Neutrinos

Alan Poon
Nuclear Science Division and
Institute of Nuclear and Particle Astrophysics

awpoon@lbl.gov

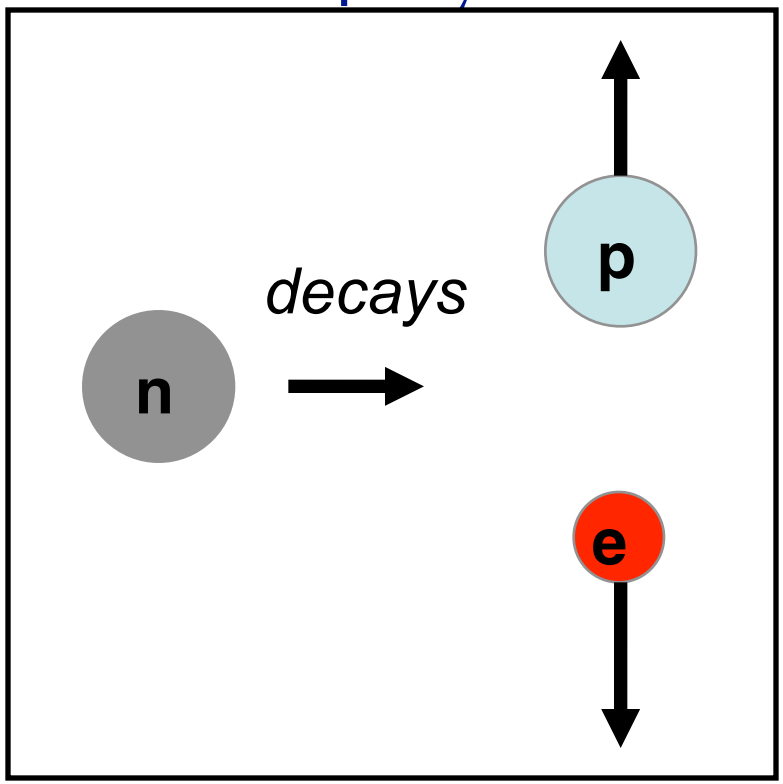
June 22, 2006

Outline

- What is a neutrino?
  - *A selective historic tour of neutrino physics from 1930s to early 1990s*
- What have we found out about neutrinos in the last several years?
  - *Many surprises*
  - *Concentrate on previously unknown properties*
- What else do we need to find out? (and how?)

Early 1900s

- William Bragg demonstrated that mono-energetic α-rays were emitted in α decays
- Therefore β-ray should be:



2-body decay ⇒
Conservation of energy ⇒
mono-energetic β rays

(right?)

An Energy Crisis

(and it did not involve Enron, nor Iran)

- Crisis: *Continuous β energy spectrum found*

⇒ **Missing Energy!**

Bohr (1932):

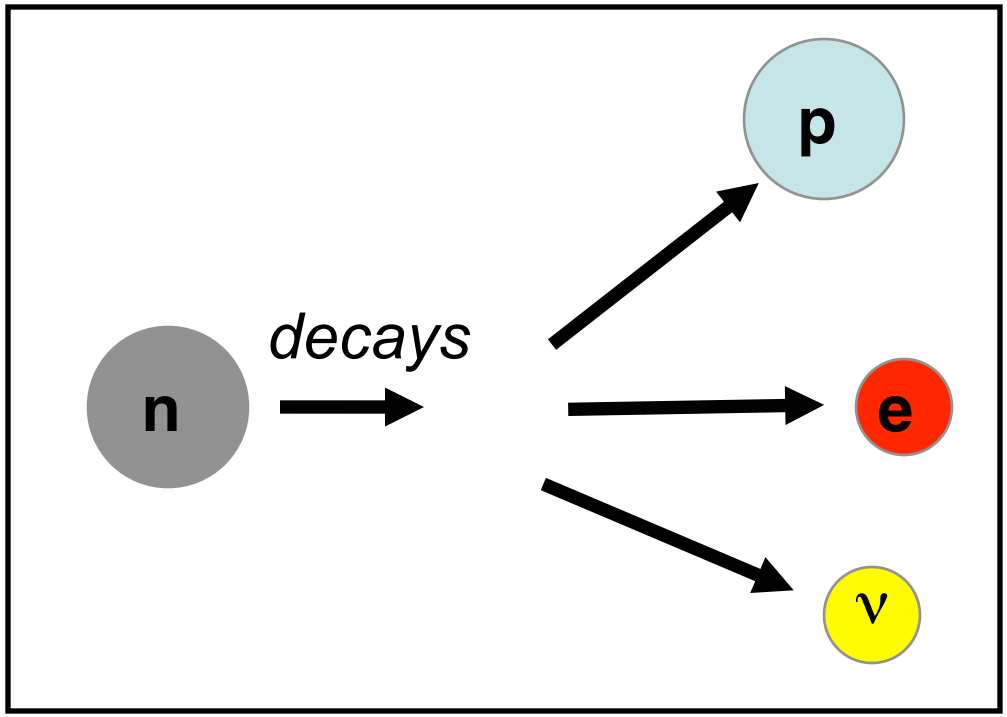
"…we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of beta-ray disintegration"

Pauli (1933):

"I have done a terrible thing, I have postulated a particle that cannot be detected."

Pauli's Solution: A tiny neutral particle

- ..which we call neutrino today (actually anti-neutrinos to be exact…later)



"ν" carries away some energy

ν in Standard Model of Particle Physics

- Mass of neutrinos = 0
- 3 flavors/types:

	I	II	III
Quarks	u	c	t
	d	s	b
Lepton	ν_e	ν_μ	ν_τ
	e	μ	τ

+ anti-particles

- Why are they called "electron", "mu" and "tau"-type neutrinos?

- Lepton flavor quantum number L_x is conserved

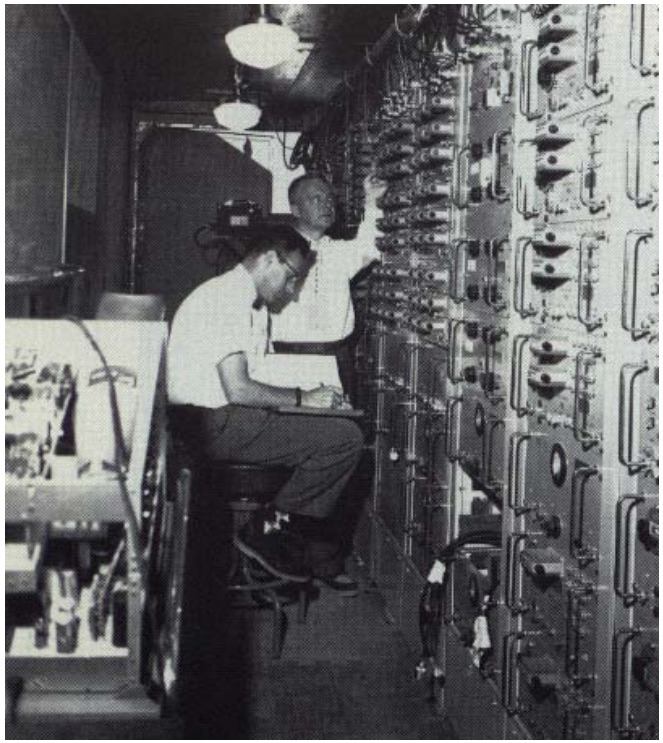
Example : Neutron β decay

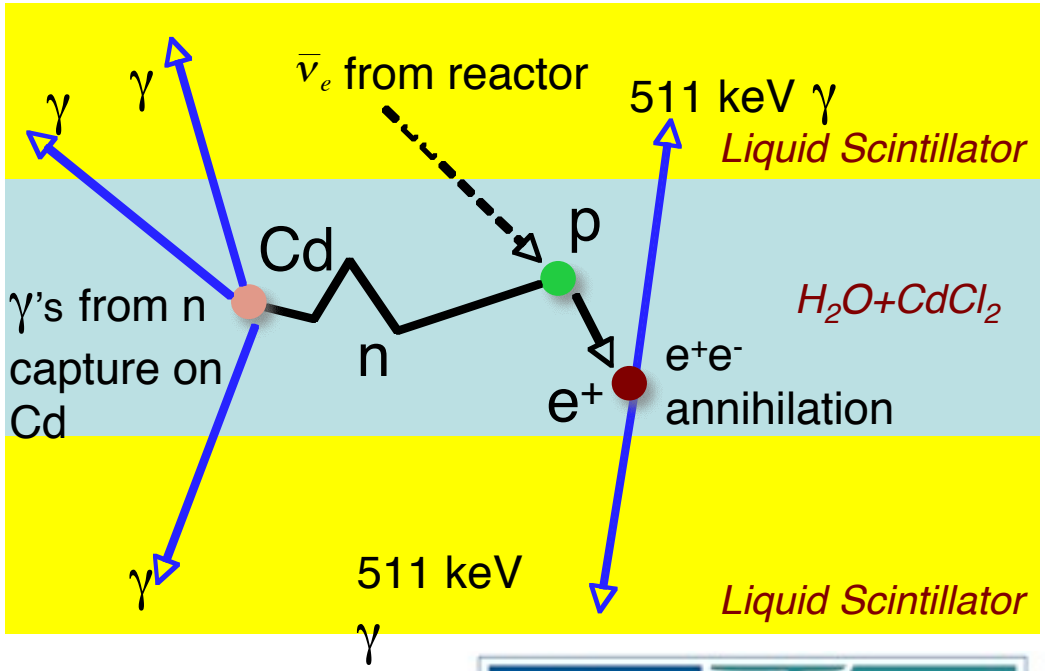
	n	→	p	+	e	+	$\bar{\nu}_e$
L_e	0		0		1		-1
L_μ	0		0		0		0
L_τ	0		0		0		0

Discovery of the (Anti-)Neutrinos

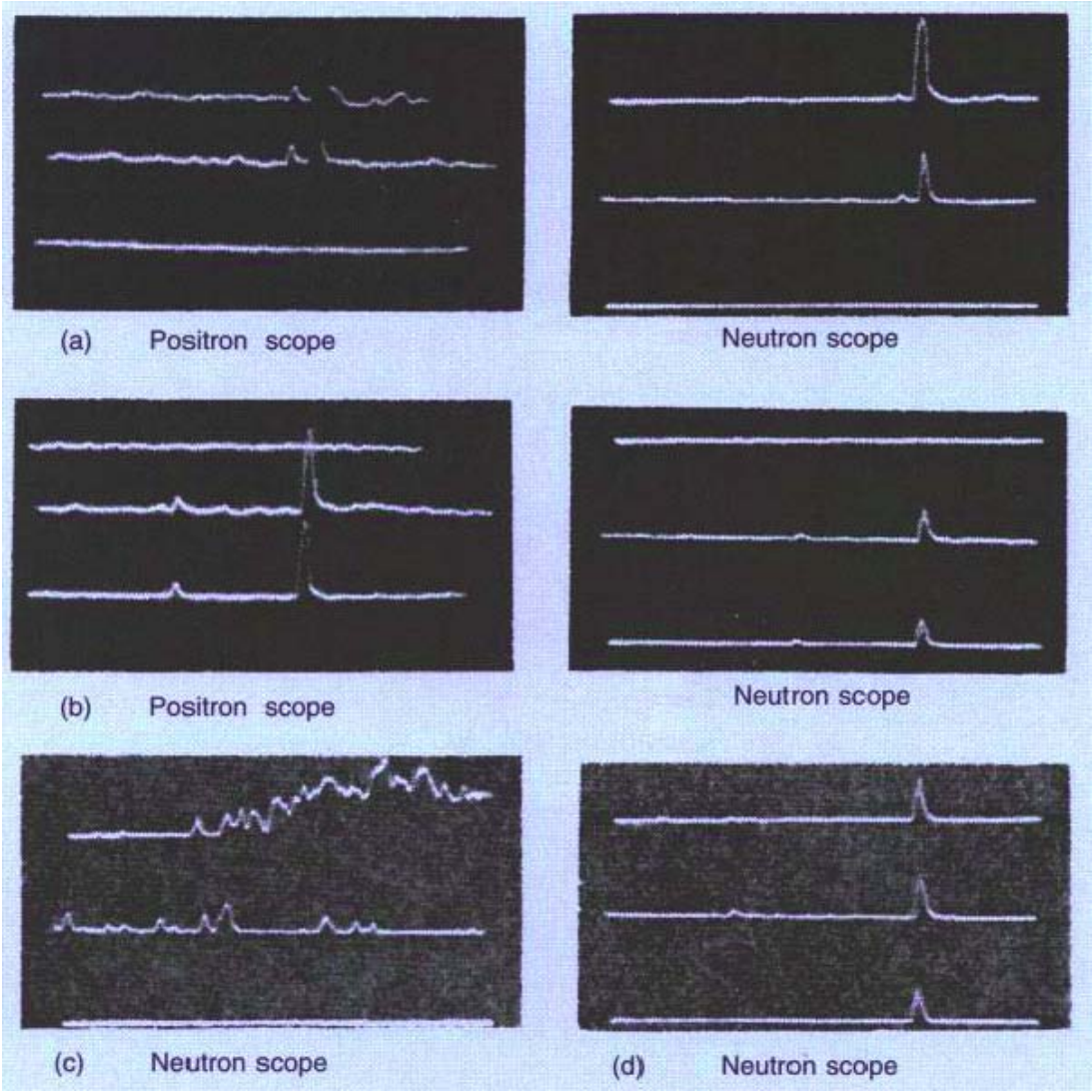
- F. Reines & C.L. Cowen @ Savannah River reactor plant
- We just celebrated the 50th anniversary of this discovery last week

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





Coincidences



neutrino

neutrino

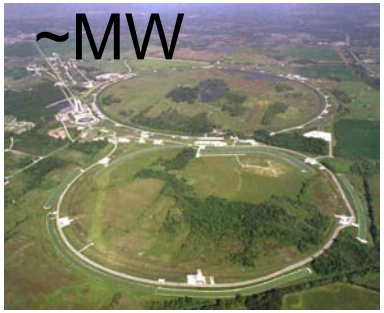
noise

cosmic ray

Detecting Neutrinos

(Why is it so hard?)

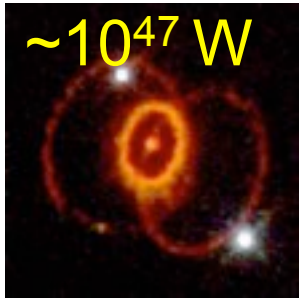
- No. of observed events:
  - ➡ ∝ (ν flux) x (prob./target) x (no. of targets) x (time)
- Neutrinos do not interact readily (small prob.)
  - ➡ Need very powerful sources:



Accelerators

Nuclear Reactors

Sun

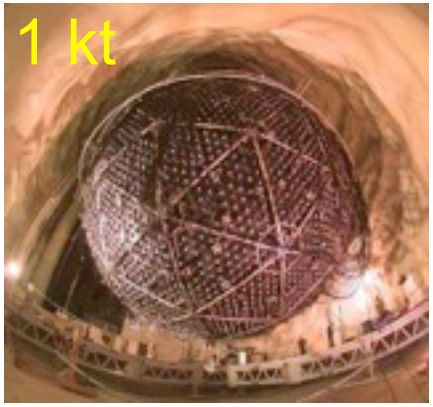


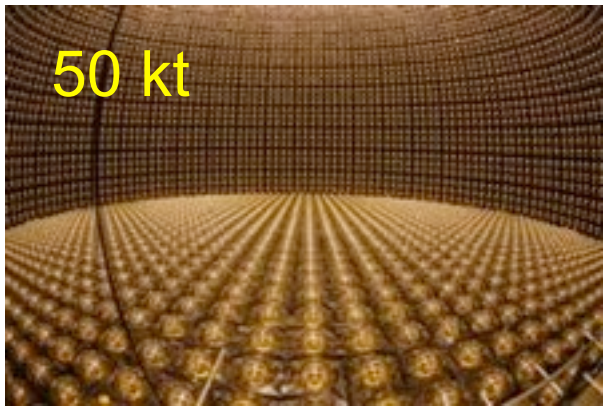
Supernovae

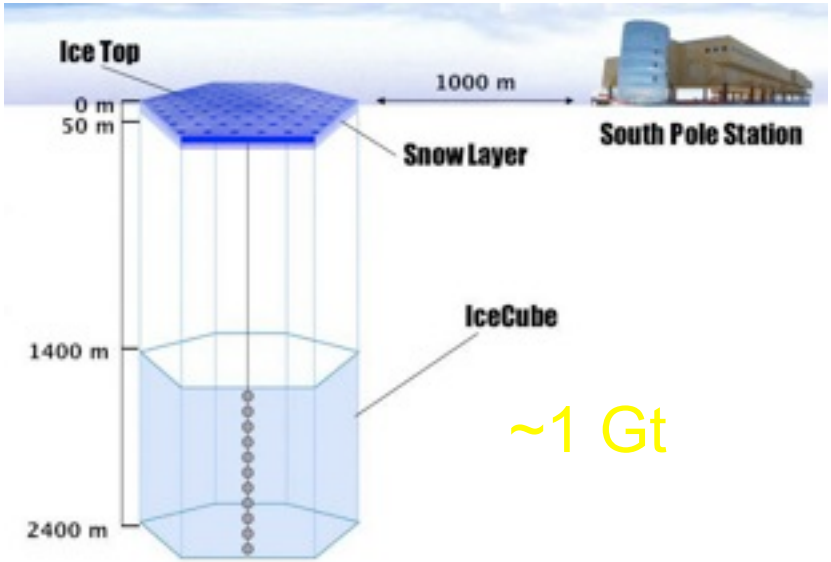
Detecting Neutrinos

(Why is it so hard?)

- Neutrinos do not interact readily (small prob.)
  - ➡ Need very large detectors:





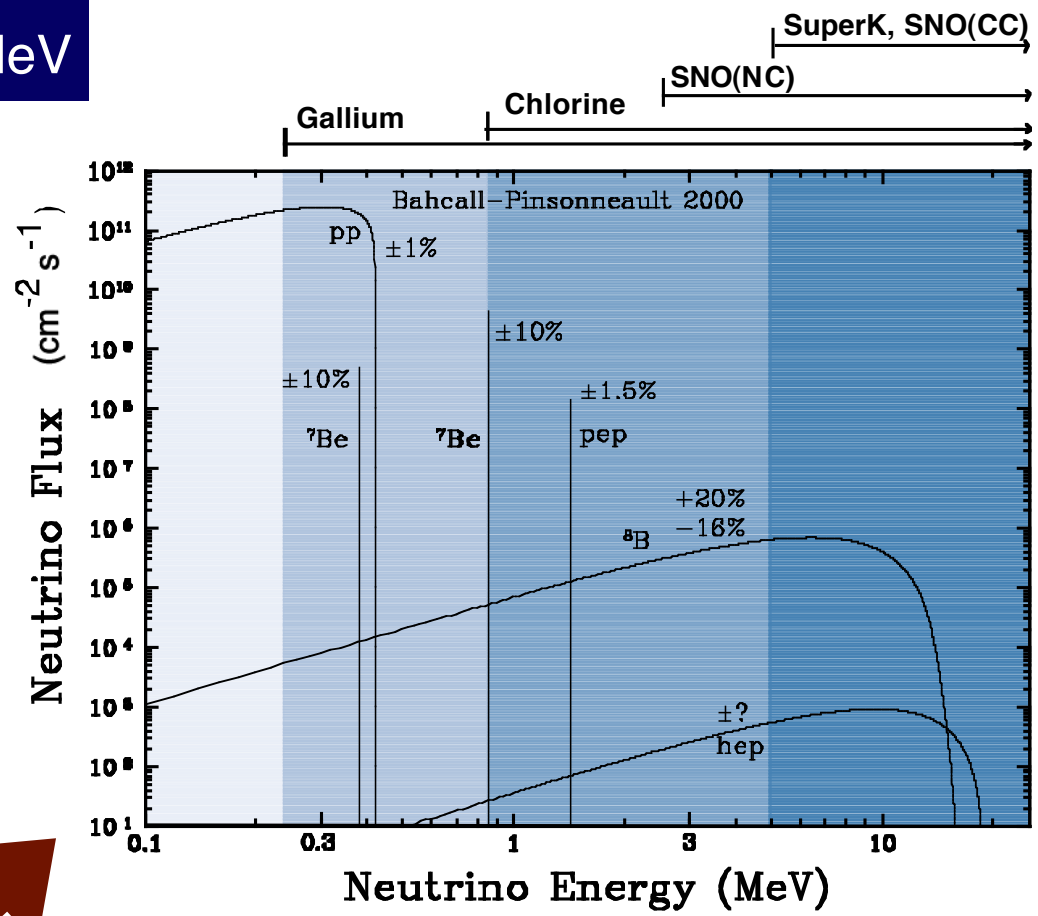


The Sun: Our Source of ν

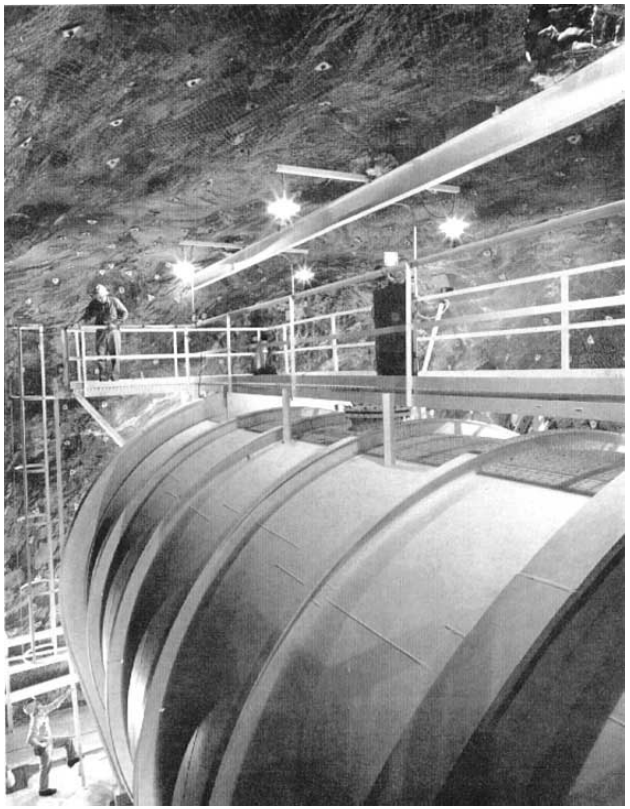
pp chain:
$4p + 2e \rightarrow {}^4He + 2\nu_e + 26.7$ MeV

Detailed computer model of solar evolution

Standard Solar Model



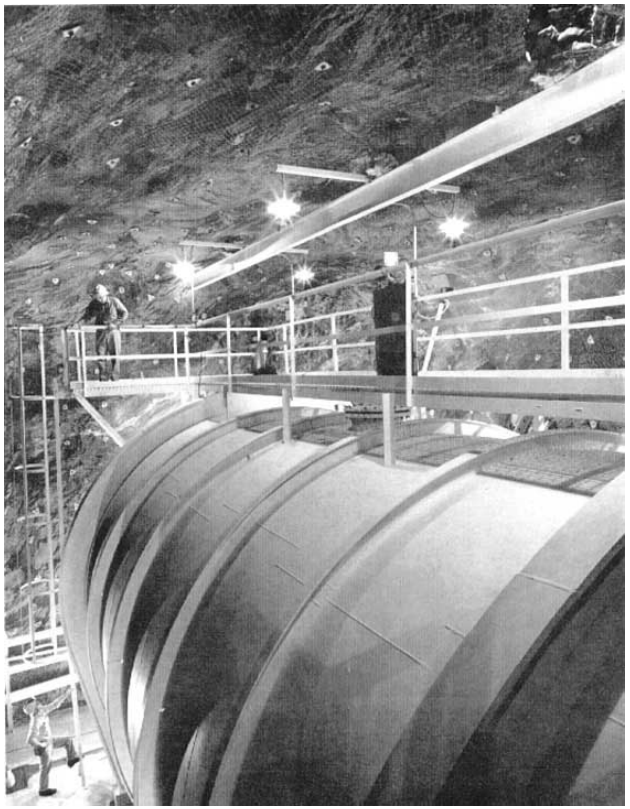
First Detection of Solar ν



Homestake, SD

- Ray Davis used this tank of cleaning fluid (615 t) C_2Cl_4 to detect solar ν
- $\nu_e + {}^{37}Cl \quad {}^{37}Ar + e^-$
- Flush tank, collect ^{37}Ar, look for its decay back to ^{37}Cl
- Only ~1/3 of the expected number found
- Other experiments show similar deficits of ν_e

First Detection of Solar ν



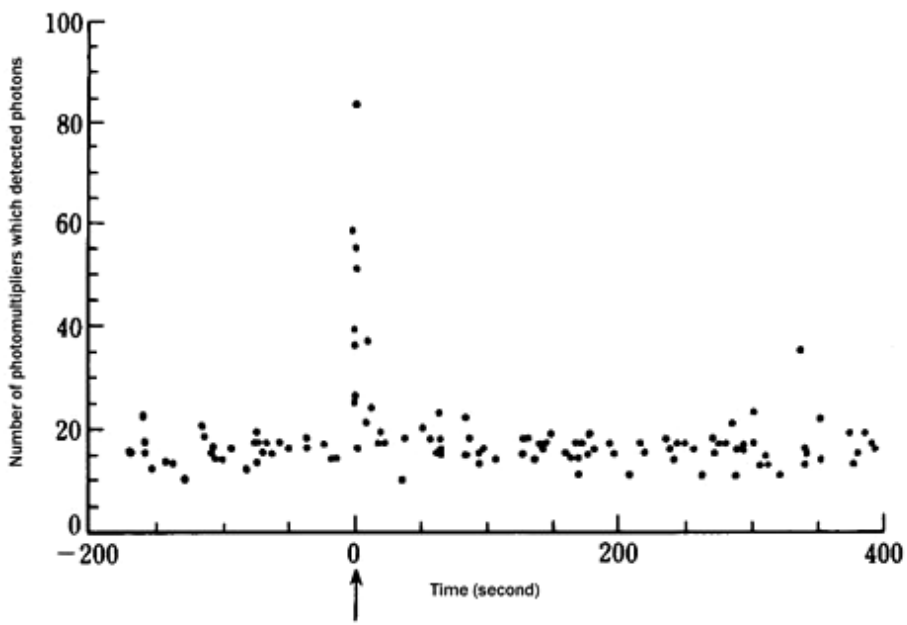
Homestake, SD

- Ray Davis used this tank of cleaning fluid (615 t) C_2Cl_4 to detect solar ν
- $\nu_e + {}^{37}Cl \quad {}^{37}Ar + e^-$
- Flush tank, collect ^{37}Ar, look for its decay back to ^{37}Cl
- Only ~1/3 of the expected number found
- Other experiments show similar deficits of ν_e

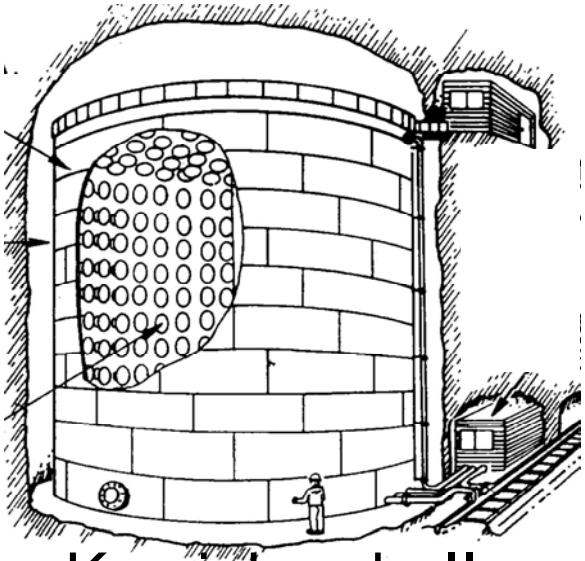
Solar Neutrino Problem

An Aside: Supernova ν

- ~150,000 years ago, a star exploded in the Large Magellanic Cloud
- νs from SN1987A were detected by 3 detectors on Feb. 23, 1987.
- ν decays cannot explain the solar neutrino deficit.

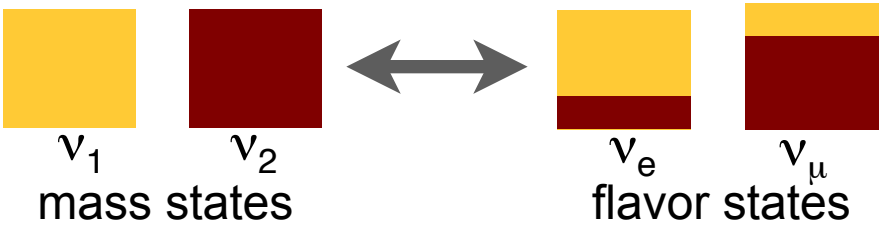


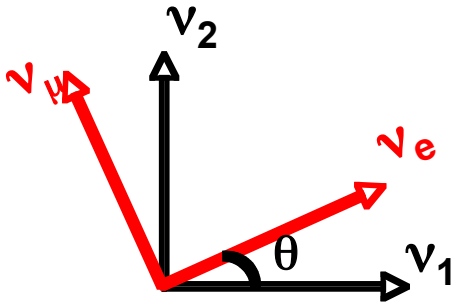
At 16:35:35 (±1 minute) on February 23, 1987, Japan time



Kamiokande-II

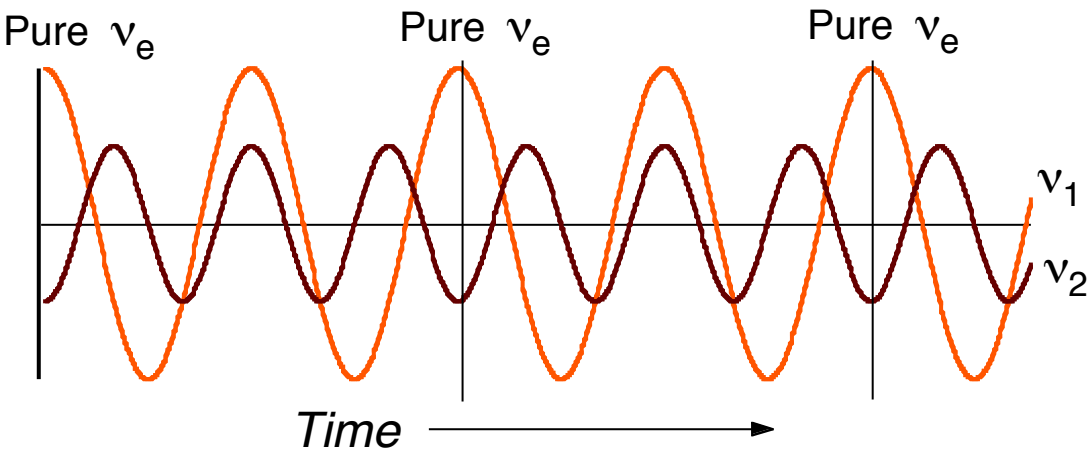
An Attractive Solution:
Neutrino Oscillations





$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$$



- Each "flavor" state contains waves of "mass" states (m≠0)
- These waves have different wavelengths

Neutrino Oscillations

- Probability of a ν (say ν_e of energy *E*) is detected to have the same flavor (ν_e) after it has traveled a distance *L*:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\ \Delta m^2{}_{[\mathrm{eV}^2]}\ \frac{L_{[\mathrm{m}]}}{E_{[\mathrm{MeV}]}}\right) \text{ where } \Delta m^2 = m_2^2 - m_1^2$$

*1 eV = 1.78×10^{-33} g

Neutrino Oscillations

- Probability of a ν (say ν_e of energy *E*) is detected to have the same flavor (ν_e) after it has traveled a distance *L*:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2[\mathrm{eV}^2]\,\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right) \text{ where } \Delta m^2 = m_2^2 - m_1^2$$

Nature

*1 eV = 1.78×10^{-33} g

Neutrino Oscillations

- Probability of a ν (say ν_e of energy *E*) is detected to have the same flavor (ν_e) after it has traveled a distance *L*:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right) \text{ where } \Delta m^2 = m_2^2 - m_1^2$$

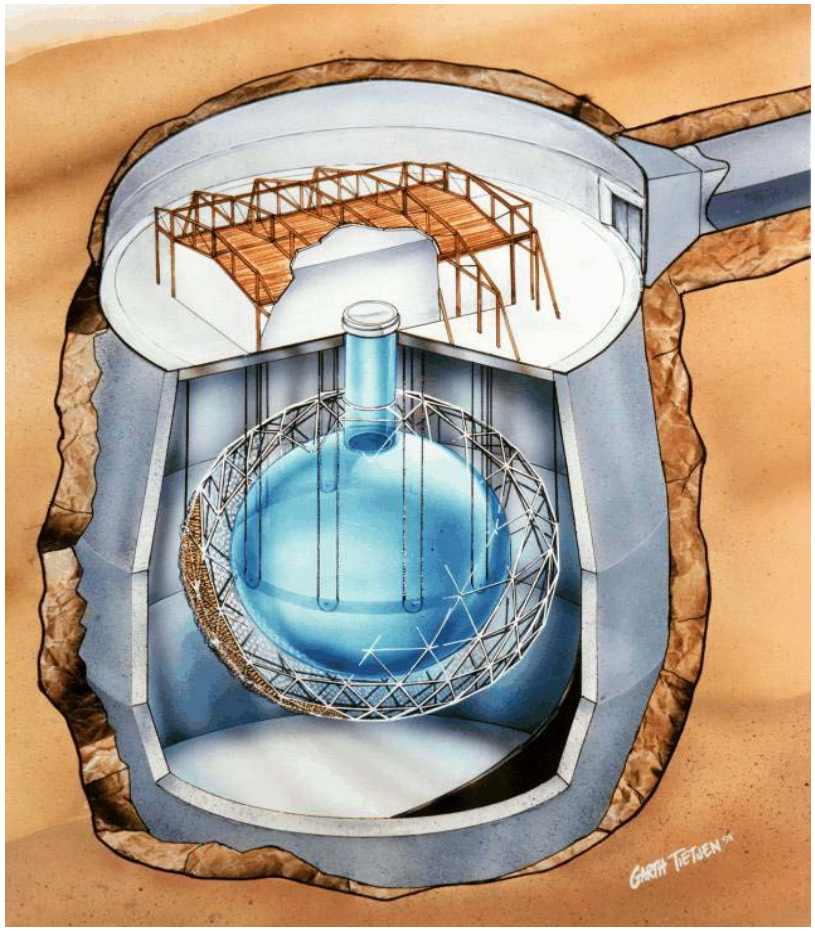
Nature

Experimenter's choice

- Choose the ν source
- Decide where to put the detector

*1 eV = 1.78×10^{-33} g

Solving the Solar Neutrino Problem



Sudbury Neutrino Observatory
(Canada)

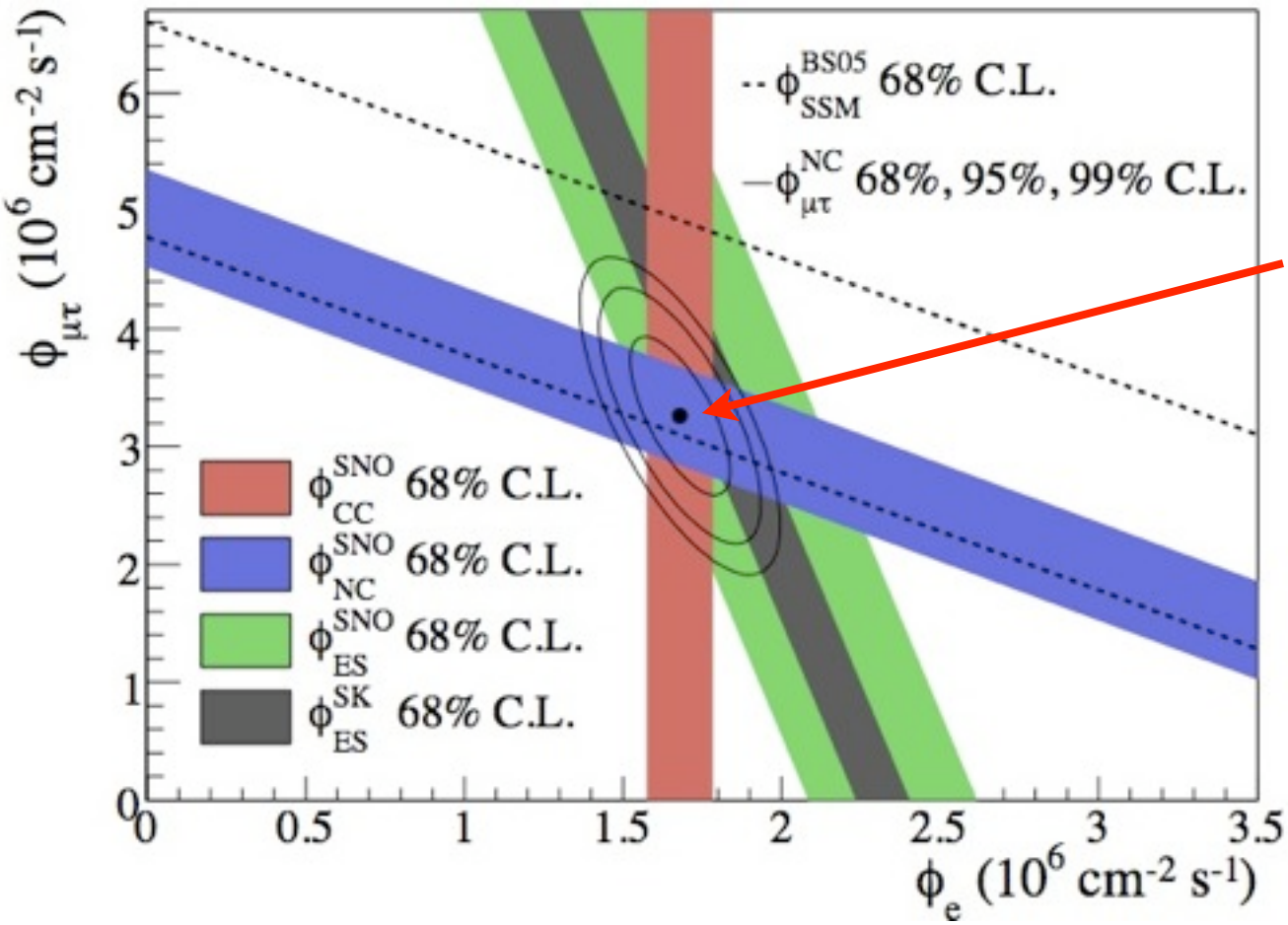
- 1 kt D_2O in SNO
- "D": heavy hydrogen
  (1 proton + 1 neutron)
- Detect ν via:

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

$$\nu_{e,\mu,\tau} + d \rightarrow p + n + \nu_{e,\mu,\tau}$$

- $\Phi(\nu_e) = \Phi(\nu_e + \nu_\mu + \nu_\tau)$?

Problem Solved



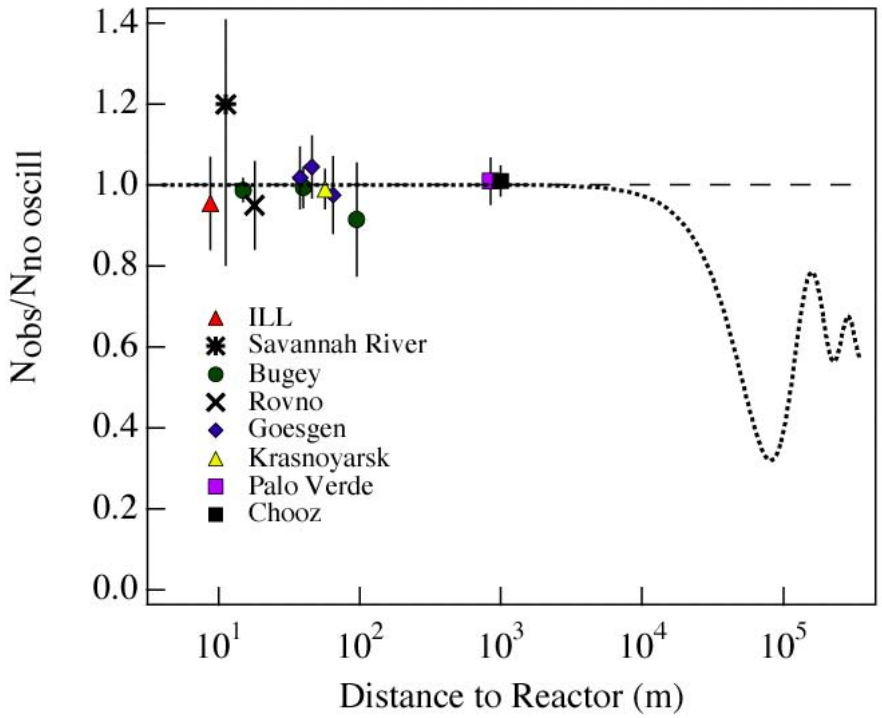
Standard Solar Model
CORRECT

Standard Model of Elementary Particles (m_ν=0)
WRONG

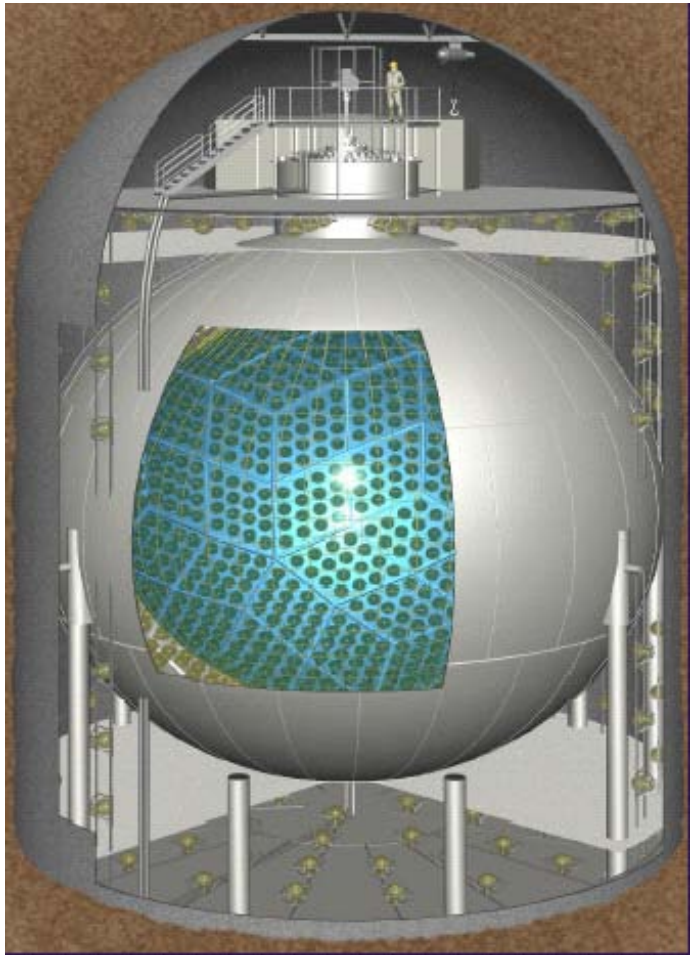
~2/3 of the ν_e produced in the Sun have transformed into ν_μ or ν_τ.

Testing Solar ν_e Oscillation

- Using anti-neutrinos from power reactors

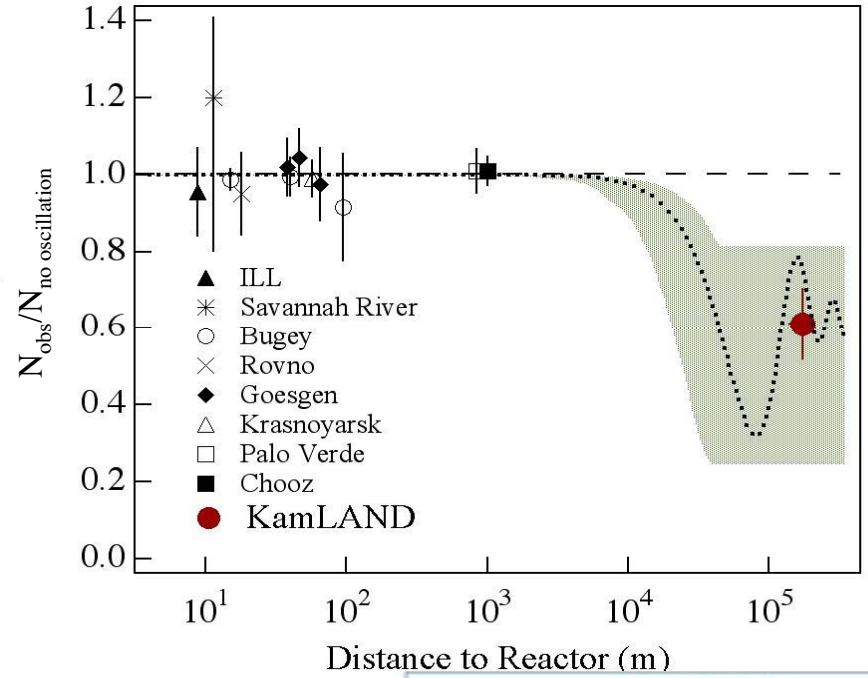


Testing Solar ν_e Oscillation

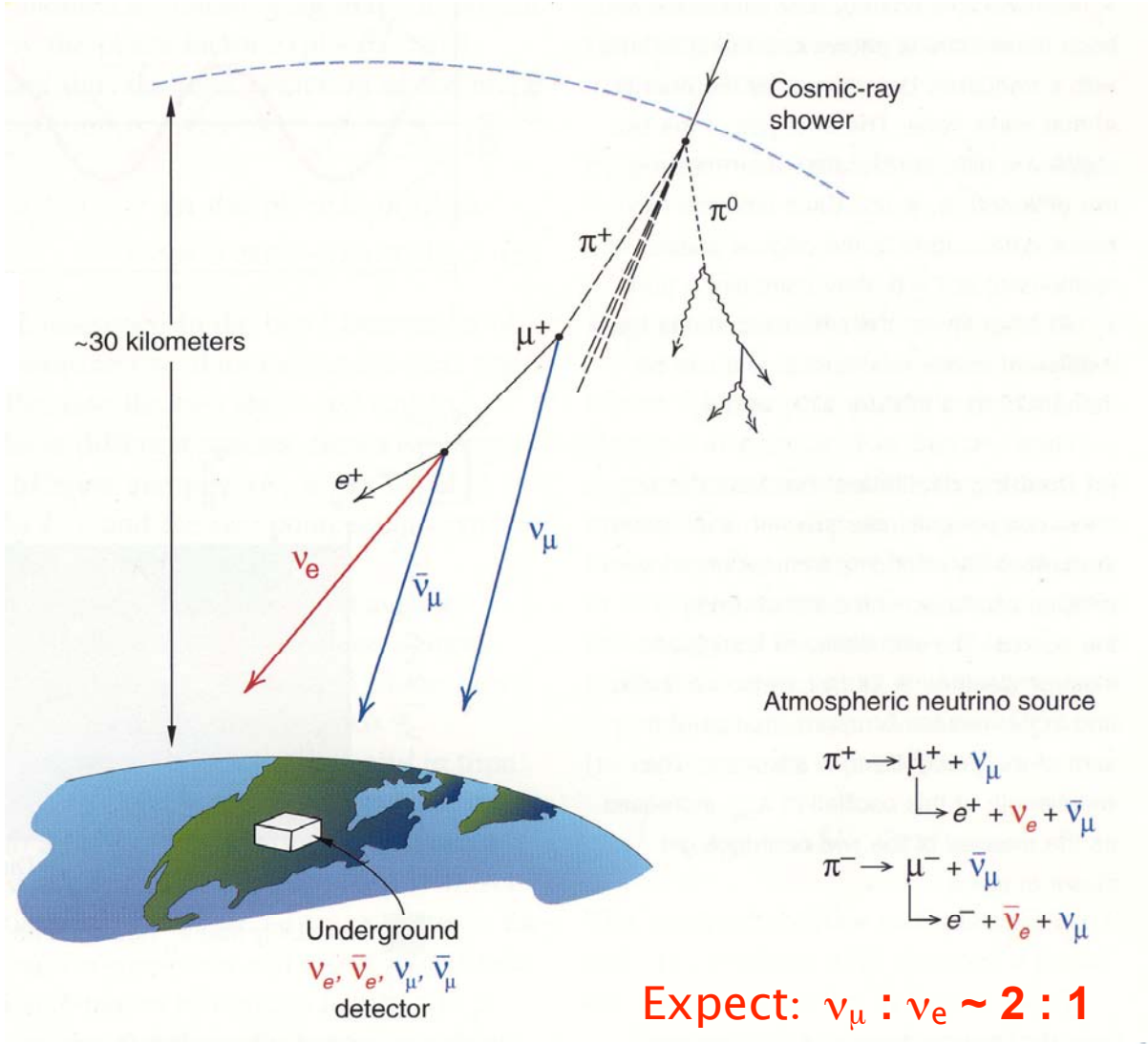


KamLAND (Japan)

- Reactor anti-neutrino deficit discovered by KamLAND

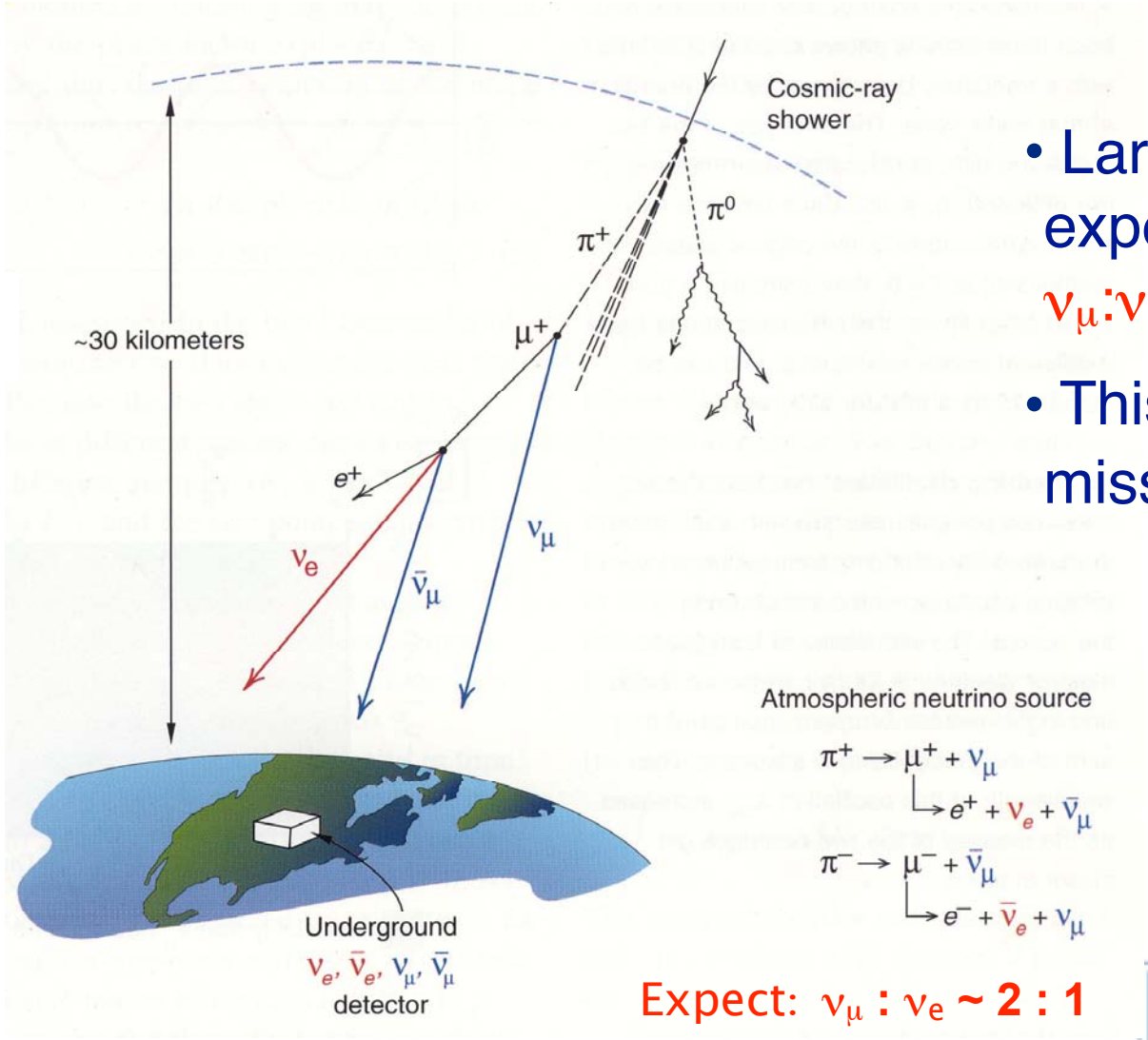


Another ν Source from the Cosmos



Expect: $\nu_\mu : \nu_e \sim 2 : 1$

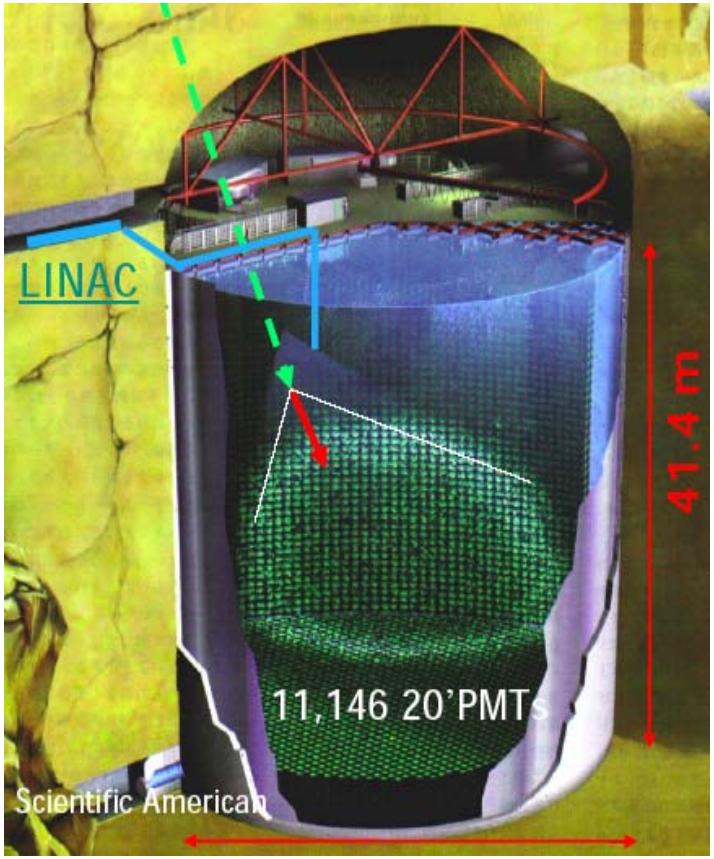
Another ν Source from the Cosmos



- Large proton decay experiments observed $\nu_\mu : \nu_e \sim 1$
- This time, ν_μ is missing

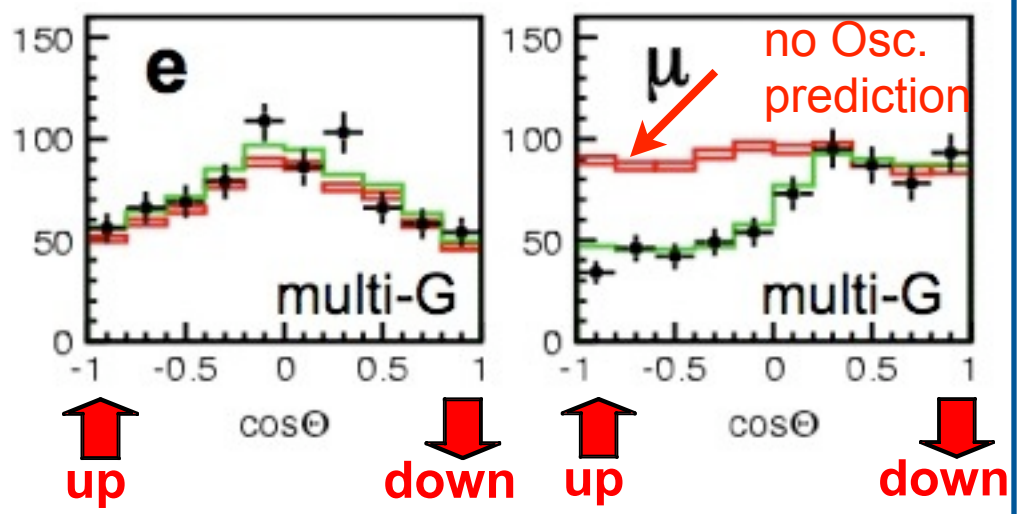
Expect: $\nu_\mu : \nu_e \sim 2 : 1$

Another ν Source, Another Puzzle



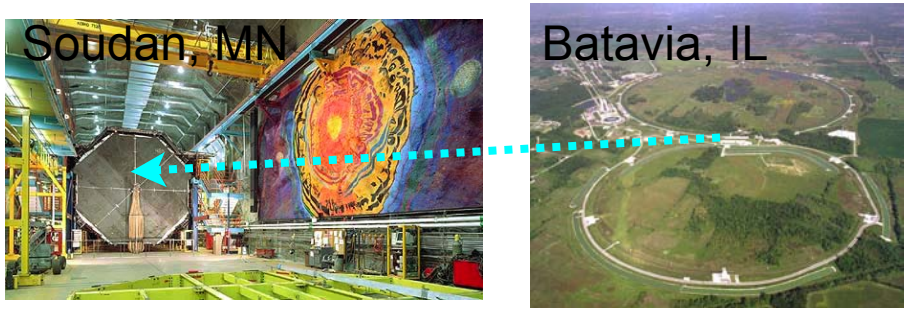
Super-Kamiokande
(Japan)

- The disappearance of ν_μ's depends on the distance that they travel

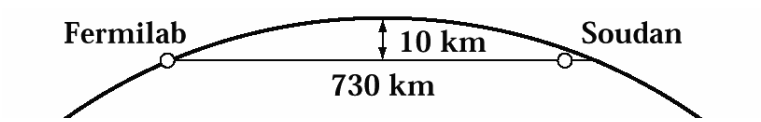


Testing Oscillation of Atmospheric ν_μ

- ν_μ from accelerators, detectors ~100s km away:

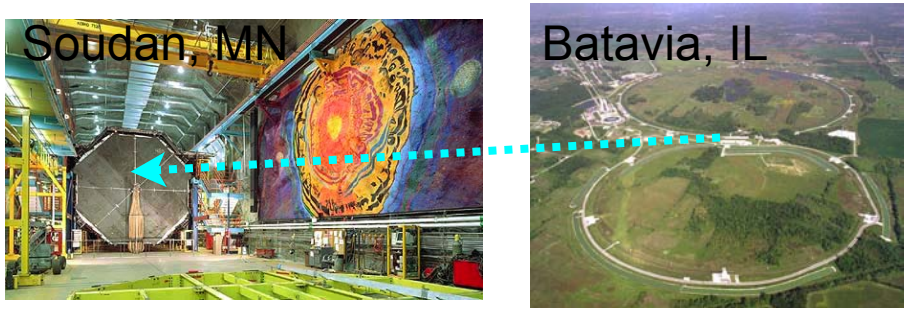


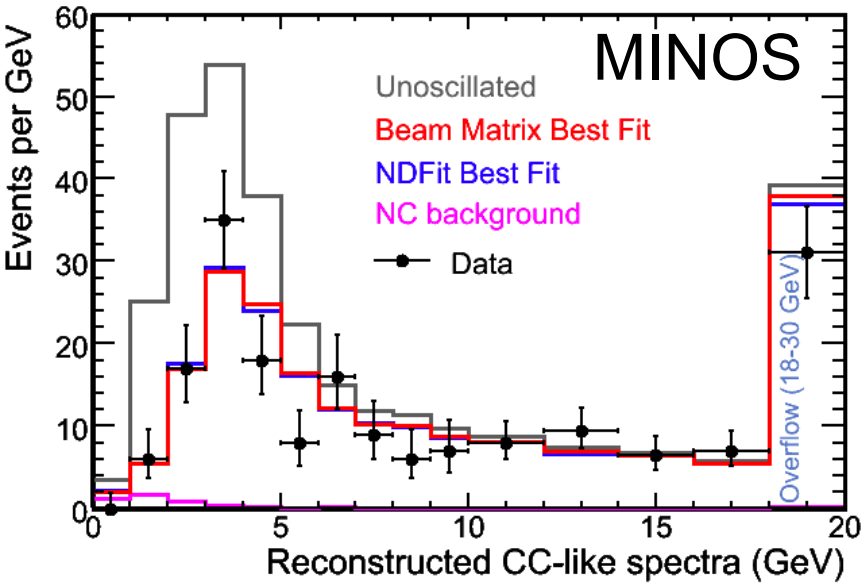
MINOS



Testing Oscillation of Atmospheric ν_μ

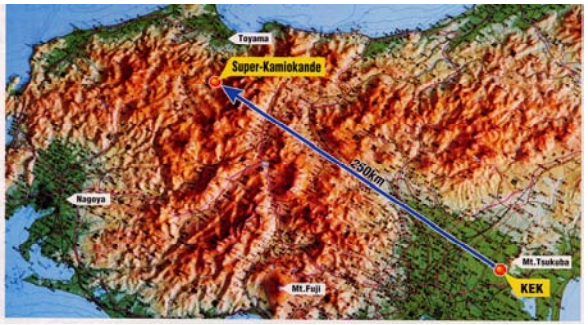
- ν_μ from accelerators, detectors ~100s km away:

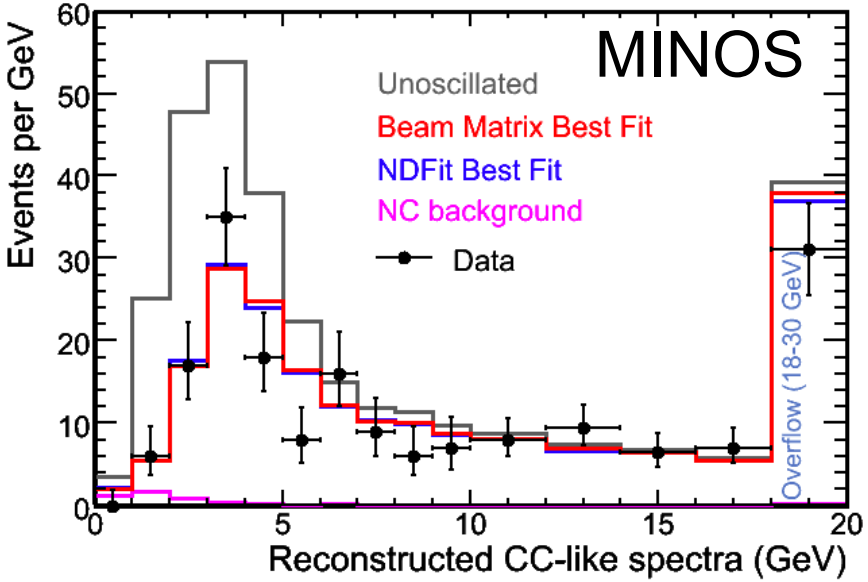


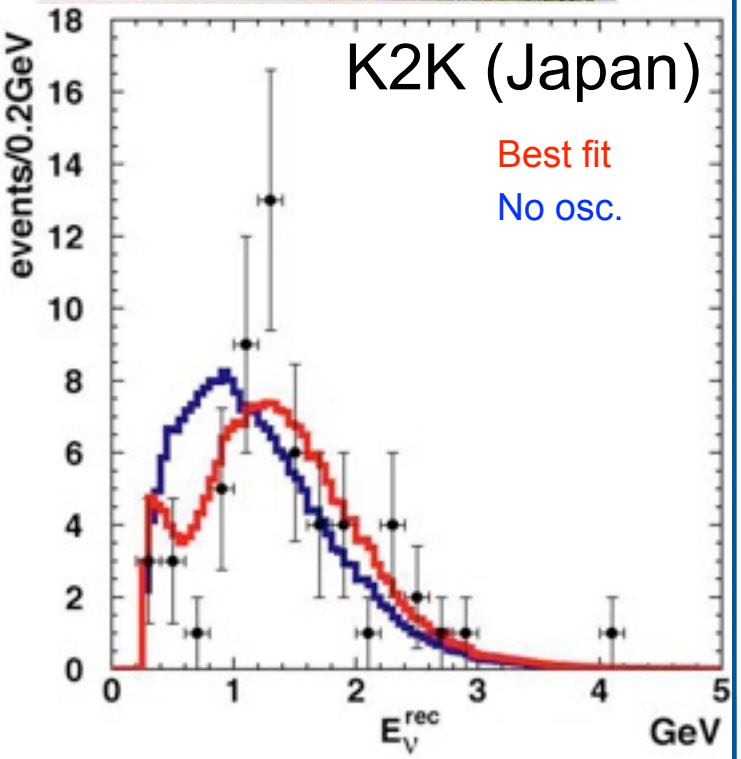


Testing Oscillation of Atmospheric ν_μ

- ν_μ from accelerators, detectors ~100s km away:







Recap

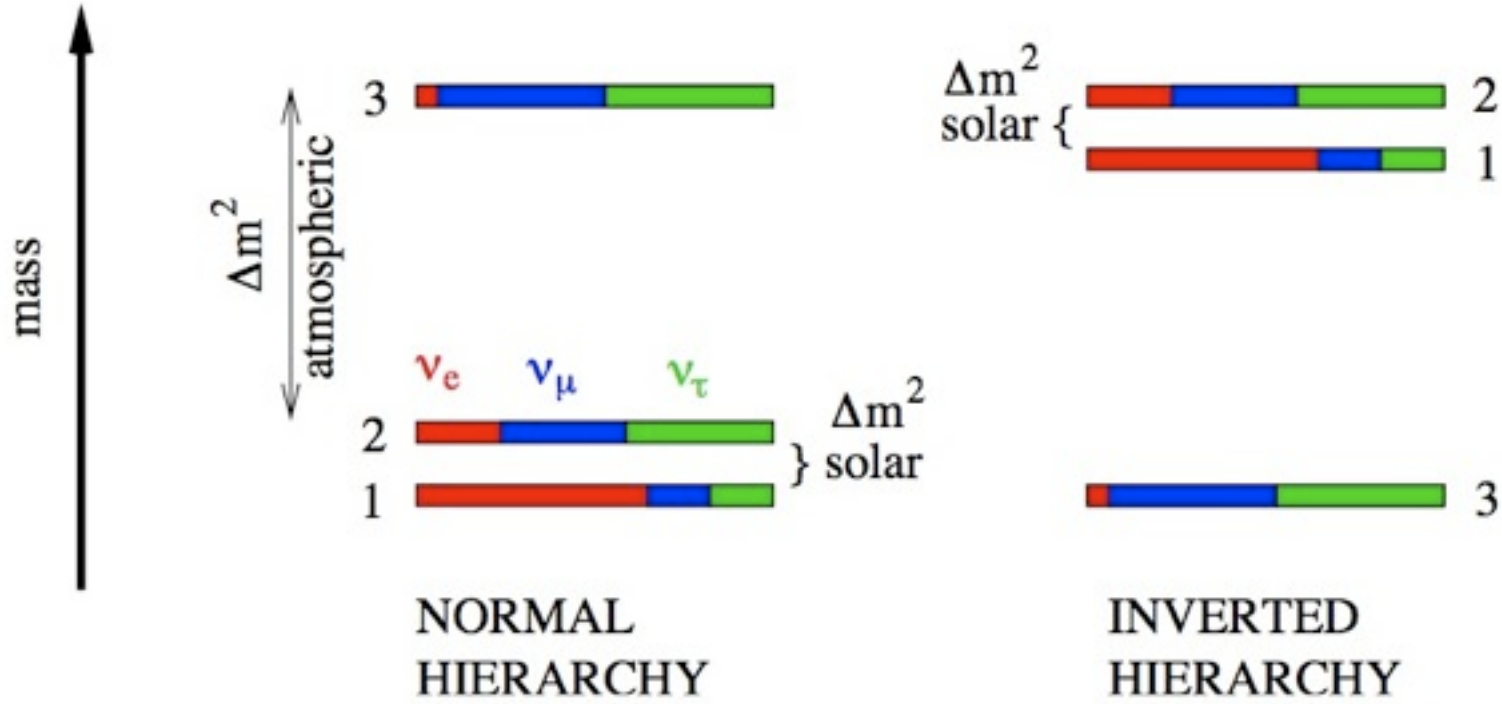
- We found that the Standard Model (SM) of Elementary Particles is incomplete:
  - $m_\nu \neq 0$
    - solar neutrinos: $\Delta m_{12}^2 \sim 10^{-5}$ eV^2
    - atmospheric neutrinos: $\Delta m_{23}^2 \sim 10^{-3}$ eV^2
  - νs oscillate:
    - solar neutrinos: $\nu_e \rightarrow$ a mixture of ν_μ and ν_τ
    - atmospheric neutrinos: $\nu_\mu \rightarrow \nu_\tau$ (mostly)
- Do theoretical physicists know how to fix the SM?

Recap

- We found that the Standard Model (SM) of Elementary Particles is incomplete:
  - $m_\nu \neq 0$
    - solar neutrinos: $\Delta m_{12}^2 \sim 10^{-5}$ eV^2
    - atmospheric neutrinos: $\Delta m_{23}^2 \sim 10^{-3}$ eV^2
  - νs oscillate:
    - solar neutrinos: $\nu_e \rightarrow$ a mixture of ν_μ and ν_τ
    - atmospheric neutrinos: $\nu_\mu \rightarrow \nu_\tau$ (mostly)
- Do theoretical physicists know how to fix the SM? **NO**

Why Not? (I)

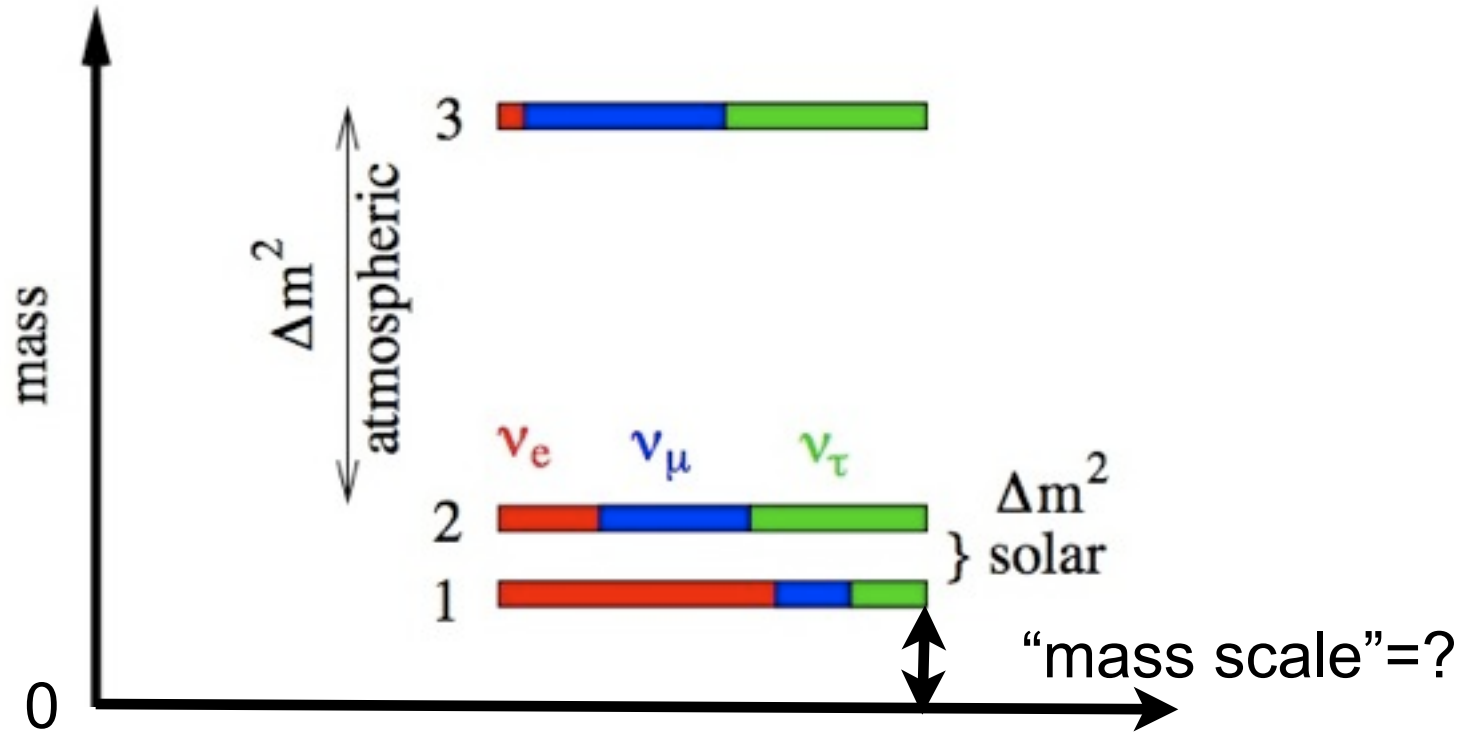
- We don't know how the mass states are arranged ("mass hierarchy") [cf. atomic state]



$m_1 < m_2 < m_3$ $\qquad$ $m_3 < m_1 < m_2$

Why Not? (II)

- We do not know the "absolute mass scale". (How much does it "weigh"?)



Why Not? (III)

- How do neutrinos acquire a mass?
  - Can neutrinos be their own anti-particles?
    - Dirac particles: particle ≠ anti-particle [e.g. (e^+,e^-)]
    - Majorana particles: particle = anti-particle

  - What is the mechanism that generates its mass? (Higgs?)

Why Not? (IV)

- Neutrino mixing properties are not completely known

$$\nu_e = 0.8\,\nu_1 + 0.5\,\nu_2 + U_{e3}\,\nu_3$$

$$\nu_\mu = -0.4\,\nu_1 + 0.6\,\nu_2 + 0.7\,\nu_3$$

$$\nu_\tau = 0.4\,\nu_1 - 0.6\,\nu_2 + 0.7\,\nu_3$$

- What is U_{e3}?

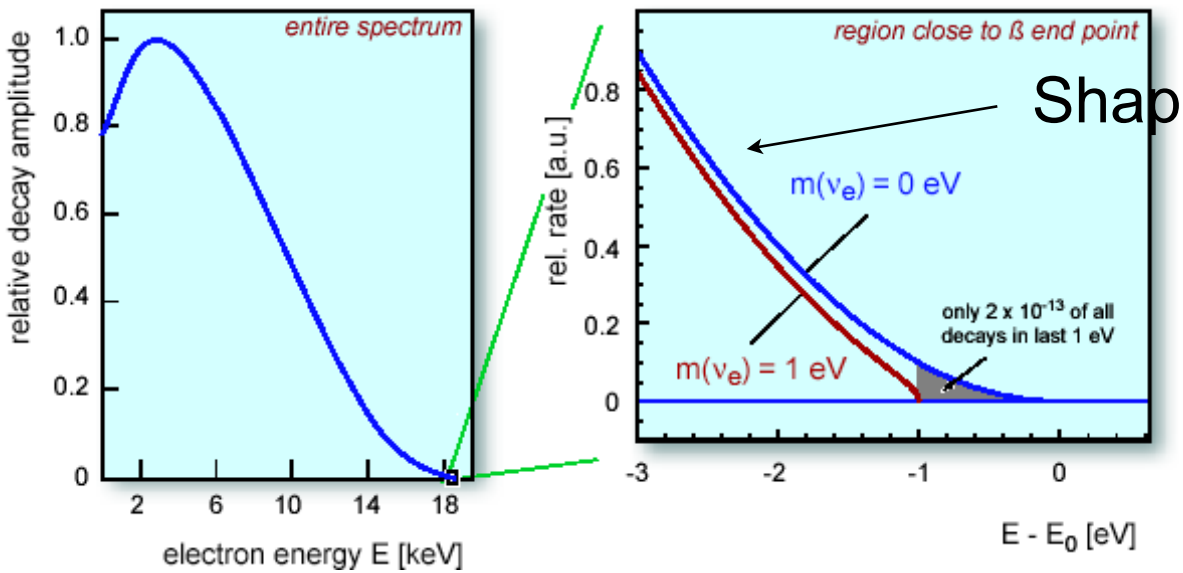
$$U_{e3} \propto \sin\theta_{13}$$

How do we measure ν mass?

- Direct kinematic measurements
- Example: Tritium (=1p+2n) β decays

$$^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + e^{-} + \nu_e$$

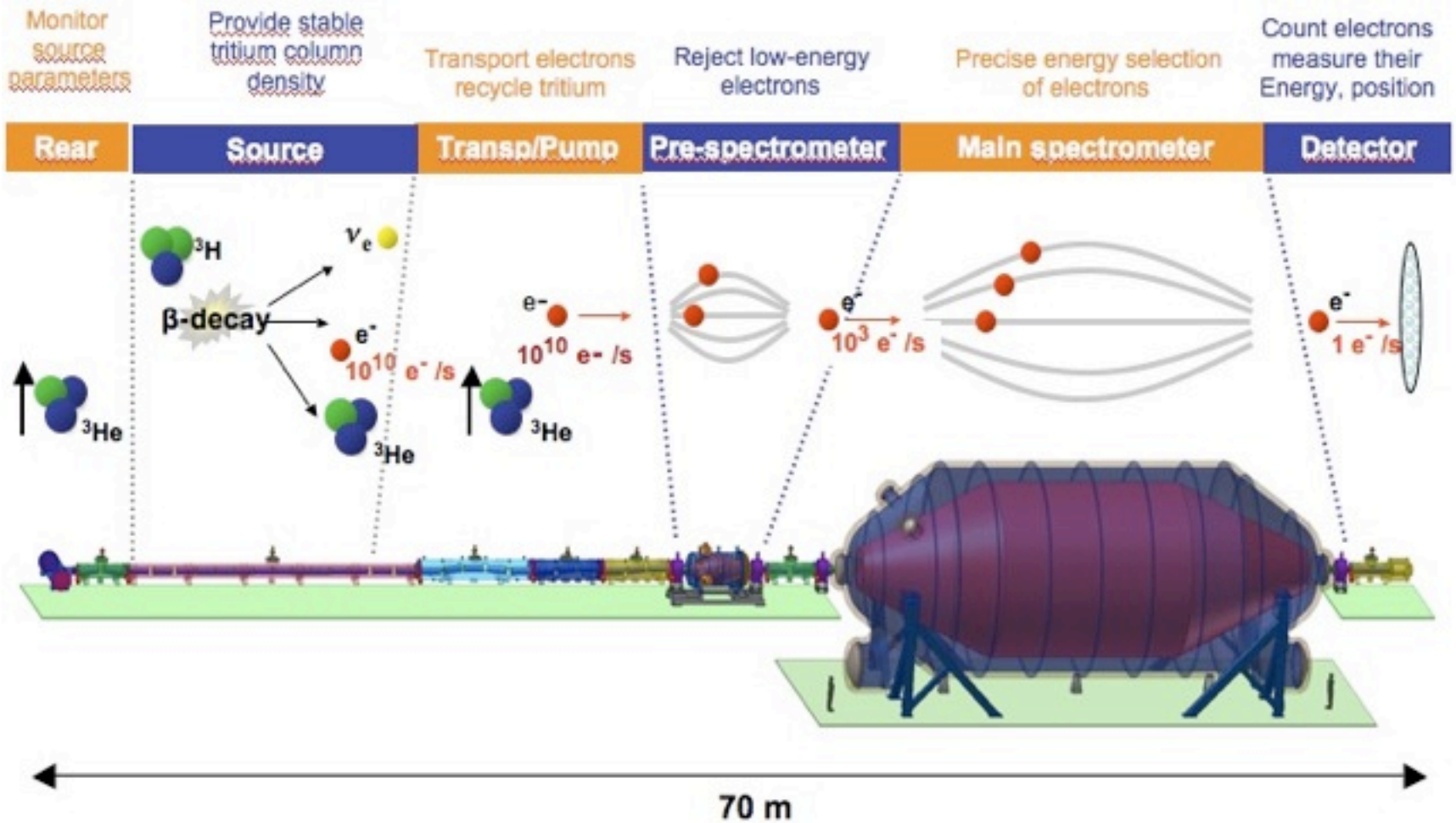
Look for distortion of β-decay spectrum



Shape ~ $[(E_0-E_e)^2-m(_i)^2]^{1/2}$

A Future ^{3}H β decay Experiment

(KATRIN)

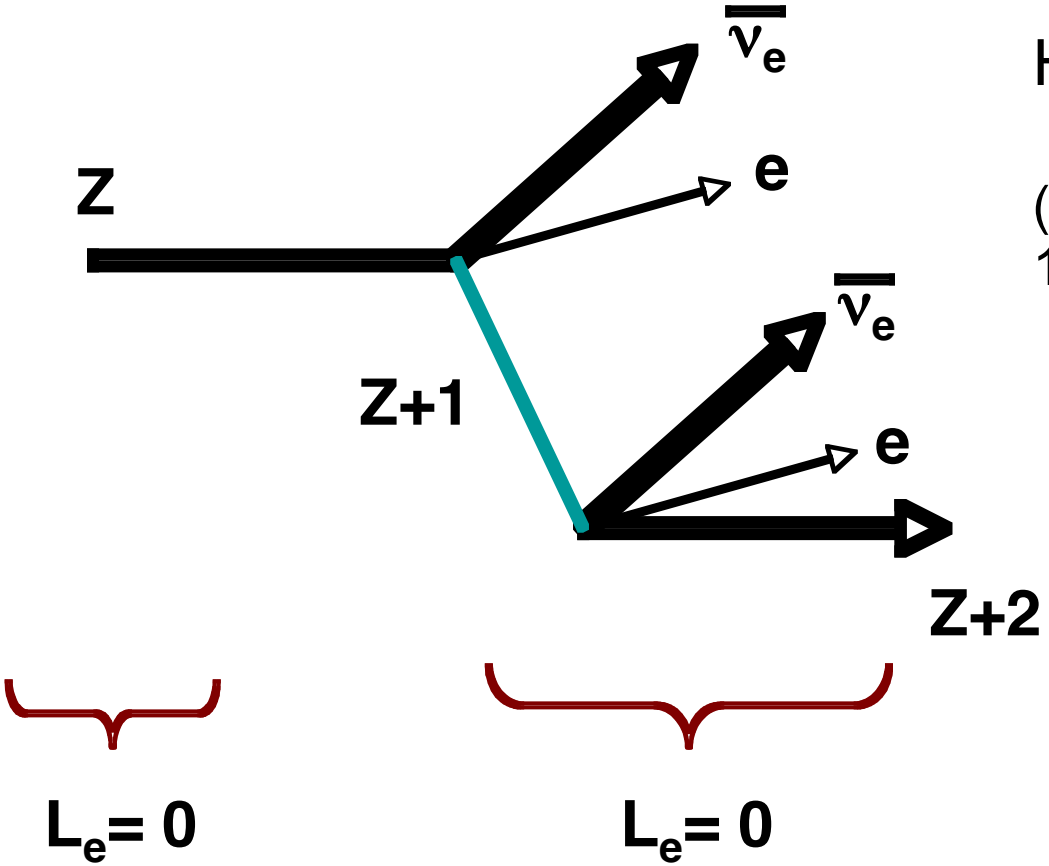


Sensitivity ~ <0.2 eV

Another way to learn about mass scale

(ββ decays)

- Allowed process:



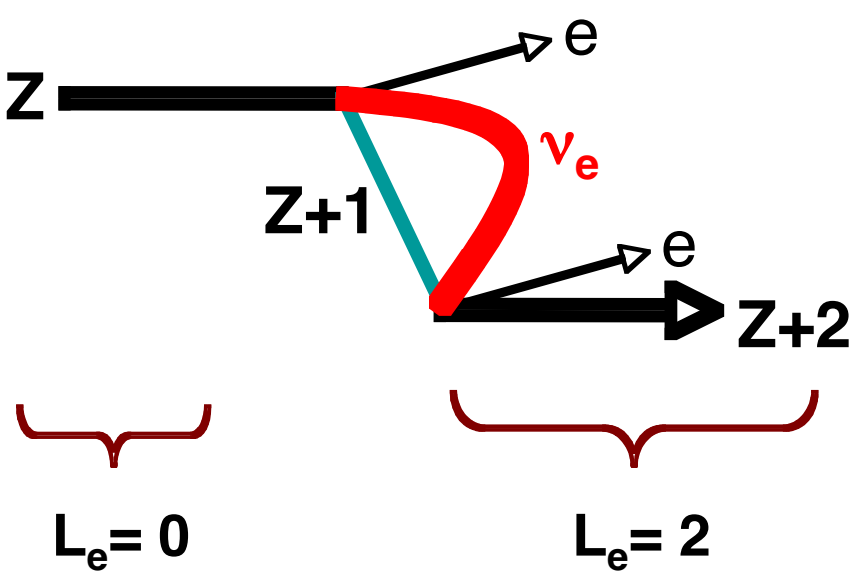
Half-life: ~10^{21} y

(cf. Age of the universe = 13.7 x 10^9 y)

Another way to learn about mass scale

(ββ decays)

- Prohibited process in SM (as this will require neutrinos to be Majorana particles):

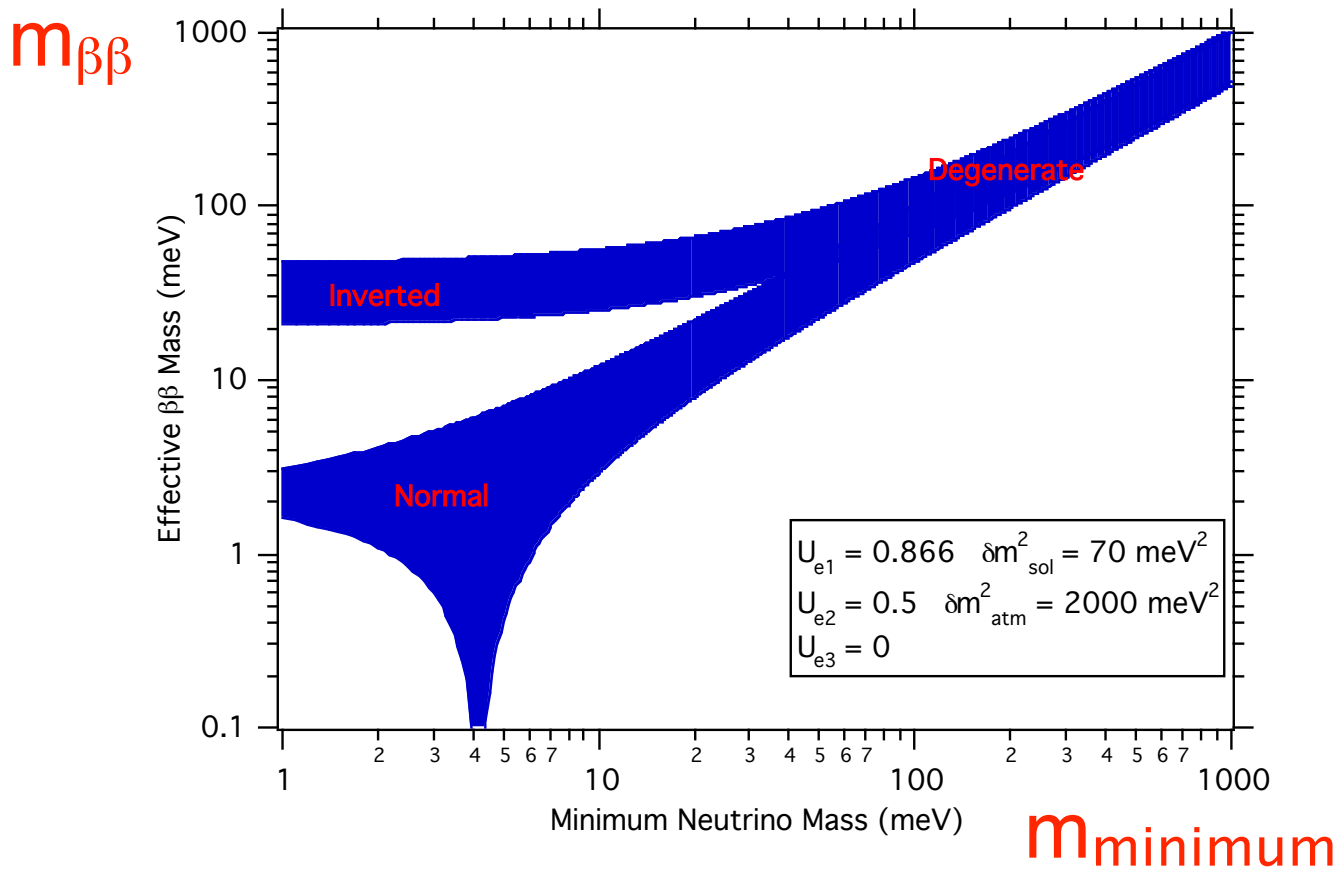


Decay rate ∝ $m_{\beta\beta}^2$

$m_{\beta\beta}$: "Majorana mass" (which relates to the "mass scale")

One way to learn about mass hierarchy

(ββ decays)



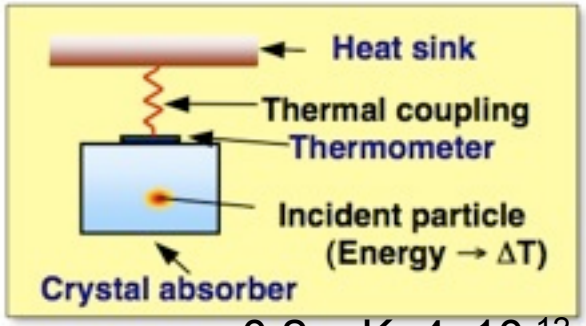
Mass hierarchy can also be measured in future dedicated "long baseline" accelerator experiments (later)

Two new 0ν ββ experiments

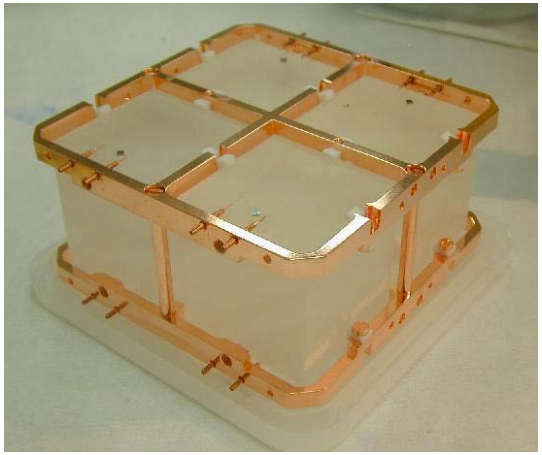
(with LBNL involvement)

CUORE ($^{130}Te_{52}$)

- Bolometer

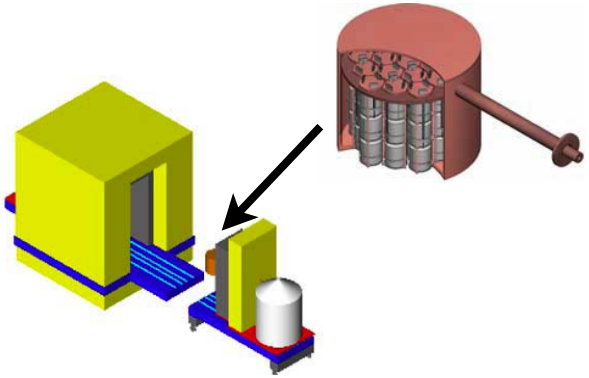


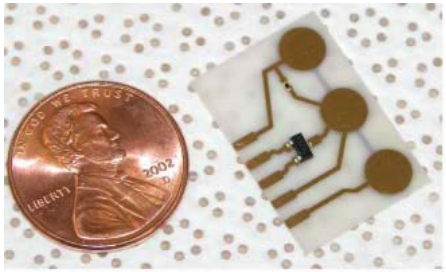
~0.2 mK, 4×10^{-12} J



Majorana ($^{76}Ge_{32}$)

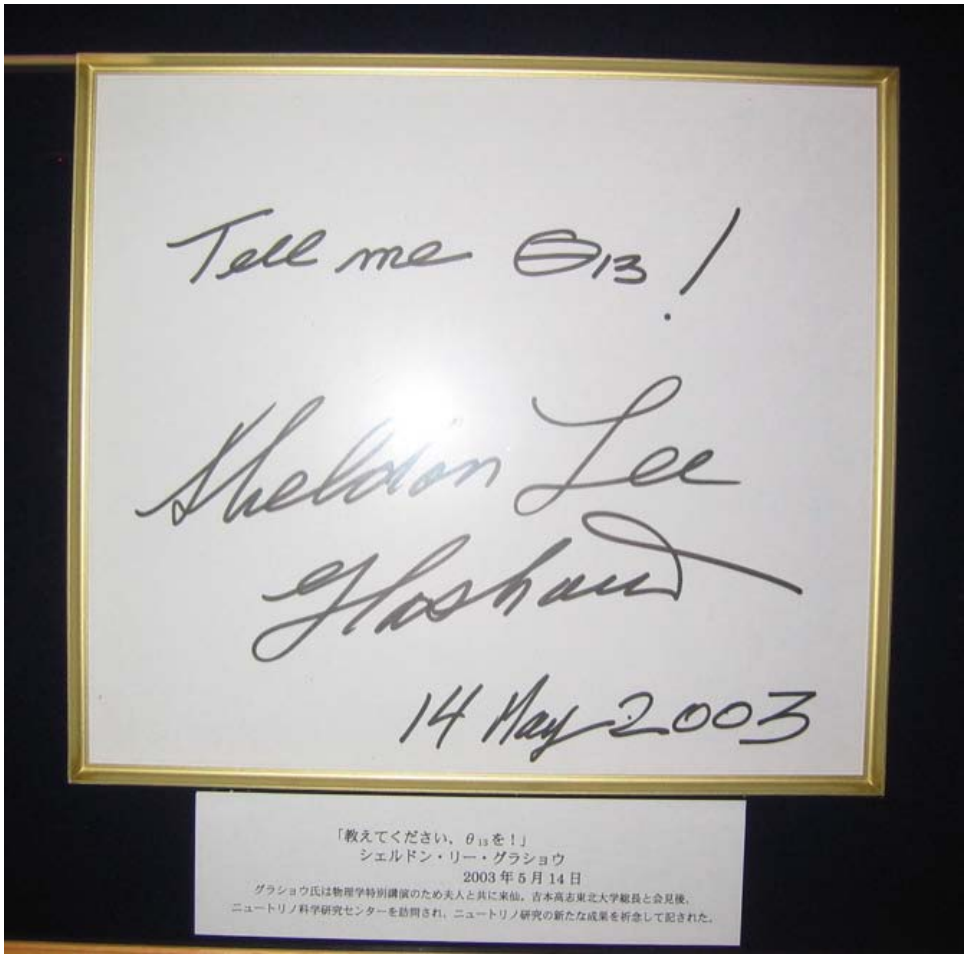
- Semi-conductor diode





Miniature electronics

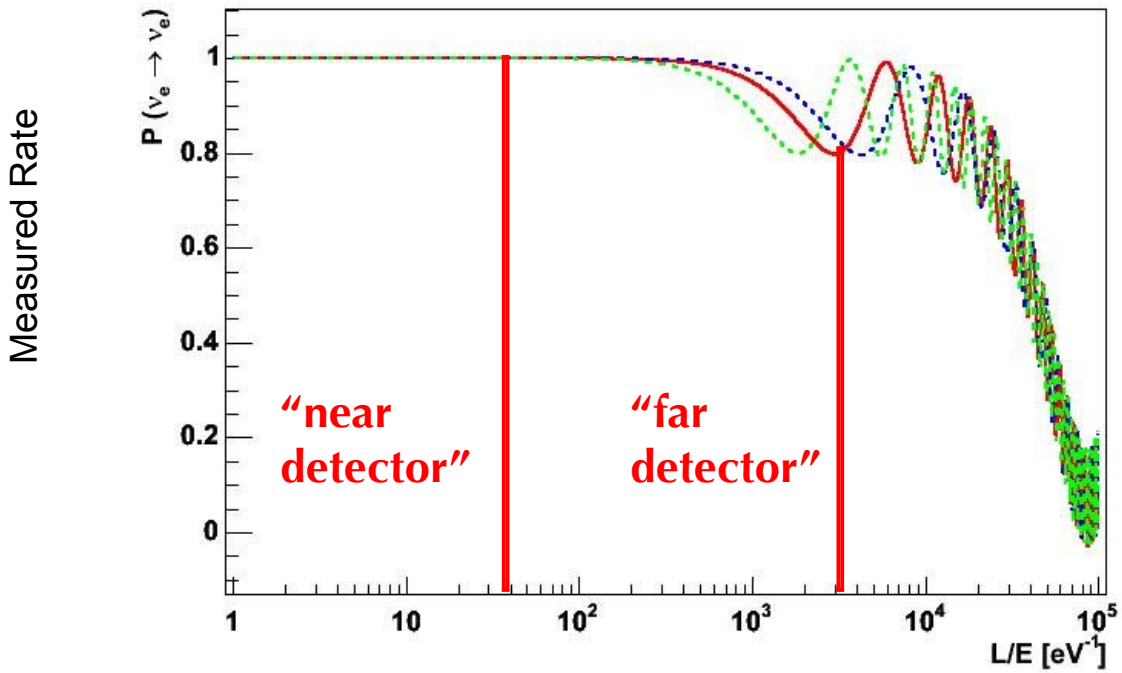
θ_{13}



S.L. Glashaw
Nobel laureate

How to measure θ_{13}

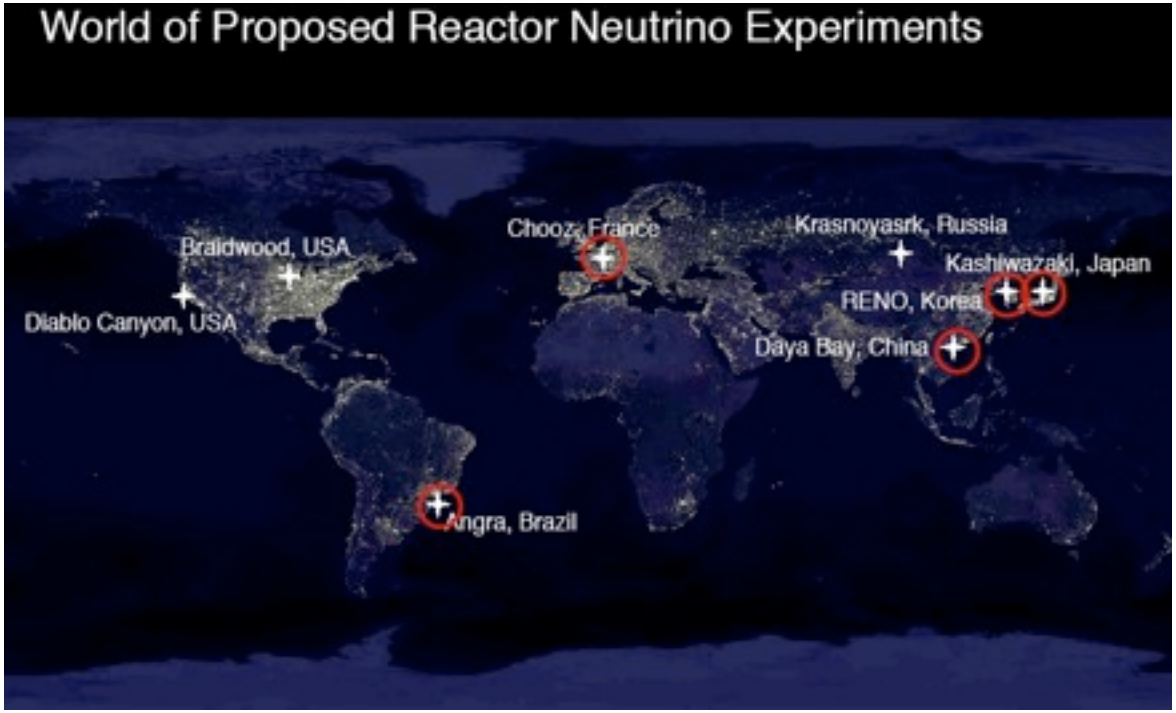
- Method 1: Improved reactor neutrino experiment



- 2 detectors: one "near" (< ~500 m) and one "far" (1-2 km)
- Difference in measured reactor neutrino rate depends on θ_{13}

How to measure θ_{13}

- Method 1: Improved reactor neutrino experiment



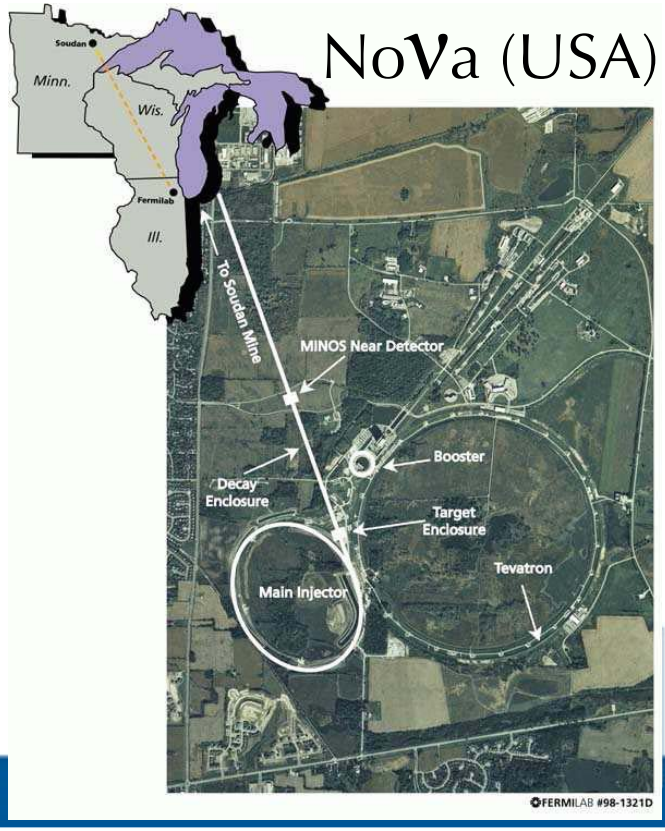
- 2 detectors: one “near” (< ~500 m) and one “far” (1-2 km)
- Difference in measured reactor neutrino rate depends on θ_{13}

How to measure θ_{13}

- Method 2: Dedicated "long baseline" (~100s to 1000s km) accelerator experiments
  - atmospheric neutrinos showed that $\nu_\mu \rightarrow \nu_\tau$ (mostly)
  - If we can find $\nu_\mu \rightarrow \nu_e$ in a dedicated experiment, then

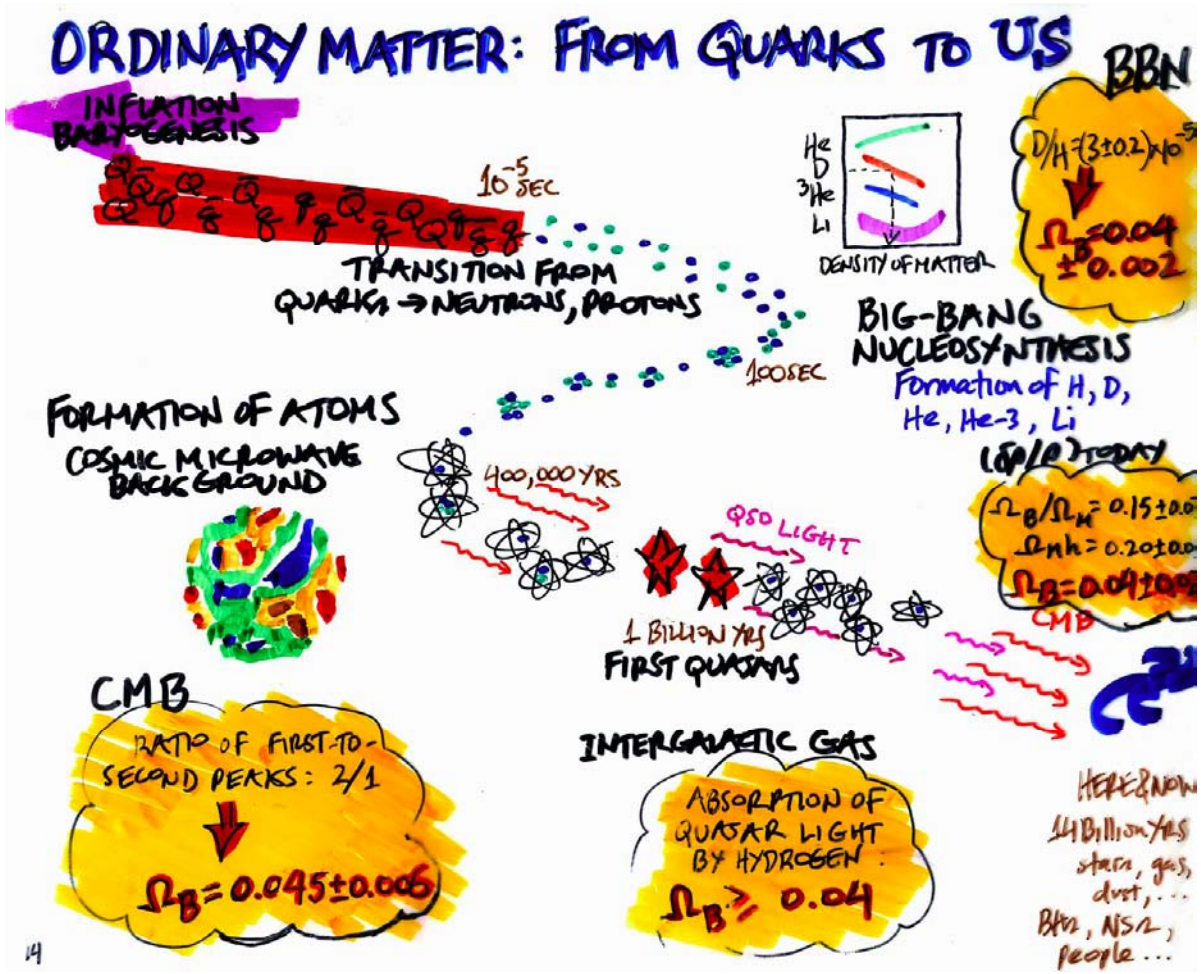
$$\text{No. of } \nu_e \propto \sin^2 2\theta_{13}$$

T2K (Japan)



NoVa (USA)

The Bigger Picture

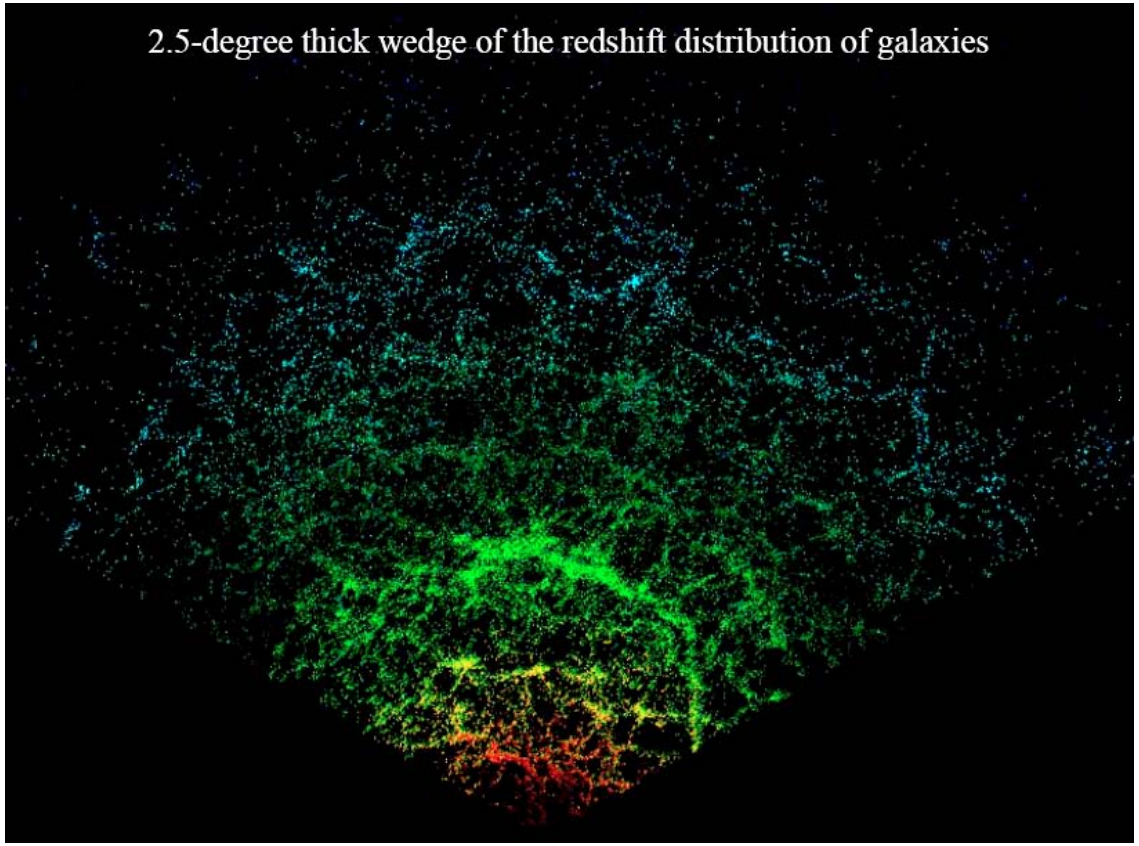


M. Turner

- Neutrinos "control" the balance of neutrons and protons (and Big Bang Nucleosynthesis) in early universe
- We owe our existence to neutrinos!

The Bigger Picture

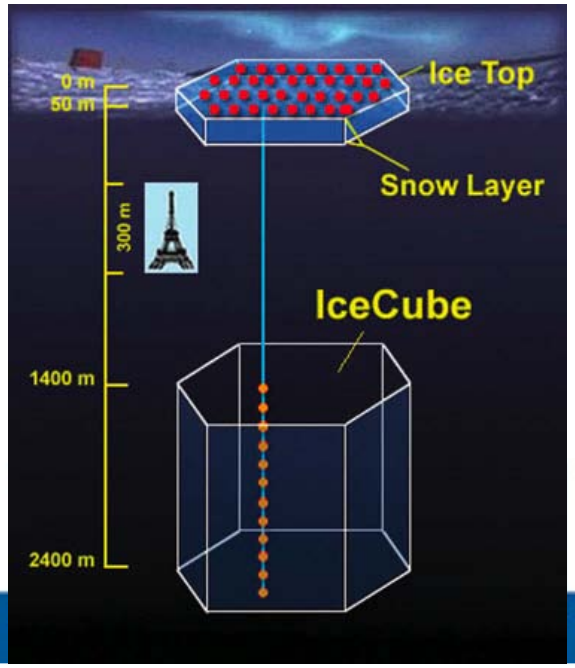
- The large-scale structure of our universe depends somewhat on the mass of neutrinos (after all, neutrinos are massive)



Neutrino Telescopes

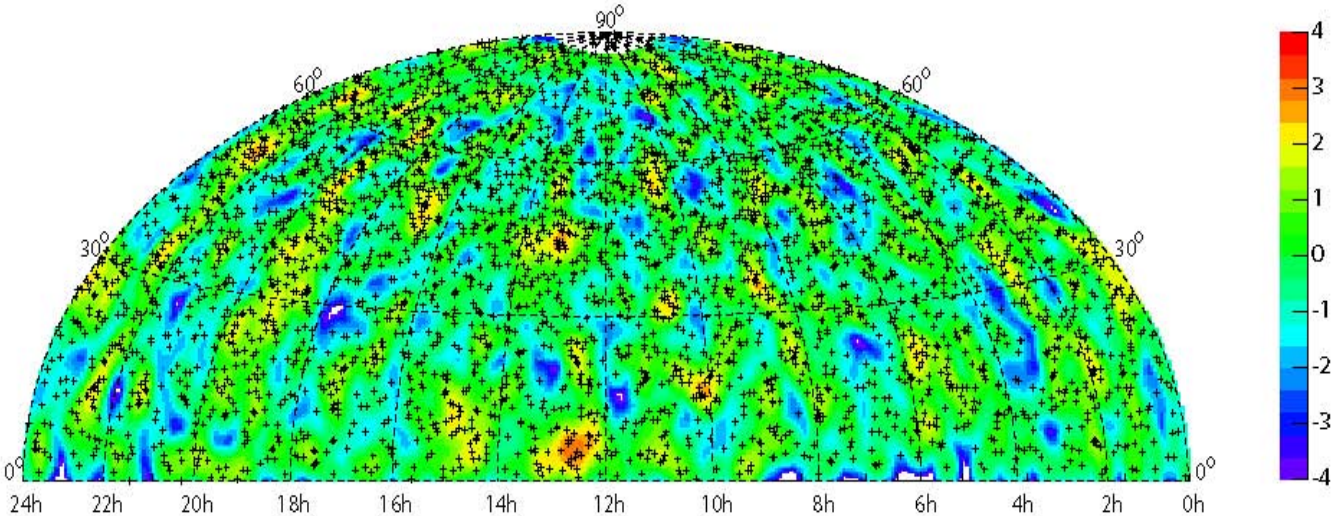
- Just as Galileo searched for astronomical objects with his telescope, we have started searching for neutrino sources with neutrino telescopes.

Other questions:
- origin of cosmic rays
- neutrino properties



The Neutrino Sky

- AMANDA(South Pole)



Neutrino Physics

(An exploding field)

- 4 Nobel Prizes so far (and counting)
  - 1967: Bethe (Sun as a neutrino source)
  - 1988: Lederman, Schwatz, Steinberger (ν_μ discovery)
  - 1995: Reines (ν_e discovery)
    Perl (τ discovery and evidence for ν_τ)
  - 2002: Davis (solar neutrino observation)
    Koshiba (supernova and solar neutrinos detection)

Neutrino Physics

The Growing Excitement of Neutrino Physics

I'm lucky to be an active participant of this field, and have witnessed several great discoveries in the past 15 years

- 1930: Pauli predicts the Neutrino
- Fermi's theory of weak interactions
- 1955: Reines & Cowan discover (anti)neutrinos
- 2 distinct flavors identified
- Davis discovers the solar deficit
- Kamioka II confirms solar deficit
- LEP shows 3 active flavors
- SAGE and Gallex see the solar deficit
- Kamioka II and IMB see atmospheric neutrino anomaly
- Kamioka II and IMB see supernova neutrinos
- **Nobel Prize** for discovery of distinct flavors!
- LSND sees possible indication of oscillation signal
- **Nobel Prize** for ν discovery!
- Super K sees evidence of atmospheric neutrino oscillations
- Super K confirms solar deficit and "images" sun
- SNO shows solar oscillation to active flavor
- **Nobel Prize** for neutrino astroparticle physics!
- KamLAND confirms solar oscillations
- K2K confirms atmospheric oscillations
- 1980
- 2005

Other References

General:

- Nikolas Solomey, "The Elusive Neutrino" (1997)
- Christine Sutton, "Spaceship Neutrino" (1992)

Introductory college-level astronomy texts:

- Chaisson & McMillan, "Astronomy Today"
  - http://wps.prenhall.com/esm_chaisson_astronomytoday_5
- Kaufmann & Freedman, "Universe"
  - http://www.whfreeman.com/universe5e/index.htm