Neutrinos II

Experimental Survey
QuarkNet Workshop for High School Teachers, Jul 1-Jul 3, 2019, BNL

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July 6^{th}, 2018

Neutrinos II

Mary Bishai
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GeV-TeV Neutrinos

MeV Neutrinos from Reactors
Exercises
Daya Bay

GeV Neutrinos from Accelerators
Exercises
Current Experiments
Future Experiments

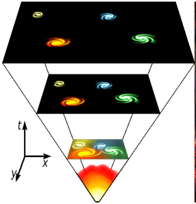
Big Bang Neutrinos

ν Applications

Conclusions

Sources of Neutrinos

Big Bang

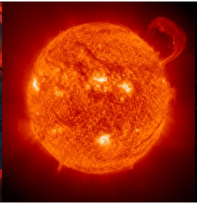


10^{-4} eV
$300/\text{cm}^3$

Reactors

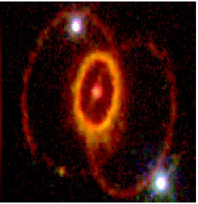
few MeV
$10^{21}/\text{GW}_{th}/\text{s}$

Sun



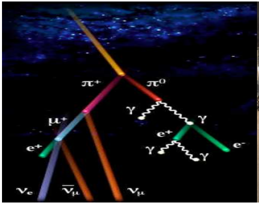
0.1-14 MeV
$10^{10}/\text{cm}^2/\text{s}$

SuperNova



$\sim$ 10 MeV
$10^{9}/\text{cm}^2/\text{s}$

Atmosphere

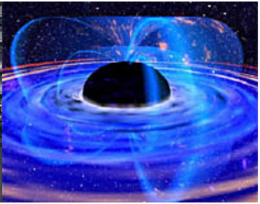


$\sim$ 1 GeV
few/cm^2/s

Accelerators

1-20 GeV
$10^{5}/\text{cm}^2/\text{s}$ (at 1km)

Extragalactic

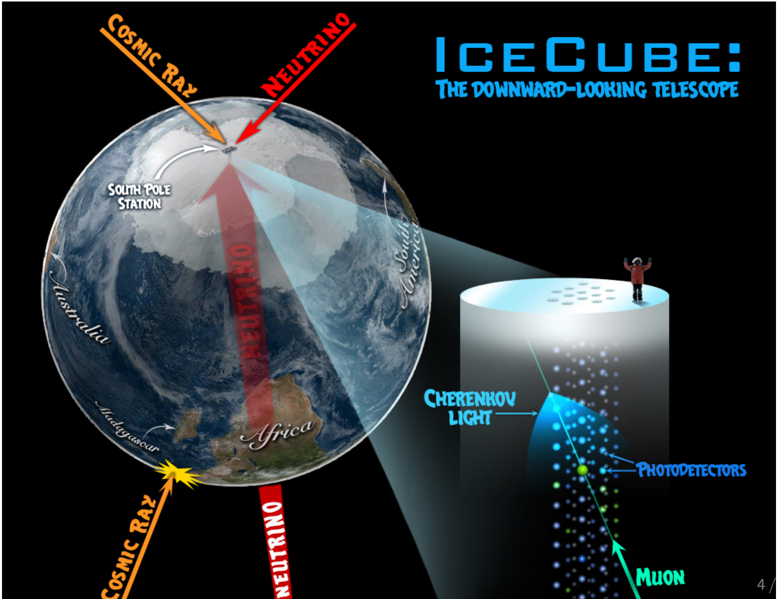


TeV-PeV
varies

Neutrino Experiments

- **MeV scale Neutrinos: The Daya Bay Reactor Experiment**
- **GeV scale Neutrinos: The T2K, NOνA and DUNE experiments**
- **TeV-PeV scale Neutrinos: The IceCUBE Experiment**
- **Big Bang Neutrinos: The PTOLEMY Experiment**

The IceCUBE Experiment



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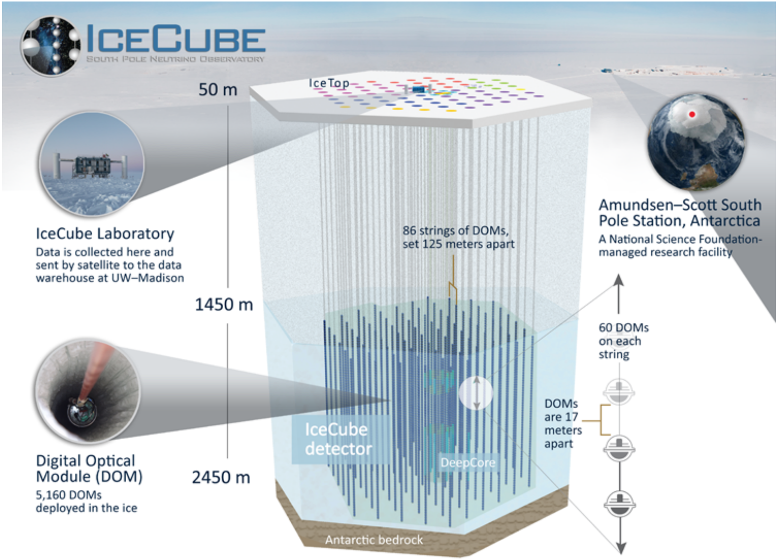
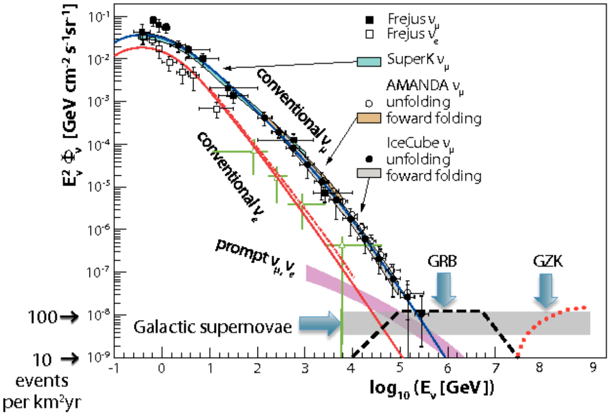
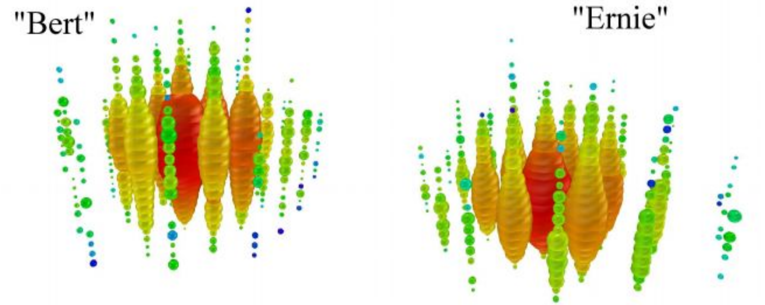


The Highest Energy Neutrinos (Gamma Ray Bursts)



The Highest Energy Neutrinos (Gamma Ray Bursts)

Neutrino events with energies $>$ PeV ($10^{15}eV$)



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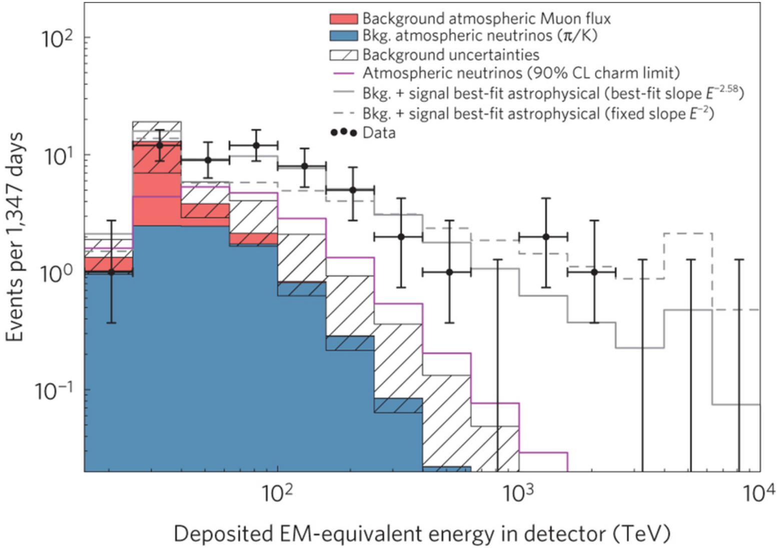
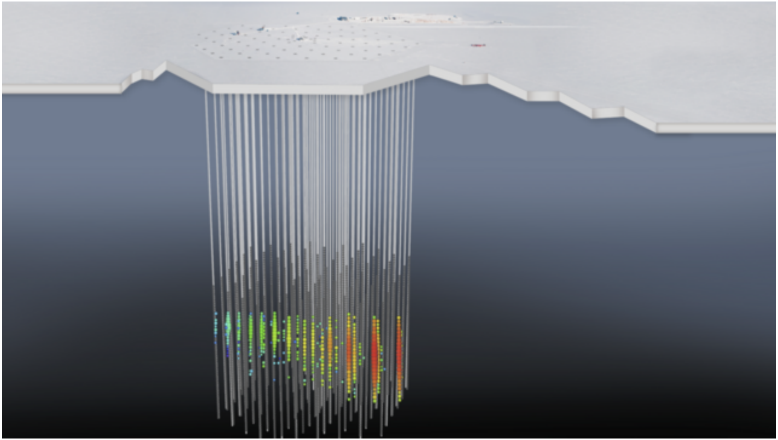


NEW RESULT FROM ICECUBE: July 12,2018

Sep 22, 2017 a very high energy muon neutrino is recorded in IceCUBE:



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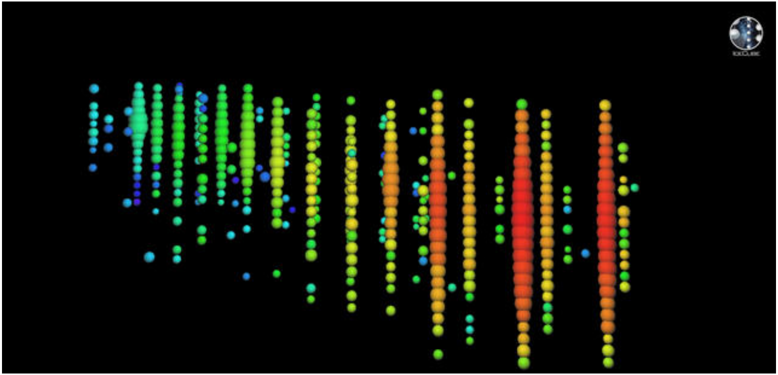
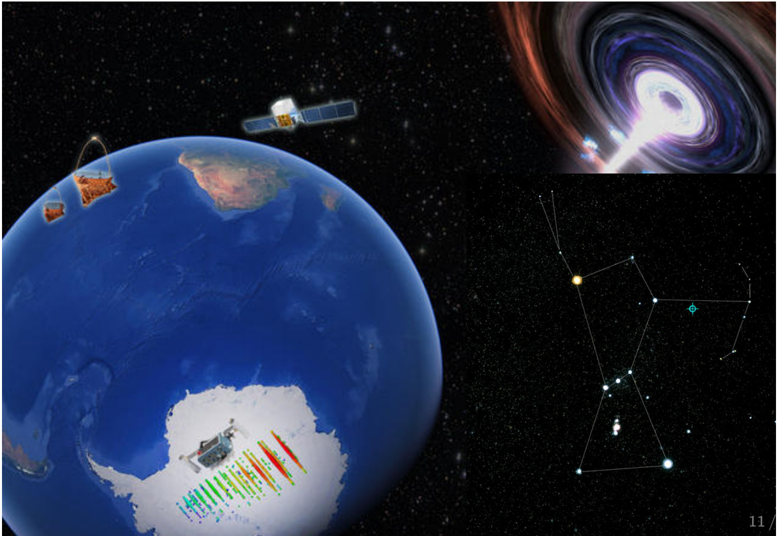


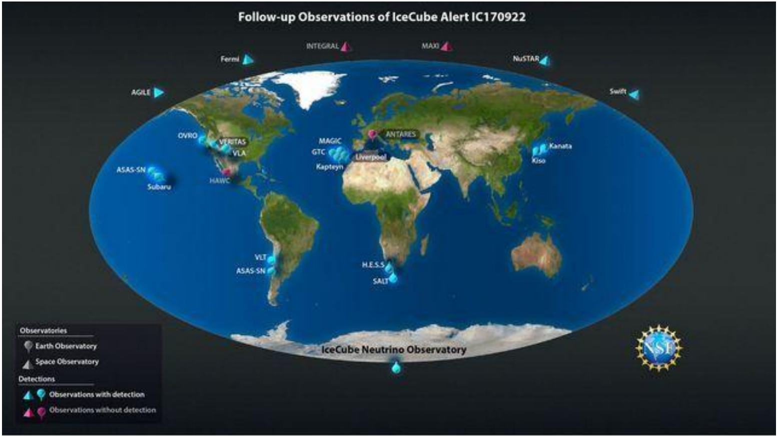
NEW RESULT FROM ICECUBE: July 12,2018

Fermi-LAT (space telescope) also sees a flare up of very high energy gamma rays from a source near Orion



NEW RESULT FROM ICECUBE: July 12,2018

Eventually many observatories see the burst in optical, γs, X-rays and radio:



ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos. The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (N = n or p).

$$\nu \text{ mean free path} = \frac{1}{\sigma \times \text{number of nucleons per cm}^3}$$

ν Exercise: What is the mean free path of a neutrino in lead?

(use Table of atomic and nuclear properties)

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$$\begin{aligned} &= \frac{1}{10^{-43}\text{cm}^2 \times 11.4\text{g/cm}^3 \times 6.02 \times 10^{23}\text{nucleons/g}} \\ &\approx 1.5 \times 10^{16} m \end{aligned}$$

How many light years is that? How does it compare to the distance from the sun to the moon?

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$$\begin{aligned} &= \text{1.6 LIGHT YEARS OF LEAD} \\ &= 100{,}000 \text{ distance earth to sun} \end{aligned}$$

A proton has a mean free path of 10cm in lead

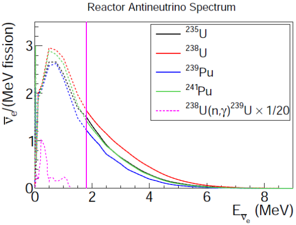
Reactor power and neutrinos

ν Exercise:

The following table shows the breakdown of energy released per fission from ^{235}U:

Fission fragment	Energy (MeV)
Fission products	175
$\langle 2.44 \rangle$ neutrons	5
γ from fission	7
γs and βs from *beta* decay	13
$\langle 6 \rangle$ neutrinos	10
Total	210

5% of a reactor's power is in neutrinos !



How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor?

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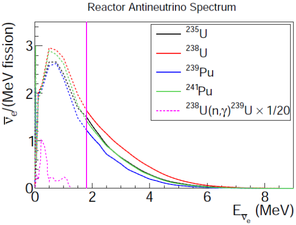
Reactor Antineutrino Spectrum

How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor?

$$\begin{aligned} 1 \times 10^{9}\ \text{Joules/sec} &= 6.242 \times 10^{18}\ \text{GeV/sec} \\ &= 3 \times 10^{19}\ \text{fissions/sec} \\ &\sim 2 \times 10^{20}\ \nu/\text{sec} \\ &= 1.6 \times 10^{13}/\text{m}^2/\text{sec at 1 km} \end{aligned}$$

Reactor Power and Neutrinos

ν Exercise:

Using the rate of neutrinos emitted from a reactor ($= 2 \times 10^{20}$/sec/GW) and the average cross-section of the inverse beta decay process ($\bar{\nu}_e + p \rightarrow e^+ + n$) is $\sigma = 10^{-43}\mathrm{cm}^2$/proton, what is the rate of neutrino interactions per day in a detector containing 100 tons of scintillator (CH_2) located 1km from a 1GW reactor? Note that the IBD process only happens on free protons (H)

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 # interactions/day = flux (ν/cm^2/day) $\times$ σ (cm^2/p) $\times$ protons/Nucleons $\times$ Nucleons/gram $\times$ 10^8 g/100tons

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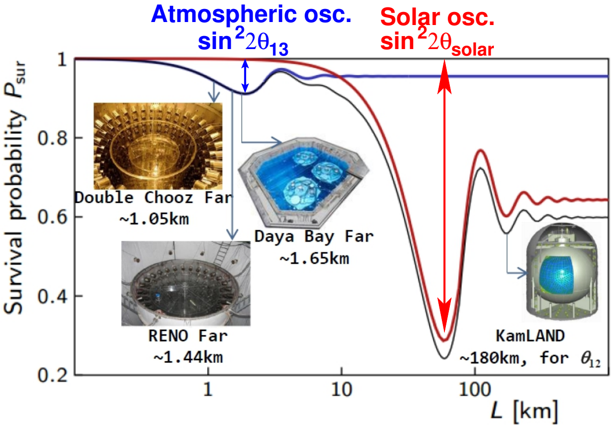
 # interactions/day = flux (ν/cm^2/day) $\times$ σ (cm^2/p) $\times$ protons/Nucleons $\times$ Nucleons/gram $\times$ 10^8 g/100tons

 # interactions/day = 118

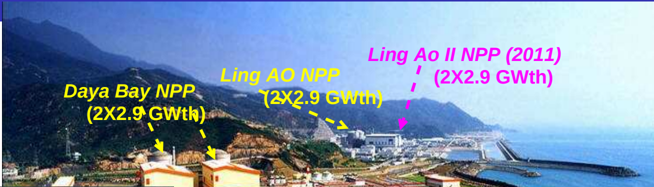
Precision ν expt: need 1 GW nuclear reactor ($1B) + 100's tons

More Reactor $\bar{\nu}_e$: Measuring Oscillation Parameters

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} L/4E)$$



The Daya Bay Reactor Complex



Reactor Specs:

Located 55km north-east of Hong Kong.

Initially: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

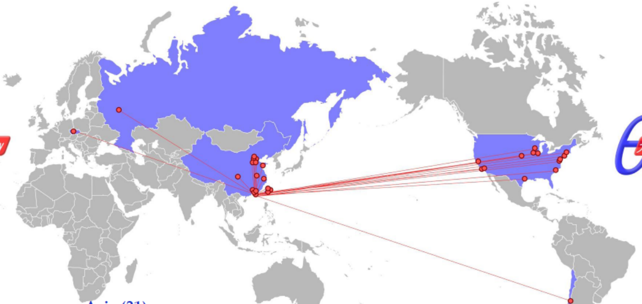
By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} $\Rightarrow$ top five worldwide

$1\ \mathrm{GW}_{th} = 2\times10^{20}\bar{\nu}_e/\mathrm{second}$

Deploy multiple near and far detectors

Reactor power uncertainties $< 0.1\%$

The Daya Bay Collaboration : 231 Collaborators



Asia (21)

Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

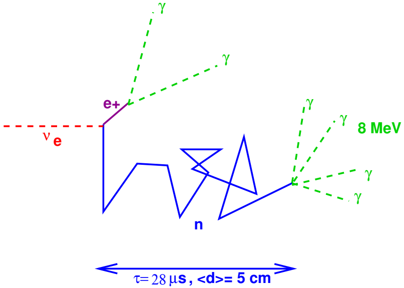
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic Univ. of Chile

Detecting Neutrinos from the Daya Bay Reactors

The active target in each detector is liquid scintillator loaded with 0.1% Gd

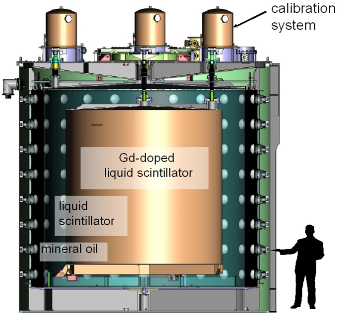


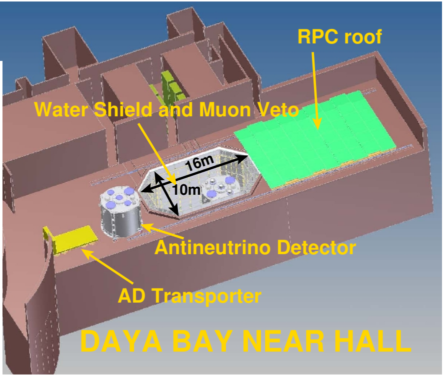
- $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV $+ T_{e^+}$, prompt)
- $n + p \rightarrow D + \gamma$ (2.2 MeV, $\tau \sim 180\mu s$). **OR**
- $n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$'s (8 MeV, $\tau \sim 28\mu s$).

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture ($>$ 6 MeV)

with a specfic energy signature

The Daya Bay Experimental Apparatus

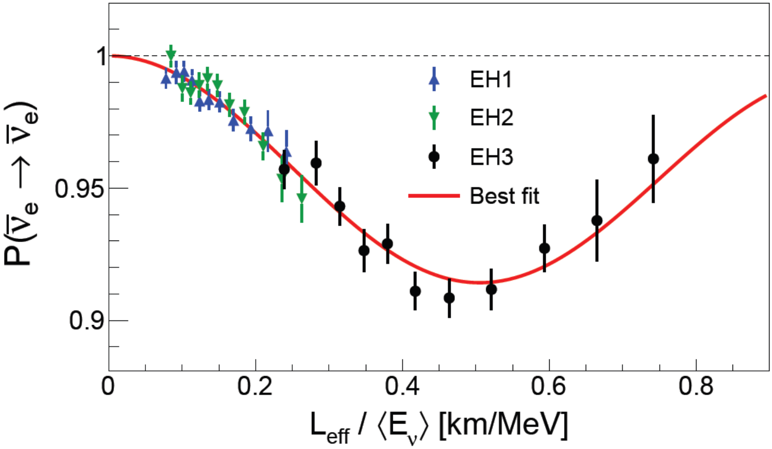




- **Multiple "identical" detectors at each site.**
- **Manual and multiple automated calibration systems per detector.**
- **Thick water shield to reduce cosmogenic and radiation bkgds.**

	DYB	**LA**	**Far**
Event rates/20T/day	**840**	**740**	**90**

Daya Bay Measurement of Non-zero θ_{13}

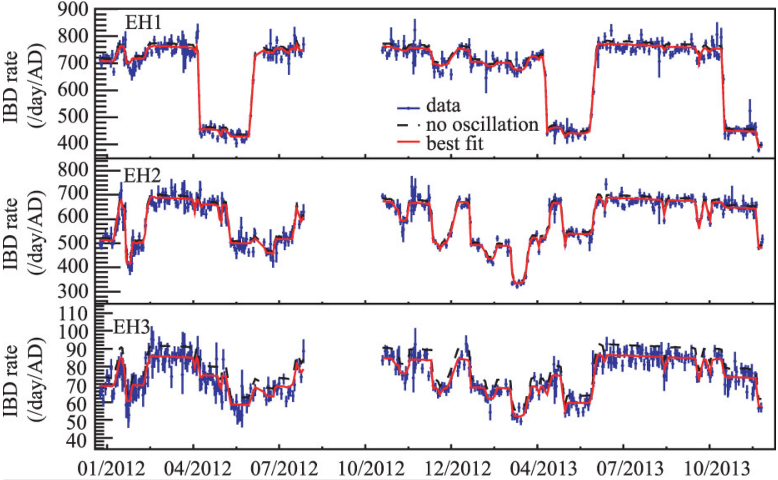


First to discover non-zero θ_{13} (2012) and currently most precise result:

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

Measured and predicted neutrino flux at DYB

—Predicted —Predicted with best fit value of θ_{13}

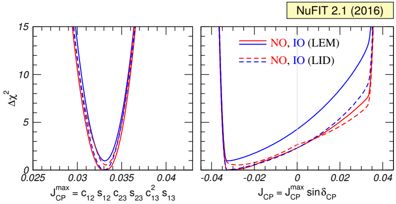


ν detectors can now monitor reactors!

CP Violation in PMNS (leptons) and CKM (quarks)

In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{\mathrm{PMNS}} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{\mathrm{CP}}.$$



(JHEP 11 (2014) 052, arXiv:1409.5439)

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{\mathrm{PMNS}} \approx 3 \times 10^{-2} \sin\delta_{\mathrm{CP}}.$$

For CKM (mixing among the 3 quark generations):

$$J_{CP}^{\mathrm{CKM}} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{\mathrm{CKM}} \approx 70°$.

$\nu_\mu \to \nu_e$ Oscillations in the 3-flavor ν SM

In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in vacuum:**

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{CP}\cos\Delta\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$

For $\bar{\nu}_\mu \to \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \to -P_{\sin\delta}}_{\text{CP asymmetry}}$,

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where **for oscillations in matter with constant density:**

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$ and $A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$.

$$\text{For } \bar{\nu}_\mu \to \bar{\nu}_e,\ \underbrace{P_{\sin\delta} \to -P_{\sin\delta},}_{\text{CP asymmetry}} \quad \underbrace{A \to -A}_{\text{matter asymmetry}}$$

Osc. vs L/E

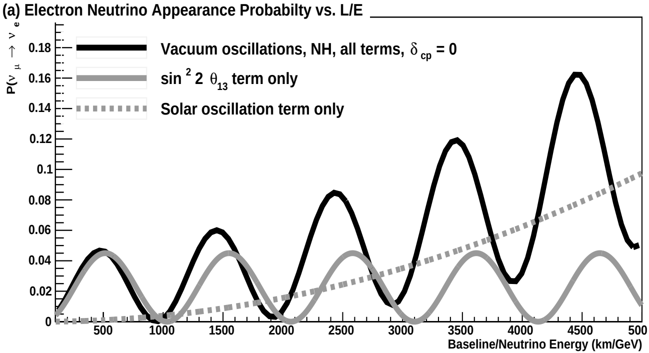
$\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \Delta m^2_{31} = \pm 2.4 \times 10^{-3}\mathrm{eV}^2$

ν Exercise: Use ROOT and reproduce the plots shown below

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Oscillations in vacuum - different terms ($\delta_{\mathrm{CP}} = 0$)



Osc. vs L/E

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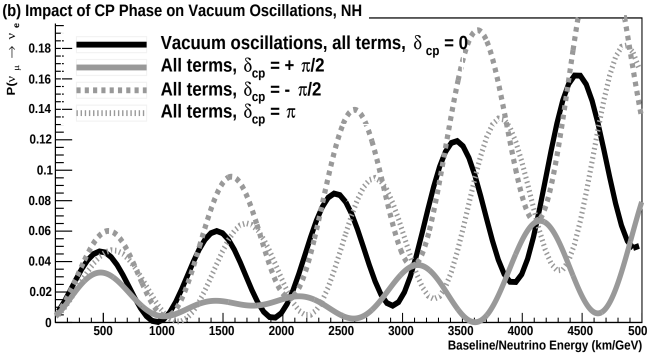
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} > 0$ (NH)



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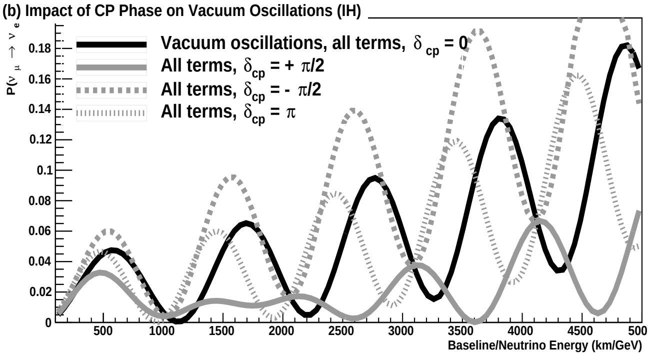
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} < 0$ (IH)



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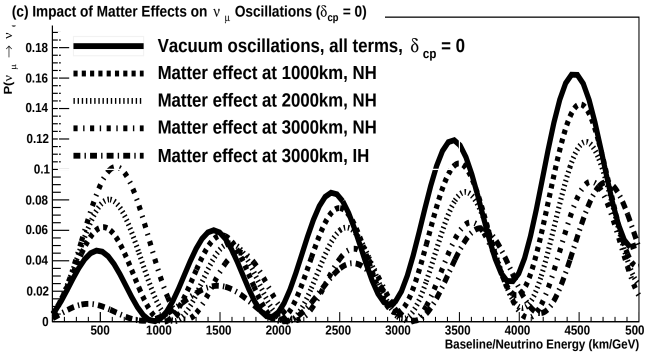
Impact of matter effect on ν_μ oscillations ($\delta_{\mathrm{CP}} = 0$)



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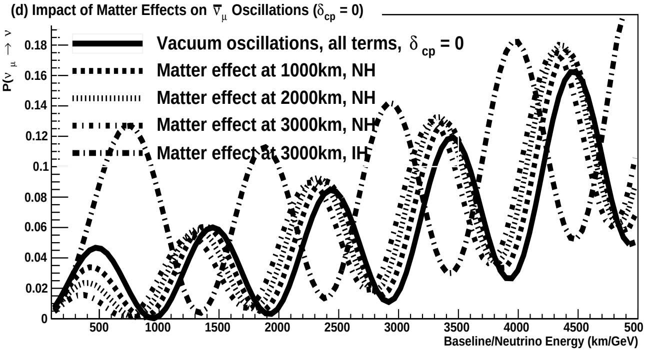
ν Exercise: Use ROOT and reproduce the plots shown below

The $\nu_\mu \rightarrow \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\text{km})}{E_n(\text{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27\times\Delta m^2_{31}(\text{eV}^2)} \approx (2n-1)\times\frac{515\ \text{km}}{\text{GeV}}$$

Impact of matter effect on $\bar{\nu}_\mu$ oscillations ($\delta_{\text{CP}} = 0$)



Expected Appearance Signal Event Rates

ν Exercise: The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N^{\text{appear}}_{\nu_e}(L) = \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino source produces a flux that is constant in energy and using only the dominant term in the probability(no matter effect)

$$\begin{aligned} \Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}/\text{sec at 1 km} \\ P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{31} L/E_\nu)}_{P_0} \\ \sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42}(\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV} \end{aligned}$$

Prove that the rate of ν_e appearing integrated over a constant range of L/E is independent of baseline!

Expected Appearance Signal Event Rates

$$N^{\mathrm{appear}}_{\nu_e}(L) \propto \text{constant term} \times \int \frac{\sin^2(ax)}{x^3}\,dx,$$

$$x \equiv L/E_\nu,\ \ a \equiv 1.27\Delta m^2_{31}\ \mathrm{GeV/(eV^2.km)}$$

ν Exercise:

$C \approx 1\times10^{17}\ \nu_\mu/\mathrm{m^2/GeV/yr}$ at 1 km (from 1MW accelerator)
$\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4\times10^{-3}\mathrm{eV^2}$

Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

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Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

$$N^{\text{appear}}_{\nu_e}(L) \approx (2 \times 10^6 \text{events/kton/yr}) \cdot (\text{km/GeV})^2 \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3}dx,$$

$$N^{\text{appear}}_{\nu_e}(L) \sim \mathcal{O}(20 - 30) \text{ events/kton/yr}$$

Neutrinos from Accelerators

To produce neutrinos from accelerators
$p^{+} + A \rightarrow \pi^{\pm} + X, \quad \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$
where A = Carbon (Graphite), Berillyium, Tungsten, X is other particles
ν Exercise: The Main Injector accelerator at Fermilab produces 4.86×10^{13} 120 GeV protons in a 10 microsecond pulse every 1.33 seconds to the NuMI beamline. What is the average power of the proton beam delivered in megawatts?

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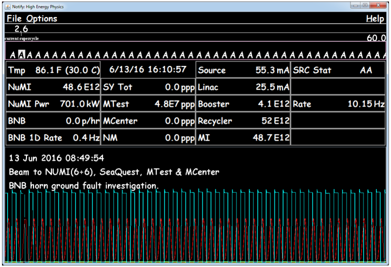
Power = 120 GeV $\times$ 4.86 10^{13} protons $\times$ 1.6 10^{-10} Joules/GeV $\times$ 1/1.33s = 702 kW

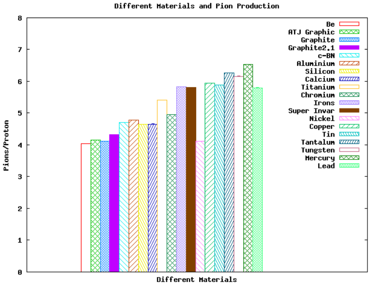


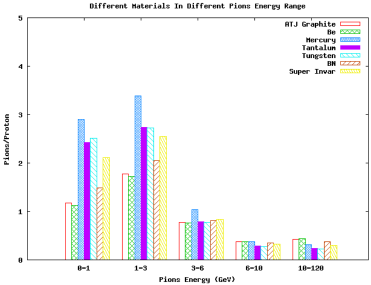
Tmp	86.1 F (30.0 C)	6/13/16 16:10:57		Source	55.3 mA	SRC Stat	AA
NuMI	48.6 E12	SY Tot	0.0 ppp	Linac	25.5 mA		
NuMI Pwr	701.0 kW	MTest	4.8E7 ppp	Booster	4.1 E12	Rate	10.15 Hz
BNB	0.0 p/hr	MCenter	0.0 ppp	Recycler	52 E12		
BNB 1D Rate	0.4 Hz	NM	0.0 ppp	MI	48.7 E12		

13 Jun 2016 08:49:54
Beam to NUMI(6+6), SeaQuest, MTest & MCenter
BNB horn ground fault investigation.

Neutrinos from Accelerators

The result of a FLUKA simulation of pion production from 120 GeV protons is shown below

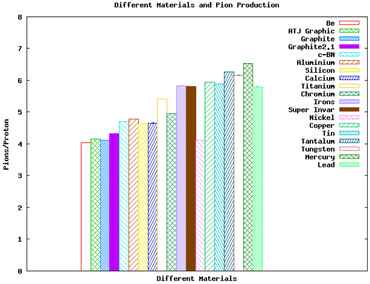


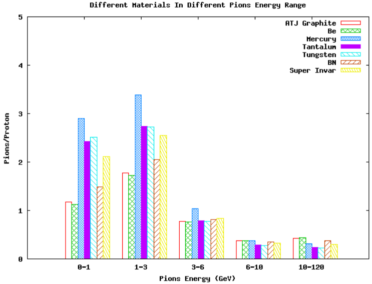


ν **Exercise: What fraction of 6 GeV pions on average will decay before reaching the end of an evacuated pipe 200m (675m) long? The π^+ rest mass and lifetime are 140 MeV and 26 ns**

Neutrinos from Accelerators

The result of a FLUKA simulation of pion production from 120 GeV protons is shown below



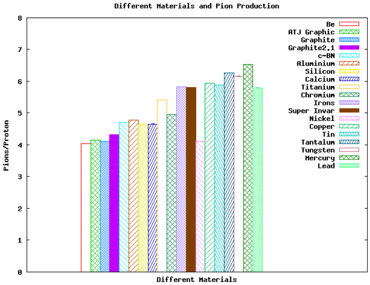


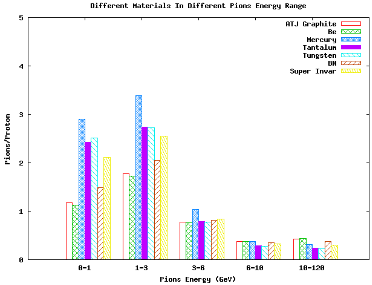
ν Exercise: **What fraction of 6 GeV pions on average will decay before reaching the end of an evacuated pipe 200m (675m) long? The π^+ rest mass and lifetime are 140 MeV and 26 ns**

$$6 \text{ GeV } \pi^+ \text{ lifetime: } \tau = \gamma\tau_0 = \frac{E}{m_0 c^2} \times 26\text{ns} = 1.1\text{ns}, \; c\tau = 334 \text{ m}$$

Neutrinos from Accelerators

The result of a FLUKA simulation of pion production from 120 GeV protons is shown below





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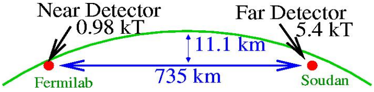
$$F_{decays} = (1 - \exp^{-l/c\tau}) = 0.45(0.87)$$

Neutrinos at the Main Injector

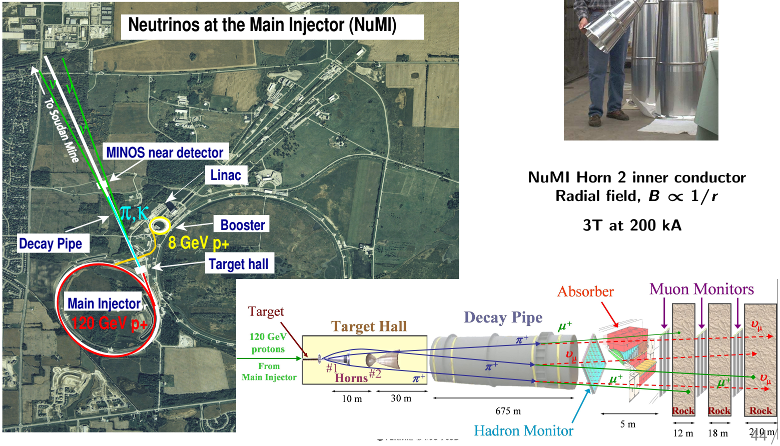
The longest baseline accel. ν expt in operation with highest power (700kW)



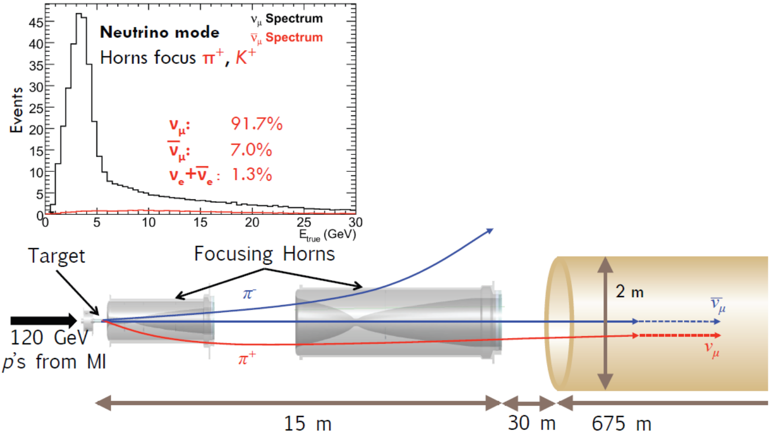
Fermi Natl. Lab., IL **Soudan Underground Lab, MN**

NuMI Horn 2 inner conductor
Radial field, $B \propto 1/r$

3T at 200 kA

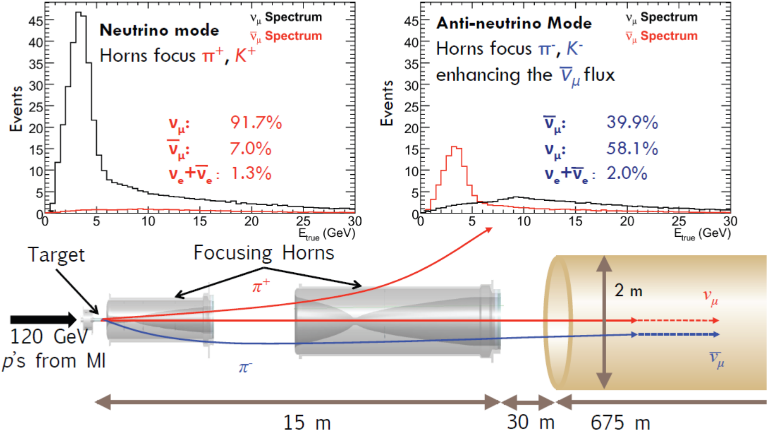


Making Neutrinos and Anti-Neutrinos



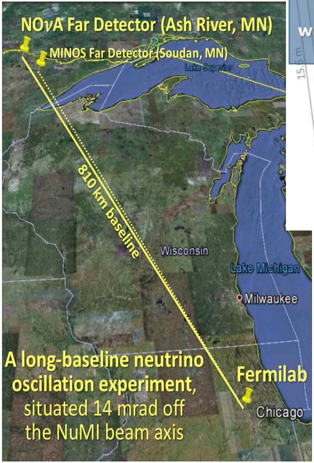
P. Vahle, Neutrino 2010

Making Neutrinos and Anti-Neutrinos



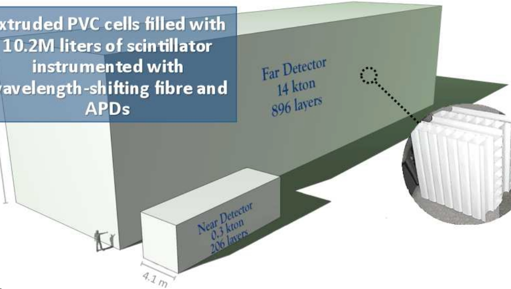
P. Vahle, Neutrino 2010

The NOνA Experiment

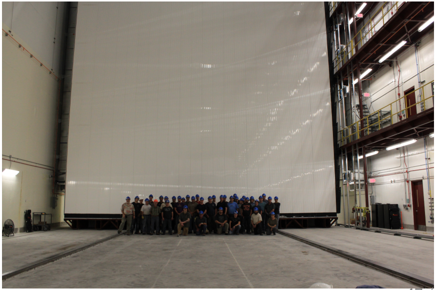


NOνA Far Detector (Ash River, MN)

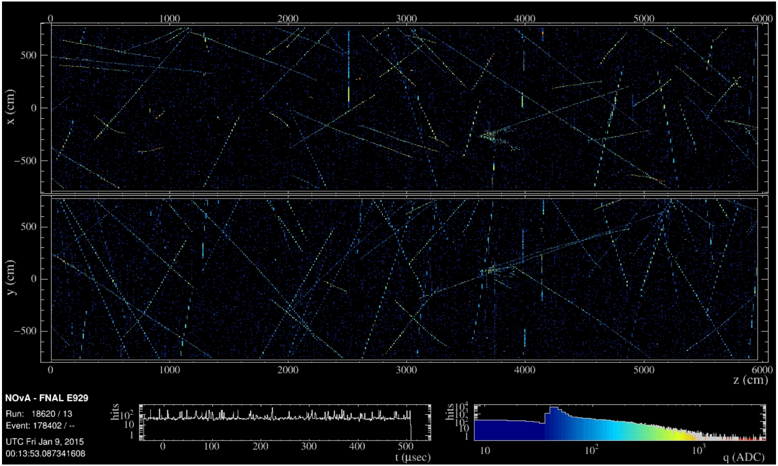
A long-baseline neutrino oscillation experiment, situated 14 mrad off the NuMI beam axis



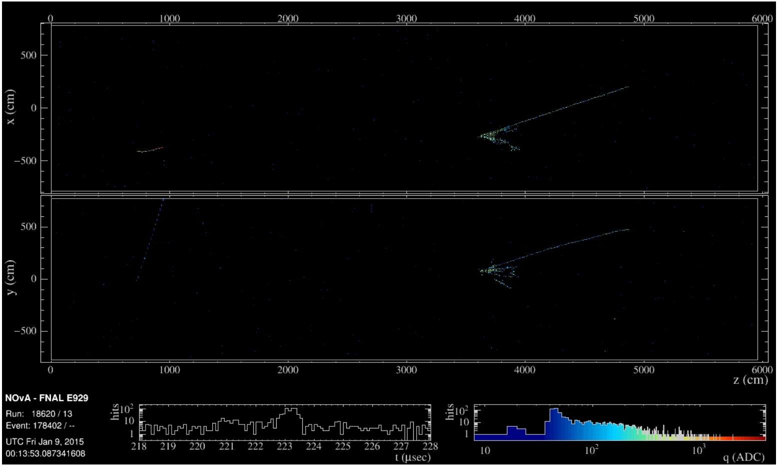
Extruded PVC cells filled with 10.2M liters of scintillator instrumented with wavelength-shifting fibre and APDs



Neutrino Events in NOνA

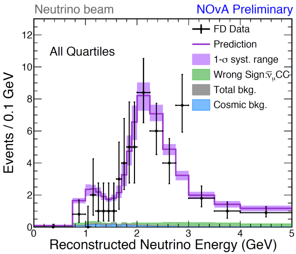


Neutrino Events in NOνA

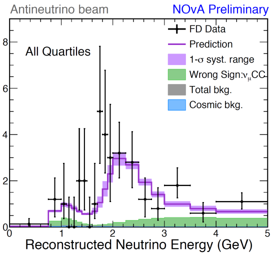


Latest results from NOνA

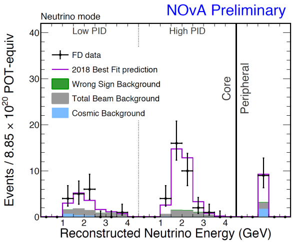
$\nu_\mu \rightarrow \nu_\mu$



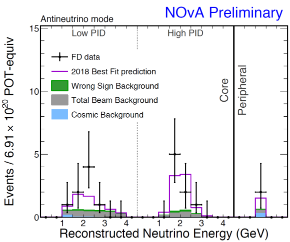
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$



$\nu_\mu \rightarrow \nu_e$



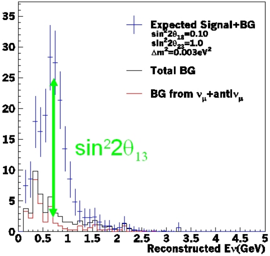
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

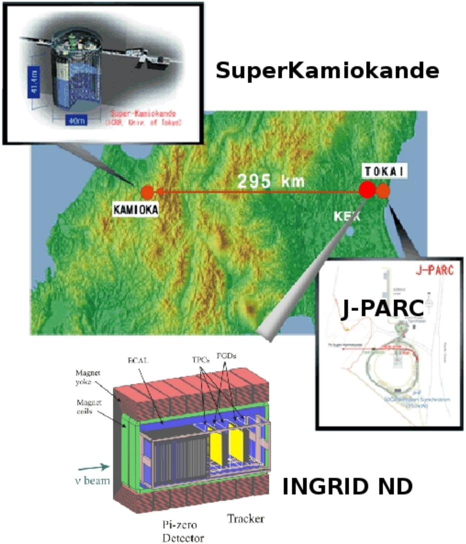


Off-axis high intensity ν_μ beams: T2K

First proposed for BNL E-889 (1995): A narrow beam of ν can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

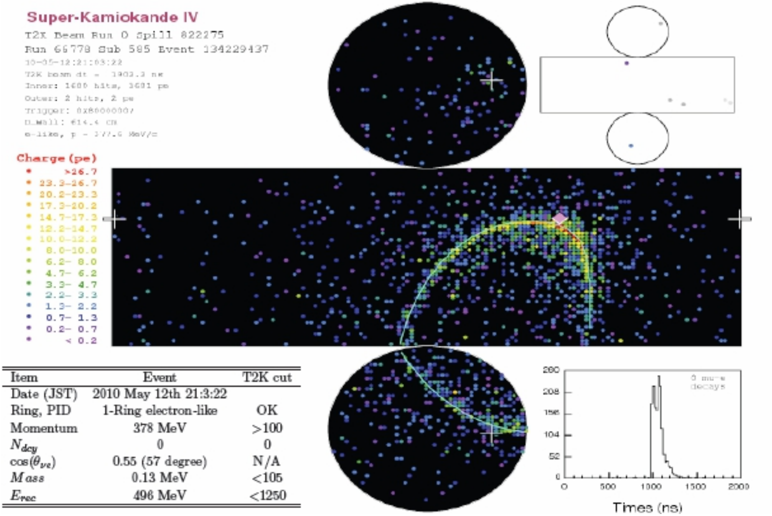
Signal at $\sin^2 2\theta_{13} = 0.1$:





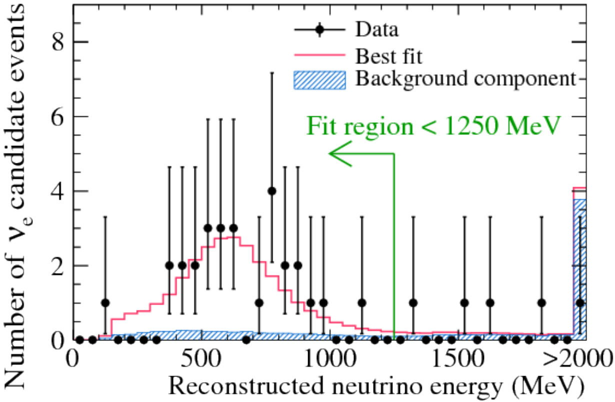
T2K first results announced in March 2011

T2K beam ν_e Candidate Event 2010



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

T2K: First Observation of $\nu_\mu \to \nu_e$ APPEARANCE

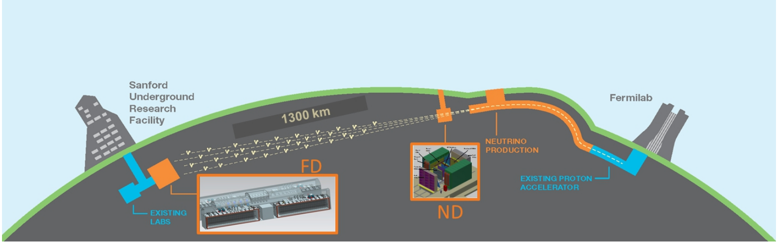


In 2014 T2K observes conversion of ν_μ to ν_e (atmospheric oscillation scale) with an amplitude of $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$.

2016 Breakthrough Prize in Fundamental Physics

The 2016 Breakthrough Prize in Fundamental Physics awarded to 7 leaders and 1370 members of 5 experiments investigating neutrino oscillation: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)

The Deep Underground Neutrino Experiment



- **A very long baseline experiment: 1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Gold Mine) in Lead, SD.**
- **A highly capable near detector at Fermilab.**
- **A very deep (1.5 km underground) far detector: massive 40-kton Liquid Argon Time-Projection-Chamber with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam from LBNF produced from the 1-2MW upgraded Main Injecctor accelerator at Fermilab.**

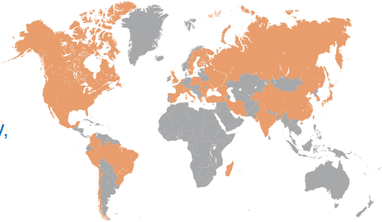
The DUNE Scientific Collaboration

As of Jan 2018:

60 % non-US

1061 collaborators from 175 institutions in 31 nations

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

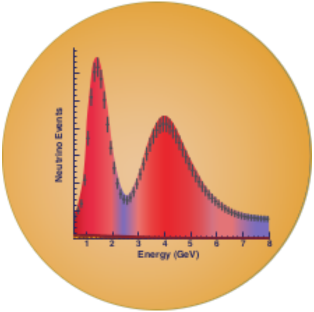


The DUNE Scientific Collaboration

2 masters (1 from ASP2016) students from Madagascar finished their thesis early 2018 with mentors from BNL and Fermilab:

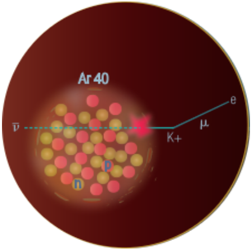
Miriama and Herilala at the Fermilab Neutrino Physics Center

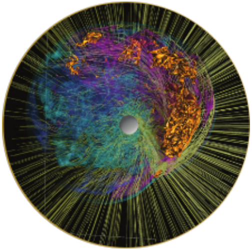
Scientific Objectives of DUNE



1. **precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase $\delta_{\rm CP}$, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \rightarrow \nu_{e,\mu}$ oscillations**

Scientific Objectives of DUNE

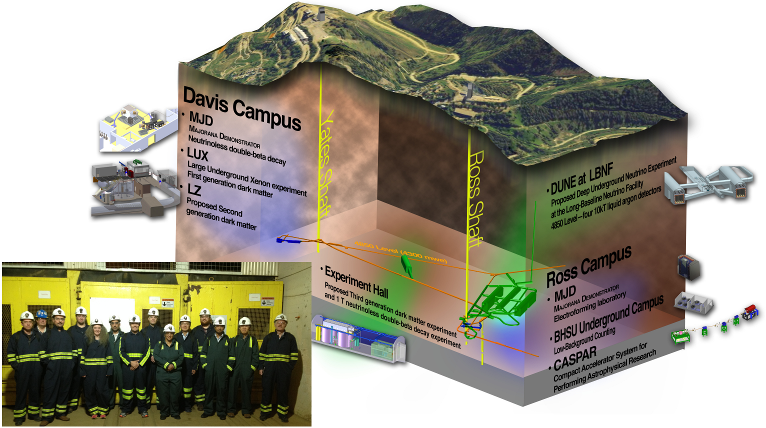




3. search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \rightarrow K^+\overline{\nu}$

4. detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE

The Sanford Underground Research Facility

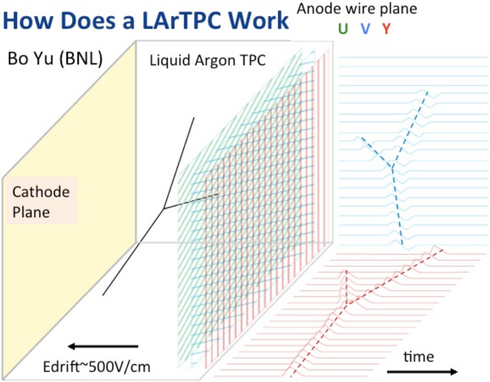


Experimental facility operated by the state of South Dakota. LUX (dark matter) and Majorana ($0\nu - 2\beta$) demonstrator operational expts at 4850-ft level. Chosen as site of G2 dark matter experiment

The DUNE Far Detector

A large cryogenic liquid Argon detector located a mile underground in the former Homestake Mine with a mass of at least 40 kilo-tons is used to image neutrino interactions with unprecedented precision:

Single Phase LArTPC



The DUNE prototype wireplane

The DUNE Far Detector

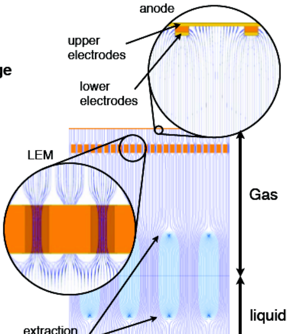
Dual Phase LArTPC

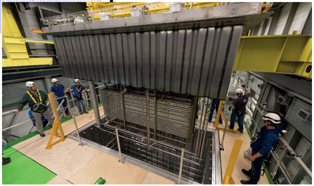
4.) Charge **collection** on a **2D anode readout** (symmetric unipolar signals with two orthogonal views)

3.) Charge multiplication in the holes of the **Large Electron Multiplier (LEM)**

2.) Drift electrons are efficiently emitted into the gas phase

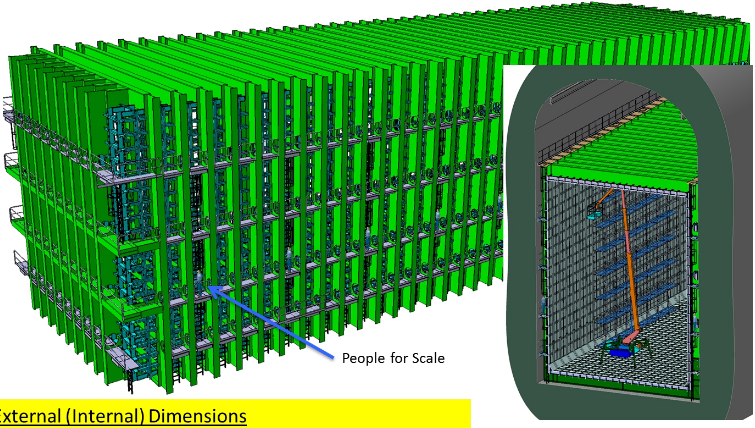
1.) Ionization electrons drift towards the liquid argon surface





The DUNE Far Detector

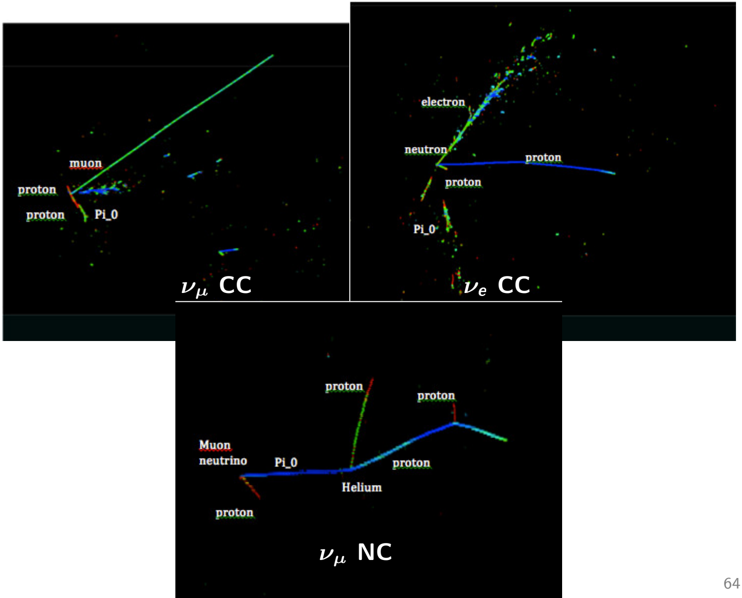
The 40-kton (fiducial) detector is constructed of four modules with a total mass of 17.4 kton each.



External (Internal) Dimensions

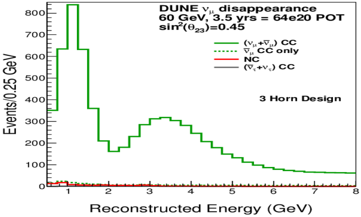
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

Reconstructed Neutrino Interactions in a LArTPC

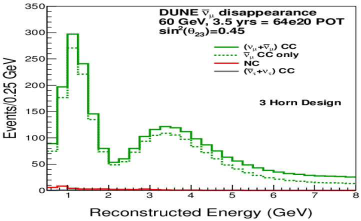


DUNE Event Spectra

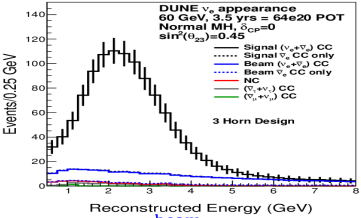
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085,\ \sin^2 \theta_{23} = 0.45,\ \delta m^2_{31} = 2.46 \times 10^{-3}\ \text{eV}^2$)



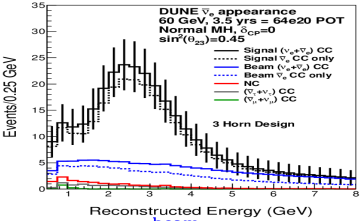
8329 ν_μ, 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



2420 $\bar{\nu}_\mu$, 791 ν_μ, 33 NC, 13 ν_τ



930 ν_e, 5 $\bar{\nu}_e$, 204 ν_e^{beam}, 17 NC, 19 ν_τ, 3 ν_μ

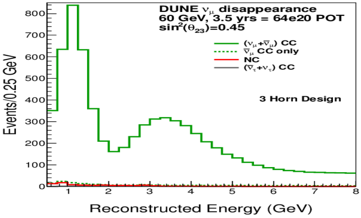


154 $\bar{\nu}_e$,32 ν_e, 98 ν_e^{beam}, 7 NC, 8 ν_τ, 1 ν_μ

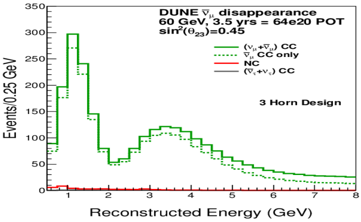
Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu$ $\Rightarrow$ explicit demonstration of CPV

DUNE Event Spectra

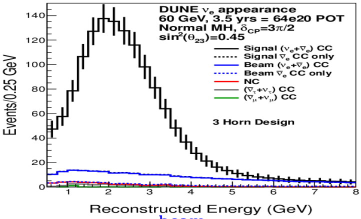
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085,\ \sin^2\theta_{23} = 0.45,\ \delta m^2_{31} = 2.46 \times 10^{-3}\ \text{eV}^2$)



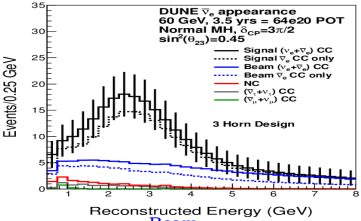
8329 ν_μ, 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



2420 $\bar{\nu}_\mu$, 791 ν_μ, 33 NC, 13 ν_τ



1171 ν_e,3 $\bar{\nu}_e$, 204 ν_e^{beam}, 17 NC, 19 ν_τ, 3 ν_μ



94 $\bar{\nu}_e$,39 ν_e, 98 ν_e^{Beam}, 7 NC, 8 ν_τ, 1 ν_μ

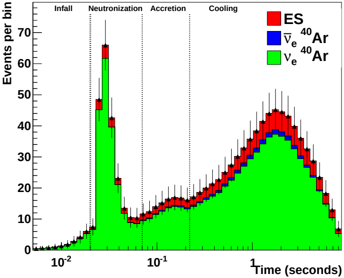
Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu$ $\Rightarrow$ explicit demonstration of CPV

Possible Supernova Signature in DUNE

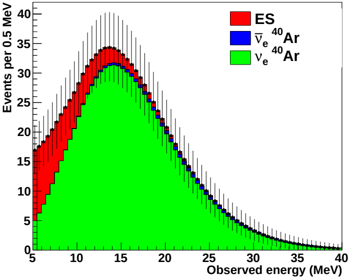
Liquid argon is particularly sensitive to the ν_e component of a supernova neutrino burst:

$$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*, \qquad (1)$$

Expected time-dependent signal in 40 kton of liquid argon for a Supernova at 10 kpc:



Time distribution



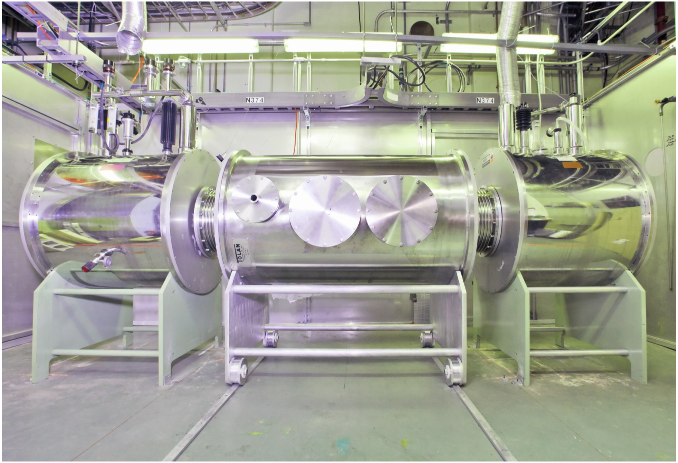
Energy spectrum (time integrated)

LBNF/DUNE Schedule

- **2017: Cavern excavation begins**
- **2018: DUNE prototypes (single & dual phase) operational in test beam at CERN**
- **2019: Technical design review (beam and far detectors) by US-DOE and international funding energies. Conceptual design for near detector ready.**
- **2021: First 10kton FD module (single phase) installation**
- **2023: Second FD module (single or dual phase) installation**
- **2024: Data taking (non-beam) starts with 20 kton operational**
- **2026: First beam operations at 1.2 MW**

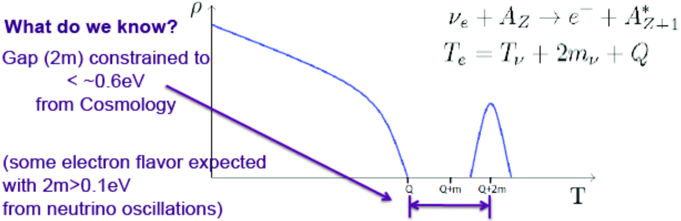
PTOLEMY: Detecting Big Bang Neutrinos

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield



How to detect Big Bang Neutrinos

From paper by Steven Weinberg in 1962 (Phys. Rev. 128:3 1457]. Detect capture of BB neutrinos on a beta decaying nucleus:



What do we know?

Gap (2m) constrained to < ~0.6eV from Cosmology

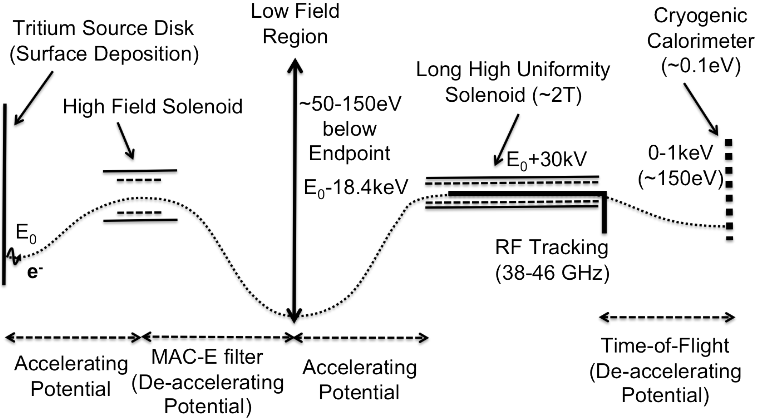
(some electron flavor expected with 2m>0.1eV from neutrino oscillations)

$$\nu_e + A_Z \to e^- + A^*_{Z+1}$$

$$T_e = T_\nu + 2m_\nu + Q$$

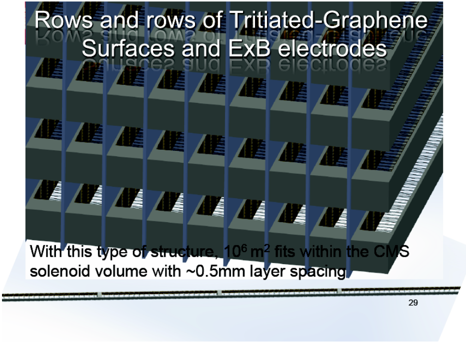
Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

Experimental Concept



Many techincal challenges!!!

The biggest nearly insurmountable problem for relic neutrino detection using capture on tritium is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium!

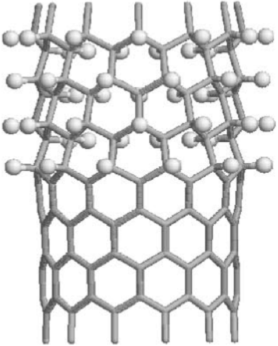


Rows and rows of Tritiated-Graphene Surfaces and ExB electrodes

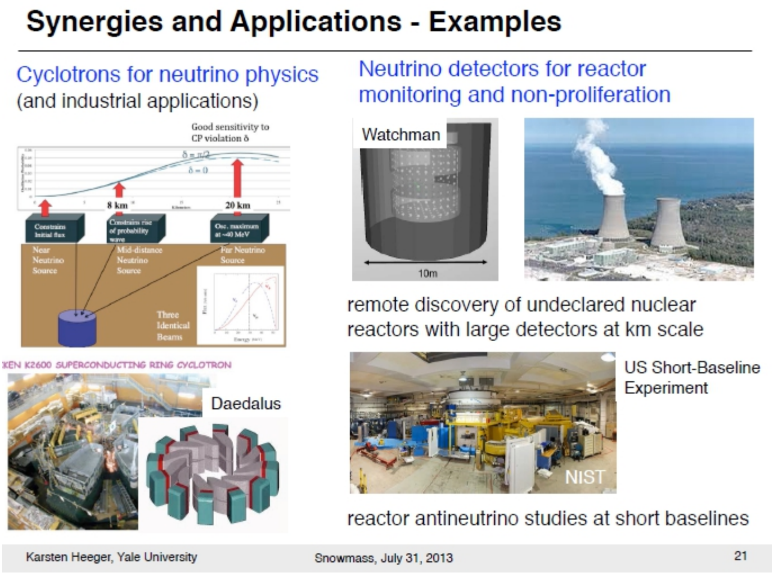
With this type of structure, 10^6 m^2 fits within the CMS solenoid volume with ~0.5mm layer spacing

29

Ultra-modern materials science needed: Use tritium trapped in very thin layers of graphene:



Practical Applications of Technologies for ν Experiments



Synergies and Applications - Examples

Cyclotrons for neutrino physics
(and industrial applications)

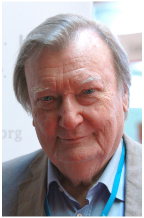
Neutrino detectors for reactor monitoring and non-proliferation

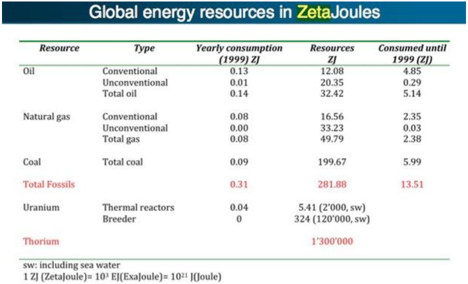
remote discovery of undeclared nuclear reactors with large detectors at km scale

reactor antineutrino studies at short baselines

Multi-MW Accelerators Driving Thorium Reactors

First proposed by Carlo Rubbia in 1995 (1984 Nobel Prize winner)





Global energy resources in ZetaJoules

Resource	*Type*	*Yearly consumption (1999) ZJ*	*Resources ZJ*	*Consumed until 1999 (ZJ)*
Oil	Conventional	0.13	12.08	4.85
	Unconventional	0.01	20.35	0.29
	Total oil	0.14	32.42	5.14
Natural gas	Conventional	0.08	16.56	2.35
	Unconventional	0.00	33.23	0.03
	Total gas	0.08	49.79	2.38
Coal	Total coal	0.09	199.67	5.99
Total Fossils		0.31	281.88	13.51
Uranium	Thermal reactors	0.04	5.41 (2'000, sw)	
	Breeder	0	324 (120'000, sw)	
Thorium			1'300'000	

sw: including sea water
1 ZJ (ZetaJoule)= 10^3 EJ(ExaJoule)= 10^{21} J(Joule)

Requires proton accelerators with powers of 10 MW. Currently neutrino and neutron experiments are driving the technology of high power MW class proton beams.

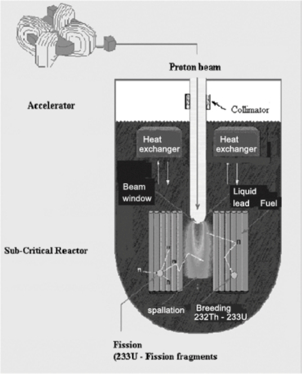
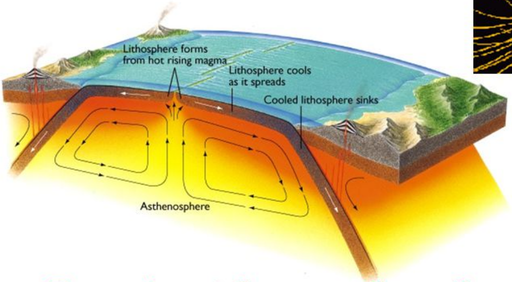
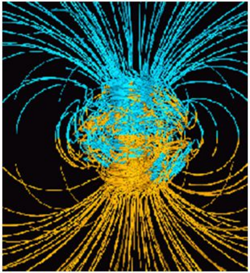


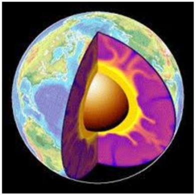
Figure 1. Schematic representation of Energy Amplifier proposed by Rubbia [4]

Neutrinos and Earth’s Geology

Plate Tectonics, Convection, Geodynamo



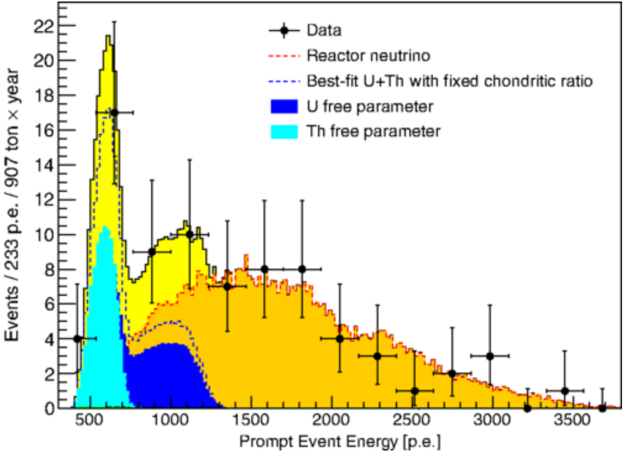




Does heat from radioactive decay drive the Earth’s engine?

Neutrinos and Earth's Geology

Signal of $\bar{\nu}_e$ from radioactive decays of U/TH in the earth observed in the BOREXINO solar neutrino experiment:



Summary

- **Neutrinos have been at the forefront of fundamental discoveries in particle physics for decades.**
- **Discoveries of neutrino properties like the very small mass, large almost maximal mixing, are the** *ONLY direct evidence for physics beyond the Standard Model of particle physics, and new hidden symmetries.*
- **Neutrinos straddle the fields of nuclear physics, particle astrophysics, cosmology and high energy particle physics. Thus, they provide a unique probe to test for consistency in our picture of the Universe from the development of the Big Bang, the mechanics of Supernova explosions, the chemistry of stars, the geology of the earth, and the nuclear physics of reactors.**
- **Studying the properties of neutrinos with energies varying from the very cold (Big Bang ν) to the PeV scale requires a huge diversity of experiments, each with its own unique technical challenges.**

THANK YOU

Click for Neutrino rap!!