New Ideas in Neutrino Physics

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Physics Colloquium
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Outline

1) Postulation of the neutrino

2) Observation of the neutrino

3) Neutrino beams

4) The search for solar neutrinos

5) The rise of the large underground detectors

6) Neutrino mixing

7) Current issues in neutrino physics

8) Future facilities for neutrino physics

9) Summary

Outline

1) Postulation of the neutrino

   a) the beta-decay puzzle

   b) the neutron puzzle

   c) Fermi's theory of beta decay

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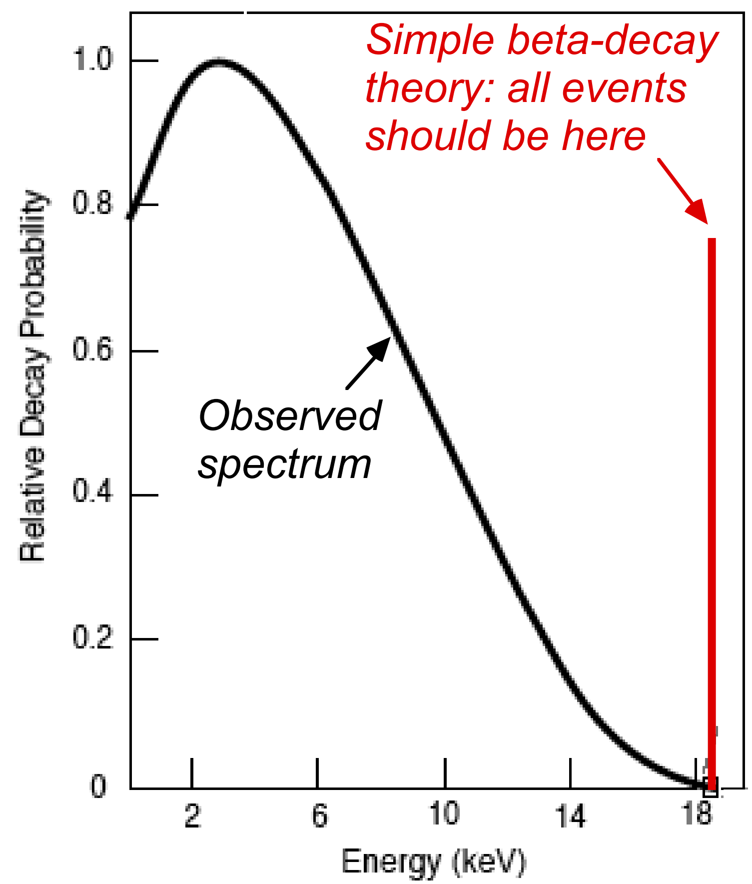
First, some history (the Beta Decay Puzzle):

- Neutrino was not "discovered" – it was postulated!
- In 1910s – '20s, experimental studies of radioactive beta decay led to a puzzle
  - beta decay: decay of a radioactive substance with emission of electron
  - e.g. beta decay of tritium to helium-3: ${}^3\text{H} \rightarrow {}^3\text{He} + e^-$ (1/2-life = 12.4 years)

  - by conservation of energy, electron energy must always equal $\left(m_{^3\text{H}} - m_{^3\text{He}}\right)c^2 = 18.6$ keV (since $E = mc^2$)
  - but experiment showed continuous spectrum:



  - also, decay violates "statistics of spin-1/2" particles:
    - a spin-1/2 particle must always decay to odd number of spin-1/2 particles

What could it mean? (the Neutron Puzzle)

1) something wrong with quantum mechanics?

2) something wrong with conservation of energy? or...

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1) something wrong with quantum mechanics?
2) something wrong with conservation of energy? or...
3) Wolfgang Pauli letter to Tübingen conference on radioactivity, 4 Dec. 1930:

*Dear **Radioactive Ladies and Gentlemen**,*

*As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N-14 and Li-6 nuclei and the continuous beta spectrum, **I have hit upon a desperate remedy to save** the "exchange theorem" of statistics and **the law of conservation of energy**. Namely, the possibility that **there could exist in the nuclei electrically neutral particles**, that I wish to call **neutrons**, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. **The continuous beta spectrum would then become understandable** by the assumption that **in beta decay a neutron is emitted in addition to the electron, such that the sum of the energies of the neutron and the electron is constant...***

*I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But **only those who wager can win**, and the difficulty of the situation of the continuous structure of the beta spectrum can be made clear by a remark of my honored predecessor, **Mr Debye**, who **told me recently** in Bruxelles: **"One does best not to think about this at all, like new taxes"**. From now on, **every solution to the issue must be discussed**. Thus, dear radioactive people, look and judge.*

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.

What could it mean? (the Neutron Puzzle)

1) something wrong with quantum mechanics?
2) something wrong with conservation of energy? or...
3) Wolfgang Pauli letter to Tübingen conference...
4) Puzzle solved in 1933: Enrico Fermi publishes theory of beta decay, renames Pauli's particle neutrino (ν)

as opposed to neutron (red herring), discovered in 1932

$\rightarrow$ beta decay always involves ν (or its antiparticle, $\bar{\nu}$)

e.g.: $^{3}\text{H} \rightarrow {}^{3}\text{He} + e^{-} + \bar{\nu}$

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

$$\left.\begin{aligned} \nu + n &\rightarrow p + e^{-} \\ \bar{\nu} + p &\rightarrow n + e^{+} \end{aligned}\right\} \text{ inverse beta decay}$$

etc...

– Neutrino is unseen particle that must be there to "balance the equation"

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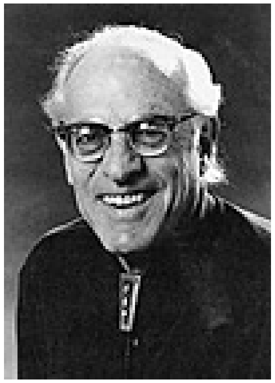
Observation of the Neutrino

- Neutrino is nearly massless neutral particle, immune to electromagnetism & strong nuclear force

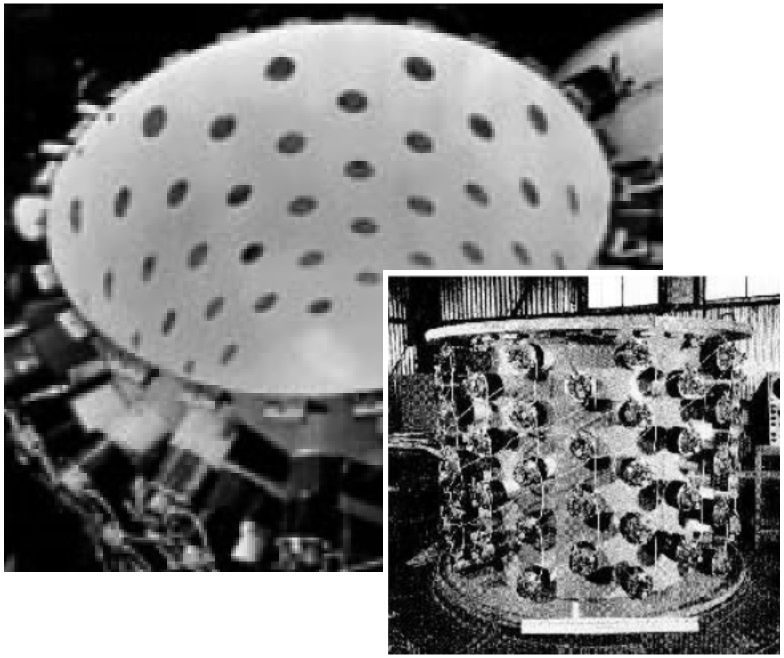
  ⇒ nearly impossible to detect, penetrate kms of lead without interacting – are they real?

- After WWII, Fred Reines at Los Alamos took on the challenge: confirm ν existence by observing ν interactions in matter



  – atom bomb might emit enough neutrinos for detection, but how build a big enough detector?

  – scintillation discovered in 1950: some materials emit quick flash of light in response to radiation



  – in 1950s, Cadillac Motors developed photomultiplier tubes (PMTs) for automatic headlight dimmers

  – Reines and Clyde Cowan designed large tank for Cd-doped liquid scintillator surrounded by PMTs

  – after test at Hanford nuclear reactor in 1953, definitive ν observation made at Savannah River reactor in 1956 with improved detector

→ Reines shared 1995 Nobel Prize in Physics (with Martin Perl, τ lepton discoverer)

  → "1st Neutrino Nobel"

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Neutrino Beams: The "Two-Neutrino" Experiment

VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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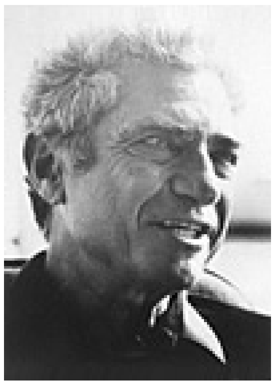
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)


- Built neutrino beam at Brookhaven AGS accelerator

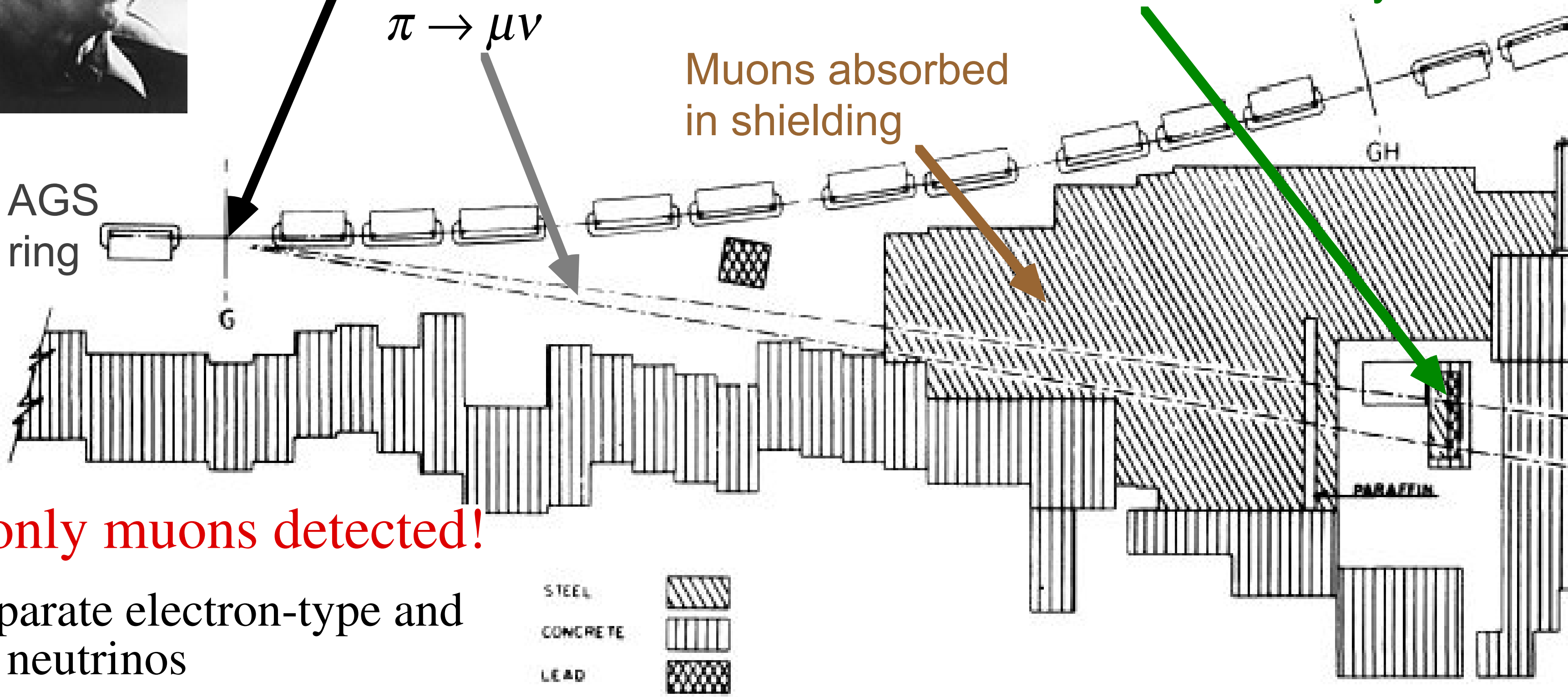
Neutrino production via

$$p + Be \to \pi + X,$$

$$\pi \to \mu\nu$$

10-ton spark-chamber array detects neutrinos interacting via inverse beta decay

Muons absorbed in shielding



- Discovery: only muons detected!

⇒ Must be separate electron-type and muon-type neutrinos

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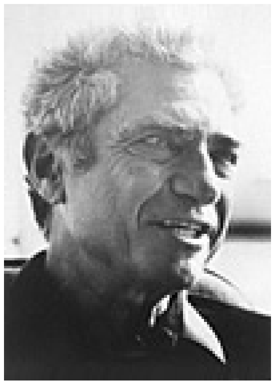


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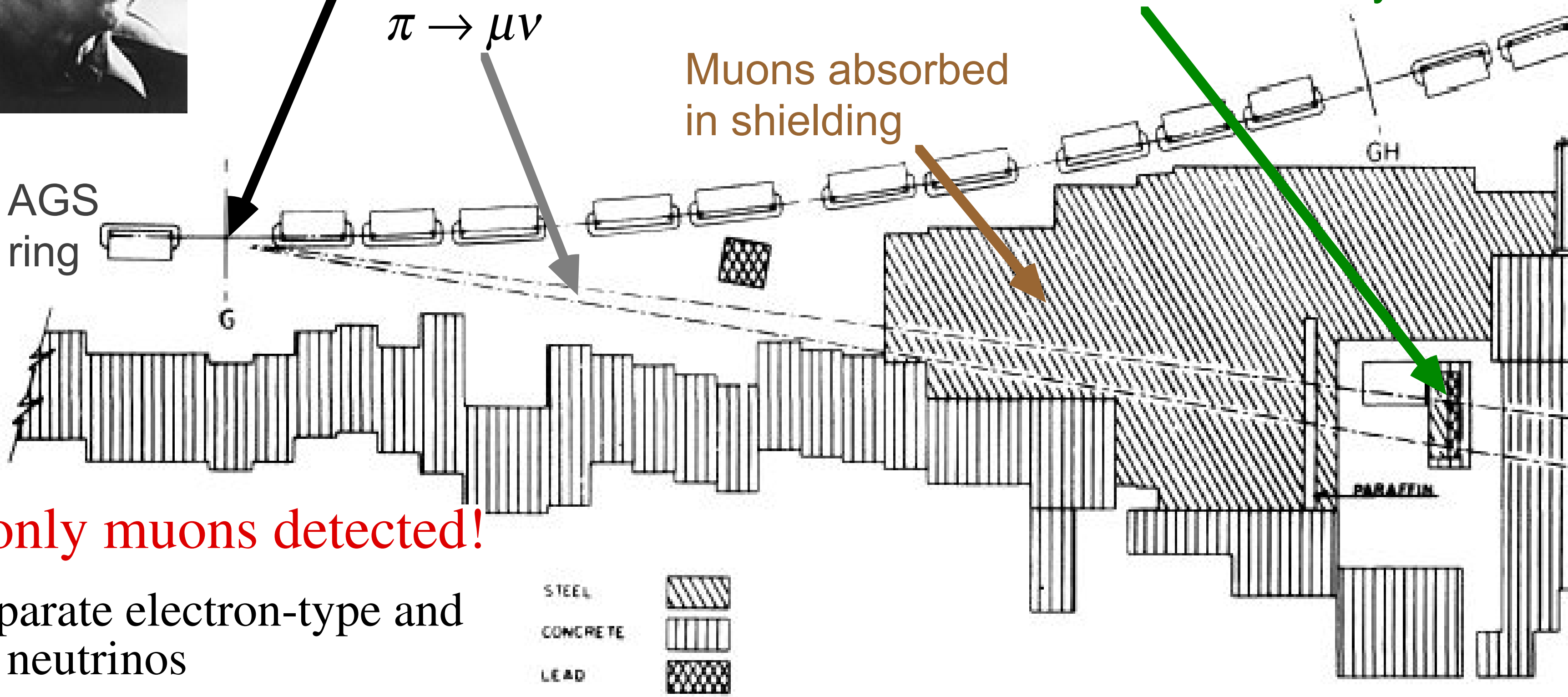

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  → Nobel Prize in Physics 1988 "2nd Neutrino Nobel"

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   a) solar neutrinos

   b) solar neutrino experiments: Homestake and its successors

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Solar Neutrinos

- No mechanism known in ≈1900 could power a star for billions of years!

- In 1938, Hans Bethe and colleagues proposed that stars shine due to nuclear-fusion reactions

  ⇒ sun is copious source of neutrinos via such processes as

$$\left.\begin{array}{l} {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \\ {}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \gamma \end{array}\right\} \times 2$$

$$ {}^{3}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$$

  thus the fusion of 4 hydrogen atoms into 1 helium atom produces 2 neutrinos

  → Nobel Prize in Physics 1967

- Solar neutrino flux is huge: 1.8×10^{39} per second
  - e.g. ~10^{14} (100 trillion) solar ν pass through our bodies each second!

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  → Can they be detected?

Solar Neutrino Experiments

(see http://www.sns.ias.edu/~jnb/Papers/Popular/snhistory.html)

- 1964: feasibility of a ^{37}Cl solar neutrino experiment proposed
  - based on inverse-beta-decay reaction $\nu_{\text{solar}} + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$
  - expected rate was about 1 argon atom per day per 100,000 liters of perchloroethylene
  - but even a few atoms of radioactive ^{37}Ar can be detected via nuclear-chemistry techniques

Three principals photographed in front of small prototype chlorine tank in 1964 (right to left): Raymond Davis, Jr., John Bahcall, and Don Harmer

- The ^{37}Cl neutrino detector is a tank containing 378,000 liters of cleaning fluid (perchloroethylene) in a cavity 1500 meters below ground in the Homestake gold mine in Lead, SD, USA

Final Homestake result:

(J. N. Bahcall, astro-ph/9911486)

- Observed rate of ^{37}Ar = 0.38 ± 0.04 atoms/day

- Solar-model prediction: 1.4 ± 0.2 atoms/day

$$\Rightarrow \frac{\text{Observed}}{\text{Predicted}} = \frac{0.38}{1.4} = 0.27 \pm 0.04$$

$\Rightarrow$ Observed only about 1/3 of predicted solar neutrino rate!

Impact of Homestake result:

- Physicists were (of course) skeptical!
  - 3 possibilities:

    1) something wrong with the experiment

    2) something wrong with the solar model

    3) something wrong with neutrino physics
  - all 3 proposed at the time; 3rd possibility turned out to be correct
- Solar-neutrino deficit subsequently corroborated by KamiokaNDE, Super-KamiokaNDE, SAGE, & GALLEX experiments
  - 3 different techniques used:
    - Homestake: ν_e capture in ^{37}Cl
    - SAGE and Gallex: ν_e capture in Ga
    - KamiokaNDE and Super-K: ν_e-e scattering in H_2O
- Davis received 2002 Nobel Prize in Physics (3rd "Neutrino Nobel"), with KamiokaNDE's Masatoshi Koshiba (and Riccardo Giacconi, for X-ray astronomy)

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Large Underground Detectors

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- KamiokaNDE* and Super-KamiokaNDE originally proposed not for neutrino physics but to search for proton decay:

* KamiokaNDE = "Kamioka Nucleon Decay Experiment", located in the Mozumi mine of the Kamioka Mining and Smelting Co. (Japan)

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Weinberg–Salaam electroweak unification, 1960s
Nobel Prize, 1979 (with Sheldon Glashow)

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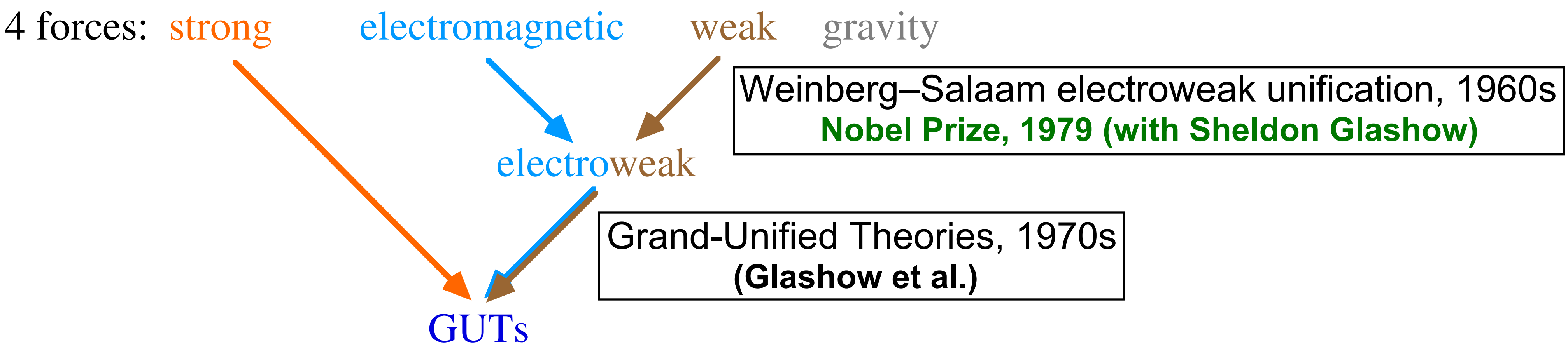

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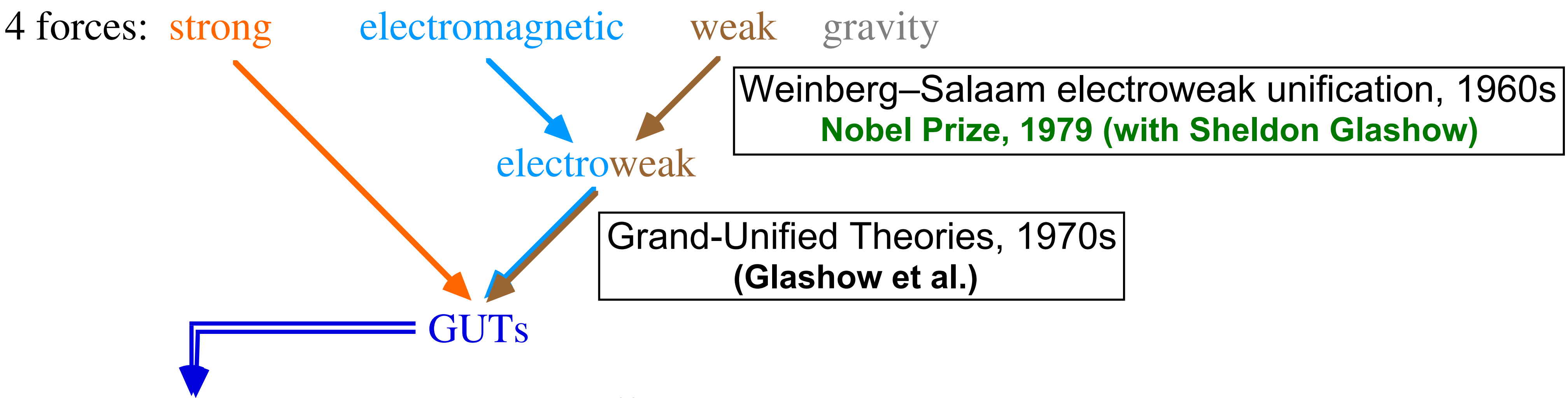

proton unstable, with lifetime ~ 10^{30} years

$\Rightarrow$ should see ~ 1 proton decay/year in sample of 10^{30} protons (≈ 1.7 kilograms)

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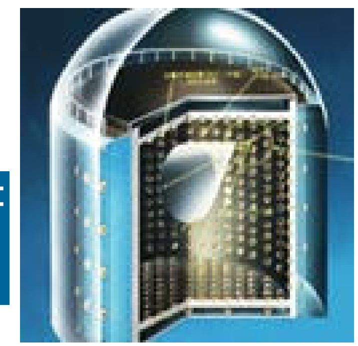
Grand-Unified Theories, 1970s
(Glashow et al.)

GUTs



Super-KamiokaNDE:
50 ktons H_2O
9000 PMTs

42 m

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$\Rightarrow$ should see ~ 1 proton decay/year in sample of 10^{30} protons (≈ 1.7 kilograms)

– led to construction of larger and larger detectors to look for evidence of proton decay, built underground to shield from cosmic-ray background

– showed proton stable with lifetime > 10^{31} to 10^{33} years (depending on decay modes)

$\Rightarrow$ "SU(5)" (simplest) grand-unified theory ruled out (other versions survive)

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4 forces: strong electromagnetic weak gravity

electromagnetic + weak → electroweak

Weinberg–Salaam electroweak unification, 1960s
Nobel Prize, 1979 (with Sheldon Glashow)

strong + electroweak → GUTs

Grand-Unified Theories, 1970s
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GUTs → proton unstable, with lifetime ~ 10^{30} years

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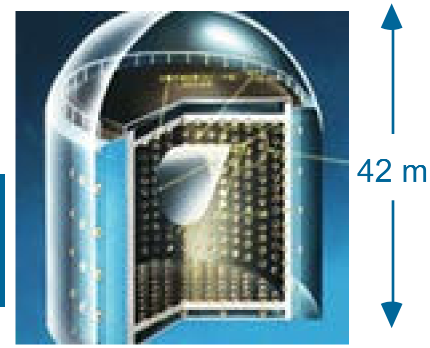

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- Irreducible background in these experiments was from neutrino interactions

$\Rightarrow$ Make a virtue out of necessity: study neutrinos as well

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   a) the atmospheric neutrino anomaly

   b) neutrino oscillations

   c) the SNO and KamLAND experiments

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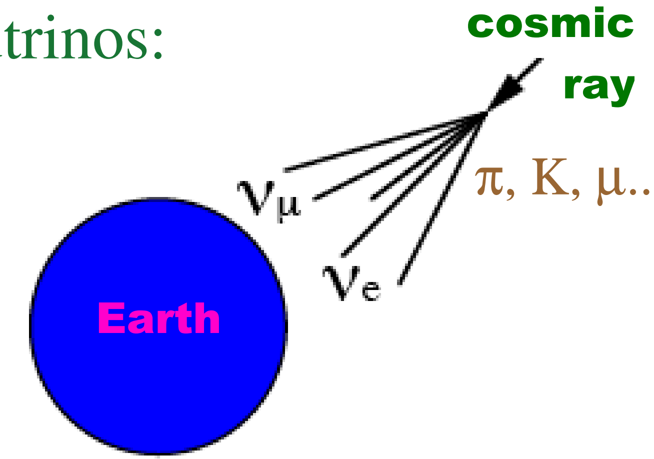
Atmospheric neutrino anomaly

- Cosmic-ray collisions with atmosphere produce neutrinos:
  - copious source of pions and kaons, which decay into muons or electrons plus neutrinos:



$$\pi^- \rightarrow \mu^- \nu_\mu$$

$$K^- \rightarrow \mu^- \nu_\mu$$

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

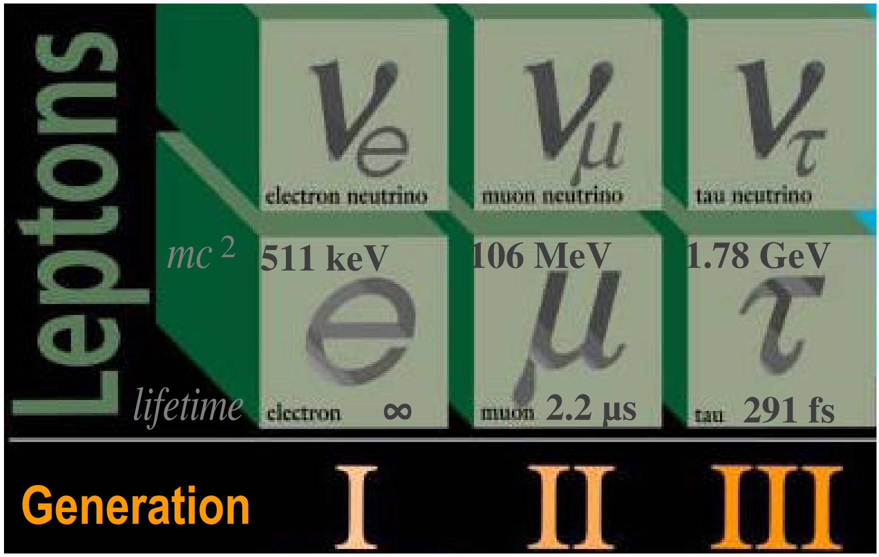
  ... as well as antiparticles: $\pi^+, K^+, \mu^+,...$

- Atmospheric neutrinos detectable in proton-decay exp'ts:
  - Soudan and Macro: sandwich of Fe plates with drift chambers or scintillators
  - KamiokaNDE and Super-K: H_2O tank w/ PMTs to detect Cherenkov light
    - Cherenkov effect: light is emitted when charged particle exceeds speed of light in medium through which it travels (recall that light slows down in a transparent medium) – like sonic boom

- KamiokaNDE was first to see atmospheric-neutrino anomaly:
  - too few upward-going muon neutrinos (compared to electron neutrinos and downward-going muon neutrinos)

Neutrino oscillations

- Neutrinos are "leptons"
  (from Greek: *leptos* = slim, delicate)
  - low-mass particles that do not feel the strong force
  - as opposed to "baryons", e.g., protons, neutrons (from Greek: *barys* = strong, heavy)
  - 3 known "generations" (or "flavors") of leptons, each with 1 charged and 1 neutral lepton (neutrino)



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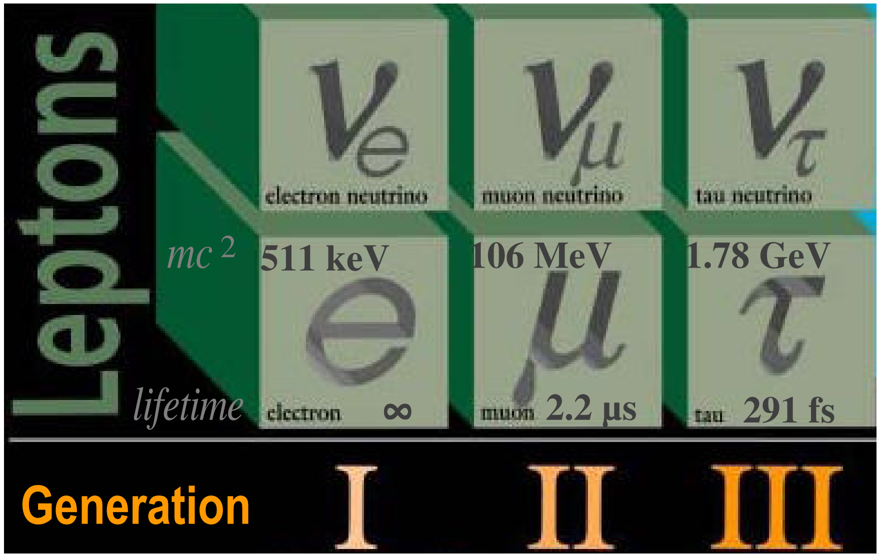
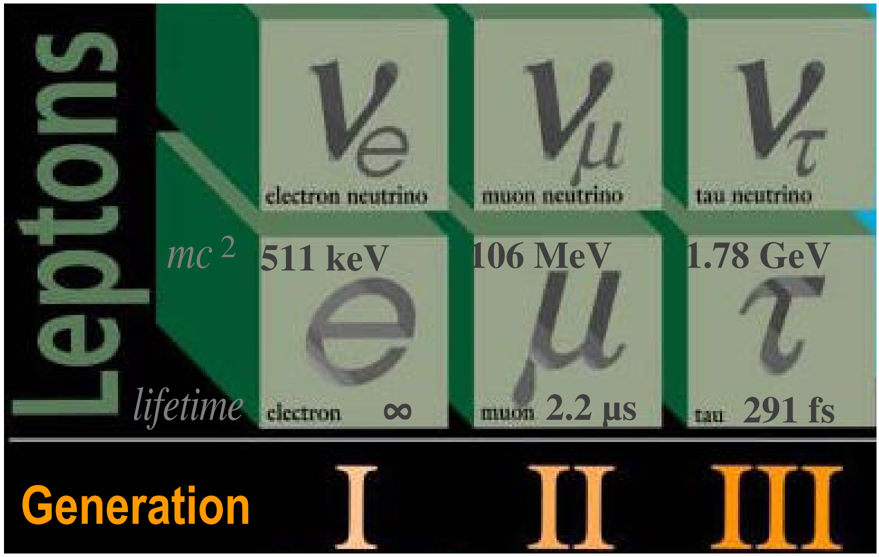


- Both solar-neutrino deficit and atmospheric-neutrino anomaly can be explained if neutrinos can change ("oscillate") from one kind into another:
  - solar neutrinos changing from ν_e to ν_μ on their way to Earth
    → deficit in ν_e detectors
  - atmospheric neutrinos changing from ν_μ to ν_τ on their way through Earth
    → deficit in ν_μ detectors

  e.g., $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu}$ $\begin{cases} \theta = \text{“mixing angle”}, \Delta m^2 = \nu \text{ mass-squared diff.} \\ L = \text{distance (m)}, \quad E_\nu = \text{neutrino energy (MeV)} \end{cases}$

- Proposed by Gribov and Pontecorvo in 1969 to explain solar-neutrino deficit, later elaborated by Wolfenstein (1978), Mikheyev and Smirnov (1985)
  - MSW effect (enhancement of neutrino oscillation rate in material of sun) gives right answer

Neutrino oscillations



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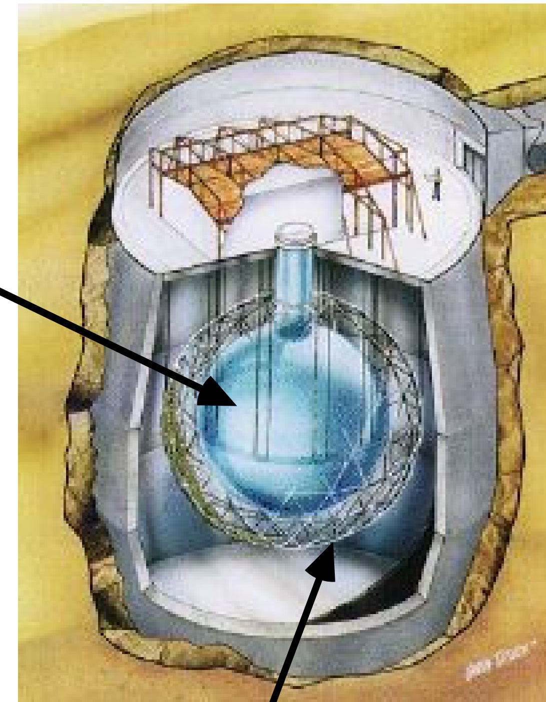
- Now confirmed by SNO and KamLAND

SNO

- Sudbury Neutrino Observatory: spherical acrylic tank 12 m in diameter, filled with heavy (deuterated) water, located underground in the Creighton mine near Sudbury, Ontario, Canada
  - neutrino interactions emit Cherenkov light, detected in array of 9600 PMTs surrounding tank



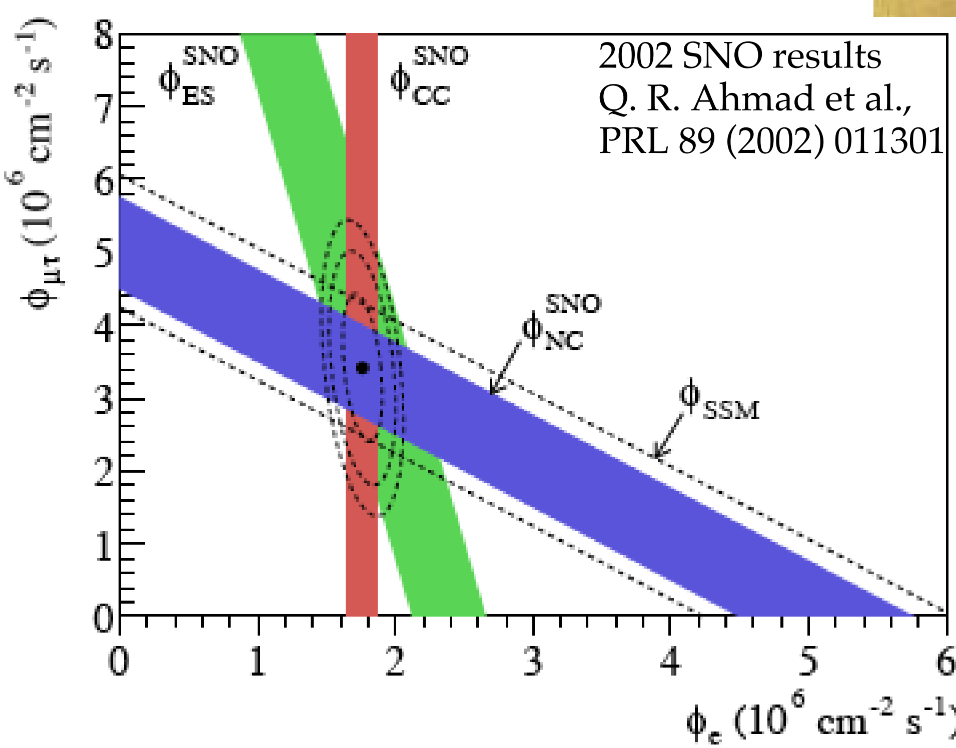
- Deuterium ($p + n \equiv {}^2$H) $\rightarrow$ 3 solar-ν reactions:

1) $\nu_e + {}^2\mathrm{H} \rightarrow p + p + e^-$ "charged-current" reaction (ν_e only)

2) $\nu_x + {}^2\mathrm{H} \rightarrow p + n + \nu_x$ "neutral-current" reaction (all ν)

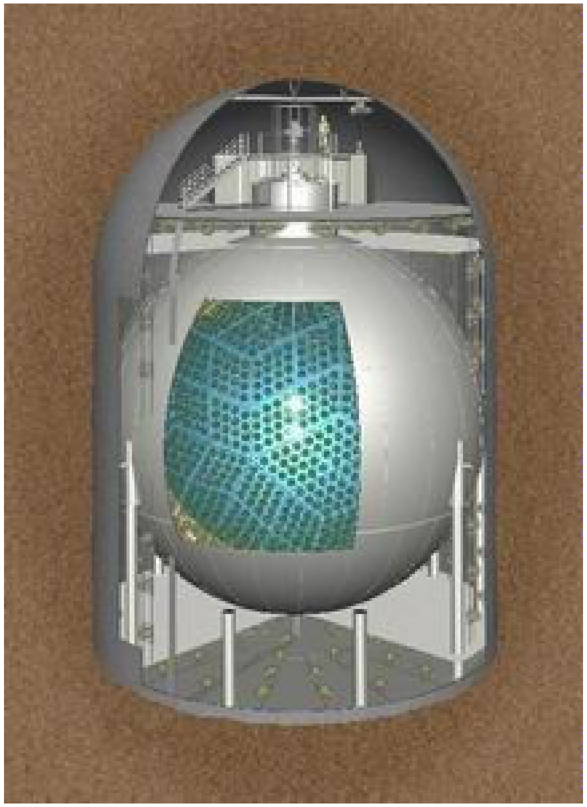
3) $\nu_x + e^- \rightarrow \nu_x + e^-$ "ν–e^- scattering" (ν_e + others/3)

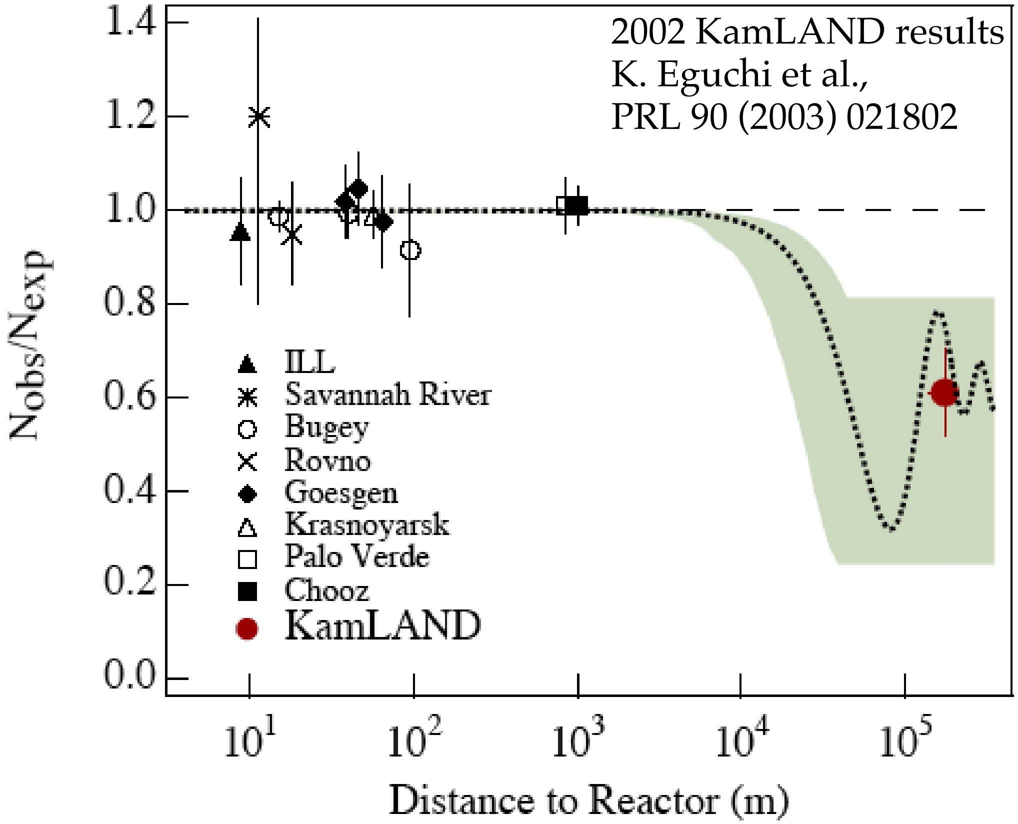
- Detector can measure each separately:
  - confirms standard solar model
  - shows directly that those solar ν not arriving as ν_e arrive as ν_μ or ν_τ

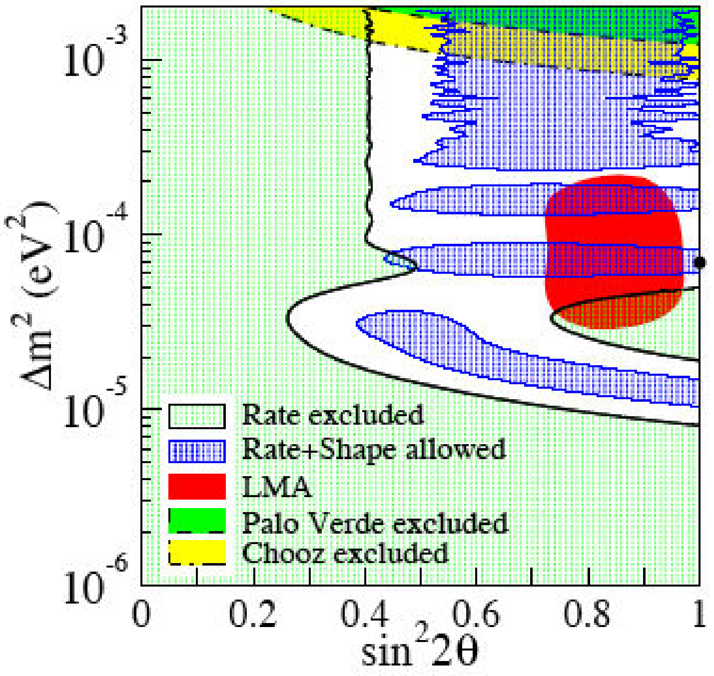


KamLAND

- Kamioka Liquid-scintillator Anti-Neutrino Detector:
  - similar to SNO, but filled with liquid scintillator rather than heavy water
  - sensitive to $\bar{\nu}_e$ from many Japanese power reactors (~100 GW), average distance from source ≈180 km
  - all previous reactor-$\bar{\nu}$ detectors were too close to source to see oscillation signal (& sources too weak to go much farther)







- Confirms "Large Mixing Angle" solar-ν solution
  - but oscillation "wiggles" smeared out

Outline

1) Postulation of the neutrino

2) Observation of the neutrino

3) Neutrino beams

4) The search for solar neutrinos

5) The rise of the large underground detectors

6) Neutrino mixing

7) Current issues in neutrino physics

8) Future facilities for neutrino physics

9) Summary

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  a) 3-generation mixing
  b) problem of baryogenesis
  c) LSND effect

8) Future facilities for neutrino physics

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Current Issues in Neutrino Physics (1)

- With confirmed oscillation signals for both ν_e to ν_μ and ν_μ to ν_τ, need 3-generation mixing description (pardon the math!):

flavor states : ν_α $\alpha = e, \mu, \tau, \ldots$

mass states : ν_i $i = 1, 2, 3, \ldots$

Vacuum oscillations: $$P(\nu_\alpha \to \nu_\beta) \cong \left| \sum_{j=1}^{n} V_{\beta j} e^{-i\frac{m_j^2}{2E}L} V_{\alpha j}^* \right|^2$$

For 3 Neutrino Mixing

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix} \begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix} \begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\left(\frac{1}{2}\phi_2\right)} & 0 \\ 0 & 0 & e^{i\left(\frac{1}{2}\phi_3 + \delta\right)} \end{bmatrix}$$

atm unknown solar Majorana phases

$$c \equiv \cos\theta \qquad s \equiv \sin\theta$$

- 3 mixing angles θ_a , θ_s , θ_x, 3 mass-squared differences
- 3 complex phases δ , ϕ_2 , ϕ_3 (CP)

Oscillation probabilities do not depend on ϕ_2 , ϕ_3

- So neutrino mixing depends on 9 numbers, of which 4 are unknown

Current Issues in Neutrino Physics (2)

- Solar and atmospheric data pin down 2 (θ_a and θ_s) of the 3 mixing angles
- To measure remaining unknowns requires new experiments:
  - unknown mixing angle θ_x and phase δ measurable in long-baseline neutrino experiments, but need intense, well understood neutrino source and big detector
  - Majorana phases measurable (in principle) in neutrinoless double-beta decay and certain other rare-decay experiments
- Problem of "baryogenesis":
  - Universe contains matter (stars, planets, people,...) but almost no antimatter!

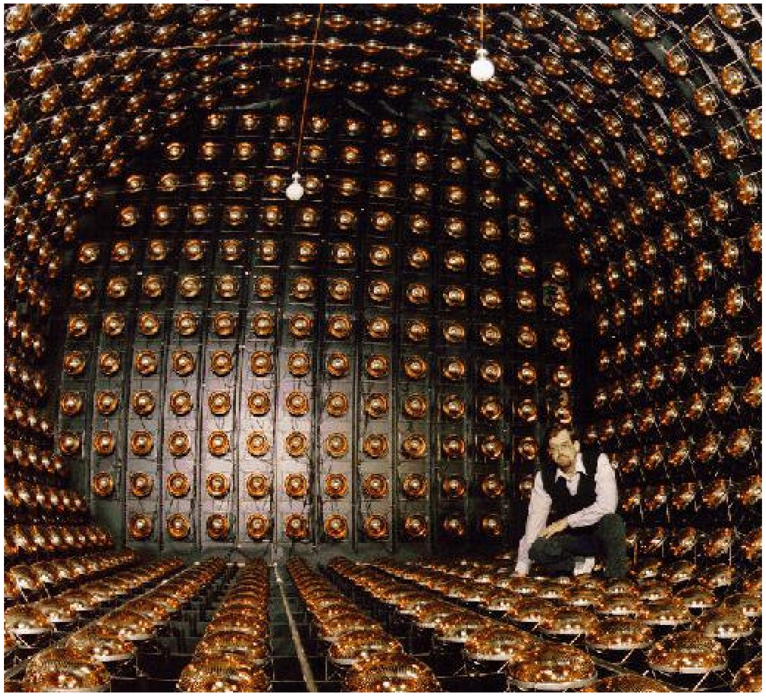
    ⇒ Universe has a net "baryon number" $B \equiv [N(p) + N(n)] - [N(\bar{p}) + N(\bar{n})]$
  - yet Big Bang would have created equal amounts of matter and antimatter

    ⇒ this is what is always observed in experiments that create matter from energy, i.e., baryon number is conserved in all known interactions

- o Sakharov (1967): net B can evolve if there is an interaction that
  1) violates baryon-number conservation,
  2) violates "CP symmetry", i.e., treats matter and antimatter differently, and
  3) operates during a period of disequilibrium, i.e., when Universe evolving rapidly

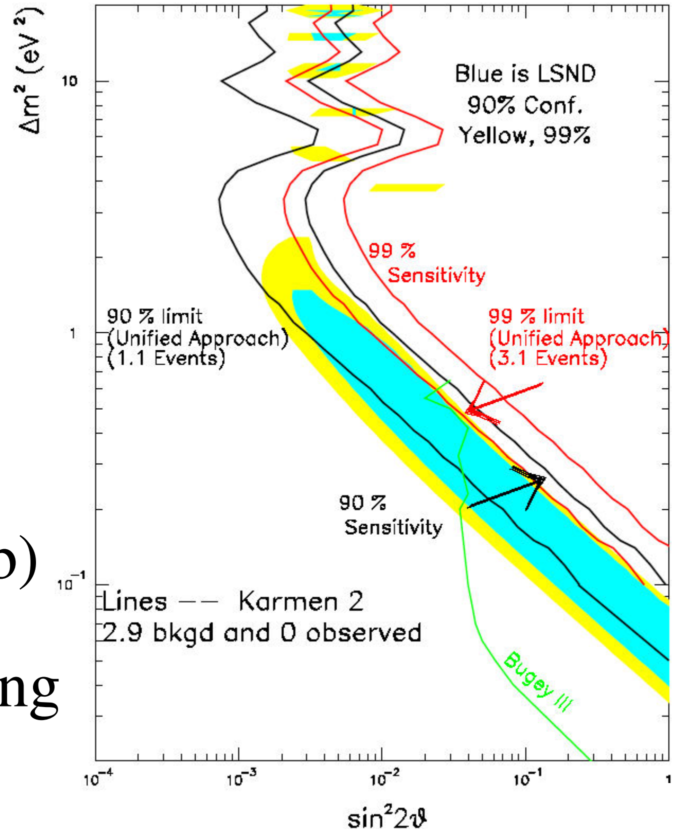
- Candidate mechanism for baryogenesis is via phase δ → CP-asymmetric decay of massive neutrinos in early Universe (Fukugita and Yanagida 1986)

Current Issues in Neutrino Physics (3)



- "LSND Effect" (Los Alamos Lab):
  - Liquid Scintillator Neutrino Detector saw evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance in 1990s
  - not confirmed by similar experiment (KARMEN) in UK, but not ruled out
  - LSND result requires $\Delta m^2 \sim 0.1 - 1$ eV$^2/c^4$
  - inconsistent with $\Delta m^2_{solar} \sim 6 \times 10^{-5}$ eV$^2/c^4$, $\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV$^2/c^4$ in 3-neutrino model, since 3 neutrinos can have only 2 independent Δm^2 values:

$$\Delta m^2_{23}\left\{ m_3^2 \ldots m_2^2 \right. ,\quad \Delta m^2_{12}\left\{ m_2^2,\ m_1^2 \right. ;\quad \left. m_3^2 \ldots m_1^2 \right\} \Delta m^2_{13} \quad \Rightarrow \Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$$



- Being tested in MiniBooNE (in progress at Fermilab)
- If LSND right, neutrino physics even more interesting than most suppose – 4 neutrinos (or more)!?

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   a) long-baseline experiments: K2K, MINOS, and CNGS

   b) Neutrino Factories

   c) neutrino SuperBeams

   d) comparing Neutrino Factories and SuperBeams

   e) muon cooling

   f) measuring neutrino mass

New Approaches for Long-Baseline Neutrino Experiments

- Can make intense ν beam with known properties at a high-energy particle accelerator
- Following Super-K's success in establishing neutrino oscillations, Japanese KEK accelerator laboratory built "K2K" neutrino beam aimed at Super-K

- Approach:

  1) aim intense high-energy proton beam at target to make pions going towards detectors

  2) focus this "secondary" beam with a "magnetic horn"

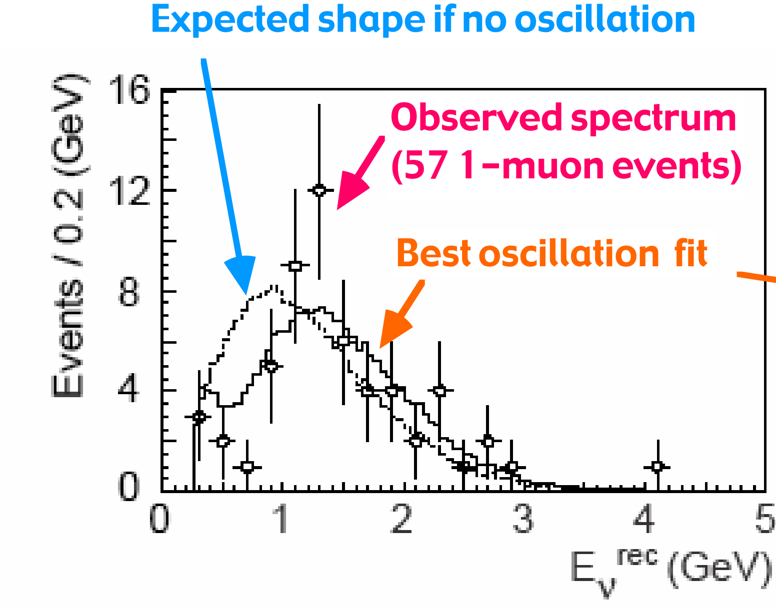
  3) allow beam to drift through a decay pipe, in which $\pi^- \rightarrow \mu^- \nu_\mu$

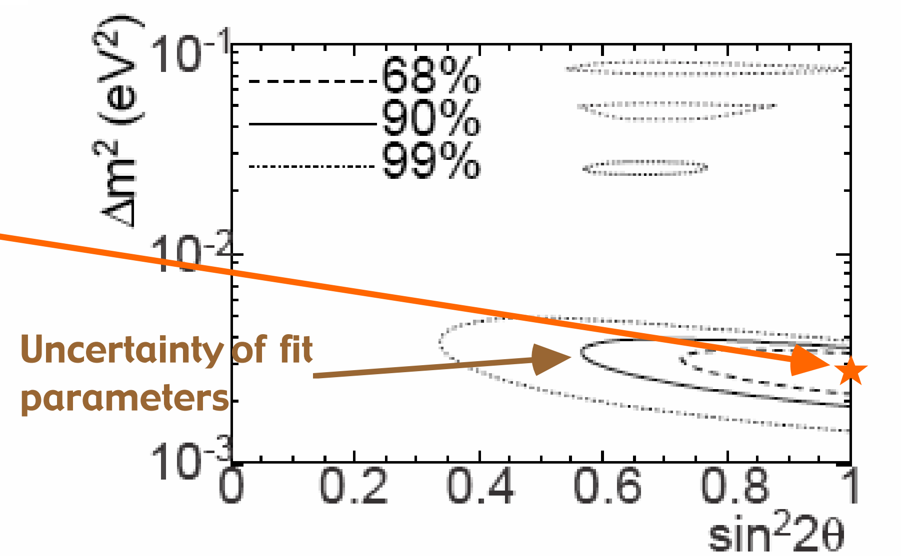
  4) allow decay products to travel through earth towards detectors (non-neutrinos absorbed)

K2K results

data from 1999–2004: C. Mariani et al., arXiv: hep-ex/050519 (2005)

- See a total of 107 events, where 151 are predicted if no oscillation:





- With more running time, more data will pin down parameters of atmospheric oscillation more precisely

- Proposed upgrades:

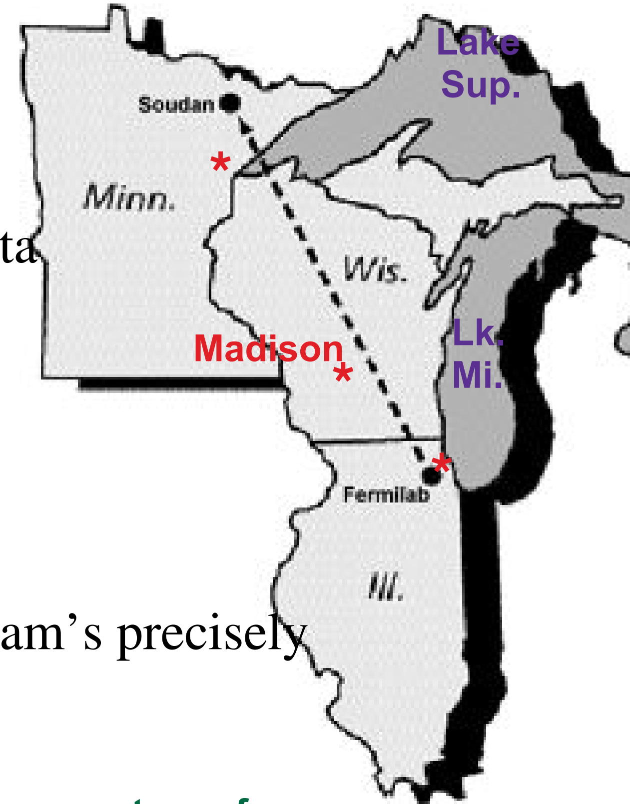
1) use J-PARC accelerator (under construction) for higher proton intensity (× ~ 100)

2) use proposed Hyper-K detector (× ~ 10) ~ Megaton water-Cherenkov detector
(×1000 in # events → $\sqrt{1000} \approx 30\times$ better measurement)

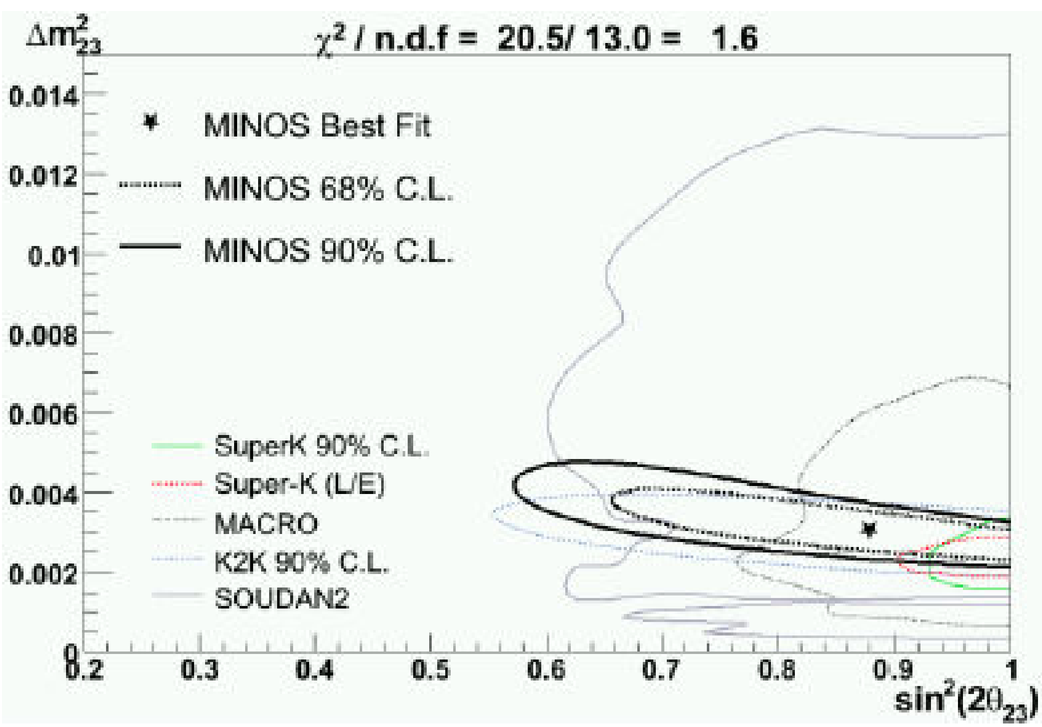
- Likely a 10-to-20-year, ~G$ research program

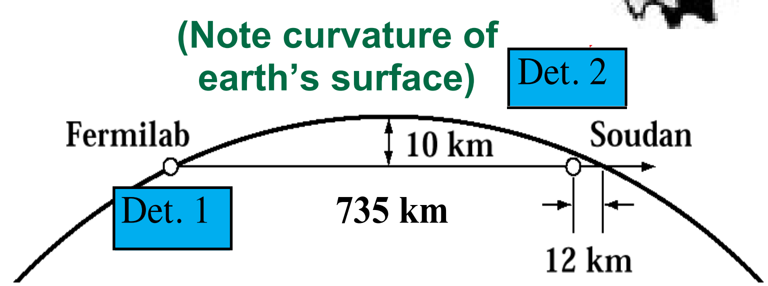
MINOS

- Main Injector Neutrino Oscillation Search
  - uses Fermilab Main Injector 120-GeV proton accelerator to send ν beam 735 km to far detector in Soudan mine in Minnesota
  - near and far detectors both magnetized-Fe/scintillator sandwich
    - near detector mass = 980 tons
    - far detector mass = 5400 tons
  - data-taking with beam started in Jan. 2005
  - goal: see oscillation curve "1st wiggle", measure oscillation param's precisely

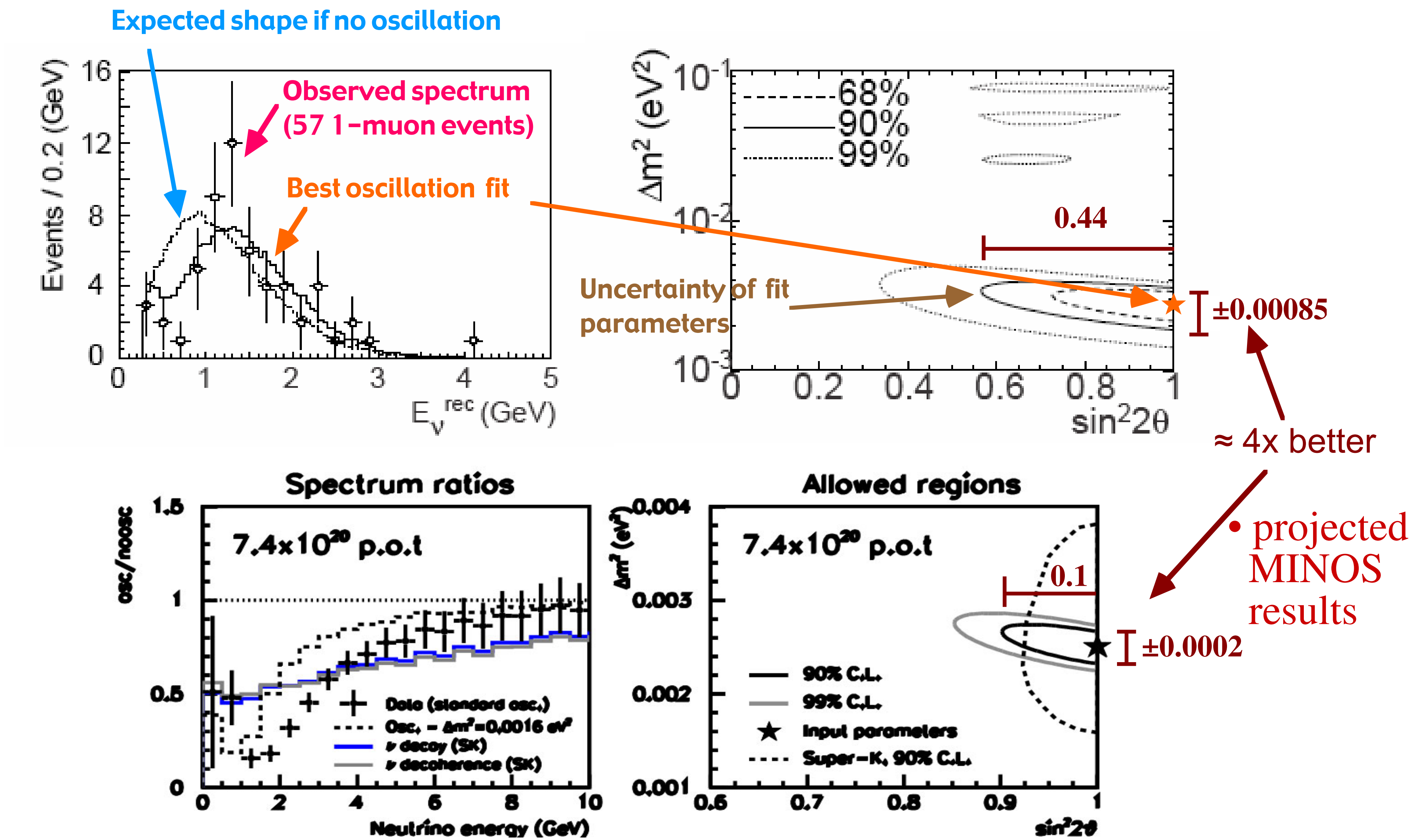


- MINOS results (3/30/06):



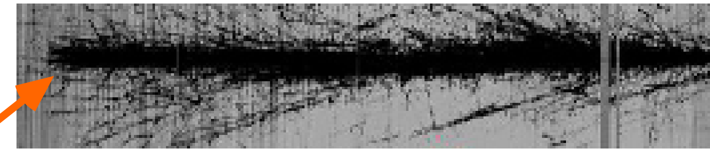


MINOS compared with K2K



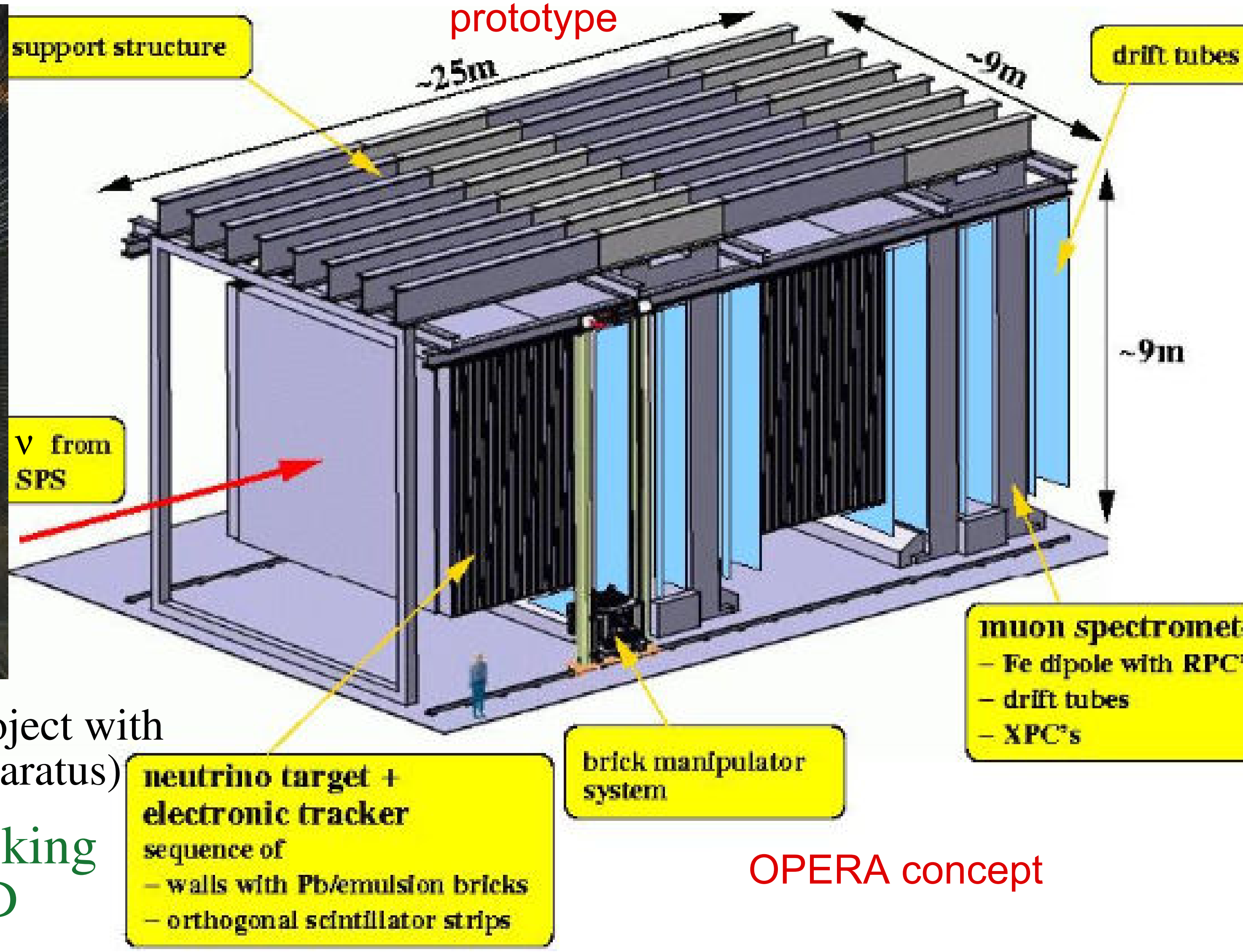
CNGS

- CERN Neutrino-beam to Gran Sasso underground lab (in tunnel under Alps)
- 2 exp'ts, emphasizing ν_τ appearance in a ν_μ beam, planned for 2006 turn-on
  - ICARUS (Imaging Cosmic And Rare Underground Signals) will image tracks of charged particles in liquid argon



cosmic-ray event in ICARUS prototype

ICARUS prototype

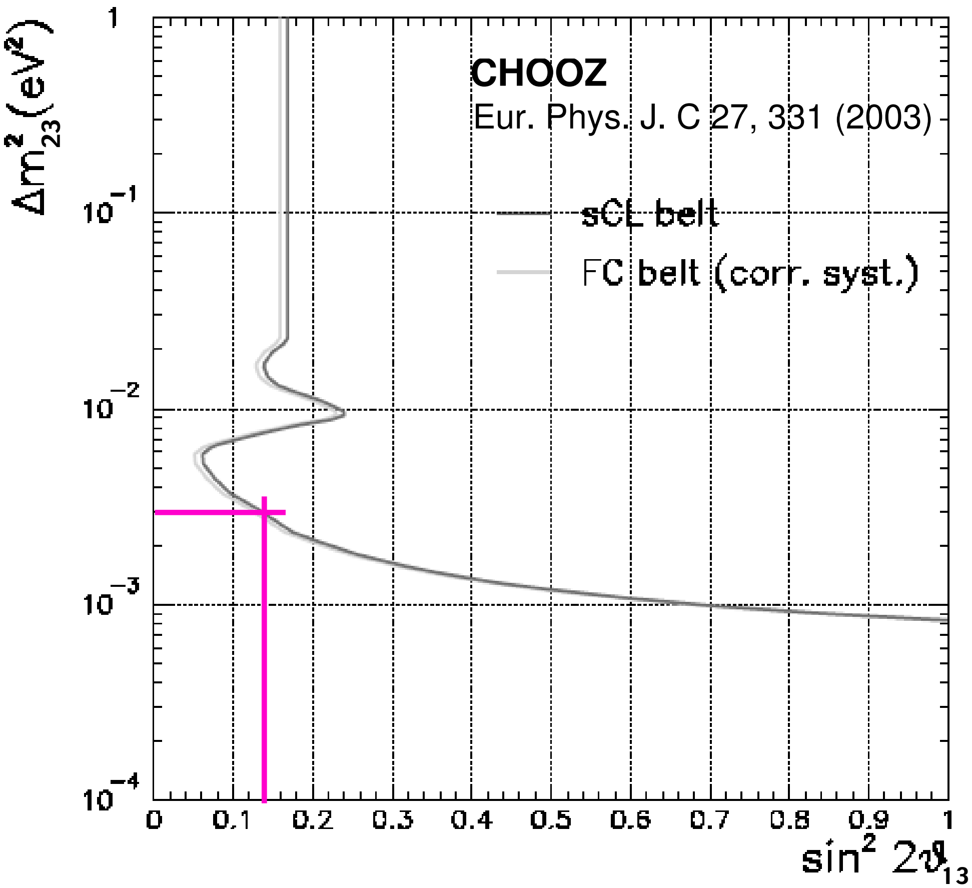


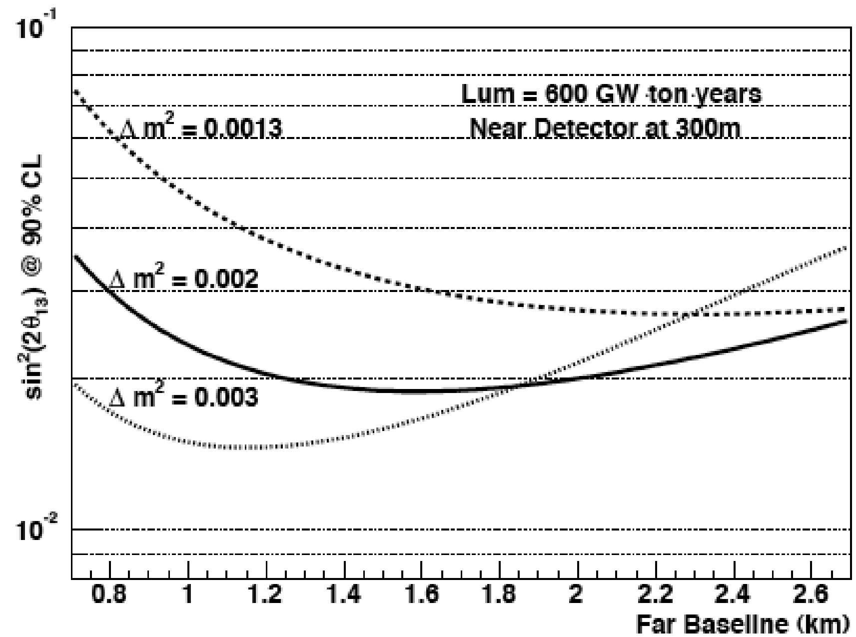
OPERA concept

  - OPERA (Oscillation Project with Emulsion-tRacking Apparatus)
- Both have precise tracking for reliable τ-lepton ID

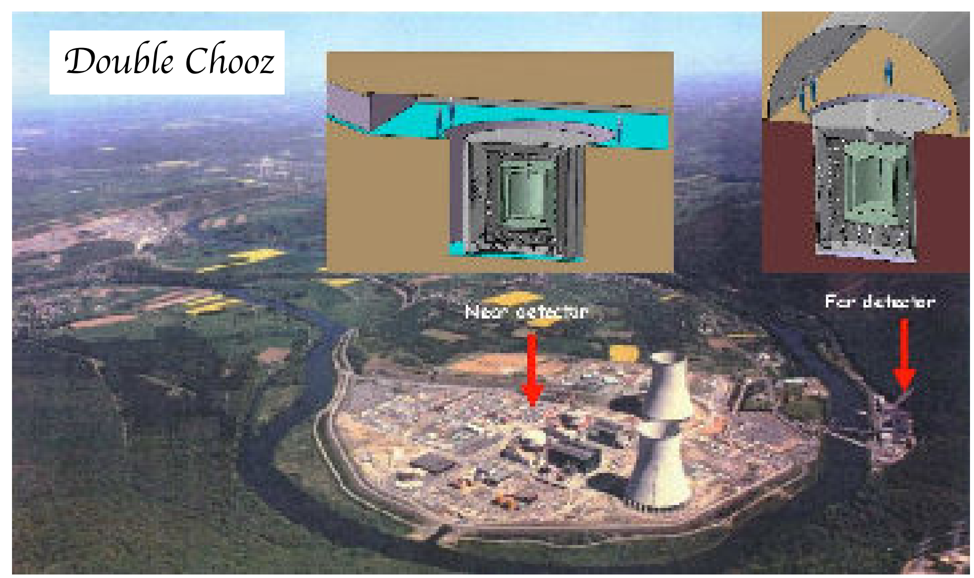
Reactor Neutrino Experiments

- To establish 3-generation oscillations, need to show $\theta_{13} > 0$
- Measured most directly via reactor-$\bar{\nu}$ disappearance exp't (best was CHOOZ)



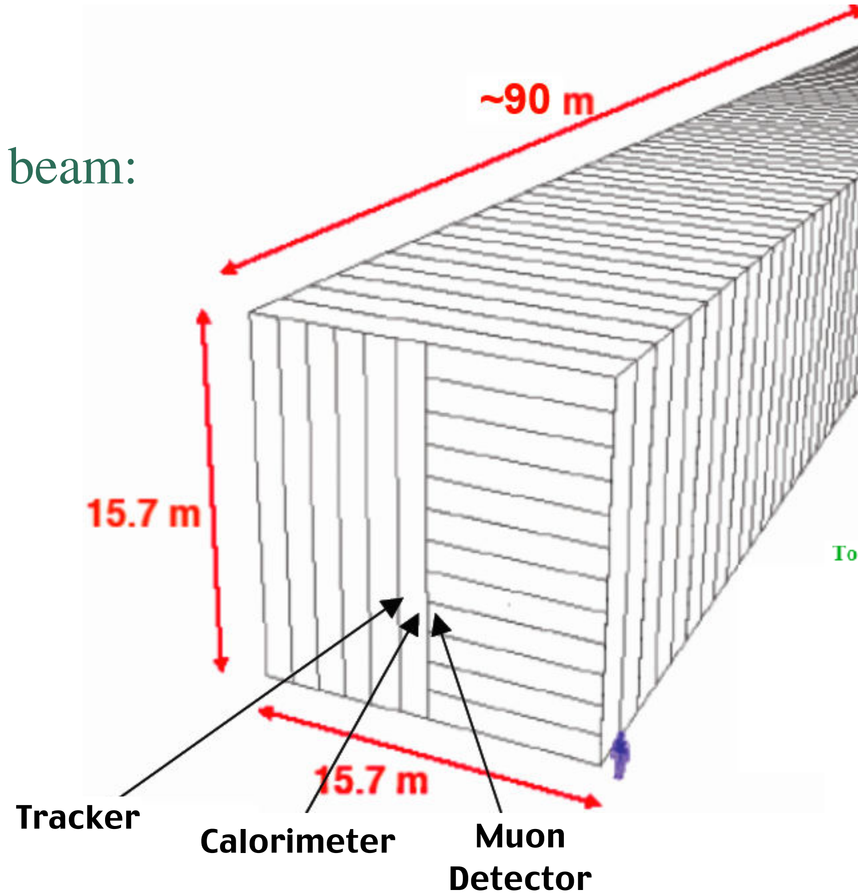


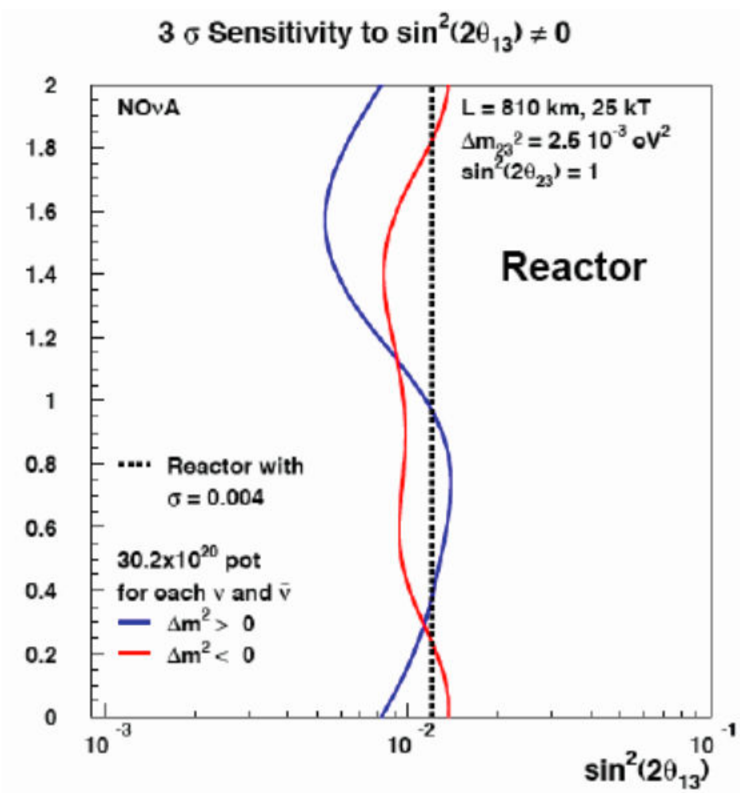
- Current projects:
  - Double Chooz (France): 2008–11(?)
  - Daya Bay (China)
- Idea: use near detector to reduce uncertainties due to $\bar{\nu}$ spectrum

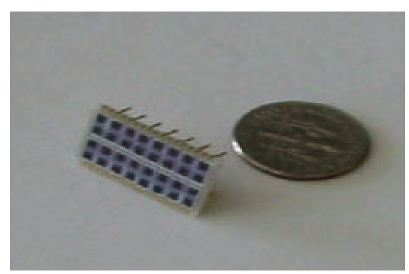


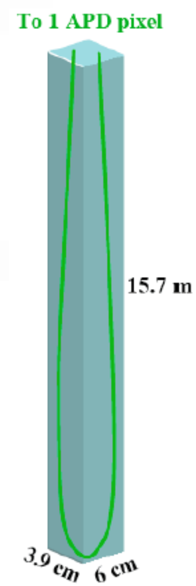
T2K and NOνA

- Even larger long-baseline experiments are planned for ≈2009–12 starts:
  - JAERI Tokai to Kamioka (T2K) and
  - NOνA:
  - *Enormous* proposed detector for NuMI beam:
    - 100% active liquid scintillator, enclosed in plastic extrusions
    - 20 kT mass
    - 0.5M detector channels, read out via avalanche photodiodes



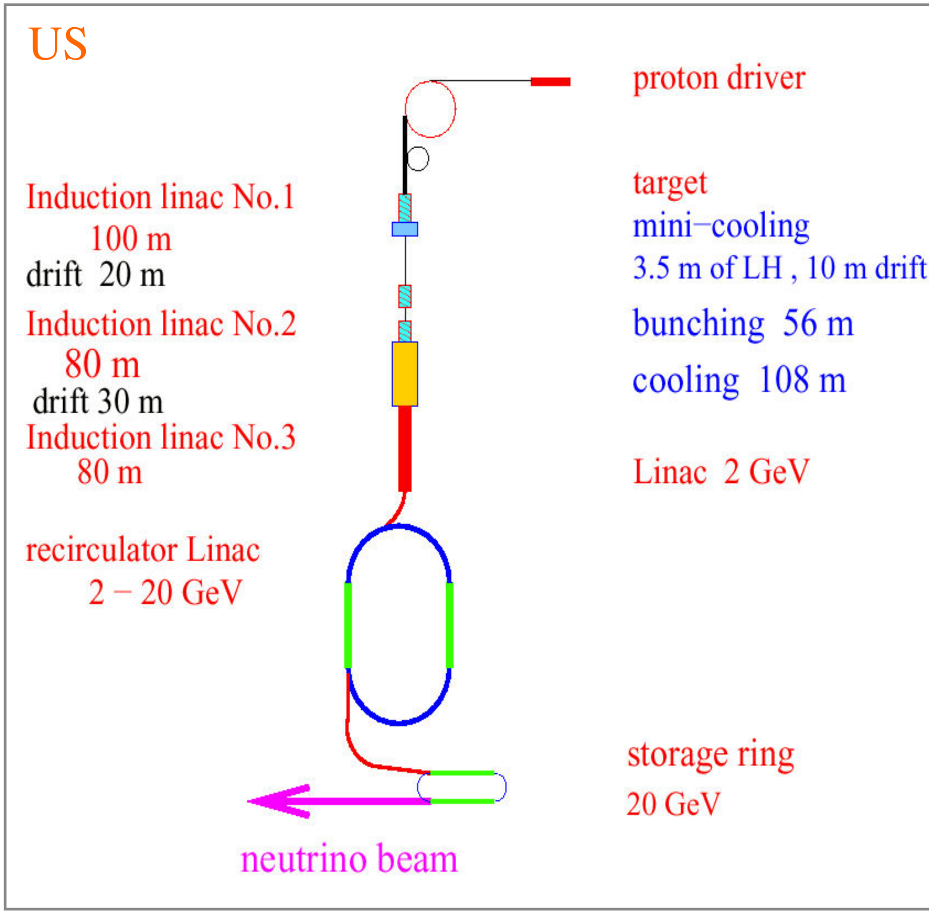


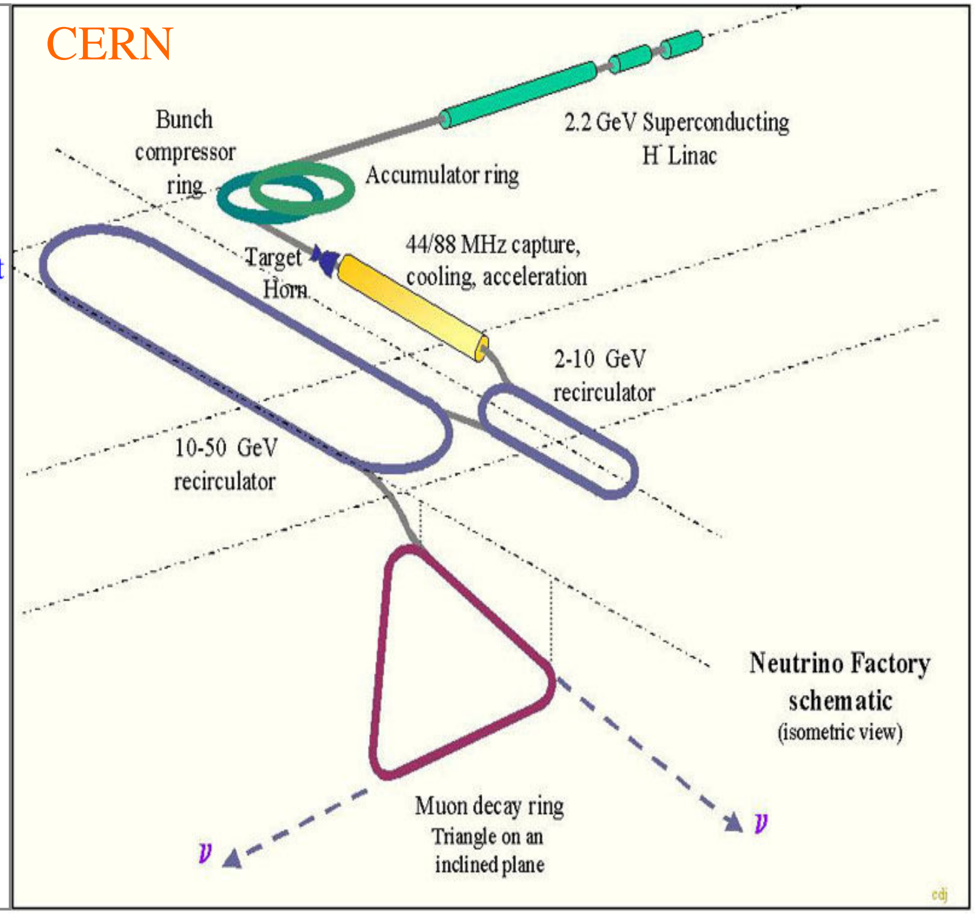




Neutrino Factories

- Since ≈1997, groups of scientists worldwide have been developing the "ultimate weapon" for neutrino-oscillation research: the Neutrino Factory





- Basic idea:
  - sensitivity of oscillation-parameter measurement ultimately limited not by # events but by event "cleanliness", e.g. probability to mistake a normal event for an oscillated event
  - cleanliness much better with electron-neutrino beam than with muon-neutrino beam: oscillated events producing muons much easier to identify than those producing electrons

Neutrino Factories (cont'd)

- To make intense beam of high-energy electron neutrinos or antineutrinos,
  1) use high-energy muon beam, since $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ and $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$
  2) store muons in a storage ring and let them decay pointed towards detectors
  3) since beam contains neutrinos of one type (e or μ) and antineutrinos of the other (μ or e),

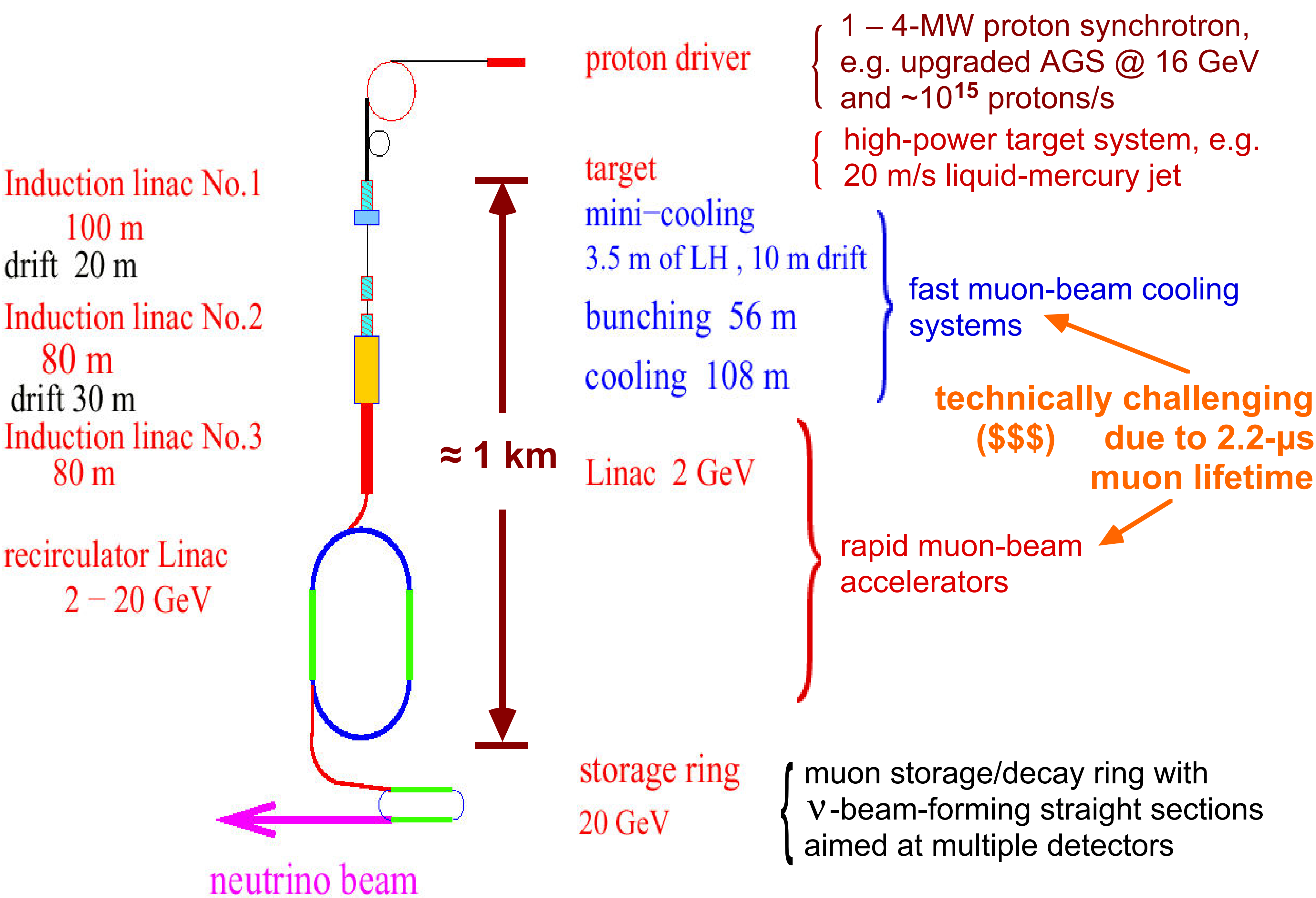
  $\to$ need detector with magnetic field to identify oscillated events

  e.g. store μ^- in ring: then
  - oscillated events are from $\bar{\nu}_e$ becoming $\bar{\nu}_\mu$, making μ^+ in detector
  - non-oscillated events are from ν_μ in beam, making μ^- in detector

- To get enough high-energy muons, need to produce and accelerate them
  - muons produced by pion decay
  - need very intense proton source to make enough pions $\Rightarrow$ develop new generation of intense proton sources
- But muon beams from pion decay are too diffuse for economical acceleration!
- Possible solutions:
  1) (Japanese approach) develop new, large-aperture acceleration technology, or
  2) (US & Europe) develop muon-beam "cooling" technology to shrink muon beam ("cooling" by analogy w/ refrigeration: reduce random motions of muons w.r.t. each other)

Neutrino Factory Example

(US Feasibility Study II design, 2001)



Neutrino "SuperBeams"

- Neutrino Factory Proton Driver can make a "Super Neutrino Beam"

  ≡ ~ 10×-more-intense conventional ν beam (from $\pi \rightarrow \mu\, \nu_\mu$)

  ⇒ is Neutrino Factory needed?

  – while Neutrino Factory feasibility established, cost not yet definitively known
    - but will be of order G$ (cf. CERN SPS accelerator: cost ≈ 1 GSF in 1976)

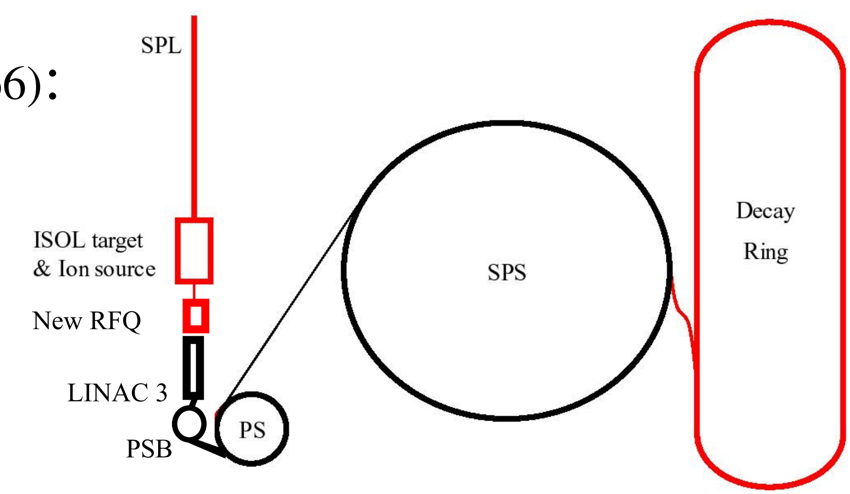
  – few-MW Proton Driver considerably cheaper:
    - ≈ few-100 M$ upgrade to existing facility

- Coupled with ~ 10×-bigger proton-decay detector → ~ 100× more ν events

  (also ~ G$ facility, but "kills 2 birds with 1 stone" – advances *p*-decay searches + ν physics)

- Examples:
  – CERN: SPL (Superconducting Proton Linac) → Frejus-tunnel concept
  – Japan: J-PARC → Hyper-K proposal

- Another idea (P. Zucchelli, Phys. Lett. B 532 (2002) 166):
  – instead of muons, use storage/decay ring of β-emitting radioactive nuclei ("Beta Beam")
  – requires very substantial upgrade of existing radioactive-beam capability
  – feasibility and cost not yet clear

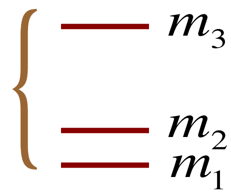


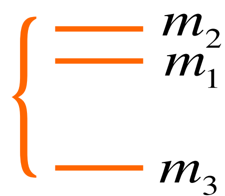
Sensitivities of SuperBeams and Factories

- Effort in progress worldwide to evaluate & compare "physics reach" of various possible future ν-physics facilities

- Measurements of greatest interest after MINOS, assuming (for simplicity) that MiniBooNE does not confirm LSND:

  $\sin^2 2\theta_{13}$ the small mixing angle ("θ_x") btw generations I and III (CHOOZ $\rightarrow$ $\theta_{13} < 10°$)

  $\mathrm{sgn}(\Delta m^2_{13})$ says whether ν masses are "normal" 

or "inverted" 

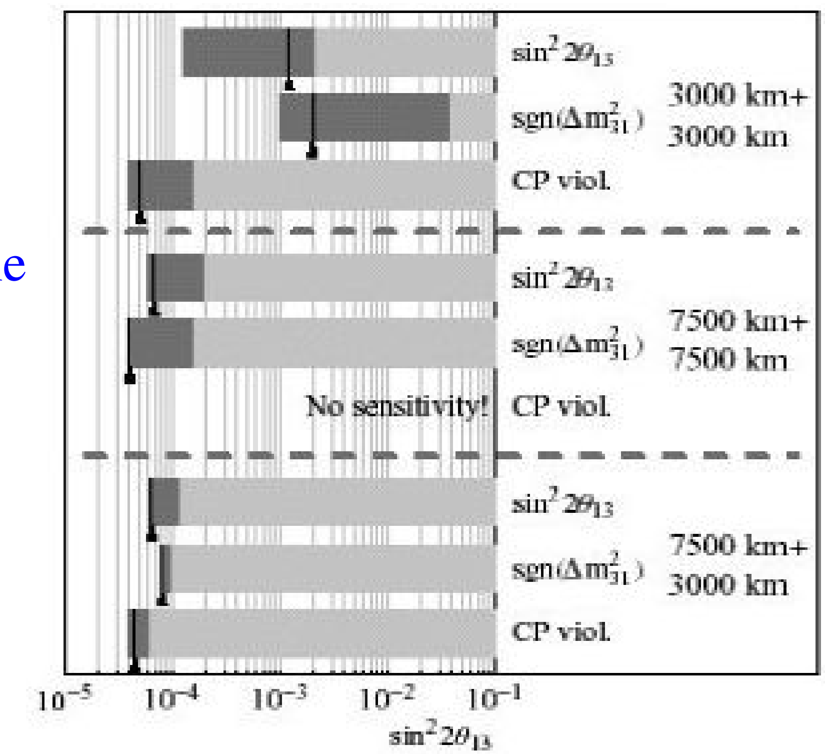
  δ CP-violating phase in mixing matrix

- Study by P. Huber & W. Winter, Phys. Rev. D68 (2003) 037301:

  – Neutrino Factory sensitivity depends on baseline and on value of θ_{13}

  – With 2 carefully chosen baselines, can make significant measurements down to $\sin^2 2\theta_{13} \sim 0.0001$ or less ($\theta_{13} < 0.3°$)

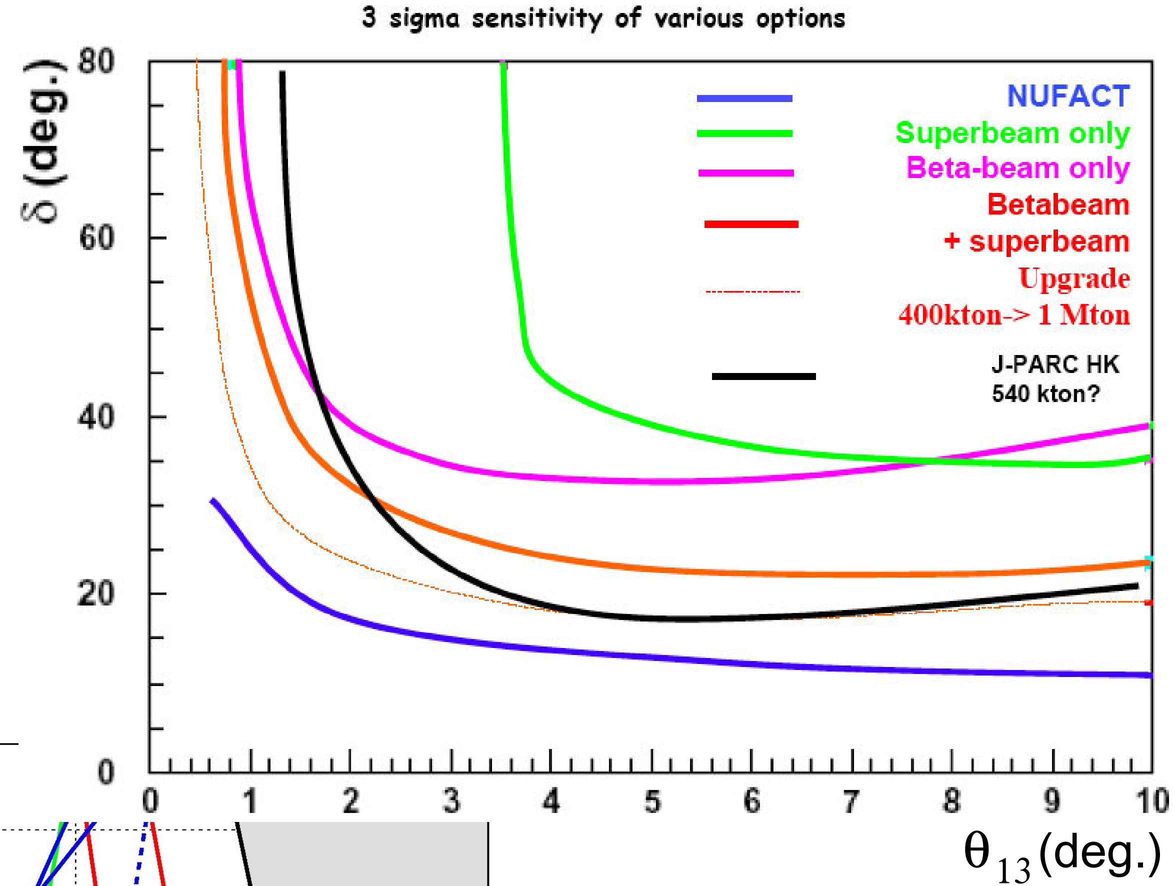
  – No other technique extends to such small θ_{13}



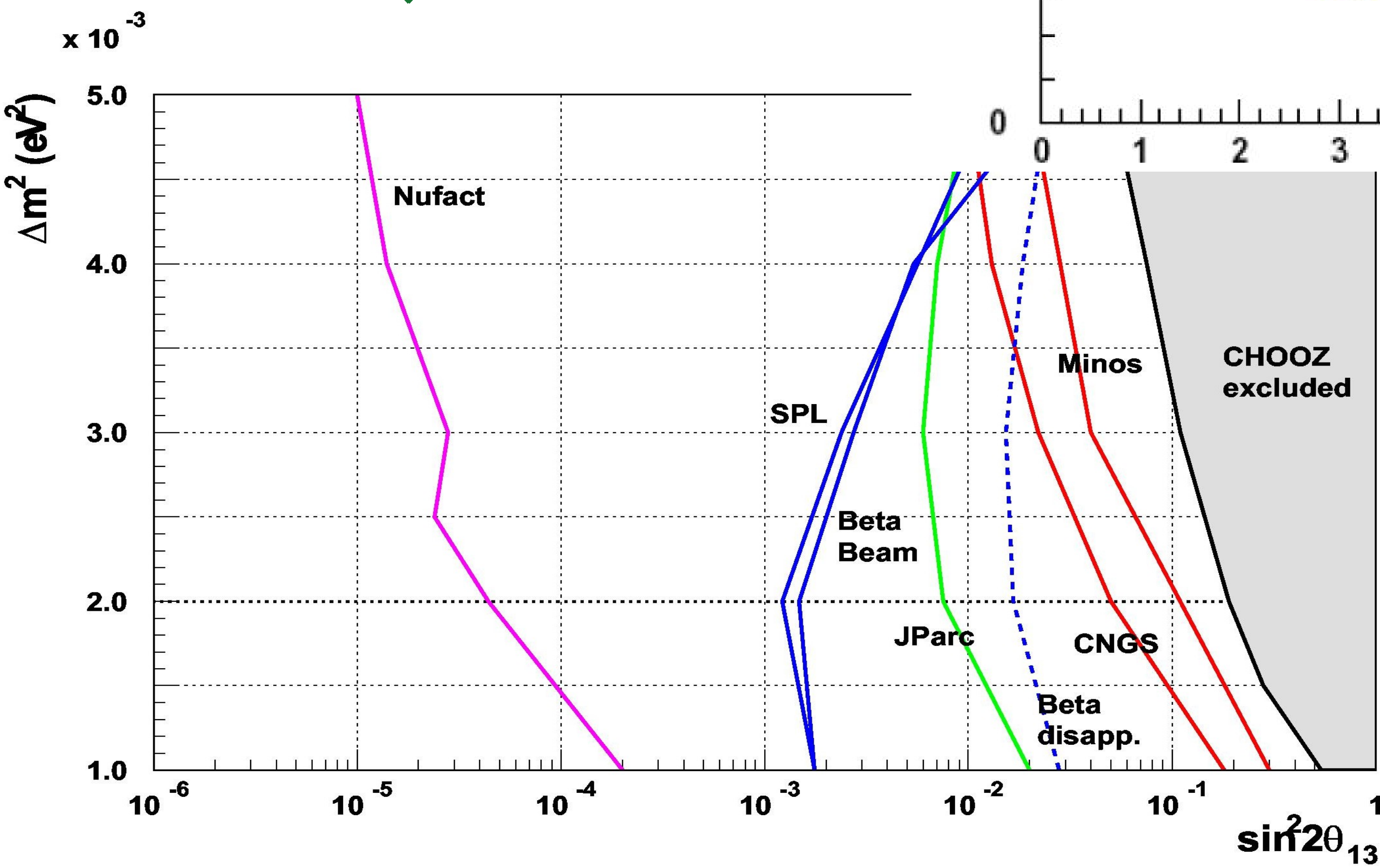
Sensitivities of SuperBeams and Factories (cont'd)

(from A. Blondel talk at NO-VE Workshop,Venice, Dec 2003)

CP-sensitivity comparison →



Oscillation-parameter comparison ↓



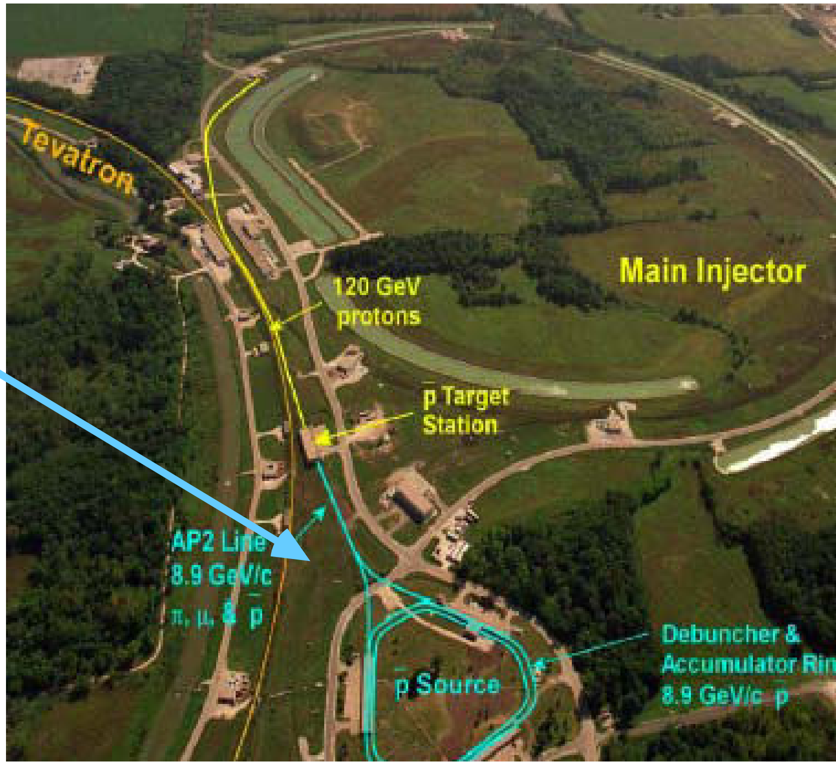
Neutrino Factory is most sensitive technique yet found!

NB: NuFact estimates assume "modest" (≈50-kton) detector

Muon Cooling R&D

- "Cooling" a particle beam to reduce its size is established technique in high-energy physics
  - e.g. antiproton cooling ring at Fermilab to increase rate of $p\bar{p}$ collisions
- But antiproton stable

  ⇒ can use "stochastic cooling" technique, which takes many hours
- What cooling technique takes microseconds?



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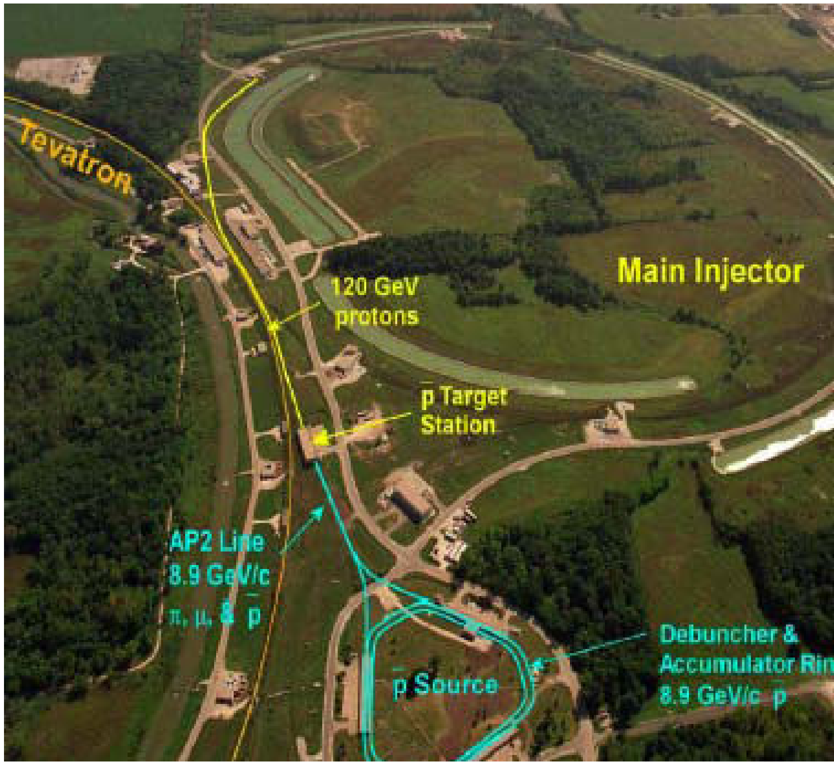
  - there is only one, and it works only for muons:



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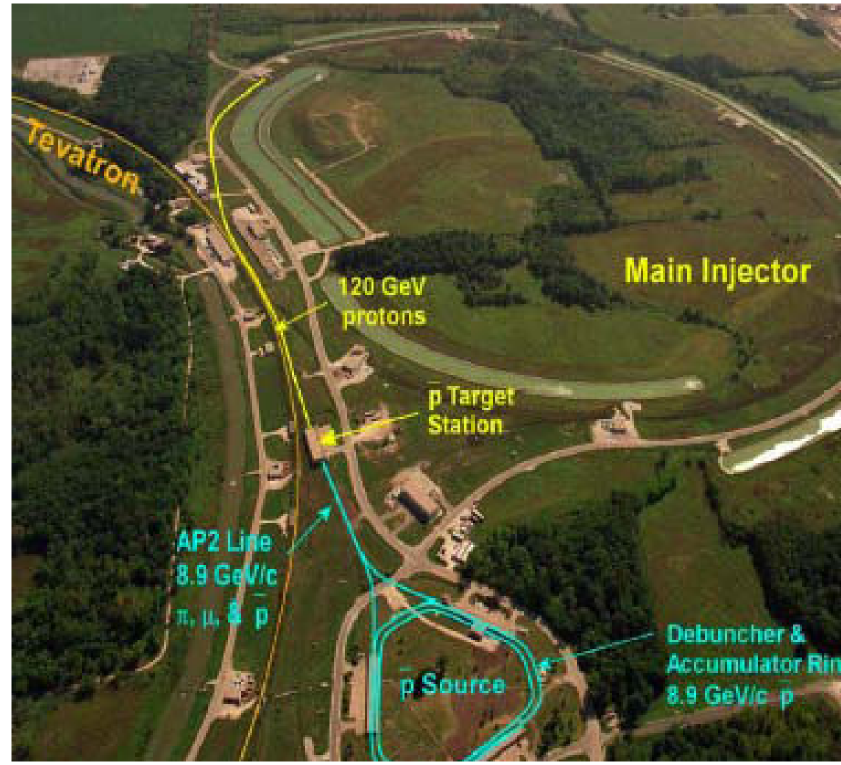

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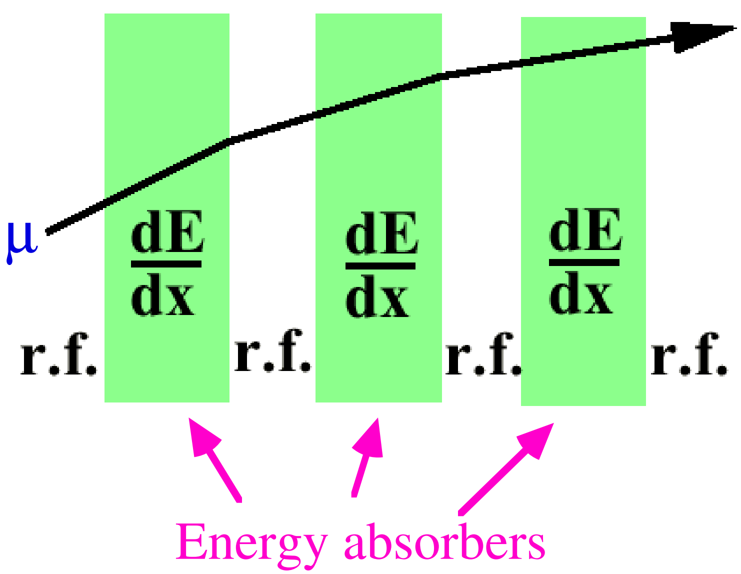
  →ionization cooling [Skrinsky & Parkhomchuk, Sov. J. of Nuclear Physics 12 (1981) 3]



1) slow muons down via ionization of absorber medium
   – reduces momentum both sideways and along beam direction
2) then reaccelerate them in radio-frequency cavities
   – puts back momentum only along beam direction
3) repeat until muons all travel in ≈ same direction

NB: for an accelerator, beam divergence, as well as size, matters

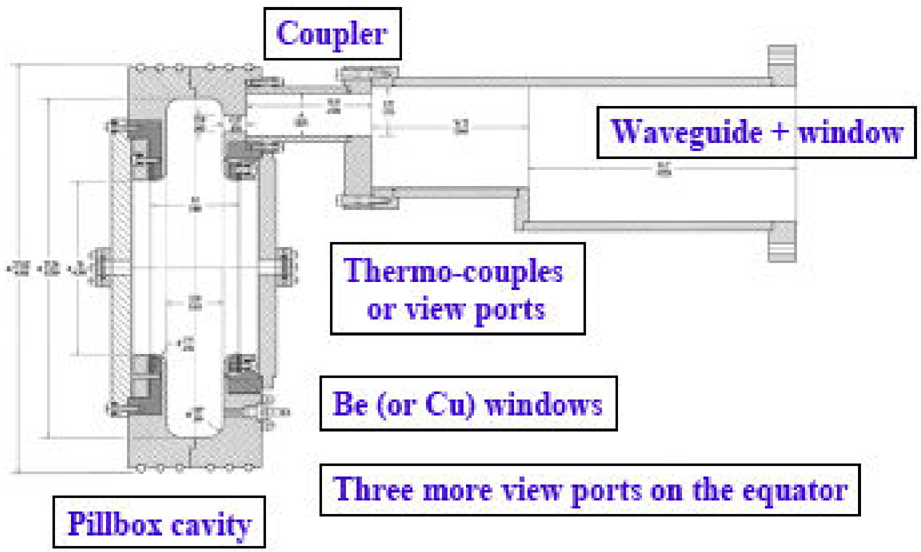
⇒ reducing divergence (as above) is also cooling

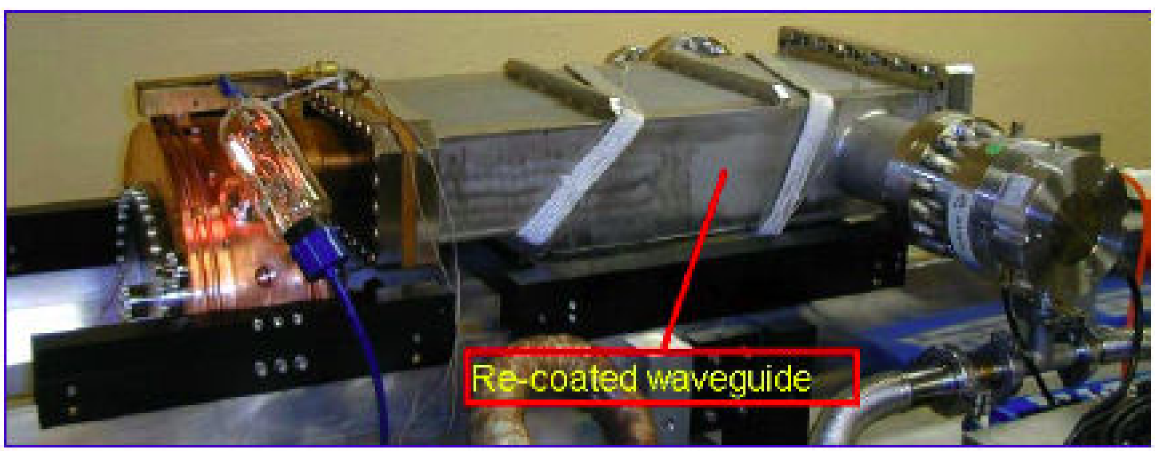
Muon Cooling R&D (cont'd)

- The (US-based, ≈140-physicist) Neutrino Factory and Muon Collider Collaboration is developing prototypes of muon ionization-cooling hardware

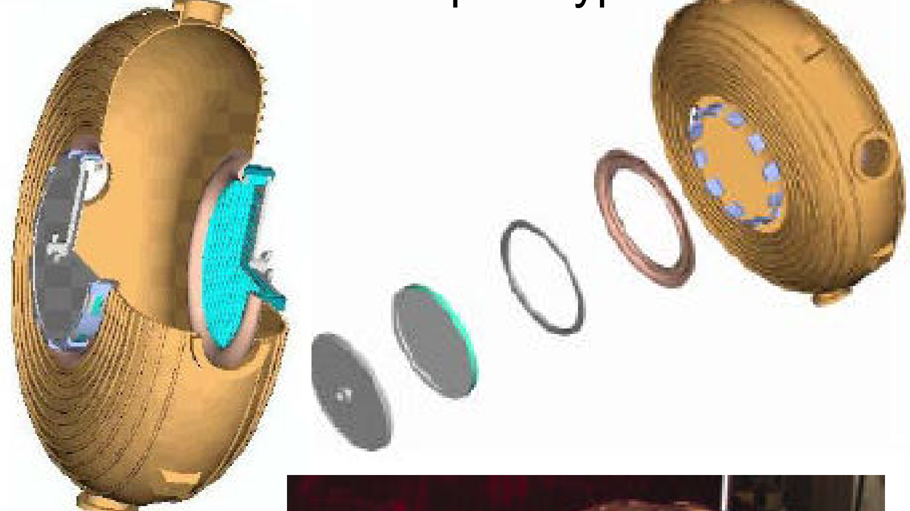
High-gradient r.f. accelerating cavities:

805-MHz prototype:





201-MHz prototype:

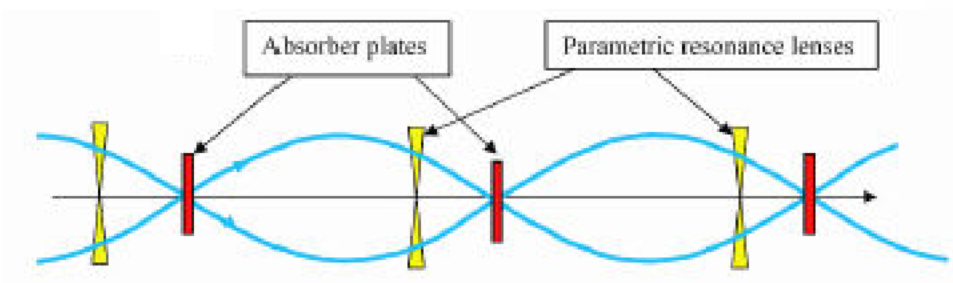


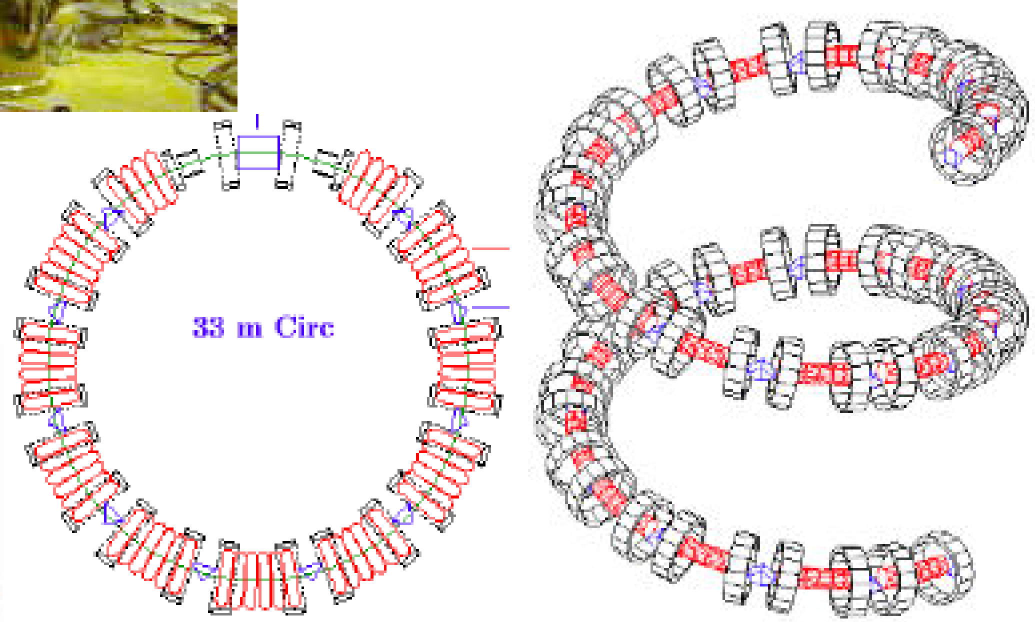
Muon Cooling R&D (cont'd)

High-power liquid-hydrogen energy absorbers:

...& test facilities for absorbers and r.f. cavities

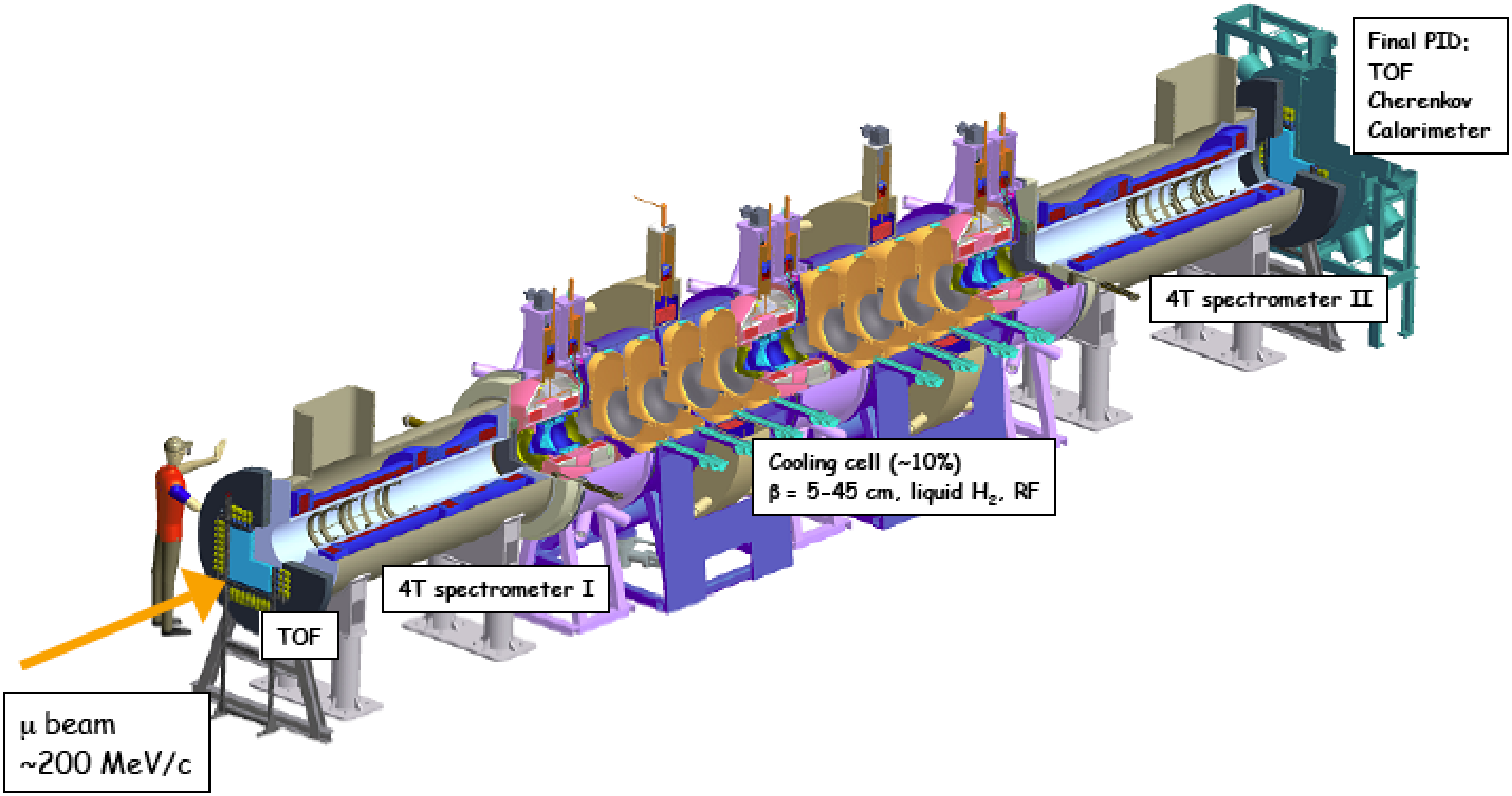
... also design studies for alternative ways of cooling:





Muon Ionization Cooling Experiment (MICE)

- To convince world's physicists (& funding agencies) that Neutrino Factory cost & performance understood, will need to demonstrate muon cooling
  - proposed MICE configuration: a "10% cooling" effect measured to 1% of itself



- Status: MICE Phase 1 funded for 2007 start at UK's Rutherford Appleton Lab
- In process of building μ beam & gathering resources for full experiment

Outline

1) Postulation of the neutrino

2) Observation of the neutrino

3) Neutrino beams

4) The search for solar neutrinos

5) The rise of the large underground detectors

6) Neutrino mixing

7) Current issues in neutrino physics

8) Future facilities for neutrino physics

   a) long-baseline experiments: K2K, MINOS, and CNGS

   b) Neutrino Factories

   c) neutrino SuperBeams

   d) comparing Neutrino Factories and SuperBeams

   e) muon cooling

   f) measuring neutrino mass

Measuring Neutrino Mass (1)

- Neutrinos are among the most abundant known particles in the Universe
  - estimated density ~ 100 ν/cm^3
- Recall Pauli's proposed neutrino had a small, but non-zero mass

  ⇒ neutrinos might be significant fraction of all mass in Universe!
- Nevertheless, before ≈2000, most physicists believed neutrinos massless
- Now we know this is wrong: neutrino oscillation requires $\Delta m_\nu^2 \neq 0 \Rightarrow m_\nu \neq 0$
- How big are the m_ν?
  - can't tell from oscillation experiments, which measure Δm_ν^2, not the m_ν themselves
- Can attempt direct measurement of m_ν, e.g., from endpoint of ^{3}H beta-decay spectrum, endpoint of $\pi \rightarrow \mu\nu$ decay spectrum, etc.
  - current endpoint experiments can't measure such small masses – only set upper limits:

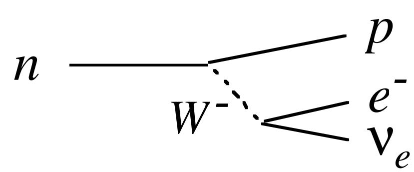
    $m(\nu_e) < 3$ eV/c^2 $\quad$ $m(\nu_\mu) < 190$ keV/c^2 $\quad$ $m(\nu_\tau) < 18.2$ MeV/c^2
  - cf. astrophysical limits on amount and structure of "dark matter" in Universe: recent WMAP results on cosmic microwave background ⇒ $|m_\nu| < 0.7$ eV/c^2
  - new ^{3}H experiments proposed, e.g., KATRIN with $m(\nu_e)$ sensitivity 0.35 eV/c^2

Measuring Neutrino Mass (2)

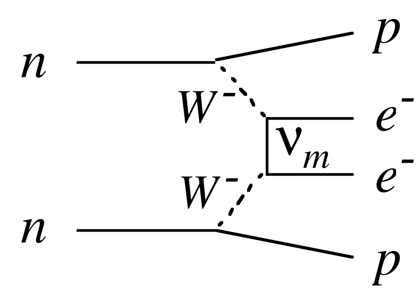
- Can neutrino masses be measured accurately enough to tell us about the evolution of the Universe (instead of vice versa)?

- Answer is yes, but – ironically! – via neutrinoless double beta decay, in which no neutrino is emitted:

ordinary β decay
(as described by electroweak theory)



neutrinoless double β decay



  - 0ν2β decay possible only if neutrino its own antiparticle, as proposed by Majorana in 1937
  - even though no neutrino emitted, predicted rate $\propto |m_\nu|^2$
  - at best a very rare process, since requires 2 simultaneous weak decays, thus very challenging to detect experimentally
  - e.g., CUORE proposal for LNGS: array of 1000 750-g TeO_2 "bolometers", operating near absolute zero ($T \approx 10$ mK), sensitive to possible decay ${}^{130}_{52}\mathrm{Te} \rightarrow {}^{130}_{54}\mathrm{Xe} + 2e^- + 2528.8$ keV
  - also other proposals, e.g., GENIUS & Majorana seeking ${}^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{34}\mathrm{Se} + 2e^- + 2039$ keV

- 0ν2β decay almost the only way to measure the Majorana parameters of the ν mixing matrix (except for other very rare processes such as $\mu^- \rightarrow e^- e^+ e^-$)

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→ 9) Summary

Summary

- Three-quarters of a century after their postulation, neutrinos continue to inform us about the Universe in surprising ways
- Recent experiments have convincingly demonstrated that neutrinos
  - have mass; and
  - spontaneously change from one flavor to another as they traverse matter and space
- Upcoming experiments over the next two decades may tell us
  - whether neutrinos are their own antiparticles
  - whether neutrino decays distinguish matter from antimatter
  - whether neutrinos are responsible for the excess of matter in the Universe
  - whether Grand-Unified Theories are correct descriptions of matter and energy at
    - high temperatures
    - short distances
    - early times in evolution of Universe
- Neutrino SuperBeams & (ultimately) Factories may be crucial
- Current R&D efforts (e.g., on muon cooling) lay the groundwork for future facilities

Some Neutrino Milestones