

# Astroparticle – Neutrinos

## From IceCube to IceCube-Gen2

Timo Karg

79<sup>th</sup> PRC Meeting - Open Session  
11 May 2015 in Hamburg

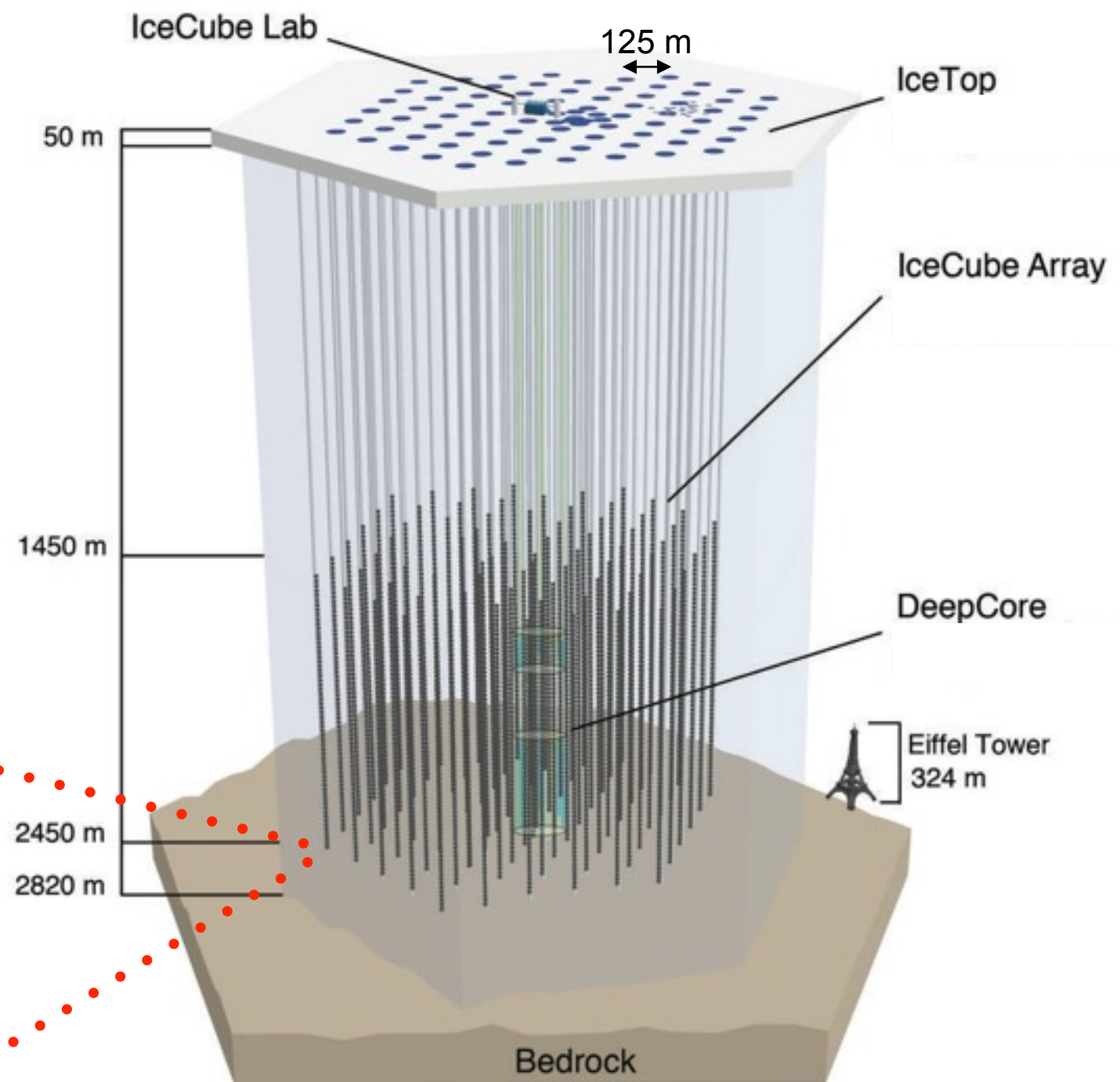
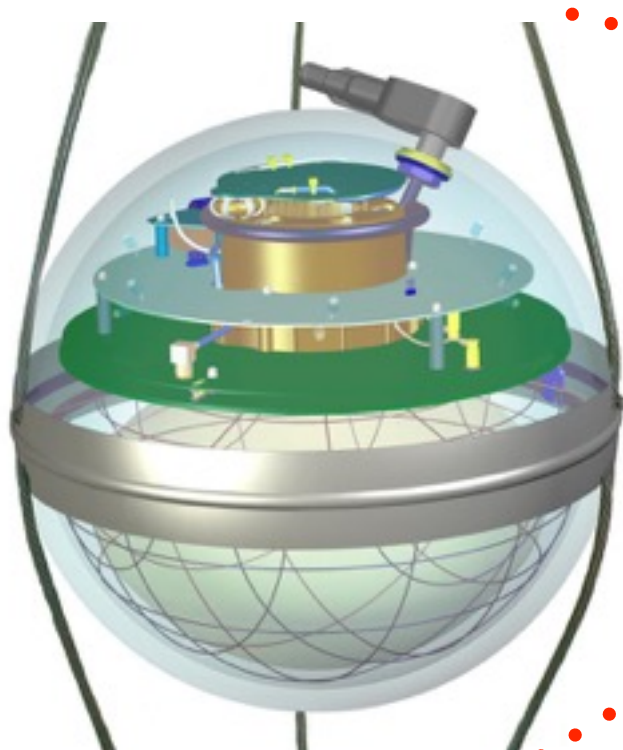
# Recent Results from IceCube

(Generation 1)

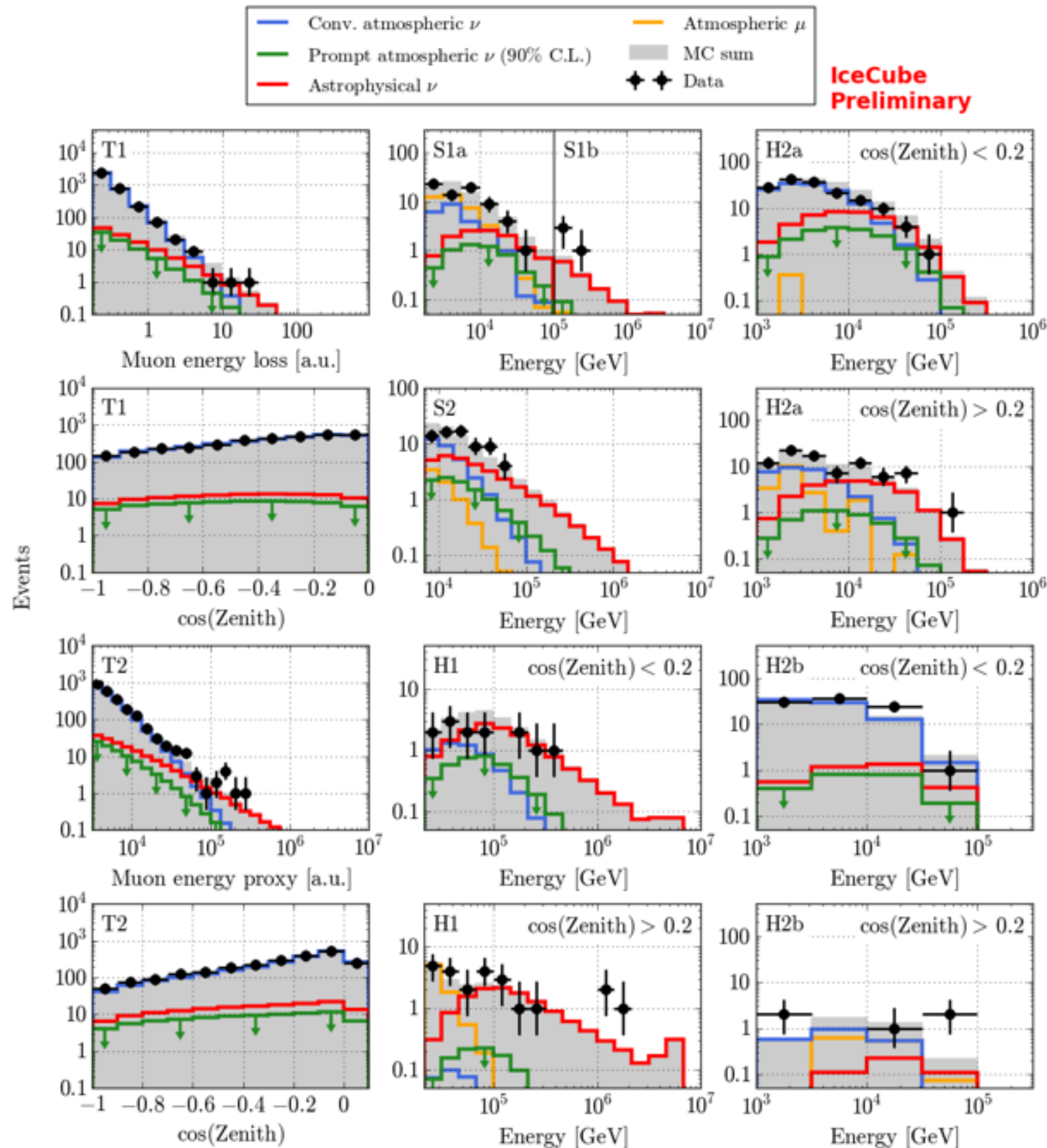


# The IceCube Neutrino Observatory

- Depth: 1450 to 2450 m
- 86 strings (60 optical modules each)
- 5160 optical modules
- Volume: 1 km<sup>3</sup>
- Completed: 18 Dec. 2010



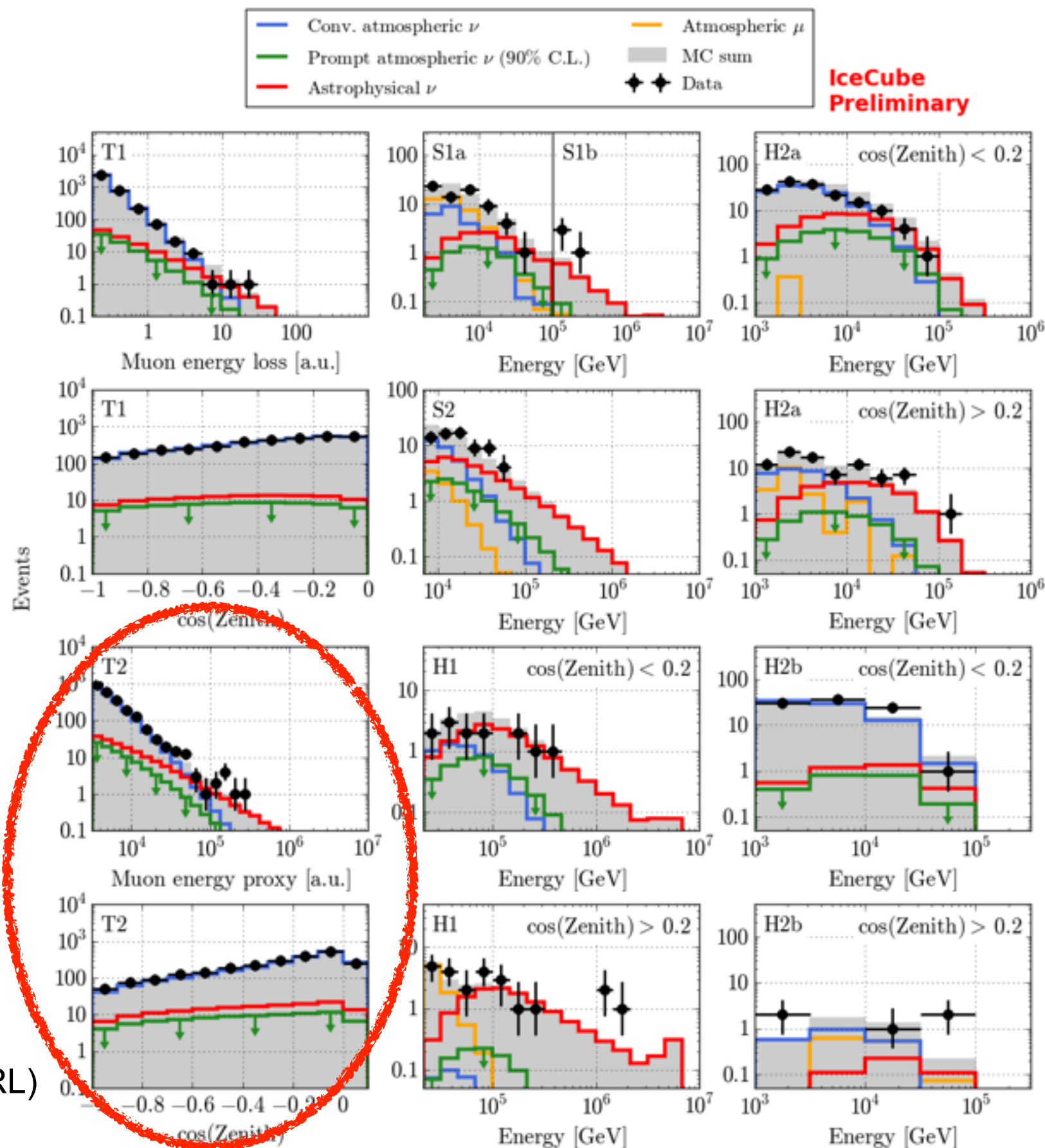
# Astrophysical Neutrinos



T: Tracks  
S: Showers  
H: Starting events



# Astrophysical Neutrinos

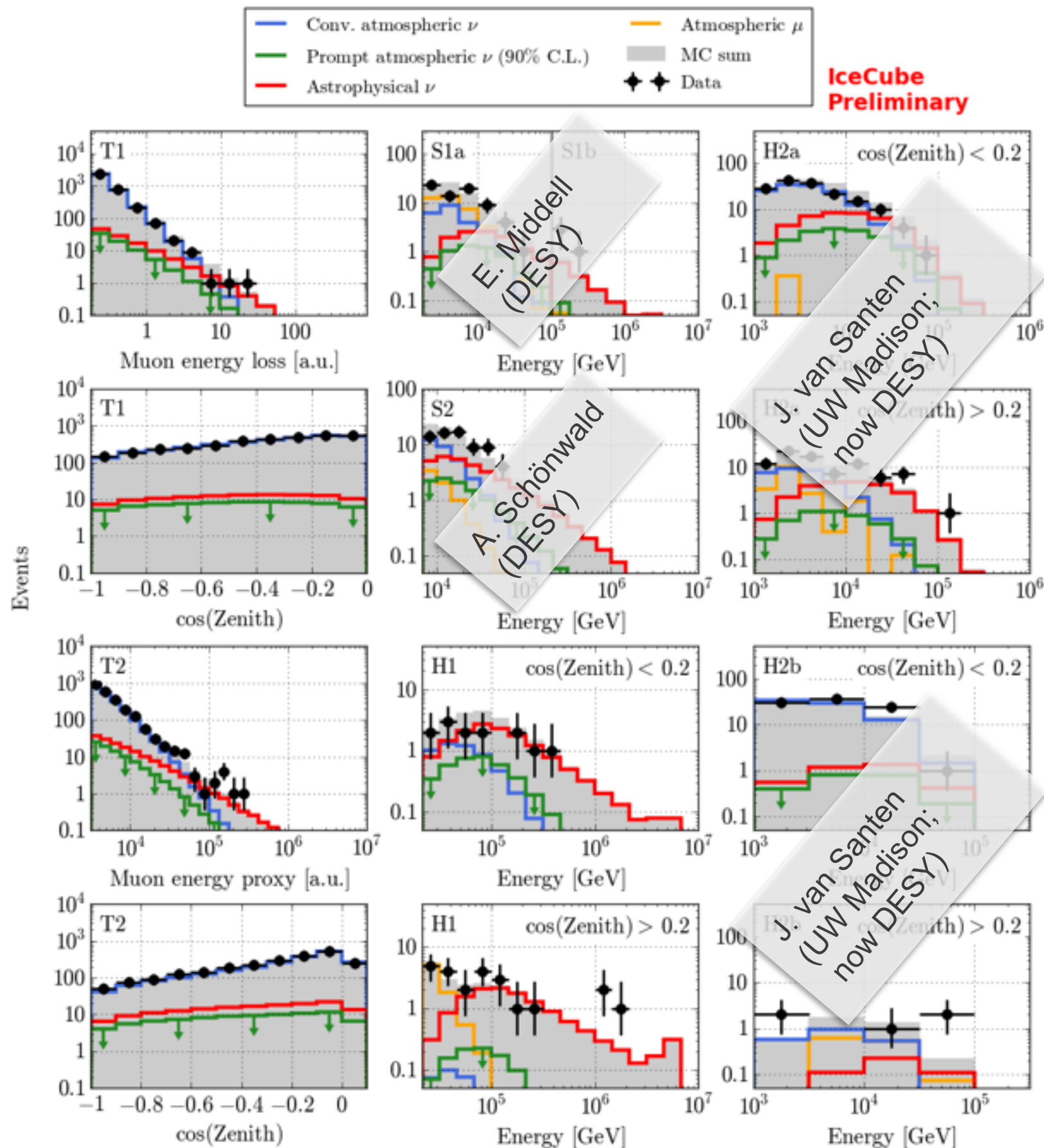


T: Tracks  
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**significant  
astrophysical signal  
in up-going  
muon tracks**  
(to be submitted to PRL)



# Astrophysical Neutrinos

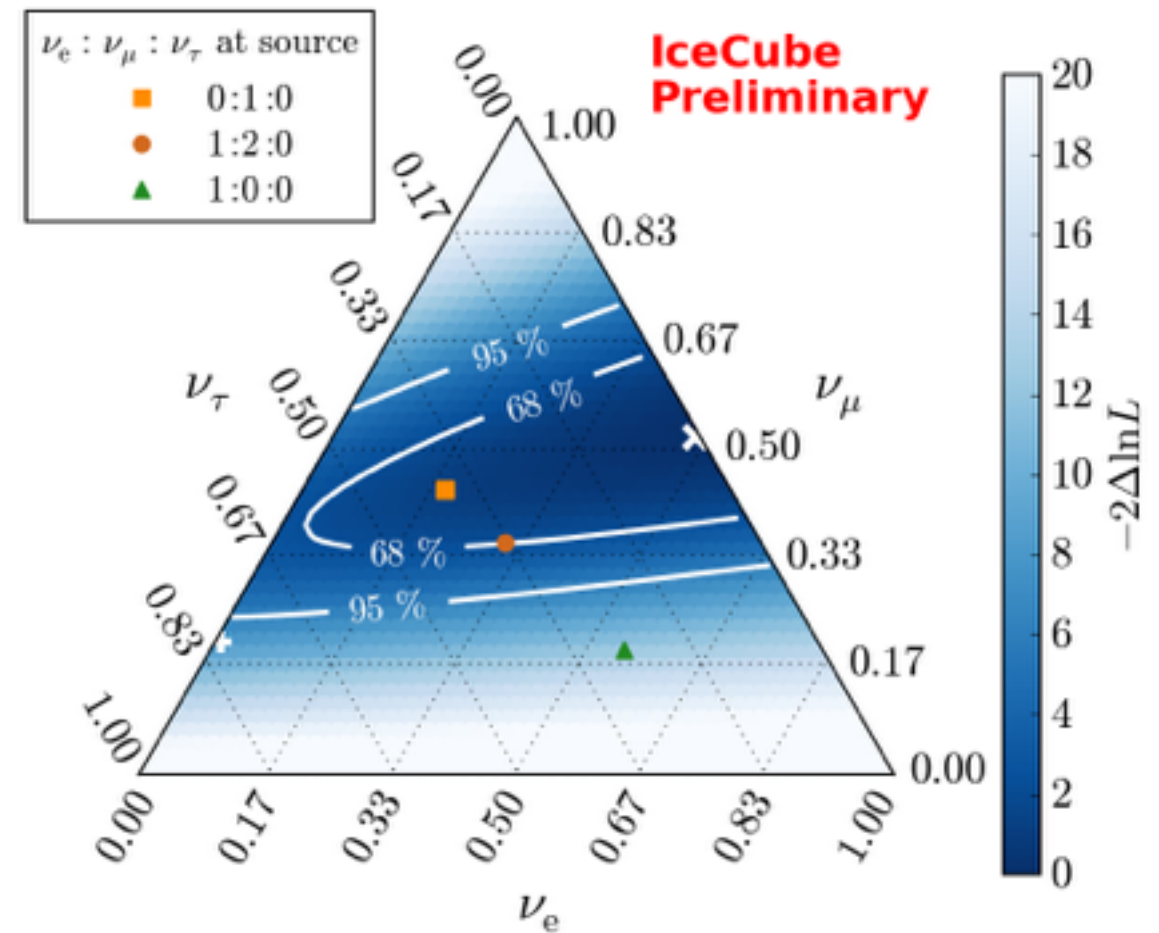
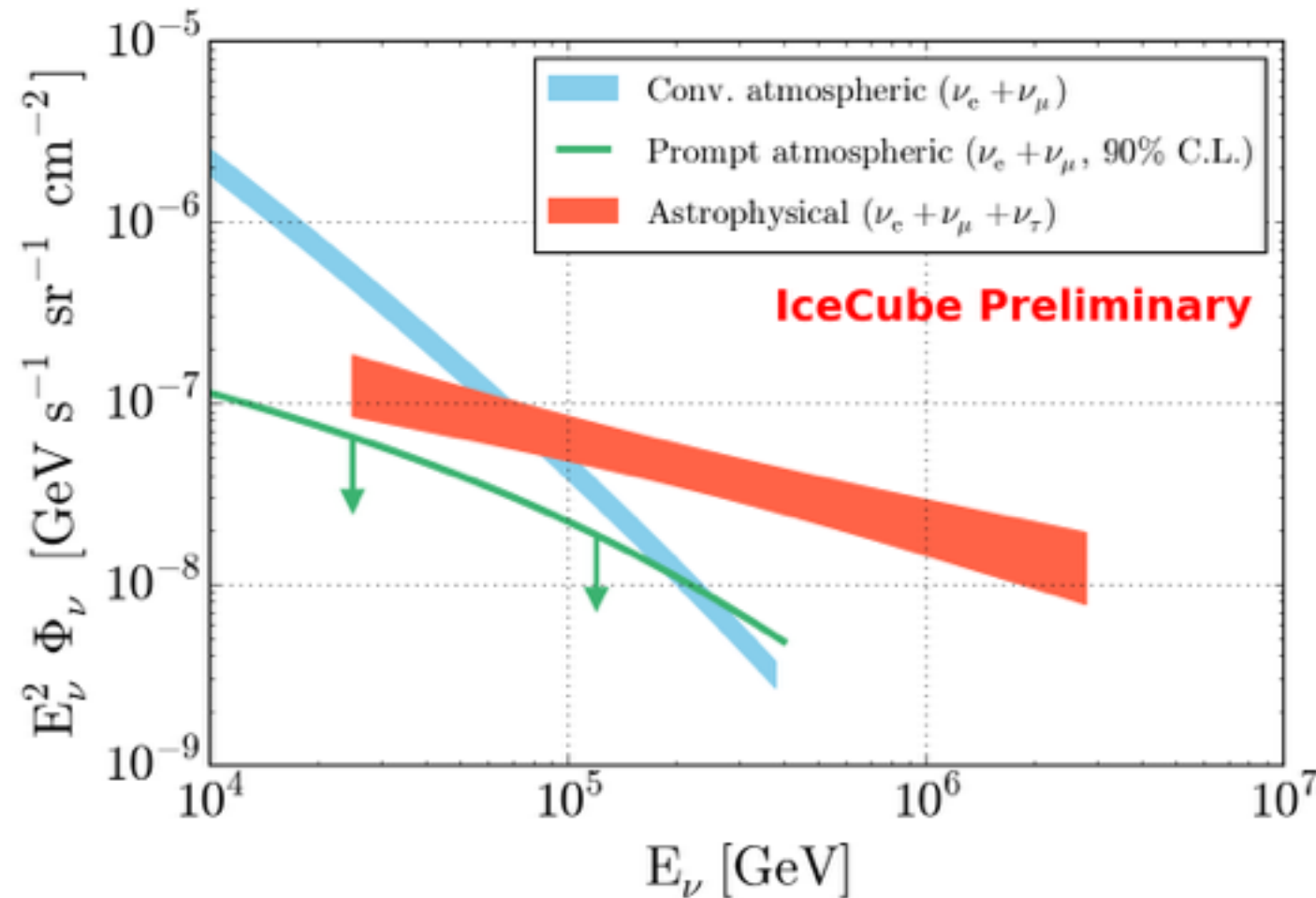


T: Tracks  
S: Showers  
H: Starting events



# Astrophysical Neutrinos — Global Fit

L. Mohrmann, DESY, to be submitted to ApJ



Single power law hypothesis best fit:  $\Phi_\nu = \phi \left( \frac{E}{100 \text{ TeV}} \right)^{-\gamma}$

$$\phi = (6.7_{-1.2}^{+1.1}) \cdot 10^{-18} \text{ GeV}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$$

$$\gamma = 2.50 \pm 0.09$$

Begin to constrain flavor composition at the source.

# Neutrino Oscillations

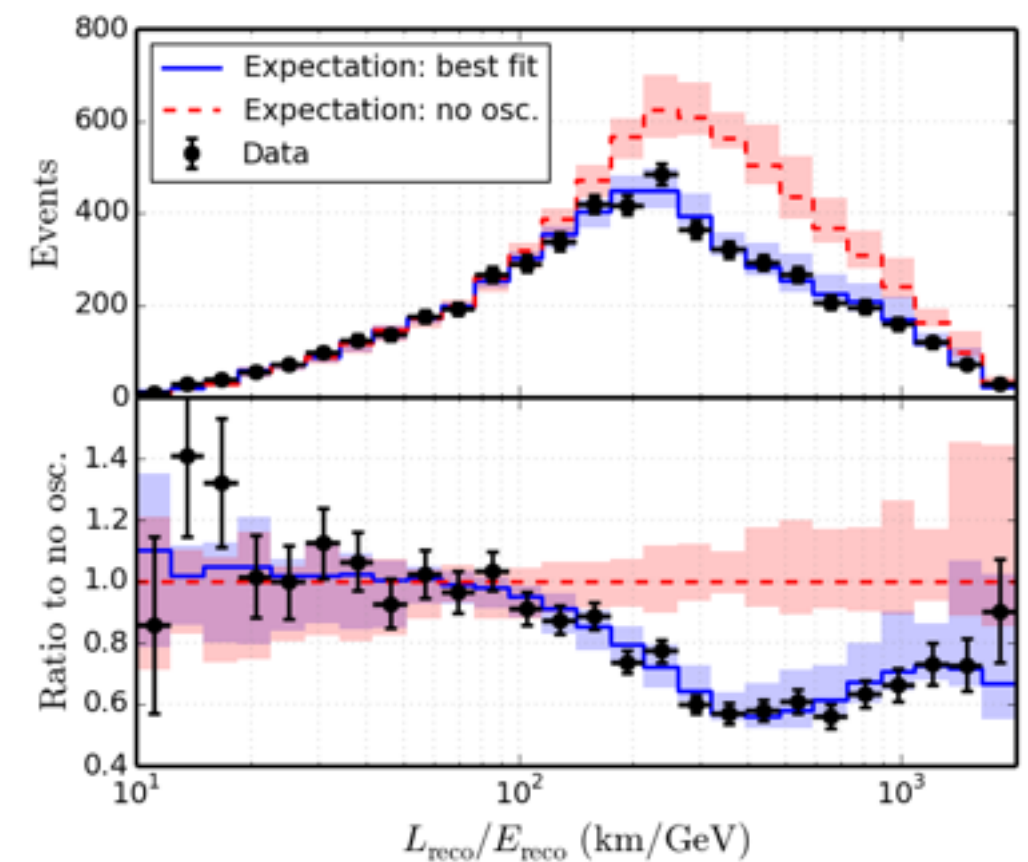
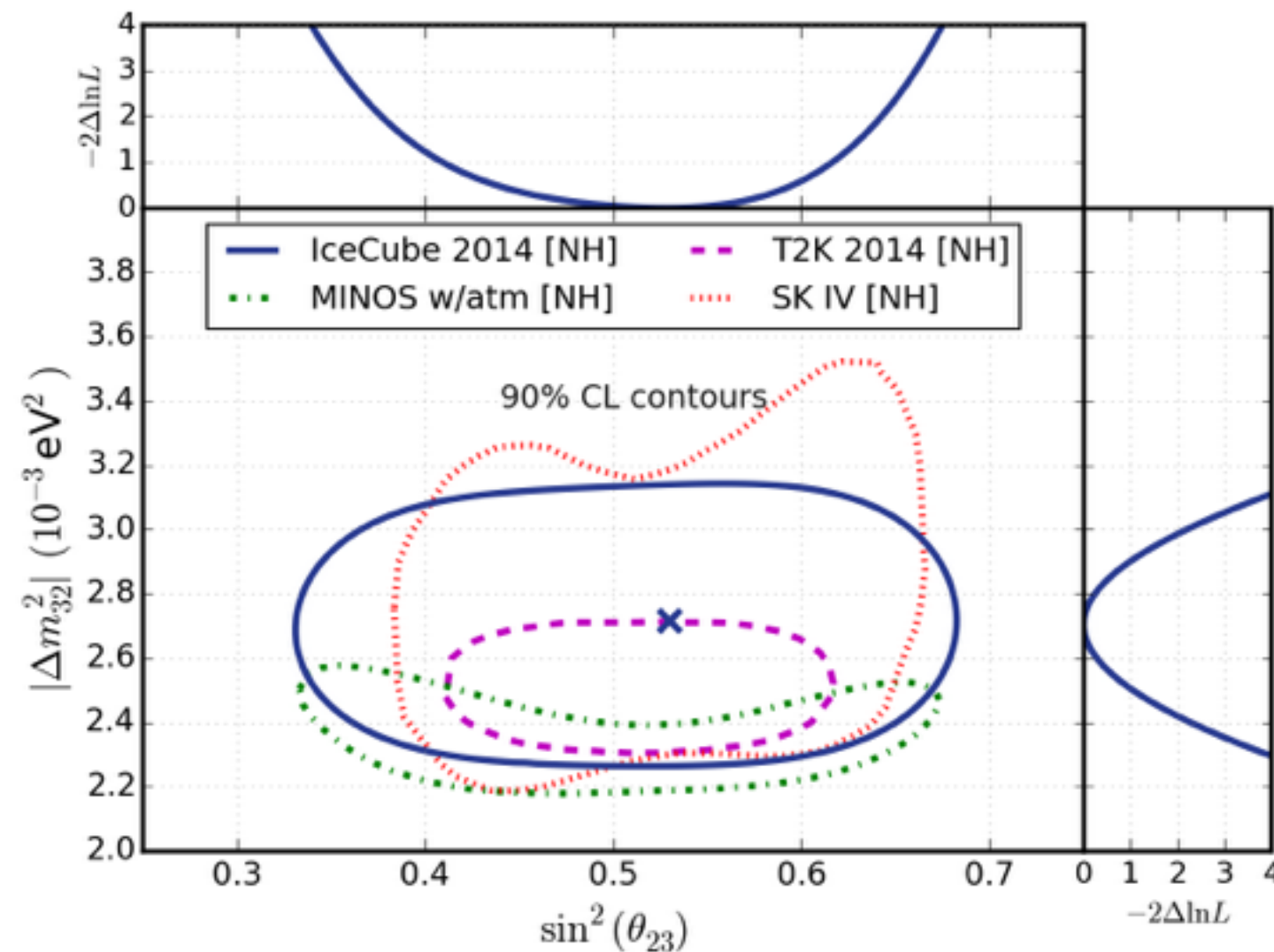
J. P. Yáñez, DESY

PRD **91** (2015) 072004

- $\nu_\mu$  disappearance
- 3 yr DeepCore data
- IceCube as veto against atm. muons



Beam:  
atmospheric vs  
typical  $E_\nu = 20$  GeV





# Neutrino Oscillations

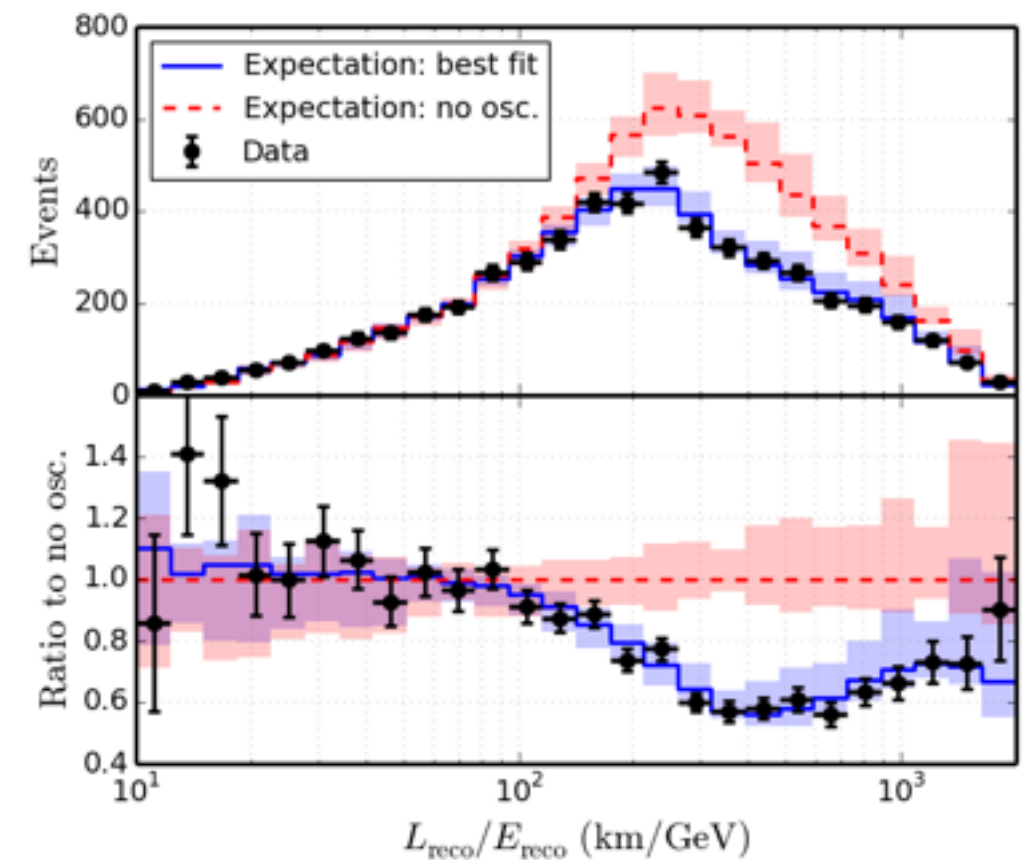
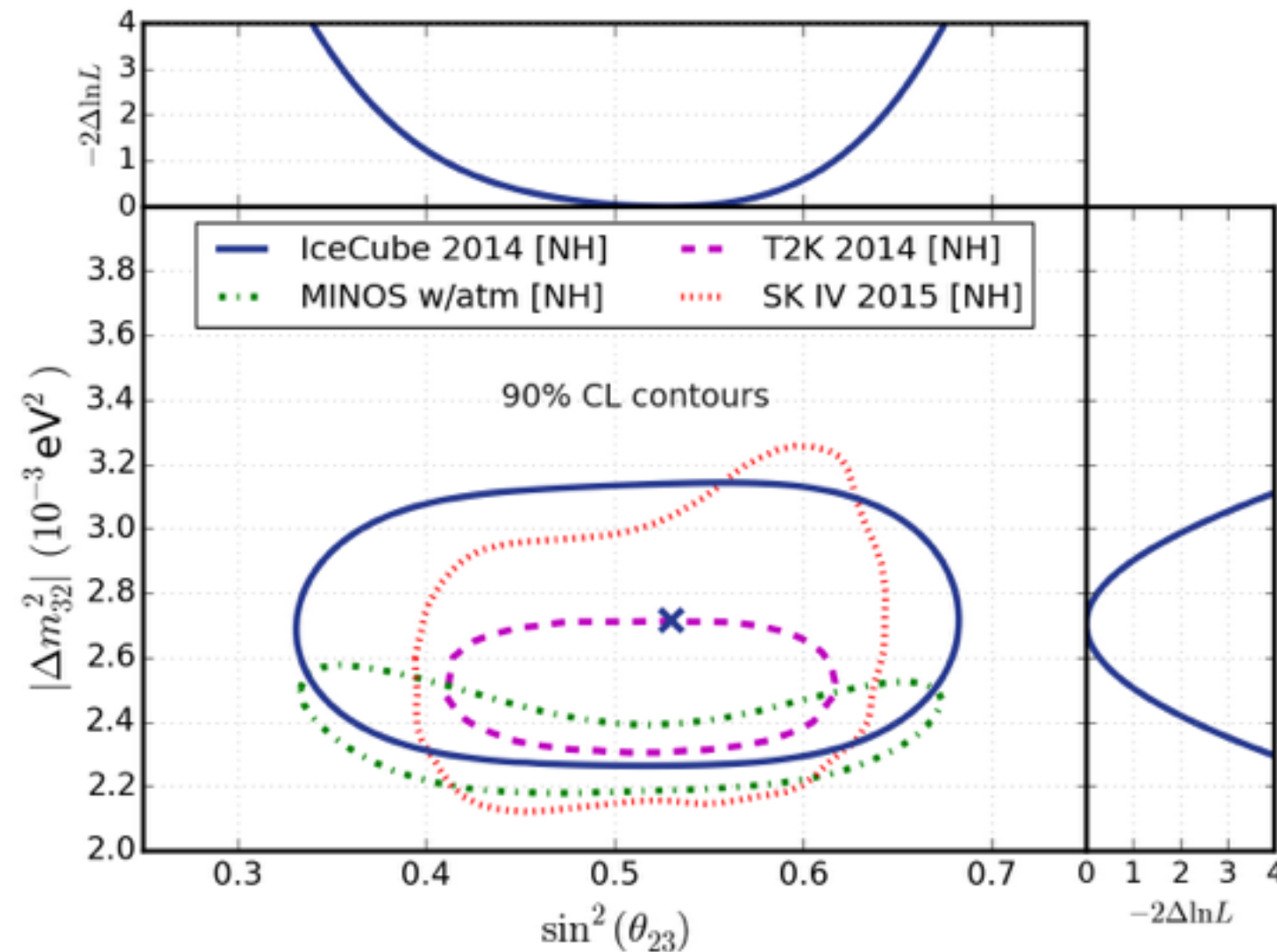
J. P. Yáñez, DESY

PRD **91** (2015) 072004

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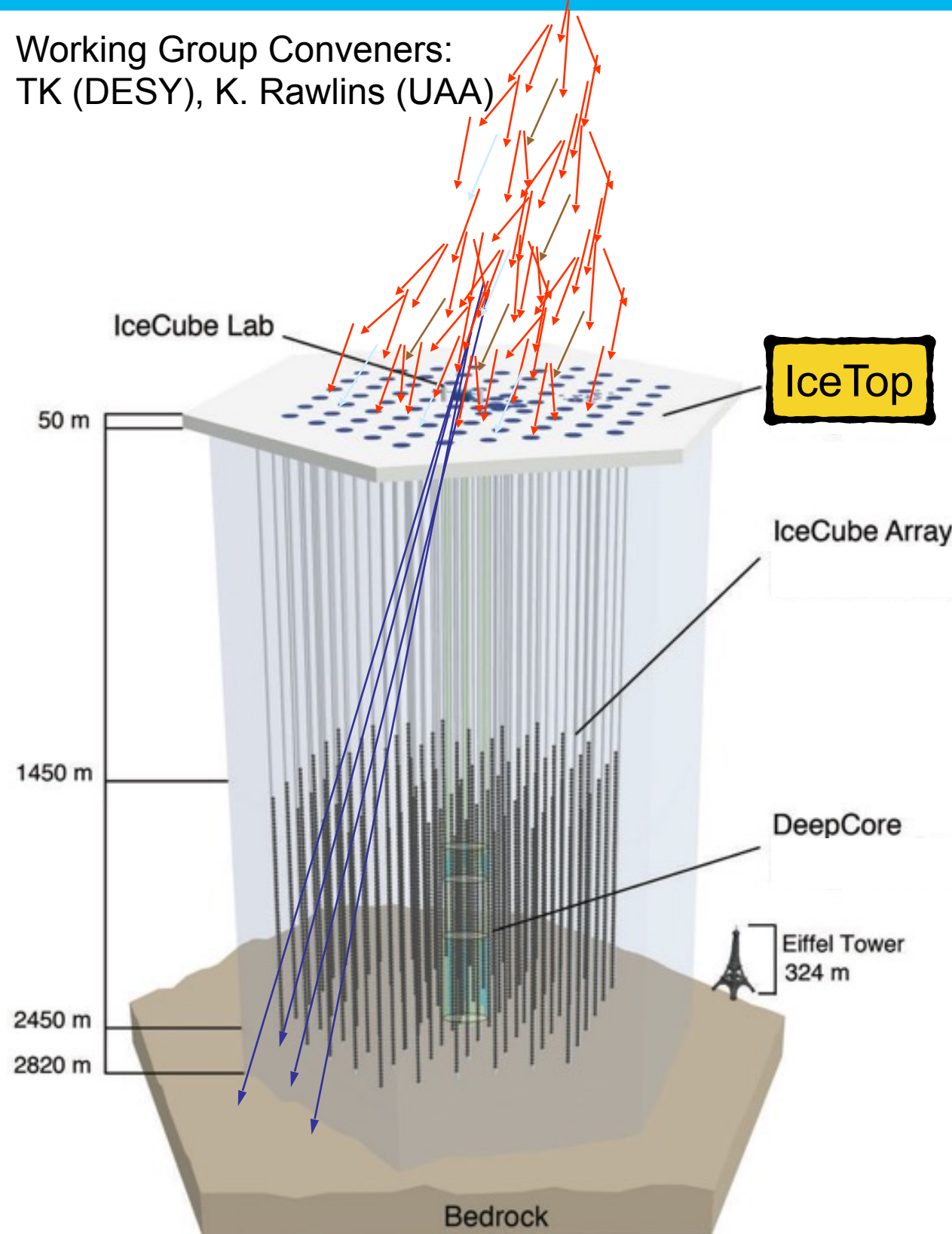


Beam:  
atmospheric vs  
typical  $E_\nu = 20$  GeV



# Cosmic-Ray Physics with IceCube & IceTop

Working Group Conveners:  
TK (DESY), K. Rawlins (UAA)



> IceCube with IceTop is a 3-dim air shower detector

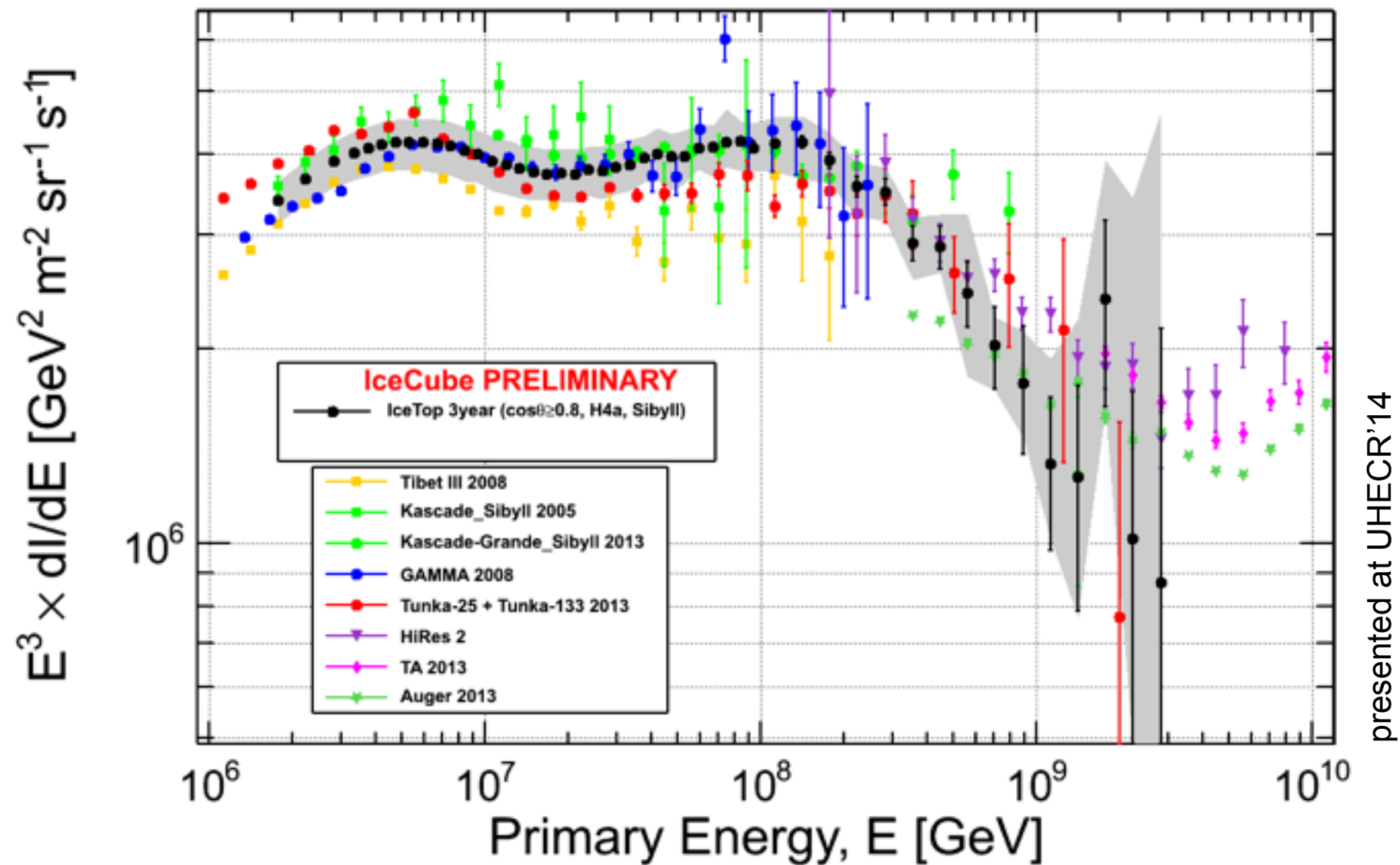
> CR Analyses

- Air showers in IceTop
- Muon (bundle)s in IceCube
- Atm. neutrinos in IceCube
- IceCube - IceTop coincidences

> CR Physics

- CR energy spectrum and composition
- CR anisotropy at different ang. scales
- Particle physics in air showers

# Energy Spectrum with 3 Years of Data

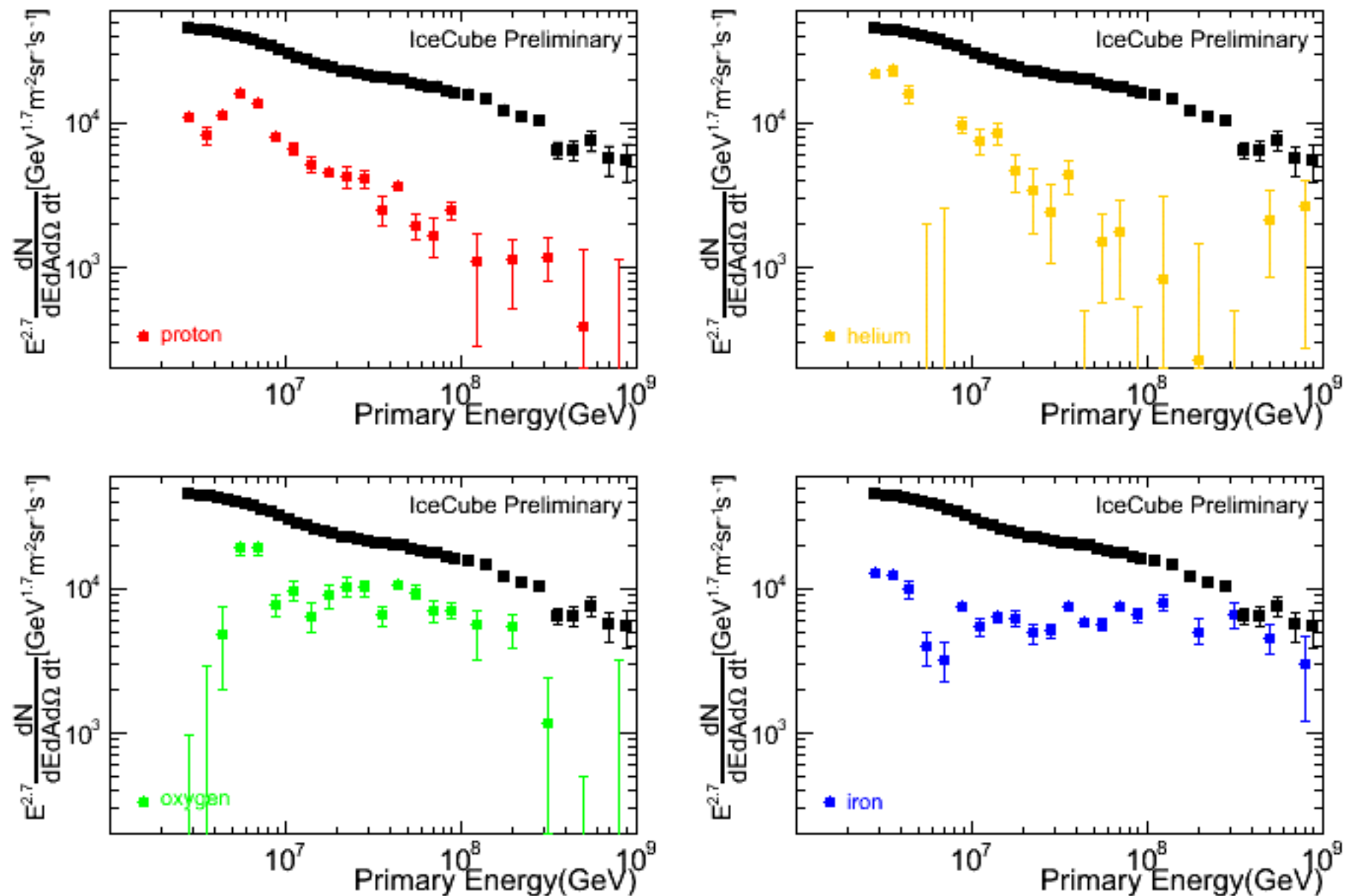


## > Not a single power law

- spectral hardening at  $\sim 20$  PeV
- steepening at  $\sim 130$  PeV

# Energy Spectra for Four Mass Groups

3 years of coincident IceTop / IceCube data



presented at UHECR'14

more statistics at high energies required to

- get overlap with Auger / Telescope Array
- measure transition from Galactic to extragalactic cosmic rays



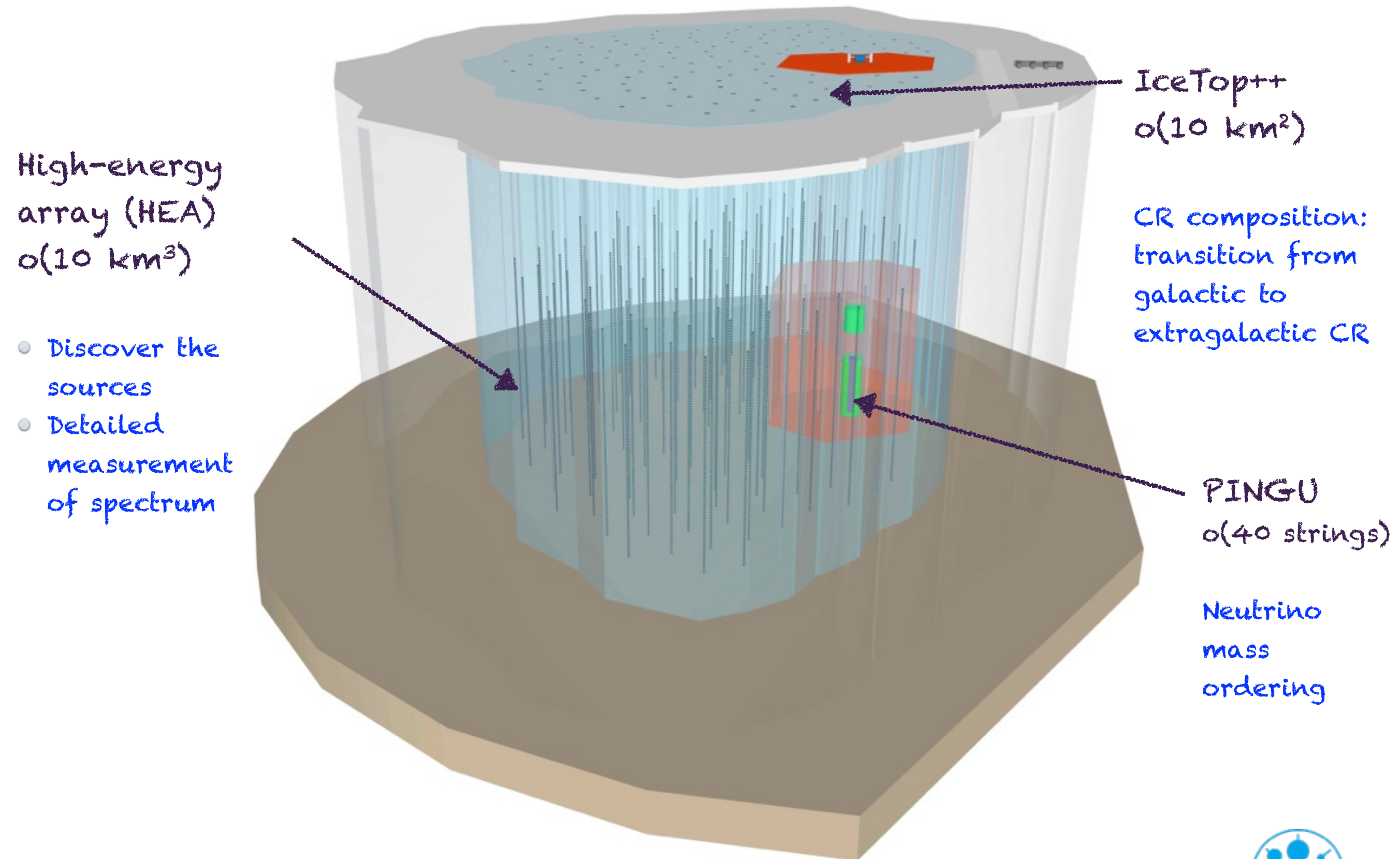


# Towards IceCube-Gen2

## Physics Goals and Technological Challenges



# The Vision: IceCube in 2027

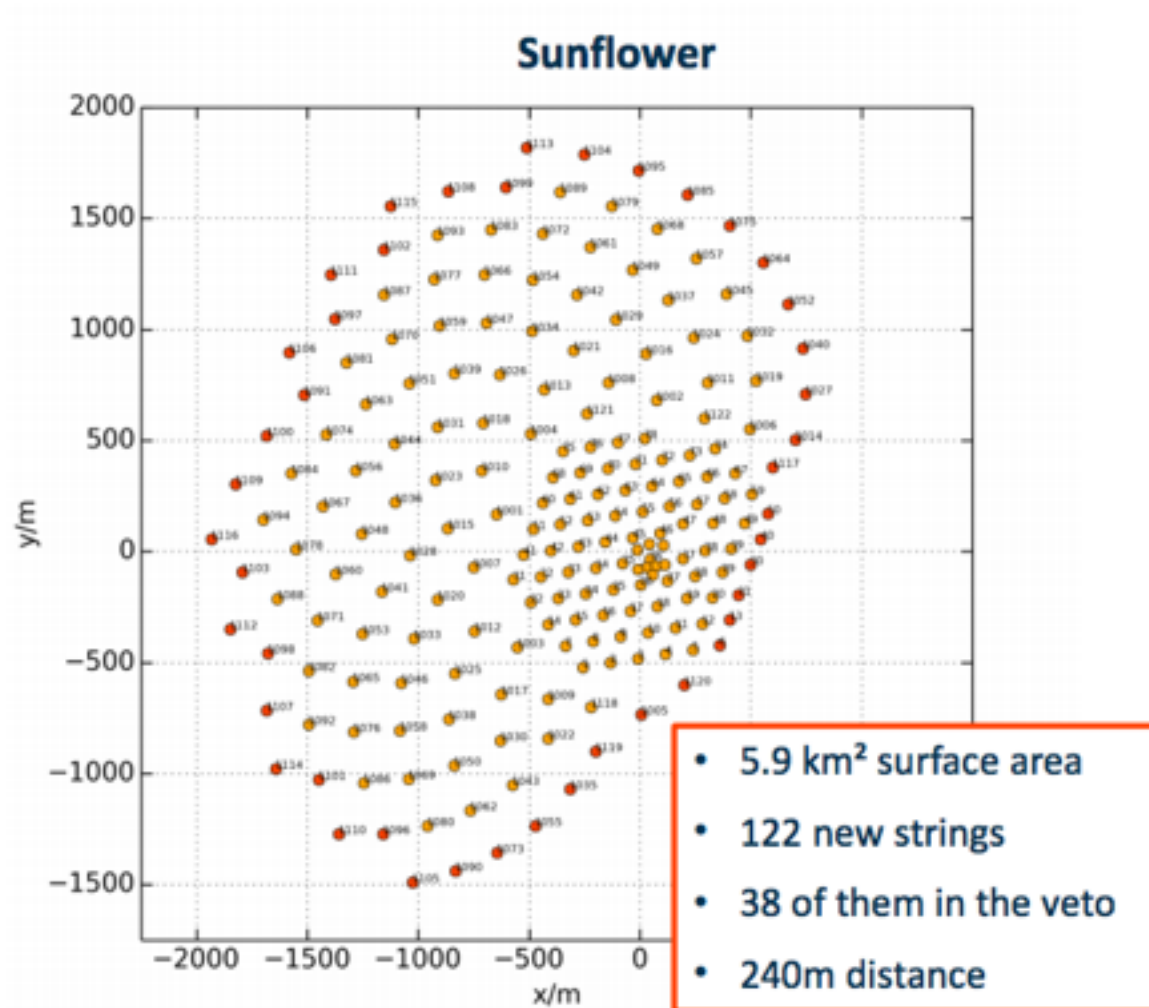


# IceCube-Gen2 Status

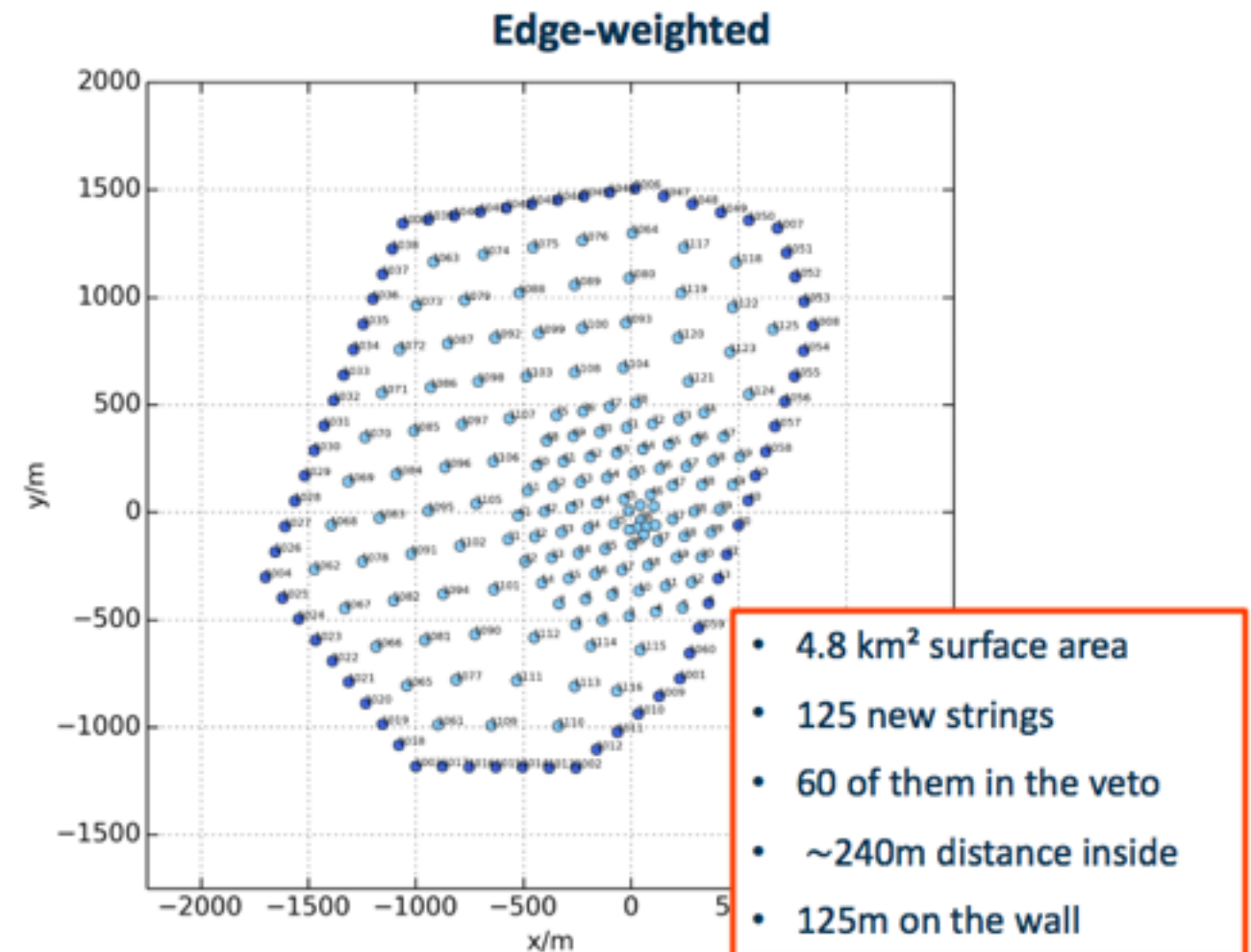
- > New collaboration formed (April 2015)
  - IceCube institutions + PINGU institutions + new institutions
- > 1<sup>st</sup> goal: work out a successful NSF proposal for IceCube-Gen2
- > PINGU: Letter of Intent published (arXiv:1401.2046 [physics.ins-det])
  - updated Lol in preparation
- > High Energy Array: “Letter of Vision” (arXiv:1412.5106 [astro-ph.HE])



# High Energy Array: Benchmark Geometries



“Sunflower” with different inter-string spacings.  
No corridors through the detector.

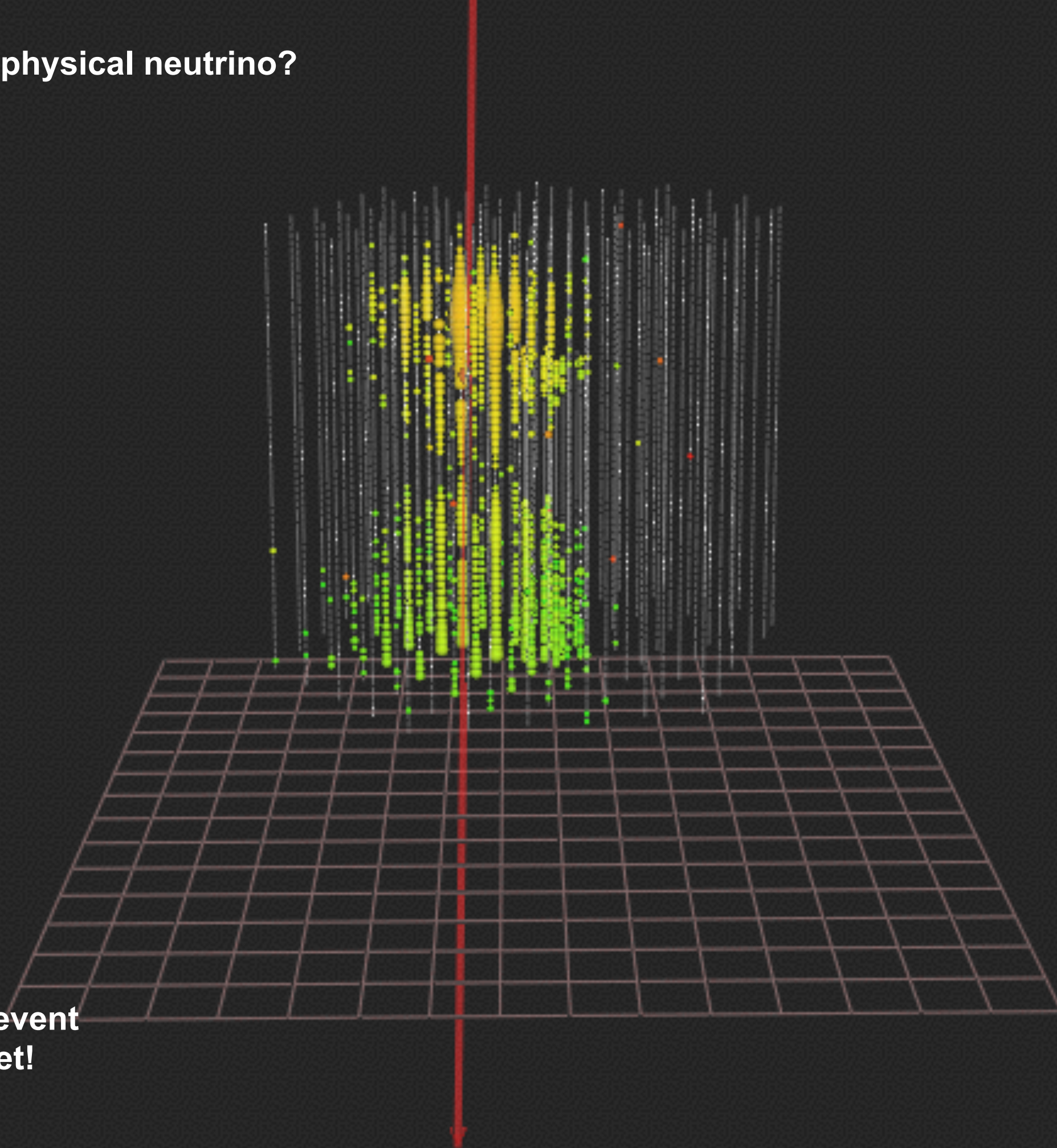


Edge-weighted improved veto against atmospheric muons



Is this an astrophysical neutrino?

4<sup>th</sup> year HESE event  
...not public, yet!

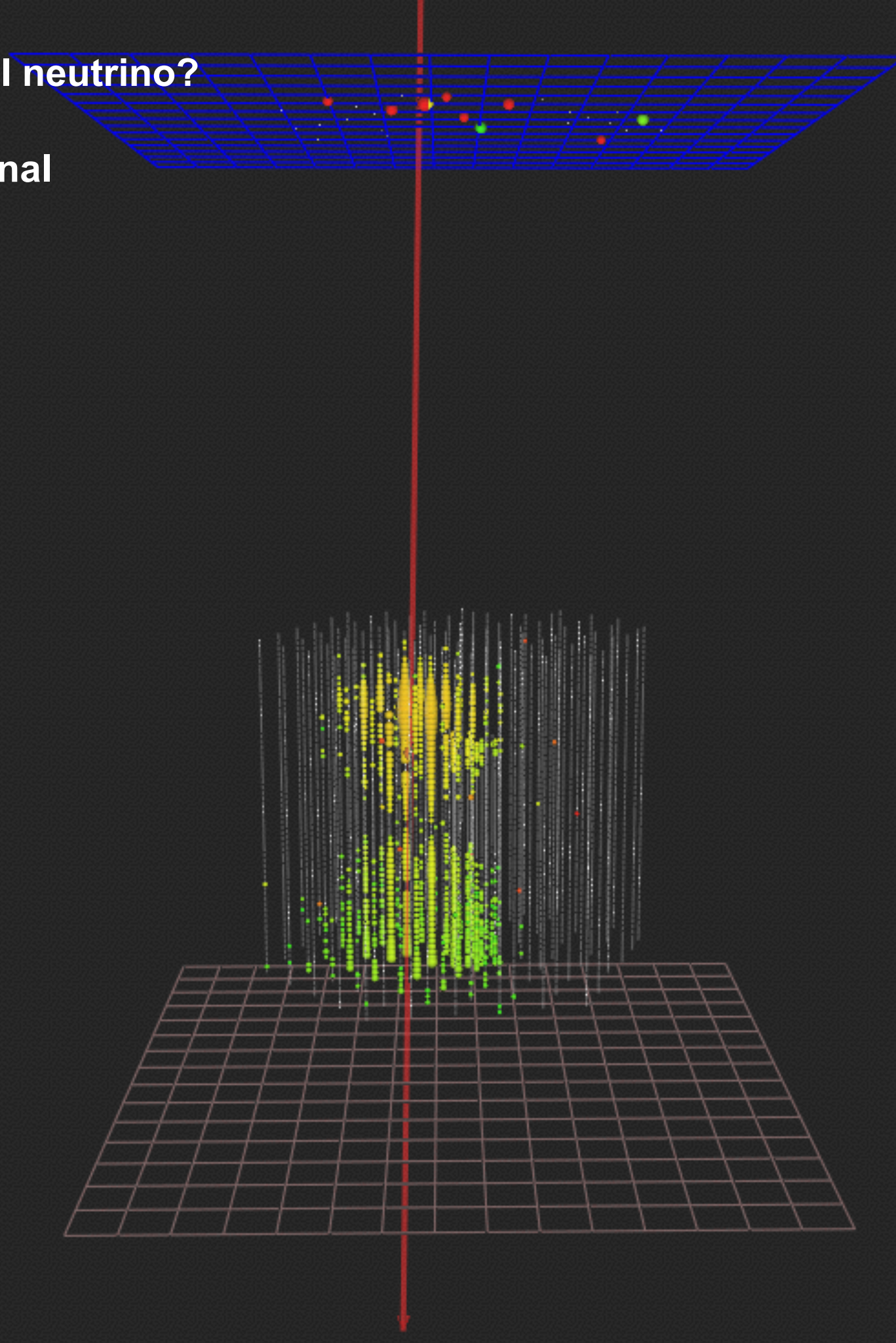


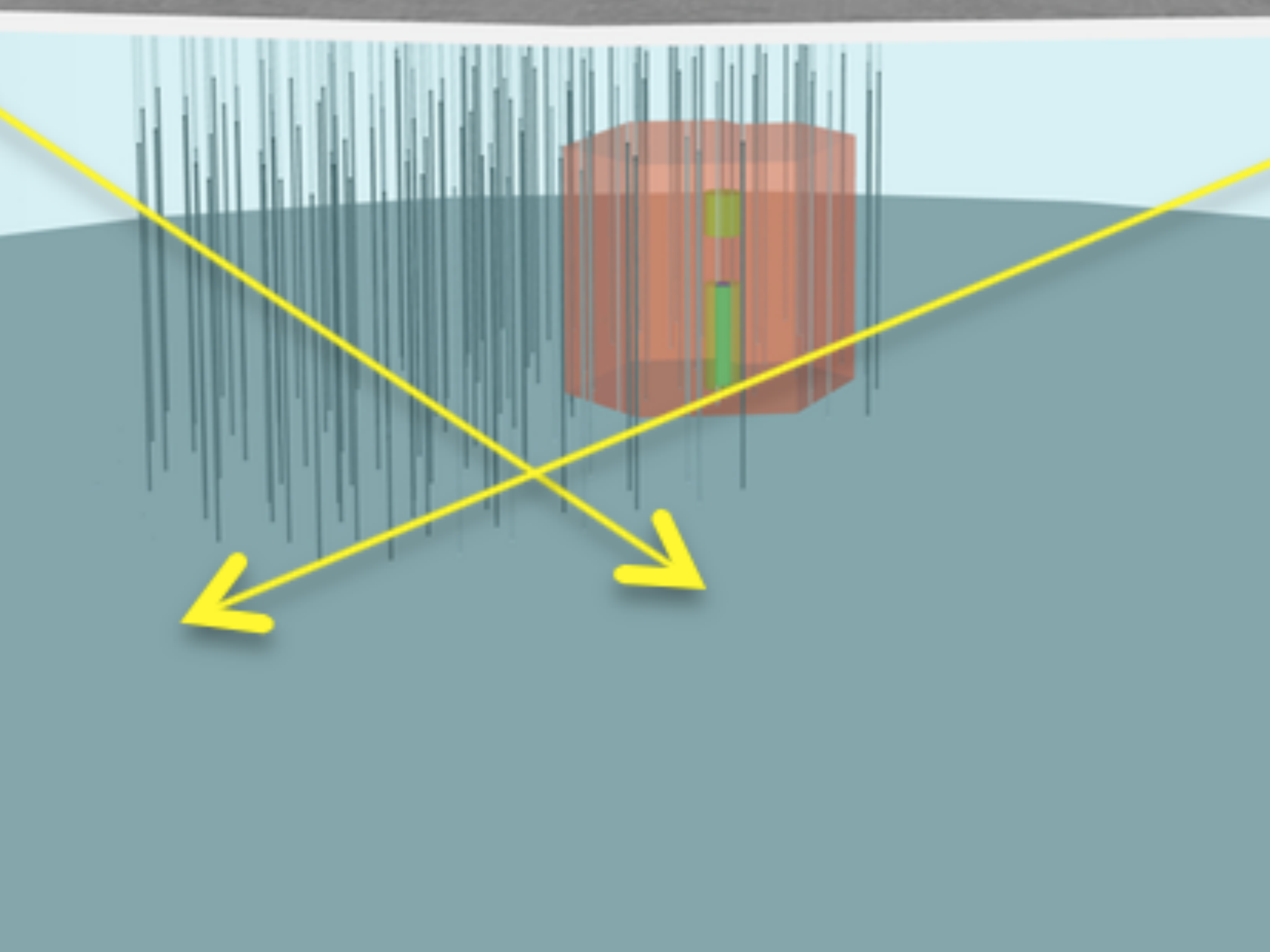


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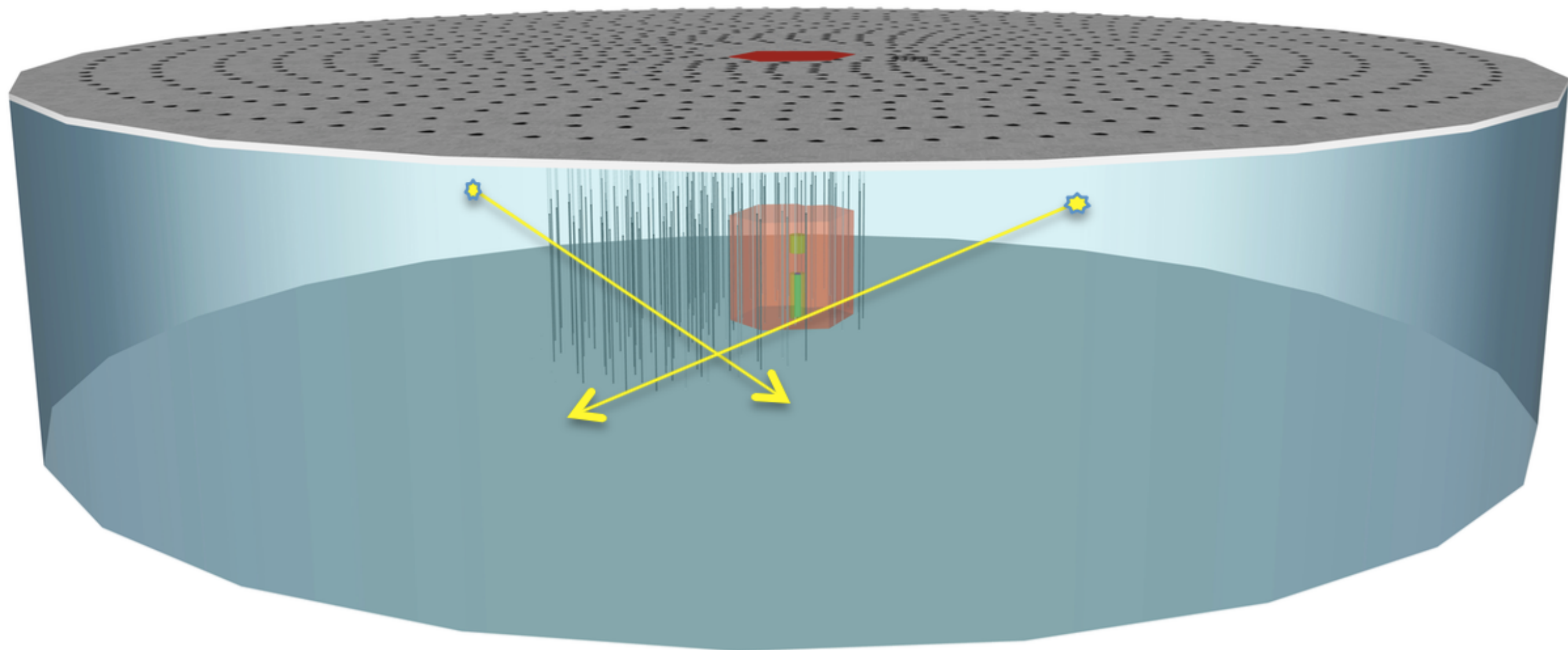
Yes! No air shower signal  
whatsoever in IceTop

4<sup>th</sup> year HESE event  
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# Surface Veto Array



- > A surface veto gives additional sensitive volume for muon-neutrino CC interactions
- > Radius of 7 km covers zenith range up to  $70^\circ$  (Galactic Center !)
- > But: Low energy threshold challenging



# R&D Efforts at DESY

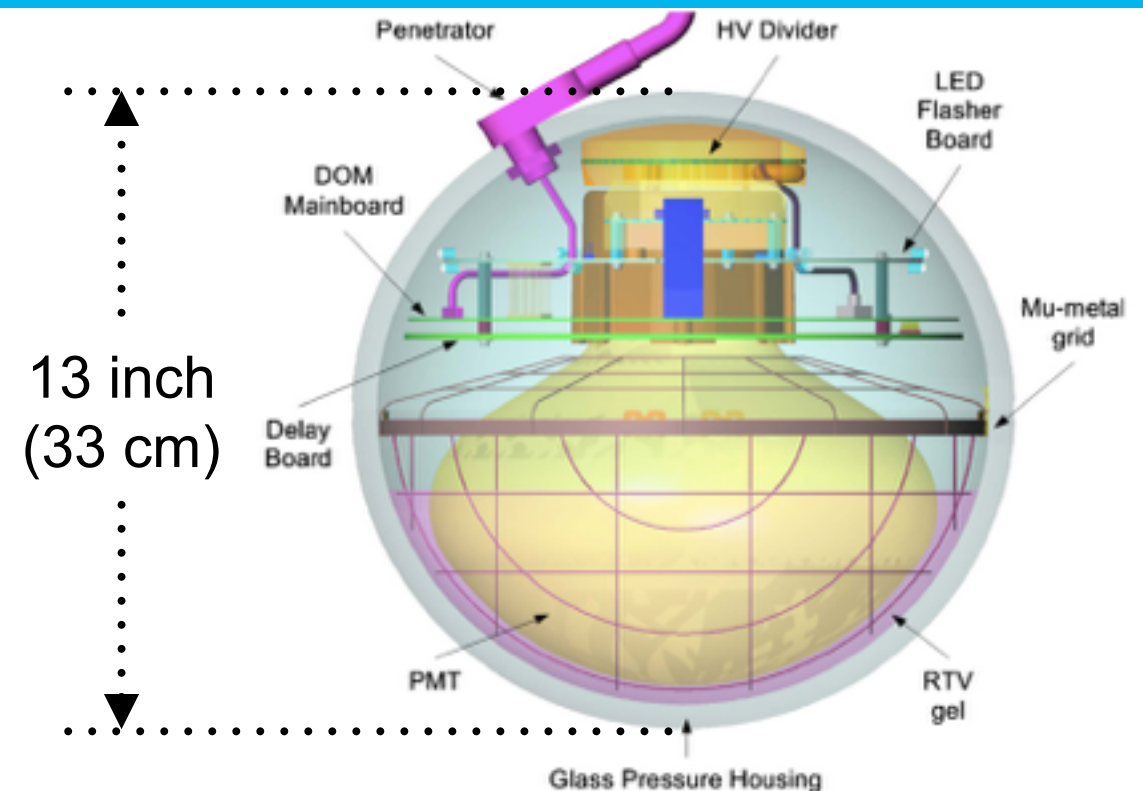
## Optical Sensors



# The IceCube Digital Optical Module (DOM)

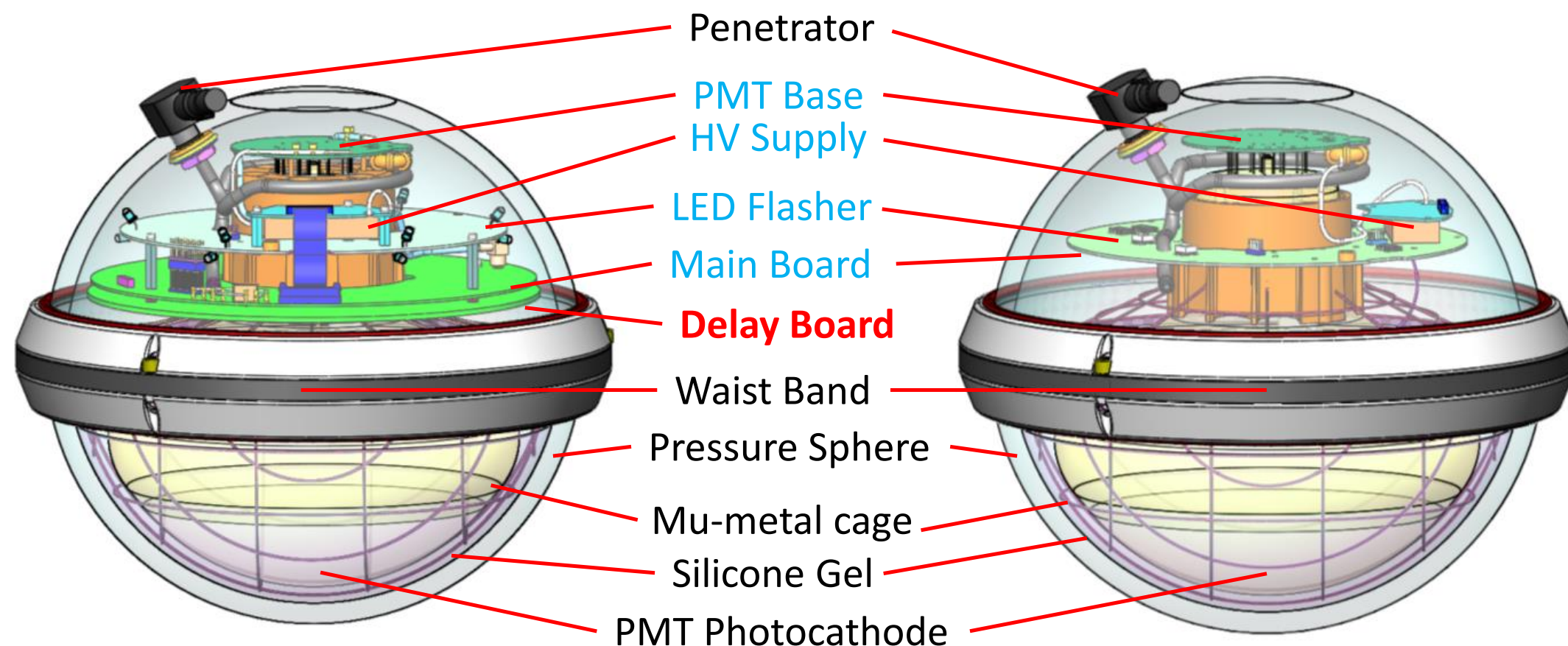
- Records PMT waveform of every “hit”
  - 300 MHz sampling
- Timing synchronization between all DOMs  $< 2$  ns
- Data/timing/power over 3.3 km copper pair
- Power consumption  $\sim 3$  W
- Withstand  $> 550$  bar freeze-in pressure
- Survive shock vibration; ships, planes, sleds
- 99% operational!

NIM A **601** (2009) 294



# Baseline Design: Gen2 DOM

Rationale: Keep as close as possible to IceCube design



IceCube  
DOM

Gen2  
DOM

**KEY:**  
Component identical  
**Component eliminated**  
Component re-designed

# Can we build something significantly better?

WishList:

- More photons / event

  - Larger photon collection area

  - Larger wavelength range

- Lower Noise

- Intrinsic direction resolution





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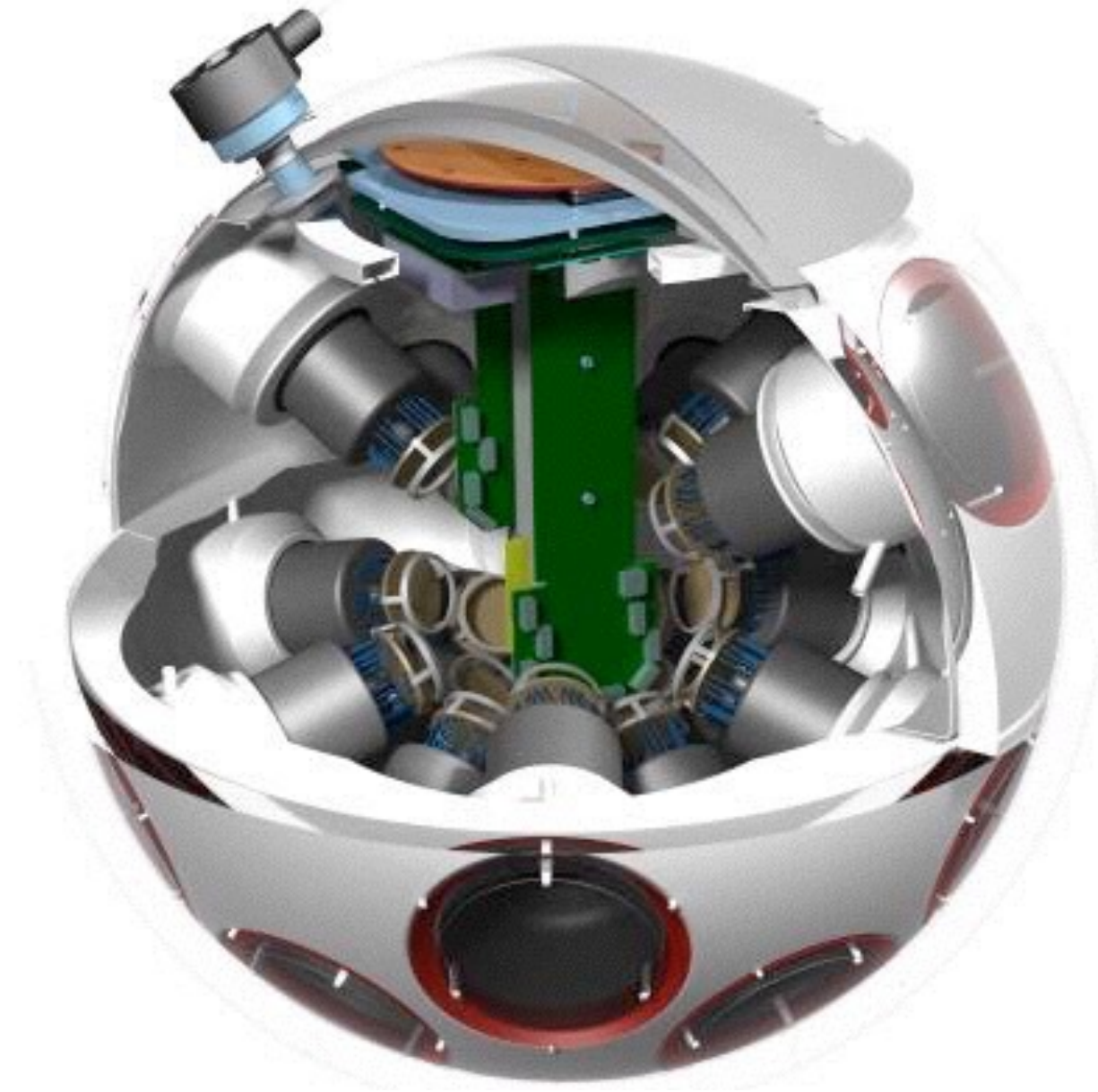
Larger wavelength range

Lower Noise

Intrinsic direction resolution

# mDOM: multi-PMT Digital Optical Module

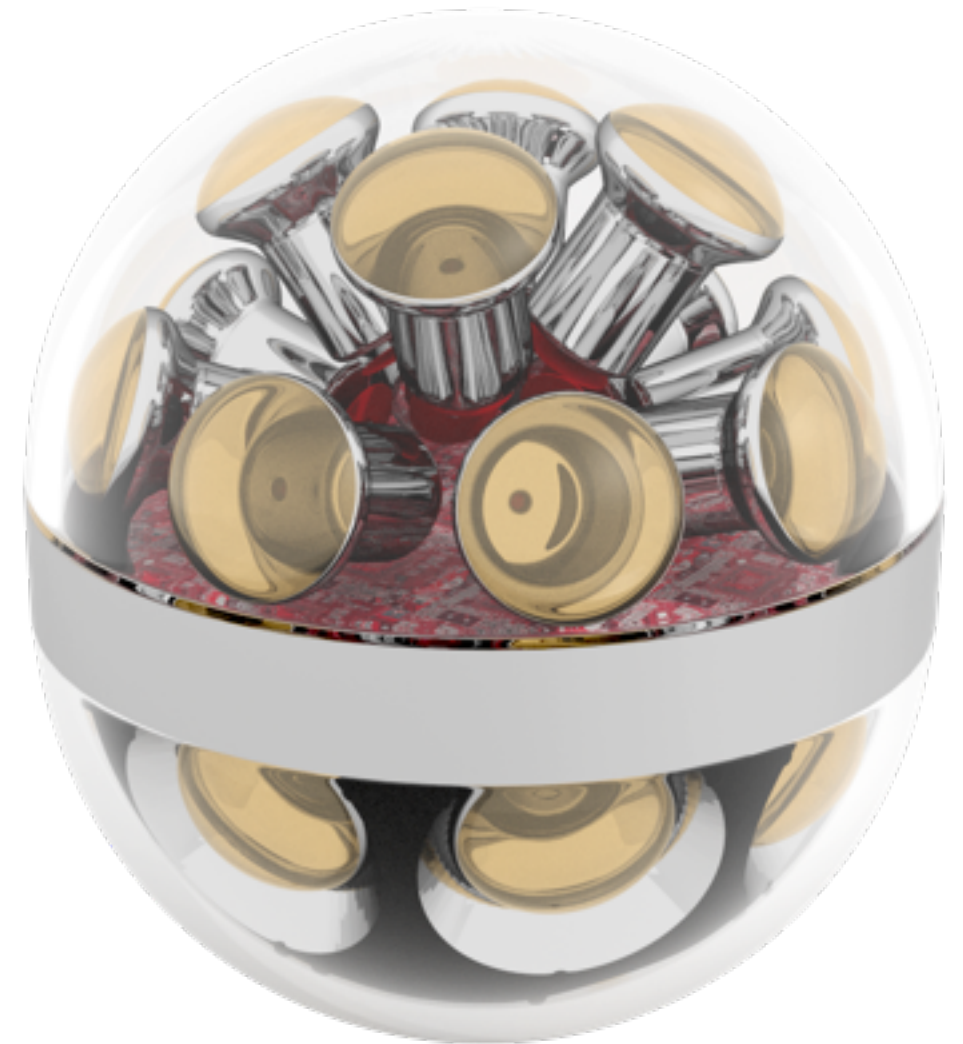
- Increased photocathode area at  $\leq$  price per photocathode area
- $4\pi$  angular acceptance
- Directional sensitivity
- Single photon counting
- Background suppression with local coincidences
- Improved timing (TTS:  $\sigma = 1.7$  ns)
- No magnetic shielding needed



KM3NeT DOM  
EPJ C 74 (2014) 3056

# A mDOM for IceCube-Gen2: Features

- Pressure vessel:
  - 14" diameter
  - rated for 700 bar
- 24 × 3" PMTs (Hamamatsu R12199-02)
- 2 × effective area of standard IceCube DOM
- Full  $4\pi$  coverage
- Effective PMT saturation level: ~5000 p.e.
- Data readout (base concept)
  - time-over-threshold for each PMT
  - waveforms of summed analog signal



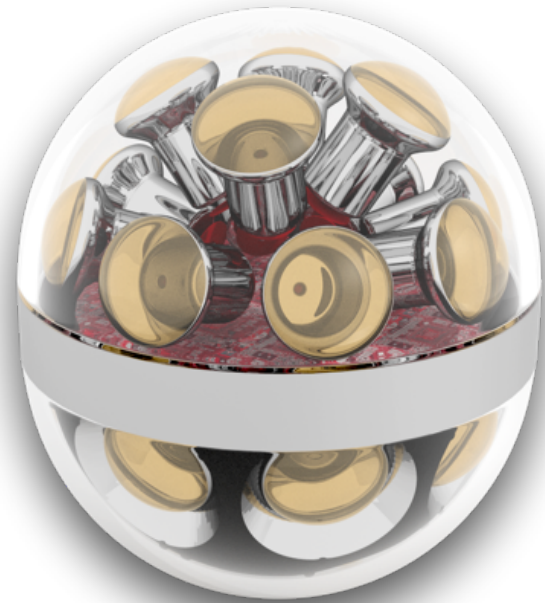
# A mDOM for IceCube-Gen2: Features

## > Mechanical design goals (Erlangen)

- size & weight similar to IceCube DOM  
no new procedures for logistics and deployment
- maximize number of PMTs under constraints
  - space for electronics, connectors, ...
  - cooling
  - electric fields

## > Electronics design goals and readout concept (DESY)

- interface to IceCube data stream
- maximize information under given power constraints
  - $\lesssim 3$  W for high-voltage, amplification, digitization, processing, communication
  - leading-edge time and time-over-threshold for all channels
  - waveforms for all channels, analog sum of all channels, analog sum of subsets?
  - waveforms for all “hits”, multi-photon hits?





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# WOM: Wavelength-Shifting Optical Module

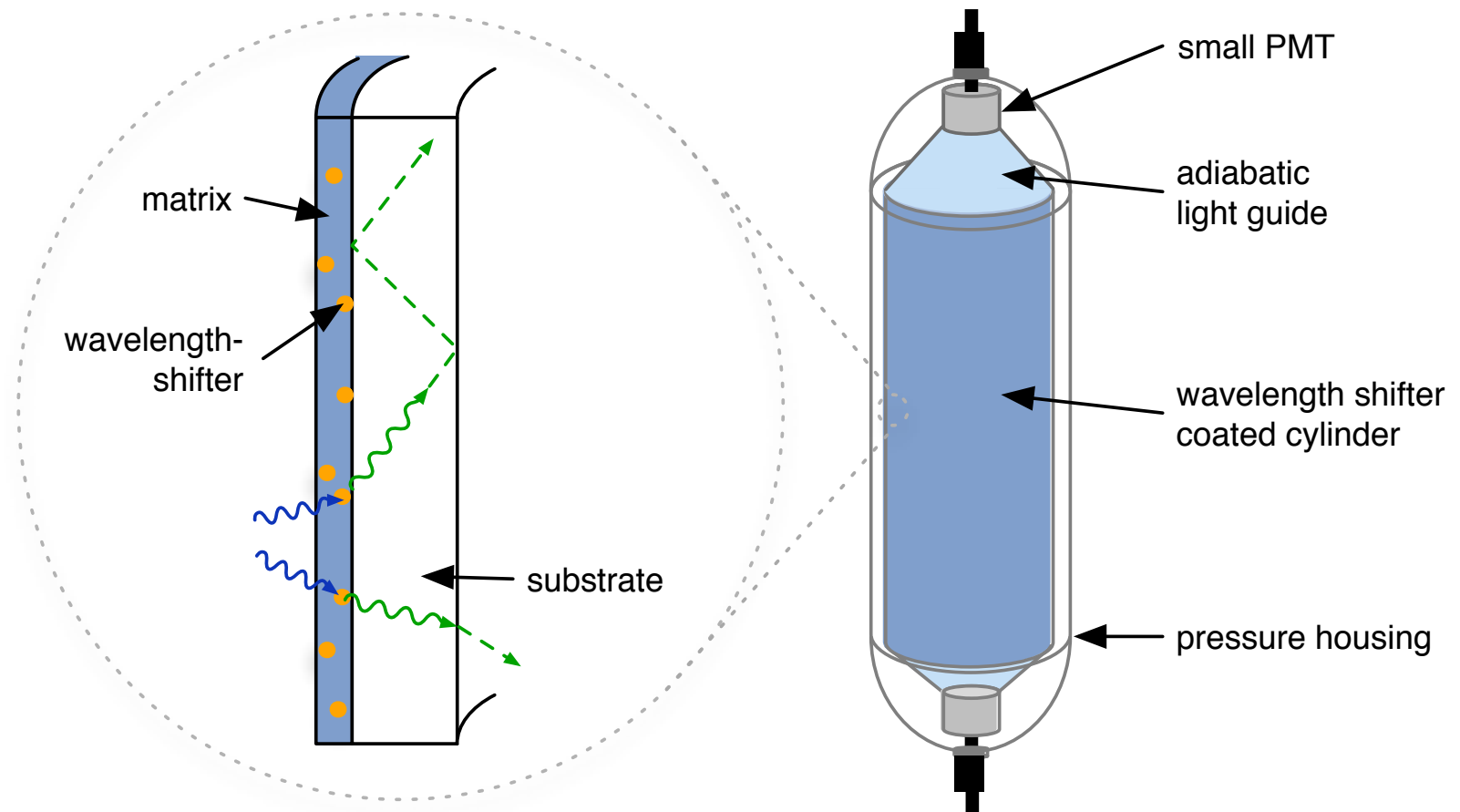
## Basic concept

### > Wavelength shifters (WLS)

- concentrate light

## Features

- > Large collection area
- > Low noise rate (few Hz)
- > Good UV sensitivity
- > Cost effective



ICRC 2013, arXiv:1307.6713 [astro-ph.IM]

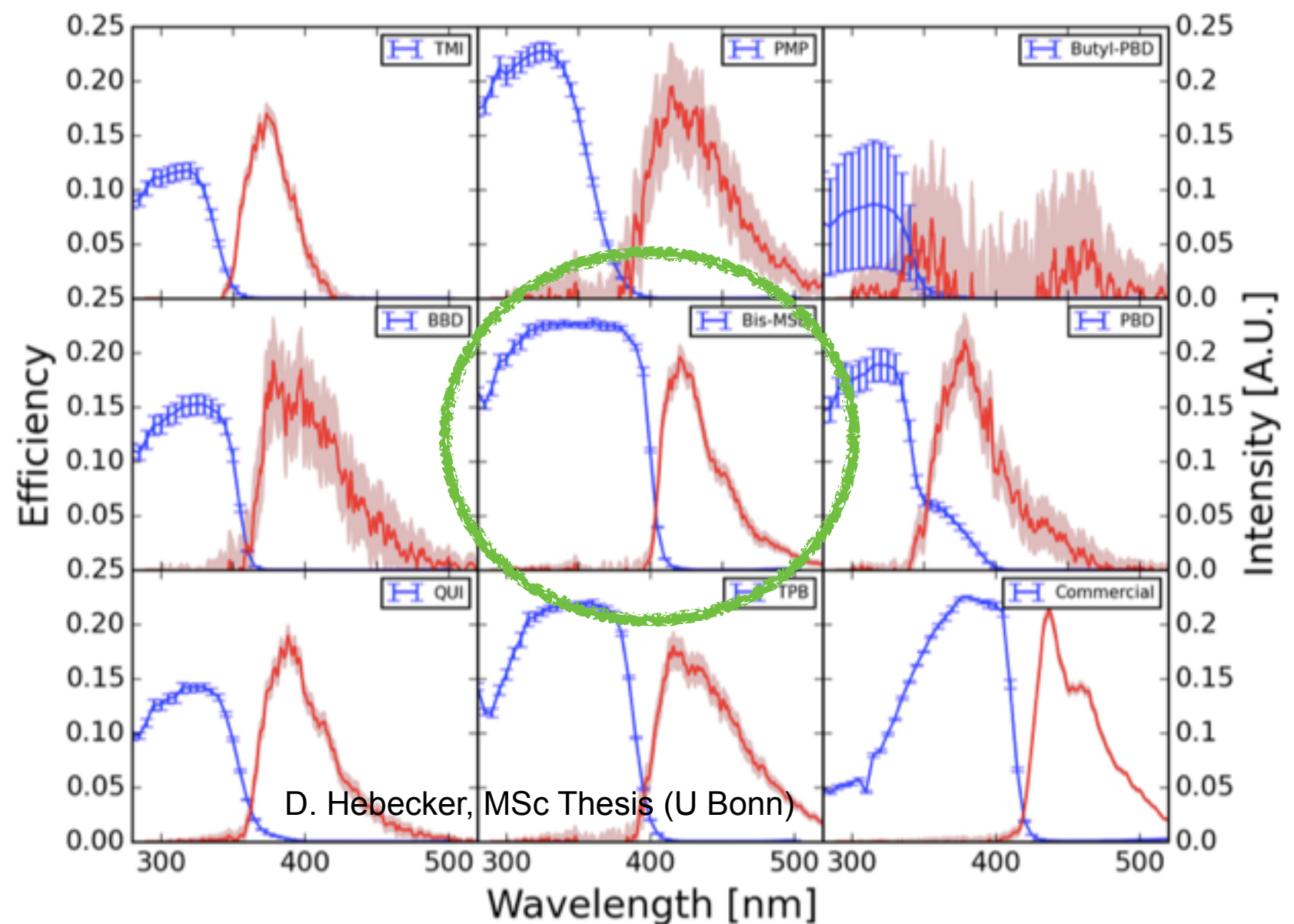
# WOM: Wavelength-Shifting Coating

## Best paint

- Bis-MSB
- PMMA
- Anisole

## Performance

- large gain in UV region
- emission slightly more green



Efficiency includes absorption, re-emission, and light guiding to photosensor



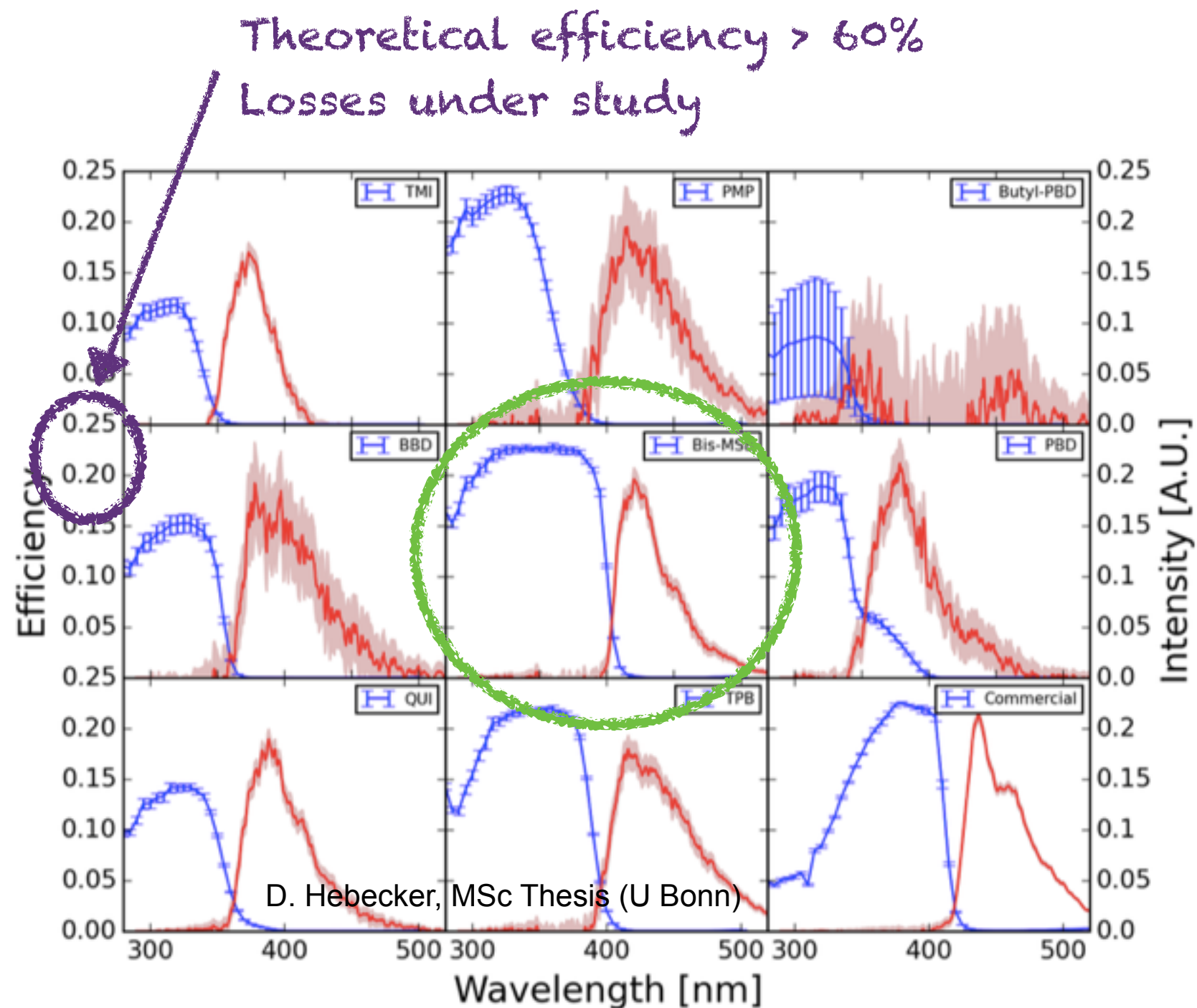
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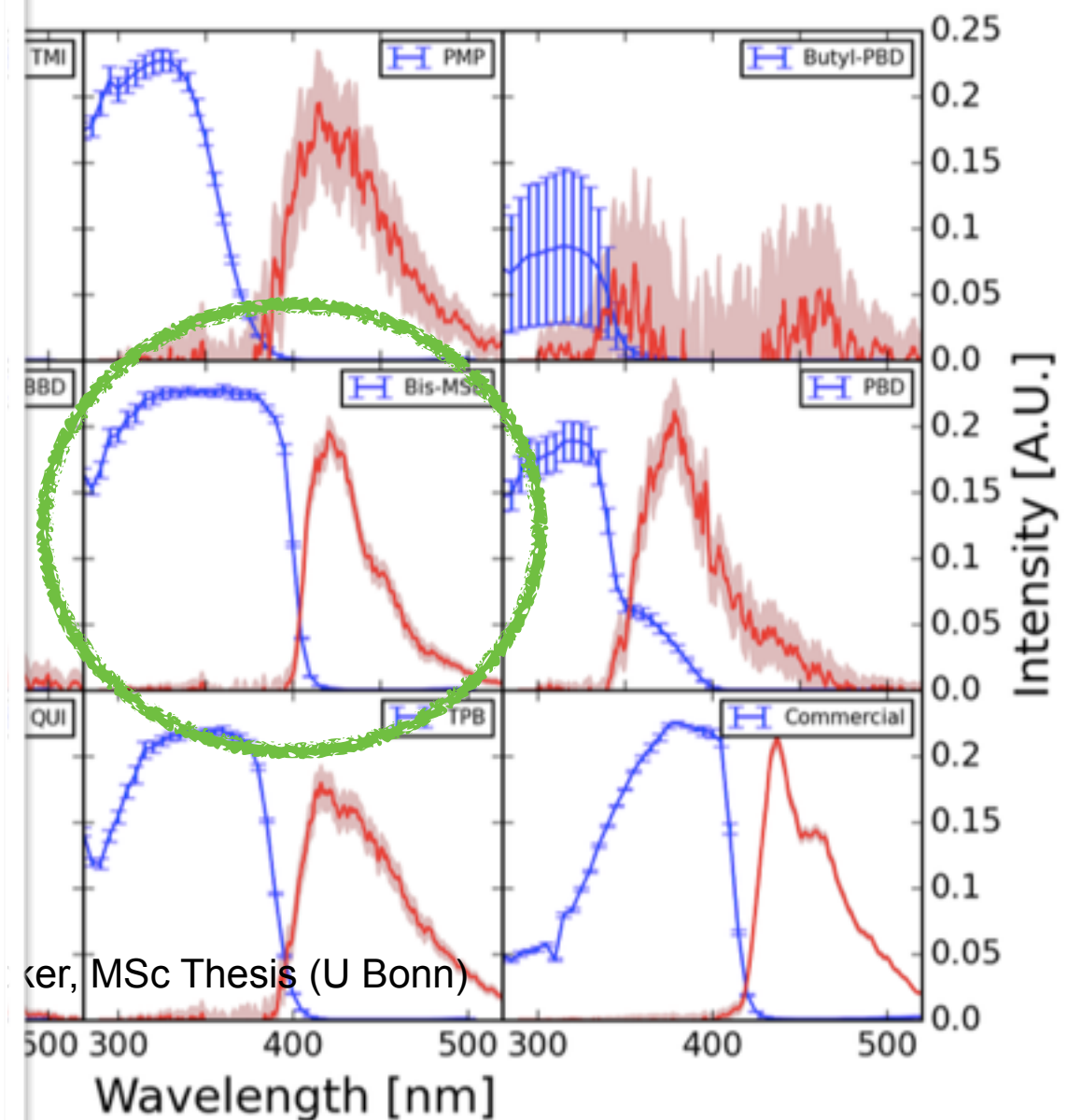
Photodiode

Front



Back

tical efficiency > 60%  
under study

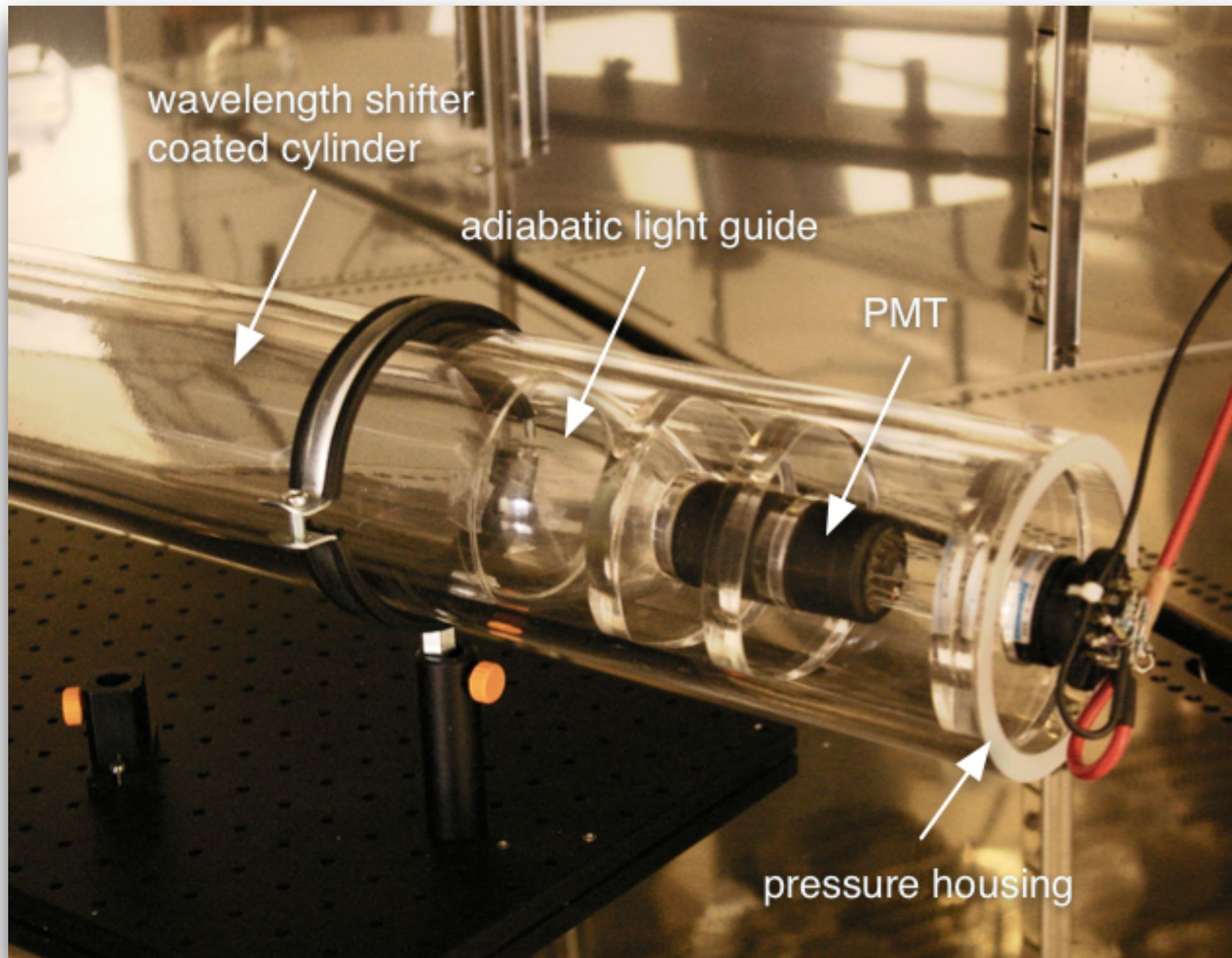


ker, MSc Thesis (U Bonn)

cludes absorption, re-emission,  
iding to photosensor



# WOM: Towards a Prototype



# Summary and Outlook

- > IceCube physics results call for a detector upgrade
  - Discover sources of astrophysical neutrinos
  - Measure neutrino mass ordering
  - Measurement of transition from Galactic to extragalactic cosmic rays
  - ...
  
- > New collaboration formed to work out detailed physics proposal and start vigorous R&D program
  
- > DESY group is in a very good position to play a leading role!

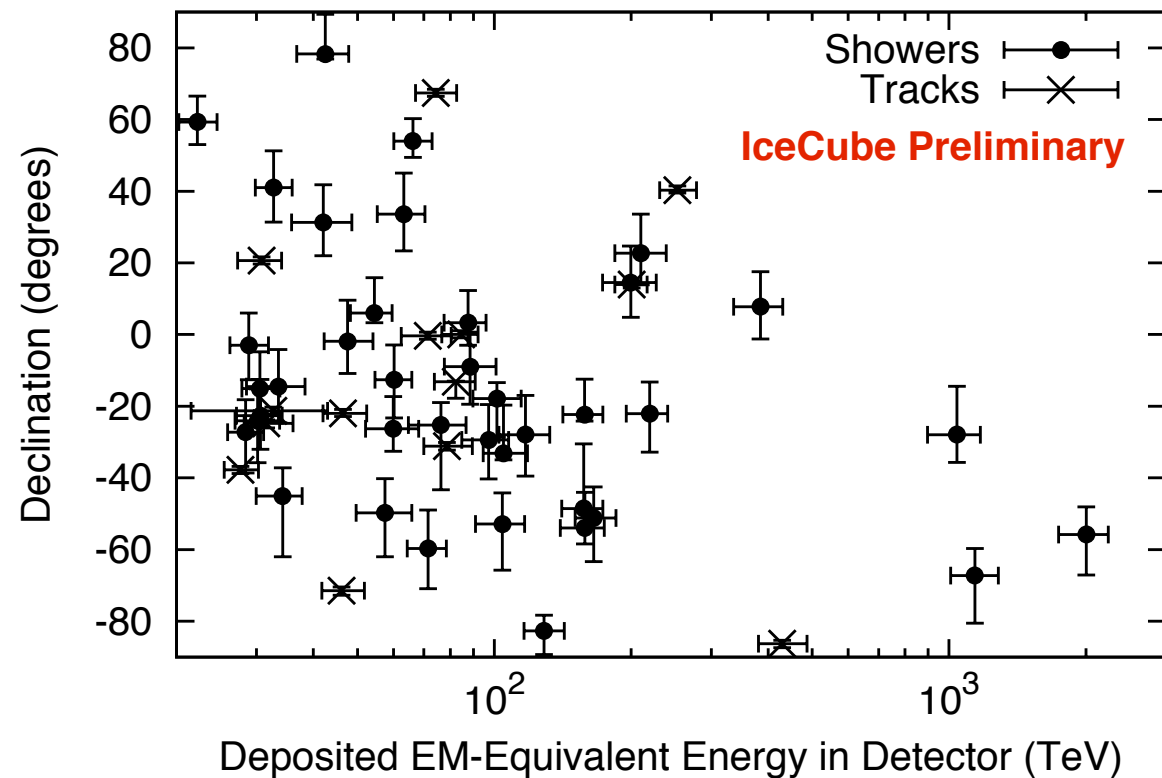




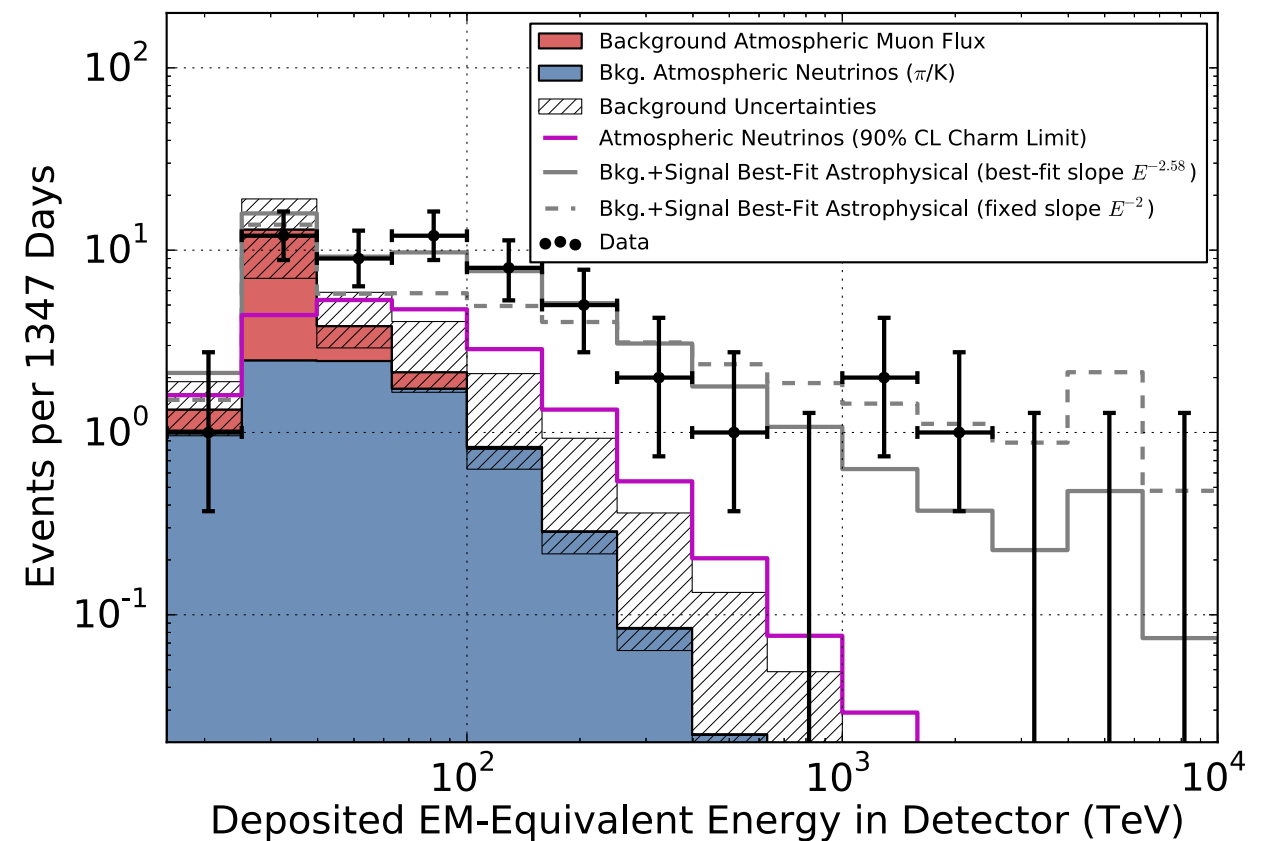
# Backup Slides



# 4 Year HESE

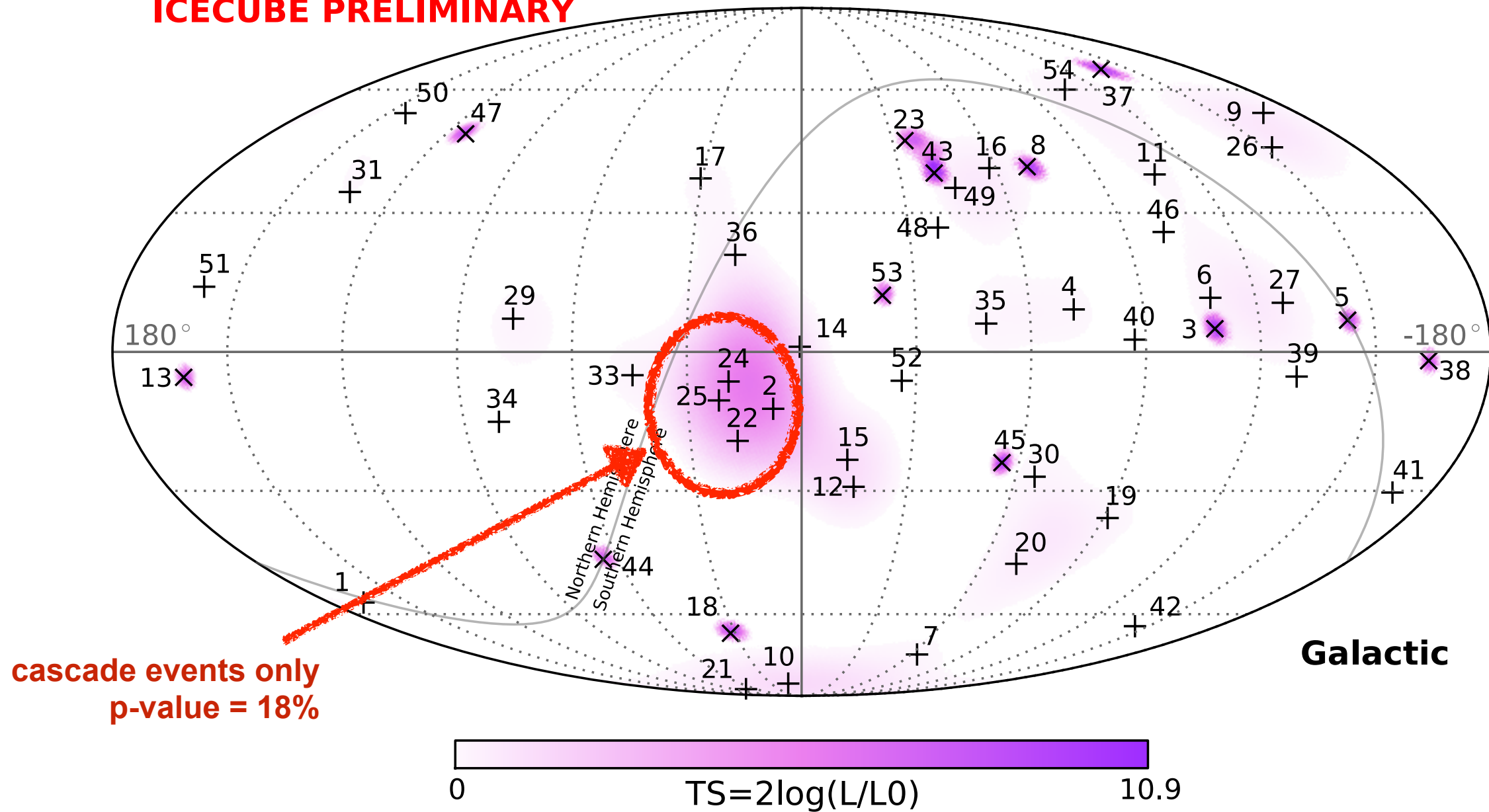


- > 54 events total ( $\sim 7\sigma$ )
- > no new PeV events
- > zenith distribution consistent with isotropic astrophysical flux

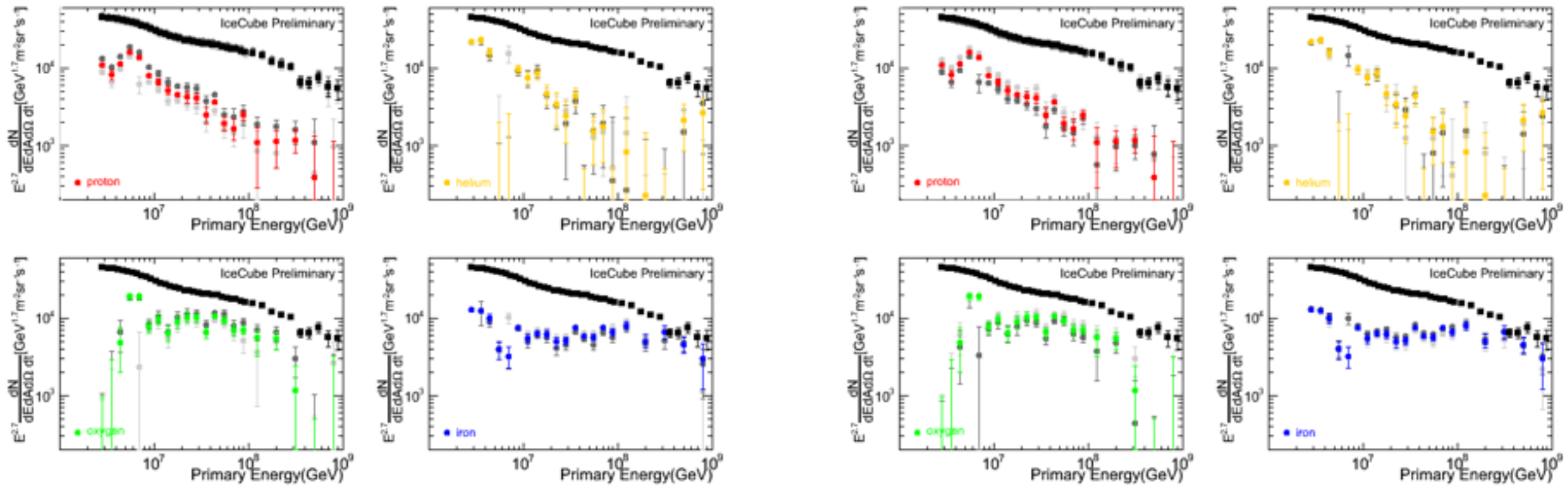


# 4 Year HESE

**ICECUBE PRELIMINARY**

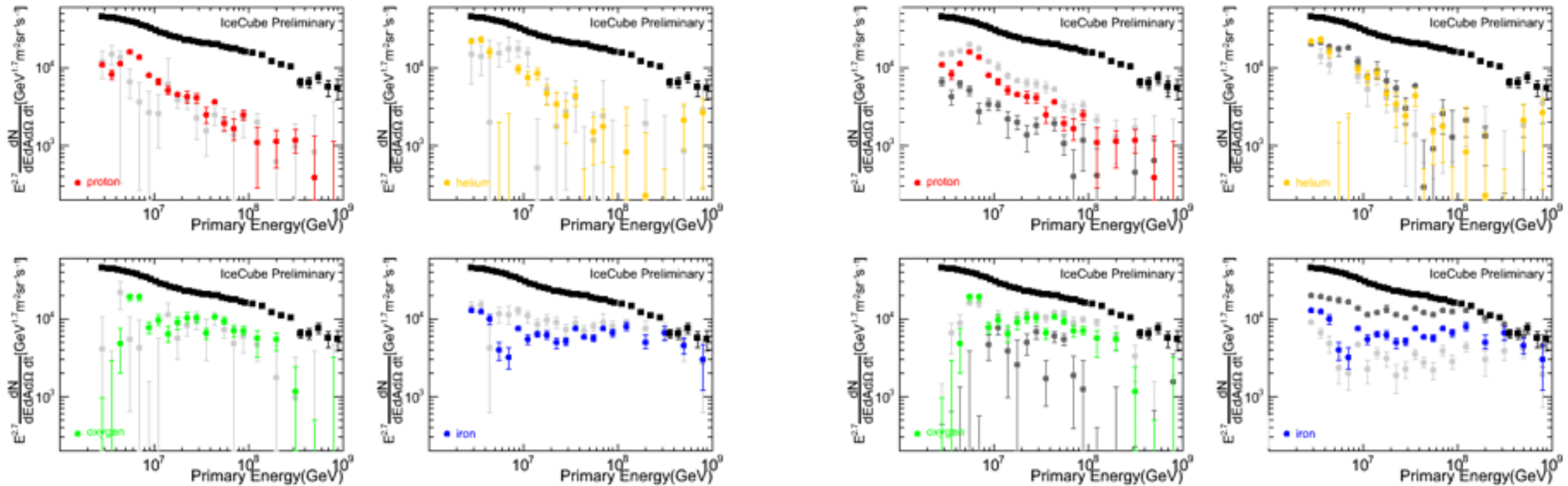


# Cosmic Ray Composition: Systematic Uncertainties



snow correction uncertainty

IceTop energy scale uncertainty



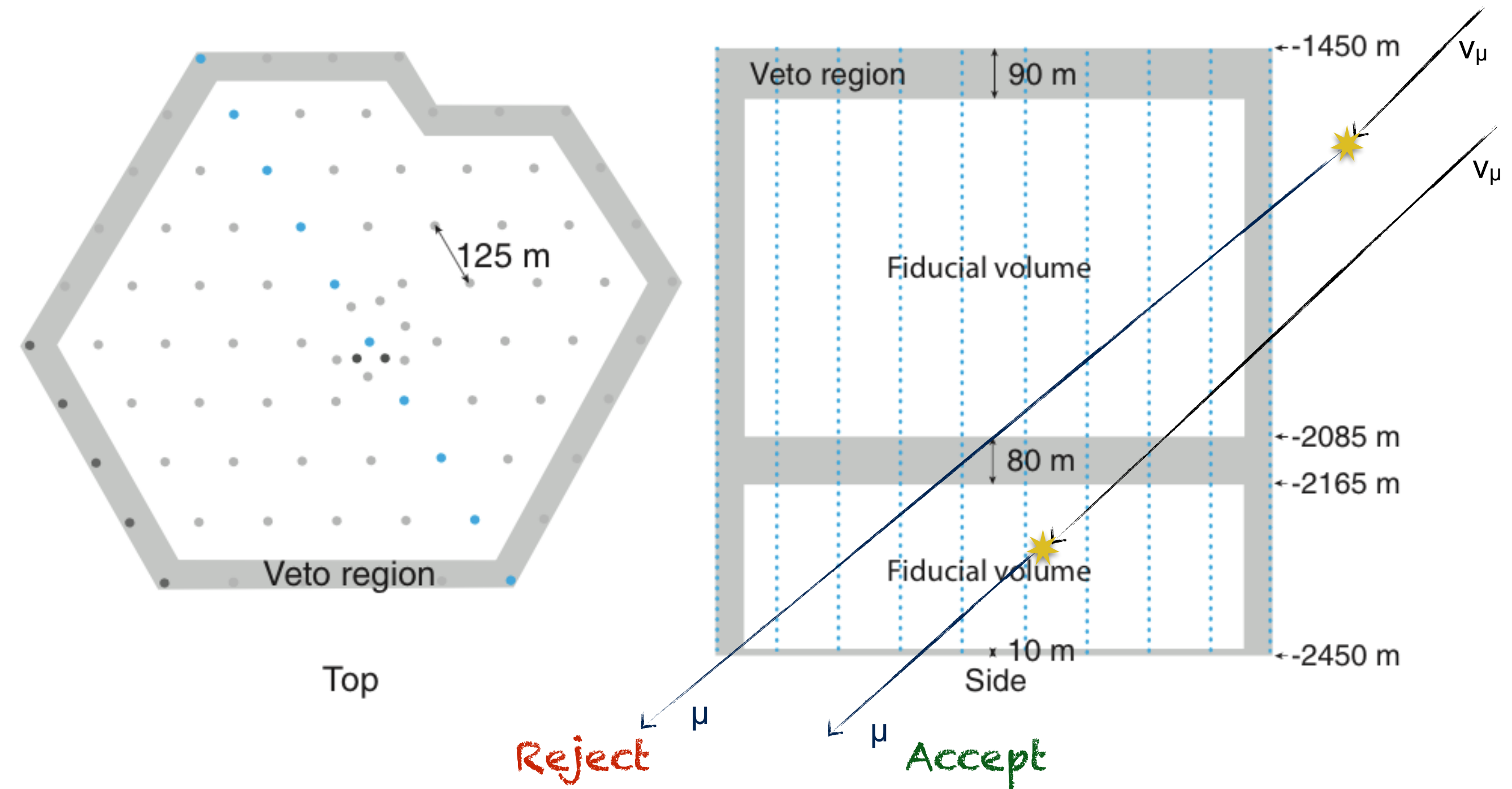
QGSJet-II-03

In-ice light yield uncertainty



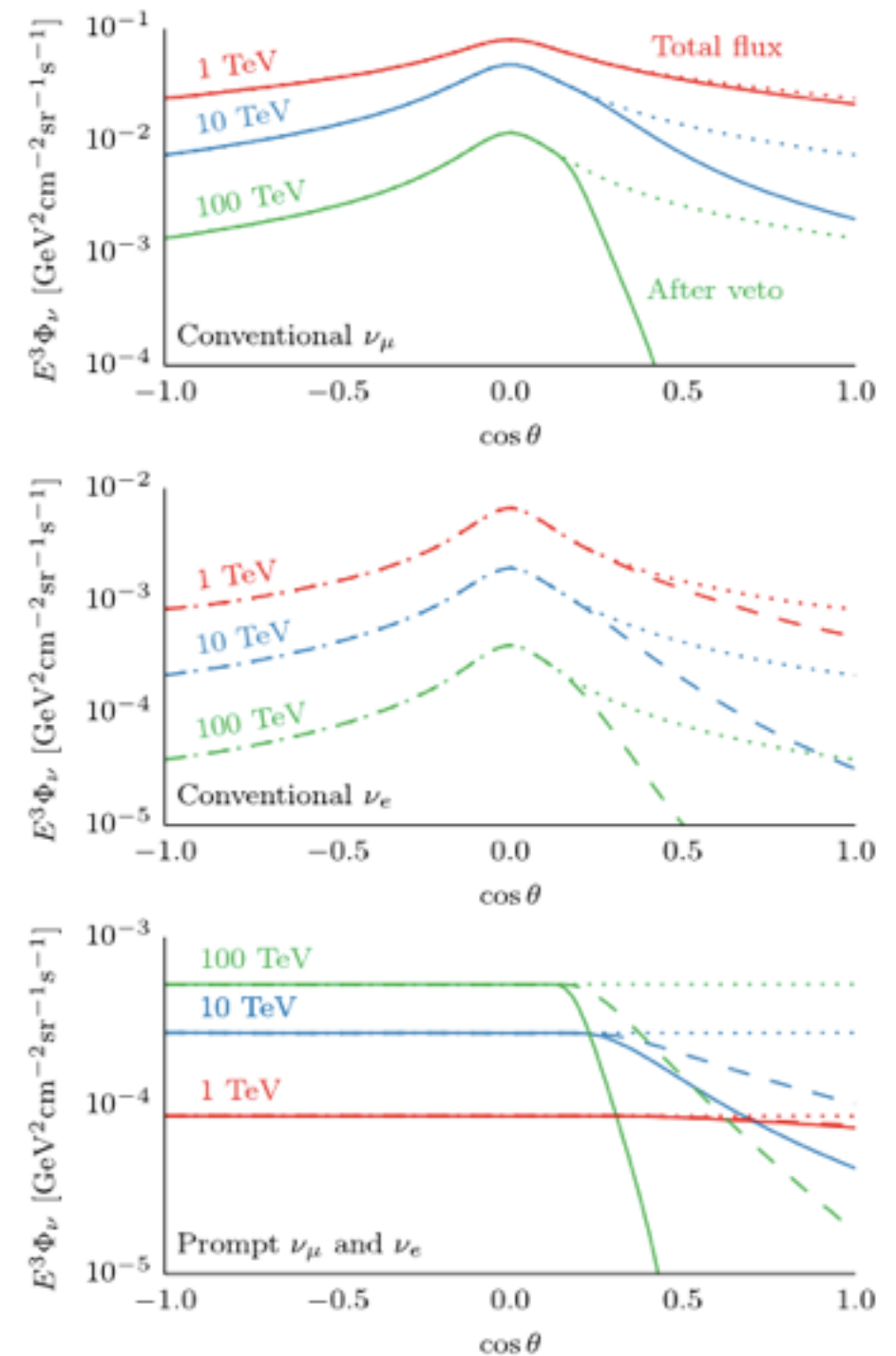
# How to Distinguish Atmospheric Muons from Neutrinos?

Search for starting events



# How to Distinguish Atmospheric Neutrinos from Astrophysical Neutrinos?

- > Atmospheric neutrinos from meson decays in air showers
- > The same air shower will also produce high energy muons
- > Look for muons coincident with neutrino in direction and time
- > Southern hemisphere atmospheric neutrinos are reducible
- > Northern hemisphere atmospheric neutrinos are irreducible

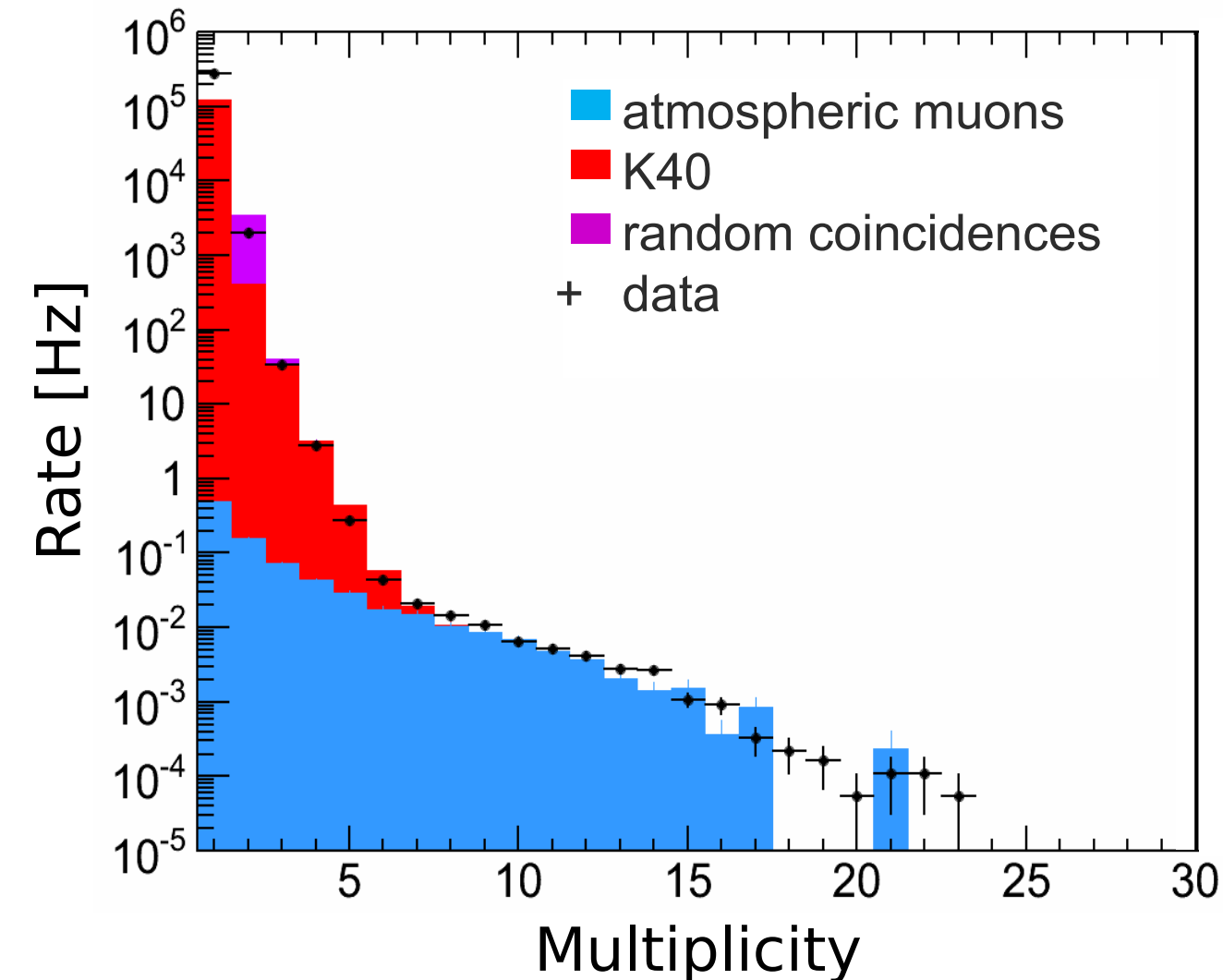


Gaisser et al., PRD **90** (2014) 023009

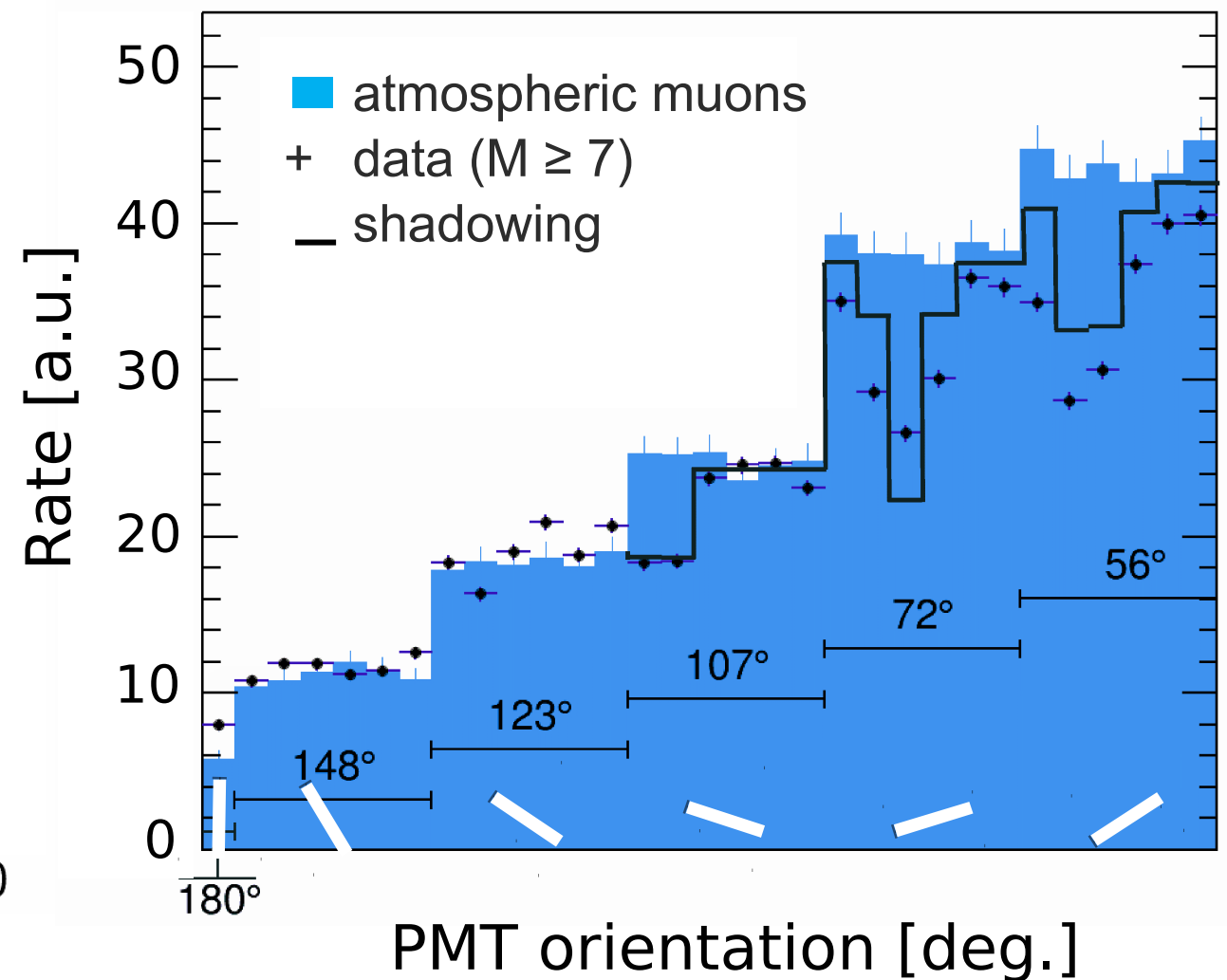


# KM3NeT Multi-PMT DOM: In-Situ Measurements

EPJ C **74** (2014) 3056



Number of PMTs hit on single DOM already allows isolation of muon sample



Occupancy reasonably well described by Monte Carlo

