Tracking Ghost Particles

high performance computing for the IceCube Neutrino Observatory

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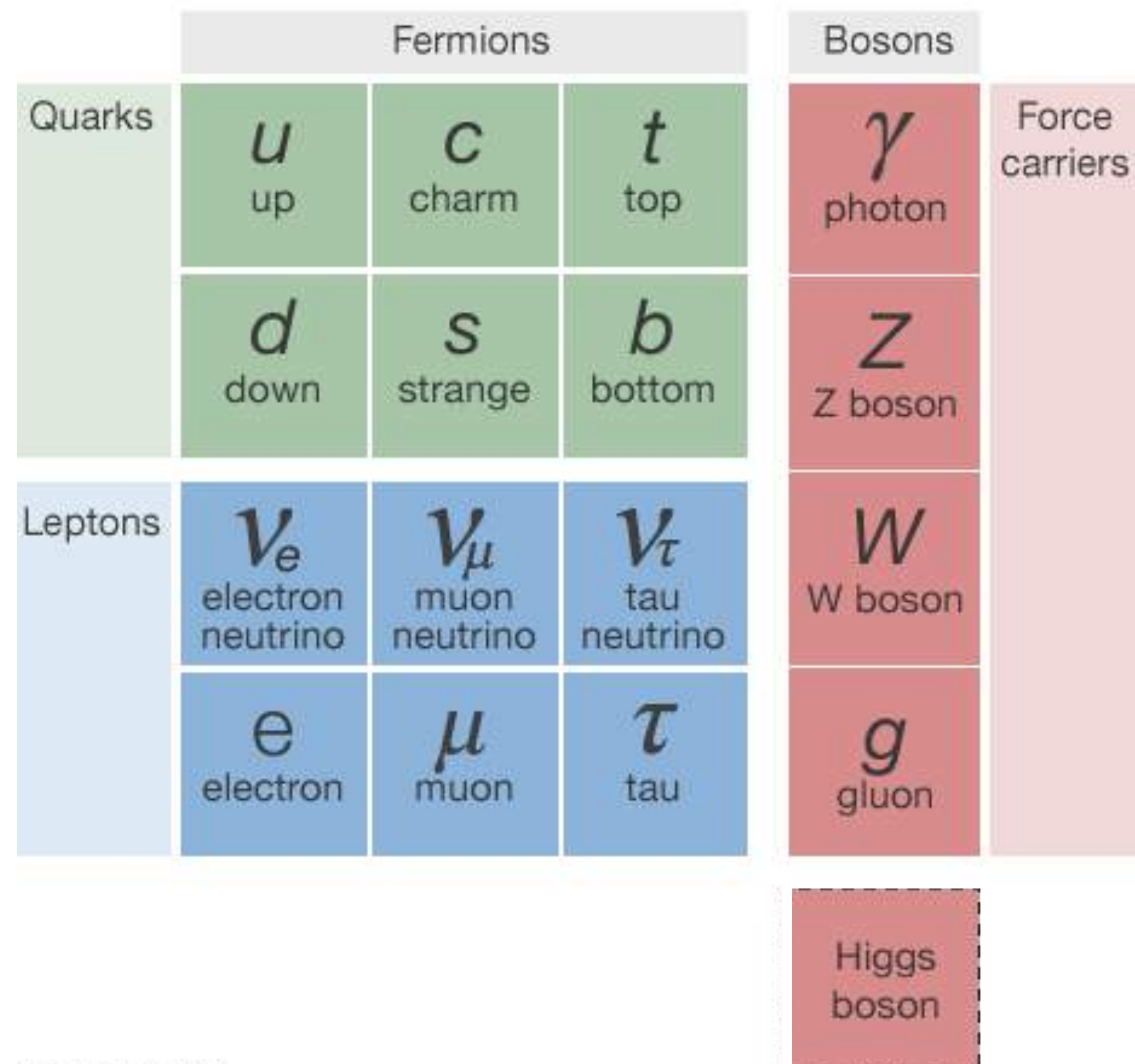
Outline

- Neutrinos and the IceCube Neutrino Observatory
- Tracking Neutrinos Through Ice
- Tracking Neutrinos Through the Earth

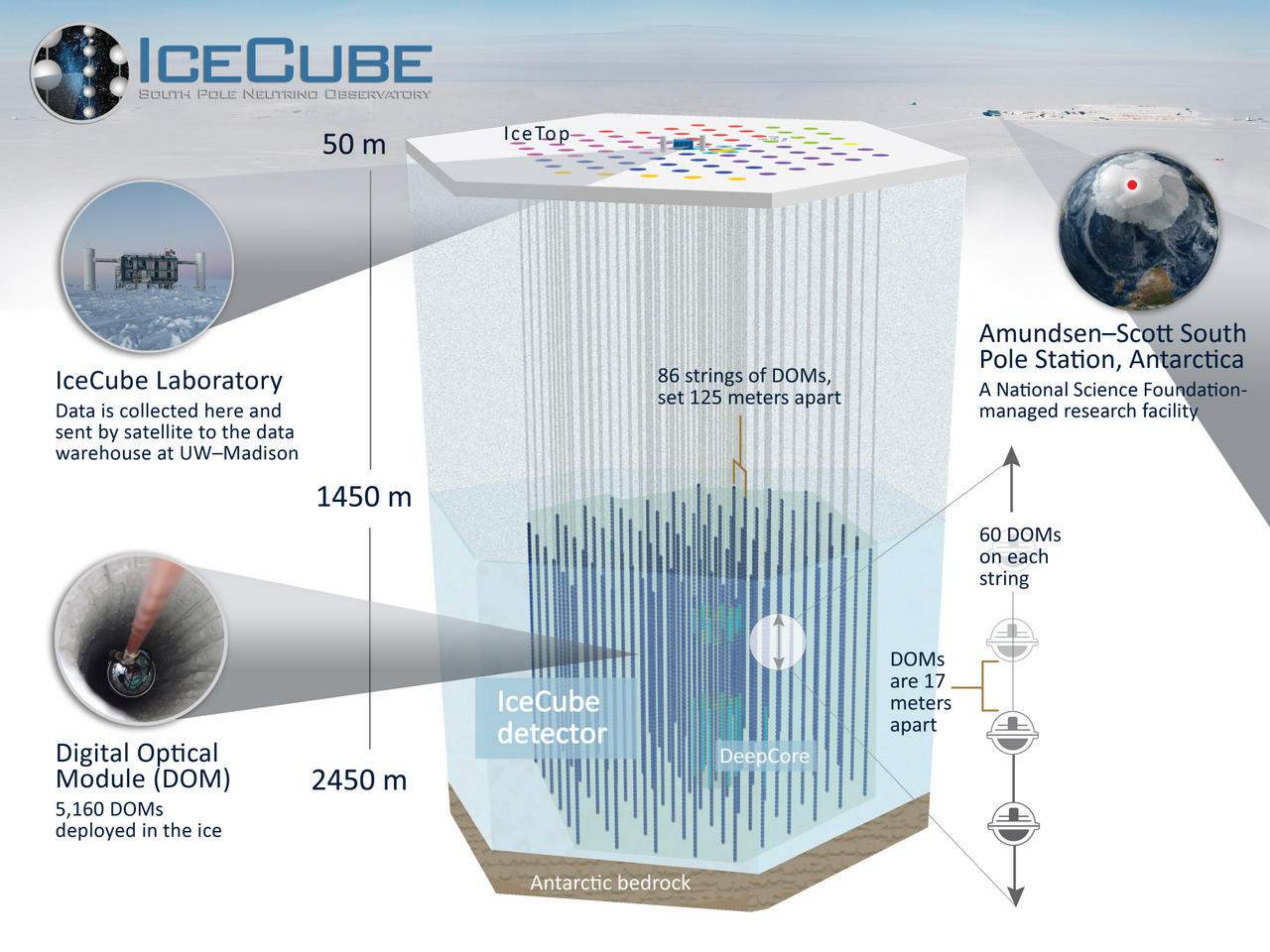
The IceCube Collaboration

Neutrinos – Nature's "Ghost Particles"

- Neutrinos are fundamental particles, but very strange
- A million times lighter than any other known particle
- Barely interact with other matter
- "Oscillate" between the three different types – an electron neutrino will spontaneously change into a tau neutrino



Source: AAAS

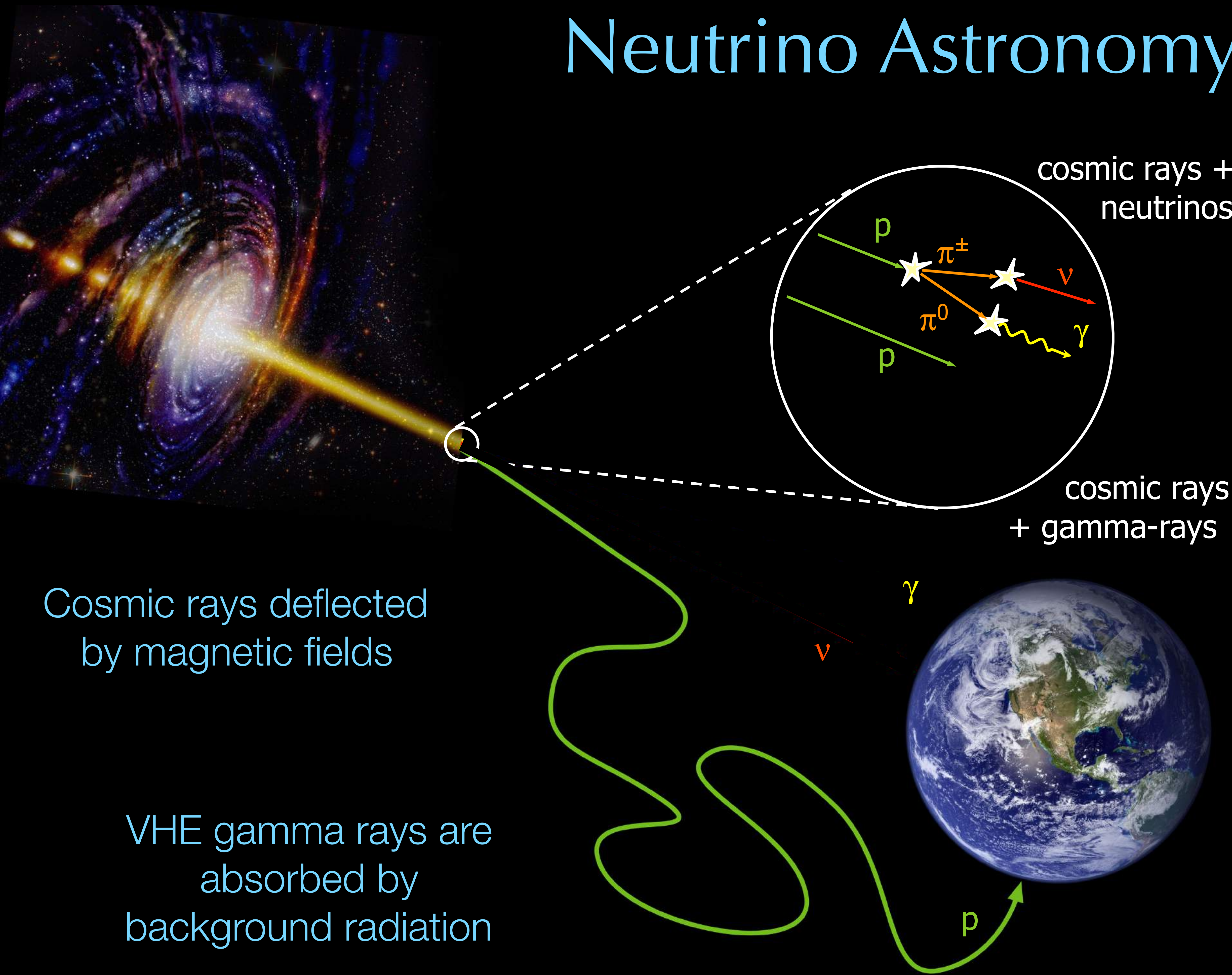

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock


U.S. AIR FORCE

The Science of IceCube

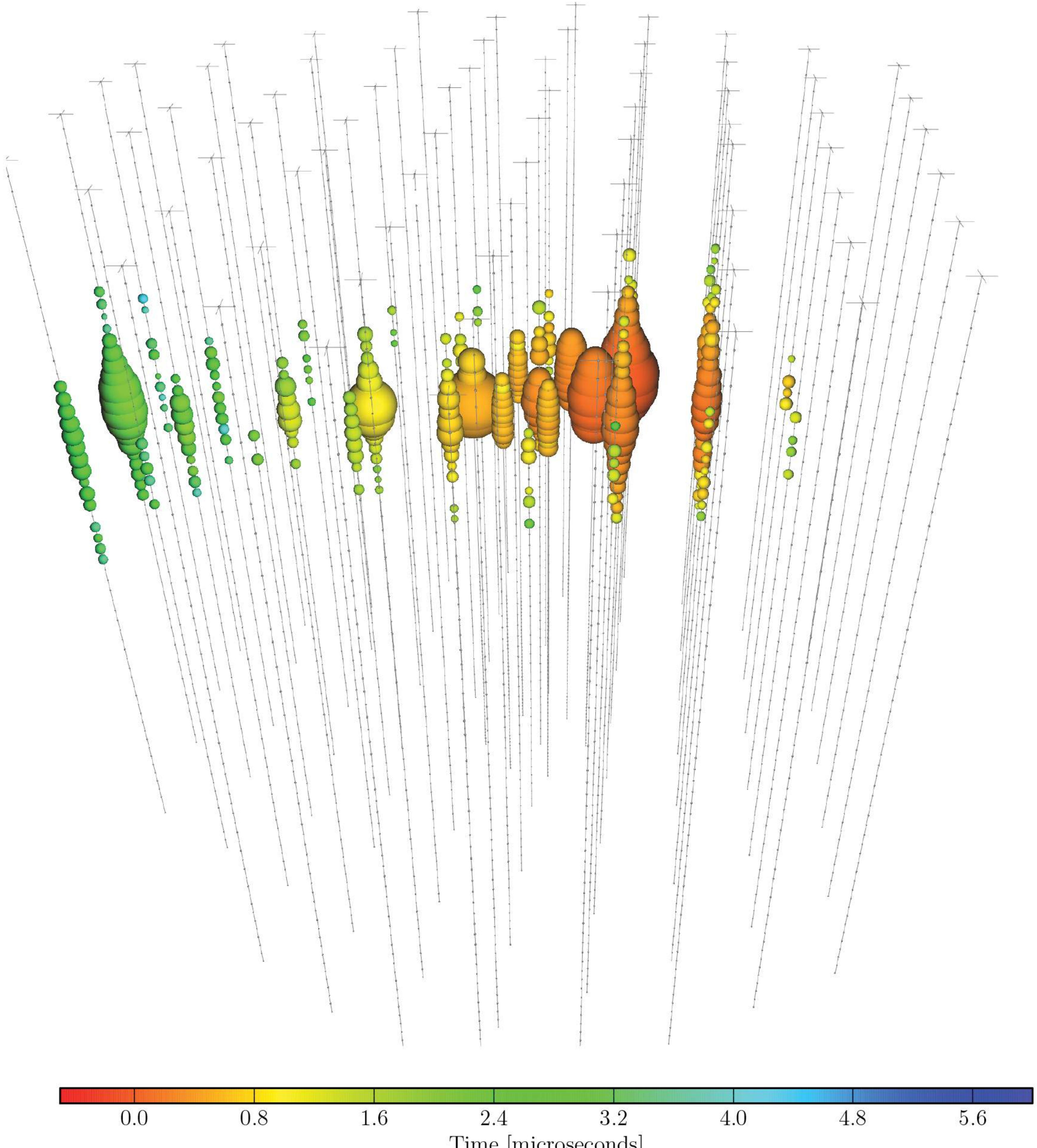
- Learning about our Universe
  - The Earth is constantly bombarded by relativistic particles from beyond our solar system – *where do they come from?*
- Understanding the nature of matter
  - *How do neutrinos behave?* Why are they so different from other particles, like the electrons and quarks that make up atoms?
  - *What is the "dark matter"* that makes up a quarter of the Universe?

Neutrino Astronomy



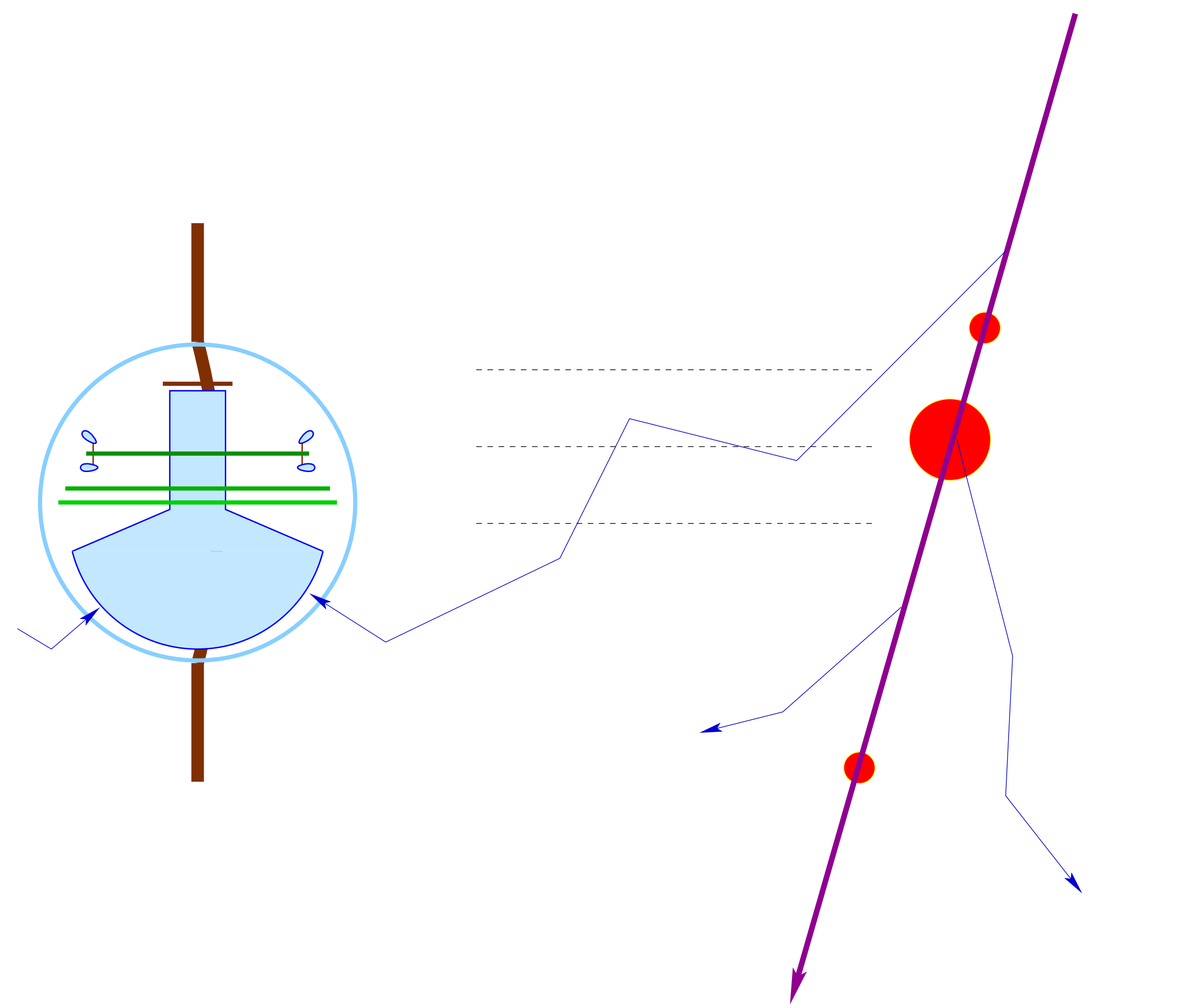
Cosmic rays deflected
by magnetic fields

VHE gamma rays are
absorbed by
background radiation

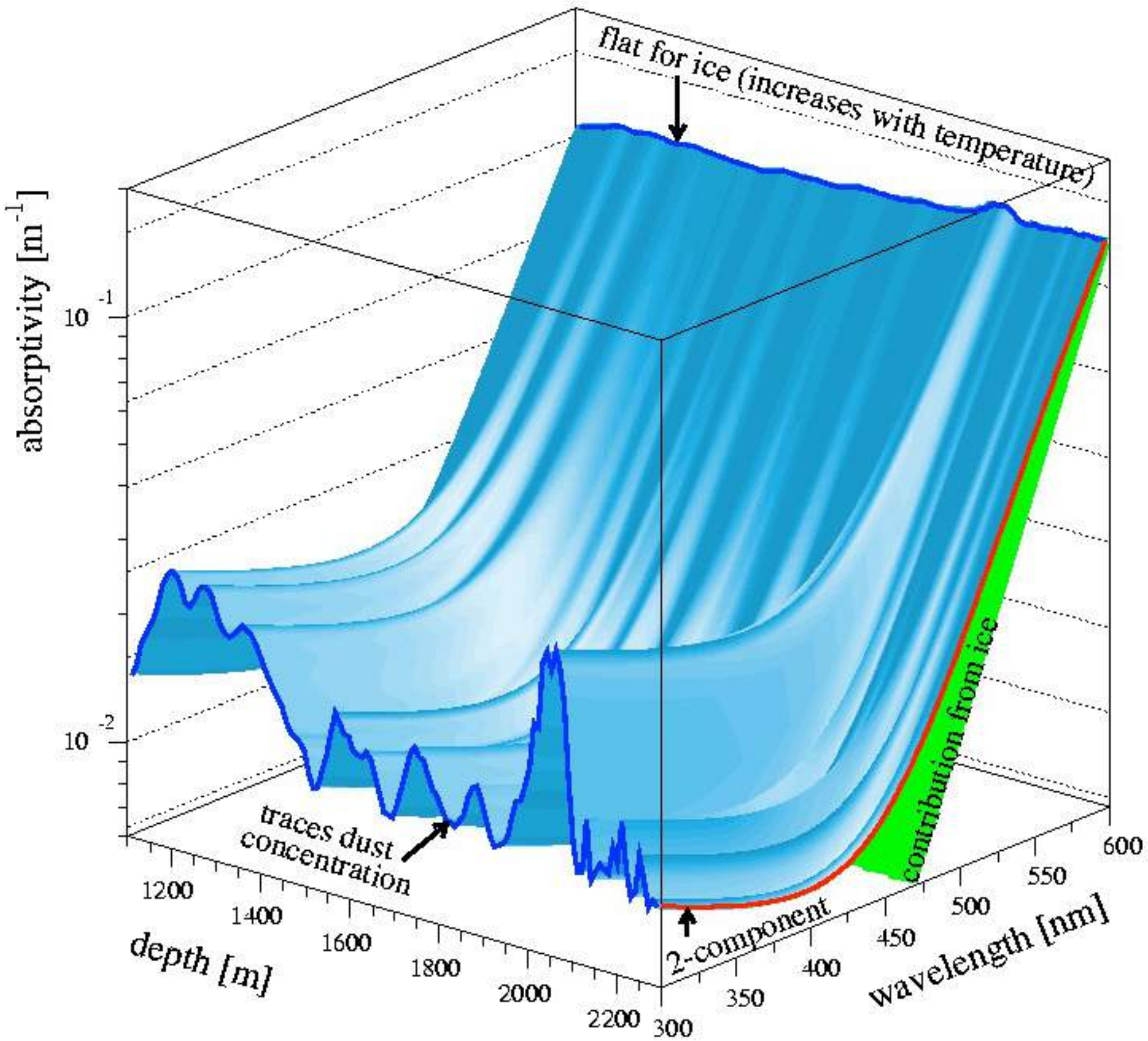

0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]

Tracking Neutrinos Through Ice

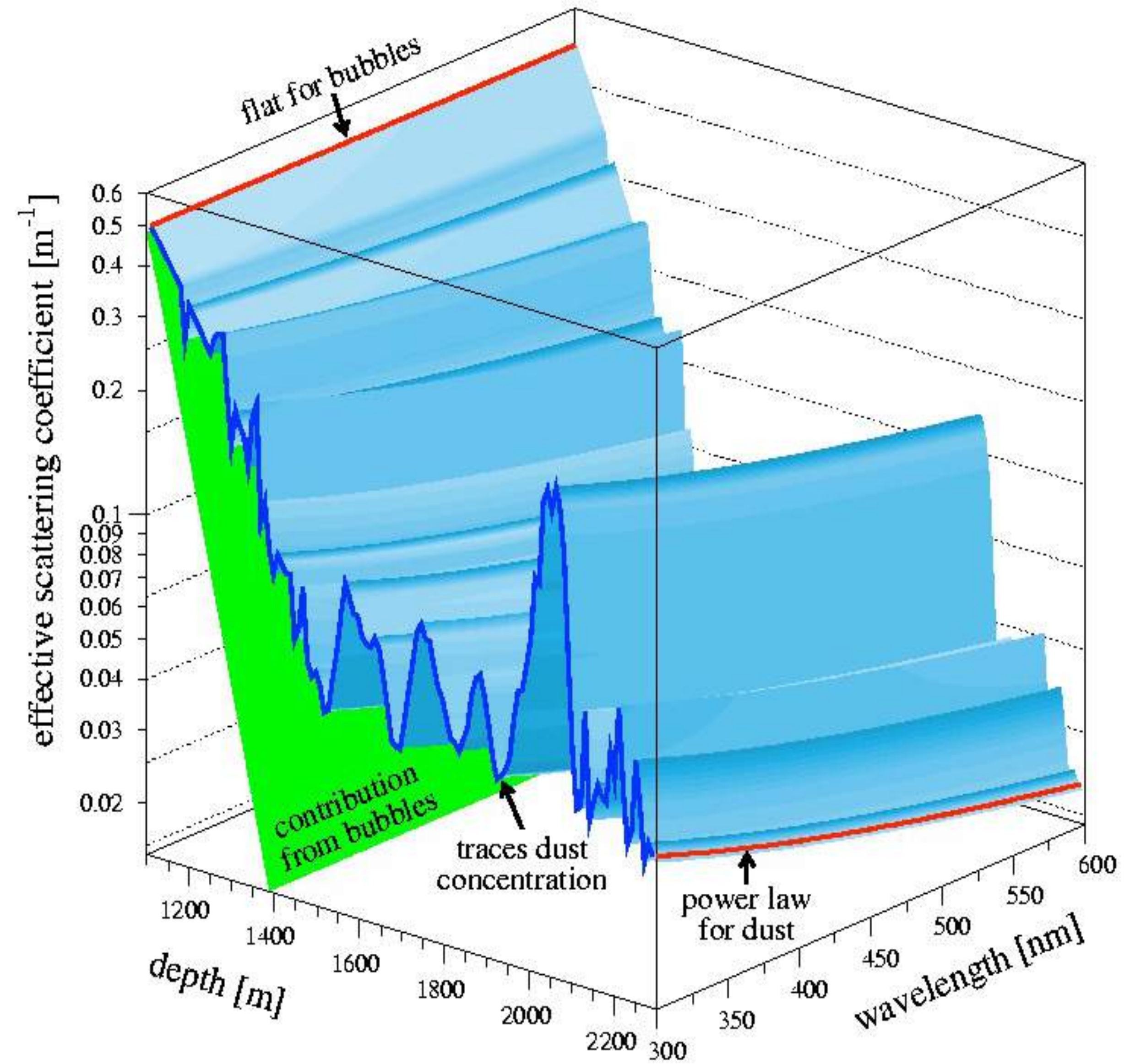
- High energy particles created when neutrinos interact in the ice emit ~160 Cherenkov photons/cm – and IceCube tracks them over a kilometer or more
  - And they undergo stochastic processes like bremsstrahlung which create even *more* photons
- Photons detected by IceCube may have traveled 100’s of meters through the ice, scattering off dust grains etc.
  - No analytic solution to photon propagation, depth-dependent optical properties
- Reconstruct events by maximum likelihood – need p.d.f.’s for every photon we detect!



Optical Properties of South Pole Ice



$\lambda_{absorption}$ ~ 100-250 m



$\lambda_{scattering}$ ~ 20-60 m

Ice optical properties reflect climatological history of the polar cap and refreezing process of ice under tremendous pressure

The Dust Logger

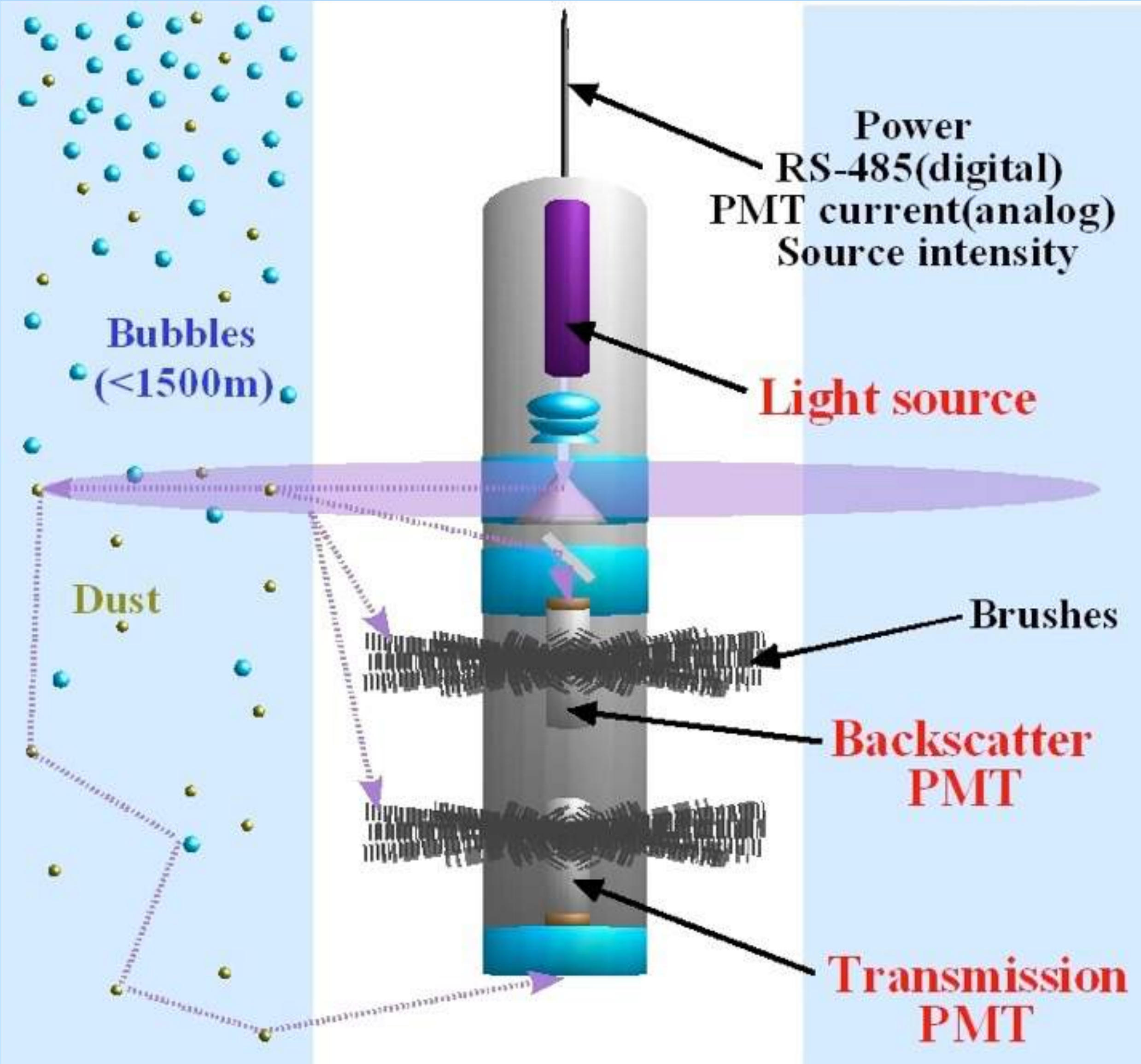
Designed to map out dust layers

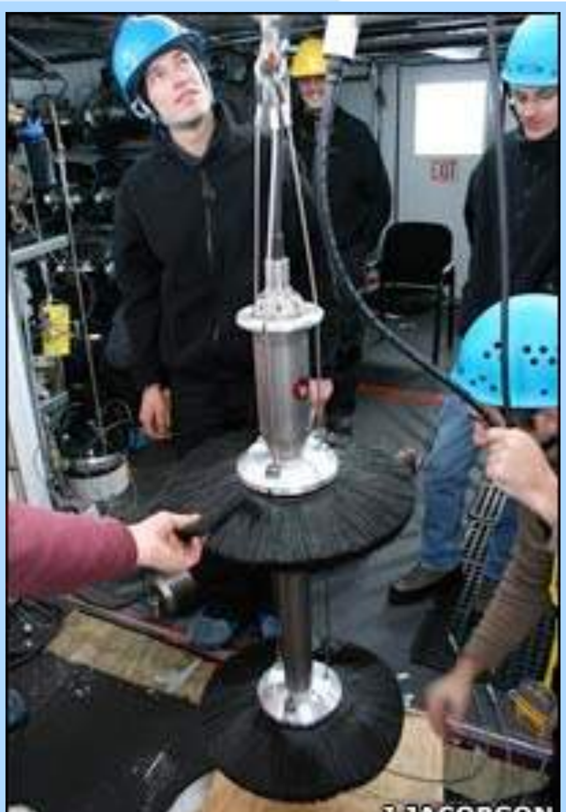
404 nm laser as light source

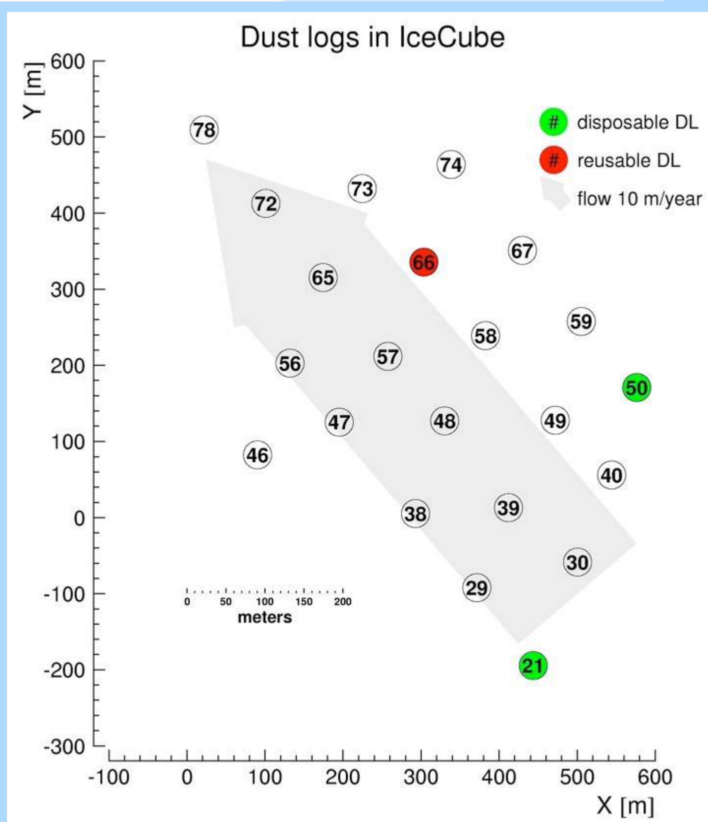
Dusty layers due to volcanic ash

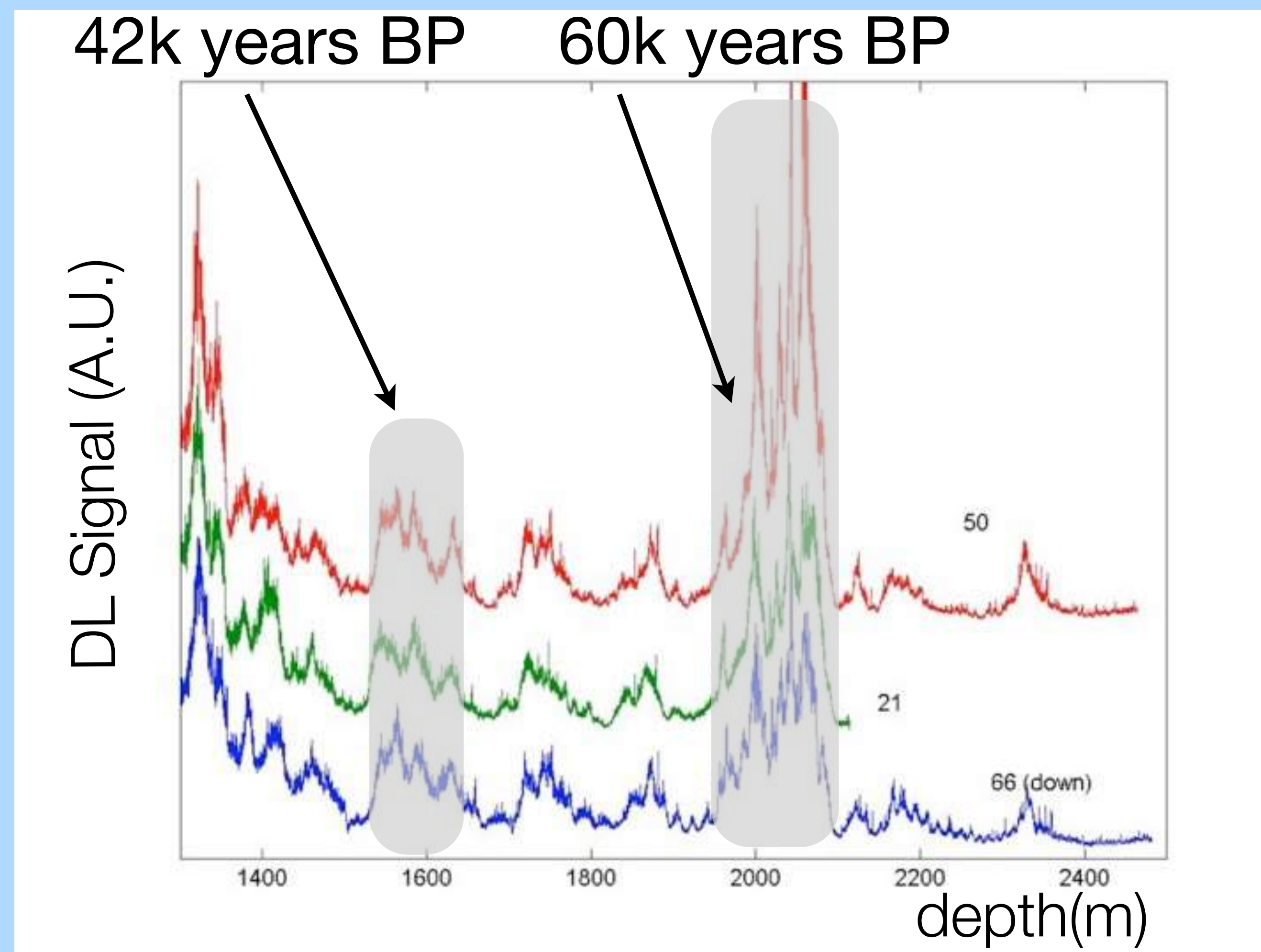
Three Dust Logger runs so far
(strings 21, 50, and 66)

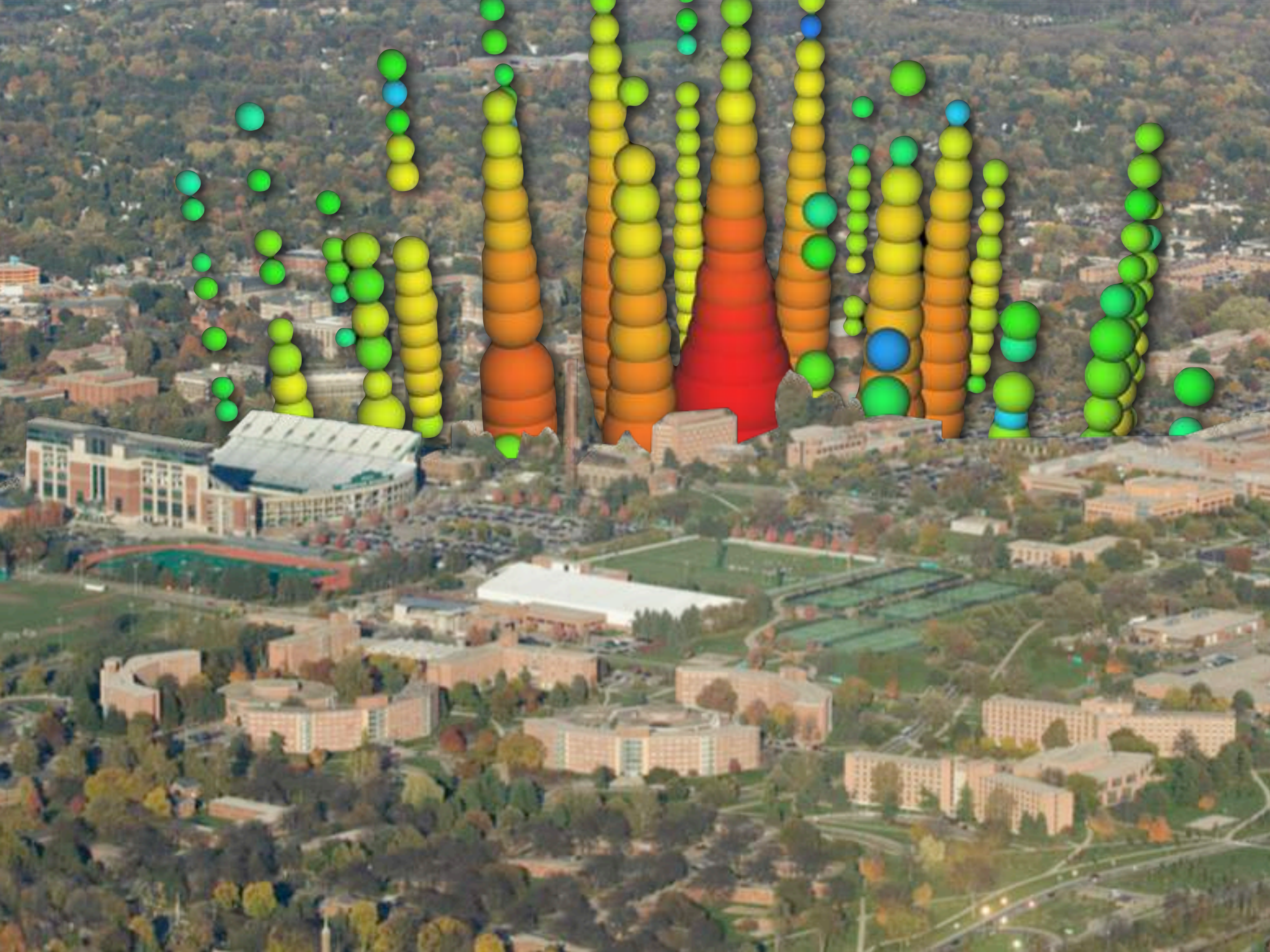
Can measure tilt of dust layers



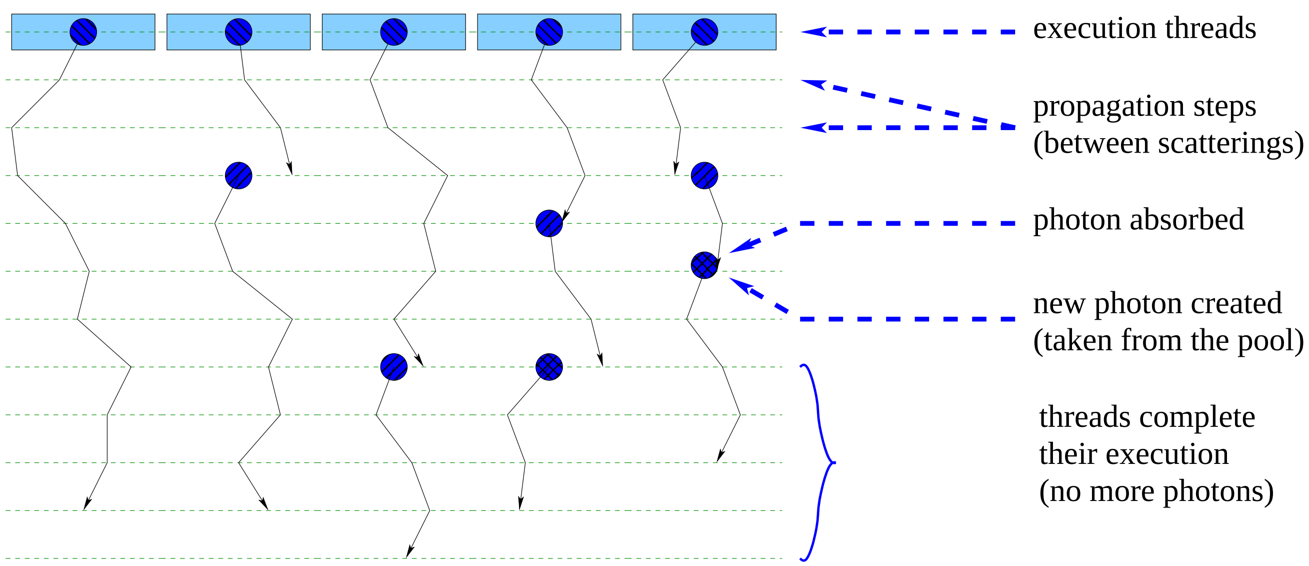


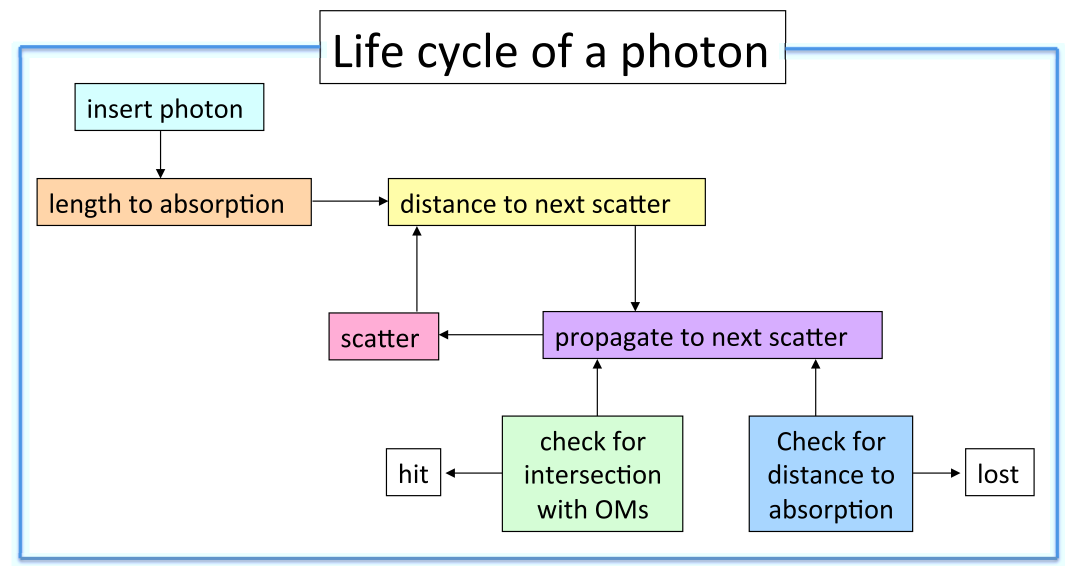




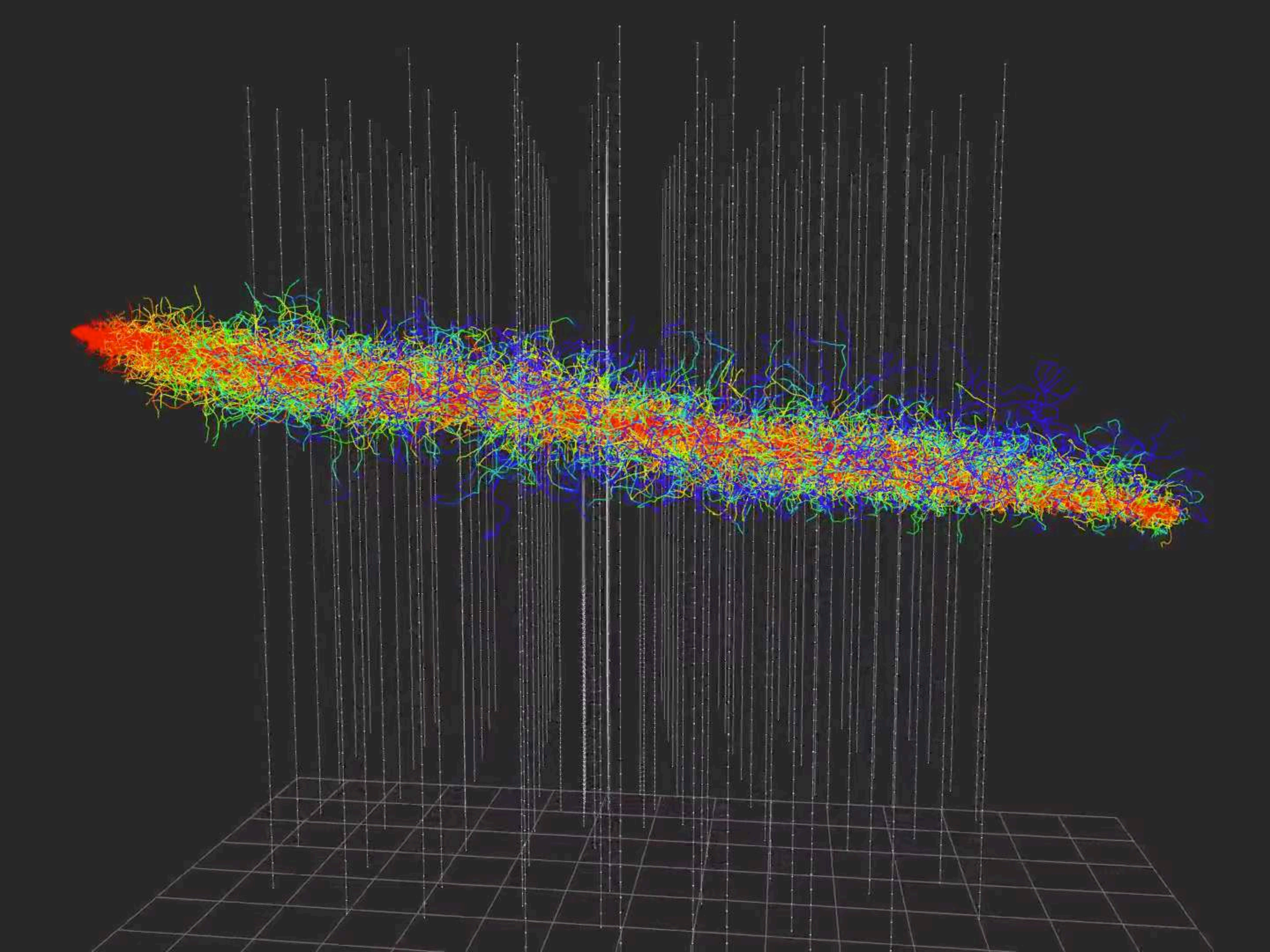


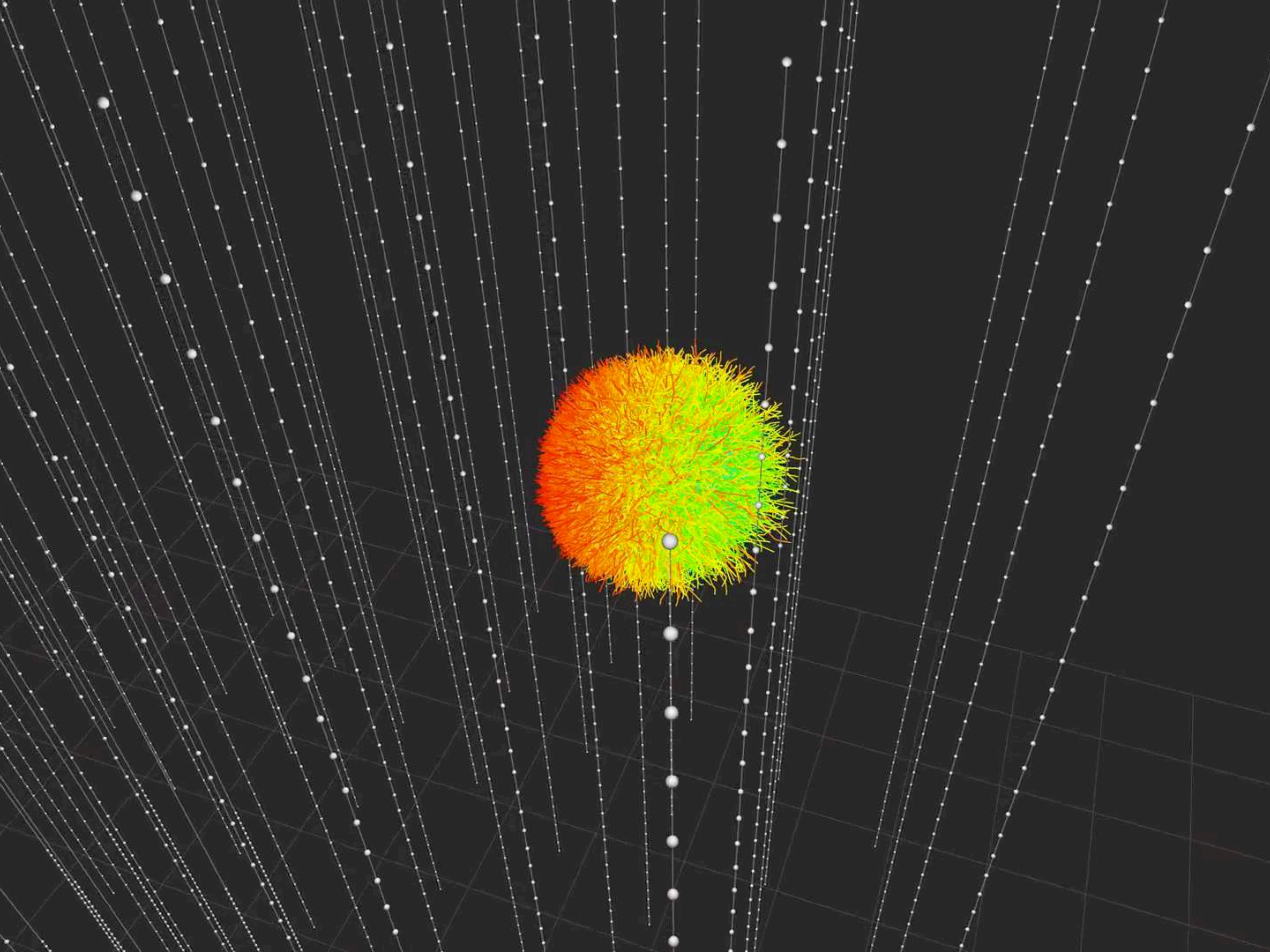
Photon Tracking with GPUs



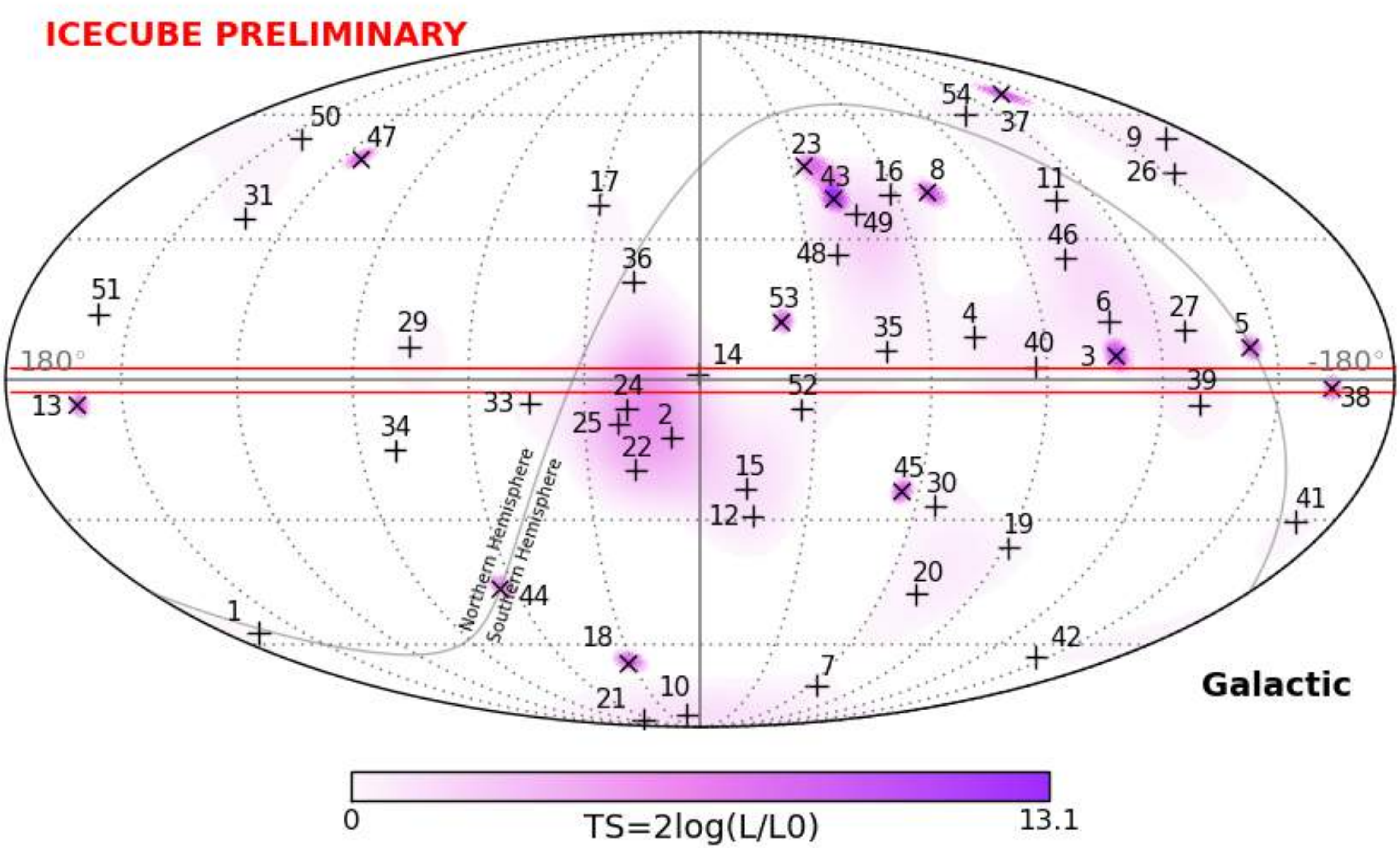


- Use graphical processing units (GPUs) to track thousands of photons in parallel
  - When a photon is absorbed by ice or a sensor, a new one is drawn to replace it from the pool waiting to be tracked
  - Two independent versions, one using CUDA and one OpenCL
- Provide acceleration factors of 150x or more compared to CPUs



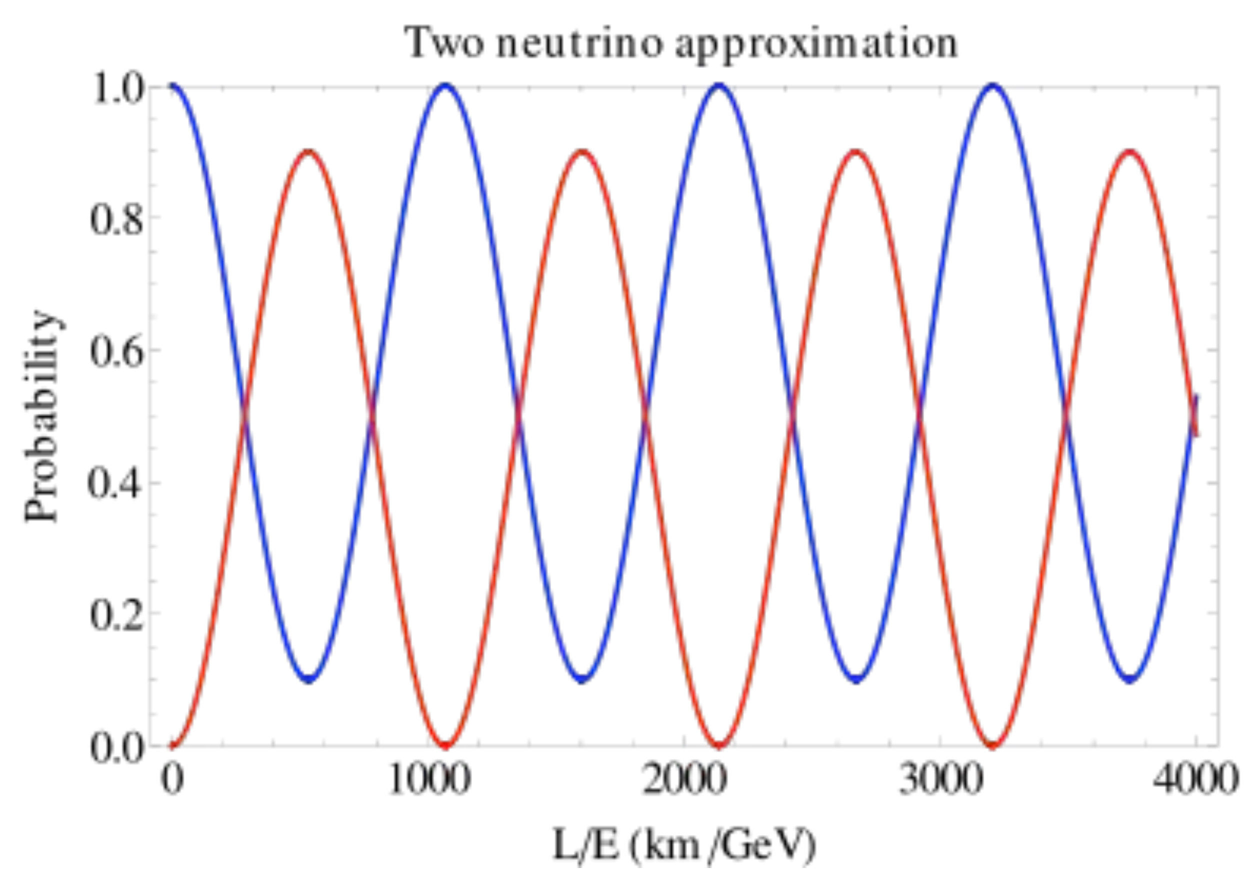


High Energy Neutrino Sky Map



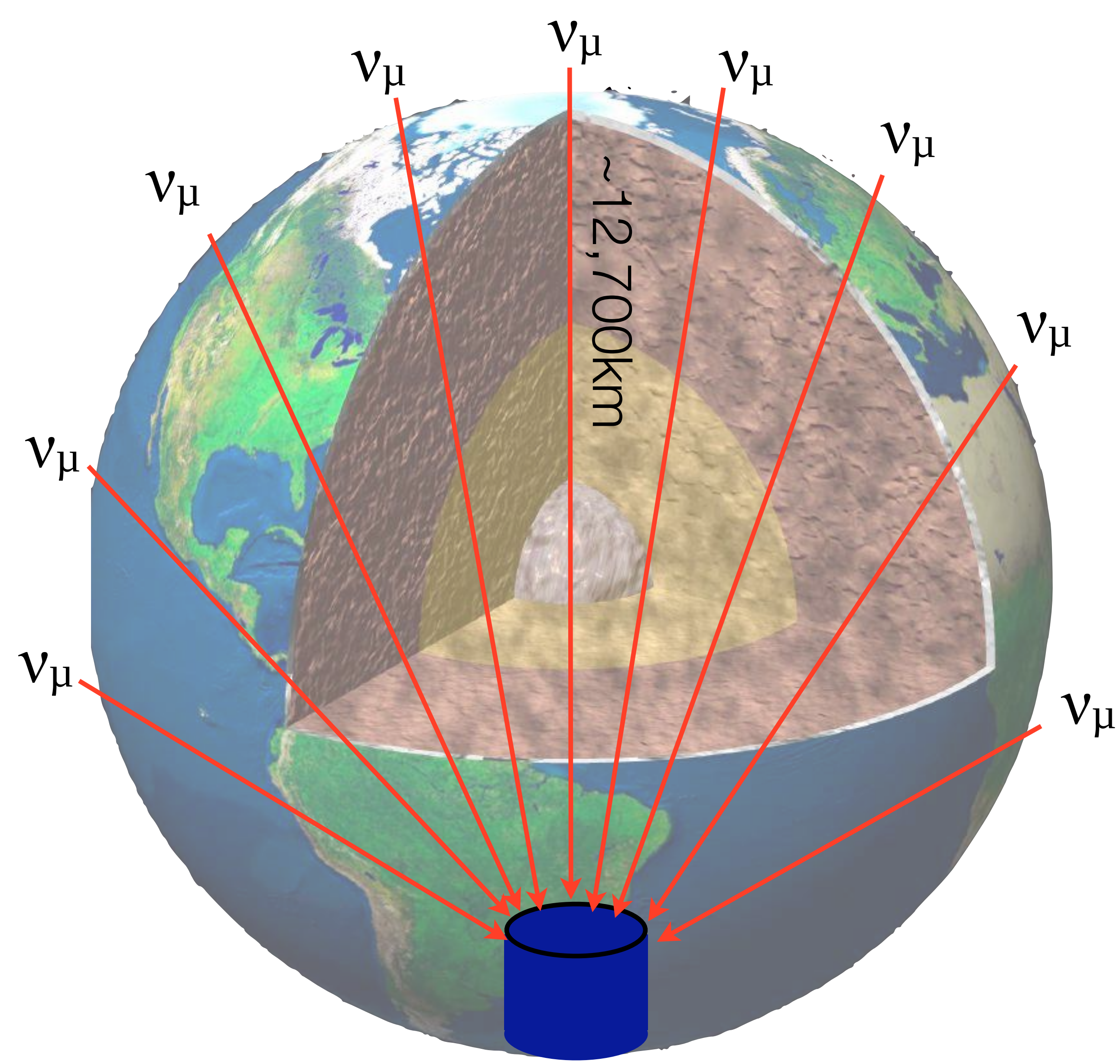
Tracking Neutrinos Through the Earth

- In particle physics, we have a very accurate Standard Model – but we know it is incomplete
- Neutrinos are the least well understood particles known
  - A better understanding of neutrinos may shed light on what lies behind the Standard Model
- Our best tool for measuring neutrino properties is their oscillations
  - Quantum mechanical interference phenomenon that converts one type of neutrino into another as they travel through space



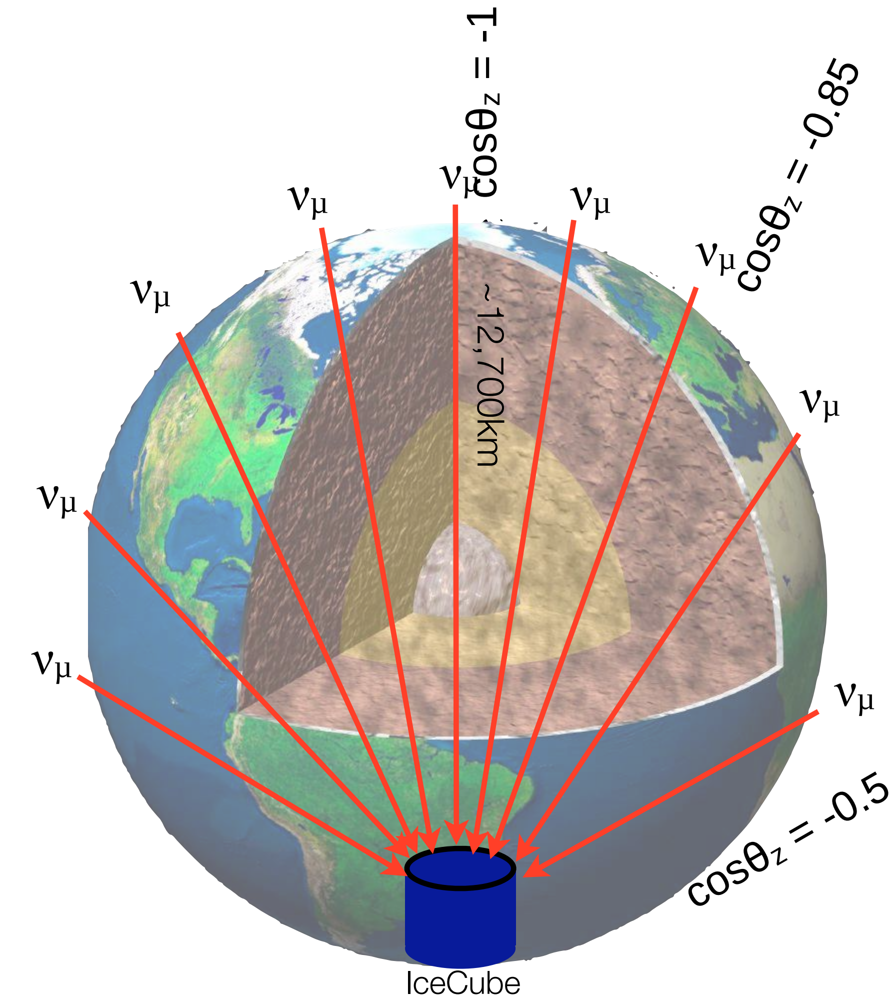
Tracking Neutrinos Through the Earth

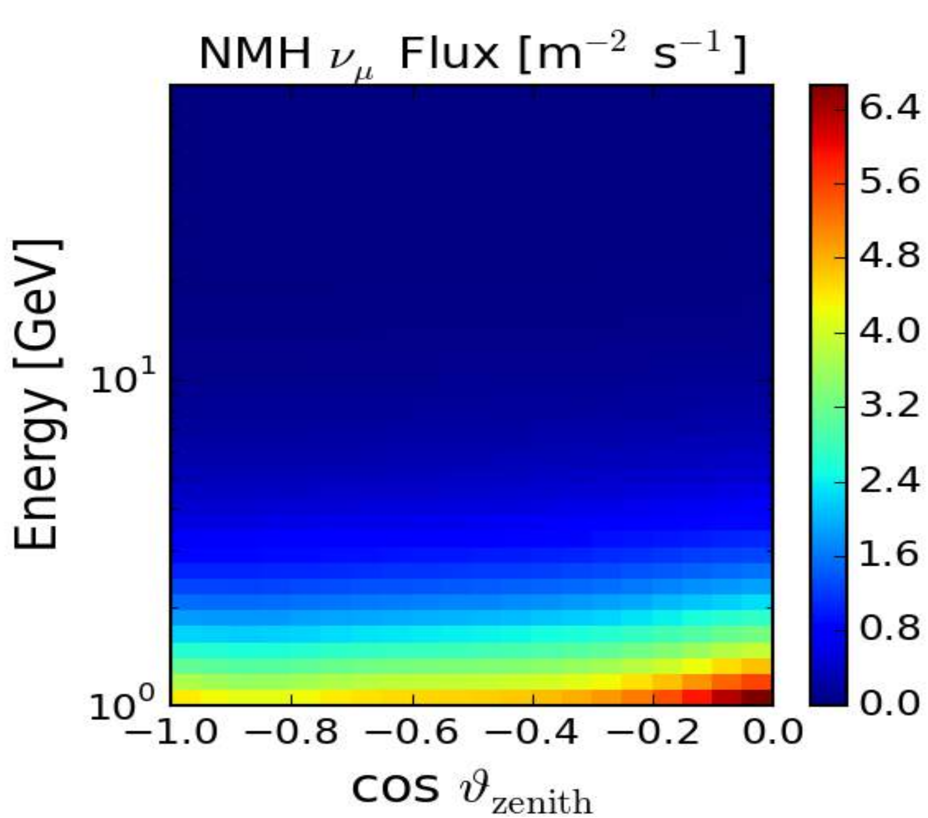
- IceCube observes neutrinos over a wide range of energies and baselines
  - Nearly 100,000 neutrino events to date in the relevant energy range – world's largest neutrino data set at these energies
- Oscillations produce distinctive pattern of flux distortions in energy-angle space
  - Precise observations of these distortions can be used to measure neutrino mixing, differences between masses



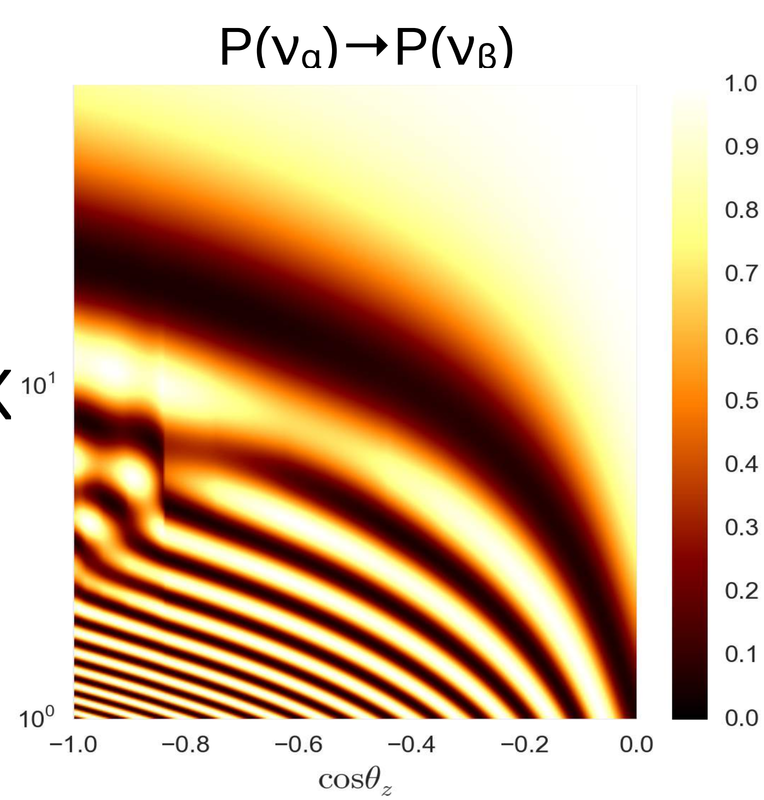
Tracking Neutrinos Through the Earth

- Neutrino flux at production is nearly isotropic, with falling power-law energy spectrum
- Probability of changing flavor is an oscillatory function of distance and energy, with additional effects due to coherent interactions with matter





X



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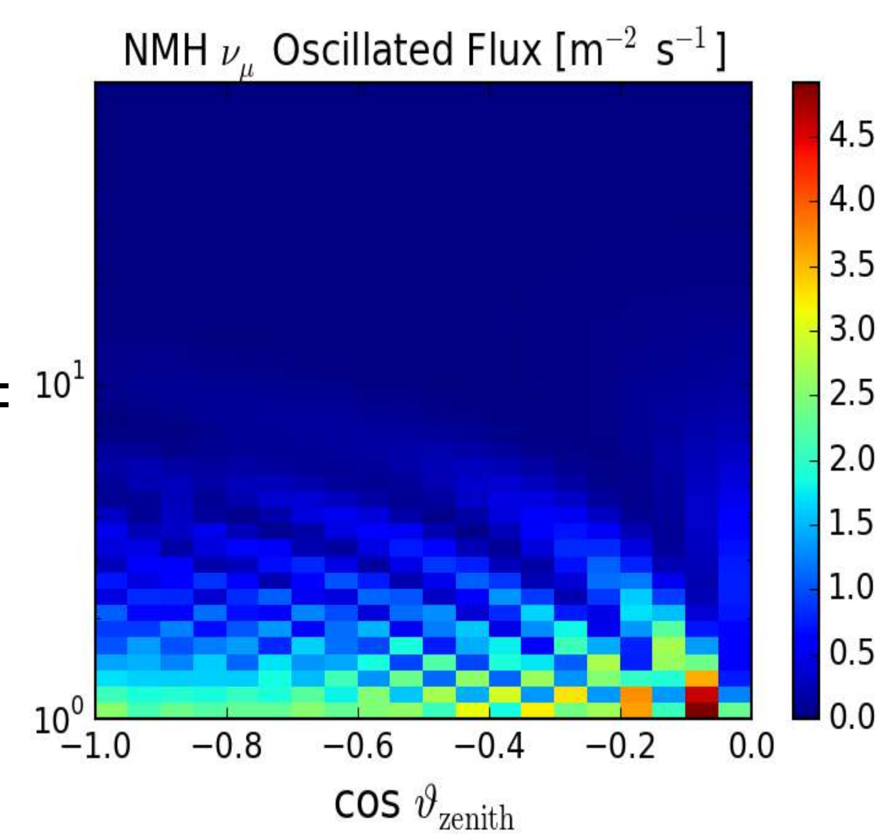
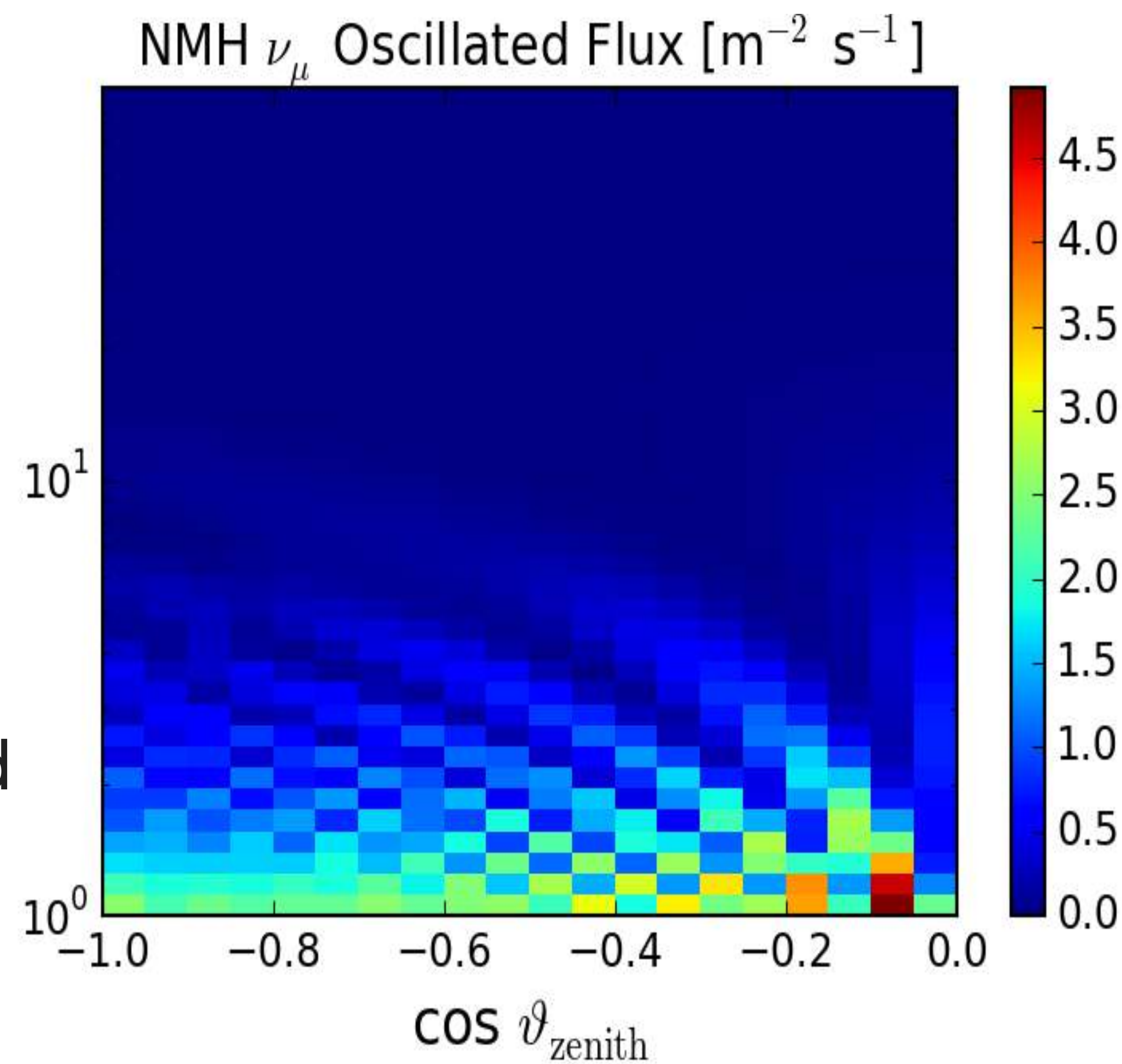


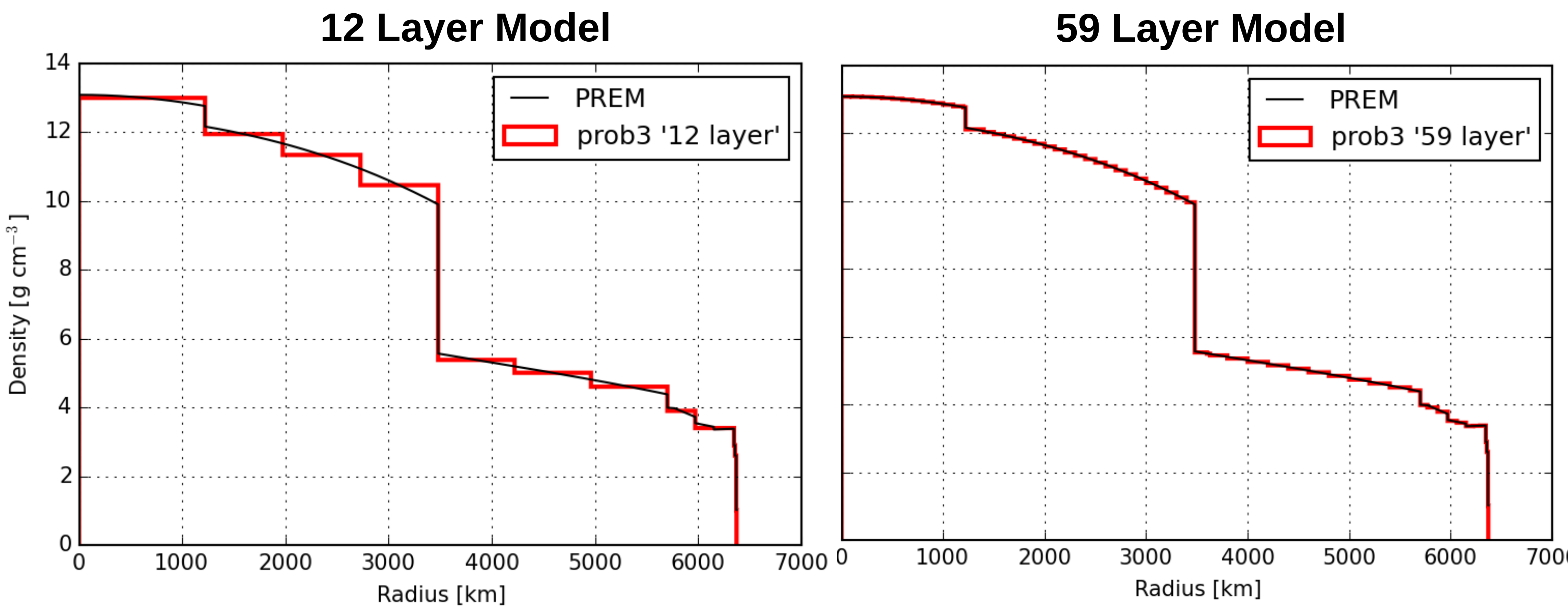
Flux X Oscillations = Oscillated Flux

Measuring Neutrino Properties

- Neutrino properties can be extracted from the precise shape of the wiggles
  - Difference between the masses of ν_1 and ν_2
  - How much overlap there is between the different types of neutrinos
- Use binned maximum-likelihood method to compare to data
  - Need to recalculate pattern repeatedly for different possible neutrino properties



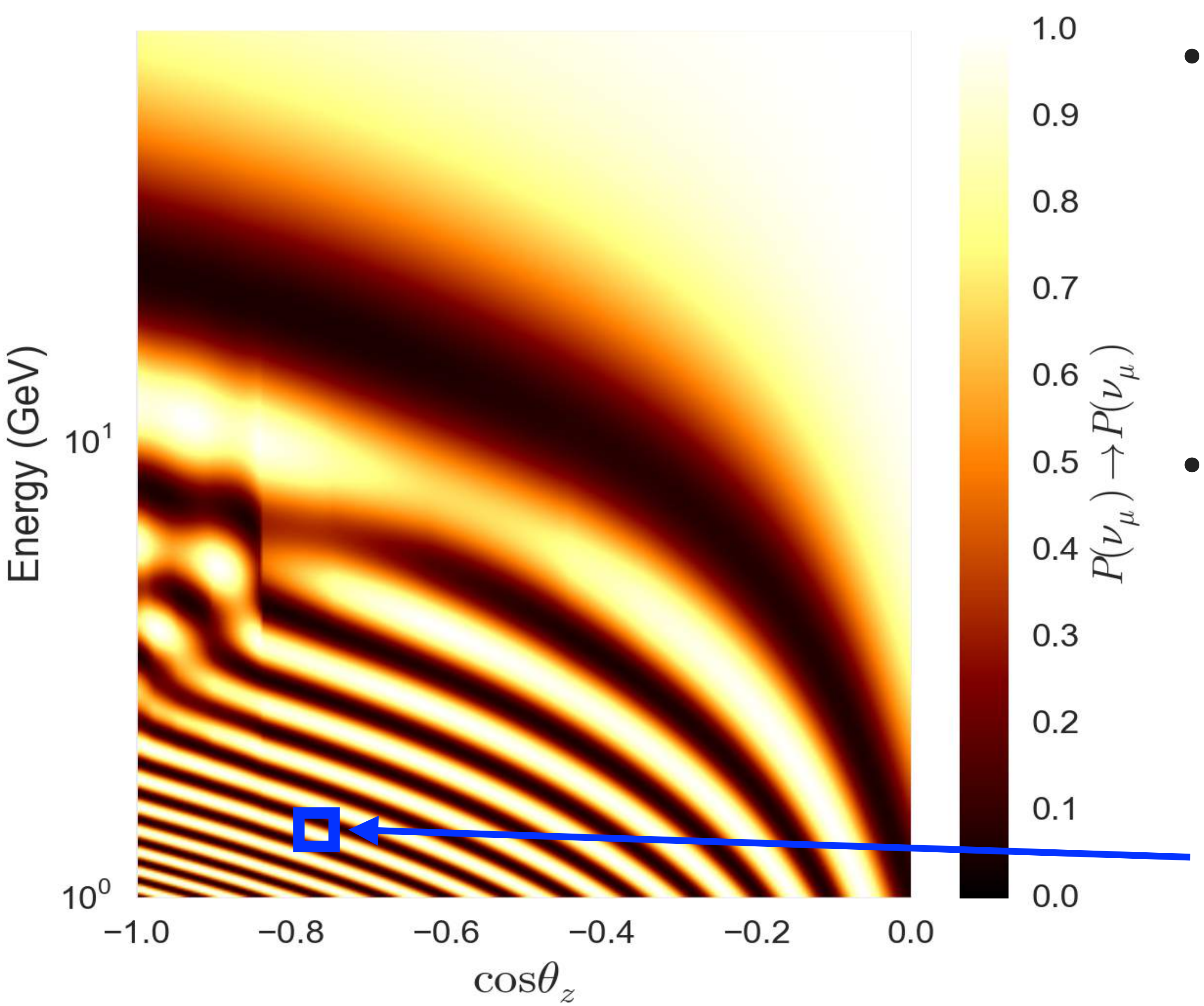
Matter Effects on Neutrino Oscillations



- Neutrino oscillations arise from solutions to Schrödinger's Equation
  - Quantum mechanical mixtures of mass eigenstates, propagating with different frequencies
- The electron density in matter affects the energy potential, and thus the frequency
  - Analytic solution exists for *constant* density, but the Earth's density isn't constant

High Resolution Oscillation Maps

- Rapid variation in oscillation probability means we can't simply calculate probabilities at centers of the 800 data bins



Analysis level bin size

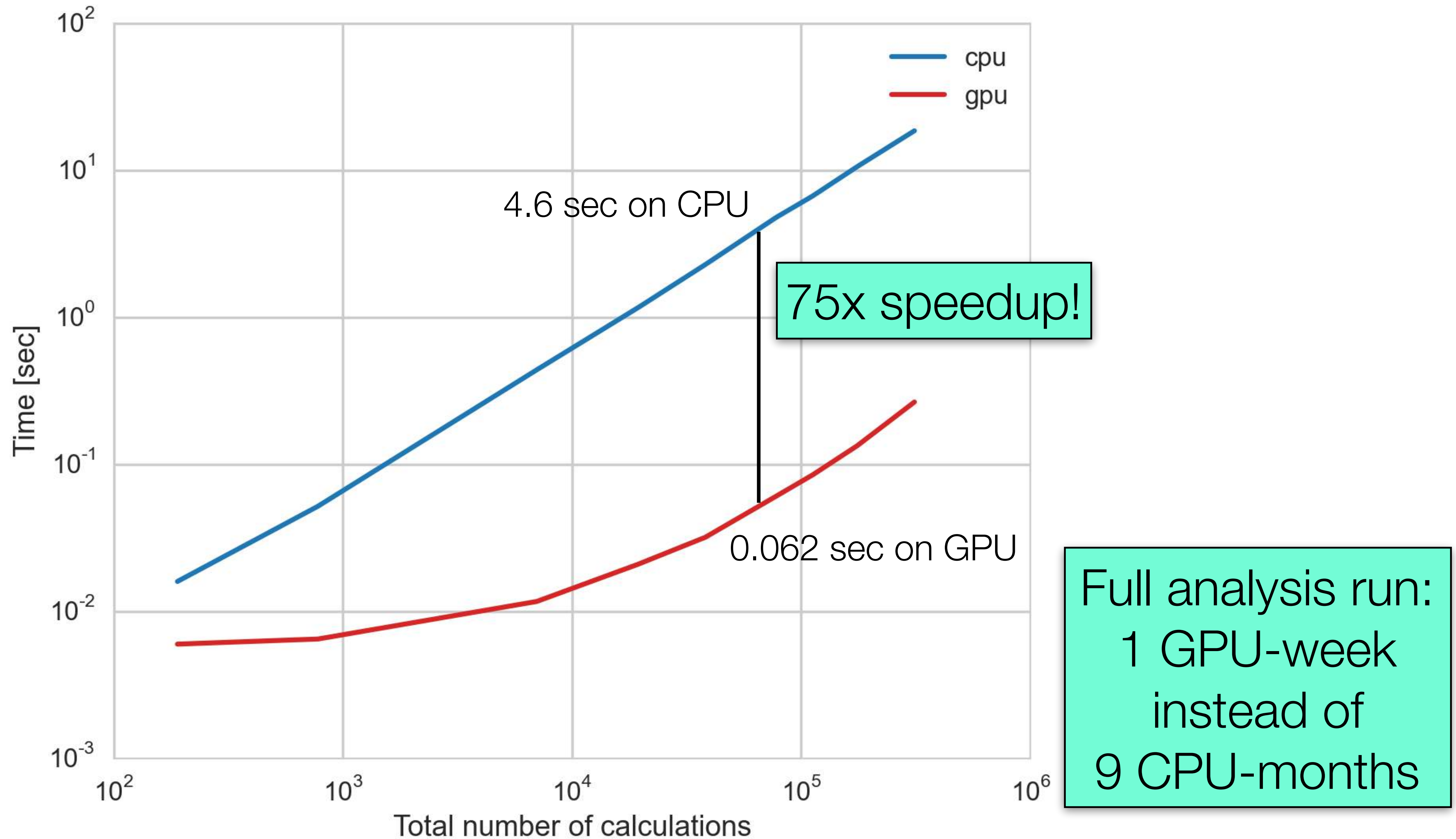
- Need to calculate average probability over the bin – subdivide real analysis bins finely enough for accuracy

- Typically use a 400 x 200 grid: 80k oscillation probabilities times up to 59 matter layers per iteration of the max-likelihood fit

Oscillation Tracking Code

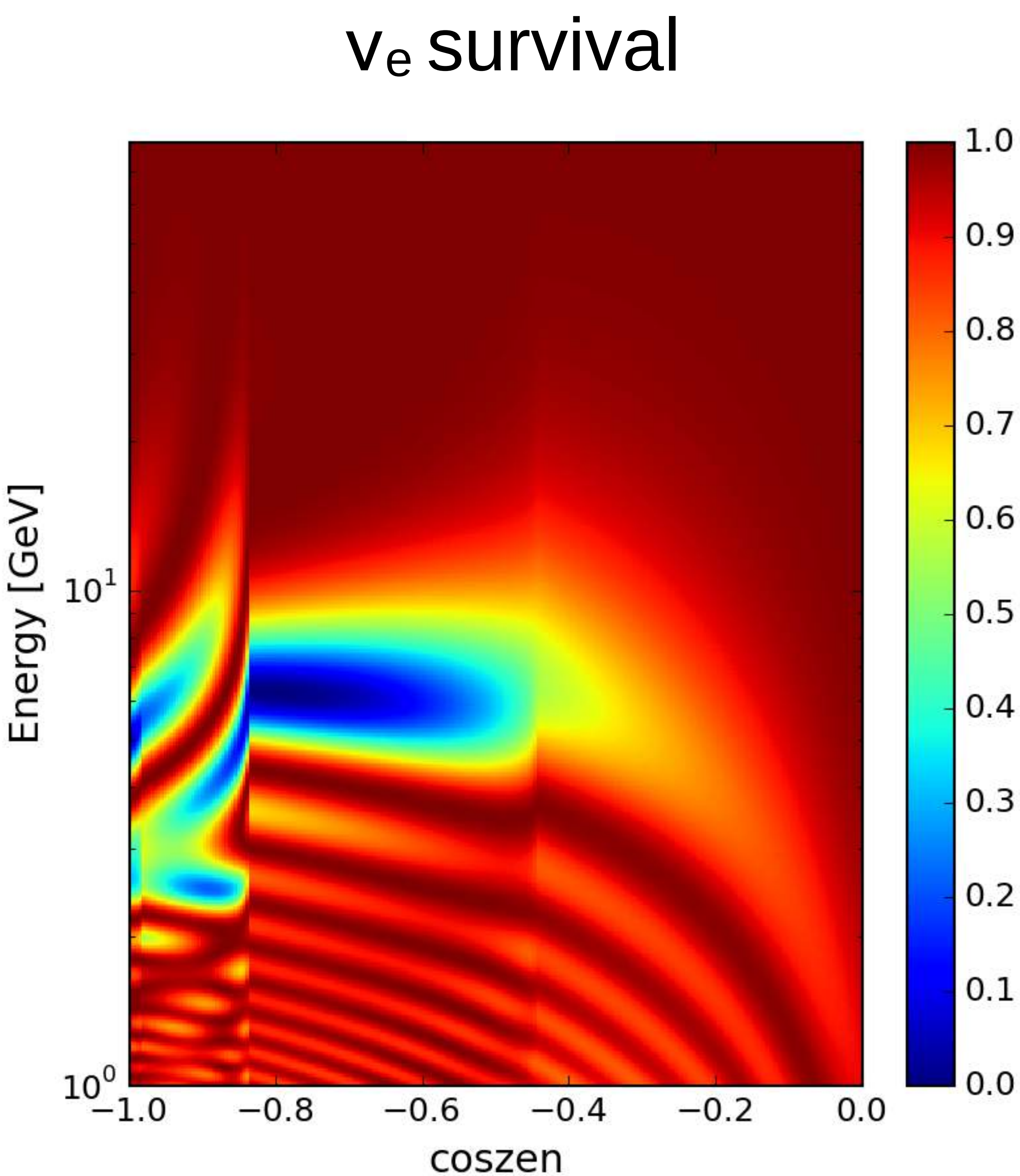
- Prob3 is a code for computing neutrino oscillation probabilities based on the work of Barger *et al*., *Phys. Rev*. D22, 2718 (1980).
    - Analytic solution for 3 ν flavors & layers of constant matter density
    - Publicly available: http://www.phy.duke.edu/~raw22/public/Prob3++/
    - Maintained by the T2K and SuperK collaborations
- Computes transition probability matrix for propagation through an arbitrary number of spherical shells of constant density
    - Good approximation for matter density of earth
- Implemented in C/C++ and optimized for speed on a CPU
    - Recently ported to CUDA by T. Arlen to run on iCER GPUs

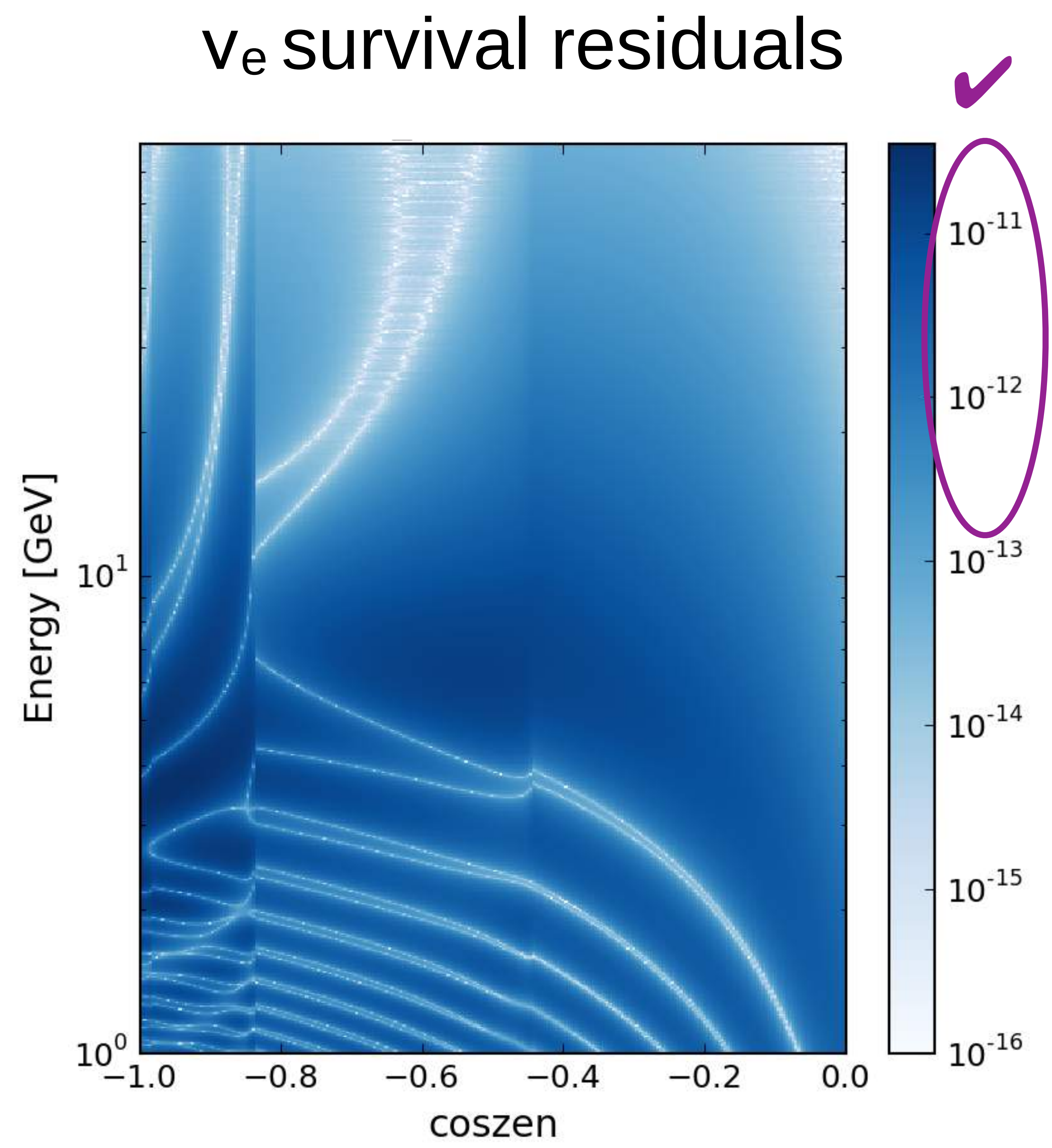
Speed Comparisons



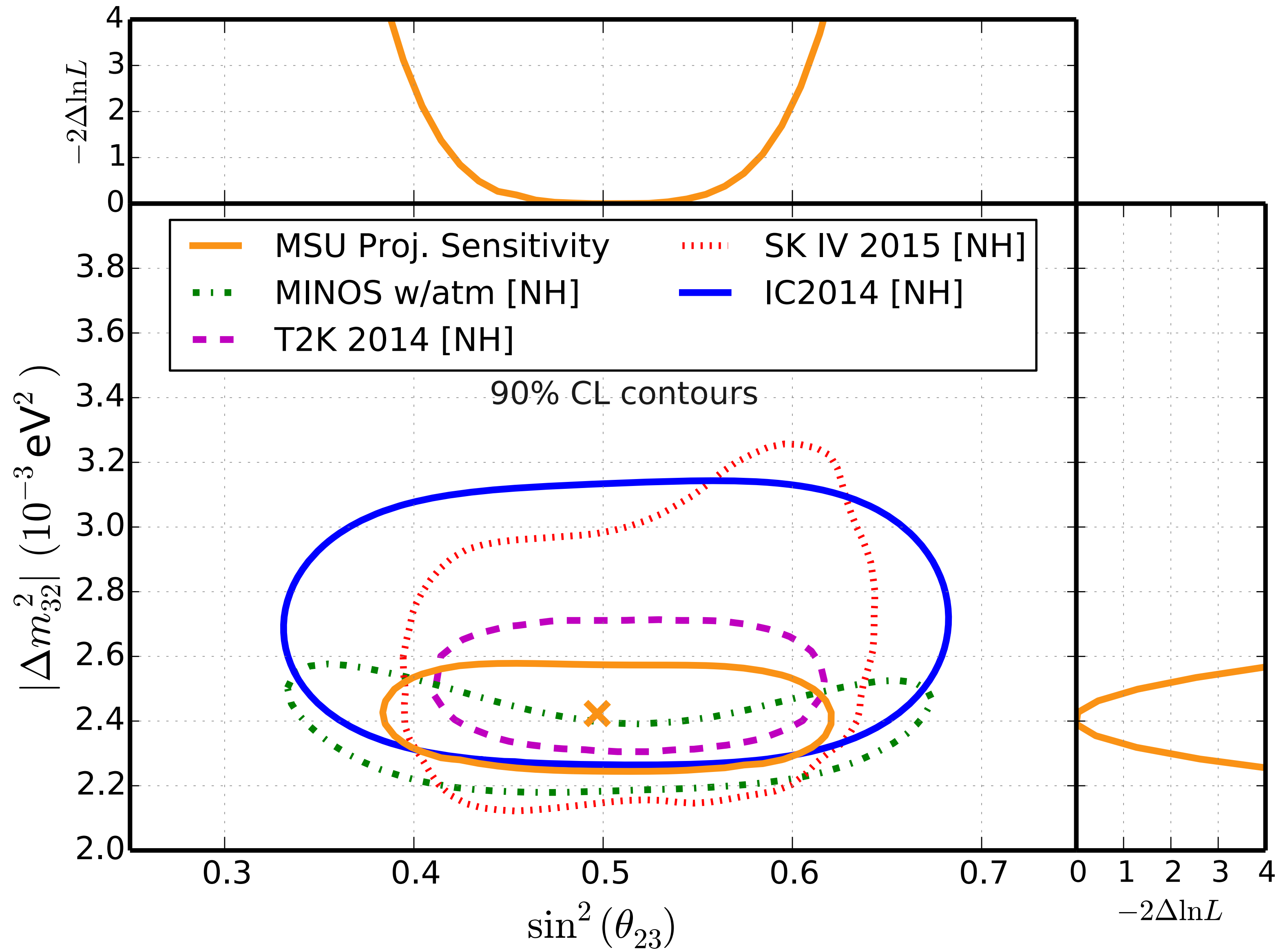
- NVIDIA K20 GPU vs. single CPU core (Intel Xeon 2.50 GHz)

Verifying Accuracy





Current and (Near-)Future Results



- IceCube is opening a new window on the Universe – as well as making some of the world's best measurements of neutrino properties!

MSU IceCubers:

Tyce DeYoung, Kendall Mahn (faculty)
J. P. de André, Joshua Hignight, Dirk Lennarz (postdocs)
Garrett Neer, Devyn Rysewyk (graduate students)
Dean Shooltz, Michael Nila (technical staff)
Neil Patel-Murray, Tawfik Abbas, Hannah Gallamore,
Ashley Richey (undergraduates)