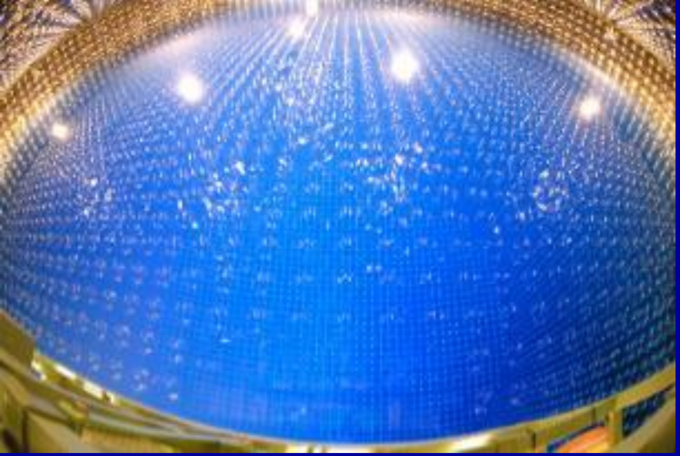


Super-KamiokaNDE:

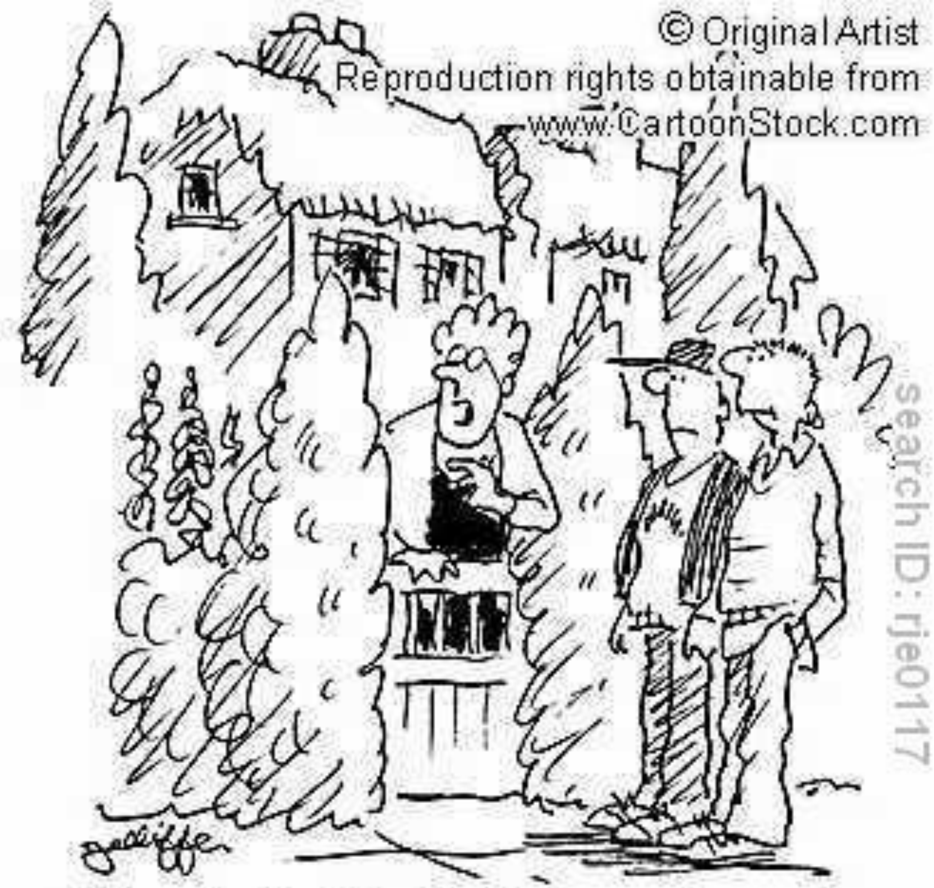
Beyond Neutrino Oscillations

A. George
University of Pittsburgh

PART 1: NUCLEON DECAY

What’s in a name?

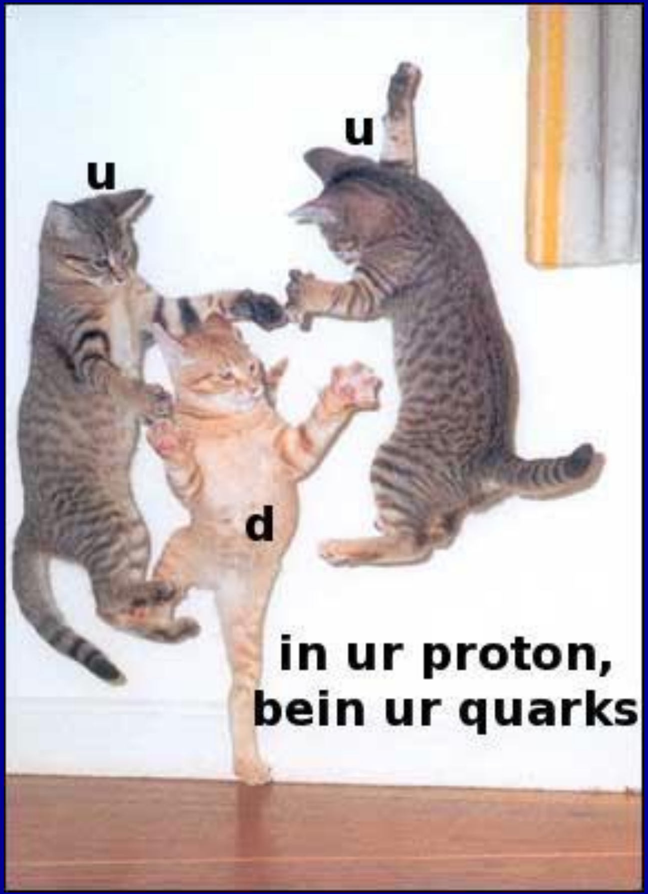
- Various stages of the experiment have been called:
  - Kamiokande
  - Kamiokande-II
  - Super-Kamiokande
  - Super-Kamiokande-II
  - Super-Kamiokande-III
- The K2K experiment is divided into I & II
- I make no effort to differentiate between any of these – I will exclusively use “Super-K” and “K2K” to describe the experiments



"Turn right at the Robinia pseudoacacia, pass the garden with the salvia officinalis, cross the road when you see the stranvaesia davidinia and the pub is on the left!"

Putting the **NDE** in SuperKamioka**NDE**

- NDE stands for *nucleon decay*, the experiment's original purpose
- It was thought (before Super-K) that protons decayed with a mean lifetime of 10^{31} years.
- The size of the detector was chosen so that 1000 protons would decay (about half of which could be detected)

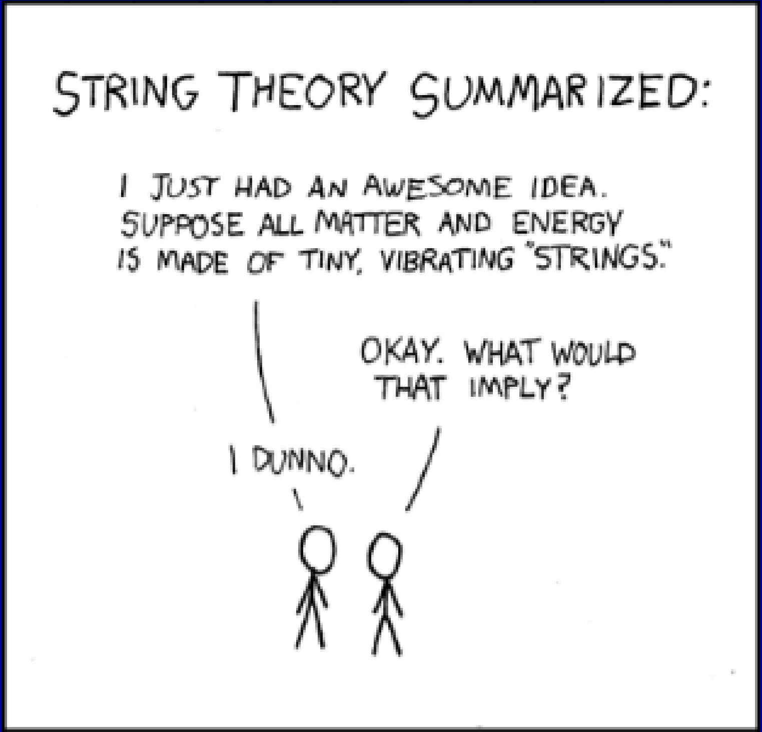


Why Should Protons Decay?

- **Baryogenesis** – where the hell is all the antimatter?
  - Must have been some symmetry breaking in the early universe
  - If true, then there must be baryon-number violating reactions (otherwise, no way for there to be more protons than antiprotons)
  - Most convincing baryon-number violating reaction is proton decay

Why Should Protons Decay?

- Predicted by Grand Unified Theories, including string theory
- Most GUTs explicitly break Baryon Number Conservation at high energy
  - These reactions are typically mediated by the Higgs Boson, or some other massive “X boson”
  - Very important because one of very few observables for GUTs – other observables including magnetic monopoles and nonzero neutrino mass
    - Non-falsifiable, basically non-provable



Gauge Symmetry

Recall

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t} \qquad \vec{B} = \nabla \times \vec{A}$$

There is a certain freedom here: a whole class of A and V can be chosen without changing E or B.

$$V \to V - \frac{\partial \lambda}{\partial t} \qquad \vec{A} \to \vec{A} + \nabla \lambda$$

$$\Psi \longrightarrow e^{ie\lambda}\Psi$$

where λ is any scalar function (the gauge)

Global vs. Local/Gauge Symmetry

- Classifying λ – does it depend on time and position?
- Consider the lagrangian for a typical particle:

$$\hat{L} = |\nabla\Psi|^2 + |\partial_t\Psi|^2 + \text{terms from interaction with field}$$

- Local/gauge symmetry (yes) – terms for interaction cause λ to drop out, regardless of what λ is
- Global symmetry (no) – no “field,” hence no terms from interaction, hence λ only drops out if not dependent on position or time
- Baryon Number – no “baryon number field,” hence symmetry is global

Consequences of Global Symmetry

- Why global symmetry is inferior:

Anomalies “quantum corrections” don’t happen to gauge symmetry, can happen to global symmetry

Example: pion loop connection, forbidden under normal laws, but allowed so long as $\Delta E \Delta t \geq \hbar^2$

- Could there be a quantum correction that affects baryon number?
  - Yes, some have already been observed
- Could one of these anomalies be proton decay?
  - Maybe

What Does Proton Decay Look Like?

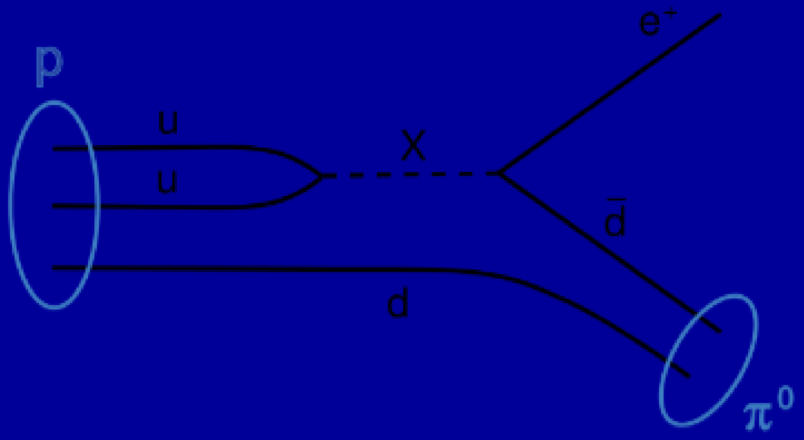
Many Possible Modes:

$$p^+ \longrightarrow e^+ + \pi^0$$

$$p^+ \longrightarrow \mu^+ + \pi^0$$

$$p^+ \longrightarrow \bar{\nu} + K^+$$

$$p^+ \longrightarrow \mu^+ + \eta$$



$$p^+ \longrightarrow e^+ + \rho$$

$$p^+ \longrightarrow e^+ + \omega$$

How Do We Search for Proton Decay?

- Detect the residual nucleus
  - Insensitive to decay mode
  - Radiochemical or nuclear experiments
  - Small quantities of nucleon sources
- Detect the products of the decay
  - Sensitive to decay mode
  - Unlimited (almost) quantities of nucleon sources
  - Very high backgrounds

Homestake

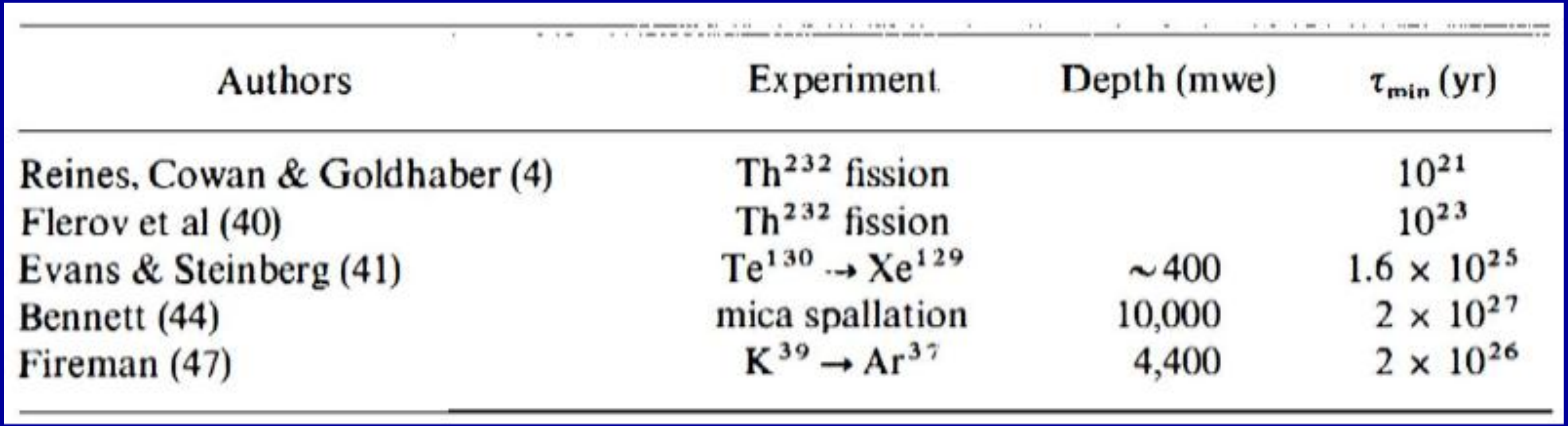
↓

IMB

↓

Super-Kamiokande

Detecting the Residual Nucleus



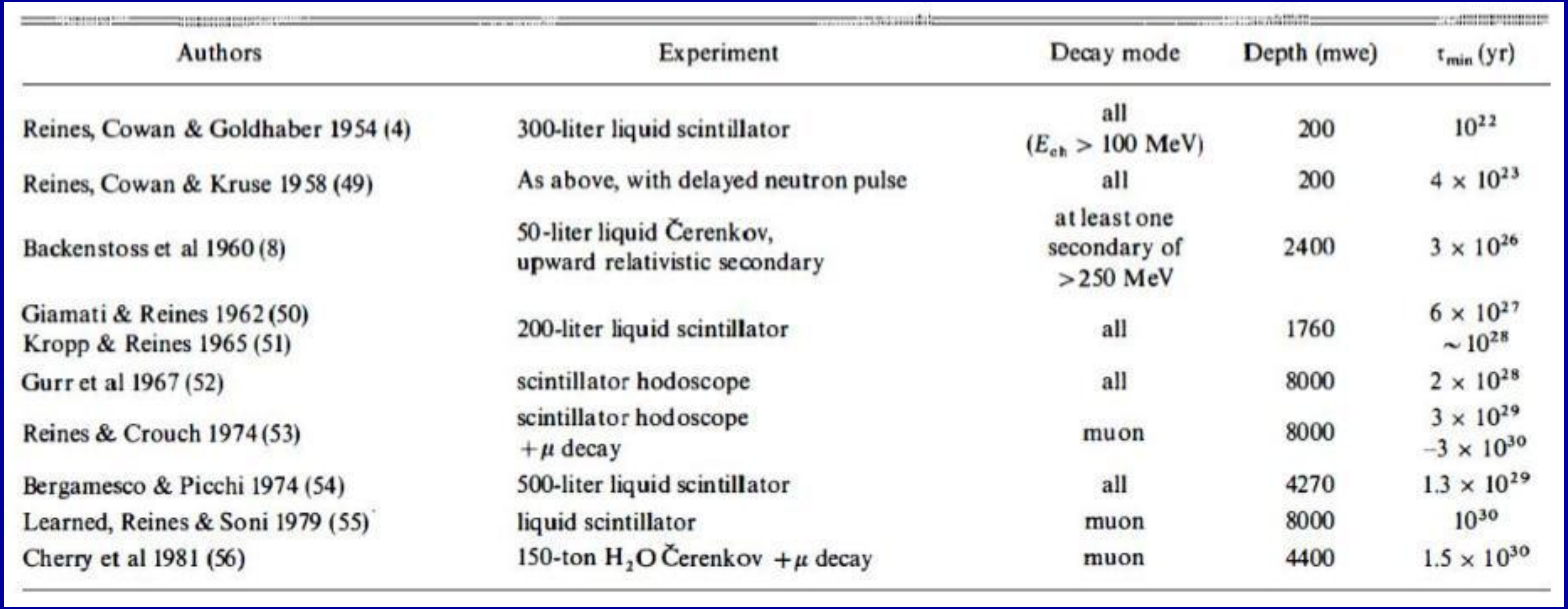
Authors	Experiment	Depth (mwe)	τ_{min} (yr)
Reines, Cowan & Goldhaber (4)	Th^{232} fission		10^{21}
Flerov et al (40)	Th^{232} fission		10^{23}
Evans & Steinberg (41)	$Te^{130} \rightarrow Xe^{129}$	~400	1.6×10^{25}
Bennett (44)	mica spallation	10,000	2×10^{27}
Fireman (47)	$K^{39} \rightarrow Ar^{37}$	4,400	2×10^{26}

- Fission – decay leaves exotic isotope, which fissions, giving energy that could be detected
- Decay – nucleon decay would cause element’s identity to change, which could be detected
- Spallation – the remaining nucleus would be destroyed, either busted up by the reaction products or left with so much energy that it would start emitting heavy particles. In mica, these tracks can be as long as 1-2 μm.

Above: pion spallation in mica

Detecting the Decay Products: The early years

- Look for decay products – could be there for many different reasons. If all such products were ascribed to nucleon decay, what would be the decay half-life?
- Eventually, methods improved



Authors	Experiment	Decay mode	Depth (mwe)	τ_{min} (yr)
Reines, Cowan & Goldhaber 1954 (4)	300-liter liquid scintillator	all ($E_{ch} > 100$ MeV)	200	10^{22}
Reines, Cowan & Kruse 1958 (49)	As above, with delayed neutron pulse	all	200	4×10^{23}
Backenstoss et al 1960 (8)	50-liter liquid Čerenkov, upward relativistic secondary	at least one secondary of >250 MeV	2400	3×10^{26}
Giamati & Reines 1962 (50) Kropp & Reines 1965 (51)	200-liter liquid scintillator	all	1760	6×10^{27} $\sim 10^{28}$
Gurr et al 1967 (52)	scintillator hodoscope	all	8000	2×10^{28}
Reines & Crouch 1974 (53)	scintillator hodoscope $+\mu$ decay	muon	8000	3×10^{29} -3×10^{30}
Bergamesco & Picchi 1974 (54)	500-liter liquid scintillator	all	4270	1.3×10^{29}
Learned, Reines & Soni 1979 (55)	liquid scintillator	muon	8000	10^{30}
Cherry et al 1981 (56)	150-ton H_2O Čerenkov $+\mu$ decay	muon	4400	1.5×10^{30}

Super-Kamiokande and Proton Decay

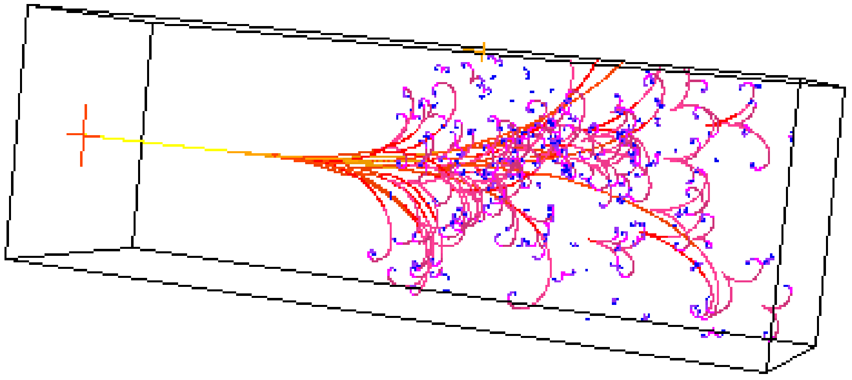
- Searching for two particular decay modes: here, we'll focus on

$$p^+ \rightarrow e^+ + \pi^0$$

- Shower from positron immediately followed by two gammas from pion decay – unique!

- Other mode Super-K searched for:

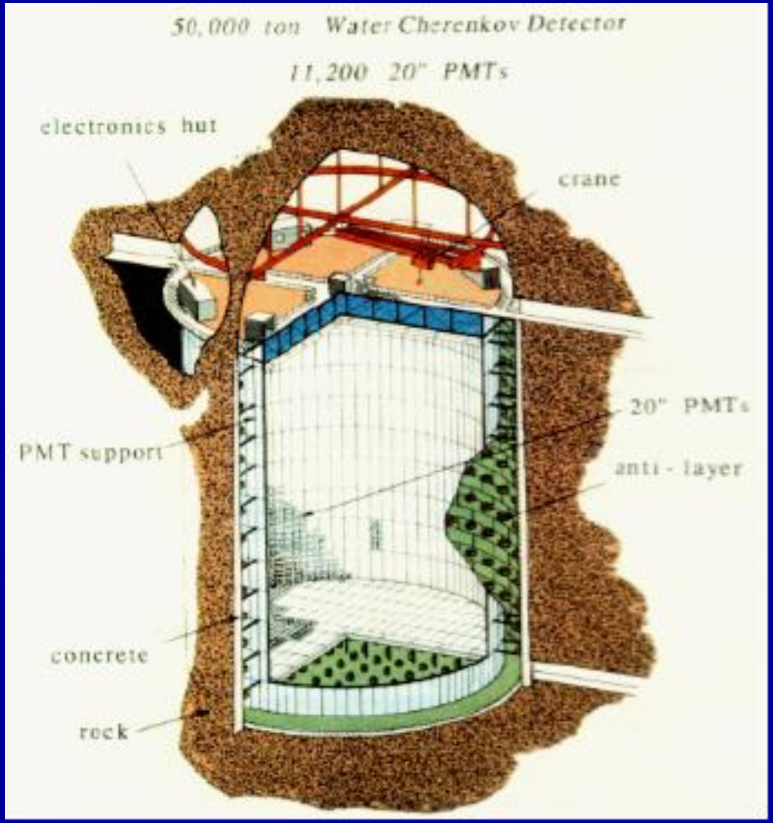
$$p^+ \rightarrow \bar{\nu} + K^+$$



$$\pi^0 \rightarrow \gamma + \gamma$$

Super-K Geometry

- Cylindrical steel tank – over 11,000 PMTs
- Surrounded by “veto region” with almost 2,000 PMTs
- Run for 414 live days
- Record (with timestamps) every PE event in the PMTs



- Inner layer – ultrapure water
- Anti-layer – muon veto

Initial Cuts on Data

Result: 600 million events!

Cuts:

1. Outer detector must be quiet
    - Eliminates cosmic ray muons
2. More than 200 total photoelectrons
    - Requires 190 MeV/c momentum for muons (22 MeV/c for photons)
3. More than one PMT must have significant activity
    - Reduces electrical noise
4. Time interval must be at least 0.1 ms
    - Reduces “after pulsing”

Results:

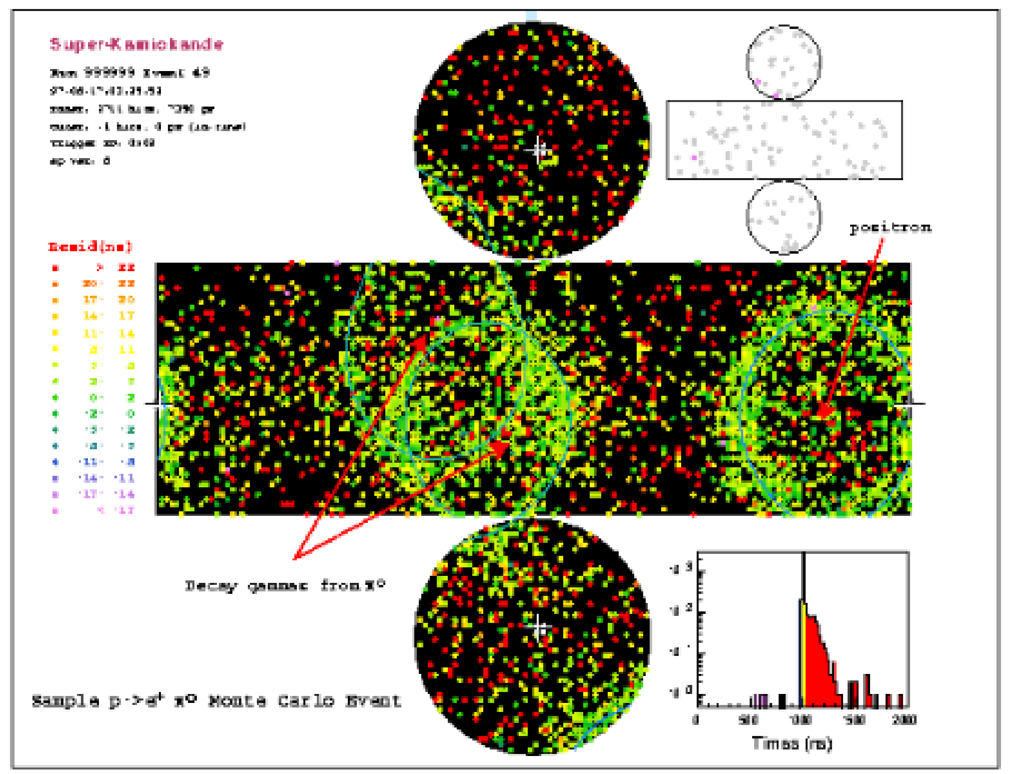
- 12 thousand events!
- Only 0.1% of good events thrown out

Further Cuts on Data

5. Hand scan using interactive display
□ 6000 events remaining
6. Only events inside fiducial volume accepted; removes last of cosmic ray muons, ensures that interactive display is correct
□ 3468 events remaining (significant loss)

Results:

- All background events gone
- 44% detection efficiency



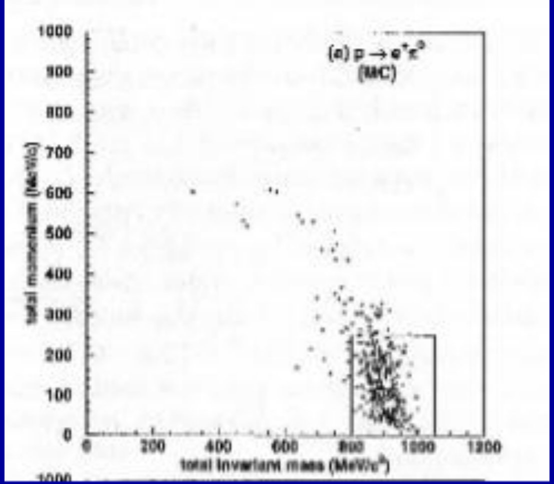
Final Cut & Results

1. We've eliminated all background – now time to eliminate other signals

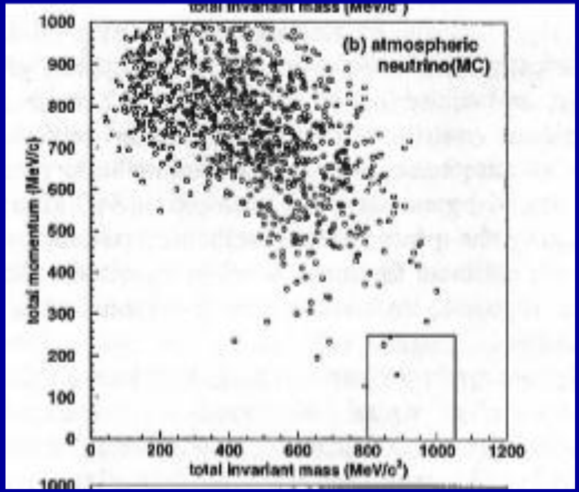
Final cuts on mass, momentum, electron presence, #s of photoelectrons, etc., made from simulations with MCs (significant loss)

Results:

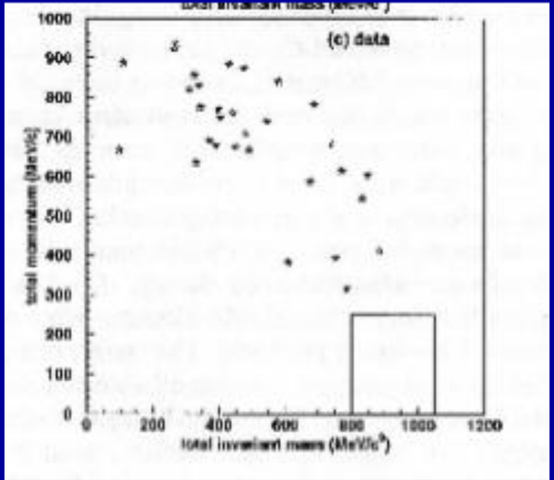
- 31 events – either neutrino events or nucleon decay events
- 44% detection efficiency



MonteCarlo event for proton decays



MonteCarlo event for atmospheric neutrino interactions

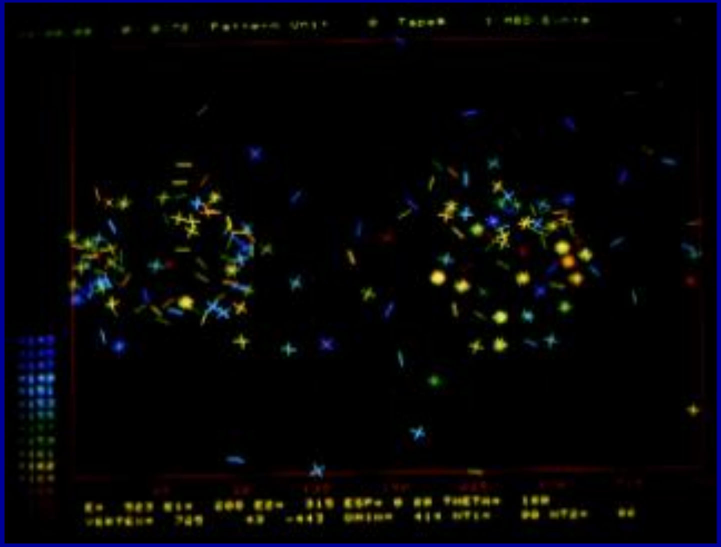


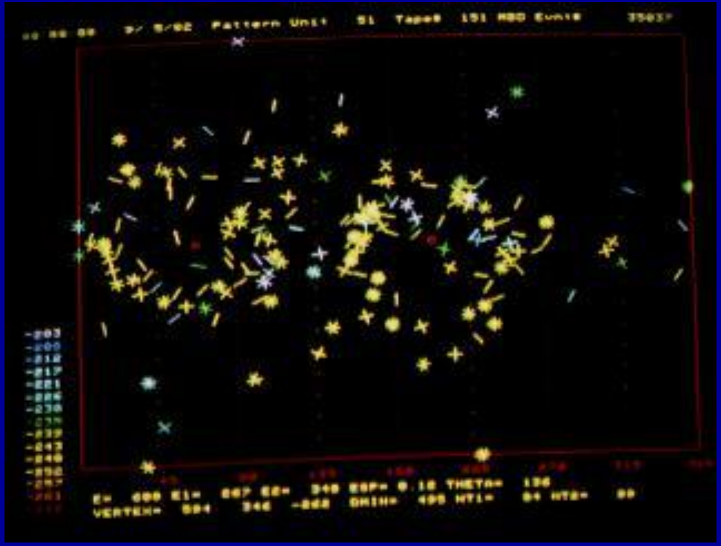
Actual Data

Result: No Proton Decay Events

Conclusion

- Lower limit on proton decay increased to 6.6 x 10^{33} years.
- 15 years later, this is still the best measurement of proton decay yet.





Above: IMB MC for proton decay
Lower: IMB Candidate event

PART 2: SUPERNOVA 1987A

This result is so frequently discussed that I give just a snapshot here.

Another Clichéd Result: Supernova 1987A

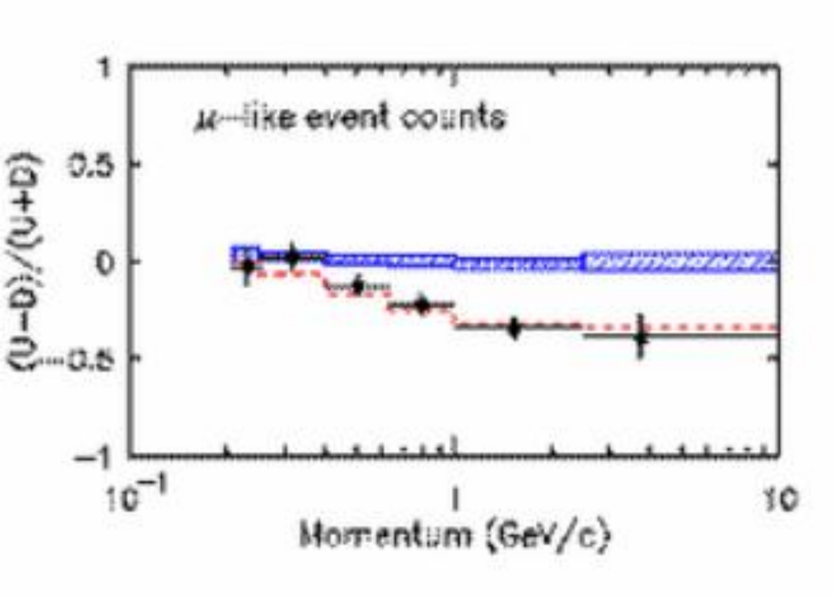
- Supernova –
  - Iron doesn’t undergo fusion or fission
  - Stars sustained by fusion in their cores
  - Eventually core becomes iron, fusion produced at larger radii
  - Degeneracy pressure of electrons overcome when iron core becomes heavy enough (1.44 solar masses)
  - Implosion results, protons and electrons form neutrons, lots of energy, enormous shock wave, only thing to escape are neutrinos (lots of them)
  - Result can be a white dwarf, neutron star, quark star (!), or black hole, depending on original size
- Super-K (as well as IMB) discovered a dozen neutrinos in just a few seconds, from the 1987A supernova
- Neutrinos & Anti-neutrinos arrived at the same time

"It's somewhere between a nova and a supernova... probably a pretty good nova."

PART 3: NEUTRINO OSCILLATION

Again, only the main points are highlighted since this topic is so frequently discussed.

Neutrinos Oscillate



- Analyzed atmospheric neutrino oscillations of the form:

$$\nu_\mu \longrightarrow \nu_\tau$$

- Zenith angle dependent deficit of muon neutrinos
- Established following oscillation parameters:

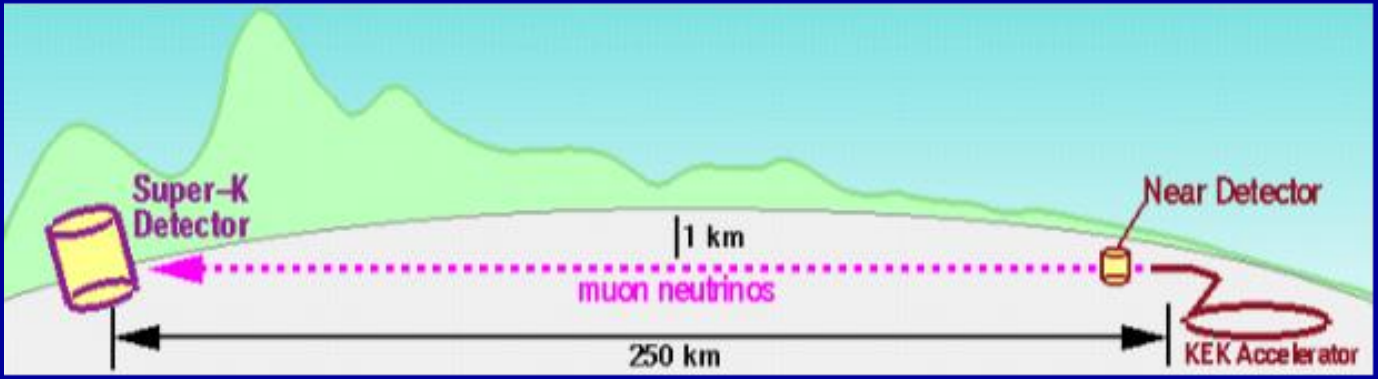
$$sin^2 2\theta > 0.82$$

$$5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3} eV^2$$

- All results at 90% confidence

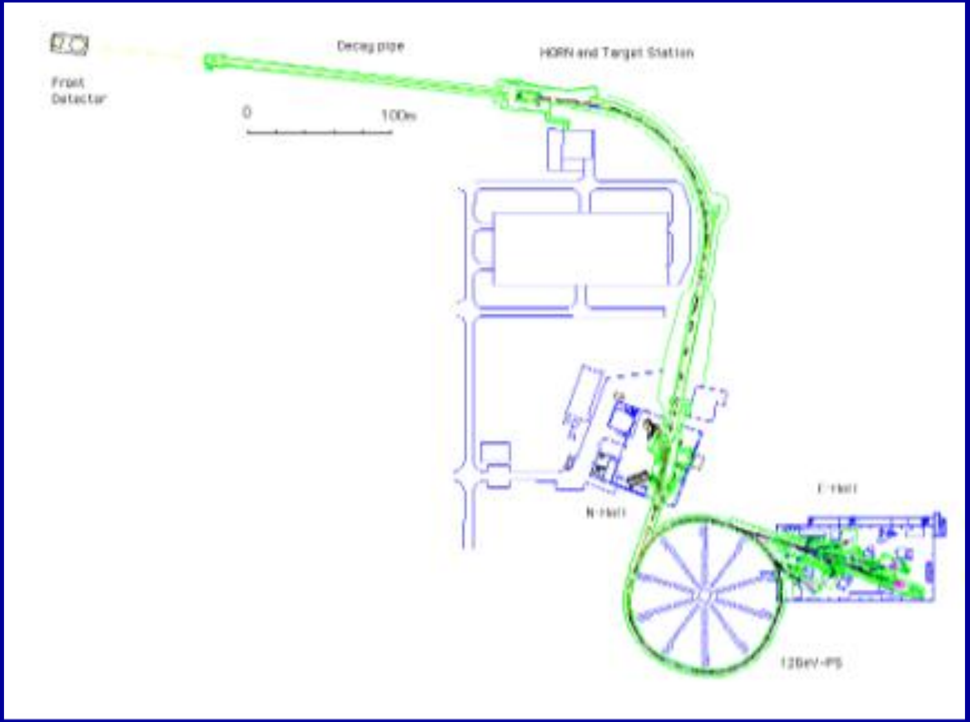
The K2K experiment: Overview

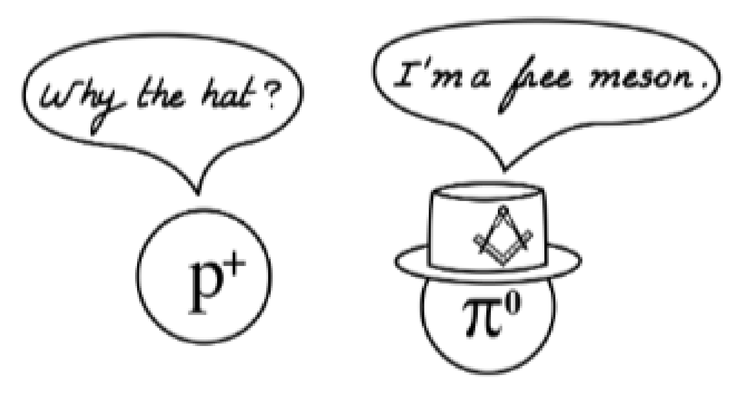
- Super-K depended on atmospheric neutrinos, which are not well-understood
- To confirm results, need to use accelerator neutrinos produced for this purpose
  - Much higher and better understood flux
  - Both inner and outer detector to take ratio, get mass *difference*
  - Both detectors can measure electron and muon neutrinos



The K2K Beam

1. Accelerate protons to 12 GeV (.997c), 10^{20} protons every 2.2 seconds
2. Magnetically turn the protons (to get rid of other stuff)
3. Crash protons into the “hadron production target,” get π^+
4. Wait for π^+ to decay into muons and muon neutrinos
5. A beam dump (iron, concrete and soil) absorbs the muons
6. The neutrinos enter the near detector and (eventually) the far detector



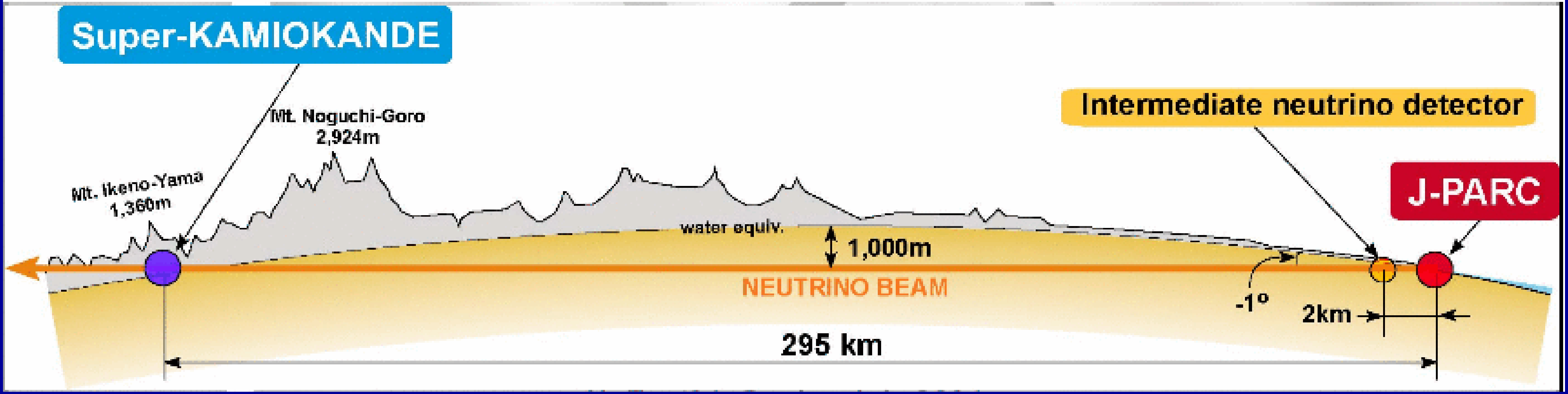


K2K Results

- Neutrinos oscillate!
  - Expect 151^{+10}_{-12} interactions (if no oscillations); only find 103 – suggests oscillations
  - No electron neutrinos beyond the background (1.2%) found; background is well-understood
  - Hence, lots of oscillations into tau neutrinos expected (or some 4th type of neutrino, no way to tell)
  - Refined oscillation parameters
  - Extensive beam studies; explores future of long-baseline experiments

The Present: T2K

- Super-K showed muon neutrinos oscillate
  - either $\nu_\mu \longrightarrow \nu_e$ or $\nu_\mu \longrightarrow \nu_\tau$
- K2K confirmed, showed $\nu_\mu \longrightarrow \nu_e$ is rare
- T2K will show if $\nu_\mu \longrightarrow \nu_e$ occurs at all
  - Put another way, will show if θ_{13} is zero.
  - Same basic setup as K2K



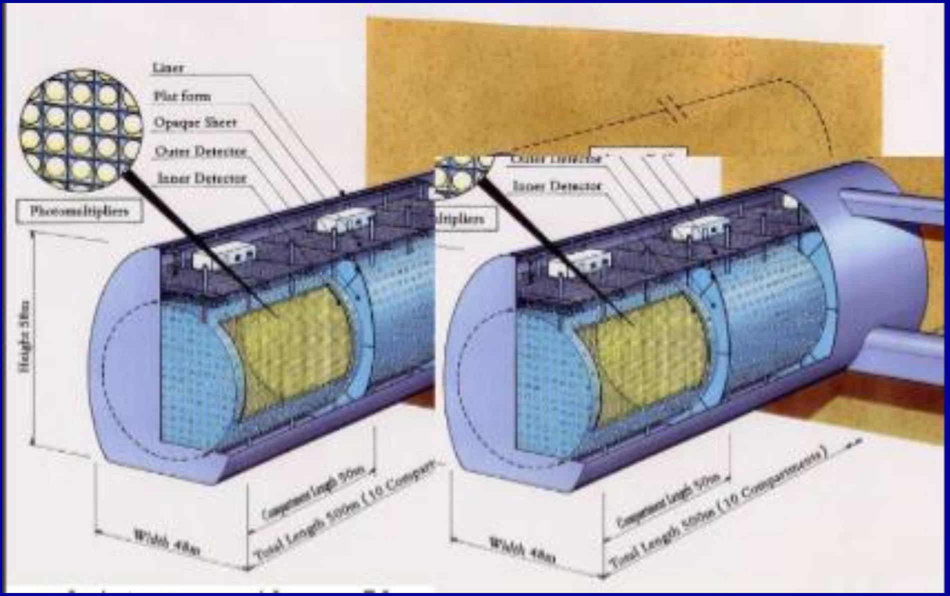
Advantages of T2K

- Protons will be accelerated to 50 GeV (instead of 12 GeV as in K2K), a speed of .9998c
- The neutrino flux improved by 110 times
- Off-axis – more desirable energy spectrum, thus higher efficiency
- State of the art near detector
  - Time projection chamber
  - Pi-zero detector
- Still using Super-K as far detector; well-understood

The Future: Hyper-K?

- T2K is essentially Super-K with a better beam
- Hyper-K would essentially be Super-K with better beam and better detector

- New detector has same principles, but 1 megaton *fiducial volume* (over 20 times larger)
- New location: perhaps Tochibora Mine
- Purposes:
  - Proton Decay search up to 10^{35} years
  - Another long-baseline experiment, to further constrain oscillation parameters
  - In addition to "normal" goals, like monitoring supernovae



Start taking data by 2020
Perhaps $400-500 million?

Summary

- Super-K proved that protons decay with a half-life of at least 6.6 x 10^{33} years, if at all
- Super-K proved that atmospheric neutrinos oscillate
- Also found supernova!
- K2K proved that terrestrial neutrinos oscillate, and gave stricter limits on the oscillation parameters
- T2K is further refining these parameters, in particular the parameter θ_{13}
- Hyper-K will, possibly, refine these even further