UNIVERSITEIT GENT

FACULTY OF SCIENCES

# Search for astrophysical $\nu_\tau$ with the IceCube Neutrino Observatory

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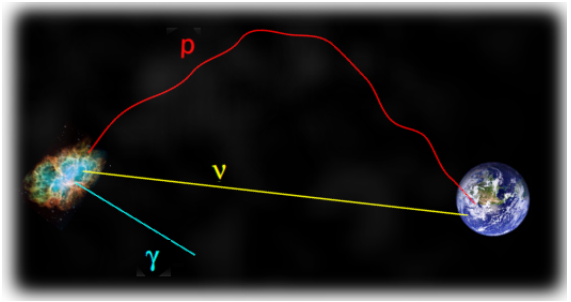
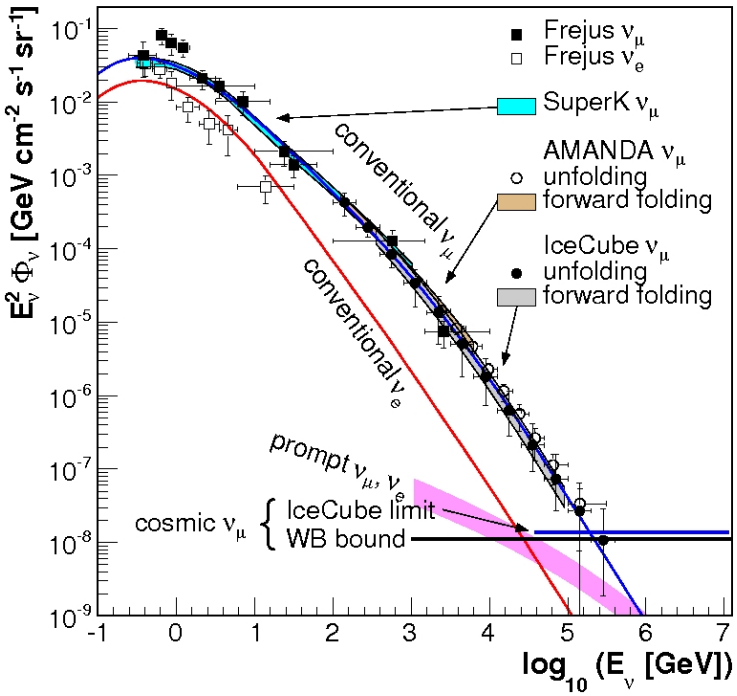
ICECUBE

# Neutrinos as astronomical messengers

- Neutrinos are ideal astronomical messengers:
  - Uncharged (unlike Cosmic Rays)
  - Low cross-section (unlike Photons)
- High energy neutrinos produced in astrophysical sources
  - At hadronic acceleration sites e.g. SNRs, AGNs, GRBs, GZK mechanism
  - Baseline flux expectation $\propto \mathrm{E}^{-2}$



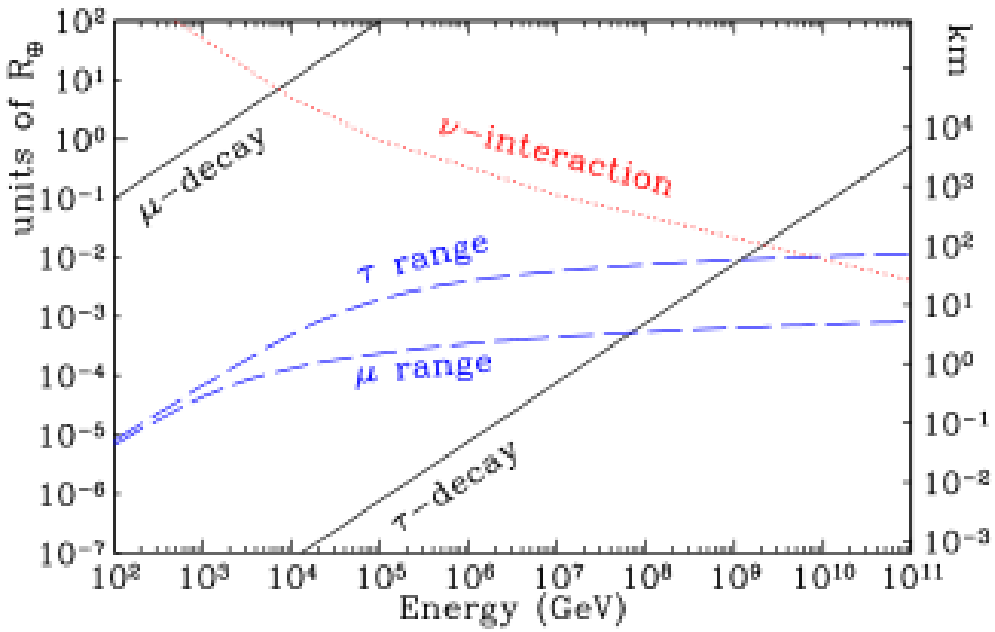

- Need very large detector
  - Use large natural transparent volume
  - Detect Cherenkov light from charged secondaries
- Huge backgrounds to overcome
  - $10^9$ times more atmospheric muons
  - $10^3$ times more atmospheric neutrinos



# Properties of astrophysical $\nu_\tau$

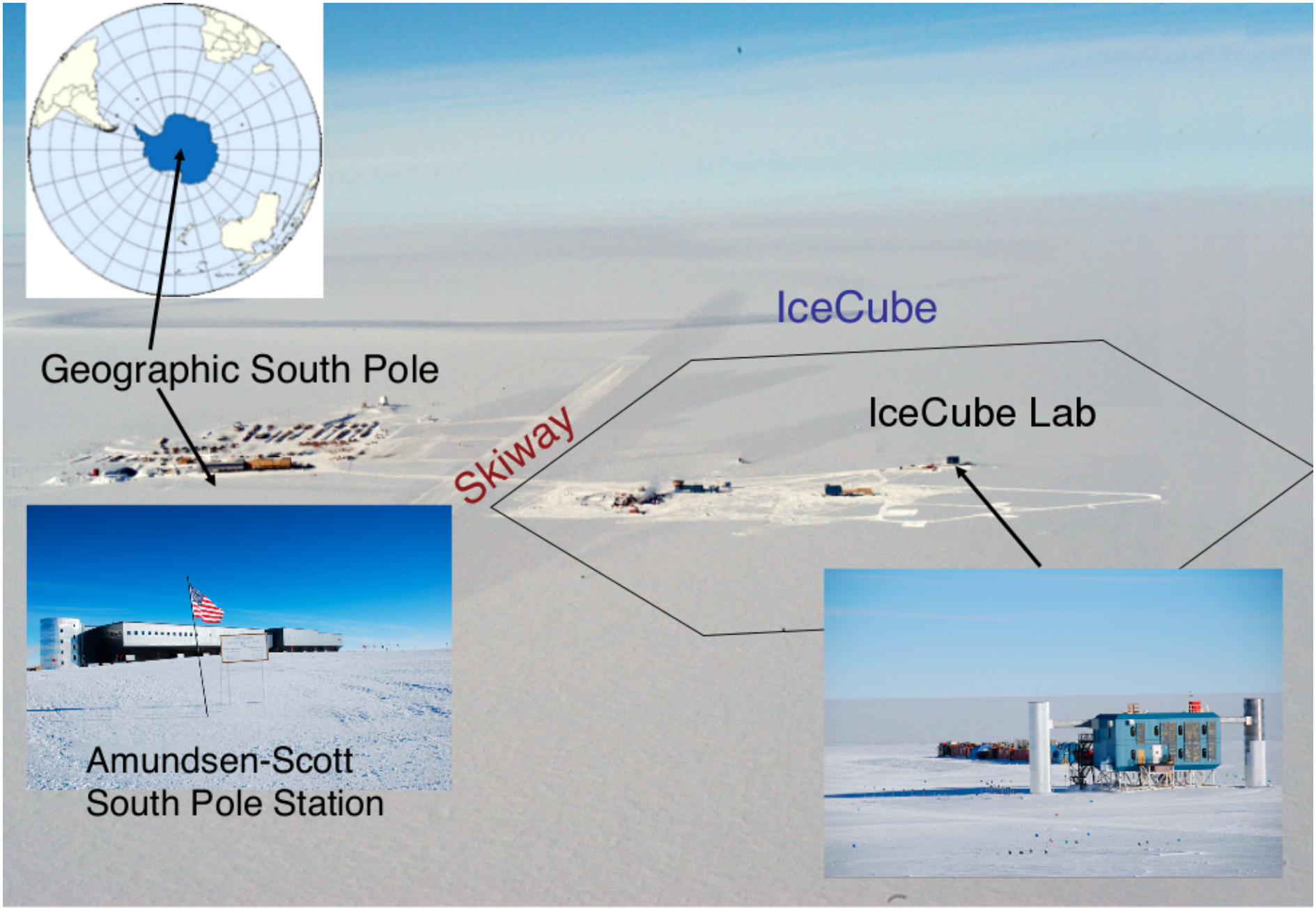
- Flavour ratio at source 1:2:0 $(\nu_e, \nu_\mu, \nu_\tau)$
- Flavour ratio at Earth 1:1:1 $(\nu_e, \nu_\mu, \nu_\tau)$
- No atmospheric $\nu_\tau$ background:
  - Negligible amount of $\nu_\tau$ produced in air showers
  - Negligible $\nu_\mu \longrightarrow \nu_\tau$ oscillations over a baseline $\leq D_{Earth}$

- Earth becomes opaque for neutrinos at the highest energies
- $\nu_\tau$ regenerated while propagating trough the Earth
- $\tau$ decay length $\mathcal{O}(50\,\mathrm{m})$ at $\mathcal{O}(\mathrm{PeV})$
- $\tau$ track dimmer than $\mu$ track

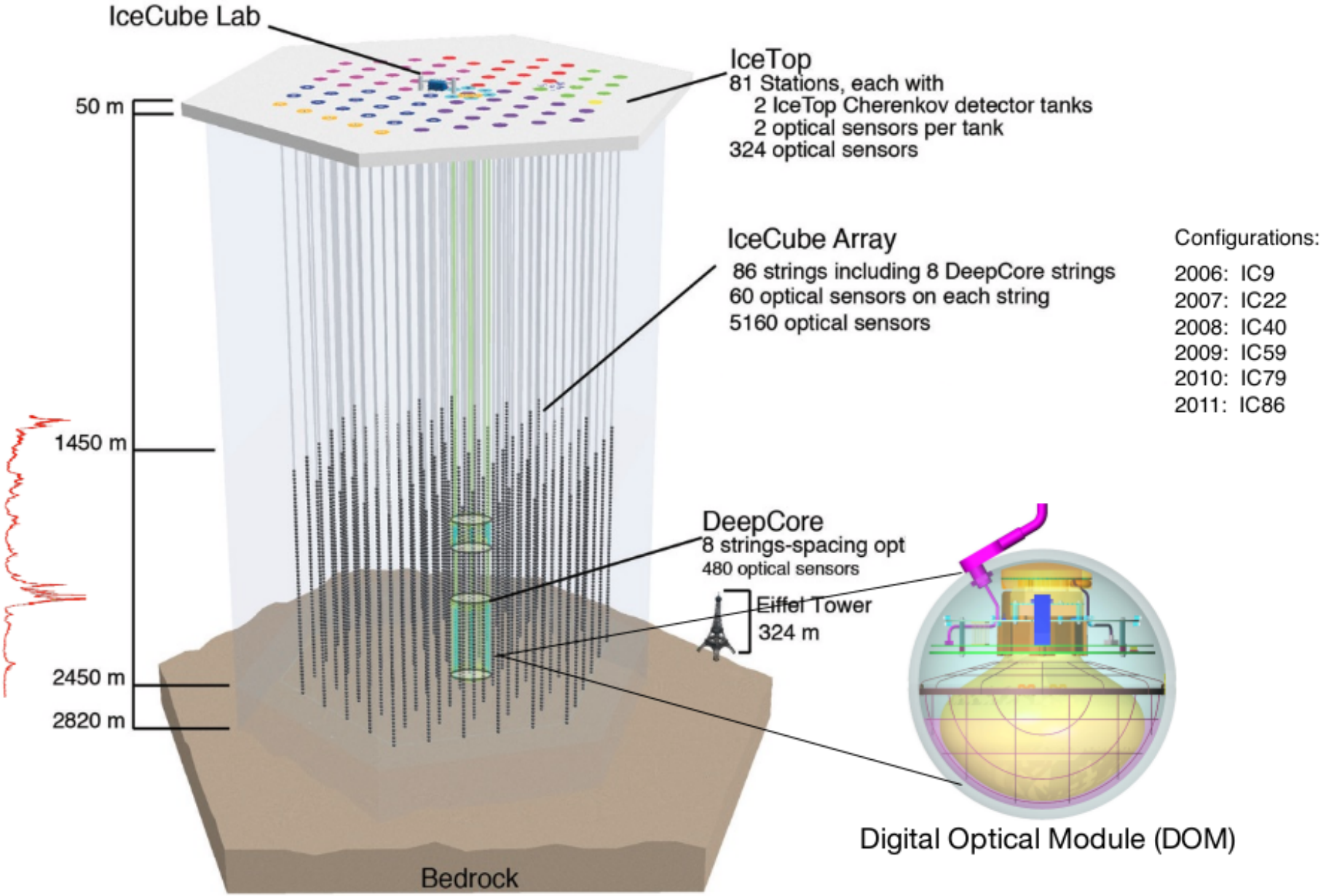



J. F. Beacom, P. Crotty and E. W. Kolb, Phys. Rev. D 66, 021302 (2002)

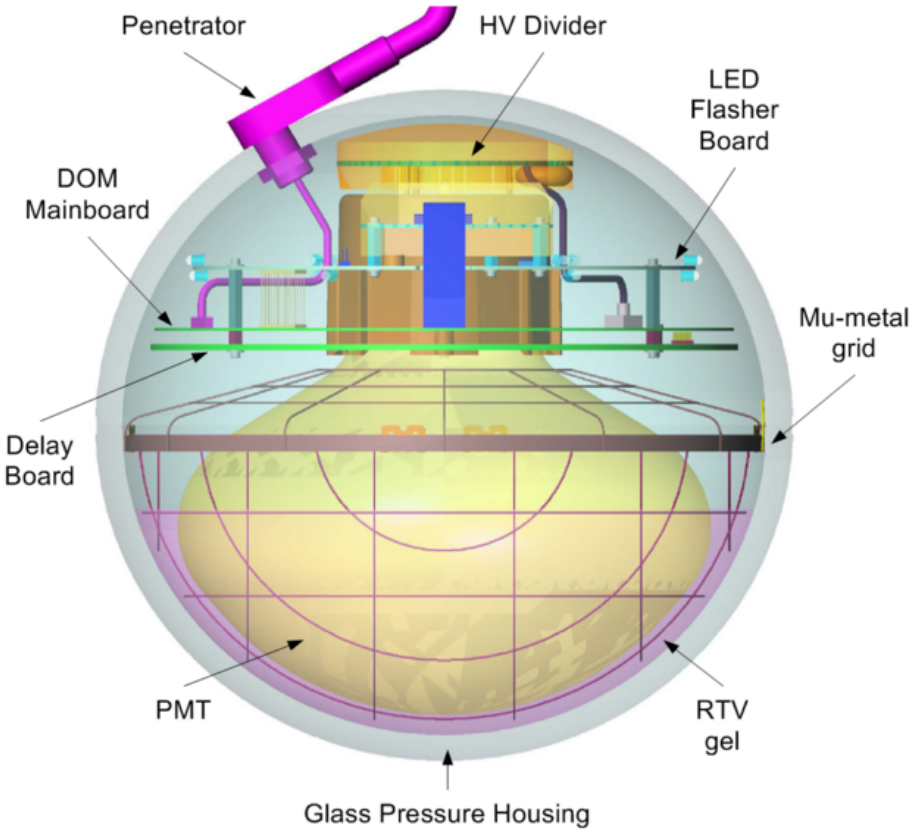
# IceCube at the South Pole



# The IceCube detector

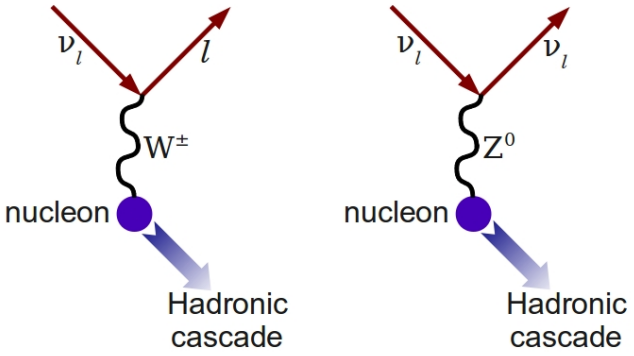


# Digital Optical Module (DOM)

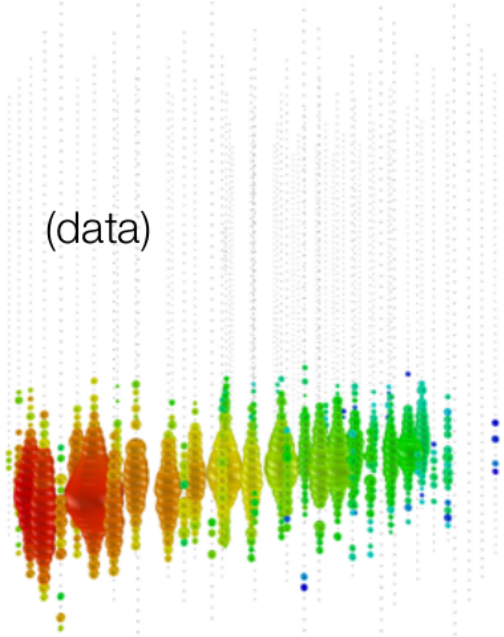


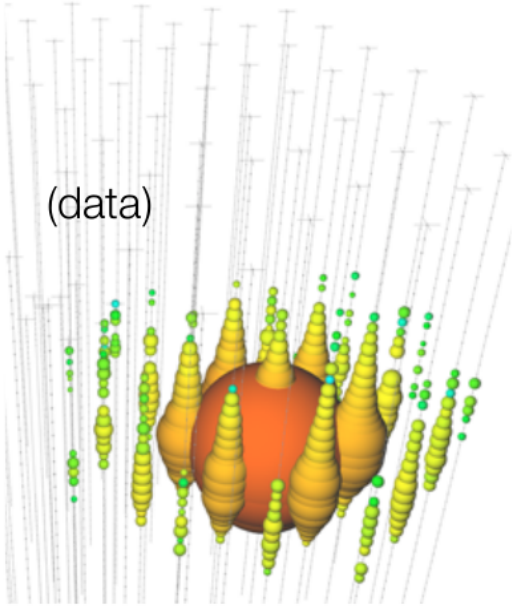

- Same modules for IceTop and IceCube
- Horizontal spacing 125 m
- Vertical spacing 17 m
- Contains 25 cm PMT
- Handles some of the low-level triggering
- Local Coincidence with neighbors
- Digitizes the recorded signals before sending them to the surface
- Flasher LEDs for in-ice calibration

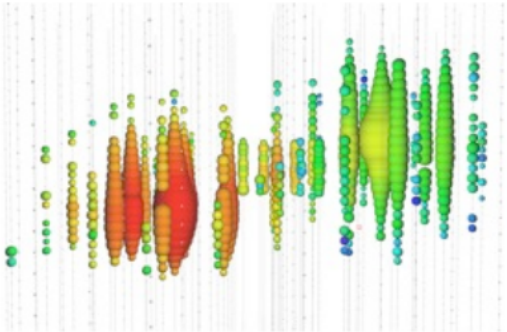
# Neutrino detection with IceCube




- All 3 neutrino flavours can interact via Charged Current (CC) or Neutral Current (NC) weak interaction




$\nu_\mu$ CC

Angular Resolution $\sim 1^\circ$
Escaping muon

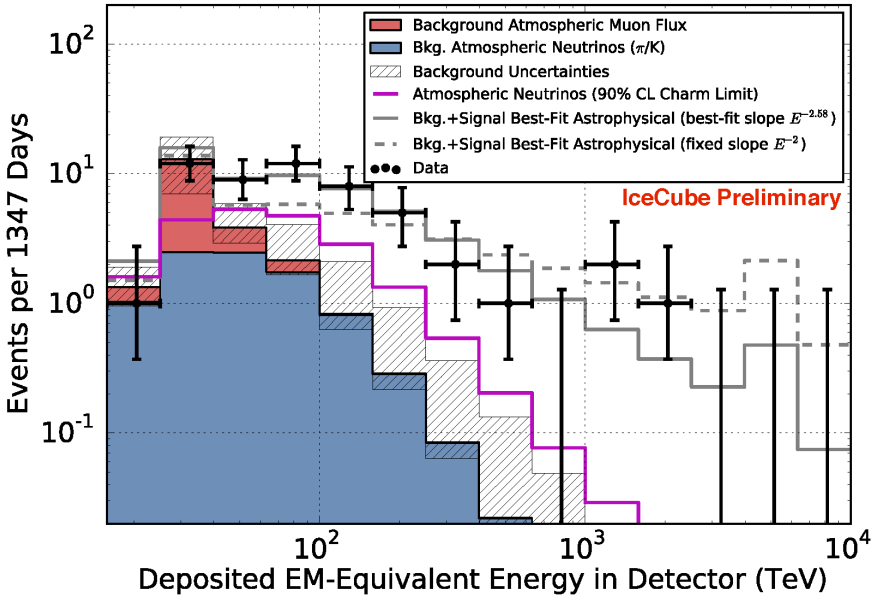
$\nu_e$ CC or $\nu_x$ NC

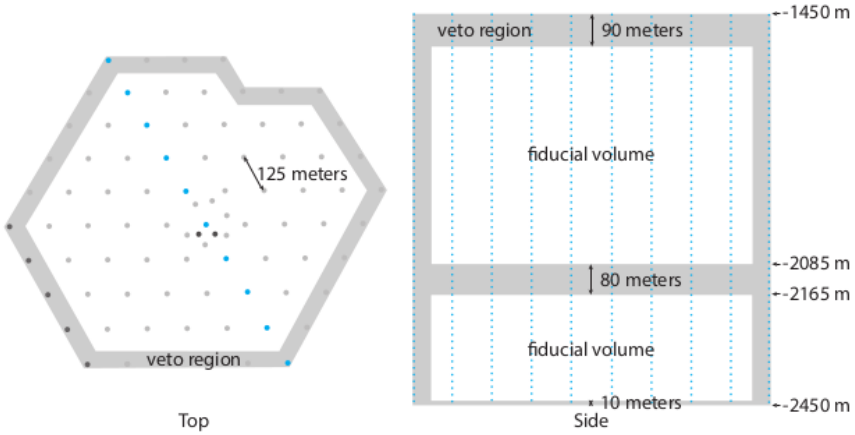
Angular Resolution $\sim 10^\circ - 15^\circ$
Energy Resolution $10 - 15\%$
(deposited energy)

$\nu_\tau$ CC

Not yet detected
Angular / Energy Resolution
depends on signature

# Status of astrophysical neutrino searches




- Detection of an astrophysical neutrino flux ($> 5\,\sigma$)
- No point-sources yet
- Combined analysis of different high-energy event samples:
  - Spectrum appears to be somewhat softer than $\propto \mathrm{E}^{-2}$
  - No $\nu_\tau$ identified yet
  - Flavor ratio agrees with 1:1:1 at the Earth

M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. 113, 101101 (2014)

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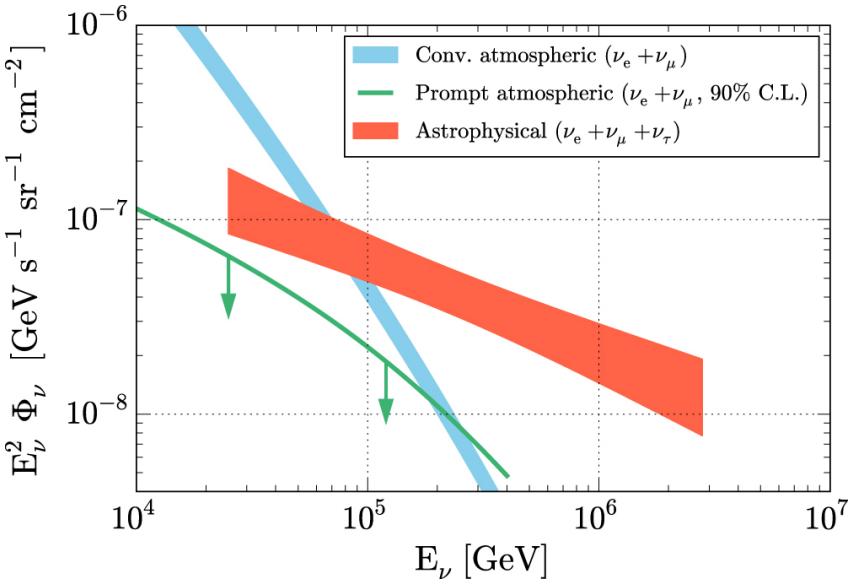


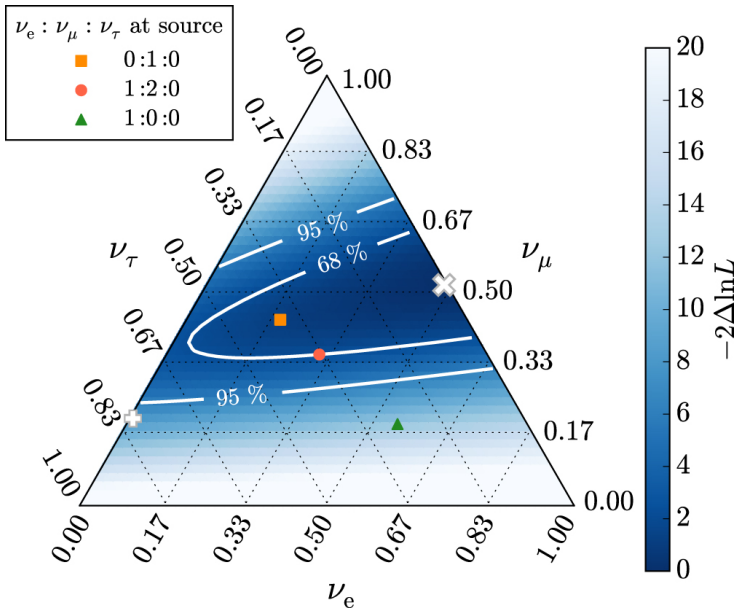


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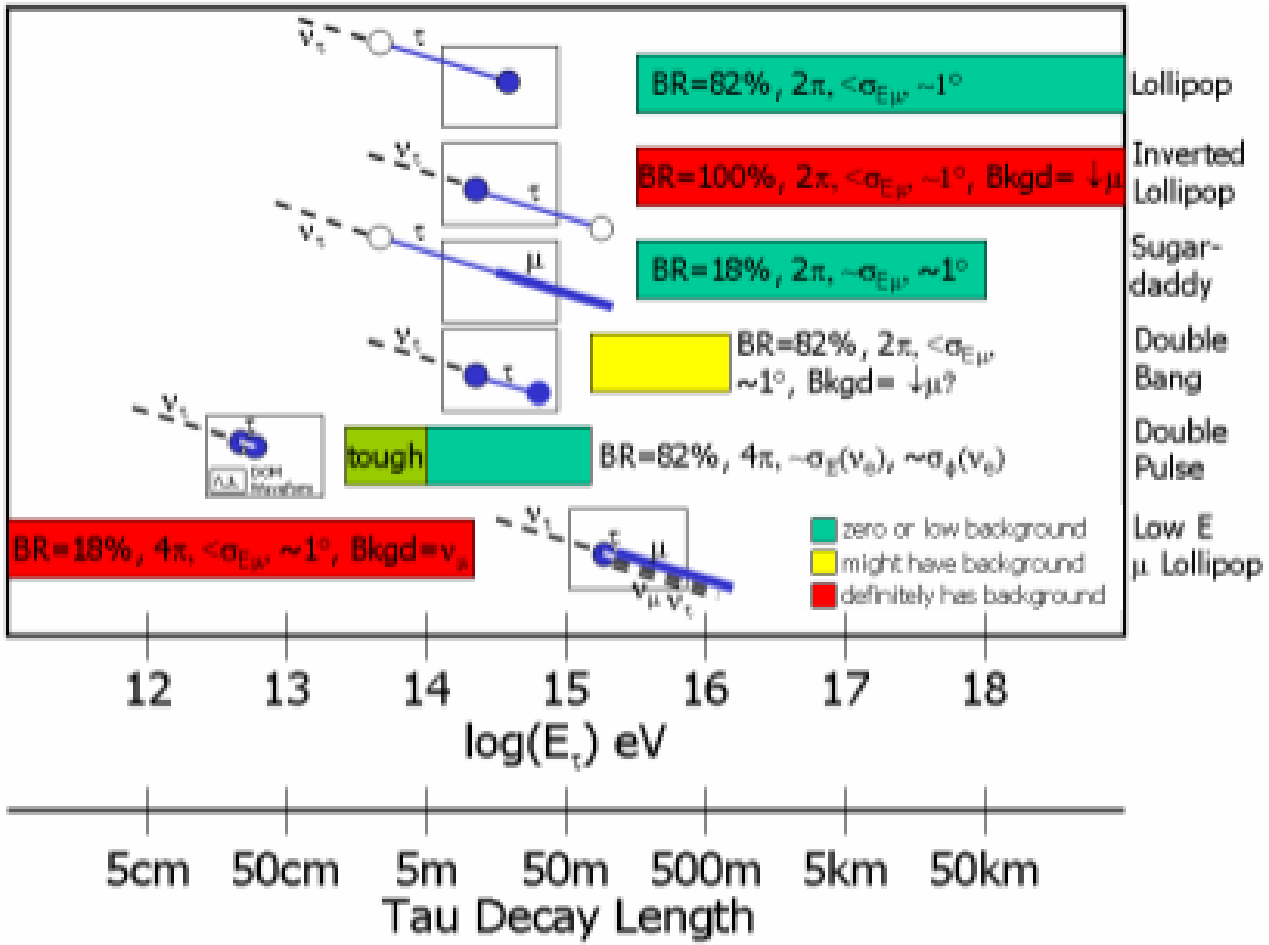
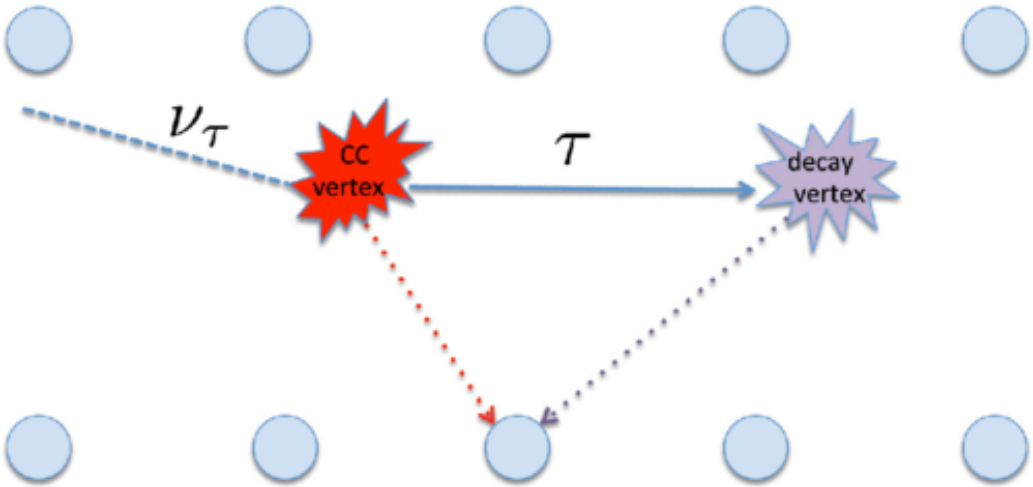
# $\nu_\tau$ signatures in IceCube

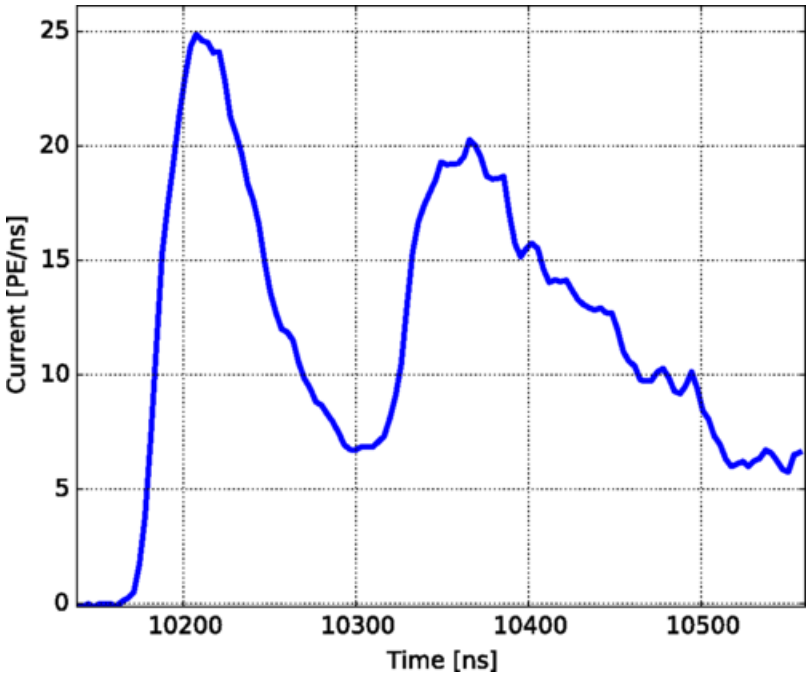
- A $\nu_\tau$ can have several different signatures in the detector, depending on the energy of the neutrino, the position of the primary interaction and the position of the decay of the $\tau$ lepton.



# $\nu_\tau$ searches: Double Pulses

- Two cascades close together
- Single DOM can detect direct light from both cascades
  - Can lead to a double peaked structure



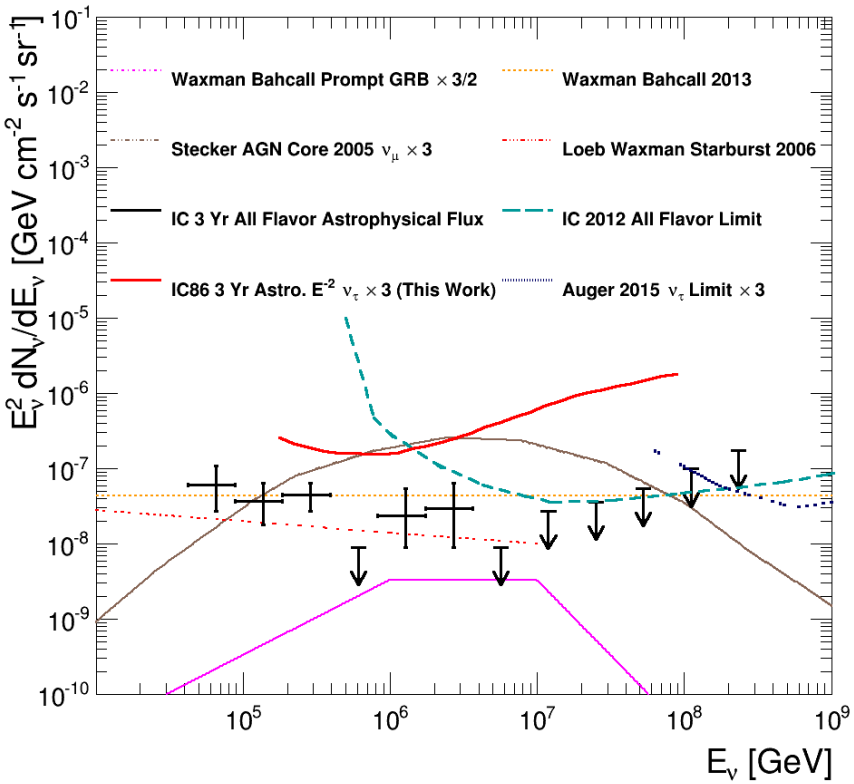




- Select high charge DOMs
- Algorithm selects waveforms with sequence of rising, falling and second rising edge
- Further cuts to reduce tracks and corner-clipping muons

M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. D 93, 022001 (2016)

# $\nu_\tau$ searches: Double Pulses

- Analysis applied to 3 years of IceCube data
- No events were found
- Differential upper limit (90% confidence) calculated:

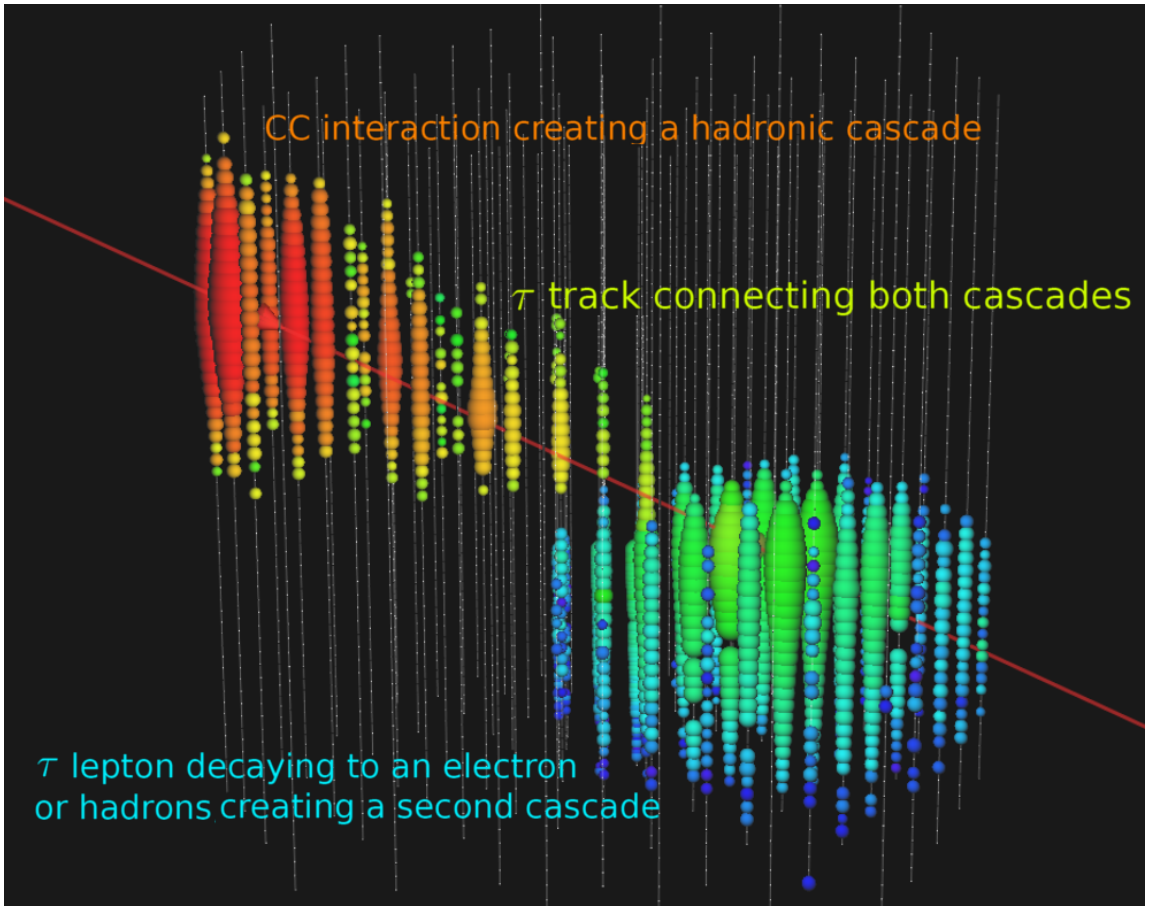



- Integrated upper limit: $\mathrm{E}^2\,\Phi_{\nu_\tau} = 5.1 \cdot 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. D 93, 022001 (2016)

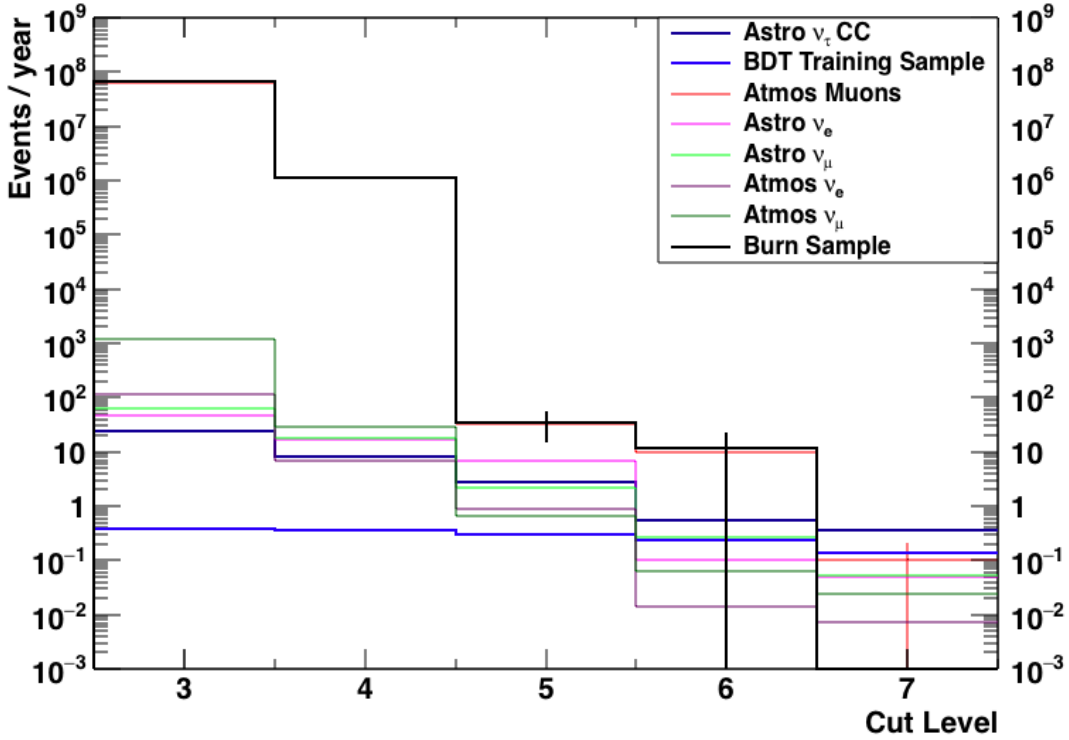
# $\nu_\tau$ searches: Double Bangs

- Goal: Select and identify tau neutrinos via the Double Bang signature
- Signal:
  - CC $\nu_\tau$ interaction with $\tau$-lepton decaying to an electron or hadrons
  - Length of $\tau$-lepton long enough for both cascades to be distinguishable
  - Both cascades points inside or close enough to the detector volume



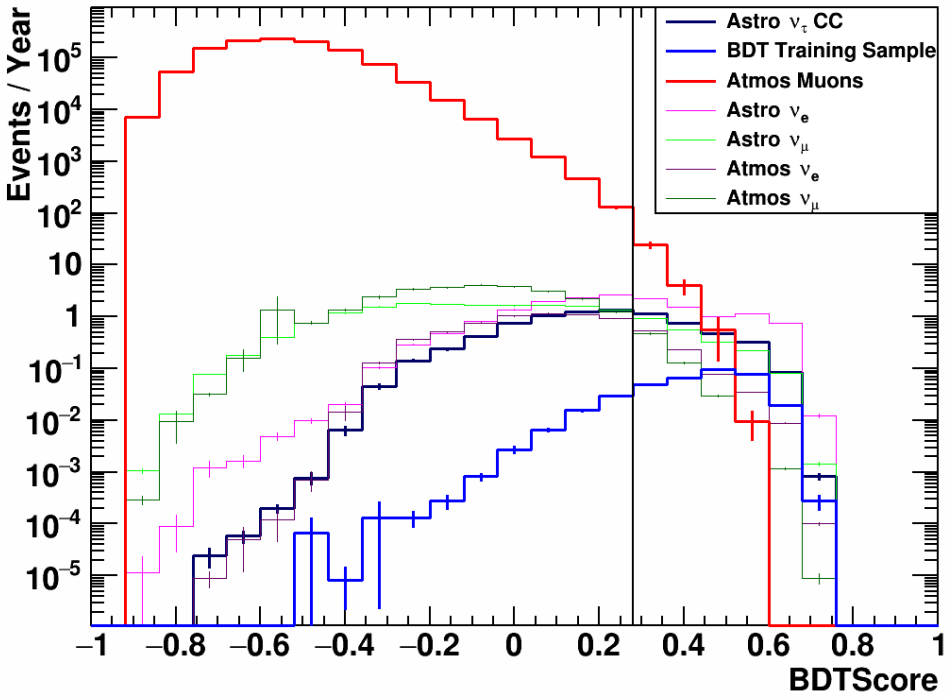
# $\nu_\tau$ searches: Double Bangs - Event Selection

- Series of cuts were developed to reduce the different backgrounds to below the signal level
  - Level 3: Require IceCube's Extremely High Energy filter
  - Level 4: Total Charge $>$ 3200 photo-electrons
  - Level 5: Cut on Boosted Decision Tree output
  - Level 6: Cuts on Double Bang reconstruction
  - Level 7: Cuts on energy-loss profile reconstruction



# $\nu_\tau$ searches: Double Bangs - BDT

- A Boosted Decision Tree is trained based on 6 variables
- Signal: Simulated Double Bangs with both cascades contained within the detector and a minimum separation of 50 m
- Background: Simulated Muon Bundles

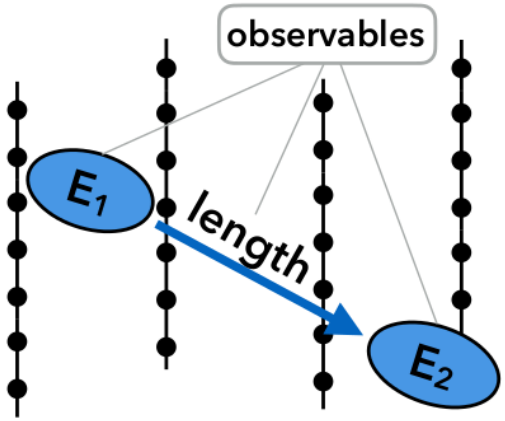



- Cut reduces Muon Bundle background by over 4 orders of magnitude

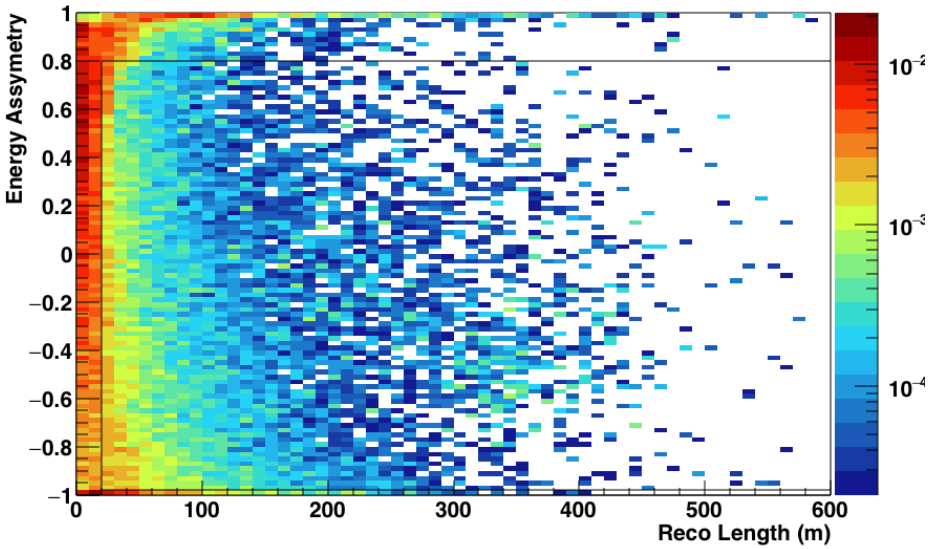
# $\nu_\tau$ searches: Double Bangs - Reconstruction

- Single cascade background rejection with Double Bang reconstruction

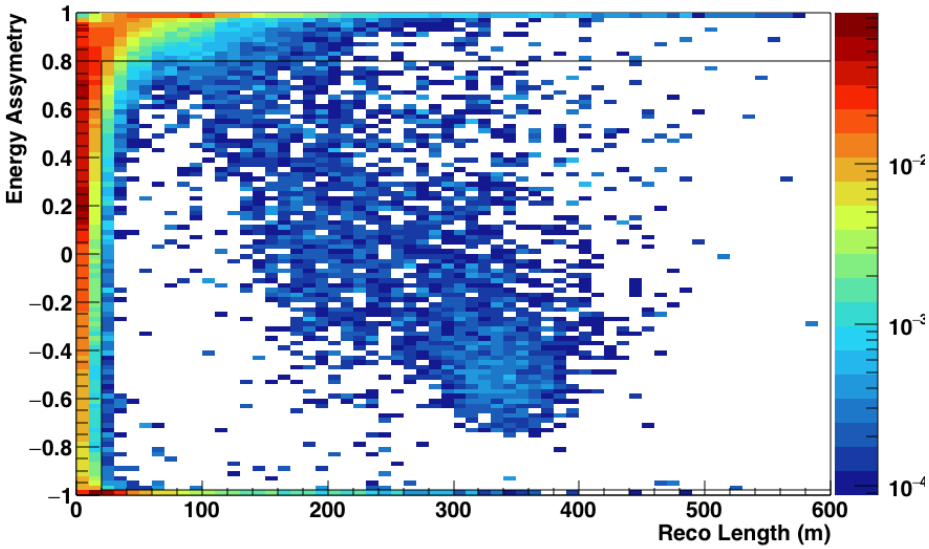
- Cut in Energy Assymetry / Reco Length - plane
  - $\text{Energy Assymetry} = \dfrac{E_1 - E_2}{E_1 + E_2}$
  - Reco Length: Reconstructed distance between the two cascades




Astro. $\nu_\tau$ CC

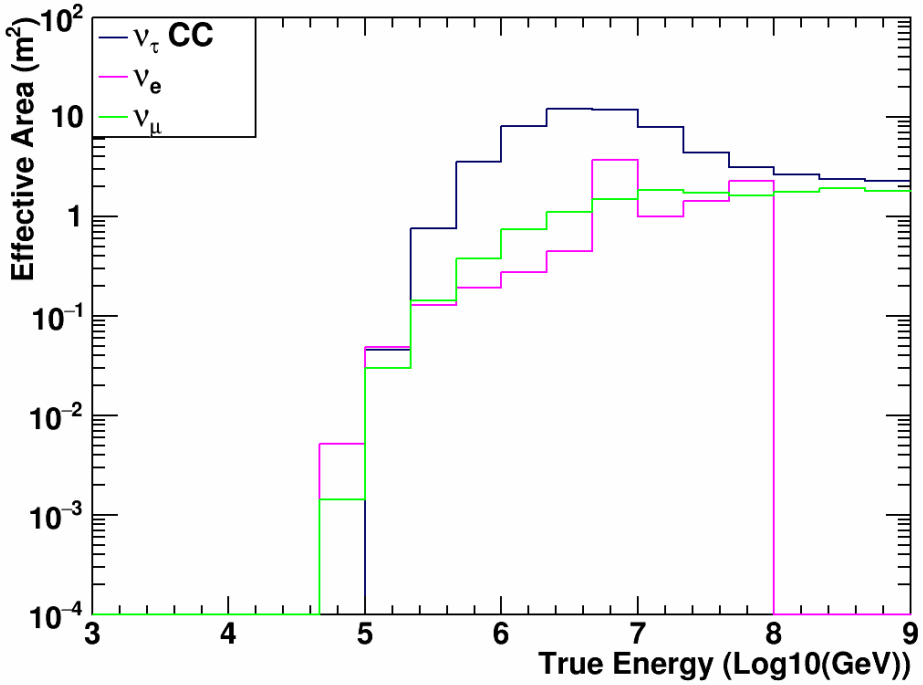



Astro. $\nu_e$



# $\nu_\tau$ searches: Double Bangs - Sensitivity

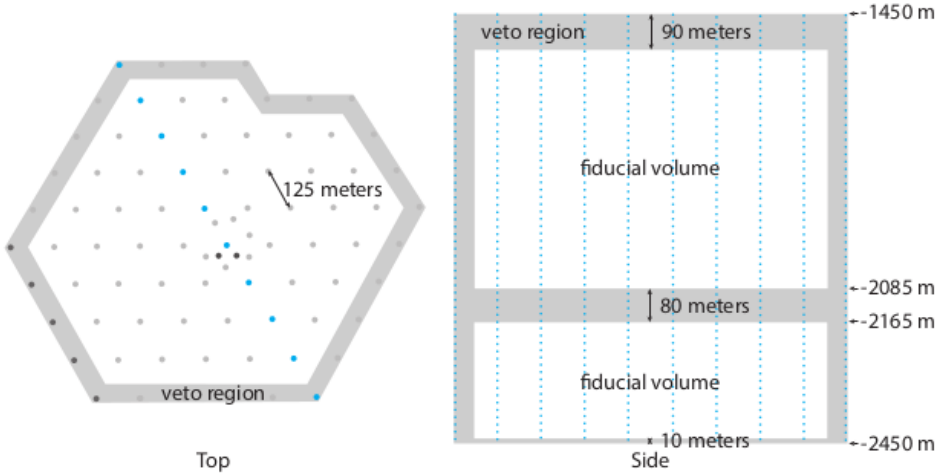
- Effective areas at final cut level

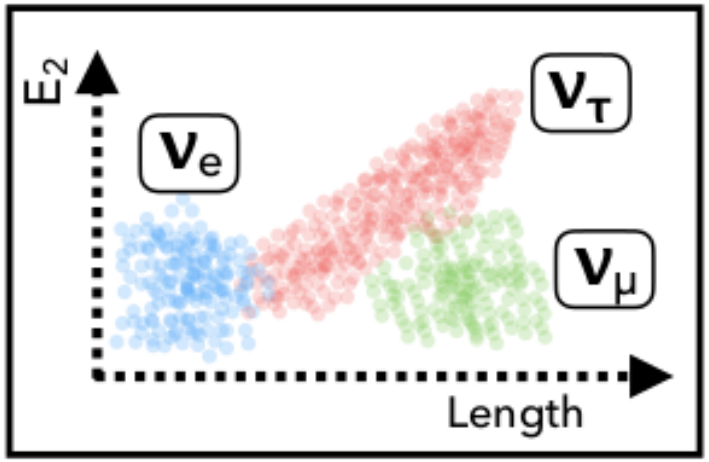



- Analysis most sensitive to $\nu_\tau$ above about 700 TeV
- More sensitive to $\nu_\tau$ than other flavors in a limited energy region
- Sensitivity (90 % confidence):
  $\mathrm{E}^2\,\Phi_{\nu_\tau} = 1.5 \cdot 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

# $\nu_\tau$ searches: HESE Double Bangs

- Uses the High Energy Starting Events sample
- Veto-based event selection
- Requires high deposited energy




- Perform detailed Double Bang reconstruction
- Find observables sensitive to neutrino flavor
- Build Probability Density Functions
- Fit flavor contributions

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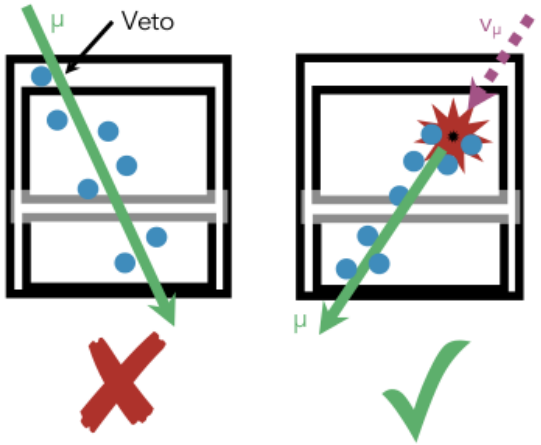


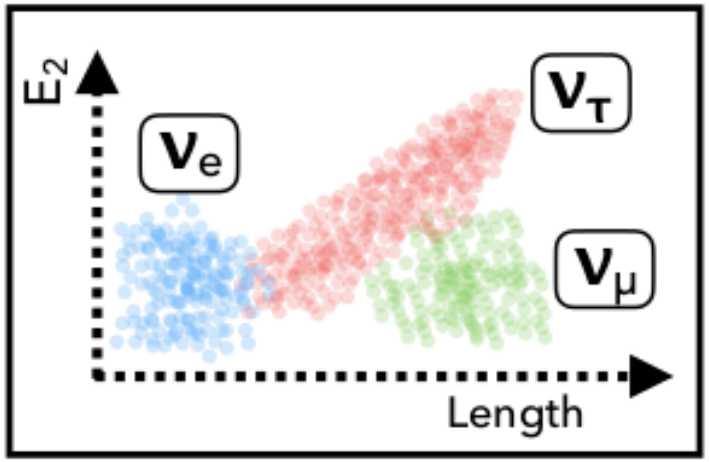


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- Fit flavor contributions

# Conclusions and Outlook

- Astrophysical $\nu_\tau$ have some nice features ...
  - No atmospheric neutrino background
  - Regeneration shifts effect of Earth opacity to higher energies
- ... and some annoying features
  - Hard to distinguish from other neutrino flavors
- No $\nu_\tau$ has been identified yet
- Would help constrain the astrophysical neutrino flavor ratio
- More sensitive analyses are on the way that are specifically looking for $\nu_\tau$ using more years of data
  - Some work still to be done
  - Stay tuned!