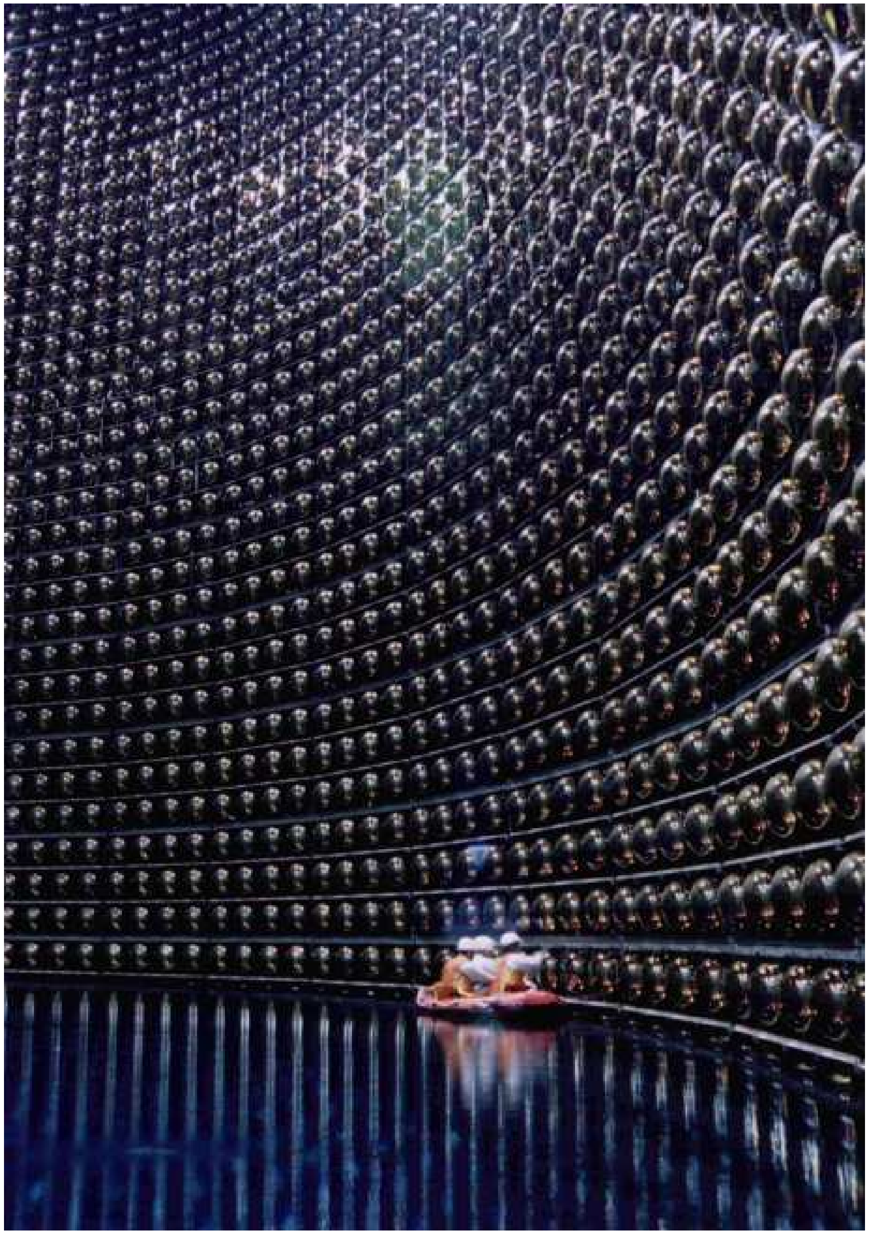
Neutrino Physics, Part 2

Beyond the

ν Standard Model

Scott Oser

UBC



Lake Louise Winter Institute

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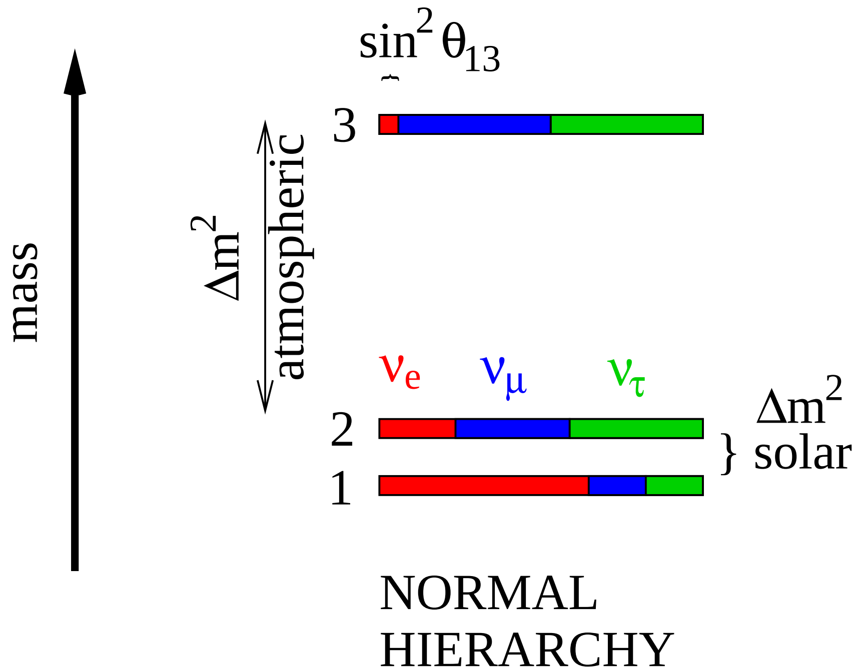
Outline

1. How Many Neutrinos Are There?
2. Neutrino Mixing Theory
3. θ_{13}: Rounding Out The Mixing Matrix
4. Neutrino Mass Measurement
5. Neutrinos at the LHC
6. An Employment Program For Neutrino Physicists

Last Time ...



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\approx \begin{bmatrix} 0.9 & 0.5 & s_{13}e^{i\delta} \\ -0.35 & 0.6 & 0.7 \\ 0.35 & -0.6 & 0.7 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m^2_{12} \approx 8 \times 10^{-5} \text{ eV}^2$$
$$|\Delta m^2_{23}| \approx 2.5 \times 10^{-3} \text{ eV}^2$$

Two Δm^2 values, but hierarchy (sign of Δm^2_{23}) uncertain.

Two well-determined mixing parameters, but θ_{13} and δ_{CP} unknown!

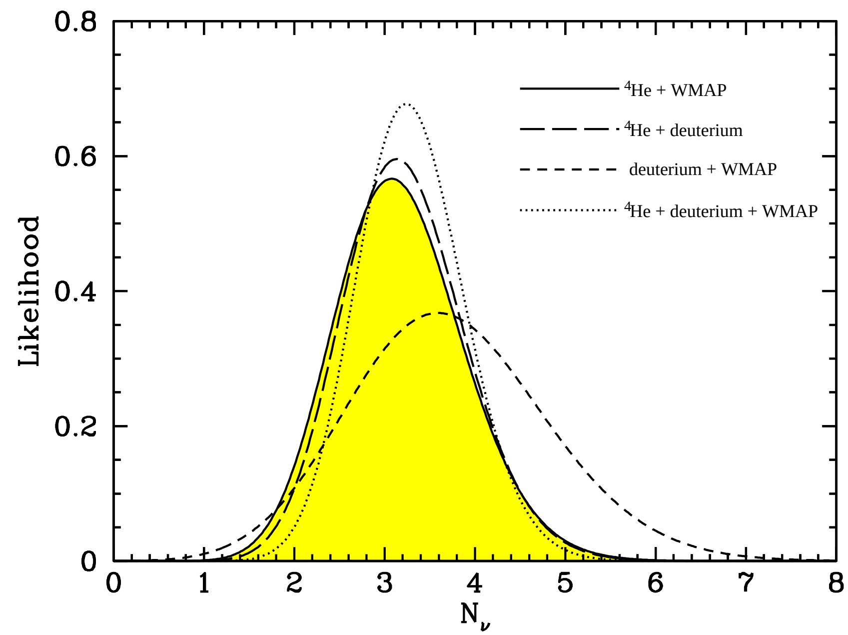
Counting Neutrinos In The Big Bang

In the early universe, relativistic light neutrinos increase the energy density, speeding up the expansion rate of the universe!

This changes the "freezeout temperature" of nucleosynthesis, at which $p \leftrightarrow n$ conversion stops. This affects the equilibrium between protons and neutrons in Big Bang Nucleosynthesis, and the baryon/photon density ratio.

Measuring the current cosmological densities of ^{4}He, deuterium, and baryons fix these parameters.

As early as 1977, $N_\nu \leq 5$ was derived from cosmology alone.



R. Cyburt *et al*, Astropart. Phys. 23 (2005), 313-323.

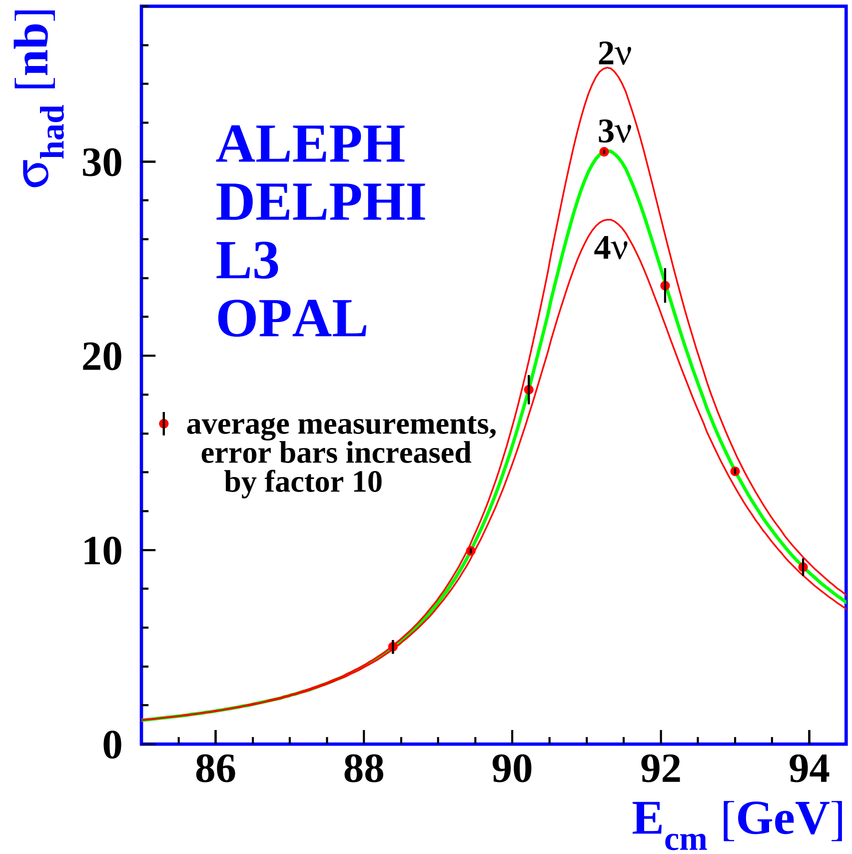
Current limit: $2.67 < N_\nu < 3.85\ (68\%\ C.L.)$

LEP results

Z decay to $\nu\bar{\nu}$ is of course invisible, but contributes to the total decay rate, and so the width of the Z mass peak.

$$N_\nu = \frac{\Gamma_{invisible}}{\Gamma_\ell} \left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}$$

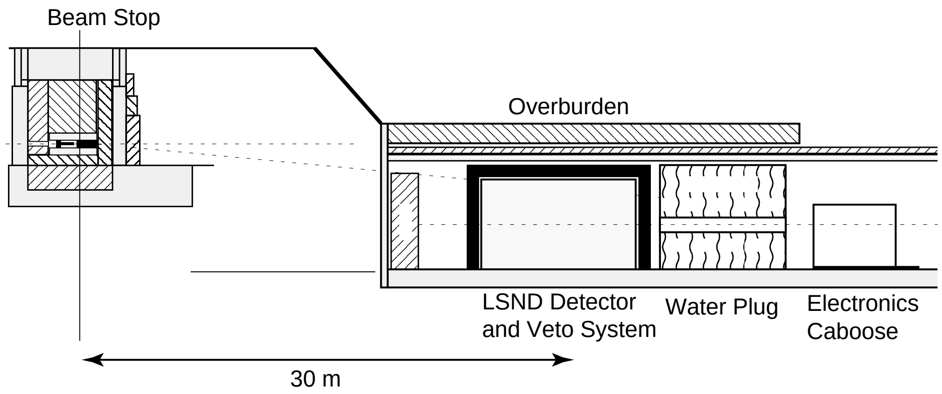
Comparing the visible width of the Z to its total width measures the number of neutrinos with $M_\nu < M_Z/2$

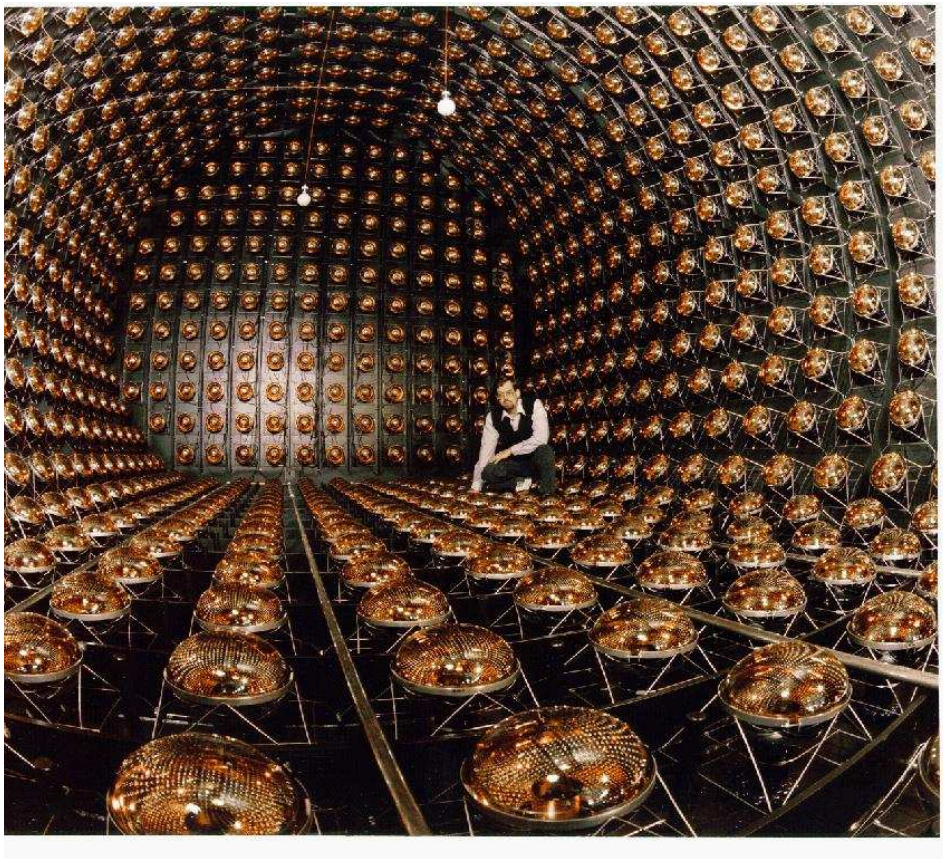


Physics Reports, hep-ex/0509008

Number of light neutrinos = 2.984 ± 0.008

LSND: $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillation?





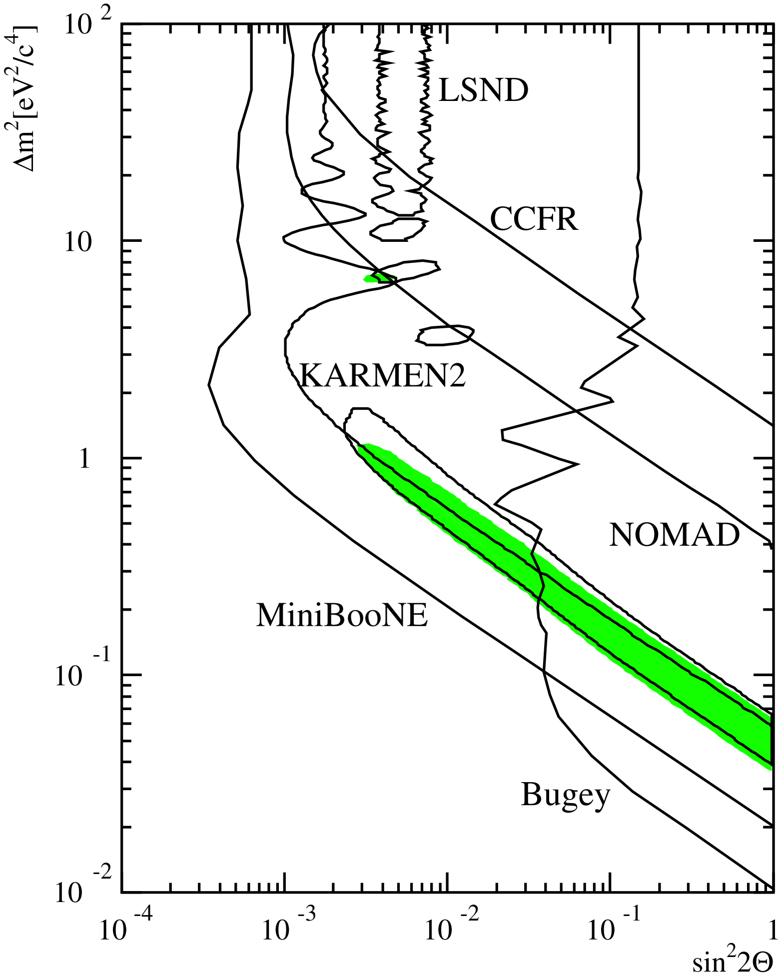
Beam consists primarily of ν_μ produced by decays of μ^+ at rest in beam dump, and ν_e and $\bar{\nu}_\mu$ from μ^+ at rest.

(Very?) small background of $\bar{\nu}_e$ from π^- and μ^- decays.

Look for $\bar{\nu}_e + p \longrightarrow e^+ + n$ in liquid scintillator detector 30 meters away.

Claimed excess! $\sim 3.8\sigma$ significance (PRD 64, 112007, 2001)

LSND vs. the World



Church *et al*, Phys.Rev. D66 (2002) 013001

LSND result almost, but not quite, ruled out by KARMEN and Bugey experiments.

OOPS! Too many Δm^2's!

$$\begin{aligned} \Delta m^2_{12} &= 8 \times 10^{-5}\,\mathrm{eV}^2 \\ \Delta m^2_{23} &= 2.5 \times 10^{-3}\,\mathrm{eV}^2 \\ \Delta m^2_{LSND} &= \sim 0.1 - 1.0\,\mathrm{eV}^2 \end{aligned}$$

You need a fourth neutrino to accomodate all results.

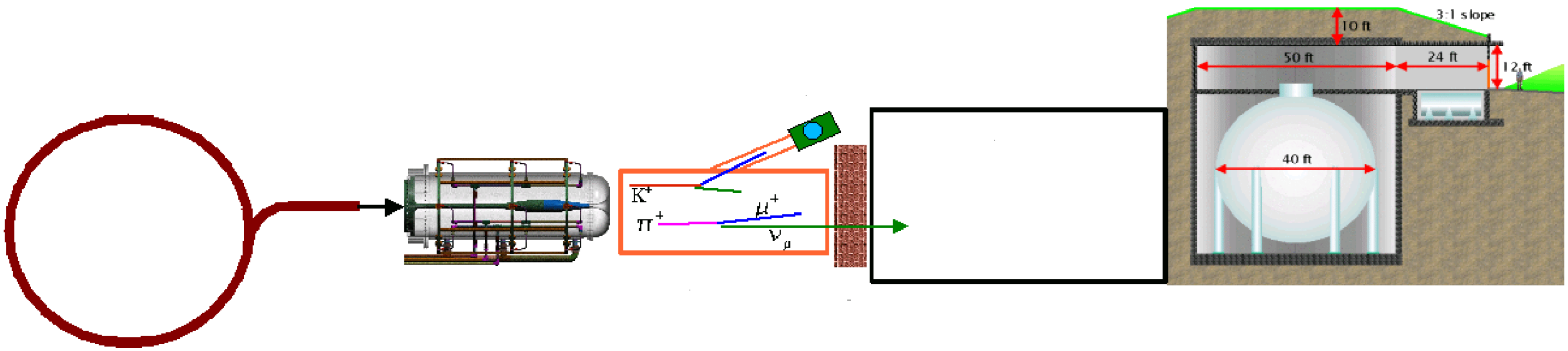
LEP results imply this neutrino must be sterile!

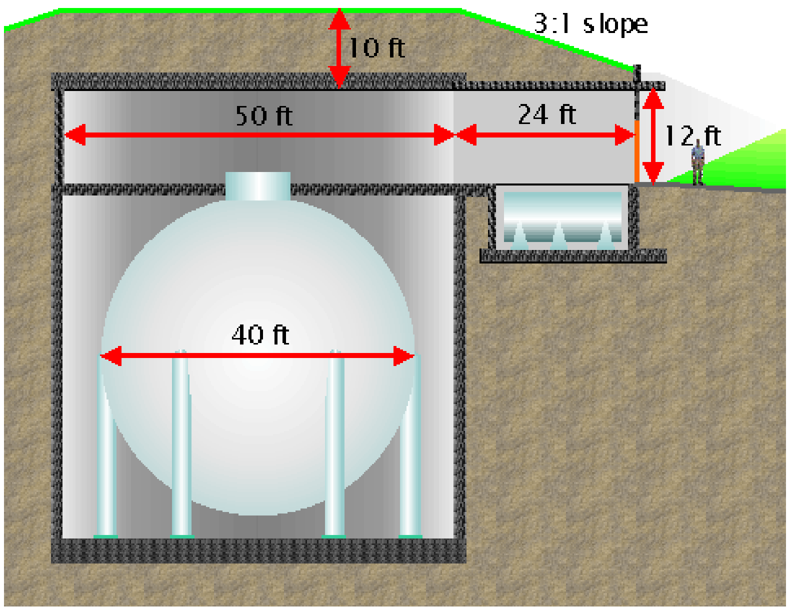
Solar, atmospheric, and KamLAND data rule out a single light sterile neutrino. Adding even more sterile ν's gives enough wiggle room to fi t everything.

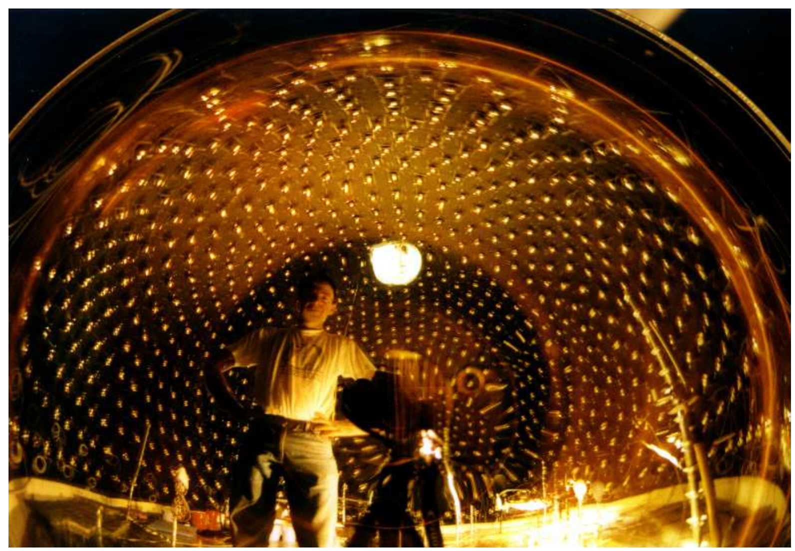
Extreme suggestions such as violation of CPT are also sometimes invoked.

Few people believe LSND, but few can coherently explain why.

MiniBooNE: A Check on LSND



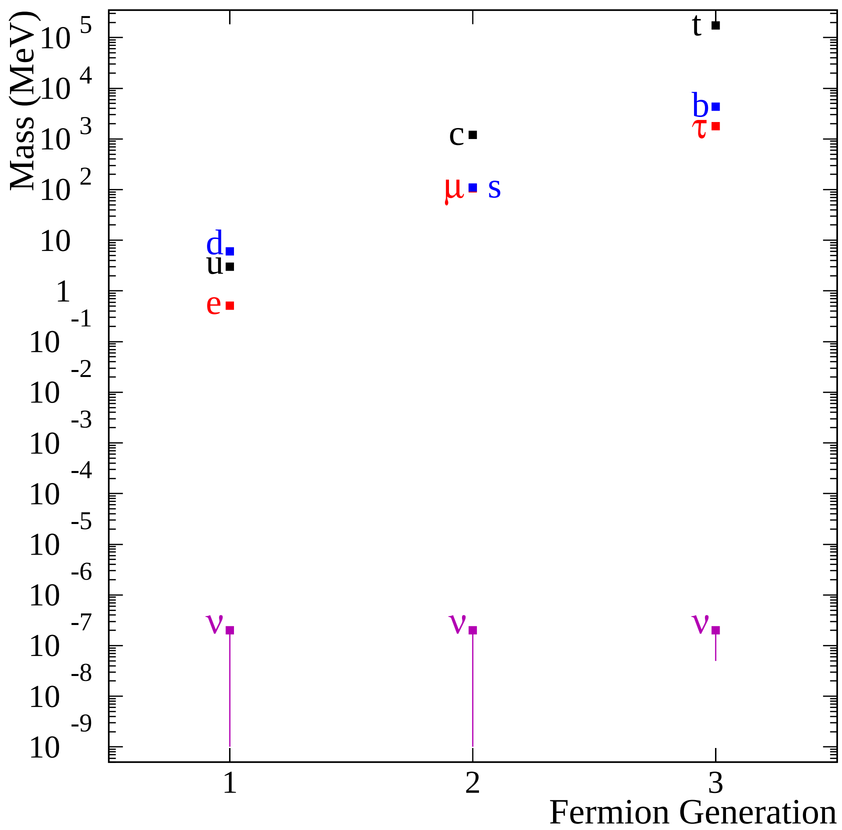




Results imminent!

How Do Neutrinos Get Mass?

The Neutrino Mass Puzzle



Within each generation, charged fermions masses are the same to 1-2 orders of magnitude.

However, neutrinos are many orders of magnitude lighter than other fermions!

This is suggestive of a new mechanism for generating neutrino mass!

How Particles Get Mass

In the Standard Model, mass comes from a term in the Lagrangian of the form:

$$-L_m = m\bar{\psi}\psi \equiv m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

A term of the form $\bar{\psi}_L\psi_R$ is called a "Dirac mass". In the Standard Model, all mass terms are Dirac masses, and so $m_R = m_L$ (i.e. left-handed and right-handed fi elds have the same mass.)

m_D is the Yukawa coupling of the Higgs fi eld to the fermion.

You *could* just choose m_D to be really small compared to charged fermion masses, and admit that you have no clue why.

But neutrinos may have a trick up their sleeve ...

Majorana Neutrinos

Unlike other fermions, neutrinos have no charge. They do have lepton number and flavour number, but these may not be conserved quantum numbers in BSM physics.

If a neutrino has no conserved quantum numbers, it could be its own antiparticle! But how do we account for the fact that ν and $\bar{\nu}$ are seemingly different?

The Majorana neutrino hypothesis: an antineutrino is just a neutrino with its spin flipped in the opposite direction!

This means you can specify a Majorana neutrino by a two-component Weyl spinor, and not a 4-component Dirac spinor like an electron needs.

Majorana Mass Terms

Imagine that ν_L is a light, left-handed neutrino that couples to weak interactions, and is its own antiparticle.

Suppose that ν_R is a very heavy, right-handed *sterile* neutrino. It's heavy because it doesn't couple to anything, and so it's an electroweak singlet, and its mass isn't protected by any electroweak symmetry.

The following mass terms are now allowed:

$$-L_m = m_D \bar{\nu}_L \nu_R + \frac{1}{2} m_L \nu_L^T C \nu_L + \frac{1}{2} m_R^* \nu_R^T C \nu_R + h.c.$$

For an electron, only the first term exists. Both e_R and e_L exist as separate fields, but have the same mass because they always appear together in the mass term. The red terms violate lepton number, and are forbidden in the SM.

For a Majorana neutrino, all three terms can exist. Both ν_R and ν_L can exist as separate fields, and can have independent mass terms m_L and m_R. They also can couple to each other through m_D.

The Seesaw Mechanism

You can write the mass term as:

$$-L_m = \frac{1}{2}(\nu_L, \nu_R) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

The off-diagonal elements are a coupling between the light ν_L and the heavy ν_R. It modifi es the phenomenological masses of ν_L and ν_R. If you diagonalize the matrix, you fi nd the effective masses are:

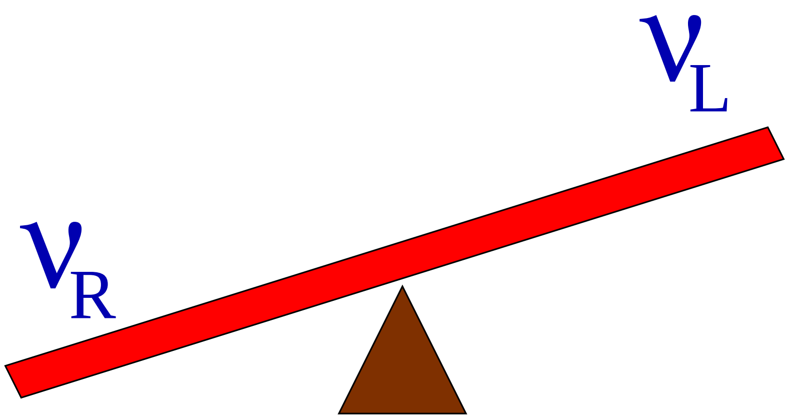
$$M_{heavy} \approx m_R, \qquad M_{light} \approx m_L - \frac{m_D^2}{m_R}$$

The Seesaw Mechanism

Suppose that $m_L \ll m_D \ll m_R$. If we take m_D to be the same order of magnitude as the Dirac mass term for other fermions (for example, $m_D \sim m_{top} \sim 200$ GeV, and take $m_R \sim M_{GUT} \sim 10^{15}$ GeV, then

$$M_{light} \sim \frac{m_D^2}{m_R} \sim \frac{(200\ \mathrm{GeV})^2}{10^{15}\ \mathrm{GeV}} = 0.04\,\mathrm{eV}$$

This is very close to the observed mass scale $\sqrt{\Delta m^2_{23}}$!



If neutrinos are their own antiparticles, then a right-handed neutrino at the GUT scale can explain the small observed light neutrino masses without fine-tuning of the Yukawa coupling!

Neutrino Oscillations *Are* Physics Beyond the Standard Model!

- At a minimum, we must introduce new right-handed sterile fermions into the SM. So we have new fields, with weird properties!
- New parameters needed: three new masses, and four mixing parameters (more if Majorana neutrinos allowed)
- Very small masses suggestive of new mass mechanisms—possibly seesaw mechanism, related to GUT-scale physics. Else a bad fine-tuning problem develops.
- Accomodating the very different mixings of quarks and leptons is a challenge for quark-lepton unification schemes.

θ_{13} and CP Violation

From ν_e appearance to θ_{13}

Super-K, K2K oscillations seem to be of type $\nu_\mu \longrightarrow \nu_\tau$

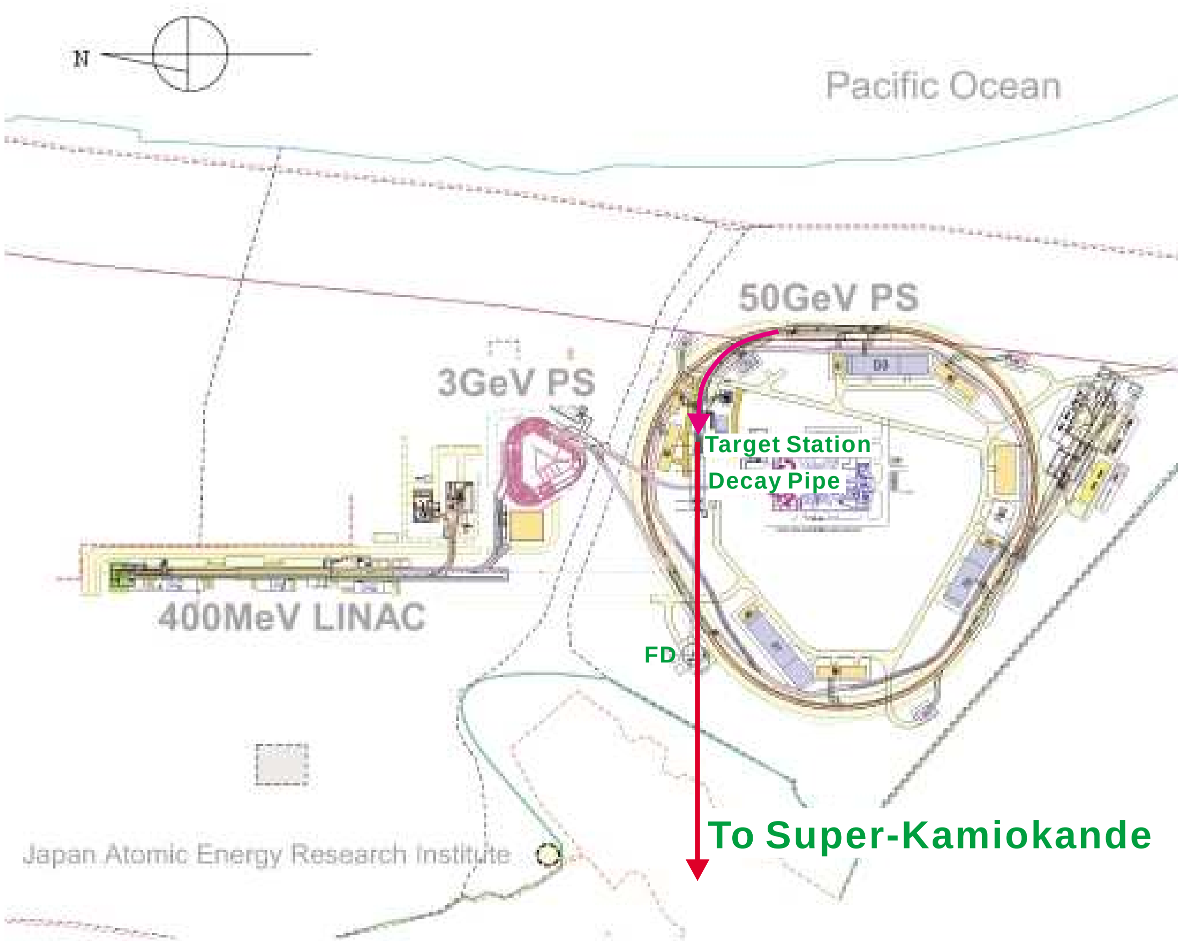
But some ν_μ should oscillate to ν_e. At Δm^2_{atmos}:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23}$$
$$\approx \frac{1}{2} \sin^2 2\theta_{13}$$

Current best limit is $\sin^2 2\theta_{13} < 0.1$, from reactor searches for $\overline{\nu}_e$ disappearance searches.

Measure $P(\nu_\mu \to \nu_e)$ to determine θ_{13}!

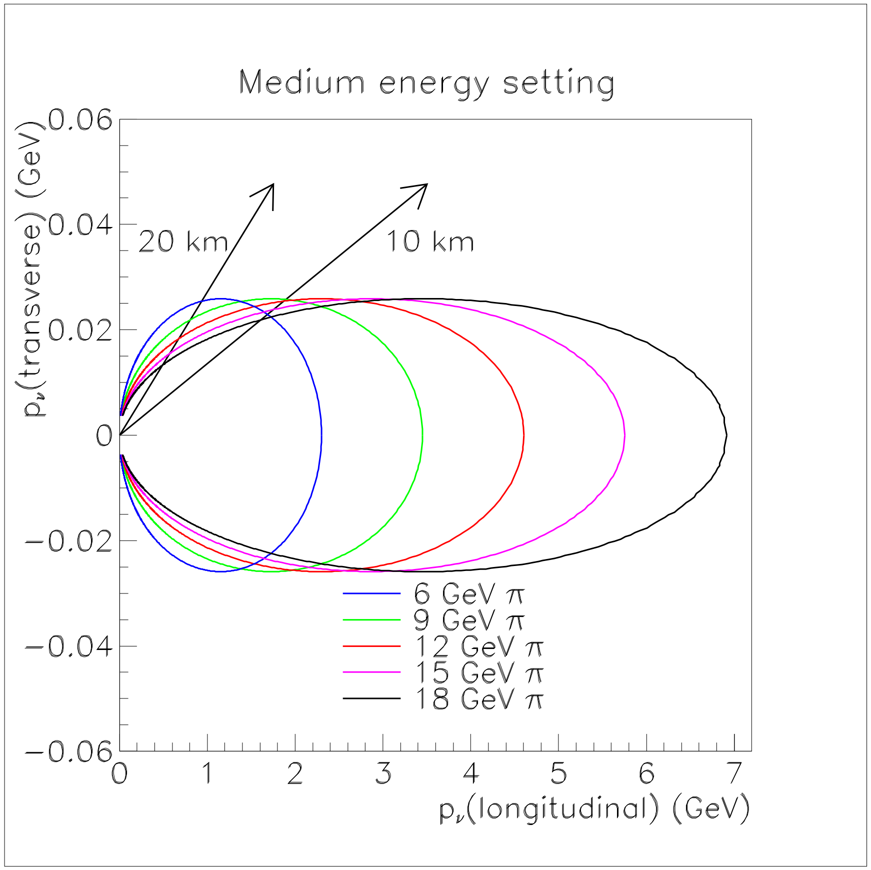
The T2K Experiment

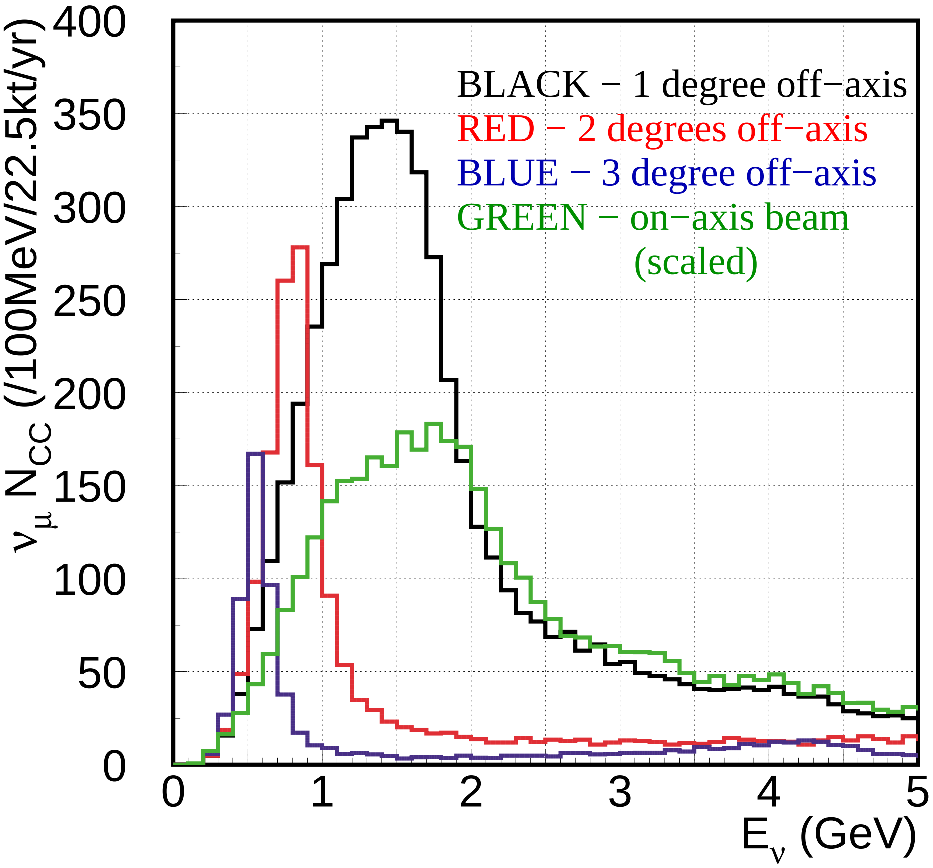


Megawatt-scale neutrino beam from Tokai to Kamioka

Funded since 2004. International collaboration includes Japan, Canada, France, Italy, Poland, Russia, South Korea, Spain, Switzerland, UK, US

Off-axis Beam Kinematics





Pions of different energies give ν's of same energy when viewed off-axis

Idea developed at TRIUMF

Important for increasing flux at oscillation maximum, reducing high energy tail (source of background)

T2K: Experimental Challenges of ν_e Appearance

Expected Interactions, 5×10^{21} protons on target, at θ_{13} upper limit

	ν_μ C.C.	ν_μ N.C.	Beam ν_e	Oscillated ν_e
Generated in F.V.	10713.6	4080.3	292.1	301.6
2) 1R e-like	14.3	247.1	68.4	203.7
3) e/π^0 separation	3.5	23.0	21.9	152.2
4) 0.4 GeV$< E_{rec} < 1.2$ GeV	1.8	9.3	11.1	123.2

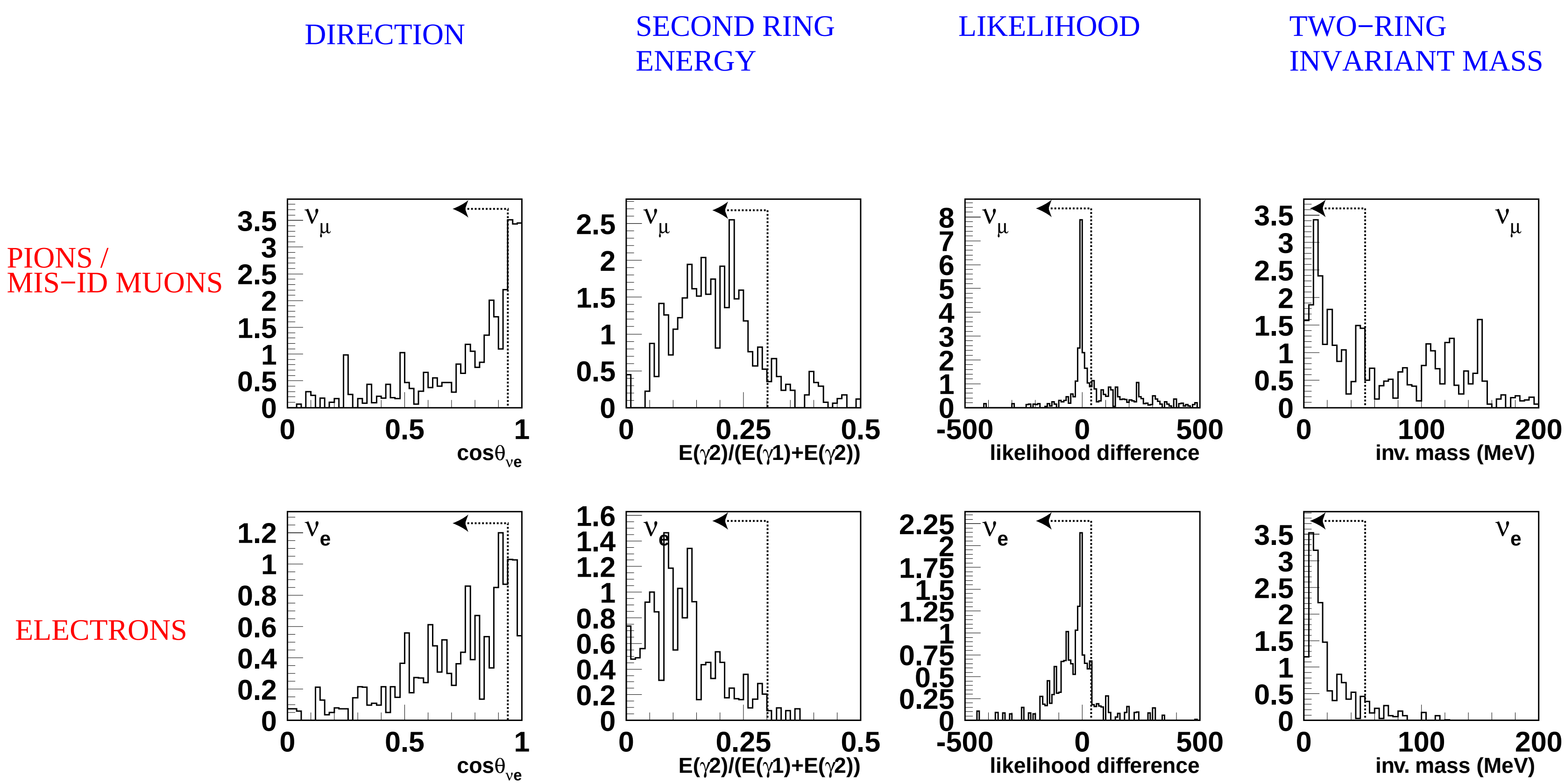
Far detector needs $\sim \times 1000$ muon rejection.

Important background is NC π^0's being mistaken for e

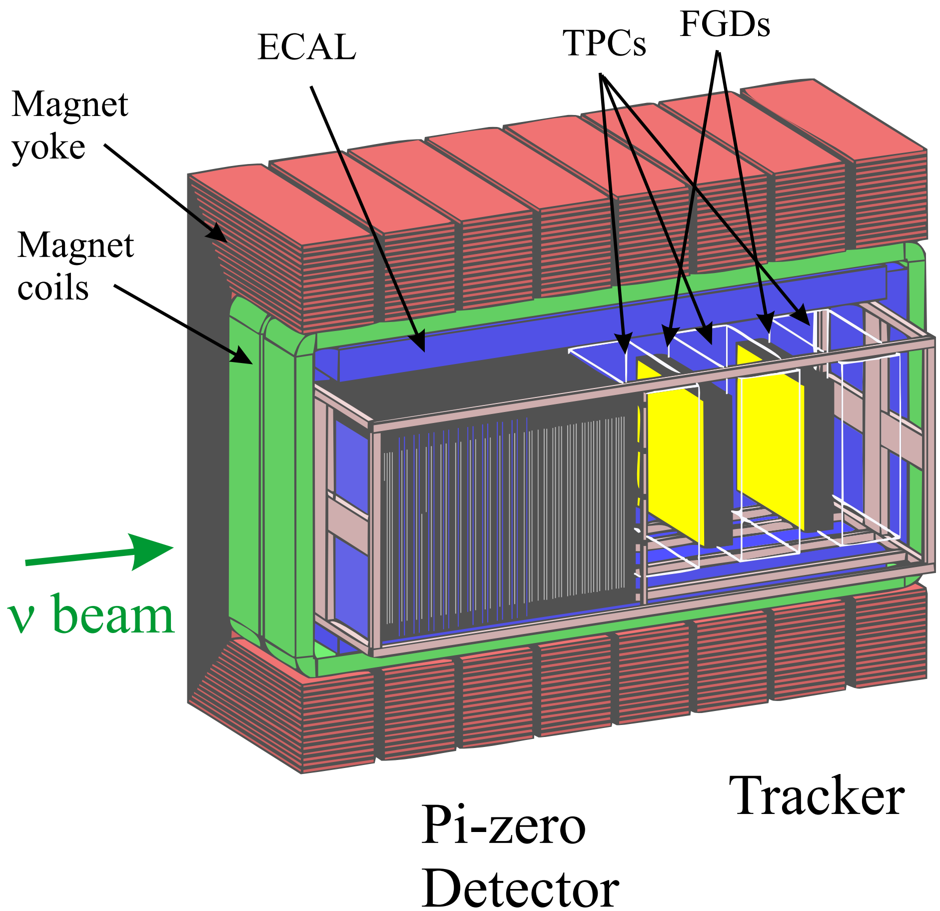
- Need $\sim \times 400$ π^0 rejection
- Need to measure to background to $\sim 10\%$.
- Large nuclear effects—desirable to measure on O nuclei

Irreducible ν_e beam background

T2K: e/π^0 separation at Super-K

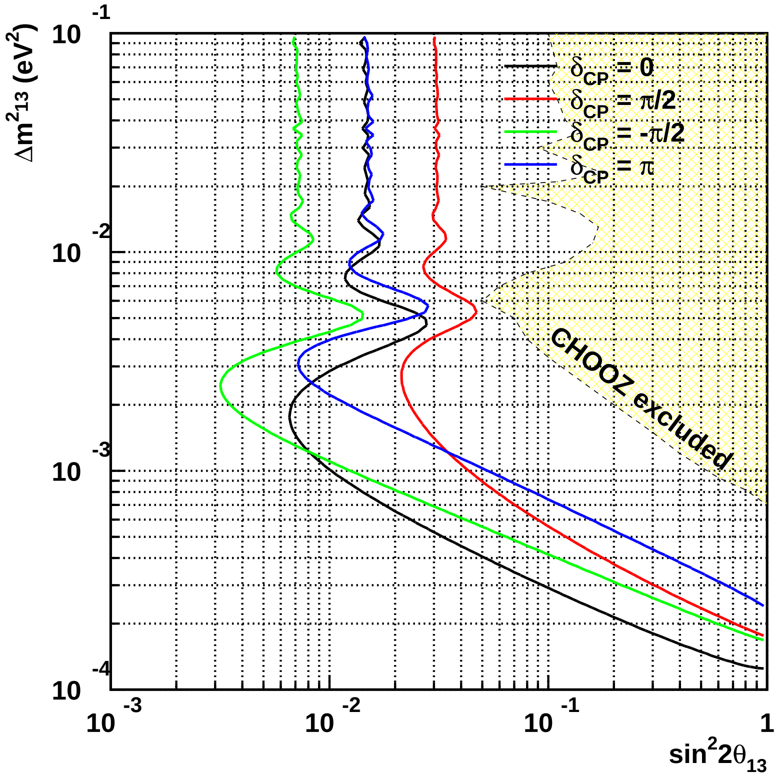


The T2K 280 m Near Detector

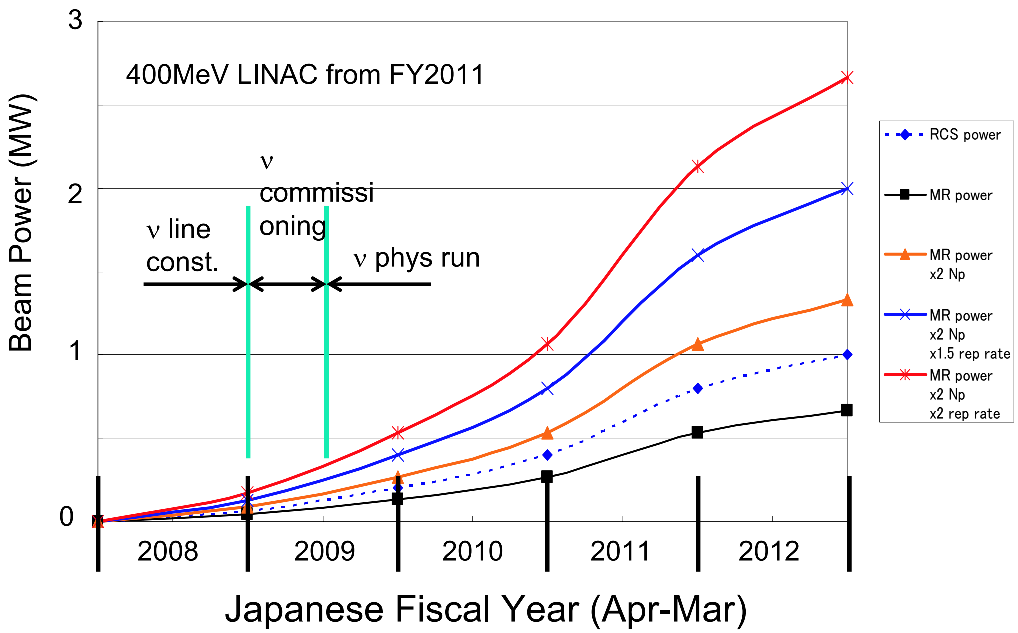


- P0D detector optimized to convert π^0's - segmented scintillator layers
- B field, gas TPCs with GEM or Micromega readout for momentum measurement
- Downstream scintillator layers (FGDs) optimized for CC interactions
- Magnet instrumented as side muon detector

T2K Expected Sensitivity



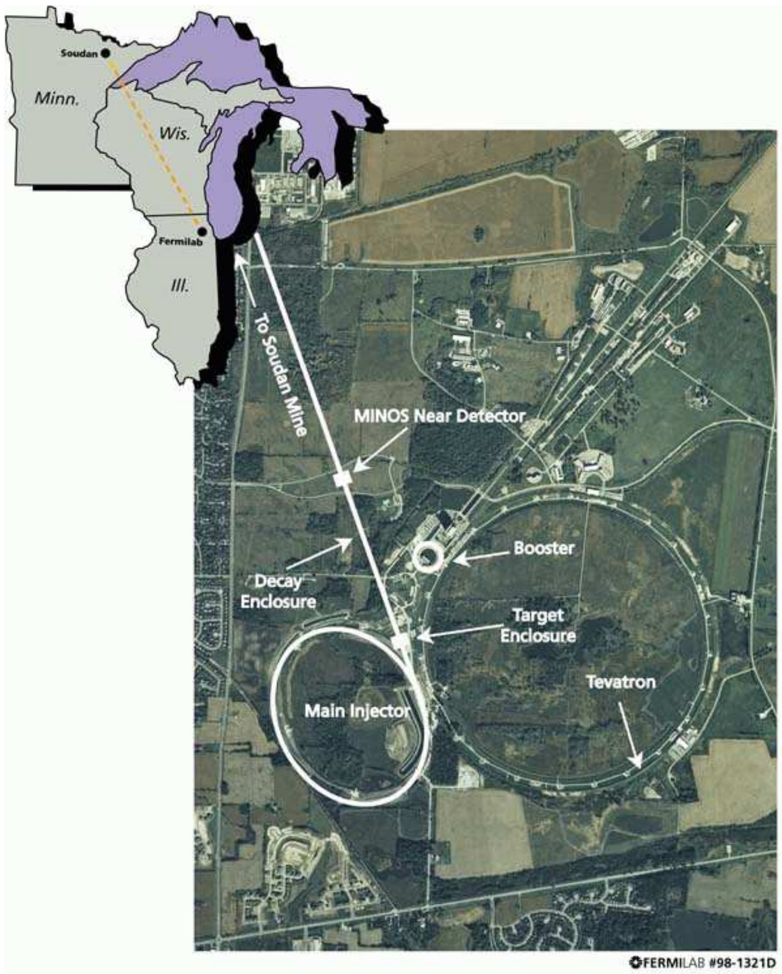
Sensitivity for 5×10^{21} protons on target

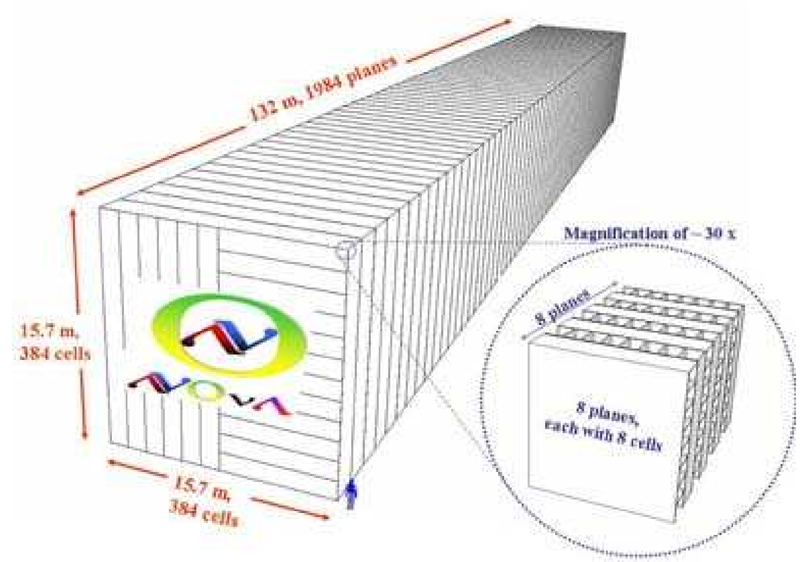


Various beam power options

The NOνA Proposal

NuMI Off-Axis ν_e Appearance Experiment





Idea: build a new detector viewing the NuMI beam used by MINOS, optimized for observing $\nu_\mu \to \nu_e$

A 30 kton active scintillator detector with fine segmentation to see ν_e appearance.

Similar concept to T2K, but with longer baseline, higher beam energy, and different far detector design.

Currently in proposal stage: $165M

From ν_e Appearance to CP Violation

CP requires $P(\nu_\mu \to \nu_e) = P(\overline{\nu}_\mu \to \overline{\nu}_e)$

For ν_e appearance at Δm^2_{atmos}:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta_{CP}$$

For CP violation to be observable, we need:

1. $\theta_{13} \neq 0$ (so we can see appearance)
2. Δm^2_{12} relatively big (CP effect comes from interference between oscillations at solar and atmospheric Δm^2's)
3. θ_{12} large

SNO fi nds, and KamLAND confi rms, solar LMA solution, guaranteeing (2)-(3)!

Mass Hierarchy from Matter Effects

Matter effects modify oscillation probability. At fi rst oscillation max:

$$P_{matter}(\nu_\mu \to \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_\mu \to \nu_e)$$

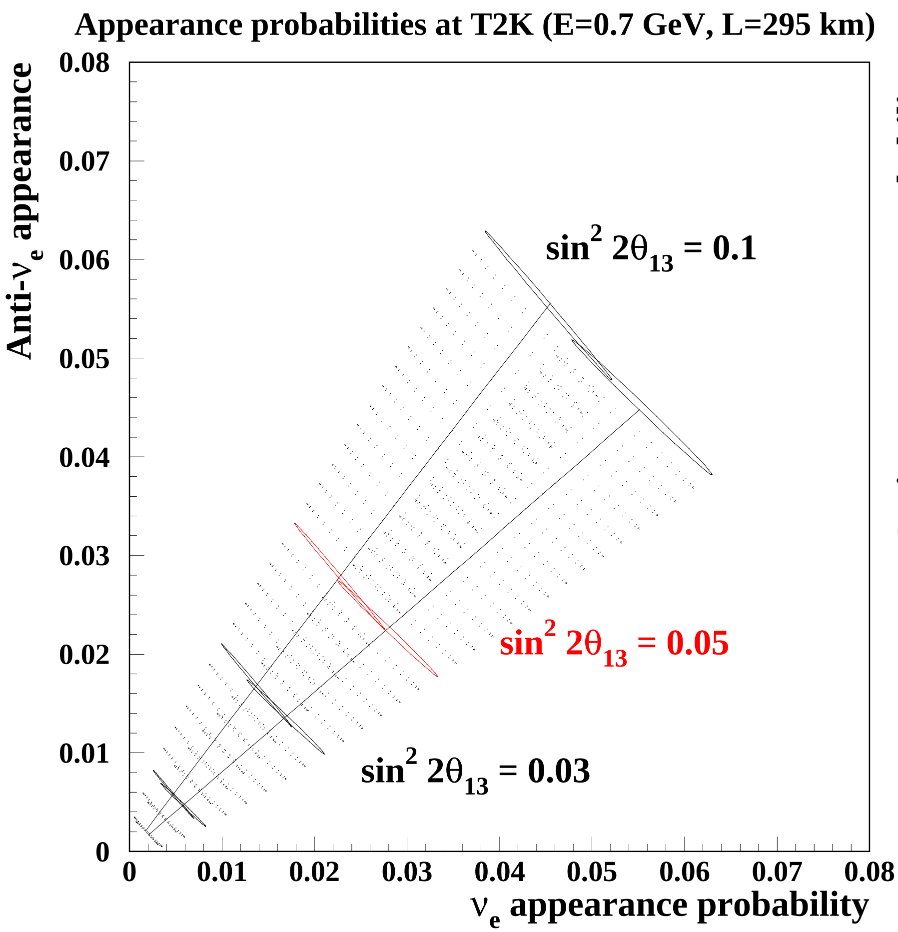
$$E_R = \frac{\Delta m^2_{32}}{2\sqrt{2} G_F N_e} \approx 13\,\mathrm{GeV} \left(\frac{\Delta m^2_{32}}{3 \times 10^{-3}\,\mathrm{eV}^2}\right)$$

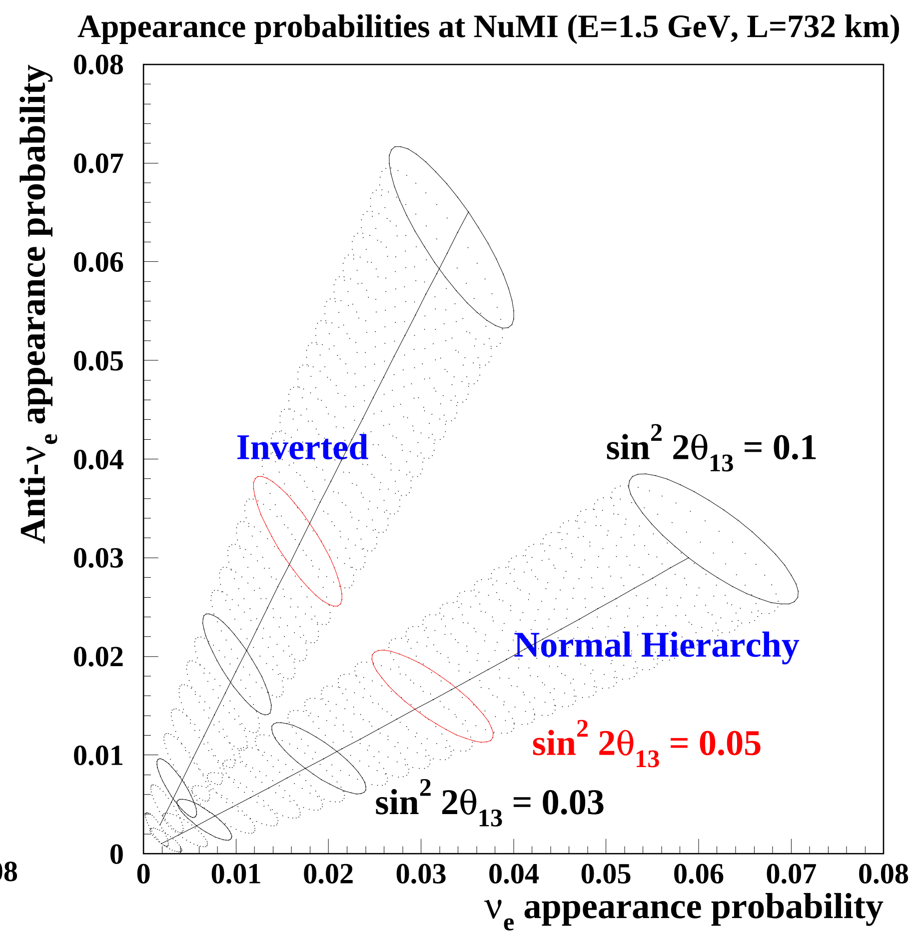
Sign of matter effect depends on mass hierarchy!

Matter effects increase with L, E.

Matter effects for ν, $\overline{\nu}$ have opposite sign—potential 'fake' A_{CP}

Separating CP Violation From Matter Effects





Leptogenesis

Sakharov conditions for baryogenesis:

- baryon number violations
- C and CP violation
- deviation from thermal equilibrium

Standard leptogenesis (Fukugita & Yanagida, Phys. Lett B 174, 45 (1986)):

- Heavy Majorana neutrinos (needed for see-saw)
- CP-violating decay modes
- Both Dirac CP phase (MNS matrix) and Majorana CP phases contribute

Asymmetry in lepton number turned into asymmetry in baryon number

Many variations:

- Leptogenesis with Dirac neutrinos (Murayama & Pierce, hep-ph/0206177)
- ~ 400 papers on XXX!
- Relation between CP violation in oscillation experiments and CP violation in leptogenesis very model-dependent!

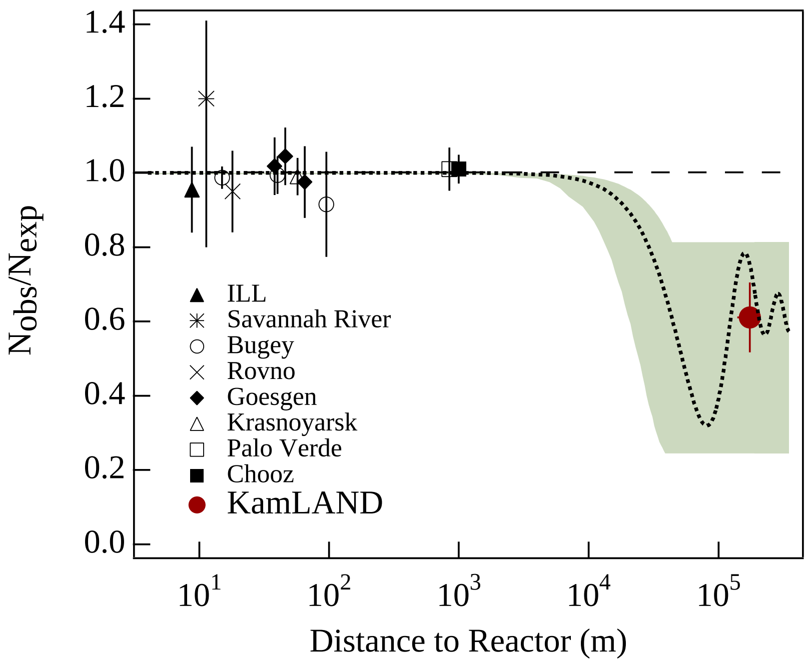
Diffi cult to connect experimental results with leptogenesis ...

but observation of large δ_{CP} would provide “circumstantial” evidence

Reactor θ_{13} Experiments

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2_{12} L}{E}\right)$$

Remember that KamLAND saw oscillation of reactor neutrinos at $L \approx 180$ km?



But what about those reactor experiments at *short* distances that saw nothing?

For $\Delta m^2_{13} \approx 2.5 \times 10^{-3}$ and $E \sim 5$ MeV, should have oscillation maximum at $L \approx 2$ km.

Since this is driven by oscillation between ν_1 and ν_3, the relevant mixing angle is the mixing between ν_e and ν_3—that is, θ_{13}.

CHOOZ limits:

$$R = 1.01 \pm 0.028\,(\text{stat}) \pm 0.027\,(\text{sys})$$

$$\sin^2 2\theta_{13} < 0.15\ (90\% C.L.)$$

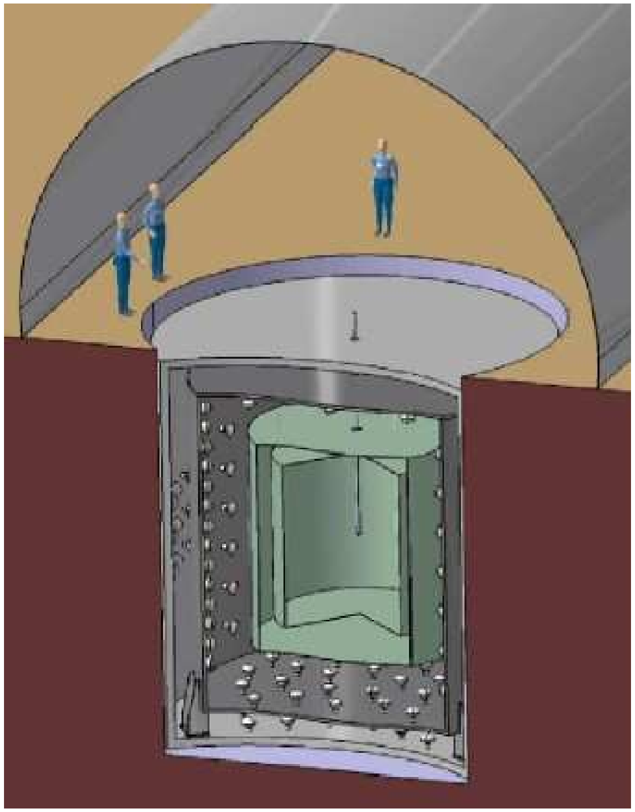
New θ_{13} Experiments

A next generation reactor experiment could improve the θ_{13} limit by an order of magnitude by:

- Large increase in statistics: use a GW-scale reactor and run for a few hundred GW-tonne-years
- Reduce systematics to $< 1\%$: use both a near and a far detector to cancel systematics.
- Better detector design

Reactor experiments sensitive *only* to θ_{13}, not δ_{CP} or matter effects. Very complementary!

Price tag: $\sim \$50$ M



The Double CHOOZ far detector

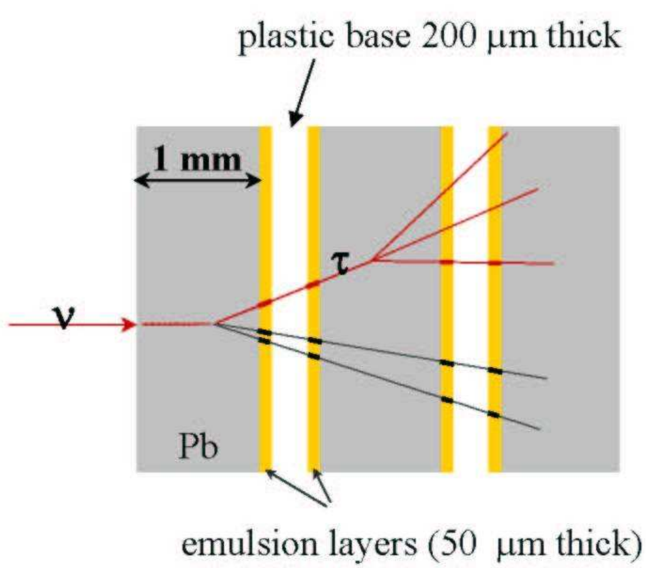
Many proposals: Double CHOOZ, Braidwood, Daya Bay, Kashiwazaki, Diablo Canyon, Angra, Krasnoyarsk, Korea ...

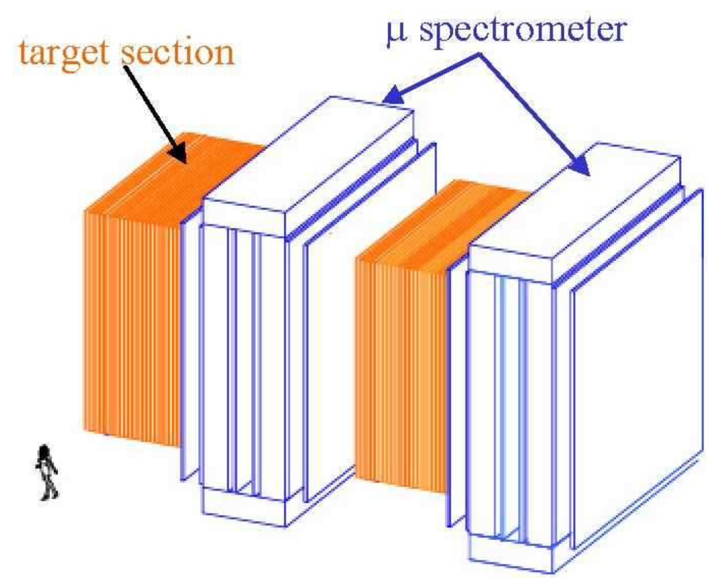
CERN to Gran Sasso

CNGS beamline produces high energy (~ 17 GeV) ν's with 400 GeV protons from the CERN SPS.

Baseline: 730 km

Experiments are optimized for ν_τ appearance:





OPERA detector: emulsion fi lms inside a magnetic spectrometer!

Low rate! For $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2:

Channel	Signal Events	Background
$\tau \to e$	3.9	0.16
$\tau \to \mu$	3.2	0.29
$\tau \to h$	3.2	0.20
Total	10.3	0.65

Determining the Absolute Neutrino Mass

What is the Absolute Neutrino Mass?

Three extreme cases:

NORMAL HIERARCHICAL	INVERTED HIERARCHY	DEGENERATE
$m_1 \ll m_2 \ll m_3$	$m_1 \approx m_2 \gg m_3$	$m_1 \approx m_2 \approx m_3$

$$\begin{aligned} m_1 &\approx 0 \\ m_2 &\approx \sqrt{\Delta m^2_{12}} \\ &\approx 0.009\,\text{eV} \\ m_3 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\text{eV} \end{aligned}$$

$$\begin{aligned} m_1 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\text{eV} \\ m_2 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\text{eV} \\ m_3 &\approx 0 \end{aligned}$$

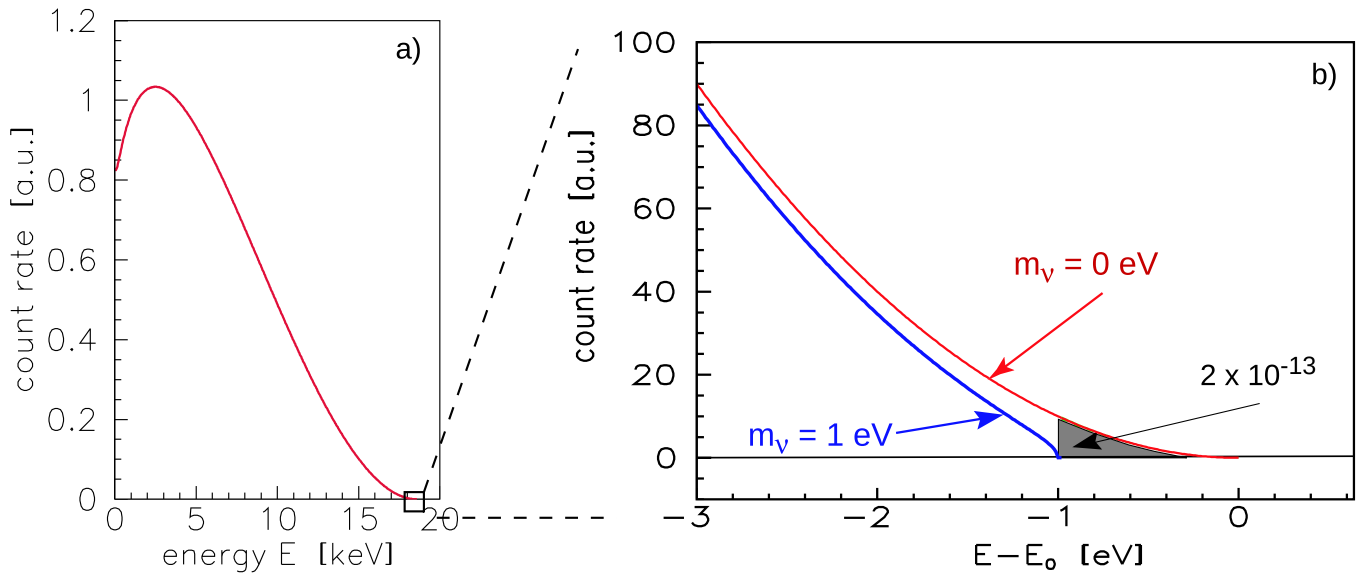
$$\begin{aligned} m_1 &\sim 0.2\,\text{eV} \\ m_2 &\sim 0.2\,\text{eV} \\ m_3 &\sim 0.2\,\text{eV} \end{aligned}$$

(Most like other fermions.

Favoured by GUTs)

Personal prejudice favors normal hierarchical, but all are possible, as are intermediate cases.

Direct Mass Limits



KATRIN collaboration, hep-ex/0109033

Most sensitive ν_e searches come from measuring the endpoint of the energy spectrum of tritium decay.

$$m(\nu_e) \leq 2.5\,\mathrm{eV}\ \ (95\%\ C.L.)$$

KATRIN proposal: new tritium endpoint measurement with sensitivity down to 0.2 eV

Collider limits:

$m(\nu_\mu) < 190$ keV (90% C.L.)

$m(\nu_\tau) < 18.2$ MeV (95% C.L.)

Cosmological Mass Limits

Neutrinos constitute "hot dark matter":

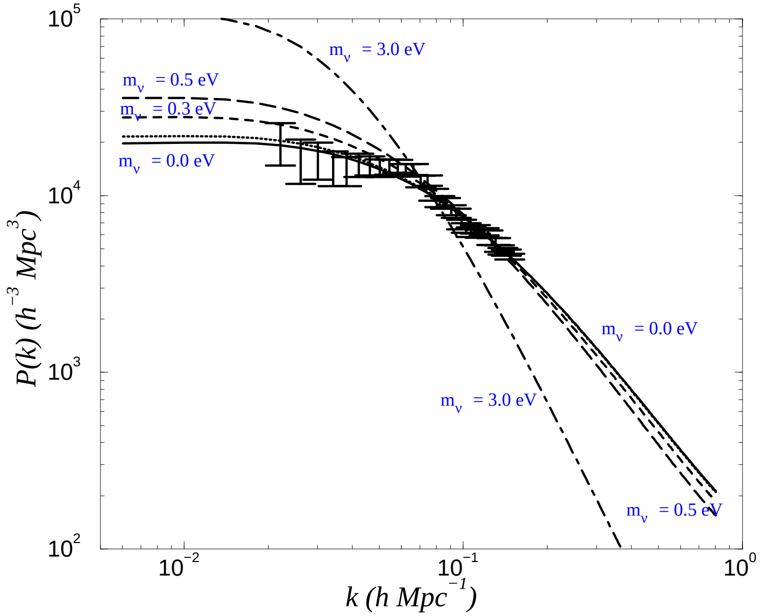
$$\Omega_\nu h^2 = \frac{m_1 + m_2 + m_3}{94\,\mathrm{eV}}$$
$$n_\nu \approx 112\,\mathrm{cm}^{-3}$$

Neutrinos reduce clustering at small angular scales during structure formation, since they "stream out of" small density perturbations.

This can leave signatures in, for example

- CMB
- large scale structure
- weak lenses

Oscillation experiments limit $\Omega_\nu > 0.001$, about the same mass as in stars!



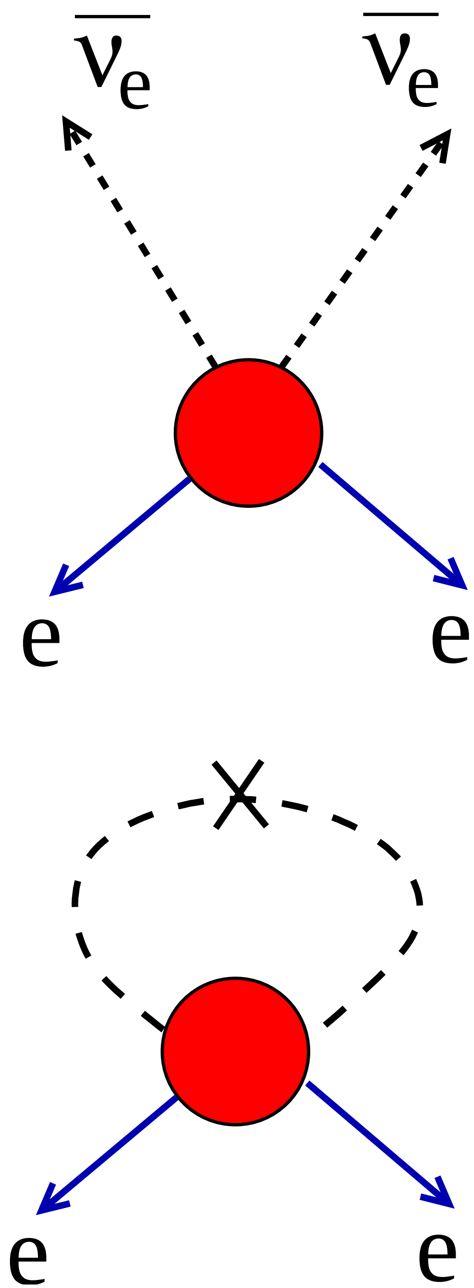
Effects of neutrino mass on large scale structure (angular power spectrum), with 2dFGRS data superimposed. Adopted from Elgaroy and Lahav, hep-ph/0412075

Various model-dependent limits:

$$\sum_i m_i <\sim 0.4 - 0.7\,\mathrm{eV}$$

Cosmology could well be the only way to determine m_ν if small!

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)



Ordinary double beta decay occurs when single beta decay is energetically surpressed, but double beta decay isn't.

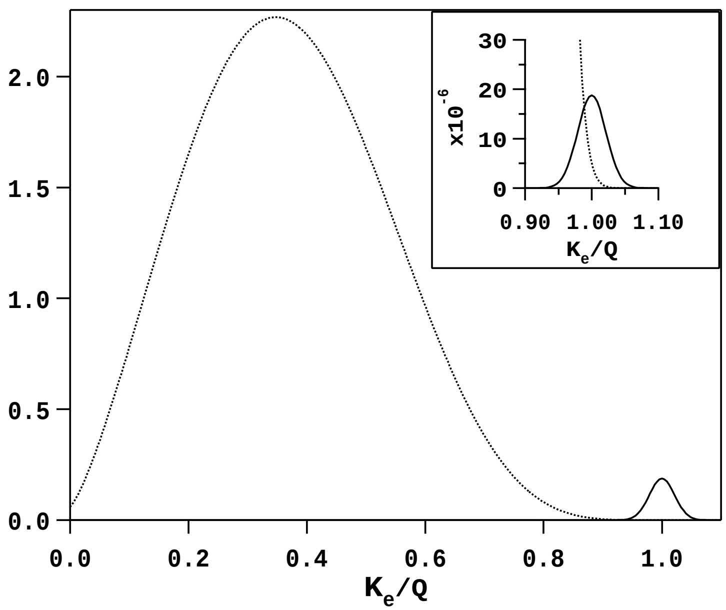
A doubly weak process—very rare!

Neutrinoless double beta decay violates lepton number ($|\Delta L| = 2$), but is allowed if a neutrino is its own antiparticle.

Rate of $0\nu\beta\beta$ decay depends on effective neutrino mass:

$$R \propto \langle m_\nu \rangle^2 = \left| \sum_i^N U_{ei}^2 m_i \right|^2$$

Double Beta Decay—Experimental Technique



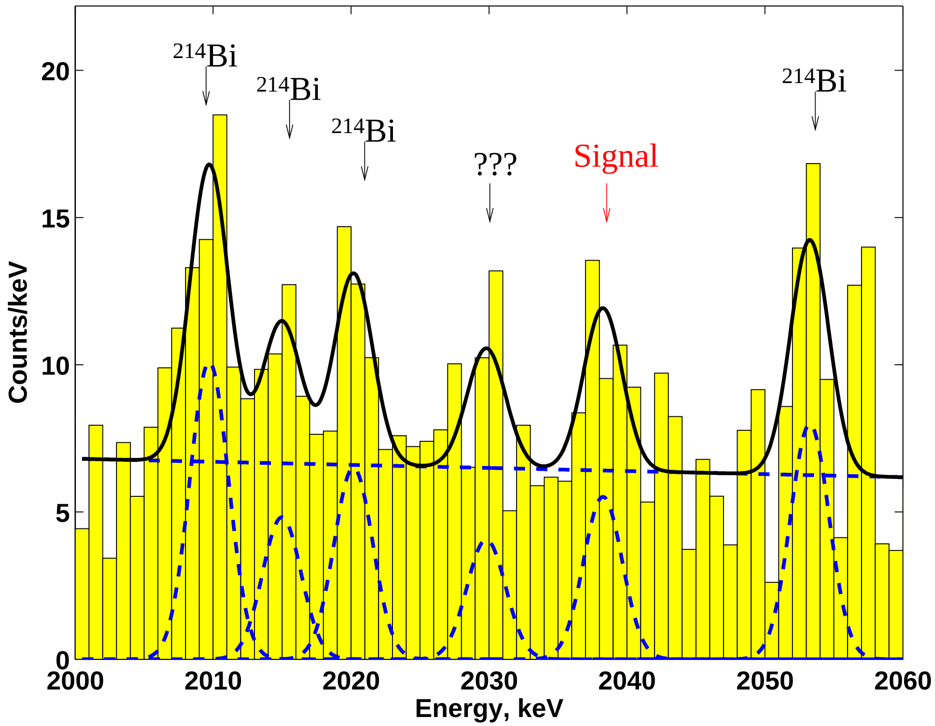
Experimental signature: the sum of the two electrons' energies yields a peak at the endpoint.

Current limits:

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21} (76\%)$	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
	$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$
^{82}Se	$> 2.7 \times 10^{22} (68\%)$	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

(Elliott & Vogel, Ann. Rev. Nucl. Part. Sci 52 (2002))

Claimed Detection for Moscow-Heidelberg Experiment



Adapted from H.V. Klapdor-Kleingrothaus, hep-ph/0512263

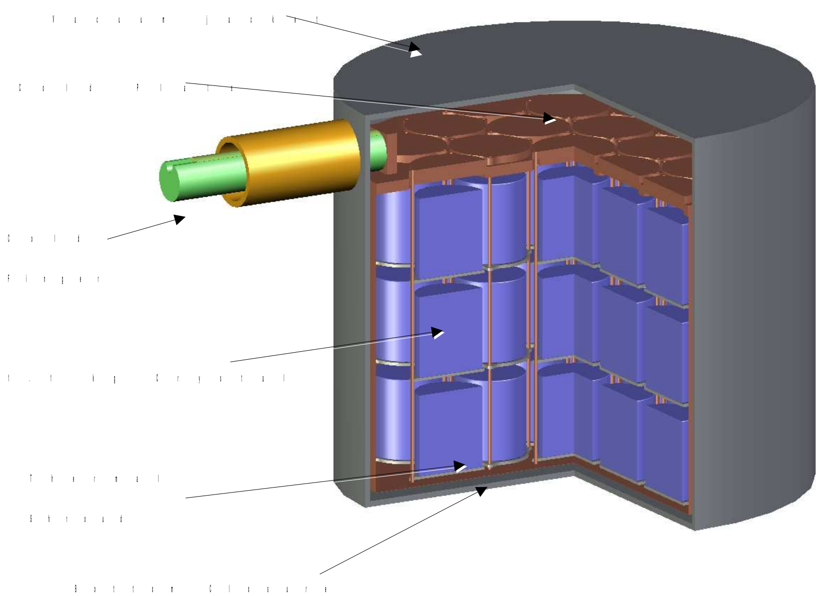
The Moscow-Heidelberg collaboration has previously published an upper limit on $0\nu\beta\beta$ decay in ^{76}Ge.

In recent years a small subset of the Moscow-Heidelberg collaboration claimed to see evidence for a positive signal (4.2σ).

Inferred effective mass is $m_\nu \approx 0.2 - 0.6$ eV

Claim is “controversial”

The MAJORANA Experiment

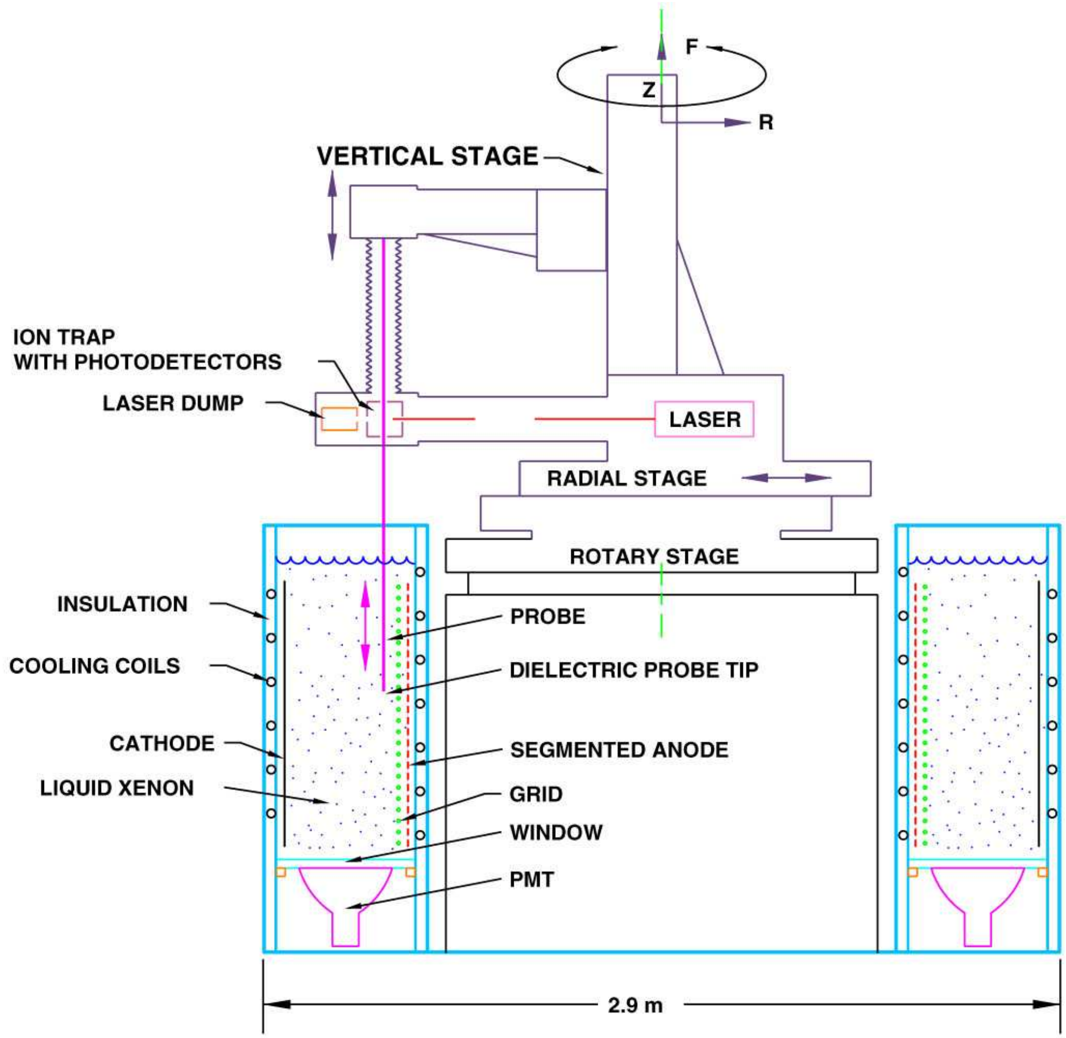


Proposal for a massive germanium experiment

- 86% enriched ^{76}Ge
- Ge gives extremely good energy resolution—great for resolving endpoint peak
- Goal is 2500 kg-years exposure
- Very clean materials, pulse shape discrimination, and segmented detectors to reject backgrounds
- “Proven” technology

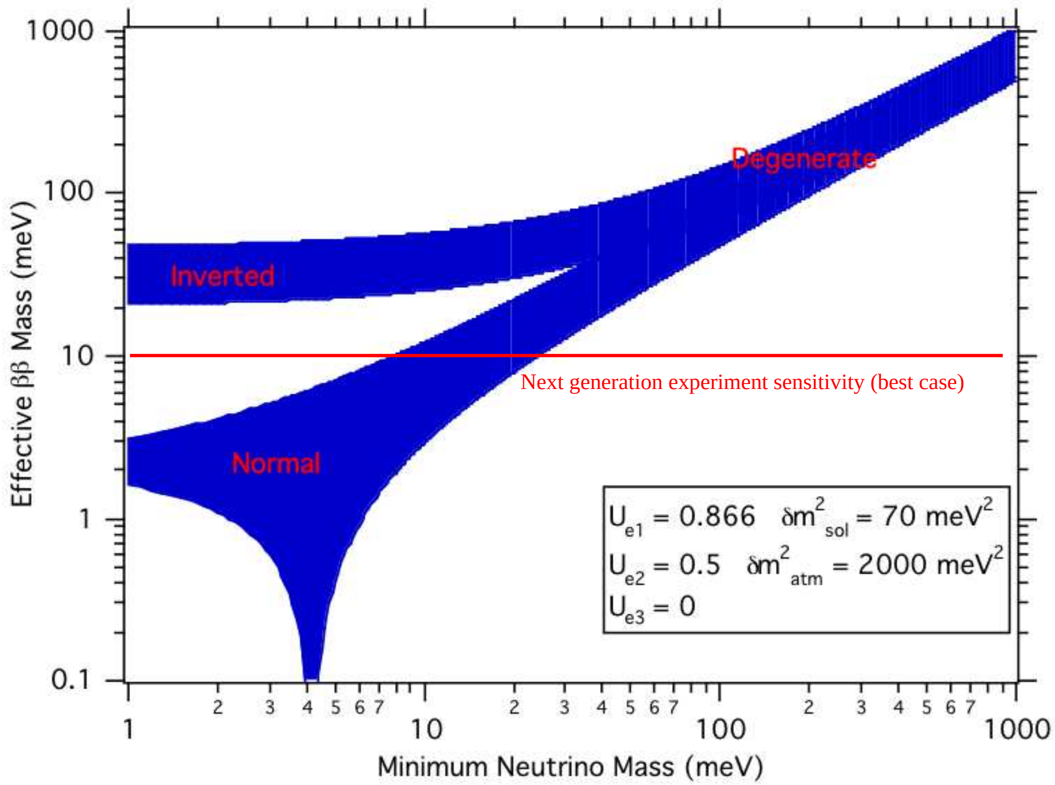
Sensitivity goal: < 50 meV

The EXO Experiment



Look at 10 tonnes of ^{136}Xe in a liquid or gas TPC. Use laser spectroscopy on the resulting ion to confirm it is barium, rejecting backgrounds. Sensitivity of ~ 10 meV

Double Beta Decay Sensitivity



Proposed double beta decay experiments, if successfully, could distinguish between normal and inverted hierarchy, but only if ν's are Majorana particles.

Null result by itself cannot rule out either Majorana neutrinos or largish masses.

No real idea how to improve sensitivity to cover normal hierarchy.

What LHC Will Tell Us About Neutrinos

What LHC Will Tell Us About Neutrinos

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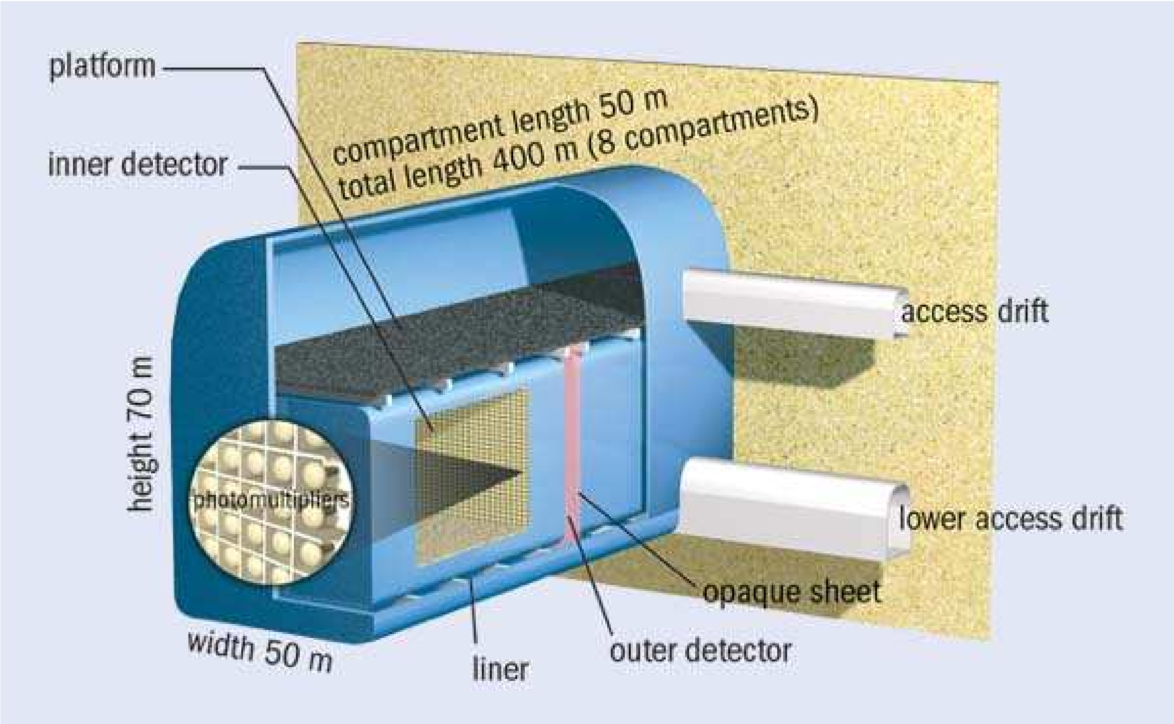
Future Initiatives: Wild-Eyed Ideas

Hyper-Kamiokande

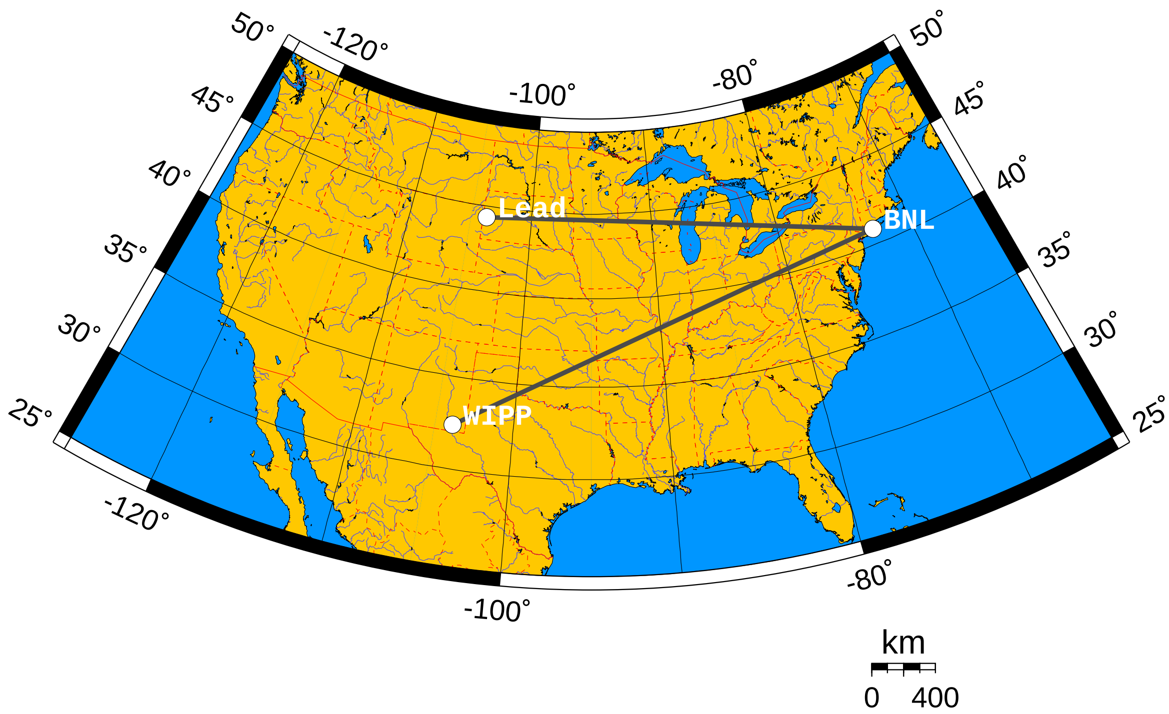


Megatonne water Cherenkov detector

Combine with 4 MW off-axis neutrino beam to look for CP violation, which needs large statistics (asymmetry in a small number).

You gain an order of magnitude improvement in proton decay for free!

Very Long Baseline Experiments

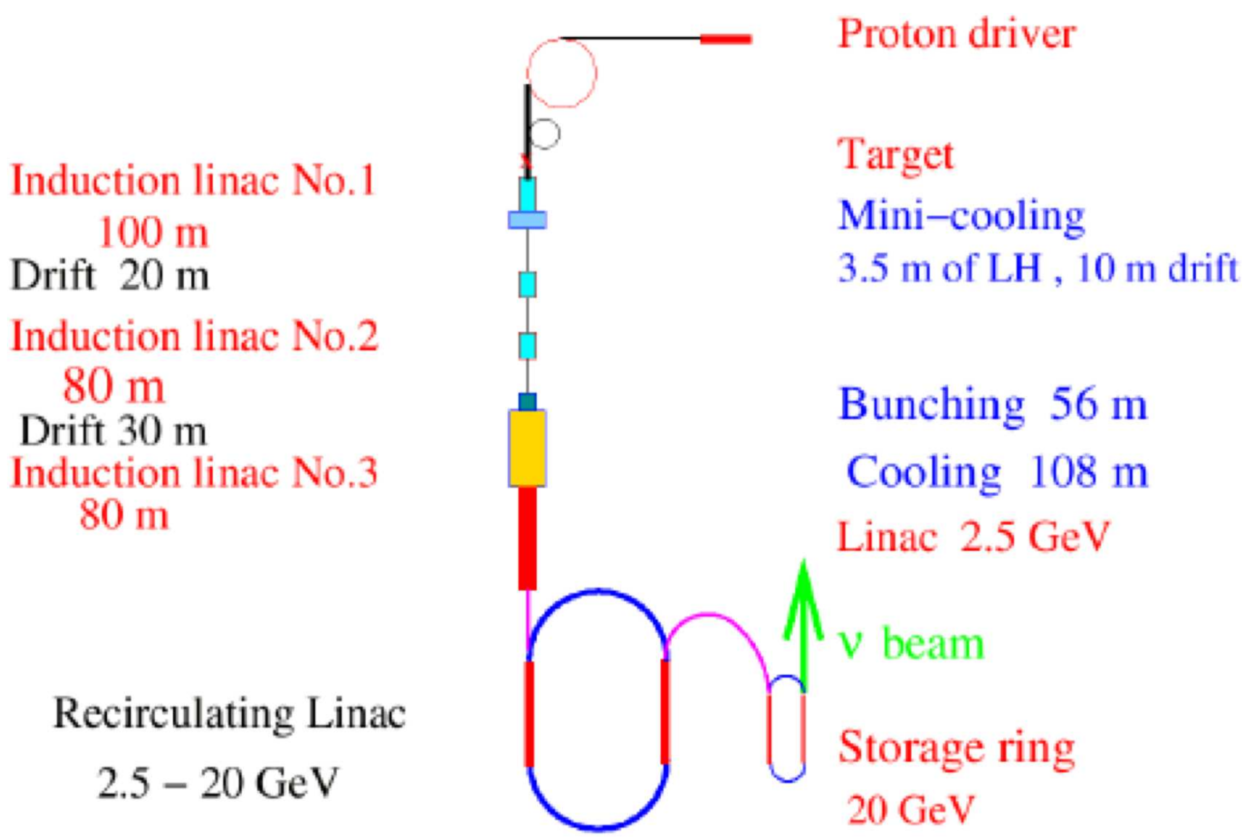


A very long baseline (> 1500 km) and a megatonne-class detector would be optimal to address mass hierarchy and CP violation.

A massive proton driver at FNAL or BNL?

Possible followup to a θ_{13} discovery.

Neutrino Factory



Neutrinos produced by $\mu^- \to e^- \nu_\mu \bar{\nu}_e$, with essentially zero contamination of wrong-signed neutrinos. This may be the only way to get around background limitations in $\nu_\mu \to \nu_e$ appearance if θ_{13} winds up being very small.

Interesting R&D already underway on muon cooling & design ideas, but conventional "superbeams" (ν's from pion decay) will be built fi rst, and may be adequate for most purposes.

Surprises

Neutrino interactions are relatively poorly constrained. Possible surprises we may find:

- sterile neutrino states (already favoured by LSND)
- neutrino decay
- unexpectedly large electric or magnetic moments
- new interactions or couplings beyond the SM
- violations of Lorentz invariance (ν's routinely have $\gamma > 10^{11}$)
- breakdown of CPT

Closing: Dawn Of A ν Era

Lepton flavour physics is now a reality. Despite superficial similarities to CKM matrix, neutrino mixings seem qualitatively different. The physics community has put four decades into measuring quark mixings—you should expect (demand?) that leptons get their due.

The future of neutrinos through rose-coloured glasses:

- New mechanisms for generating mass (Majorana neutrinos)
- GUT-scale physics (Majorana ν's, flavour symmetries, quark-lepton unification)
- The origin of the matter-antimatter asymmetry (ν CP violation, leptogenesis)

Neutrino experiments are still an order of magnitude smaller and cheaper than collider experiments, yet are exploring physics beyond the Standard Model that colliders cannot. JOIN US NOW!

No, Really, Join Us!

Postdoctoral Position in Experimental Neutrino Physics

University of British Columbia

http://www.physics.ubc.ca/∼oser/postdoc_ad.html

Applications are invited for a postdoctoral position in experimental neutrino physics at the University of British Columbia to work on the T2K experiment. T2K is a long-baseline neutrino oscillation experiment between the Japan Proton Accelerator Research Complex (J-PARC) and the Super-Kamiokande detector. The goal of T2K is to measure the neutrino mixing angle θ_{13} by observing $\nu_\mu \rightarrow \nu_e$ oscillations, with data-taking commencing in April 2009. The UBC and TRIUMF T2K groups are involved in the design and construction of time projection chambers and fine-grained tracking scintillator detectors for T2K's 280m near detector. UBC neutrino scientists are also involved with the K2K and SNO experiments, and collaborate closely with nearby neutrino groups at TRIUMF and Victoria. The successful applicant is expected to take a leading role in detector design, simulation, and construction of the fine-grained scintillator detectors, as well as data analysis for the T2K near detector.