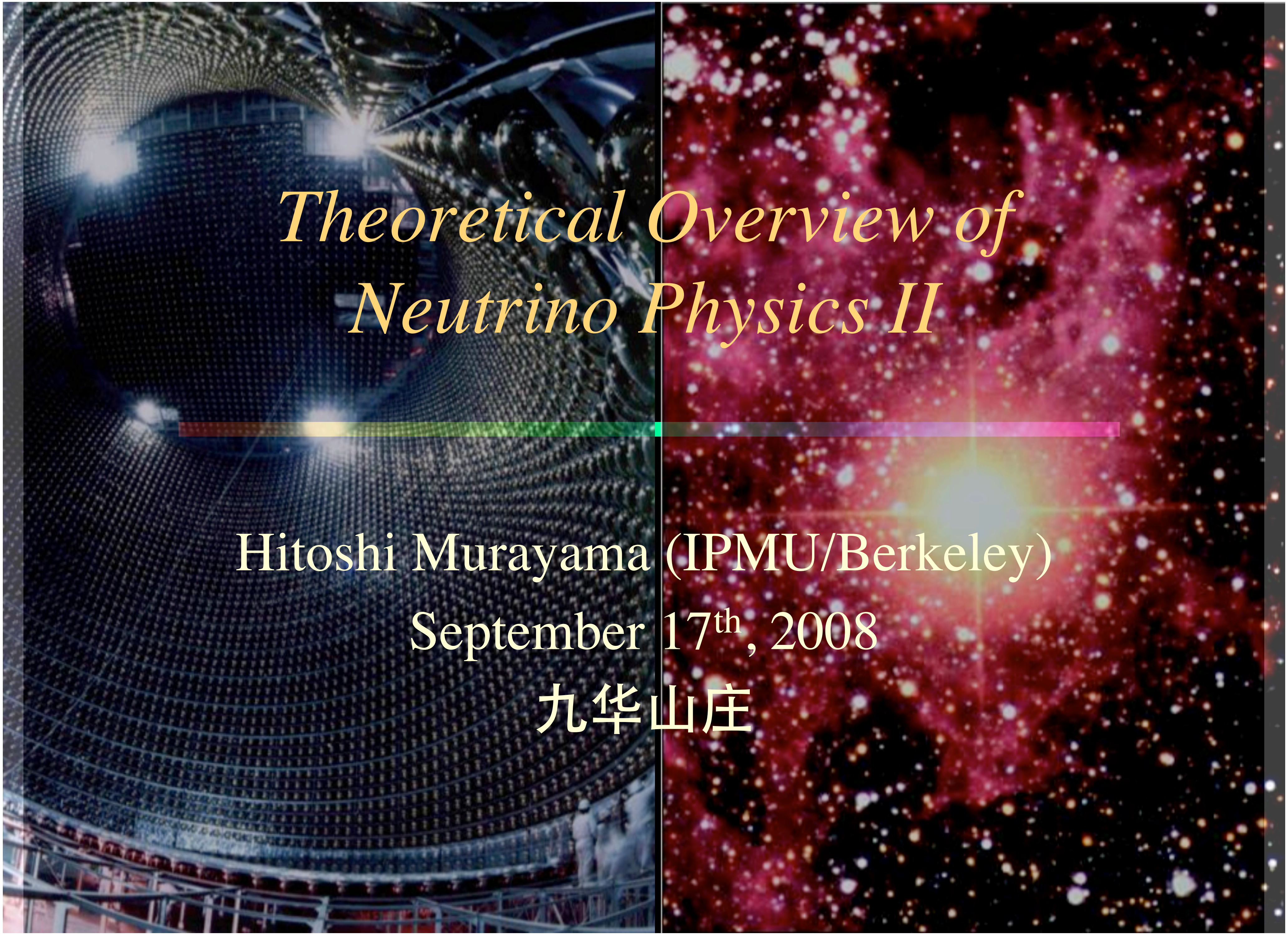
# *Theoretical Overview of Neutrino Physics II*

Hitoshi Murayama (IPMU/Berkeley)

September 17$^{th}$, 2008

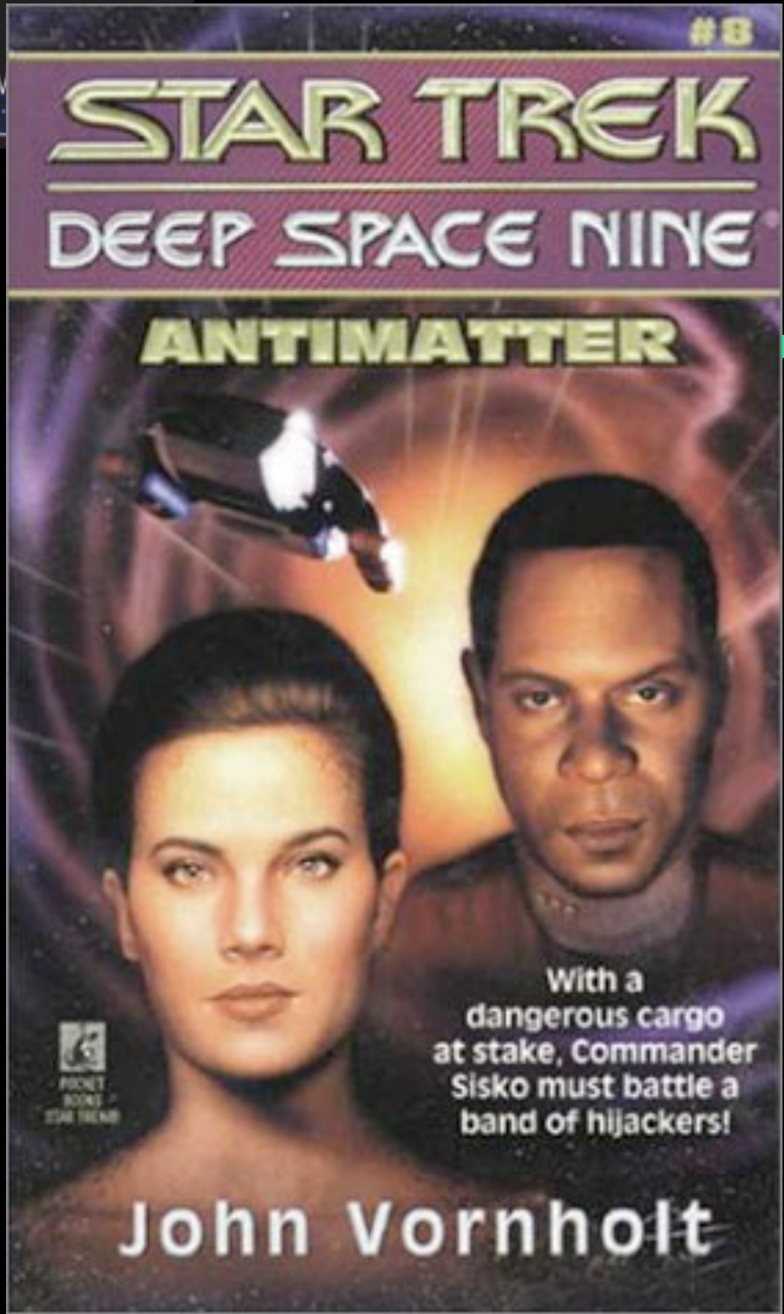
九华山庄

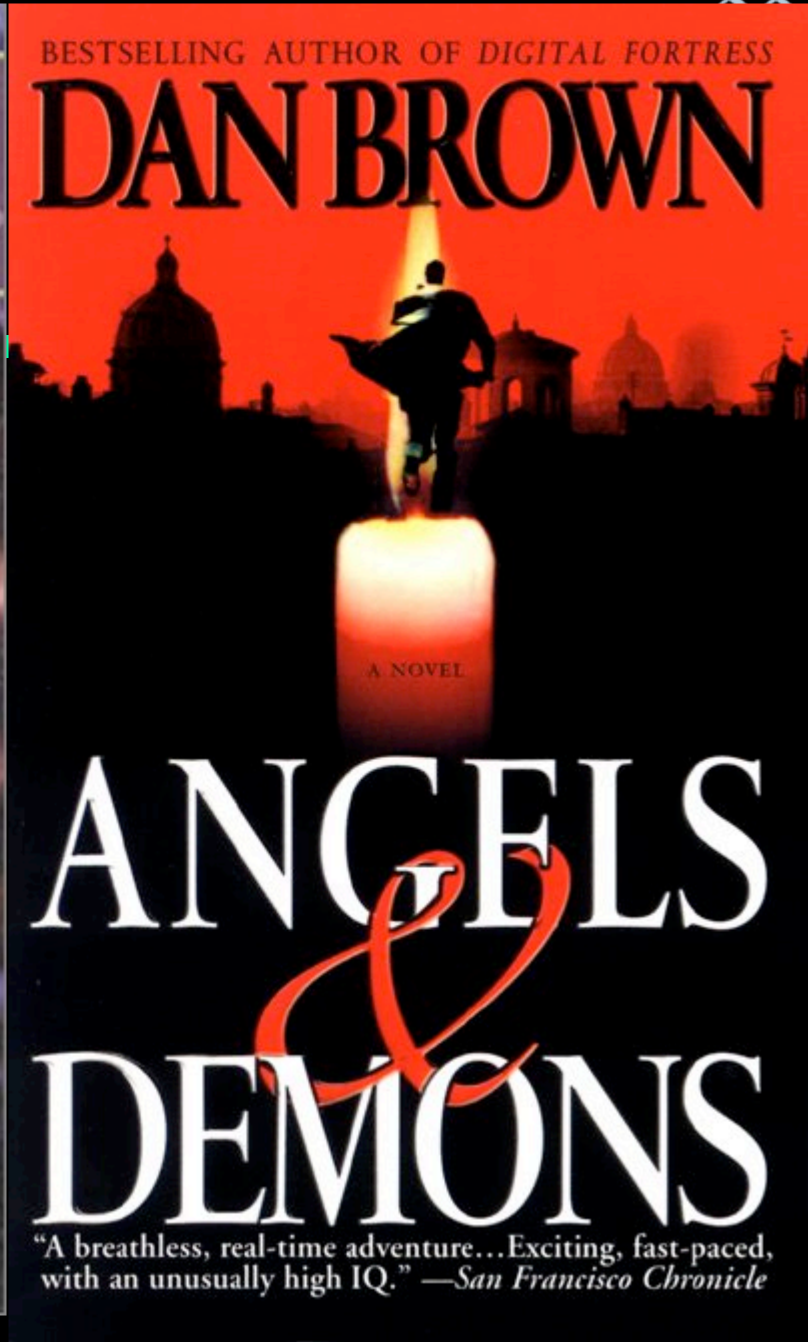


# *Outline*

- Why do we exist?
- Solar Neutrinos
- Massive Neutrinos and Structure Formation

# *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


BESTSELLING AUTHOR OF DIGITAL FORTRESS
DAN BROWN
A NOVEL
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"A breathless, real-time adventure…Exciting, fast-paced, with an unusually high IQ." —San Francisco Chronicle

# *Matter and Anti-Matter Early Universe*

| Matter | Anti-matter |
|---|---|
| 1,000,000,001 | 1,000,000,000 |

# *Matter and Anti-Matter Current Universe*

us

1

Matter

Anti-matter

*The Great Annihilation*

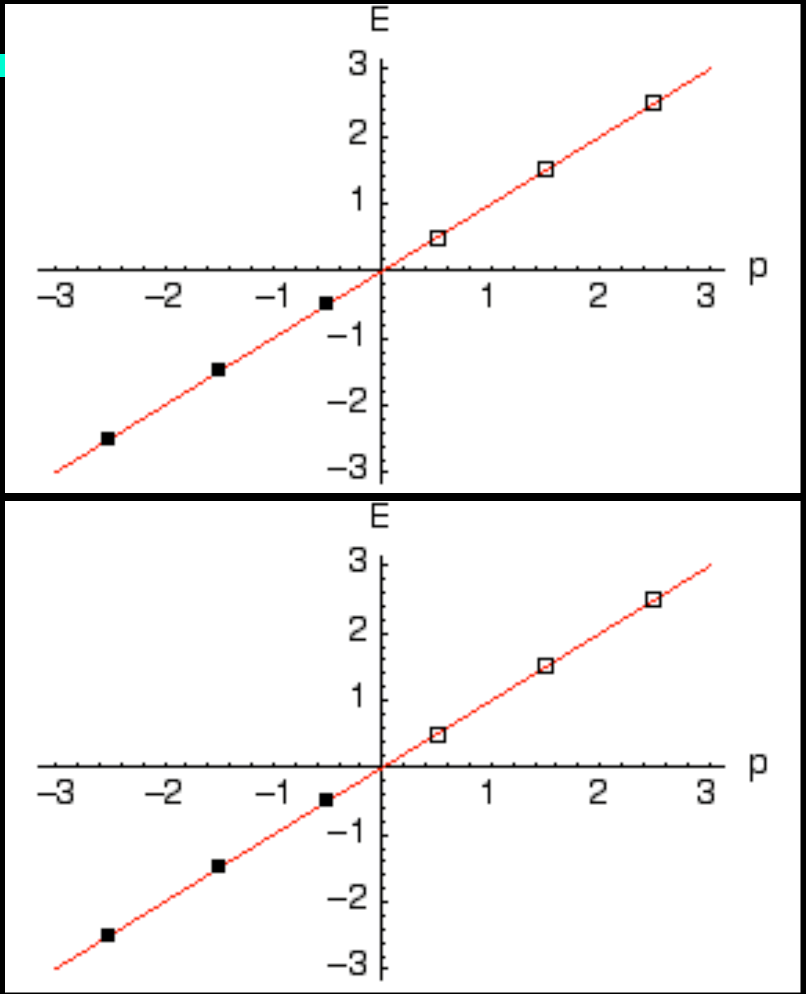
# *Baryogenesis*

- 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

    $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- It looks like neutrinos have no role in this…

# *Electroweak Anomaly*

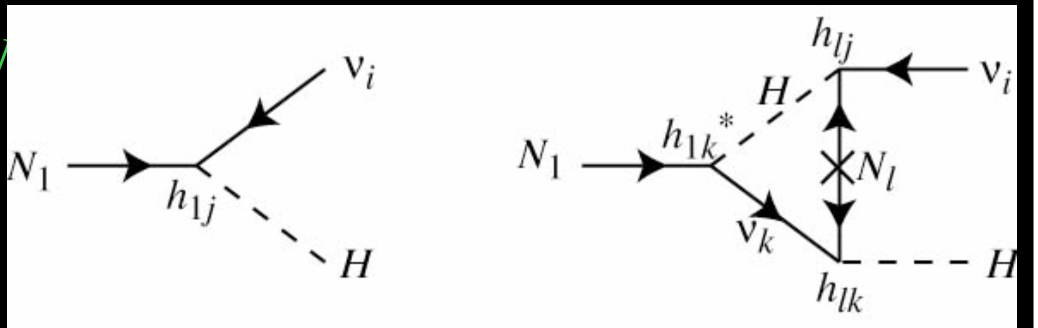



- Actually, SM converts $L$ ($\nu$) to $B$ (quarks).
  - In Early Universe ($T >$ 200GeV), $W$ is massless and fluctuate in $W$ *plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly

$$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta(B-L) = 0$$

# *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

$\Rightarrow$ More matter than anti-matter

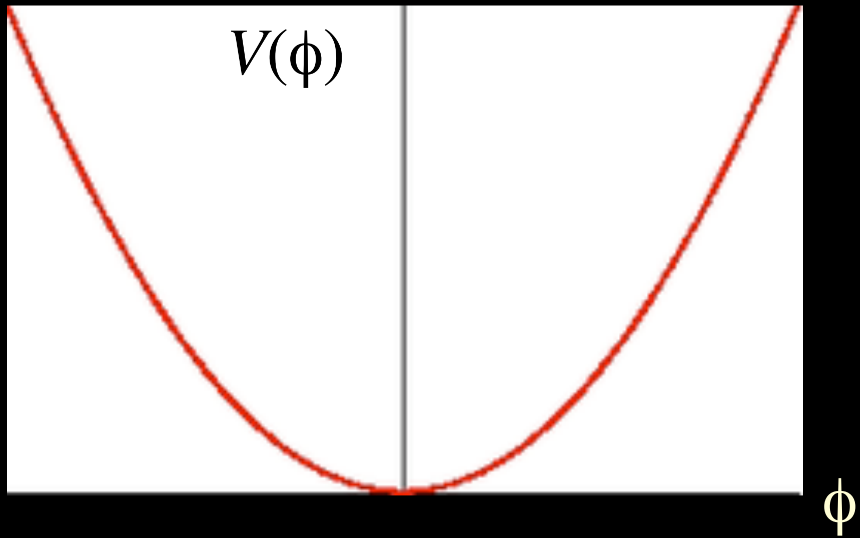
$\Rightarrow$ *We have survived "The Great Annihilation"*

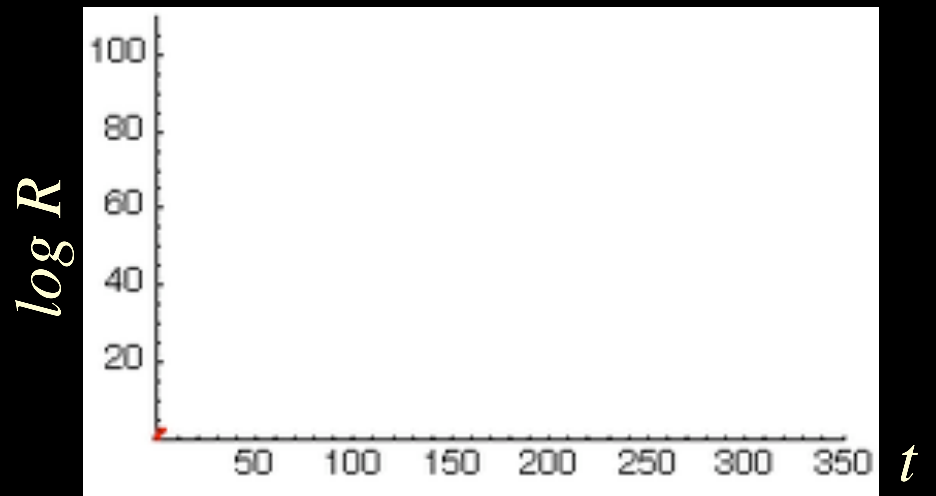
# Origin of Universe

- Maybe an *even bigger* role
- Microscopically small Universe at Big Bang got stretched by an exponential expansion (inflation)
- Need a spinless field that
  - slowly rolls down the potential
  - oscillates around it minimum
  - decays to produce a thermal bath
- *The superpartner of right-handed neutrino fits the bill*
- When it decays, it produces the lepton asymmetry at the same time

(HM, Suzuki, Yanagida, Yokoyama)

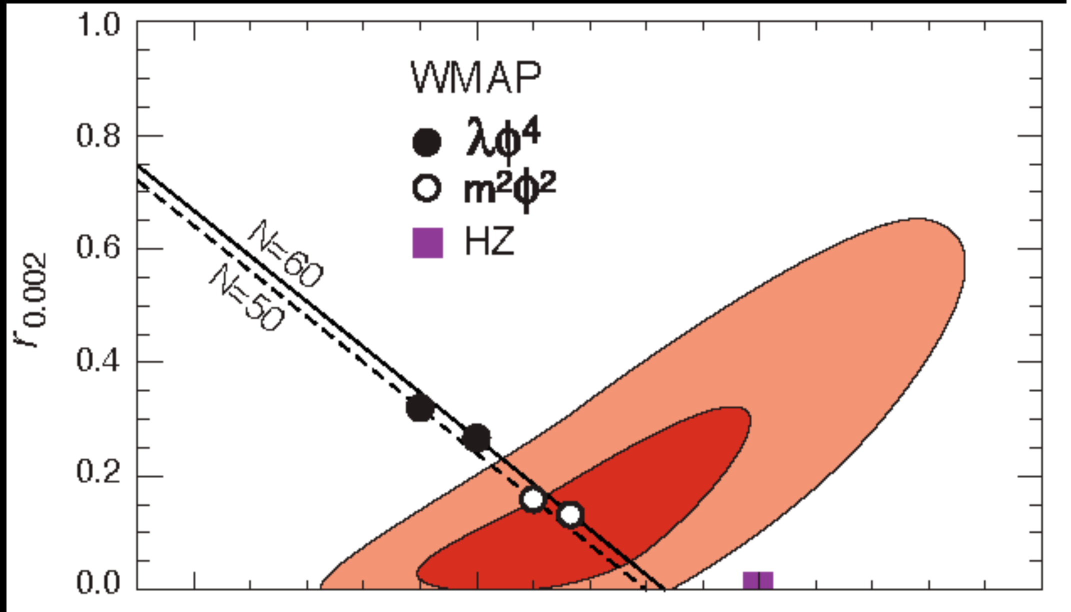
*Neutrino is mother of the Universe?*



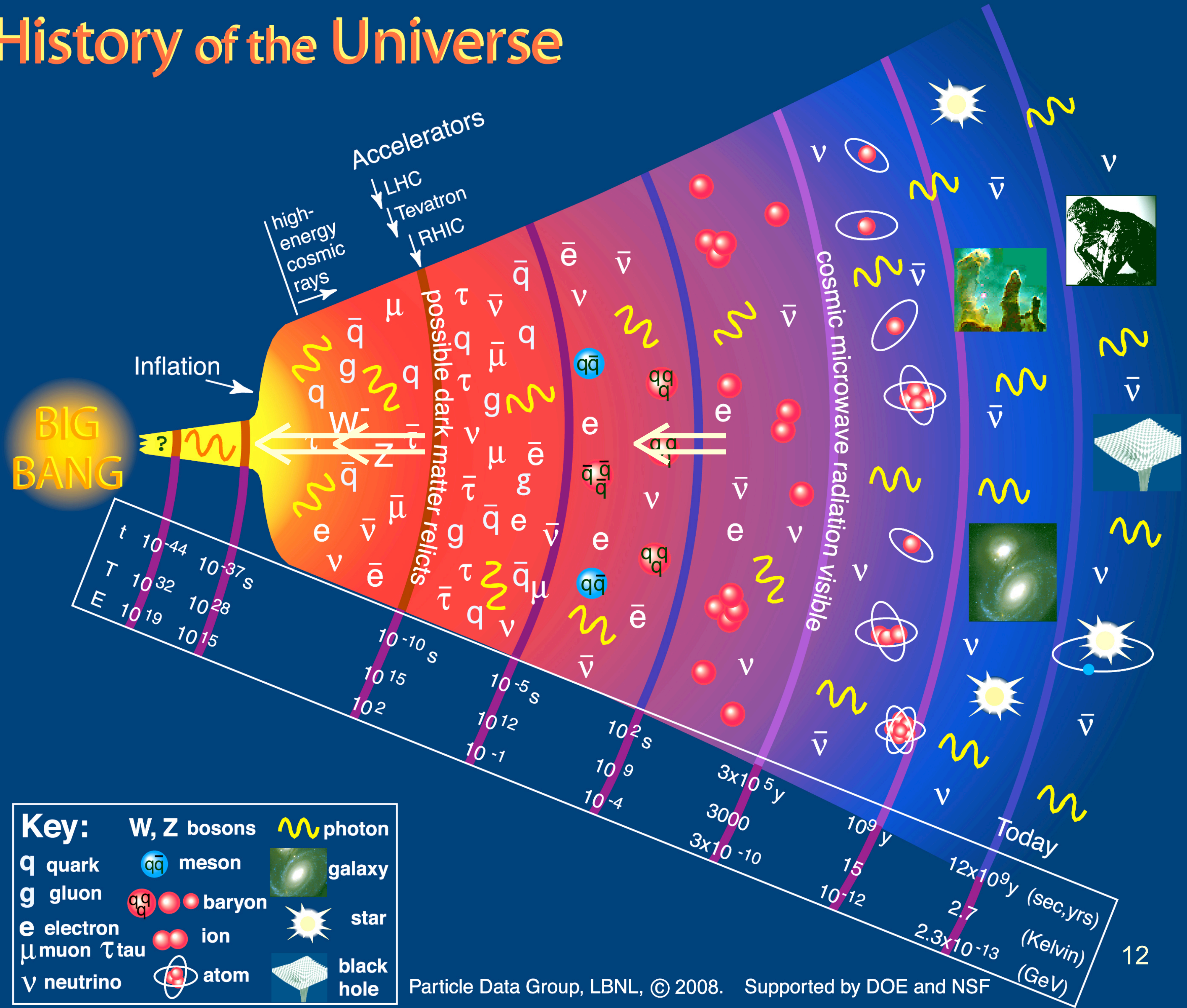



# *Origin of the Universe*

- Right-handed scalar neutrino: $V=m^2\phi^2$
- $n_s$~0.96
- $r$~0.16
- Need $m$~$10^{13}$GeV
- Still consistent with latest WMAP
- But $V=\lambda\phi^4$ is excluded
- Verification possible in the near future



# History of the Universe

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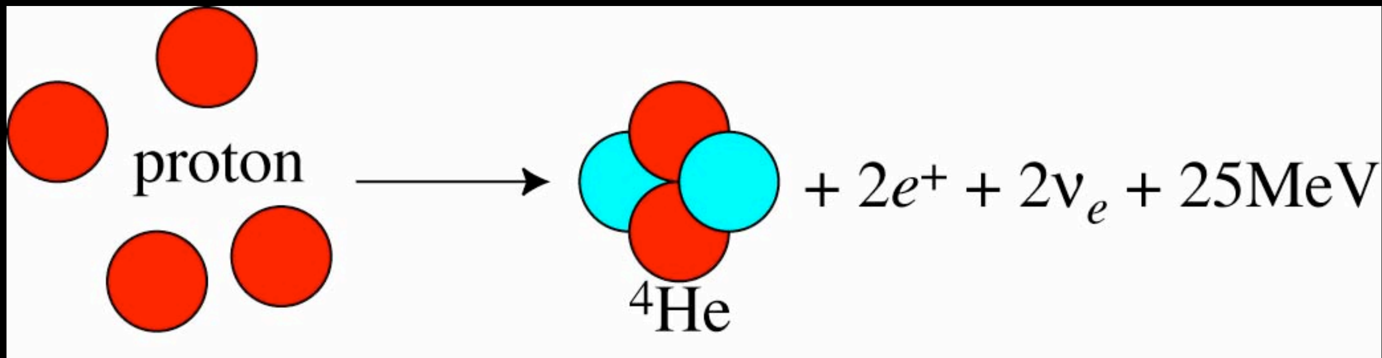
# *Solar Neutrinos*

# *How the Sun burns*

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




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

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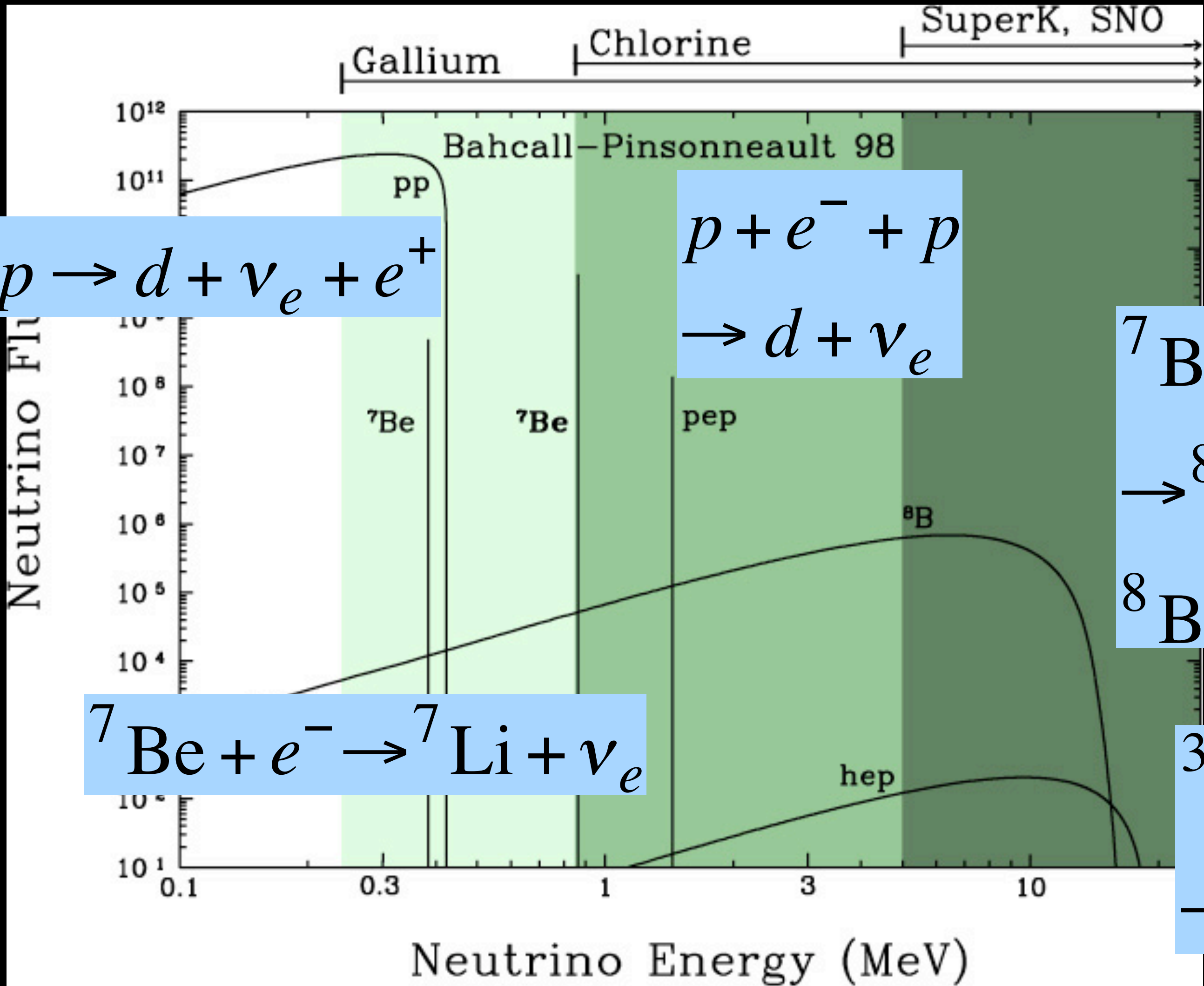
# *Solar Neutrino Spectrum*




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

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

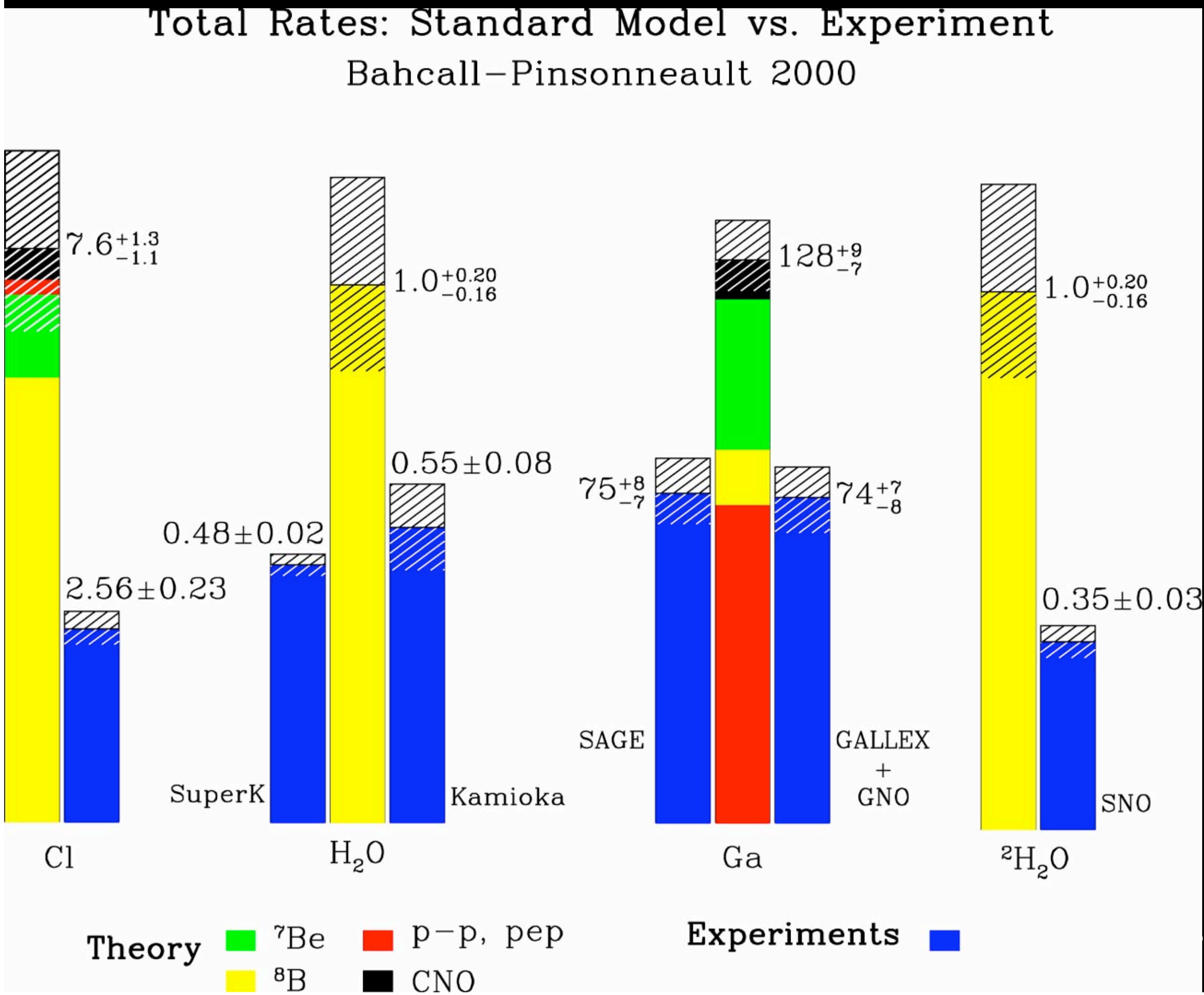
$$^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$$

$$^8\mathrm{Be} \rightarrow 2\alpha$$

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$

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

# *We don't get enough*



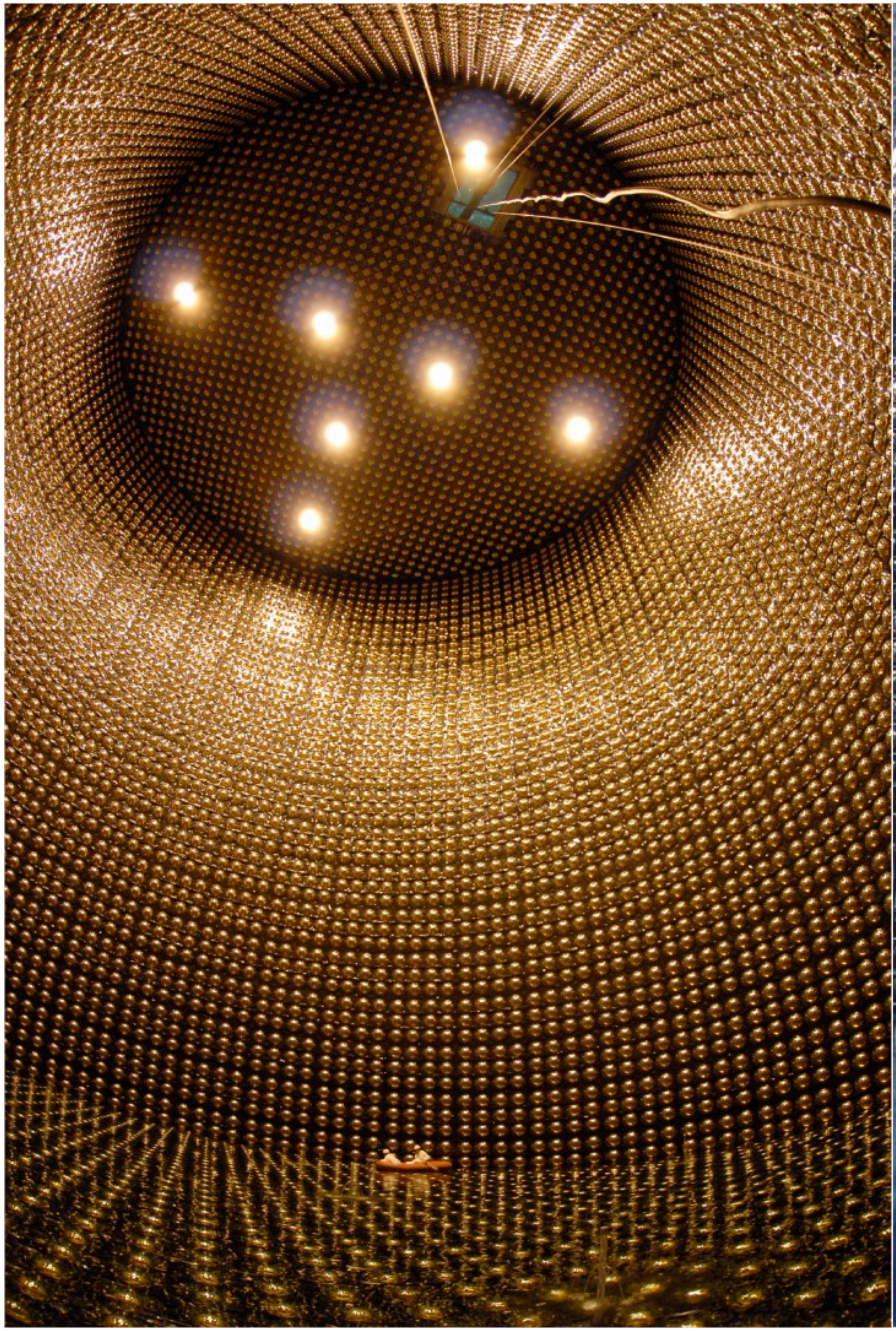
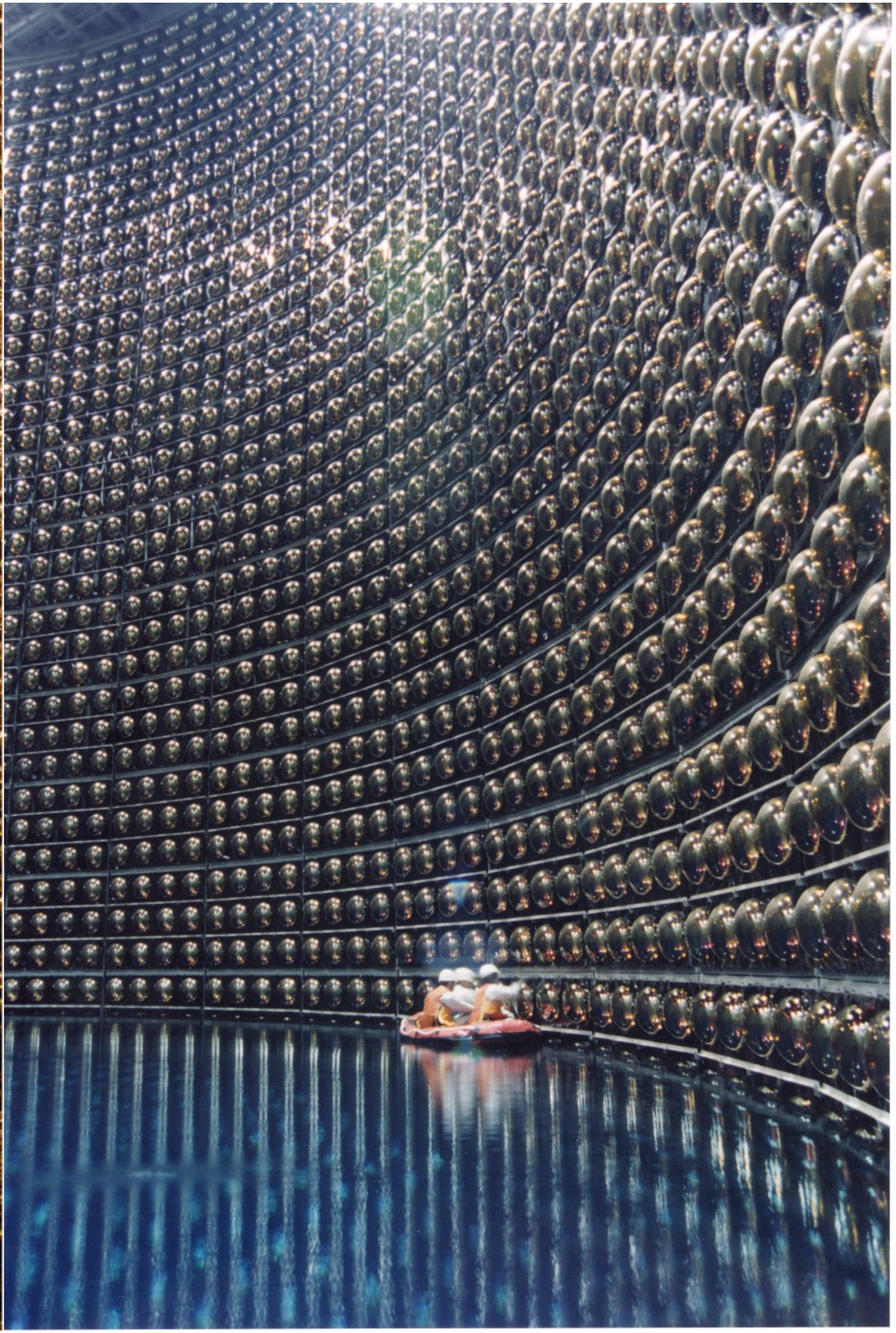

- Neutrino oscillation?
- Something wrong with our understanding of the Sun?

# *Homestake Experiment*

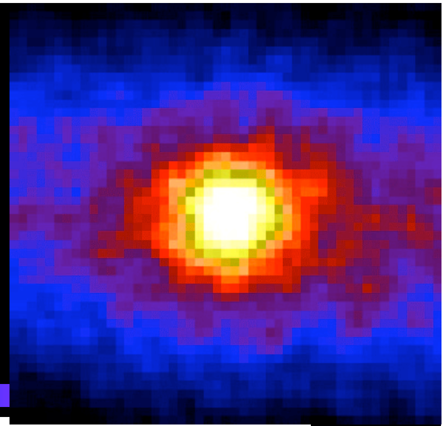
- The first solar neutrino experiment 1970-98
- 600t dry cleaning fluid $Cl_2C{=}CCl_2$ perchloroethylene
- $\nu_e\ {}^{37}\mathrm{Cl}\ (24\%) \rightarrow e^-\ {}^{37}\mathrm{Ar}$
- Makes ~0.5atom/day
- Extract them by He bubbling every ~2wks
- Count $^{37}$Ar decay in a proportional counter $\tau_{1/2}$=35.04 days

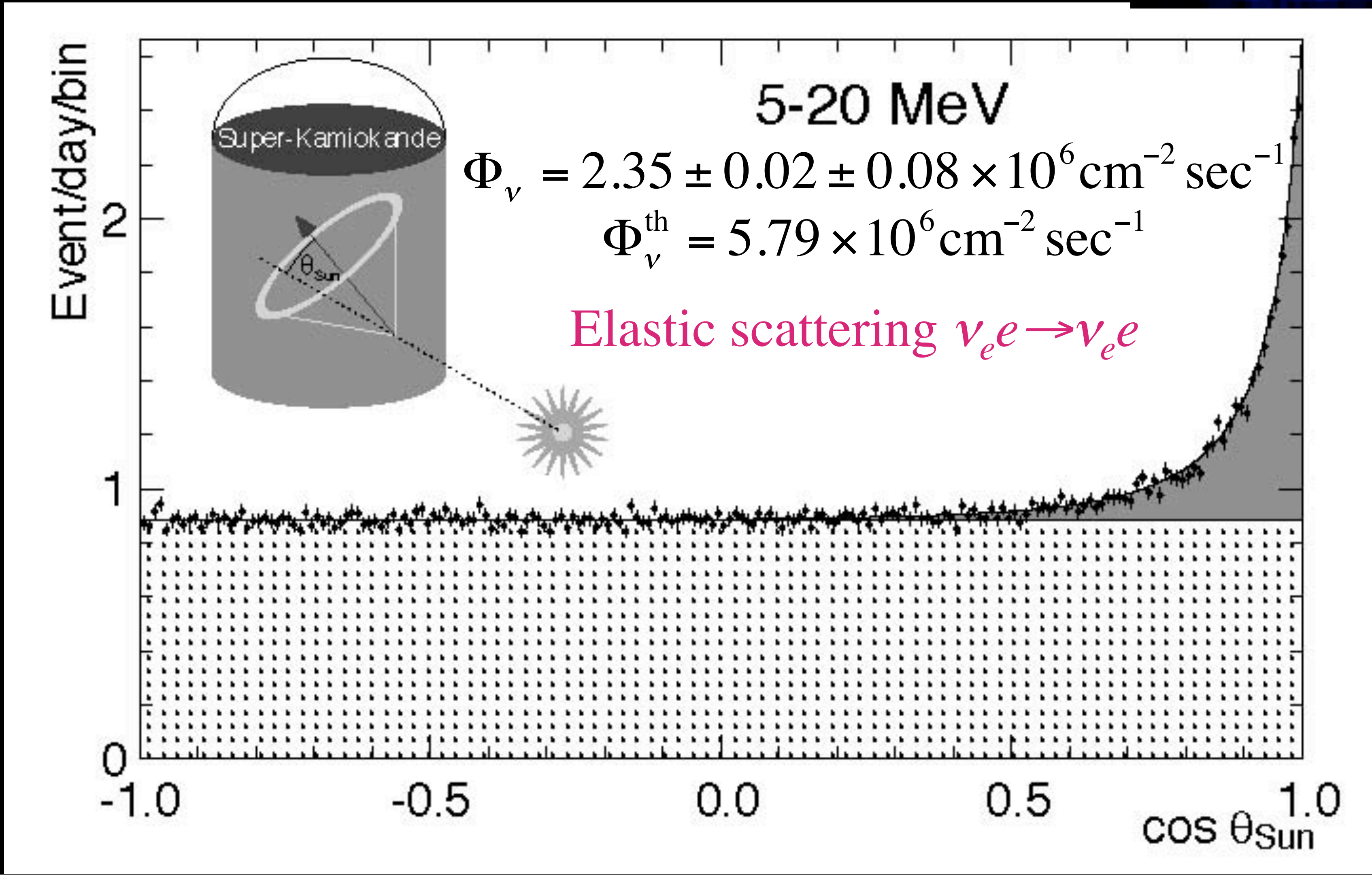
2.56±0.23 SNU vs 7.6+1.3−1.1 predicted

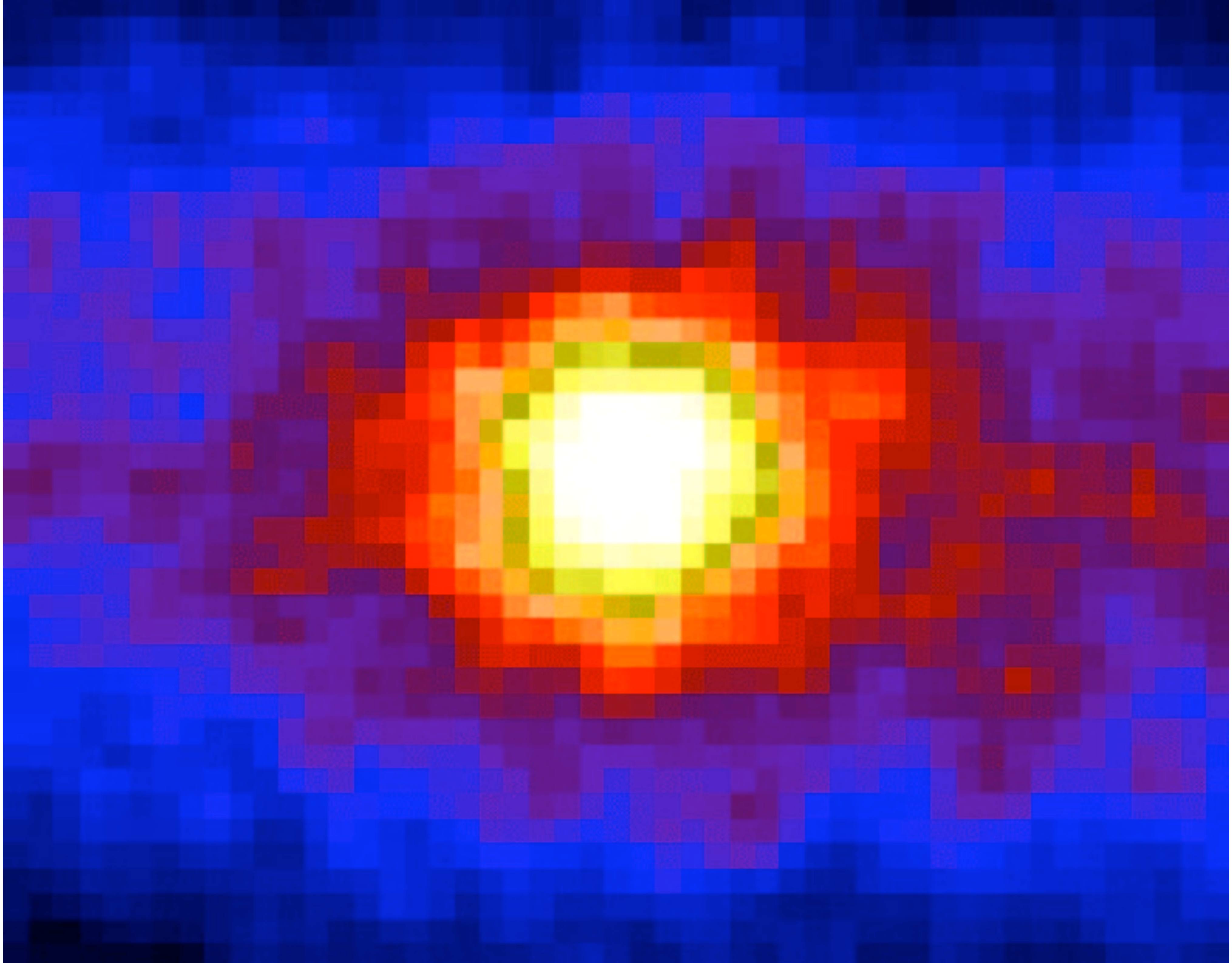
1 SNU = $10^{-36}$ captures/atom/sec

# *SuperK sees the Sun*

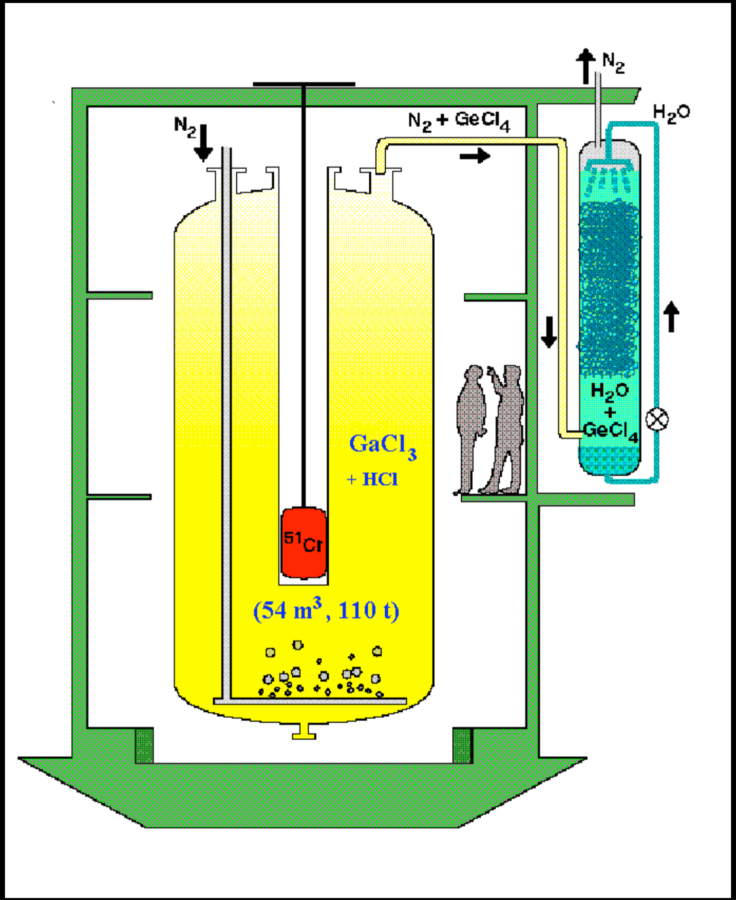






# *Ga Experiments*

- $\nu_e{}^{71}\mathrm{Ga}$ (40%)$\rightarrow e^{-}\,{}^{71}\mathrm{Ge}$
- Low threshold $E_\nu > 0.23\mathrm{MeV}$, sensitive to *pp* $\nu$'s
- Radiochemical
- GALLEX in Gran Sasso, SAGE in Baksan
- Capture cross section calibrated by $^{51}$Cr source (>60 PBq)!



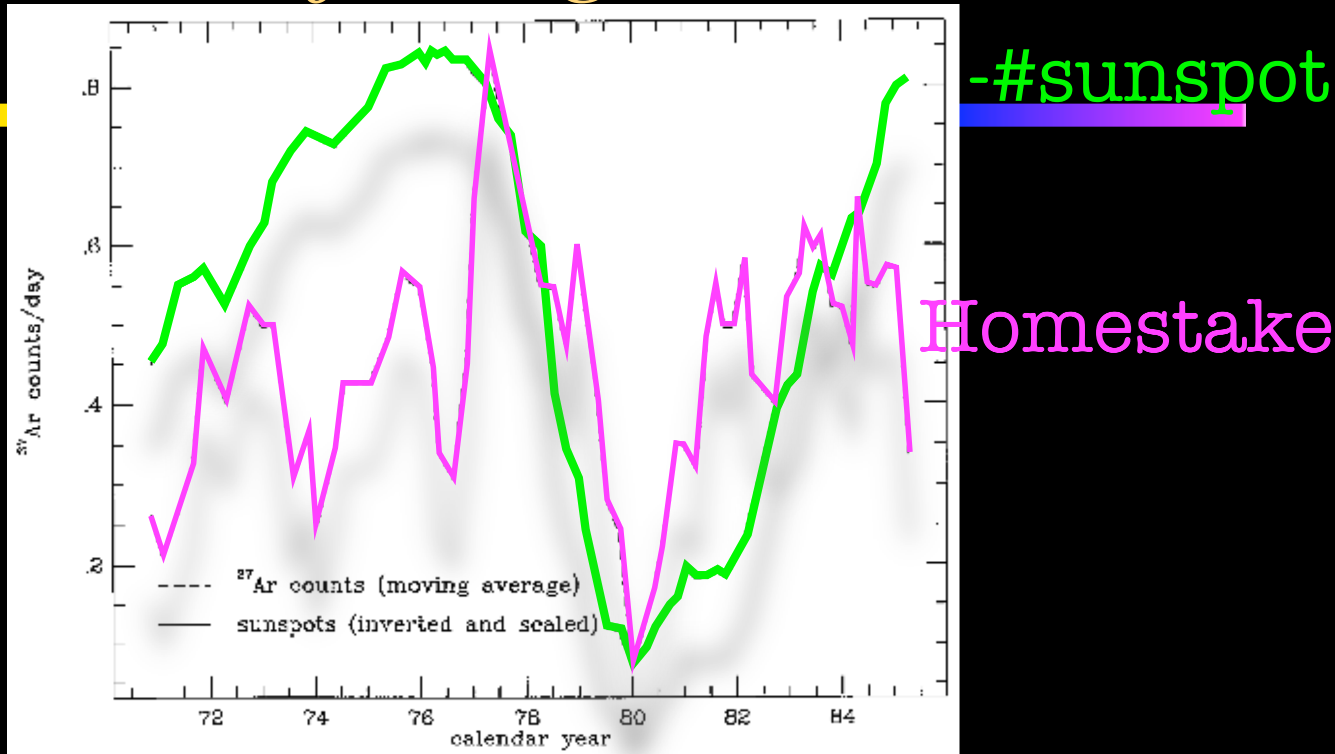

74+7−8 (GALLEX) 75+8−7 (SAGE) SNU

*cf*. 128+9−7 predicted

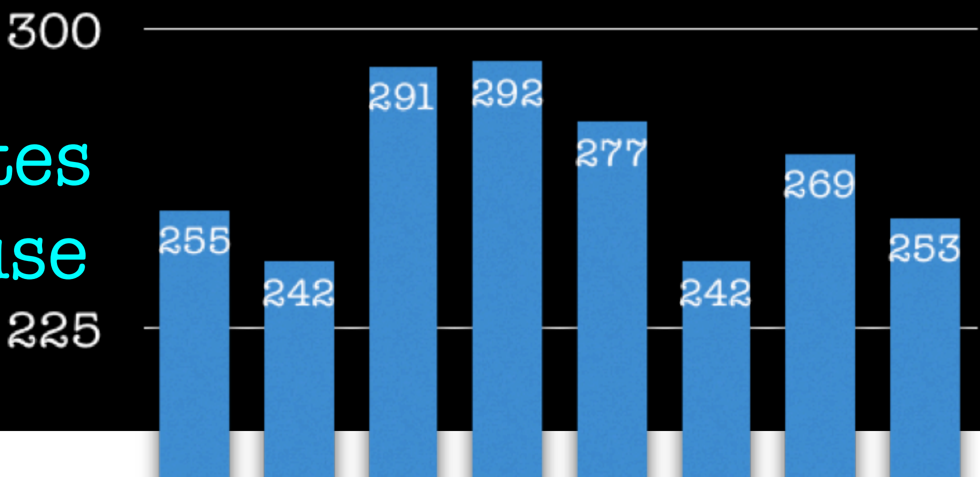
# *Why?*

1. Astrophysics is wrong
   – *pp* neutrino flux tied to solar luminosity
   – Change $^7$Be, $^8$B arbitrarily $\Rightarrow$ can't fit the data
2. Some of the data are wrong
   – Even if only one experiment correct, the puzzle remains
   – Need both 1. & 2. to explain the situation
3. Something is wrong with neutrinos

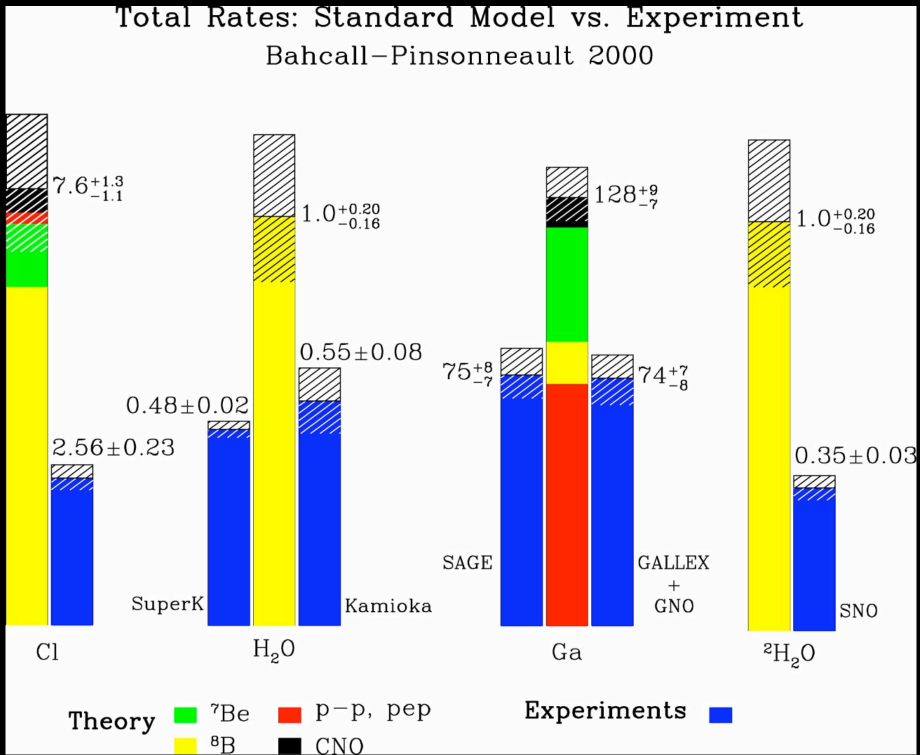
# Confusing data

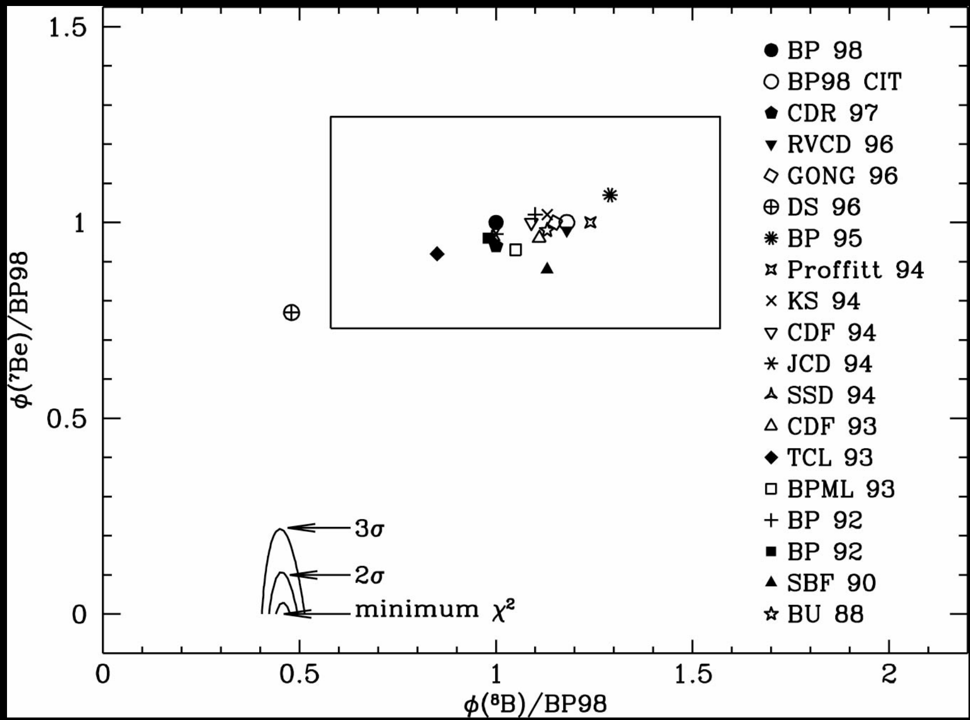



#Democrates in the House



# Astrophysics wrong?



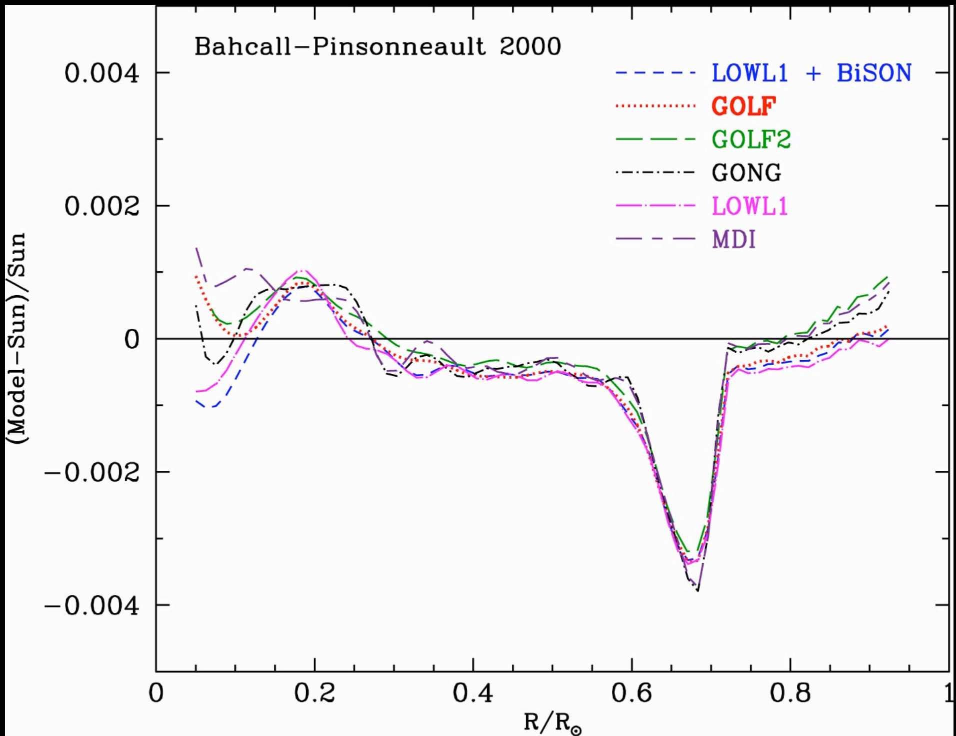



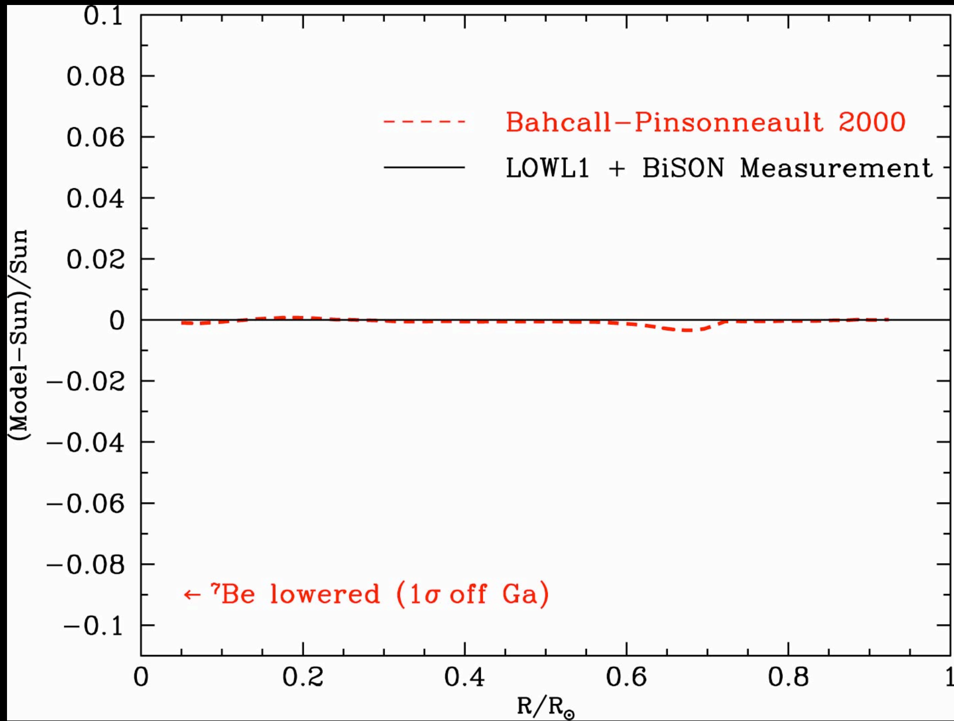

Fit data with arbitrary $^7$Be, $^8$B

Best fit needs negative $^7$Be
Remember $^8$B is a product of $^7$Be!

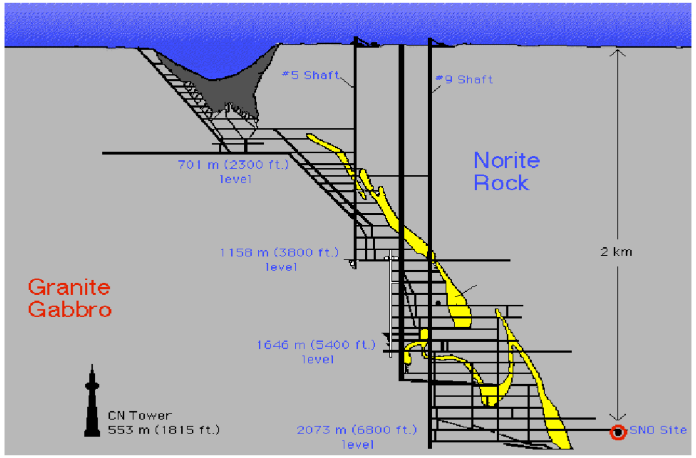
# *Astrophysics wrong?*

- Helioseismology data agree well with the SSM




See, however, recent developments in Raffelt's lecture




# Sudbury Neutrino Observatory

**1000 tonnes $D_2O$**

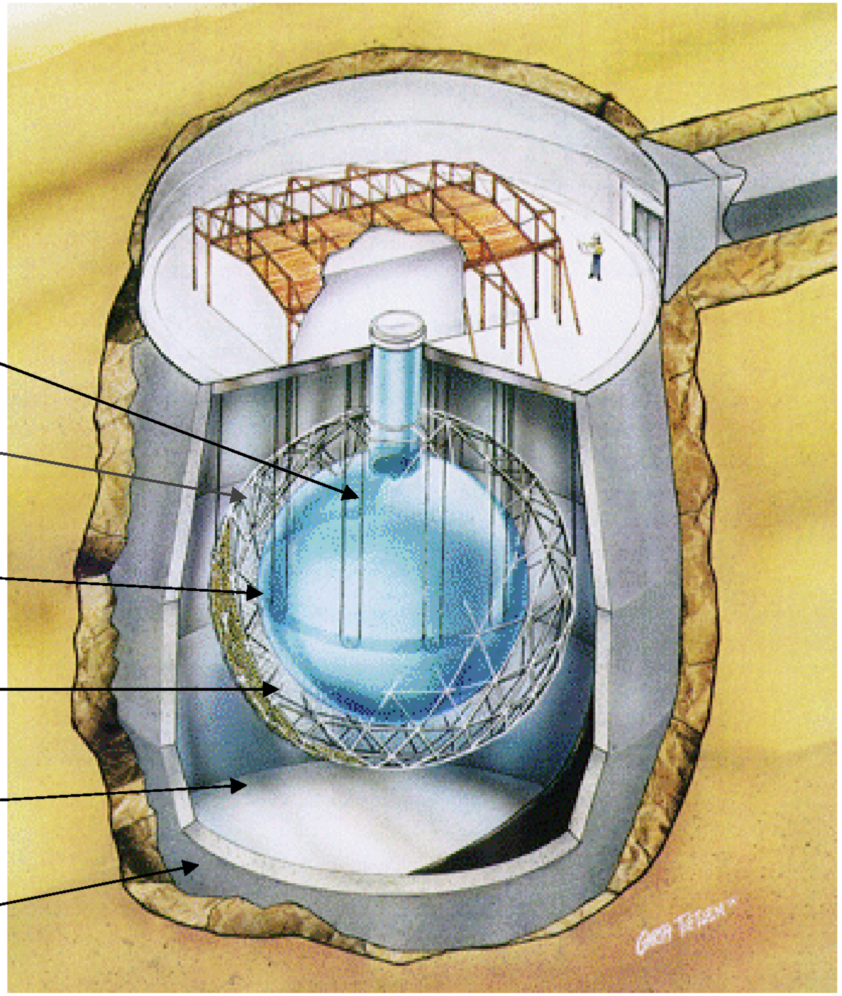
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding $H_2O$

5300 tonnes Outer Shield $H_2O$

Urylon Liner and Radon Seal



# *SNO comes to the rescue*

- Charged Current: $\nu_e$

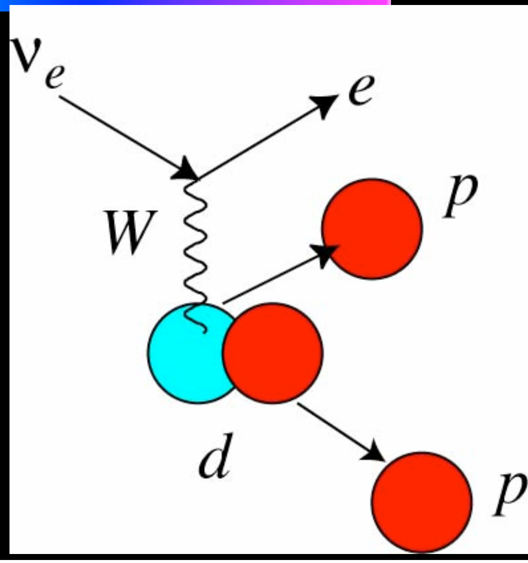
$$\phi_{CC} = 1.68^{+0.06}_{-0.06}(\mathrm{stat.})^{+0.08}_{-0.09}(\mathrm{syst.})$$

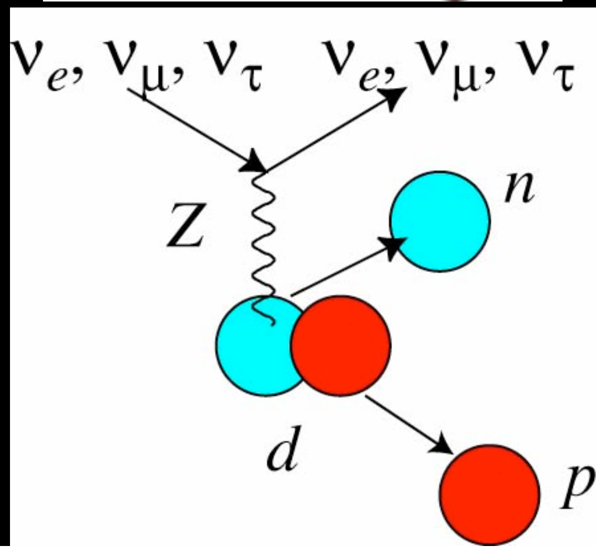
- Neutral Current: $\nu_e + \nu_\mu + \nu_\tau$

$$\phi_{NC} = 4.94^{+0.21}_{-0.21}(\mathrm{stat.})^{+0.38}_{-0.34}(\mathrm{syst.})$$

- 7.9σ difference

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

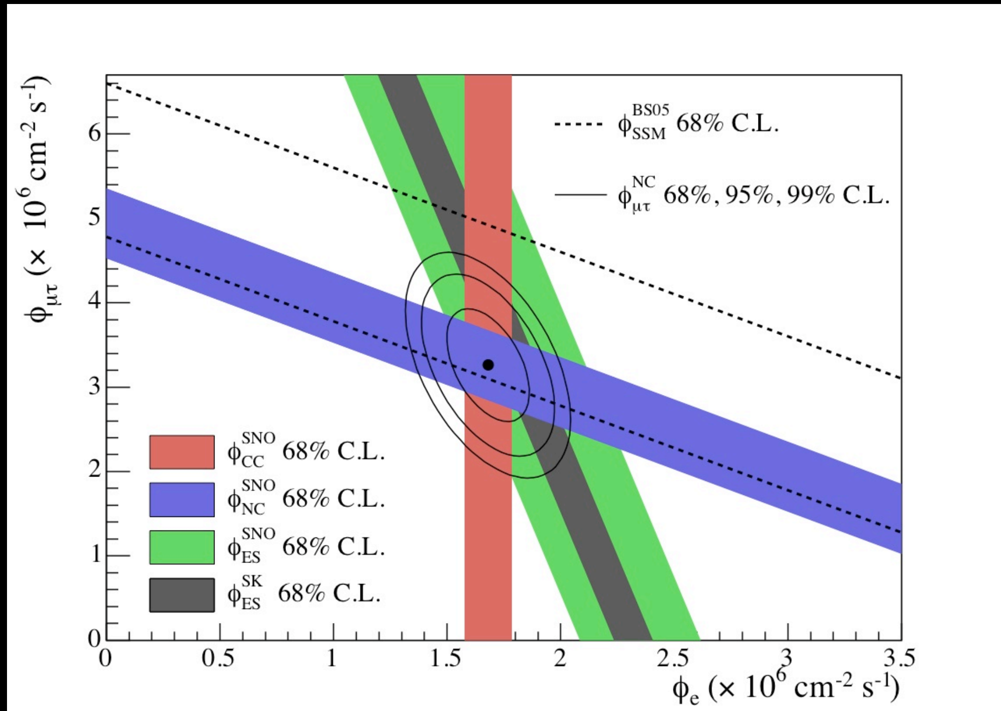


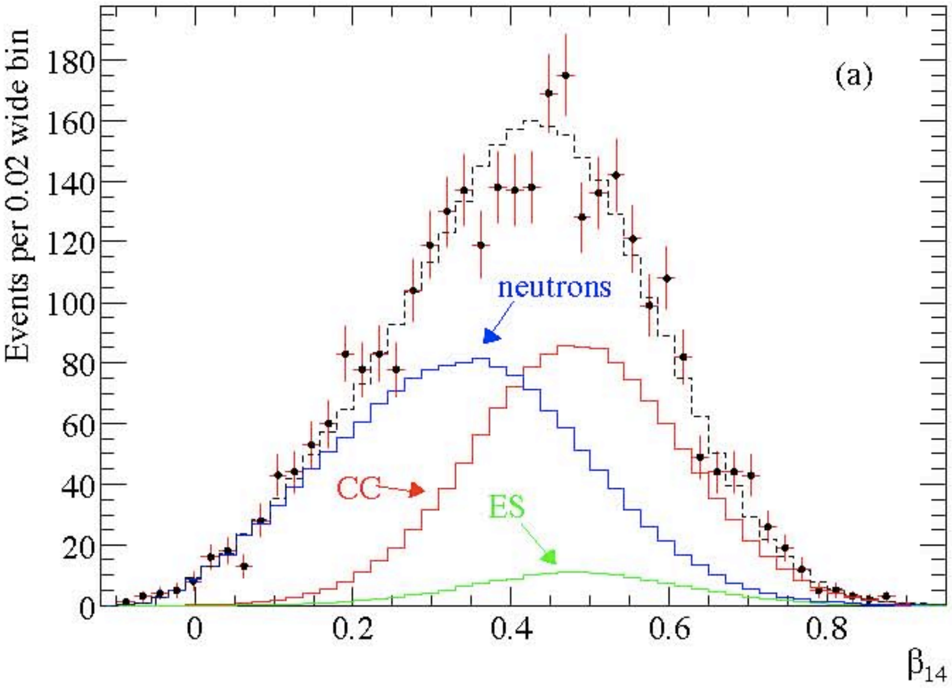



# *Wrong Neutrinos*

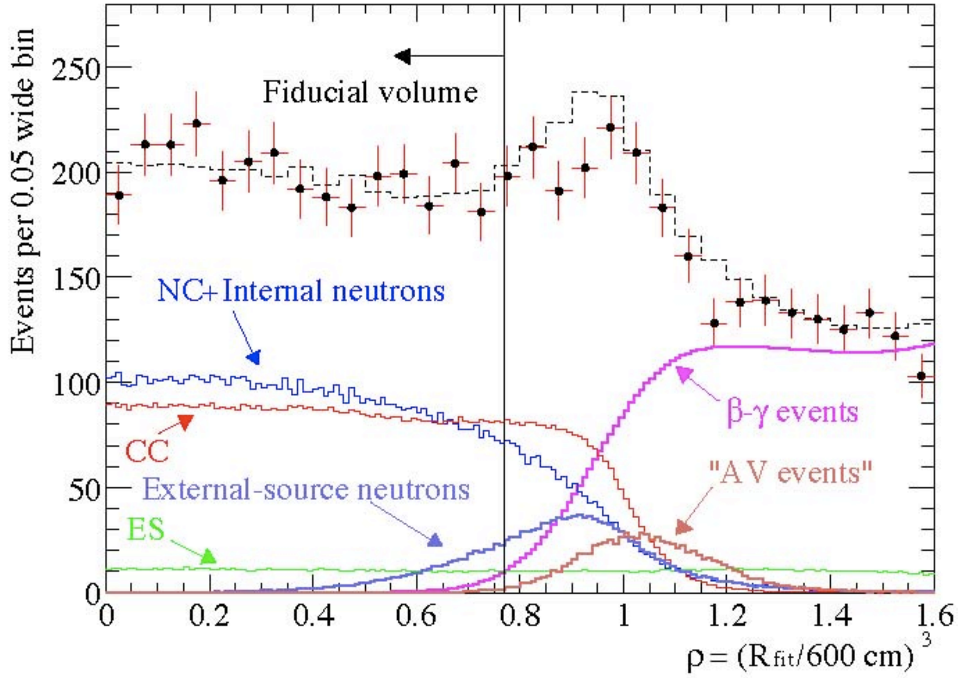
- Only $\nu_e$ produced in the Sun
- Wrong Neutrinos $\nu_{\mu,\tau}$ are coming from the Sun!
- Somehow some of $\nu_e$ were converted to $\nu_{\mu,\tau}$ on their way from the Sun's core to the detector

$\Rightarrow$ neutrino oscillation!

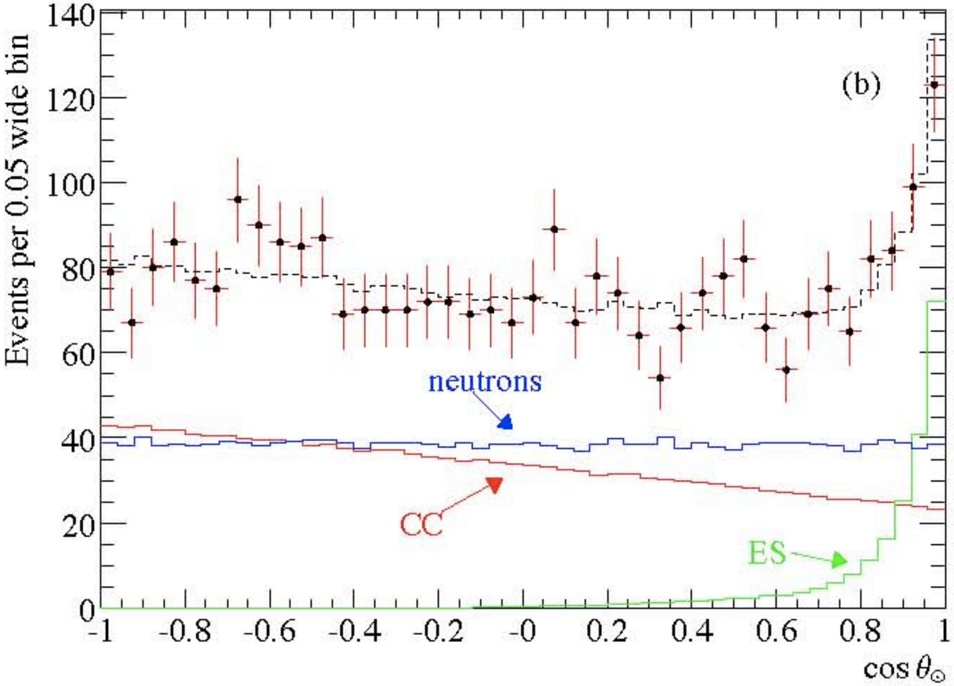




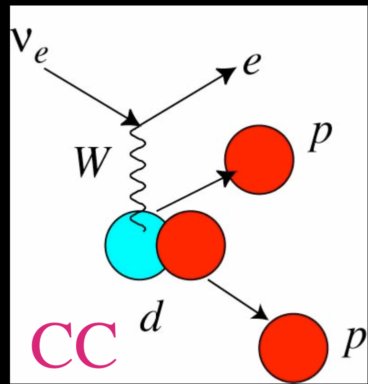
(a)
Events per 0.02 wide bin
neutrons
CC
ES
$\beta_{14}$
0 20 40 60 80 100 120 140 160 180
0 0.2 0.4 0.6 0.8

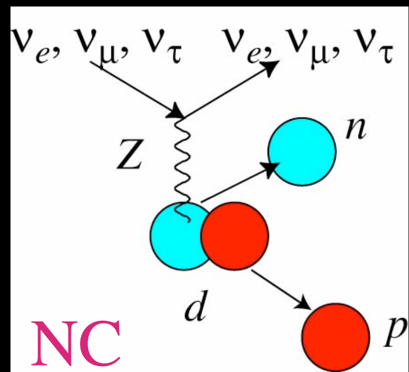
Events per 0.05 wide bin
Fiducial volume
NC+Internal neutrons
CC
External-source neutrons
ES
β-γ events
"AV events"
$\rho = (R_{fit}/600\ cm)^3$
0 50 100 150 200 250
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

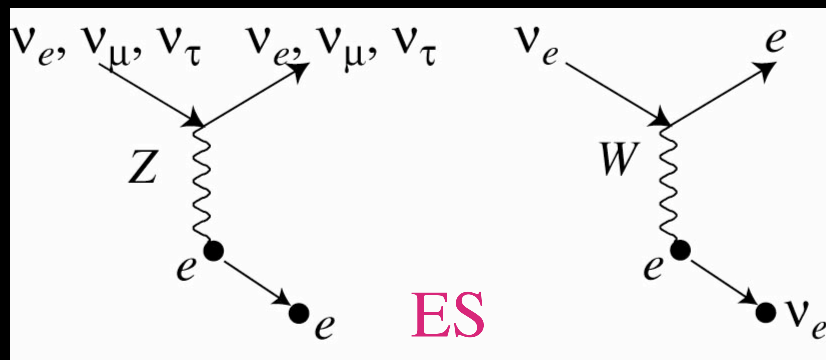
(b)
Events per 0.05 wide bin
neutrons
CC
ES
$\cos\theta_\odot$
0 20 40 60 80 100 120 140
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1

$\nu_e$
$e$
W
$p$
$d$
$p$
CC

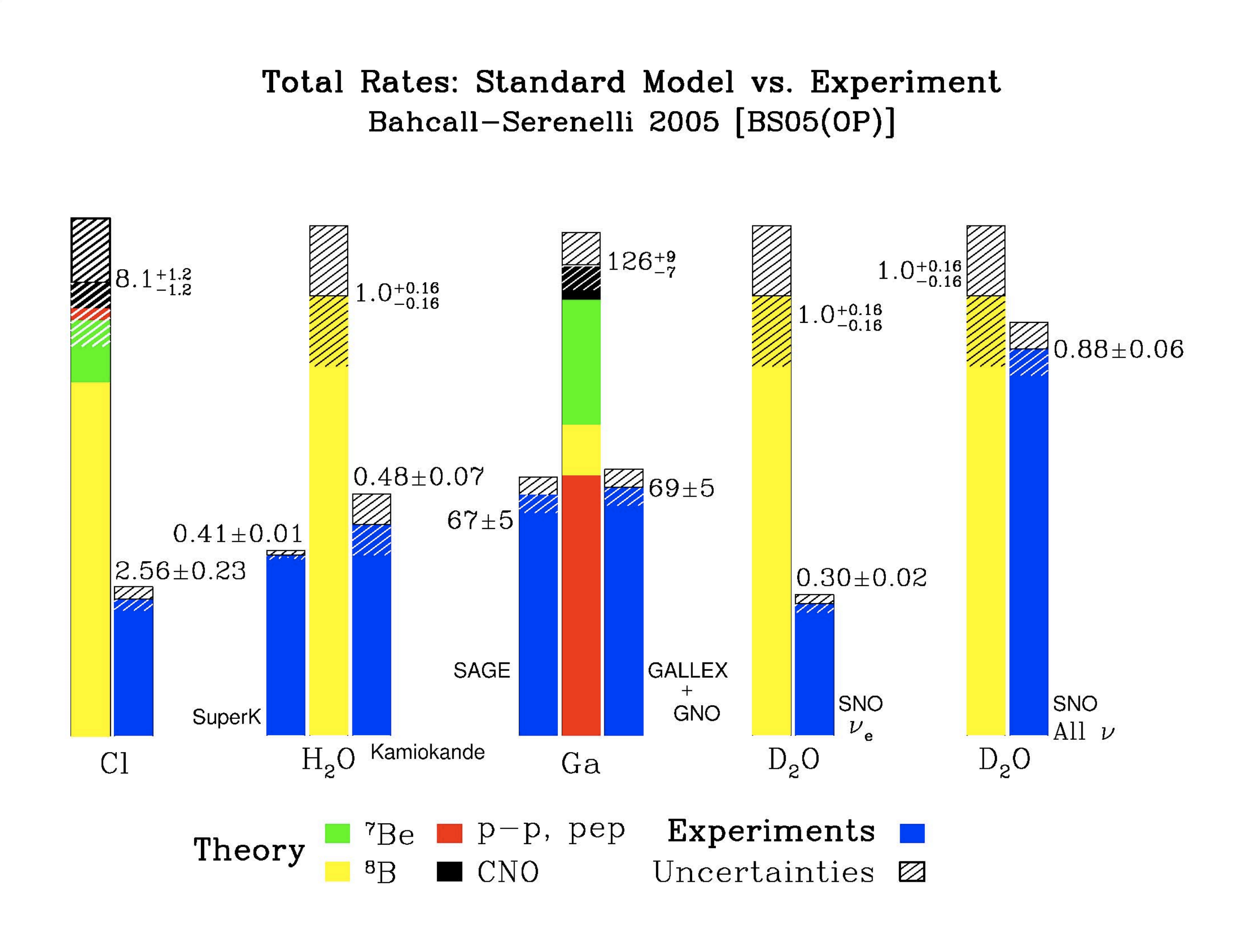
$\nu_e, \nu_\mu, \nu_\tau$
$\nu_e, \nu_\mu, \nu_\tau$
Z
$n$
$d$
$p$
NC

$\nu_e, \nu_\mu, \nu_\tau$
$\nu_e, \nu_\mu, \nu_\tau$
Z
$e$
$e$
$\nu_e$
$e$
W
$e$
$\nu_e$
ES


600

# We don't get enough



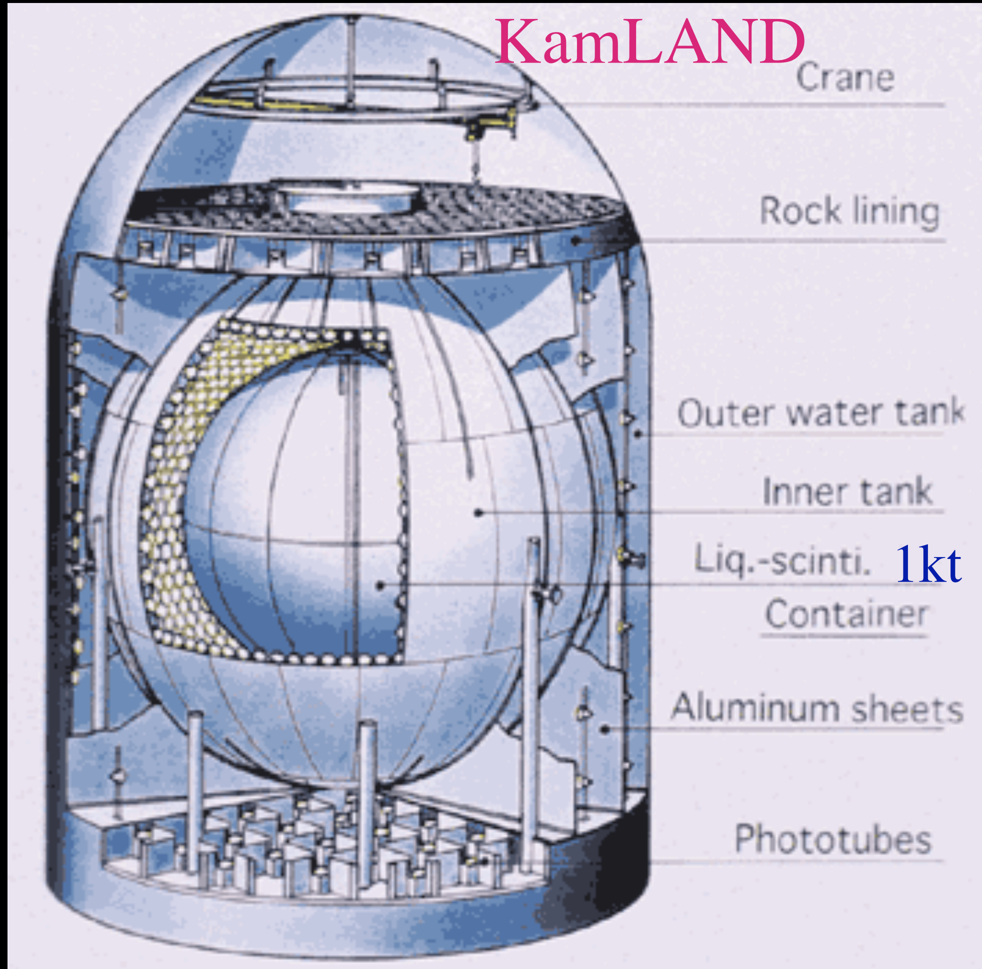

- Neutrino oscillation?
- Something wrong with our understanding of the Sun?

# *Terrestrial "Solar Neutrino"*

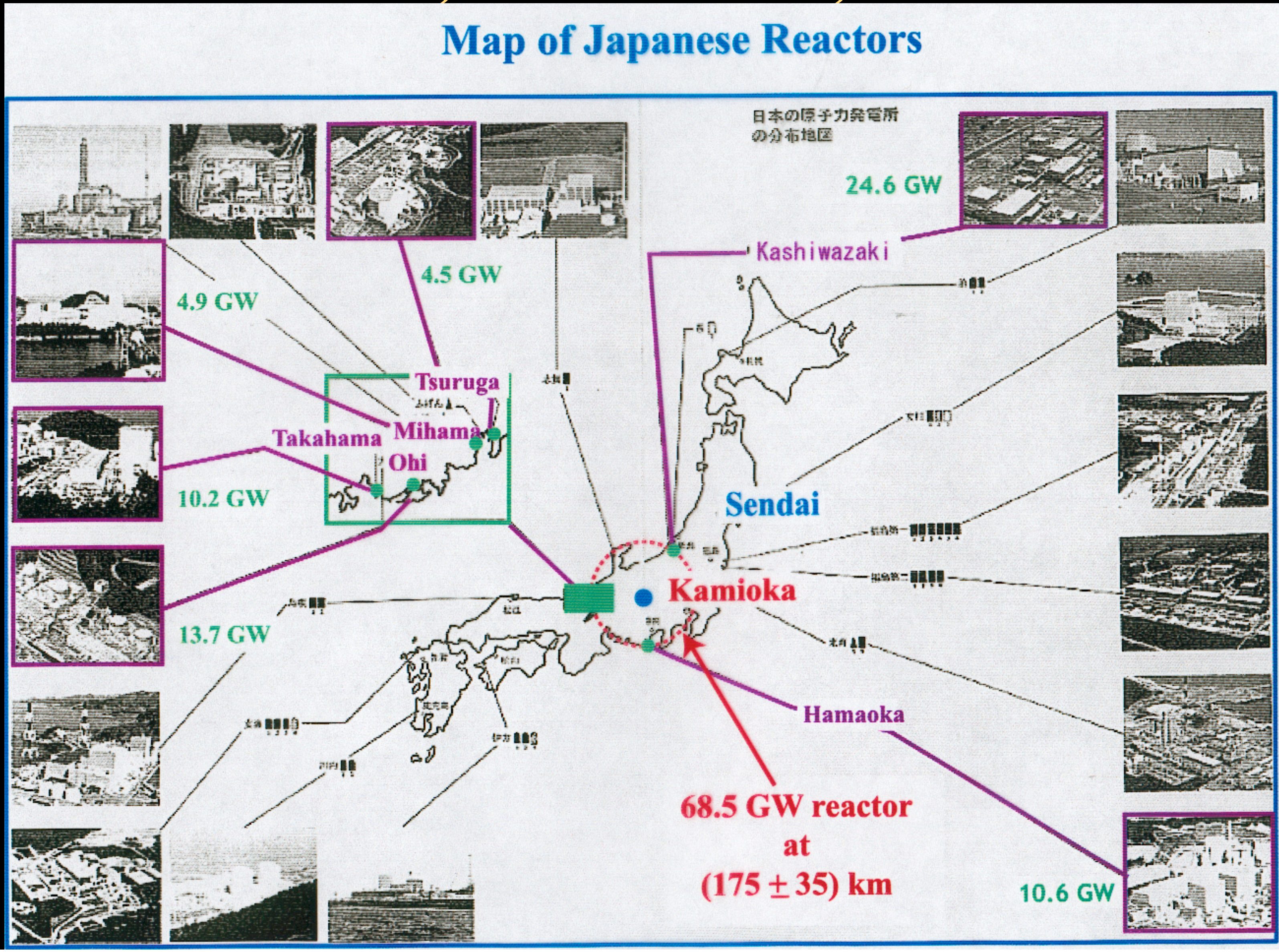
- Can we convincingly verify oscillation with man-made neutrinos?

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

- Hard for low $\Delta m^2$
- To probe LMA, need L~100km, 1kt
- Need low $E_\nu$, high $\Phi_\nu$
- Use neutrinos from nuclear reactors

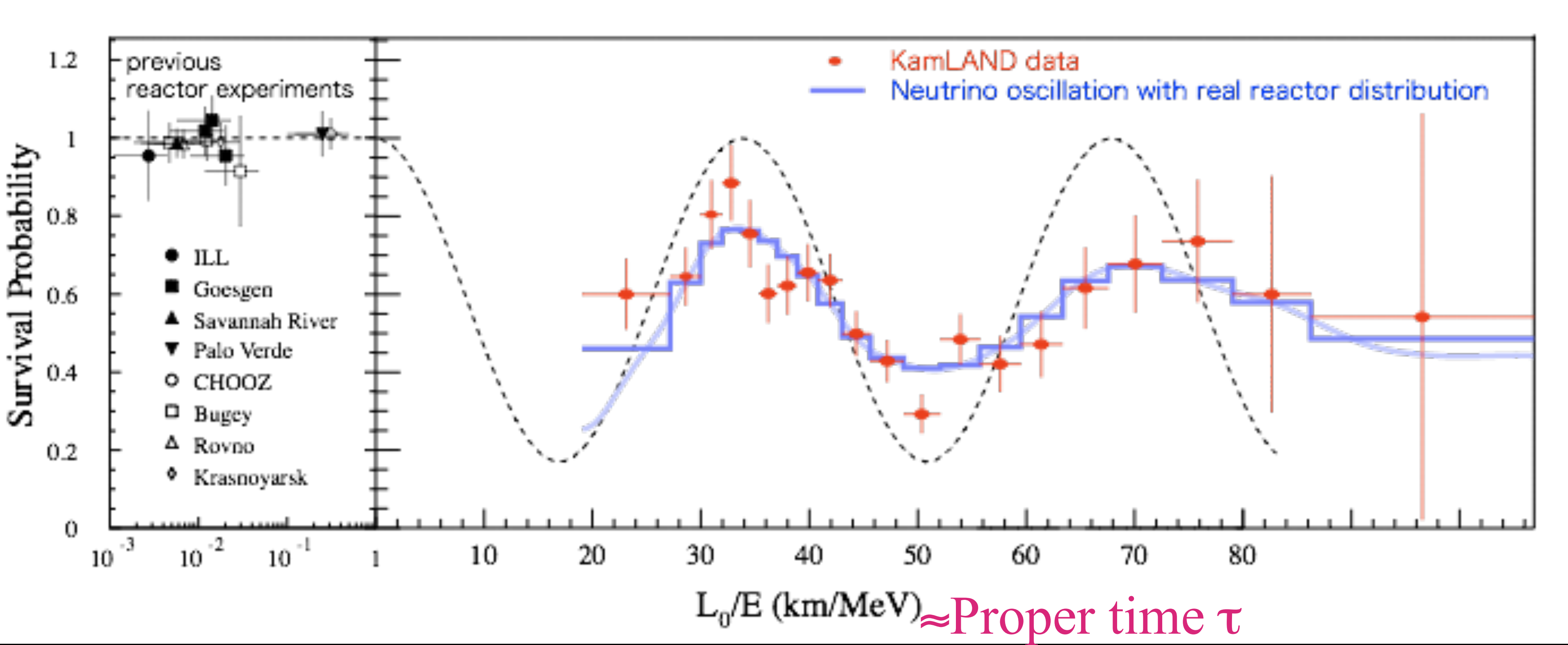


# Location, Location, Location



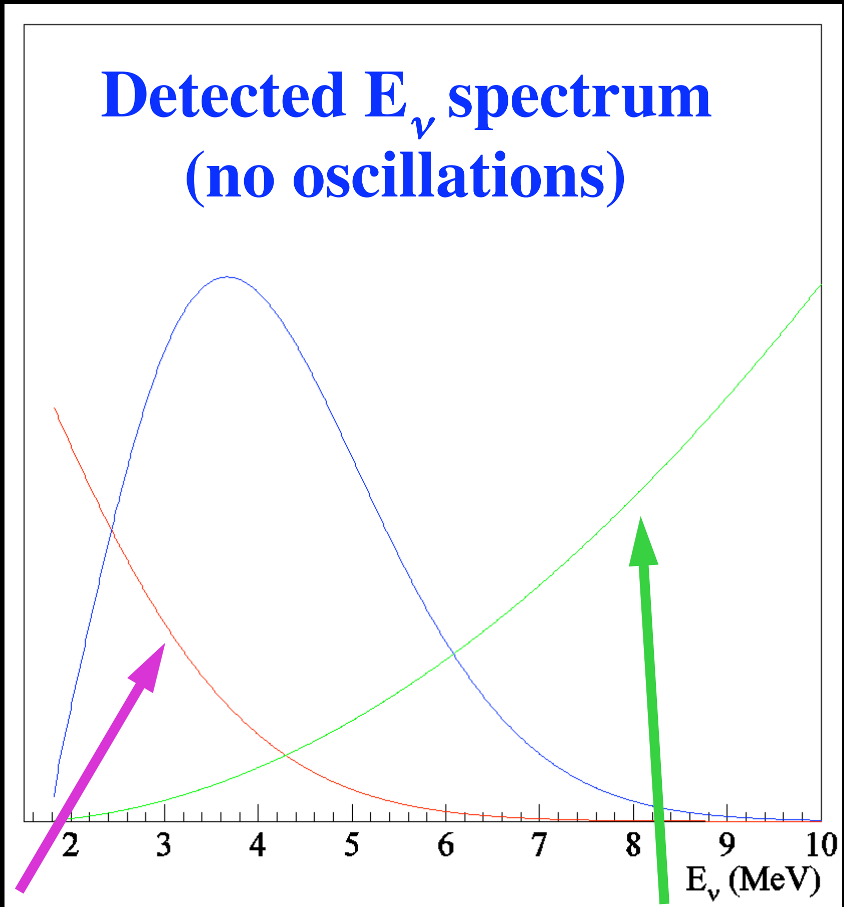
# KamLAND 2008

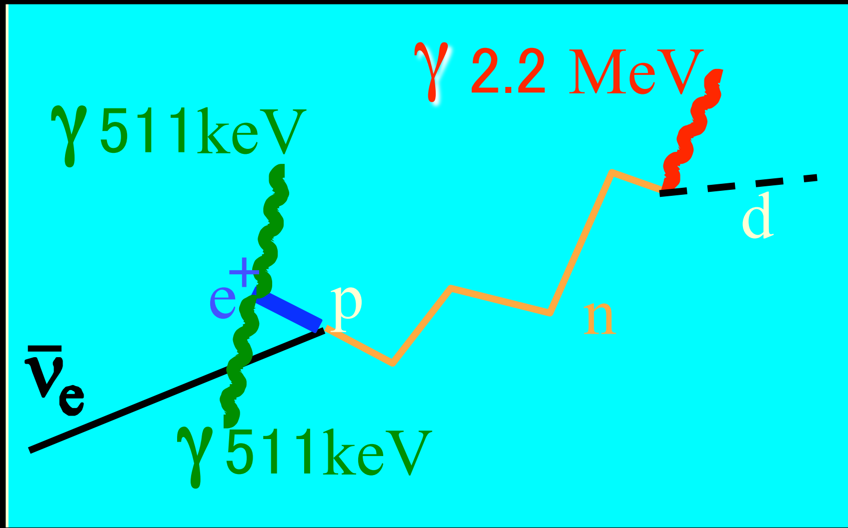
# Reactor neutrinos do oscillate!




$L_0$=180 km

# *Detection Principle*




Coincidence signal: detect

Prompt

Delayed

Reactor $\nu_e$ spectrum

Cross section for $\nu_e + p \rightarrow e^+ + n$

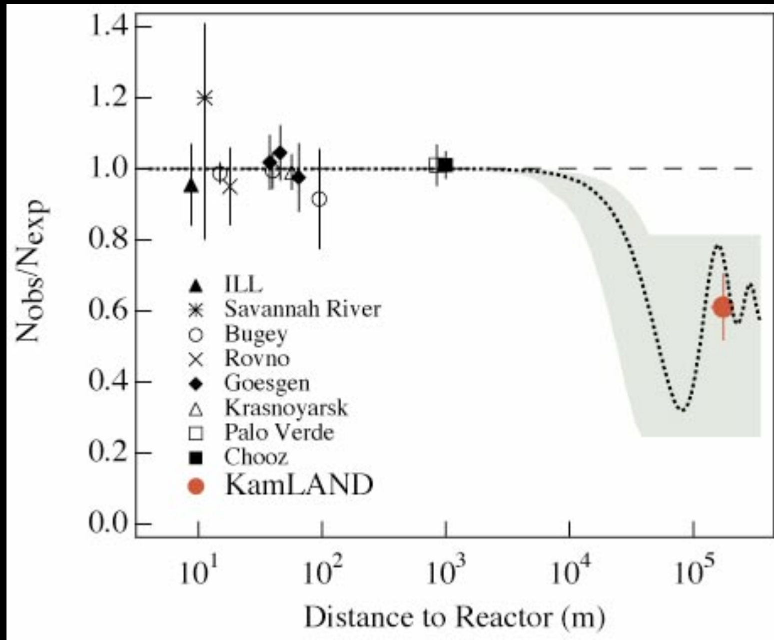
180 $\mu$s capture time

# *KamLAND result*

- First terrestrial expt relevant to solar neutrino problem

*Dec 2002*

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




No oscillation hypothesis
Excluded at 99.95%

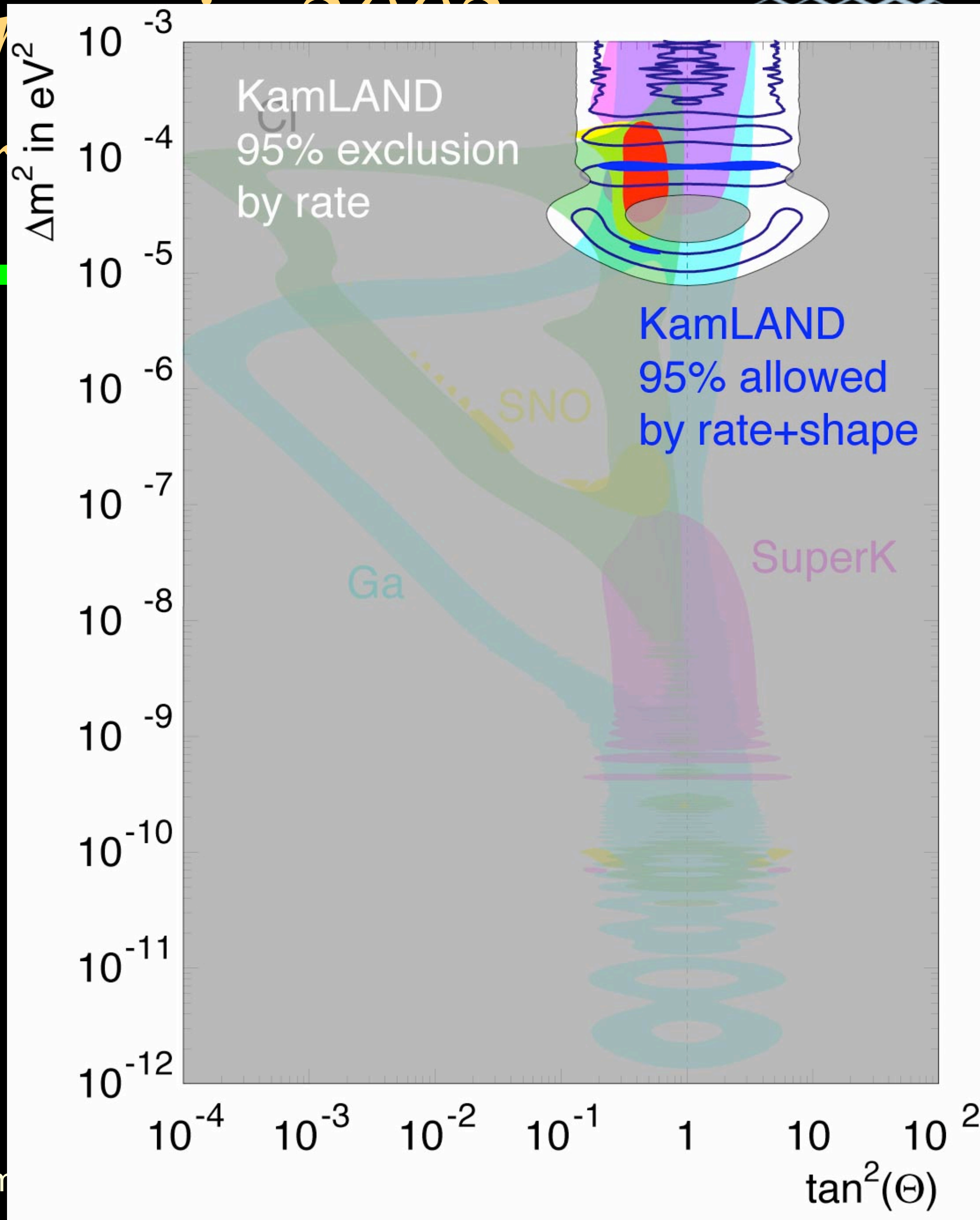
# Progr
# on the Solar

March 2002

April 2002
with SNO

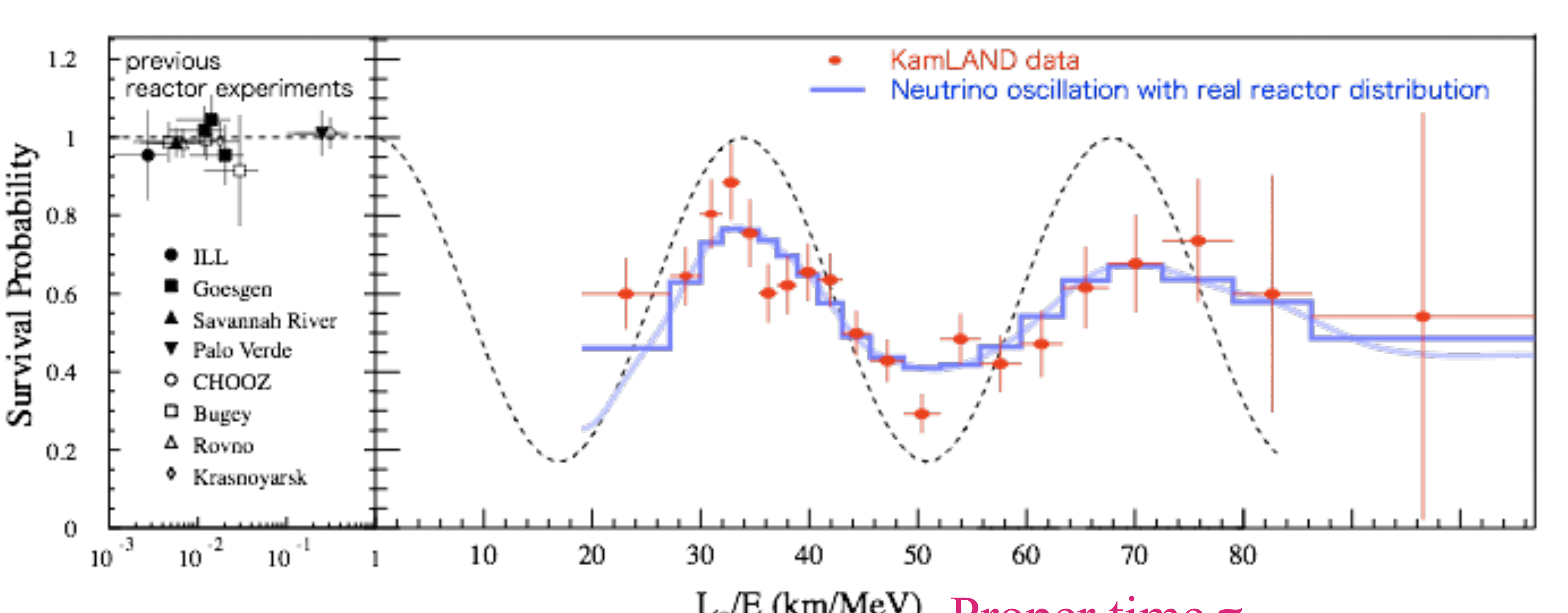
Dec 2002
with KamLAND

June 2004
with KamLAND



# KamLAND 2008

# Reactor neutrinos do oscillate!




≈Proper time τ

$L_0$=180 km

# *No other solution than oscillation*

- Neutrino decay
  – Wrong energy dependence
- Spin-resonant flip
  – Relies on a large solar magnetic field
- New flavor-changing neutral current
  – Relies on a high solar matter density
- Violation of the equivalence principle
  – Relies on the strong solar gravitational potential

# *Two-Neutrino Oscillation*

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

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

- No longer 100% $\nu_\mu$, partly $\nu_\tau$!
- "Survival probability" for $\nu_\mu$ after $t$

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

Usually plotted on ($\Delta m^2$, $\sin^2 2\theta$)

# *Dark Side of Neutrino Oscillation*

- Traditional parameterization of neutrino oscillation in terms of $(\Delta m^2, \sin^2 2\theta)$ covers only a *half* of the parameter space
  (de Gouvêa, Friedland, HM)
- Convention: $\nu_2$ heavier than $\nu_1$
  – Vary $\theta$ from 0˚ to 90˚
  – $\sin^2 2\theta$ covers 0˚ to 45˚
  – Light side (0 to 45˚) and Dark Side (45˚ to 90˚ )

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

# *Dark Side of Neutrino Oscillation*

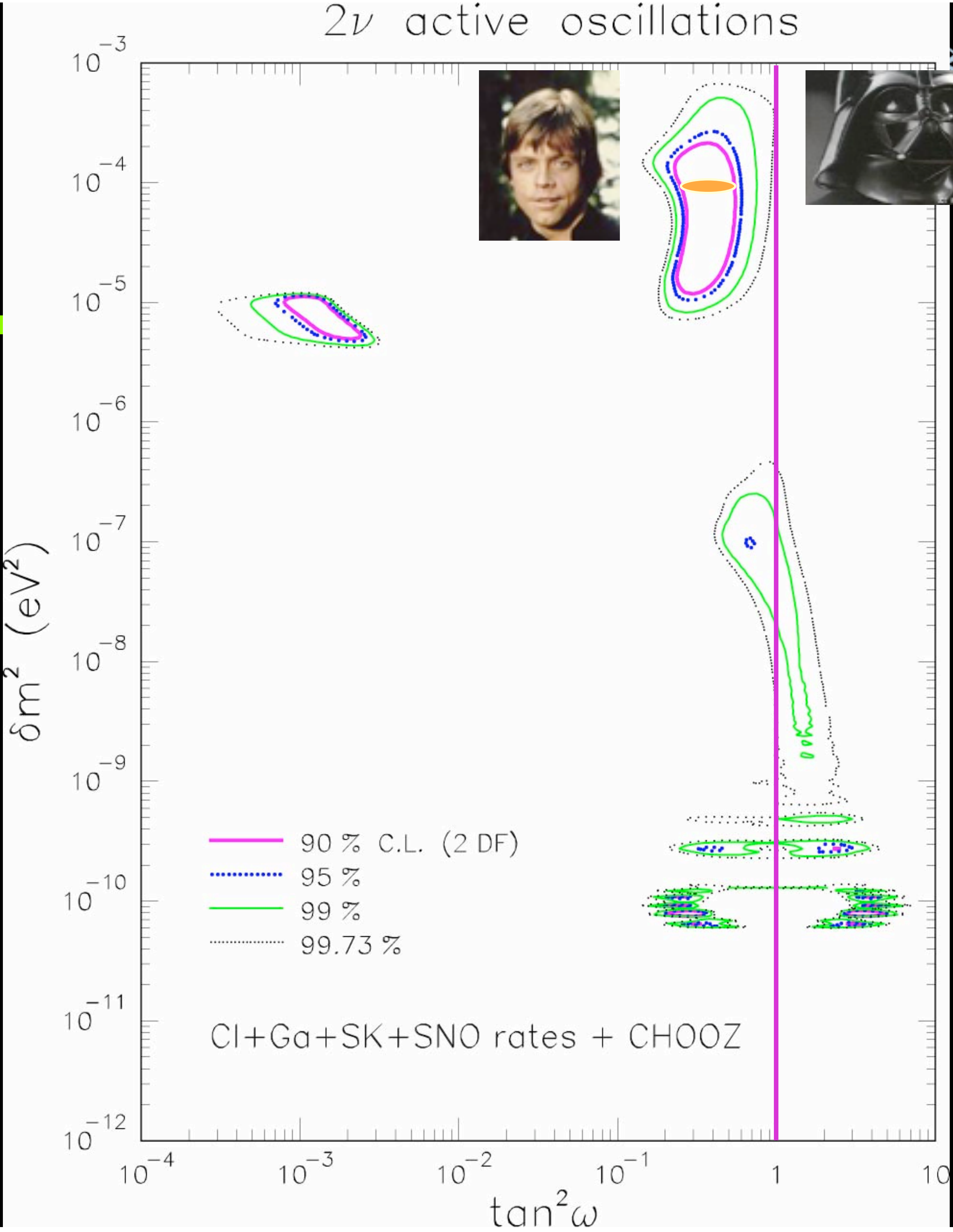
- To cover the whole parameter space, can't use ($\Delta m^2$, $\sin^2 2\theta$) but ($\Delta m^2$, $\tan^2\theta$) instead.

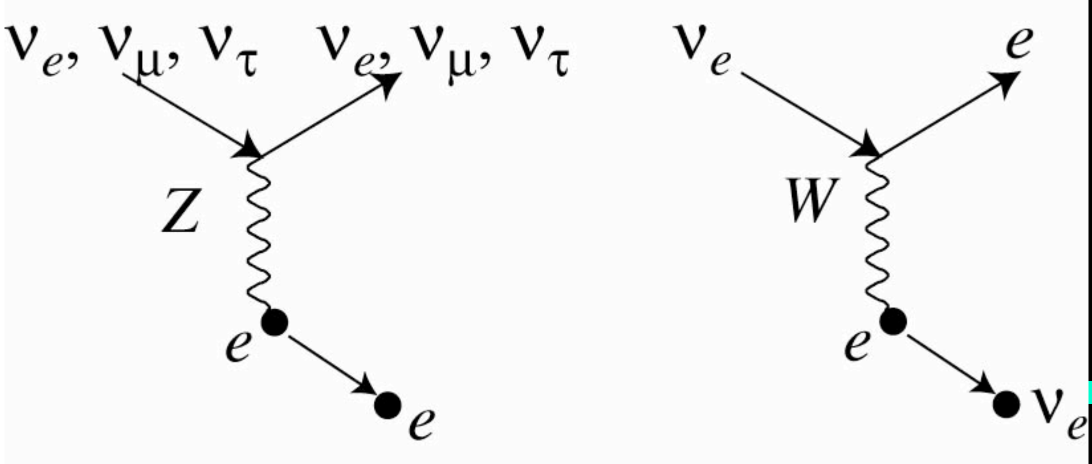
  (Fogli, Lisi, Montanino; de Gouvêa, Friedland, HM)
- In vacuum, oscillation probability depends only on $\sin^2 2\theta$, *i.e.*, invariant under $\theta \leftrightarrow 90° - \theta$
- Seen as a reflection symmetry on the log scale $\tan^2\theta \leftrightarrow \cot^2\theta$
- Or use $\sin^2\theta$ on the linear scale $\sin^2\theta \leftrightarrow \cos^2\theta$

Fit to the rates of solar neutrino events from all experiments (Fogli et al)

How do we understand this Plot?

Focus on the final answer



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# *Matter Effect*

- CC interaction in the presence of non-relativistic electron

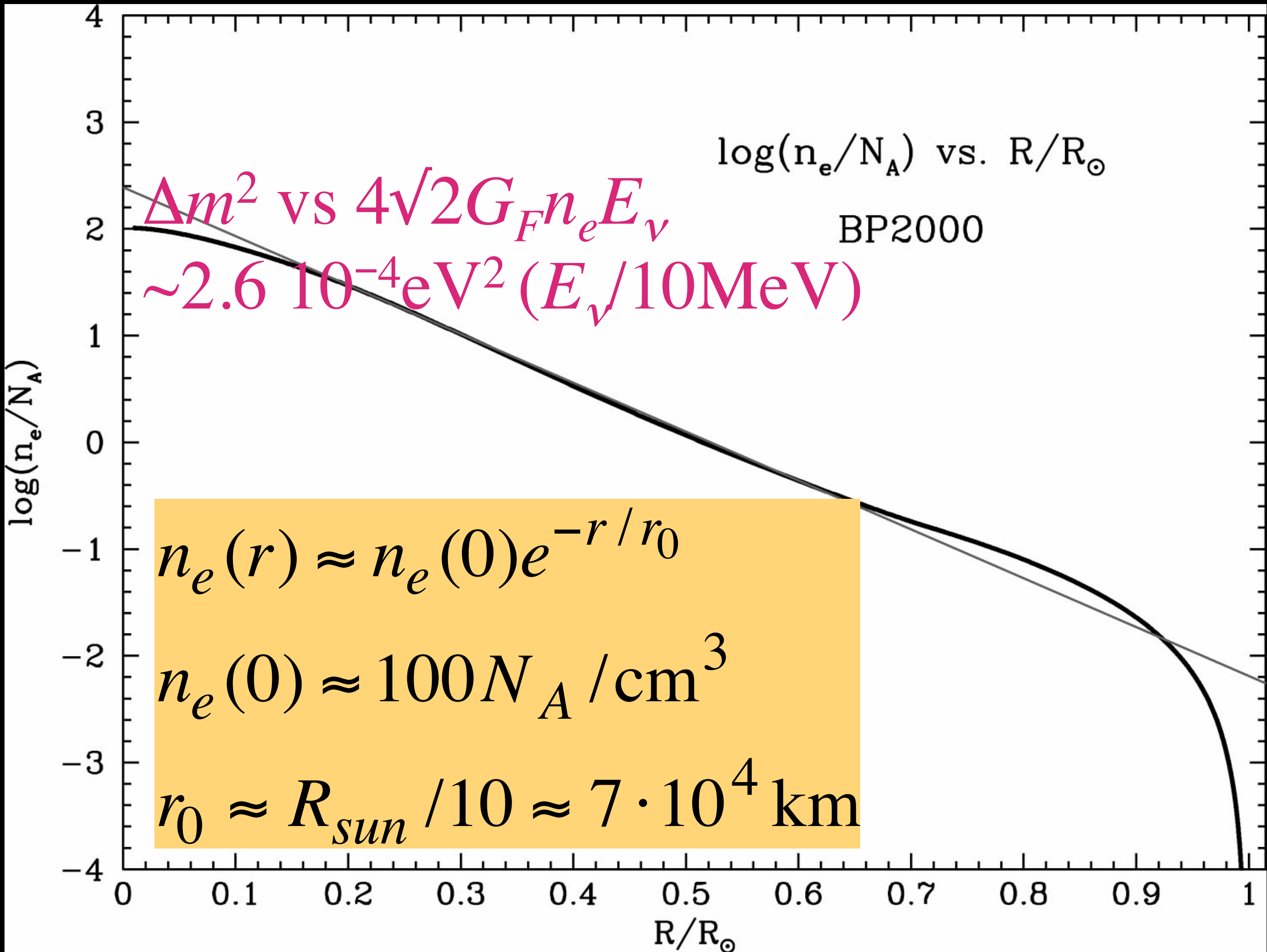
$$L = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu (1-\gamma_5)\nu_e \bar{\nu}_e \gamma^\mu (1-\gamma_5) e$$
$$= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu (1-\gamma_5) e \bar{\nu}_e \gamma^\mu (1-\gamma_5)\nu_e$$
$$= -\sqrt{2} G_F n_e \bar{\nu}_e \gamma^0 \nu_e$$

- Neutrino Hamiltonian

$$H = \text{common} + \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Electron neutrino higher energy in the Sun

# *Electron Number Density*




$\Delta m^2$ vs $4\sqrt{2} G_F n_e E_\nu$
$\sim 2.6\ 10^{-4}\mathrm{eV}^2\,(E_\nu/10\mathrm{MeV})$

$$n_e(r) \approx n_e(0) e^{-r/r_0}$$

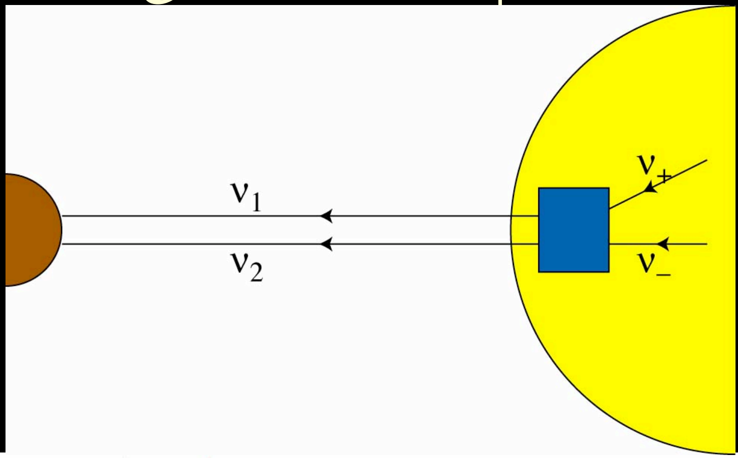
$$n_e(0) \approx 100 N_A/\mathrm{cm}^3$$

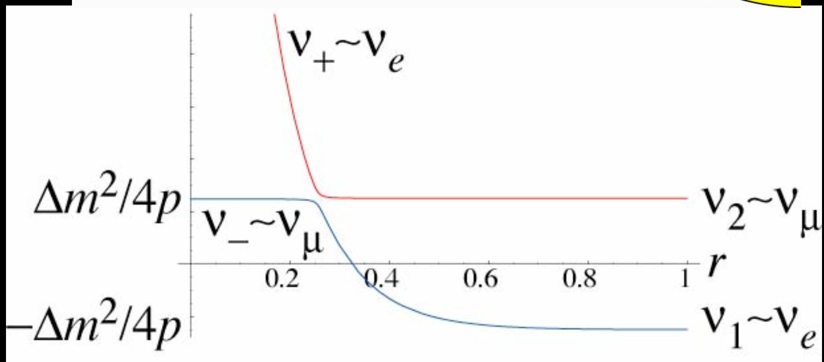
$$r_0 \approx R_{sun}/10 \approx 7\cdot 10^4\ \mathrm{km}$$

Nearly exponential for most of the Sun's interior $\Rightarrow$ oscillation probability can be solved analytically with Whittaker function

# *Adiabatic*

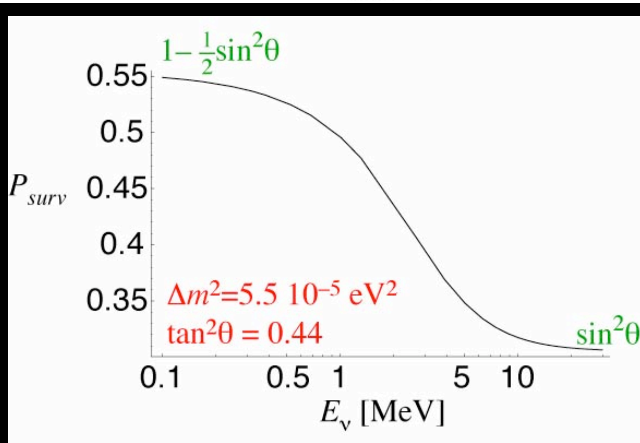
- Use "instantaneous" eigenstates $\nu_+$ and $\nu_-$




- For the LMA region, the dynamics is adiabatic: there is no hopping between states

$$P_{\rm surv} = \cos^2\theta\cos^2\theta_m + \sin^2\theta\sin^2\theta_m$$



# *Loose Ends*

- Energy dependence in the solar neutrino survival probability not fully demonstrated
  - $pp$, $^7$Be solar neutrino experiments
- Evidence for $\nu_\tau$ “appearance” in atmos $\nu$ still not strong enough (99%CL)
  - OPERA, ICARUS

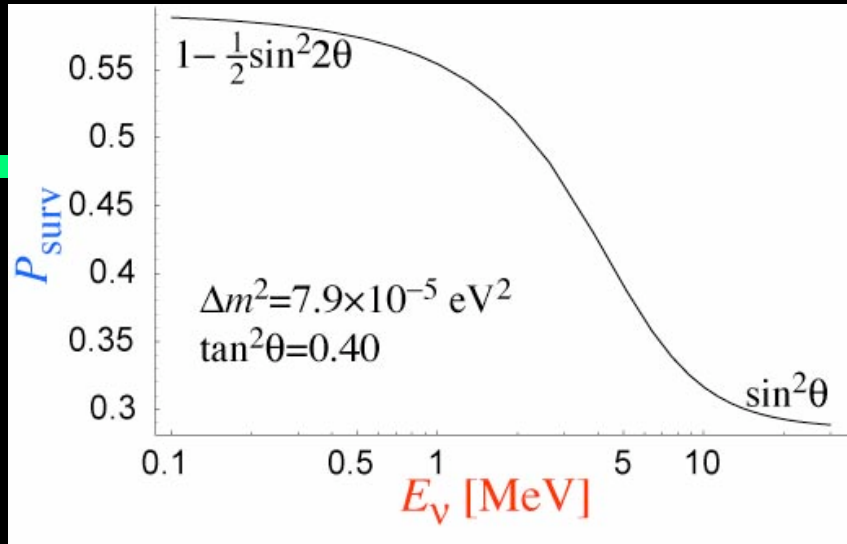
# *Low-Energy Solar Neutrinos*

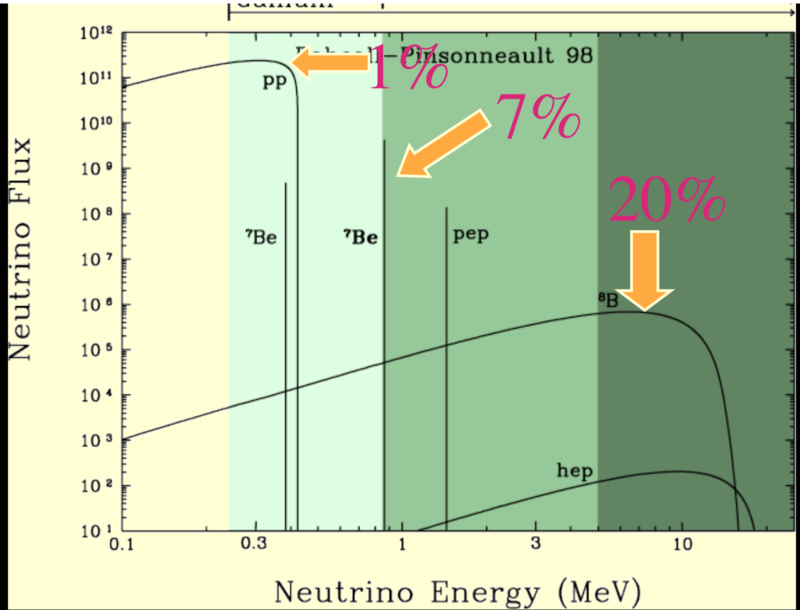
- Solar neutrino data suggest energy -dependent survival probability

  $\Rightarrow$ tests MSW effect

  $\Rightarrow \theta_{12}$

  $\Rightarrow$ Helps interpretation of CP violation, double beta decay data

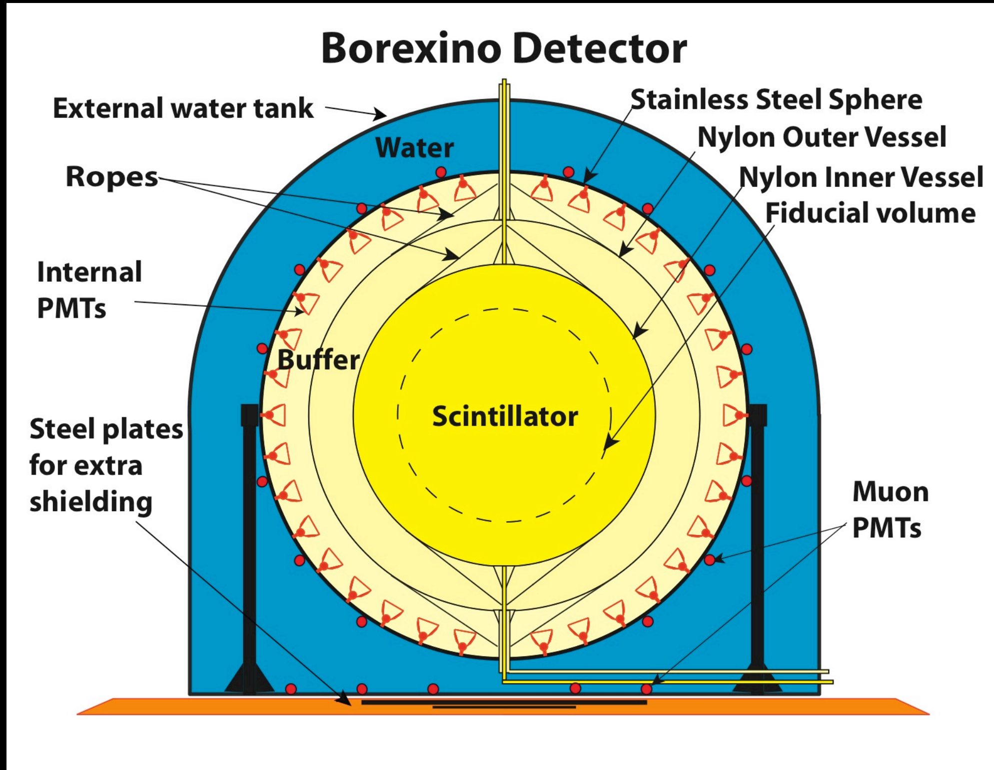


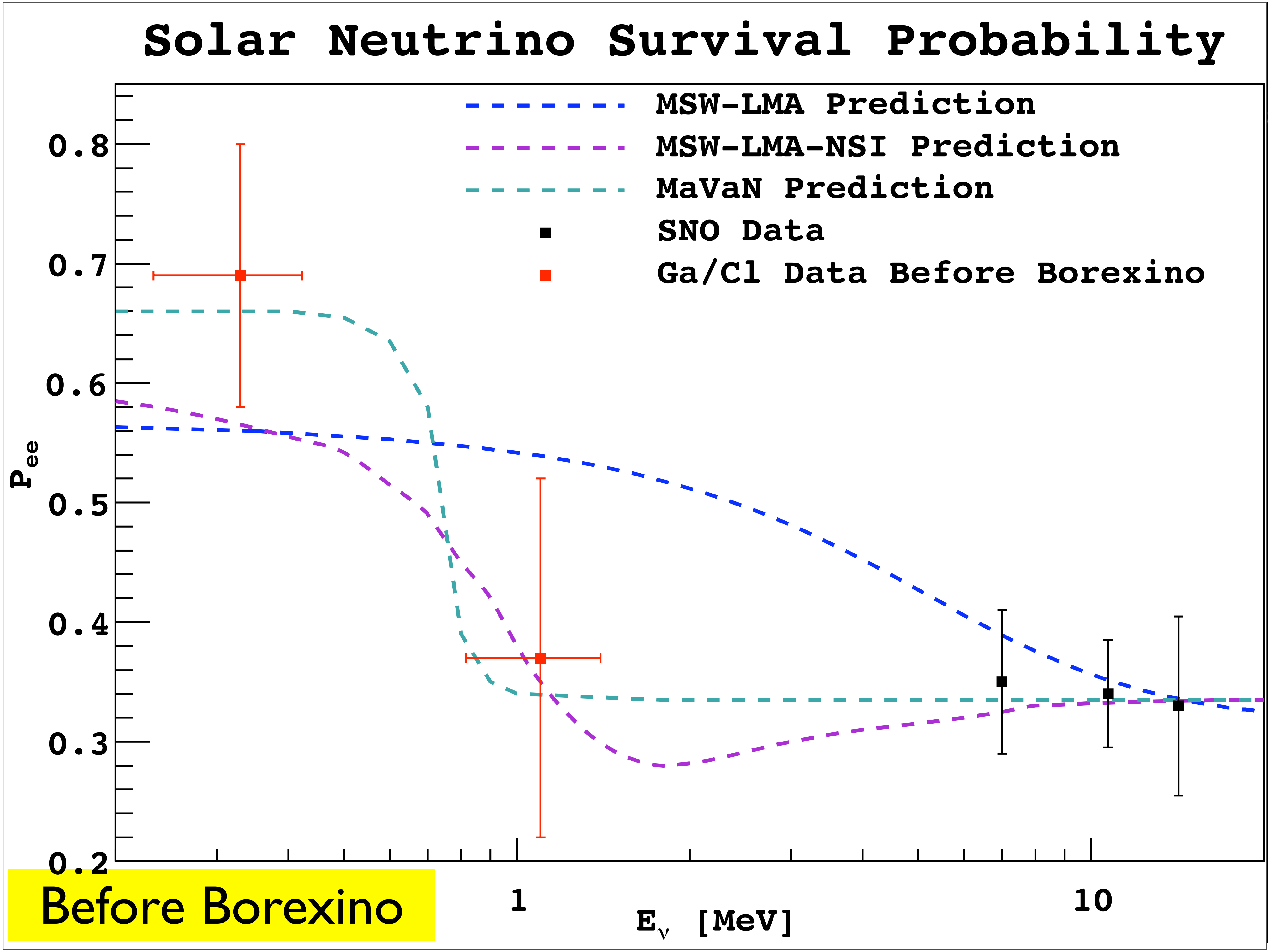



# *Transition from matter to vacuum*

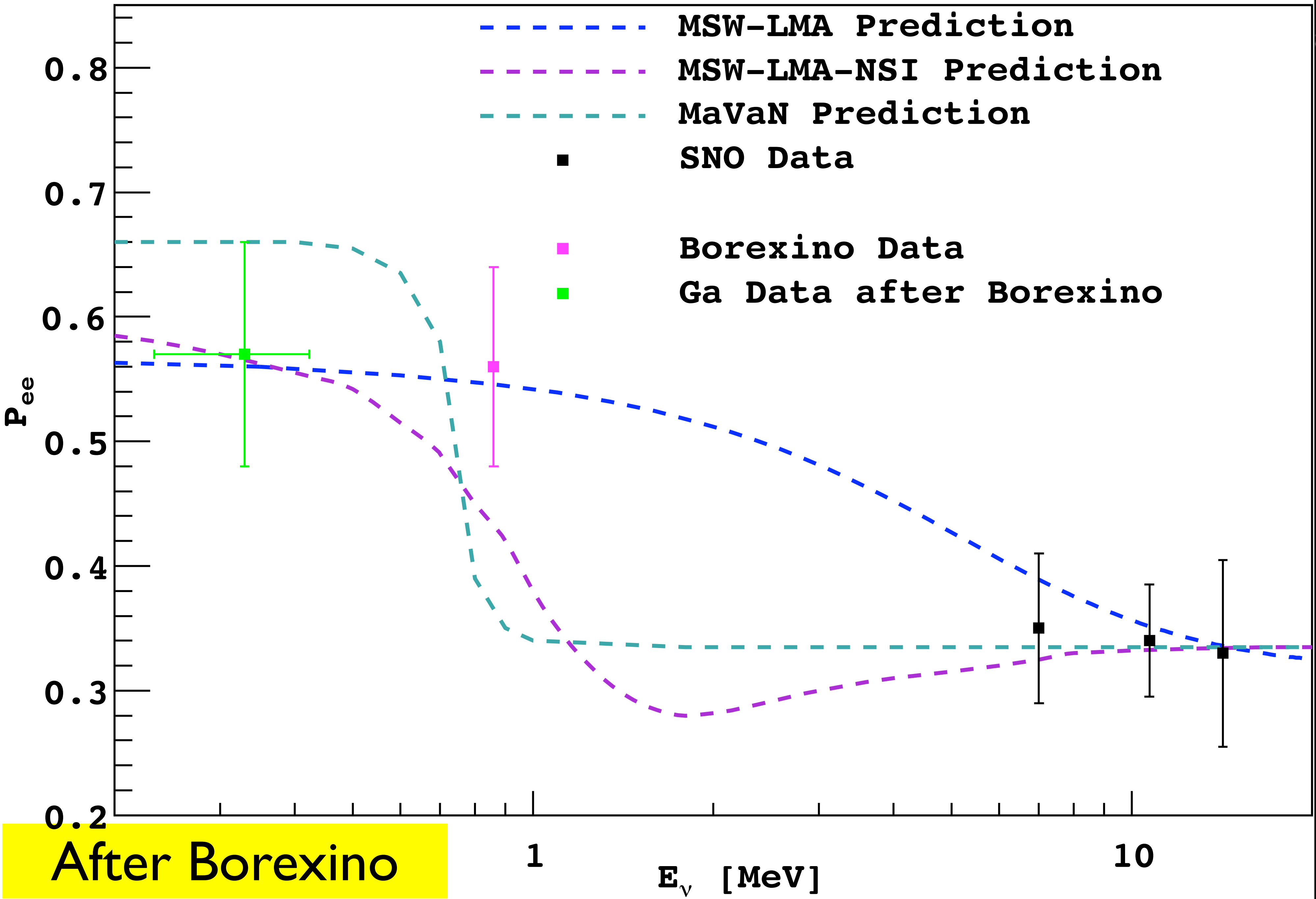
- Measuring low-energy (< MeV) solar neutrino flux is a *great* experimental challenge
- Low cross section
- Can't even make an electron
- Radioactivity background is *huge!*
- Need U, Th < $10^{-16}$g/g
- Can't clean water to that level
- But oil? (liquid scintillator)
- Elastic scattering $\nu_e e \rightarrow \nu_e e$
- Good light yield: ~11K photons/MeV
- Achieved 500 p.e./MeV

- Borexino
- organic liquid scintillator




Solar Neutrino Survival Probability
MSW-LMA Prediction
MSW-LMA-NSI Prediction
MaVaN Prediction
SNO Data
Ga/Cl Data Before Borexino
$P_{ee}$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
10
$E_\nu$ [MeV]
Before Borexino

# Solar Neutrino Survival Probability



# Massive Neutrinos and Structure Formation

# *Neutrino Dark Matter?*

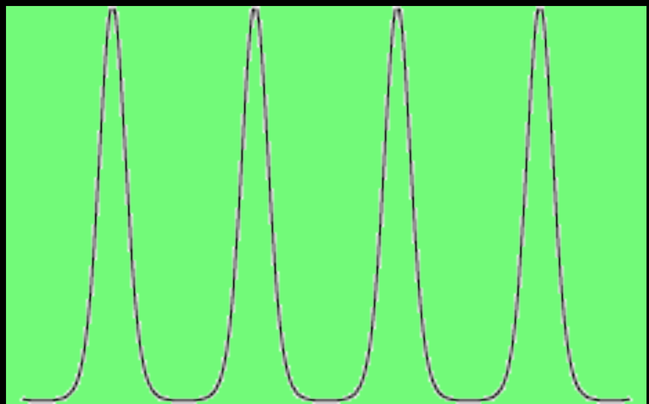
- Now that we seem to know neutrinos are massive, can't they be dark matter?

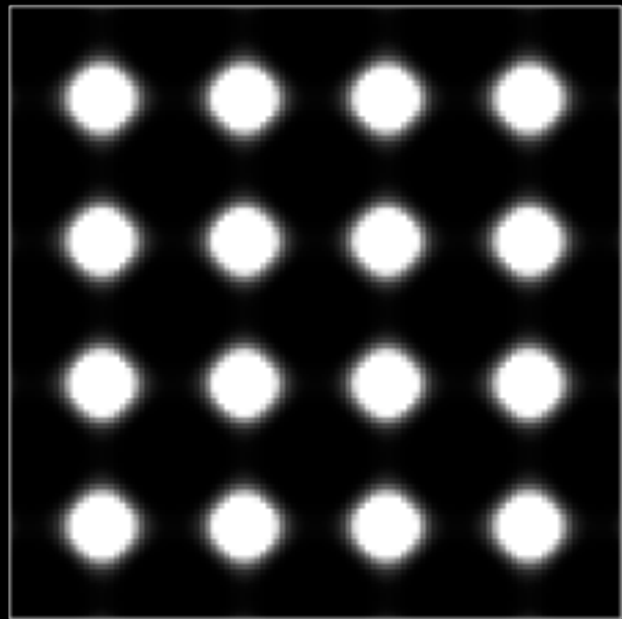
$$\boxed{\Omega_\nu h^2 = \frac{m_\nu}{97\text{eV}}}$$

- Problem: neutrinos don't clump!

# *Cold Dark Matter*

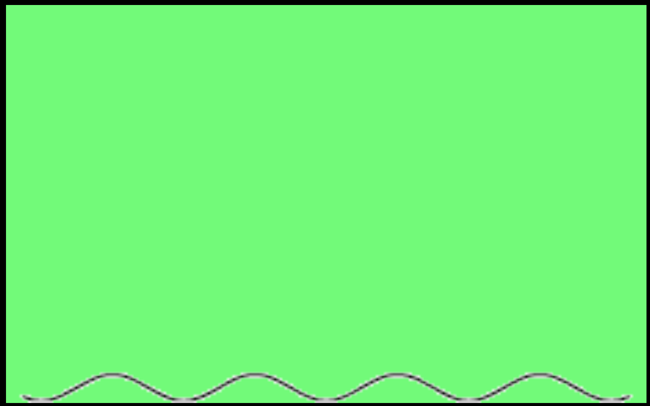
- Cold Dark Matter is not moving much
- Gets attracted by gravity

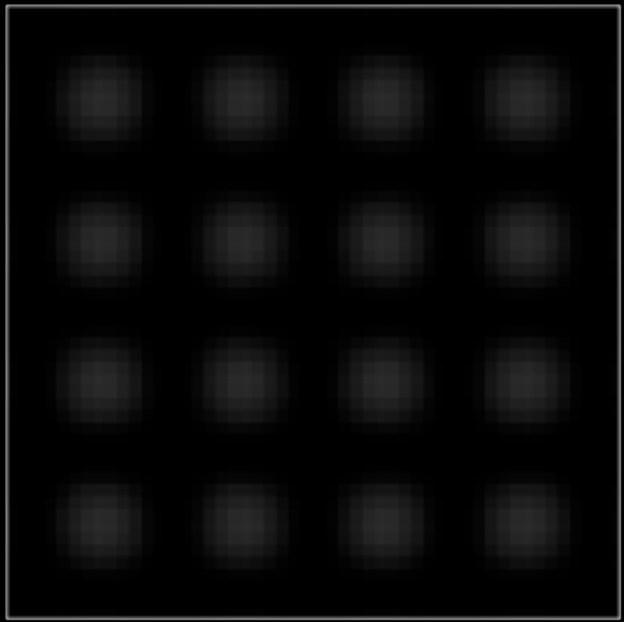




# *Neutrino Free Streaming*

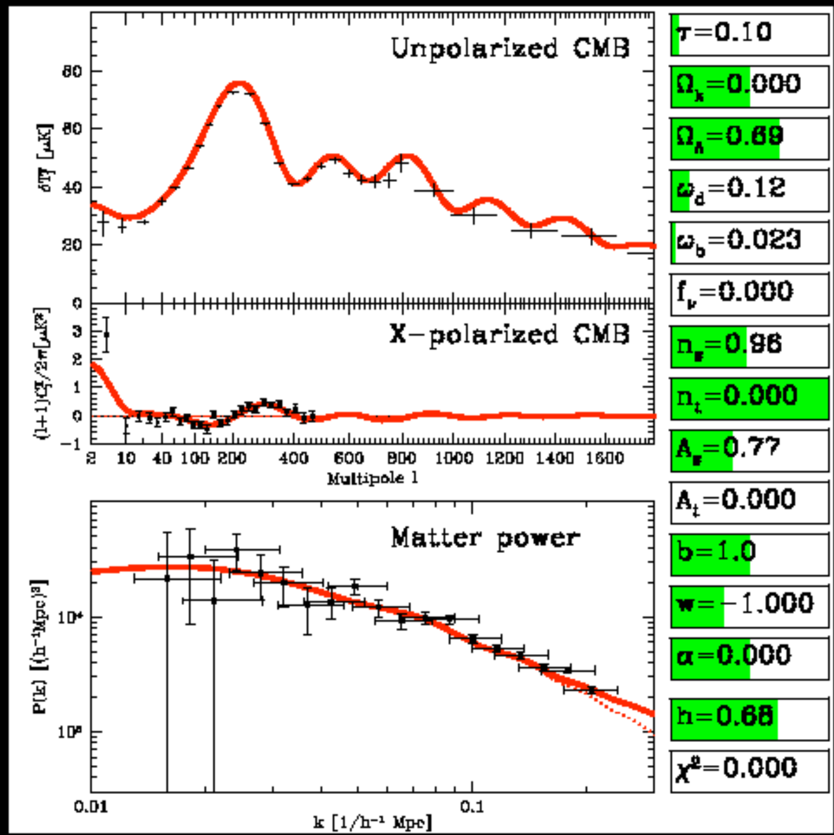
- Neutrinos, on the other hand, move fast and tend to wipe out the density contrast.





# *Small Scale Structure Suppressed*

- Because the neutrino free streaming wipes out density fluctuation, structure is suppressed at small distance scales



# *Limits*

- Depends on the details of the analysis
- Use Lyman alpha?
- Allow for scale -dependent bias?
- *e.g.*, M. Tegmark et al, astro-ph/0608632 using Luminous Red Galaxies $m_\nu$<0.3eV