Neutrinos:

A fascinating quest for masses and oscillations

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U. Granada

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Fundamental Blocks

				Electric Charge
Leptons	e	μ	τ	-1
	ν_e	ν_μ	ν_τ	0
Quarks	u	c	t	2/3
	d	s	b	–1/3

Interaction	Electromagnetic	Weak	Strong	Gravity
Mediator	γ	$W^{\pm}$ Z	g	*¿graviton?*

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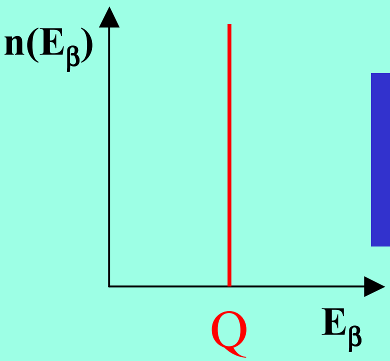
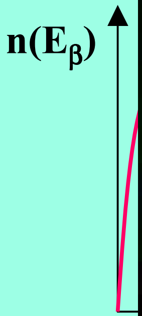
The neutrino "birth" (1930)

- β decay: (A,Z)→(A,Z+1) e⁻ ν

Q=M$_Z$



Expected:
Monochromatic spectrum



- Niels Bohr puts forward
  is not conserved in nucl

A desperate

Pauli postulates the existence of a new neutral particle, with spin ½ , extremely penetrating emitted along with the electron: **the neutrino**

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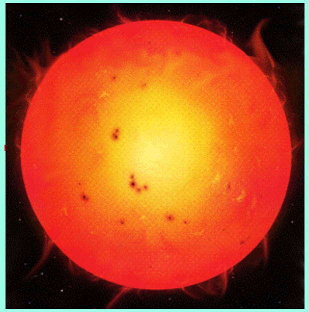
Can we detect neutrinos?

$$\sigma(\overline{\nu}_e + p \rightarrow e^+ + n) = 10^{-43}\left(\frac{E}{MeV}\right)^2 cm^2$$

Inverse β decay

d ≈ 1.5 x10^{8} km



We need 20 MILLION times
this distance to capture a ν

"...no one will be ever able to detect a ν"

Bethe & Peierls, 1934

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The neutrino discovery

- Reines and Cowan (1956)
  - Savannah River Nuclear Plant (EE.UU.)

$$\overline{\nu_e}\, p \rightarrow e^+\, n$$

- Lederman, Schwartz, Steinberger (1962)
  - AGL Acelerator (Brookhaven, EE.UU.)

$$\nu_\mu N \rightarrow \mu^-\, X$$

- DONUT Collaboration (2000)
  - Booster (Fermilab, EE.UU.)

$$\nu_\tau N \rightarrow \tau^-\, X \qquad \tau^- \rightarrow \mu^- \nu_\tau \overline{\nu_\mu}$$

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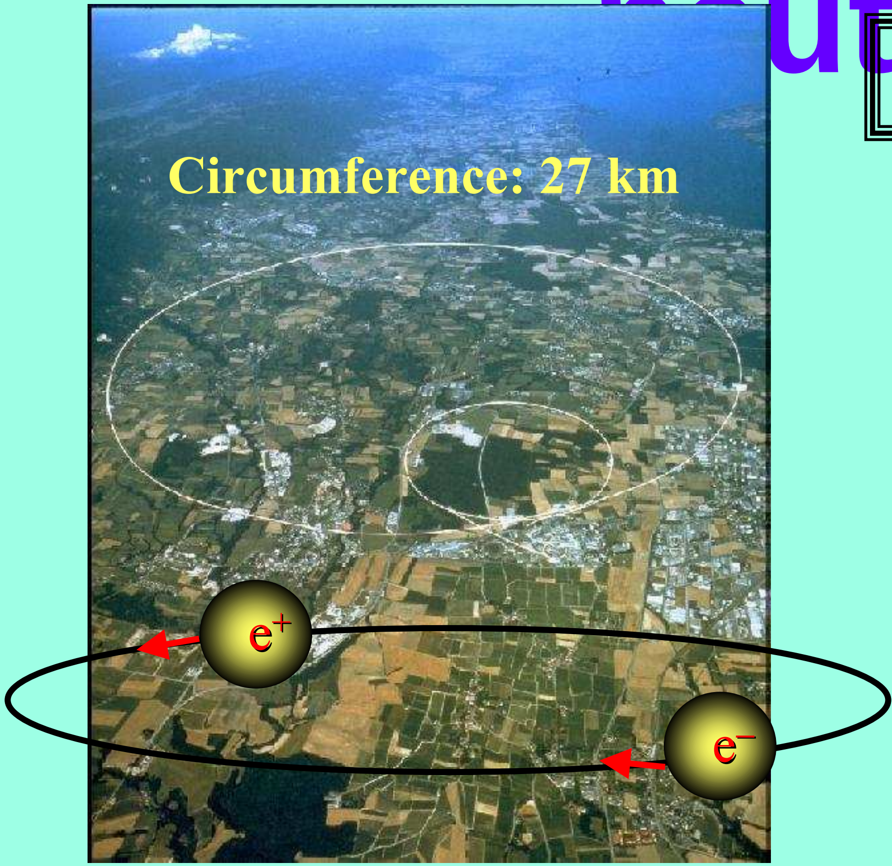
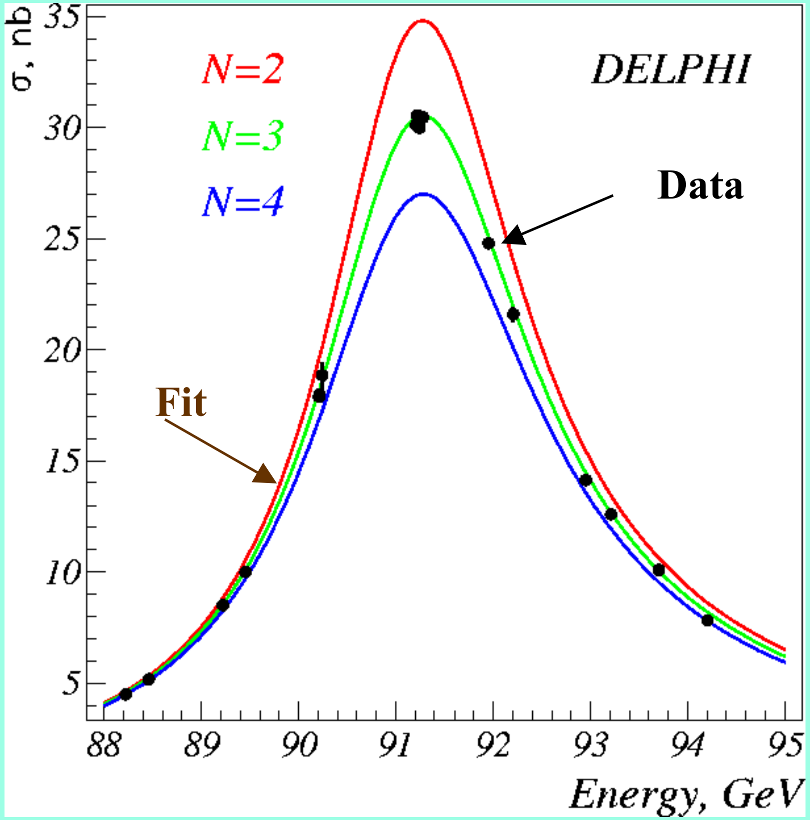
Number of light neutrinos

LEP (electron-positron collider)



$e^+ + e^- \rightarrow Z \rightarrow X$



Only three families of Light neutrinos

What is a neutrino?

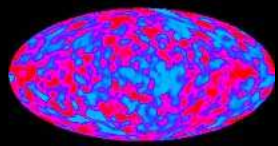
Electric Charge	0
Spin	1/2
Chirality	It seems 100% left-handed
Interaction	Weak only
Mass	Unknown
Lifetime	Unknown
Magnetic Moment	Unknown
Nature: Dirac, Majorana?	Unknown

70 later we still know few things about neutrinos

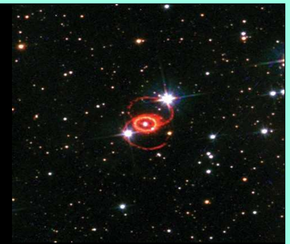
Neutrino Sources

Natural

Big Bang

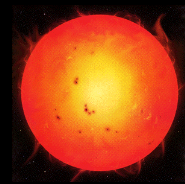


Supernovae



Atmosphere

Sun



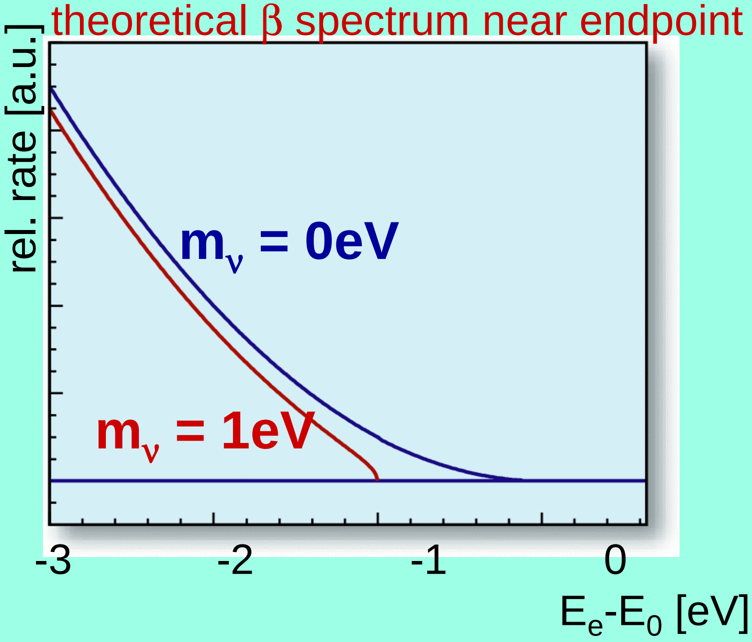
Artificial

Reactors

Accelerators

Direct Search for Neutrino Masses

- $m_{\nu e}$<2.2 eV (95% C.L.)
  - End point of tritium beta decay
  - Transition energy $E_0 = E_e + E\nu$ (+ recoil corrections)



- $m_{\nu\mu}$<170 KeV (90% C.L.)
  - From $\pi^+ \to \mu^+ \nu_\mu$ decays
- $m_{\nu\mu}$<18.2 MeV (95% C.L.)
  - From $\tau \to$hadrons + ν_τ decays

Neutrino Oscillations (B. Pontecorvo, 1957)

- An oscillation takes place when in a detector we observe flavour eigenstates different from the ones originally created $\Rightarrow$ neutrinos have mass

Flavour Eigenstates → $$|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$$ ← Mass Eigenstates

$U_{\alpha i}$: Unitary Mixing Matrix

- ν_α produced at time t_p and spatial location x_p by means of a weak interaction

$$|\psi_\alpha^P> = \sum_k U_{\alpha k} |\nu_k, p_k>$$

$$|\psi_\alpha^P(x)> = <x|\psi_\alpha^P> = \sum_k U_{\alpha k} <x|p_k> |\nu_k> = \sum_k U_{\alpha k} e^{ip_k(x-x_p)} |\nu_k>$$

Oscillation Probability (I)

$$i\frac{d}{dt}|\psi_\alpha^P(x,t)> = H|\psi_\alpha^P(x,t)> = \sum_k U_{\alpha k} e^{ip_k(x-x_p)} E_k |\nu_k>$$ Free Neutrino Propagation

$$|\psi_\alpha^P(x,t)> = \sum_k U_{\alpha k} e^{ip_k(x-x_p)-iE_k(t-t_p)} |\nu_k>$$

$$|\psi_\alpha^P(x,t)> = \sum_\beta \left(\sum_k U_{\alpha k} e^{ip_k(x-x_p)-iE_k(t-t_p)} U^*_{\beta k}\right) |\nu_\beta>$$

Schrödinger's equation solution

Probability to detect a ν_β *in a beam initially composed of* ν_α *only*

$$P_{\nu_\alpha\to\nu_\beta}(L,T) = |A_{\nu_\alpha\to\nu_\beta}(L,T)|^2 = |<\nu_\beta|\psi_\alpha^P(x=x_D, t=t_D)>|^2$$

$$L \equiv x_D - x_P \quad T \equiv t_D - t_P$$

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Oscillation Probability (II)

$$P_{\nu_\alpha \to \nu_\beta}(L,T) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\,\mathrm{Re}\sum_{k>j} U_{\alpha k} U^*_{\beta k} U_{\alpha j} U^*_{\beta j} e^{i(p_k - p_j)L - i(E_k - E_j)T}$$

$$E_k^2 = p_k^2 + m_k^2 \qquad p_k >> m_k \qquad p_k \cong E_k - \frac{m_k^2}{2E_k}$$

$$E_j^2 = p_j^2 + m_j^2 \qquad p_j >> m_j \qquad p_j \cong E_j - \frac{m_j^2}{2E_j}$$

Assume relativistic neutrinos

Oscillation Probability

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\,\mathrm{Re}\sum_{k>j} U_{\alpha k} U^*_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left[-i \frac{\Delta m_{kj}^2}{2E} L\right]$$

$$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$$

Oscillation Length

$$L_{kj} = \frac{4\pi E}{\Delta m_{kj}^2}$$

Three Family Mixing

$$|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$$

Mixing Matrix

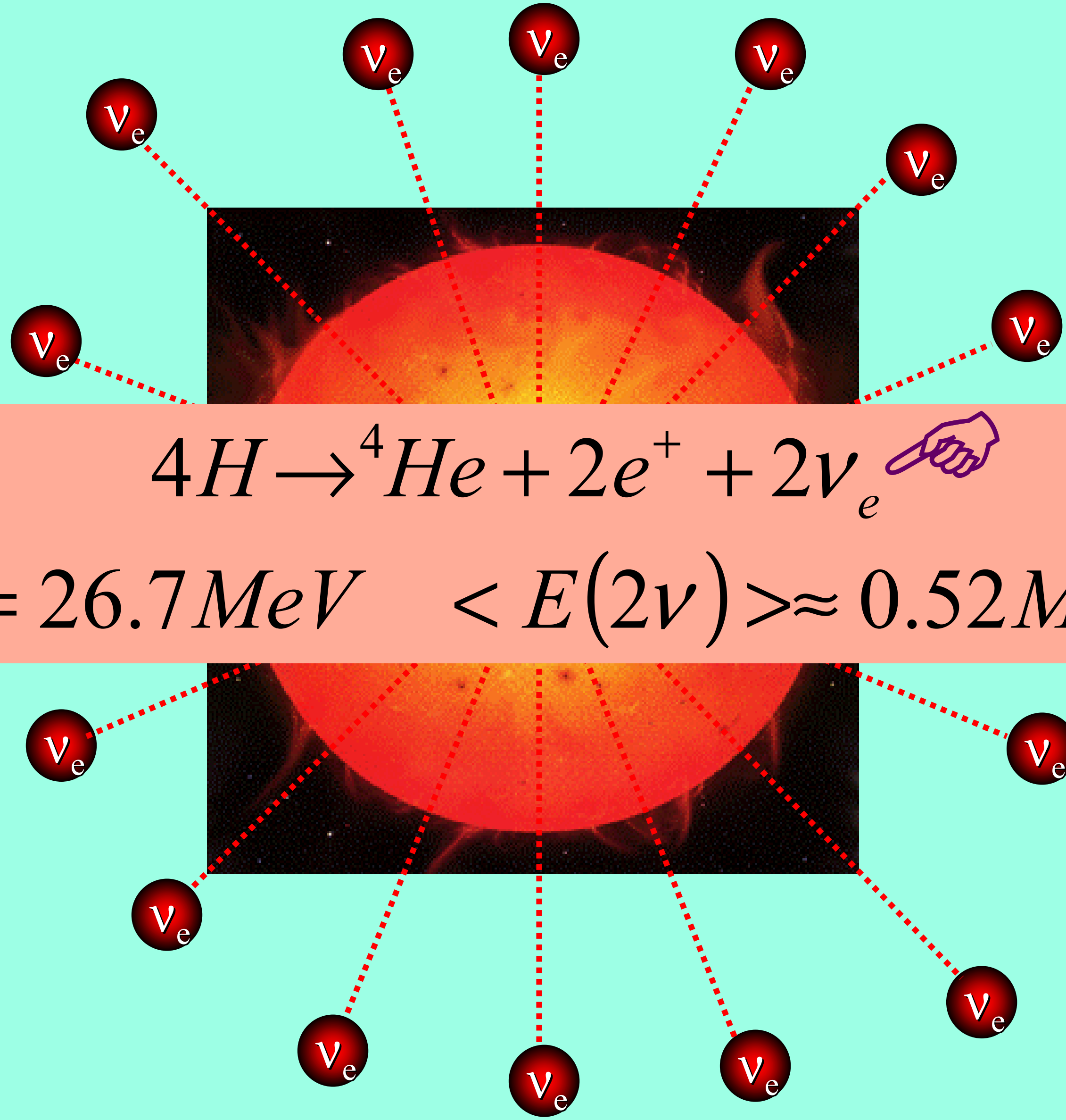
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor Eigenstates

Mass Eigenstates

Three mixing angles (θ_{12}, θ_{13}, θ_{23}), a complex phase δ
Two mass differences: Δm^2_{12}, Δm^2_{23}

Solar Neutrinos



$$4H \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e}$$

$$Q = 26.7\,MeV \qquad < E(2\nu) > \approx 0.52\,MeV$$

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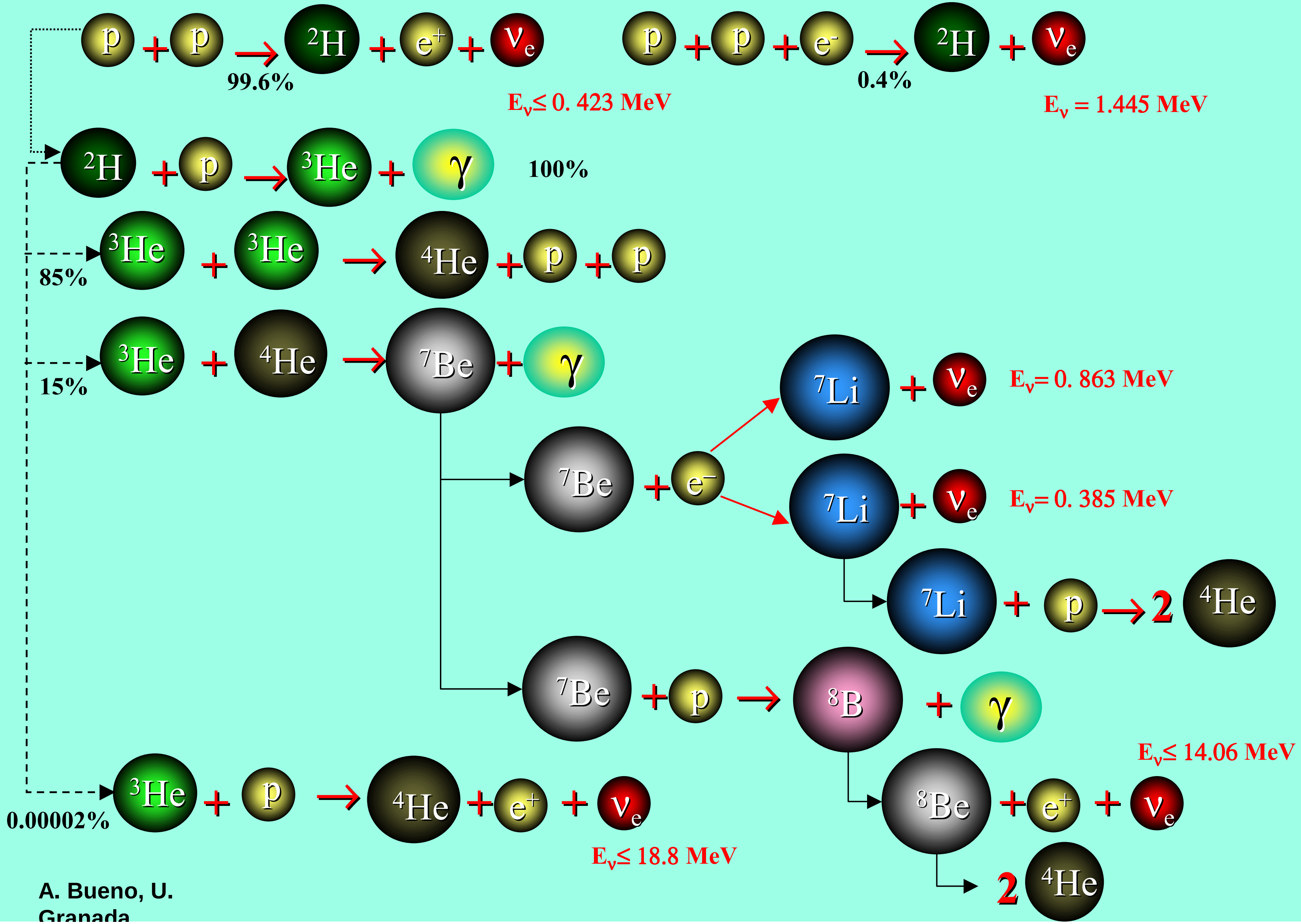
PP Chain



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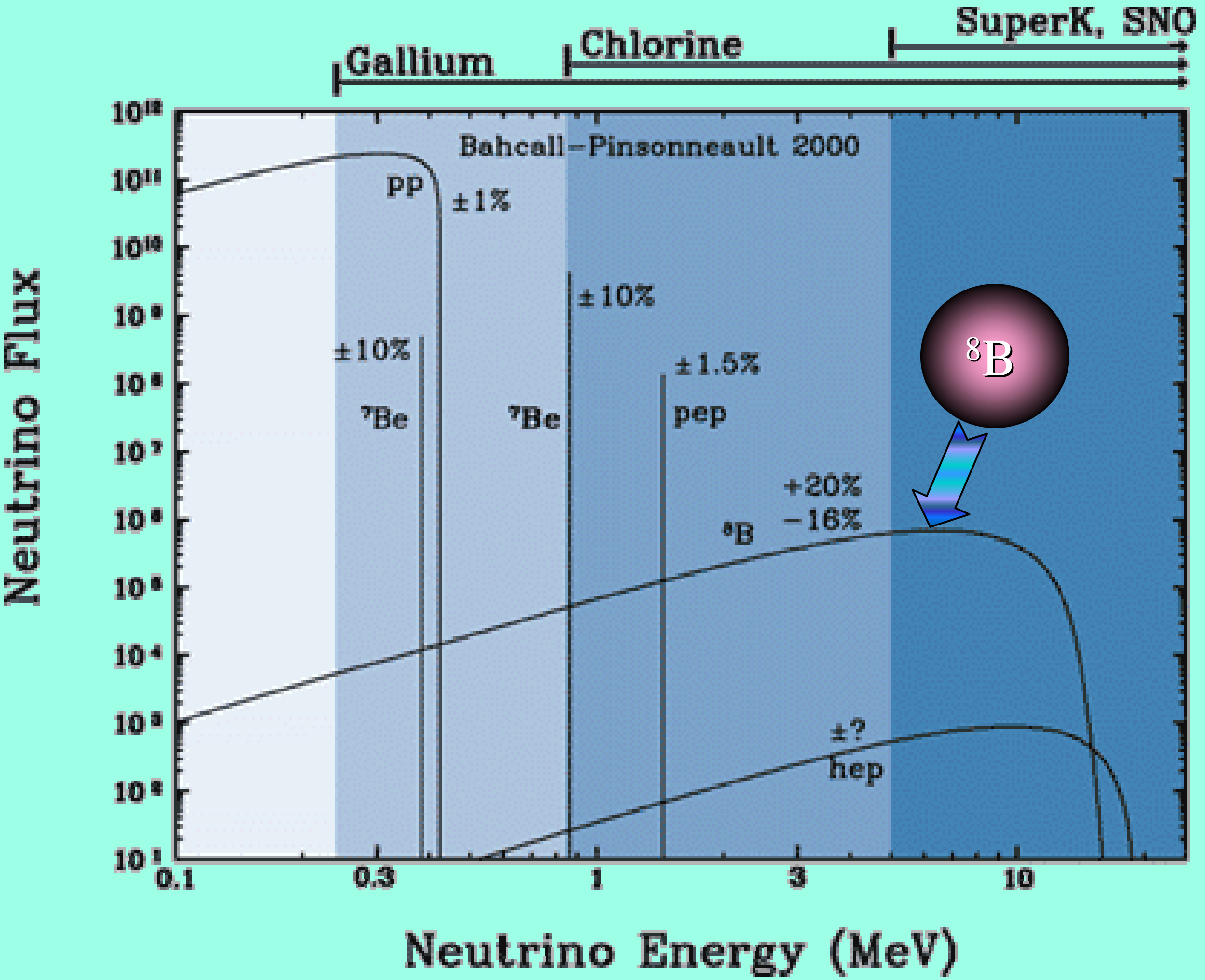
Solar Neutrino Energy Spectrum

Detection Technique



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Solar Neutrino Flux

- Sun Luminosity = 3.86 x 10^{26} joules/s
- Each reaction frees 4 x 10^{-12} joules (26.7 MeV)

$$\phi_{\nu}^{Sol} \approx 2 \times 10^{38} \nu / s$$

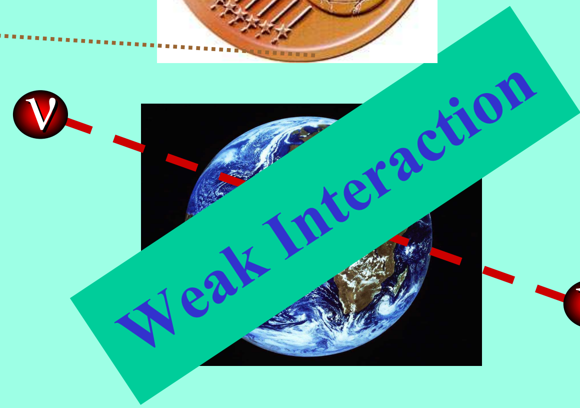
- Each second 7 x 10^{28} ν traverse Earth's surface

Surface = 2 cm^2

$$\phi \approx 6 \times 10^{10} \nu / s / cm^2$$

Impossible to see neutrinos?

Problem



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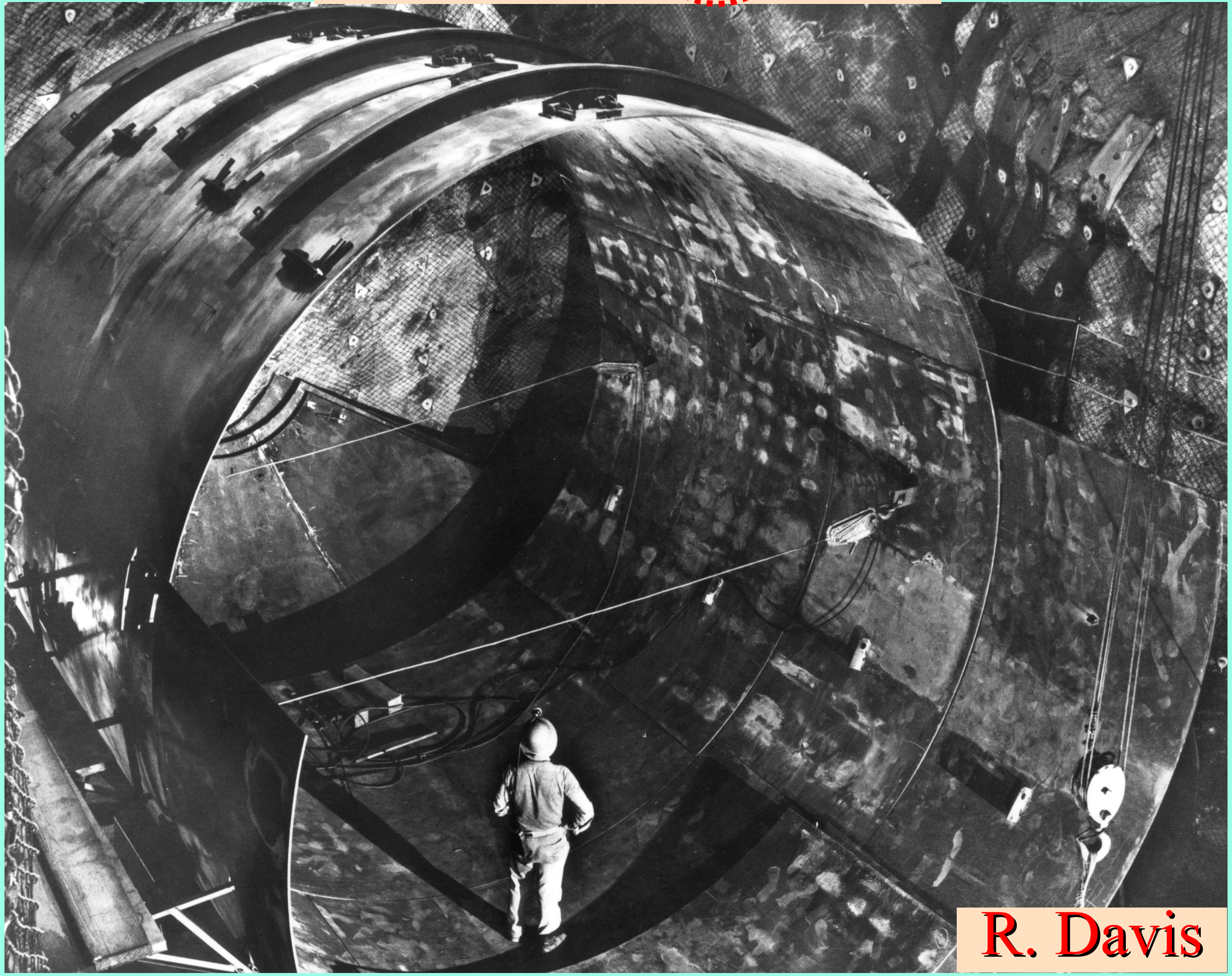
A Massive Chlorine Detector

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

B. Pontecorvo, 1949



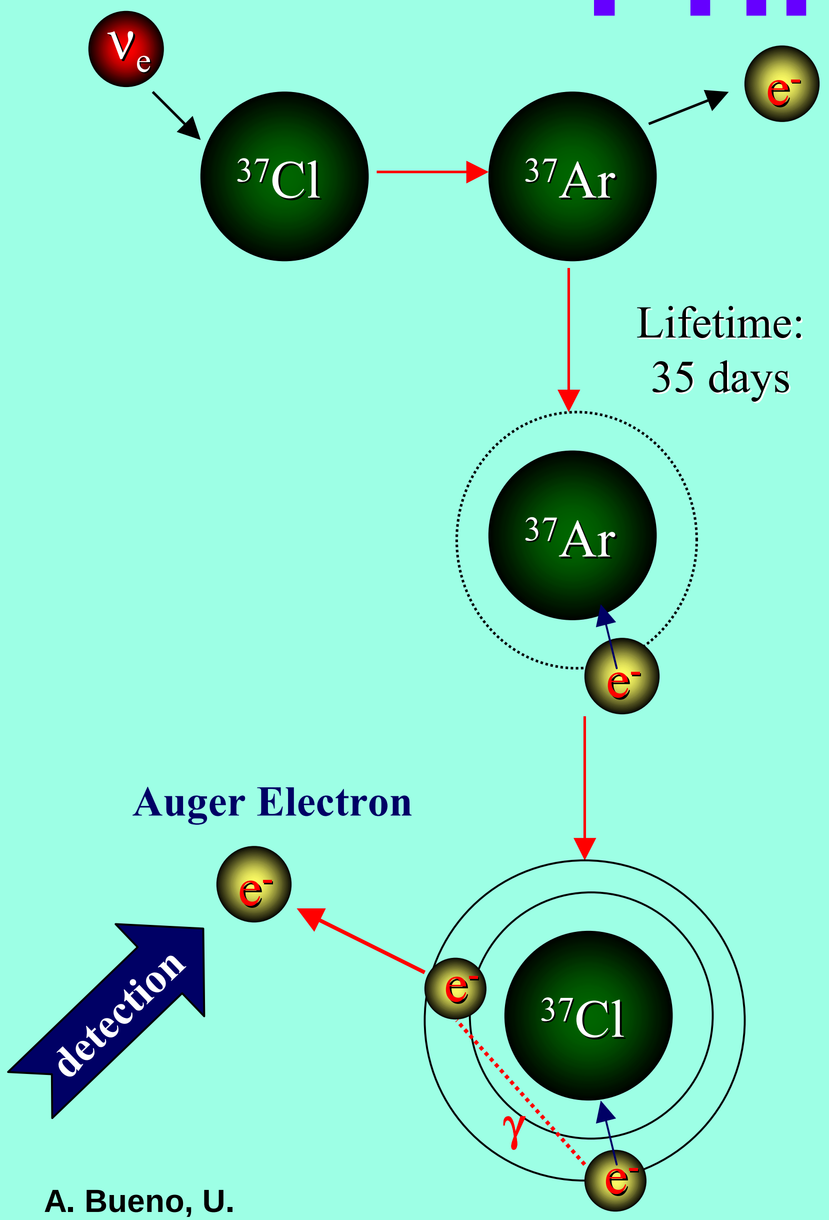
R. Davis

1965-1966: Stainless Steel Container

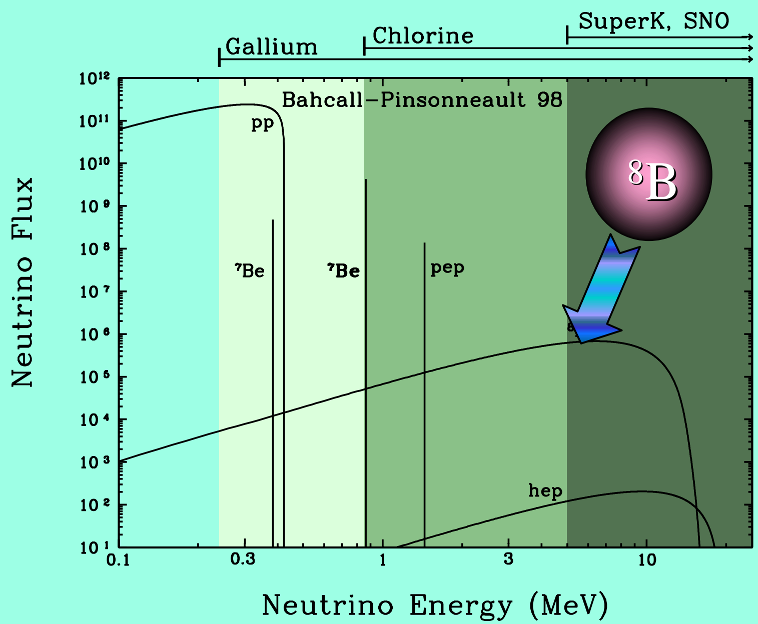
The Homestake Detector

- Homestake Gold Mine
  - ➢ 1500 m depth (4200 m w.e.)
- 14.6 m long
- 6.1 m diameter
- 615 tons (380 000 l) de C_2Cl_4
- Detector surrounded by water to suppress background

Homestake: Detection Principle



Capture energy threshold
0.86 MeV



Expected rate
1.5 ^{37}Ar atoms/day

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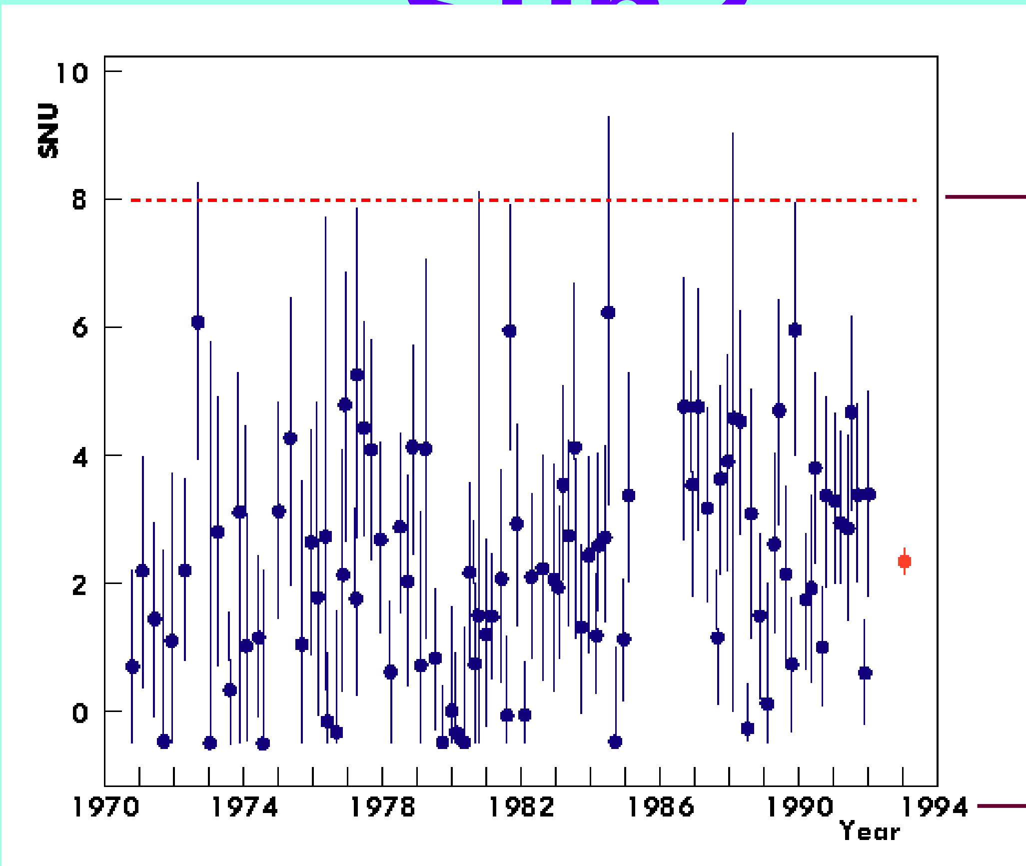
are emitted by the

SNU≡ Solar Neutrino Unit ≡ 1 capture per second per 10^{36} átoms of ^{37}Cl



Expected theoretical value

More than 20 years of data taking

In total they found about 2000 ^{37}Ar atoms

Only one third of the expected neutrinos is measured

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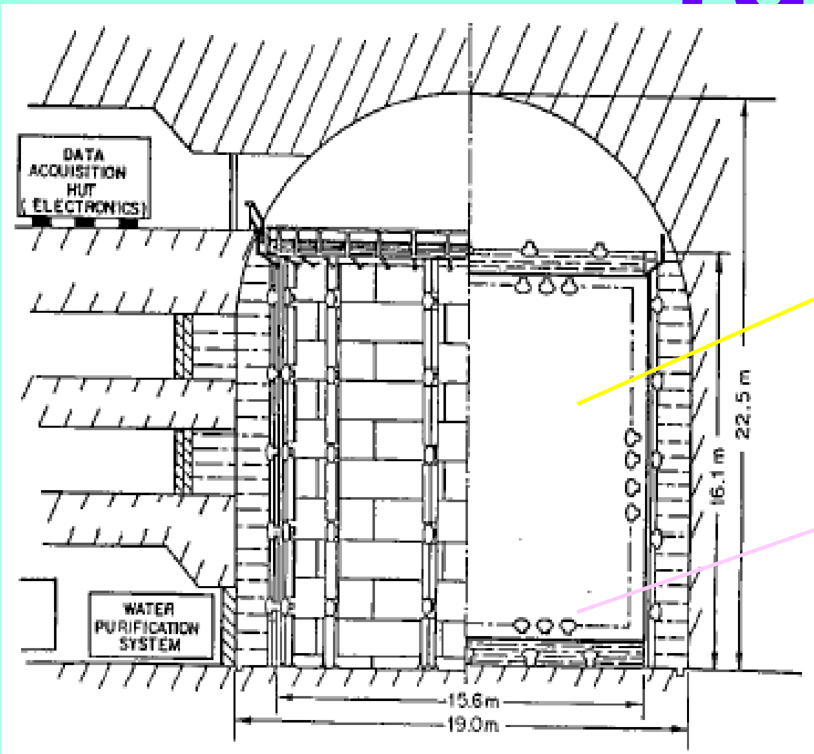
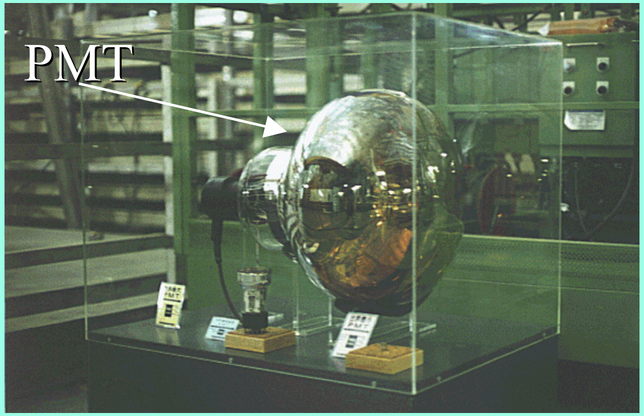
Kamiokande (1982-1990)

M. Koshiba



3 ktons of H_2O

Walls covered with 1000 PMTs



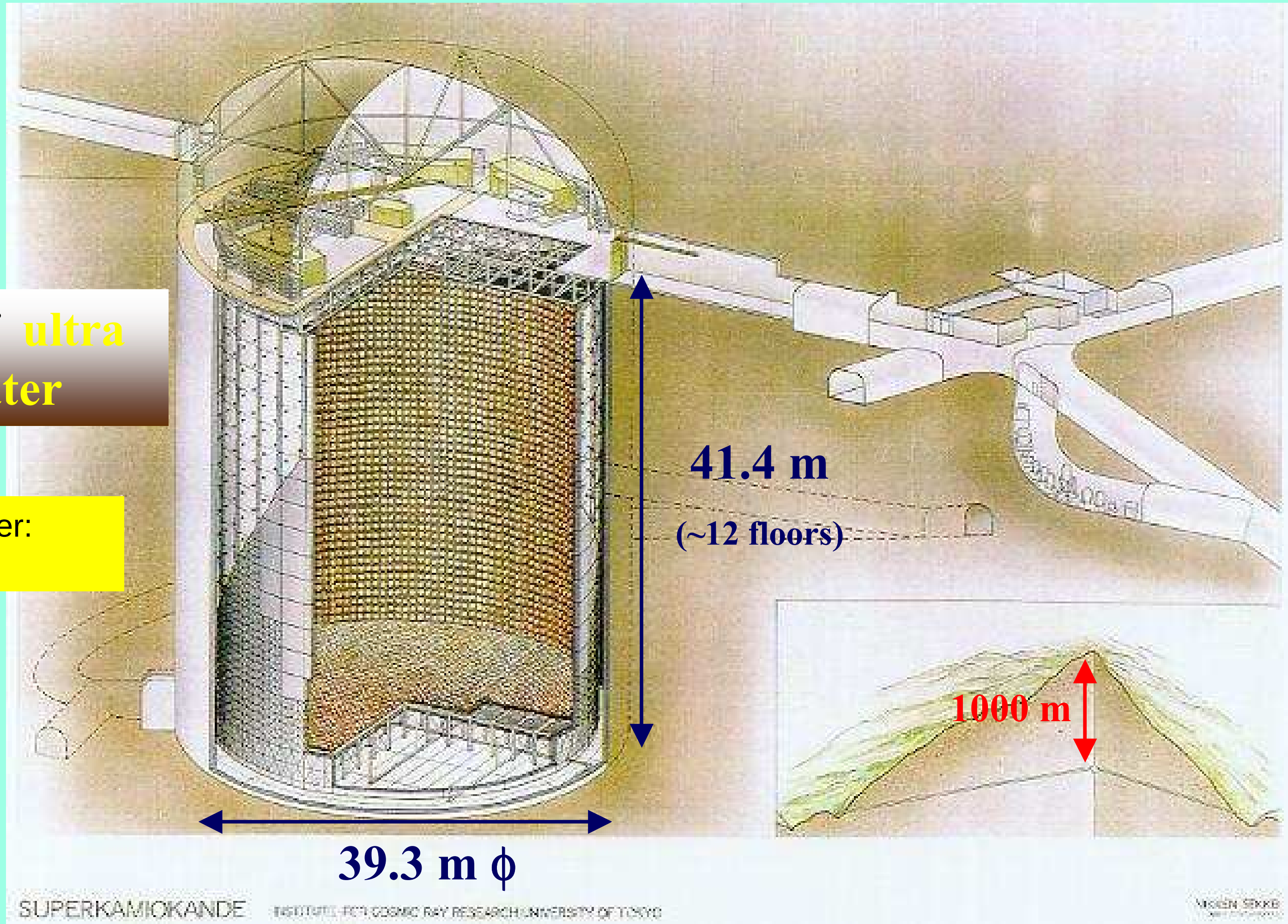
1000 m underground (2700 m w.e.)

1987: first demonstration that neutrinos come from the Sun

Super-Kamiokande

50 ktons of ultra pure water

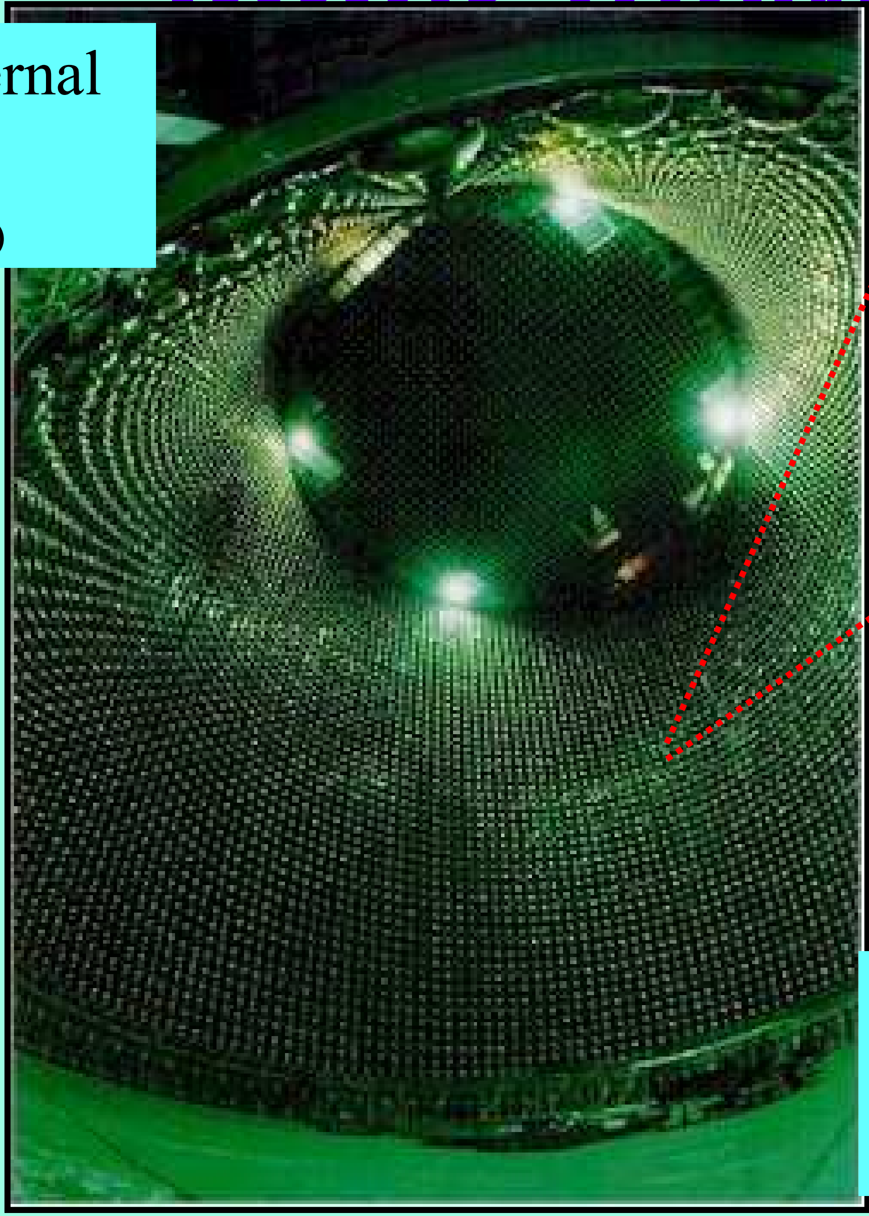
Eiffel Tower:
10 ktons

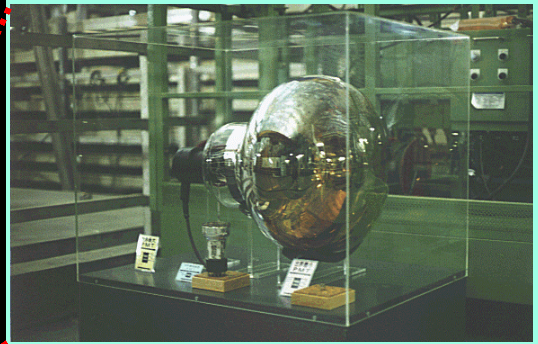


Super-Kamiokande Inner View

11146 internal PMT

(20 inches)





1885 external PMT

(8 inches)

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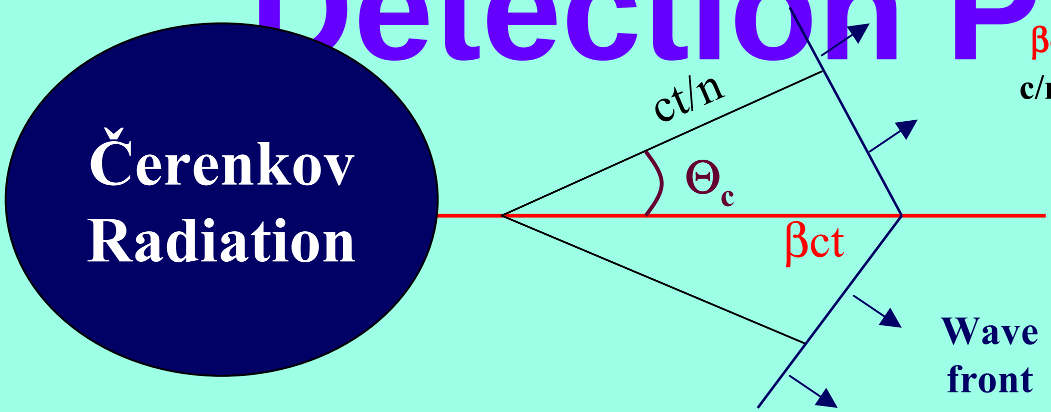
Kamiokande: Detection Principle

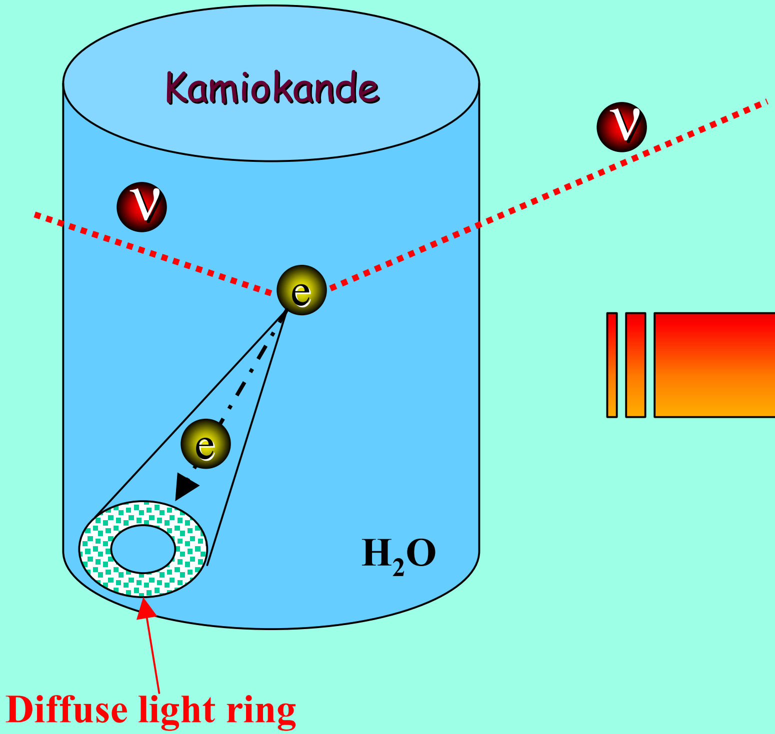


βct = particle velocity

c/n = radiation velocity

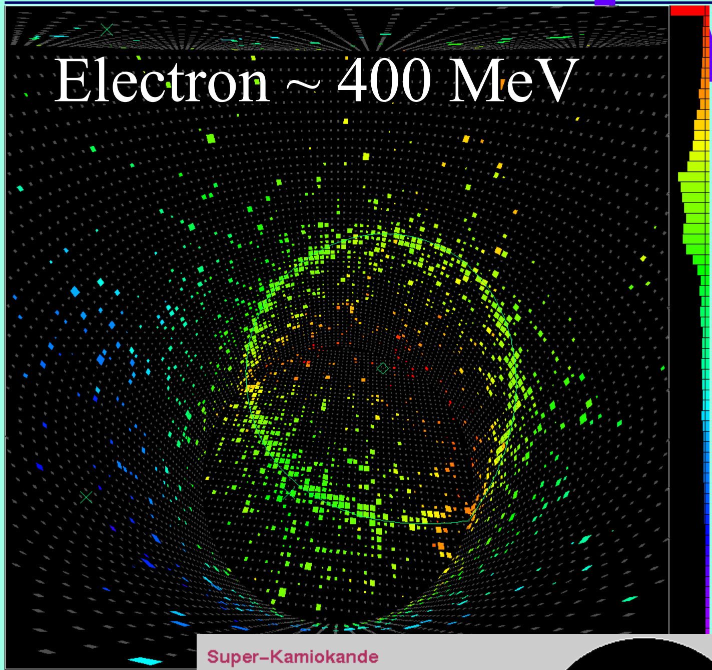
n = refraction index

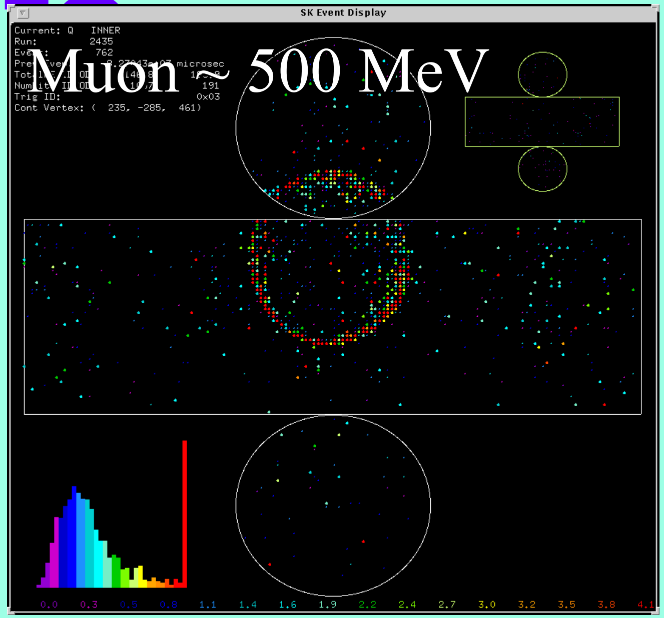
$$\Theta_c = \arccos\left(\frac{1}{n\beta}\right)$$

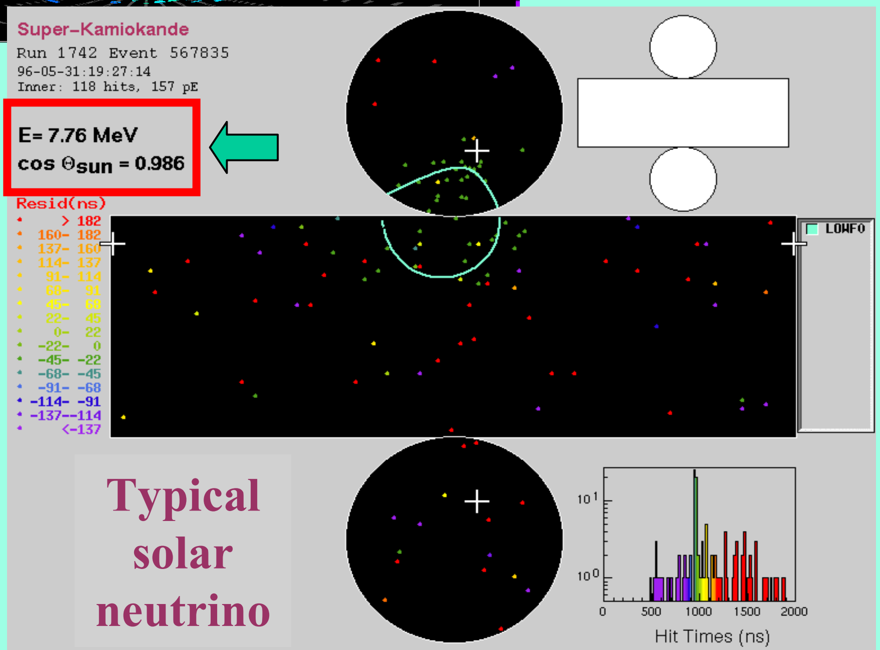


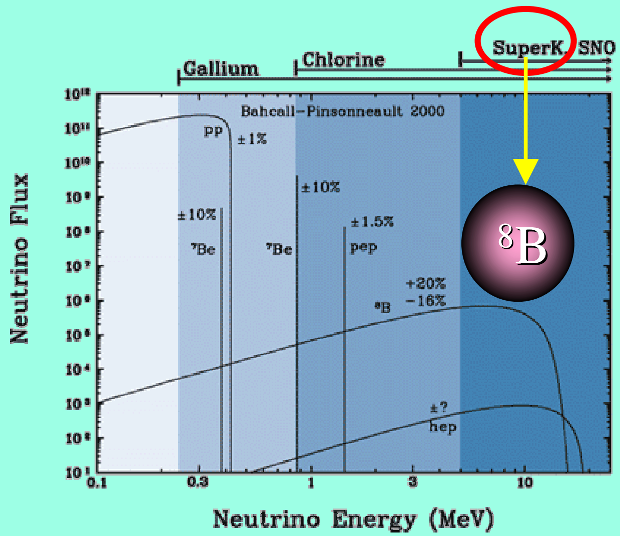
- Direction:
  - Ring axis
- Energy:
  - Light intensity
- Time:
  - Signal arrival time

Super-Kamiokande Events









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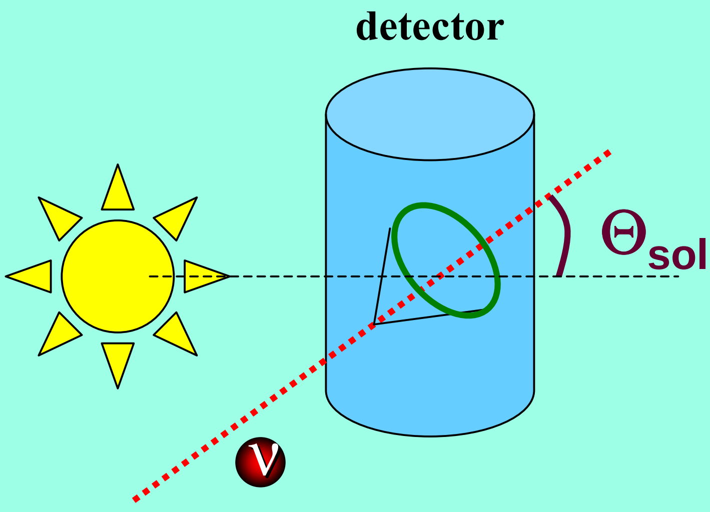
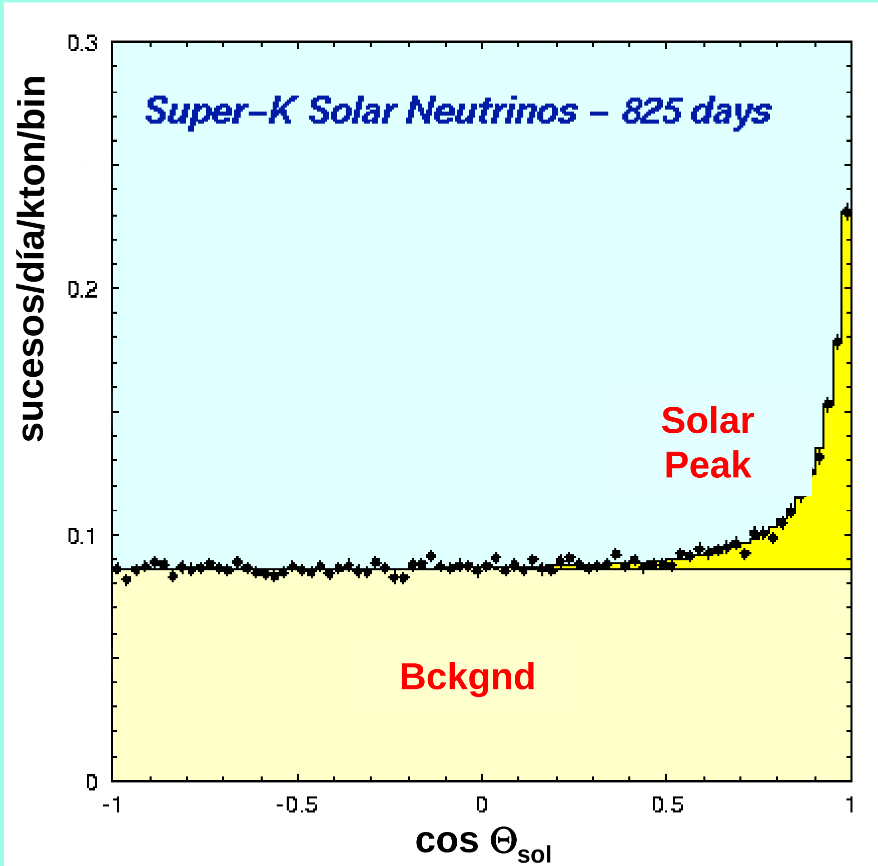
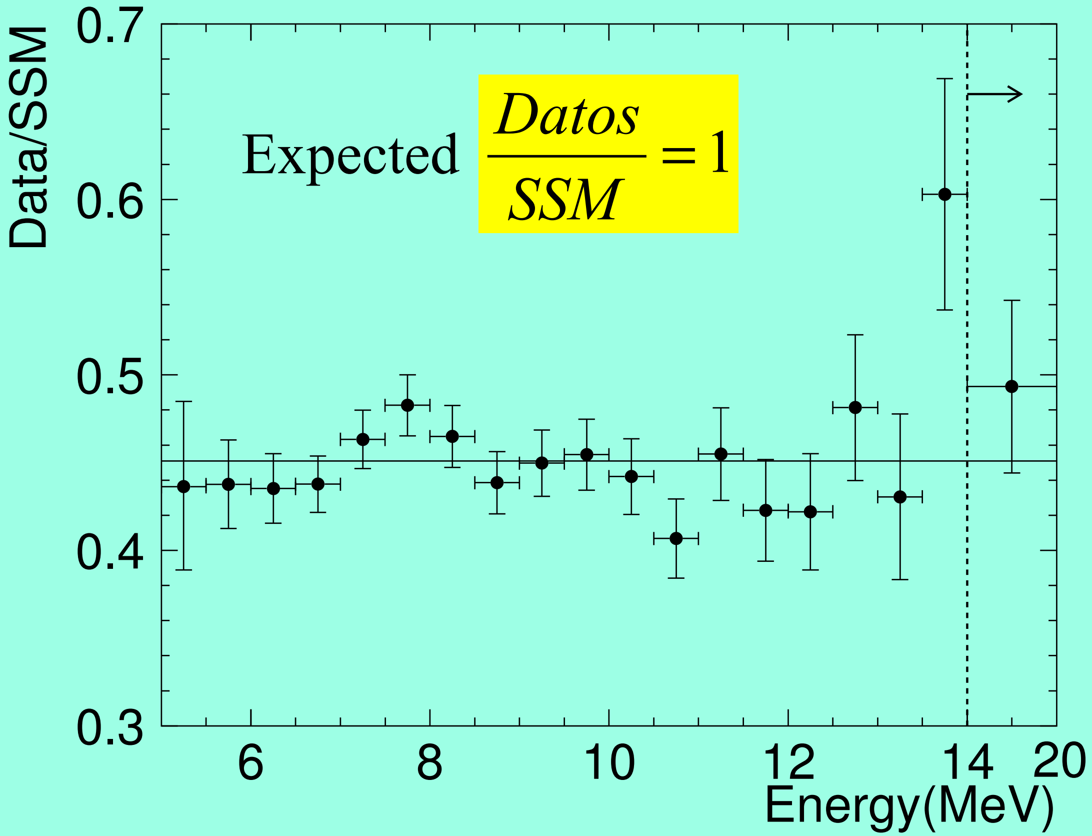
Neutrinos do come from the Sun





Solar Neutrino Deficit



As in Homestake, SuperK measured less neutrinos than expected

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SNO and the Solar Neutrino Problem

$$\nu_e + d \rightarrow e^- + p + p \,(CC)$$

$$\nu_X + d \rightarrow \nu_X + p + n \,(NC)$$

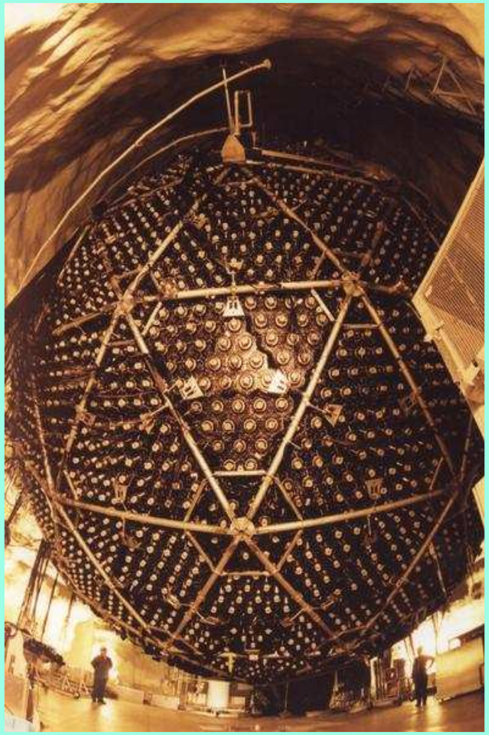
$$n + d \rightarrow {}^3H + \gamma, \gamma + e^- \rightarrow \gamma + e^-$$

$$\nu_X + e^- \rightarrow \nu_X + e^- \quad (ES)$$

In absence of oscillations $\Phi_{CC} = \Phi_{NC} = \Phi_{ES}$

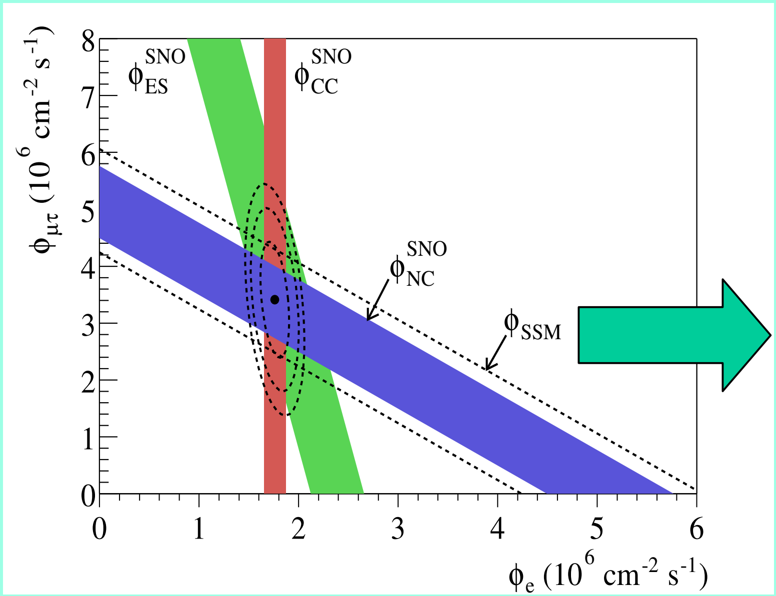
$$\Phi_{CC} = \Phi(\nu_e) = 1.76 \pm 0.10 \quad \Phi_{ES} = \Phi(\nu_e) + 0.154\Phi(\nu_{\mu\tau}) = 2.39 \pm 0.26$$

$$\Phi_{NC} = \Phi(\nu_e) + \Phi(\nu_{\mu\tau}) = 5.09 \pm 0.62$$



1 ton of D_2O

9600 PMTs



Measured flux equal to predicted one

ν_e seem to transform into ν_μ, ν_τ

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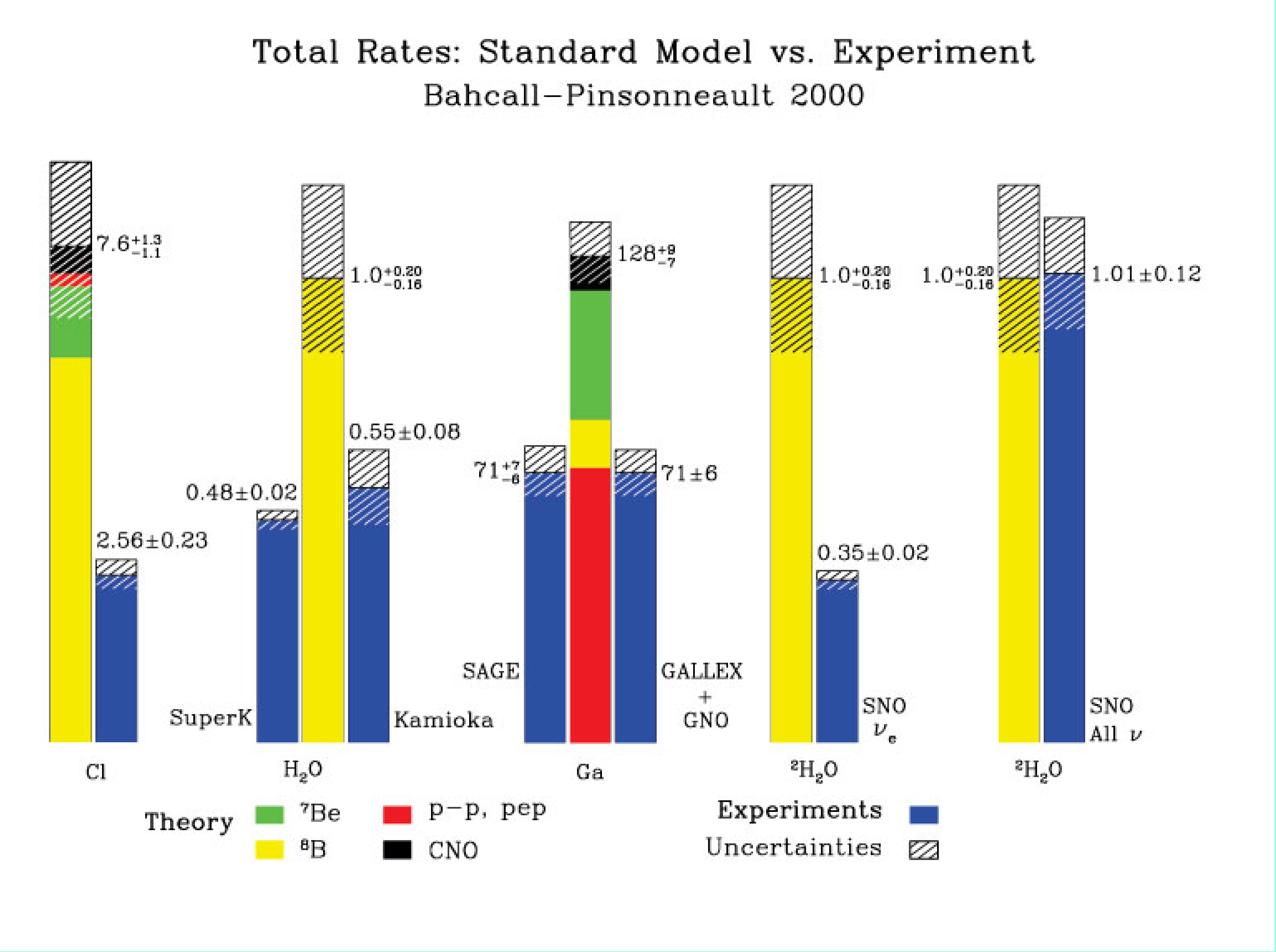
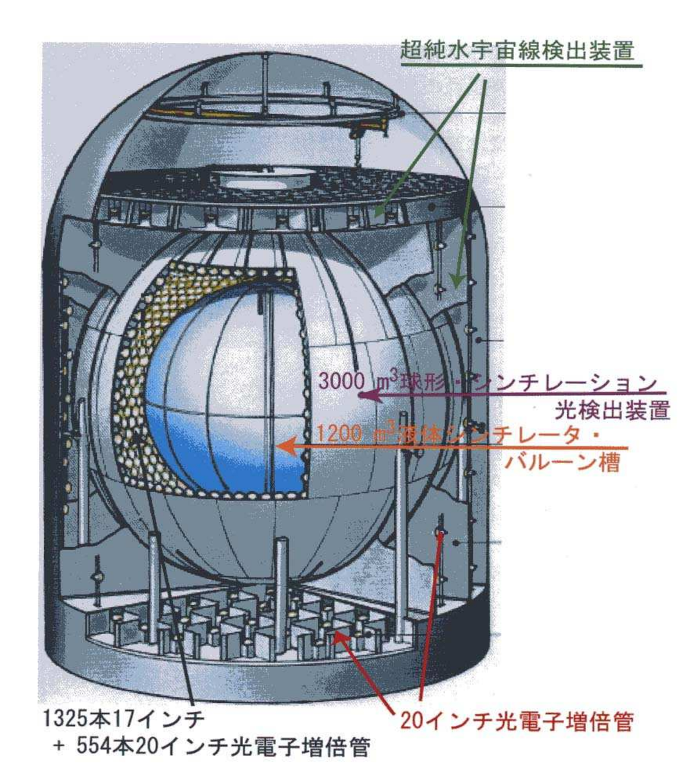
Solar Neutrinos After SNO



Long Baseline Experiments:Kamland

Kamland <L>= 180 km

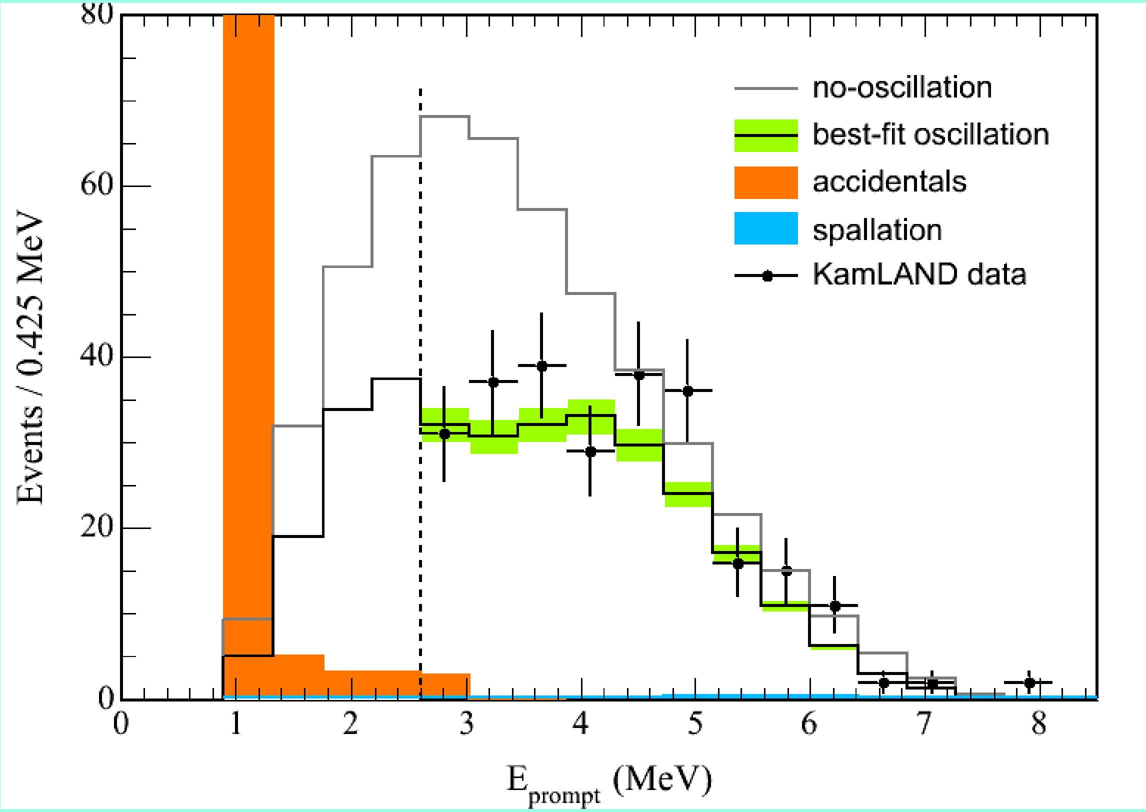


- Neutrinos from several reactor sources
- Disappearance of anti-ν_e
- 1Kton liquid scintillator
  - ❑34% photocathode coverage
  - ❑$\sigma(E)/E \sim 6.2$ at 1 MeV
- 766.3 tons x years accumulated so far

258 observed,
365 ± 64 expected

Agreement with solar neutrino experiments

Kamland Results



Best KamLAND fit to oscillations $\Delta m^2 = 8.3 \cdot 10^{-5}\ eV^2,\ \sin^2 2\theta = 0.83$

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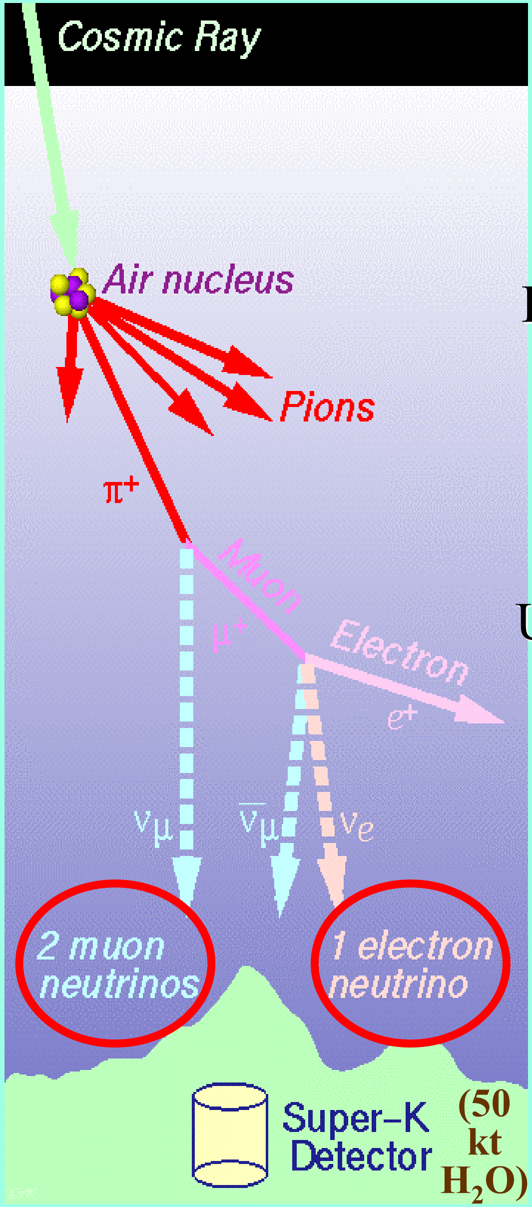
Atmospheric Neutrinos



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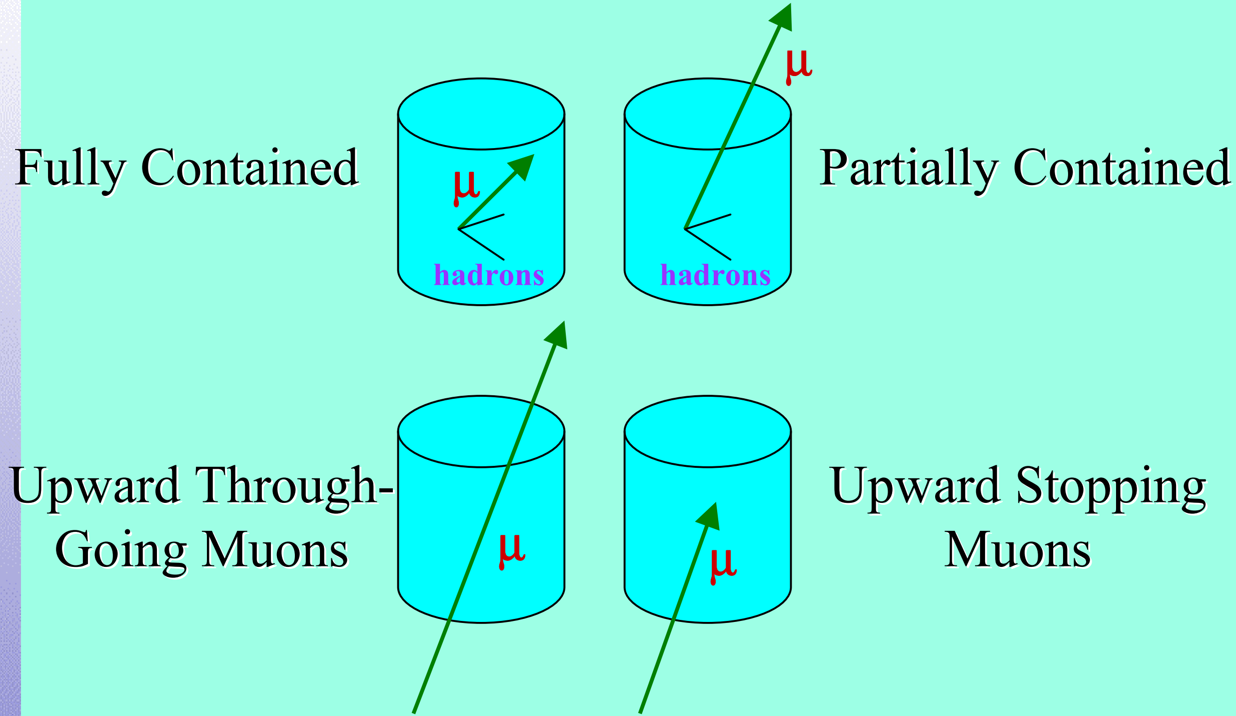
Event Classification

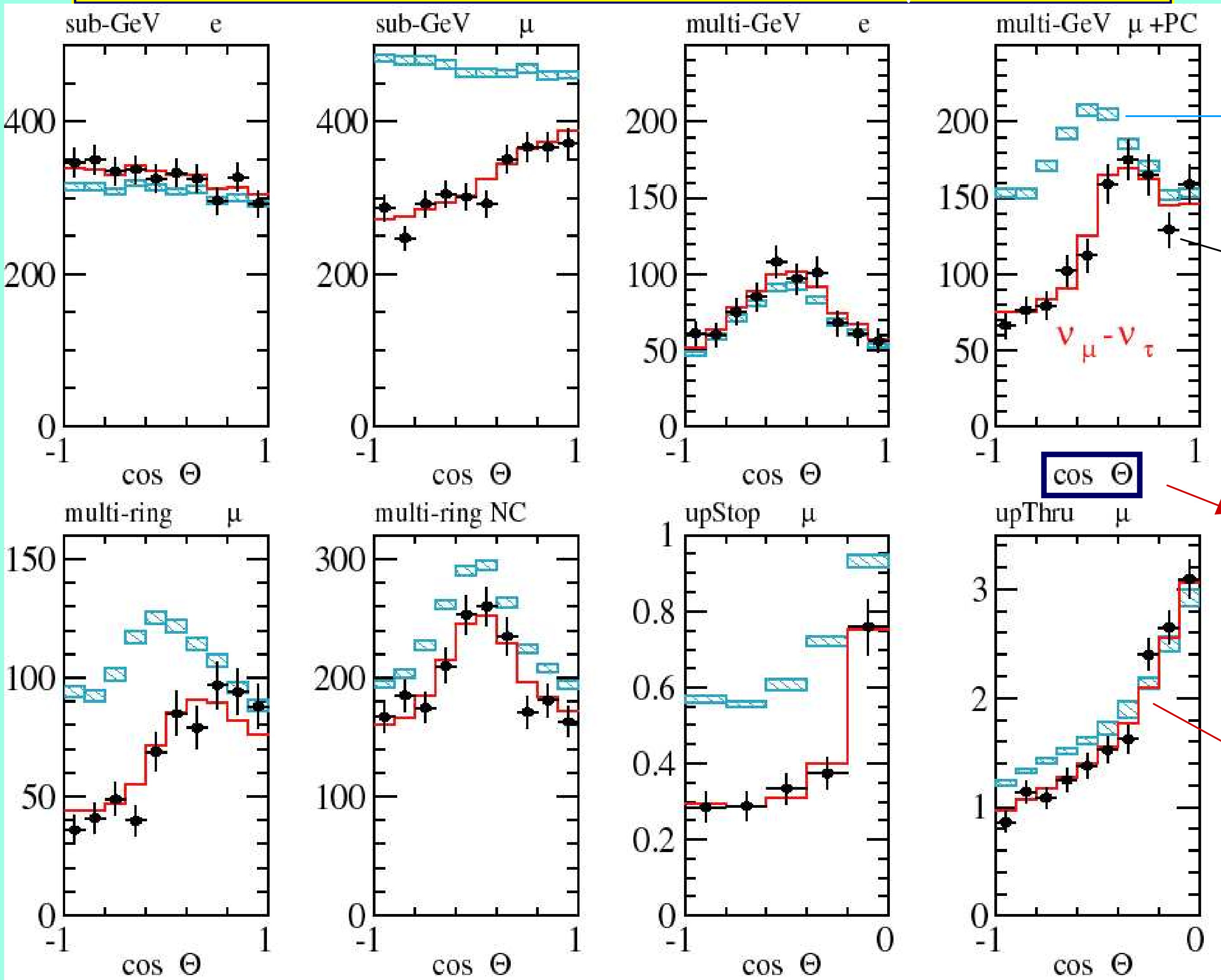


And there also…

- **Sub-GeV (P_{lepton}<1.33 GeV), Multi-GeV (P_{lepton}>1.33 GeV)**
- **Single-ring, multi-ring**

Atmospheric Neutrino Deficit

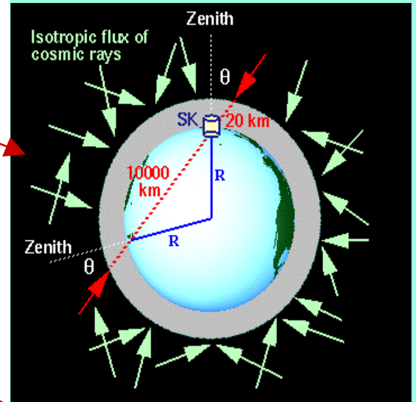
SuperKamiokande measures a ν_μ deficit



THEORY

(no osc)

DATA



THEORY

(oscillations)

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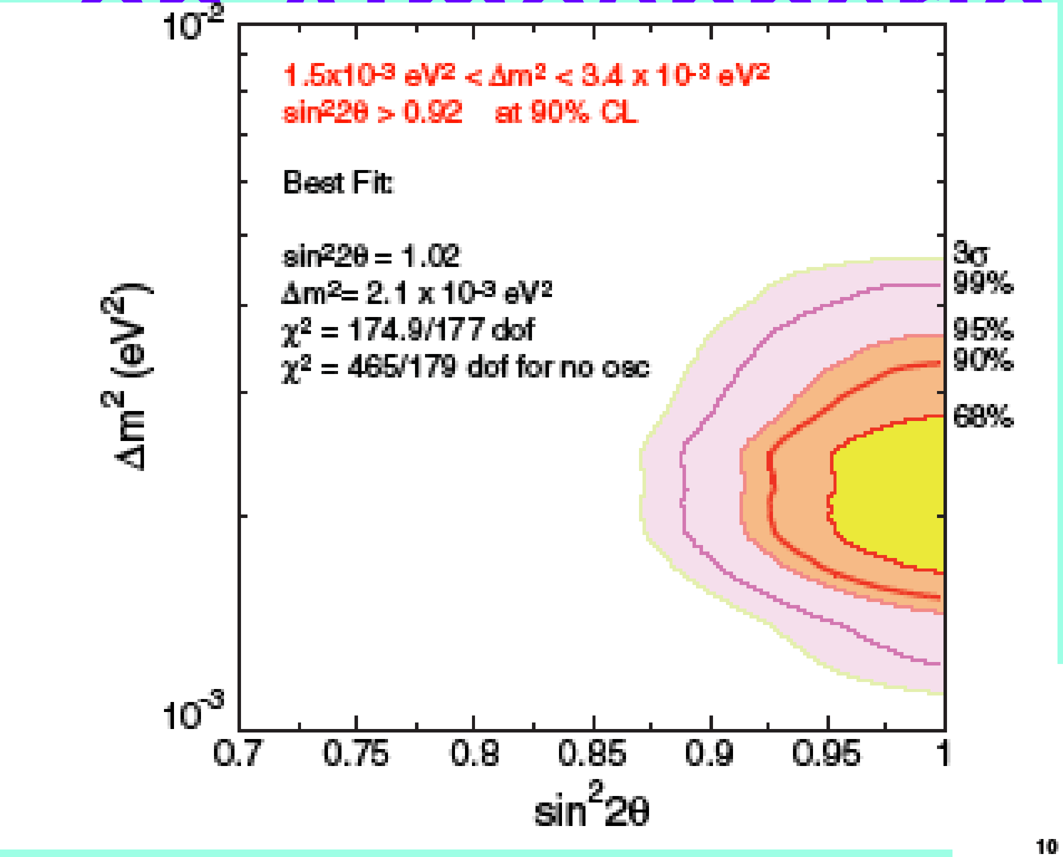
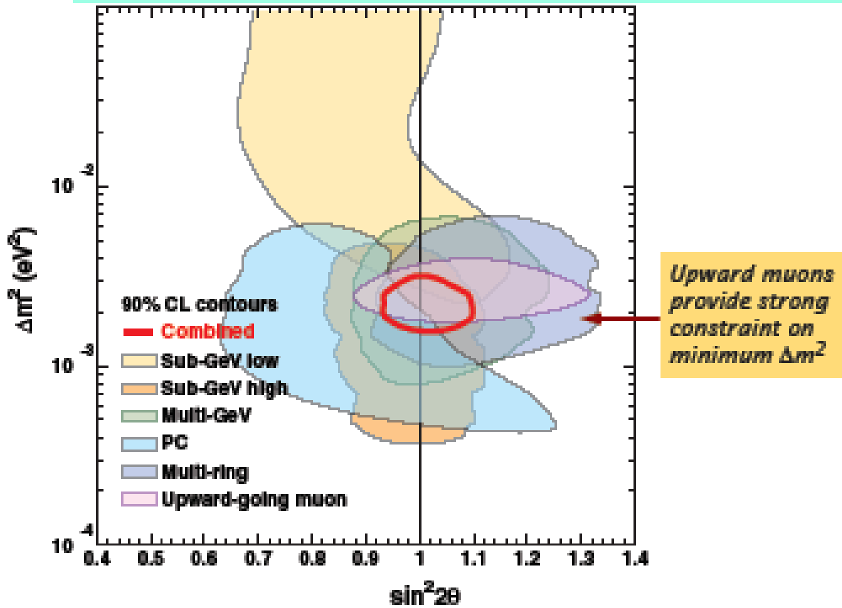
SuperKamiokande Results on Atmospheric Neutrinos



$\nu_\mu \rightarrow \nu_\tau$ **oscillations is most plausible explanation**



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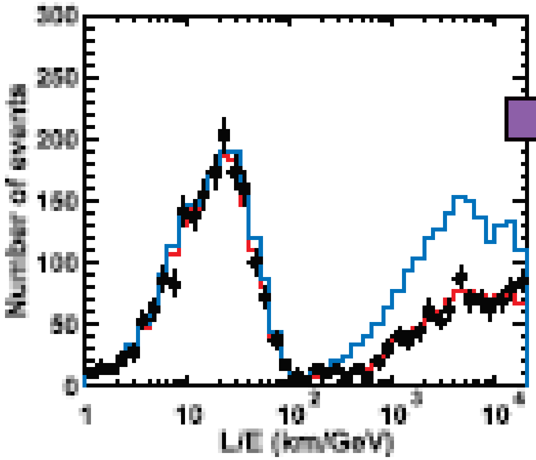
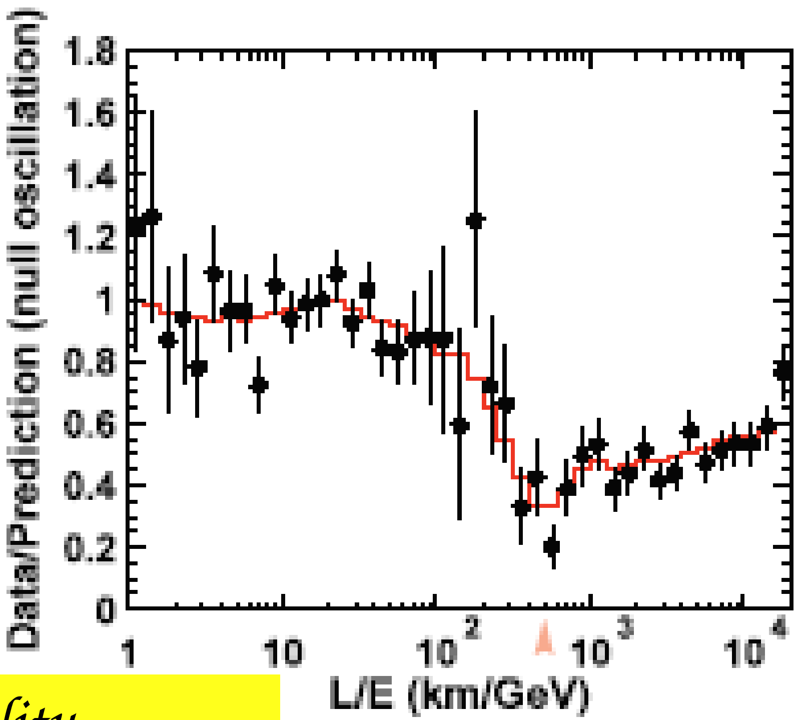
Super Kamiokande: L/E Distribution





oscillation dip seen at ~500 km/GeV

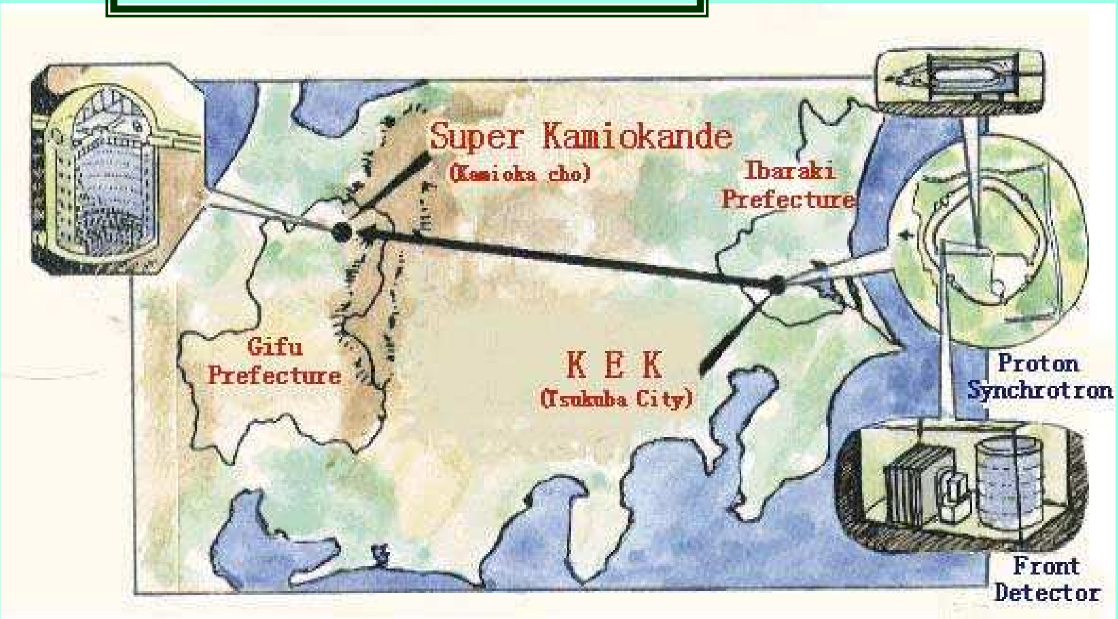
Two Family Oscillation Probability

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\Theta \sin^2\left[1.27\Delta m^2_{kj}\left(\frac{L}{E}\right)\right]$$

$$\Delta m^2_{kj} \equiv m^2_k - m^2_j$$

Long Baseline Experiments: K 2K

K2K L= 250 km



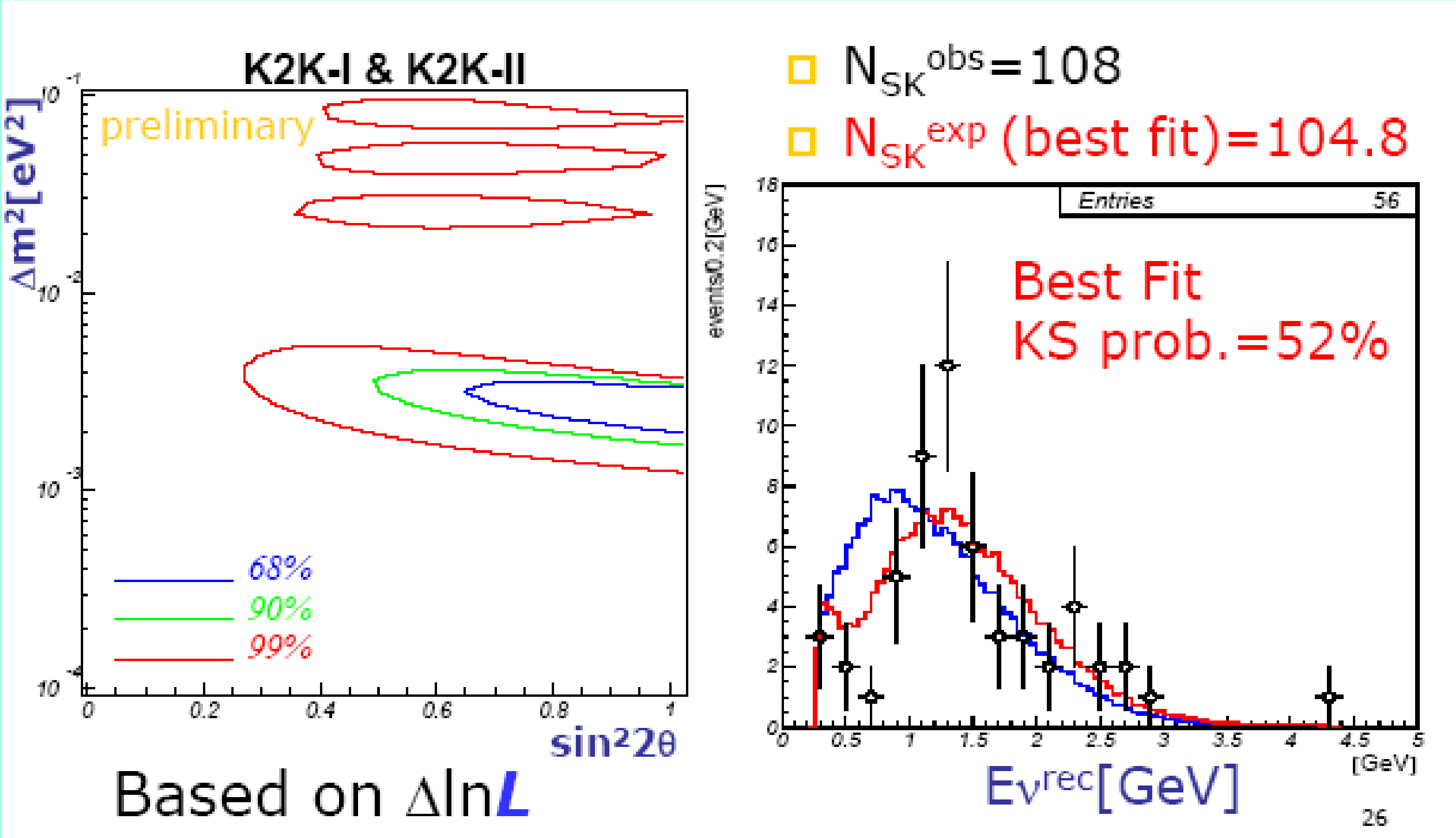
- Accelerator neutrinos
- <E>=1.4 GeV
- Disappearance of ν_μ

N_{SK}^{exp}=150.9+11.6-10.0

N_{SK}^{obs}=108

With 8.9×10^{19}POT, K2K *has confirmed has confirmed* neutrino oscillations at **3.9**σ.

K 2 K Results



Best Fit Values in Physical Region

- $\sin^2 2\theta = 1.00$
- $\Delta m^2\,[\mathrm{eV}^2] = 2.73\times10^{-3}$

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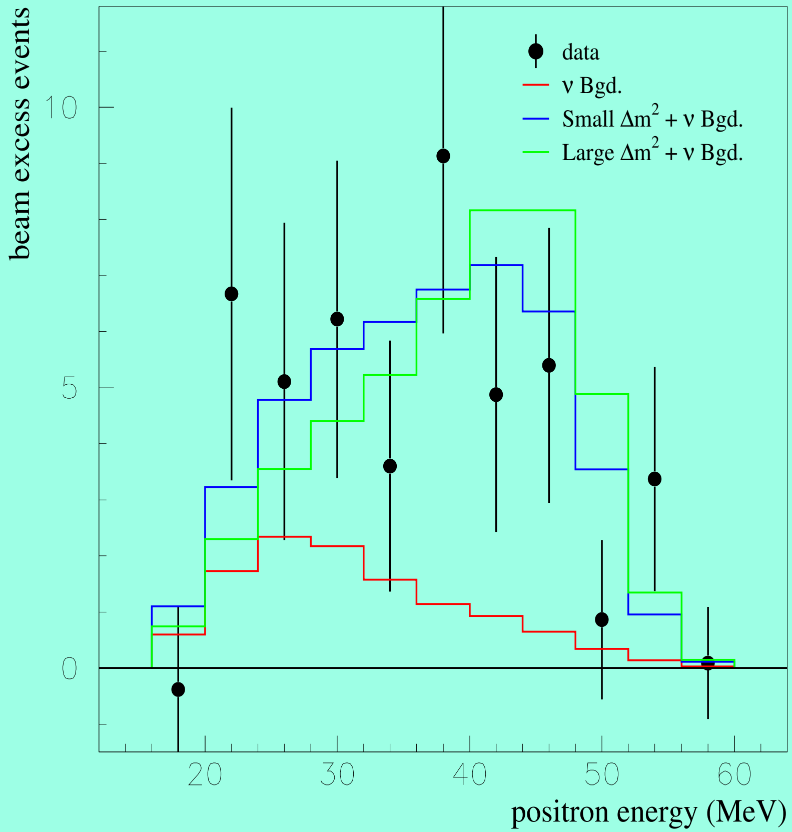
Accelerator Neutrinos: LSND

- anti-ν_μ beam coming from π^+ and μ^+ decays at rest
- Contamination of anti-ν_e: 10^{-4} in the range $36<E_\nu<53$ MeV

$$\overline{\nu}_e p \rightarrow e^+ n$$
$$np \rightarrow d\gamma(2.2\,MeV)$$



- anti-ν_e excess: **33.9 ± 8.0**
- Decays in flight: beam of ν_μ

$$\nu_e C \rightarrow e^- X$$

- Electron excess: **18.1+6.6-3.5**

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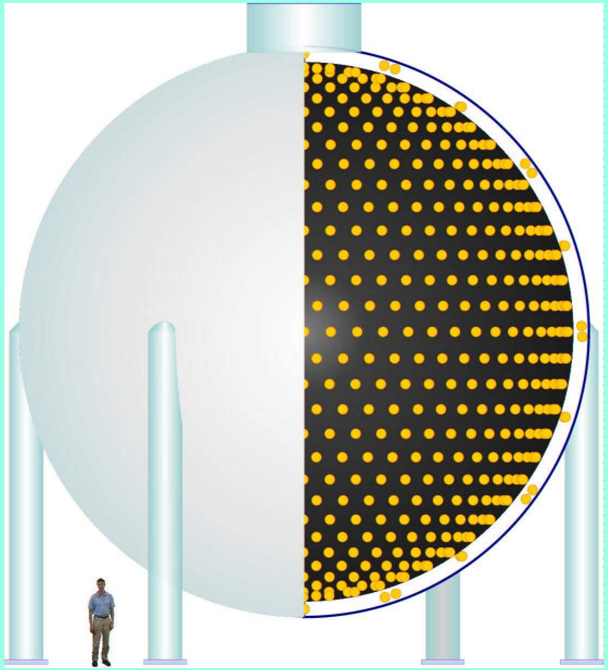
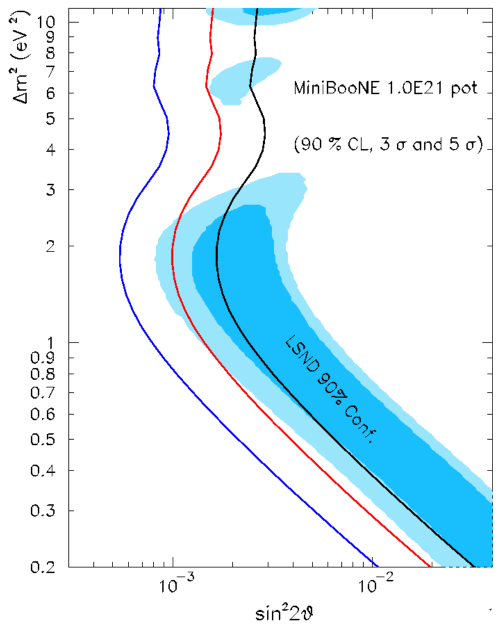
Mini-Boone



- 12 m diameter sphere
- 950 litres of pure mineral oil
- 1280 inner 8” PMTs (10% coverage)
- 240 PMT outer veto region



L=540 m <E> =500 MeV

One third of data already taken

ν_e appearance in a ν_μ beam: analysis with 10^{21} pot hopefully ready for 2005

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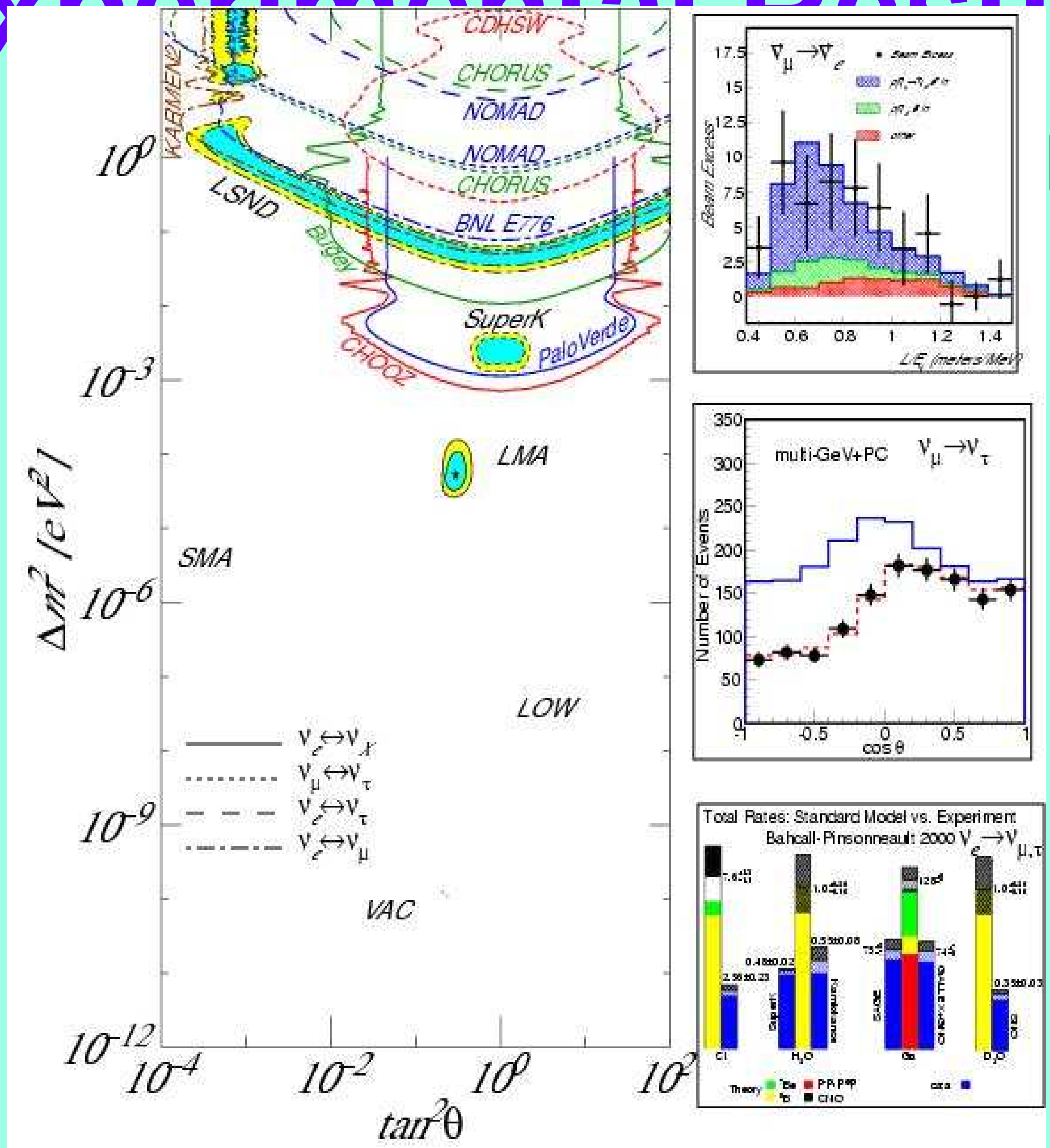
Summary of Experimental Results



LSND

Atmospheric

Solar

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Known and Unkown Things

ATMOSPHERIC, K2K

$$1.9\times10^{-3}\,eV^2 < \Delta m^2_{23} < 3.0\times10^{-3}\,eV^2$$

$$\sin^2 2\Theta > 0.90 \quad at\ 90\%\ C.L.$$

SOLAR, KAMLAND

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5}\times10^{-5}\,eV^2$$

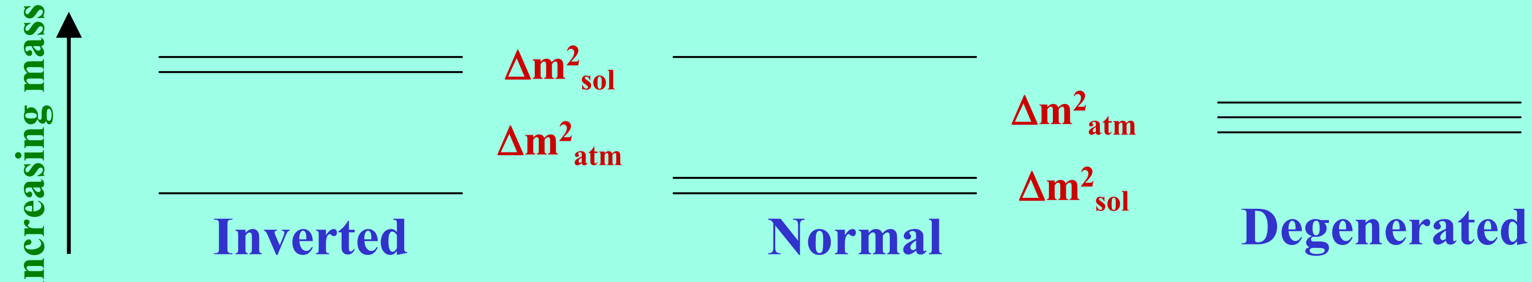
$$\tan^2\vartheta_{12} = 0.40^{+0.09}_{-0.07}$$

ATMOSPHERIC, K2K, SOLAR, REACTOR

$$\Theta_{13} < 14^\circ$$

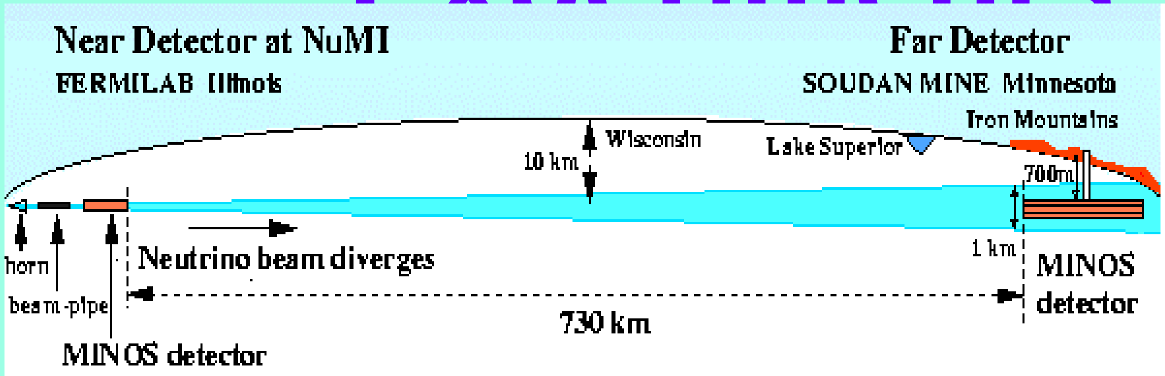
But, we do not know yet…

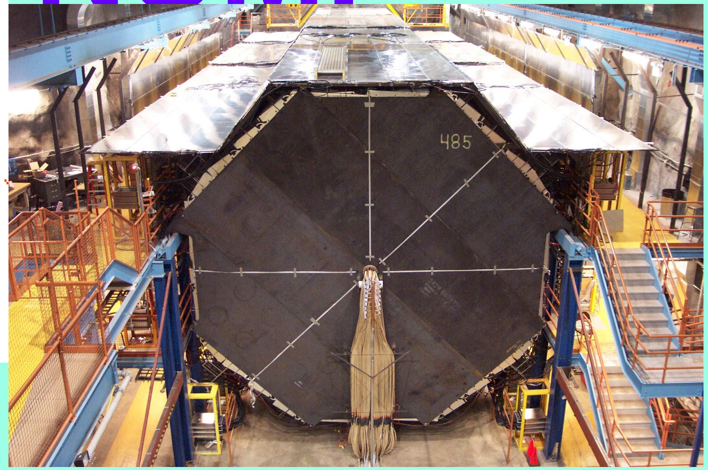
Θ_{13} different from zero? δ value? mass hierarchy?



$m^2 >> \Delta m^2$

Long Baseline Experiments: NUMI



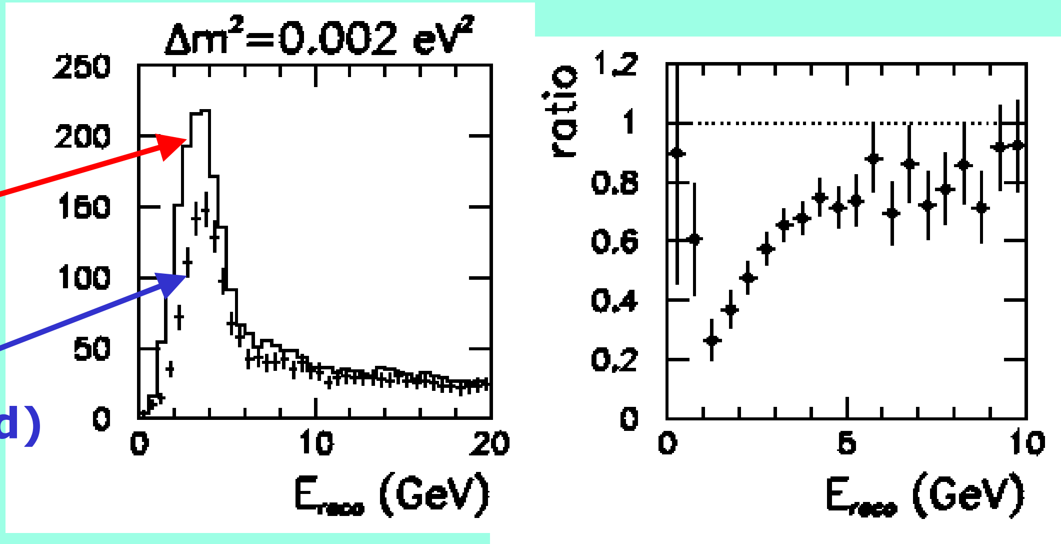


Magnetized Iron (1.5 T)

5.4 ktons

Near (unosc)

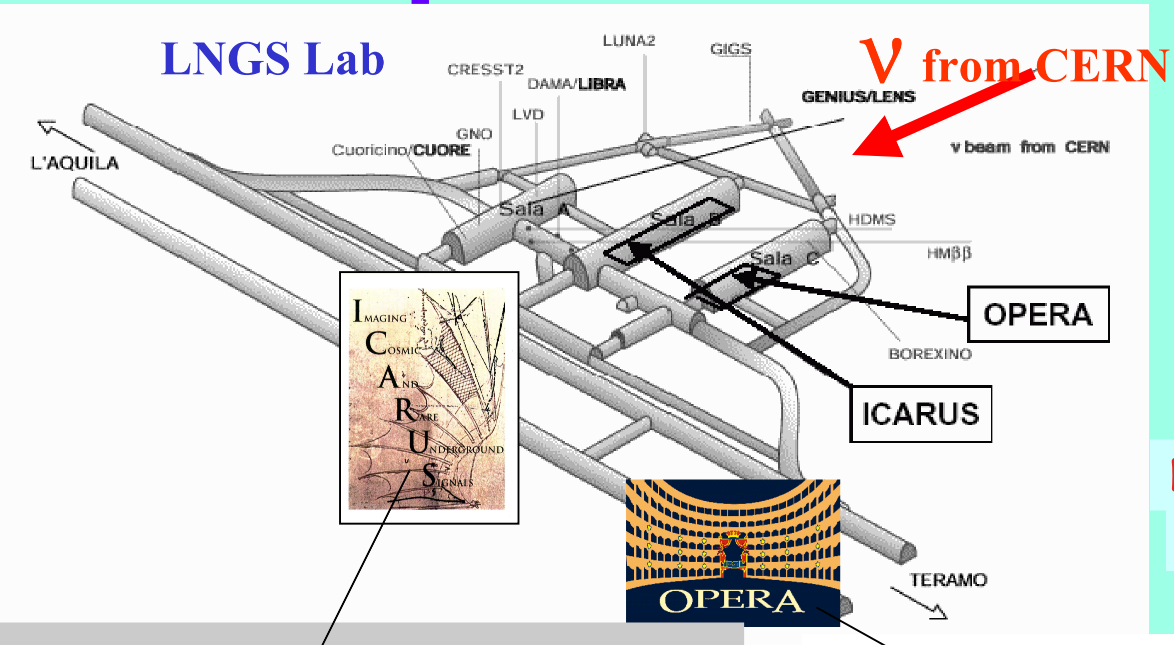
Far (oscillated)



Depth of minimum ➡ $\sin^2 2\theta$

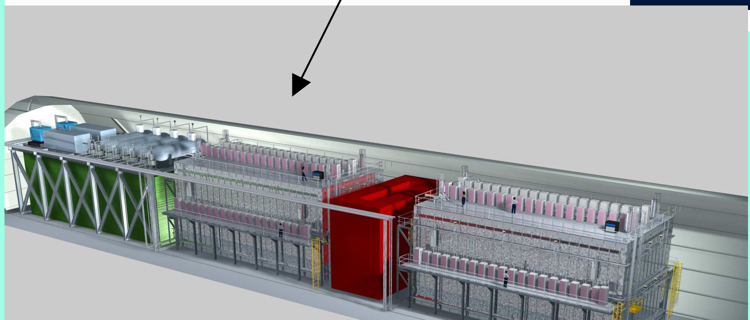
Position of minimum ➡ Δm^2

Experiments: CNGS

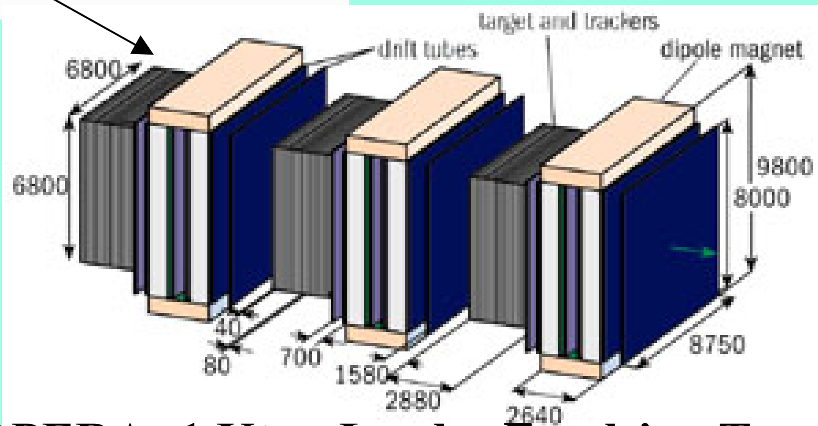


Neutrinos de *Long Baseline*

$L_{CERN-Gran\ Sasso}$ = 730 km



ICARUS: 3 Kton LAr + μ Spectrometer

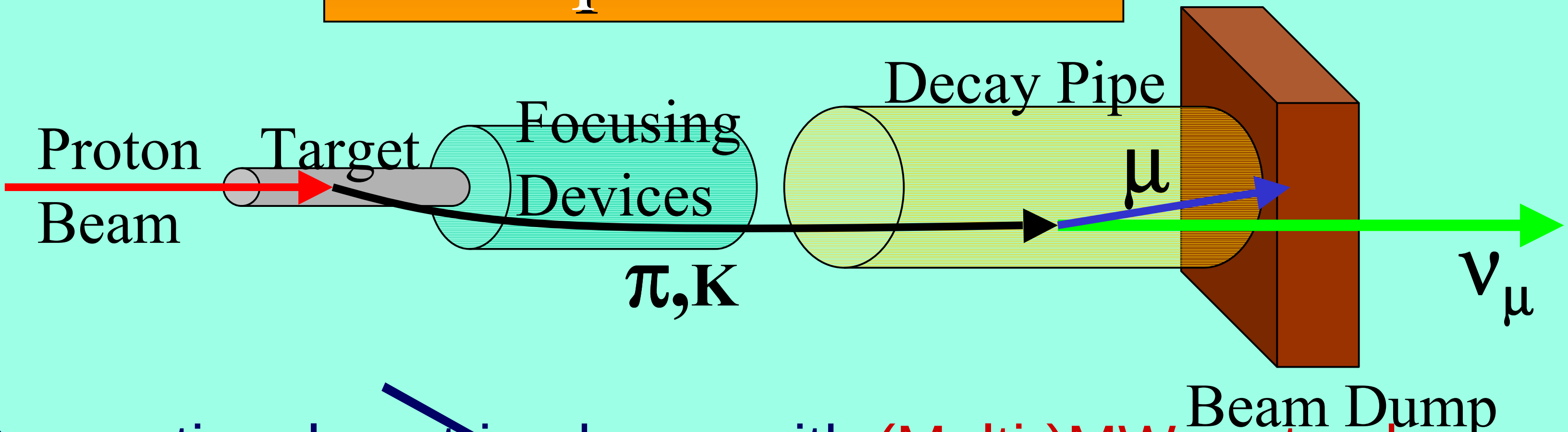


OPERA: 1 Kton Lead + Emulsion Target

Explicit search for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations

The Future is Bright…

Super-Beams



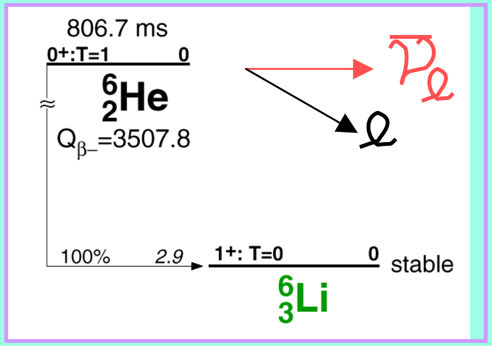
- Conventional neutrino beam with (Multi-)MW proton beam
  Pure ν_μ beam (~99%)
- ν_e (~1%) from $\pi \rightarrow \mu \rightarrow e$ chain and K decay(Ke3)
- ν_μ/anti–ν_μ can be switched by flipping polarity of focusing device
- Experiments under consideration:
  - *(Multi-)MW beam + Mton detector (or Liq.Ar)*
  - *Japan: 4MW 50GeV @ J-PARC → Mt Hyper-Kamiokande*
  - *Europe: 4MW 2.2GeV SPL → Mt UNO*
  - *US-BNL: 1(2)MW AGS → UNO(Liq.Ar)@~2500km*
  - *US-FNAL: 2MW PD/MI → NOνA/ UNO(liq.Ar)@~1300km*

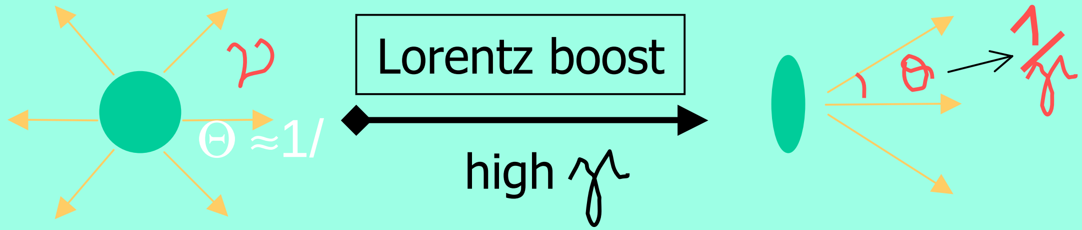
...and Brighter...

Beta Beams

THE CONCEPT : P. Zucchelli, PLB 352 (2002) 166

A novel method to produce neutrino beams based on beta-decay (accelerate and store radioactive ions)





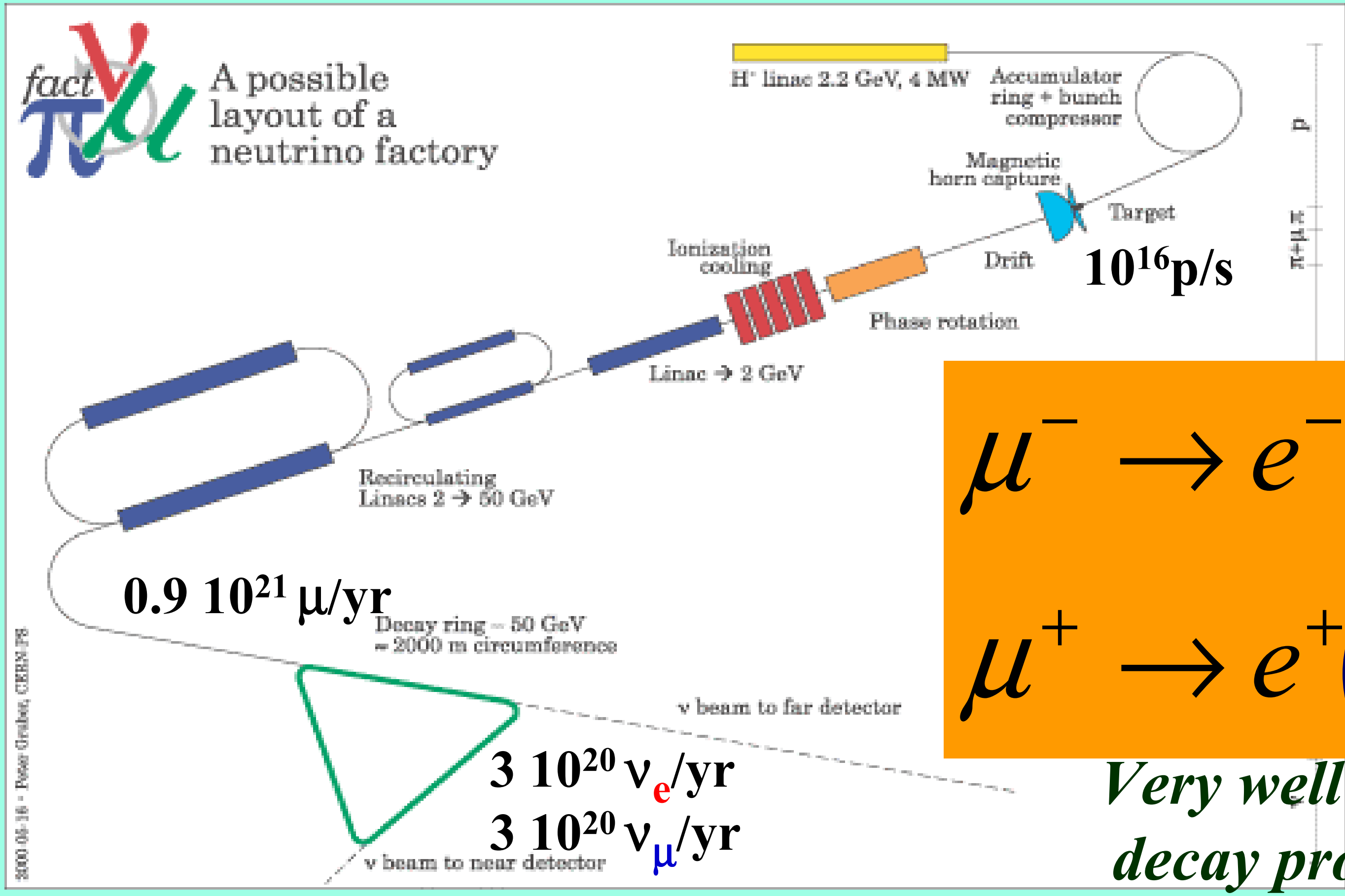
ADVANTAGES OF BETA-BEAMS :

- Pure (ν_e or $\bar{\nu}_e$) beams.
- Well known neutrino fluxes.
- Strong collimation.

A NOVEL METHOD TO PRODUCE INTENSE, COLLIMATED, PURE HIGH ENERGY NEUTRINO BEAMS FROM BOOSTED RADIOACTIVE IONS.

...and even Brighter

Neutrino Factory



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

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Very well known decay processes

Ultimate tool to understand neutrino properties

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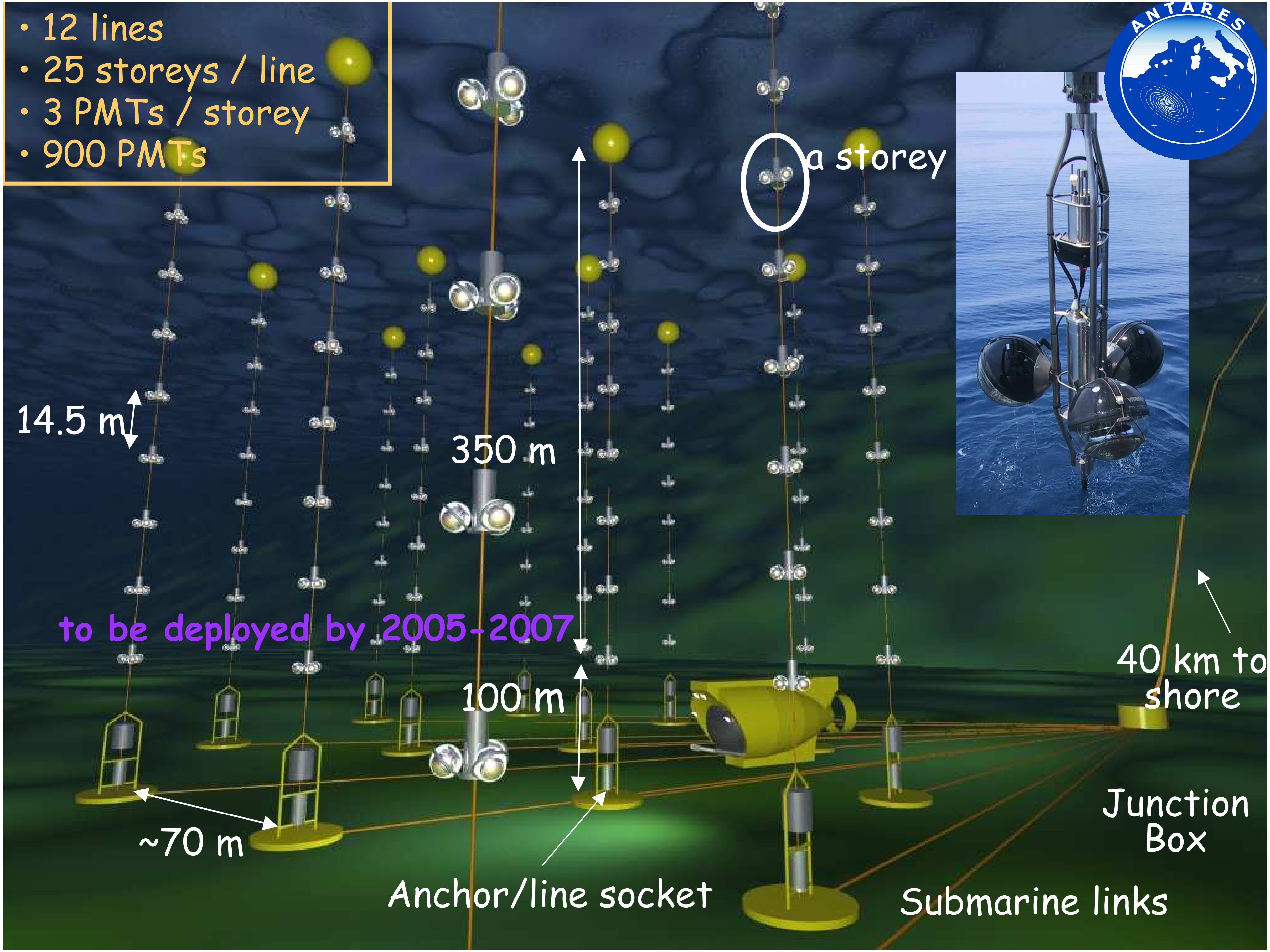
• 12 lines
• 25 storeys / line
• 3 PMTs / storey
• 900 PMTs
a storey
14.5 m
350 m
to be deployed by 2005-2007
100 m
~70 m
Anchor/line socket
40 km to shore
Junction Box
Submarine links
ANTARES

Conclusions

- Contrary to the low-level past, sad present, negative surprises and dark future (if any)…

- *Neutrino Physics had an outstanding past and a brilliant present. Its future is bright and hopefully it has a full stock of (positive) surprises*

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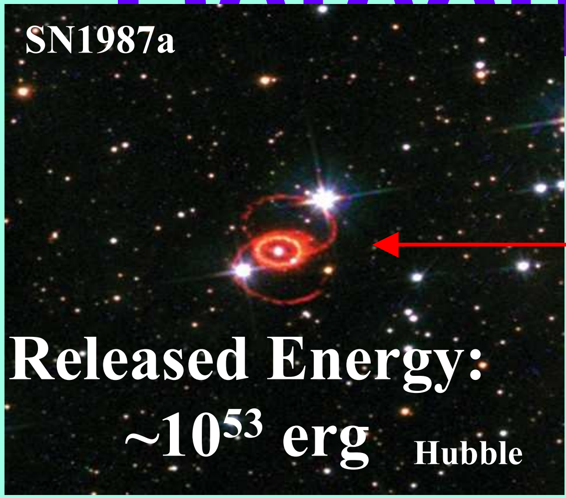
Back-Up

Supernova Neutrino Detection in Super-K



d = 170 000 light-years

$\approx 10^{58}$ ν emitted
$\langle E_\nu \rangle = 10$ MeV

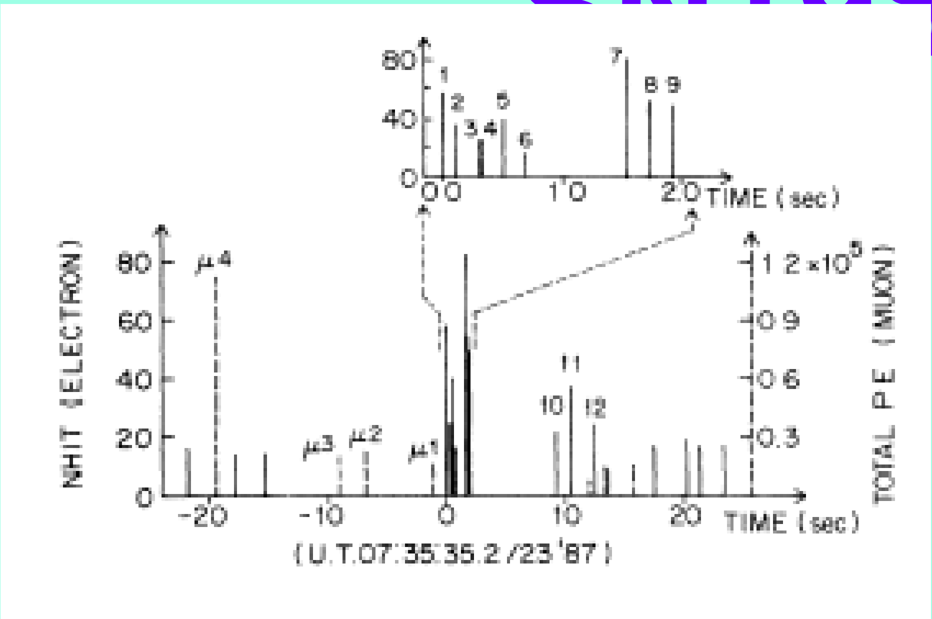
$\approx 5\times10^{10}$ ν/cm^2

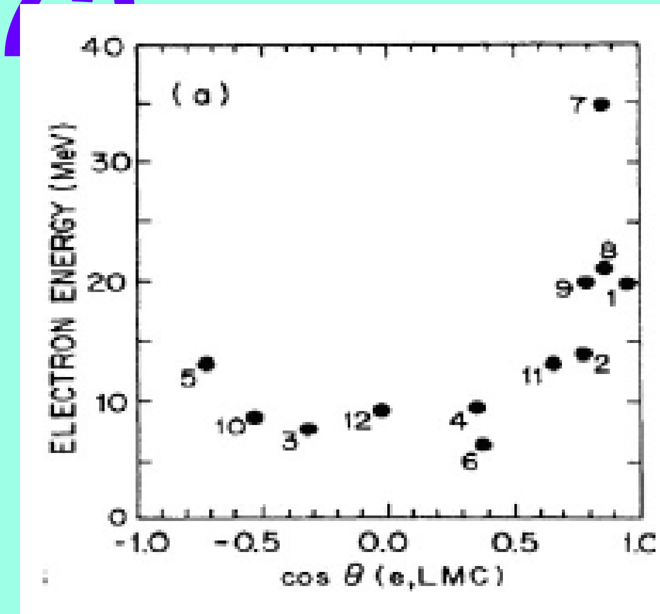
REACTIONS

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

$$\nu e^- \rightarrow \nu e^-$$

Kamiokande y SN1987a





Doce sucesos detectados en una ventana de tiempo de 13 s

Confirmación de teorías sobre formación de estrellas de neutrones

Primera detección de neutrinos extra-galácticos

Inicio de la

Astronomía de Neutrinos

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