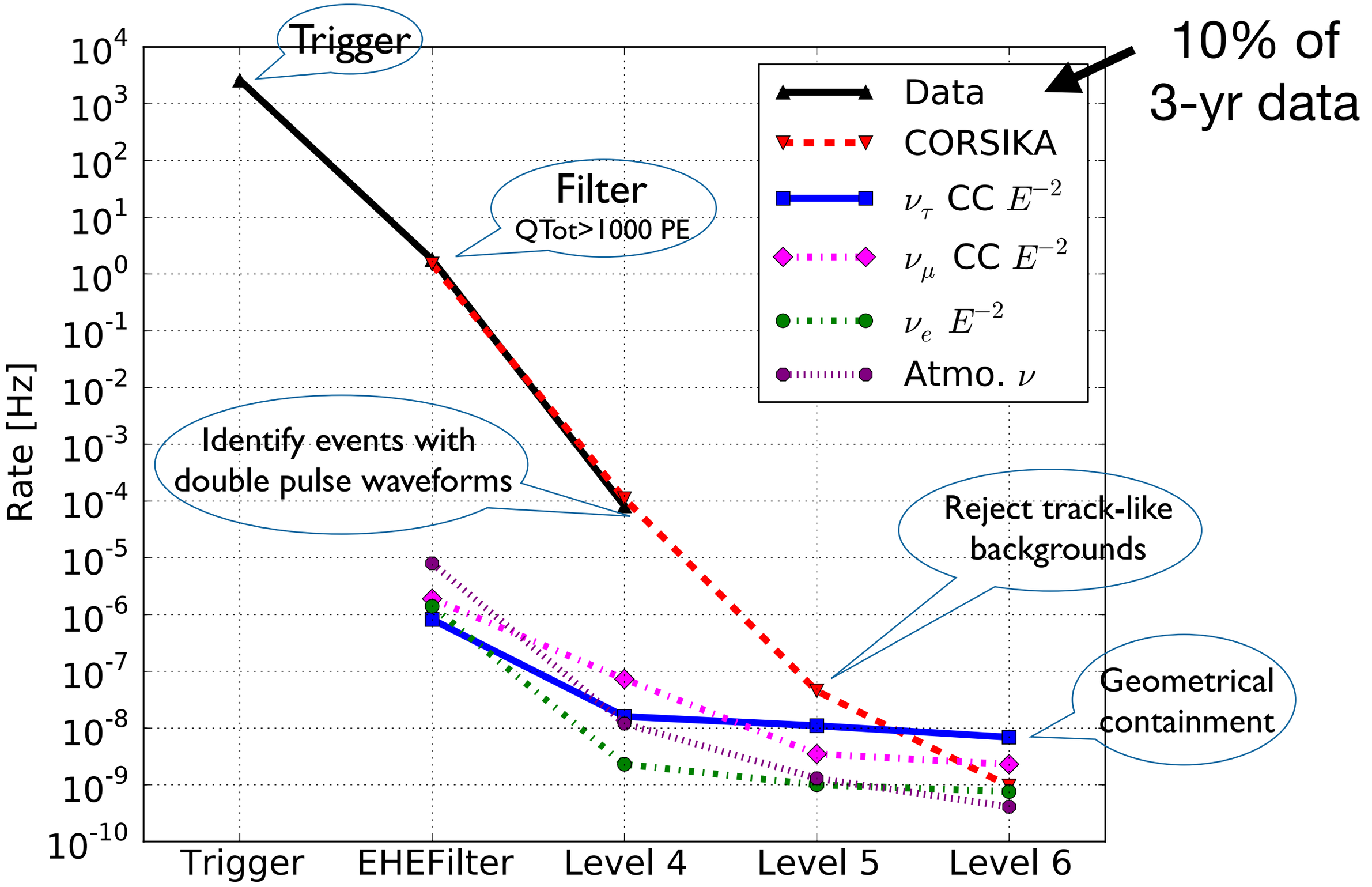






Most important to reject at waveform level

Event Selection and Cut Efficiency



Sensitivity:

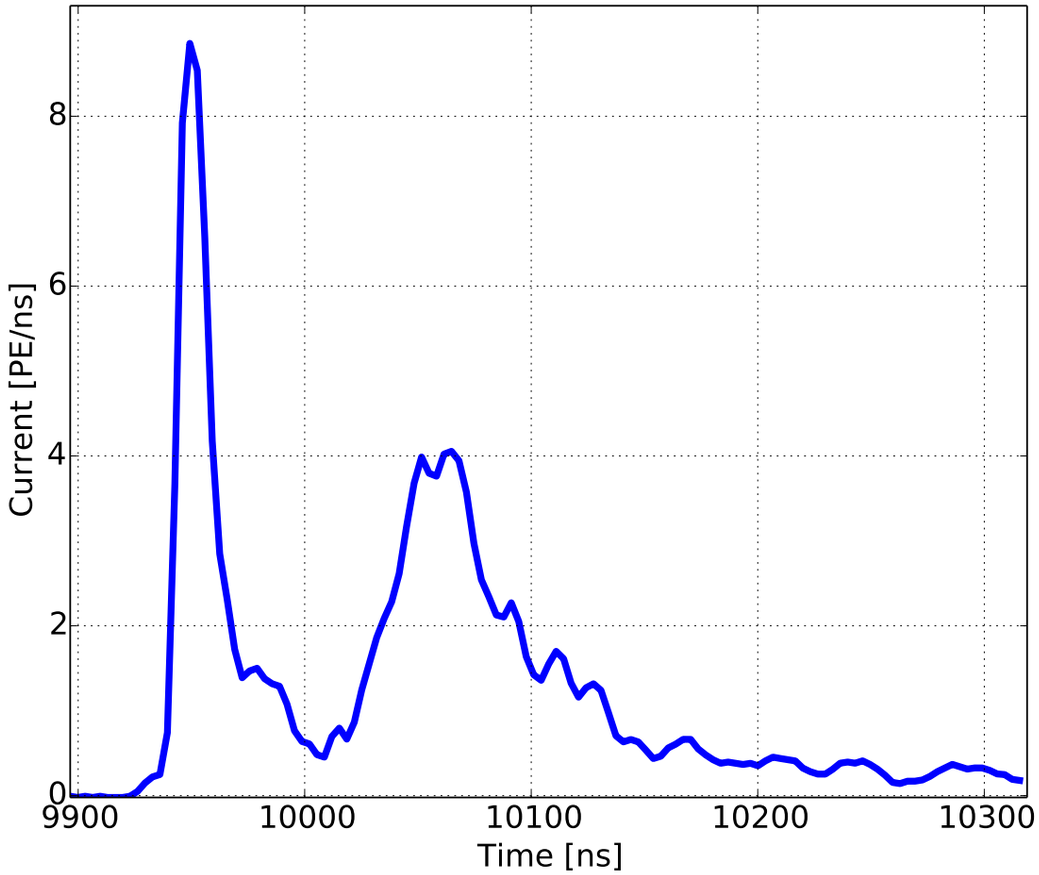
	In 914.1 days
Signal	**0.54±0.01**
Total background	**0.35±0.06**

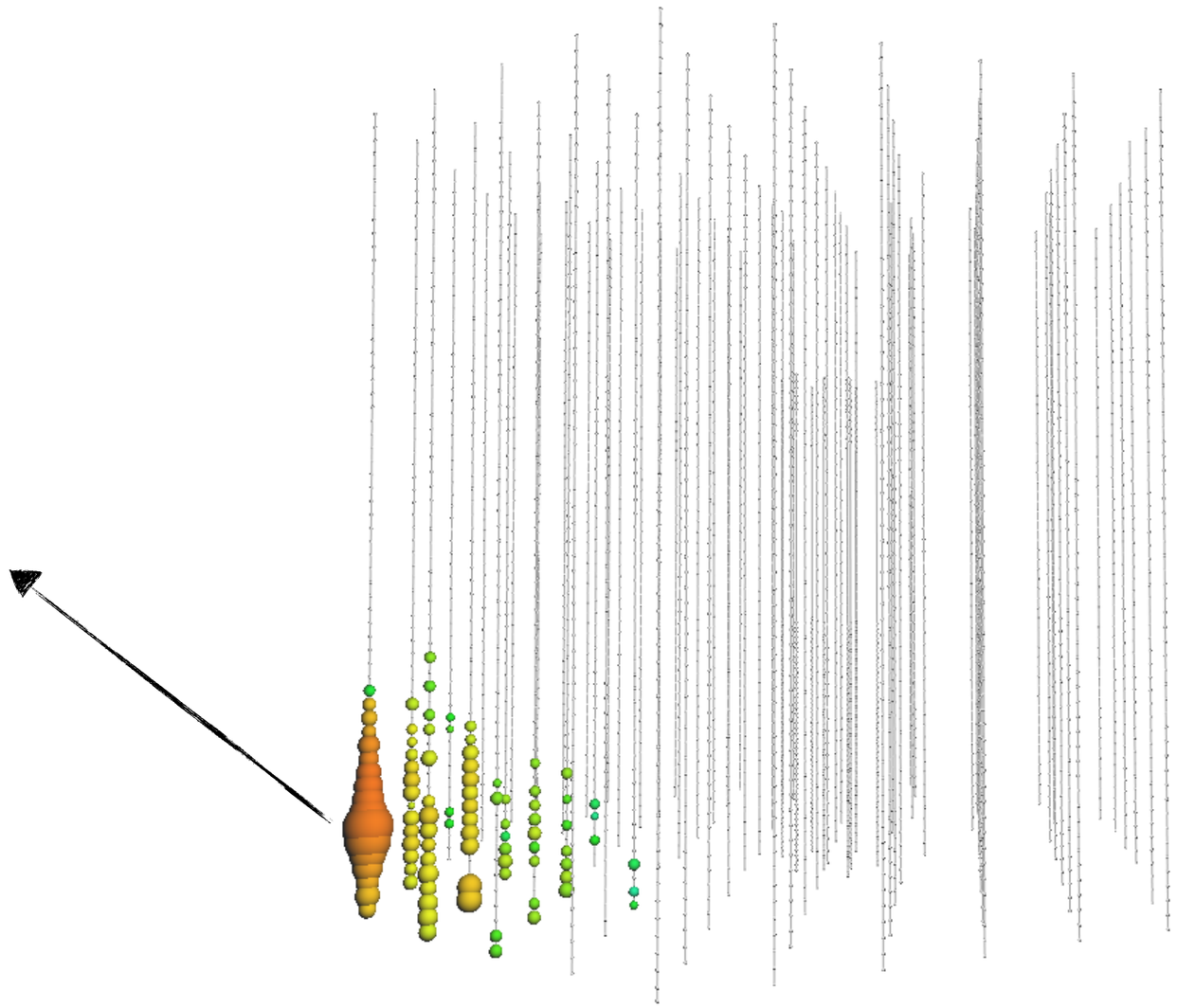
- Sensitivity: 5.1 $\times 10^{-8}$ GeV cm^{-2} sr^{-1}s^{-1}
  - Flux per flavor: 1.0 $\times 10^{-8}$ GeV cm^{-2} sr^{-1}s^{-1} (Phys. Rev. Lett. **113**, 101101)
- Middle 90% signal energy range: 214 TeV - 72 PeV

Unblinding Results:

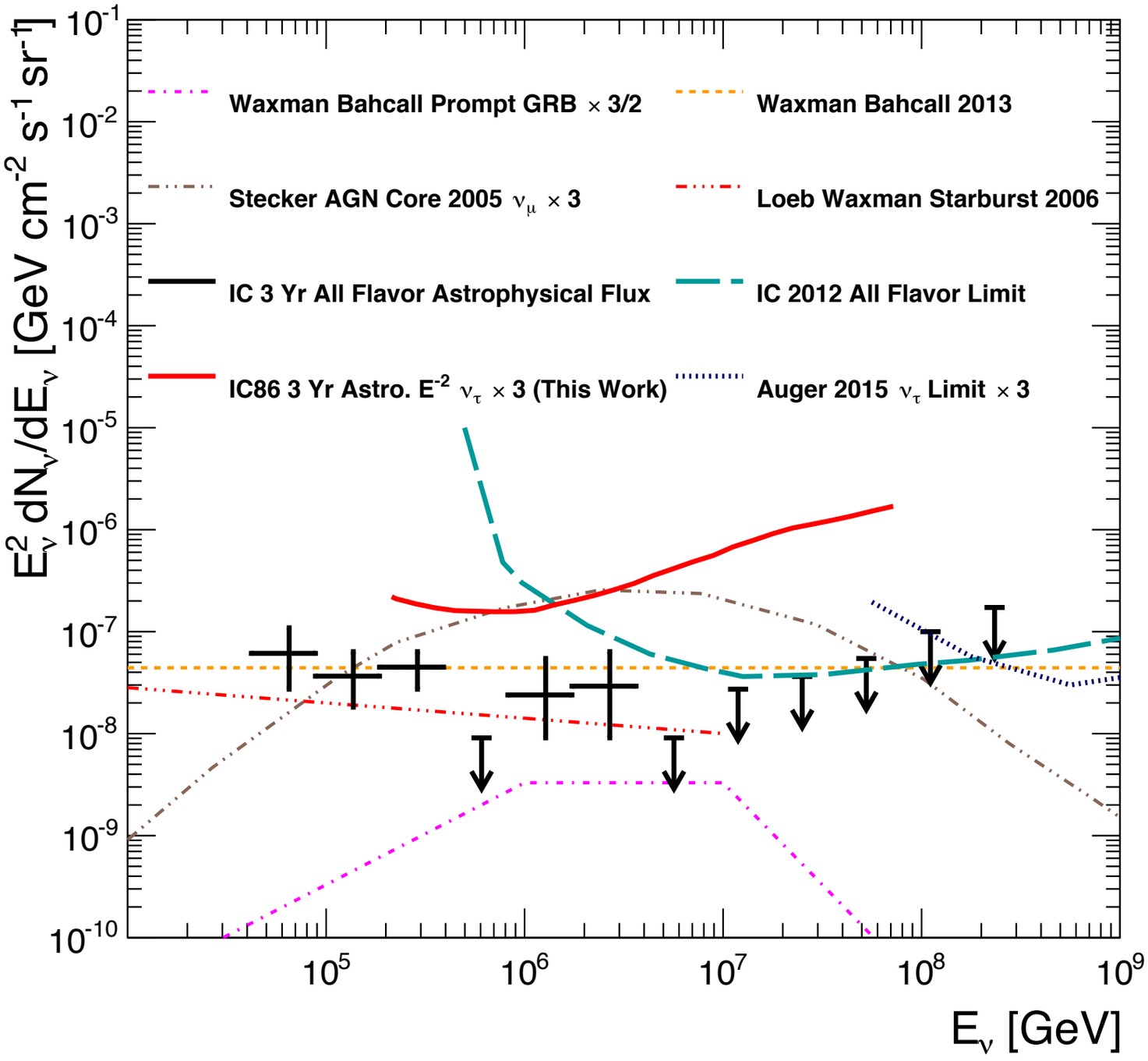
Rates in 914.1 days	L5	L6
CORSIKA	3.5±3.4	0.08±0.06
Blind Sample	**3±2**	**0**

Three double pulse events found before containment cut





Differential Upper Limit



- Zero events found in 914 days
- Integrated limit:
$E^2\phi_\nu = 5.1\times10^{-8}$ GeV^{-1} s^{-1} sr^{-1} cm^{-2}
- Middle 90% energy range:
214 TeV - 72 PeV

Phys. Rev. D 93, 022001
http://arxiv.org/abs/1509.06212

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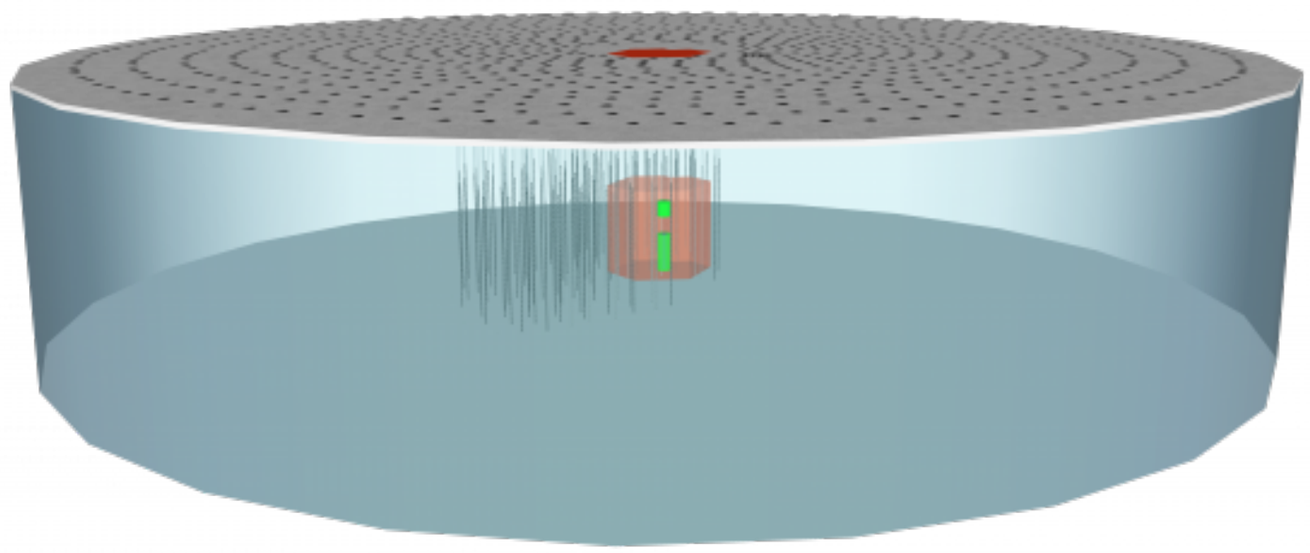
- Double cascades:
  - Double pulse waveform method - **“Double Pulse”**
    (re-optimizing DP waveform identification, machine learning, …)
  - Dedicated double-vertex reconstructions - **“Double Bang”**
    (ice properties, likelihood reconstructions, PDF templates, …)

- Future IceCube-Gen2: https://arxiv.org/abs/1412.5106
- ~ 2-3 times sensitivity ↑ for double pulse events
- ~10 times sensitivity ↑ for double bang events



Conclusion & Outlook

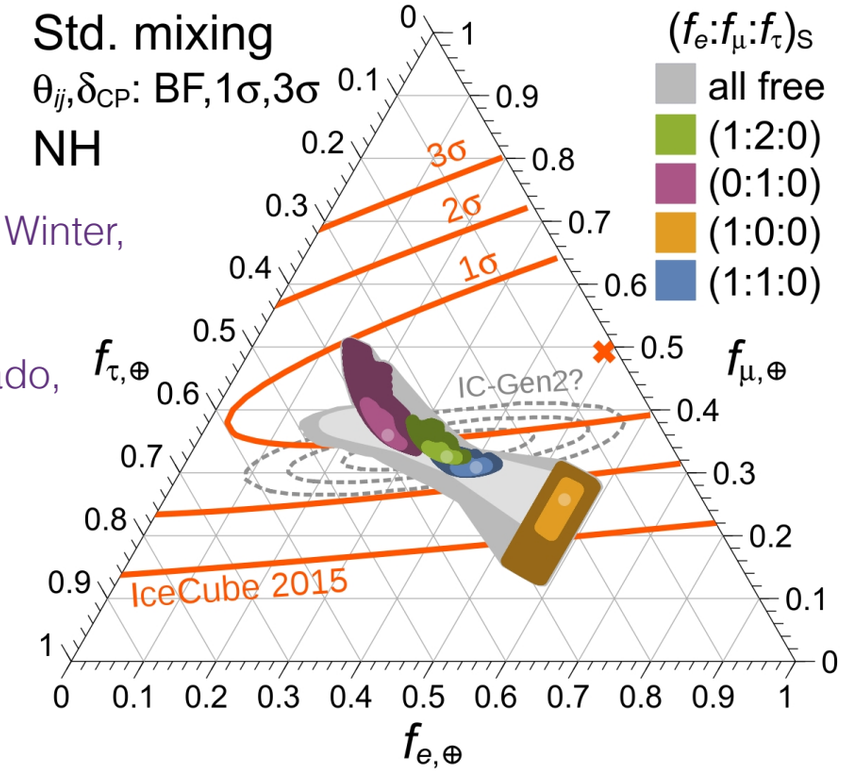
- IceCube has detected a diffuse astrophysical neutrino flux
- The first tau neutrino search with the complete IceCube detector found **zero events in three years (0.54 expected)**
- First upper limit set for astrophysical tau neutrinos at the *O*(PeV) region
- A **new method** for astrophysical tau neutrino search in the waveforms: **lower detection energy threshold to *O*(100 TeV)**
- Dedicated tau neutrino search analyses are ongoing
- Future IceCube-Gen2 is expected to see up to an order of magnitude increase in sensitivity for astrophysical tau neutrinos

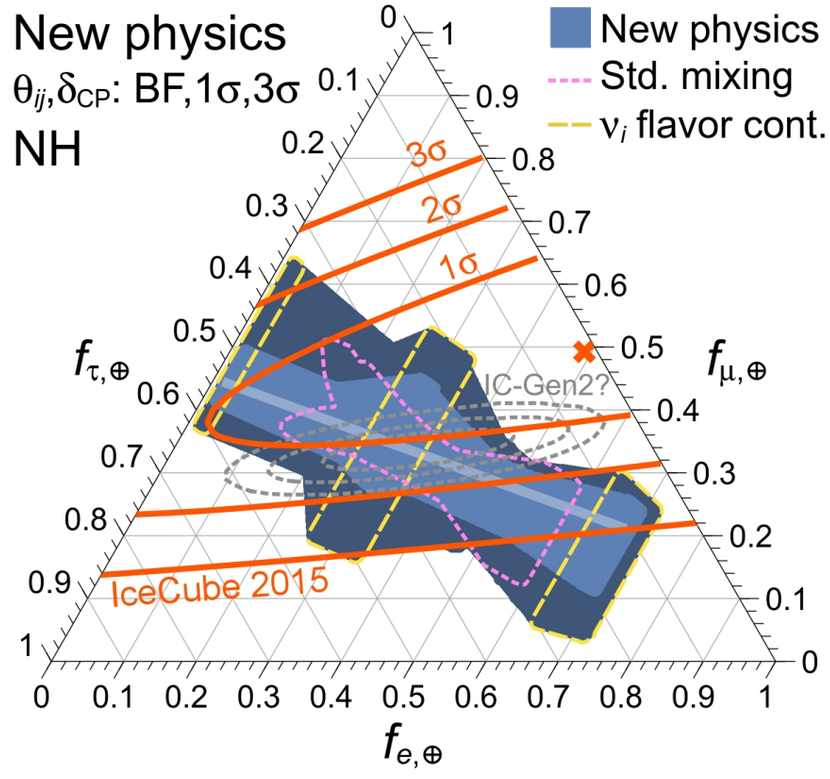
Backup Slides

- **Astrophysical ν:** atmospheric ν_τ production is negligible, one ν_τ event can be 5σ astrophysical.
- **Fundamental properties:**
  - Precision measurement of neutrino flavor ratio at Earth
    - Test standard oscillation over extremely long baselines
    - Probe dominant emission processes at source
    - Constrain new physics models.

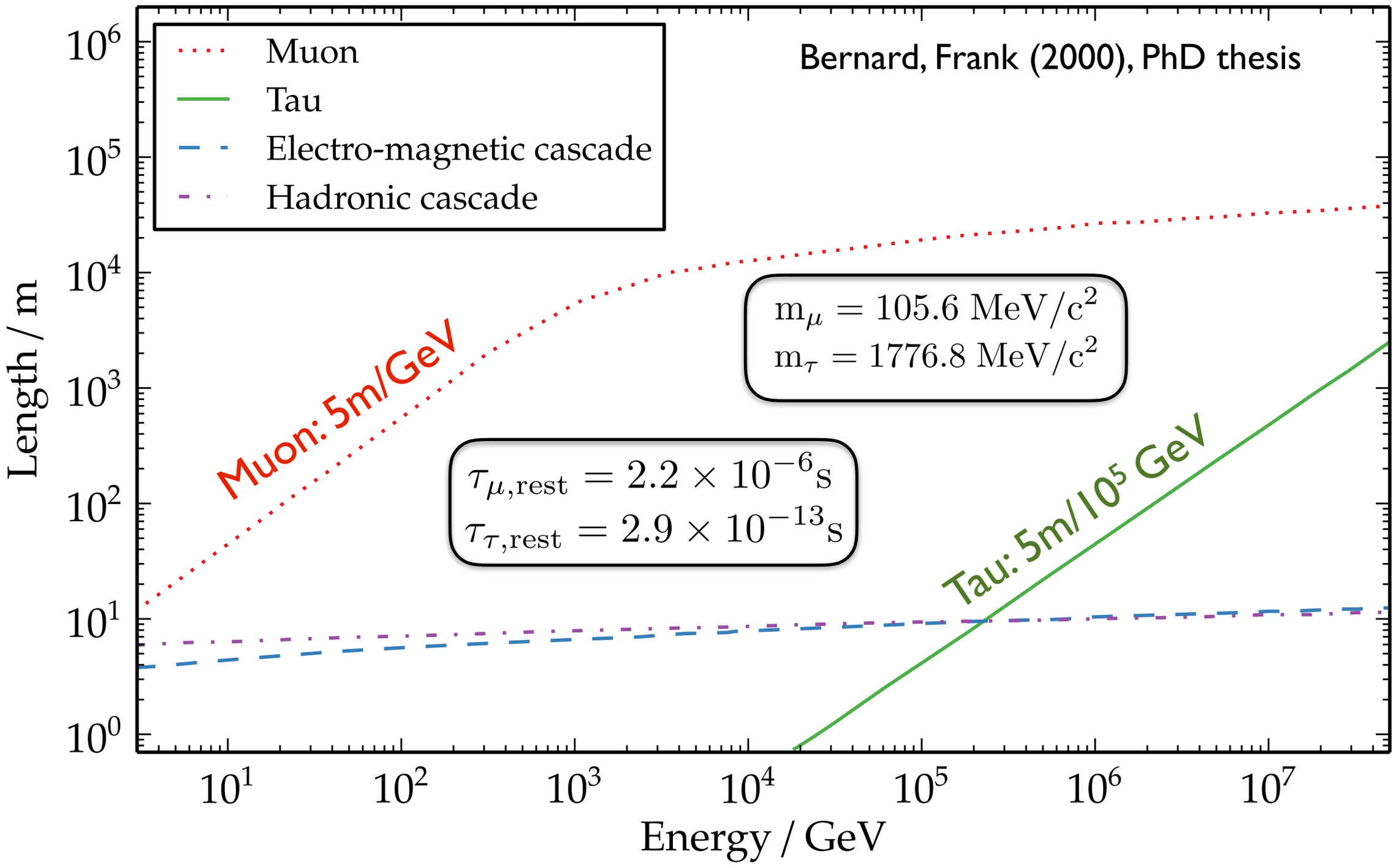
M. Bustamante, J. F. Beacom, and W. Winter, Phys. Rev. Lett. 115, 161302 (2015).

C. A. Argüelles, T. Katori, and J. Salvado, Phys. Rev. Lett. 115, 161303 (2015).

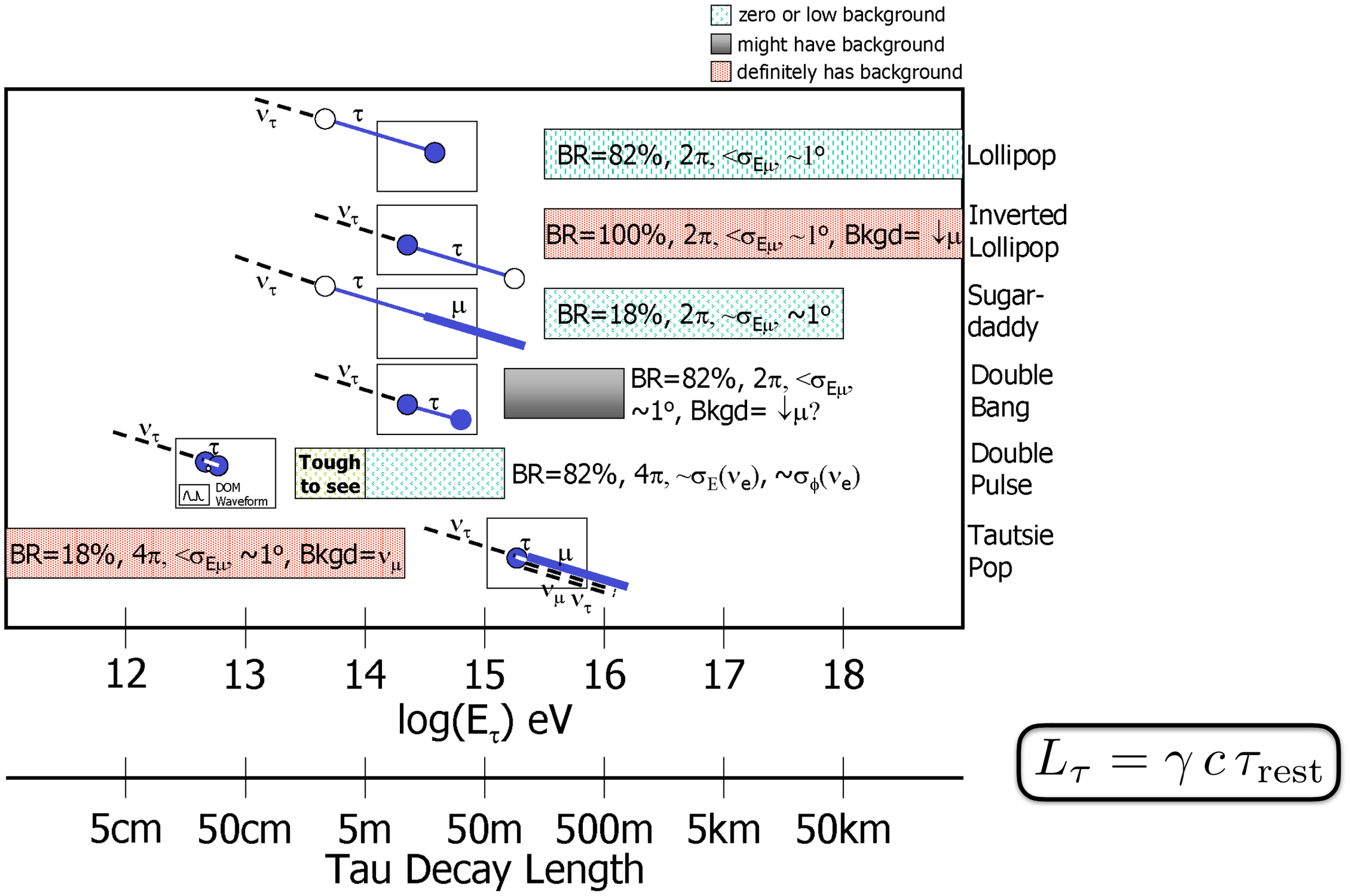




Tau vs Muon

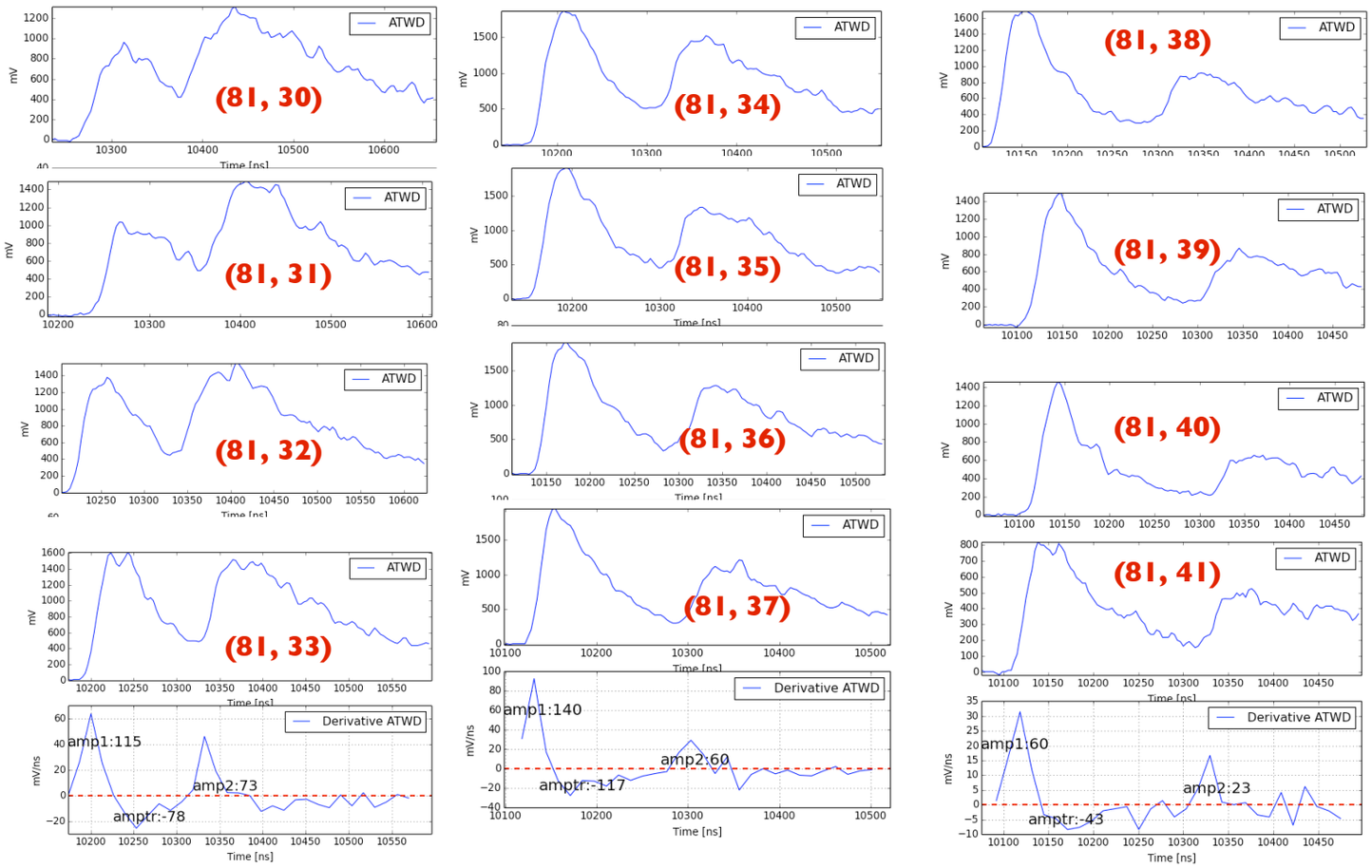


Tau Neutrino Signatures in IceCube



$$L_\tau = \gamma\, c\, \tau_{\text{rest}}$$

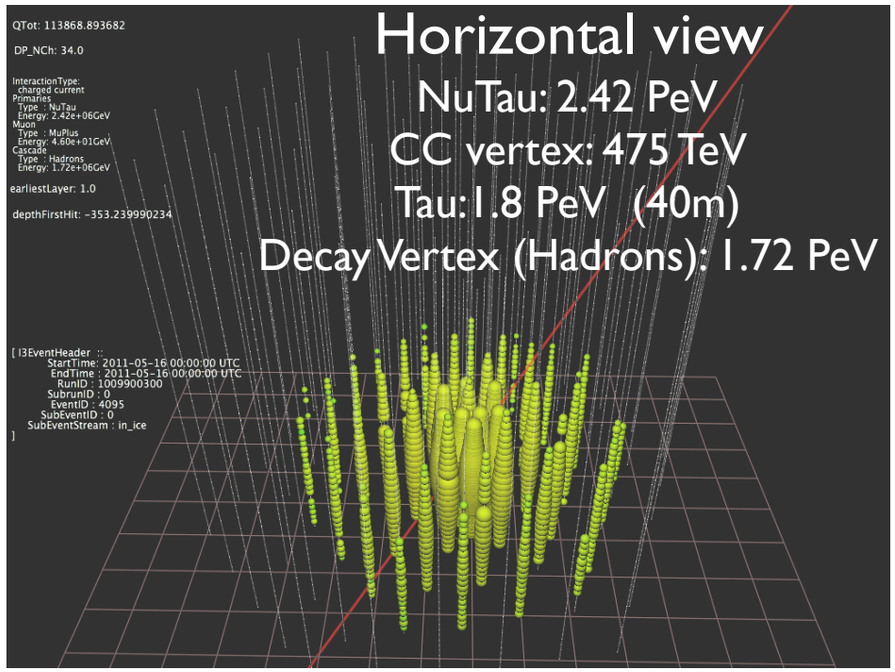
Simulated NuTau CC Event with DP Waveforms

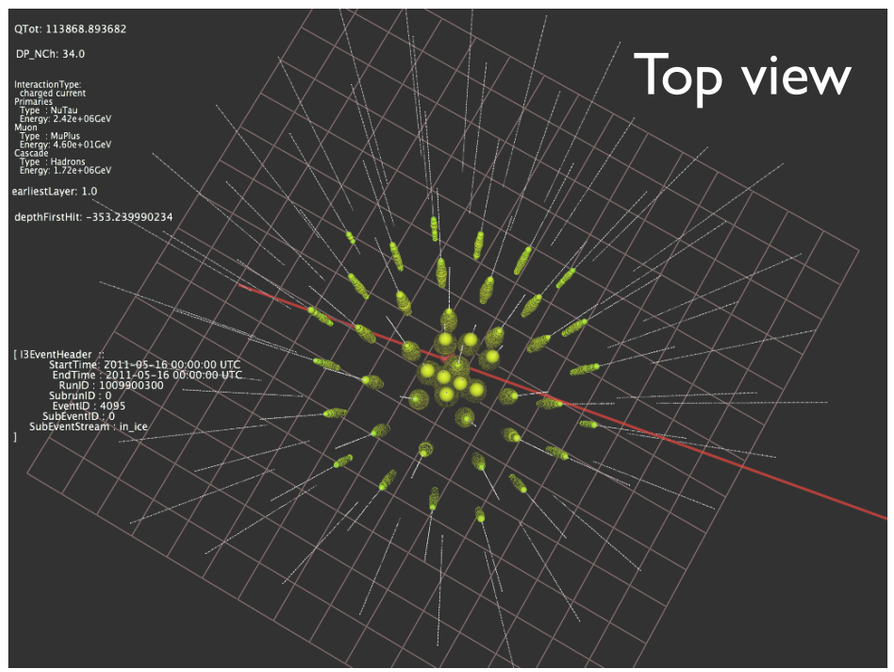


plus 22 additional DP waveforms from OMs on other strings = 34 DP waveforms

- DP events with vertices near DeepCore

are golden events as they make multiple adjacent DP waveforms on the same string





A ν_τ CC DP event

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Effective Areas at Final Cut

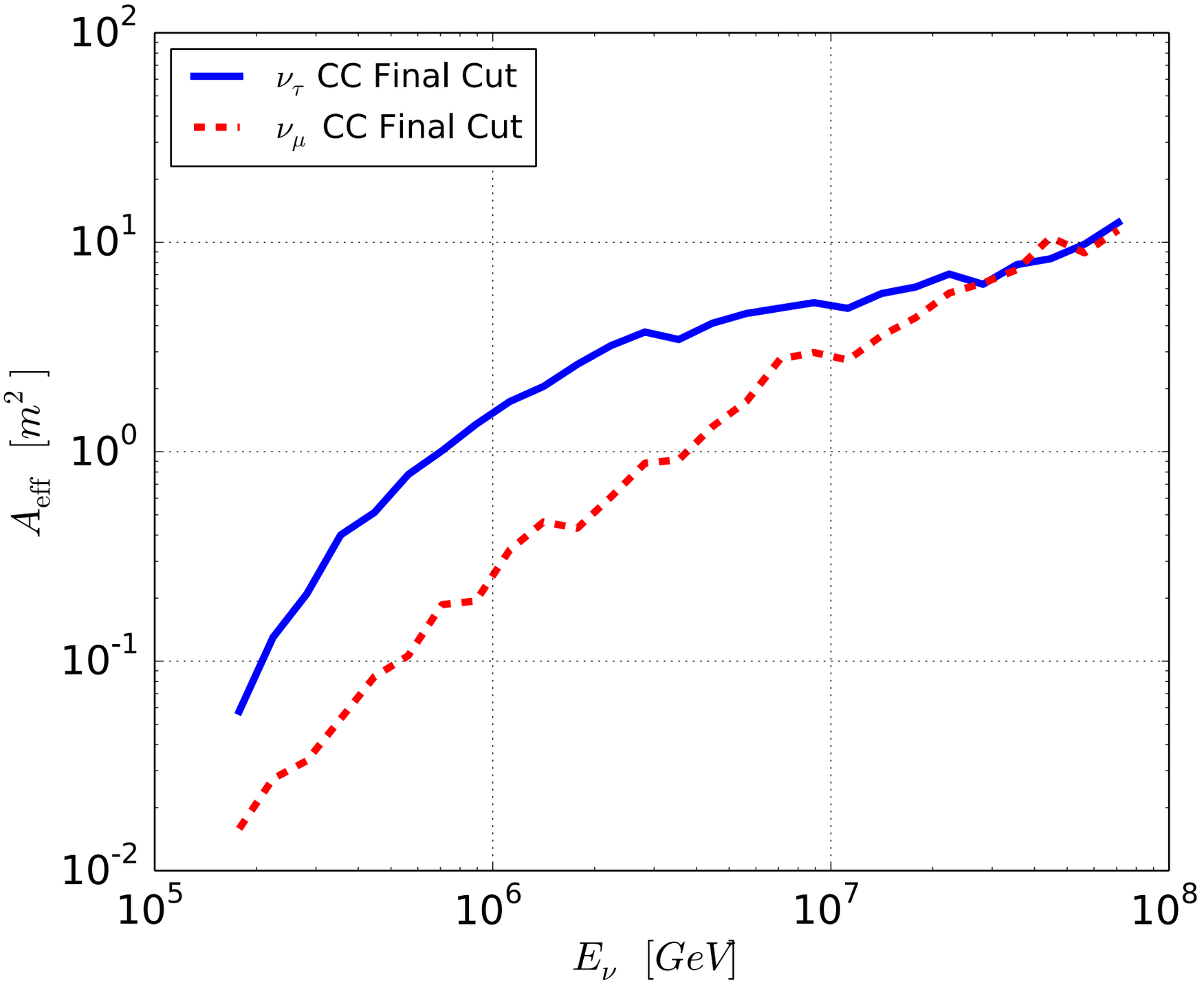

TABLE II. Source of systematic uncertainty in the signal.

Neutrino cross sections	-5%
Anisotropy in the optical scattering in ice	-7%
Optical scattering and absorption lengths in ice	$^{+8.1\%}_{-4.9\%}$
DOM efficiency	$^{+6.7\%}_{-1.6\%}$
Total	$^{+10.5\%}_{-10.0\%}$

Phys. Rev. D 93, 022001
http://arxiv.org/abs/1509.06212