UNIT1: Experimental Evidences of Neutrino Oscillation Atmospheric and Solar Neutrinos

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HEP PostGraduate Lectures 2016
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Neutrino Sources

- Artificial:
  - nuclear reactors
  - particle accelerators

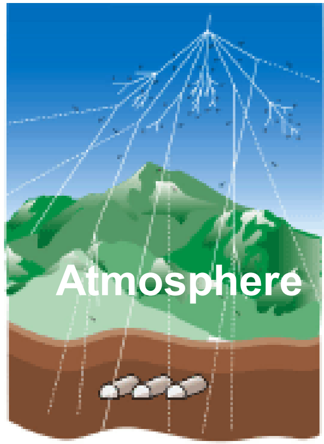
First detected neutrinos

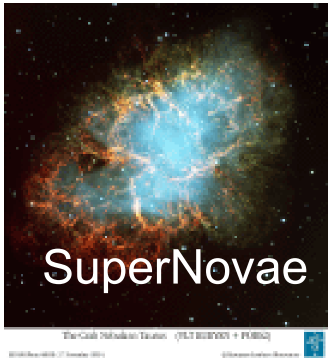
- Natural:
  - Sun
  - Atmosphere
  - SuperNovae
  - fission in the Earth core (geoNeutrinos)
  - Astrophysical origin (Old supernovae, AGN, etc.)

Expected, but undetected so far,:

- relic neutrinos from BigBang (~300/cm^3)

Neutrinos are everywhere!

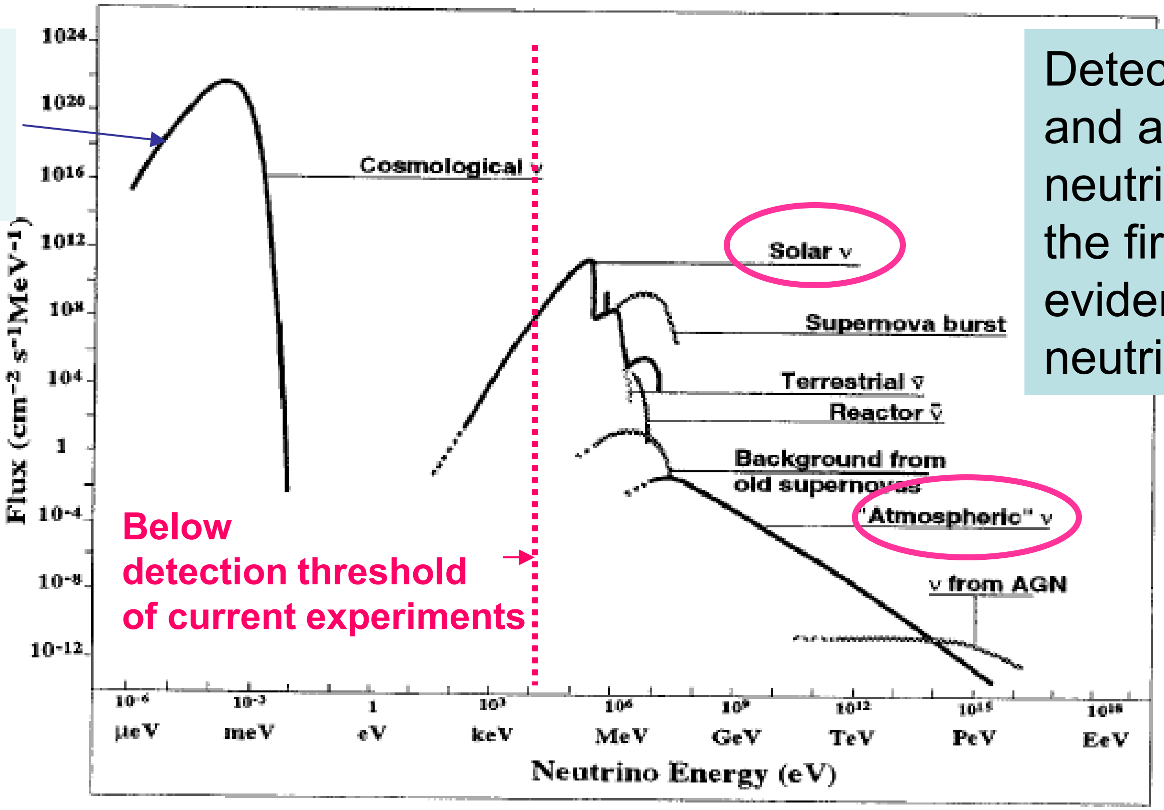




Neutrino Flux vs Energy

The Sun is the most intense detected source with a flux on Earth of of 6 $10^{10}\ \nu/cm^2s$

Abundant but challenging detection

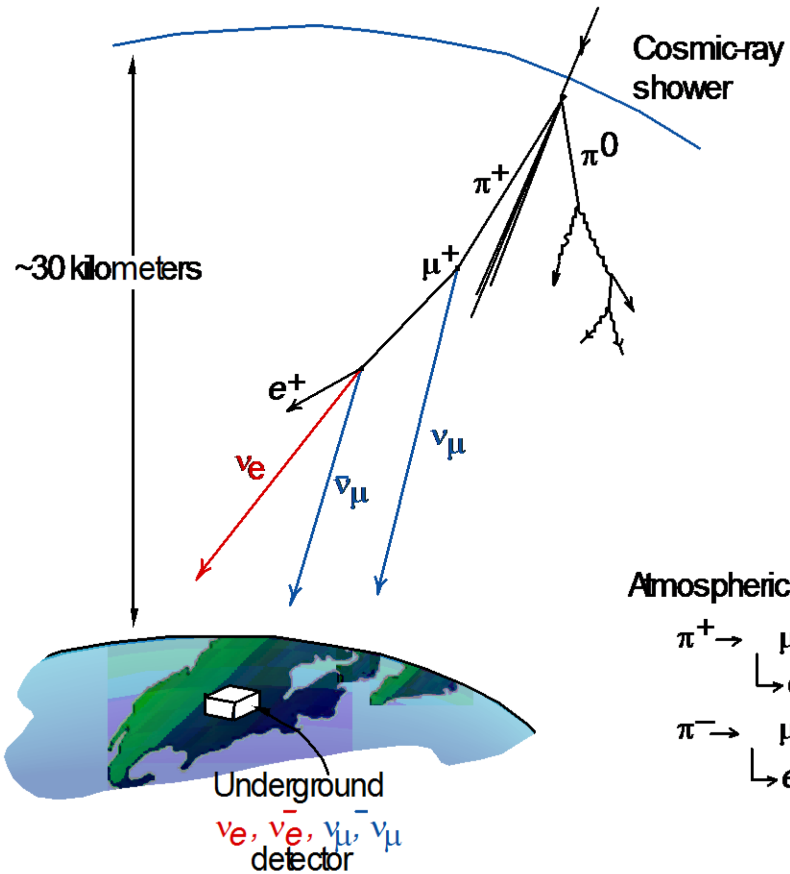


Detection of solar and atmospheric neutrino has provided the first compelling evidence of neutrino oscillations

D.Vignaud and M. Spiro, Nucl. Phys., A 654 (1999) 350

Atmospheric Neutrinos

Neutrino Production in the Atmosphere



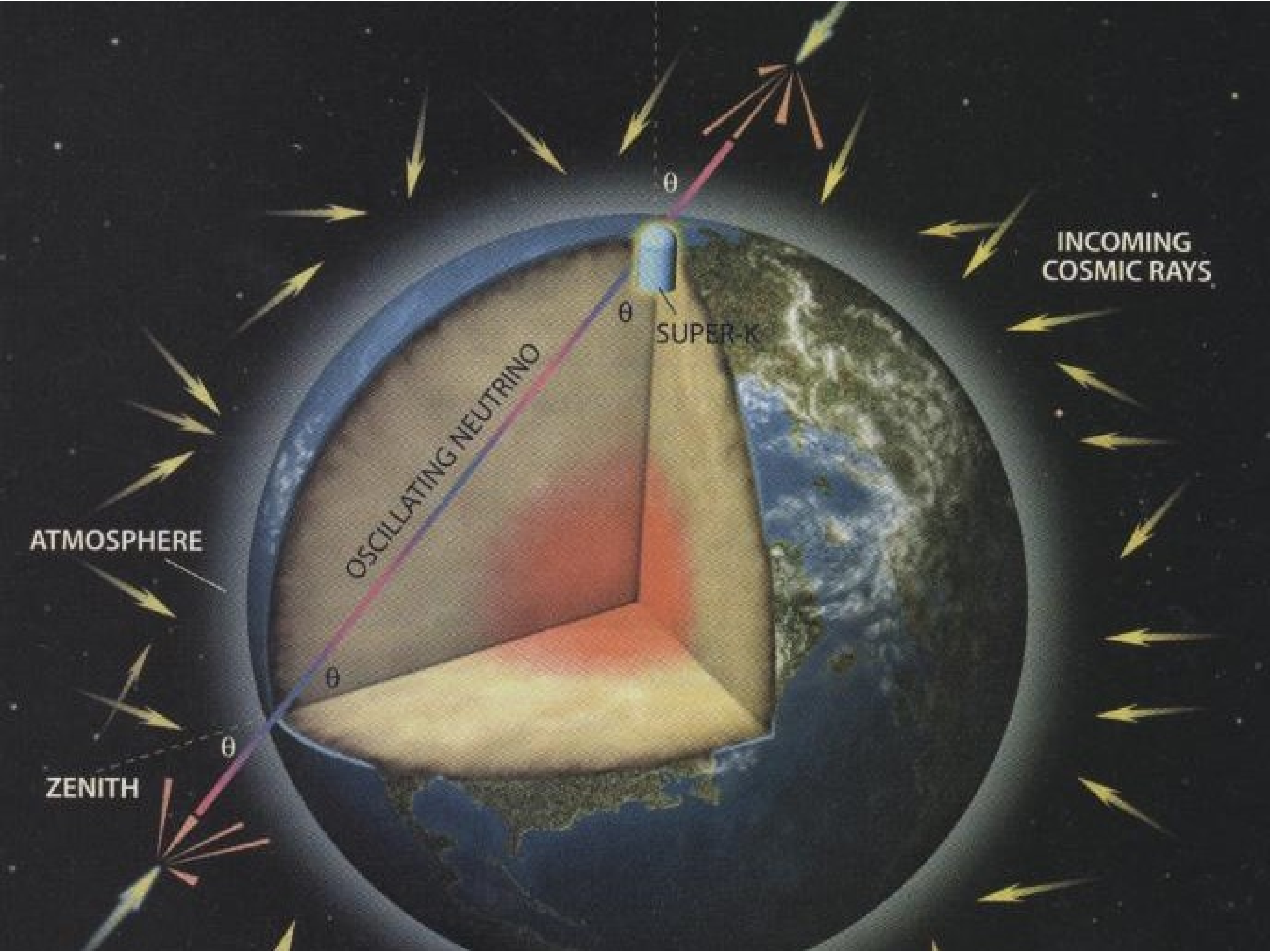
Atmospheric neutrino source

$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

Absolute ν flux has ~10% uncertainty
But muon/electron neutrino ratio is known with ~3% uncertainty. Expected:

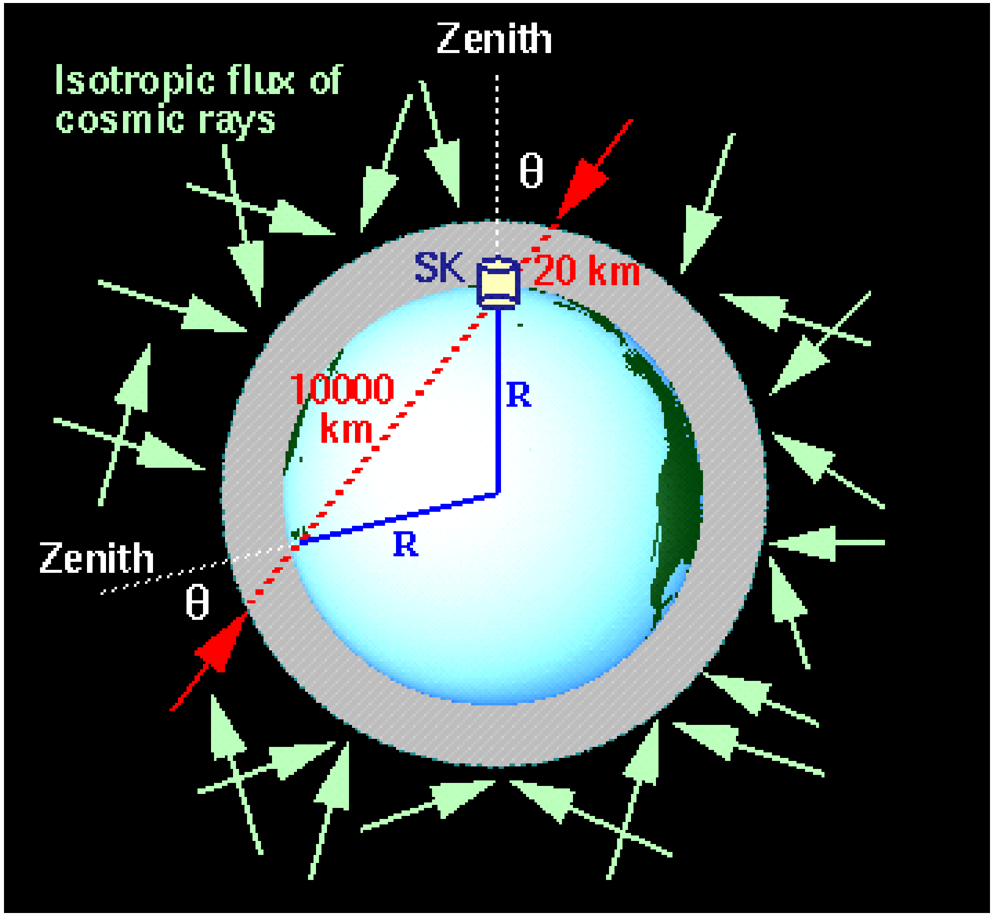
$$\frac{\phi(\nu_\mu + \overline{\nu}_\mu)}{\phi(\nu_e + \overline{\nu}_e)} \approx 2$$


INCOMING
COSMIC RAYS
SUPER-K
OSCILLATING NEUTRINO
ATMOSPHERE
ZENITH
θ
θ
θ
θ

Cosmic Flux Isotropy

We expect an isotropic Flux of neutrinos at high energies (earth magnetic field deviate path of low-momentum secondaries only : East-West effects)

For E_{ν} > a few GeV, and a given ν flavour
(Up-going / down-going) ~ 1.0 with <1 % uncertainty



Note the baseline (= distance νproduction-νdetection) spans 3 order of magnitudes!

Atmospheric neutrino detectors

Neutrinos in 100 MeV – 10 GeV energy. Flux ~ 1 event/(cm^2 sr sec)
$\Rightarrow$**Quasi-elastic interaction region**

Small cross-section $\Rightarrow$ Massive Detector (kTons)
Background from charged cosmic rays $\Rightarrow$ deep underground location:mines, caverns under mountains, provide >1 Km rock overburden necessary to reduce the muon flux by 5-6 orders of magnitude

2 detection techniques:
- Calorimetric - iron and tracking detectors (Nusex, Frejus, Soudan)
- Cherenkov - water (Kamiokande, IMB)

First detectors built to search for proton-decay. Atmospheric neutrinos studied as they constitute a background for this search. First “anomalies” seen in the flux ratio.

The first experiment to claim model-independent observation of oscillation (non-uniform zenith angle distribution) is SuperKamiokande (1998). Super = 20 times bigger than Kamiokande.

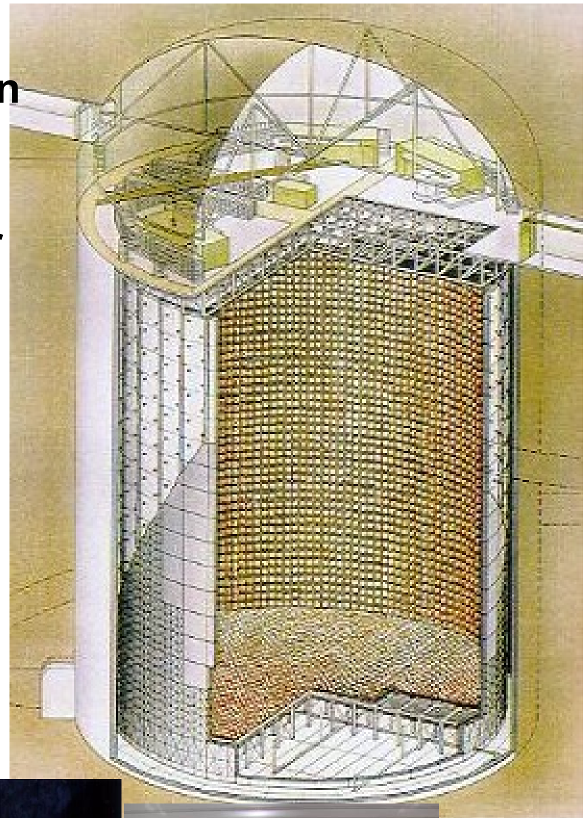
SUPER-KAMIOKANDE (SuperK)

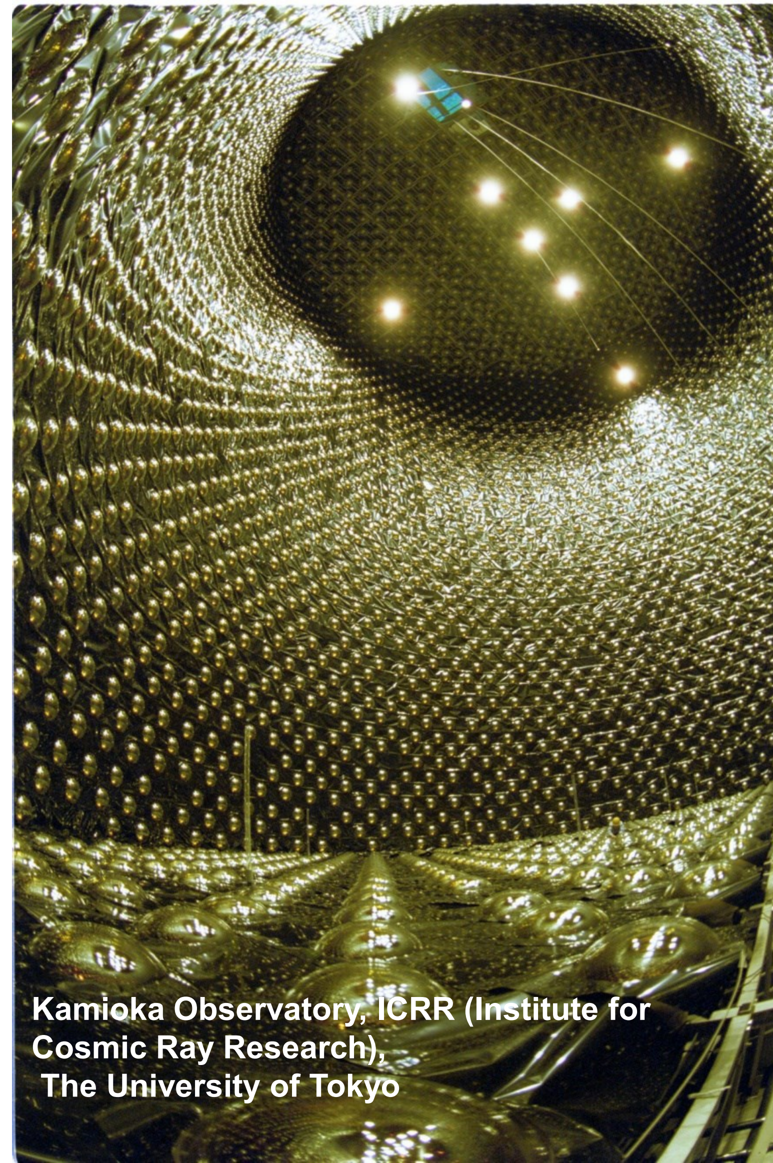
Kamioka Mine in Japan

- **1400m underground**

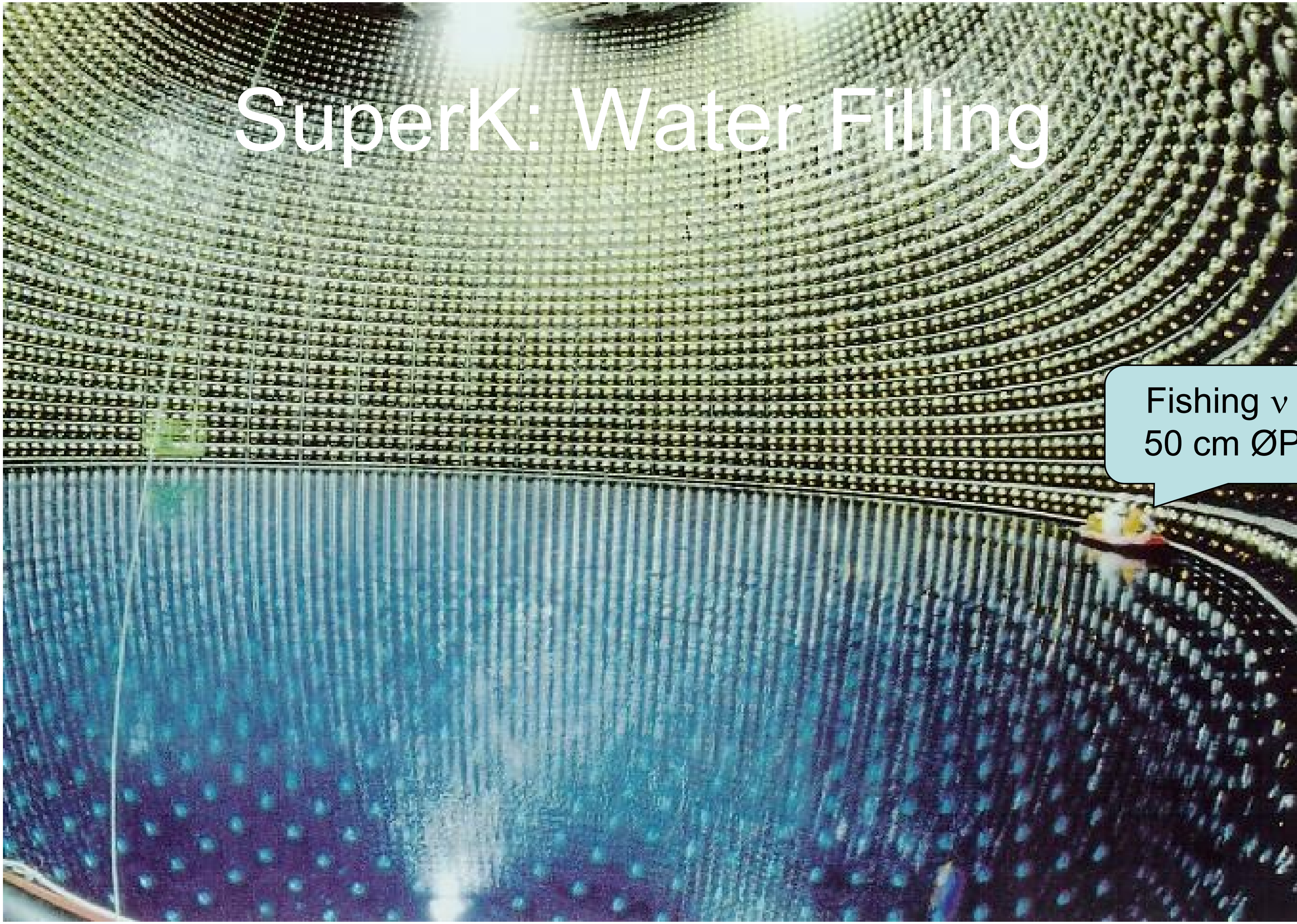
50 ktons of pure water (Fiducial volume for analysis 22.5 ktons)

- **10,000 PMT inner detector**
- **2,000 PMT outer detector (cosmic ray veto)**





SuperK: Water Filling



Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

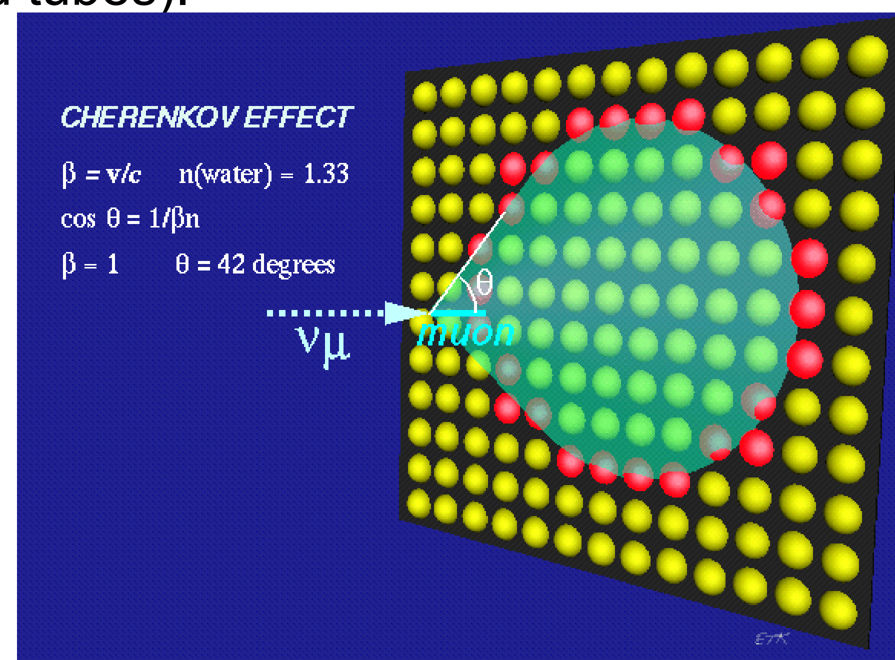
Detection Principle

Super-Kamiokande is a water Cherenkov detector.
Charged particles traveling in water with speed higher than c/n (i.e., above threshold for Cherenkov light production) emit Cherenkov light.
Most important reaction: quasi-elastic $\nu_e\, n \rightarrow p\, e^-$, $\bar{\nu}_e\, p \rightarrow n\, e^+$

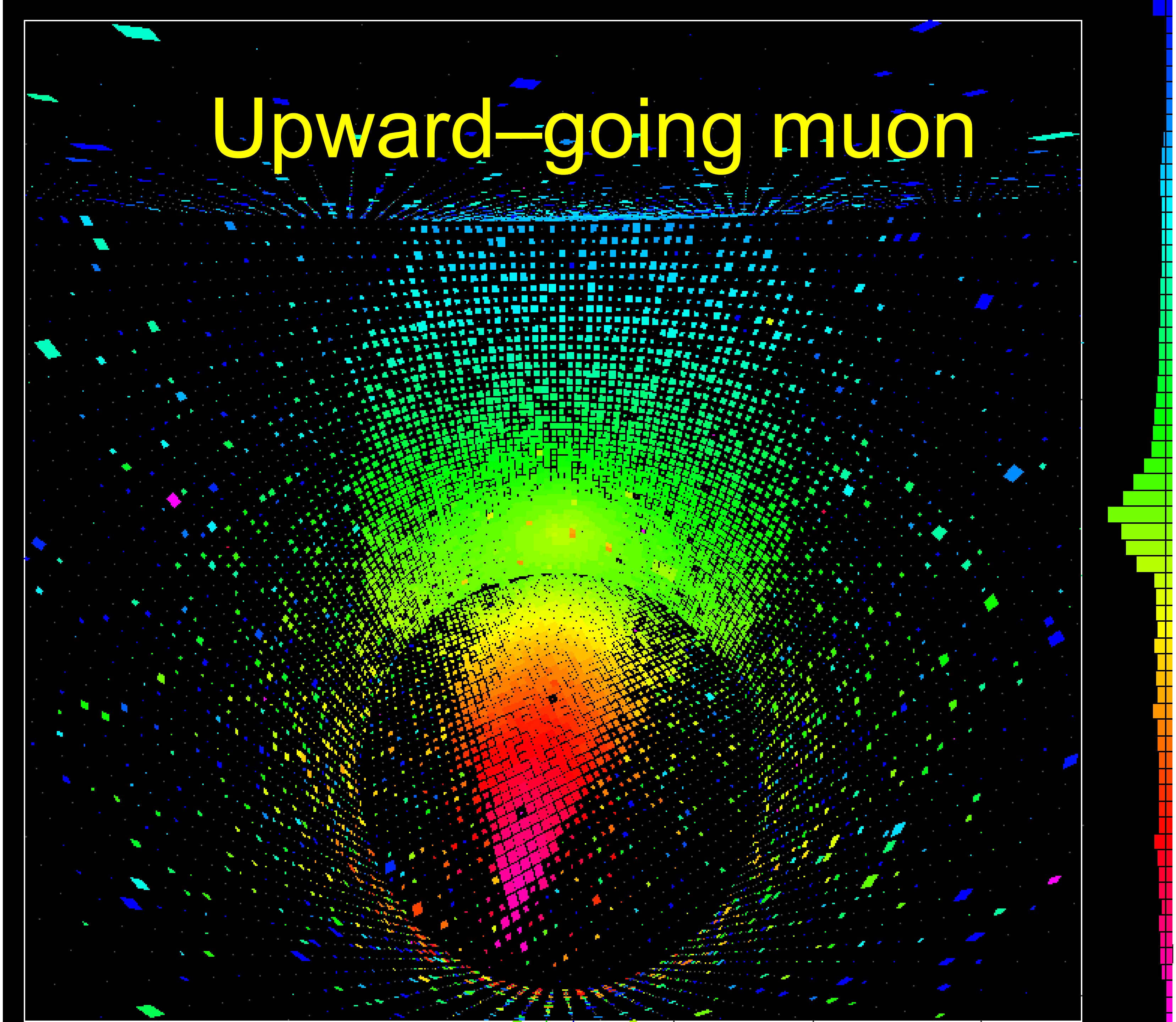
$\nu_\mu\, n \rightarrow p\, \mu^-$, $\bar{\nu}_\mu\, p \rightarrow n\, \mu^+$

Only leptons above Cherenkov threshold detected, charge not identified
Cherenkov light is detected by an array of light sensitive photomultipliers.
The image is in the form of a ring (red tubes).

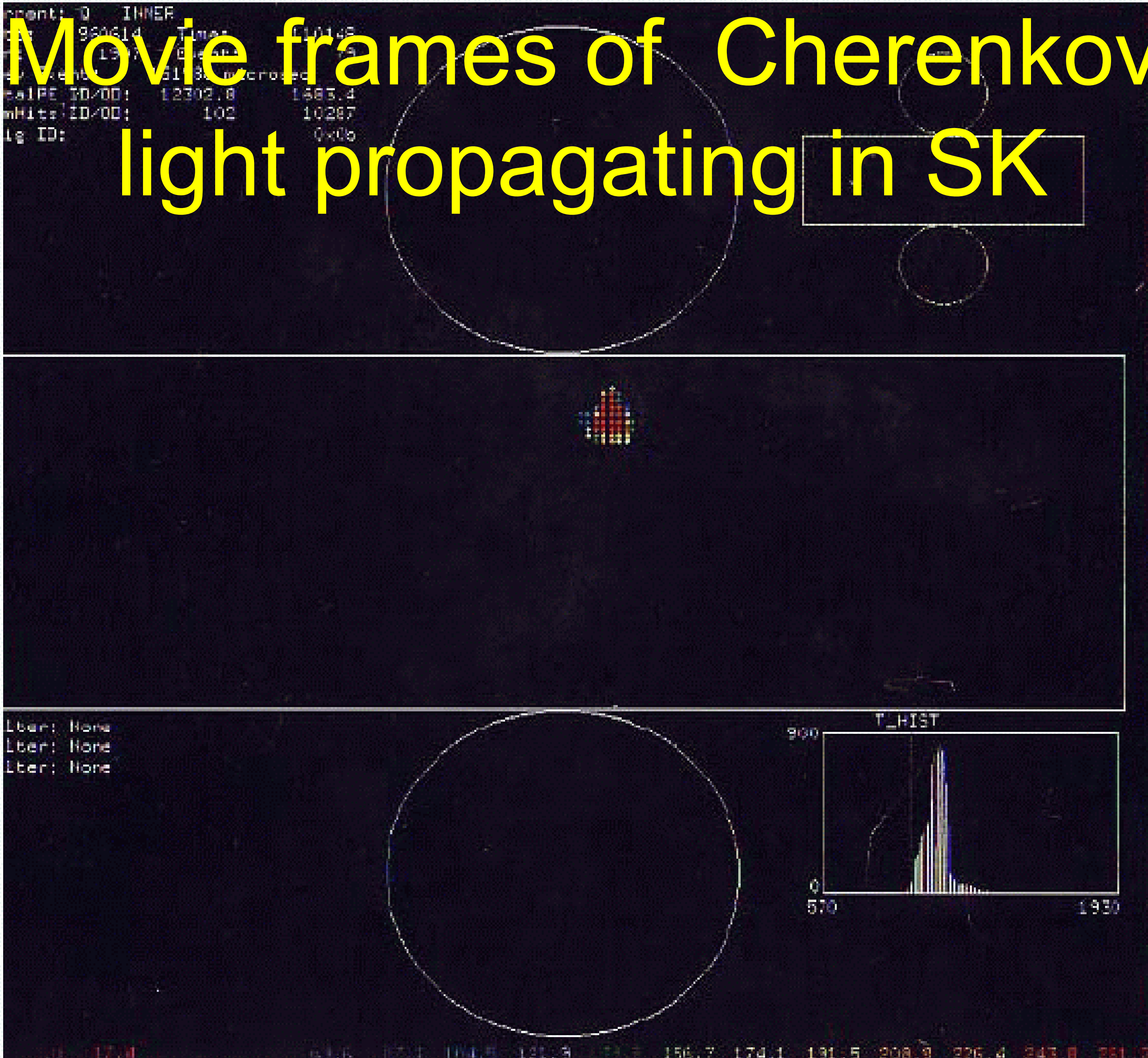
The cone aperture determines velocity. If we can identify the particle than we know its mass, and from velocity we can compute its energy or momentum: $\beta = p/E$, $E^2 = m^2 + p^2$



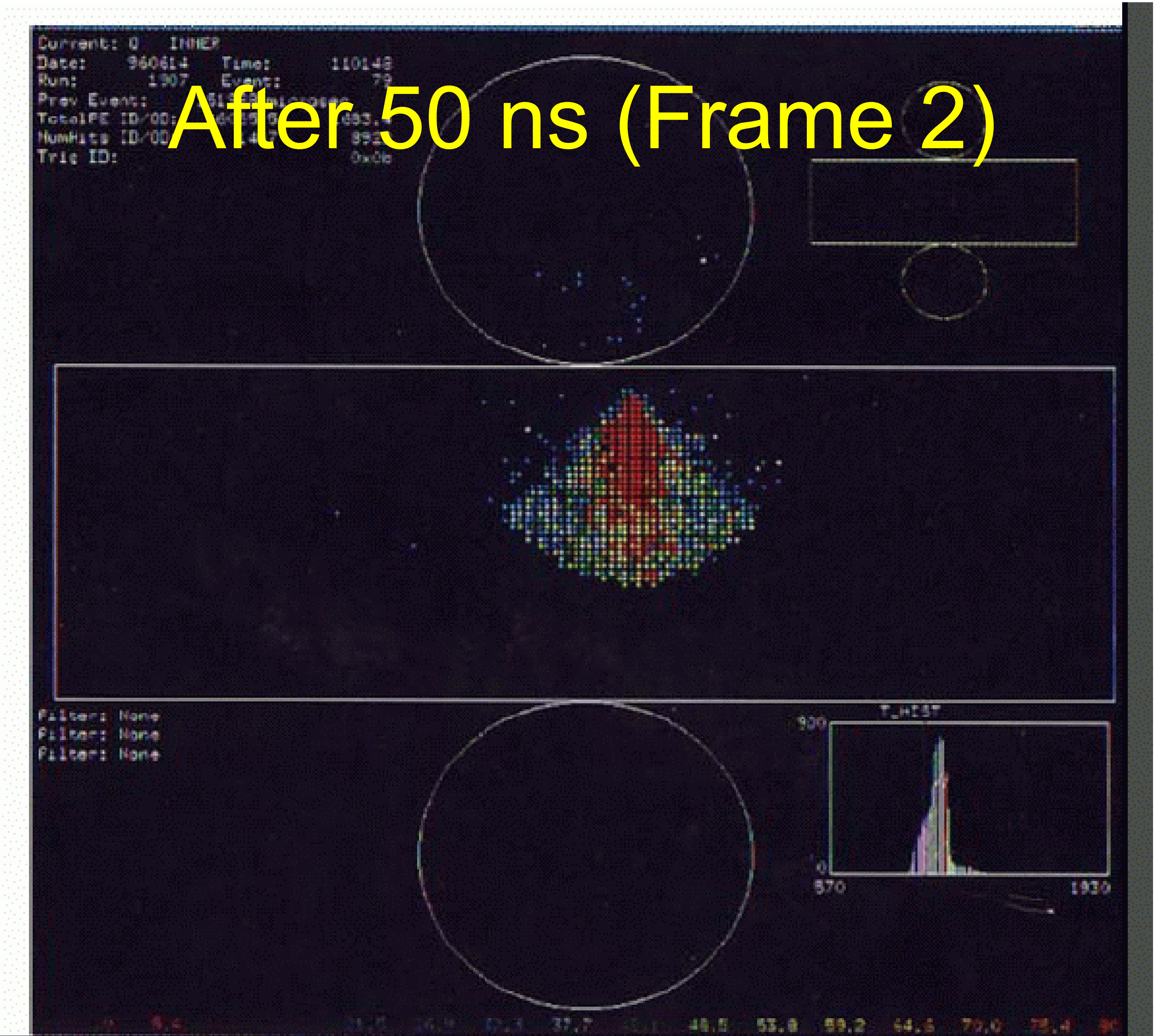
Upward–going muon

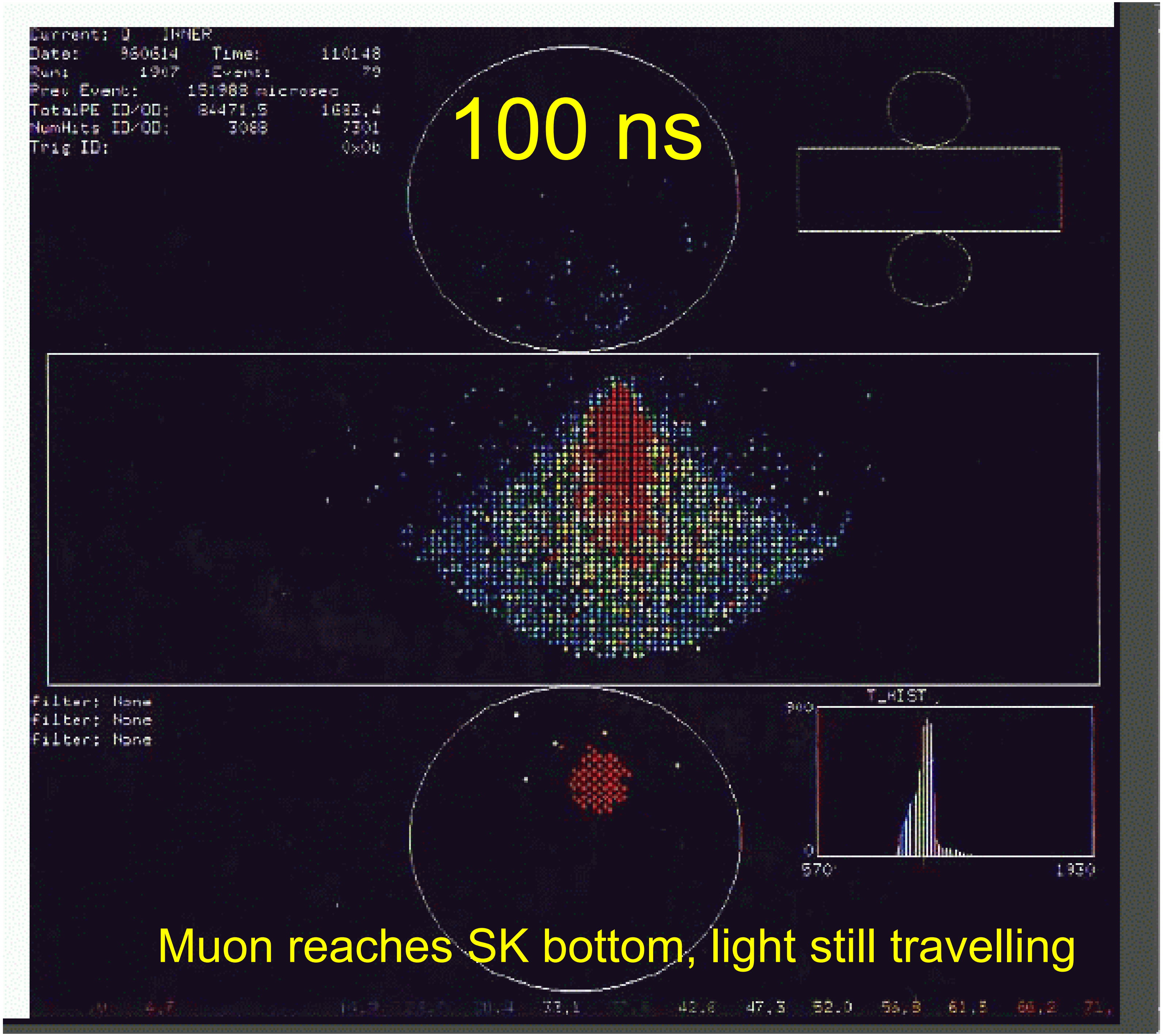


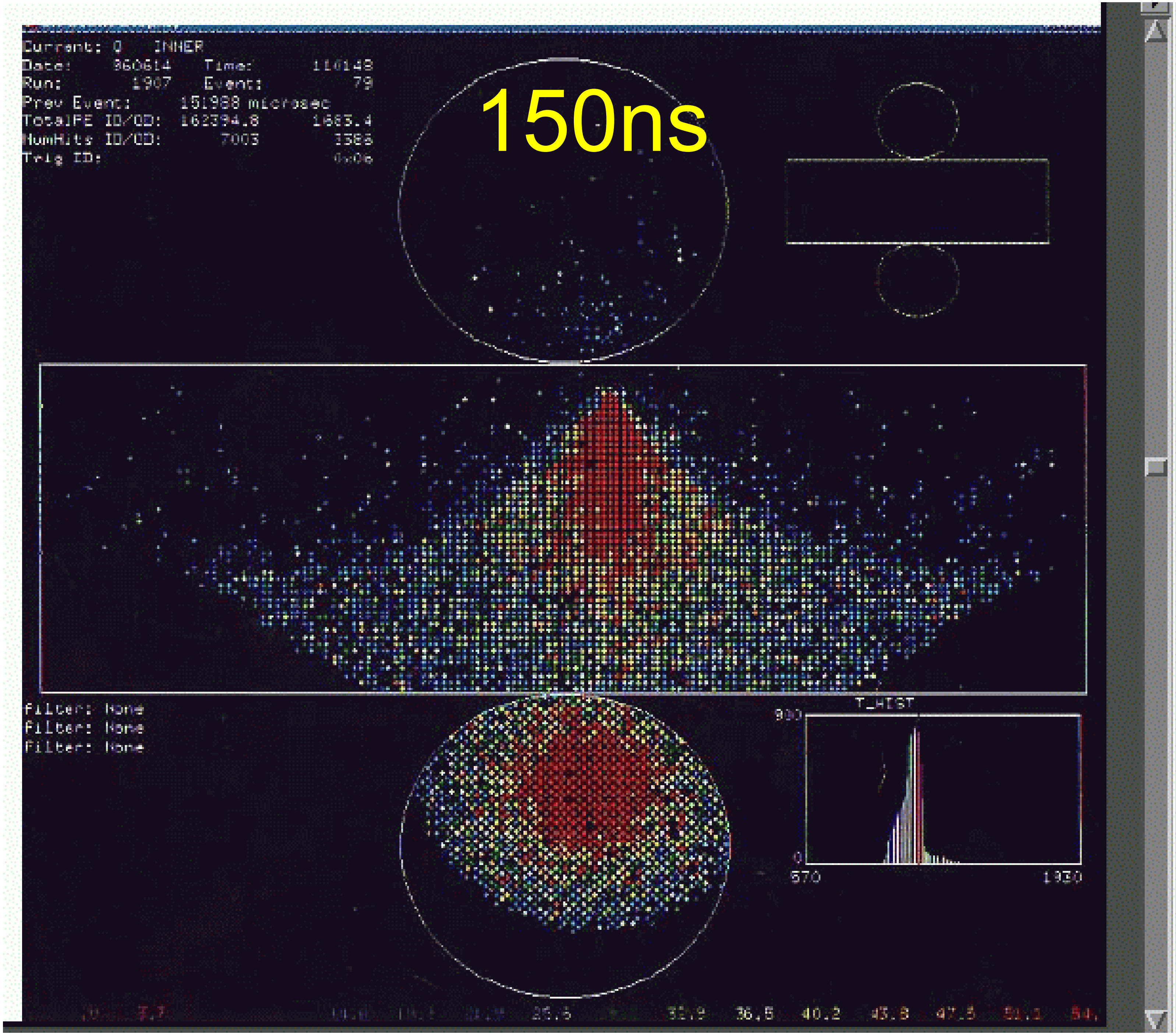
Movie frames of Cherenkov light propagating in SK

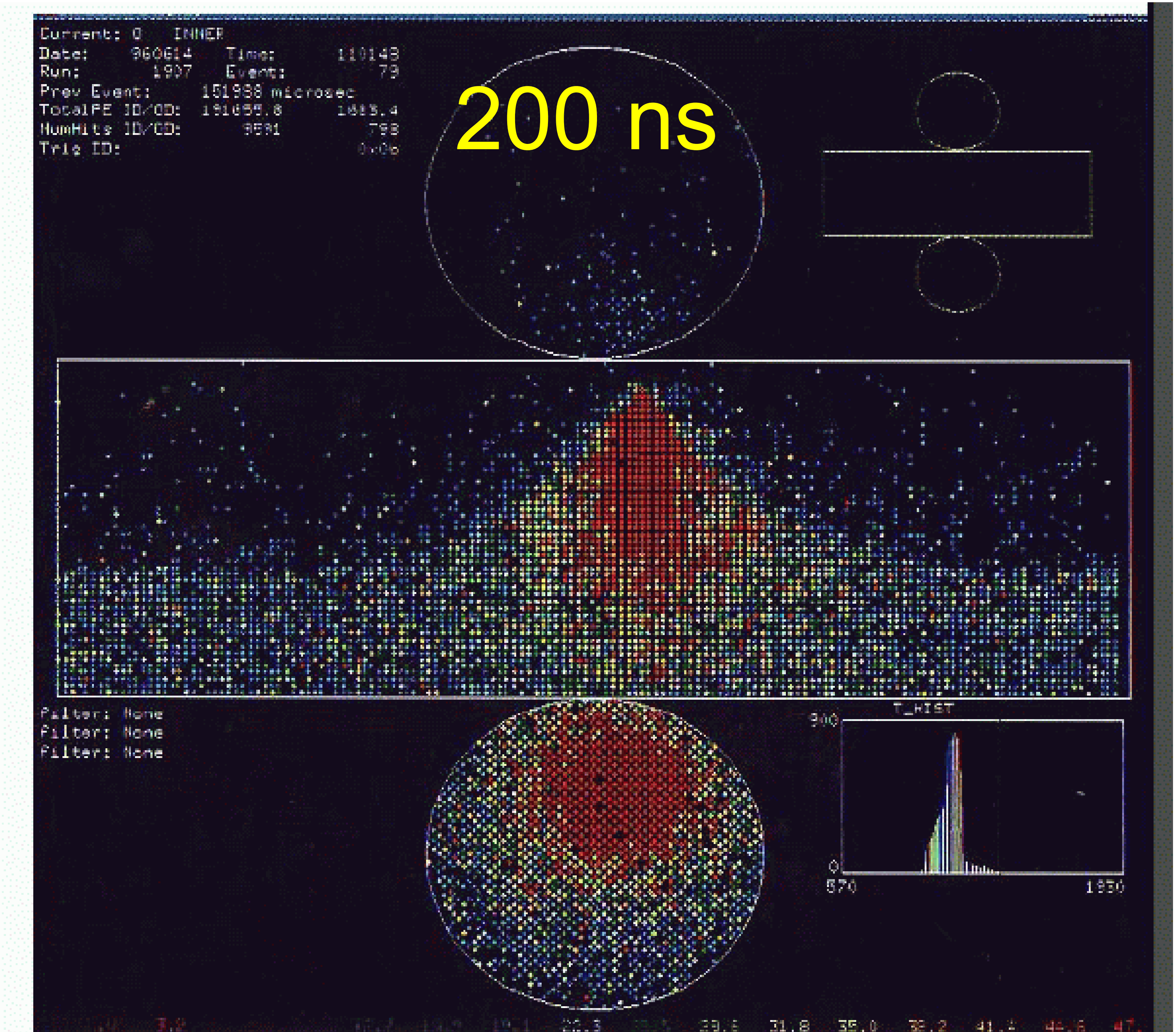


After 50 ns (Frame 2)

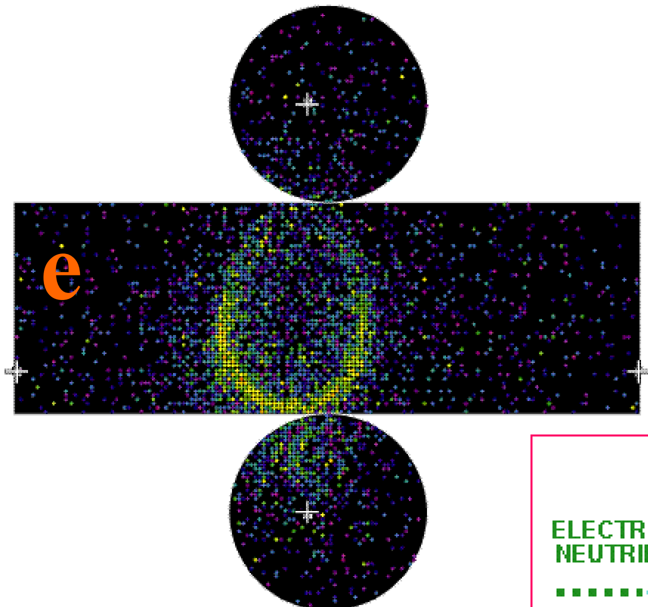


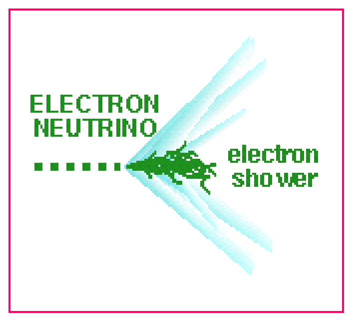

Current: 0 INNER
Date: 960614 Time: 110148
Run: 1907 Event: 79
Prev Event: 151988 microsec
TotalPE ID/OD: 84471.5 1683.4
NumHits ID/OD: 3088 7301
Trig ID: 0x06
100 ns
Filter: None
Filter: None
Filter: None
T_HIST
Muon reaches SK bottom, light still travelling

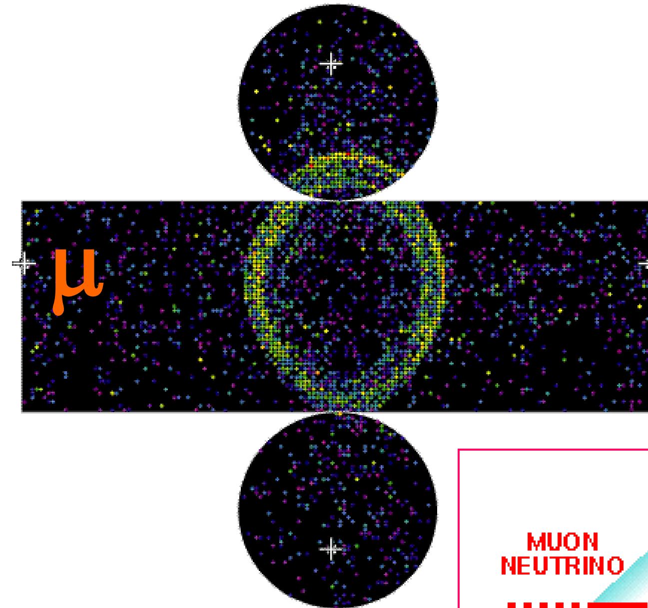

150ns
Current: 0 INNER
Date: 960614 Time: 110148
Run: 1907 Event: 79
Prev Event: 151988 microsec
TotalPE ID/OD: 162394.8 1663.4
NumHits ID/OD: 7003 1386
Trig ID:
Filter: None
Filter: None
Filter: None
T_HIST
0
570
1930
25.6
32.9
36.5
40.2
43.8
47.5

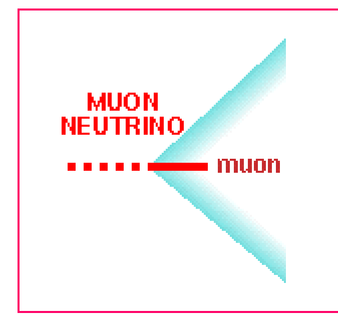

200 ns
Current: 0 INNER
Date: 960614 Time: 110148
Run: 1907 Event: 79
Prev Event: 151998 microsec
TotalPE ID/OD:
NumHits ID/OD: 9591
Trig ID:
Filter: None
Filter: None
Filter: None
T_HIST

Electron and Muon Identification





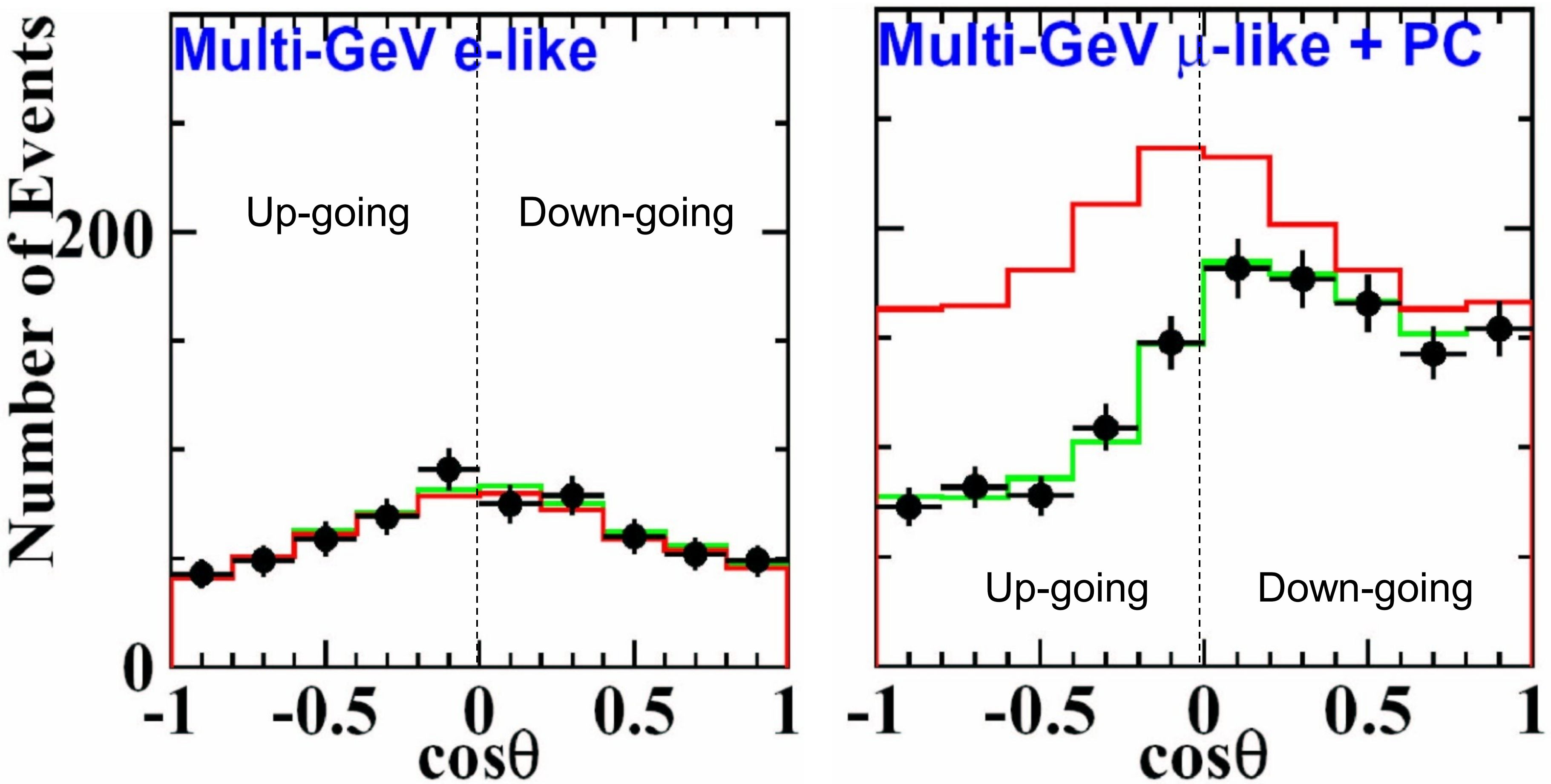




Electron ring is fuzzier than muon ring. Electron produces shower of gammas, electrons and positrons. Gammas don't produce Cherenkov light. Electrons and positrons do. In the shower each of them flies at a little bit different angle and each of them makes its own weak Cherenkov ring. All those rings added together produce the observed fuzzy ring. This difference in sharpness of muon and electron rings is used to identify muons and electrons in Super-Kamiokande.

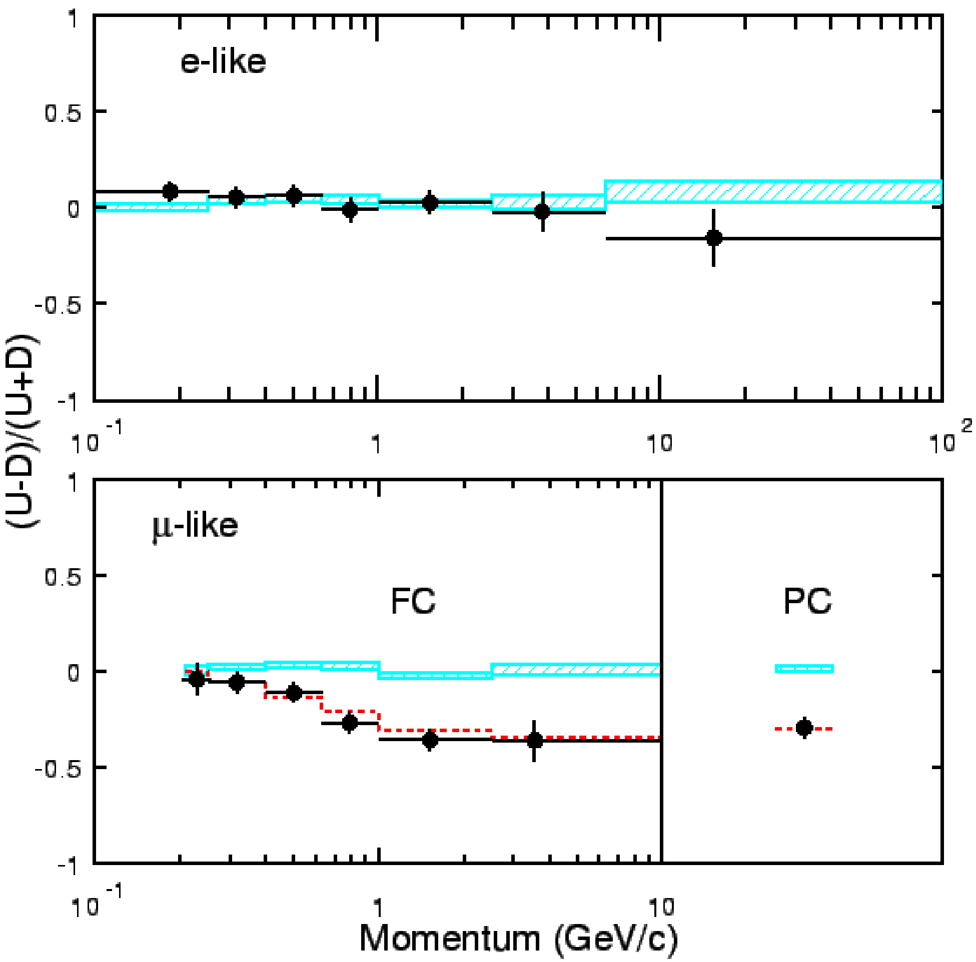
From the Official SuperK WEBSite: http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/index.html

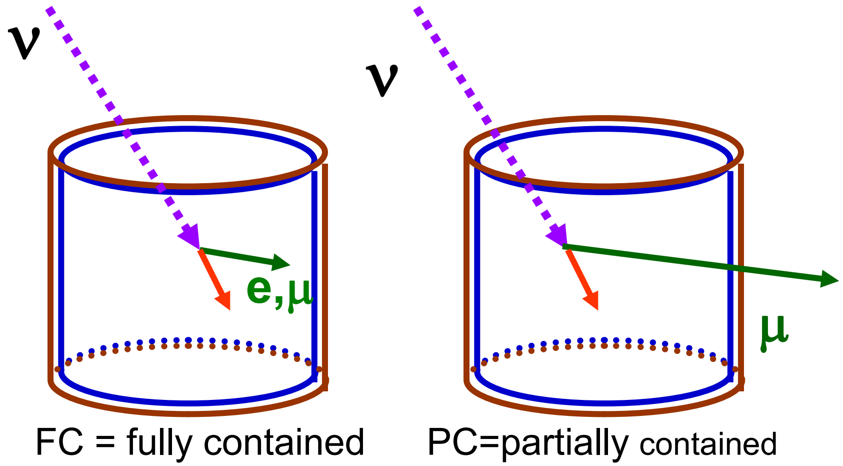
Zenith angle Distribution



Half of the ν_μ are lost!

Up-down Asymmetry (SuperK)





The mechanism to produce the asymmetry must depend on the distance traveled and on ν energy ⇒ν Oscillations

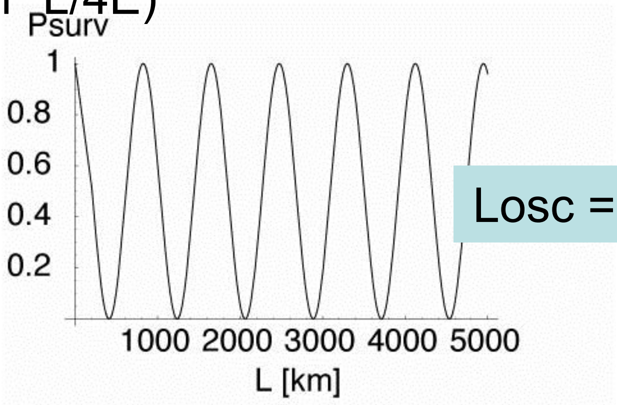
The hatched region shows the theoretical expectation without neutrino oscillations. The dashed line for μ-like events represents the fit of the data in the case of two-generation $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 = 3.5\ 10^{-3}\ eV^2$ and $\sin^2 2\theta = 1.0$

Survival Probability

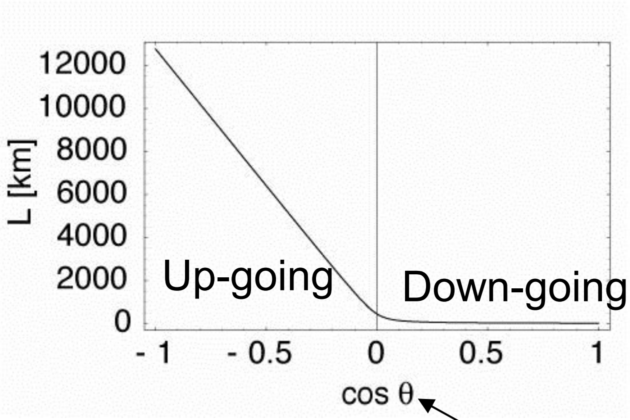
$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2 2\theta \sin^2(\Delta m^2 L/4E)$

Mixing angle

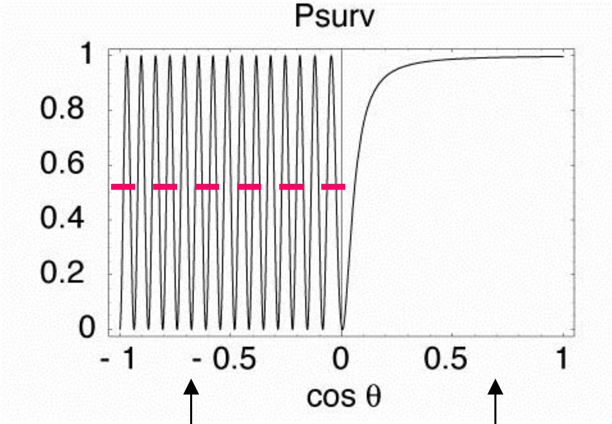
Using E = 1 GeV, $\sin^2 2\theta = 1$
$\Delta m^2 = 10^{-2}$ (eV^2)
we obtain this oscillation pattern vs L



$L_{osc} = 4\pi E/\Delta m^2$



Zenith angle



Up-going flux suppressed by about 50%

Down-going flux not suppressed

$\Delta m^2 - \sin^2 2\theta$ Plane

Interpretation of Atmospheric neutrino results:
ν_e flux as expected $\Rightarrow$ it is not $\nu_\mu \rightarrow \nu_e$ oscillations
3 ν generations $\Rightarrow$ it must be $\nu_\mu \rightarrow \nu_\tau$ oscillations, where ν_τ is not seen
(most of ν_τ under threshold for τ production in CC interactions (E_{th} >3 GeV)
Oscillation to sterile neutrinos excluded by analysis of NC

$$P_{\mu\tau} = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2\, L / E)$$

<L> ~ 10^3 Km, <E>~1GeV

Max P (=1)

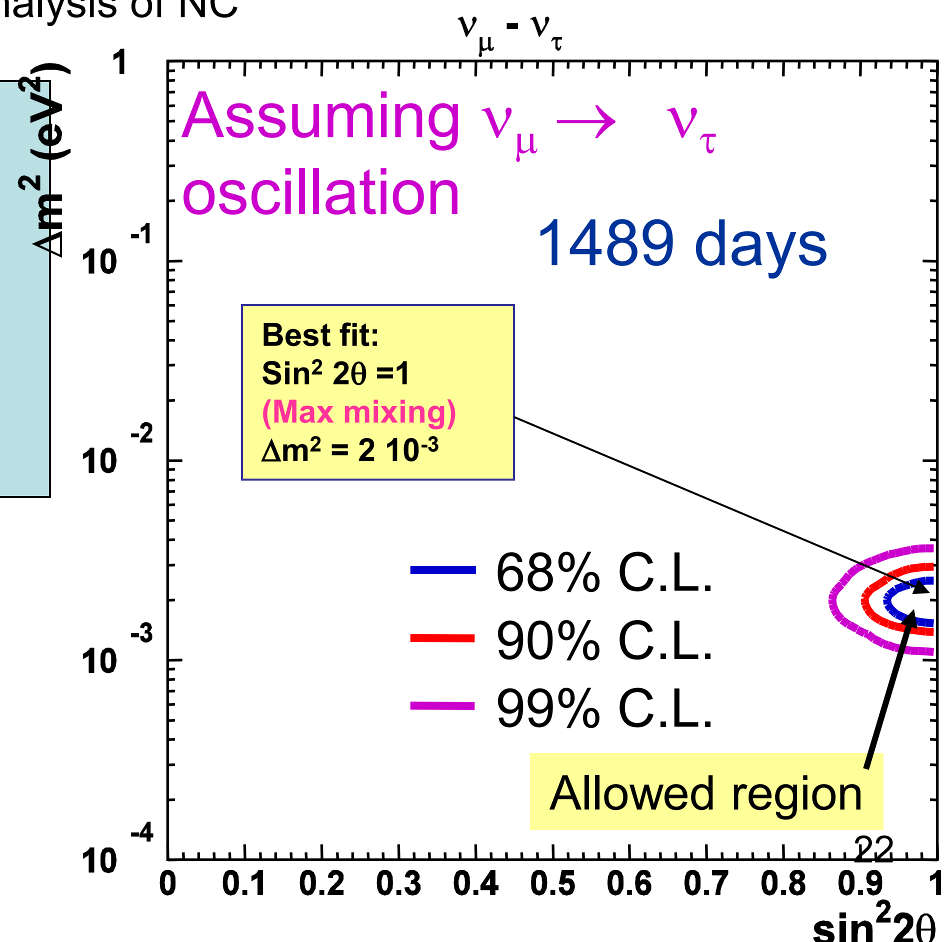
$\Rightarrow \sin^2(2\theta) = 1$

$\Rightarrow \Delta m^2 \sim E/L \sim 10^{-3}$

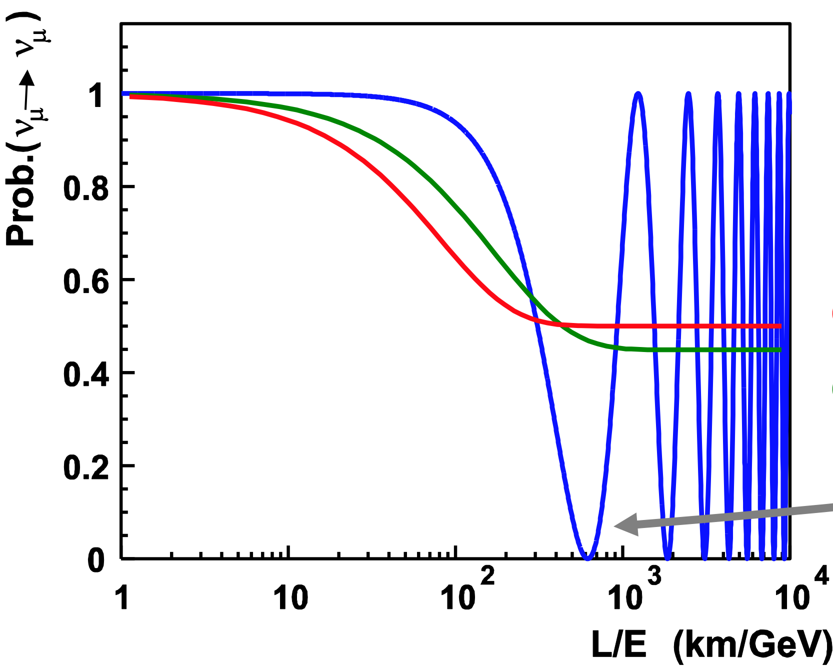
Need to take into account:

- Flux Spectrum,
- Baseline variations
- Detection Resolution

for a rigorous measurement

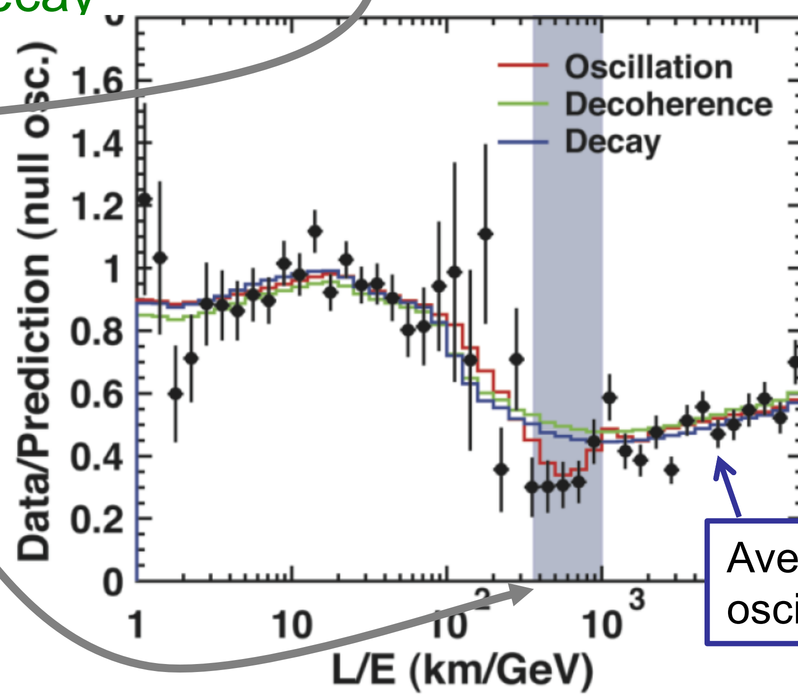


The "dip" in the L/E Analysis



$L = D_{Earth} \times \cos\theta_Z$
θ_Z, zenith angle

Should observe first dip!



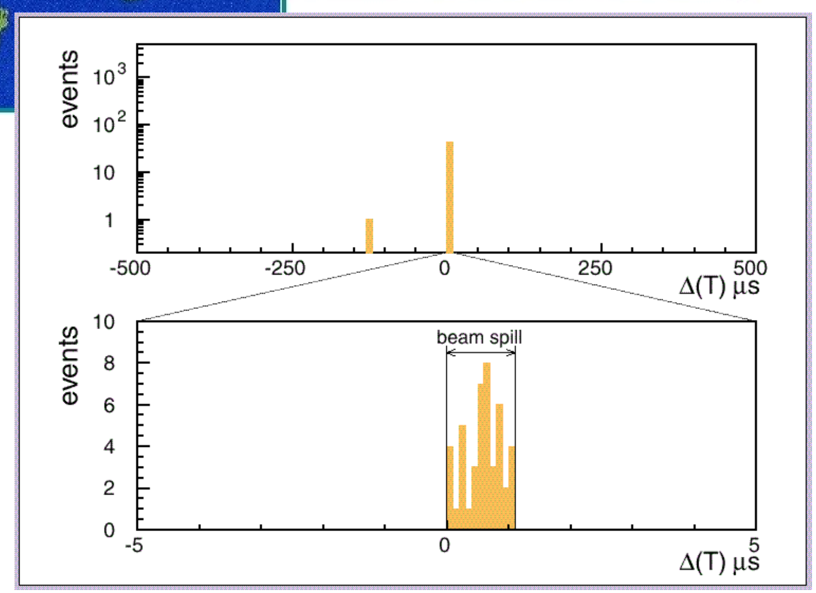
Averaged oscillations

First dip in μ-like events deficit observed by SK!

Decay and decoherence disfavored at 4 and 5σ level, respectively.

I.Sekiya, Jul 30th 2008, Philadelphia, ICHEP2008

First confirmation with Man-made neutrino beam (K2K)



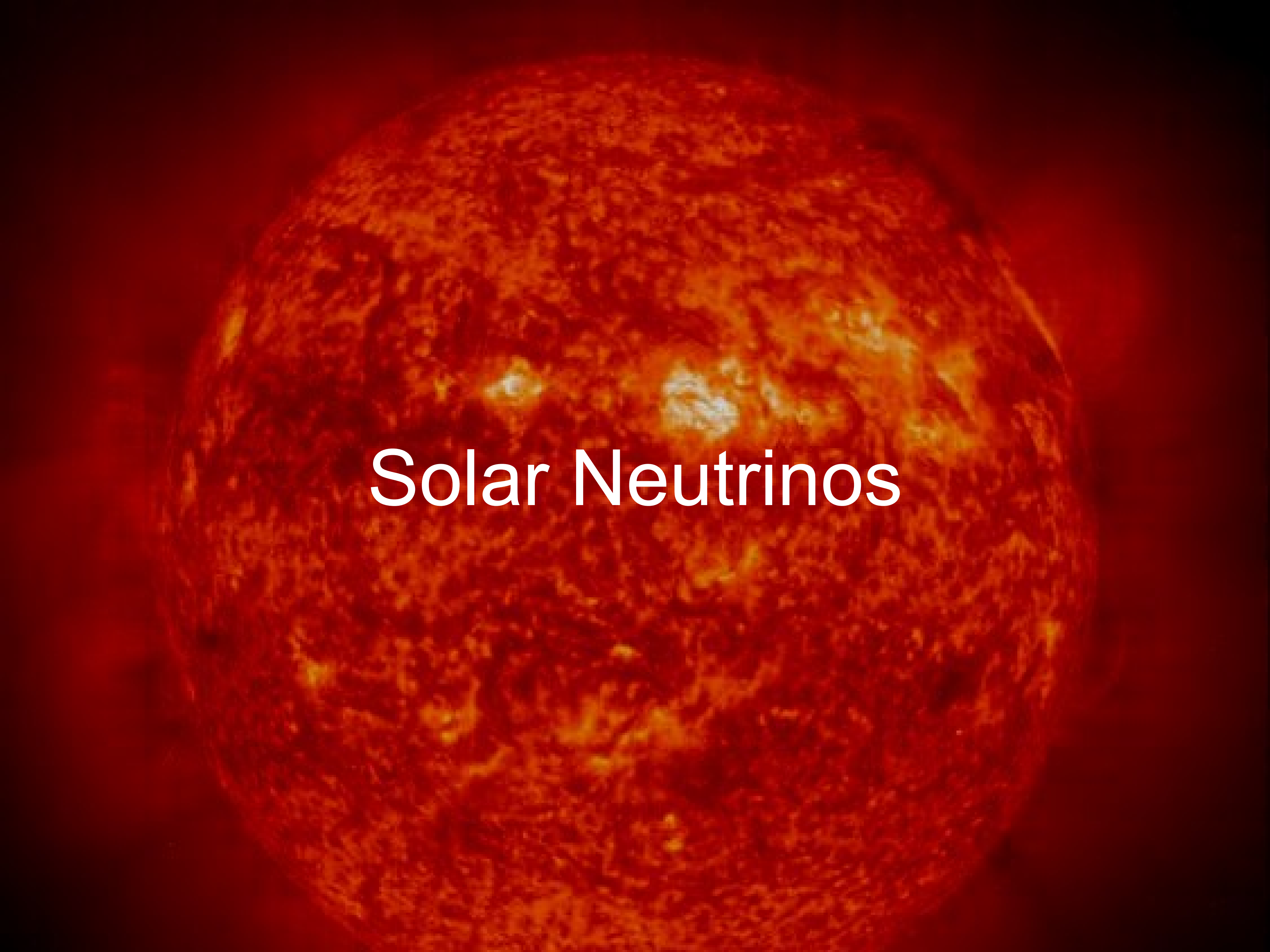
K2K experiment (1999-2004)

150±10 events if no oscillation

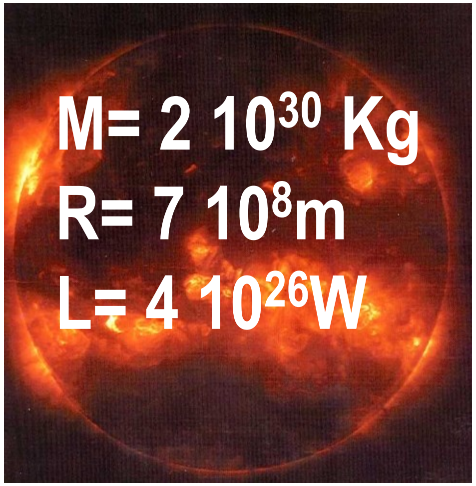
108 events observed

Deficit at ~4σ level

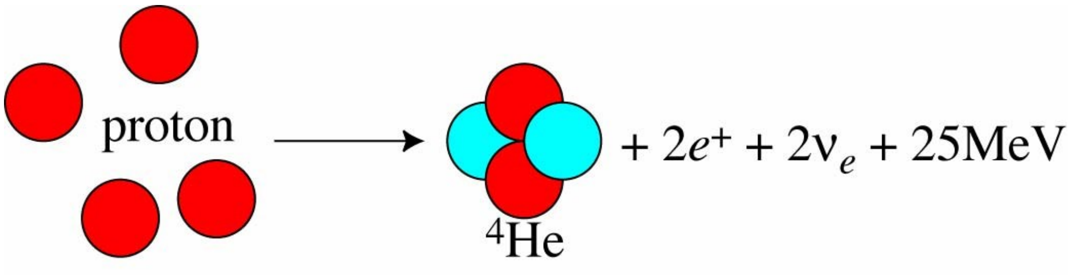
Solar Neutrinos



Standard Solar Model (SSM)



Hydrogen fusion in the Sun:



Observables:

-Mass

-Luminosity

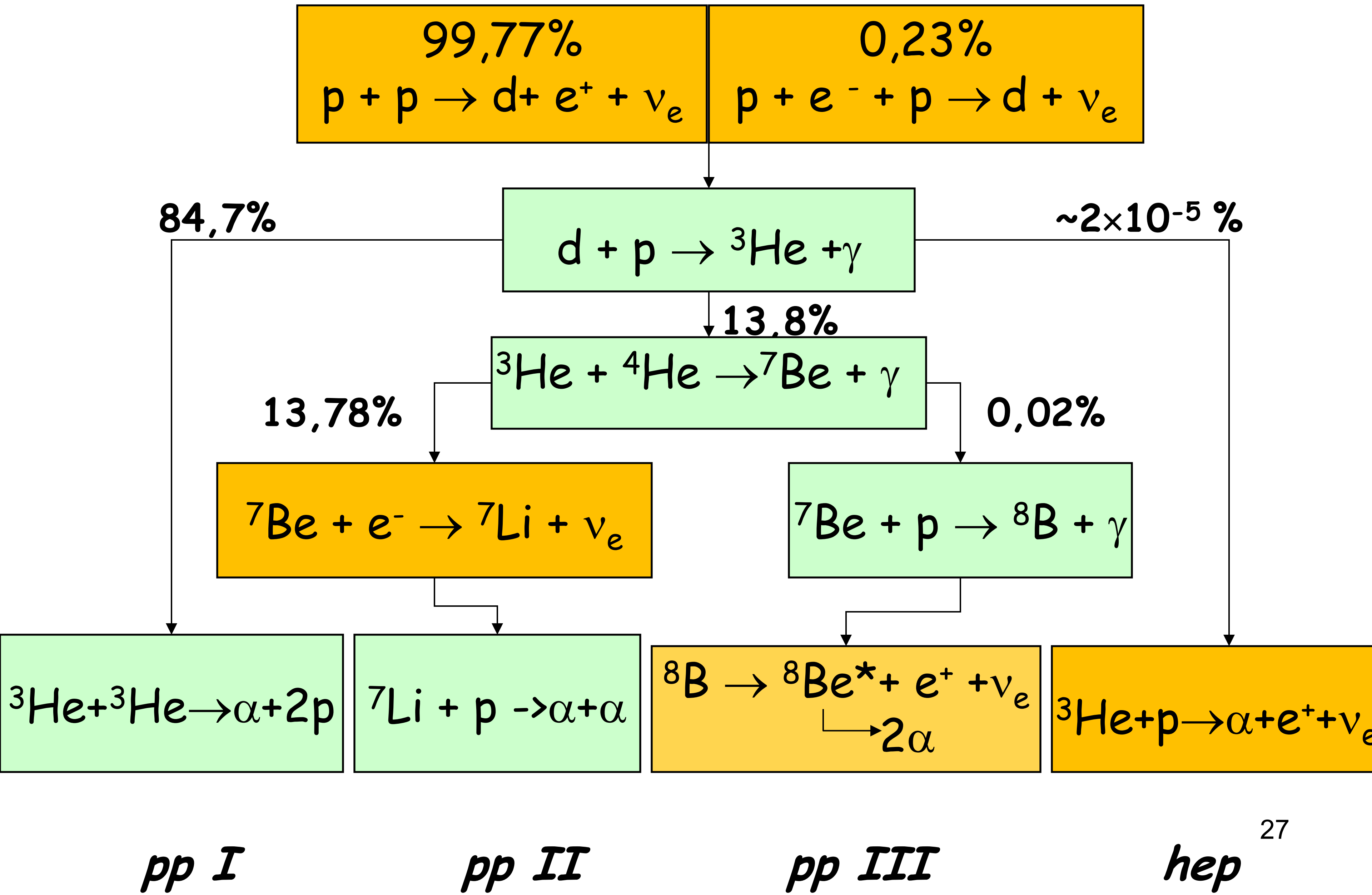
- Radius,
- Metal content of the photosphere
- Age

Inferences on solar interior (ρ, P, T)

SSM describes the evolution of an initially homogeneous solar mass M_o up to the sun age t so as to reproduce L_o, R_o and $(Z/X)_{photo}$

⇒ Predicts solar neutrino flux (intensity and spectrum)

The pp-chain


99,77%
p + p → d+ e+ + νe
0,23%
p + e - + p → d + νe
84,7%
d + p → 3He +γ
~2×10-5 %
13,8%
3He + 4He →7Be + γ
13,78%
0,02%
7Be + e- → 7Li + νe
7Be + p → 8B + γ
3He+3He→α+2p
7Li + p ->α+α
8B → 8Be*+ e+ +νe
2α
3He+p→α+e++νe
pp I
pp II
pp III
hep

Solar Neutrino Energy Spectrum

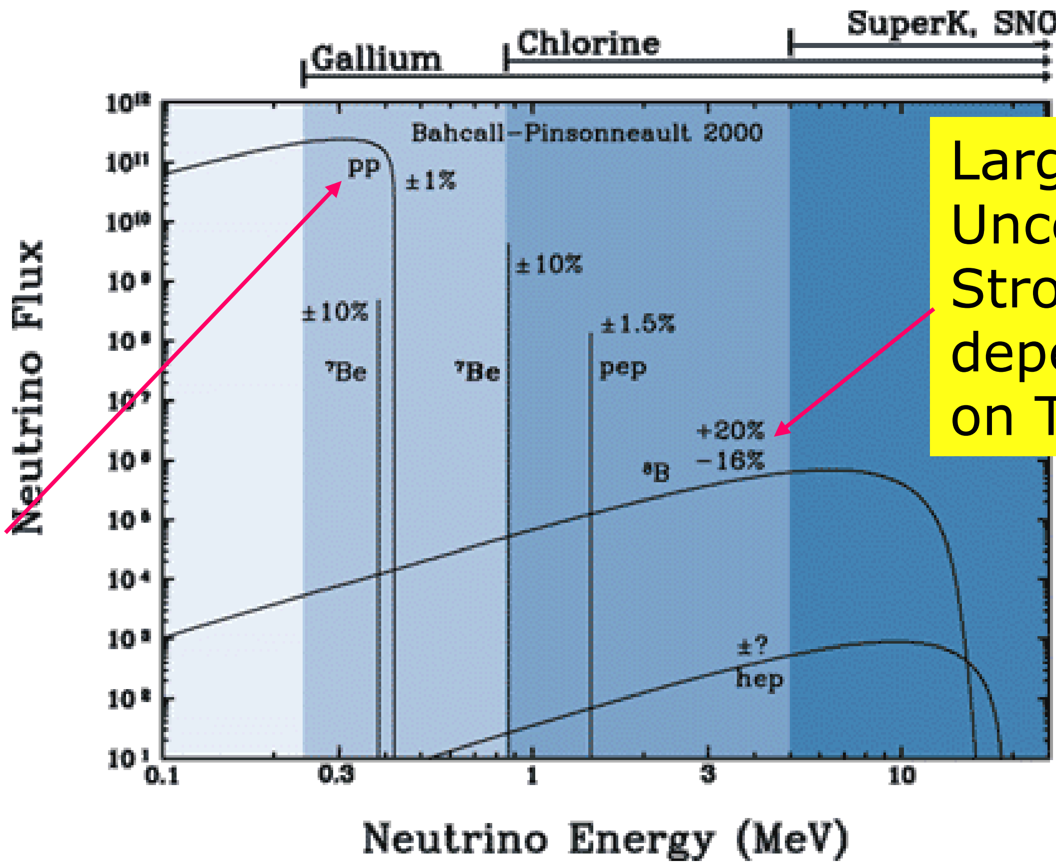
Sun luminosity: L = 8.6 10^{11} MeV cm^{-2} s^{-1}

Total Neutrino flux (only ν_e): $\Phi(\nu_e)$= 2 x L/(26 MeV) = 6.6 10^{10} cm^{-2} s^{-1}

Small theoretical uncertainty (~1%): total flux is constrained by solar luminosity

Spectra and relative abundances have larger uncertainties

Small Uncertainty: Luminosity constrained



Large Uncertainty: Stronger dependence on T ($\propto T^{24}$)

Experiments and Detection methods

Solar ν	Important detector parameters
Small x-section	⇒ Big Target Mass, O(kT)
Low energy	⇒ Low Detection Threshold
⇓	
Cosmic rays Background	⇒ Deep underground

- Radiochemical detectors (integrated flux)

	Start	Method	Thresh.(MeV)
• Homestake	1969-1999	^{37}CL	0.8
• Sage	1990	^{71}Ga	0.2
• Gallex/GNO	1991	^{71}Ga	0.2

- Real-time detector (differential flux:time,E,θ)

•Kamioka/SuperK	1985	H_2O	5
•SNO	1999	D_2O	5
•Kamland	2001	Liq Scint	5.5
•Borexino	2007	Liq Scint.	<1

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

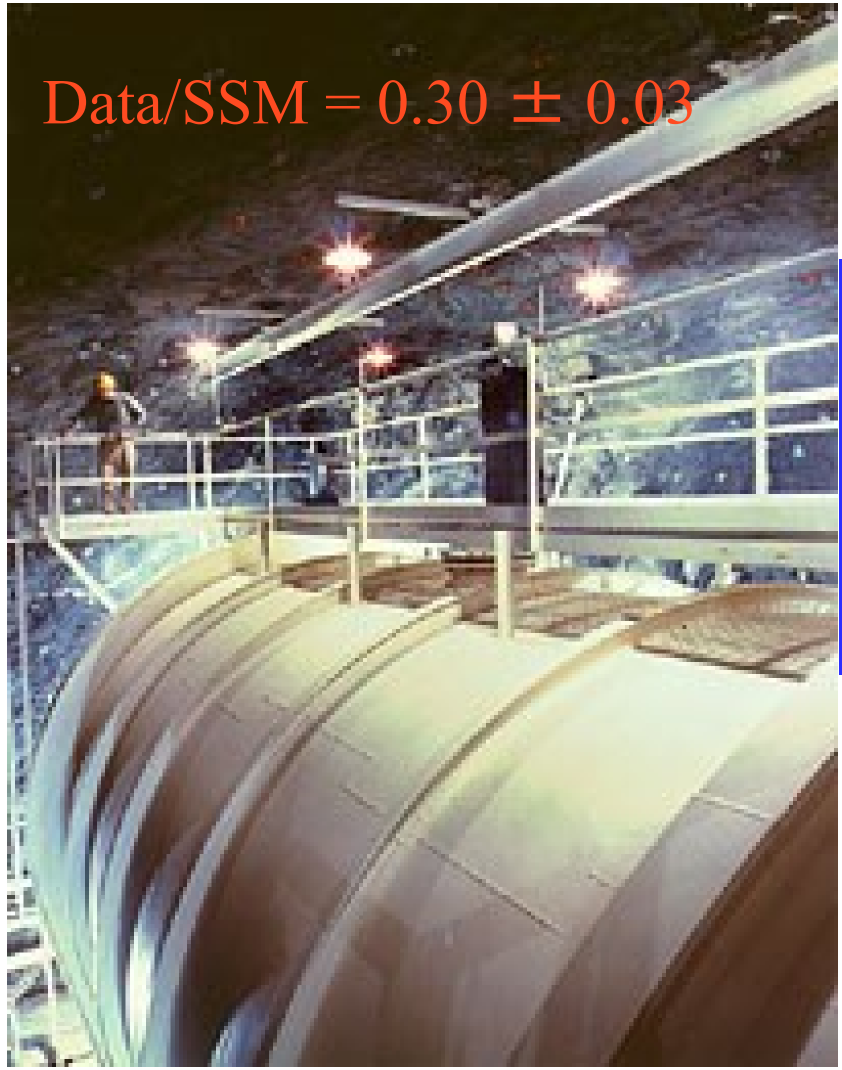
Homestake (1969 ~99)

380,000 l of C_2Cl_4 (615 tons)

Homestake Mine, 1400 m deep

$E\nu > 0.8$ MeV
Sensitive to ^{8}B + ^{7}Be

Extract ^{37}Ar once per month by flushing He together with small (known) amount of stable ^{36}Ar to measure extraction efficiency



^{37}Ar is radioactive and decays with half-life of 35 days

UNIT

$$\text{RATE} = \sum(\text{FLUX}) \times (\text{CROSS SECTION})$$

$$\sim 10^{10}\ \text{cm}^{-2}\text{s}^{-1} \times 10^{-46}\ \text{cm}^2$$

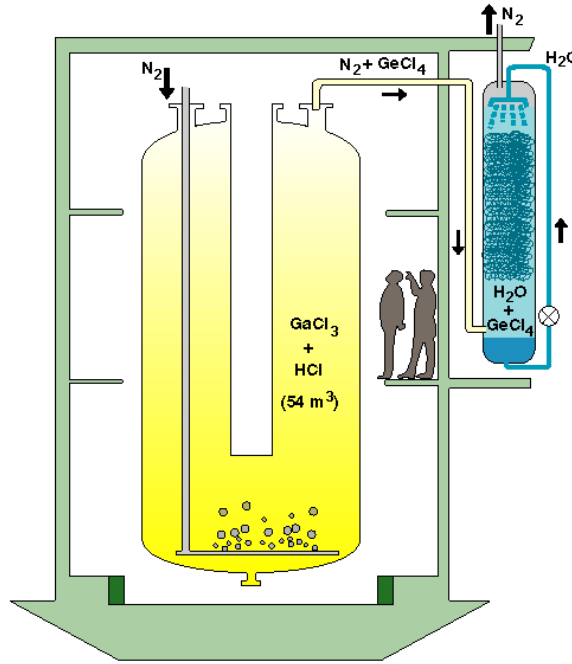
$$1\ SNU = 10^{-36}\ \text{INTERACTIONS PER TARGET ATOM PER SEC}$$

Predicted rate
8.5± 1.8 SNU

Observed rate
2.56± 0.23 SNU
~0.5 atoms/day!

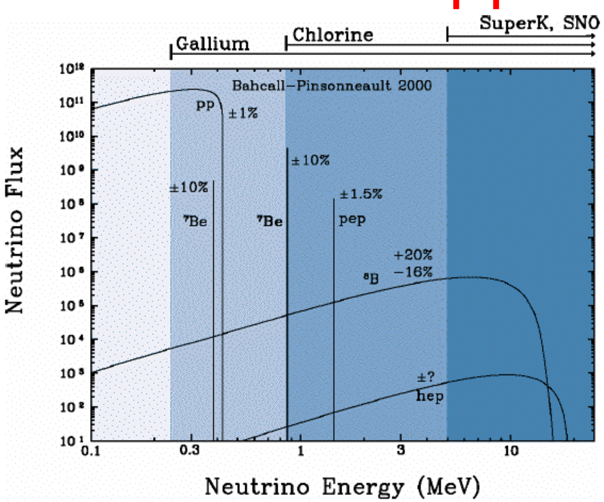
Gallium Experiments

$\nu_e \; {}^{71}Ga \rightarrow {}^{71}Ge \; e^-$



Gallex/GNO
Calibrated with
High intensity
^{51}Cr ν source

Eν > 0.23 MeV
Sensitive to pp

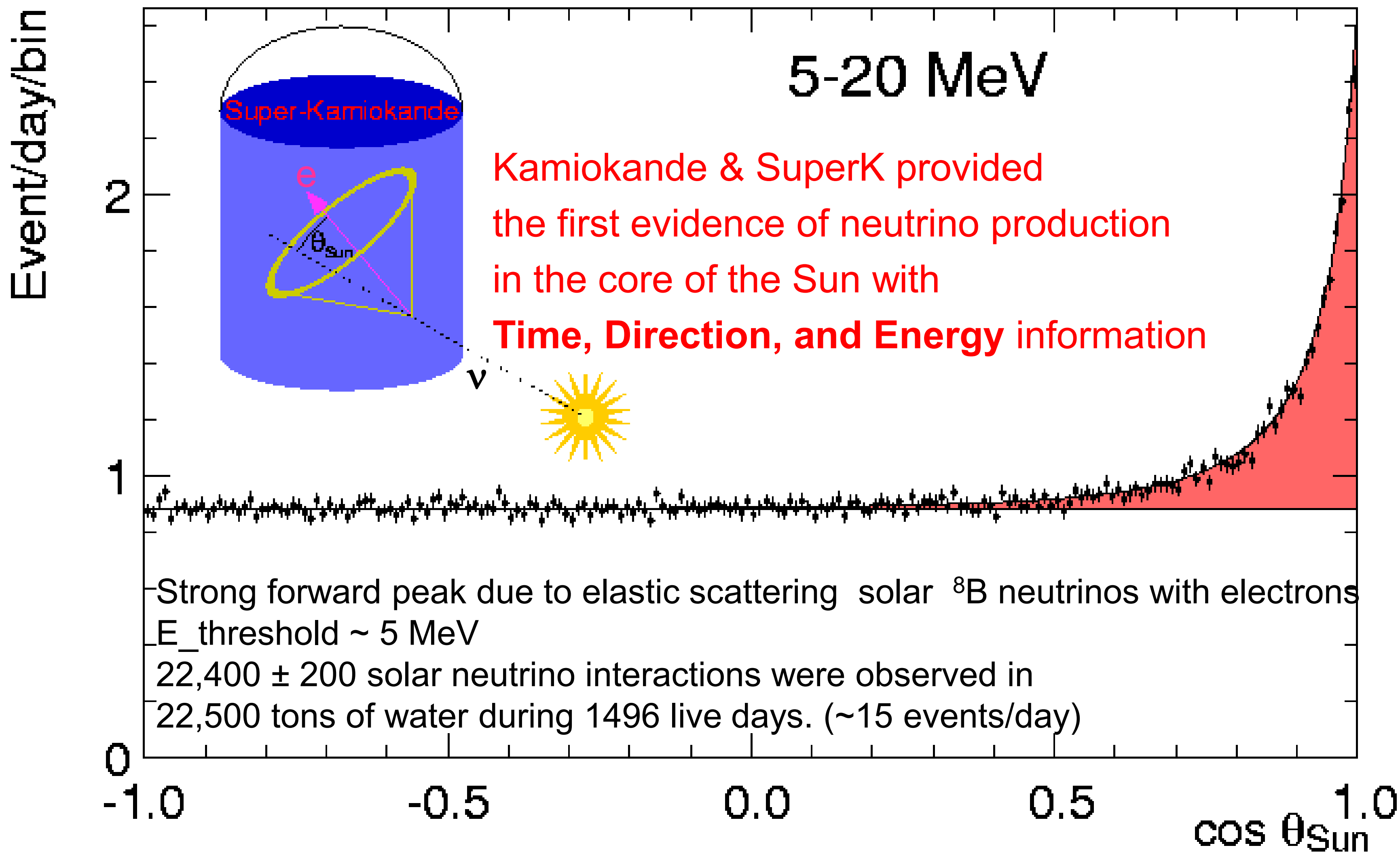


http://www.sns.ias.edu/~jnb/

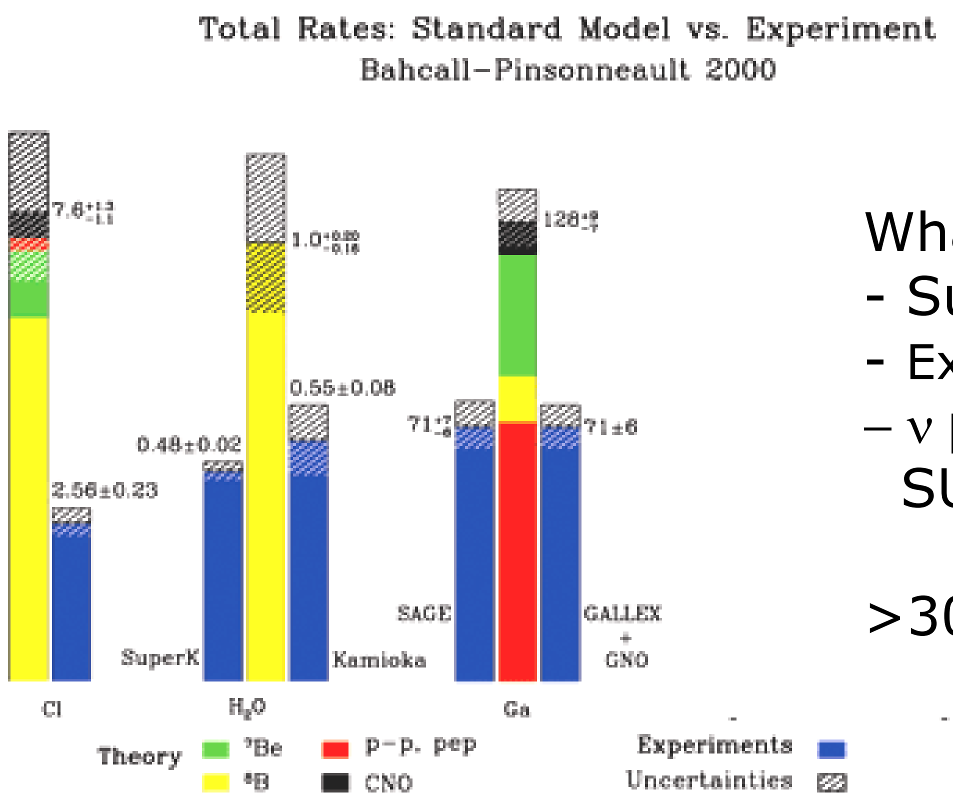
- Observed (Data): 68.1 ± 3.75 SNU (GALLEX + GNO + SAGE)
- Predicted (SSM): 131^{+12}_{-10} SNU
- **Data / SSM = 0.52 ± 0.03**

SuperK

ν_e e- → ν_e e-)



SOLAR Neutrino PROBLEM



What can be wrong?
- Sun model
- Experiments
– ν propagation from SUN to Earth

>30 years of debate!

A ν trick?

ν decay? Excluded by SN1987A

$\gamma\,\tau = (E\nu / m\nu)\,\tau > 8$ min

Best bet: $\nu_e \rightarrow \nu_x$ oscillation

Flux suppression could have the right energy dependence according to chosen oscillation mechanism and parameters (Δm^2, $\sin^2 2\theta$)

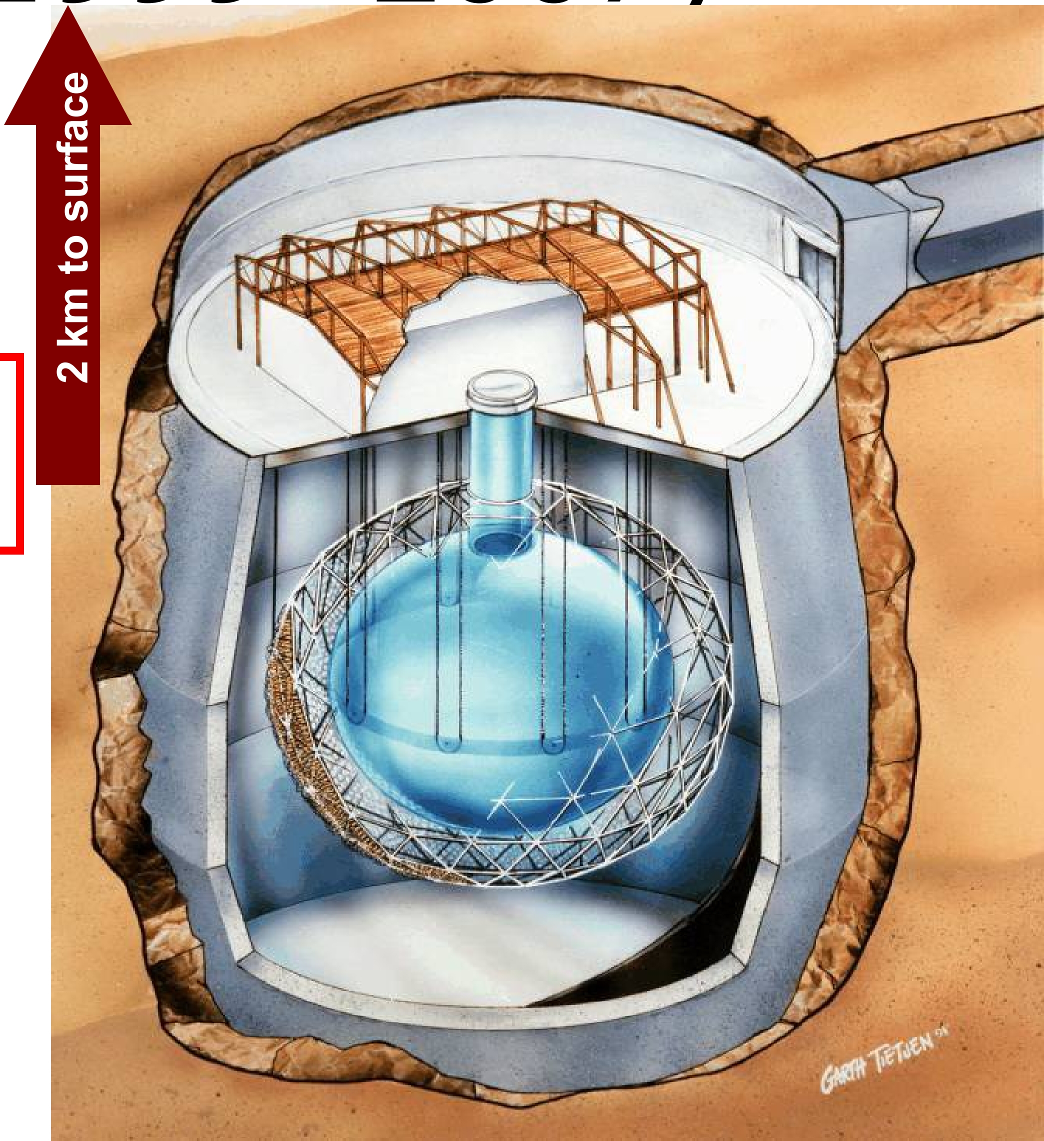
Confirmation could come from an experiment equally sensitive to all ν flavor, via detection of NC interactions: SNO

Sudbary Neutrino Observatory (Ontario, 1999~2007)

1 Kton D_2O

SNO can determine both:
$\Phi(\nu_e)$ and $\Phi(\nu_e + \nu_\mu + \nu_\tau)$

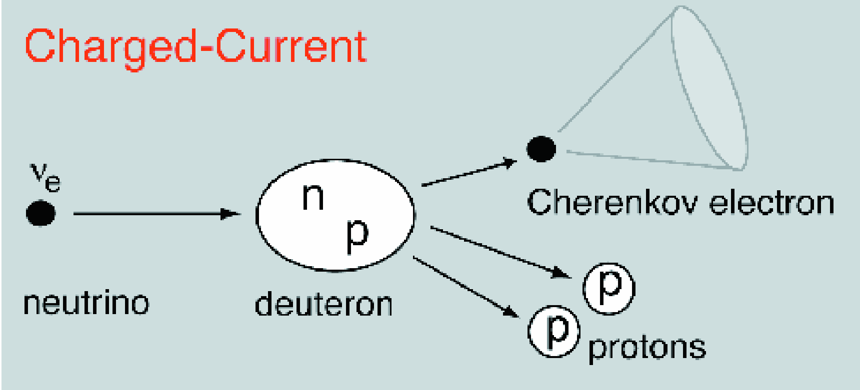
Threshold energy for neutrino detection 5MeV
$\Rightarrow$Sensitive to ^8B neutrinos



ν Detection at SNO

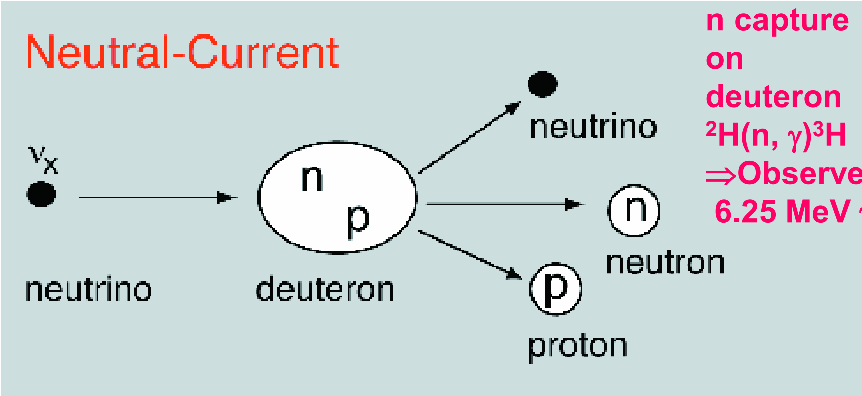
CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality



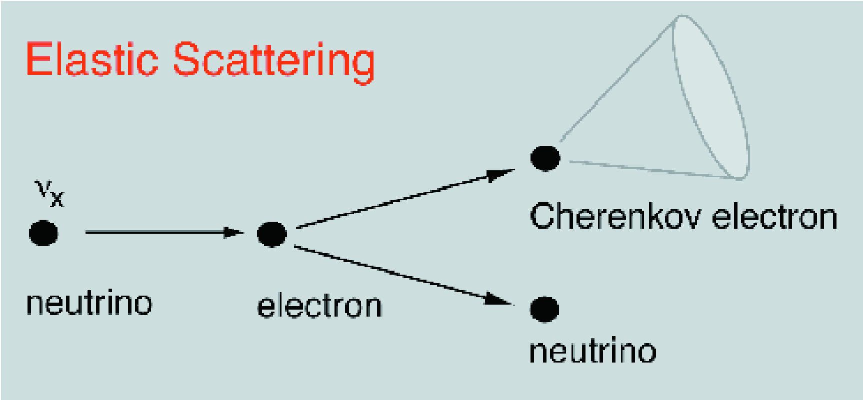
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Measure total ^8B ν
- Equally sensitive to ALL ν
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\sigma(\nu_e) \approx 7\ \sigma(\nu_\mu) \approx 7\ \sigma(\nu_\tau)$
- Strong directionality



First SNO RESULTS (April 2002)

- The measured total B neutrino flux is in excellent agreement with the SSM prediction.

SSM is right

- Only 1/3 of the B-neutrinos survive as ν_e

All Experiments are right!

$\Rightarrow$ 2/3 of the produced ν_e transform into active neutrinos (ν_μ or ν_τ, indicated as $\phi_{\mu\tau}$)

Evidence of flavour transformation!

(independent of SSM)

$$\phi_{CC}(\nu_e) = \phi_e$$
$$\phi_{NC}(\nu_x) = \phi_e + \phi_{\mu\tau}$$
$$\phi_{ES}(\nu_x) = \phi_e + 0.15\phi_{\mu\tau}$$

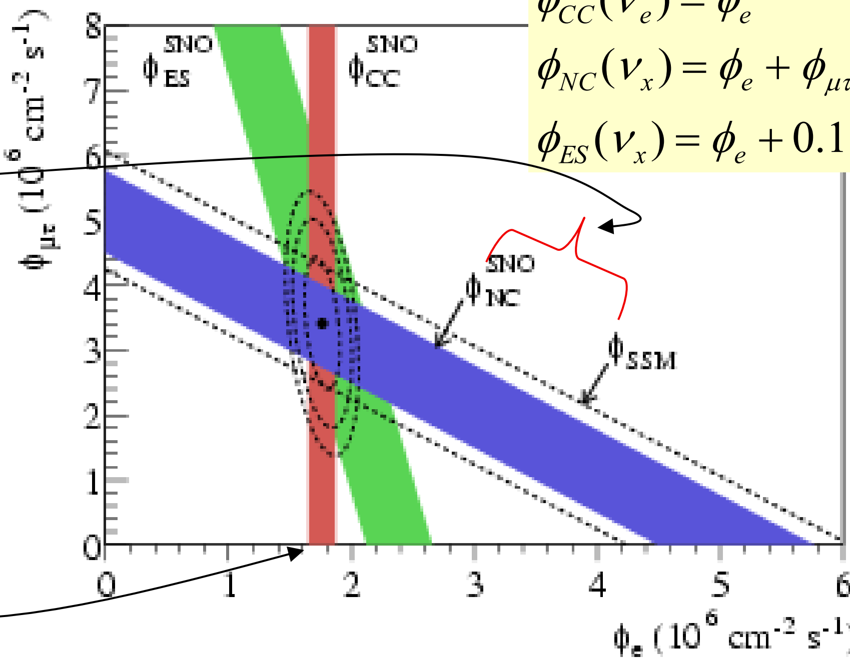
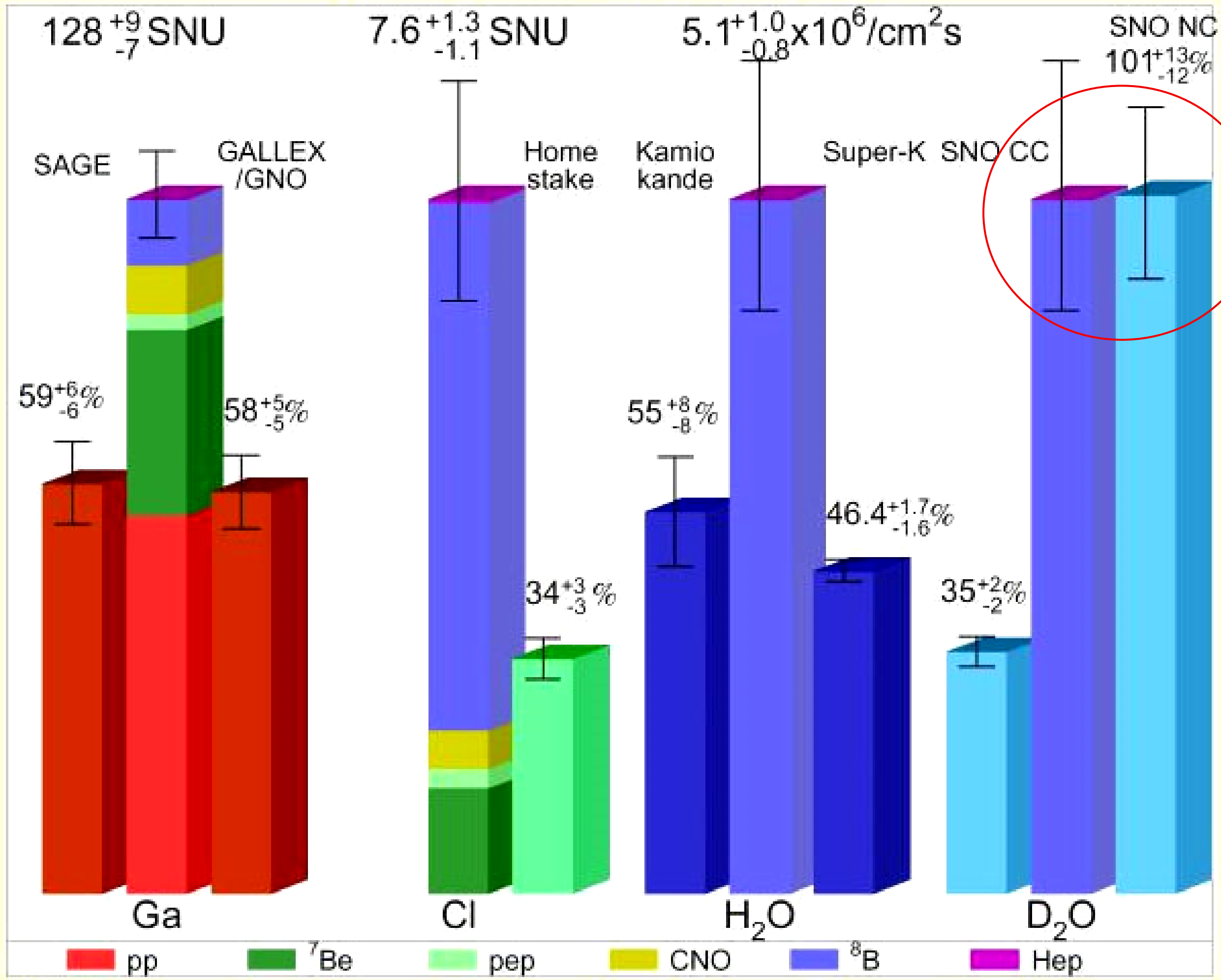


FIG. 3: Flux of ^{8}B solar neutrinos which are μ or τ flavor vs flux of electron neutrinos deduced from the three neutrino reactions in SNO. The diagonal bands show the total ^{8}B flux as predicted by the SSM [11] (dashed lines) and that measured with the NC reaction in SNO (solid band). The intercepts of these bands with the axes represent the $\pm 1\sigma$ errors. The bands intersect at the fit values for ϕ_e and $\phi_{\mu\tau}$, indicating that the combined flux results are consistent with neutrino flavor transformation assuming no distortion in the ^{8}B neutrino energy spectrum.

Solar ν Problem

2002 A.D.

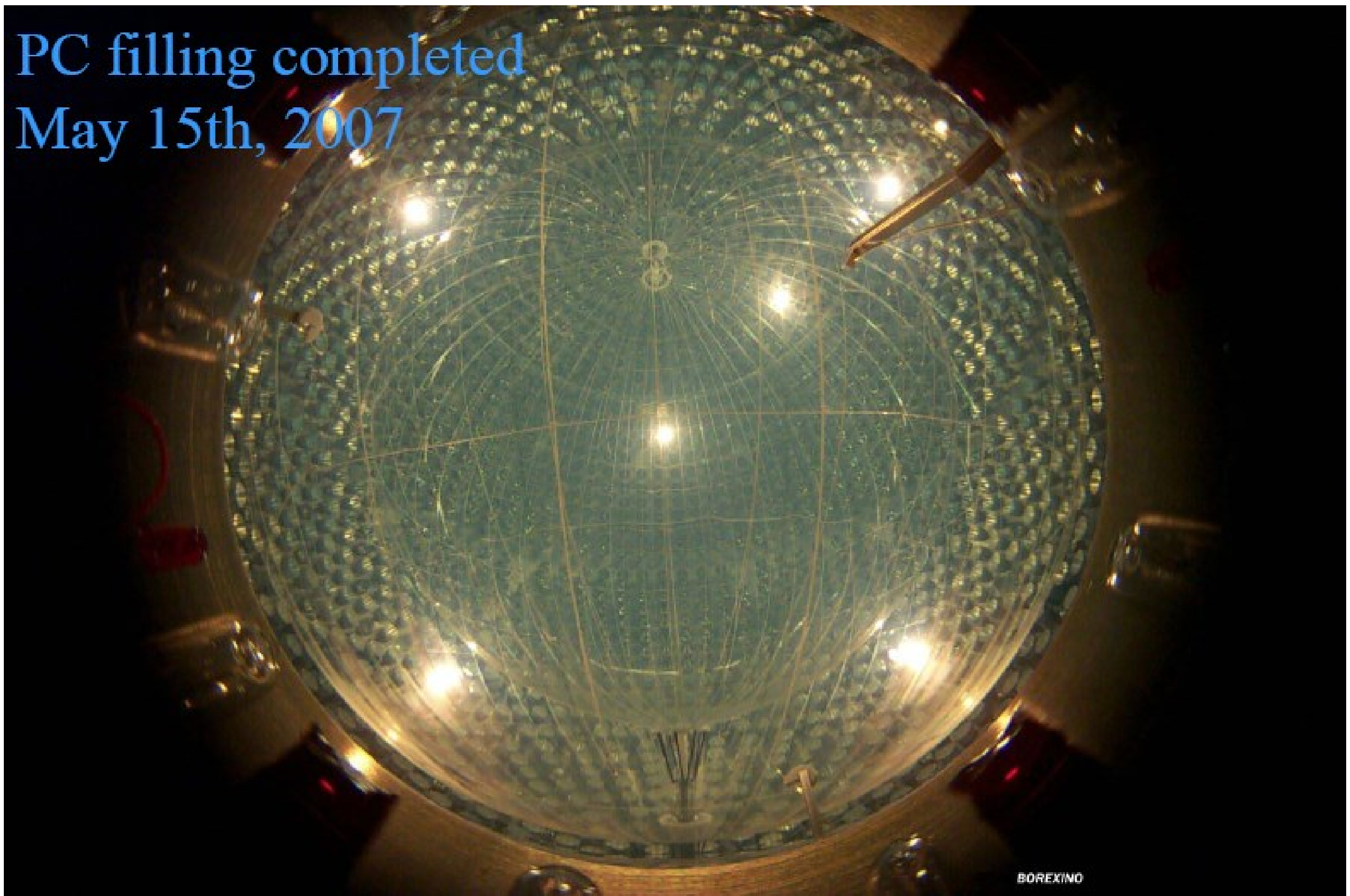


Michael Smy, UC Irvine

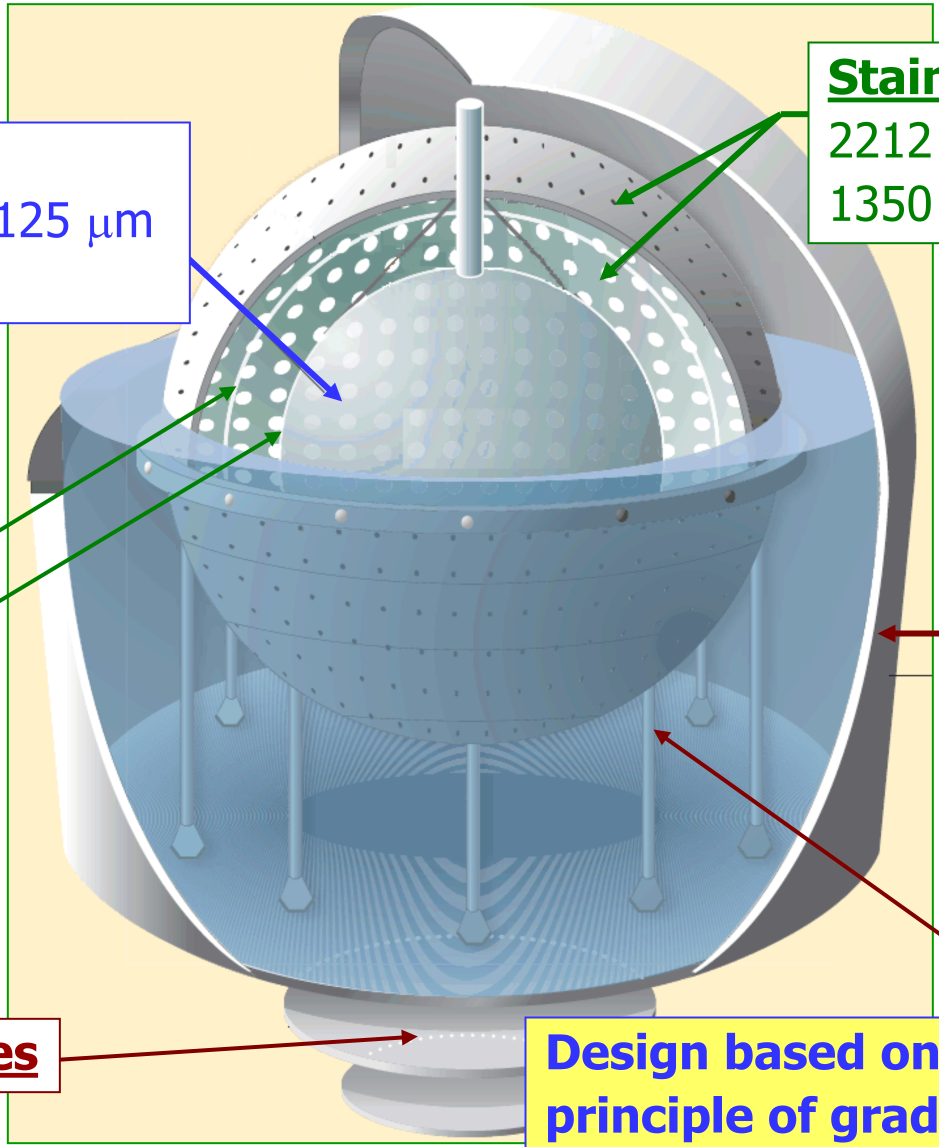
SNO solves it!

Borexino

- First real-time detection of ^{7}Be, Gran Sasso Labs (Italy)
- 270t Extreme radio-purity liquid scintillator doped with PC+PPO in a 125μm thick nylon vessel



Borexino detector



Scintillator:
270 t PC+PPO in a 125 μm thick nylon vessel

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Water Tank:
γ and n shield
μ water Ch detector
208 PMTs in water
2100 m^3

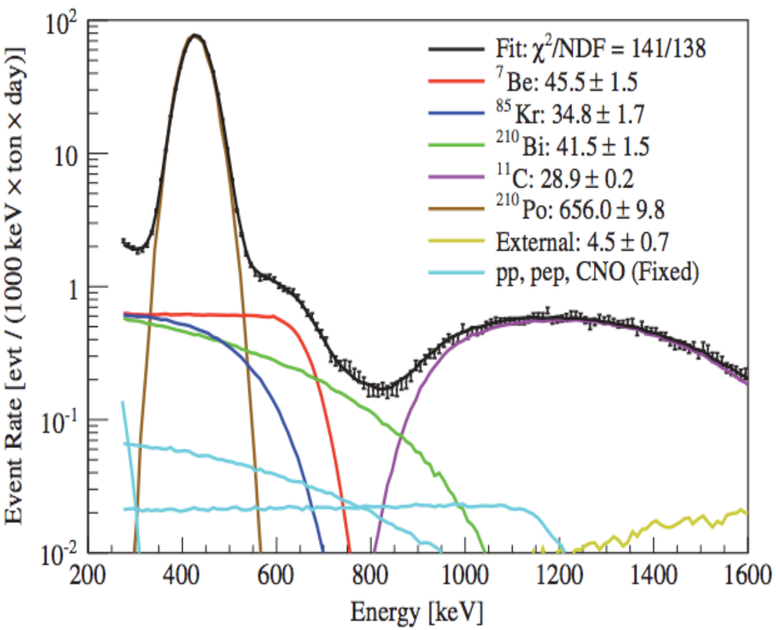
20 legs

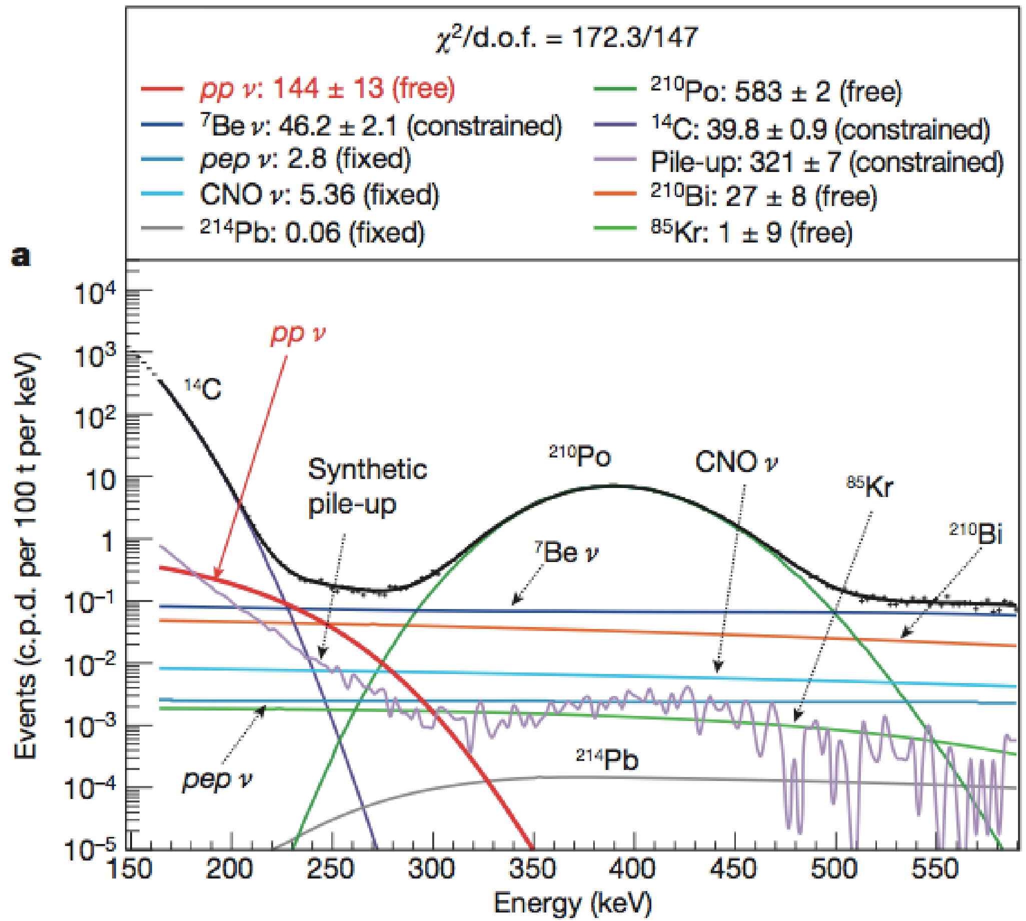
Carbon steel plates

Design based on the principle of graded shielding

Borexino observe low energy ν flux

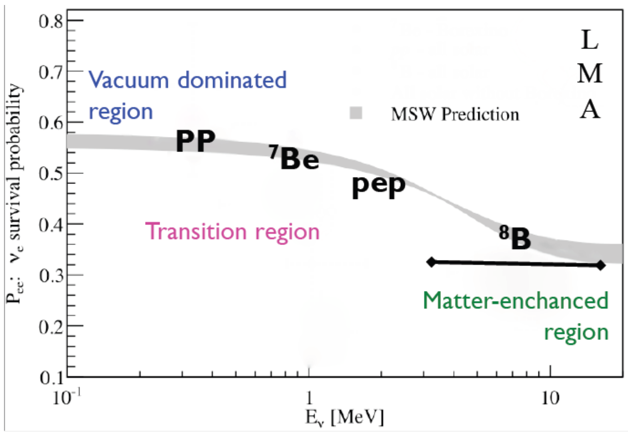
^{7}Be flux, 5% accuracy
PRL 107,1411302, 2011

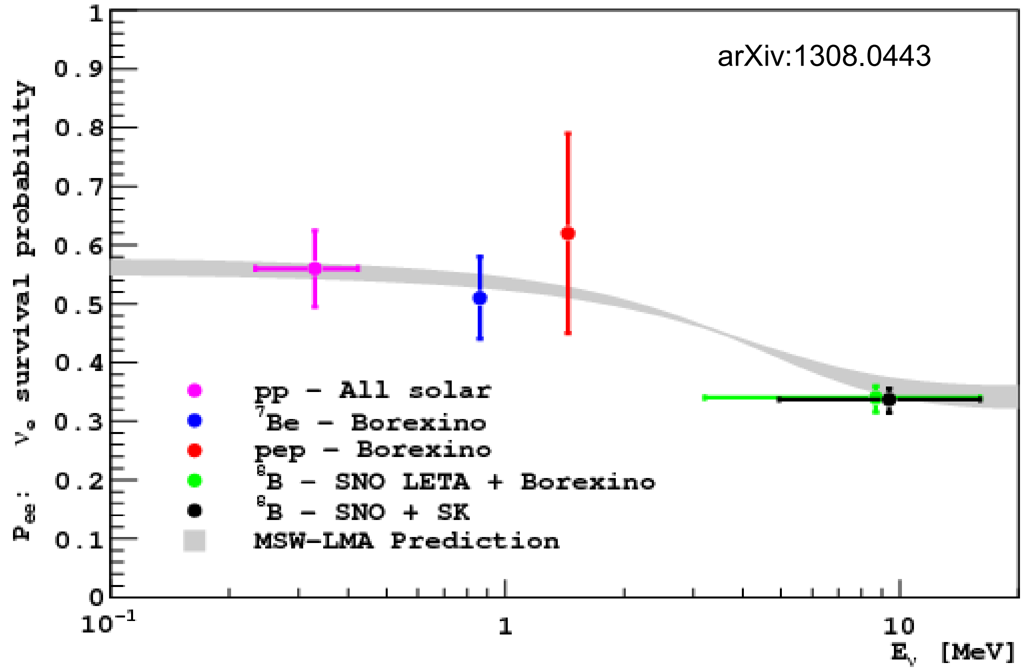




pp-ν flux, 10% accuracy
Nature 512,383---386, (2014)

Borexino results fit validate current ν-oscillation framework





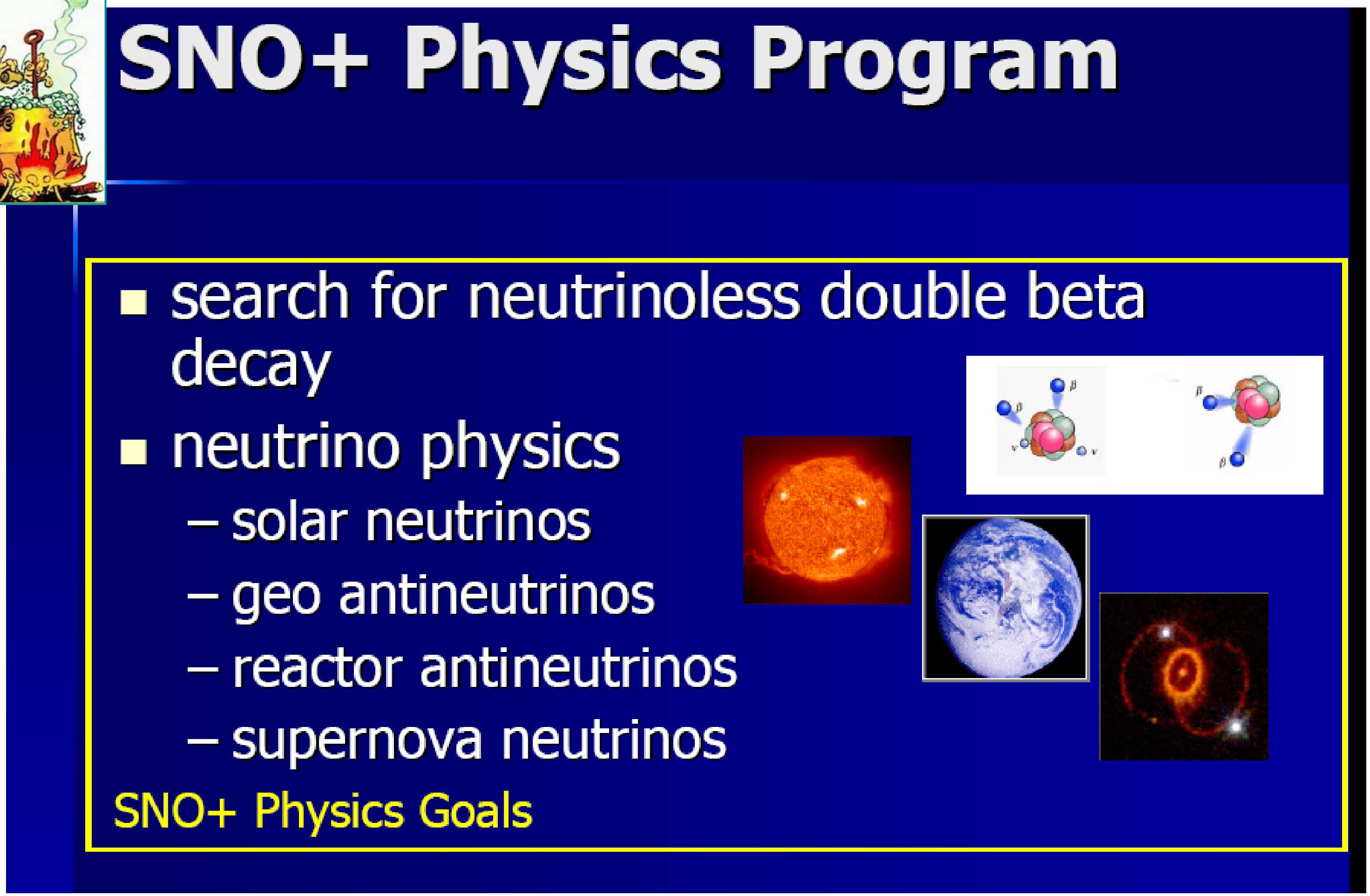
Borexino data validate the MSW-LMA model in the vacuum dominated region

Next:

- look for CNO neutrinos. Important for solar models (constrain Sun metallicity)
- More precise measurements of ^{8}B spectrum (1-5 MeV transition region sensitive to new physics effects)

SNO+ (SNO tank to be filled with Te^{130}-loaded scintillator)

Deepest detector ⇒ unique sensitivity to pep neutrinos ⇒ sensitivity in transition region



Summary

- Atmospheric neutrinos:
  - Flux properties: numu/nue, isotropic
  - Evidence of oscillation in SuperK:
    1. Numu/nue ratio
    2. Up-down asymmetry (cos theta distribution)
    3. Dip in L/E
  - Terrestrial (accelerator) confirmation: K2K experiment (and recently MINOS, OPERA, T2K, as we will see in the next lectures)
  - Detection techniques for GeV neutrinos
  - Benefit of Cerenkov: big mass, PID, works well in MeV-GeV range (elastic and quasi-elastic interactions)

Summary/2

- Solar Neutrinos
  - SSM
  - Detection techniques for solar neutrinos
  - Solar neutrino problem
  - SNO and solution to solar neutrino problem
  - Current/near future solar neutrino experiments