united nations educational, scientific and cultural organization

international atomic energy agency

the abdus salam international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-12

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Solar and Reactor Neutrinos

D. Cowen

Pennsylvania State University
U.S.A.

Solar and Reactor Neutrinos*

- First neutrino detection by Reines & Cowan (no relation ☹)
  - “You can observe a lot by watching.” –Y. Berra
- Solar neutrinos as verification that fusion powered the sun → solar neutrino flux deficit
  - "If you don't know where you are going, you will wind up somewhere else.“–Y. Berra
- The solar neutrino problem: Homestake, confirmed by SAGE, GALLEX, Kamiokande…
  - "This is like deja vu all over again.“–Y. Berra
  - "I wish I had an answer to that, because I'm tired of answering that question."–Y. Berra
  - The solution: Solar neutrinos are not 100% ν_e when they arrive on earth: SuperK & SNO, with help from KamLAND
  - "You better cut the pizza in four pieces because I'm not hungry enough to eat six."–Y. Berra

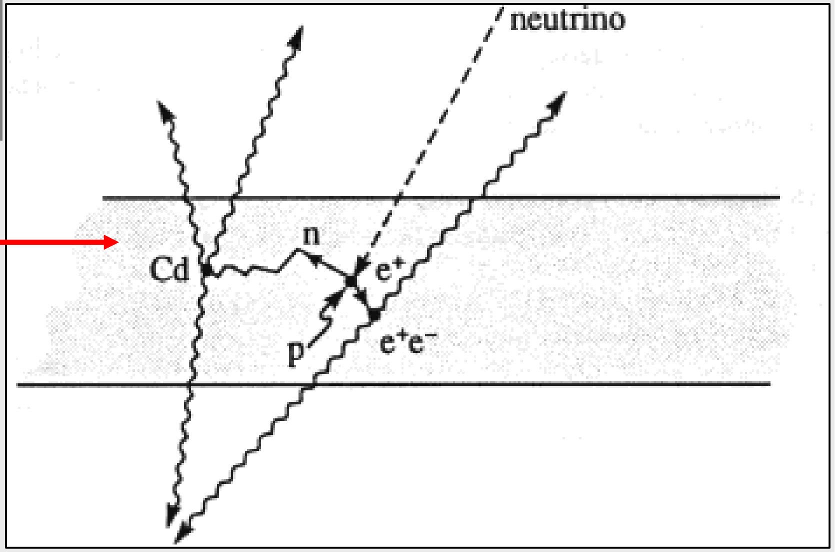
***With Apologies to Yogi Berra, famous American philosopher**

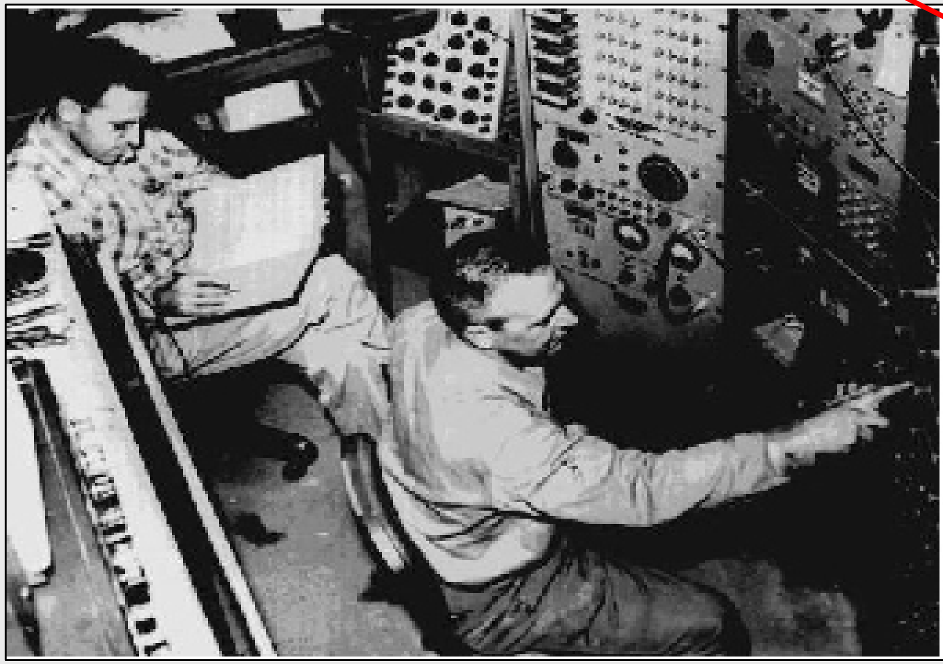
First Neutrino Detection

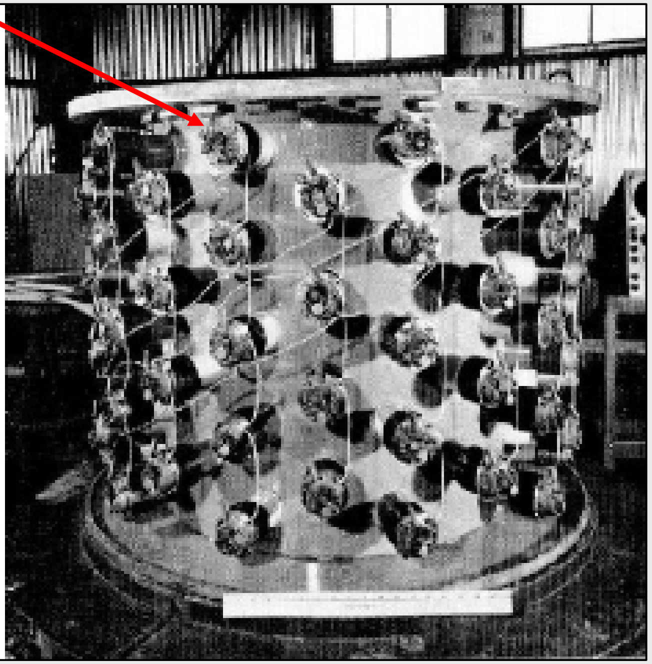
- 1930: Neutrino proposed by Pauli
- 1956: Electron anti-neutrinos discovered by Reines & Cowan
  - First thought they'd use a nuclear explosion
  - Opted instead for a nuclear reactor

First Neutrino Detector

- First detector used scintillator and photomultiplier tubes (PMTs)

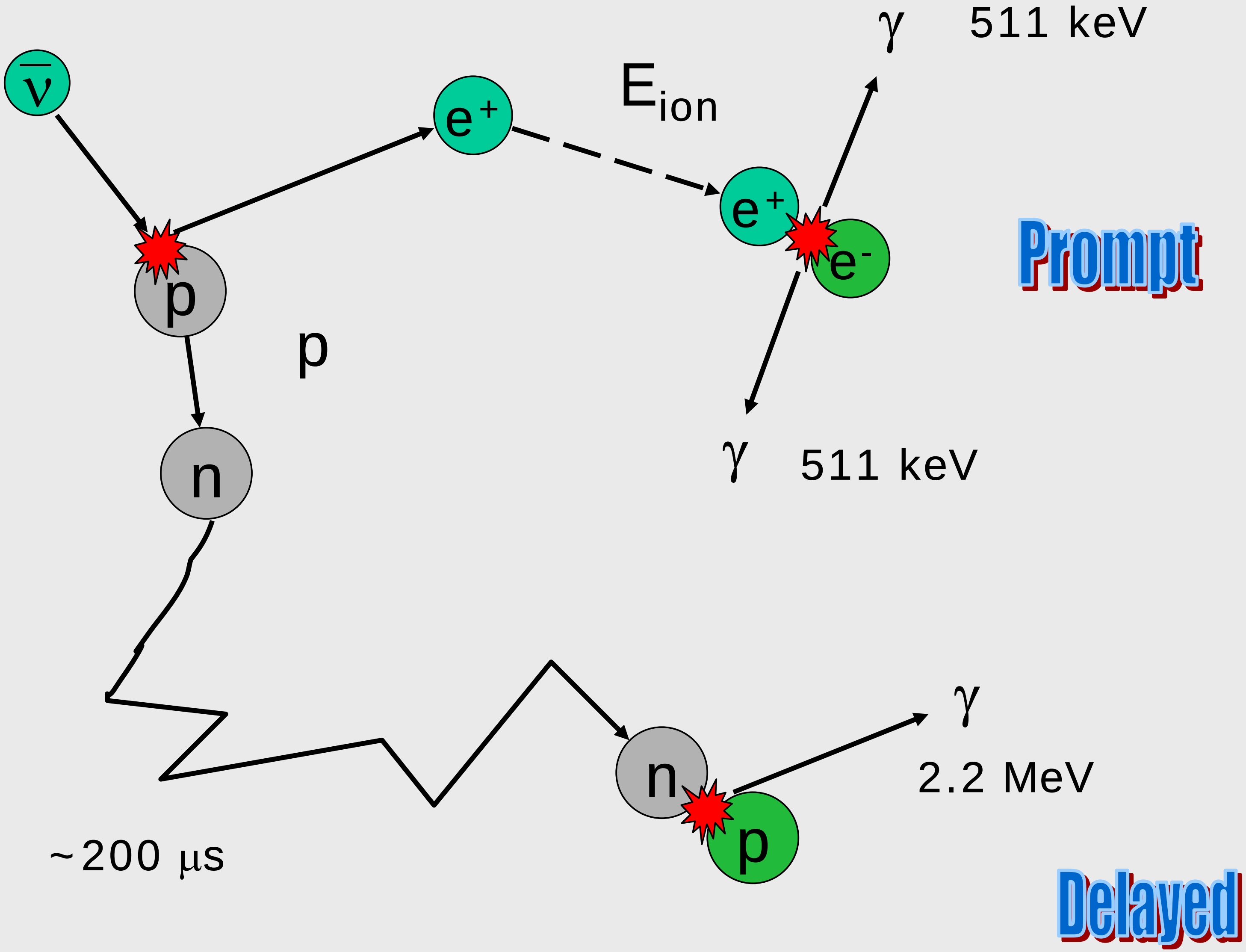






R. Svoboda, LSU/ANL Workshop

Inverse Beta Decay

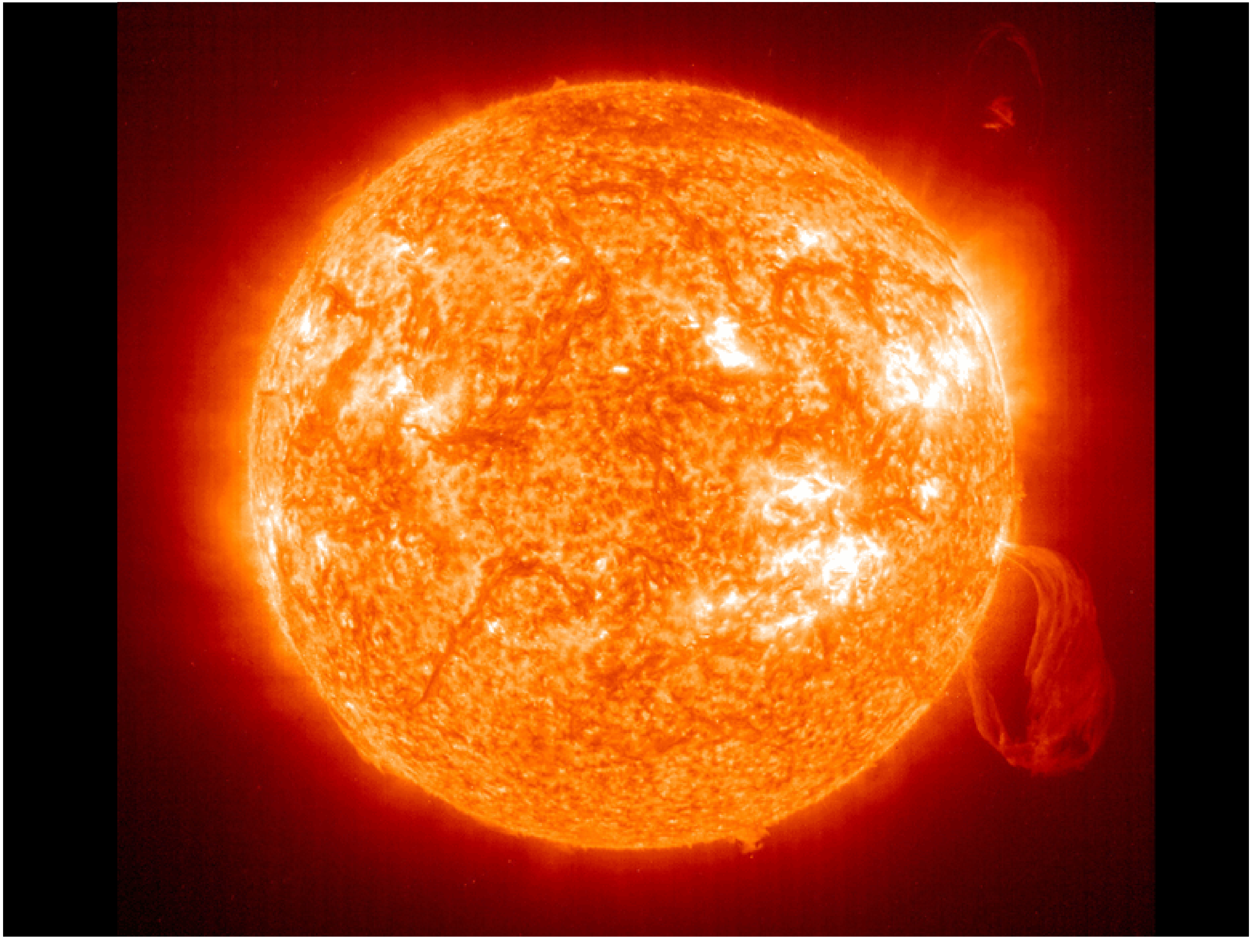


First Neutrino Detection(s)

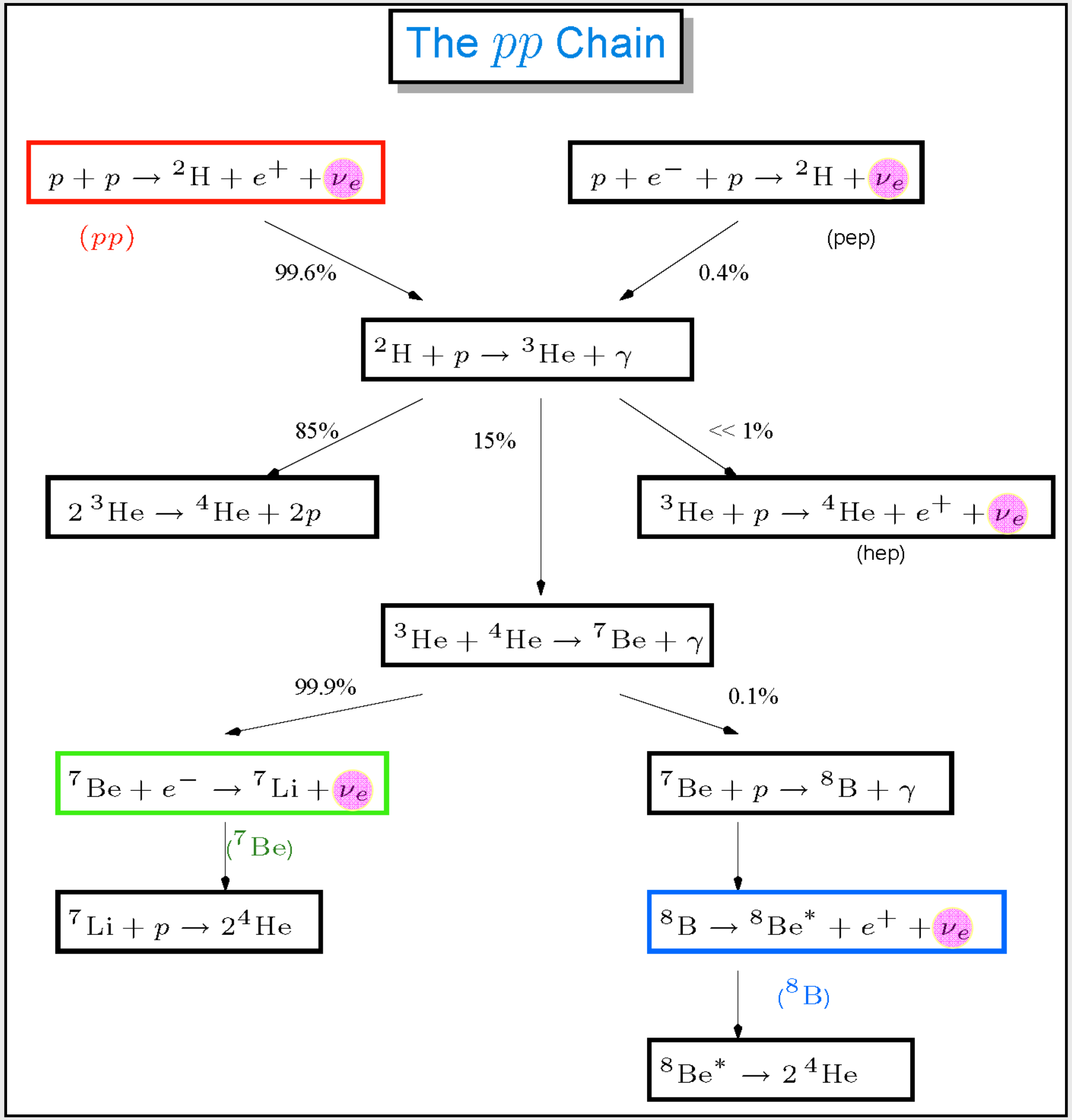
- *1930: Neutrino proposed by Pauli*
- *1956: (Electron anti-)neutrinos discovered by Reines & Cowan*
  - *First thought they'd use a nuclear explosion*
  - *Opted instead for a nuclear reactor*
- 1962: Muon neutrinos discovered
- 1964: Davis & Bahcall discuss detection of *solar* neutrinos
  - 1930s: Bethe asserts sun powered by fusion
    - ∴Neutrinos must also be present
      - their detection was aim of Davis' experiment
- 1968: First radiochemical solar neutrino results obtained from the Homestake Experiment
  - This was the beginning of ~30 years of head-scratching and general angst in the neutrino community

The Solar Neutrino Problem

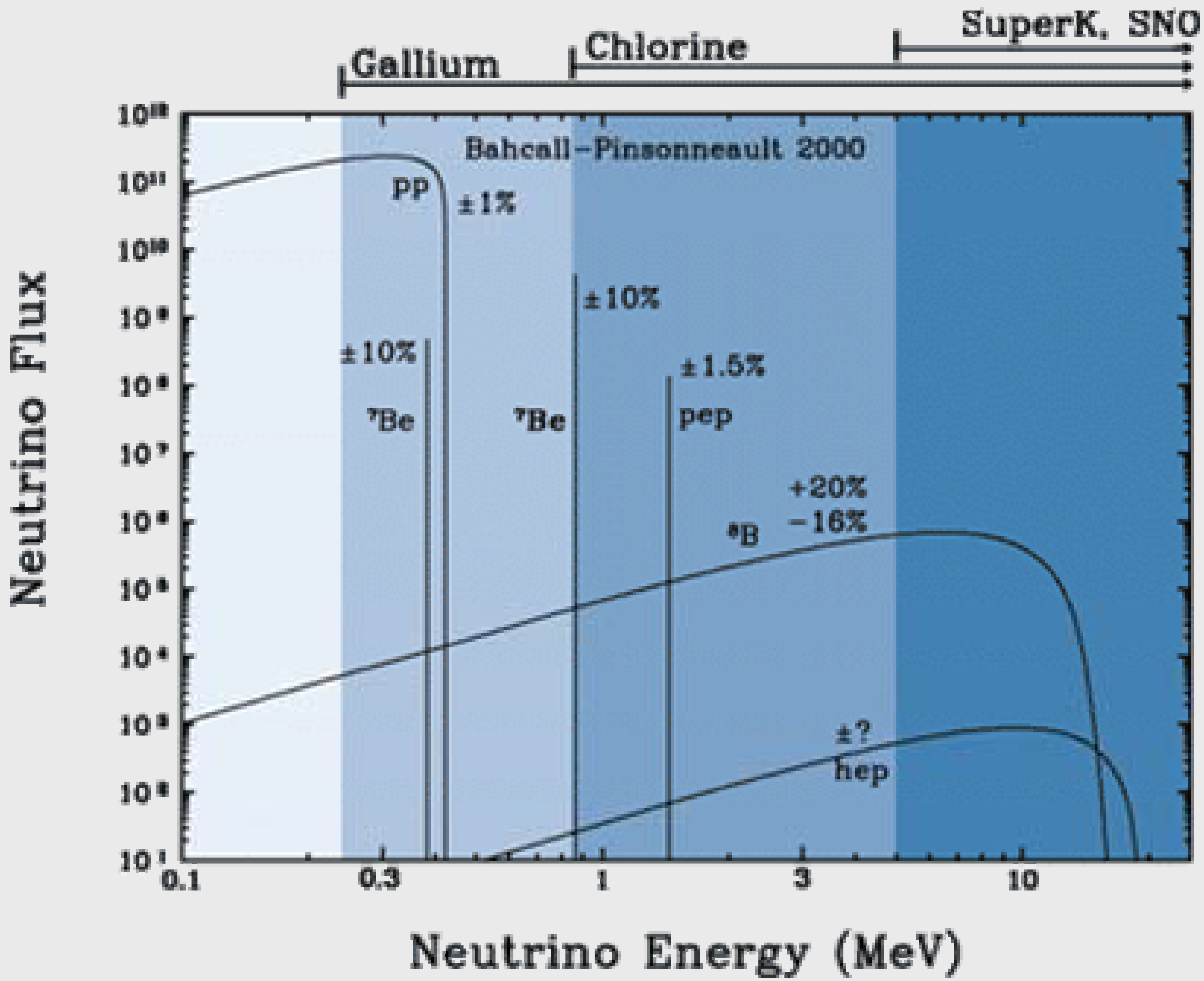
- Homestake (and other subsequent experiments) and the Standard Solar Model disagreed
- The Standard Solar Model:
  - Gravity compresses and heats interior
  - Nuclear fusion of H to ^{4}He occurs
    - Electron neutrinos are an important by-product and carry away 3% of the total solar energy
  - Resulting radiation pressure pushes out
  - Star shines in a stable fashion until nuclear fuel is spent



Standard Solar Model Neutrinos



SSM Neutrino Flux Predictions



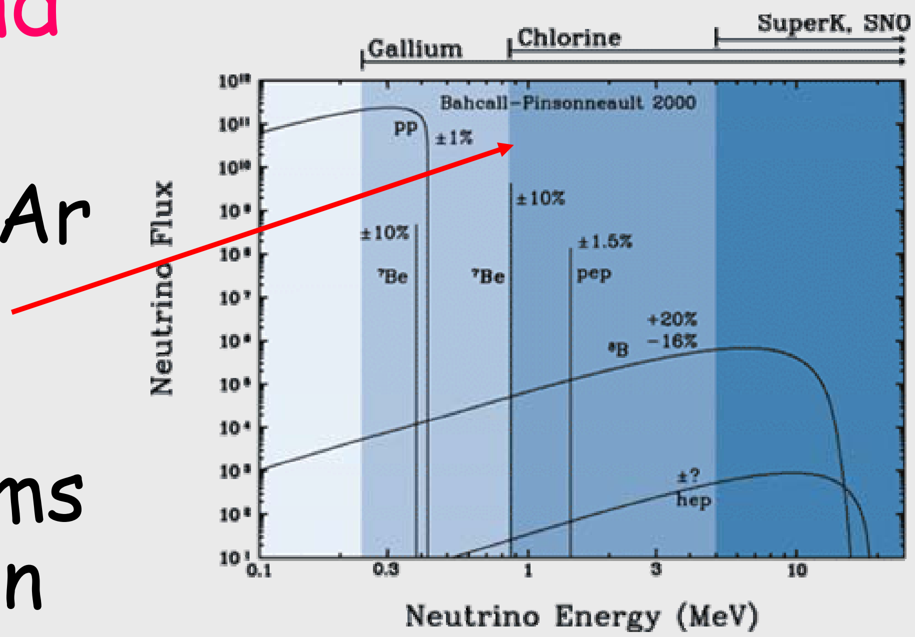
The Experiments

- Homestake, a 30-year experiment(!)
- Facts:
  - Detector size: tank 20 feet in diameter and 48 feet long
  - Detector active medium: 615 tons of perchloroethylene (cleaning fluid, has lots of Cl)
  - Detector location: 4,900 feet below ground surface (4100 m.w.e.) in Lead, South Dakota.
- References:
  - http://www.bnl.gov/bnlweb/raydavis
  - http://ist-socrates.berkeley.edu/~jpf/Astro228Pres/

Homestake

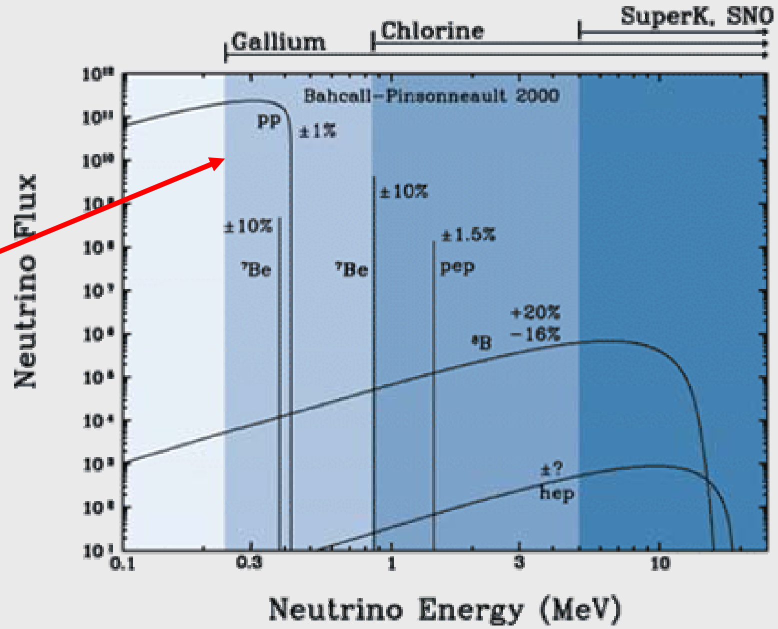
How Homestake Detected ν's

- Answer: Slowly and laboriously
  - $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
    - Energy threshold: 0.814 MeV
  - Extract ^{37}Ar atoms and detect them in a cold trap when they decay
    - Observed ~1 daily



How Other Radiochemical Detectors (GALLEX, SAGE) Did It

- Answer: Slowly and laboriously
  - $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$
    - Energy threshold: 0.233 MeV
    - First to see "p-p" ν's
  - Extract ^{71}Ge atoms and detect them
    - Observe ~1 daily

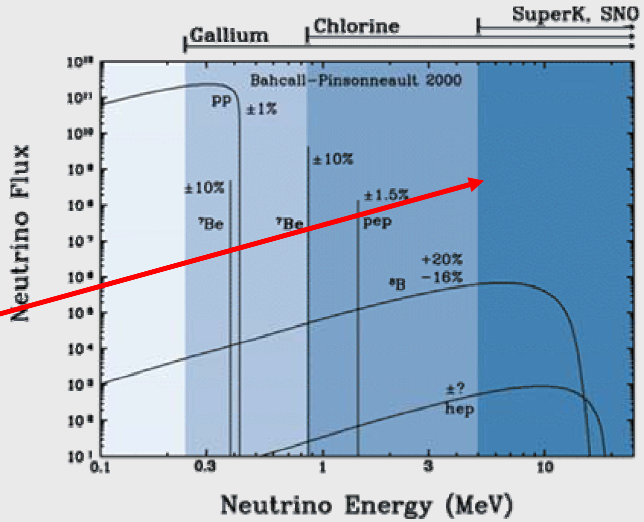


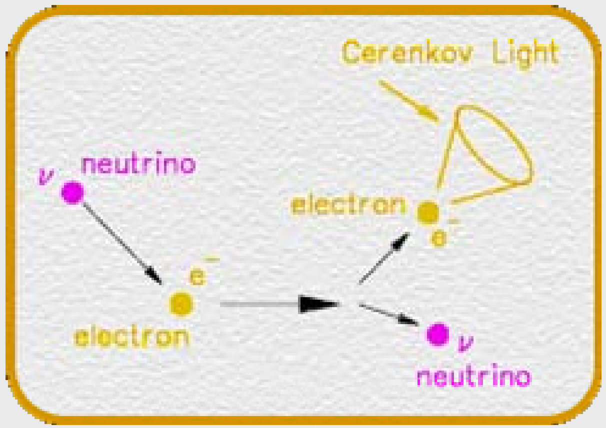
How Non-Radiochemical, Real-Time Detectors Did It

- Real-time detectors are a big improvement
  - Unlike radiochemical experiments, real-time experiments do not integrate over time. They measure when neutrino arrived
  - Real-time experiments also know from where neutrino arrived
  - Some real-time experiments also can distinguish neutrino flavors
- In other words: Real-time detectors get the "when, where, which and how many" while radiochemical only get the "how many."
- Main disadvantage: higher energy threshold…

Kamiokande & SuperKamiokande

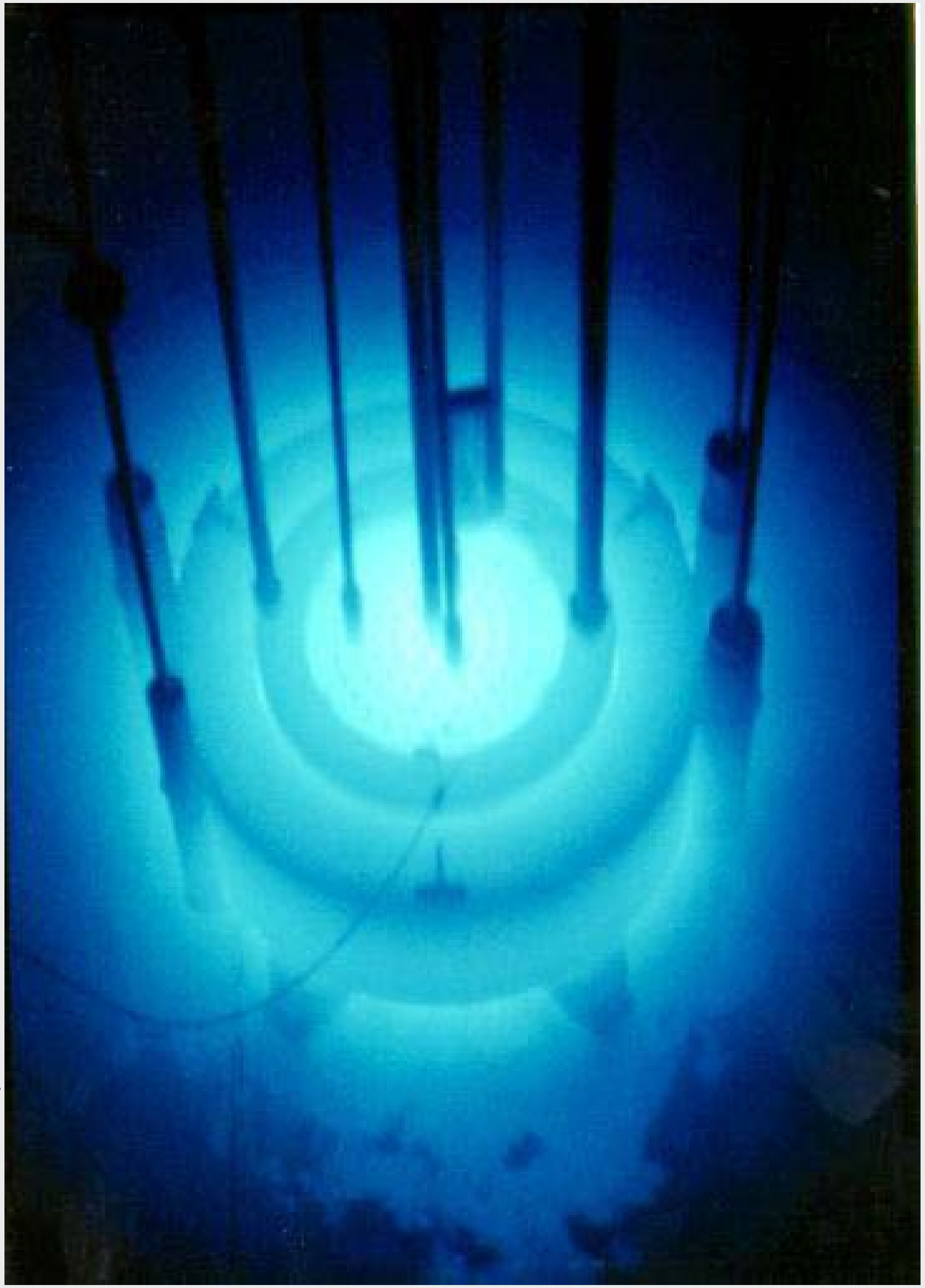
- Use interaction of neutrinos with electrons:
  - Neutrino bangs into electron
  - Electron moves off relativistically, in a direction correlated with incoming neutrino's direction
  - Electron emits Cherenkov light in a cone about its direction of travel
  - Cherenkov light is detected by array of phototubes surrounding the (clear) medium in which the neutrino-electron interaction occurred





The correlation is better than that shown here.

Man-made Cherenkov Light

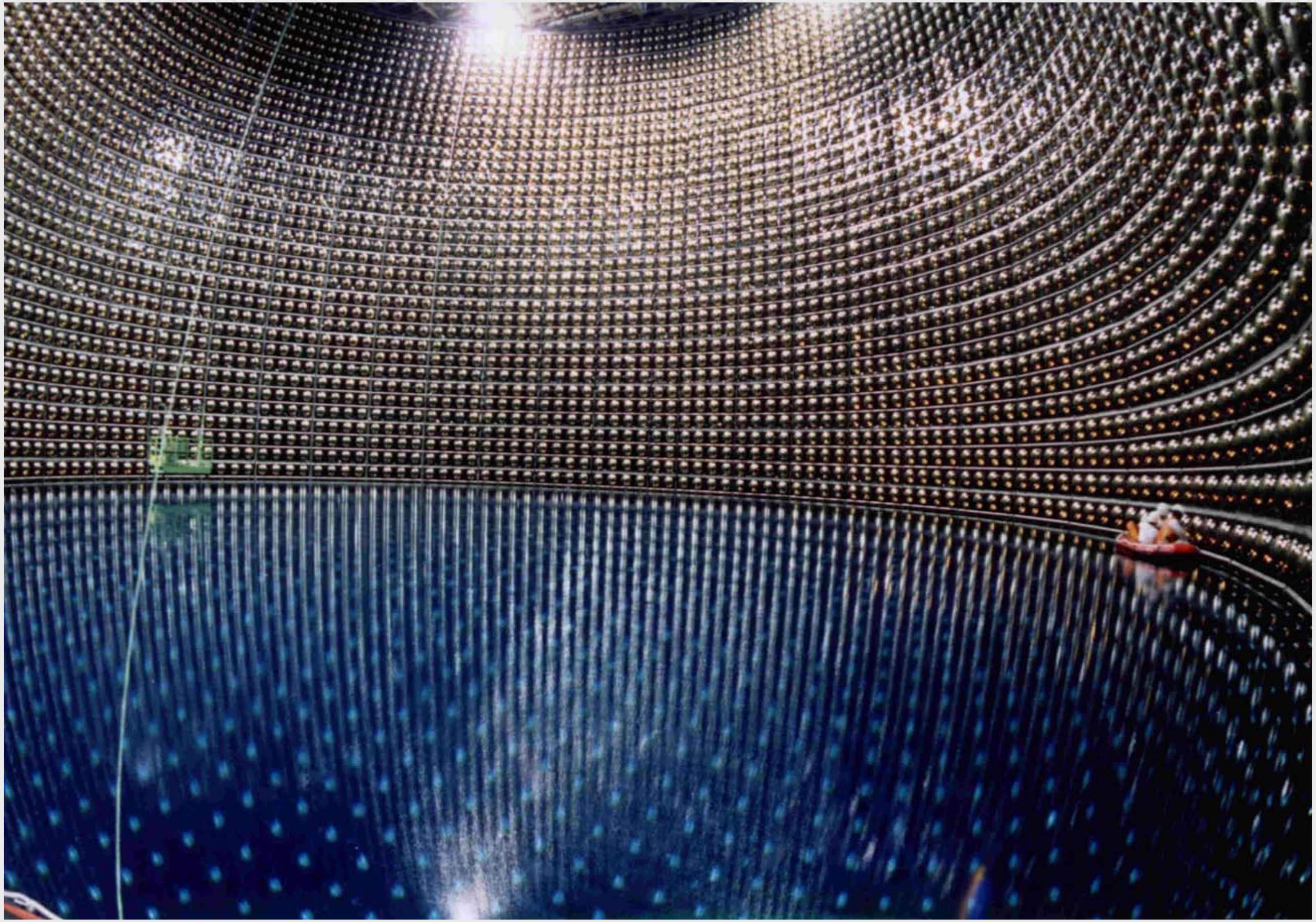


Glow of a nuclear reactor core

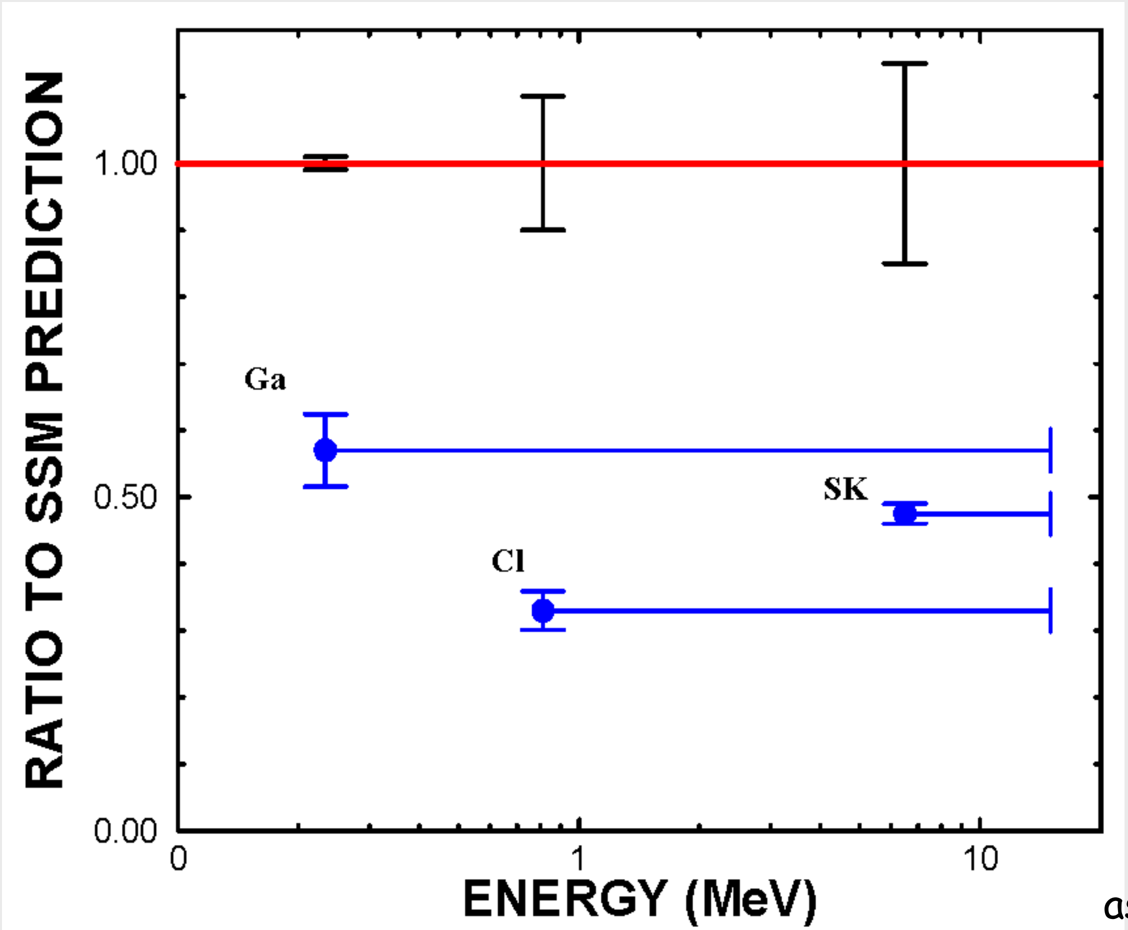
SuperKamiokande

- Began operations in 1996
- Facts:
  - Volume: 50,000 tons (fiducial: 22ktons)
    - 40m x 40m cylinder
  - number of PMTs: ~11,200
  - location: 1,000m underground at the Mozumi mine of the Kamioka Mining and Smelting Co.)
  - Detect ~150 solar neutrinos/day!
- References:
  - http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/super-kamiokande.html

SuperKamiokande



Results of Radiochemical & First Real-time Detectors



astro-ph/0204245,
hep-ex/0006034

Possible Explanations

- SSM was wrong
- Detector(s) were crummy
- Neutrinos were doing something not seen before

<u>BUT</u>

- The SSM made other predictions and got them correct
- The detectors were very different from one another yet all saw a similar neutrino deficit
- Detectors were principally sensitive to ν_e, not ν_μ nor ν_τ. Mounting evidence for neutrino oscillations, where $\nu_e \rightarrow$ another flavor

Neutrino Oscillations (very briefly)

- If the mass and weak eigenstates are not identical, then we can have (say)

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

$$\nu_2 = \nu_e \sin\theta + \nu_\mu \cos\theta$$

- And, with a bit of QM and some algebra, the probability a ν_e remains a ν_e is given by

$$P_{ee} = 1 - \sin^2[2\theta]\sin^2[k\Delta m^2 L/E]$$

- See "Neutrino Oscillations for Dummies" http://arxiv.org/abs/physics/0303116

First Clear Evidence for Neutrino Oscillations: Atmospheric Neutrinos

- 1998: MACRO and IMB saw *hints* of neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$)
  - hep-ex/9807005
  - Phys.Lett. B434 (1998) 451-457)

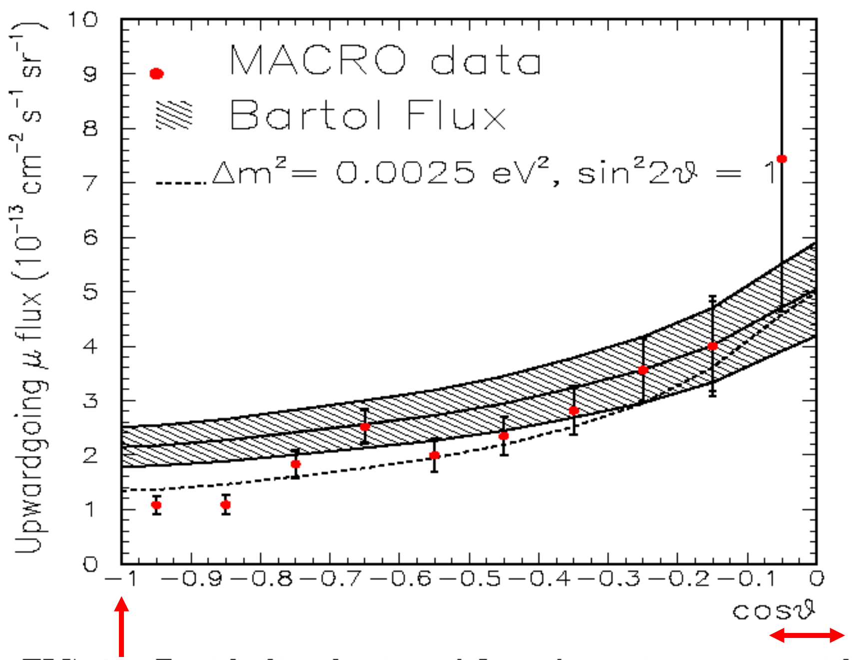


FIG. 2. Zenith distribution of flux of upgoing muons with energy greater than 1 GeV for data and Monte Carlo for the combined MACRO data. The solid curve shows the expectation for no oscillations and the shaded region shows the uncertainty in the expectation. The dashed line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

SuperKamiokande Result, 1998

- 1998: SuperK nailed it—much larger volume than all previous experiments, it had the requisite statistics
  - hep-ex/9812014
  - Phys.Rev.Lett. 82 (1999) 2644-2648

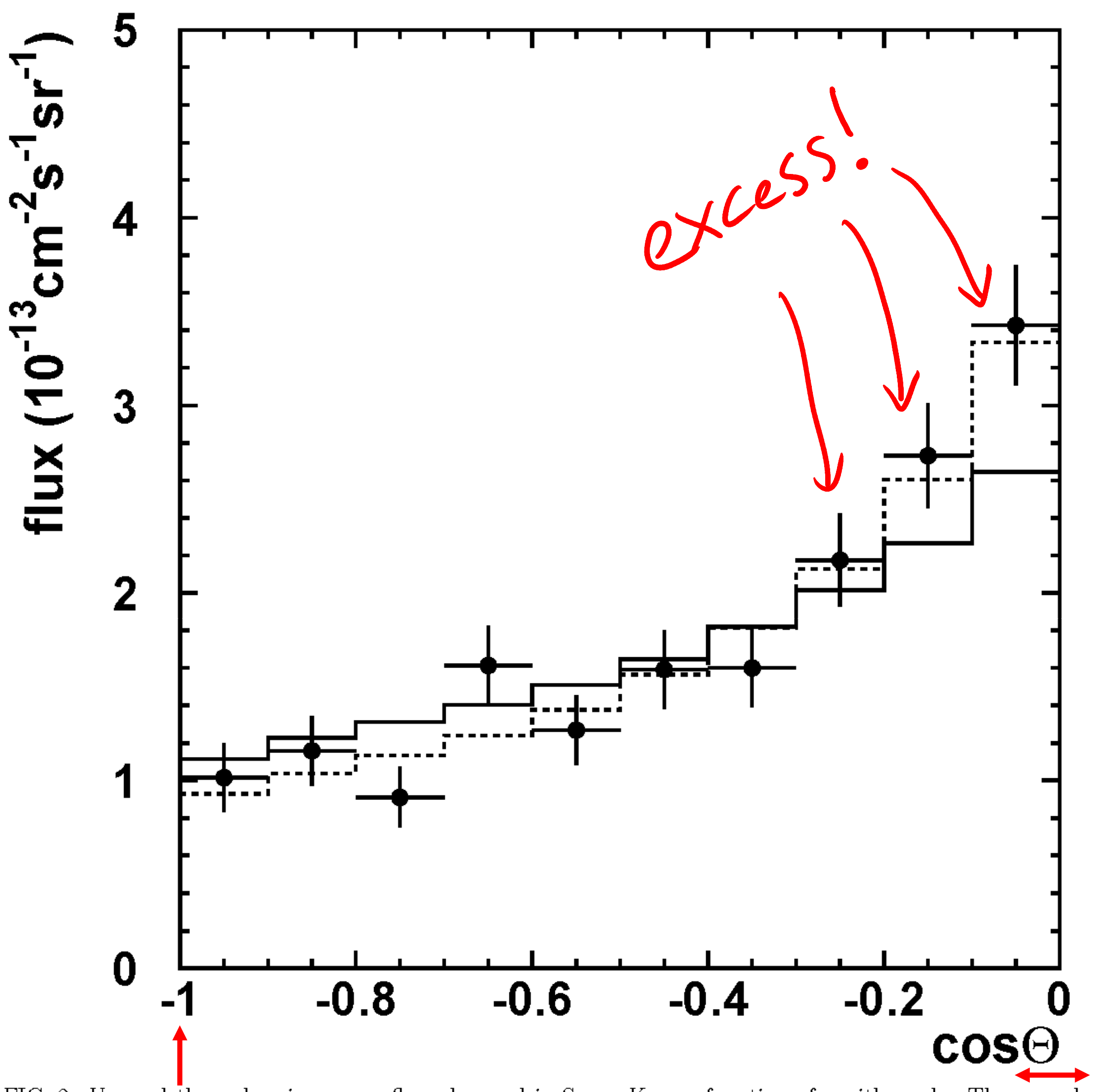
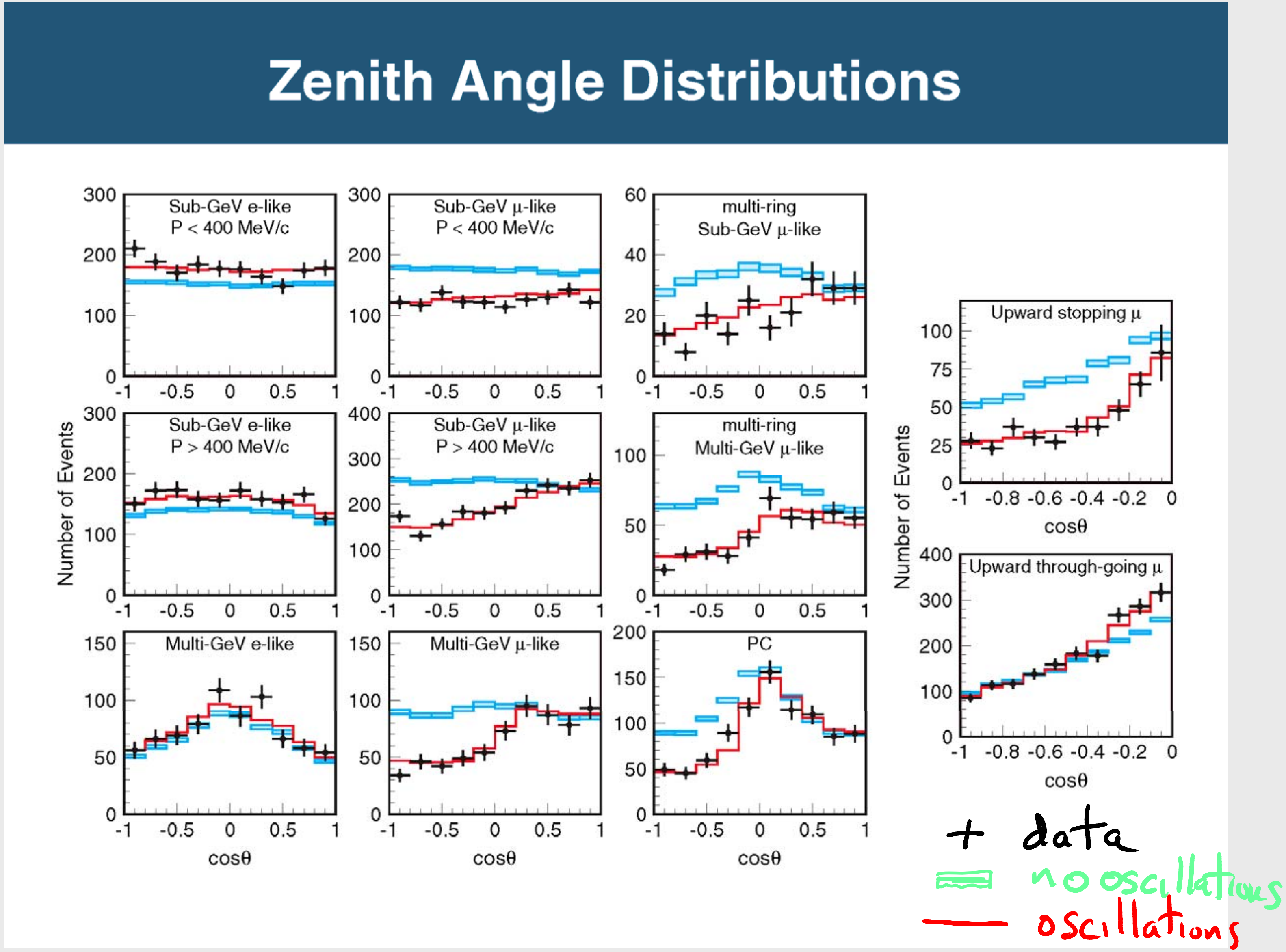


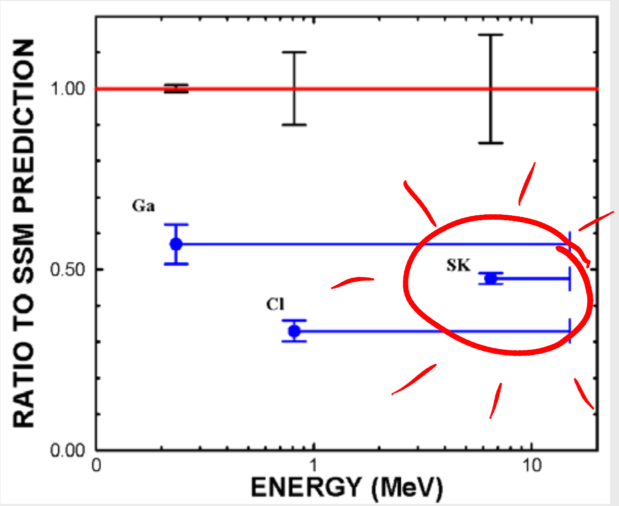
FIG. 2. Upward through-going muon flux observed in Super-K as a function of zenith angle. The error bars indicate uncorrelated experimental systematic plus statistical errors added in quadrature. The solid histogram shows the expected upward through-going muon flux with normalization ($\alpha_\mu = -14\%$) based on the Bartol neutrino flux for the null neutrino oscillation case. Also shown as a dotted line is the expected flux assuming the best fit parameters at $(\sin^2 2\theta, \Delta m^2) = (0.95, 5.9 \times 10^{-3}\mathrm{eV}^2)$, $\alpha_\mu = +12\%$ for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation case.

SuperK Atm. ν Result, June 2004



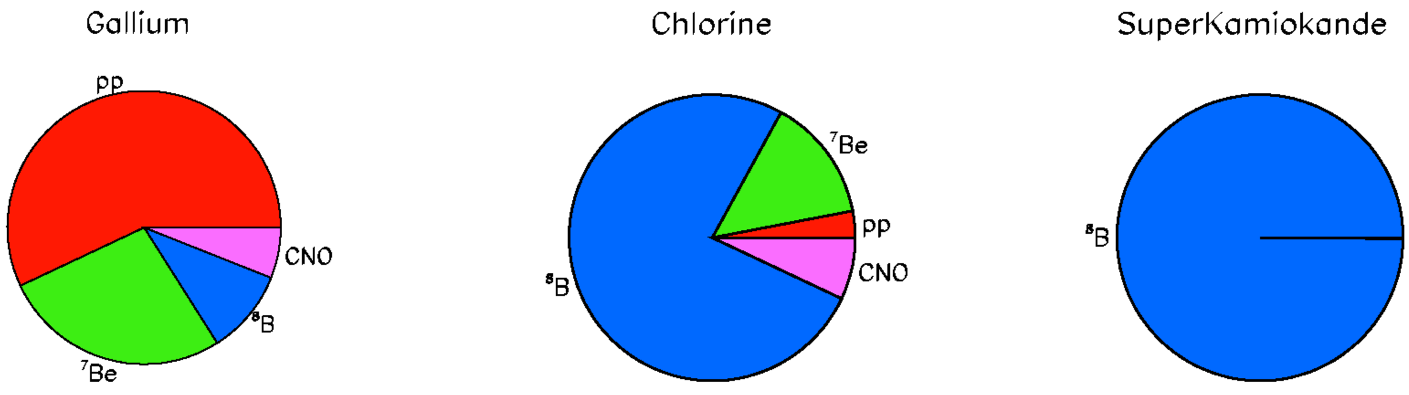
SuperK and Solar Neutrinos

- SuperK only sees neutrinos through the elastic scattering (ES) interaction
  - ~Flavor-blind, unfortunately
- As such, it could only measure the total flux [$\Phi(\nu_e)$+ $\Phi(\nu_{\mu\tau})/6$]
- SuperK saw a deficit of solar neutrinos, as did previous detectors, but it could not claim that solar neutrinos were oscillating

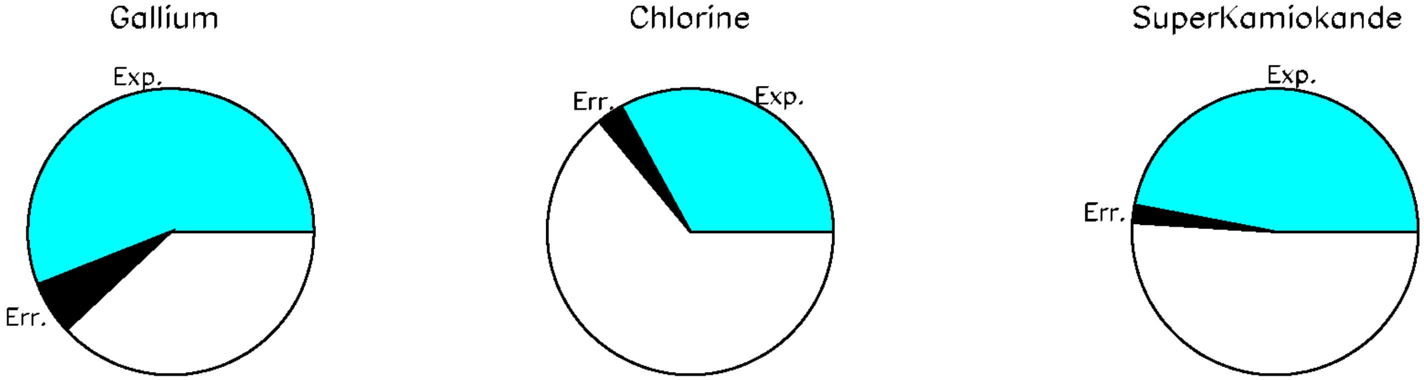


Solar Neutrino Problem in Pie Charts

- Standard Solar Model Predictions:



- Measurements:



The Sudbury Neutrino Observatory (SNO) to the Rescue!

- SNO was designed to measure solar neutrinos 3 different ways, with each way having different sensitivity to flavor content
  - SNO is able to tease out the composition of the solar neutrino flux

Sudbury Neutrino Observatory

2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

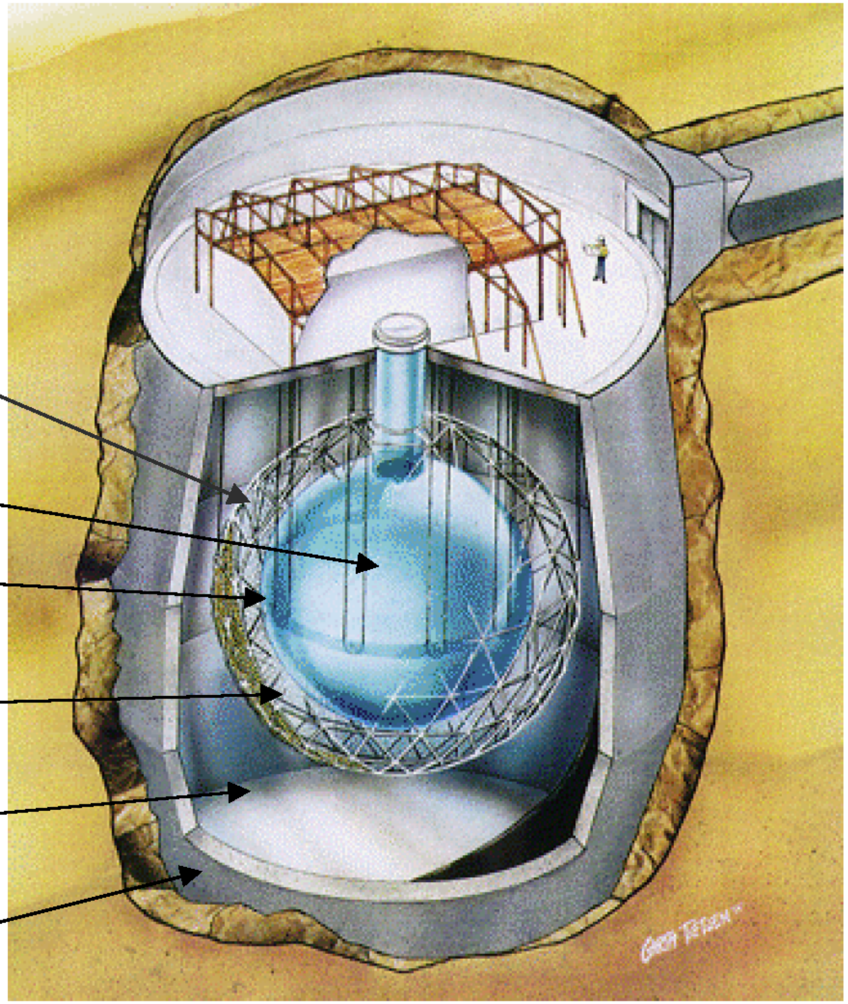
1000 Tonnes D_2O !

12 m Diameter Acrylic Vessel

1700 Tonnes Inner Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Slide courtesy S.Oser

Solar ν Interactions in SNO

Elastic Scattering (ES) $\quad \nu_x + e^- \rightarrow \nu_x + e^-$

- Cross-section for ν_e is $6.5\times$ larger than for $\nu_{\mu\tau}$

Charged Current (CC) $\quad \nu_e + d \rightarrow p + p + e^-$

- good E_ν sensitivity (ν_e spectrum)

Neutral Current (NC) $\quad \nu_x + d \rightarrow n + p + \nu_x$

- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \rightarrow t + \gamma$ (6.25 MeV)

Each reaction has different sensitivity to ν flavor content

Slide courtesy S.Oser

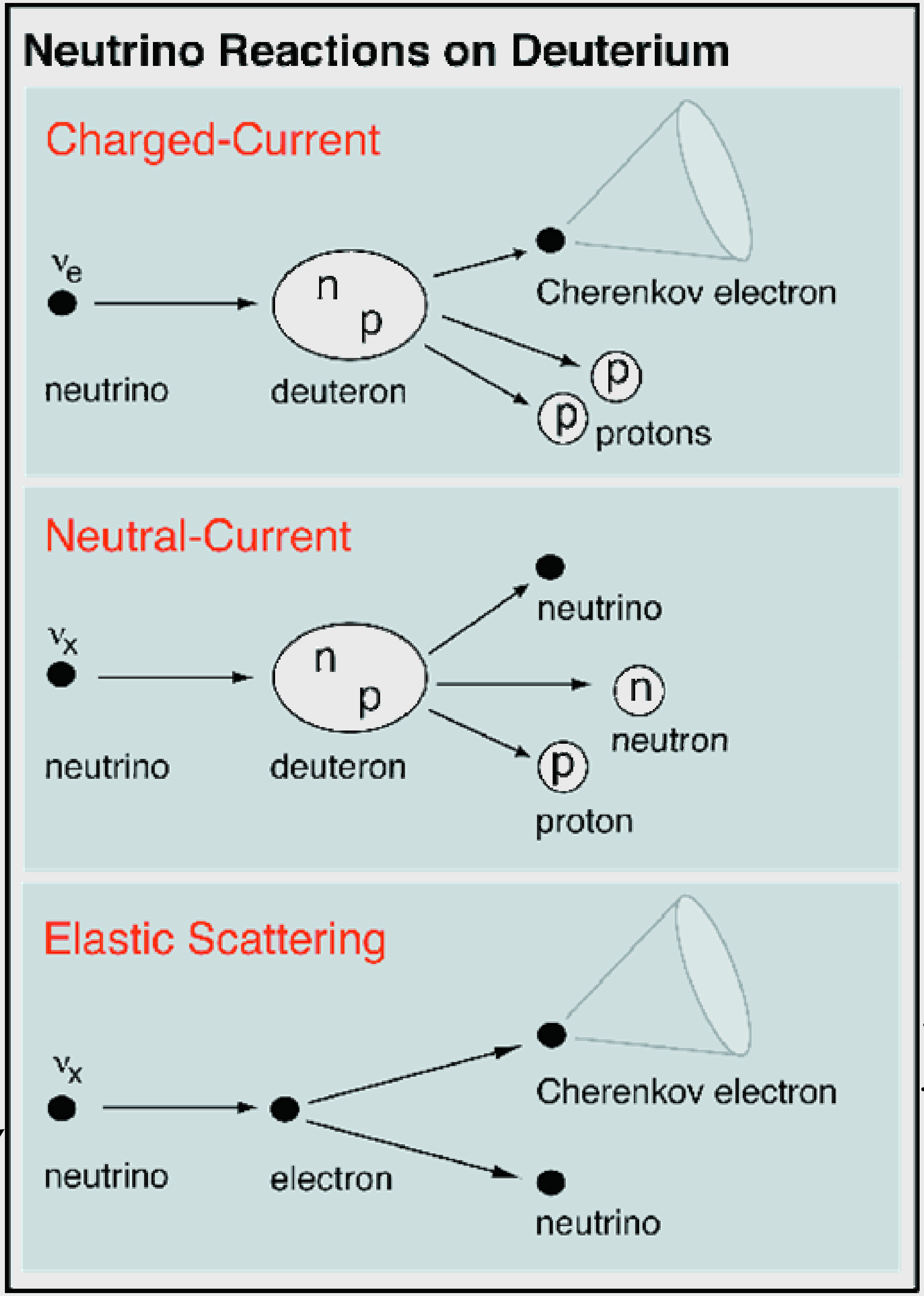
SNO Reactions

ν_e only, Energy

Flavor-Blind

Directionality

SuperK only
saw ES interaction

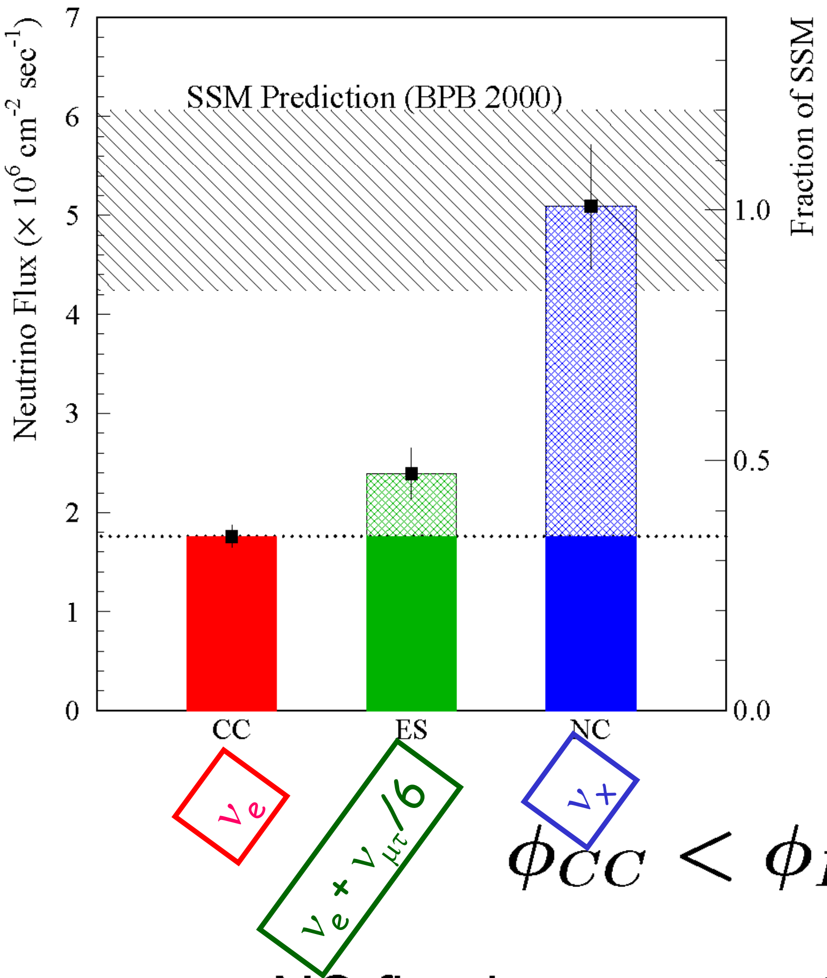


www.europhysicsnews.com

Initial SNO Measurement: Pure D_2O

- SNO used its CC measurement with SuperK's ES measurement
  - CC is sensitive to just ν_e
  - ES is sensitive to mainly ν_e but also $\nu_{\mu\tau}$
    - SNO's ES measurement was much lower in statistics than SuperK's at the time
- Compared what expected to measure in one experiment given the measurement in the other, assuming no neutrino oscillations
  - the measurements disagreed at 3.3σ level
  - "…evidence for non-electron flavor active neutrino component in the solar flux."
    - nucl-ex/0106015, Phys.Rev.Lett. 87 (2001) 071301

Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

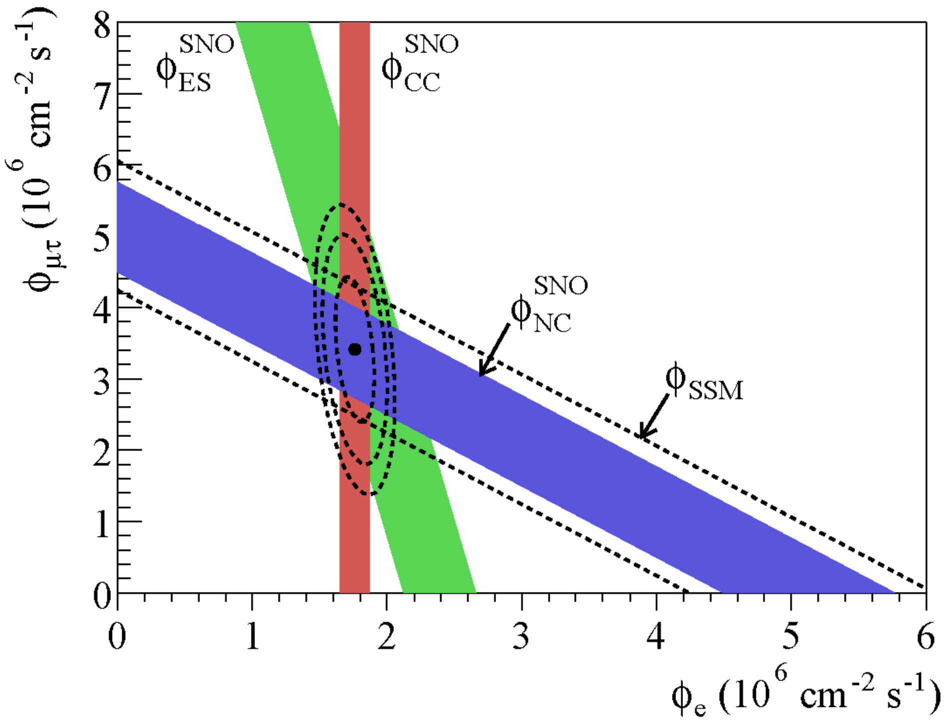
(nucl-ex/0204008)

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!

Slide courtesy S.Oser

SNO: Flavor Content



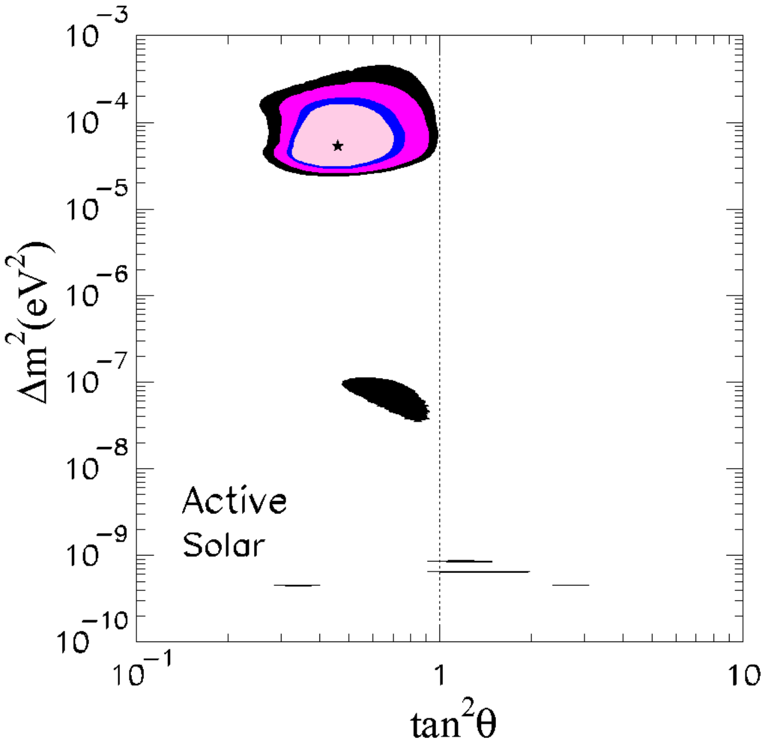
$$\phi_e = 1.76 \pm 0.06 \pm 0.09 \quad \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

$$\phi_{\mu\tau} = 3.41 \pm 0.45^{+0.48}_{-0.45} \quad \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

$\phi_{\mu\tau} > 0$ at 5.3σ level!

Slide courtesy S.Oser

Global Solar Neutrino Analysis Results



Bahcall, Gonzalez-Garcia,

& Peña-Garay

hep-ph/0212147 v3

Fit to all solar ν data strongly favors LMA solution

LOW, vacuum oscillations ruled out at $\sim 99\%$ C.L.

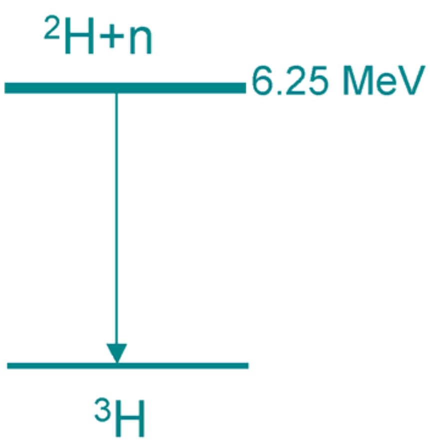
For LMA, maximal mixing excluded at 3σ level

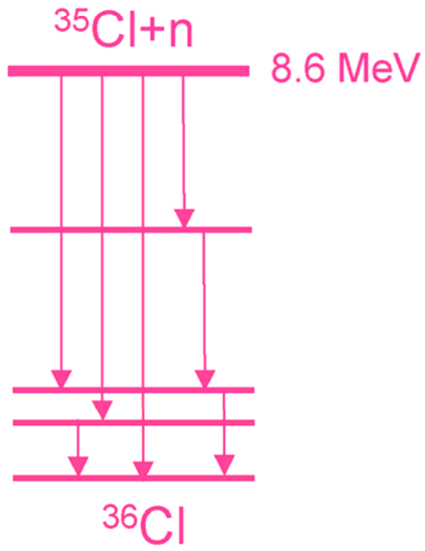
- Equivalent to $m(\nu_1) < m(\nu_2)$
- Indirect evidence for matter effects

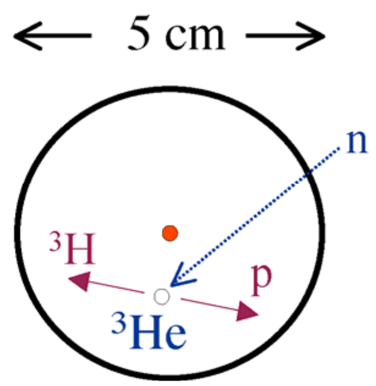
Slide courtesy S.Oser

SNO Phases II & III: Salt and NCDs

Phase I (D_2O)	Phase II (salt)	Phase III (^3He)
Nov. 99 - May 01	July 01 - Sep. 03	Summer 04 - Dec. 06
n captures on $^2H(n, \gamma)^3H$ σ = 0.0005 b Observe 6.25 MeV γ PMT array readout Good CC	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$ σ = 44 b Observe multiple γ's PMT array readout Enhanced NC	40 proportional counters $^3He(n, p)^3H$ σ = 5330 b Observe p and ^3H PC independent readout Event by Event Det.







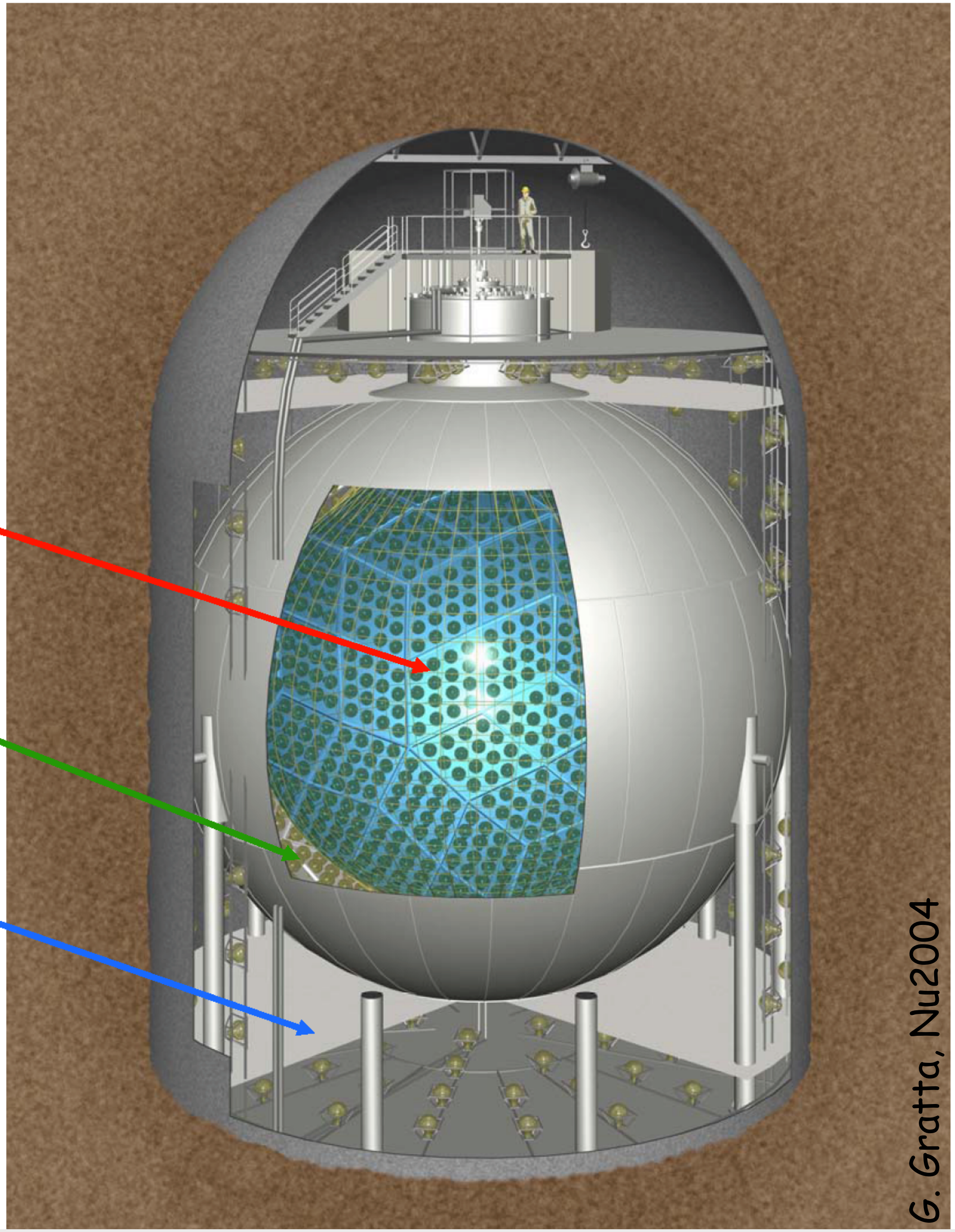
$n + {}^3He \rightarrow p + {}^3H$

KamLAND

- The Kamioka Liquid scintillator Anti-Neutrino Detector was built to probe solar neutrino mixings with reactor neutrinos
  - In many ways, it is the original Reines-Cowan experiment but with a much large detector and lots more neutrino flux
- Look for anti-electron neutrinos from reactors in Japan and Korea
  - $\nu_e + p \rightarrow e^+ + n$
  - See coincident signal: e^+ Cherenkov light followed by neutron capture
- Expect—from SNO LMA solution—disappearance of reactor anti- ν_e

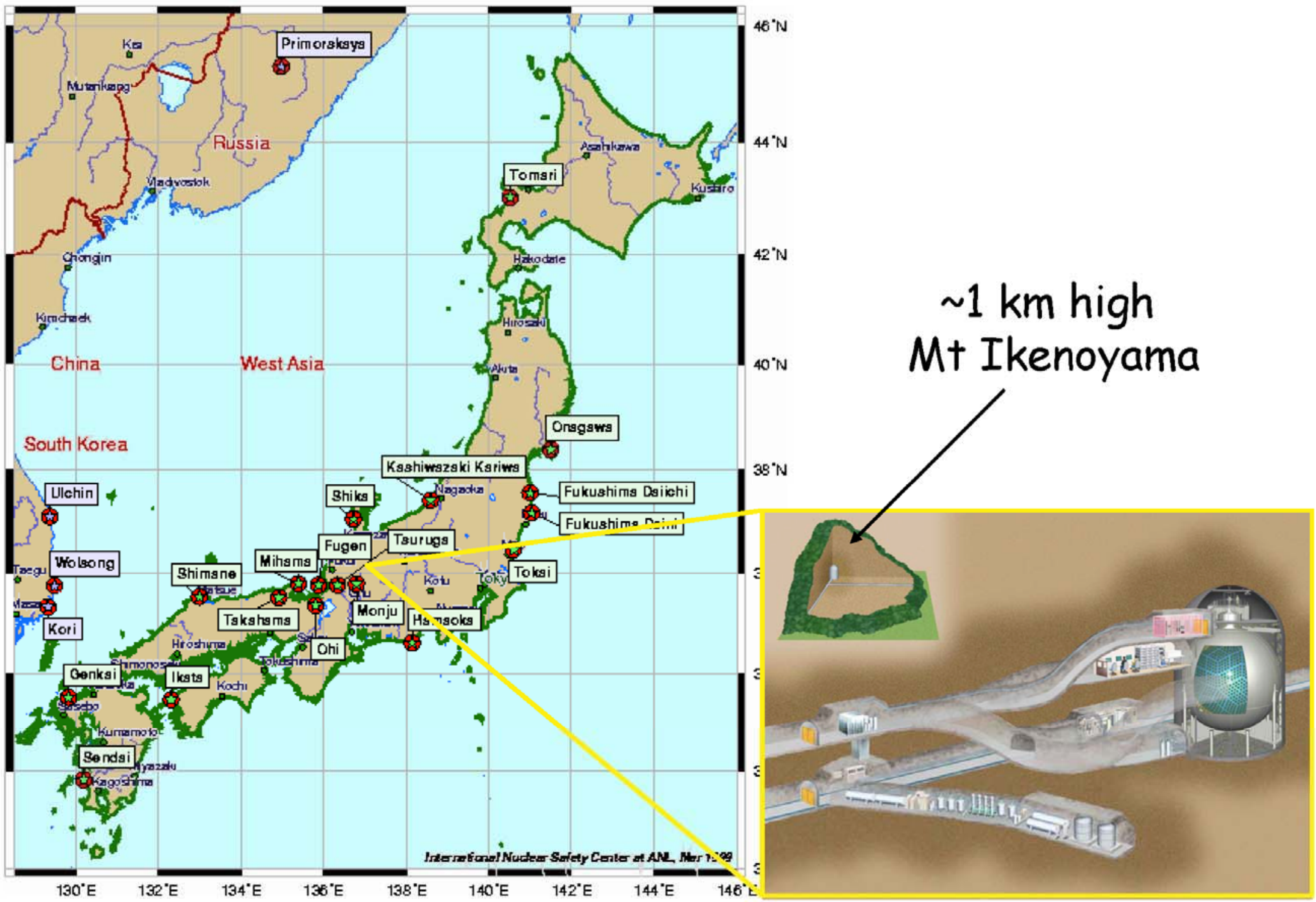
KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector
  in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



G. Gratta, Nu2004

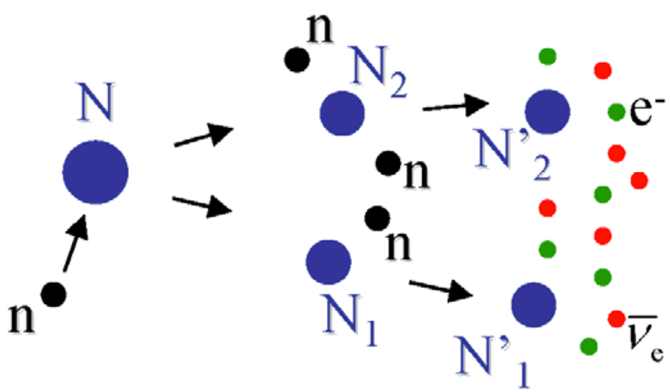
KamLAND's Neutrino Sources



G. Gratta, Nu2004

KamLAND's Neutrino Sources

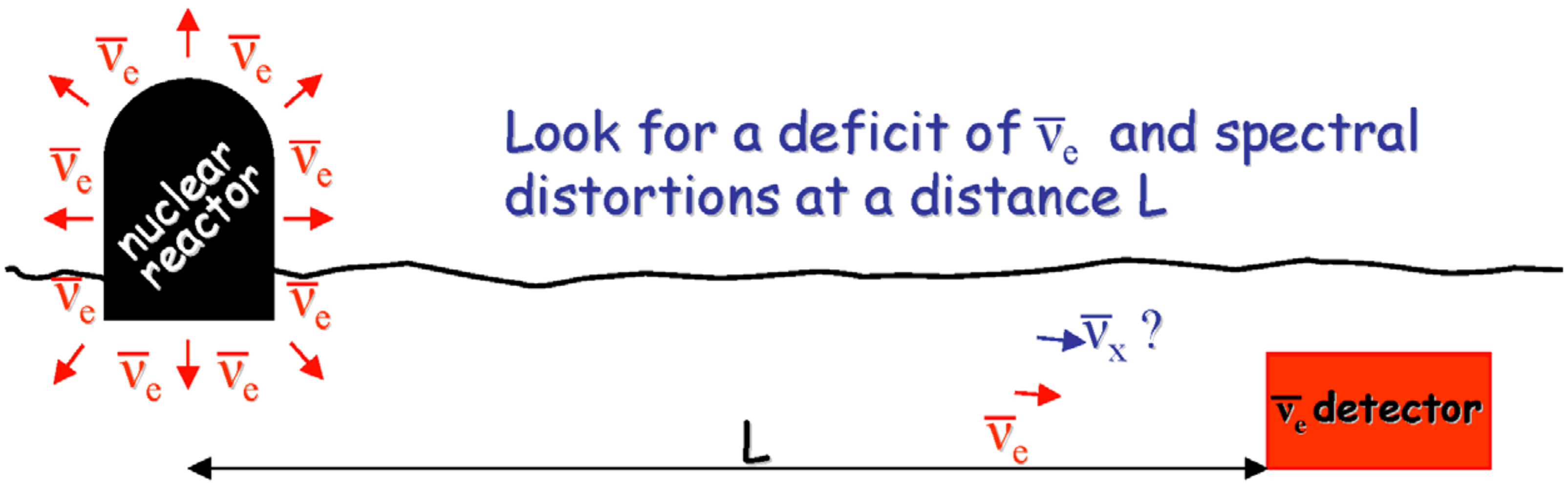
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments



Yield :

$200\,MeV\,/\,fission$

$6\bar{\nu}_e\,/\,fission$



Look for a deficit of $\bar{\nu}_e$ and spectral distortions at a distance L

G. Gratta, Nu2004

KamLAND Results

Results

(766.3 ton·yr, ~4.7× the statistics of the first paper)

Observed events	258
No osc. expected	365±24(syst)
Background	7.5±1.3

Background	Events
Accidentals	2.69±0.02
$^8He/^9Li$	4.8±0.9
μ-induced n	<0.89
Total	7.5±1.3

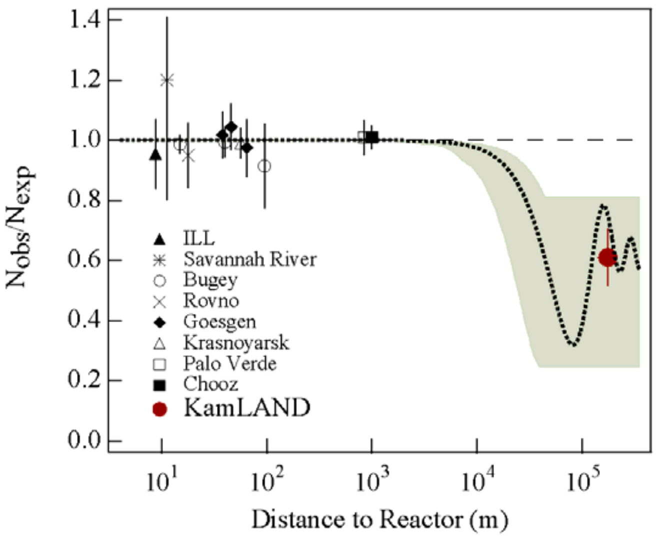
Inconsistent with simple $1/R^2$ propagation at 99.995% CL

(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

G. Gratta, Nu2004

KamLAND Results



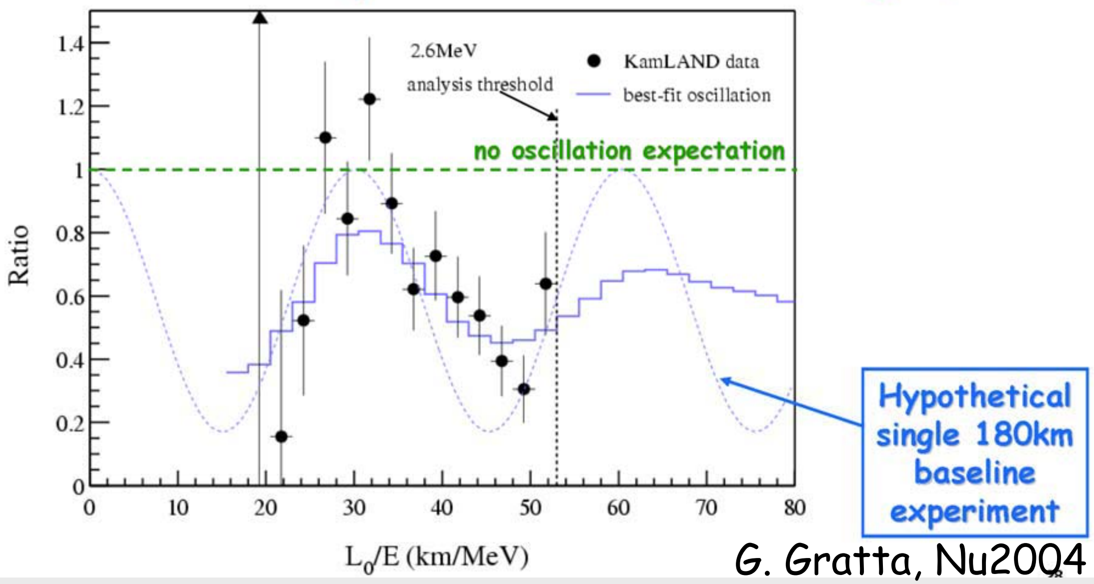
$$R = 0.611 \pm 0.085 \pm 0.041$$

No oscillations hypothesis ruled out at 99.95% C.L.

S.Oser, SUGRA20

KamLAND uses a range of L and it cannot assign a specific L to each event

Nevertheless the ratio of detected/expected for L_0/E (or 1/E) is an interesting quantity, as it decouples the ***oscillation pattern*** *from the reactor energy spectrum*



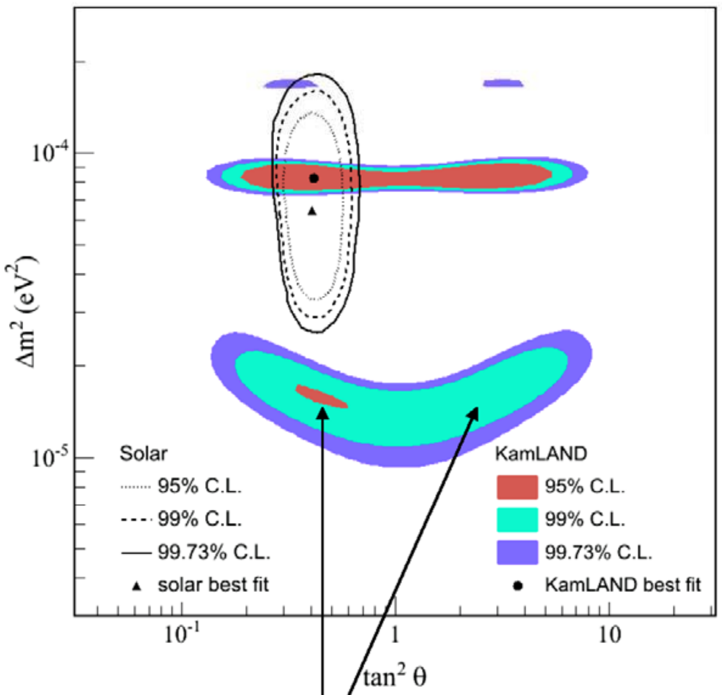
G. Gratta, Nu2004

Solar + KamLAND

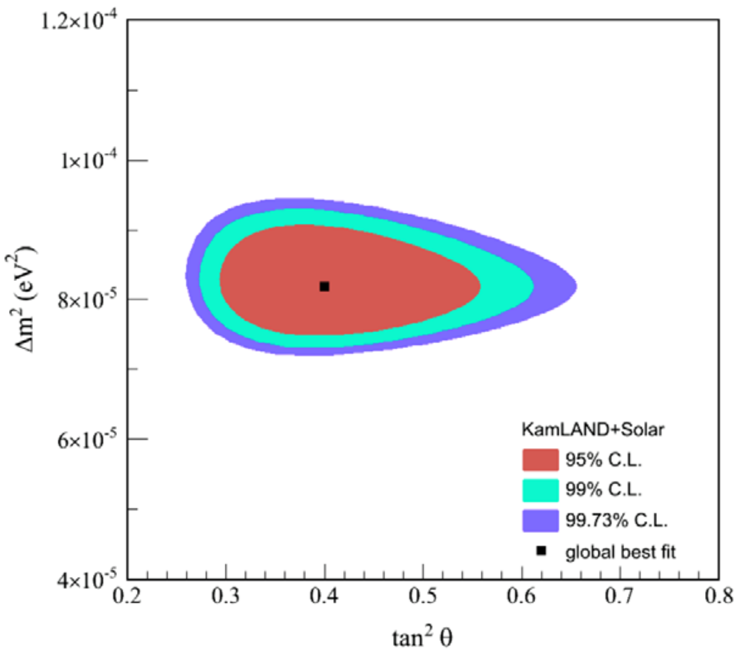
Combined solar ν - KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

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

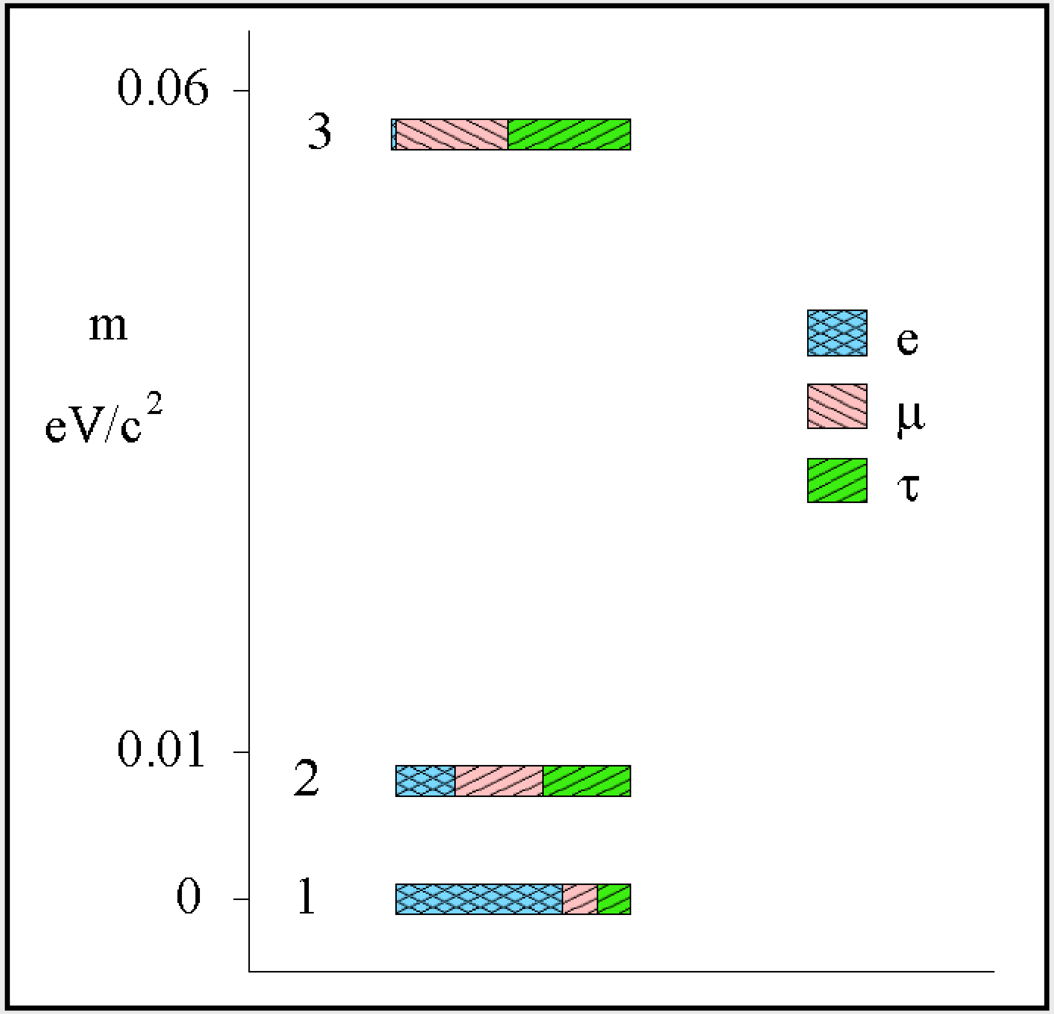


Includes (small) matter effects



G. Gratta, Nu2004

What Neutrinos are Made Of



LMA solution assumed. ν_1 assumed to have zero mass.
--from C. Waltham, "Neutrinos for Dummies"

Conclusions & Questions

- Neutrinos have mass and they oscillate
- The sun produces neutrinos as expected—so far
- Questions still to answer
  - Exactly how do neutrinos oscillate?
    - 3 flavor?
    - CP violation?
    - What are their masses? (Other expts. have to address this question!)
  - Does the sun produce "pp" neutrinos as expected?—need lower energy threshold, high statistics detectors. Many such detectors are being planned.
    - CLEAN, HERON, MOON, LENS, XMASS, GENIUS
    - Thus far, we've only really looked at 2% of solar neutrino spectrum
- Are there any more interesting quotes from Y. Berra that I can add to this talk?
- Is Y. Berra the only quotable source I know about?

The End

- Parting comment from Y. Berra, possibly relevant for Trieste hotels:
  - "The towels were so thick there I could hardly close my suitcase."
- Of course, it is not only American baseball that provides us with linguistic entertainment:
  - "It's now 1-1, an exact reversal of the score on Saturday."
    - **Radio 5 Live**. [European football]

Solar and Reactor Neutrinos

- Historical perspective
  - Discovery of the neutrino by Reines & Cowan (no relation ☹)
  - The Solar Neutrino Problem
    - Grandparent: Homestake experiment
- Modern experiments
  - Solar: SAGE, GALLEX, SuperK, SNO
  - Reactor: CHOOZ, KamLAND
- The answer to the solar neutrino problem