Big World of Small Neutrinos

Hitoshi Murayama
UC Berkeley / LBNL
Harvard, Dec 9, 2002

"Wimpy and Abundant" Neutrinos are Everywhere

- They come from the Big Bang:
  - When the Universe was hot, neutrinos were created equally with any other particles
  - They are still left over: ~300 neutrinos per cm^3
- They come from the Sun:
  - Trillions of neutrinos going through your body every second
- They are shy:
  - If you want to stop them, you need to stack up lead shield up to three light-years

Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Solar Neutrinos
- Implications of Neutrino Mass
- Why do we exist?
- Conclusions

Neutrinos in the Standard Model

Puzzle with Beta Spectrum

- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because

$$E_{\alpha,\gamma} = E_i - E_f$$

- But β spectrum continuous

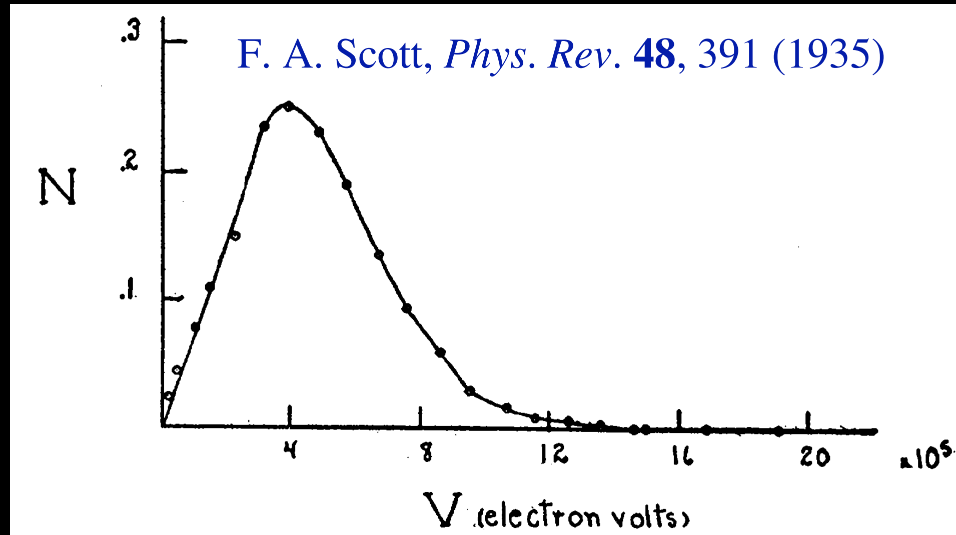


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*

Desperate Idea of Pauli

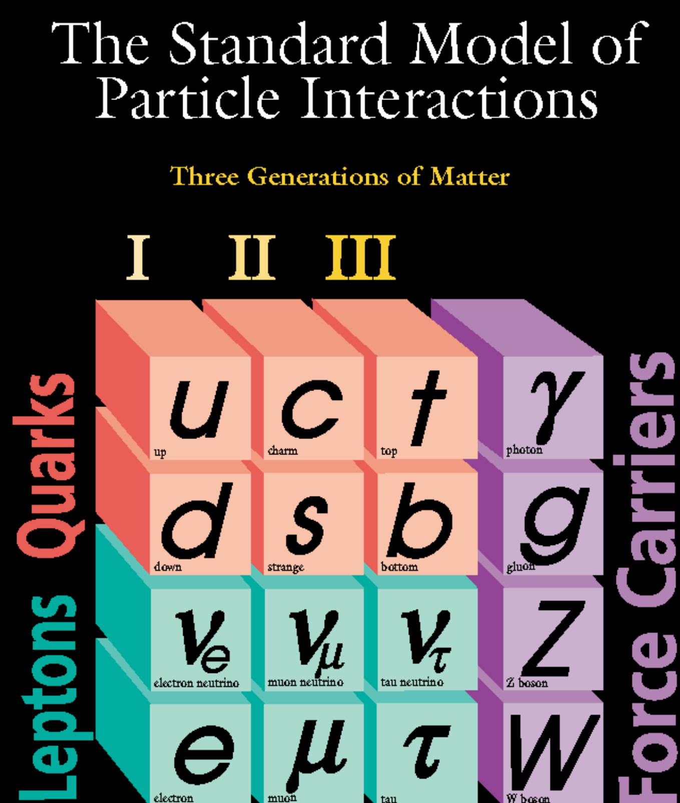
4th December 1930

Dear Radioactive Ladies and Gentlemen,

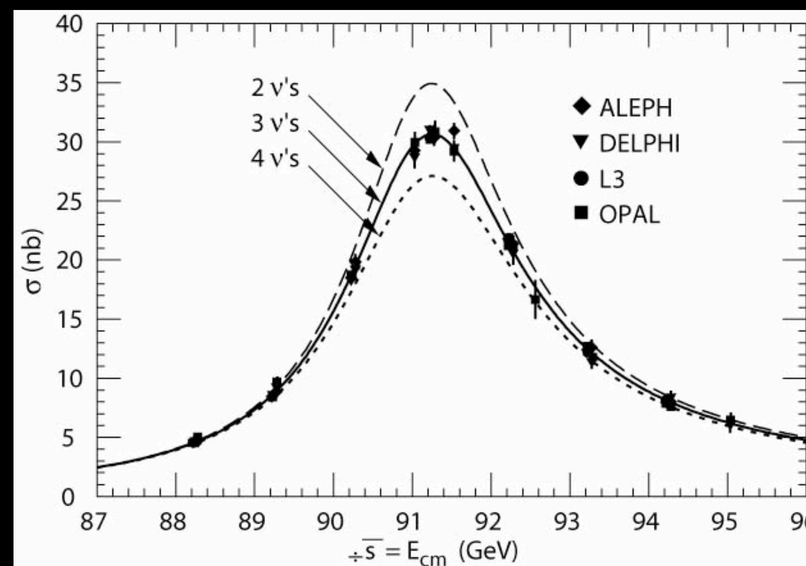
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation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

Three Kinds of Neutrinos

- There are three



- And no more



Neutrinos are Left-handed

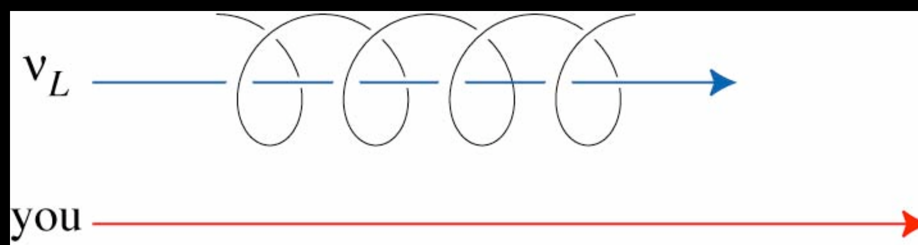
Helicity of Neutrinos*

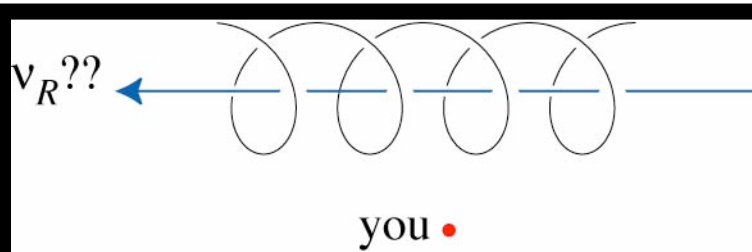
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

- All neutrinos left-handed □ massless
- If they have mass, can't go at speed of light.



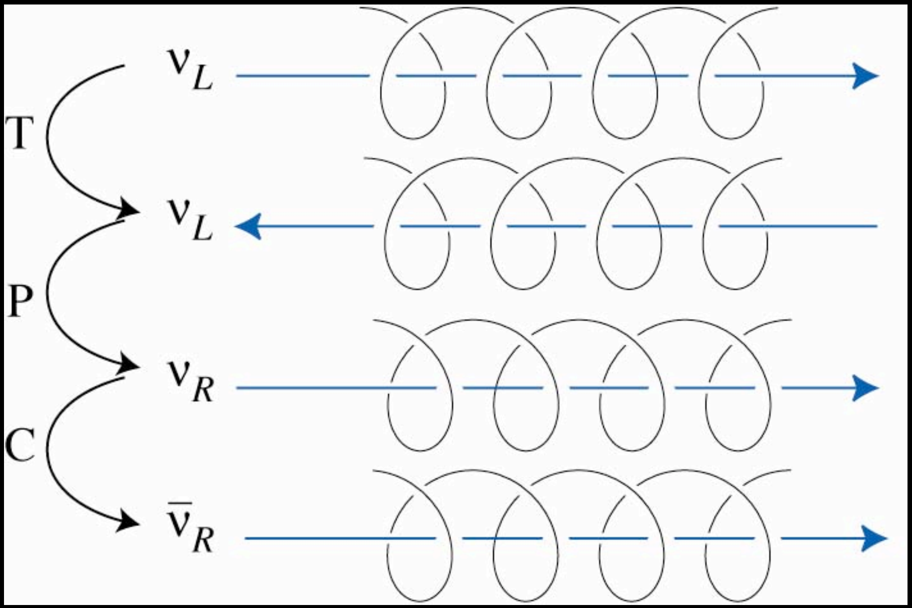


- Now neutrino right-handed??

□ contradiction □ can't be massive

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particles & anti-particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\bar{\nu}_R$



Other Particles?

- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak interaction acts only on left-handed particles" yet they are massive.

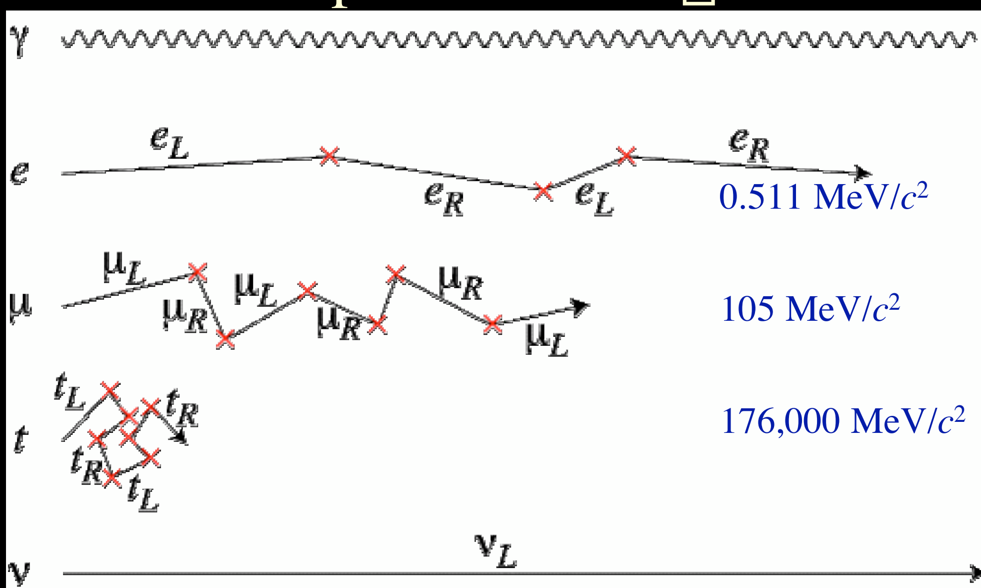
Isn't this also a contradiction?

No, because of the Higgs condensate:

Bose-Einstein condensate in Universe

Universe is filled with Higgs

- Empty looking space is filled with Higgs
- Particles bump on it, but not photon because Higgs neutral.
- Can’t go at speed of light (massive), and right-handed and left-handed particles mix no contradiction



But neutrinos can’t bump because there isn’t a right-handed one stays massless

Standard Model

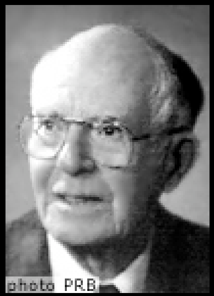
- Therefore, neutrinos are strictly massless in the Standard Model of particle physics

  Finite mass of neutrinos imply the Standard Model is incomplete!

- Not just incomplete but probably a lot more profound

Neutrinos from backstage to center stage

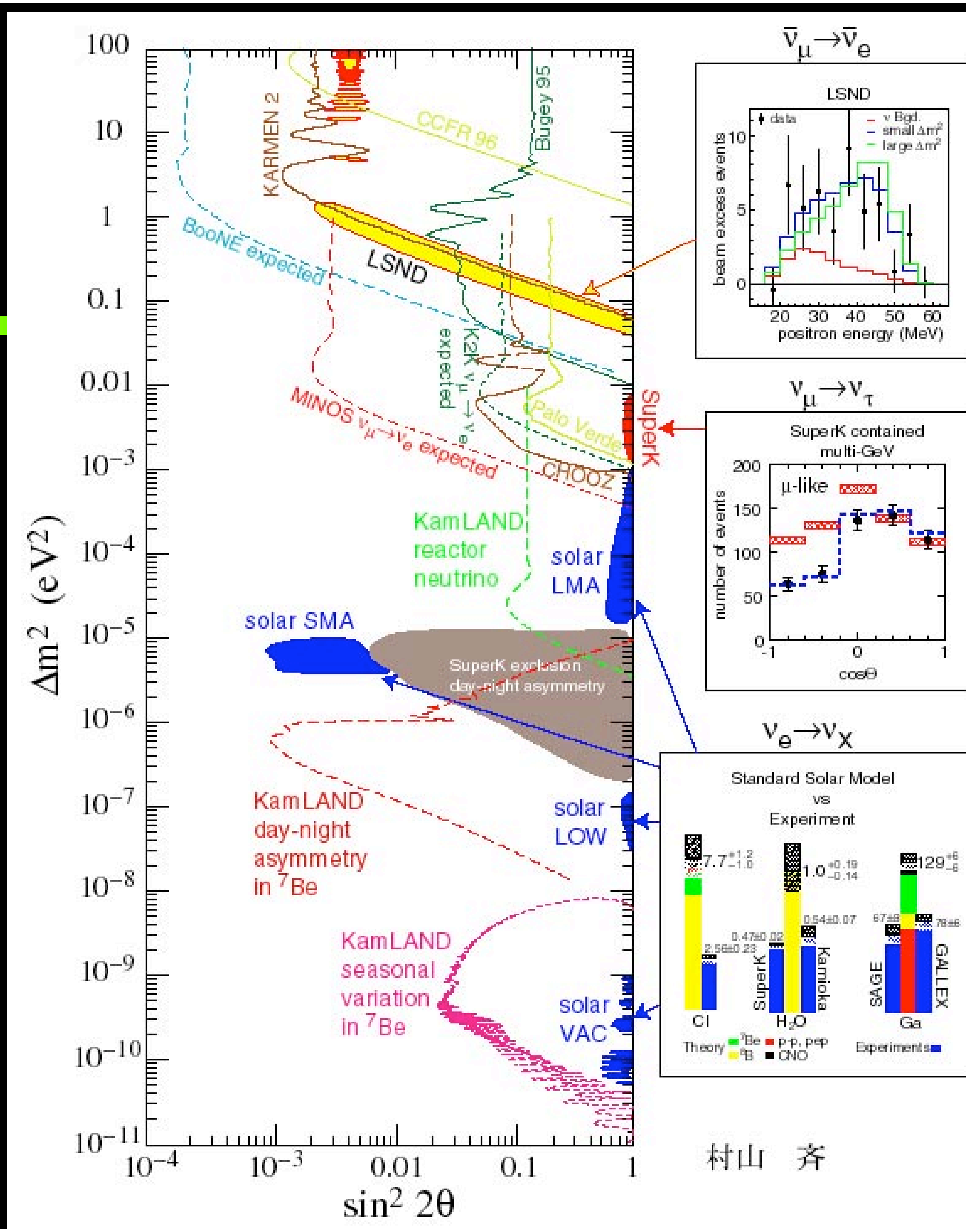
- Pauli bet a case of champagne that noone will discover neutrinos
- Finally discovered by Cowan and Reines using a nuclear reactor in 1958
- Massless Neutrinos in the Standard Model (‘60s)
- Evidence for neutrino mass from SuperK (1998) and SNO (2002)
- *First evidence that the minimal Standard Model of particle physics is incomplete!*
- 2002 Nobel to pioneers: Davis and Koshiba



Lot of effort since '60s

Finally convincing evidence for "neutrino oscillation"

Neutrinos appear to have tiny but finite mass



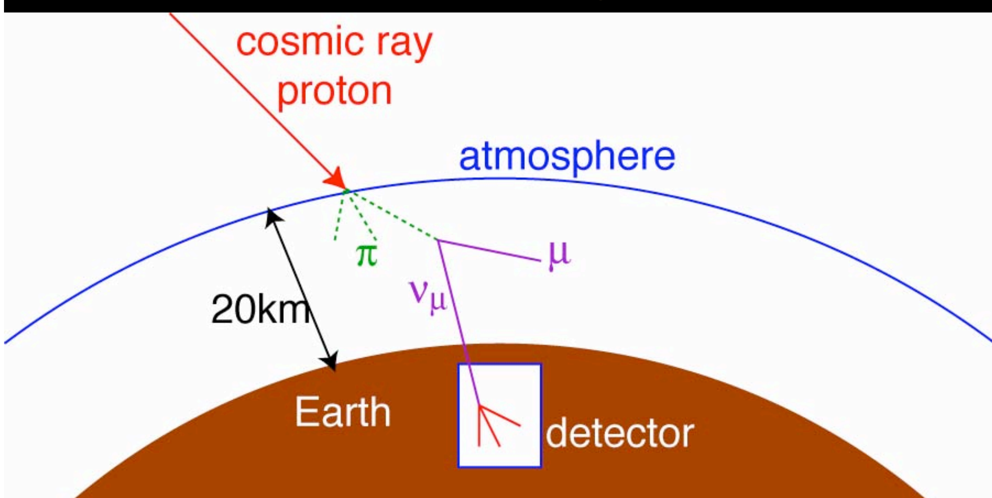
Evidence for Neutrino Mass

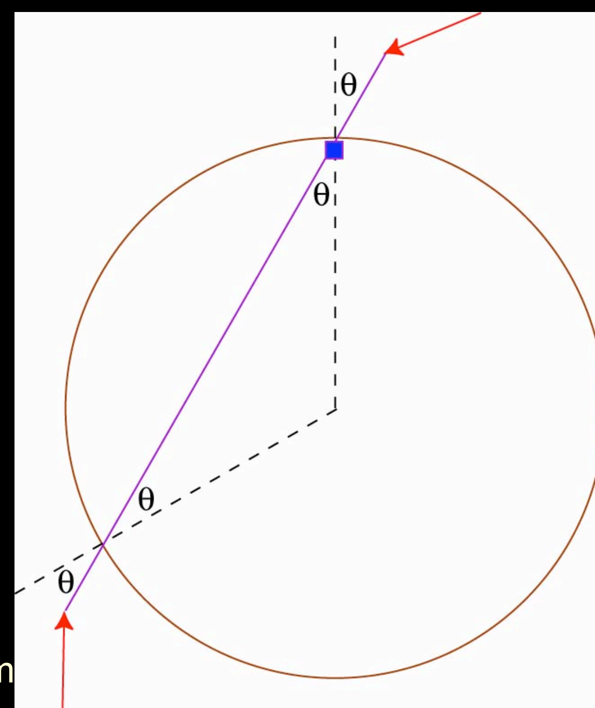
Super-Kamiokande (SuperK)

- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs

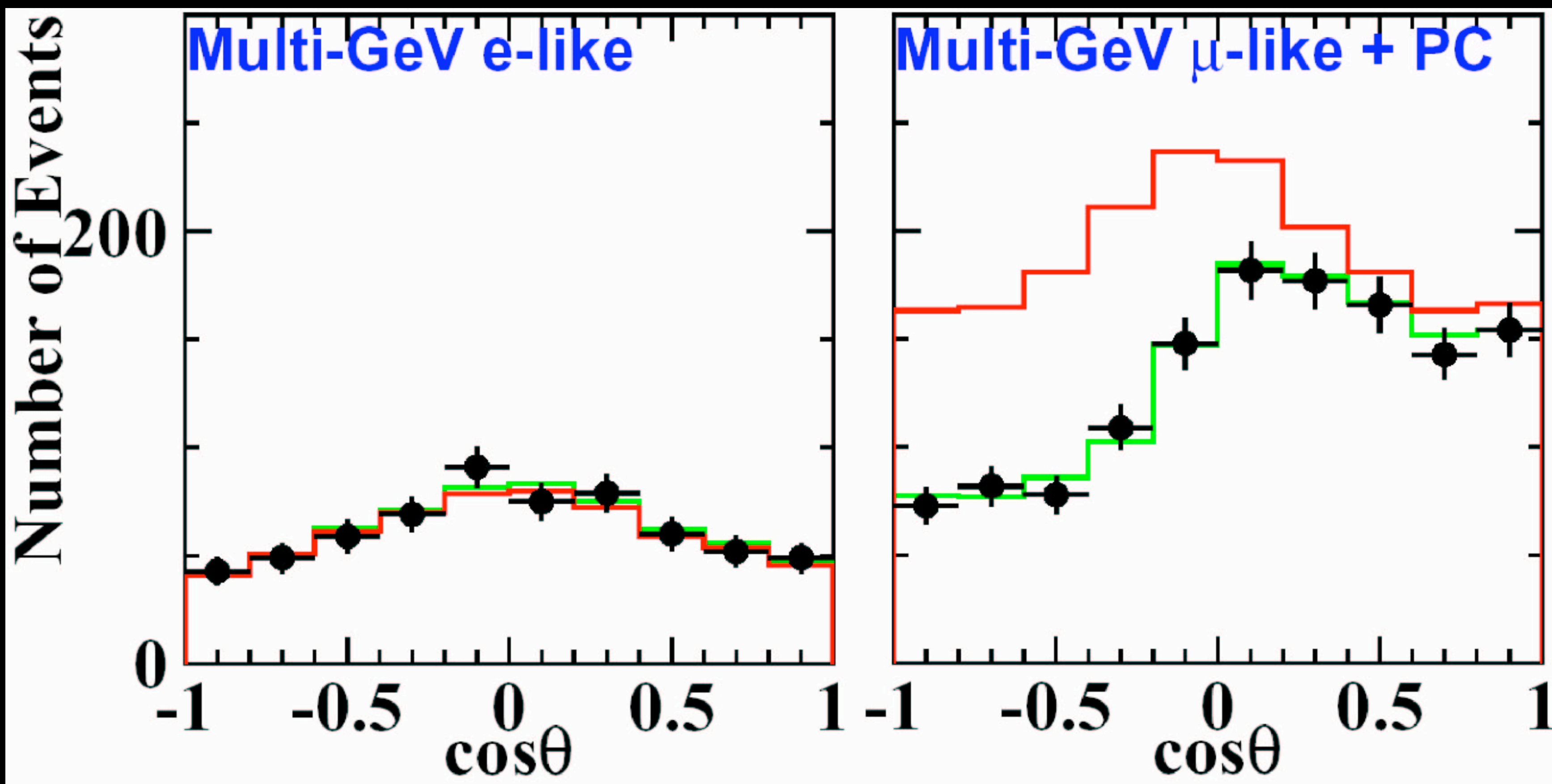
SuperKamiokaNDE Nucleon Decay Experiment

- $p \to e^+\pi^0, K^+\nu$, etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric





A half of ν_μ lost!



Neutrino's clock

- Time-dilation: the clock goes slower

$$\Delta\tau = \Delta t\sqrt{1-\frac{v^2}{c^2}}$$

- At speed of light $v=c$, clock stops
- But something seems to happen to neutrinos *on their own*

- Neutrinos' clock is going
- Neutrinos must be slower than speed of light

$\Rightarrow$ Neutrinos must have a mass

The Hamiltonian

- The Hamiltonian of a freely-propagating massive neutrino is simply

$$H = \sqrt{\vec{p}^2 + m^2} \simeq p + \frac{m^2}{2p}$$

- But in quantum mechanics, mass is a matrix in general. 2×2 case:

$$M^2 = \begin{pmatrix} m^2{}_{11} & m^2{}_{12} \\ m^2{}_{21} & m^2{}_{22} \end{pmatrix}$$

$$M^2|1\rangle = m_1^2|1\rangle$$
$$M^2|2\rangle = m_2^2|2\rangle$$

Two-Neutrino Oscillation

- When produced (*e.g.*, $\pi^+ \to \mu^+ \nu_\mu$), neutrino is of a particular type

$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta\, e^{-i m_1^2 t / 4p} + |2\rangle \sin\theta\, e^{-i m_2^2 t / 4p}$$

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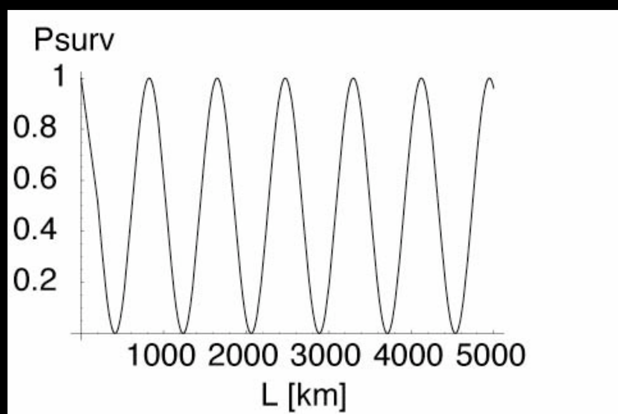
- No longer 100% ν_μ, partly ν_τ!
- "Survival probability" for ν_μ after t

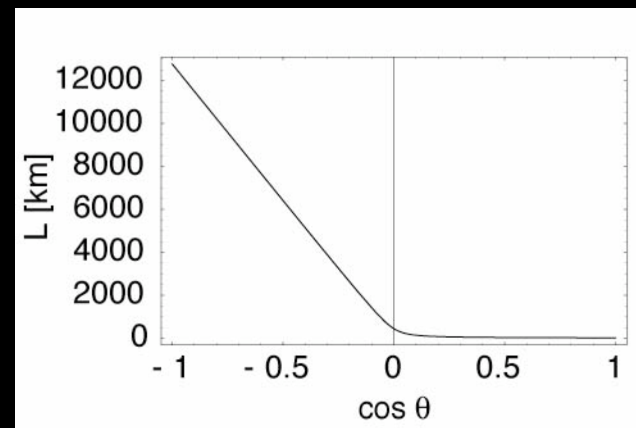
$$P = \left|\left\langle \nu_\mu \middle| \nu_\mu, t\right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\text{eV}^2} \frac{\text{GeV}}{c|\vec{p}|} \frac{ct}{\text{km}}\right)$$

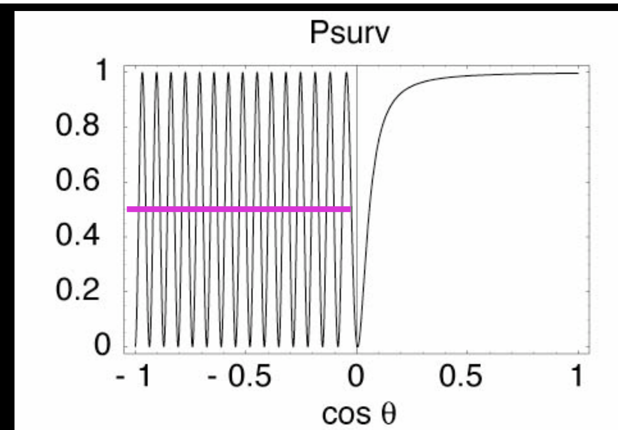
Survival Probability

p=1 GeV/c, $\sin^2 2\theta=1$

$\Delta m^2=3\times10^{-3}(\mathrm{eV}/c^2)^2$

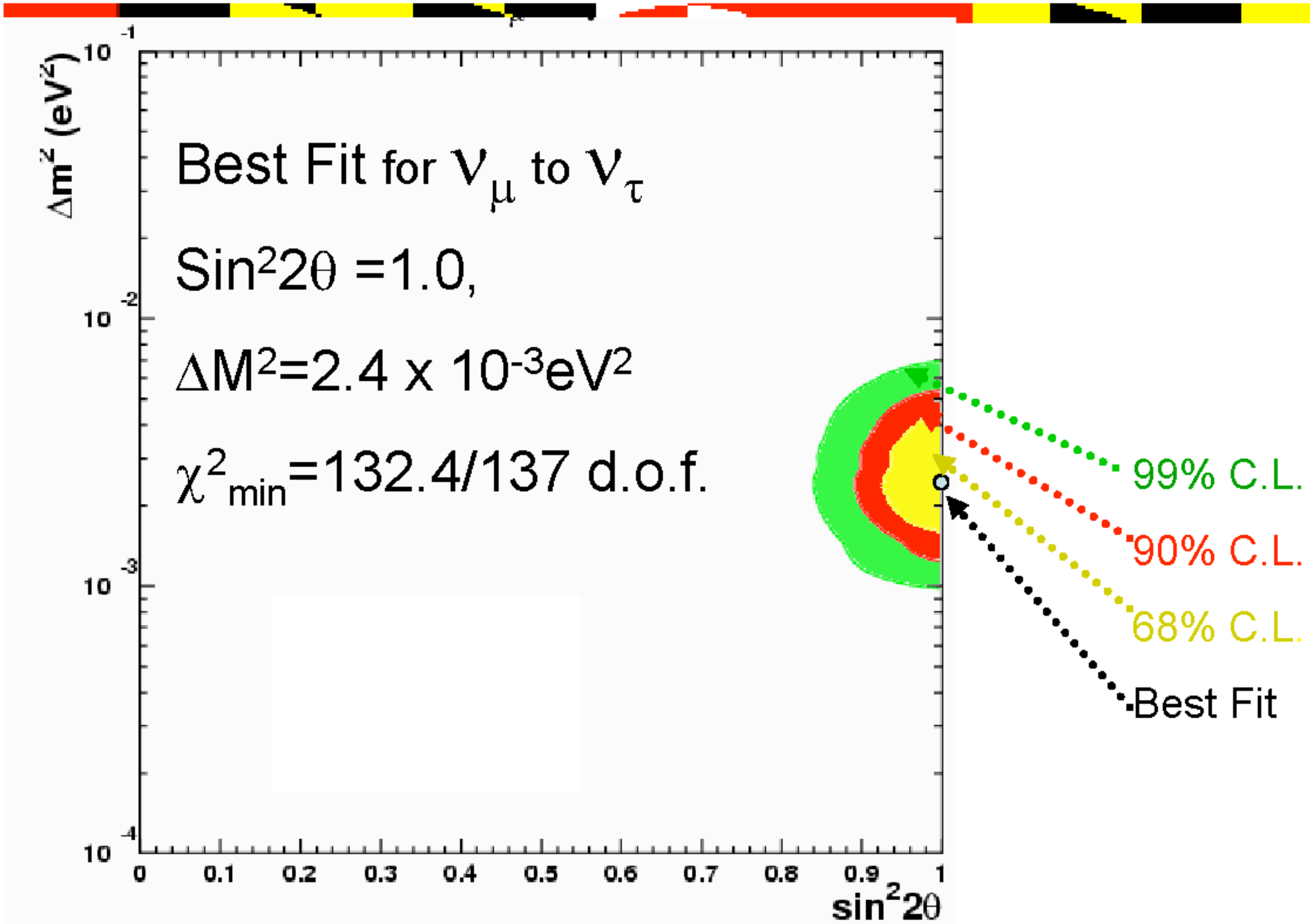






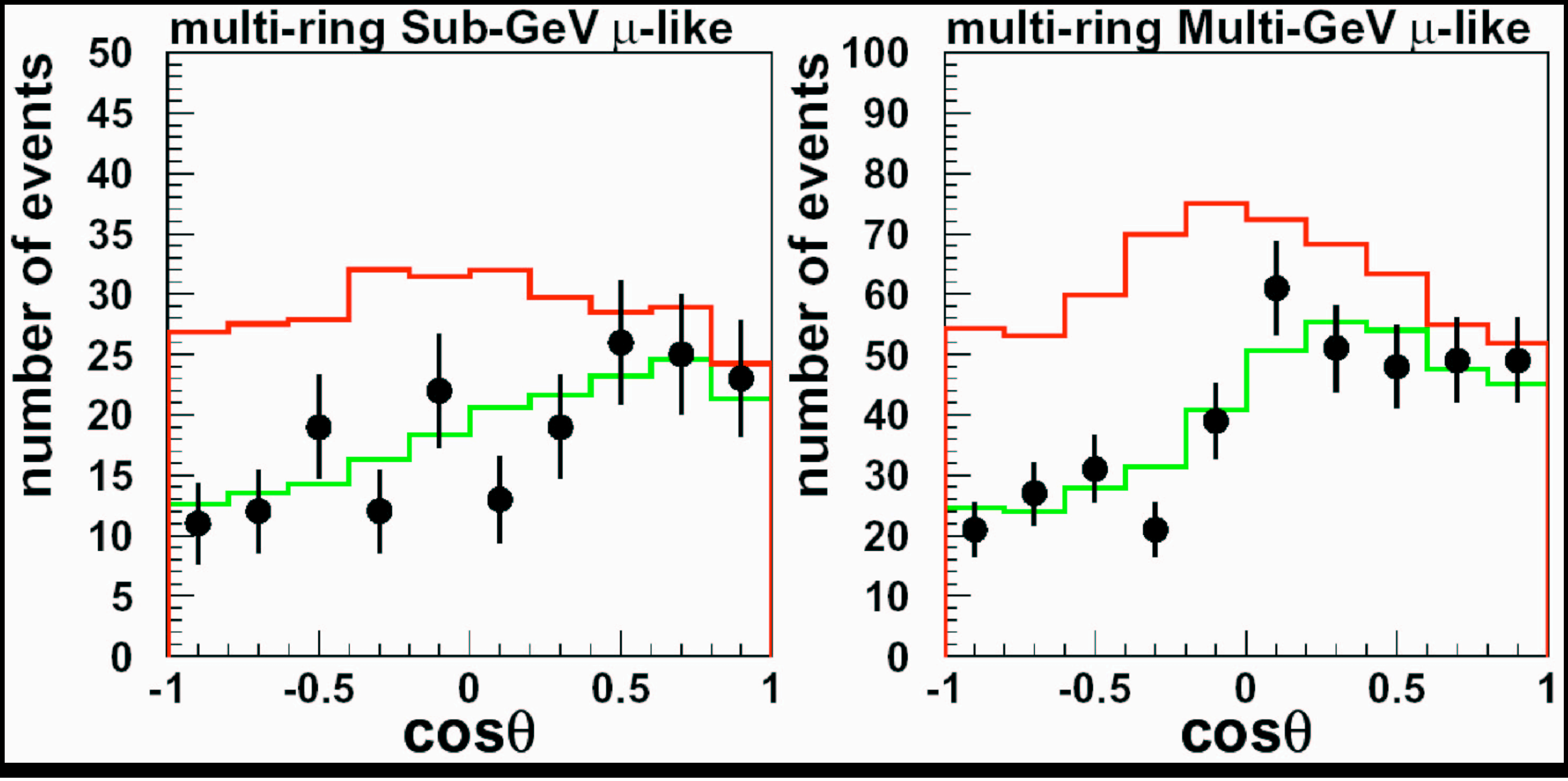
Half of the up-going ones get lost

Summary of Atmospheric Results

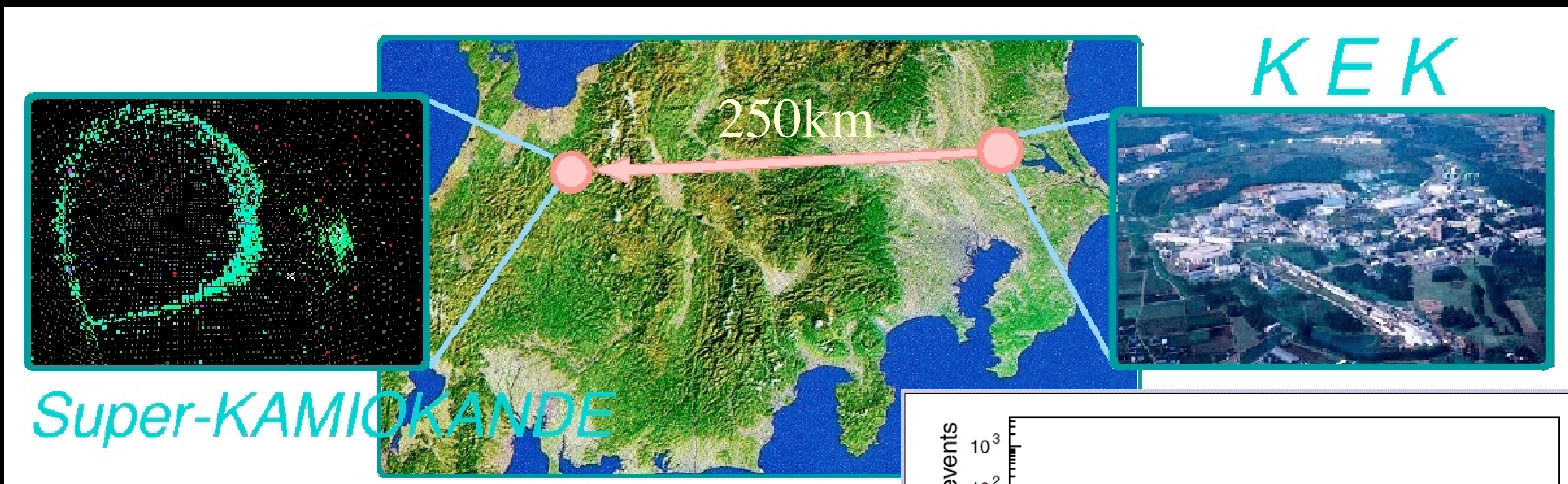


More cross checks

- Multi-ring events can be used to provide useful cross checks (Hall, HM)



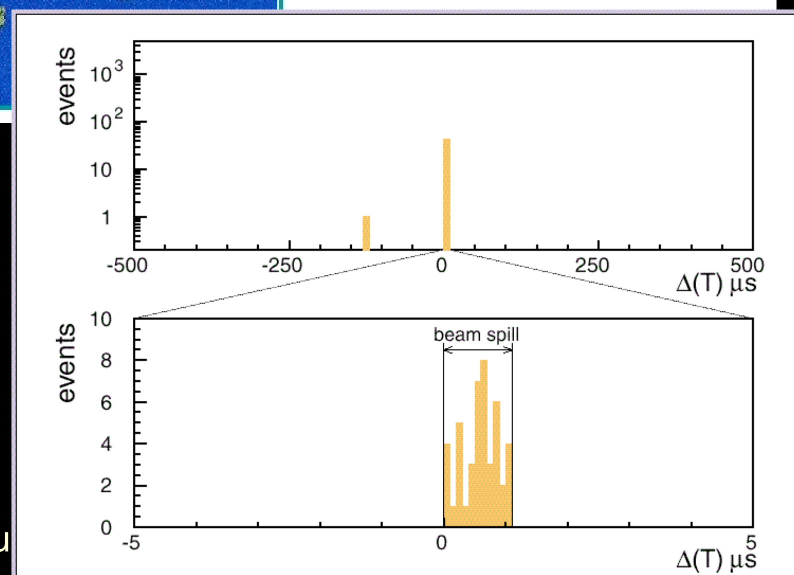
More to come



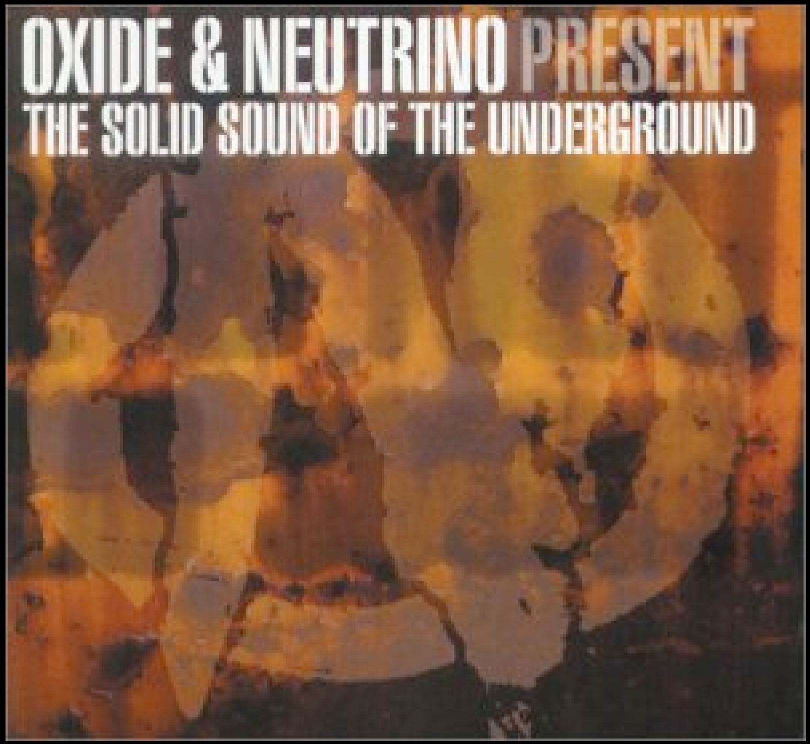
#events if no oscillation $80.1^{+6.2}_{-5.4}$

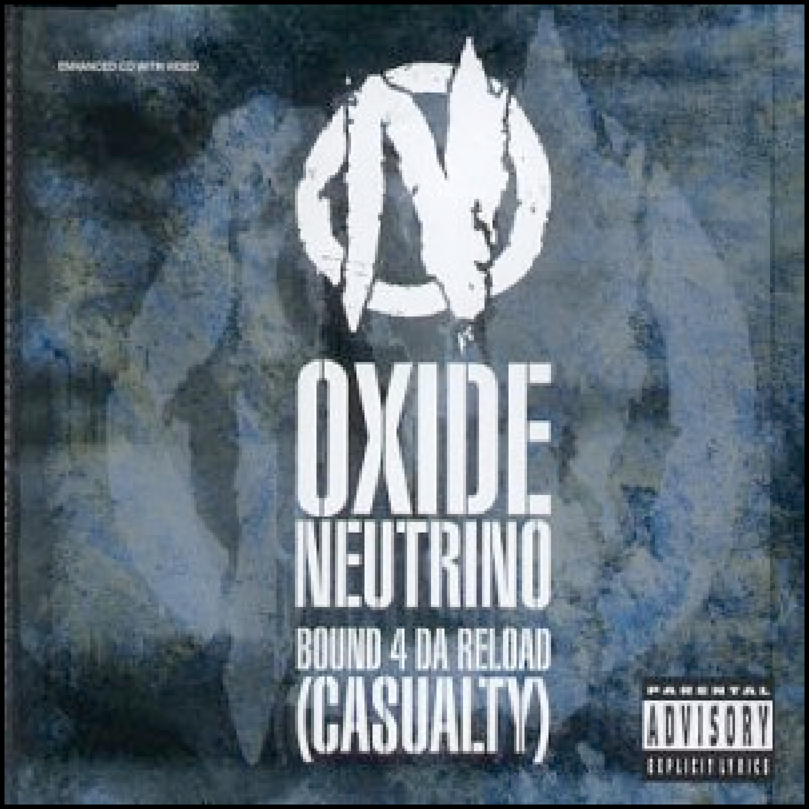
#events observed: 56

MINOS (IL → MN) 2005



Public Interest in Neutrinos



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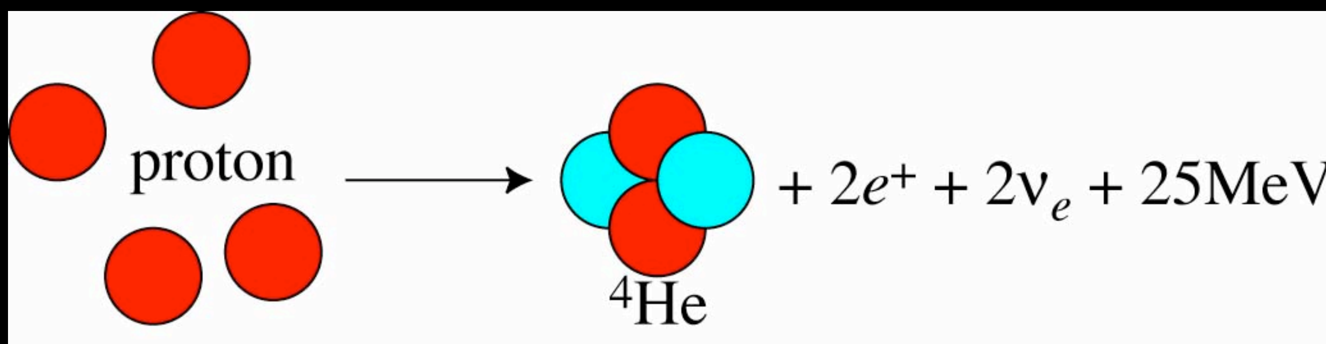
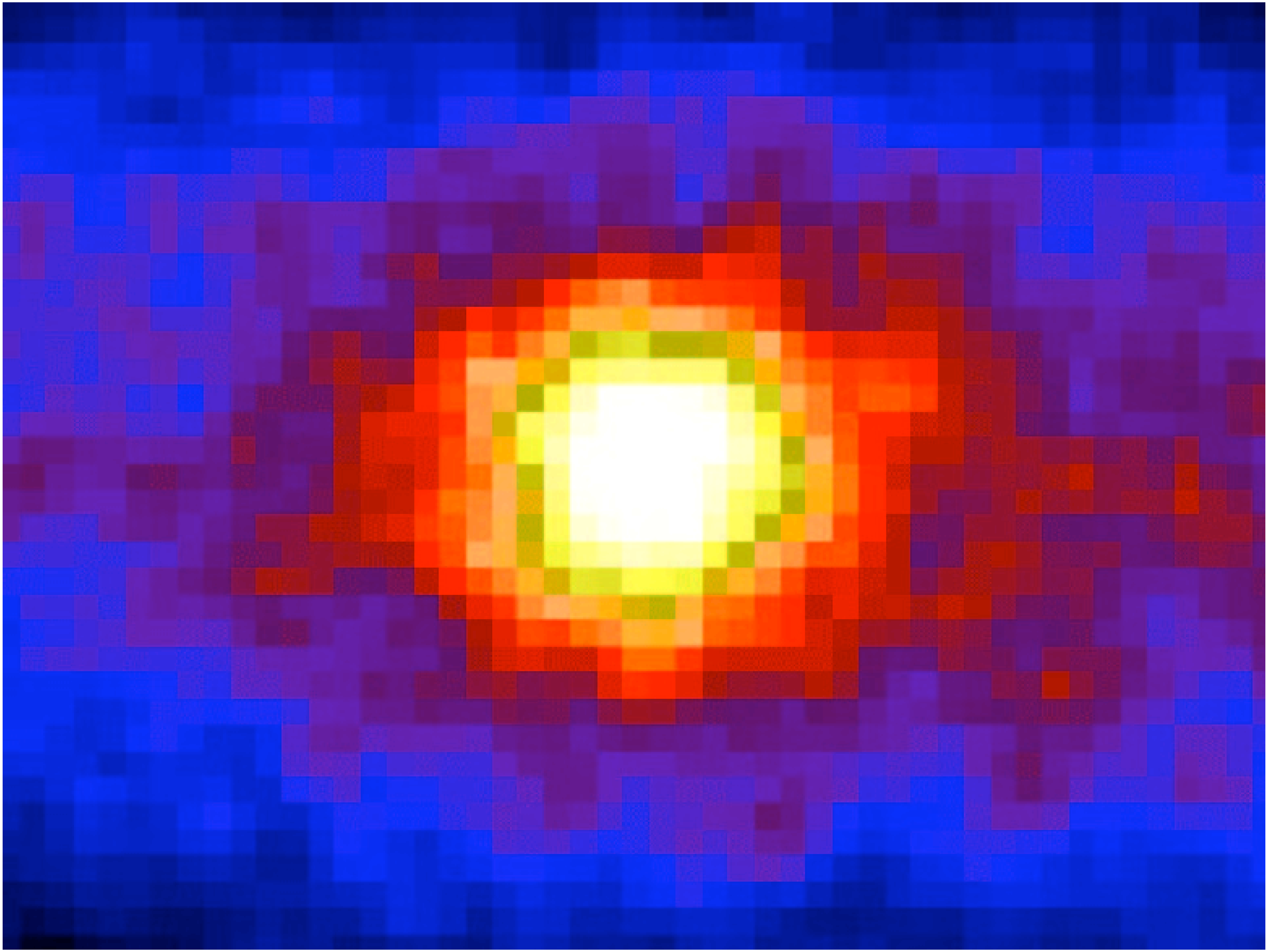
Solar Neutrinos

How the Sun burns

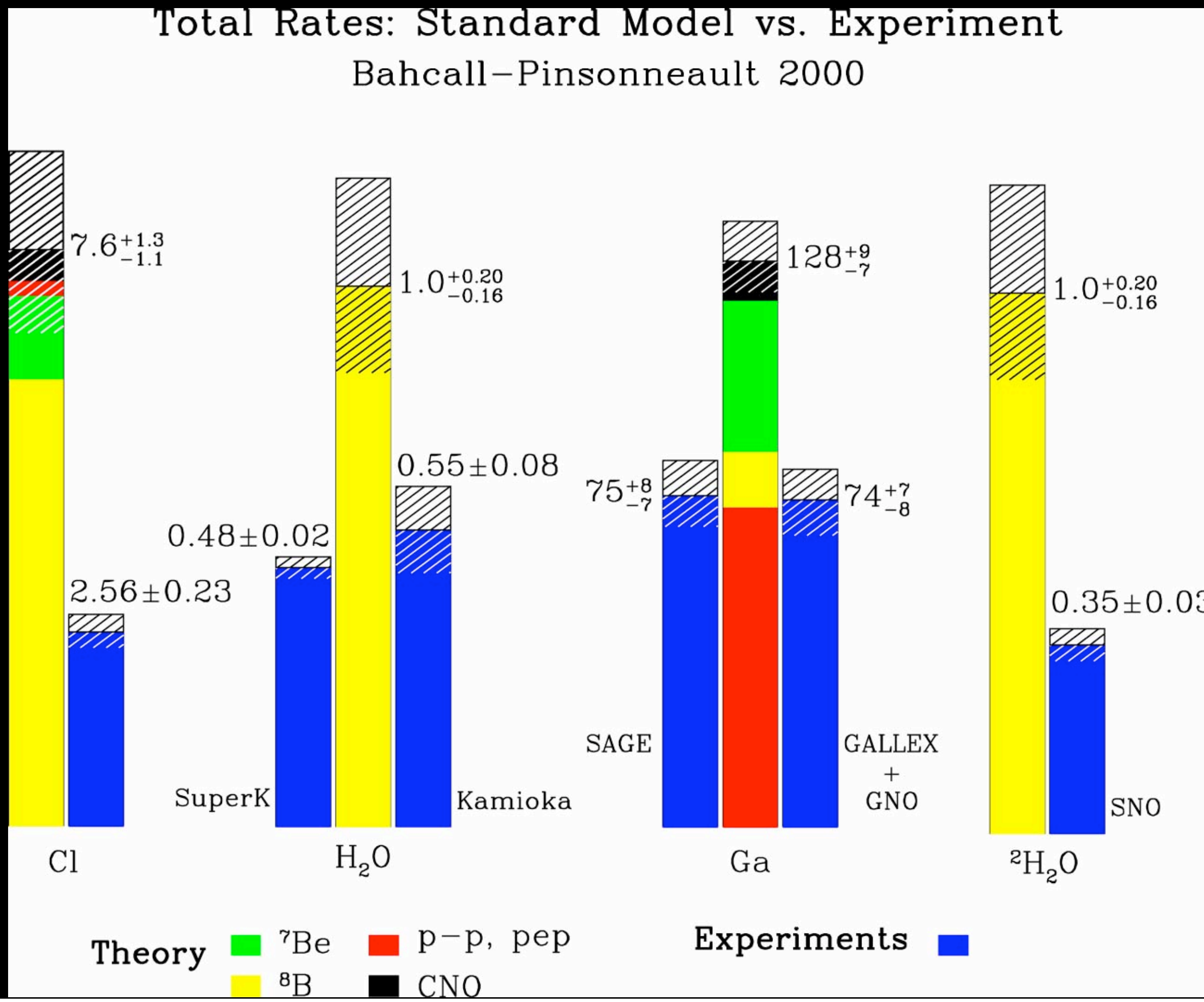
- The Sun emits light because nuclear fusion produces a lot of energy



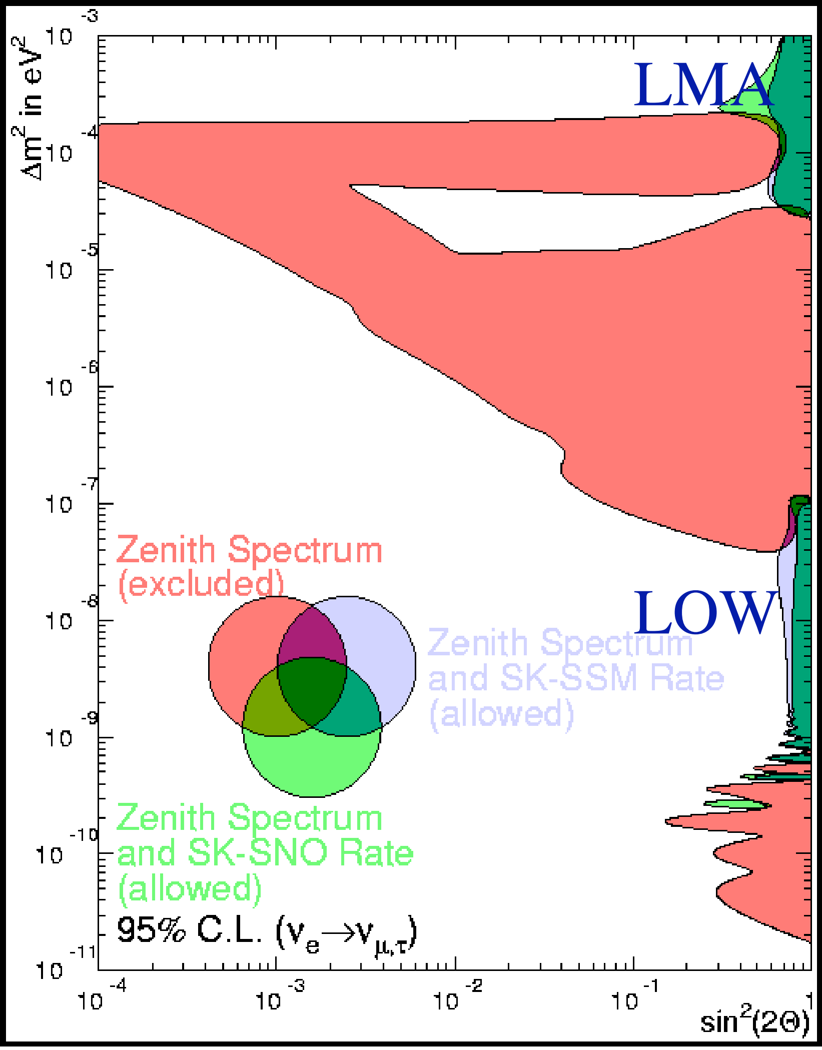
$$\Phi_{\nu} = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10}\ \text{sec}^{-1}\ \text{cm}^{-2}$$



We don't get enough

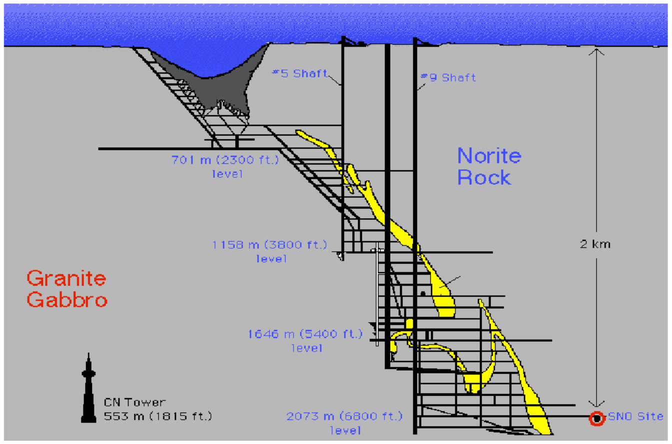


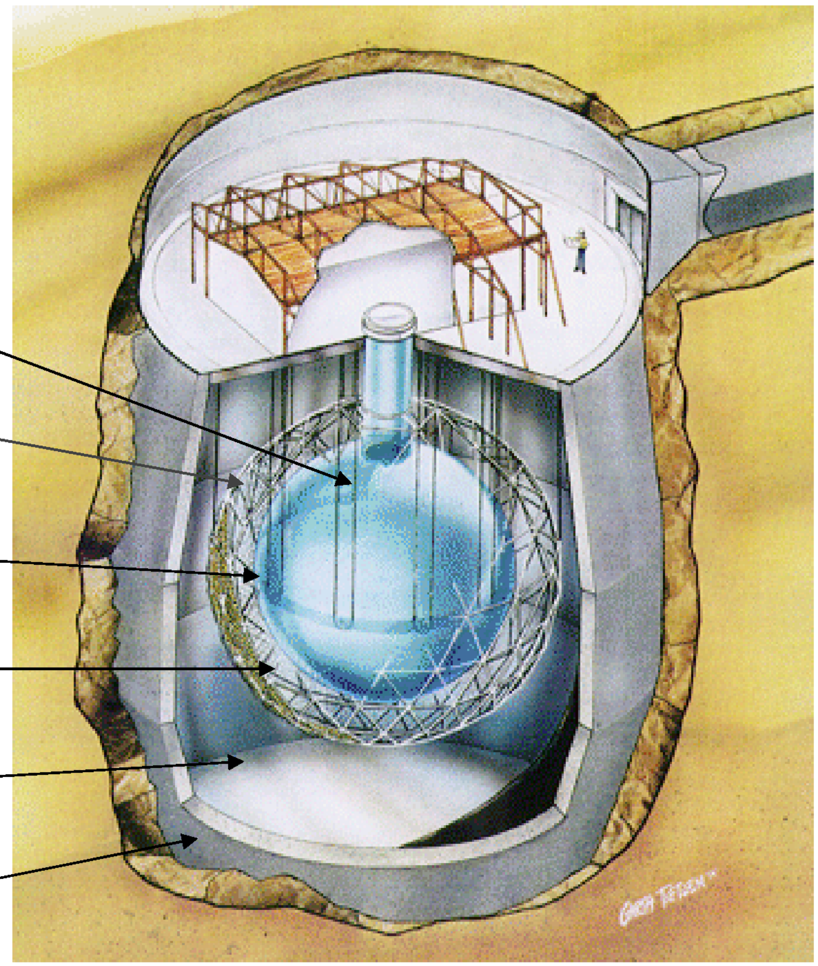
Neutrino oscillation?



- Can explain the data
- Two major solutions:
  - LMA
  - LOW/Quasi-Vacuum (Friedland)
- Biggest systematics is the solar neutrino flux calculations
- *Problem with the solar model?*

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

Josh Klein, Lepton Photon 2001

SNO comes to the rescue

- Charged Current: ν_e

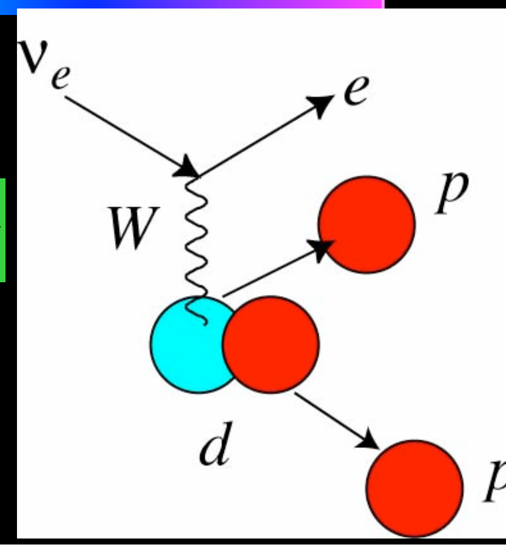
$$\phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

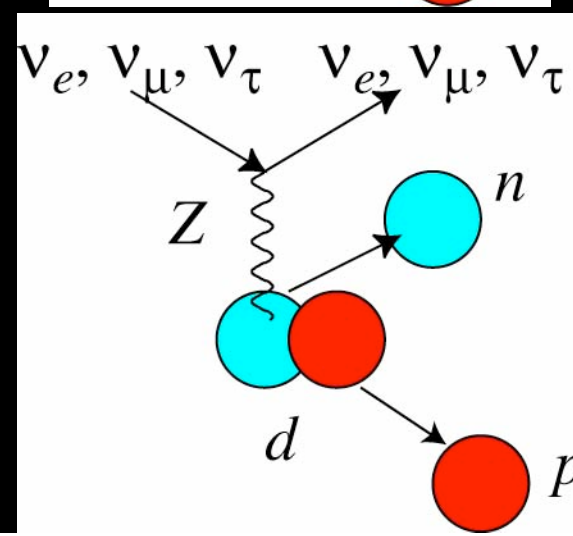
- Neutral Current: $\nu_e + \nu_\mu + \nu_\tau$

$$\phi_{NC} = 5.09\,{}^{+0.44}_{-0.43}\,{}^{+0.46}_{-0.43} \cdot 10^6\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

- 5.3σ difference

$\Rightarrow$ $\nu_{\mu,\tau}$ are coming from the Sun!

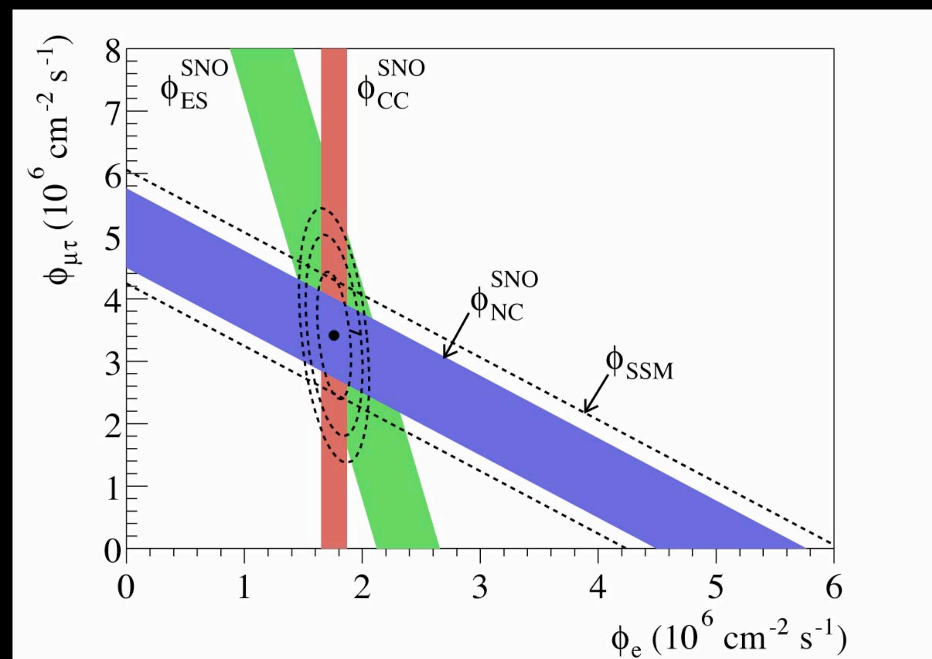




Wrong Neutrinos

- Only ν_e produced in the Sun
- Wrong Neutrinos $\nu_{\mu,\tau}$ are coming from the Sun!
- Somehow some of ν_e were converted to $\nu_{\mu,\tau}$ on their way from the Sun's core to the detector

$\Rightarrow$ neutrino oscillation!



Dark Side of Neutrino Oscillation

- Traditional parameterization of neutrino oscillation in terms of (Δm^2, $\sin^2 2\theta$) covers only a *half* of the parameter space

  (de Gouvêa, Friedland, HM)

- Convention: ν_2 heavier than ν_1
  - Vary θ from 0˚ to 90˚
  - $\sin^2 2\theta$ covers 0˚ to 45˚
  - Light side (0 to 45˚) and Dark Side (45˚ to 90˚)

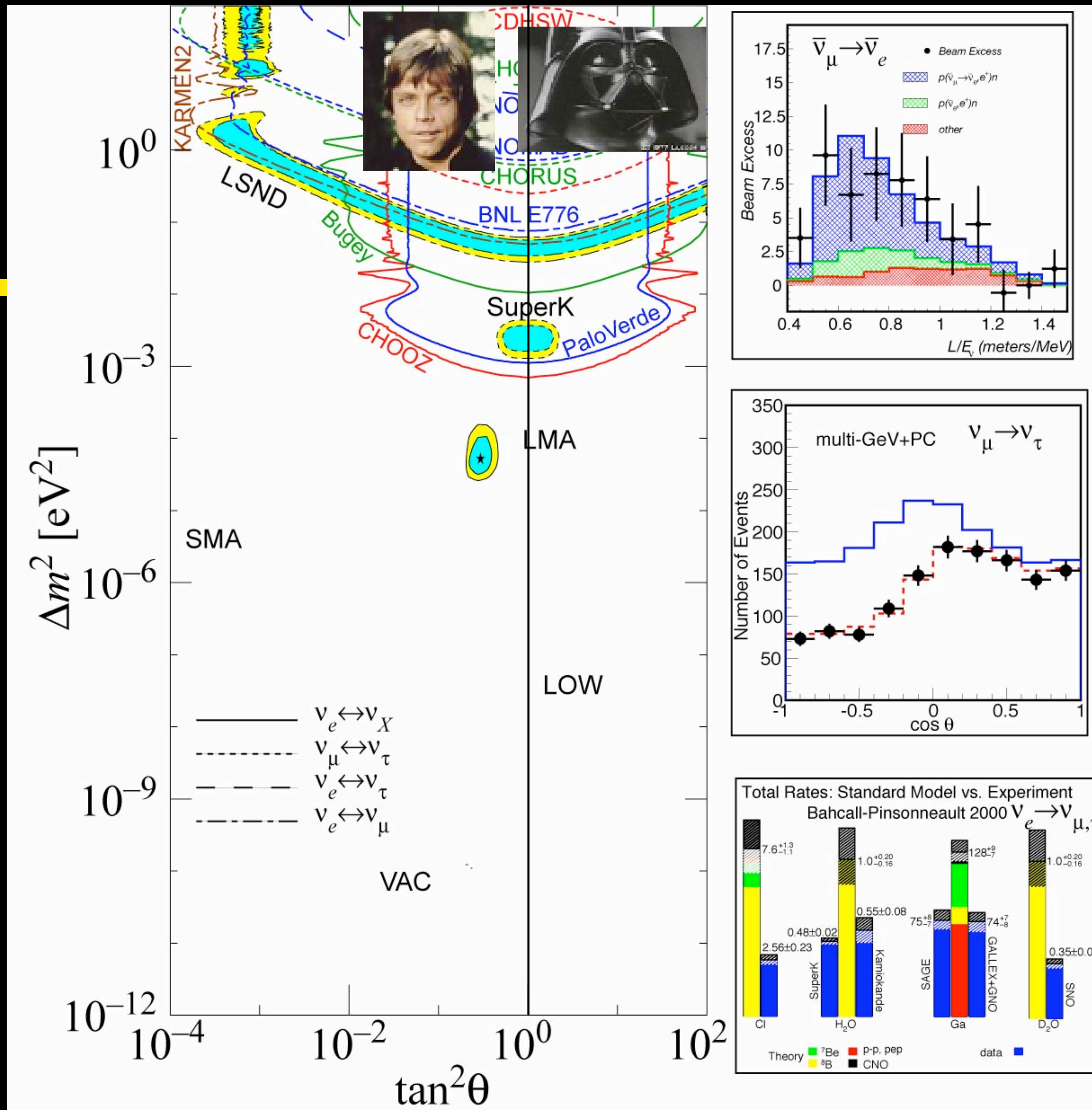
$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

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

- To cover $0° \le \theta \le 90°$, use $\tan^2\theta$

March 2002

April 2002
with SNO

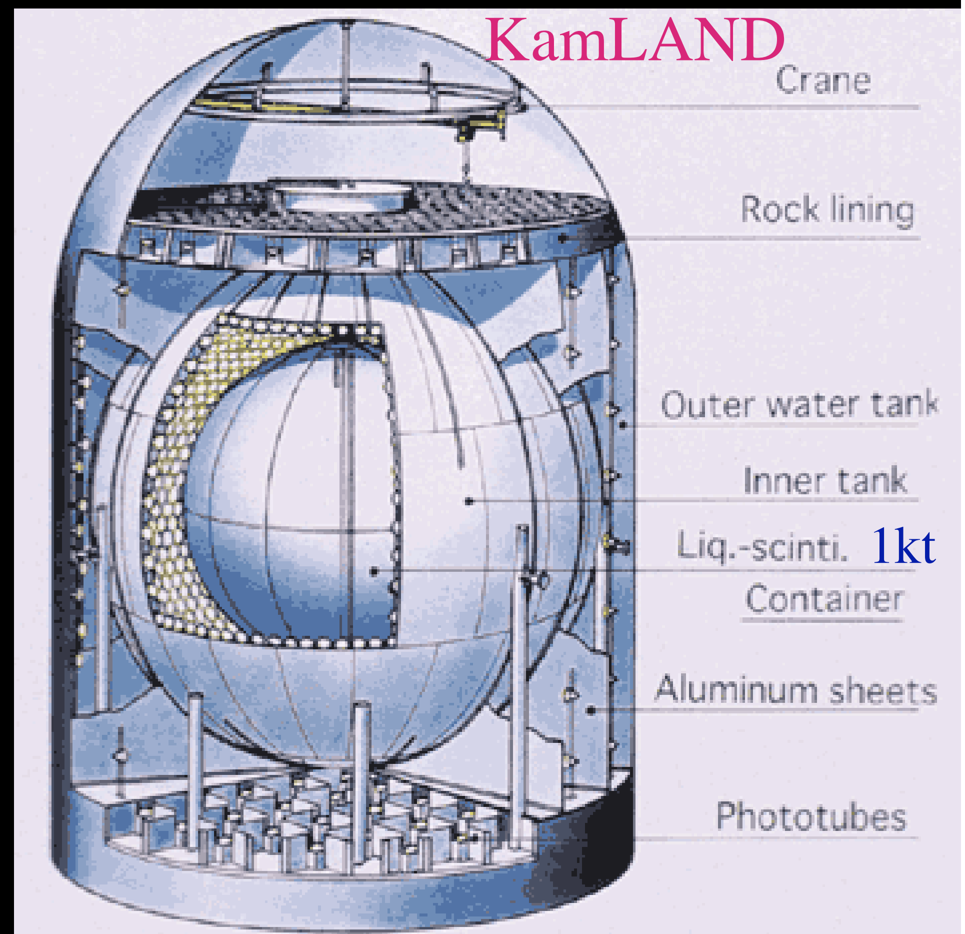


What Next?

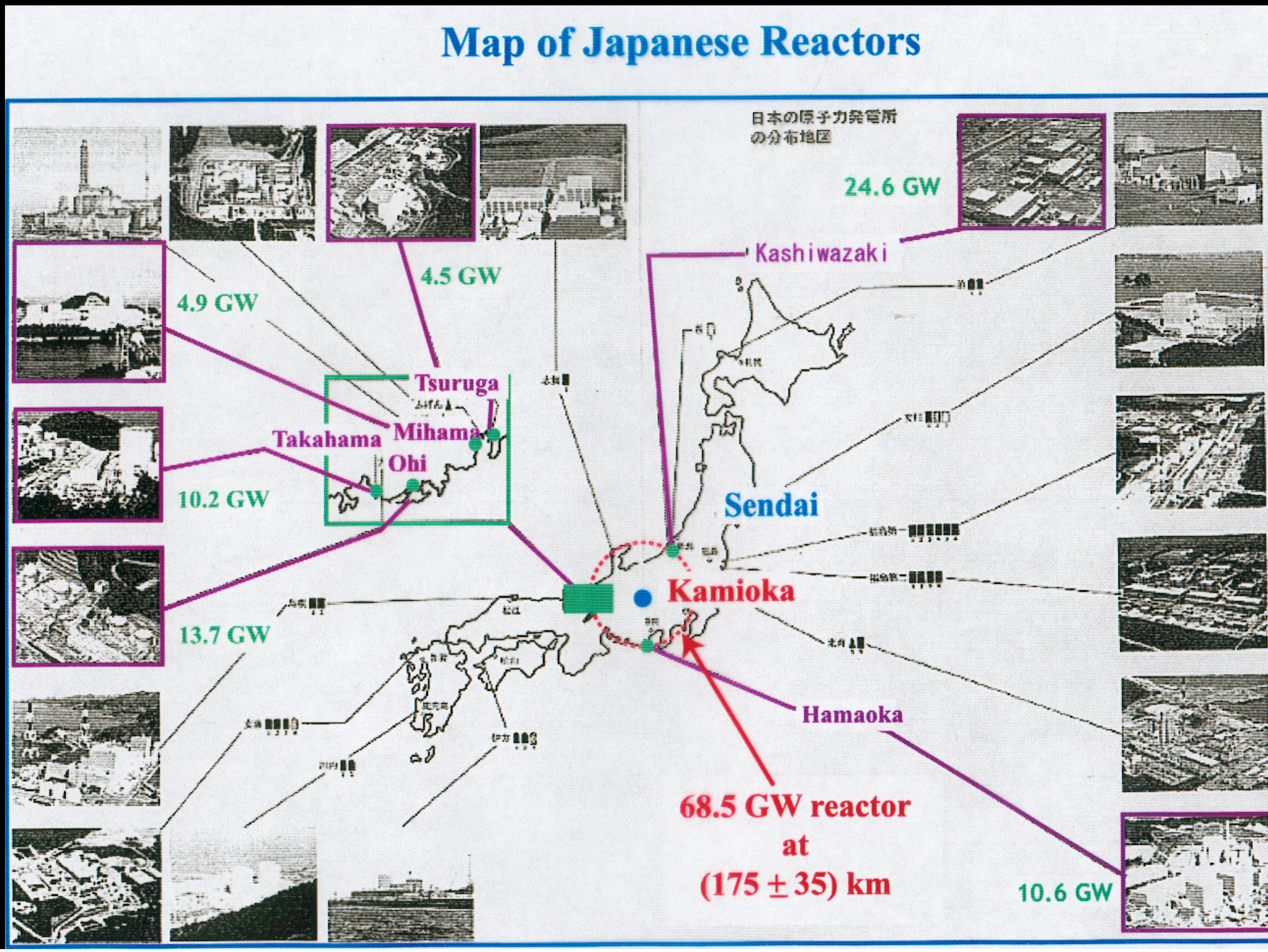
- Can we convincingly verify oscillation with man-made neutrinos?

$$P_{surv} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\mathrm{eV}^2} \frac{\mathrm{GeV}}{E_\nu} \frac{L}{\mathrm{km}}\right)$$

- Hard for low Δm^2
- To probe LMA, need L~100km, 1kt
- Need low E_ν, high Φ_ν
- Use neutrinos from nuclear reactors

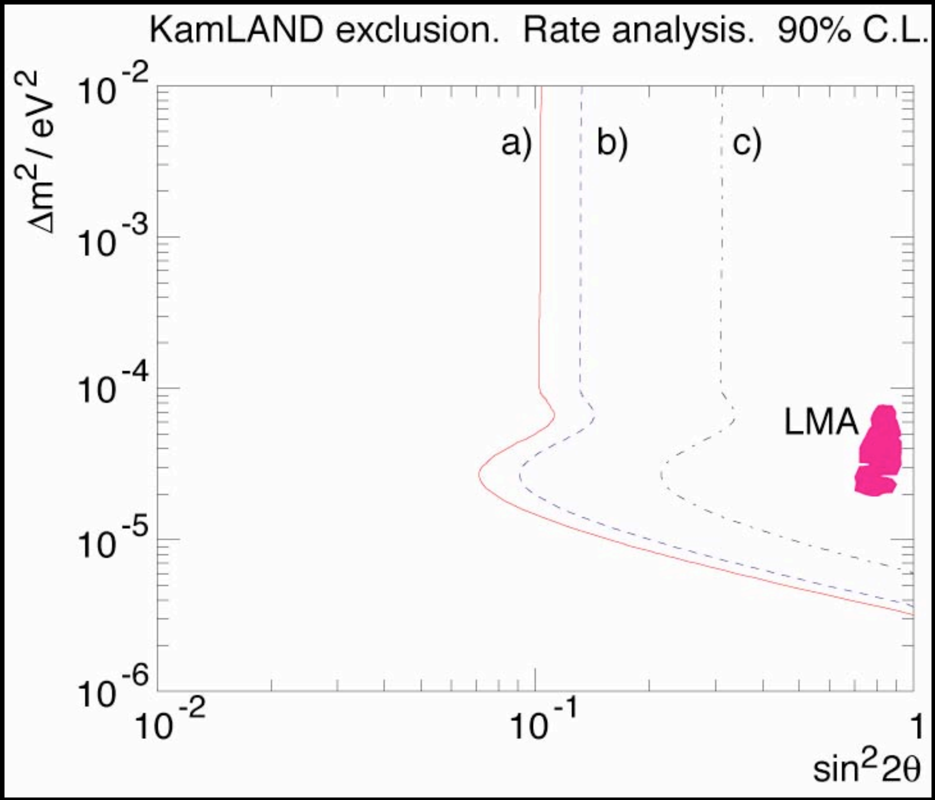


Location, Location, Location



KamLAND sensitivity on LMA

- First terrestrial expt relevant to solar neutrino problem
- KamLAND will exclude or verify LMA definitively
- *Data taking since March this year*

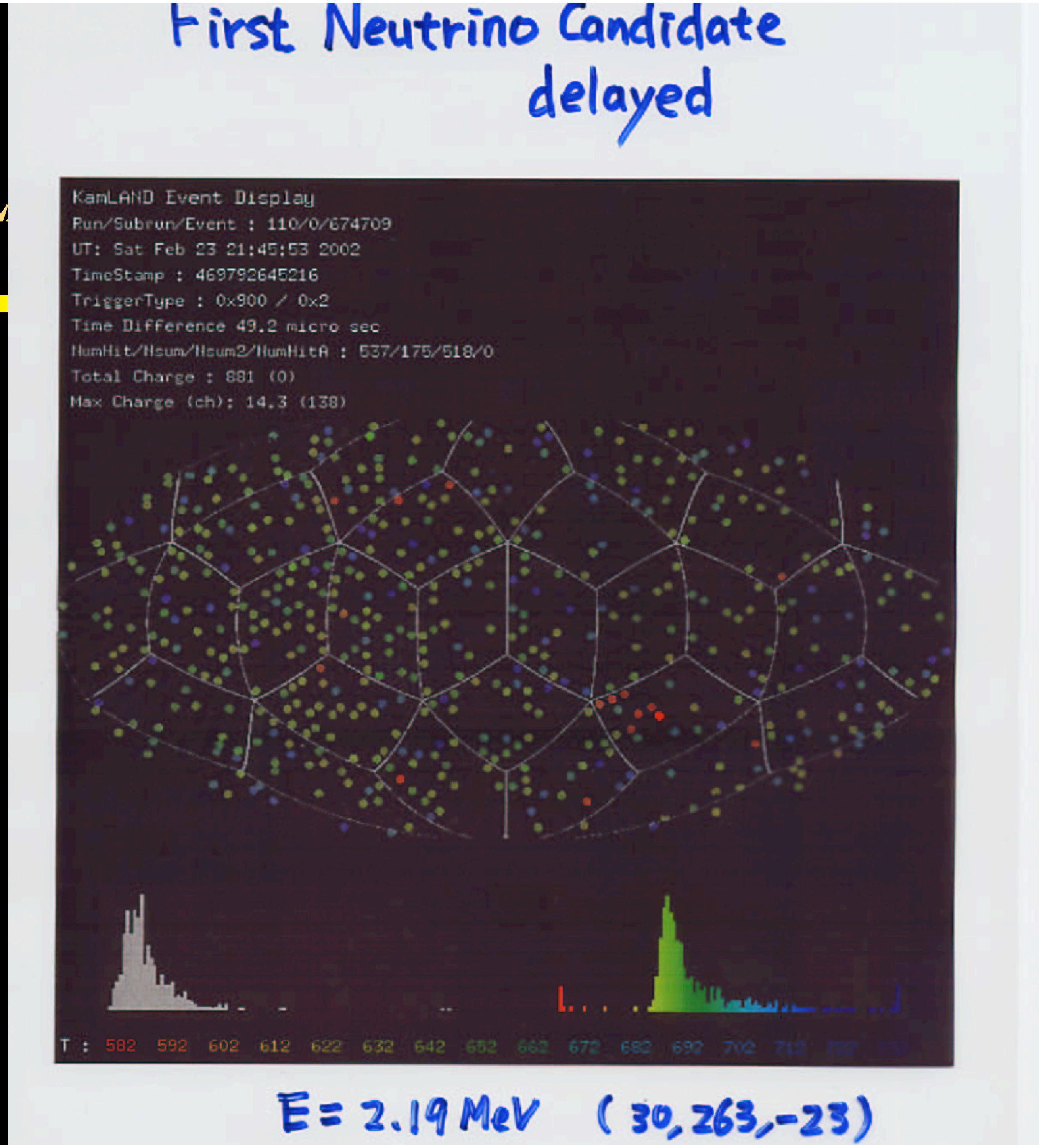


KamL

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

49.2 μs later

$np \to d\gamma$



December 6, 2002

research **news**

Disappearing Neutrinos at KamLAND Support the Case for Neutrino Mass

Contact: Lynn Yarris (510) 486-5375
lcyarris@lbl.gov

The New York Times
nytimes.com

SPONSORED BY STARBUCKS.COM

December 7, 2002

Researchers Make the Best Argument Yet That Neutrinos Are Capable of Changing Form

By GEORGE JOHNSON

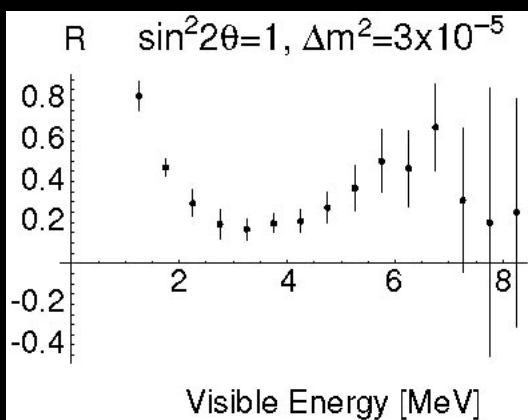
Expected #events: 86.8±5.6
Background #events: 0.95±0.99
Observed #events: 54

No oscillation hypothesis
Excluded at 99.95%
More details @10:20 am
Tuesday, Italy

Measurements at KamLAND

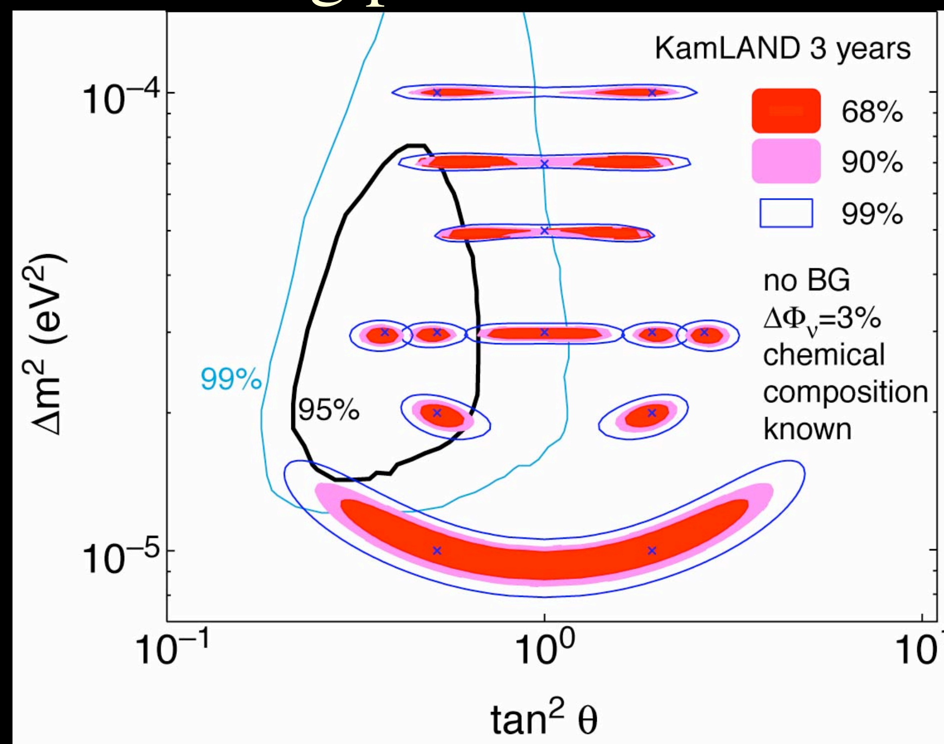
- Can see the dip when $\Delta m^2 = 2\text{–}10 \times 10^{-5} eV^2$

(Pierce, HM)



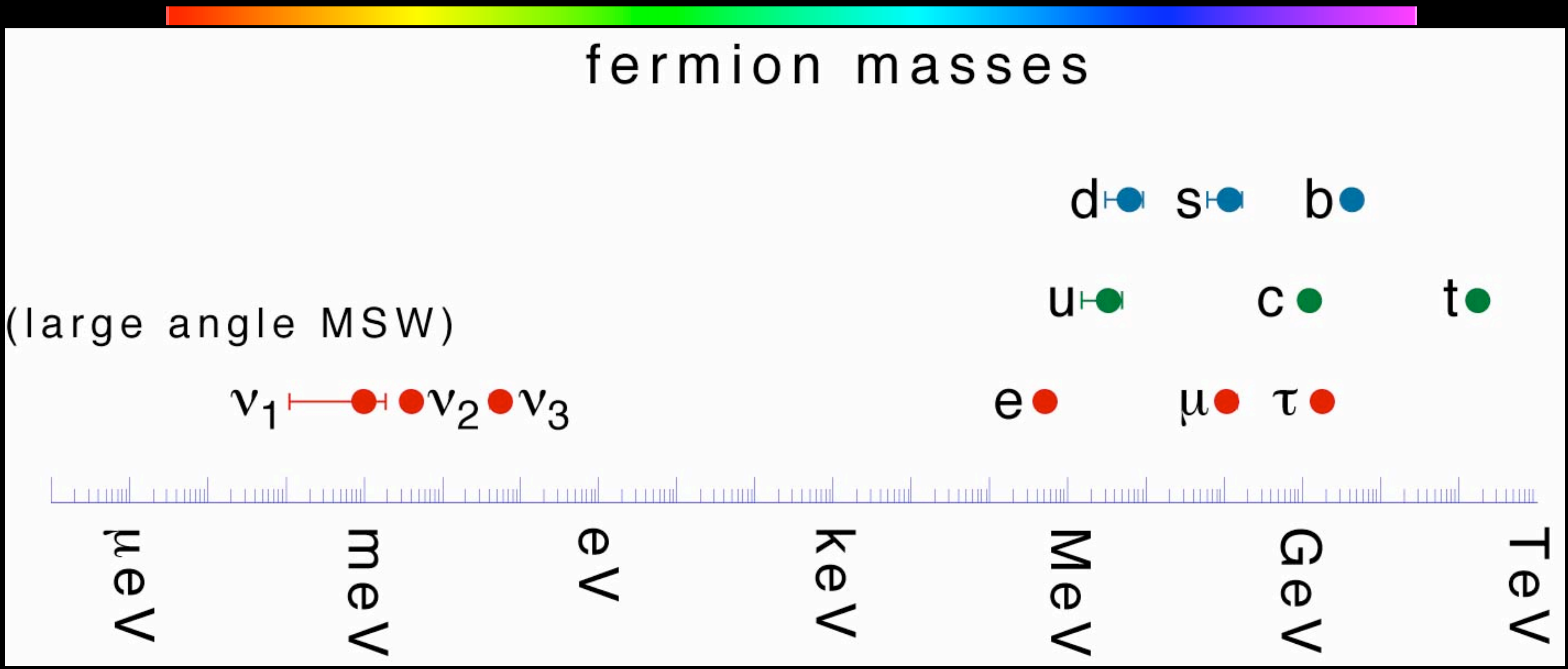
Data/theory

- Can measure mass & mixing parameters



Implications of Neutrino Mass

Mass Spectrum

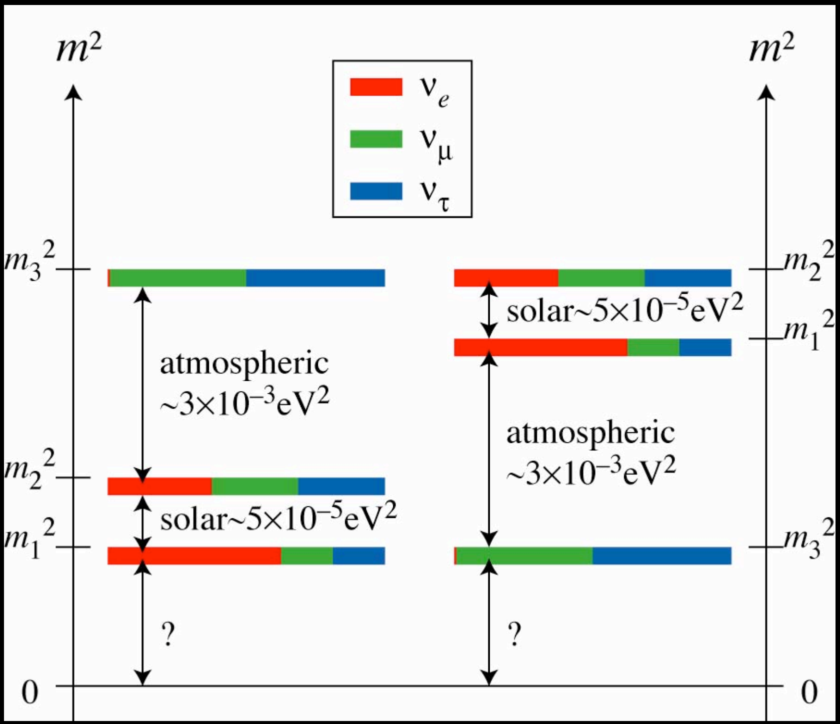


What do we do now?

Raised More Questions

- Why do neutrinos have mass at all?
- Why so small?
- We have seen mass *differences*. What are the masses?

  $\square_{\square} \sim m_{\square}/15\text{eV}$
- Do we need a fourth neutrino?
- Are neutrinos and anti-neutrinos the same?

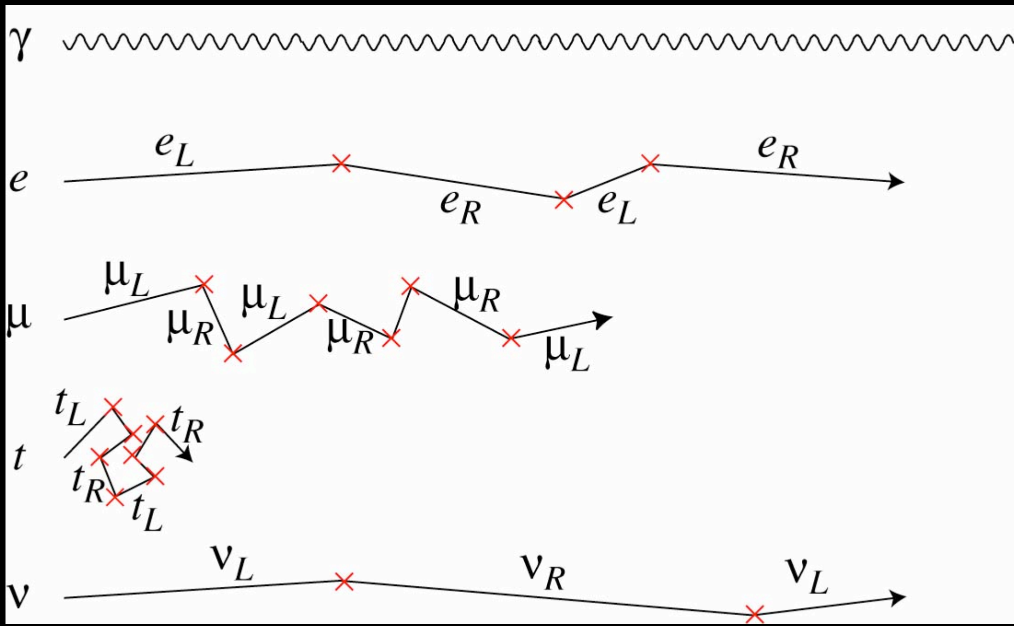


- How do we extend the Standard Model to incorporate massive neutrinos?

Two ways to go

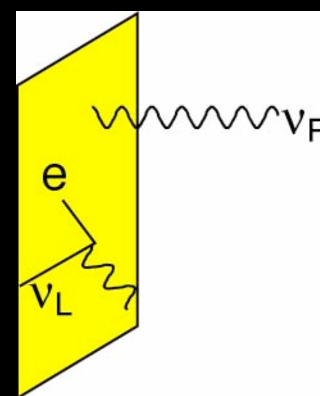
(1) Dirac Neutrinos:

- There are new particles, right-handed neutrinos, after all
- Why haven't we seen them?
- Right-handed neutrino must be *very very weakly coupled*
- Why?



Extra Dimensions

- All charged particles are on a 3-brane
- Right-handed neutrinos SM gauge singlet
  $\Rightarrow$ Can propagate in the "bulk"
- Makes neutrino mass small
  (Arkani-Hamed, Dimopoulos, Dvali, March-Russell; Dienes, Dudas, Gherghetta; Grossman, Neubert)



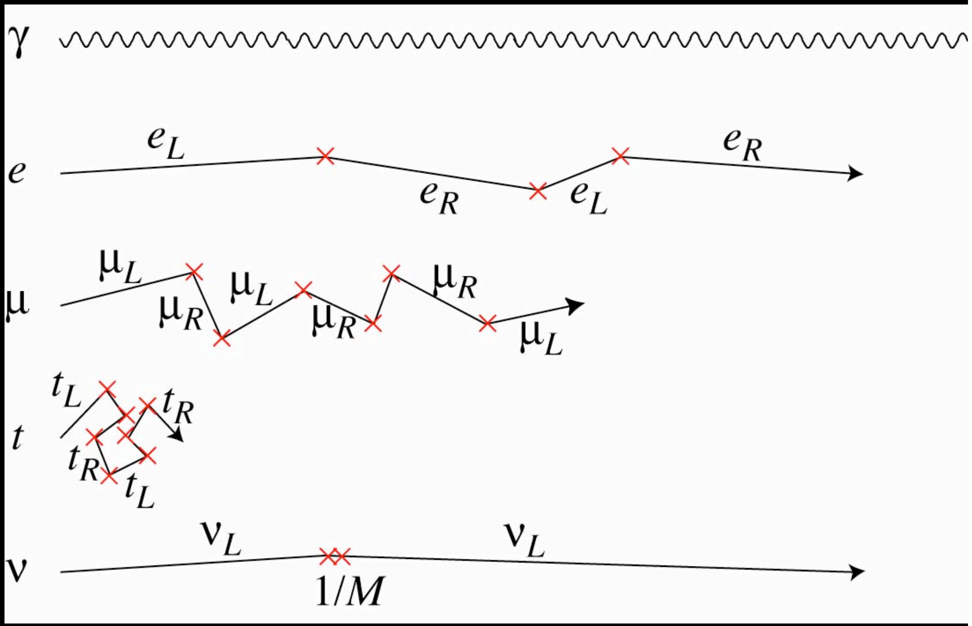
- $m_\nu \sim 1/R$ if one extra dim $\Rightarrow$ $R\sim 10\,\mu$m
- An infinite tower of "sterile" neutrinos
- Or SUSY breaking
  (Arkani-Hamed, Hall, HM, Smith, Weiner; Arkani-Hamed, Kaplan, HM, Nomura)

$$\int d^4\theta \frac{S^*}{M}(LH_uN)$$

Two ways to go

(2) Majorana Neutrinos:

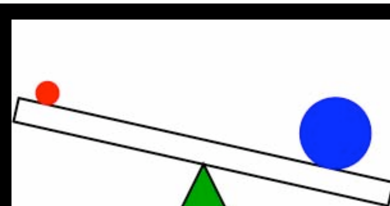
- There are no new light particles
- What if I pass a neutrino and look back?
- Must be right-handed *anti*-neutrinos
- No fundamental distinction between neutrinos and anti-neutrinos!



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

$$(\bar{\nu}_L \quad \bar{\nu}_R)\begin{pmatrix} & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



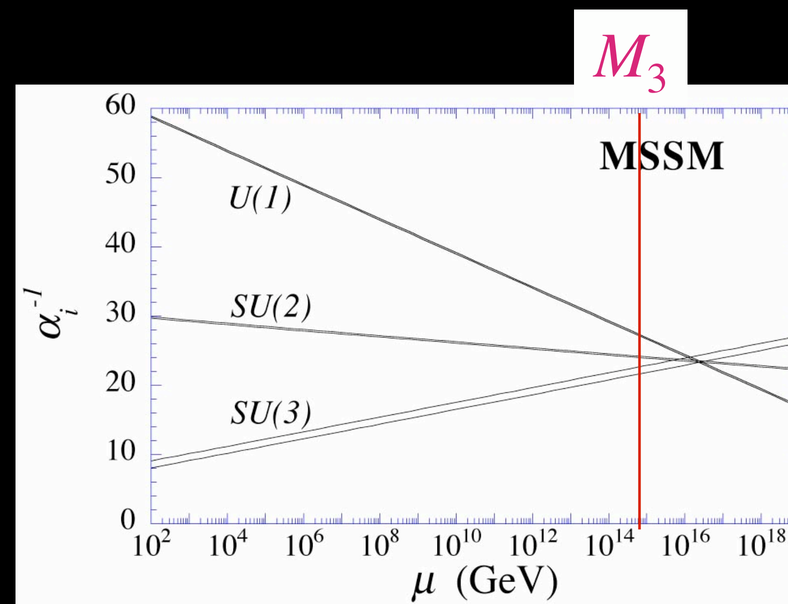
To obtain $m_3 \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become the same at 10^{16} GeV if supersymmetry
- To obtain

$m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$

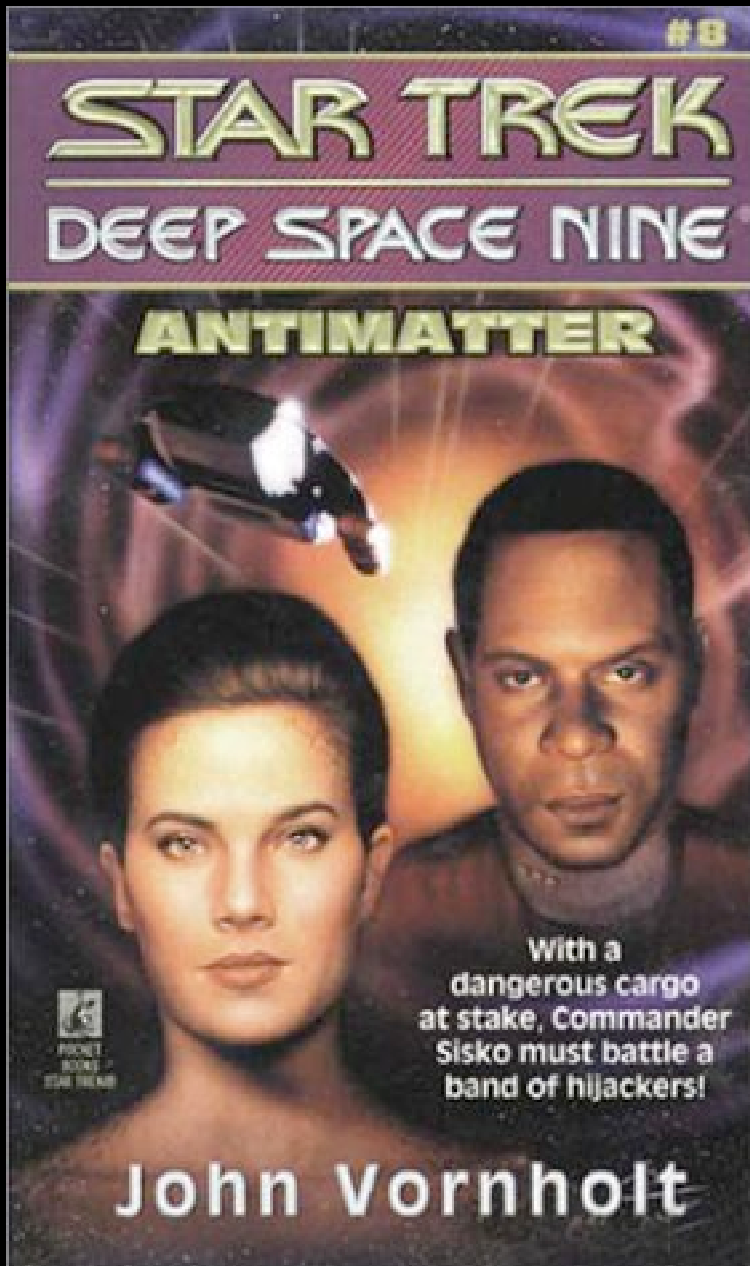
$\Rightarrow$ $M_3 \sim 10^{15}$GeV!

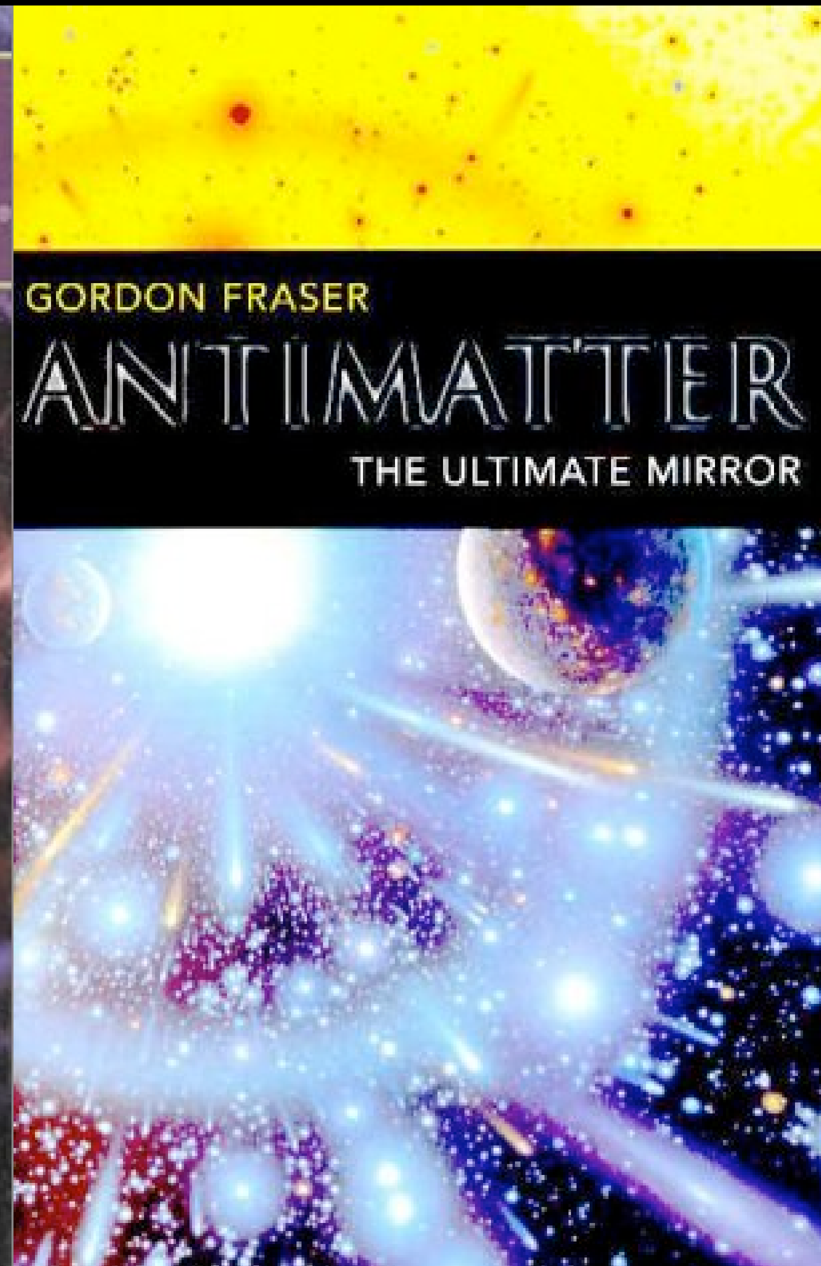


Neutrino mass may be probing unification:

Einstein's dream

Why do we exist?
Matter Anti-matter Asymmetry


#8
STAR TREK
DEEP SPACE NINE
ANTIMATTER
With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!
John Vornholt


GORDON FRASER
ANTIMATTER
THE ULTIMATE MIRROR

Matter and Anti-Matter Early Universe

10,000,000,001

Matter

10,000,000,000

Anti-matter

Matter and Anti-Matter Current Universe

us

1

Matter

Anti-matter

The Great Annihilation

Baryogenesis

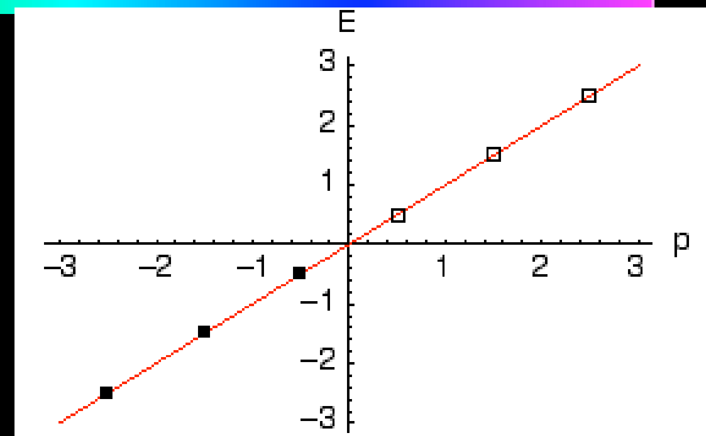
- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation

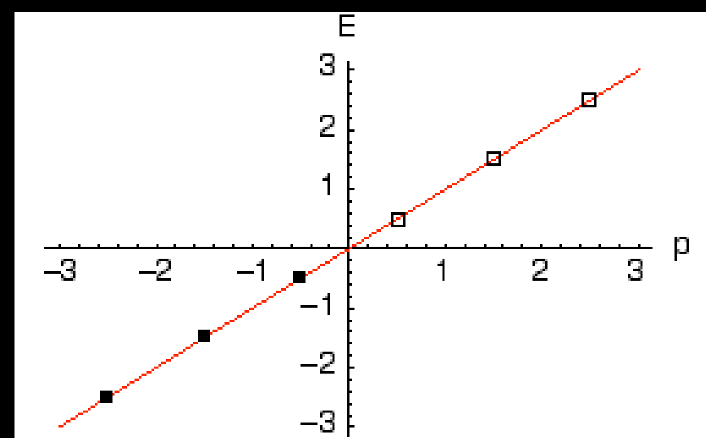
    (subtle difference between matter and anti-matter)
  - Non-equilibrium

  □ □(□*B*>0) > □(□*B*<0)
- It looks like neutrinos have no role in this…

Electroweak Anomaly

- Actually, SM converts *L* to *B*.
  - In Early Universe ($T >$ 200GeV), *W*/*Z* are massless and fluctuate in *W*/*Z plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspondingly

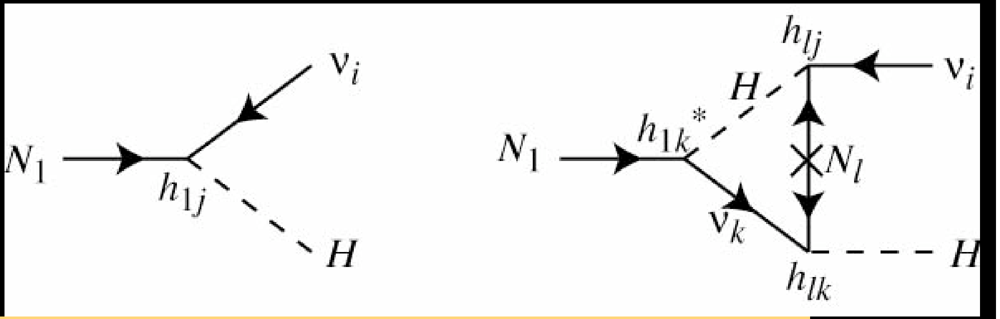




□L=□Q=□Q=□Q=□B=1 □ □(B–L)=0

Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate L from the direct CP violation in right-handed neutrino decay



$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

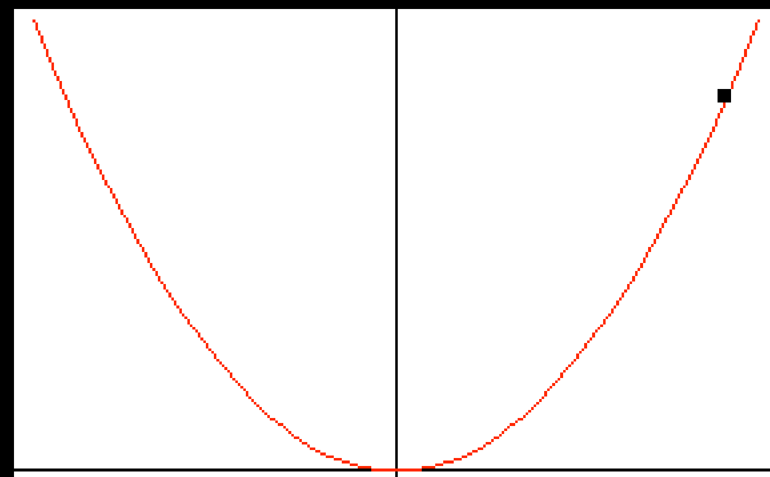
- L gets converted to B via EW anomaly

⇒ More matter than anti-matter

⇒ *We have survived "The Great Annihilation"*

Leptogenesis Works!

- Coherent oscillation of right-handed sneutrino
  (Bose-Einstein condensate)
  (HM, Yanagida+Hamaguchi)
  - Inflation ends with a large sneutrino amplitude
  - Starts oscillation
  - dominates the Universe
  - Its decay produces asymmetry
  - Consistent with observed oscillation pattern
  - isocurvature fluctuation testable by MAP? (Moroi, HM)

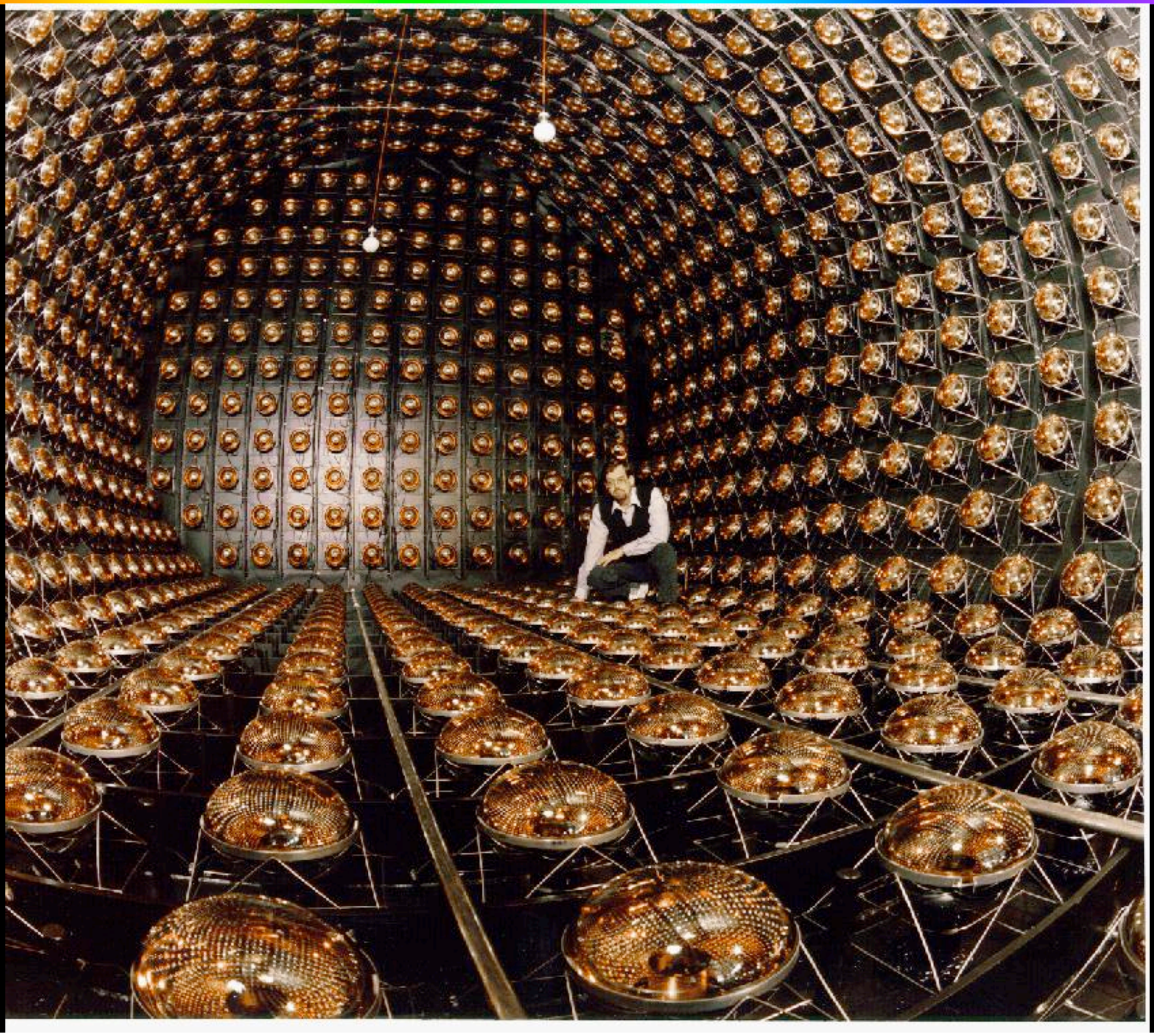


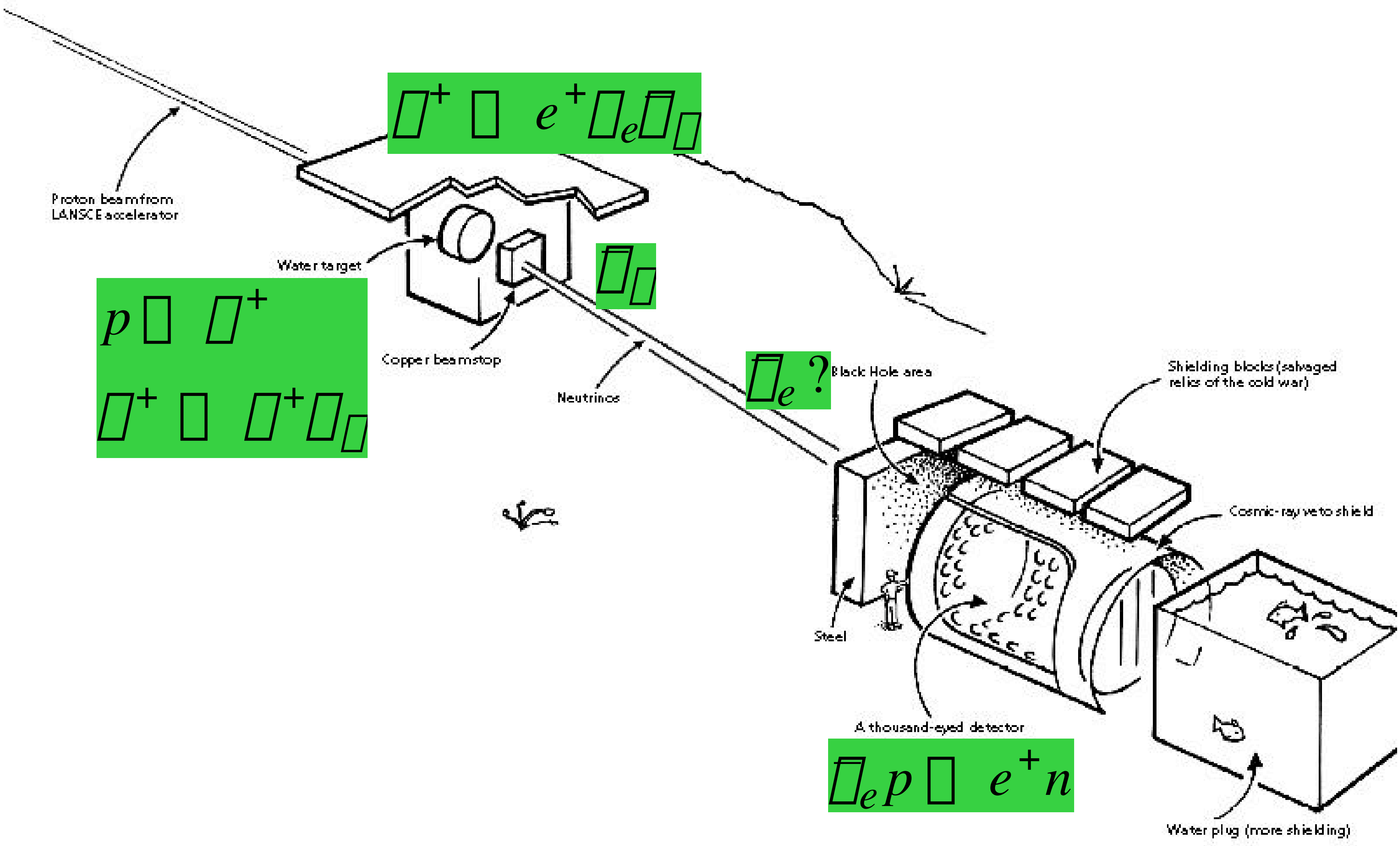
$$\frac{n_B}{s} \sim \frac{T_{decay}}{M_1} \sim \left(\frac{n_B}{s}\right)_{obs} \frac{T_{decay}}{10^6\,\text{GeV}} \arg\frac{h_{13}^2}{h_{33}^2}$$

Conclusions

- Neutrinos are *weird*
- Strong evidence for neutrino mass
- Small but finite neutrino mass:
  - Need drastic ideas to understand it
- *Neutrino mass may be responsible for our existence*
- A lot more to learn in the next few years

LSND

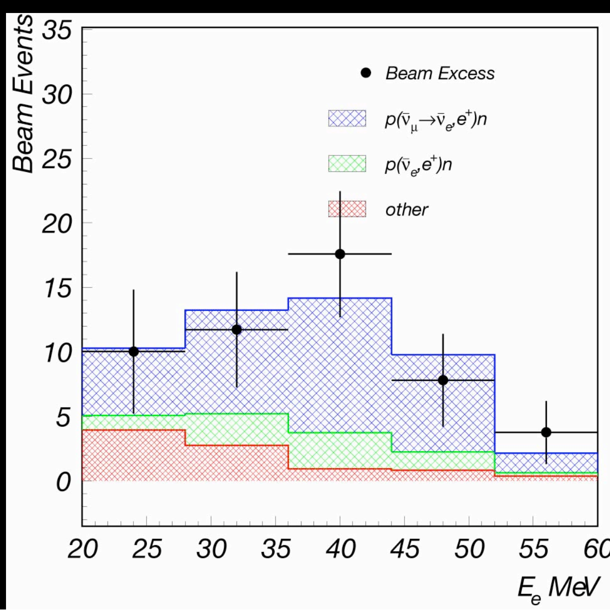



$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
Proton beam from LANSCE accelerator
Water target
$p \to \pi^+$
$\pi^+ \to \mu^+ \nu_\mu$
Copper beamstop
$\bar{\nu}_\mu$
Neutrinos
$\bar{\nu}_e$?
Black Hole area
Shielding blocks (salvaged relics of the cold war)
Cosmic-ray veto shield
Steel
A thousand-eyed detector
$\bar{\nu}_e p \to e^+ n$
Water plug (more shielding)

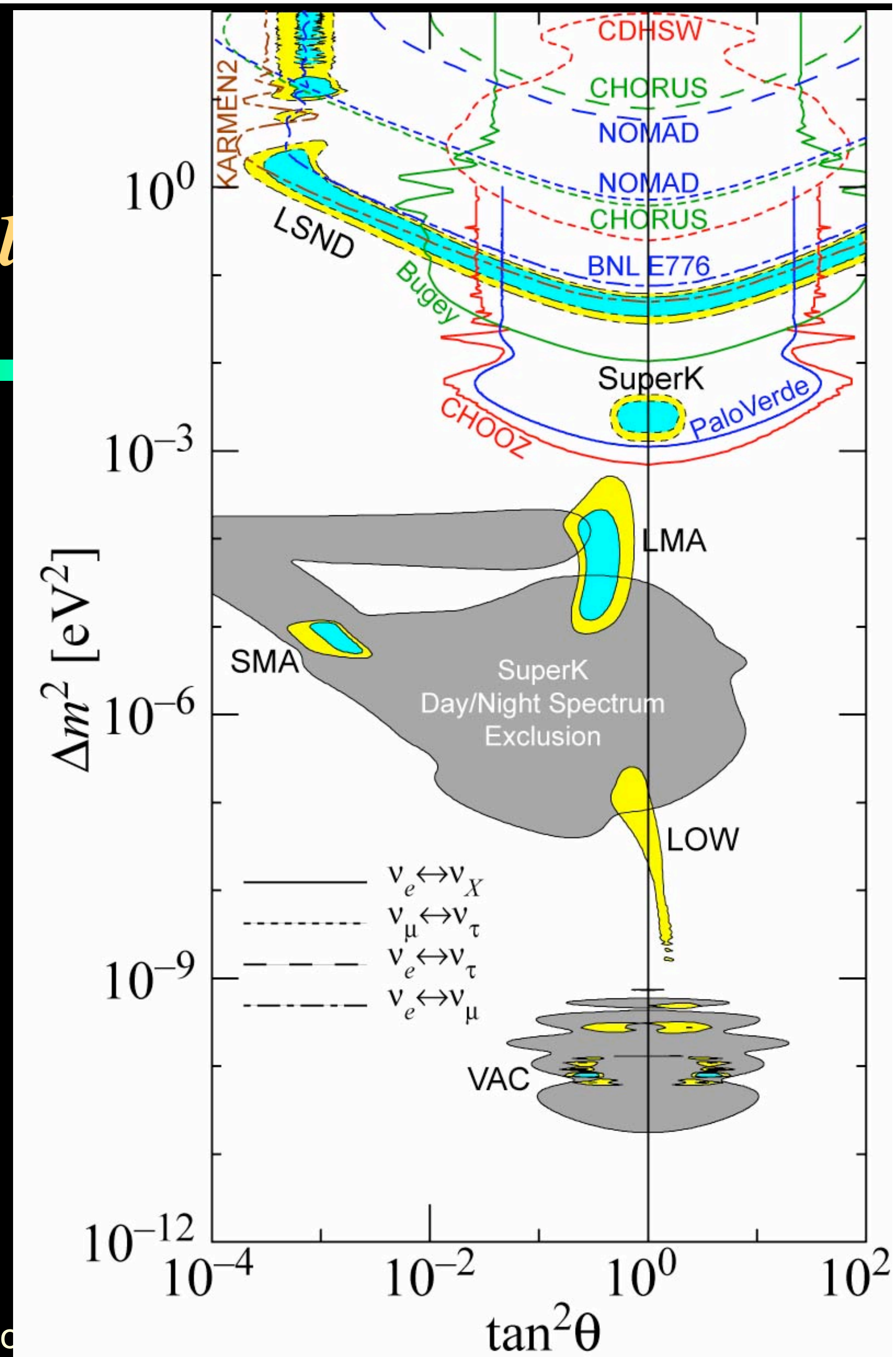
3.3 St

- Excess positron events over calculated BG

$$P(\bar{\nu}_\mu \to \bar{\nu}_e)$$
$$= (0.264 \pm 0.067 \pm 0.045)\%$$



Harvard collo



Sterile Neutrino

- LSND, atmospheric and solar neutrino oscillation signals

  $\Delta m^2_{\mathrm{LSND}} \sim \mathrm{eV}^2$

  $\Delta m^2_{\mathrm{atm}} \sim 3\times10^{-3}\mathrm{eV}^2$

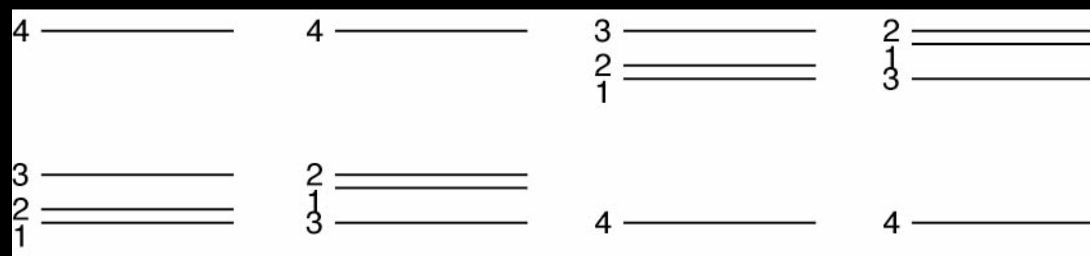
  $\Delta m^2_{\mathrm{solar}} < 10^{-3}\mathrm{eV}^2$

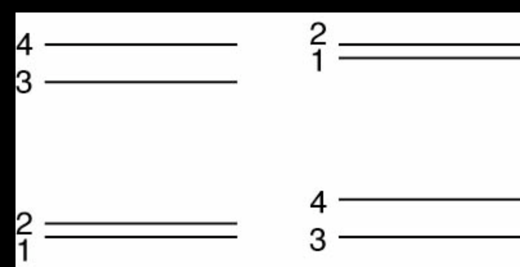
  ⇒ Can't be accommodated with 3 neutrinos

  ⇒ Need a *sterile neutrino*

  New type of neutrino with no weak interaction

- 3+1 or 2+2 spectrum?





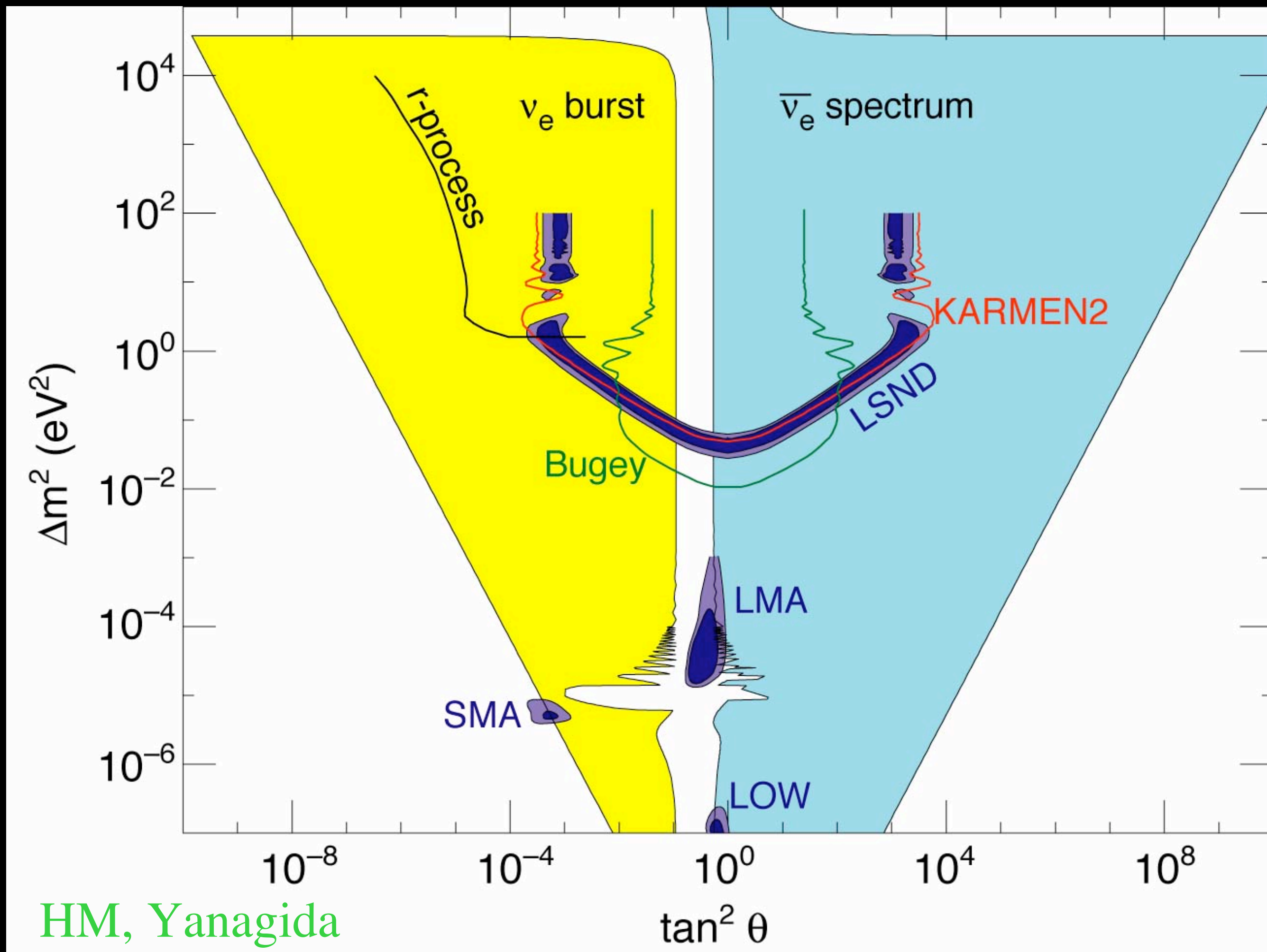
Sterile Neutrino getting tight

- 3+1 spectrum: $\sin^2 2\theta_{LSND} = 4|U_{4e}|^2 |U_{4\mu}|^2$
  - $|U_{4\mu}|^2$ can't be big because of CDHS, SK U/D
  - $|U_{4e}|^2$ can't be big because of Bugey
  - Marginally allowed (90% excl. vs 99% allw'd)
- 2+2 spectrum: past fits preferred
  - Atmospheric mostly $\nu_\mu \to \nu_\tau$
  - Solar mostly $\nu_e \to \nu_s$ (or vice versa)
  - Now solar sterile getting tight due to SNO

(Barger et al, Giunti et al, Gonzalez-Garcia et al, Strumia)

$\Rightarrow$ *Both scenarios disfavored at 90-99% CL*

SN1987A neutrino burst doesn't like LSND



HM, Yanagida

CPT Violation?
"A desperate remedy…"

- LSND evidence:

  anti-neutrinos

- Solar evidence:

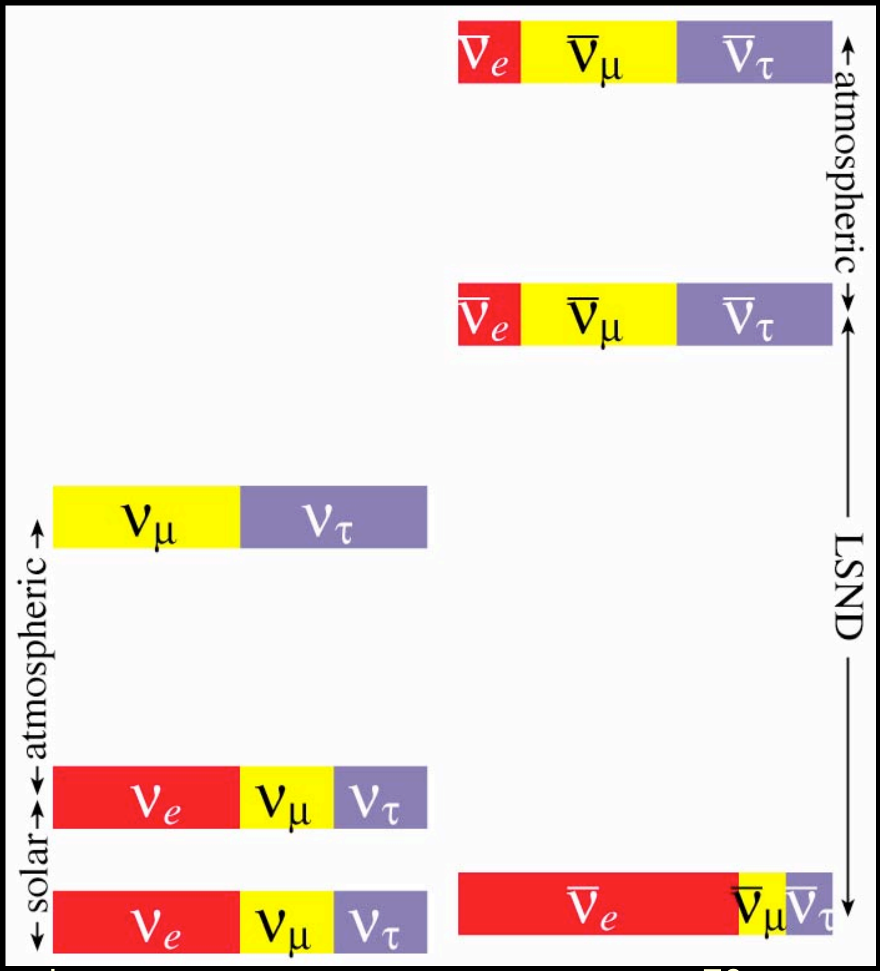
  neutrinos

- If neutrinos and anti-neutrinos have different mass spectra, atmospheric, solar, LSND accommodated without a sterile neutrino

  (HM, Yanagida)

  Best fit to current data

  (Strumia)



CPT Theorem

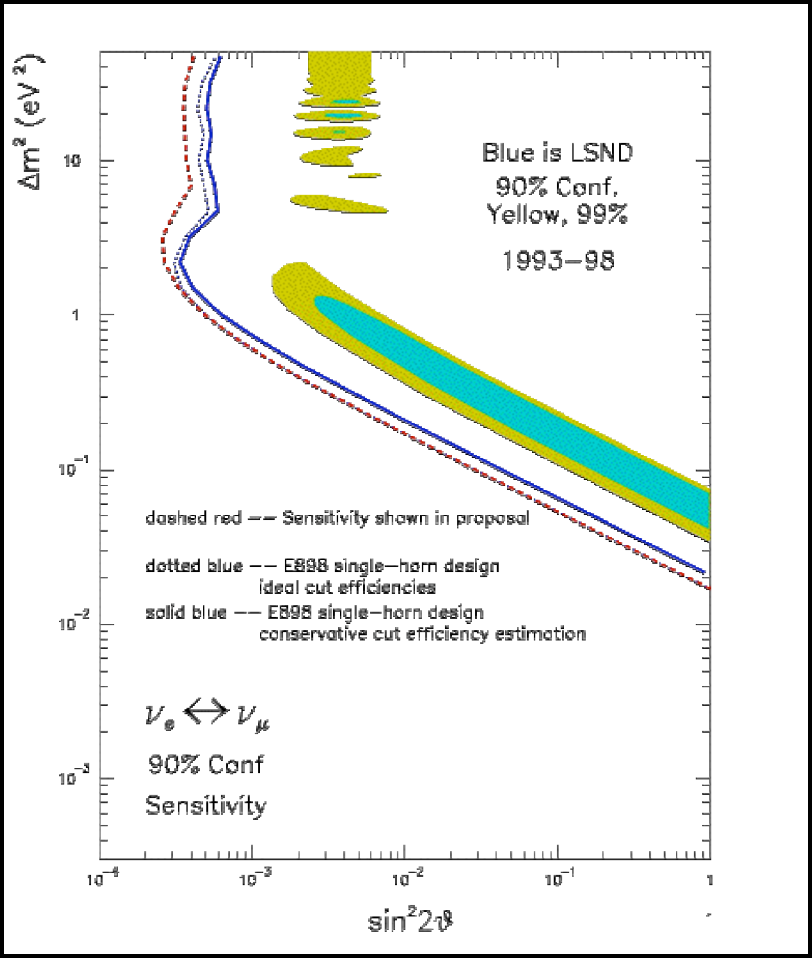
- Based on three assumptions:
  - Locality
  - Lorentz invariance
  - Hermiticity of Hamiltonian
- Violation of any one of them:

  big impact on fundamental physics
- Neutrino mass: tiny effect from high-scale physics
  - Non-local Hamiltonian? (HM, Yanagida)
  - Brane world? (Barenboim, Borissov, Lykken, Smirnov)
  - Dipole Field Theory? (Bergman, Dasgupta, Ganor, Karczmarek, Rajesh)

Implications on Experiments

- Mini-BooNE experiment will not see oscillation in neutrino mode, but will in anti-neutrino mode
- KamLAND will not see LMA
- SNO, Borexino establish LMA by exclusion

   We'll see!



Maybe even more surprises in neutrinos!