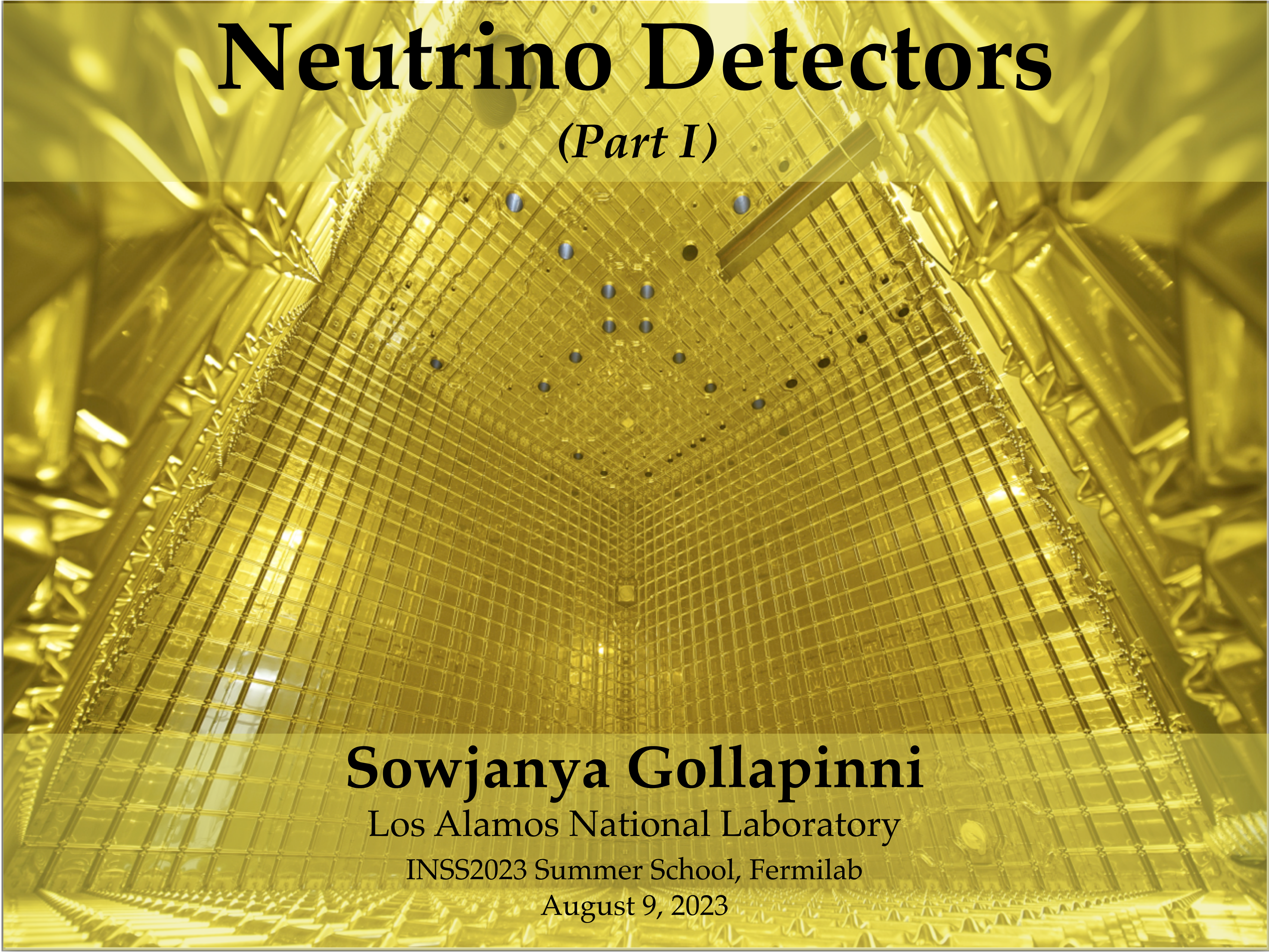


Neutrino Detectors

(Part I)

Sowjanya Gollapinni

Los Alamos National Laboratory

INSS2023 Summer School, Fermilab

August 9, 2023

About Myself

My first trip to Fermilab as a graduate student (2009)

- I am an Experimental Particle Physicist
- Ph.D. (Wayne State University)
  - CMS experiment at CERN, LHC
- Postdoc (Kansas State University)
  - *Switched to neutrinos as a postdoc — best decision of my life!*
  - *Spent most of my postdoctoral career on MicroBooNE*
- Faculty (University of Tennessee, Knoxville, 2016-19)
- Senior Scientist at Los Alamos National Lab since 2019
- Experimental collaborations
  - Short and long-baseline oscillation experiments (MicroBooNE, SBND, DUNE)
  - Neutron cross section experiments (ARTIE, MarEX)
- Involvement
  - *Oscillations, argon cross sections, detector physics & calibration analyses*
  - *Detector R&D, calibration & cryogenic instrumentation, slow controls*

Constructing MicroBooNE TPC

Neutrino Detector Lectures

We have two 1-hour lectures

- Lecture 1: Neutrino Detection Basics
- Lecture 2: Detector Technologies

Disclaimer:

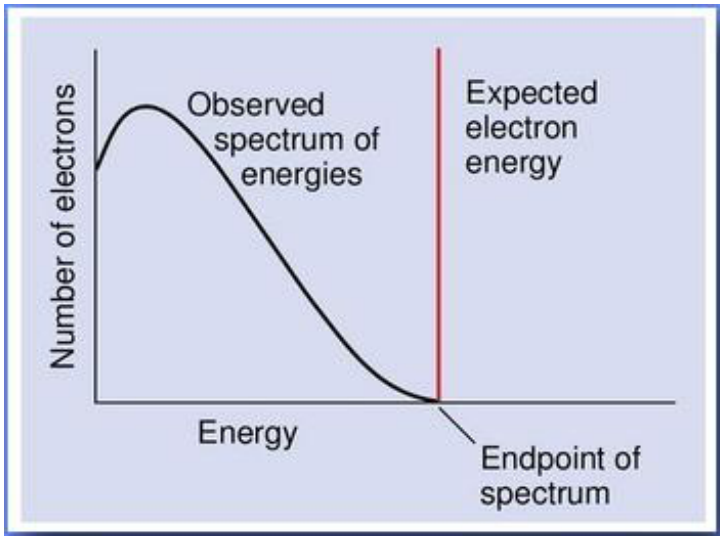
- There is no way I can cover everything…plus I have my own biases
- My goal with these lectures is to cover the general principles of neutrino detection, their interactions and experimental signatures along with an overview of technologies.
- Biggest challenge in preparing these lectures: *getting the CaPiTaLiZatioN right!*

Lecture 1: Outline

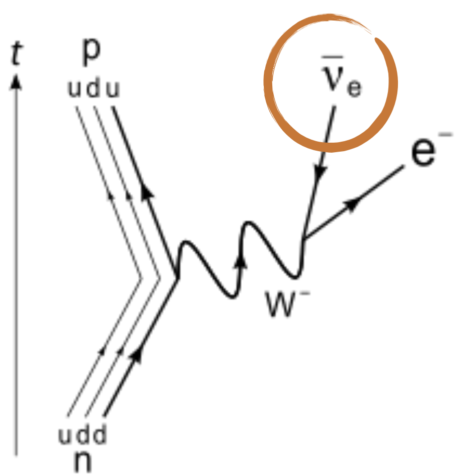
- Lecture 1 (Neutrino Detection Basics)
  - Brief Intro to Neutrinos
  - Neutrino Sources
  - Neutrino Detection Challenges
  - Neutrino Detector Goals
  - Neutrino Interactions
  - Passage of Particles in Matter

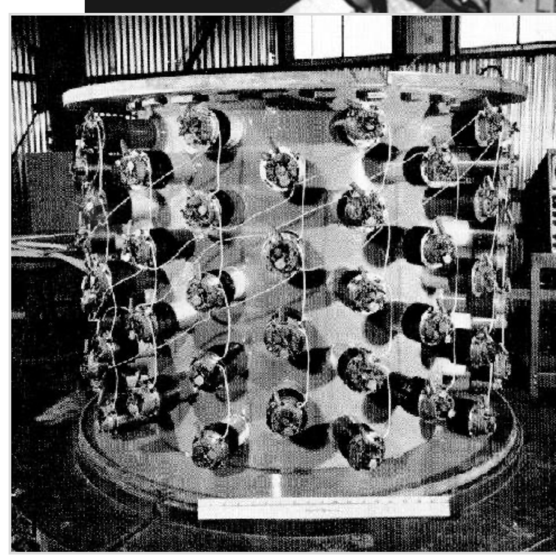
Project Poltergeist

A desperate remedy by Pauli to explain the observed energies in β decay (1931)



Nuclear β decay





1956: F. Reines and C. Cowen from LANL detected the first neutrino from a nuclear reactor

(Nobel Prize 1995)

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collect-

ed by the de... ence of neutr... sentially rule...

Dr. Yoji T... coalition and... mioka Neutri... the undergrou... 30 miles north... Alps, acknowle... announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

And Detecting Their Mass

By analyzin... physicists d... neutrinos ha... their journey... form, they m...

Source: Univers...

Neutrinos Oscillate and so they have mass!

(albeit very tiny)

June 5, 1998

Until as recently as 1998, neutrinos were considered to be *massless*

We have detected oscillations from

- Atmospheric
- Solar
- Accelerator
- Reactor

There is still a lot we don't know

SM = Standard Model

Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac? **Are neutrinos their own anti-particles?**
- Precision Measurement of neutrino mixing parameters?
- Which neutrino is the lightest?
- CP violation in the neutrino sector? **Matter-antimatter puzzle**

Beyond SM 3-flavor mixing

- Absolute mass of neutrinos? Are there more than 3 neutrinos? **Candidates for dark matter?**
- Other New physics e.g. non-standard interactions

We have been studying neutrinos for about a century now and there is still a lot we don't know. The story of neutrinos is far from being complete

There is still a lot we don't know

Direct Mass Measurement Experiments

Neutrinoless Double Beta Decay Expts.

Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac?
- Precision Measurement of mixing parameters?
- Neutrino mass ordering?
- Is θ_{23} maximal mixing?
- CP violation in the neutrino sector?

Long-Baseline Neutrino Oscillation Experiments

Beyond SM 3-flavor mixing

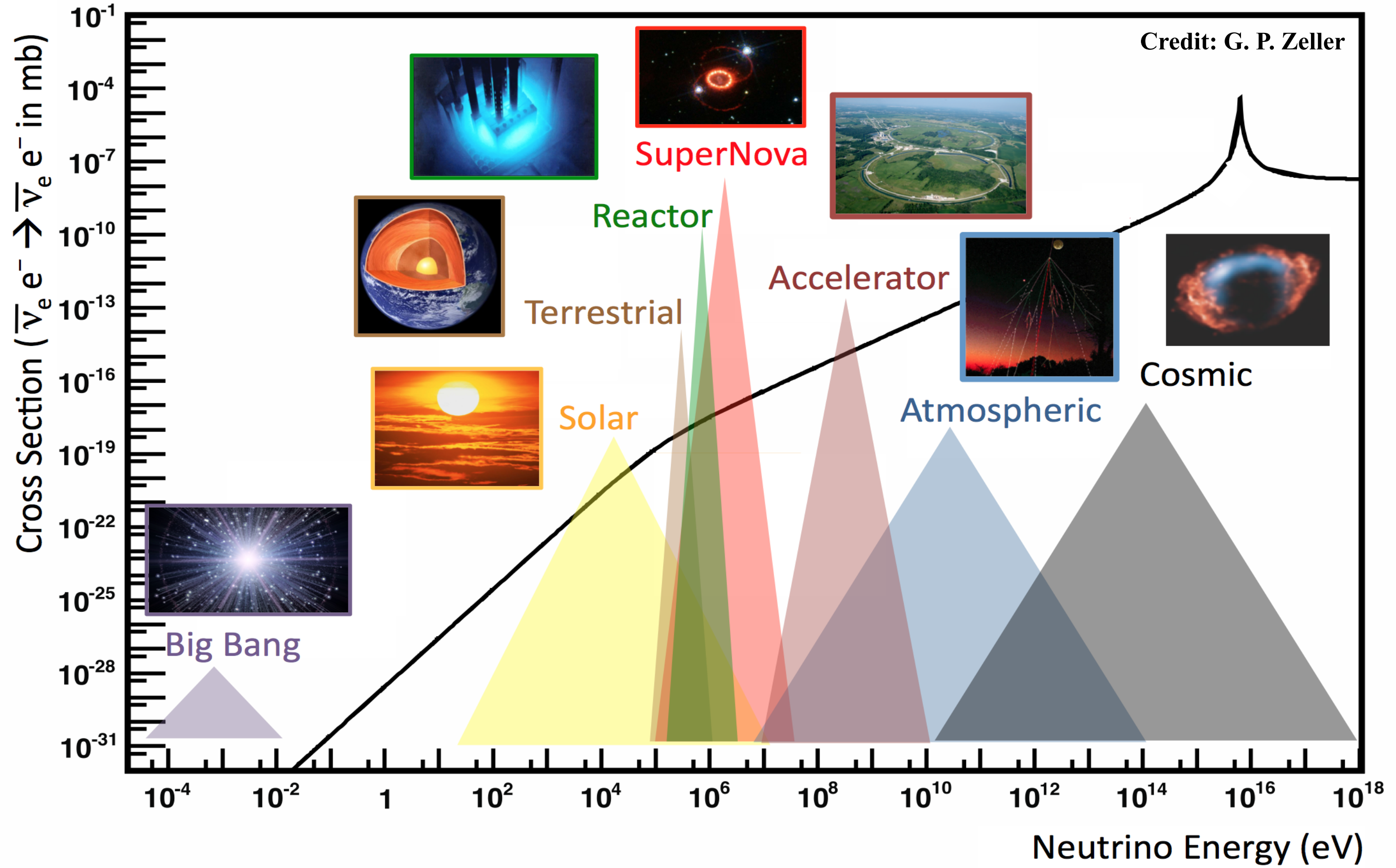
- Absolute mass of neutrinos? Are there more than 3 neutrinos?
- Other BSM physics e.g. non-standard interactions

Short-Baseline Neutrino Experiments

Short- and Long-Baseline Experiments

Neutrino Physics is a very active field and will be for the next few decades!

Neutrino Sources

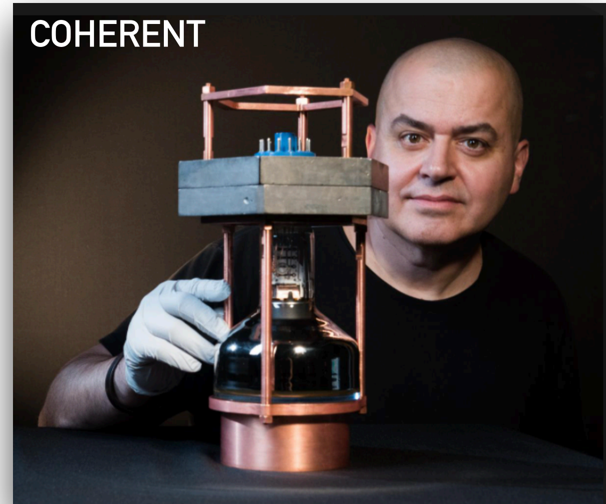


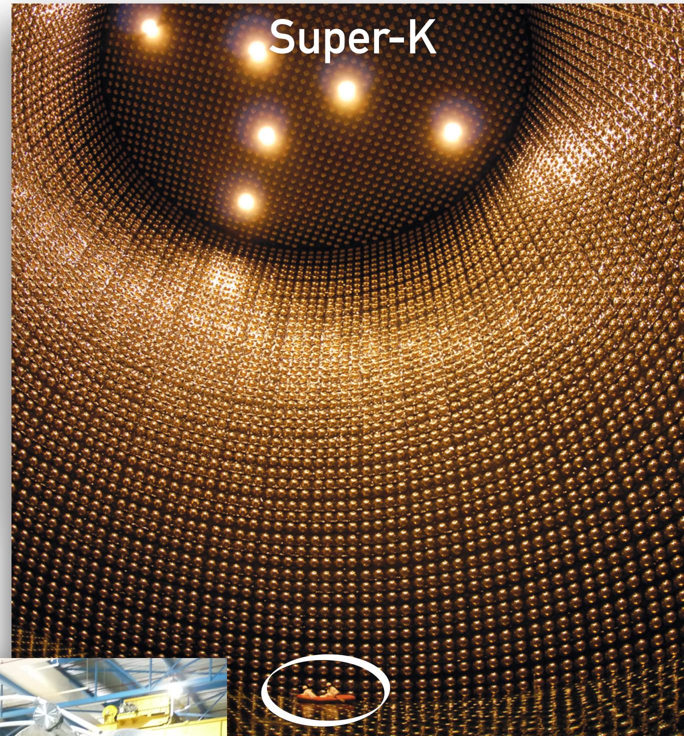
Neutrinos span multiple frontiers!

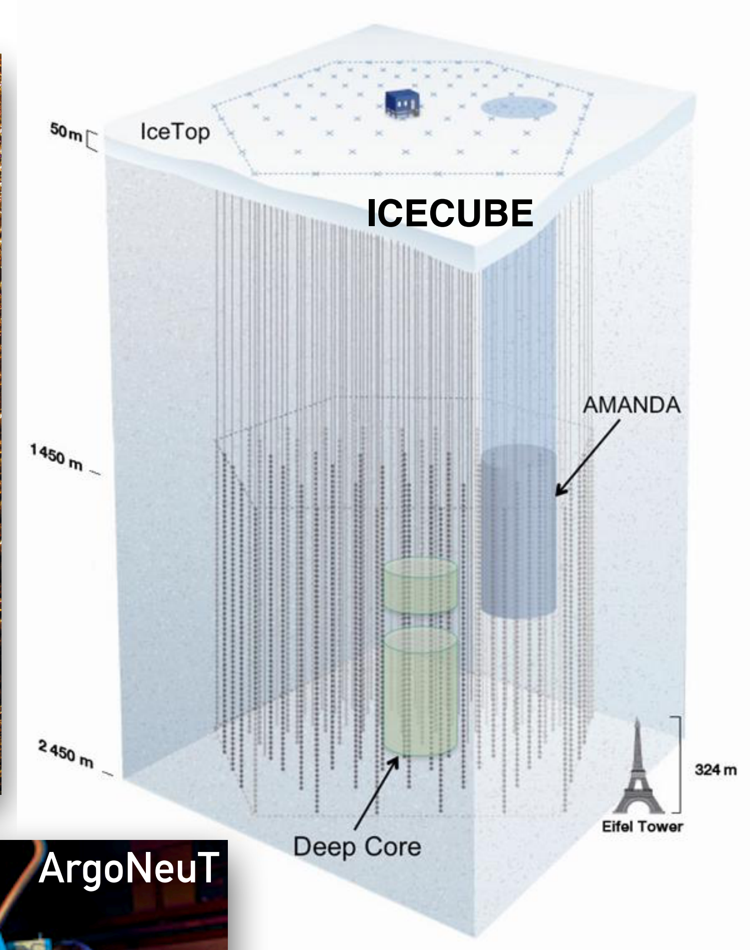
- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

- Overwhelming number of sources, wide range of energies
- Need wide spectrum of experiments and technologies!

Neutrino Detectors at All Scales

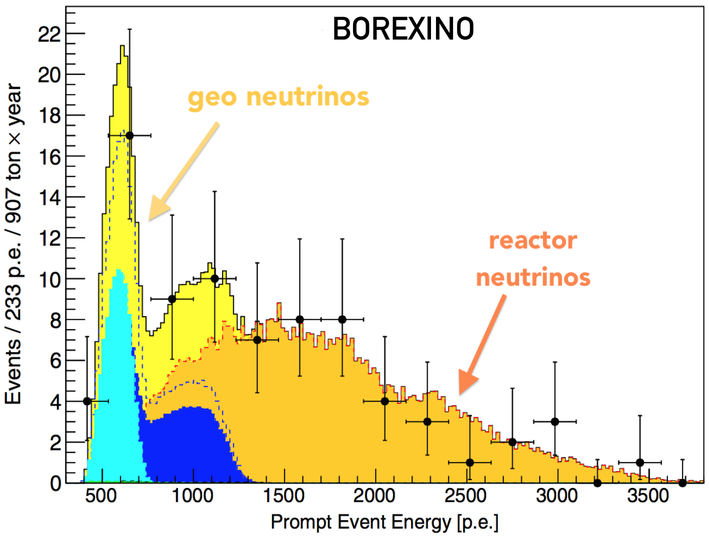




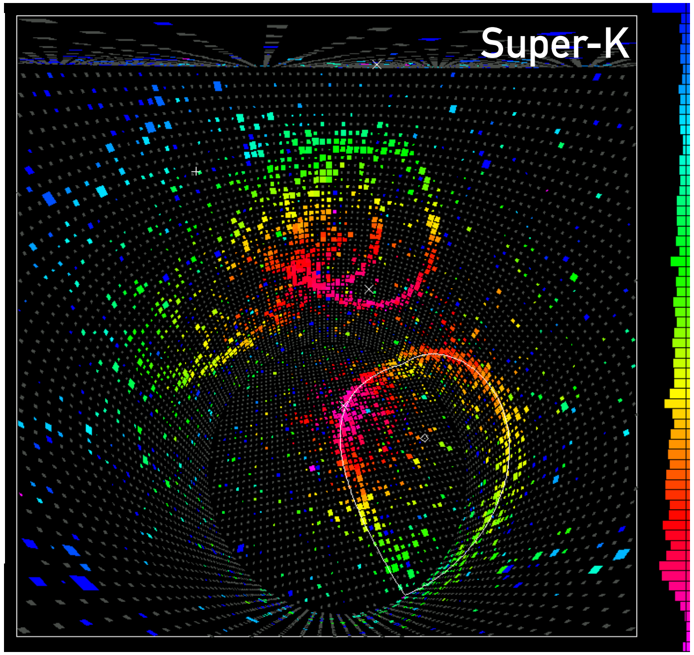


Technologies advances at every turn have enabled and continue to enable neutrino discoveries

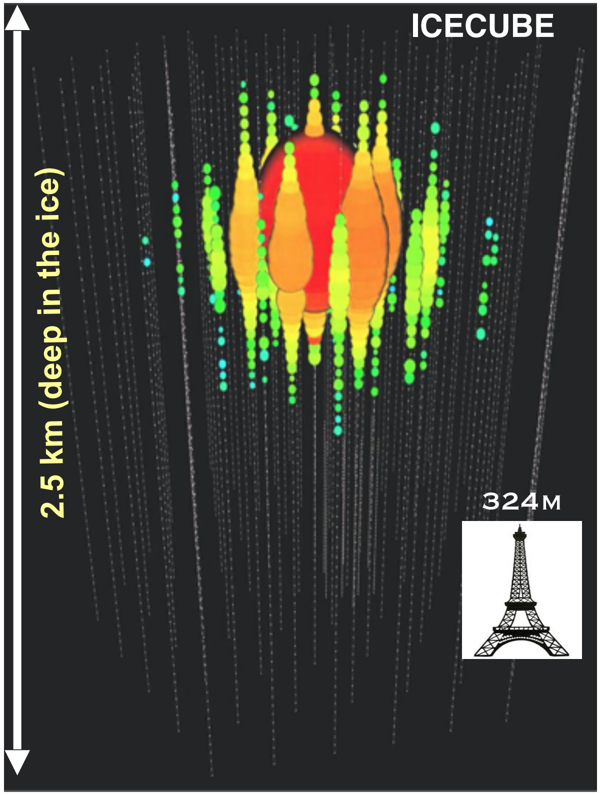
Visualizing Neutrinos



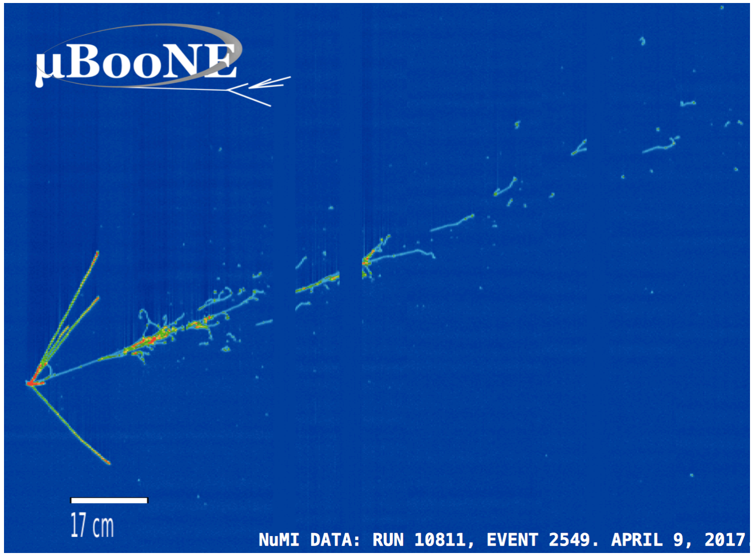
MeV-scale neutrino



A few-100 MeV neutrino



A 2 PeV scale astro physical event in the detector



MeV → PeV
We have observed neutrinos at wide range of energies

Detecting Neutrinos is Challenging

- They are invisible (no charge)
- They are *extremely weakly* interacting

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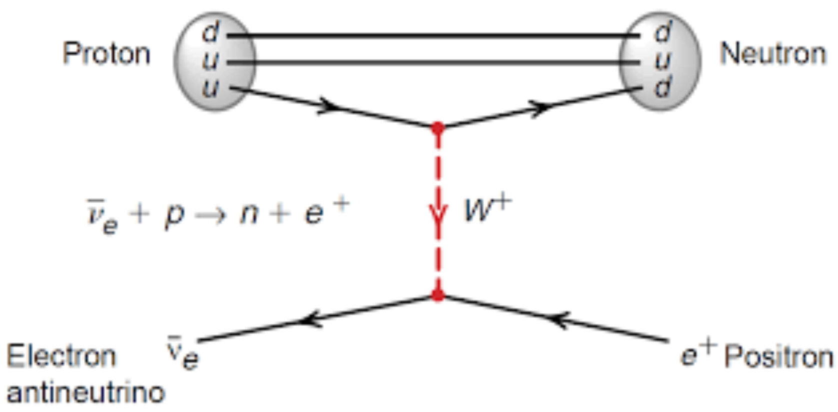
- In other words, they have very small interaction cross sections
- MeV-scale neutrino (typical energy of a neutrino emitted from sun or a nuclear reactor) has a cross section, $\sigma \sim 10^{-44}$ cm^2 — tiny!

Inverse Beta Decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



$$\sigma_{\bar{\nu}p} \approx 5 \times 10^{-44}\, cm^2 \quad for \quad (E_{\bar{\nu}} \sim 2\ MeV)$$

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- GeV-scale neutrino (typical energy of a neutrino from a particle accelerator) has a cross section, $\sigma \sim 10^{-40}$ cm² — still tiny!
- Mean free path of a neutrino in lead
  - MeV-scale neutrino: ***$d_{lead} \sim 10^{16}$ m*** (over a light year of lead!)
  - GeV-scale neutrino: ***$d_{lead} \sim 10^{12}$ m*** (still almost a trillion miles of lead!)
- What about a GeV-scale proton? $\sigma \sim 10^{-25}$ cm²
  - GeV-scale proton: ***$d_{lead} \sim 10$ cm!***

atomic mass unit

$$d_{lead} = \frac{1.66 \times 10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}$$

ν-N cross-section

density of lead

Detecting Neutrinos 101

- *Basic Strategy*
  - Produce them in large quantities in a well defined area
  - Put something very **Dense**, very **BIG** and very **Sensitive** for neutrinos to interact

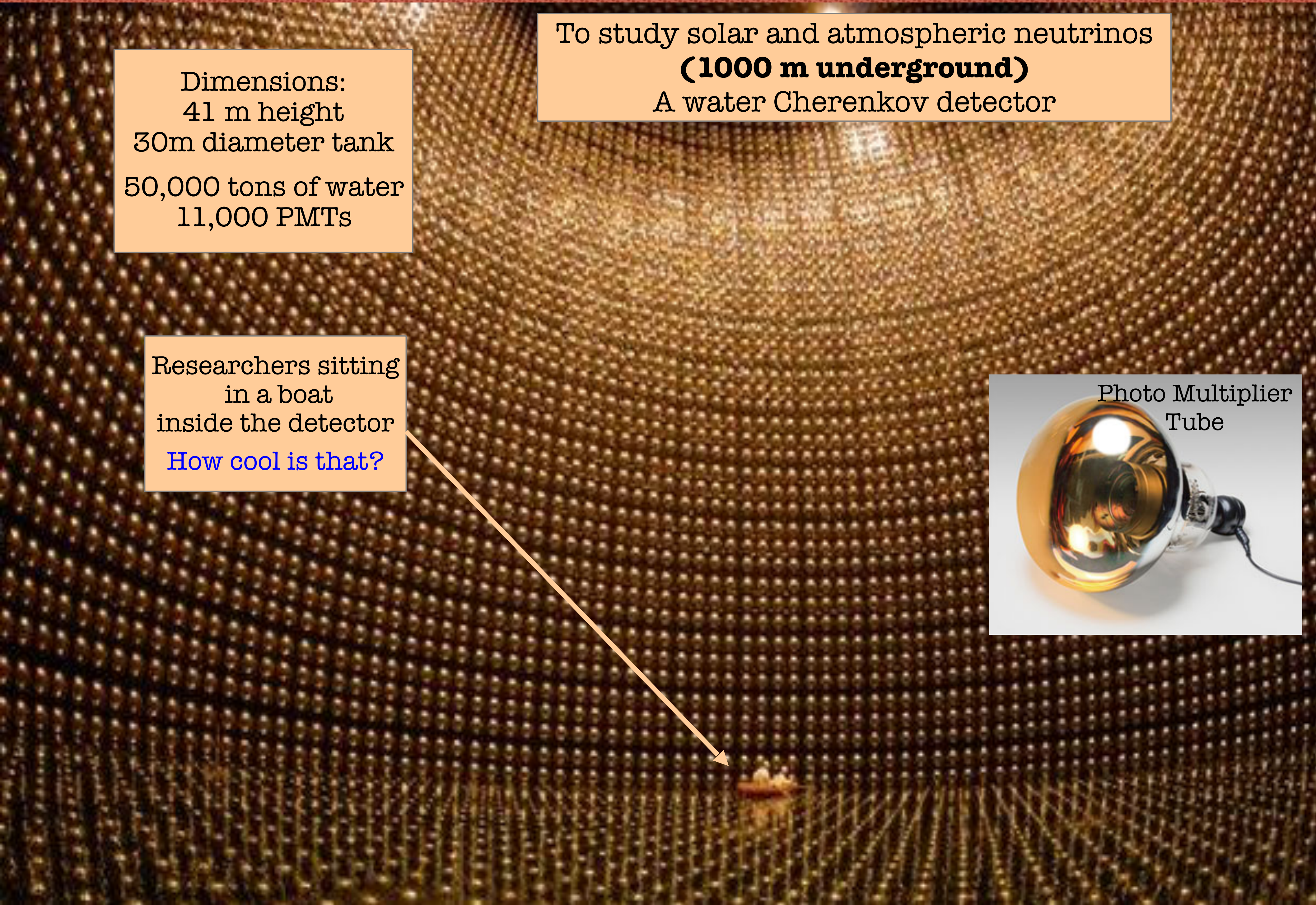
- *In other words*
  - High intense beams (typically kW beams, now moving to MW)
  - Large neutrino fluxes
  - Long exposure time
  - Dense targets (e.g. Argon)
  - Large target mass (tens of meters, hundreds to multi-kiloton-scale)
  - Low background (place them underground; design for maximum signal sensitivity; efficient background tagging etc.)

The Super Kamiokande Experiment (Japan)

To study solar and atmospheric neutrinos
(1000 m underground)
A water Cherenkov detector

Dimensions:
41 m height
30m diameter tank

50,000 tons of water
11,000 PMTs



Researchers sitting in a boat inside the detector

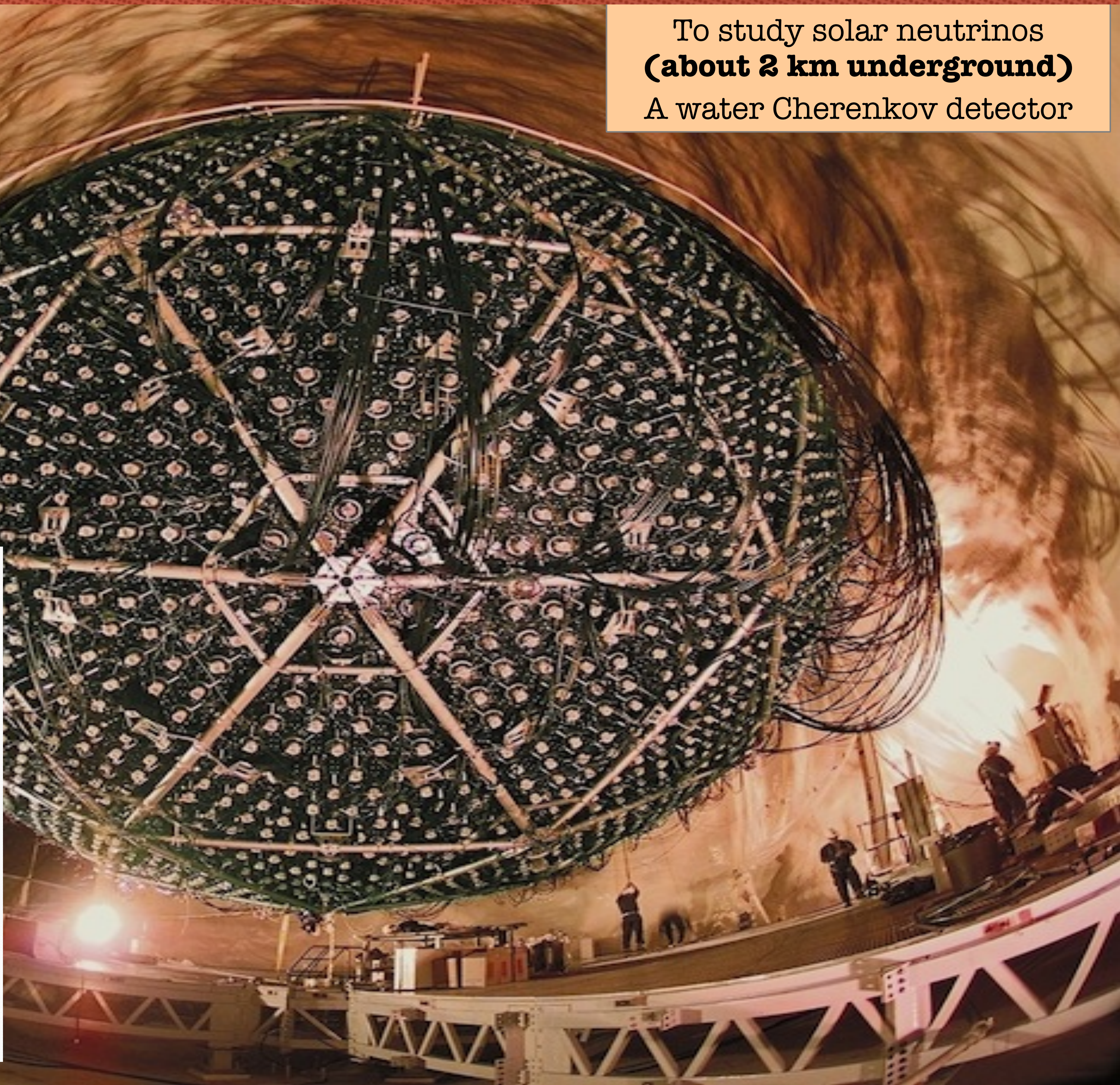
How cool is that?

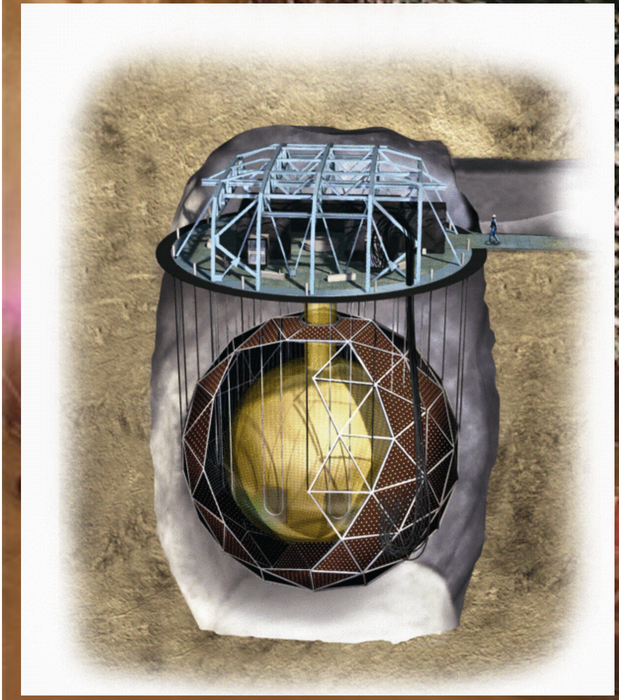
The Sudbury Neutrino Observatory (Canada)

Dimensions:
12m diameter tank

1000 tons of heavy water
9000 PMTs

To study solar neutrinos
(about 2 km underground)
A water Cherenkov detector



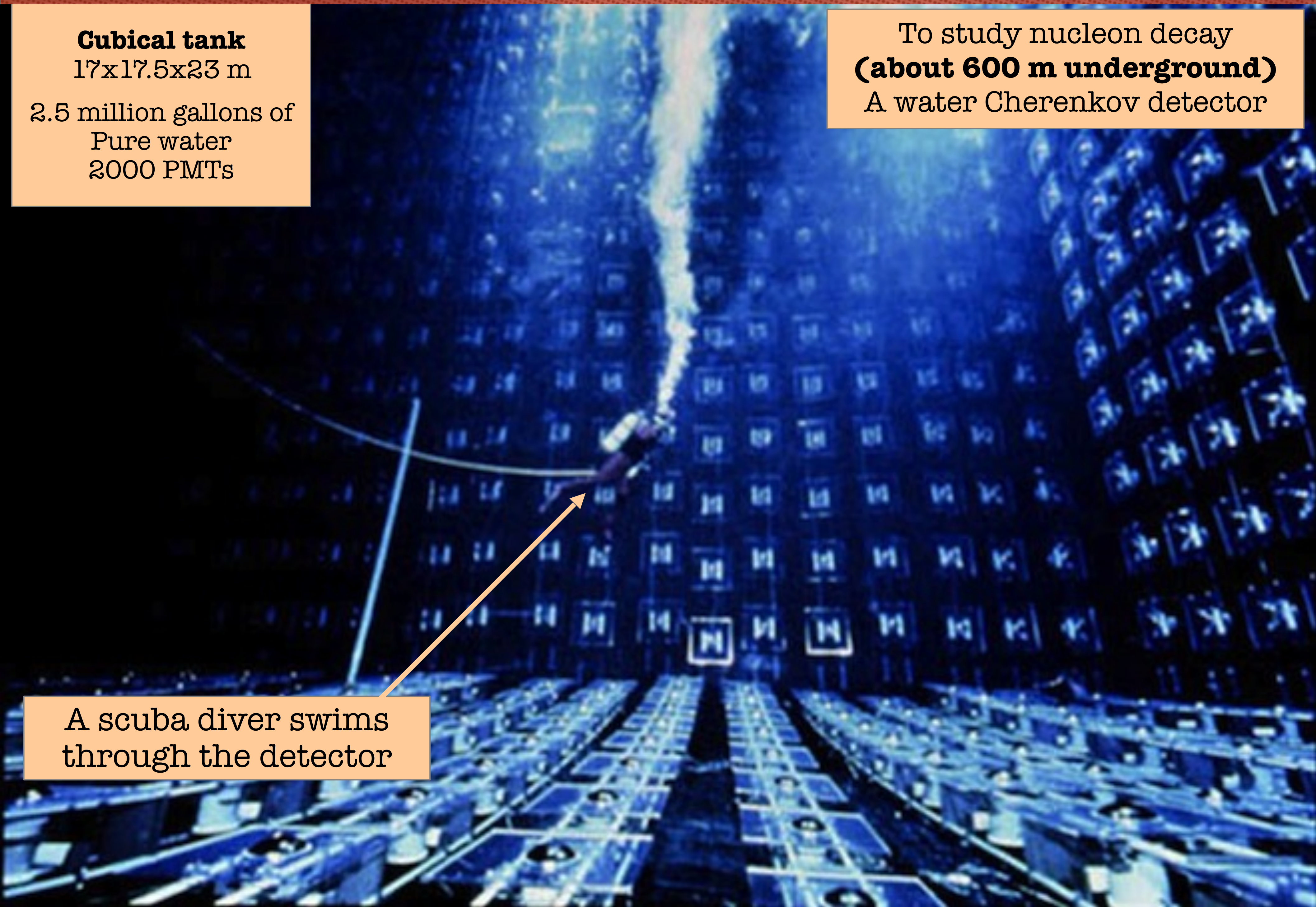


The Irvine-Michigan-Brookhaven Detector

Cubical tank
17x17.5x23 m

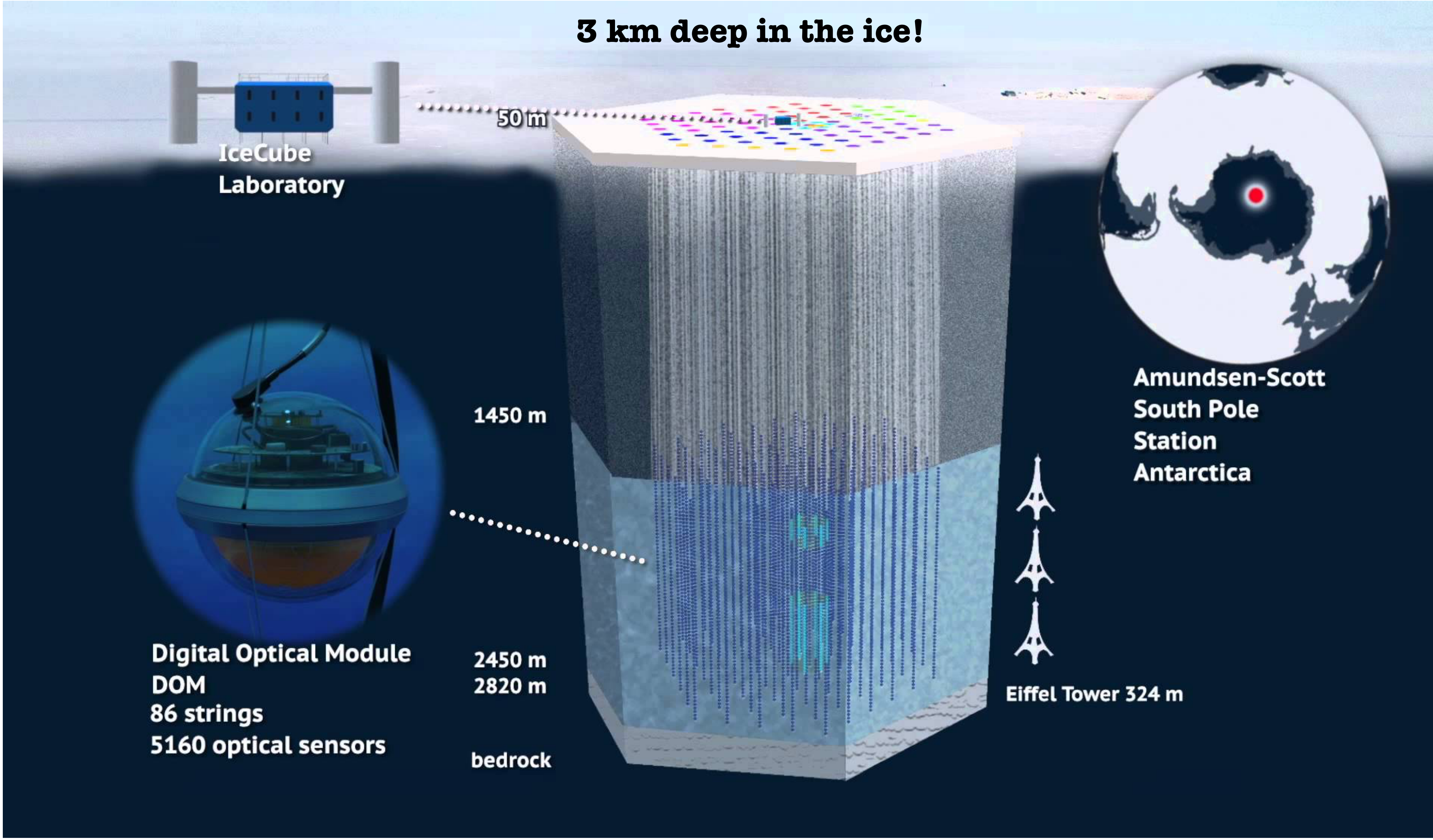
2.5 million gallons of
Pure water
2000 PMTs

To study nucleon decay
(about 600 m underground)
A water Cherenkov detector



A scuba diver swims
through the detector

The IceCUBE Experiment (South Pole)



searches for neutrinos from the most violent astrophysical sources: exploding stars, gamma-ray bursts, black holes and neutron stars.

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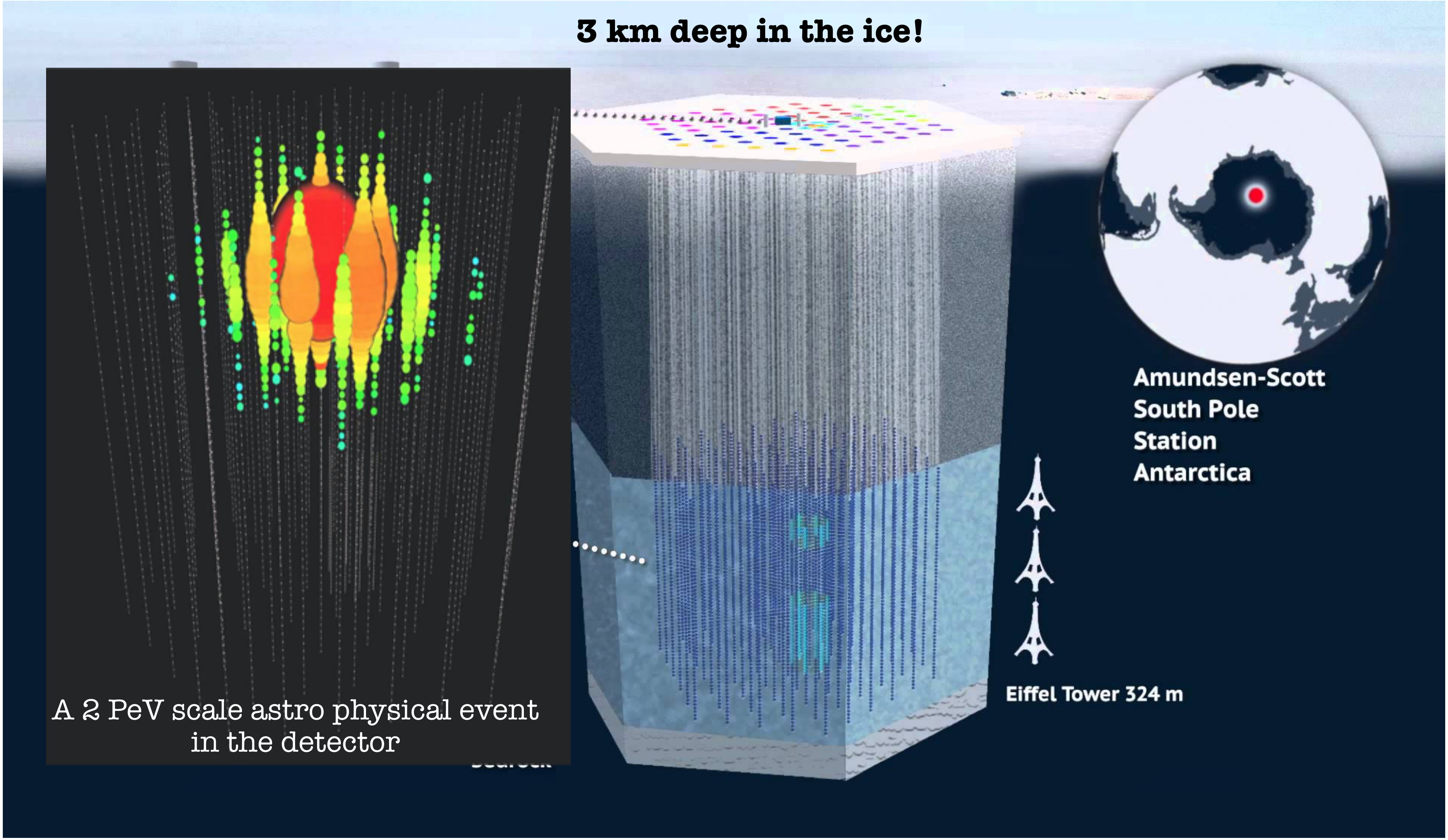

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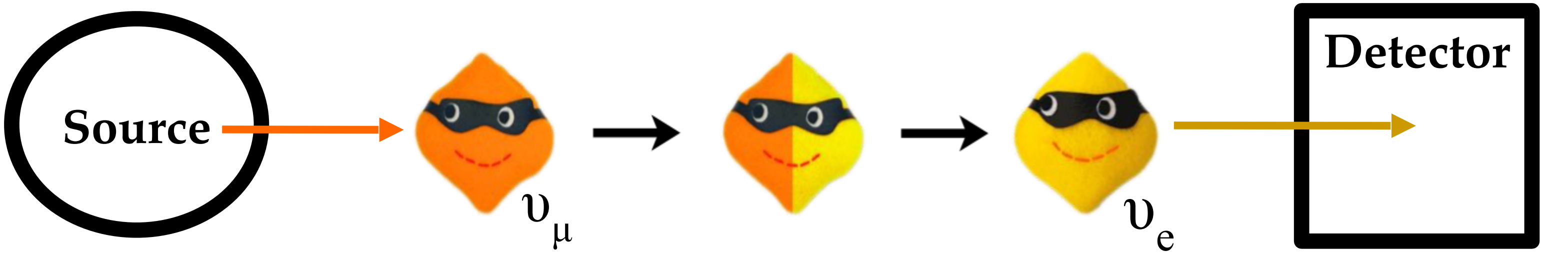
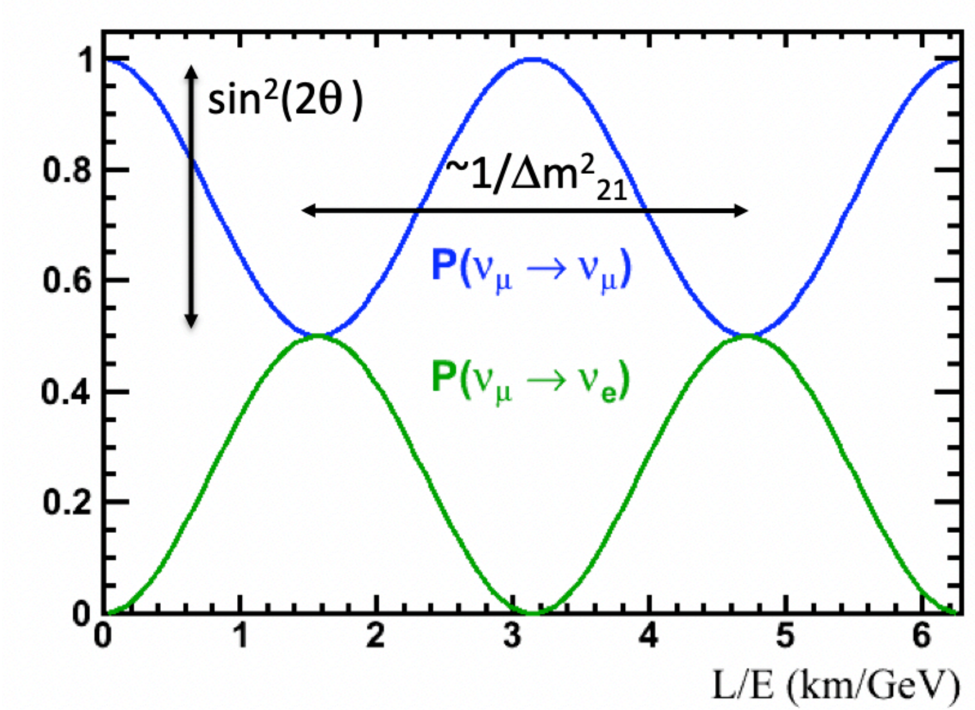
2-Flavor Oscillations



Oscillation Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

$$\Delta m^2_{21} = m^2_2 - m^2_1$$



Experimental parameters: **L, E**

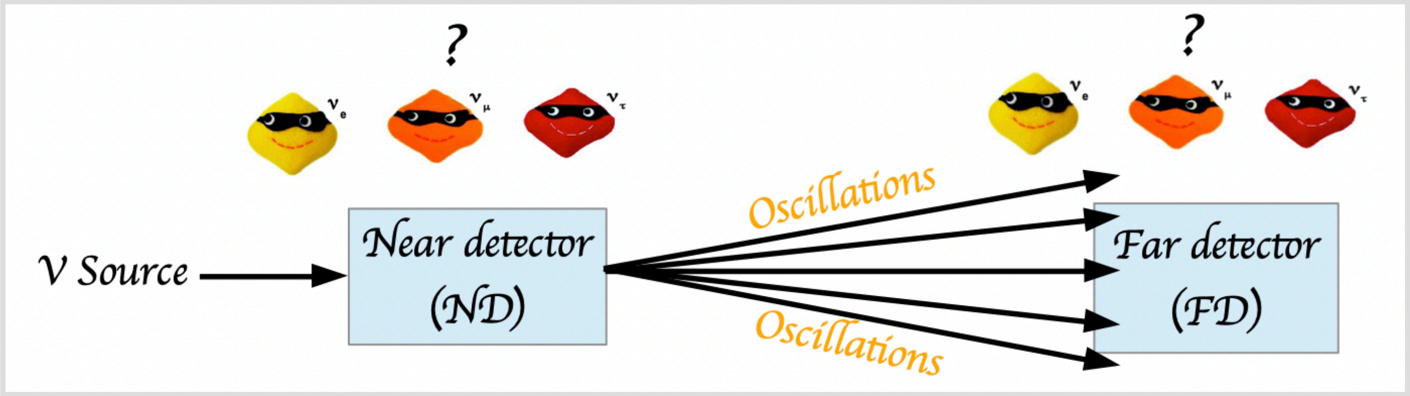
Parameter of nature: **Δm², Sin²2θ**

Long-baseline: L ~ 1000 km

Short-baseline: L ~ 1 km

A Typical Oscillation Experiment

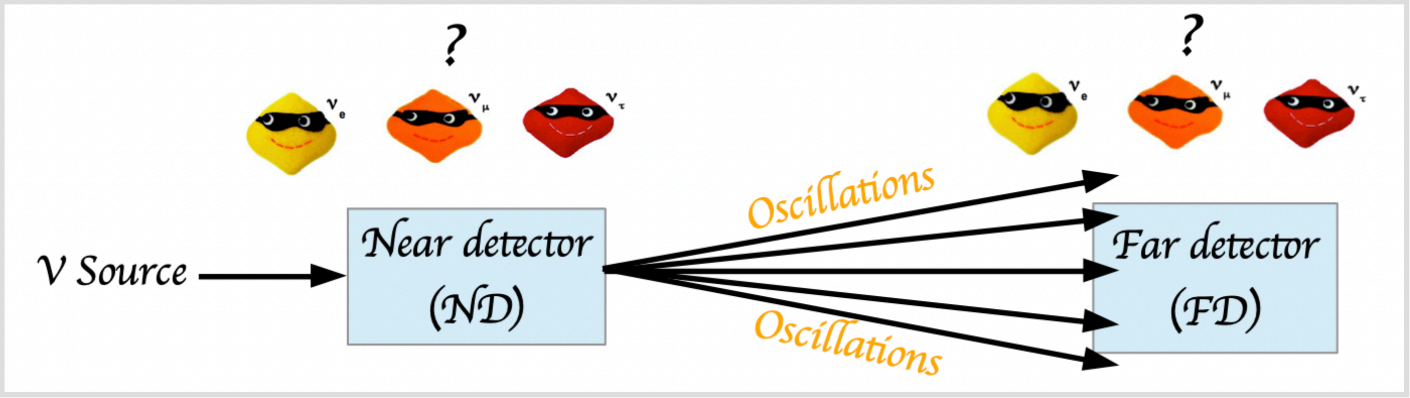
A Typical Oscillation Experiment *Oscillation experiments are basically counting experiments*



- Start with an intense source of neutrinos (e.g. υ_{μ})
- Build a near detector and a far detector with distance optimized for oscillations to occur
- Measure unoscillated flavor and energy spectrum at L~0 (near detector)
- Measure oscillated flavor and energy spectrum again at L~oscillation maximum (far detector)
- Compare

A Typical Oscillation Experiment

A Typical Oscillation Experiment *Oscillation experiments are basically counting experiments*



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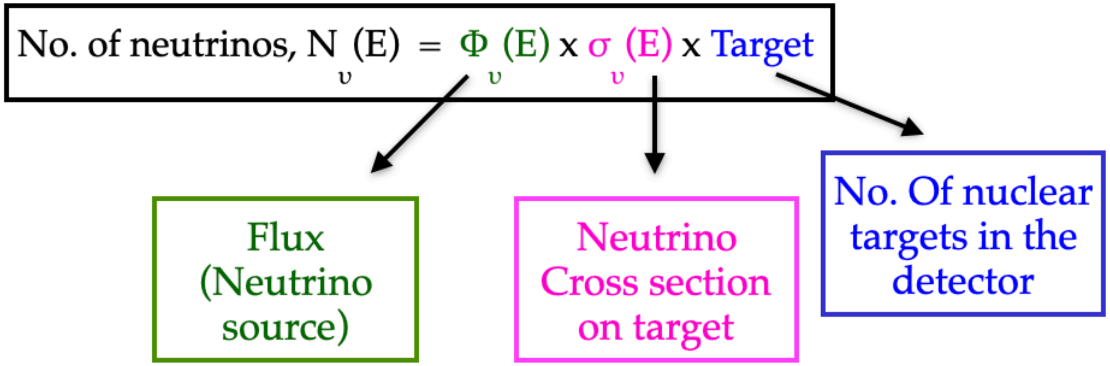
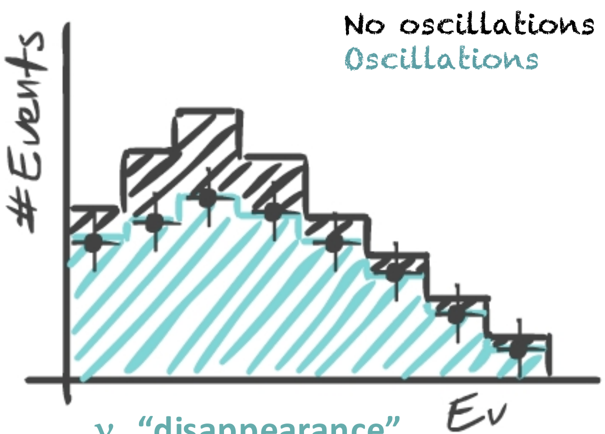


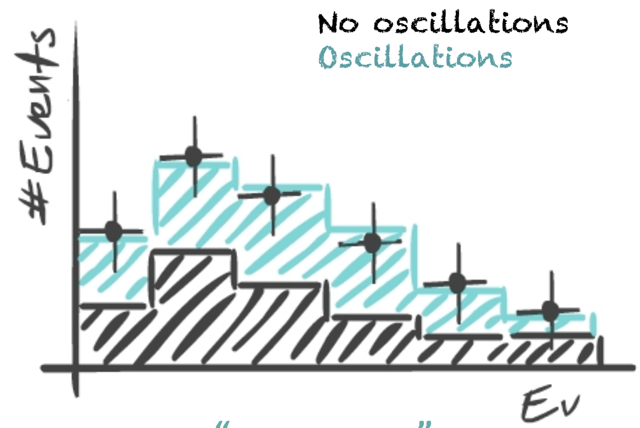
A Typical Oscillation Experiment

Image credit: G. Karagiorgi



ν_α "disappearance"

(look for <u>deficit</u> of ν_α events)



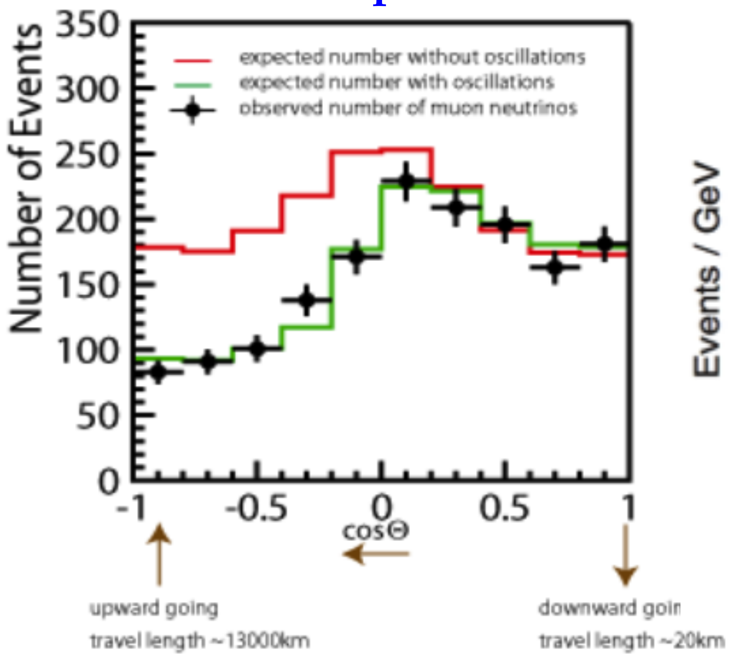
ν_β "appearance"

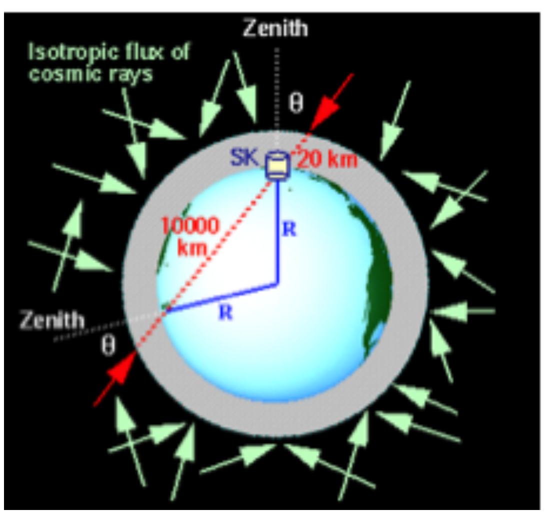
(look for <u>excess</u> of ν_β events)

Can perform **"Appearance"** or **"Disappearance"** measurements

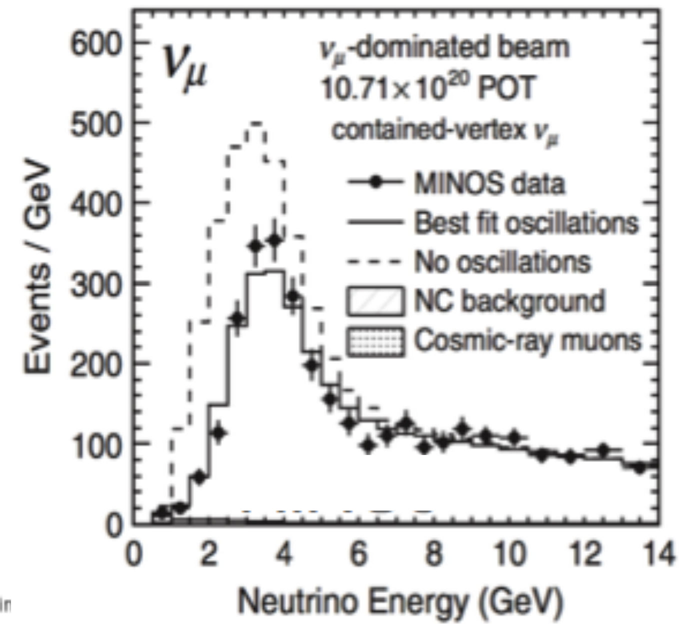
Oscillation Experiments

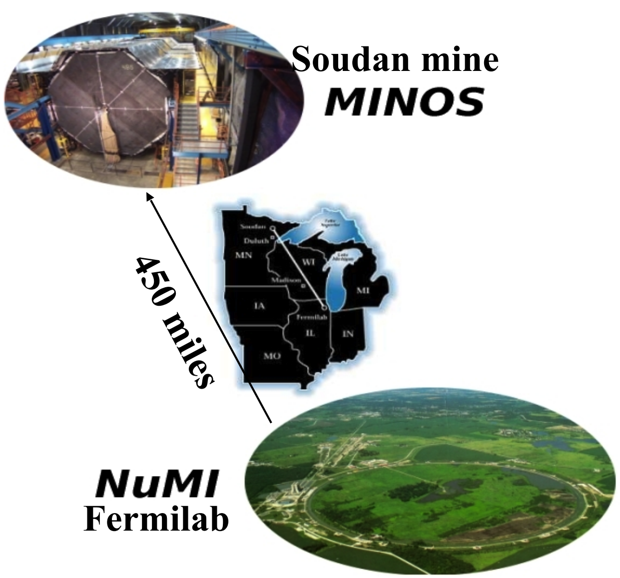
SUPER-K
Atmospheric



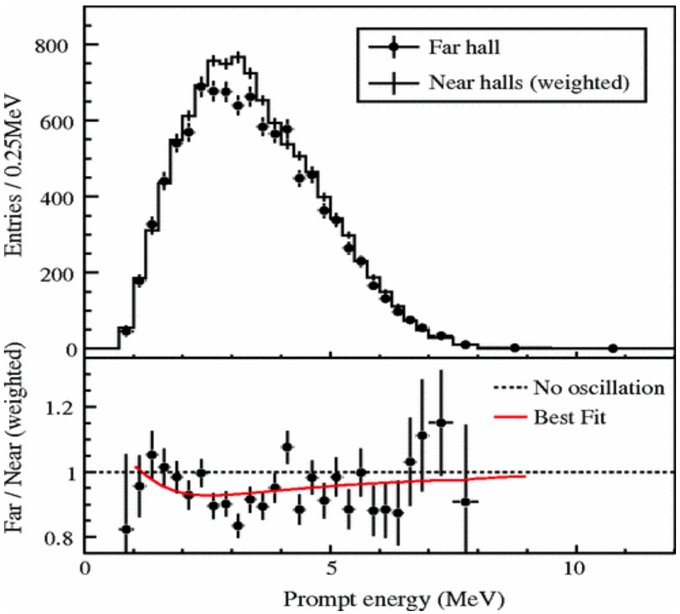


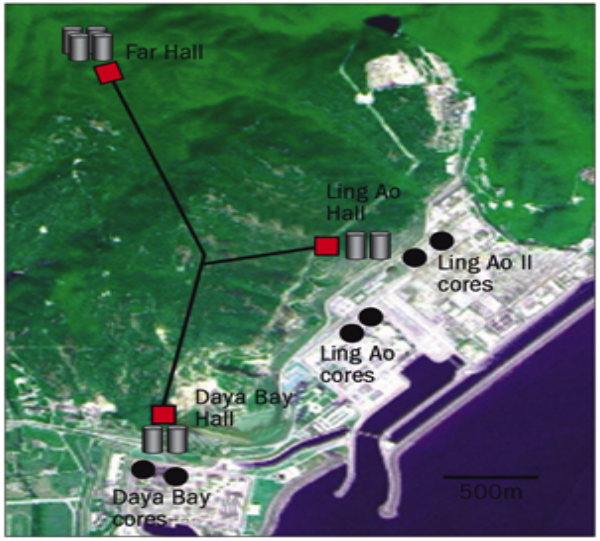
MINOS
Accelerator





DAYABAY
Reactor source

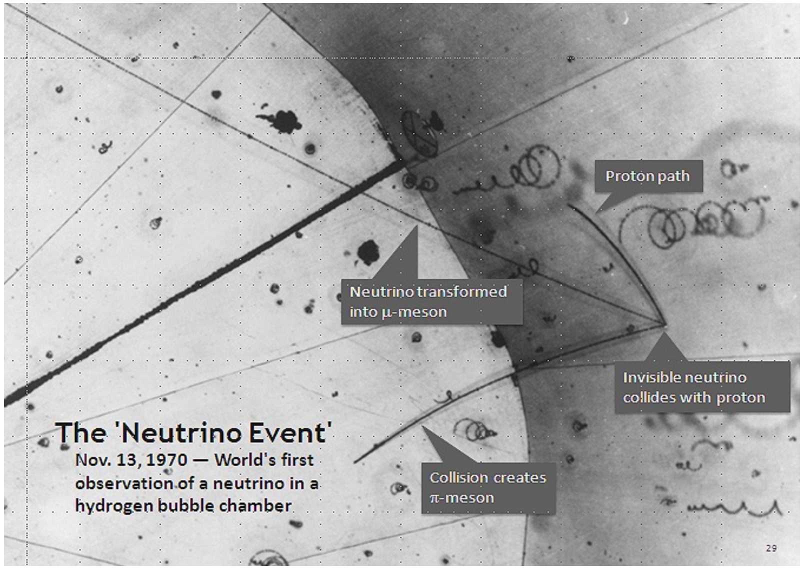




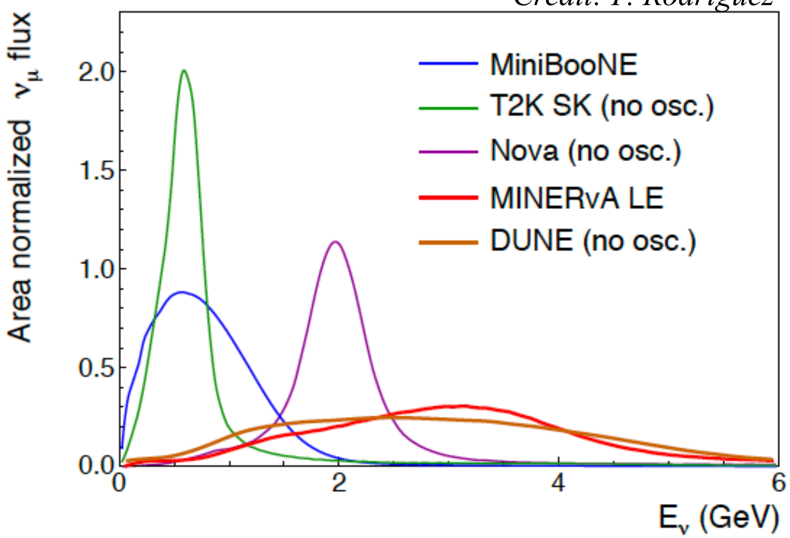
Neutrino Detection Goals

This depends on the experiment but typically

- **Identify the flavor of the neutrino**
  - Only indirect detection *via* particles produced in neutrino interactions
  - Need to know the reaction channel
    - Charged Current vs Neutral Current
    - Various interaction modes within each reaction channel
- **Measure the E_υ as accurately as possible**
  - Not easy since neutrino sources are not always monochromatic
- **Neutrino or Anti-neutrino?**
  - differentiate this e.g. oscillation experiments aiming to measure Charge-Parity Violation
  - Charged Current interactions can provide handles



Credit: P. Rodriguez

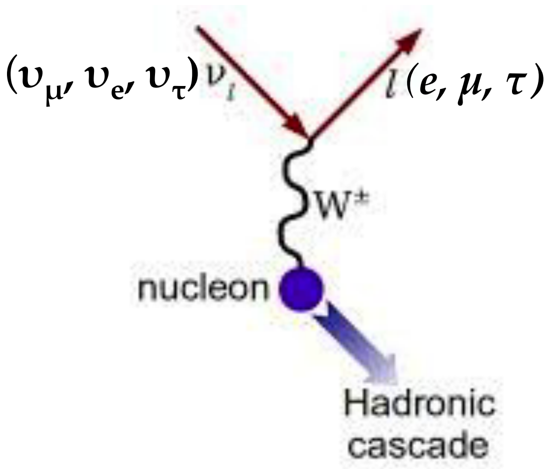


Neutrino Flavor Tagging

Charged Current (CC)

($W^{+/-}$ exchange)

Neutrino-nucleon scattering



- Outgoing lepton determines the υ flavor
- Outgoing hadrons: protons, neutrons, pions
- Typically, your signal event

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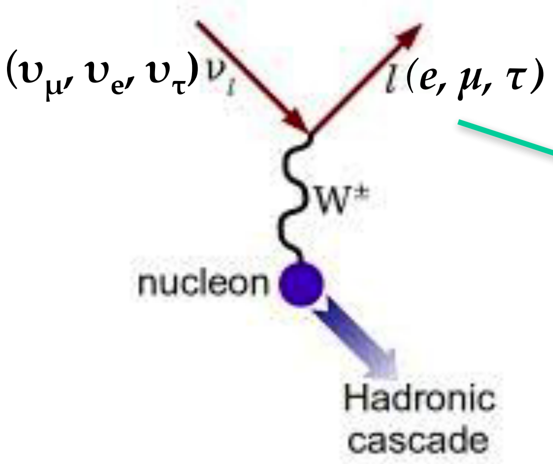

- Production of a lepton requires minimum energy. Thresholds
  - E_υ ~ 500 keV (for an electron)
  - E_υ ~120 MeV (for a muon)
  - E_υ ~3.5 GeV (for a tau)

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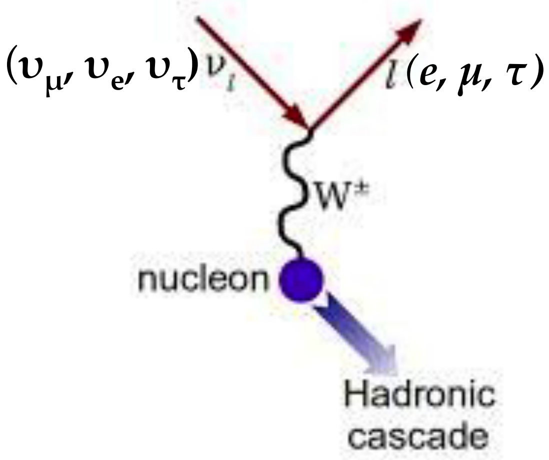
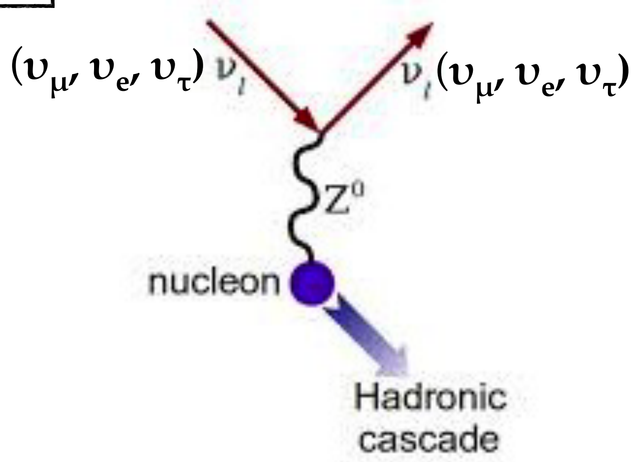
Neutrino Flavor Tagging

Charged Current (CC)
($W^{+/-}$ exchange)

Neutrino-nucleon scattering

Neutral Current (NC)
(Z exchange)





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  - E_υ ~ 500 keV (for an electron)
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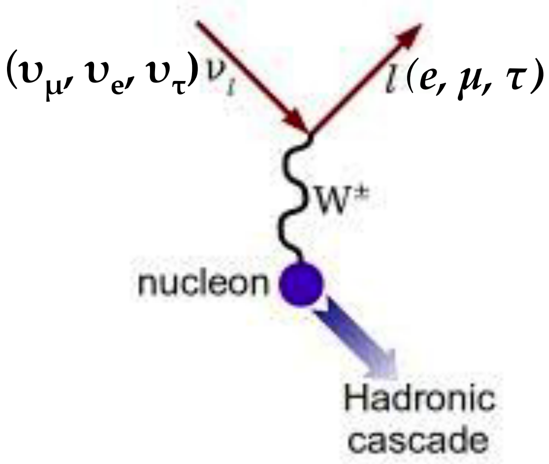
- No outgoing lepton to tag the υ type
- Can only see hadrons in the final state
- Typically, your background event (e.g. in "appearance oscillation" measurements)

Neutrino Flavor Tagging

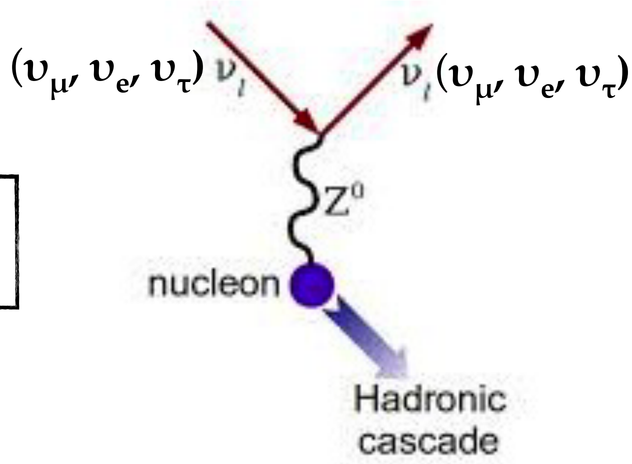
Charged Current (CC)

($W^{+/-}$ exchange)

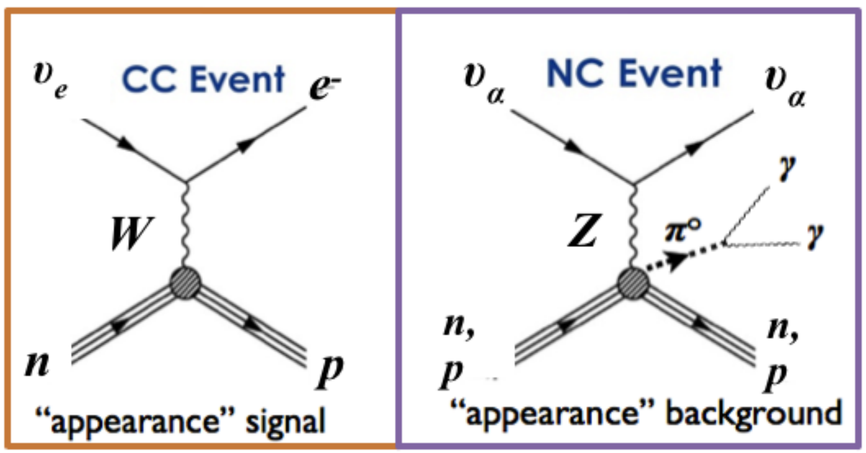


Neutral Current (NC)

(Z exchange)



Neutrino-nucleon scattering



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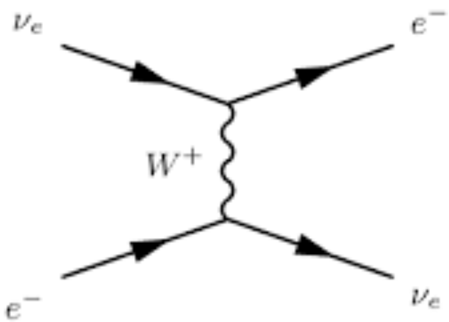
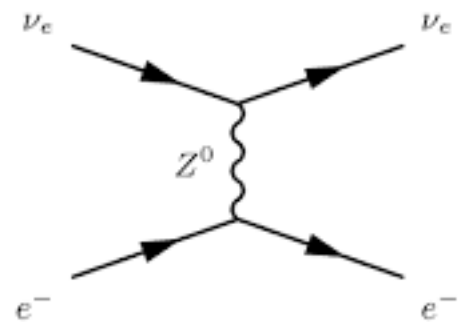
Charged Current (CC)
($W^{+/-}$ exchange)



Neutrino-electron scattering

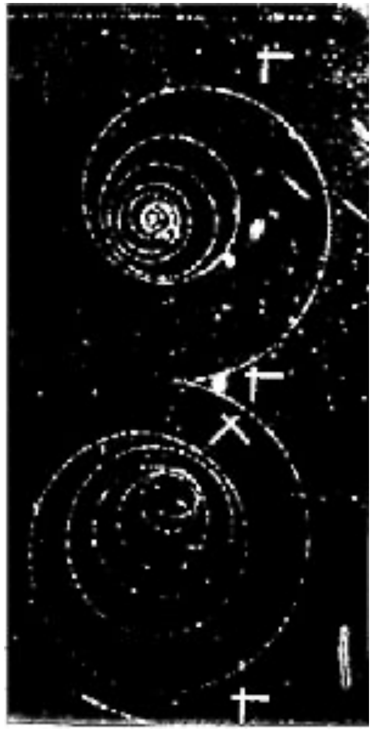
Neutral Current (NC)
(Z exchange)



- Neutrino scattering off of an electron
- Signal is a single final state electron

Neutrino vs Anti-Neutrino Tagging

- Key for many experimental searches such as oscillation experiments looking to measure charge-parity violation in the neutrino sector
- Magnetic field is ideal for charge sign determination, however,
    - Neutrino detectors are typically huge
    - High volume magnetic field is hard
    - Expensive
    - Impacts other detector elements e.g. electronics



Neutrino vs Anti-Neutrino Tagging

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- Magnetic field is ideal for charge sign determination, however,
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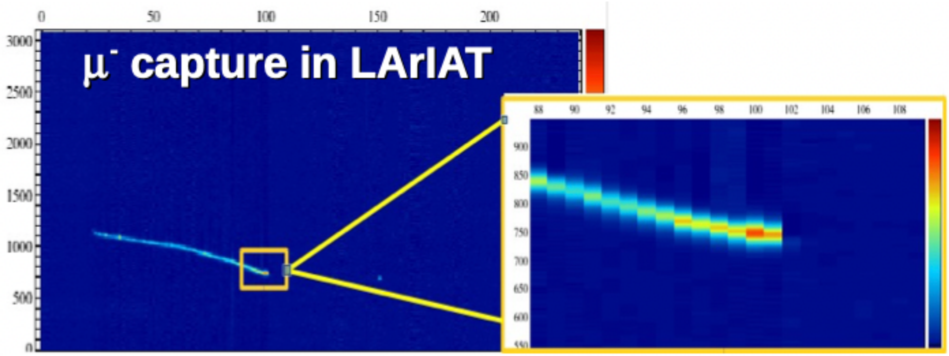
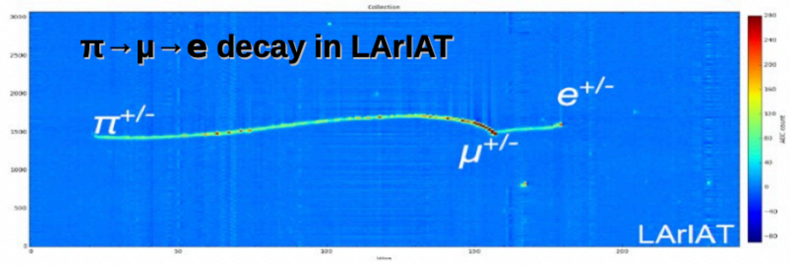
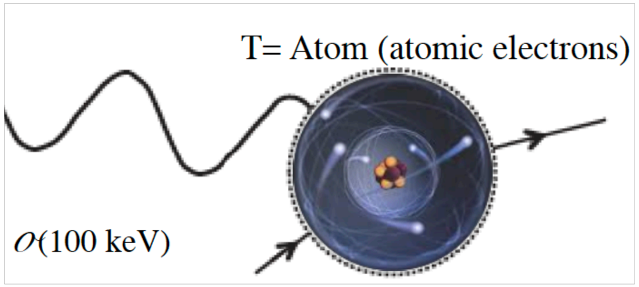
    - High volume magnetic field is hard
    - Expensive
    - Impacts other detector elements e.g. electronics

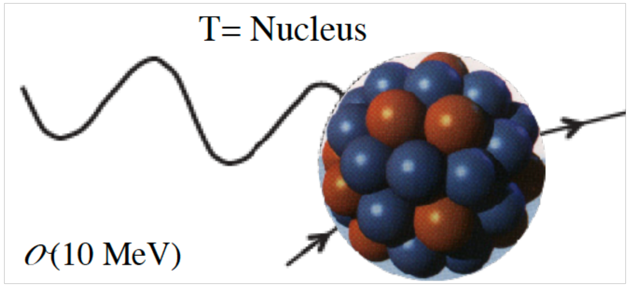
- One can use topology (e.g. decay vs capture) for particle sign identification in the absence of a magnetic field
- NC interactions cannot distinguish
- But, CC can distinguish b/n υ and anti-υ using
    - opposite lepton charge
    - different final state hadrons
    - Muons from hadron decays
    - Requires good final state reconstruction



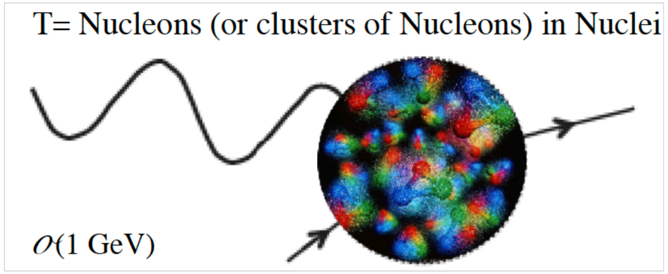


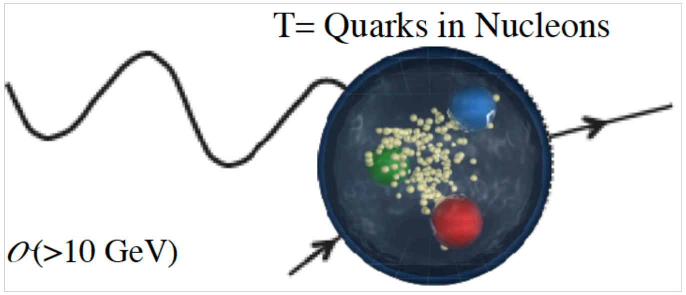
Neutrino Interactions are Complex





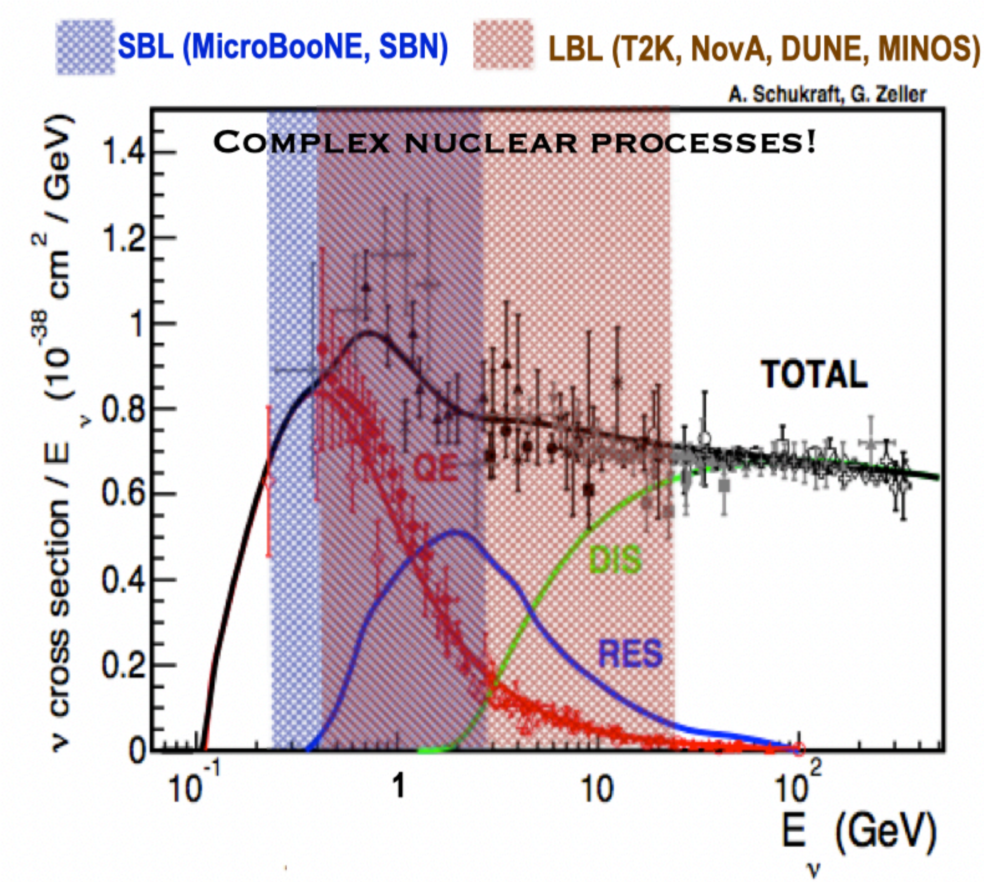
Neutrinos probe matter from its Atomic structure to quark structure depending on the energy of the incoming neutrino

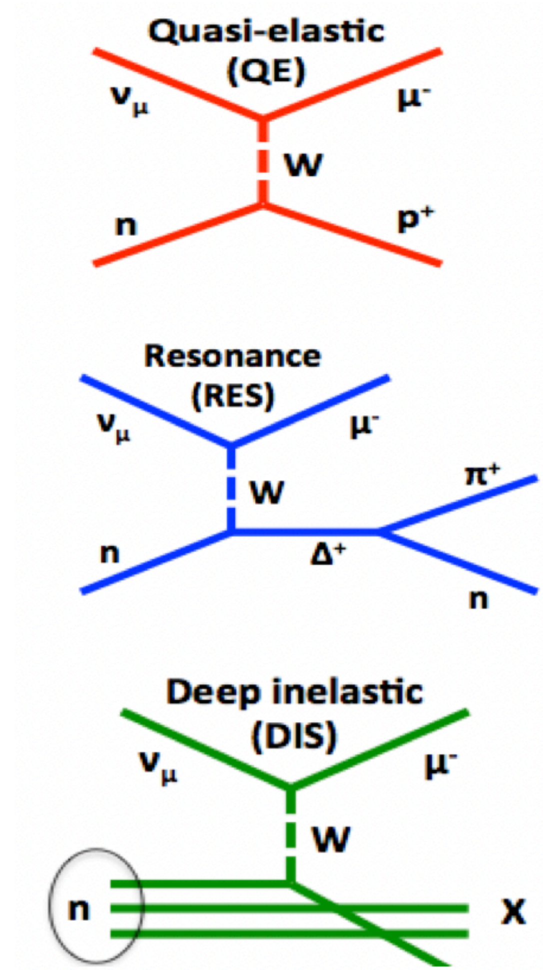




Neutrino Interactions are Complex

Current and future neutrino oscillation experiments focus in the few GeV range





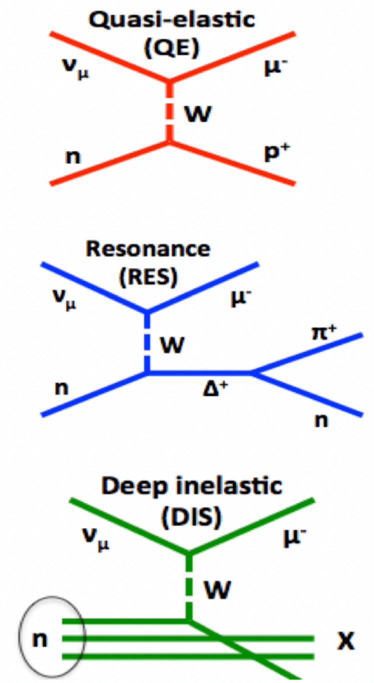
- Higher energies are more messy due to superposition of different channels

Neutrino Energy Reconstruction

- Neutrino energy from charged lepton kinematics for CCQE

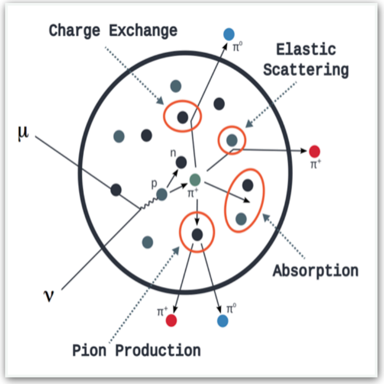
$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}^2 E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos\theta_{\mathrm{beam}})}$$

(2 body kinematics; assumes the target nucleon is at rest)

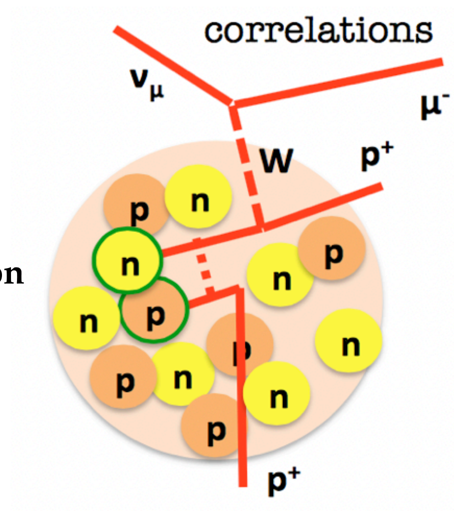


- More complicated final states for RES and DIS channels
- Both lepton and hadron kinematics important for an accurate measurement for all reaction channels
- Modern experiments use denser targets (e.g. Argon) making this picture even more complex — thorough understanding of neutrino-nucleus interaction theory is key

Final State Interactions

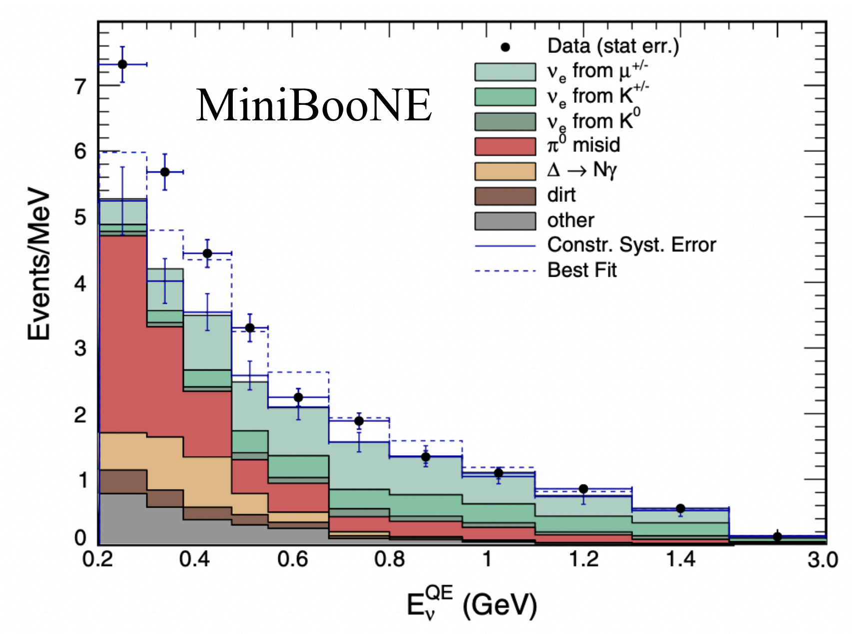


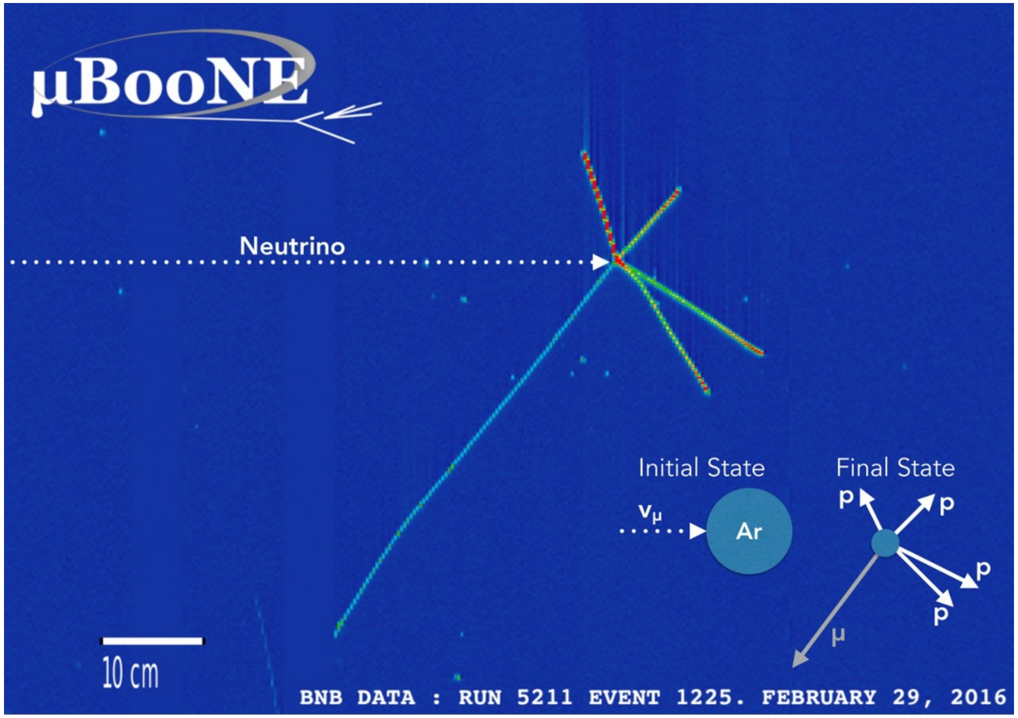
Nucleon-nucleon correlations



Neutrino Detector Goals

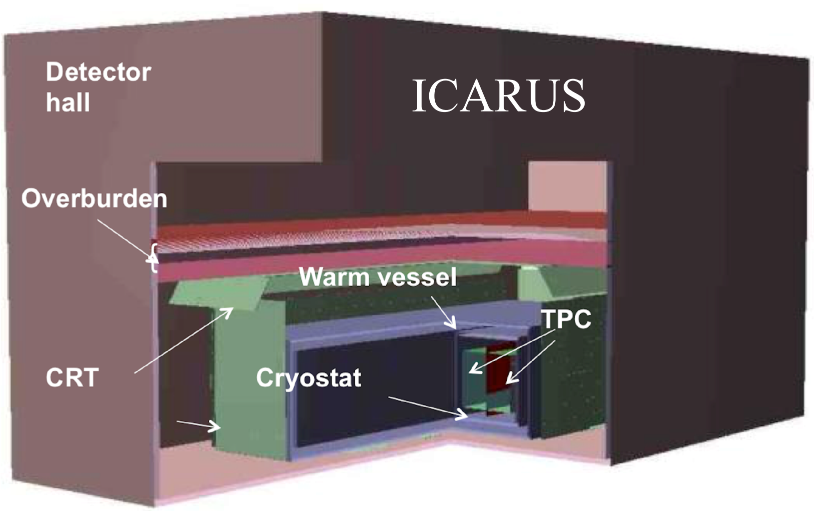
- Neutrino detectors need to work over a broad energy range (from MeV to PeV)
- They should
  - detect leptons and hadrons (protons, pions etc.)
  - distinguish electrons from photons (key for $\upsilon_\mu \rightarrow \upsilon_e$ Appearance experiments)
  - reduce backgrounds and measure them when necessary

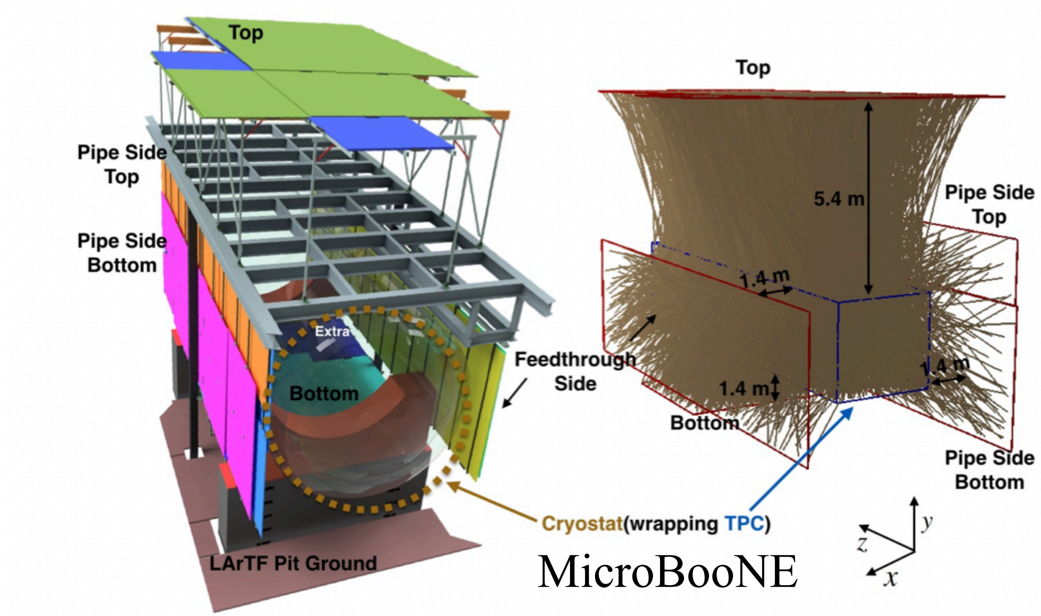




About Backgrounds

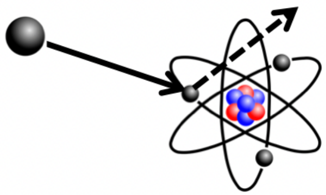
- Backgrounds vary with neutrino energy
  - backgrounds for MeV-scale are not the same as GeV-scale neutrinos)
- Cosmic rays are a worrisome background, many ways to handle this
  - place your detector underground when possible
  - Take beam-off runs to measure cosmic ray background
  - If on surface, implement a cosmic veto/tagger system and/or shielding/overburden
- Reactors produce copious amounts of low-energy (< 10 MeV) neutrinos
  - place your detectors far away from reactors
- Low-energy backgrounds are a concern for many experiments (e.g. reactor, solar/atmospheric, geo-neutrino etc.)



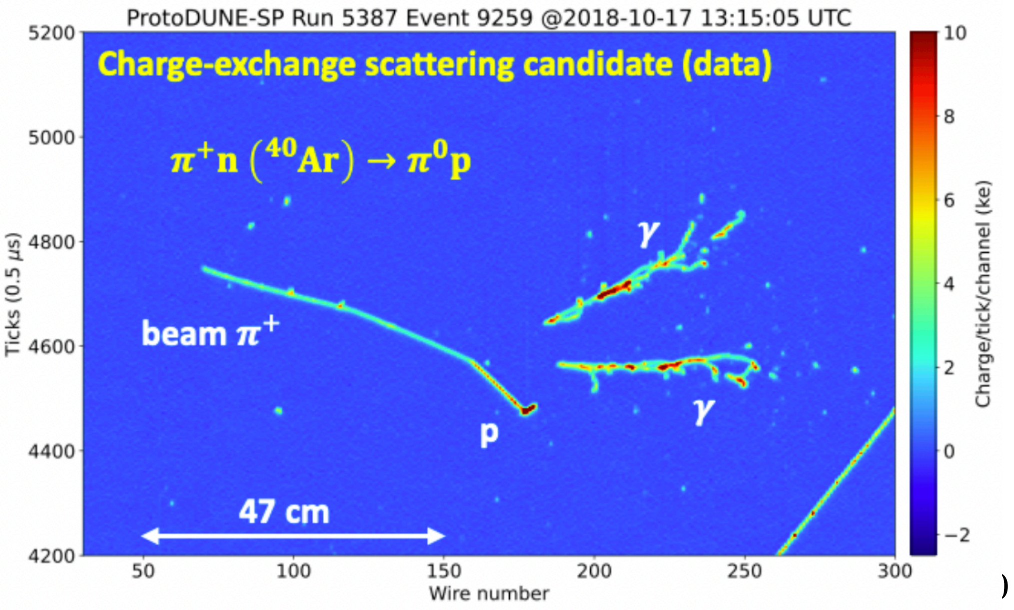


Particle Interactions in Matter

- As particles move through matter, many things can happen
  - Ionization: strip electrons off of atoms in the medium
  - Scintillation: excite atoms and produce scintillation light
  - Cherenkov radiation
  - Decay into other particles
  - Produce new particles



- Many processes can occur that can result in energy loss of the particle
  - Common energy loss process is inelastic collisions with atomic electrons (Ionization)
  - Elastic scattering from nuclei
  - Atomic excitations
  - Hadronic interactions
  - Compton scattering
  - Bremsstrahlung
  - Pari production
  - Photoelectric effect…and so on



)

Particle Interactions in Matter

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- M…
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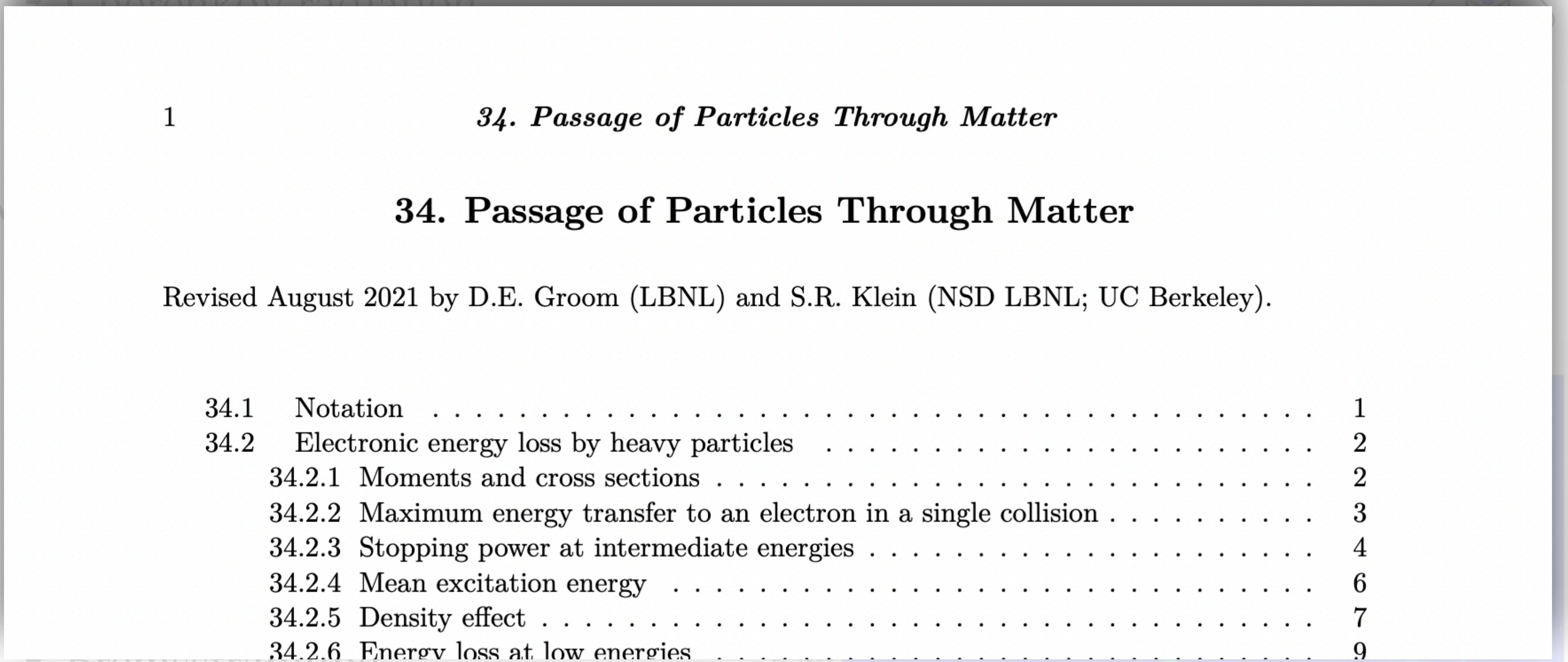
Read PDG Review on this (available online)
A great resource!



34. Passage of Particles Through Matter

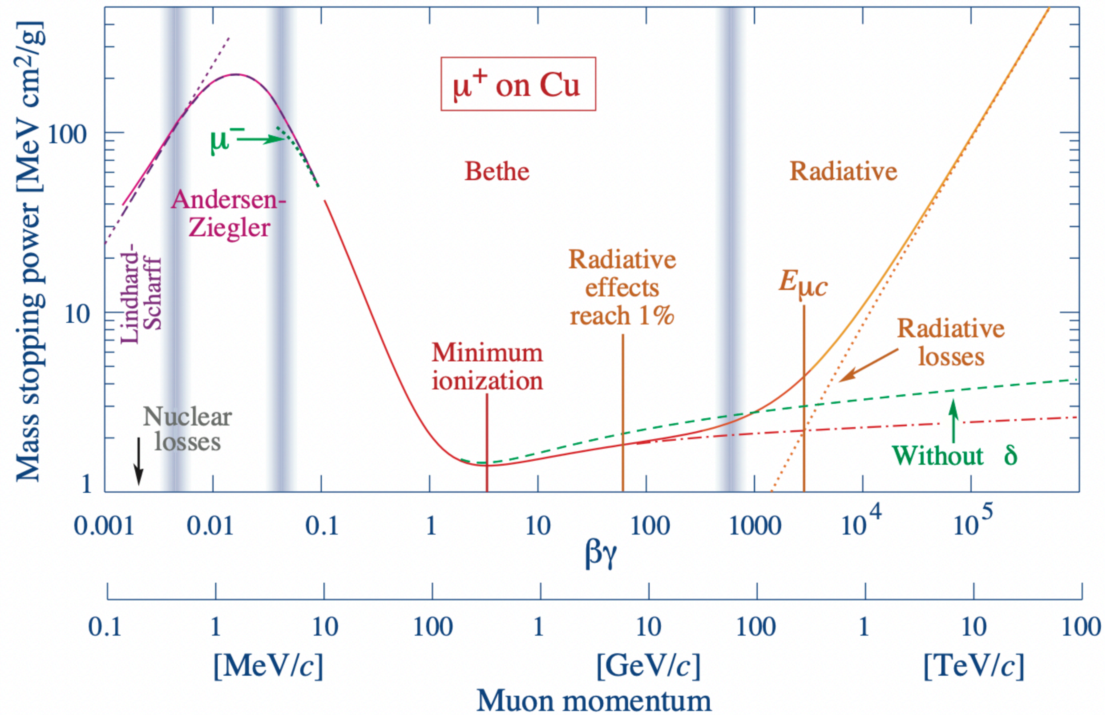
Revised August 2021 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

Energy Loss of Particles (Heavy Charged Particles)

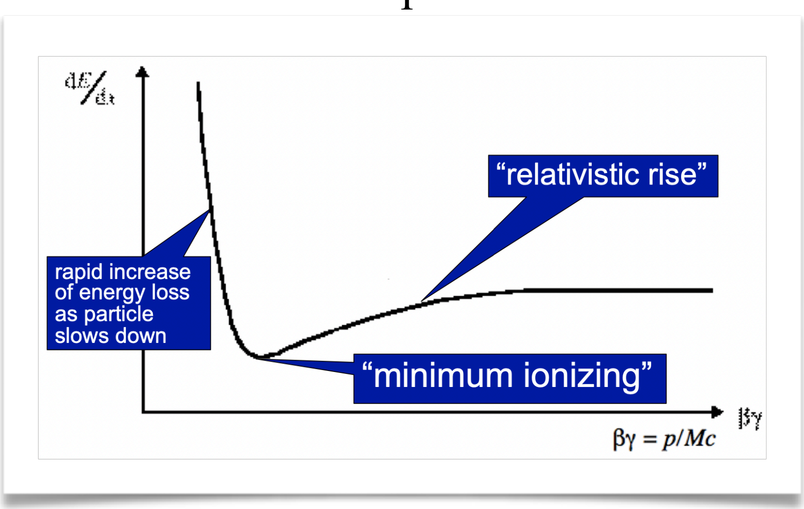
- Mean rate of energy loss for heavy (heavier than $e^{+/-}$) charged particles
  - muon, pion, proton, kaon etc.

- Good to a few % in the MeV to GeV energy range and for intermediate Z materials

$$0.1 \lesssim \beta\gamma \lesssim 1000$$



Basic shape of the curve

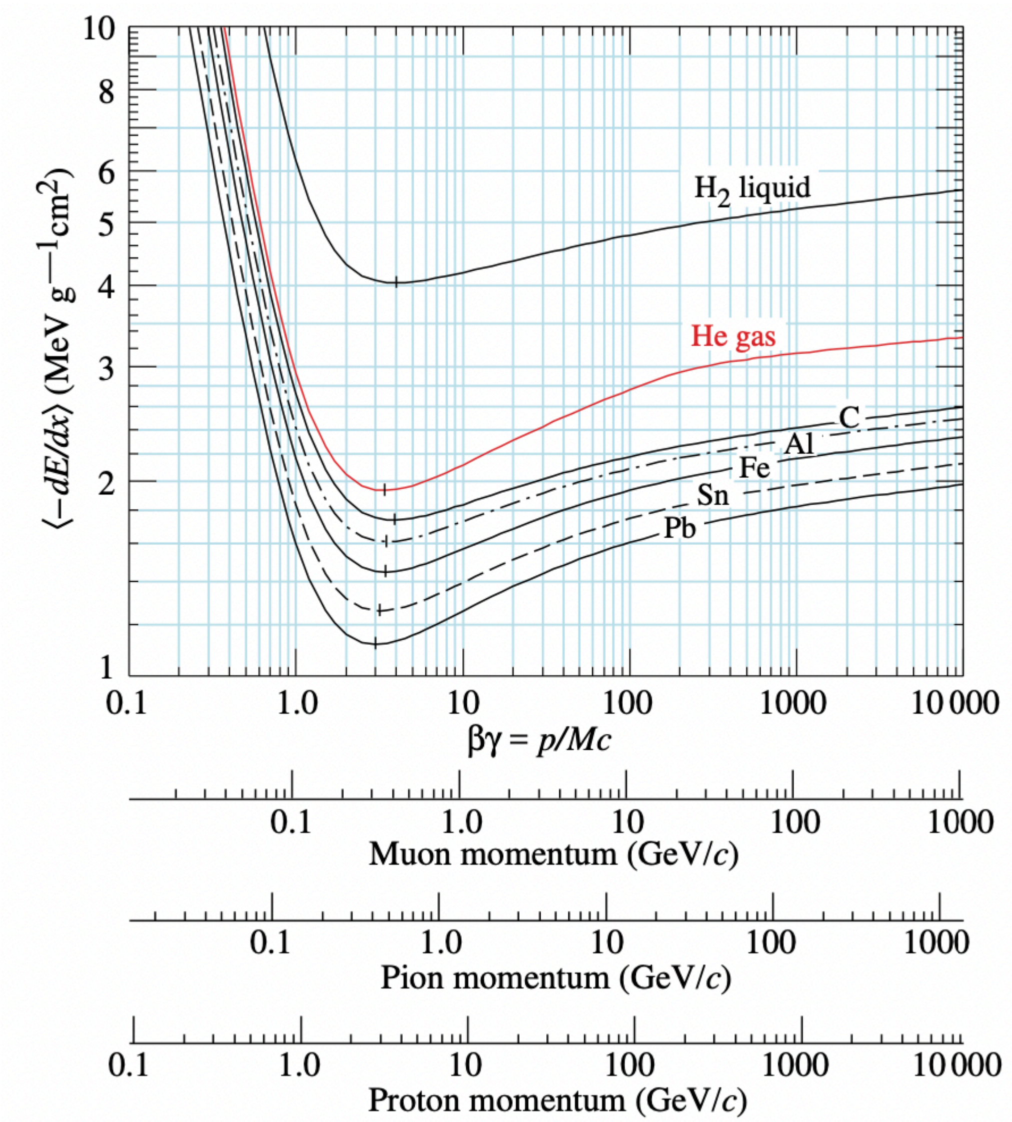


$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Bloch Equation

Energy Loss of Particles (Heavy Charged Particles)

- Mean rate of energy loss for different materials and different incident particles

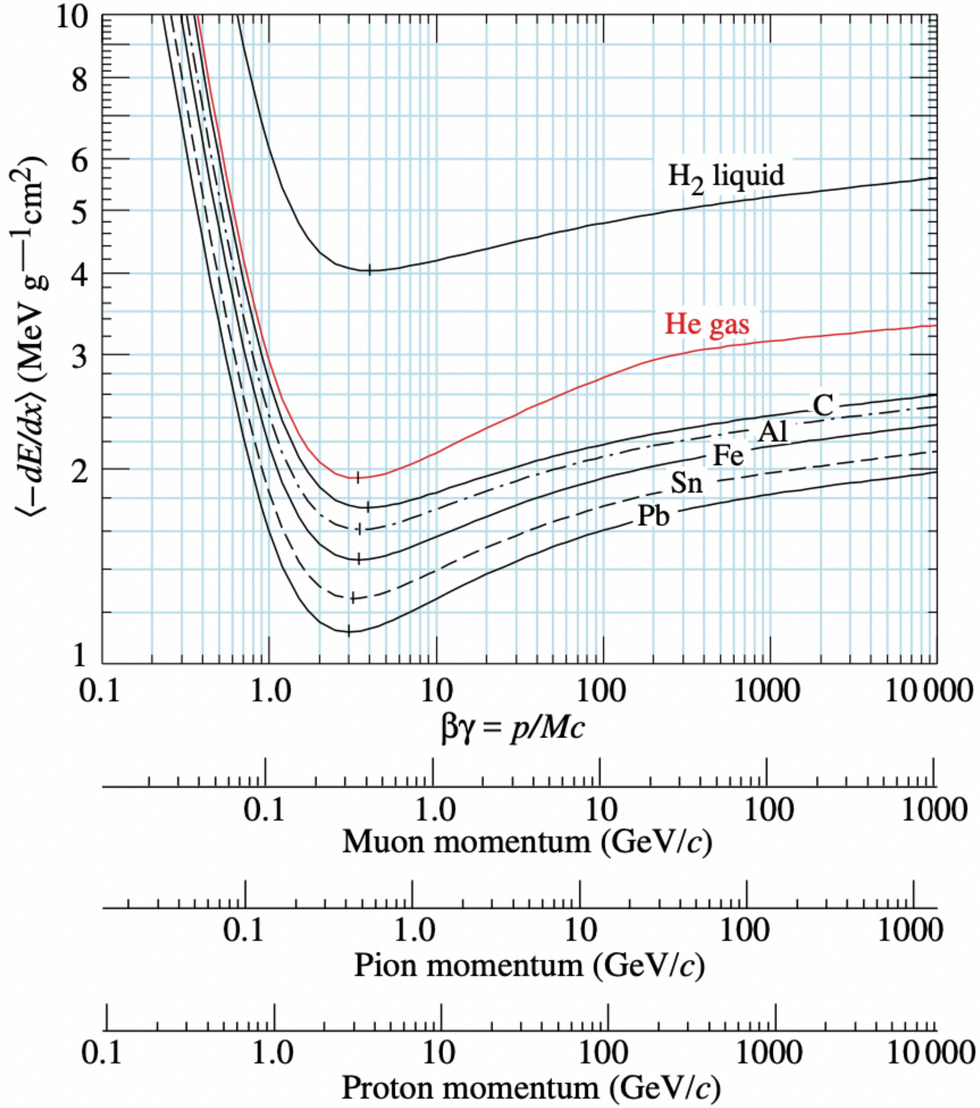


Material	Minimum Ionizing dE/dx (MeV/cm)
Liquid Argon	2.1
Water	2.0
Steel	11.4
Scintillator (CH)	1.9
Lead	12.7

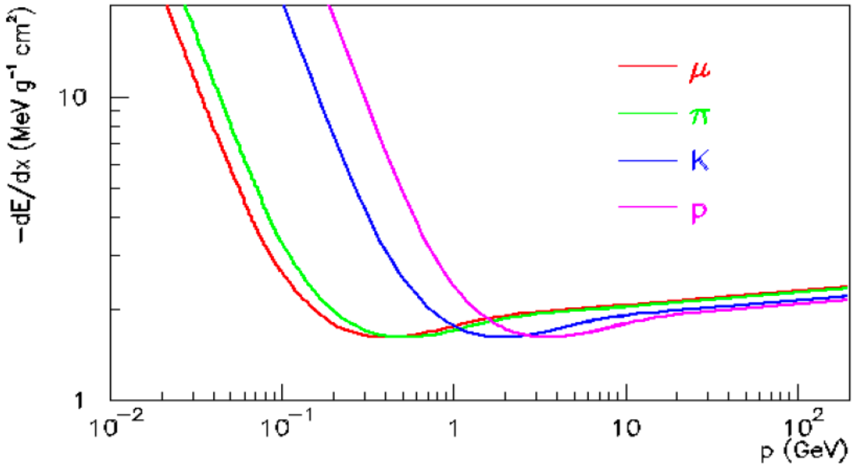
- Stopping power is an important number as it tells you how far a particle can travel in the detector medium
- Important for determining how big your detector needs to be

Energy Loss of Particles (Heavy Charged Particles)

- Mean rate of energy loss for different materials and different incident particles

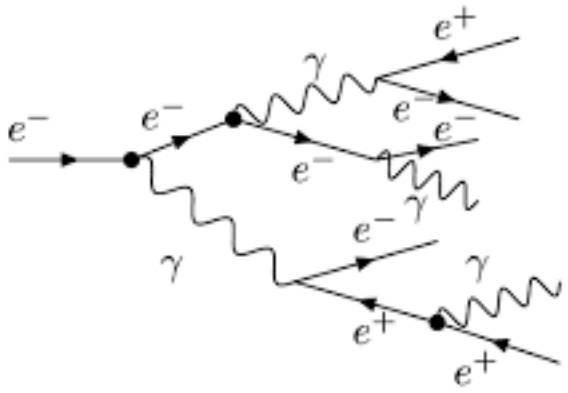


If you know dE/dx and p, you can do particle ID — a common technique used in experiments



Energy Loss of Particles (Electrons)

- Electrons act differently in a detector medium
- Electrons above the critical energy (E_c) lose energy via both radiation (Bremsstrahlung) and collisional processes resulting in a electromagnetic shower (or spray) in the detector
  - Electrons above E_c create photons via Bremsstrahlung which then produce e^+e^- pairs which then go on to produce more photons until energies drop below E_c

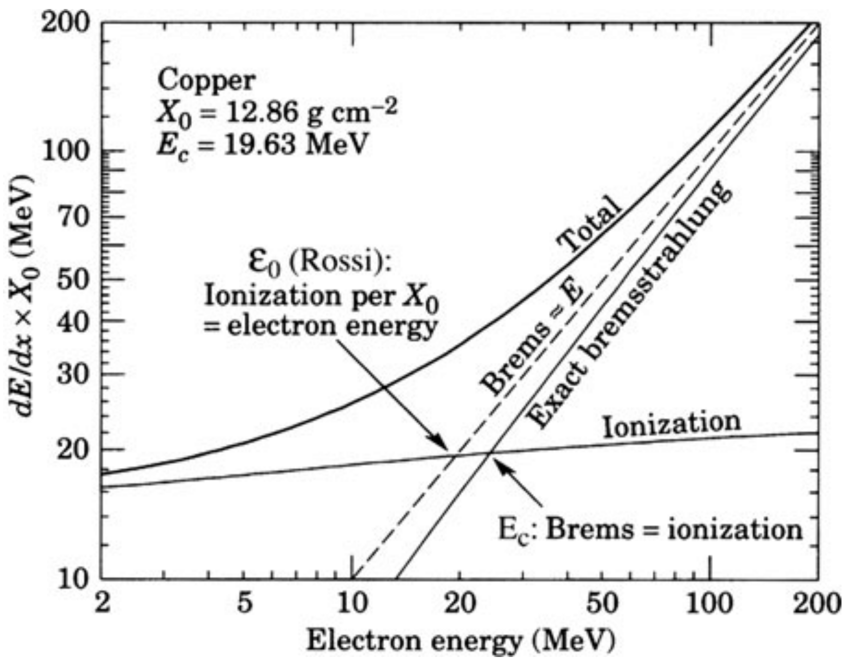


- Critical energy depends on the medium (typically few tens of MeV) and is defined as the cross over point where Bremsstrahlung energy loss > ionization loss

Bethe-Heitler approximation

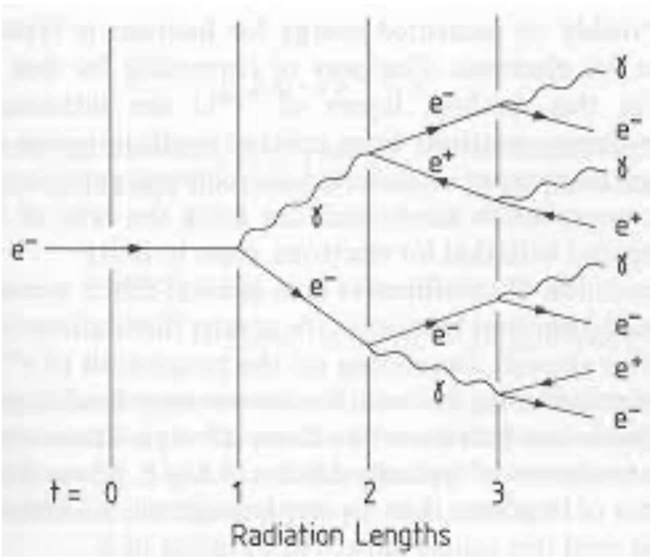
$$E_c \approx \frac{1600 m_e c^2}{Z}$$

Material	E_c (MeV)
Lead	9.51
Aluminum	51.0
Iron	27.4
Copper	24.8
Water	92



Energy Loss of Particles (Electrons)

- Radiation length (X_0) is an important parameter for electromagnetic showers
- It is defined as the distance over which electrons lose 1/e of their energy by radiation i.e., at every X_0 an election would Bremsstrahlung creating a photon

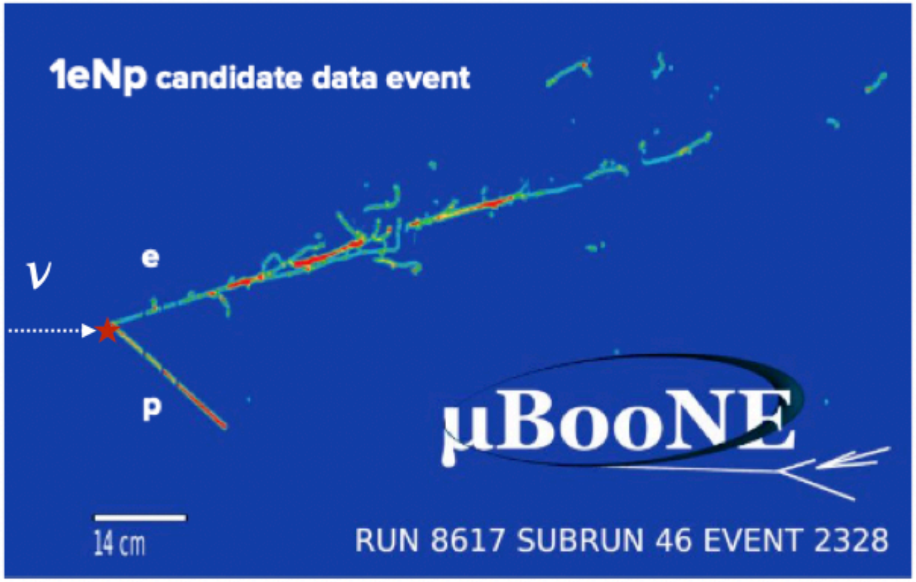


$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \left[\frac{\text{g}}{\text{cm}^2}\right]$$

- Distance over which photons pair produce is (9/7) X_0
- Electromagnetic shower size estimate after "t" radiation lengths

$$t_{\max} = \frac{\ln(E_0/E_c)}{\ln 2}$$

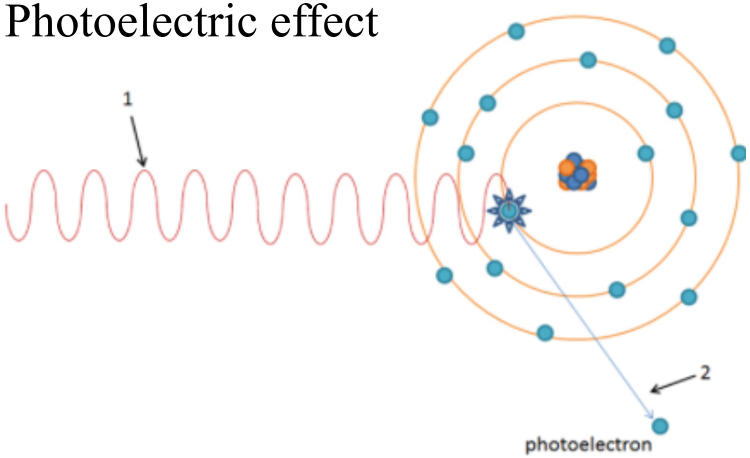
Material	X_o (cm)
Liquid Argon	14
Water	37
Steel	1.76
Scintillator (CH)	42
Lead	0.56

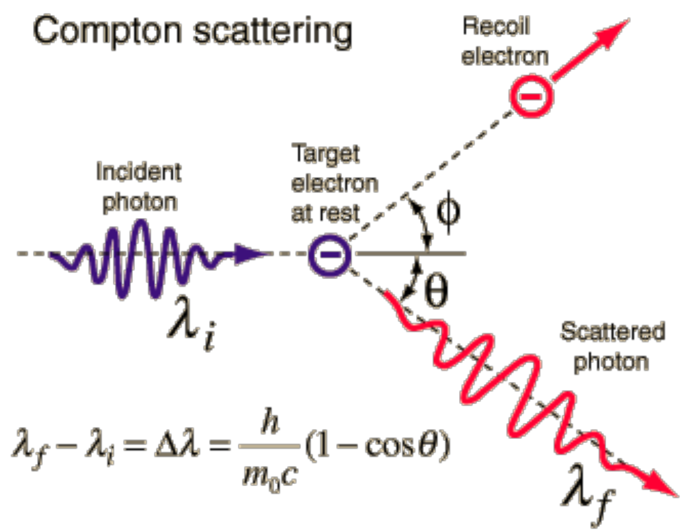


Energy Loss of Particles (Photons)

- Photon primarily lose energies through 4 ways

Photoelectric effect





Pair production

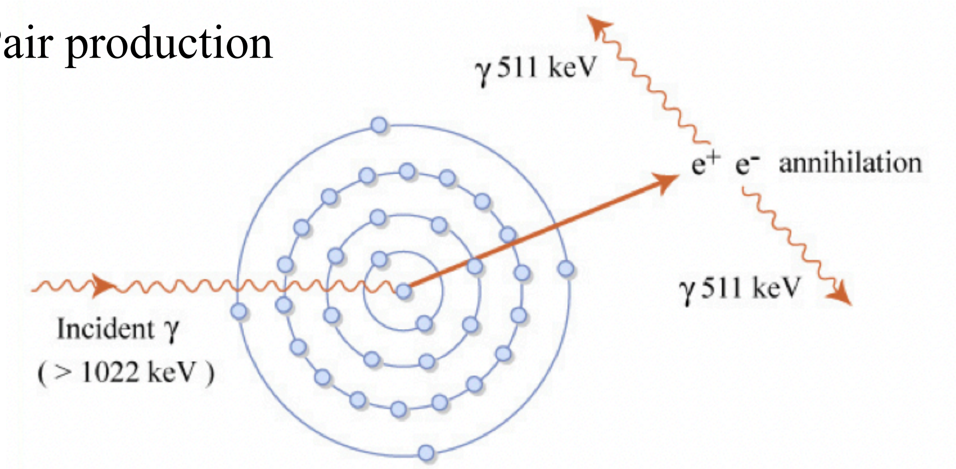
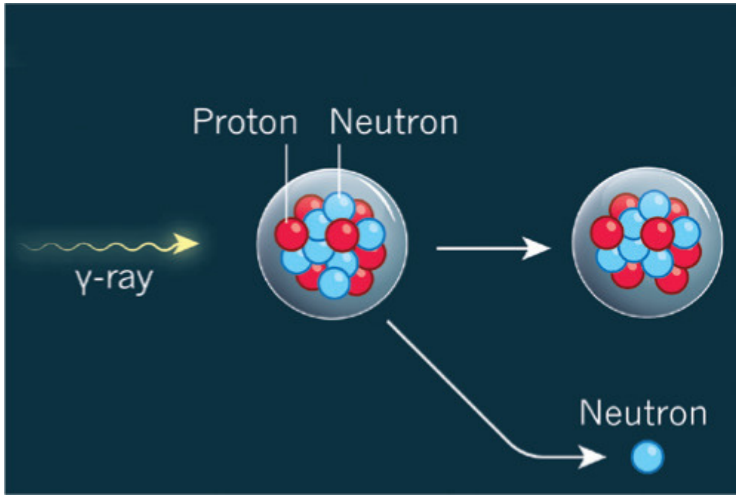


Photo-nuclear effect



Energy Loss of Particles (Photons)

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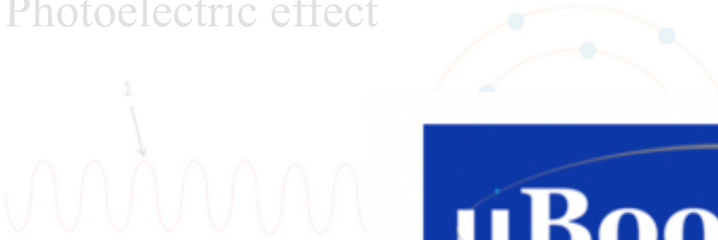
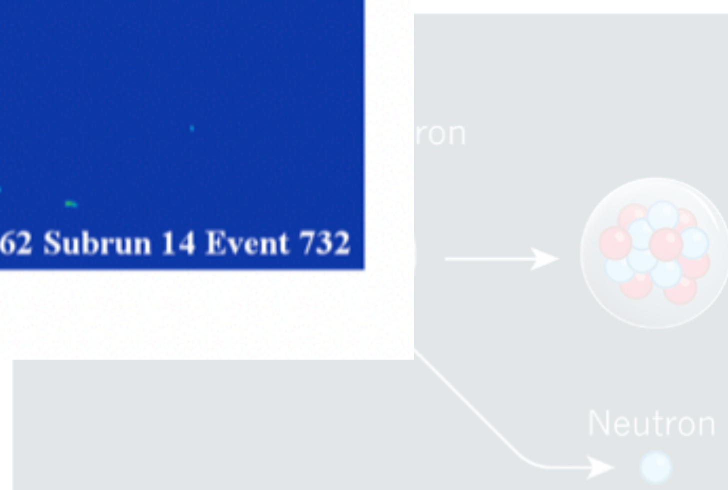
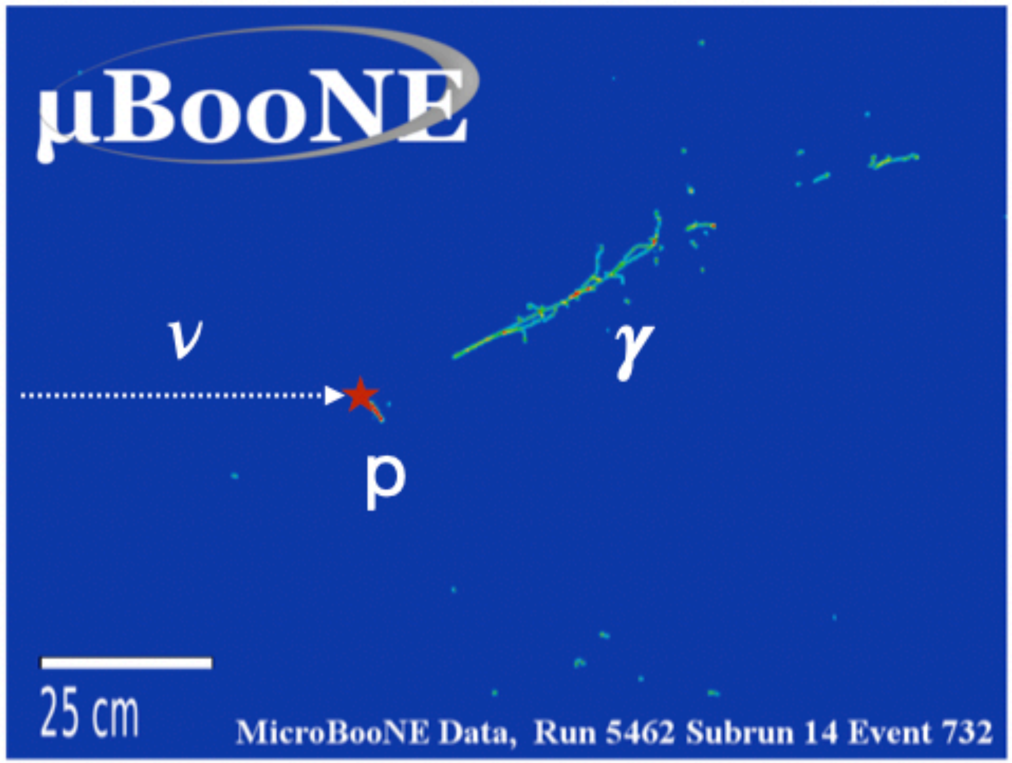


Compton scattering

Pair production

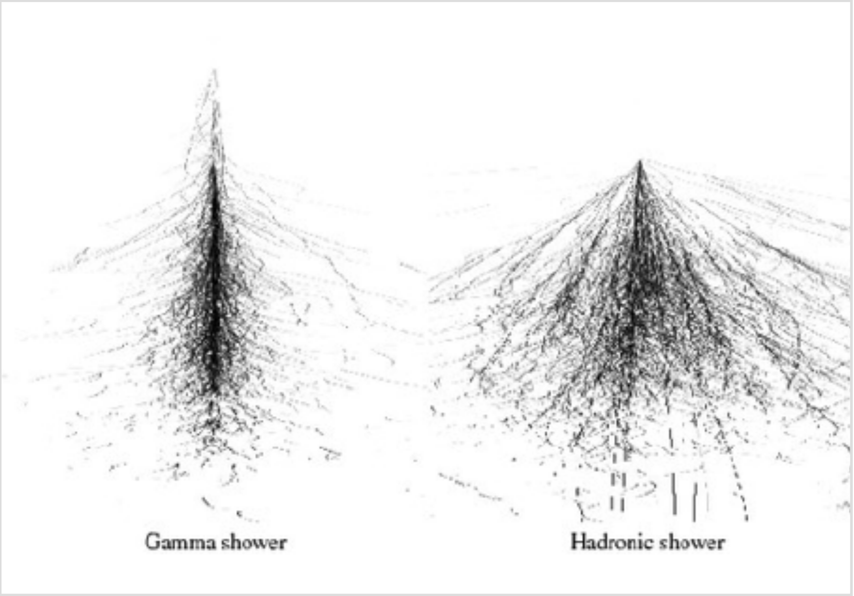


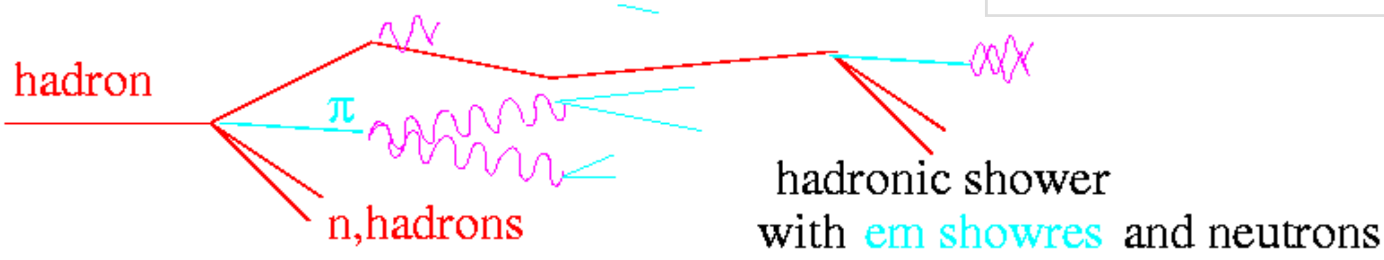


Energy Loss of Particles (Hadrons)

- For hadrons, interaction (λ) length defines the distance they travel before undergoing a strong nuclear interaction
- Neutron, for example, interacts via the weak force and undergoes energy loss through various mechanisms
  - Elastic scattering, inelastic scattering, neutron capture, hadronic showers etc.
  - Elastic scattering on nuclei is the main mechanism of energy loss for neutrons
  - Neutron capture import for low energy neutrino experiments
- Hadron interaction lengths are longer than radiation lengths
- At higher energies, hadronic showers initiated by e.g. proton, neutron become relevant
- Hadronic showers are broader than EM showers

Material	X_0 (cm)	λ_{INT}(cm)
Liquid Argon	14	83.5
Water	37	83.6
Steel	1.76	17
Scintillator (CH)	42	~80
Lead	0.56	17






Thank you, we will continue tomorrow!