Experimental Neutrino Physics

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TRISEP Summer School

With much help from

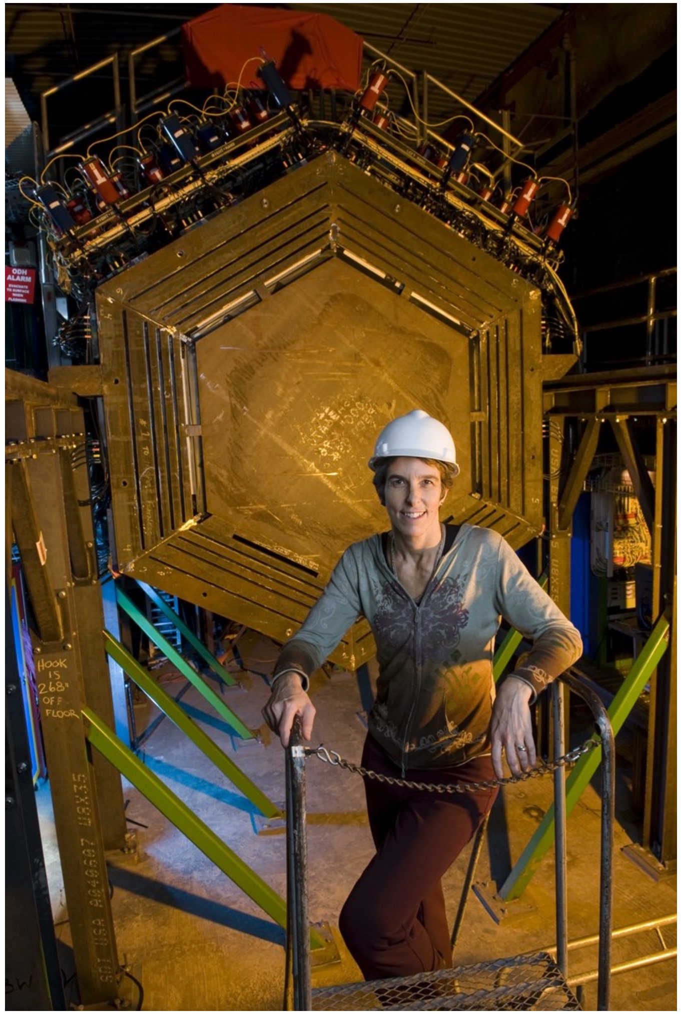
International Neutrino Summer Schools of the past

and the

Neutrino 2022 Conference: https://indico.kps.or.kr/event/30/

Who am I?

- This is my fourth year at York University, with a joint appointment with Fermilab, (the TRIUMF of the US).
- Before that, I worked 20 years as a Scientist at Fermilab
- Have seen different aspects of particle physics:
  - Graduate thesis looking for CP-violation in rare Kaon decays
  - Spent postdoc years studying weak interactions with high energy (~100GeV) neutrinos
  - Started working on neutrino oscillations (~GeV neutrinos)
    - Initially worked on neutrino beam designed for MINOS
    - Started worrying about neutrino interactions-enter MINERvA!
    - Collaborator on T2K & DUNE



What this course will cover

- Neutrino Oscillations
- Neutrino Mass and Neutrinoless Double Beta Decay
- Neutrino Telescopes

- Experimental Details: How these measurements are made

$$N = \Phi\sigma \mathrm{M}\epsilon$$

Events=flux [ν/area]*cross section [per nucleon]*detector mass [# nucleons]*efficiency

“Experimental ν Physics in 25 words or less”

$$N = \Phi\sigma\mathrm{M}\epsilon$$

- Neutrino Sources (Φ)
  - Neutrinos are everywhere
- Neutrino Interactions (σ)
  - It’s all about thresholds
- Neutrino Detectors $(\mathrm{M}\epsilon)$
  - Different strategies for different energies (and helicities)
- Current Results
  - Precision $\nu_e(\bar{\nu}_e)$ Appearance *and* $\nu_\mu\bar{\nu}_\mu, \bar{\nu}_e$ Disappearance
- Next Steps
  - Bigger Detectors, more intensity, new windows

Neutrino Oscillations

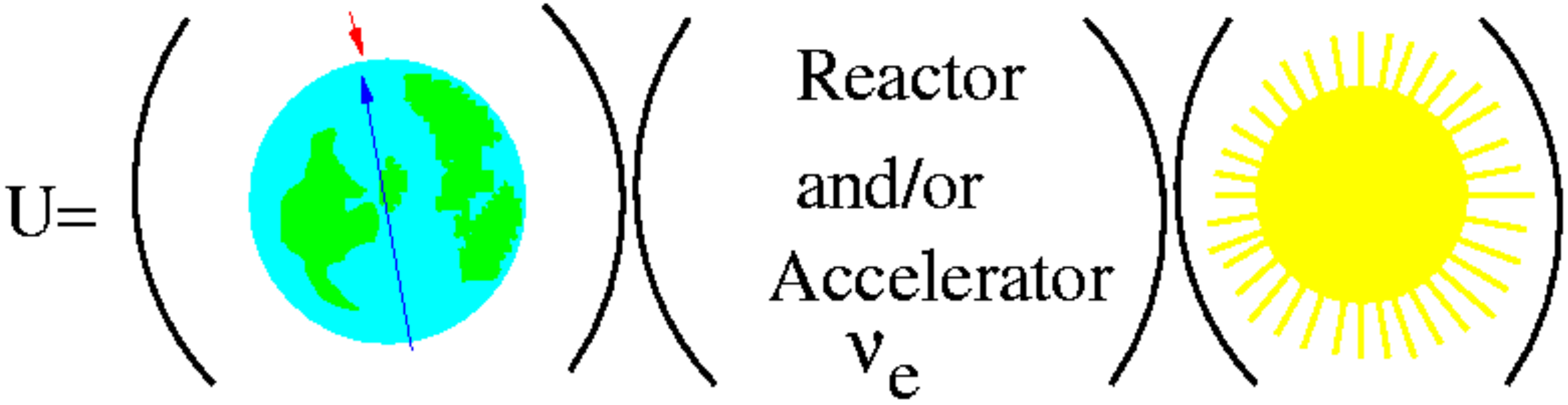
How do neutrinos change flavour over time?

3-Generation Neutrino Oscillation Mixing

Unitary matrix defined by 3 mixing angles and a phase

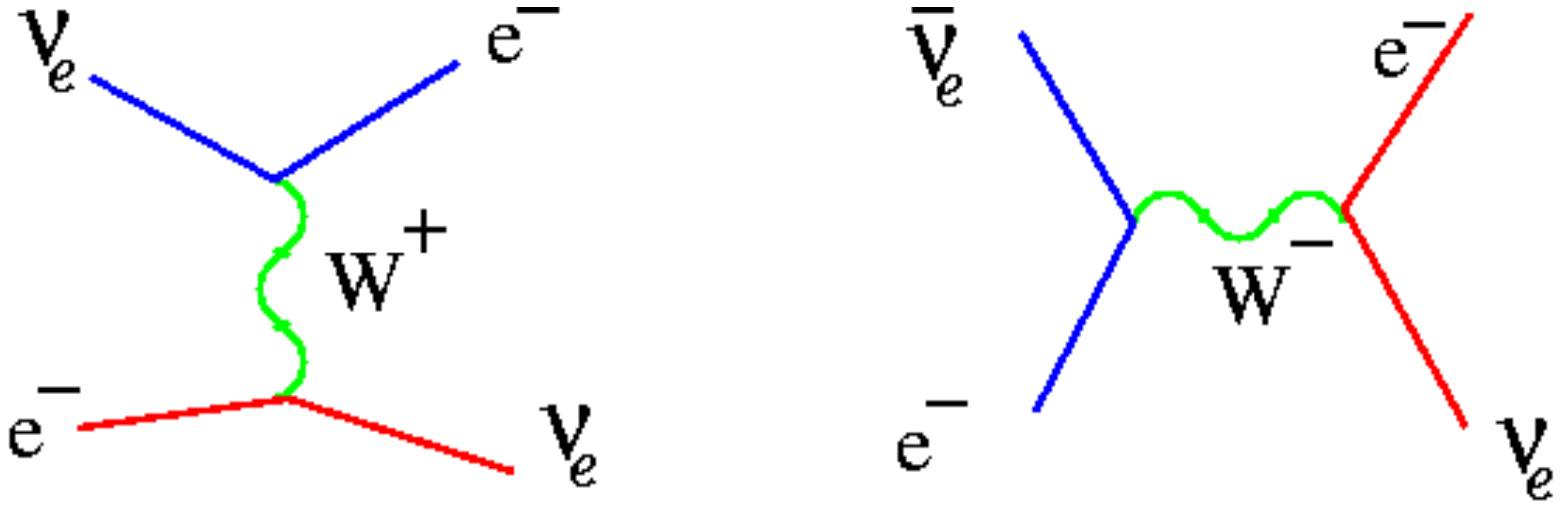
Call angles $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ denote $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Additional Complication: Matter Effects

- The oscillation probability changes differently for electron neutrinos vs antineutrinos when they propagate through matter:



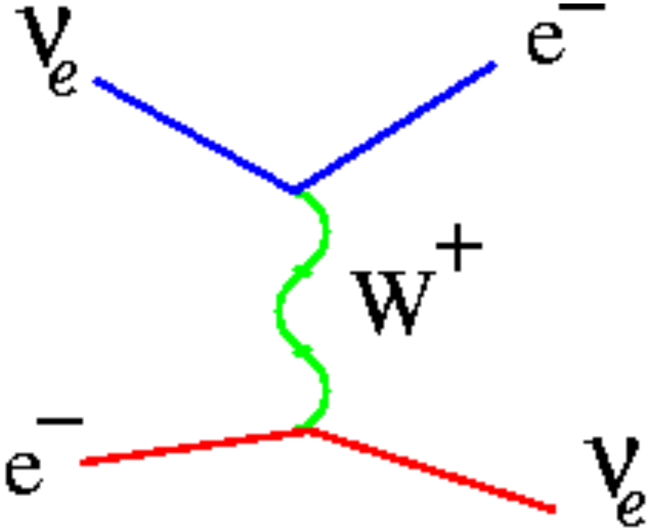
Wolfenstein,
PRD (1978)

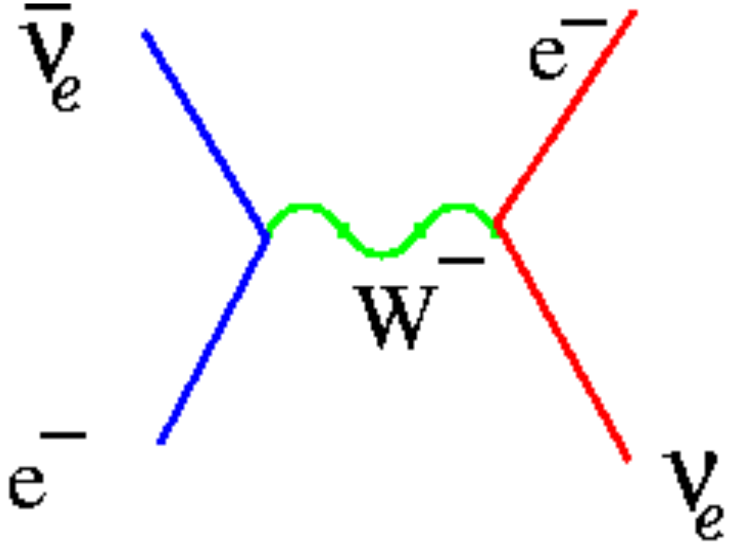
  - Can’t treat neutrinos propagating through earth simply as mass eigenstates, have to take into account electron flavor
  - This would give an apparent CP violation just because the earth is not CP-symmetric

Additional Complication: Matter Effects, with math…

- Remember the 2-generation formula?

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$





Wolfenstein,
PRD (1978)

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \qquad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

ν Oscillation Probabilities

- ν_μ Disappearance: $1-\sin^2 2\theta_{23}\sin^2(\Delta m^2_{32}L/4E)$
- ν_e Disappearance:

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

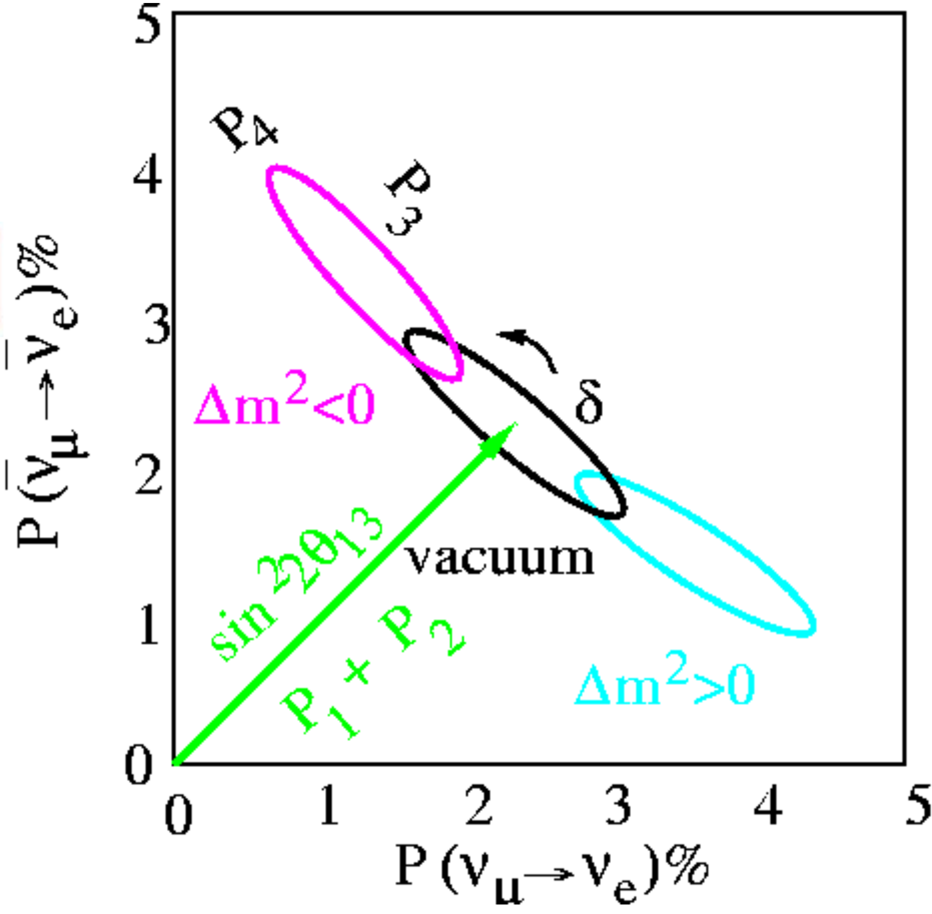
- ν_e appearance in a ν_μ beam: even more complicated…
- $P(\nu_\mu\to\nu_e)=P_1+P_2+P_3+P_4$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$



Minakata & Nunokawa JHEP 2001

Measuring Oscillation Probability:

$$\Phi_\beta(t) = \Phi_\alpha(0)P_{\alpha\to\beta}(t) = \Phi_\alpha(L=0)P_{\alpha\to\beta}({}^{L}/_{E})$$

$$N = \Phi\sigma\mathrm{M}\epsilon$$

$$N(E_\nu) = \Phi(E_\nu)\sigma(E_\nu)\mathrm{M}\epsilon(E_\nu)$$

- Must know or measure Neutrino Flavor
- Distance between creation and detection
- Neutrino Energy
  - No source we can use today is monochromatic!
  - Initial state: neutrino plus nucleus or electron
  - Final state: a bunch of stuff you only measure so well, sometimes you only measure the charged lepton
- Neutrino or Antineutrino?
  - Accelerator-based beams are always a mixture of both
  - Atmospheric neutrinos are also a mixture
  - Reactors and the sun are only one or the other

Measuring Oscillation Probabilities

For a given number N_β of ν_β events in a detector,
If you are starting with a source of ν_α: look for

$$N_\beta(E) = \Phi_\alpha(E) P_{\alpha\rightarrow\beta}\left({}^{L}/_{E}\right)\sigma_\beta(E)\mathrm{M}\epsilon_\beta(E)$$

ϕ=flux, σ= cross section ε=efficiency M=detector mass

Simple, right?

Neutrino Sources

- Key Parameters:
  - Flux
  - Energy
  - Baseline(s) available
  - Neutrino Beam Flavor and Helicity Composition
  - Are there matter Effects?
    - What do the neutrinos travel through between production and detection

Neutrinos from a Reactor

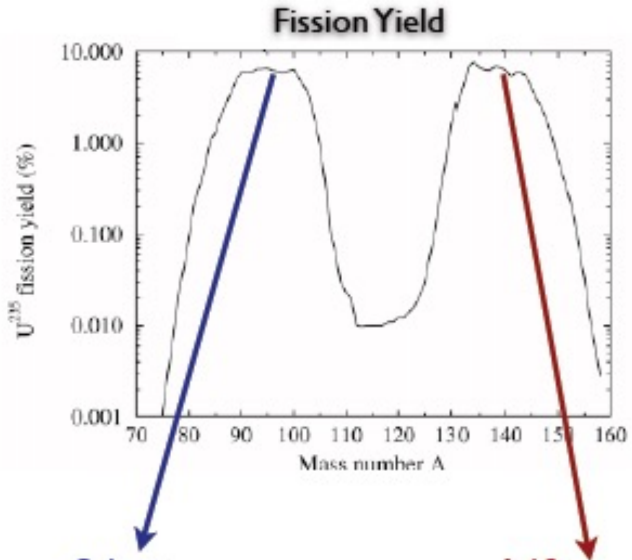
- What happens when a nucleus breaks apart?

$$ {}^{235}_{92}U + n \to X_1 + X_2 + 2n \to \ldots {}^{94}_{40}Zr + {}^{140}_{58}Ce $$

Sample Fission: ^{235}U

^{235}U

^{239}Pu

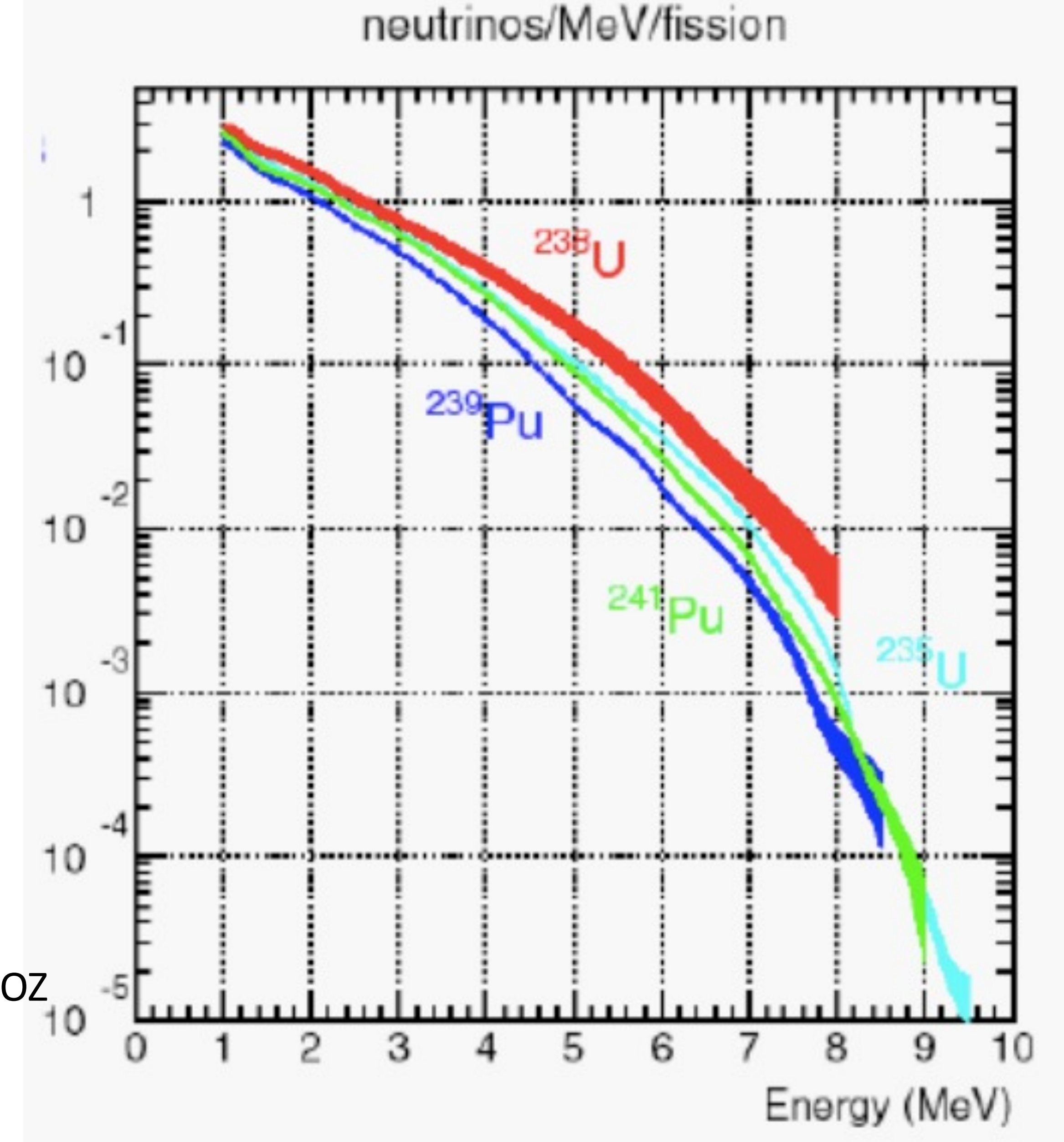


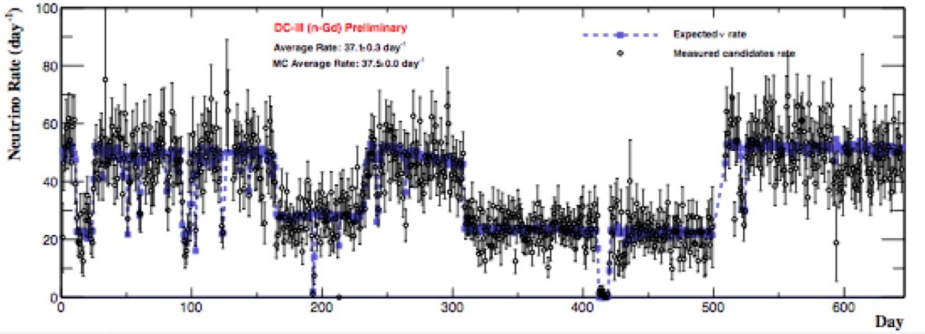
^{94}Zr

^{140}Ce

Reactor Energy Spectrum

- Several processes occurring during the fuel cycle of a reactor, with different yields and energy spectra
- One complex may have several cores, not all at the same point in their fuel cycles, not at same distance
- Different cores may turn on and off, rare for all cores to turn off at once



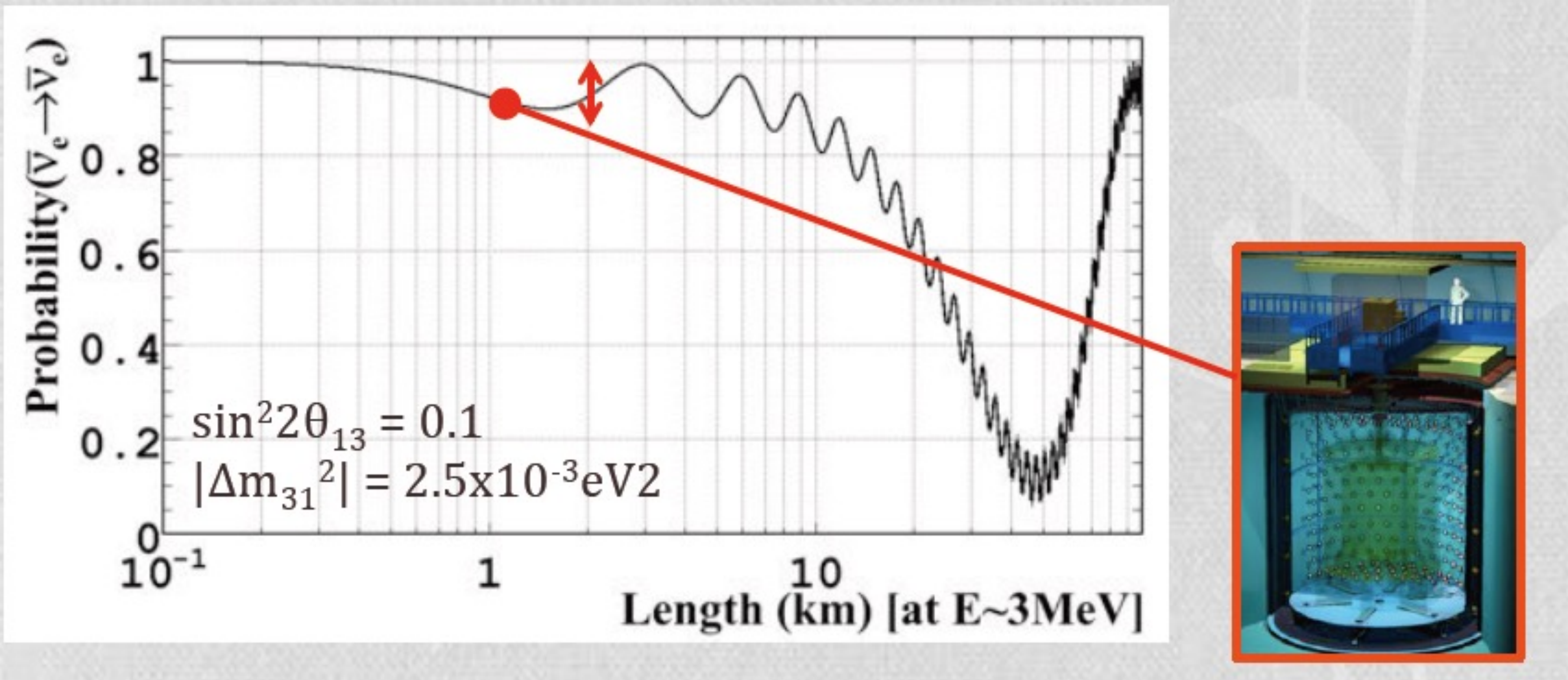


Time dependence from Double-CHOOZ

Baselines

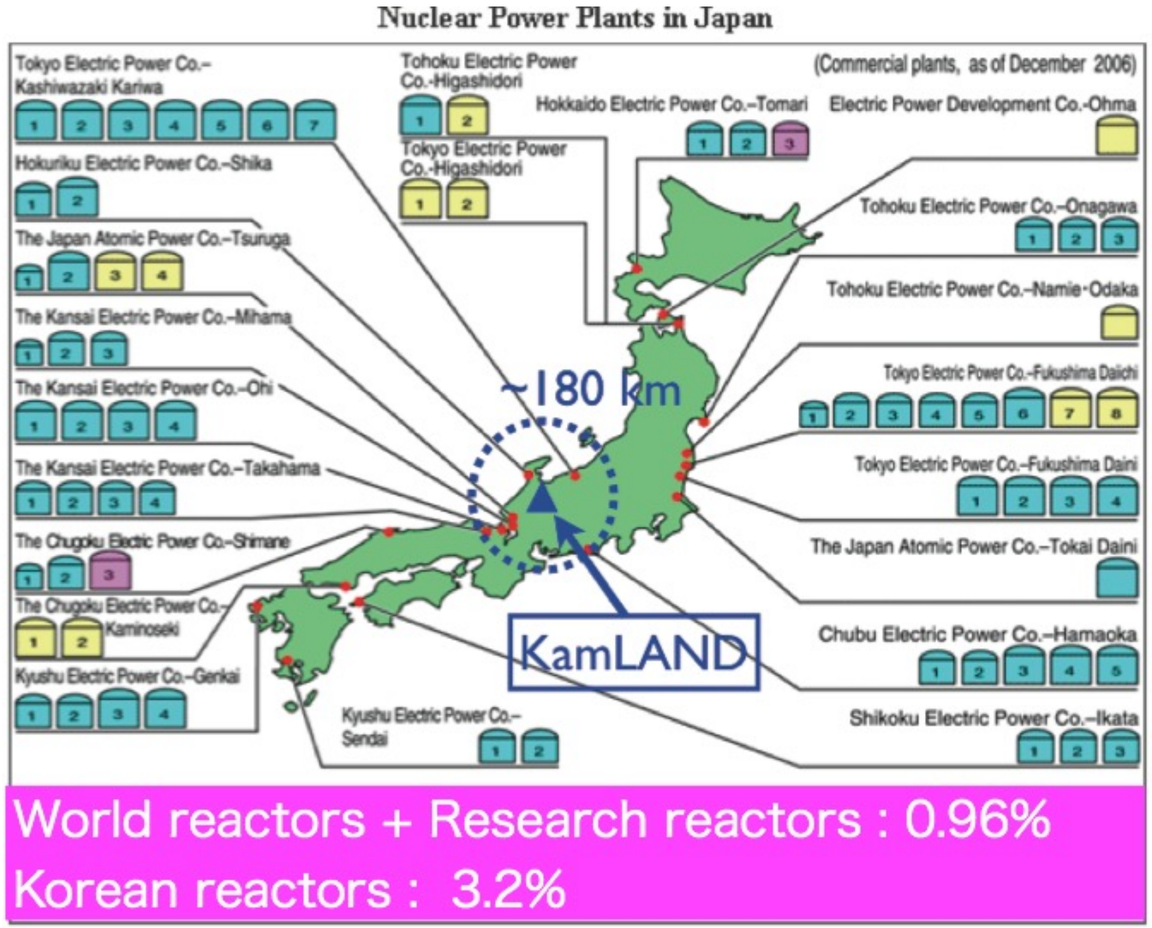
$$\boxed{P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{31}L/4E\right)-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}L/4E\right)}$$

- Reactors send out neutrinos in all directions, detector location depends on local geography
- Different physics can be reached at different baselines



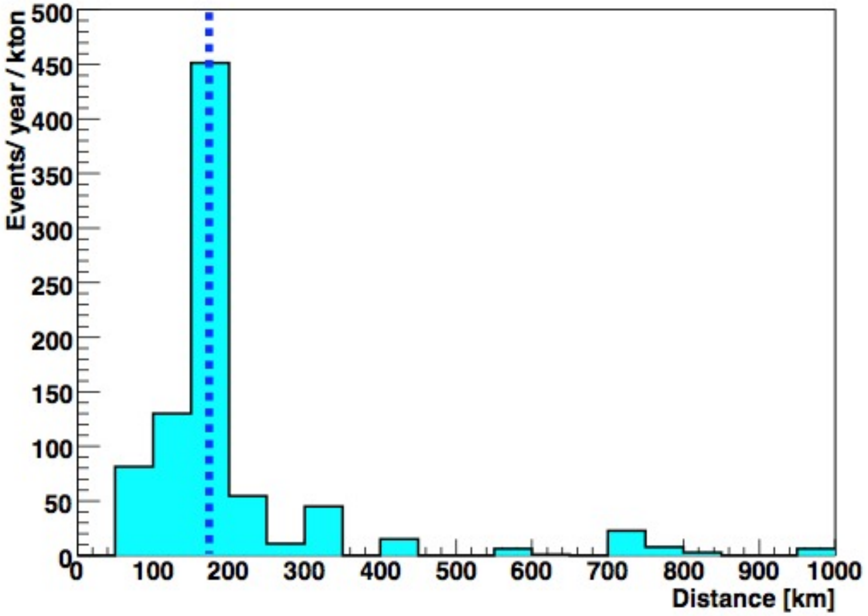
Extreme Example of Long baseline

- Kamland experiment: saw neutrinos from large array of reactors in Japan



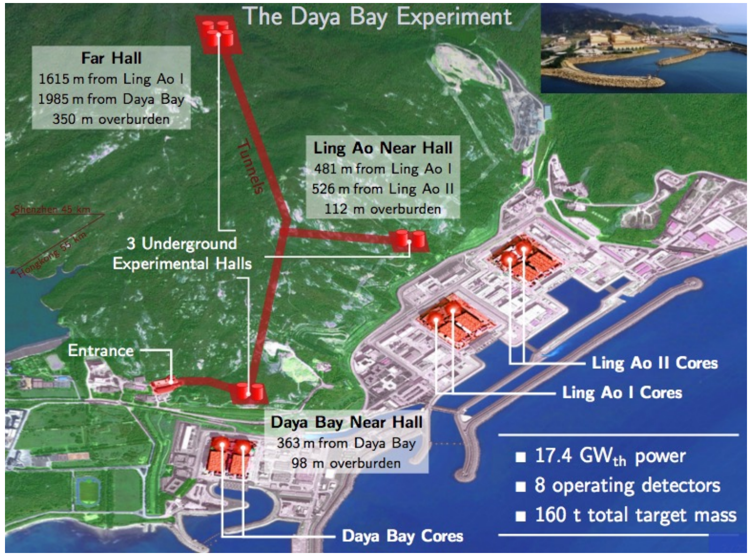
Effective baseline

~180 km



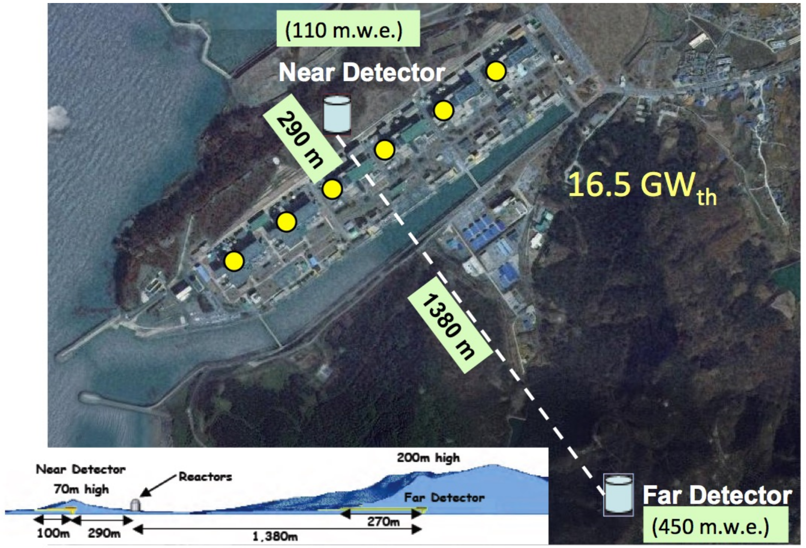
Ichimura, ν2008

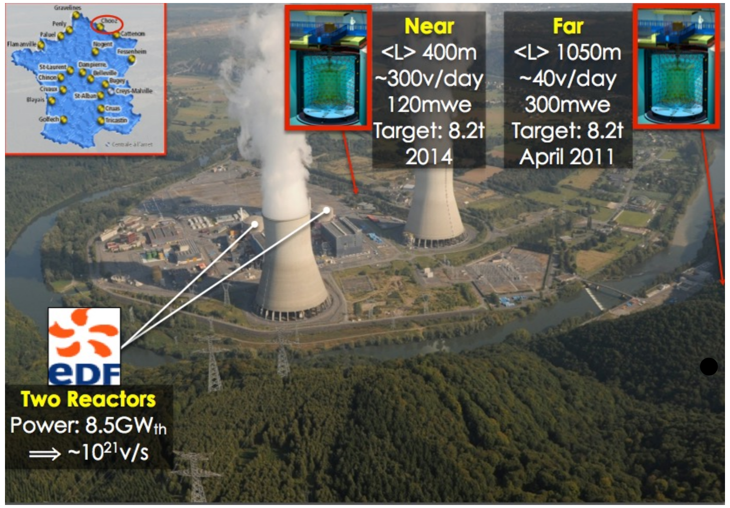
Shorter Baselines used



- Daya Bay: 3 cores, 3 halls, baselines of 1.6-2.0km

Reno: 6 reactor cores, 2 halls, baseline(s) ~1.3km

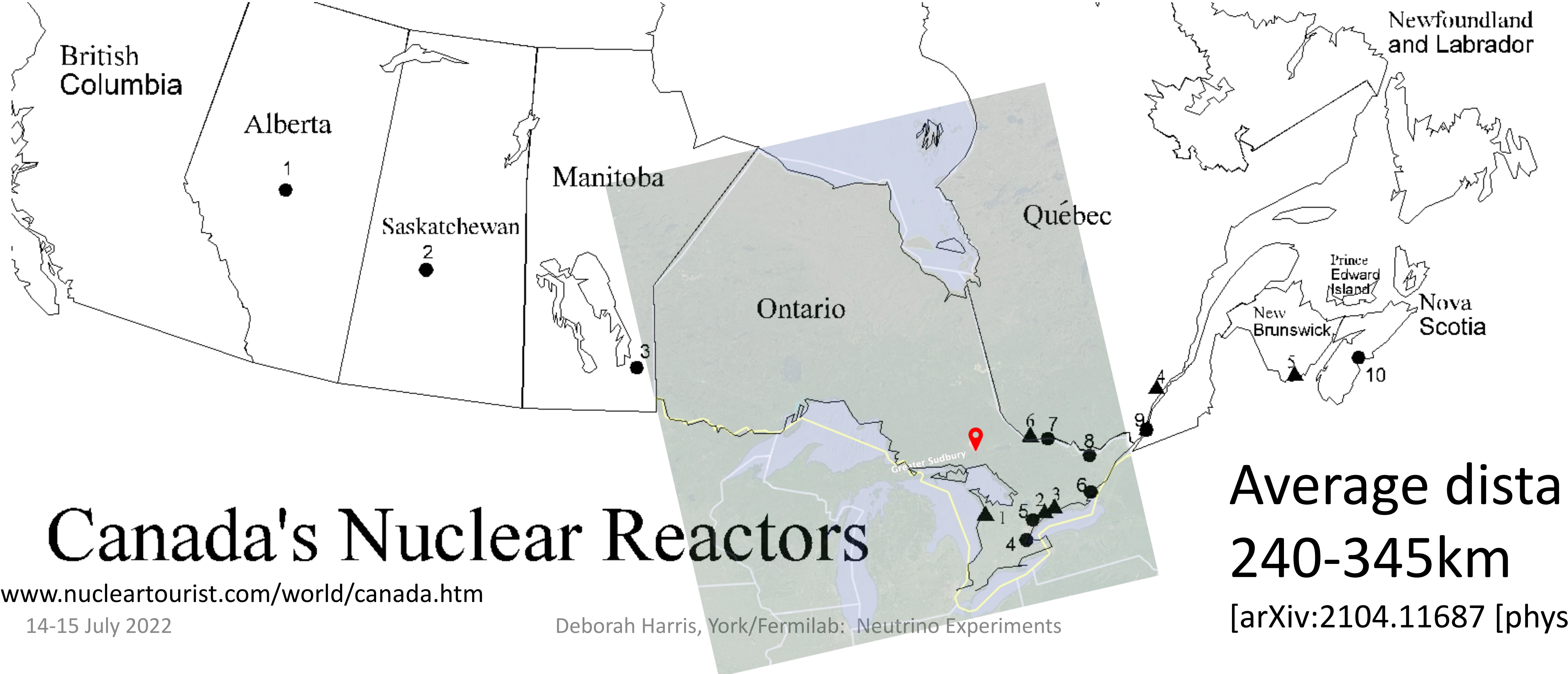




- Double Chooz: 2 cores, 2 halls at 0.4 and 1.0km

What about SNO+ and reactors in Canada?

- SNO+ in Sudbury, ON is a detector that is sensitive to reactor neutrinos…

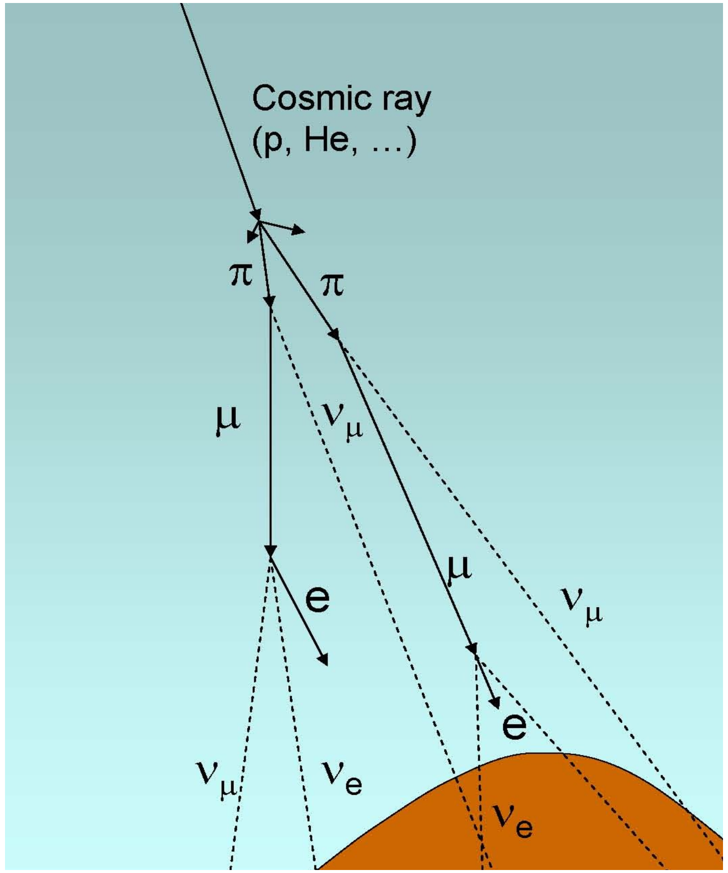


http://www.nucleartourist.com/world/canada.htm

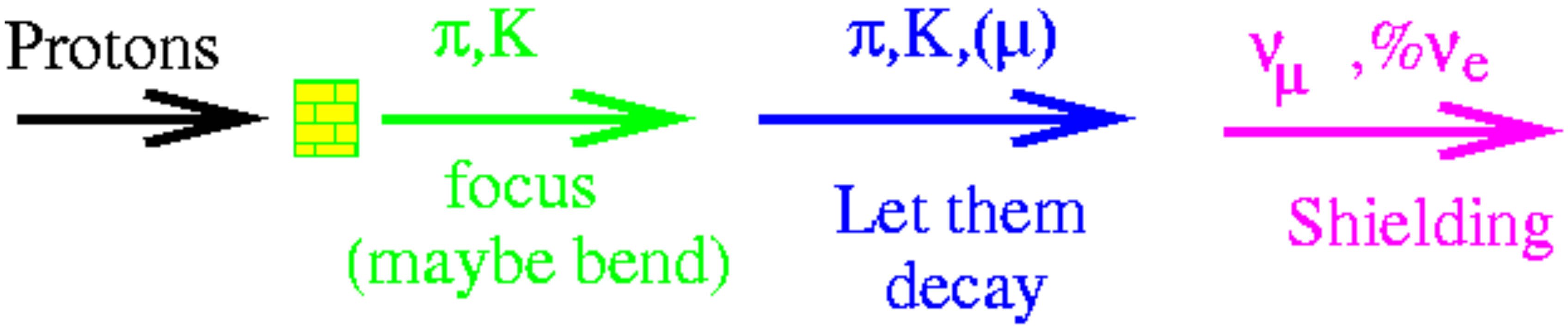
Average distance: 240-345km

[arXiv:2104.11687 [physics.ins-det]

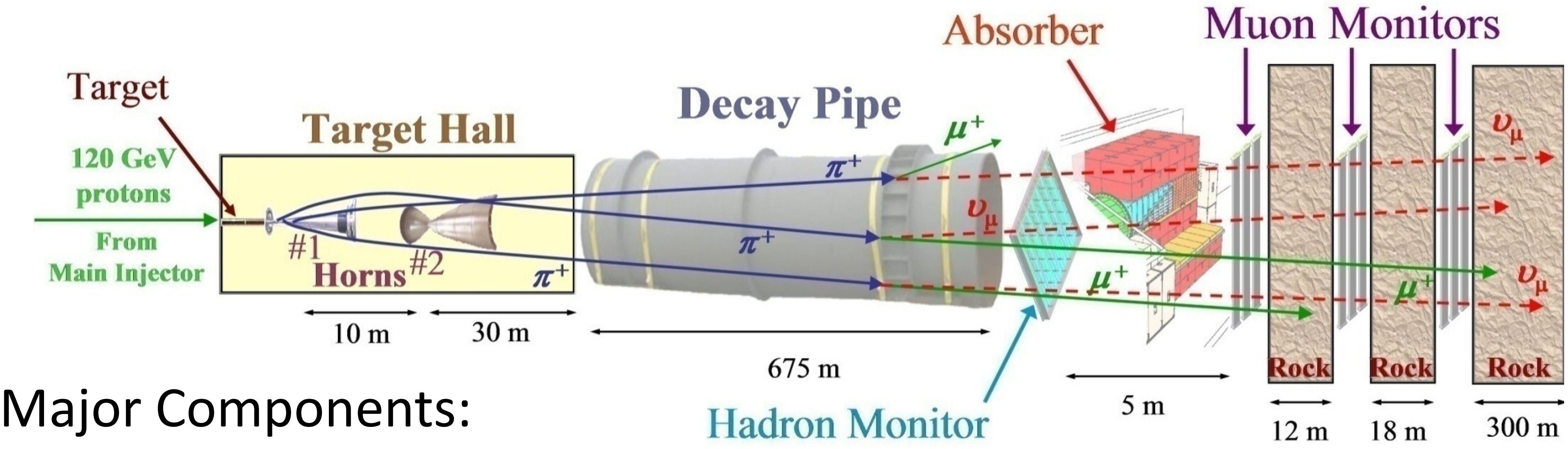
Atmospheric and Accelerator ν's



- Atmospheric Neutrino Beam:
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons also decay
- Conventional Neutrino Beam: very similar!



Example: NuMI beamline at Fermilab



Major Components:

- Proton Beam
- Pion Production Target
- Focusing System
- Decay Region
- Absorber
- Shielding…

Most ν_μ's from 2-body decays:

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$

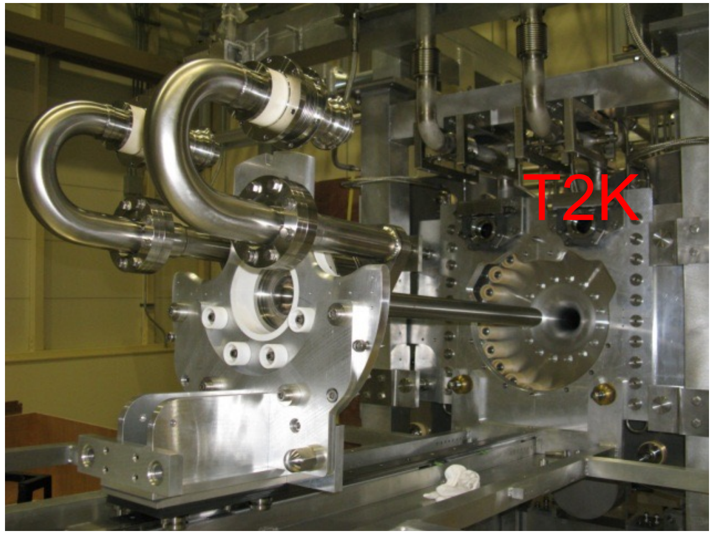
Most ν_e's from 3-body decays:

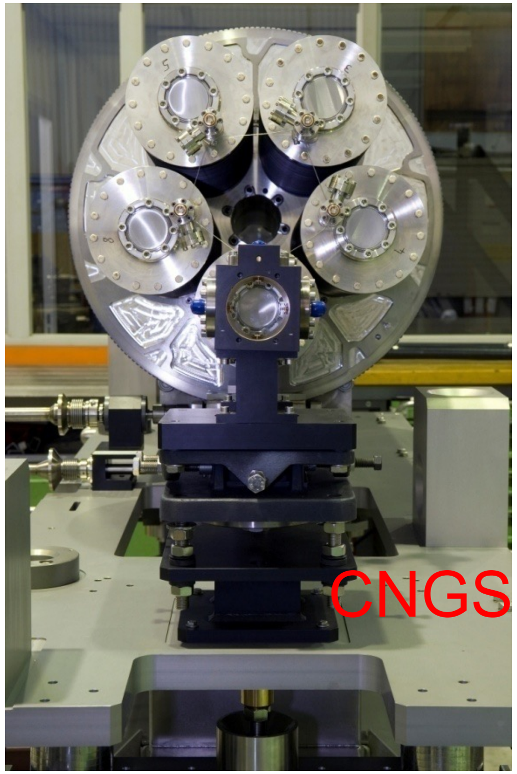
$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

Neutrino Production Targets

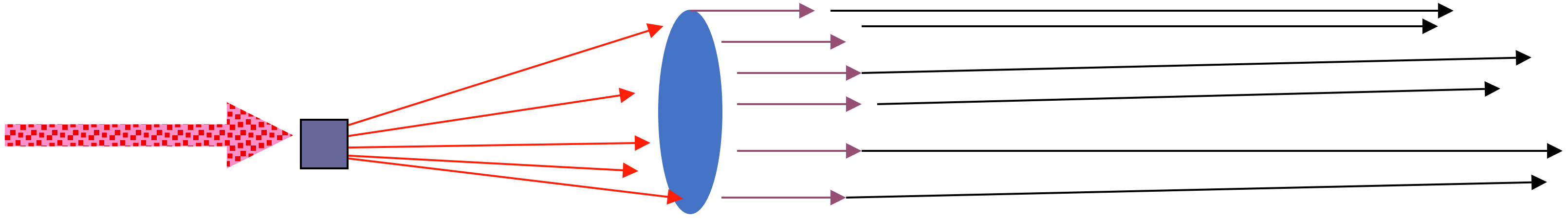
- Have to balance many competing needs:
  - The longer the target, the higher the probability the protons will interact
  - The longer the target, the more the produced particles will scatter
  - The more the protons interact, the hotter the target will get—targeting above ~1MW not easy!
  - Rule of thumb: want target to be 3 times wider than +- 1 sigma of proton beam size

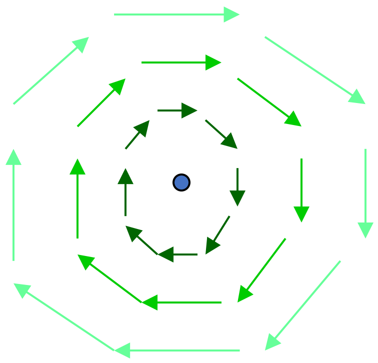




What focusing works best?

- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn





B Field from line source of current is

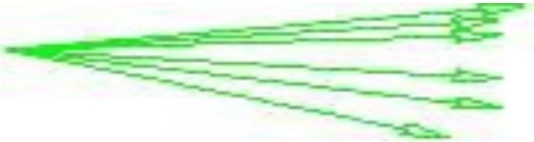
in the Φ direction

but has a size proportional to 1/r

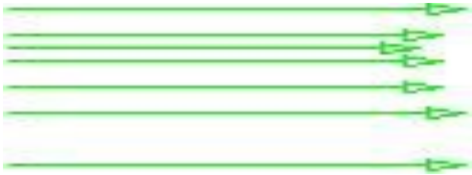
How do you get around this? (hint: $\partial pt \propto B\times \partial l$)

What should the B field be?

FROM

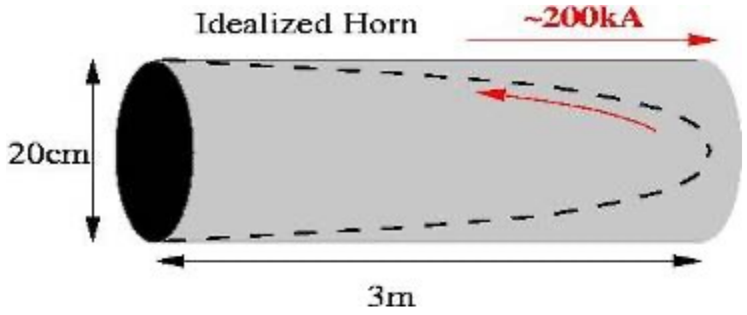


TO



- Make the particles at high radius go through a field for longer than the particles at low radius. ($B \propto 1/r$, but make $dl \propto r^2$)
- Horn: a 2-layered sheet conductor
- No current inside inner conductor, no current outside outer conductor
- Between conductors, toroidal field proportional to 1/r

$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta$$



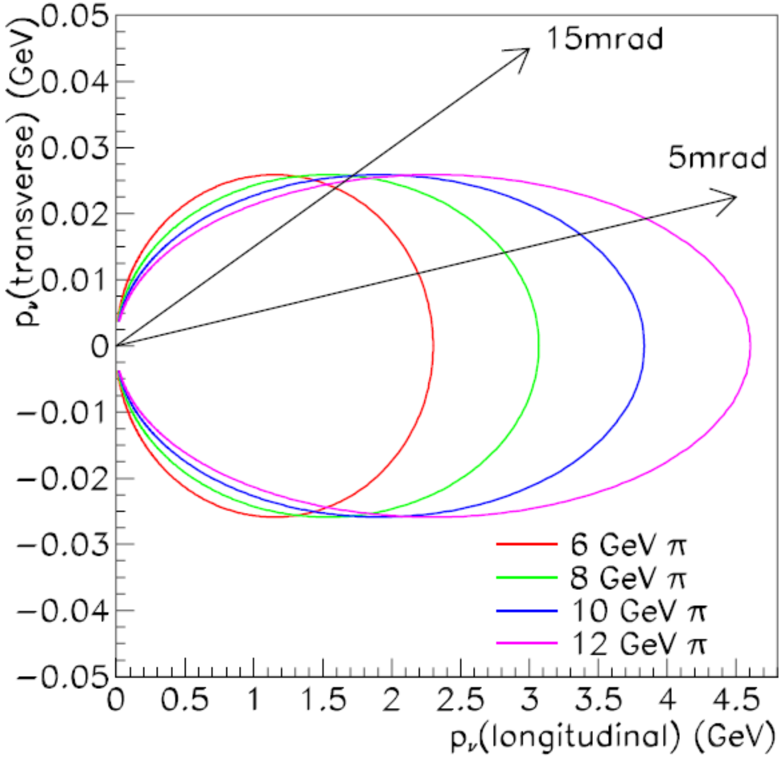
Horn Photo Album

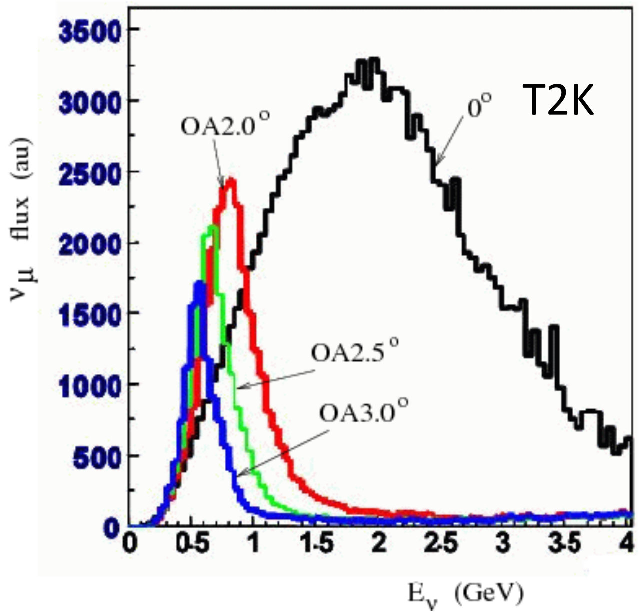
	Length (m)	Diameter (m)	# in beam
K2K	2.4,2.7	0.6,1.5	2
MBooNE	~1.7	~0.5	1
NuMI	3,3	0.3,0.7	2
CNGS	6.5m	0.7	2
T2K	1.4,2,2.5	.47,.9,1.4	3

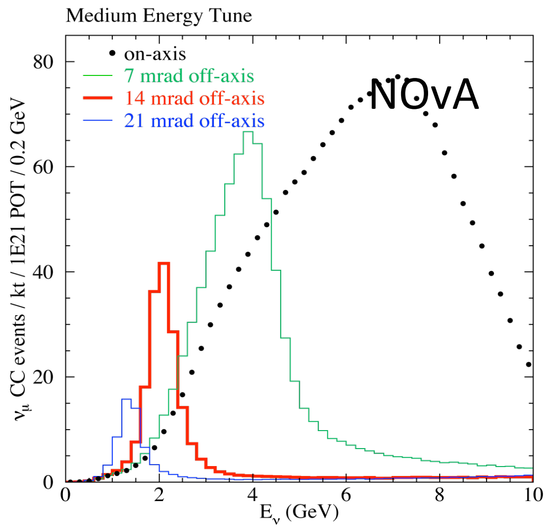
Need enormous currents: 200-300 kA!

Off-Axis Technique

- 1-1 relationship between neutrino energy and pion energy+angle between neutrino and pion
- Off axis neutrino beams: aim pions and kaons AWAY
  from detector
  - Ref: D. Beavis et al, BNL No. 52459, 4/95
  - T2K and NOvA both use this







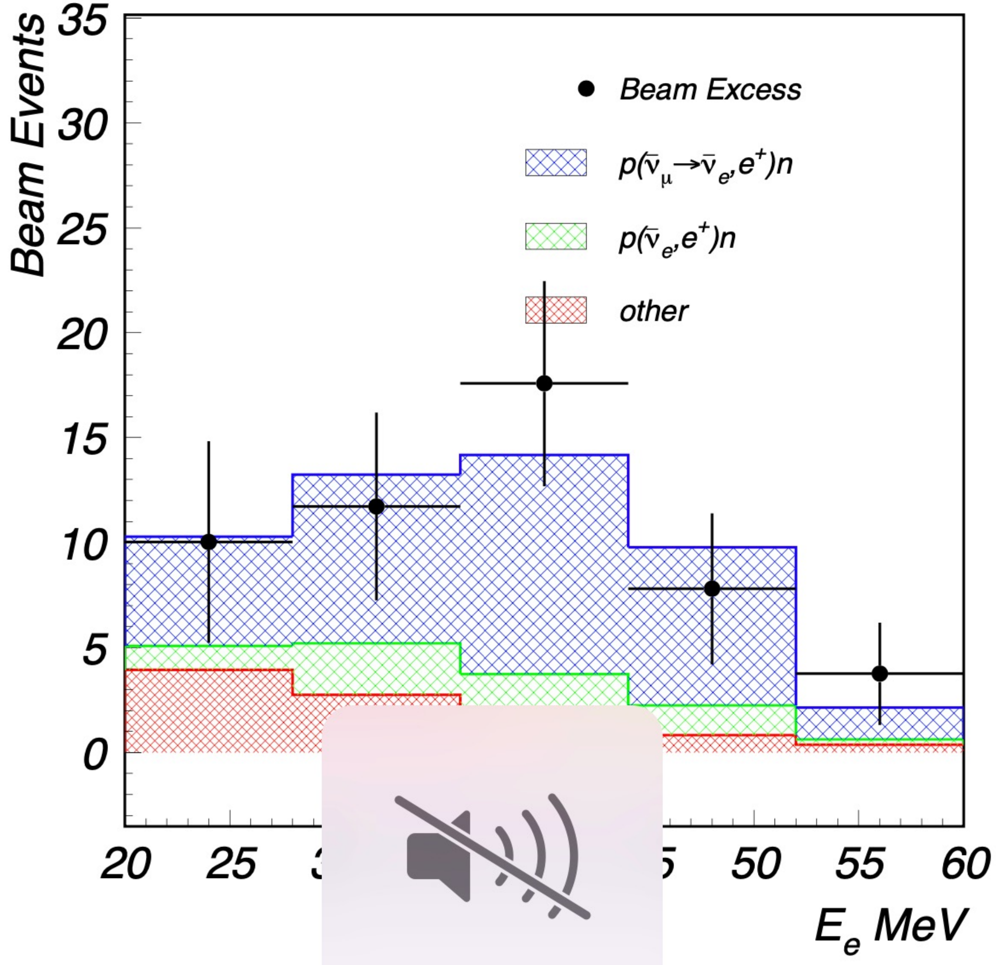
Oscillation Neutrino Source Summary

Source	Flux	ν Energy	Composition	Baseline	Matter Effects?
Sun	6×10^{10} $\nu/cm^2/sec$	0.1-10MeV	ν_e (ν_2)	10^8km	yes
Reactor	10^{20} $\nu/sec/GW$	1-10MeV	Anti-ν_e	1-180km	Technically no….
Atmosphere	1 $\nu/cm^2/sec$	0.1-10^4GeV	$\nu_e+\nu_\mu$ and anti-	80-10^4km	yes
Accelerator	18×10^5 $\nu/cm^2/sec$ @1km*	0.1-100GeV	$\nu_\mu+\%\nu_e$ or anti-$\nu_\mu+\%\nu_e$	1-1000km	yes

* NuMI beamline, "Medium Energy Tune"

Group Work

- Let's say that there was evidence for electron antineutrino appearance from Pion Decays at rest $(\pi\rightarrow\mu\nu_\mu)$.
- Let's say that the measurement implied a mass squared splitting that was >> 25x larger than the sum of the atmospheric and solar neutrino mass splitting:
- How might you confirm or refute this evidence?
    - Reactor Source
    - Accelerator Source



LSND, Phys.Rev.D 64 (2001)

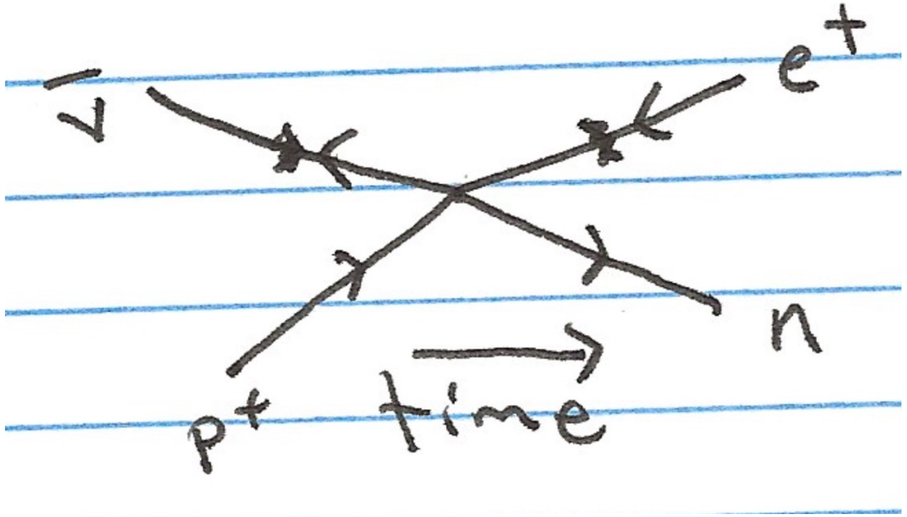
Neutrino Interactions

So we have a neutrino source, now what?

Energies useful for oscillation measurements range from 1MeV to 100GeV!

Reminder from Last Week's Lectures

- July 5 lecture from Andrew Leprowski:

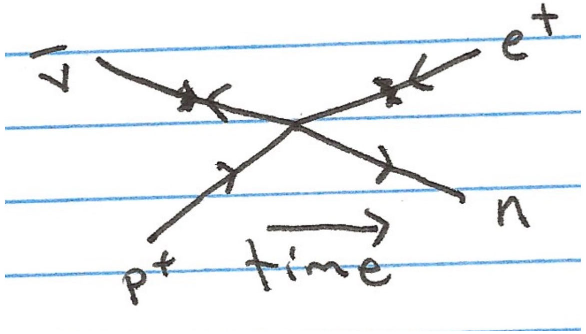


- He calculated the cross section:

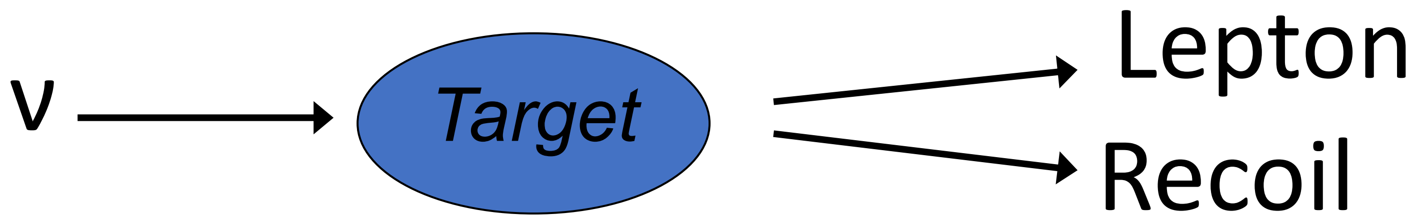
$$\sigma(\bar{\nu} p^+ \to e^+ n) \sim \frac{1}{E_{cm}^2} G_F^2 E_{cm}^4 \sim G_F^2 E_{cm}^2 \sim G_F^2 2 m_p E_{cm}$$

- Then talked about problems with the high energy limit
- But there's more to it than that…especially at low energies

Thresholds and Processes



- We detect neutrino interactions only in the final state,
  …..and often with poor knowledge of the incoming neutrinos
- Creation of that final state may require energy to be transferred from the neutrino



- In charged-current reactions, where the final state lepton is charged,
  this lepton has mass
- The recoil may be a higher mass object than the initial state,
  or it may be in an excited state

K. McFarland, INSS 2013

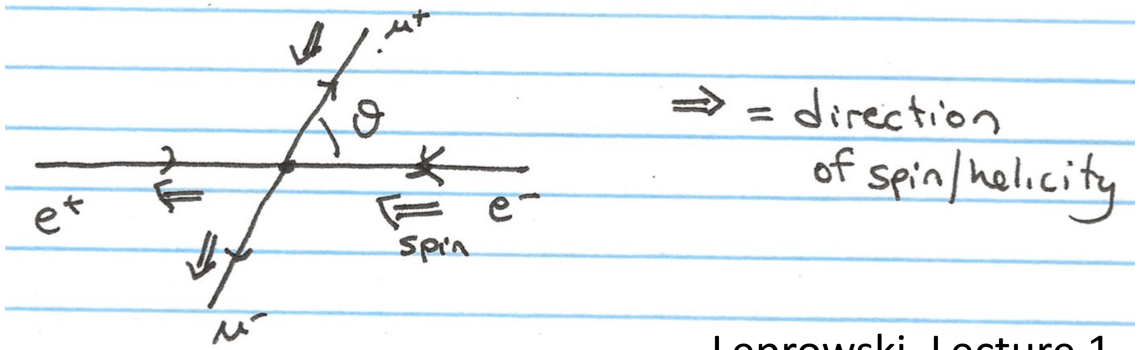
Thresholds and Processes at Very low energy

Process	Considerations	Threshold (typical)
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small) CEνNS!	none
$\nu_e n \rightarrow e^- p$	In some nuclei (mostly metastable ones), this reaction is exothermic if proton not ejected	None for free neutron
$\nu e \rightarrow \nu e$ (elastic)	Most targets have atomic electrons	~ 10eV – 100 keV
$\bar{\nu}_e p \rightarrow e^- n$	$m_n > m_p$ & m_e. Typically more to make recoil from stable nucleus.	1.8 MeV (free p). More for nuclei.
$\nu_\ell n \rightarrow \ell^- p$ (quasielastic)	Final state nucleon is ejected from nucleus. Massive lepton	~ 10s MeV for ν_e +~100 MeV for ν_μ
$\nu_\ell N \rightarrow \ell^- X$ (inelastic)	Must create additional hadrons. Massive lepton.	~ 200 MeV for ν_e +~100 MeV for ν_μ

- Energy of neutrinos determines available reactions, and therefore experimental technique

K. McFarland, INSS 2013

Neutrino Electron Elastic Scattering (reprise)

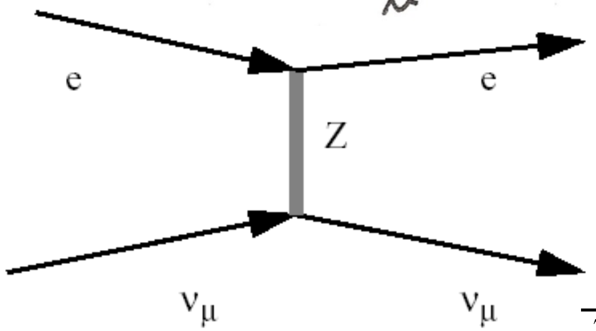


Leprowski, Lecture 1

- Elastic scattering:

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

  - Recall, EW theory has coupling to left *or* right-handed electron
  - Total spin, J=0,1



Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2 - 2/3 \sin^2\theta_W$	$- 2/3 \sin^2\theta_W$
d , s , b	$-1/2 + 1/3 \sin^2\theta_W$	$1/3 \sin^2\theta_W$

- Electron-Z^0 coupling
  - Left-handed: $-1/2 + \sin^2\theta_W$

$$\sigma \propto G_f^2 E_{cm}^2 \left(\frac{1}{4} - \sin\theta_W{}^2 + \sin\theta_W{}^4\right)$$

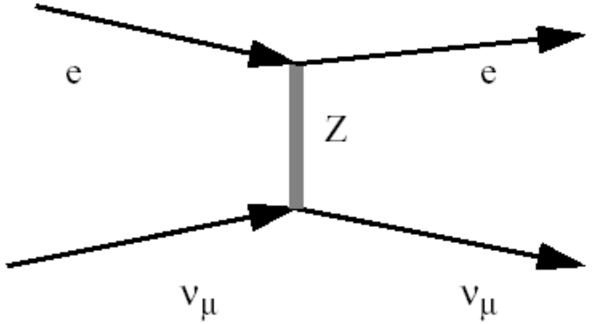
  - Right-handed: $\sin^2\theta_W$

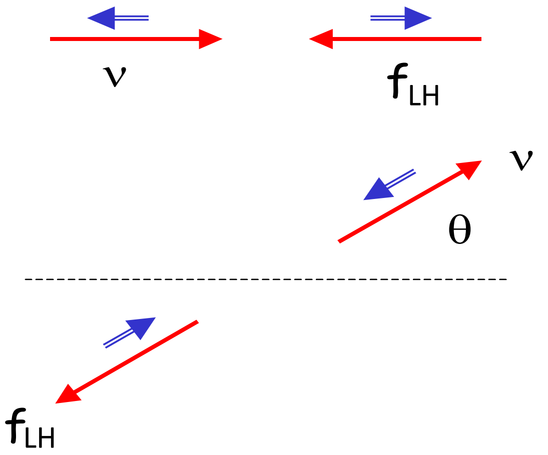
$$\sigma \propto G_f^2 E_{cm}^2 (\sin\theta_W{}^4)$$

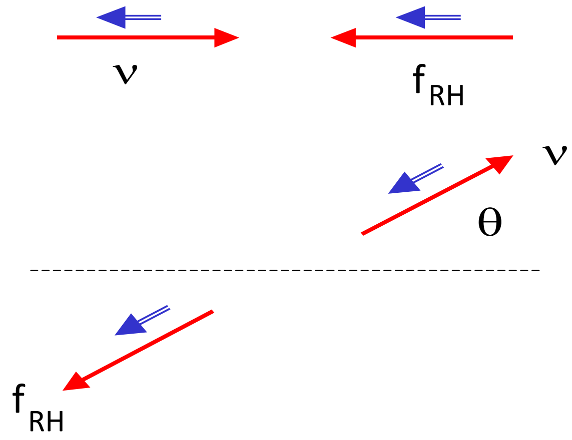
K. McFarland, INSS 2013

Neutrino Electron Scattering, cont'd

- What are relative contributions of scattering from left *and* right-handed electrons?







Backwards scattering is disfavored

$$\frac{d\sigma}{d\cos\theta} = \text{const}$$

$$\frac{d\sigma}{d\cos\theta} = \text{const} \times \left(\frac{1+\cos\theta}{2}\right)^2$$

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What about ν_e scattering off e's?

The reaction

$$\nu_\mu + e^- \to \nu_\mu + e^-$$

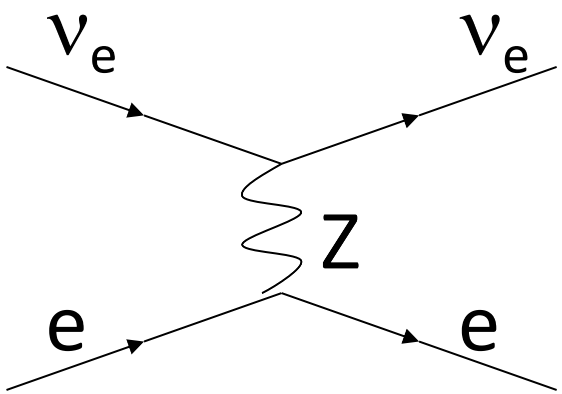
has a much smaller cross-section than

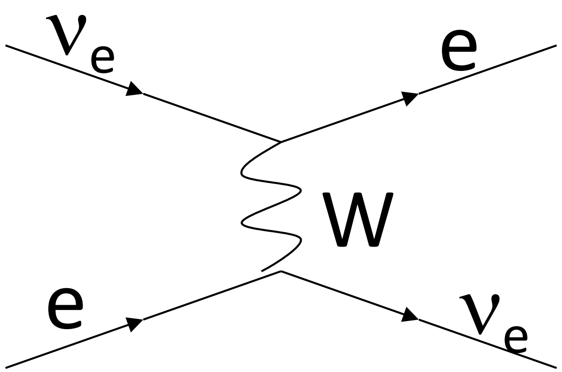
$$\nu_e + e^- \to \nu_e + e^-$$

Why?

$$\nu_e + e^- \to \nu_e + e^-$$

has a second contributing reaction, charged current





Although rate is higher for ν_e, compared to ν_μ or ν_τ this channel hasn't been used for oscillations at accelerator-based long baseline experiments: why?

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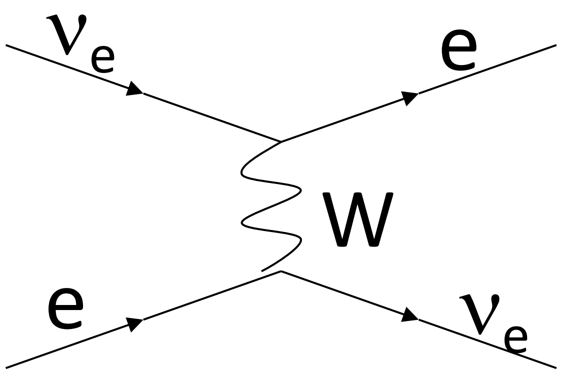
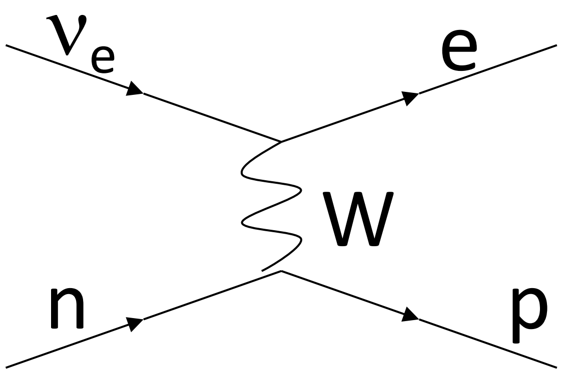
Consider this:

- How does the cross section for neutrino scattering off protons and neutrons compare to scattering off electrons?





$$\sigma \propto G_f^2 E_{cm}^2 \propto G_f^2 m_{target} E_\nu$$

Scattering off protons and neutrons

- Imagine now a proton target
  - Neutrino-proton elastic scattering:

$$\nu_e + p \rightarrow \nu_e + p$$

  - "Inverse beta-decay" (IBD):

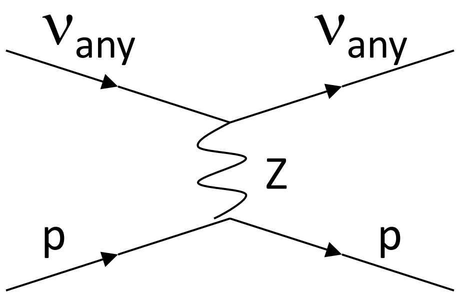
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

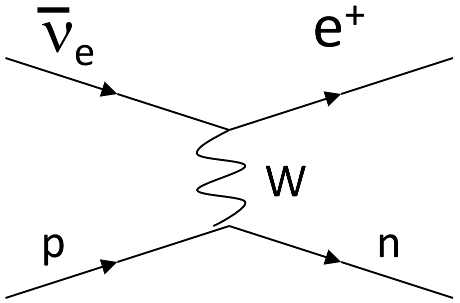
  - and "stimulated" beta decay:

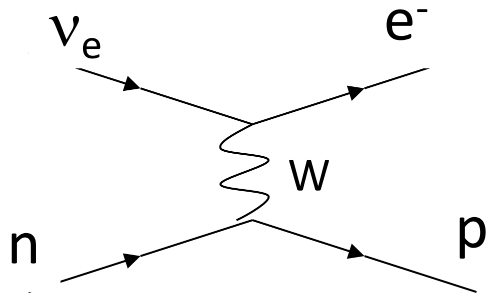
$$\nu_e + n \rightarrow e^- + p$$

  - IBD was the Reines and Cowan discovery signal
- Cross section much higher

$$\sigma \propto G_f^2 E_{cm}^2$$







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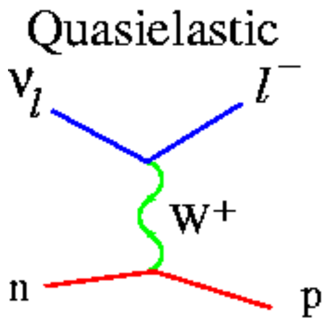
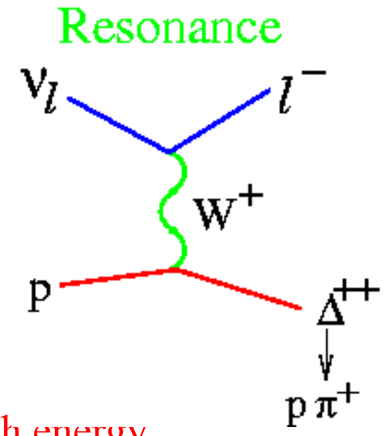
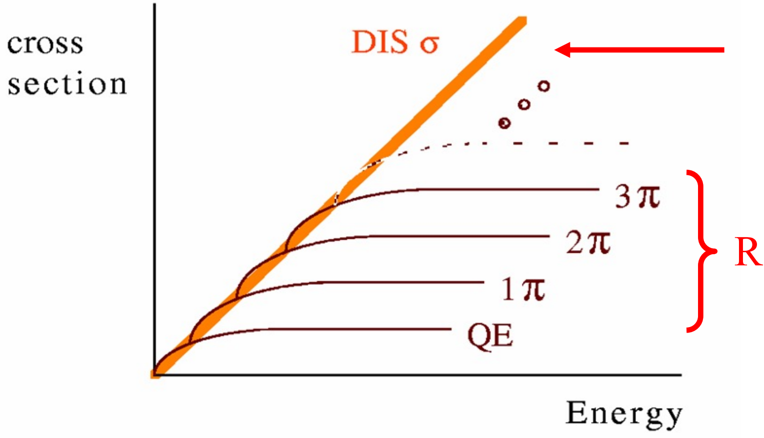
Neutrino-Nucleon Scattering

- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0 \quad (N^* \text{ or } \Delta)$
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark'}$

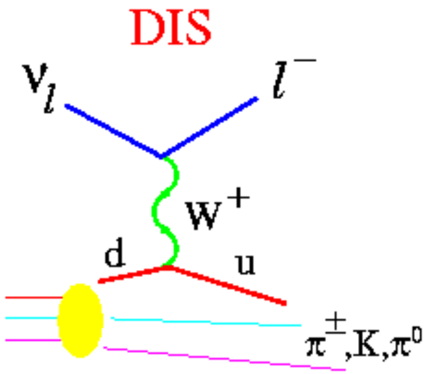






Linear rise with energy

Resonance Production



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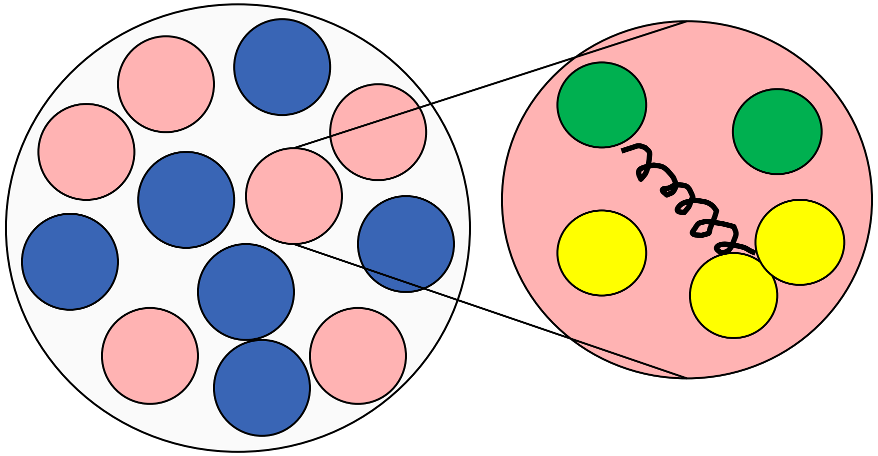
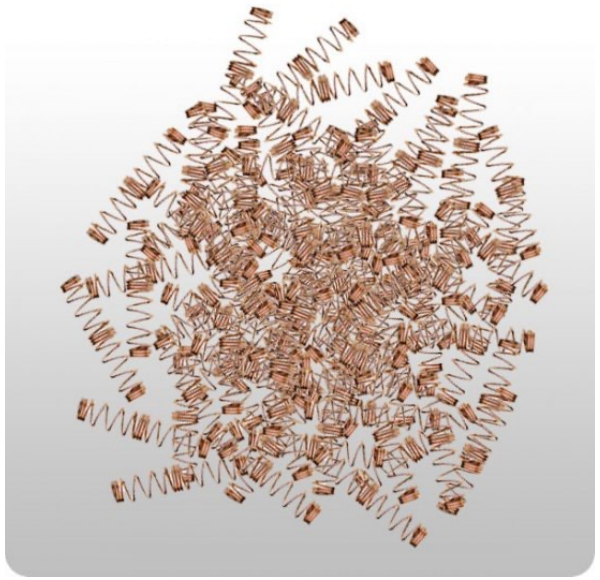
Scattering off Nuclei



- The fundamental theory allows a complete calculation of neutrino scattering from quarks
- But those quarks are in nucleons (PDFs), and those nucleons are in a strongly interacting tangle
- Imagine calculating the excitations of a pile of coupled springs. Very hard in general.



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Group Work

- For experiments looking for ν_μ → ν_e oscillations in a ν_μ beam :

- What are some possible backgrounds if you have a perfect detector?

- Is ν–electron scattering a background? Why or why not?

Summary for Neutrino Interactions

- Total cross section proportional to neutrino energy
- Angular dependence because of ν helicity and conservation of spin
  - Consequence: Neutrinos have higher cross section than anti-neutrinos
- ν-e scattering is the ONLY perfectly known cross section
- Everything else is more complicated:
- Dedicated cross section programs to help clarify the role the nucleus plays: MINERvA
- **NEED THEORY PREDICTIONS!**
- The higher the ν energy, the more final state particles produced
  - Need to understand how ν energy shows up in detector, AND backgrounds

Neutrino Detectors

What makes Neutrino Detectors special?

I know what you’re thinking:

“Wait, I already learned everything I need to know about detectors from Ian Shipsey on Monday and Tuesday…”

- Neutrino beams are much larger than charged particle beams
- Neutrino cross section is very low, need large target mass
- Solution: make detector and target mass out of the same material
- Practical challenge: cost of making bulk material “active”

Oscillation Detector Goals

- Identify flavour of neutrino
  - Need charged current events!
  - Accelerator sources: Lepton Identification (e,μ,τ)

$$P = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Measure neutrino energy
  - Charged Current Quasi-elastic Events
    - In principle, all you need is the lepton angle and energy *(derive)*
  - Everything Else
    - Need to measure energy of lepton and of X, where X is the hadronic shower, the extra pion(s) that is (are) made..

$$\bar{\nu} p \rightarrow l^+ n$$

$$\nu n \rightarrow l^- p$$

$$\nu N \rightarrow l X$$

Neutrino Oscillation Goals vs ν Sources

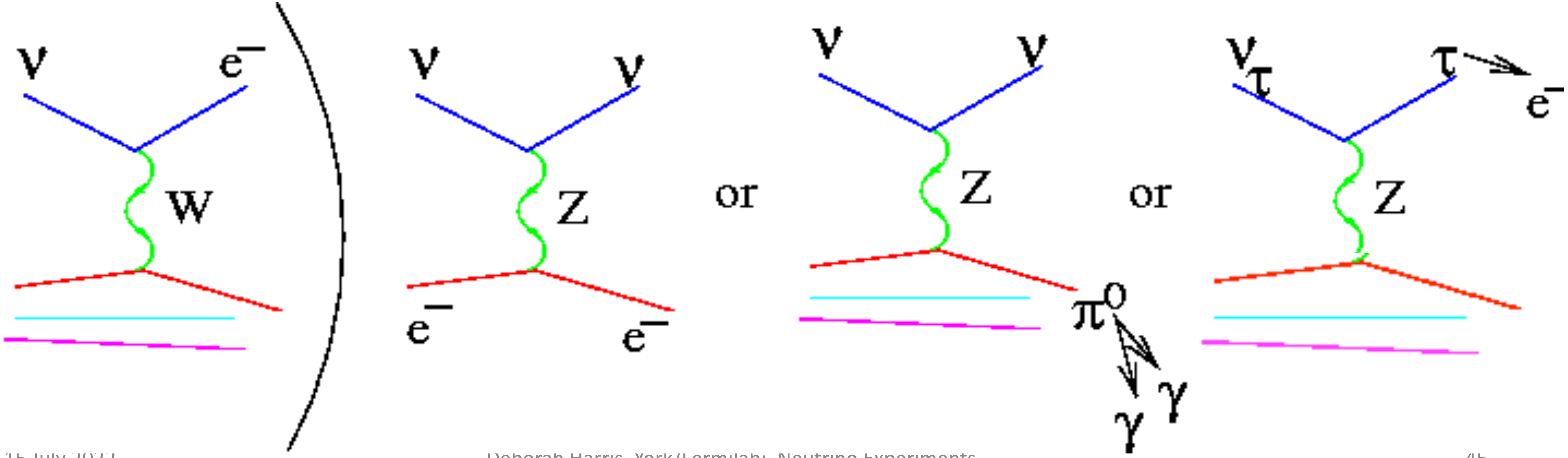
- Reactor
  - Need to identify neutrino interaction (see the electron plus neutron tag)
  - Need to measure electron energy to deduce neutrino energy
- Atmosphere (ν_μ, ν_e and anti-ν_μ, anti-ν_e)
  - Need to identify at least muons
  - Need direction of outgoing e or μ to know baseline
- Conventional Beams (ν_μ, %ν_e)
  - Identify muon and electron in final state
- Thought question:
  - Do you need a magnetic field in your detector?
    - Depends on whether you need to distinguish ν_μ, ν_e from anti-ν_μ, anti-ν_e

Detectors and Backgrounds…

- Depending on your detector, you may see lots of things that look like signal but aren't…

Charged Current

Neutral Currents



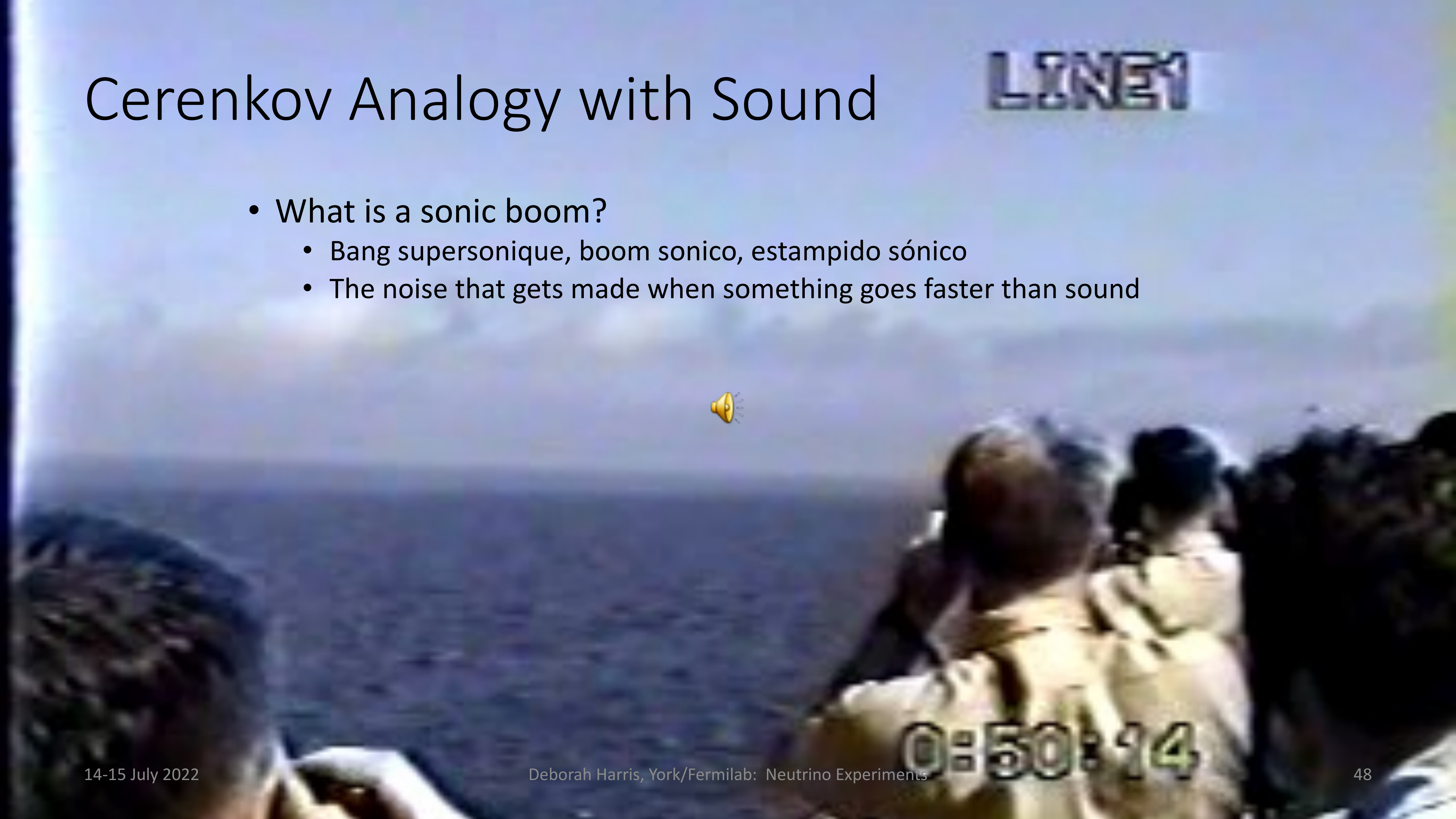
Very Incomplete Survey of Neutrino Detectors

- Cerenkov Detectors
  - Water Cerenkov
  - Will cover “Ice Cerenkov” detector tomorrow
- Scintillator Detectors
  - Liquid Scintillator
  - Segmented scintillator
- Liquid Argon TPC

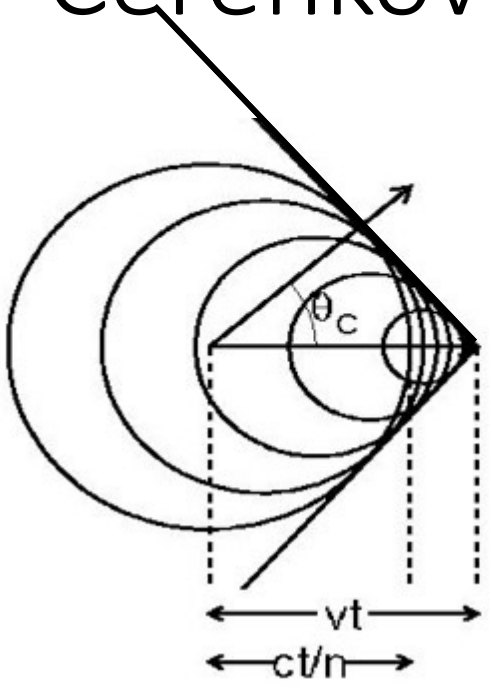
Cerenkov Detectors

Cerenkov Analogy with Sound

- What is a sonic boom?
  - Bang supersonique, boom sonico, estampido sónico
  - The noise that gets made when something goes faster than sound



Cerenkov Light



As **CHARGED** particles move faster than the speed of light in that medium, they emit a “shock wave” of light

$$\beta \equiv \frac{v}{c} \qquad \beta > \frac{1}{n}$$

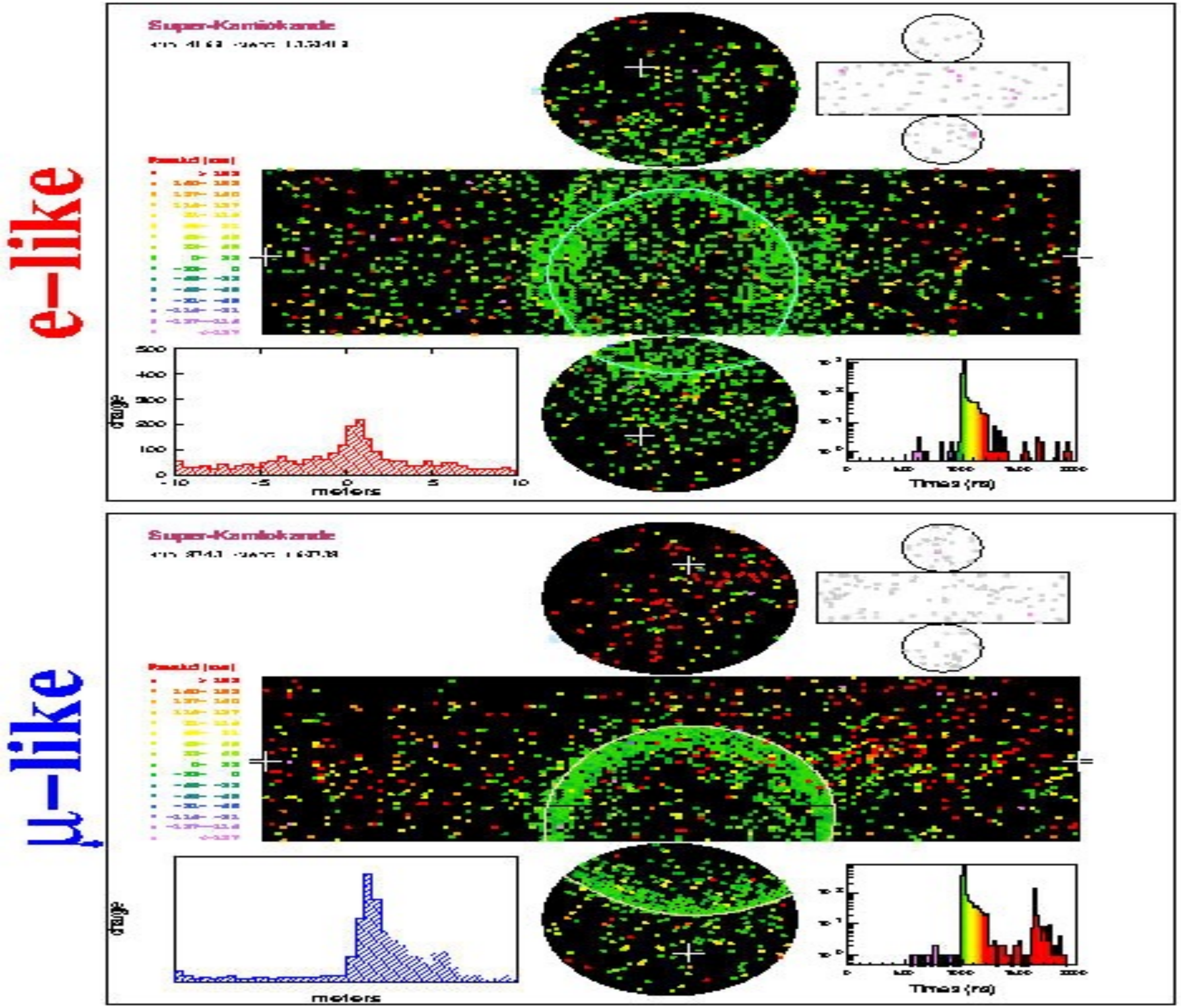
$$\theta_c = \cos^{-1}(1/n(\lambda))$$

$$p_{threshold} = \frac{m}{\sqrt{n^2 - 1}}$$

particle	p (threshold)
e	660keV
μ	137MeV
$\pi^{\pm}$	175MeV
K	650MeV
p	1300MeV

- For water, n(280-580nm)~1.33-6, so $p_{threshold}$≈1.3*mass
- Threshold Angle: 42°

2GeV neutrino
Interaction in SuperK
50m across
40m tall
Water tank

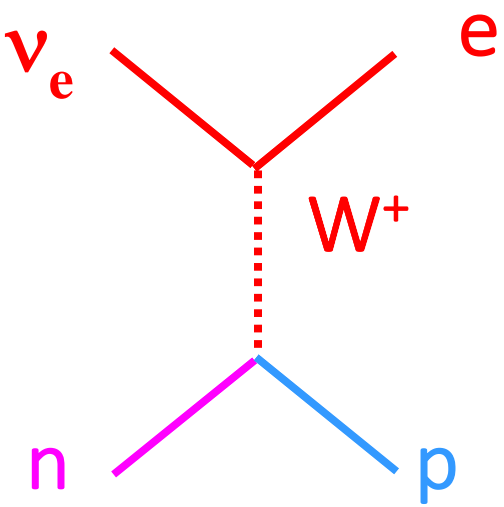


Measuring Neutrino Energy

- Should be easy, right?
  - Assume neutron or proton at rest
  - IF you know initial direction of neutrino…
  - Final direction and energy of electron should suffice to get to the neutrino energy

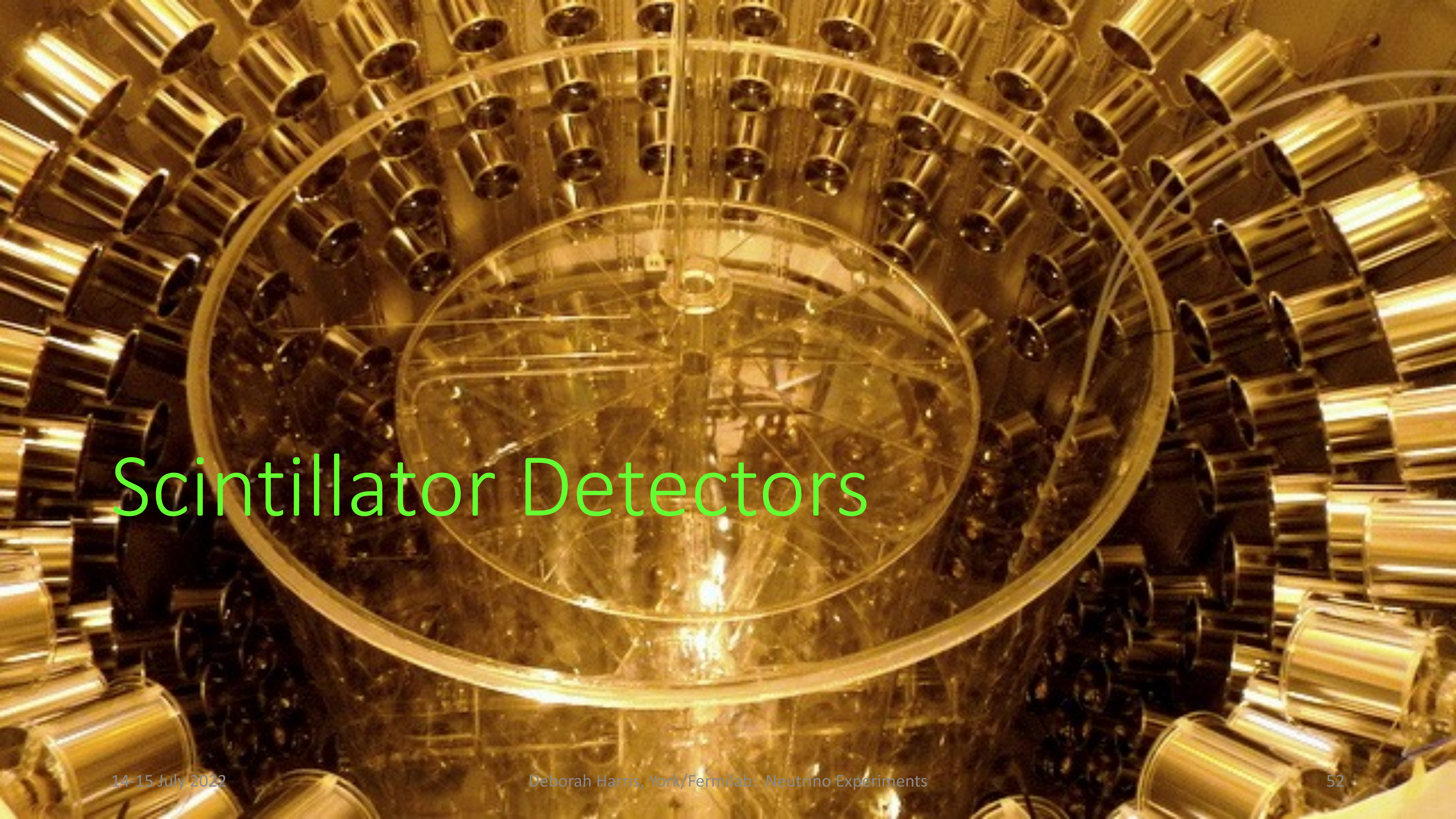
$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right)E_\mu - \left[\left(M_n - E_B\right)^2 + m_\mu^2 - M_p^2\right]}{2\left[\left(M_n - E_B\right) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$



$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

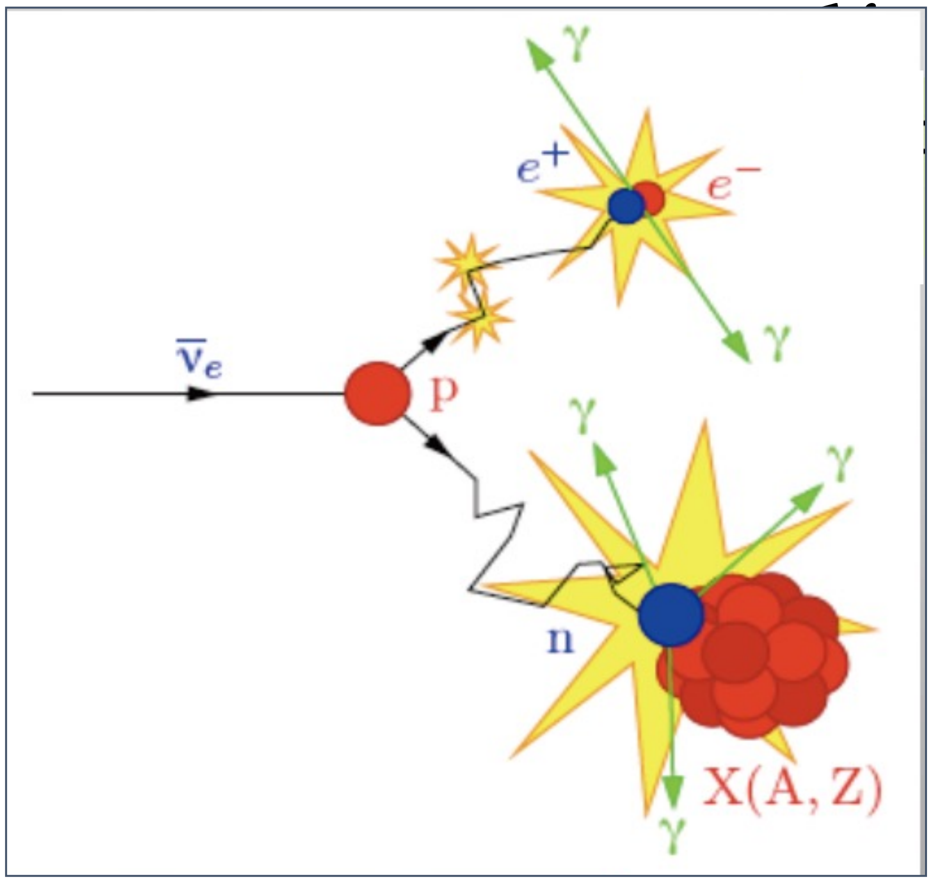
- Caveats:
  - lots of things that look quasi-elastic are NOT, if you can't see pions!
  - Need to include details on initial neutron momentum, binding energy, nuclear physics!



Scintillator Detectors

Anti-neutrinos in Scintillator

$$+ p \rightarrow e^{+} + n$$



Neutron capture time ~ 30μsec for typical θ_{13} experiments

Scintillator Oil alone: capture the neutron on Hydrogen, make 2.2MeV gamma

Neutrino capture on Gd has advantages (compared with that on hydrogen):

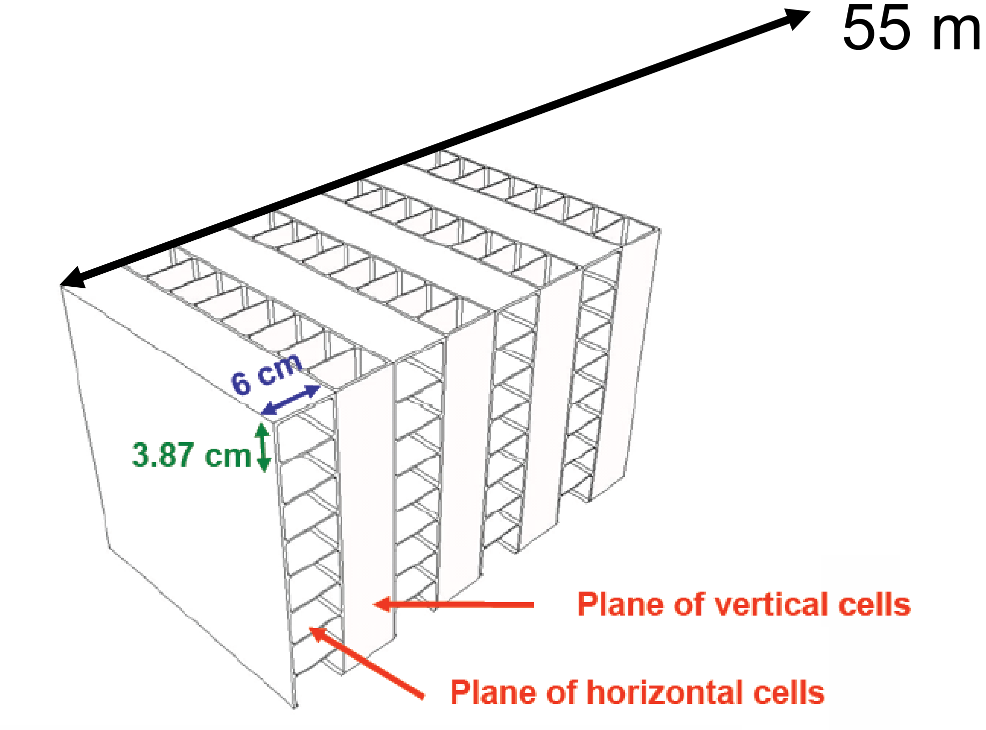
- ✓Higher total gamma ray energy (8 MeV)
- ✓Shorter neutron capture time (~30 μsec vs. ~200 μsec)

➔Better signal to noise ratio

T. Kajita, INSS 2013

Segmented Scintillator (NOvA)

- PVC extrusions
    - 16m tall x 16m wide x 55m long
    - 3.9 cm transverse, 6.6 cm wide in beam direction
- All Liquid Scintillator
    - 85% scintillator, 15% PVC



To Build:
Glue Planes of Extrusions together
Rotate them from horizontal to vertical
Fill Extrusions with Liquid Scintillator
Each box gets a WLS fiber loop (bent at far end)
Instrument WLS fibers with Advanced PhotoDiodes, repeat

Detector Volume

- Scaling detector volume is not trivial

- NOvA detector larger than ATLAS+CMS+ CDF+D0 together, at 14kTon

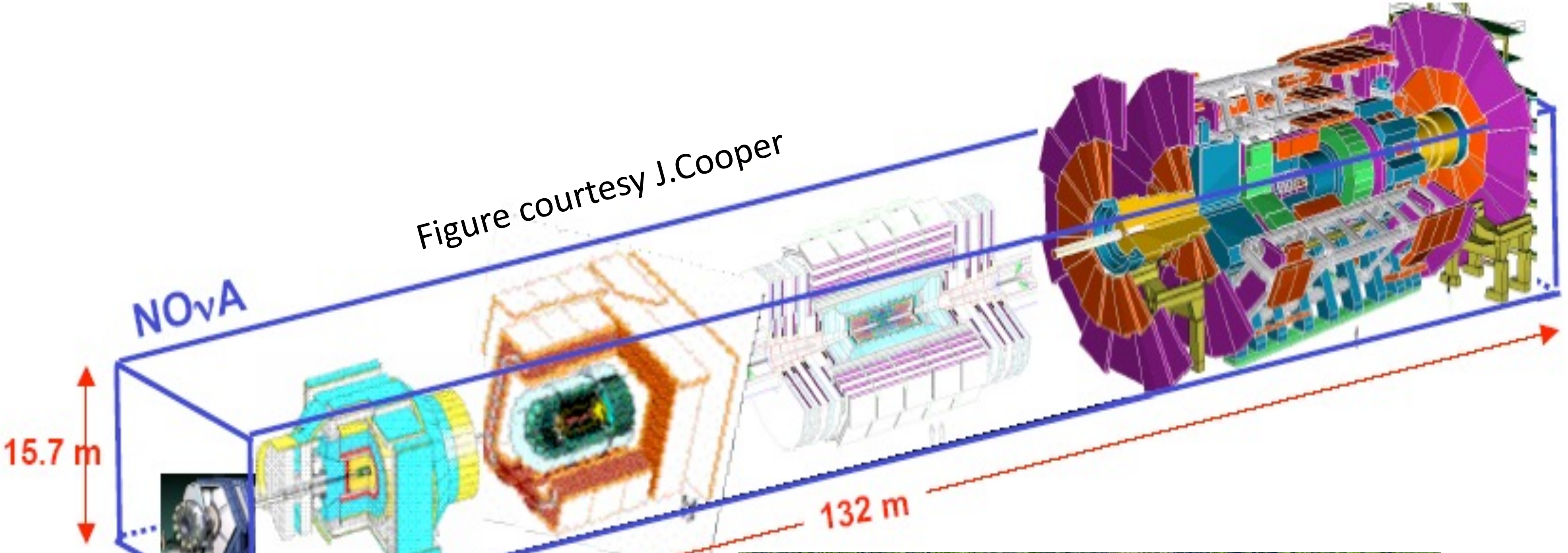
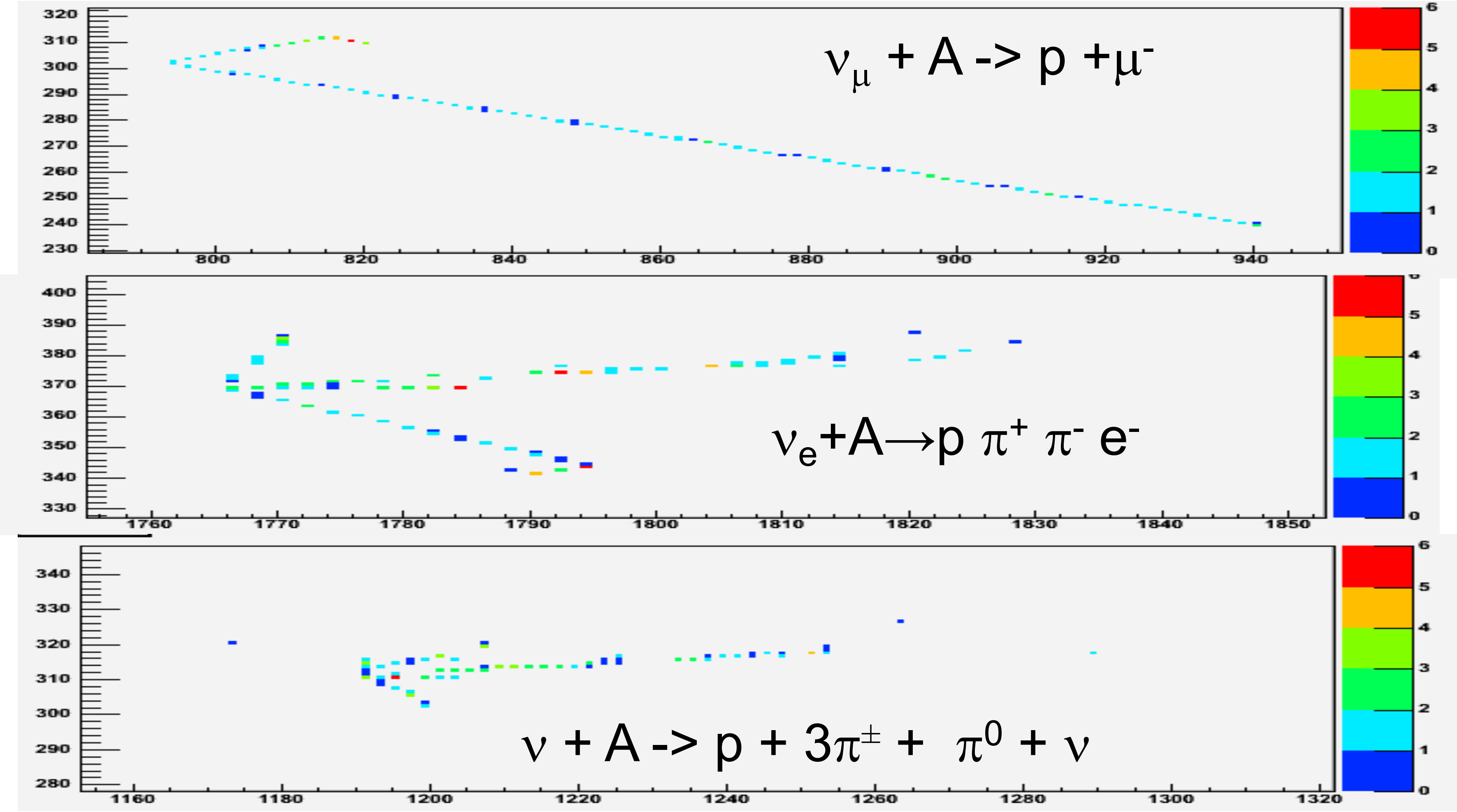


Figure courtesy J.Cooper

Scintillator Events (2GeV)



One unit is 4.9 cm (horizontal)
4.0 cm (vertical)

Energy measurement: muon plus everything else

Particle ID:

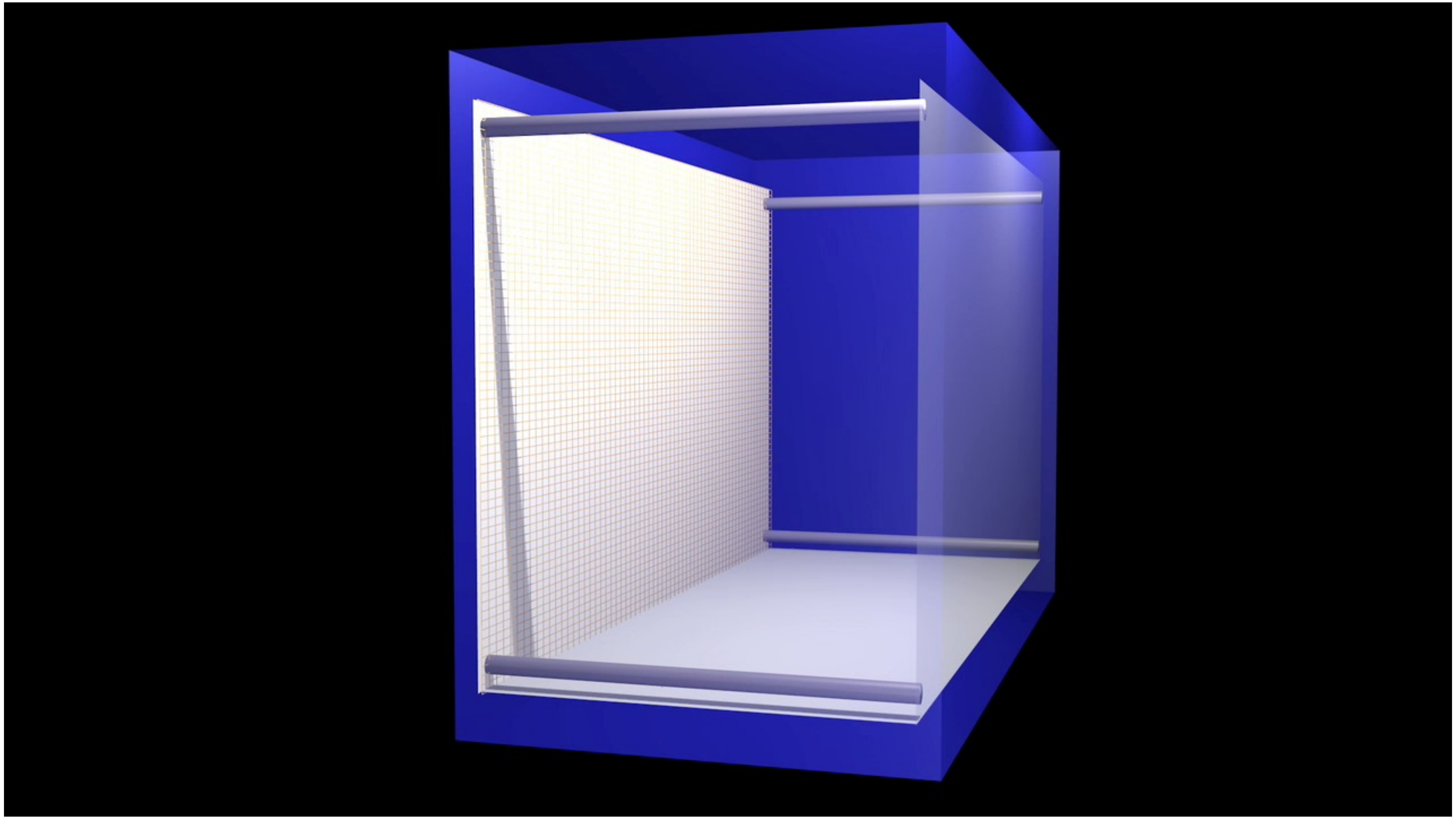
particularly "fuzzy" e's

long track, not fuzzy (μ) gaps in tracks (π^0 ?)

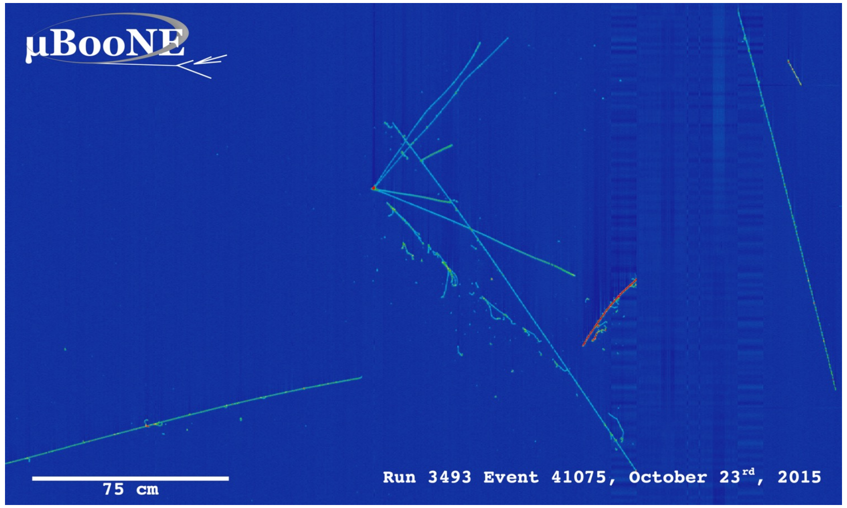
large energy deposition (proton?)

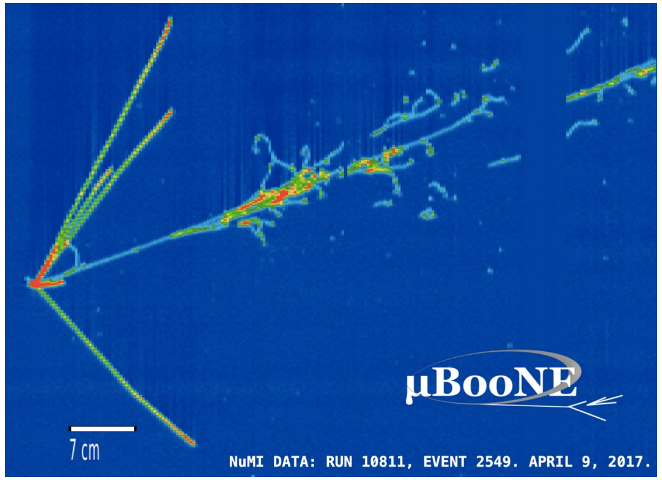
Liquid Argon TPC

Liquid Argon Time Projection Chamber

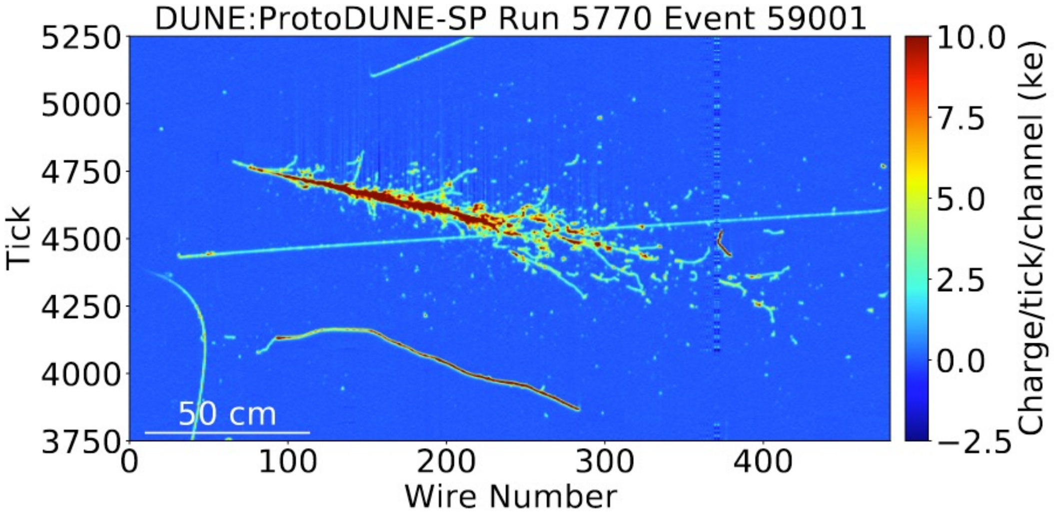


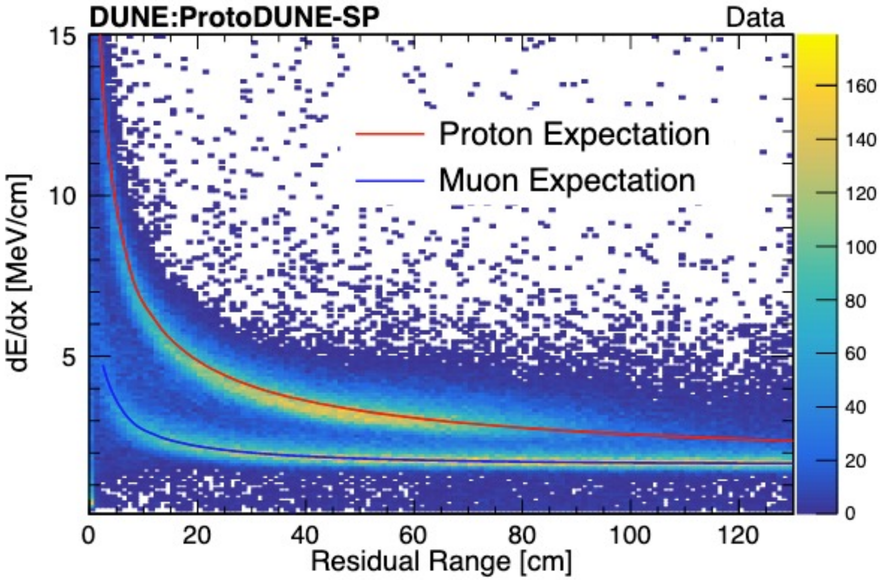
ν and e Events in Liquid Argon





https://microboone-exp.fnal.gov





JINST 15, P12004 (2020) arXiv:2007.06722

Neutrino Detector Summary

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal ν Energy Range
		ν_e	ν_μ	ν_τ		
Liquid Ar TPC	0.77	✓	✓		Not yet	huge
Water Cerenkov	50 (or 1000*)	✓	✓	✓ **		<2GeV 10-1000GeV*
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	14	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV

*if you include ICECUBE…

Moral of this story: how you measure a neutrino’s energy varies greatly…

Measuring Oscillation Probabilities

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \to \nu_x) \varepsilon_x M_{far} + B_{far}$$

ϕ=flux, σ= cross section ε=efficiency M=mass

$$P(\nu_\mu \to \nu_x) = \frac{N_{far} - B_{far}}{\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}}$$

B_{far}= Backgrounds at far detector, from any flux

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{far}$$

Need to understand Signal and Background Cross sections, and efficiencies!

Uncertainties on Probabilities

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{N_{far} - B_{far}}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}[\delta(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)]^2$$

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\varphi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + f(N_{far} - B_{far})\left(\left[\frac{\delta\varphi_{\nu_\mu}}{\varphi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right)$$

3 Regimes:

$N_{far} \gg B_{far}$

$N_{far} \approx B_{far}$

$N_{far} \ll B_{far}$

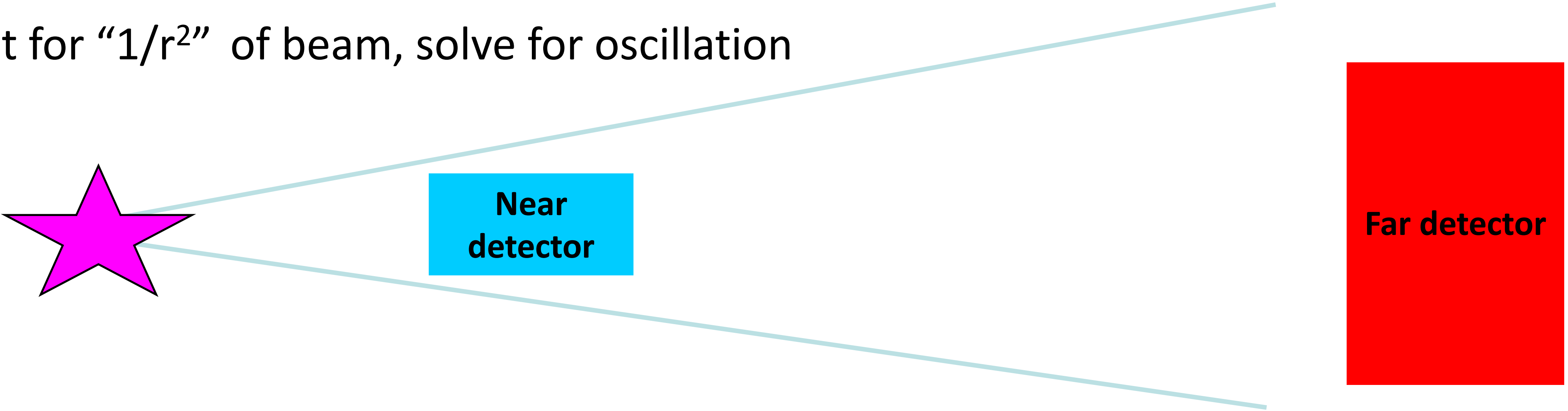
Where we are now:

Reactor Experiments: low backgrounds, high statistics, need to focus on systematic uncertainties

Accelerator Experiments: $N_{far} \geq B_{far}$ but now we are looking for the difference between ν and $\bar{\nu}$

Near Detector Strategy (in theory)

- Make two (or more!) detectors :
  - Near detector sees beam before oscillations
  - Far detector measures beam after oscillations
  - Require Neutrino Flavor and Neutrino Energy measurement
  - Correct for “$1/r^2$” of beam, solve for oscillation



Near Detector Strategy (in practice)

$$B_{far} = \int dE_\nu \sum_{i=\mu,e} N_{near,i}(E_\nu) \left(\frac{\int \phi_{\nu_i\, far} \sigma_{\nu_i} \varepsilon_{ix}(E_\nu) dE_\nu}{\int \phi_{\nu_i\, near} \sigma_{\nu_i} \varepsilon_{ix}(E_\nu) dE_\nu} \right) \frac{M_{far}}{M_{near}}$$

- But ratios don't cancel everything
- Underlying problem: fluxes may be different
  - "$1/r^2$" only works for a point source
- Also, ν_μCC oscillations may create change on TOP of what you are trying to measure
- All of these terms are functions of energy
  - Uncertainties in energy dependence of cross sections translate into far detector uncertainties…

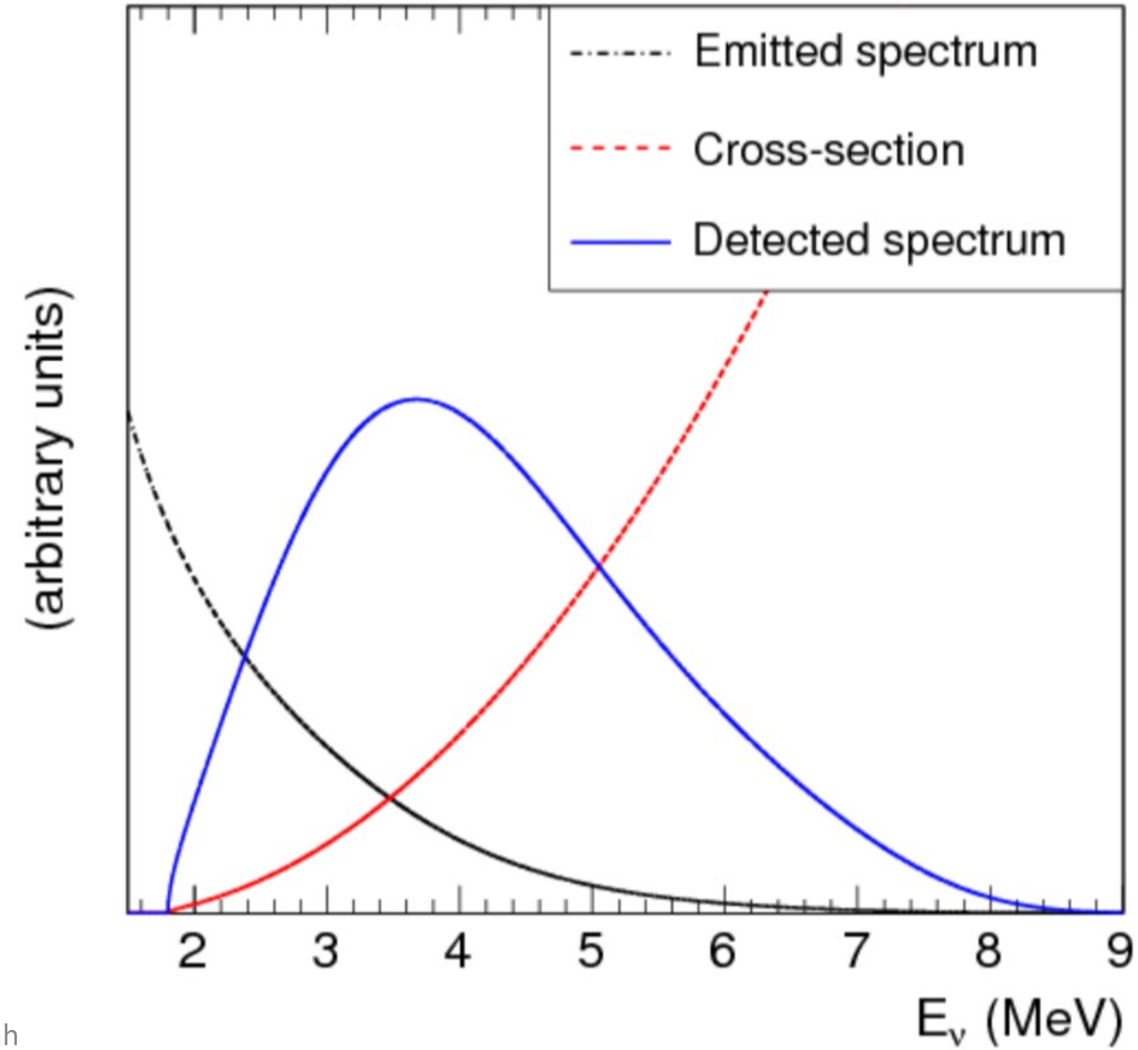
Current Results and Next Steps: Reactor Neutrino Example

Taken mostly from Neutrino 2022

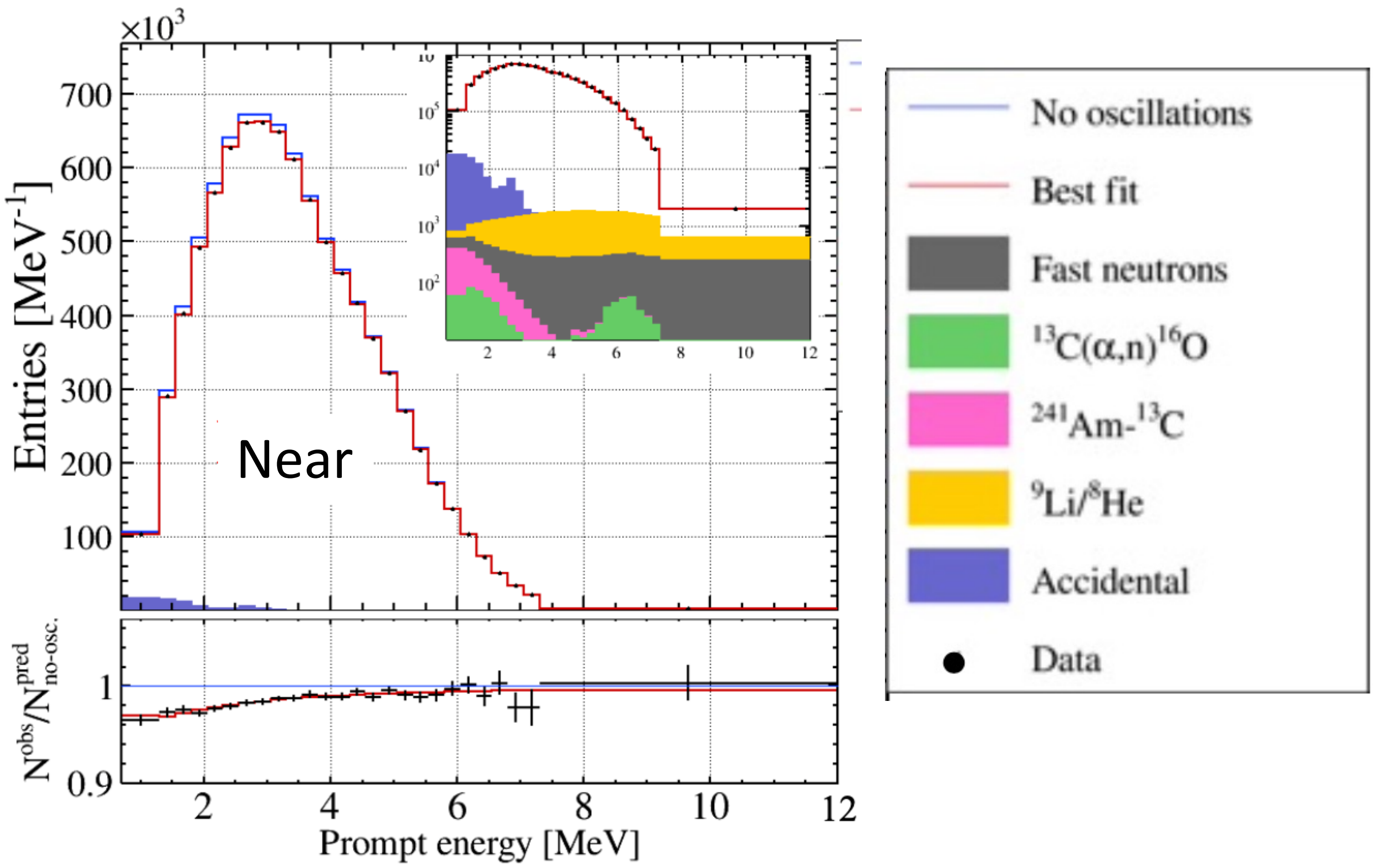
What do reactor experiments see?

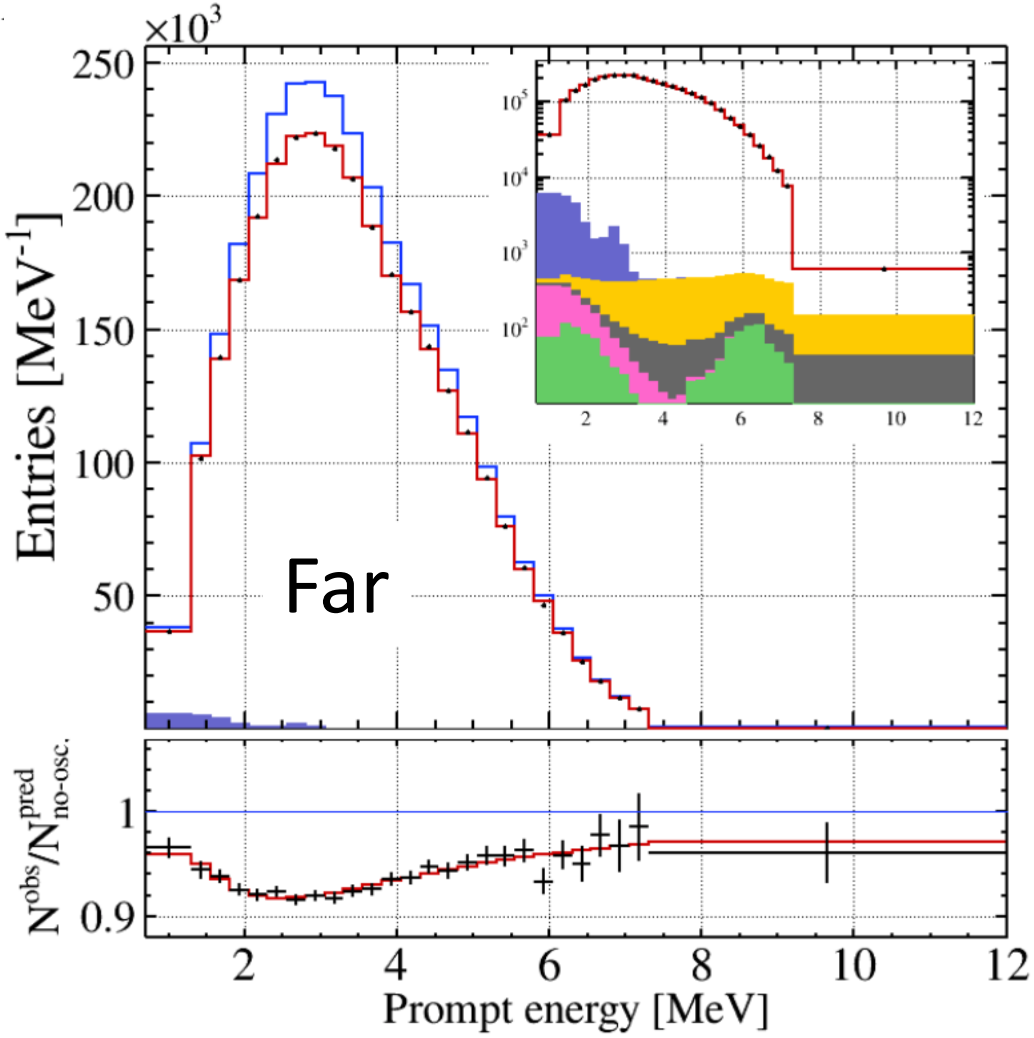
$$N = \Phi\sigma \mathrm{M}\epsilon$$

- Flux at reactors falls with energy
- Cross section rises with energy



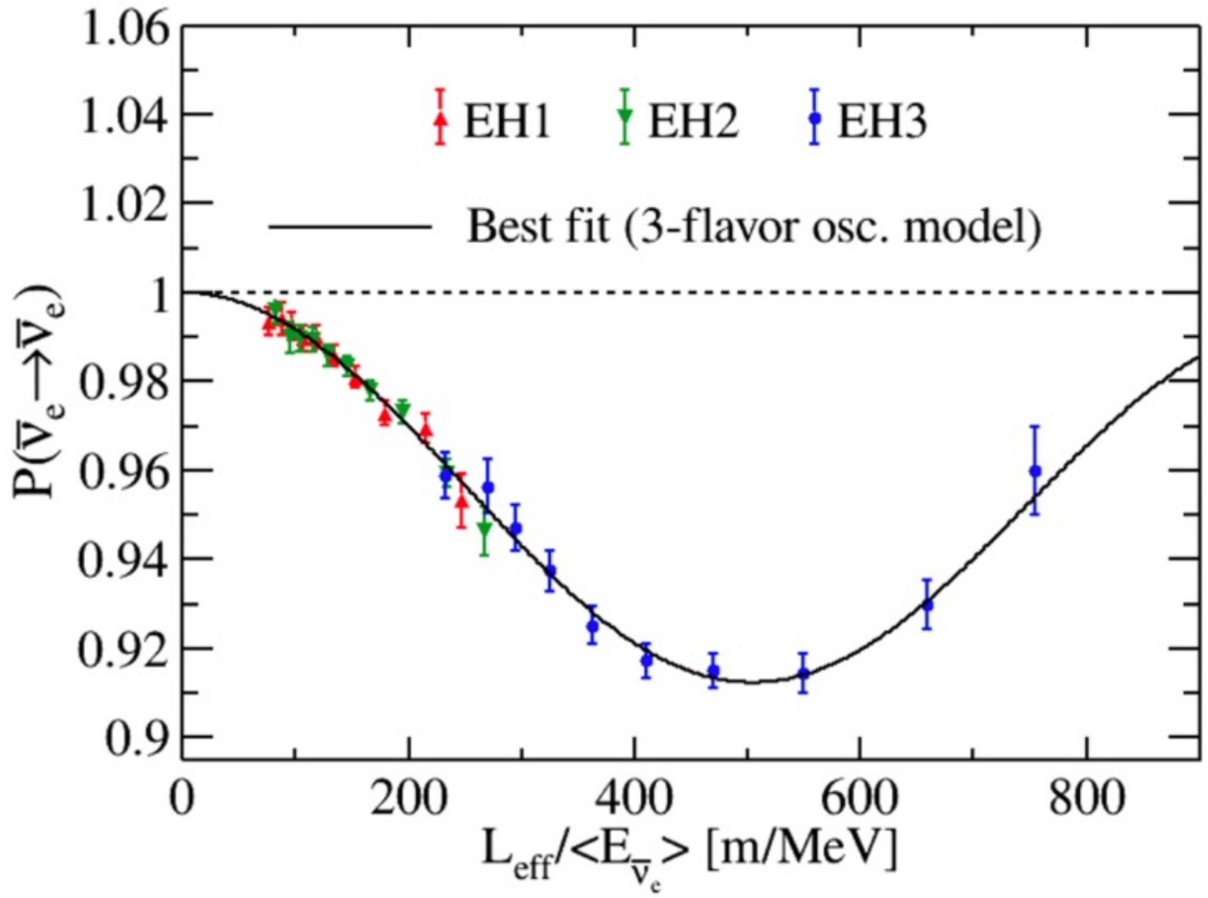
Precision Disappearance of Reactor Neutrinos

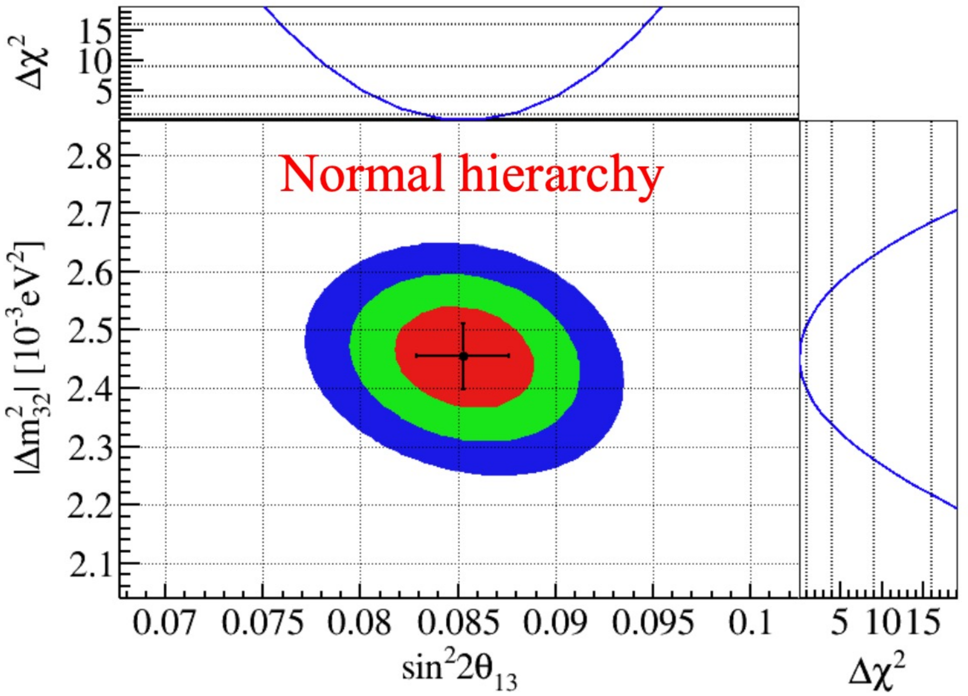




- Daya Bay, Neutrino 2022

Reactor Constraint on Oscillation Parameters





Best-fit results: $\chi^2/\mathrm{ndf} = 559/518$

$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)

- Daya Bay, Neutrino 2022

Next Steps in Reactor Experiments

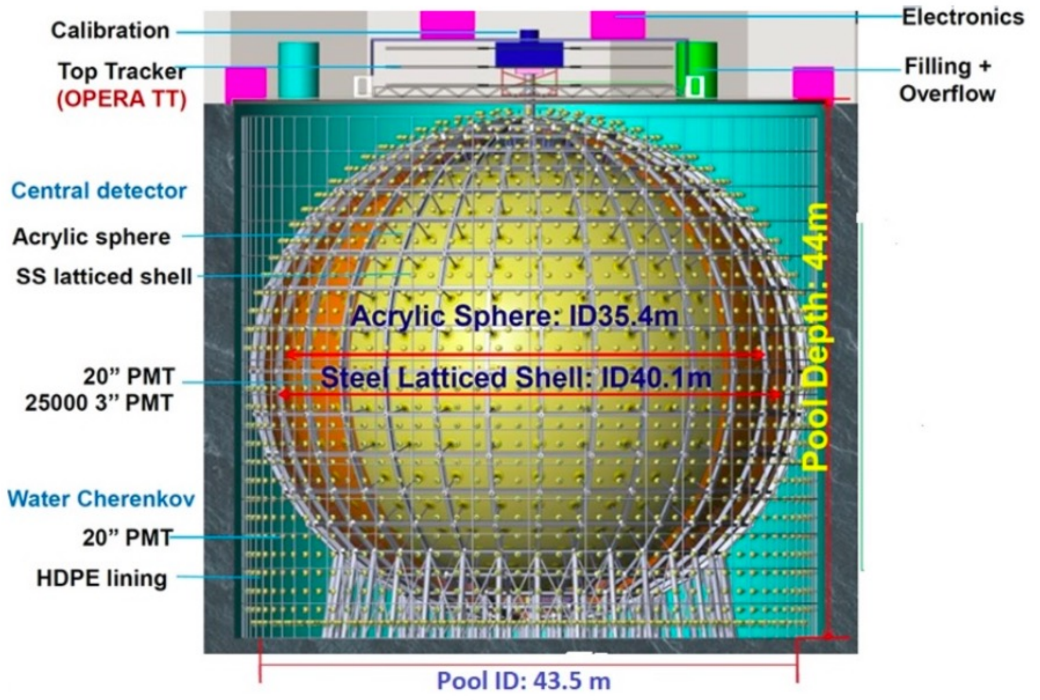
- JUNO: not just an award that Drake and Allison Russell received….
- JUNO: Reactor $\bar{\nu}_e$'s + 20kton Liquid Scintillator
- Goal is to measure whether mass ordering is inverted or normal
- How can it do this?
- Consider "largest mass splitting" from ν_μ disappearance

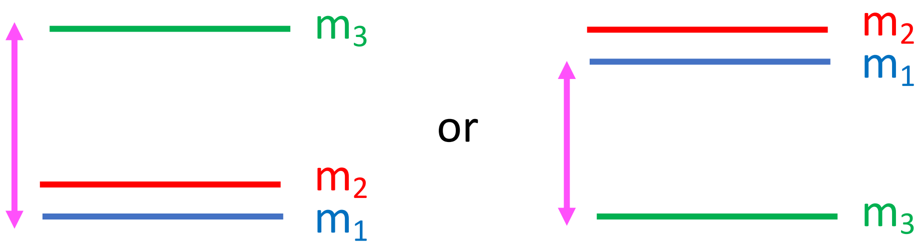
$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - \sin 2\theta_{13}{}^2 \sin\left({}^{\Delta m^2_{13}L}/_{4E}\right)^2$$

- Now consider "largest mass splitting" from ν_e disappearance:

$$P_{\nu_\mu\rightarrow\nu_e} = \sin 2\theta_{13}{}^2 \sin\left({}^{\Delta m^2_{23}L}/_{4E}\right)^2$$

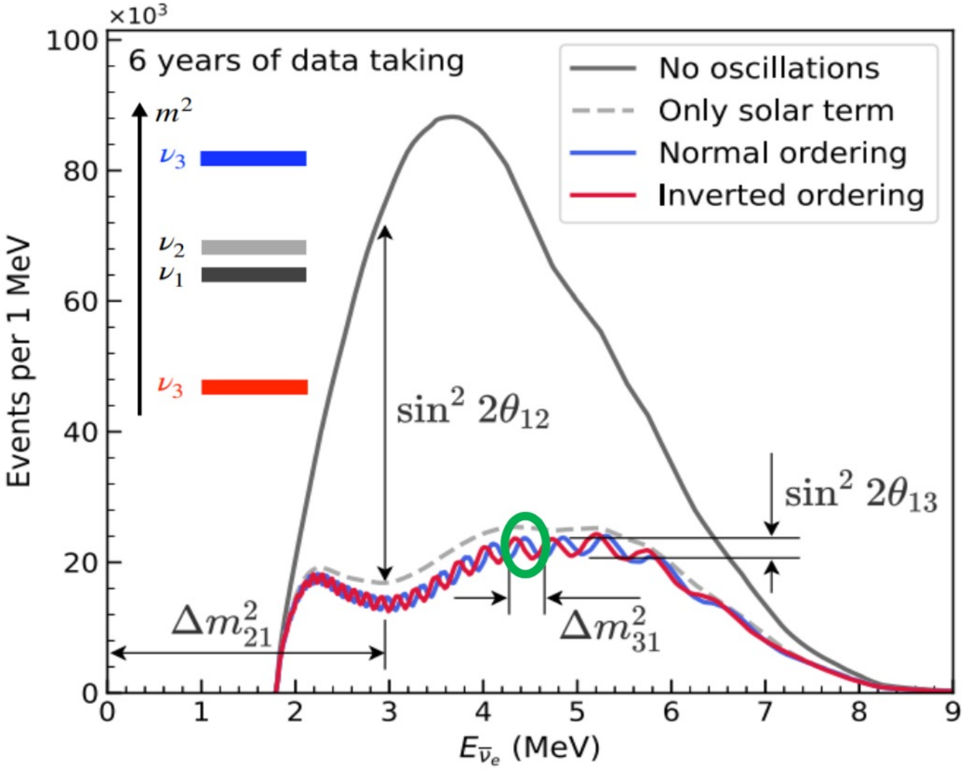
20kton Liquid Scintillator

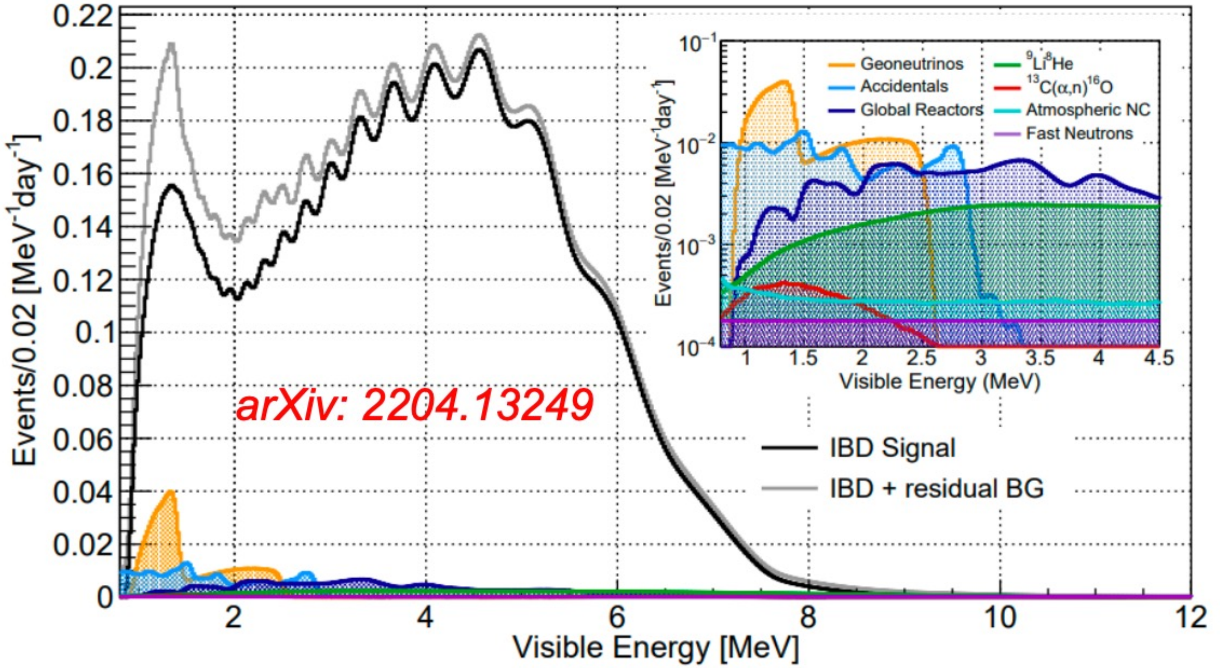




What this means in practice…

- Remember, neutrino mass splittings differ by a factor of 30!
- Need Fantastic Energy Resolution, high statistics, and precise calibration





JUNO @ Neutrino 2022

Tomorrow….

- Accelerator-Based Oscillation Measurements
    - Current Results
    - Next steps
- Absolute Neutrino Masses
- Are Neutrinos their own Antiparticles?