Physics from the Never-Setting* Neutrino Sun

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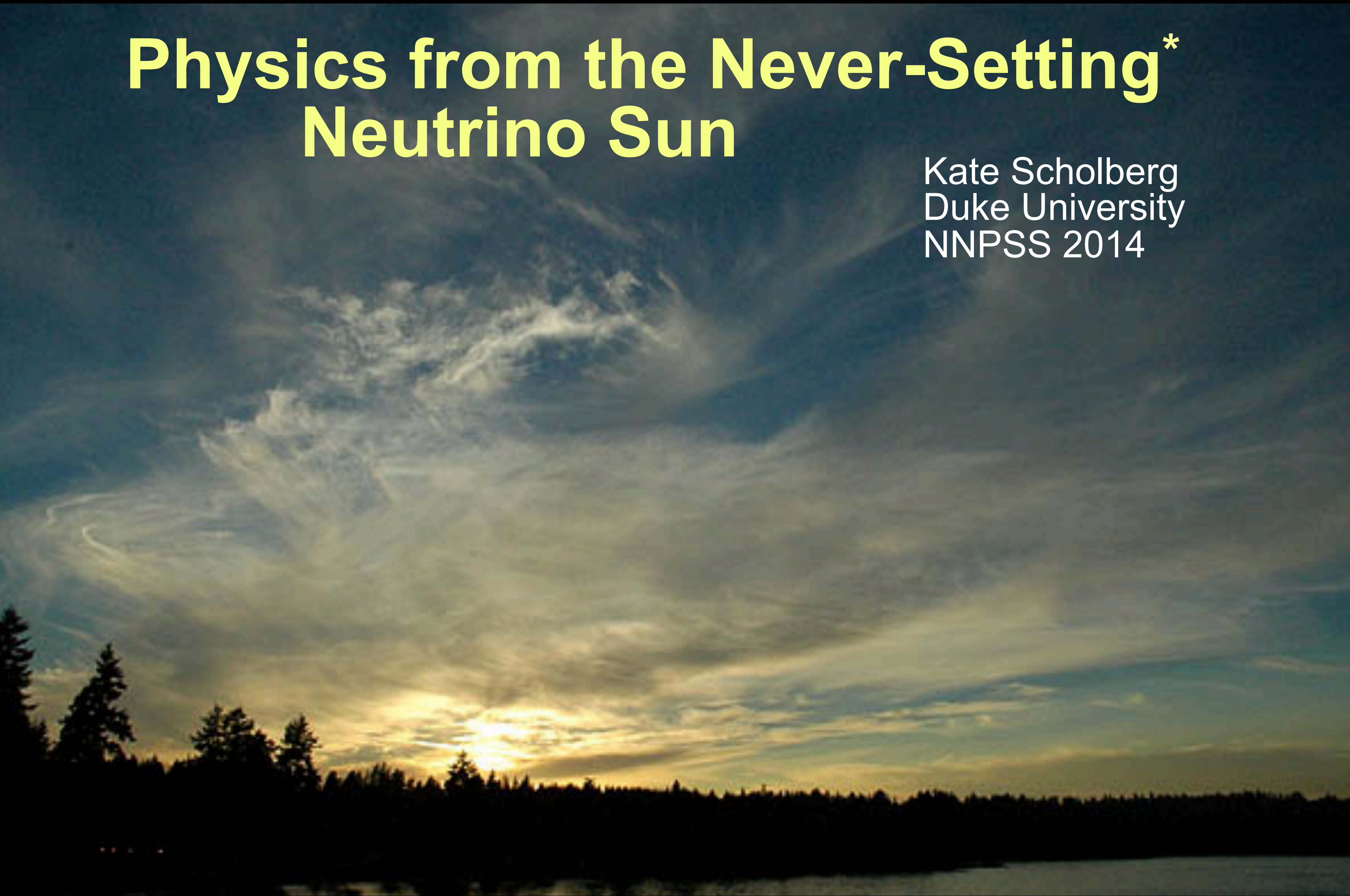
Duke University
NNPSS 2014



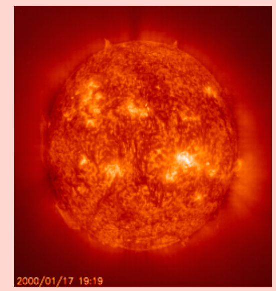
*or anti-setting?

Lecture Plan

Lecture #1: **Neutrino Mass and Oscillations**

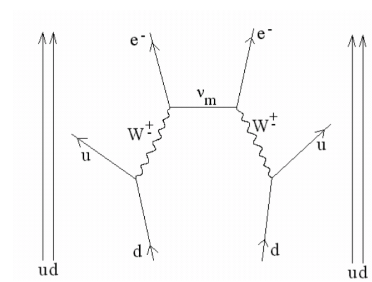
Lecture #2: **Solar Neutrinos**

and the rest of the oscillation story



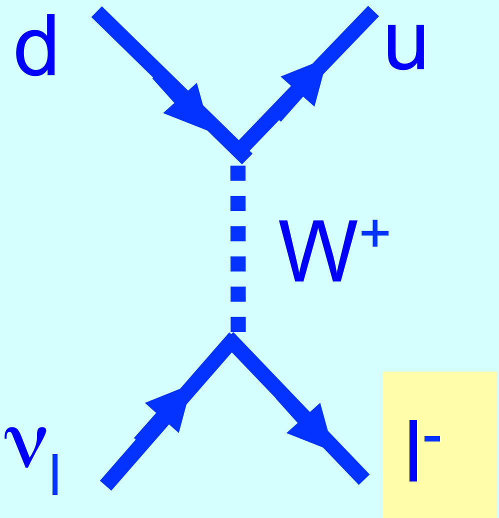
Lecture #3: **Supernova Neutrinos**

Lecture #4: **Absolute Mass and Neutrinoless Double Beta Decay**



Reminder: neutrino interactions with matter

Charged Current (CC)

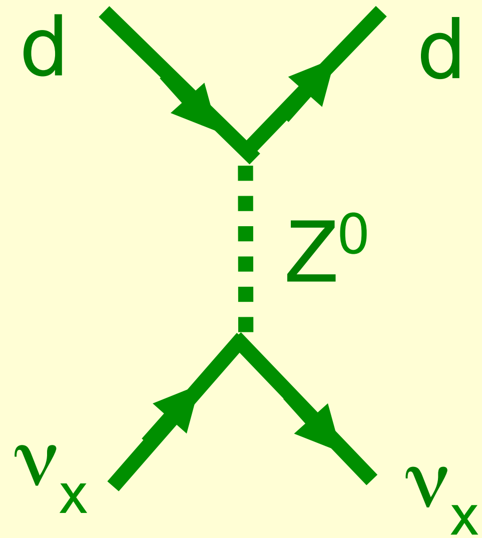


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

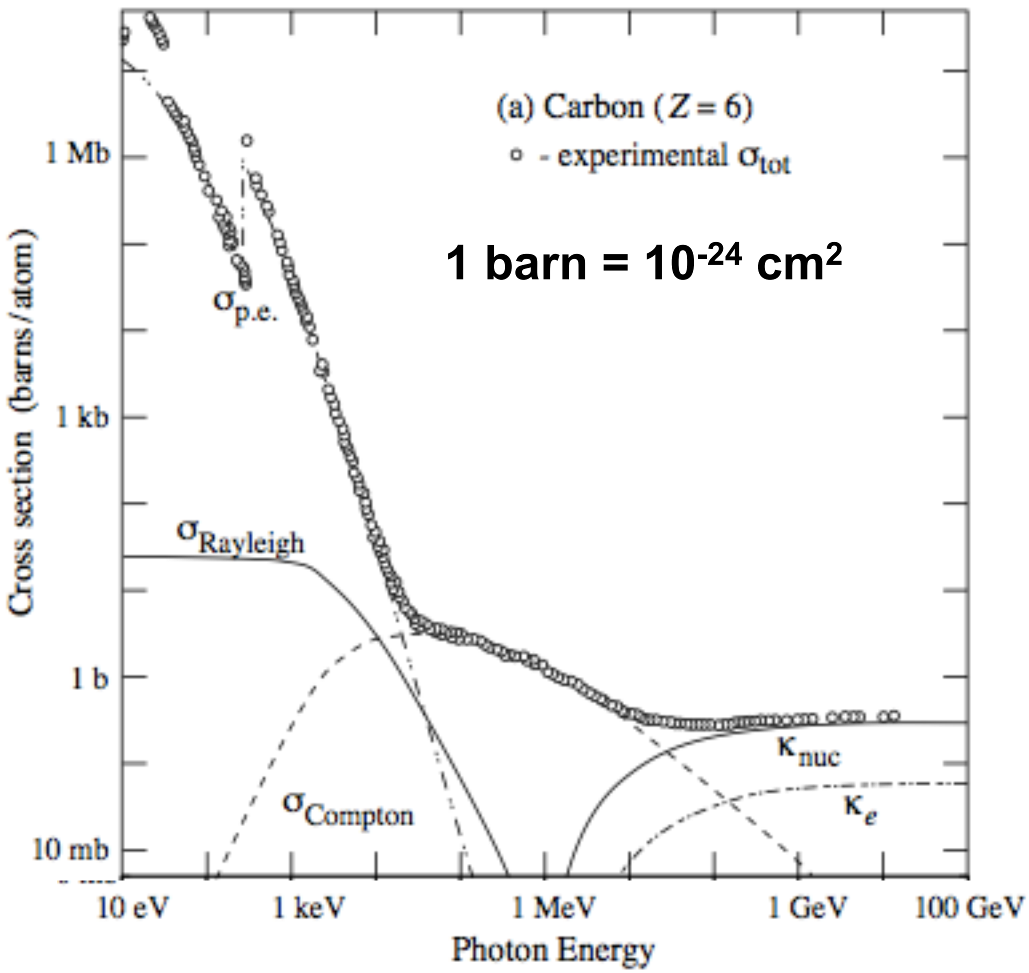
Neutral Current (NC)



Flavor-blind

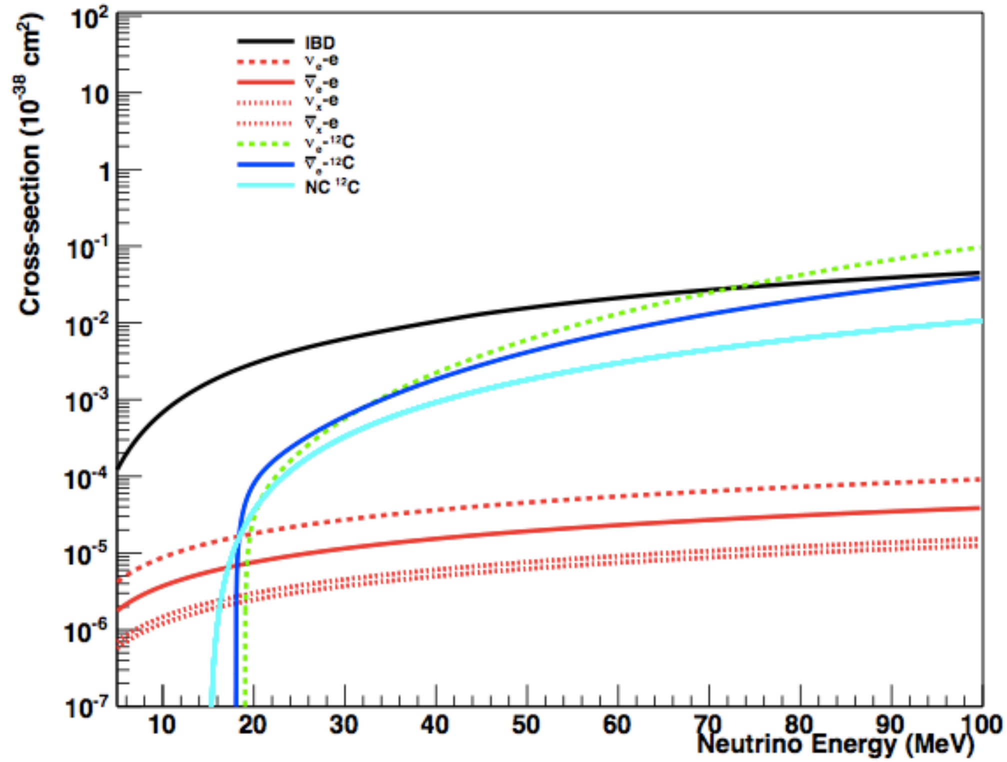
It's called the weak interaction for a reason

Photon-matter
cross-sections



~10^{-24} cm^2

Neutrino-matter
cross-sections



~10^{-40} cm^2

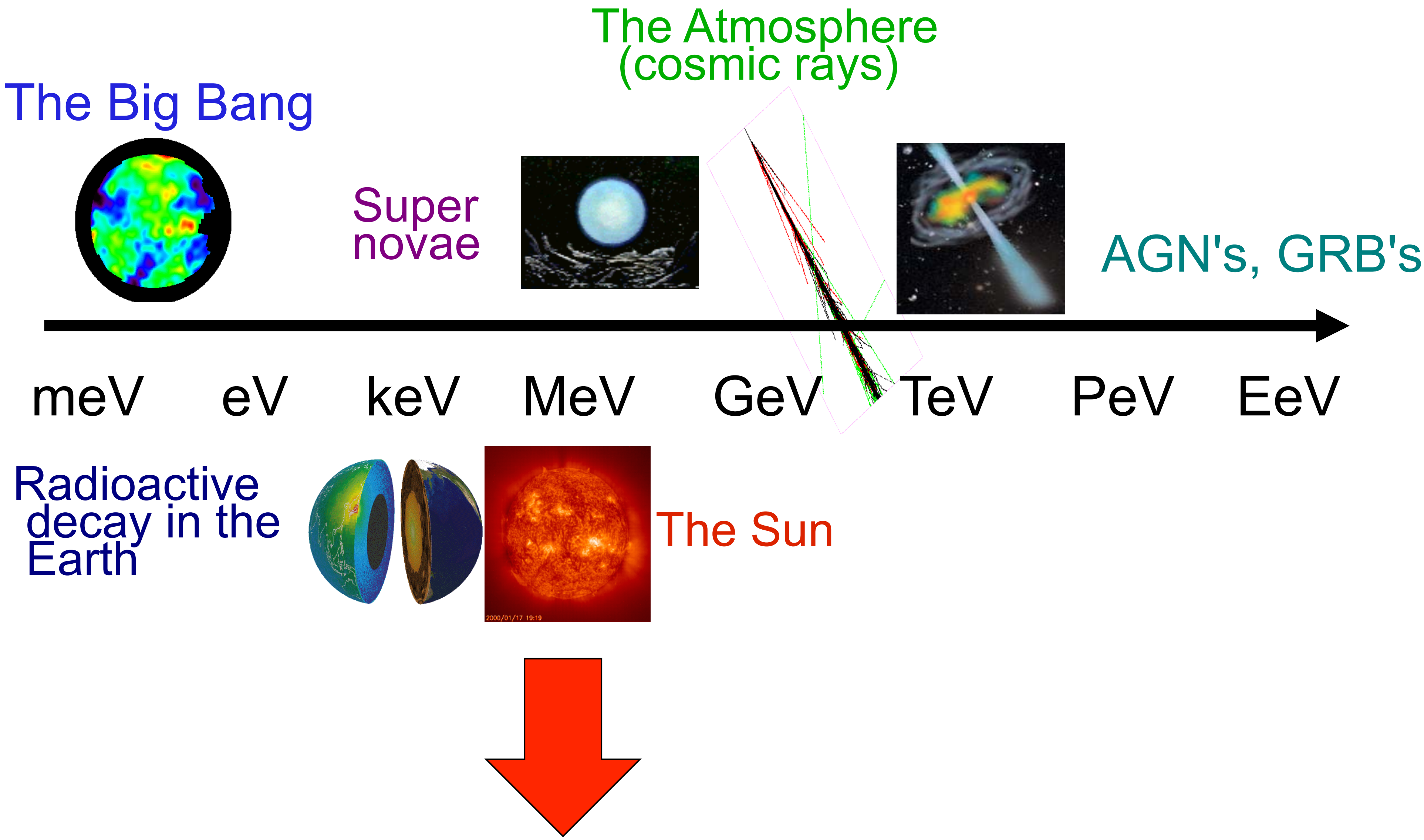
~16-17 orders of
magnitude smaller

In astrophysics, the weakness of the interaction is both a blessing and a curse...

- they bring information from deep inside objects, from regions where photons are trapped

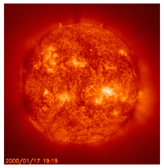
- but they require heroic efforts to detect!

Sources of wild neutrinos



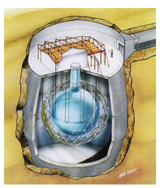
neutrinos leak energy
& bring information from
deep inside the Sun

The Story of Solar Neutrinos

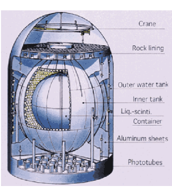


How does the Sun shine?

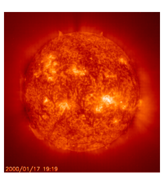
ν-raying the Sun: a classic problem



An anomaly resolved ... with new physics!



“Tame” neutrinos complement the “wild” ones



How does the Sun shine?
(or maybe yet more new physics...)

How does the Sun shine?

von Helmholtz, Mayer, Lord Kelvin:

gravitational contraction

radioactivity, nuclear reactions?

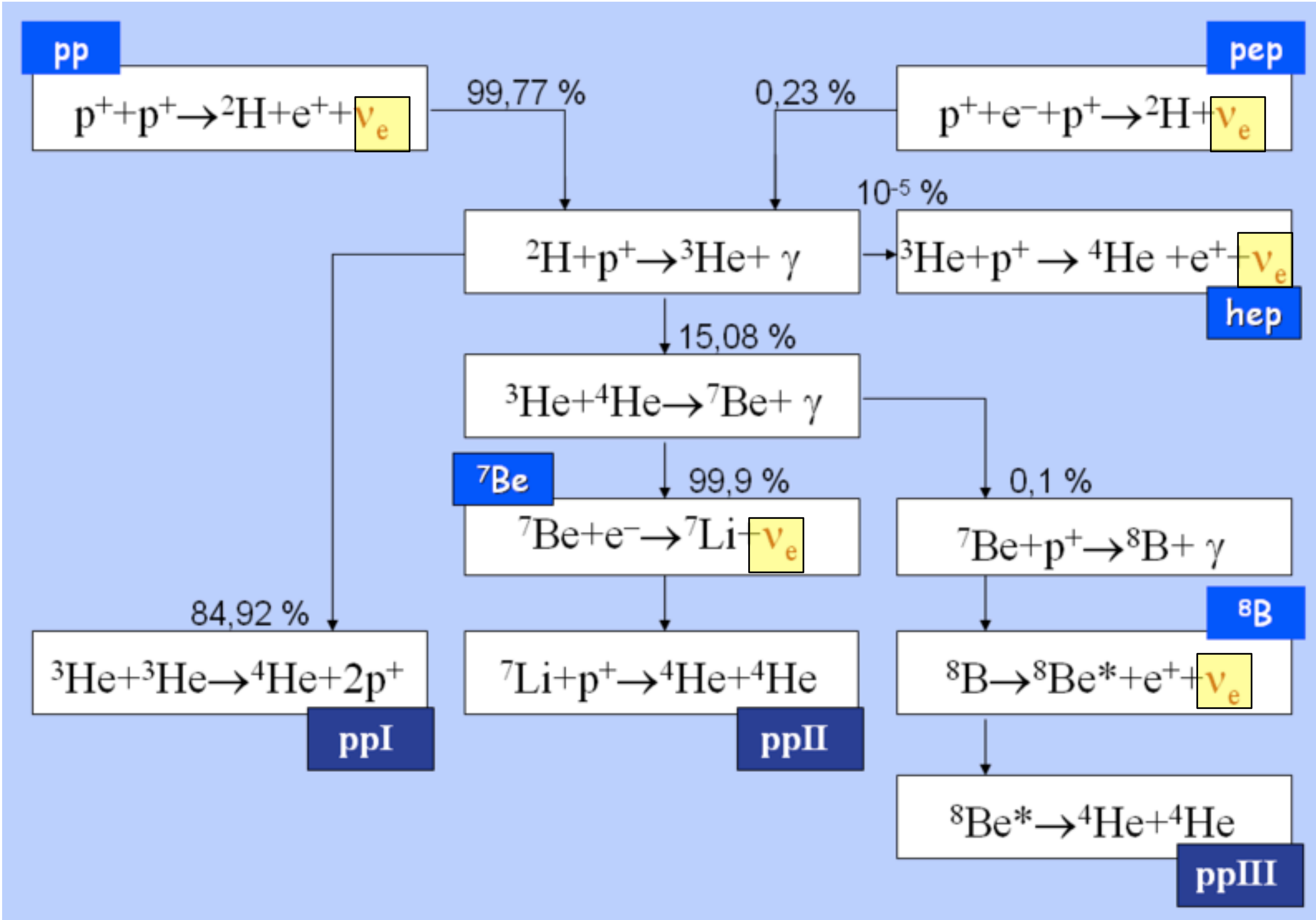
Eddington, Gamov, Bethe:

nuclear fusion

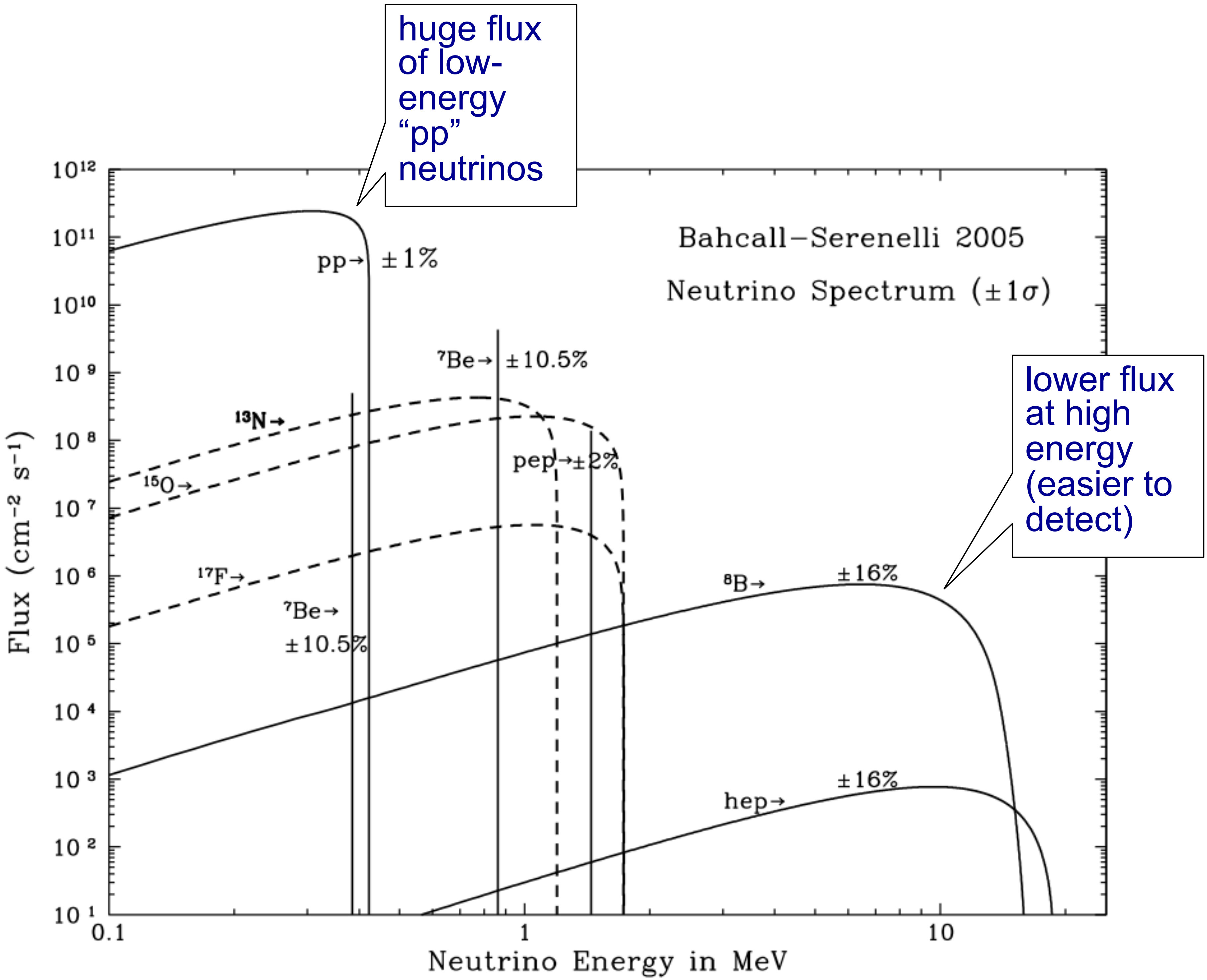
The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

-They Might Be Giants

Solar fusion reactions



Electron flavor neutrinos generated in solar fusion; spectrum is pretty well understood from weak physics


huge flux of low-energy "pp" neutrinos
lower flux at high energy (easier to detect)
Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
⁷Be→
±10.5%
pep→±2%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10

Homestake Chlorine Radiochemical Detector

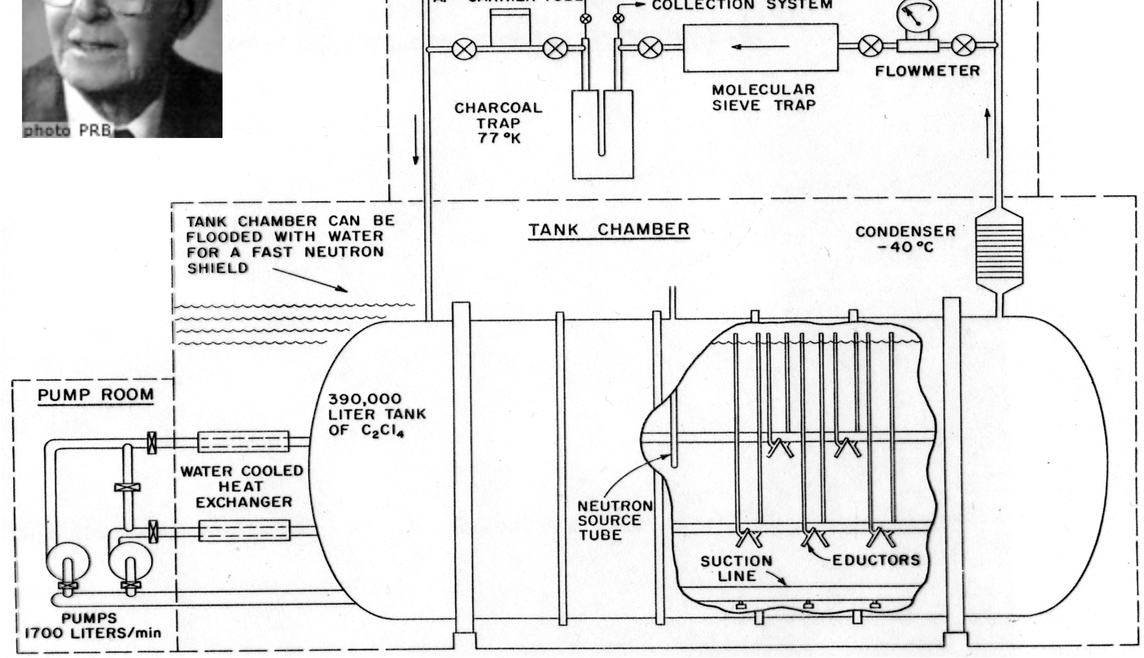


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

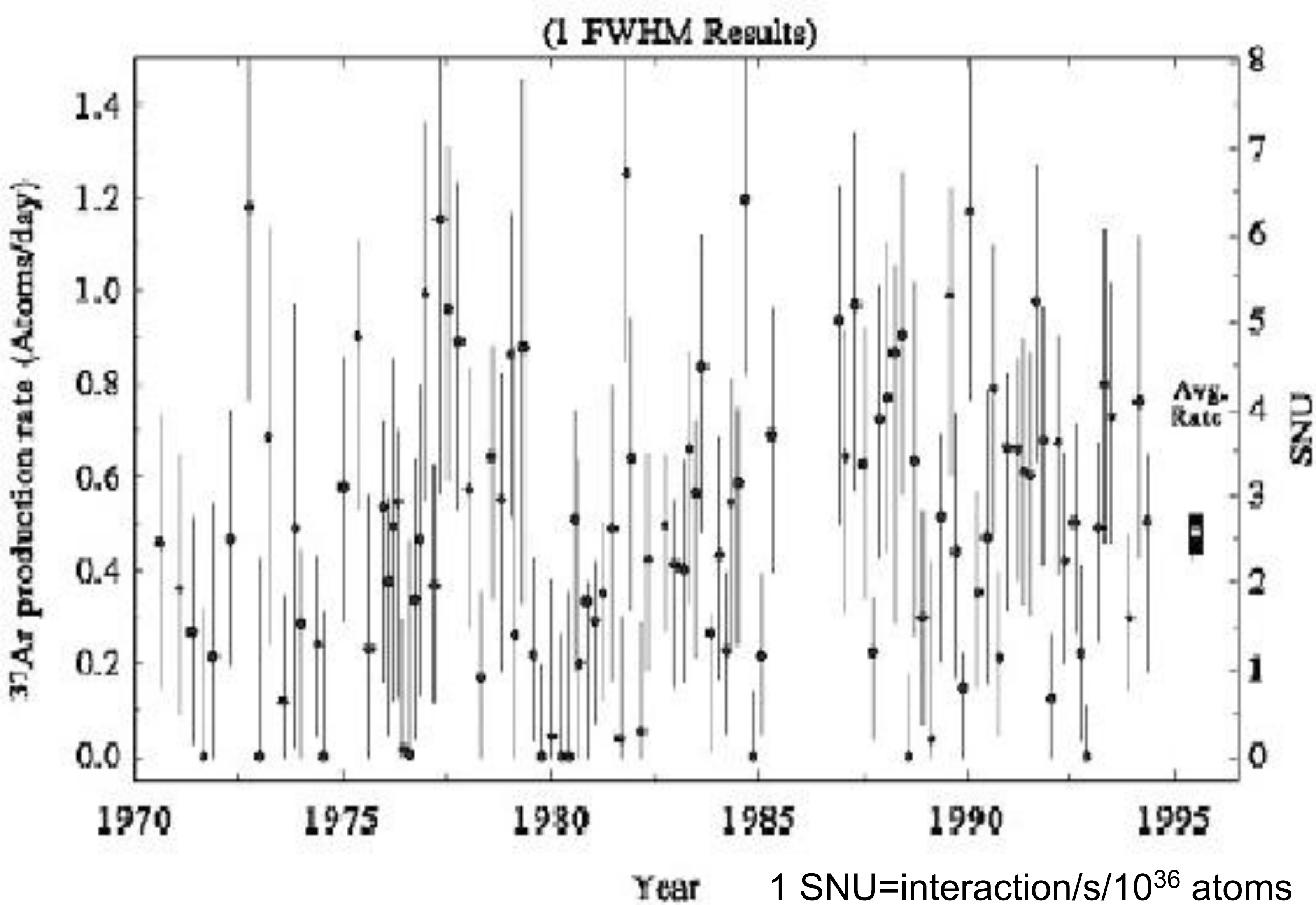
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

600 tons of cleaning fluid

Threshold: 0.81 MeV

Extract atoms of ^{37}Ar every few months
and count decays (35-day half life): ~ 12 per month!

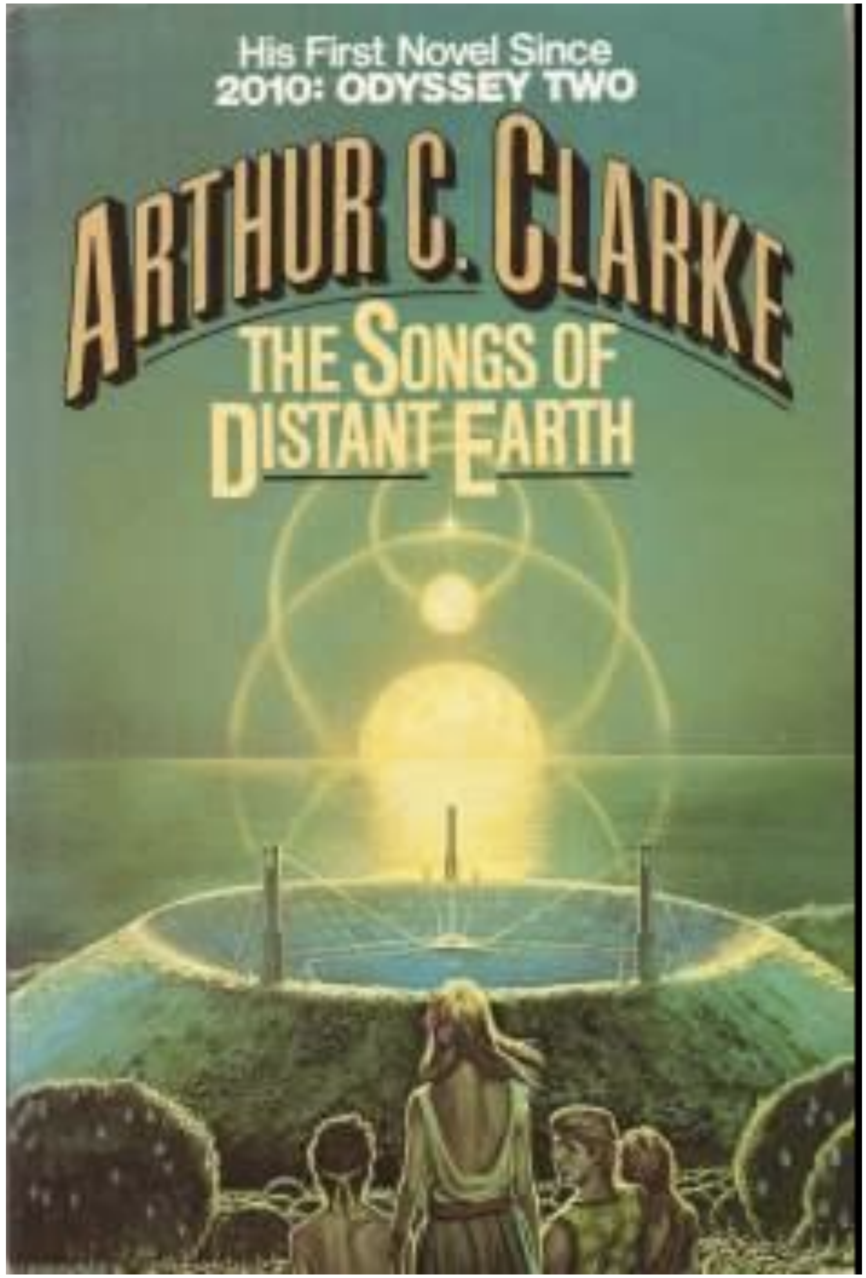
Davis and Bahcall in 1967



1 SNU=interaction/s/10^{36} atoms

Saw about 1/3 of the expected neutrinos

Could the Sun be going out??



Less apocalyptic (and less fine-tuned) ideas:

blame the Sun

Something wrong with the solar model?

mixing between layers, abundances not understood...?

blame the neutrinos

Something funny about neutrinos?

magnetic moment, decay...

or neutrino *oscillations*...?

Suppose electron neutrinos oscillate into ν_μ or ν_τ flavors, which don't have the oomph to make μ & τ via CC, ... so they effectively disappear

Pontecorvo

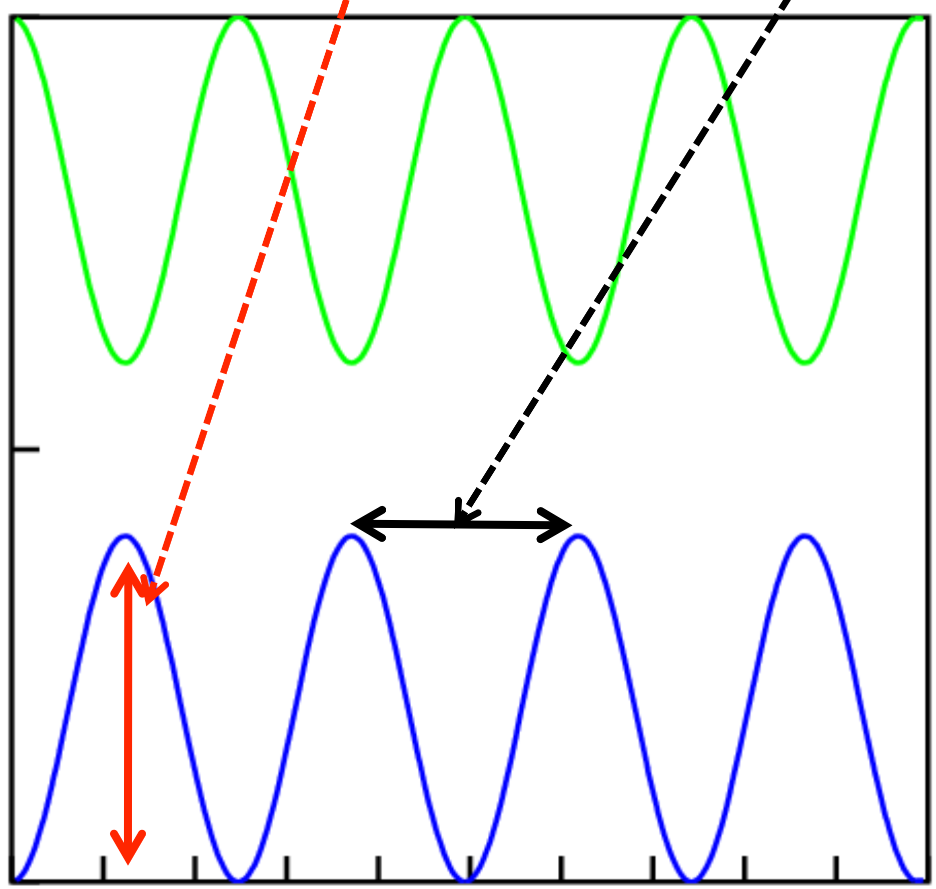
Oscillations, in 2-flavor approximation:

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

amplitude

wavelength= $\pi E/(1.27\Delta m^2)$

$P(\nu_f \rightarrow \nu_f)$



$P(\nu_f \rightarrow \nu_g)$

Distance traveled

Δm^2, $\sin^2 2\theta$ are the parameters of nature;

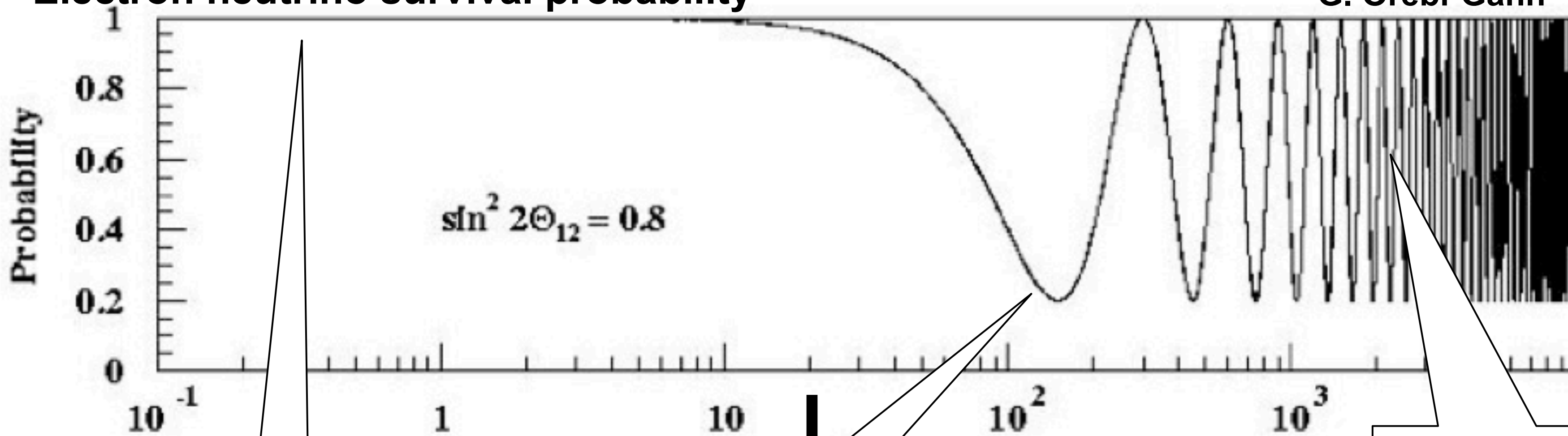
L, E depend on the experimental setup

Does it work out? Not really: for simplest case don’t get the right suppression

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Example of oscillations in vacuum, for fixed ν energy

Electron neutrino survival probability G. Orebi-Gann



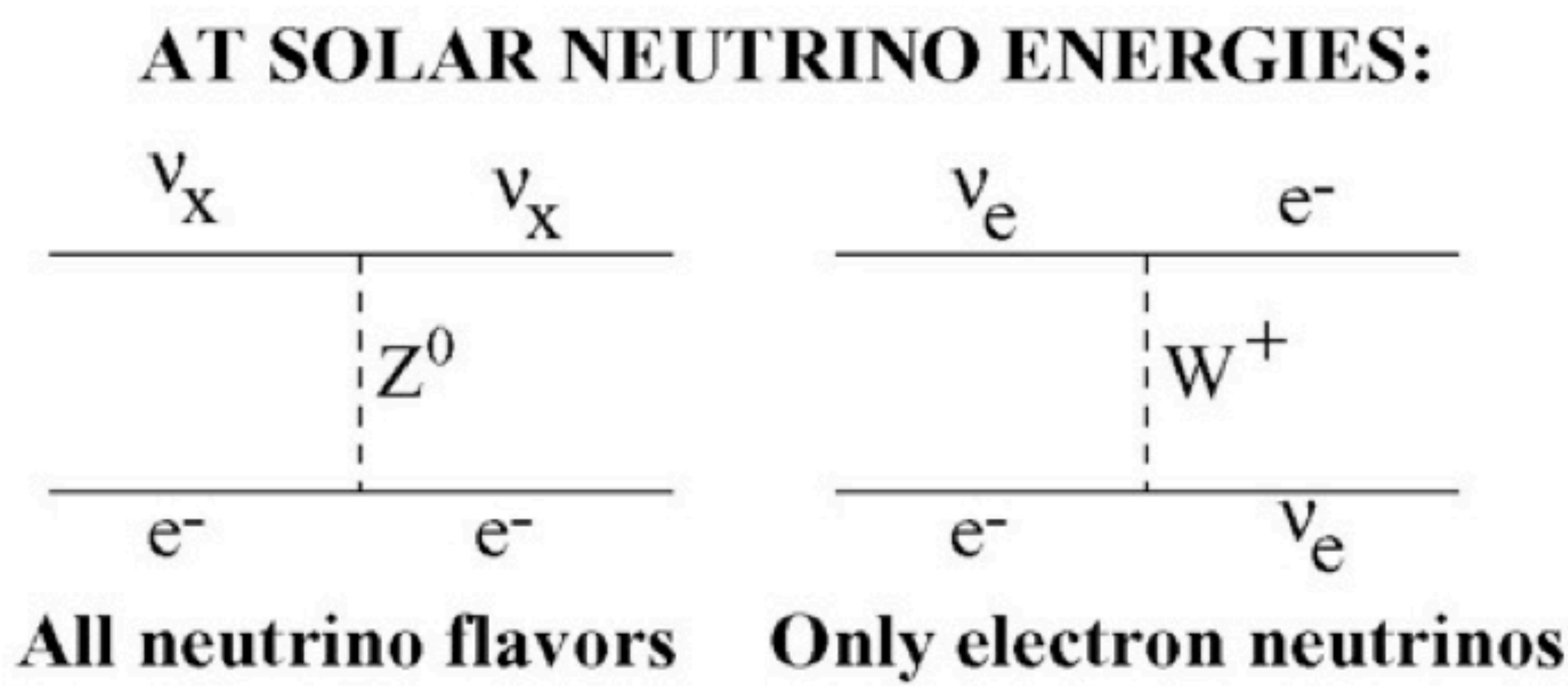
No mixing

In principle can get suppression, but for “just-so” distance, and requires large mixing angle

“Washed out”, P_{surv}>~50%

Quark mixing angles are small, so neutrino mixing angles must be small too, right?

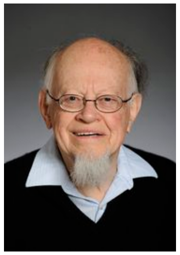
Evolving ideas about oscillations...



The Sun tastes like electrons to solar ν_e

Mikheyev

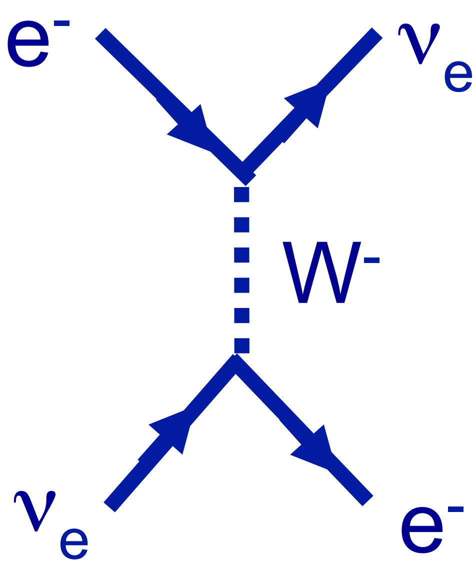
Smirnov



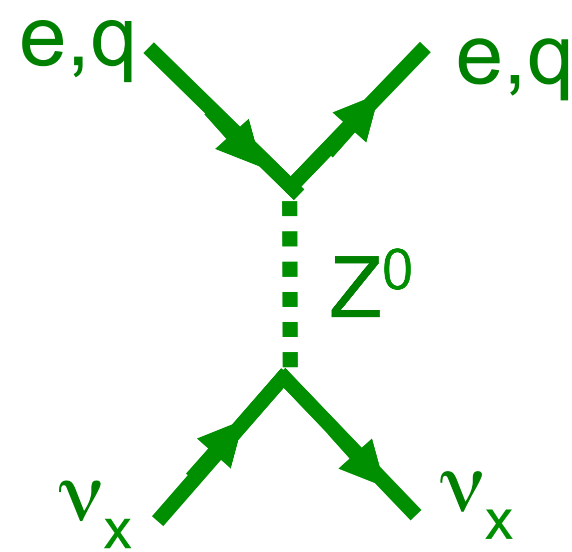
Wolfenstein

The Mikheyev-Smirnov-Wolfenstein (MSW) Effect a.k.a. "Matter Effects"

The Sun tastes like electrons to solar ν_e



vs.



extra energy $\sqrt{2}\, G_F N_e$ for ν_e **vs.** NC only for $\nu_{\mu,\tau}$

extra forward scattering amplitude → need to modify Hamiltonian

$$|\nu(t)\rangle = a_e(t)\,|\nu_e\rangle + a_\mu(t)\,|\nu_\mu\rangle$$

$$i\frac{d}{dx}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix} = \frac{1}{4E}\begin{pmatrix} 2E\sqrt{2}G_F N_e(x) - \Delta m^2\cos 2\theta_\nu & \Delta m^2 \sin 2\theta_\nu \\ \Delta m^2 \sin 2\theta_\nu & -2E\sqrt{2}G_F N_e(x) + \Delta m^2 \cos 2\theta_\nu \end{pmatrix}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix}$$

evolution of flavor states depends on matter density profile and vacuum oscillation parameters

results in *modified effective mixing parameters*

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

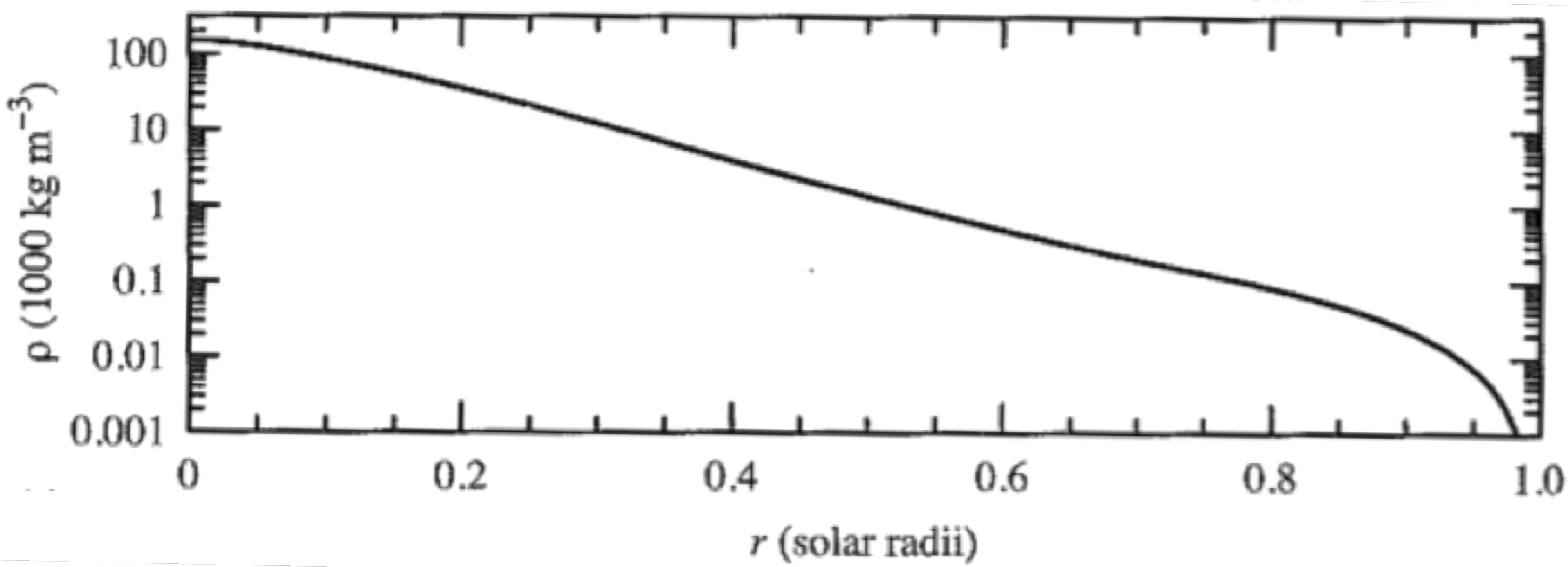
$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

depends on matter density

Notice the mixing amplitude gets large if:

$$\frac{\Delta m^2}{2E}\cos 2\theta = \sqrt{2}G_F N_e$$

Density varies continuously in the Sun



So for a given E, *some* density could satisfy the condition

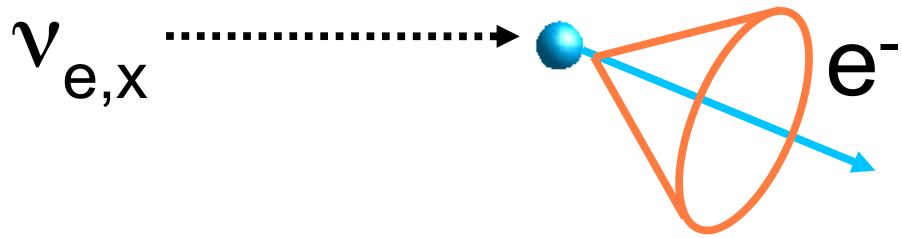
$$\frac{\Delta m^2}{2E}\cos 2\theta = \sqrt{2}G_F N_e$$

and lead to large flavor transition, even for small intrinsic mixing: MSW resonance

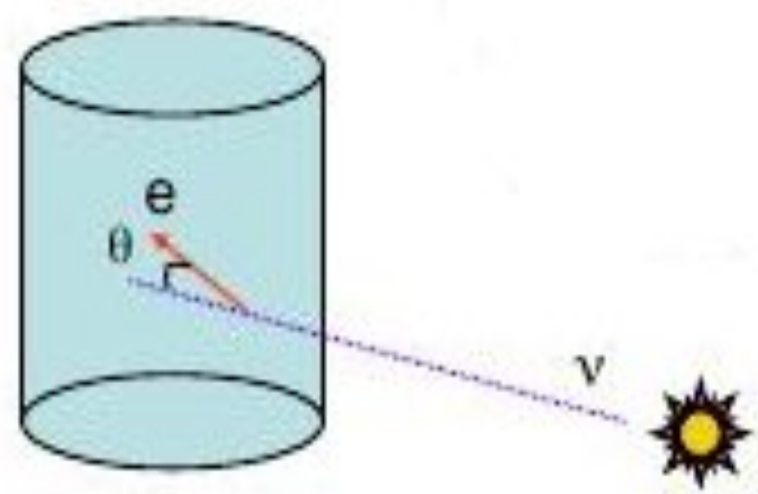
Is this what's happening?

More experimental information coming in...

Water Cherenkov Detectors



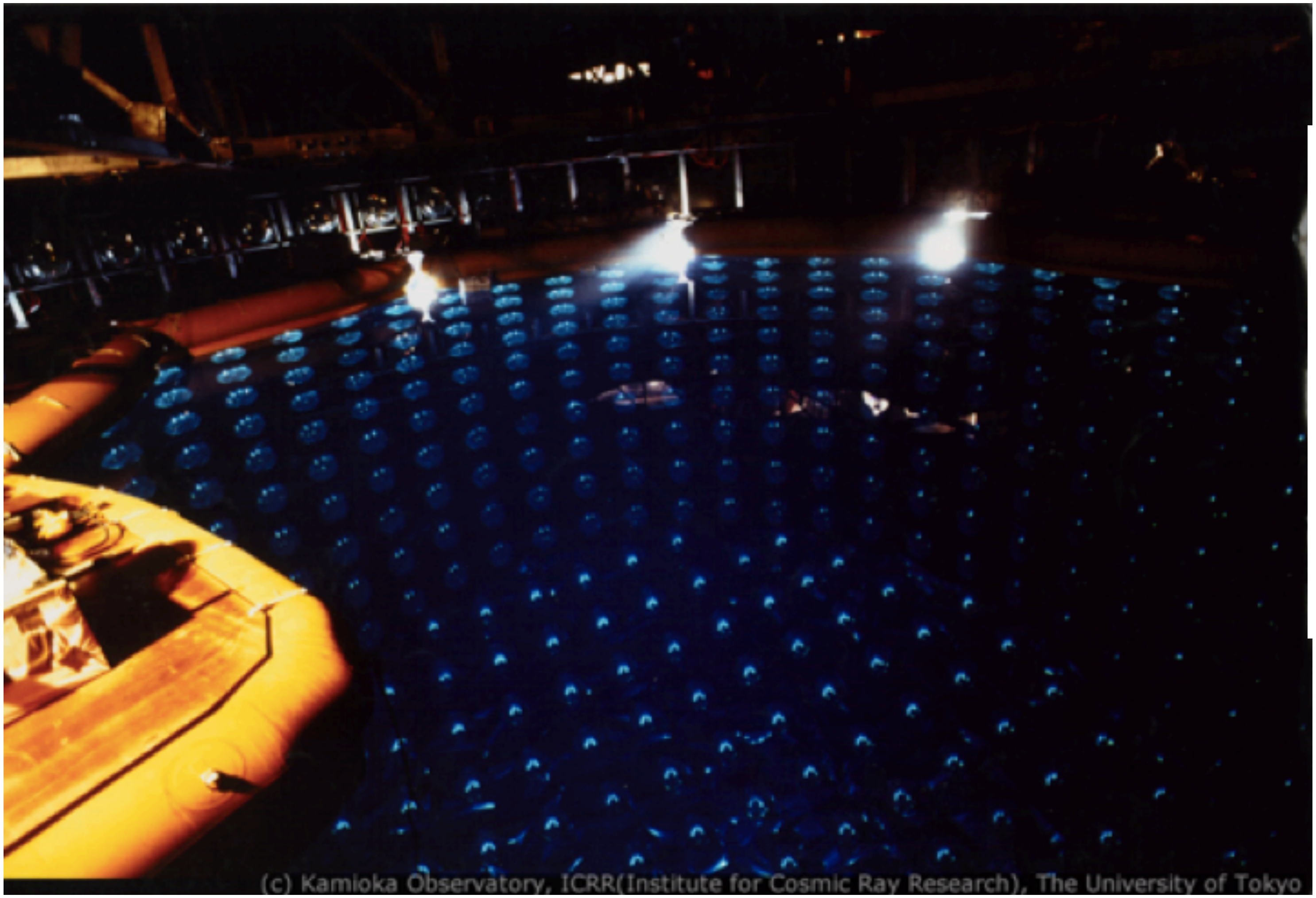
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

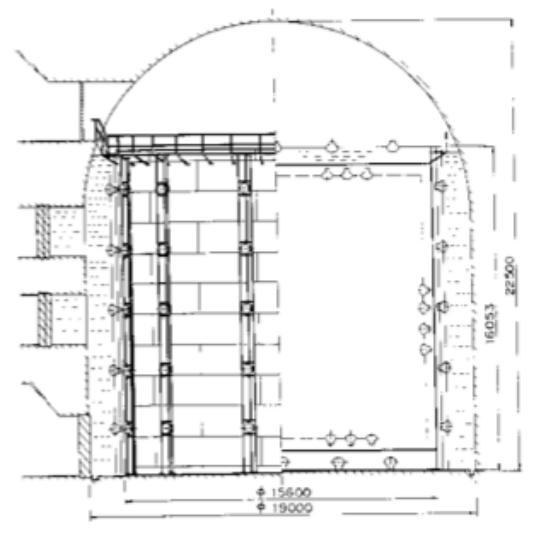


Elastic scattering of ~MeV solar ν's on electrons

real time detection, with *directionality*

Kamiokande II in Japan
(original motivation: search for proton decay)

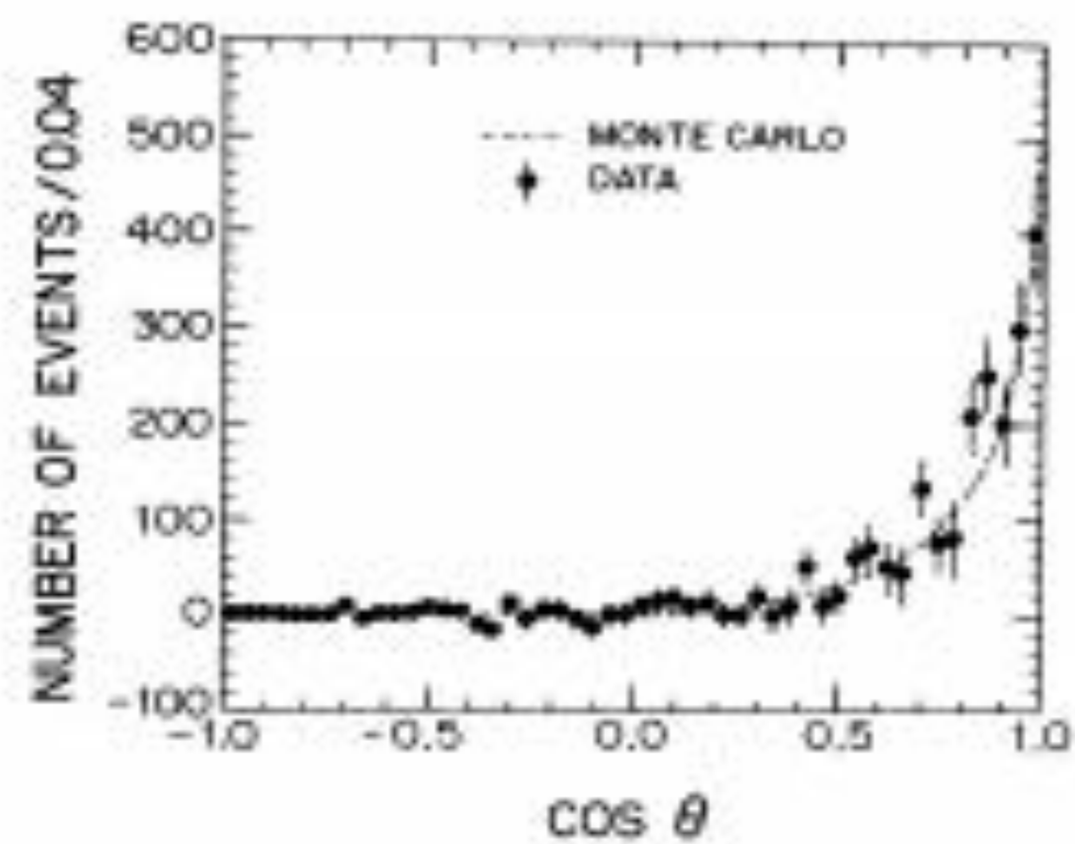




2.1 kton

E>~7 MeV : sensitive to ^{8}B tail of spectrum

Kamiokande-II, 1991

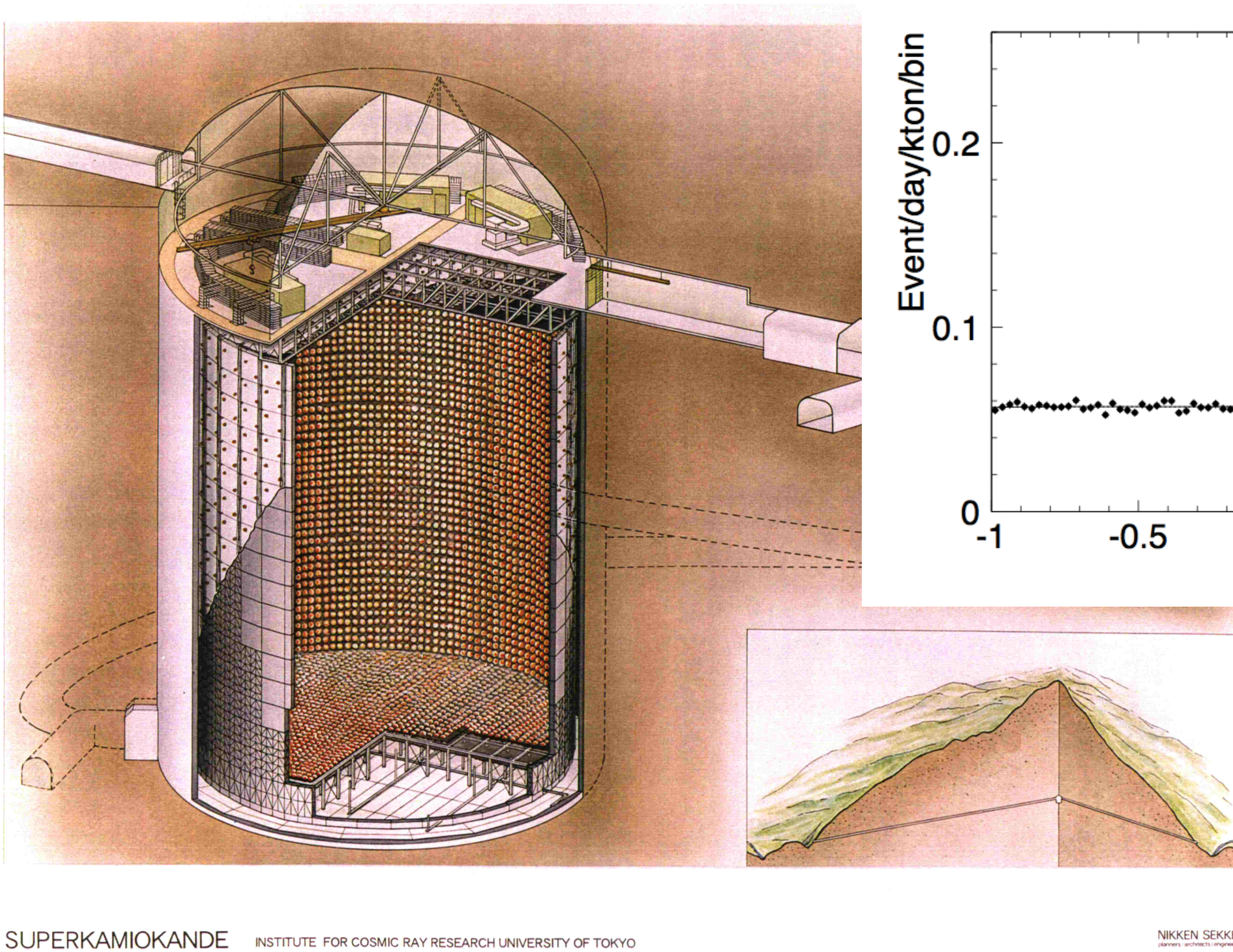


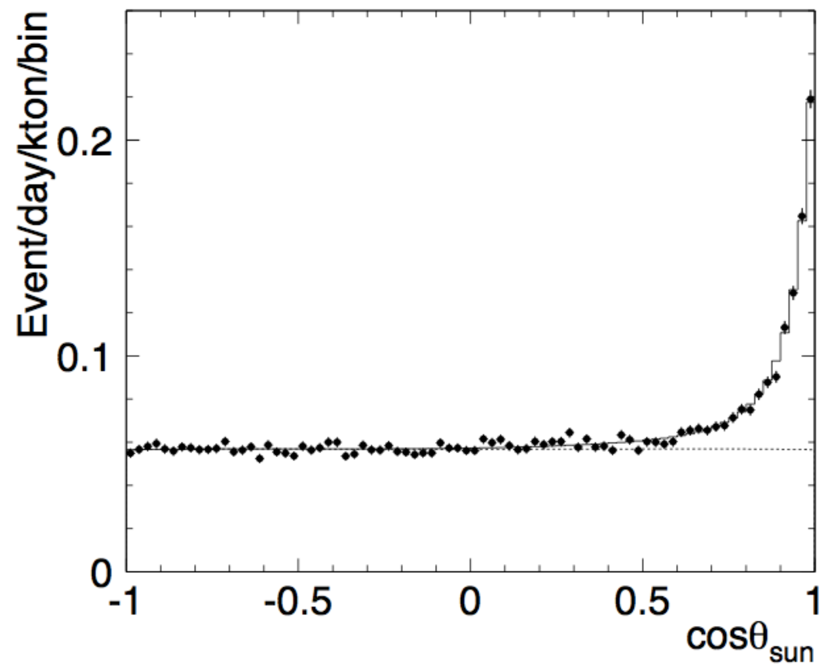
The events point back to the Sun!

It's really solar neutrinos

~40% of expectation: still a deficit

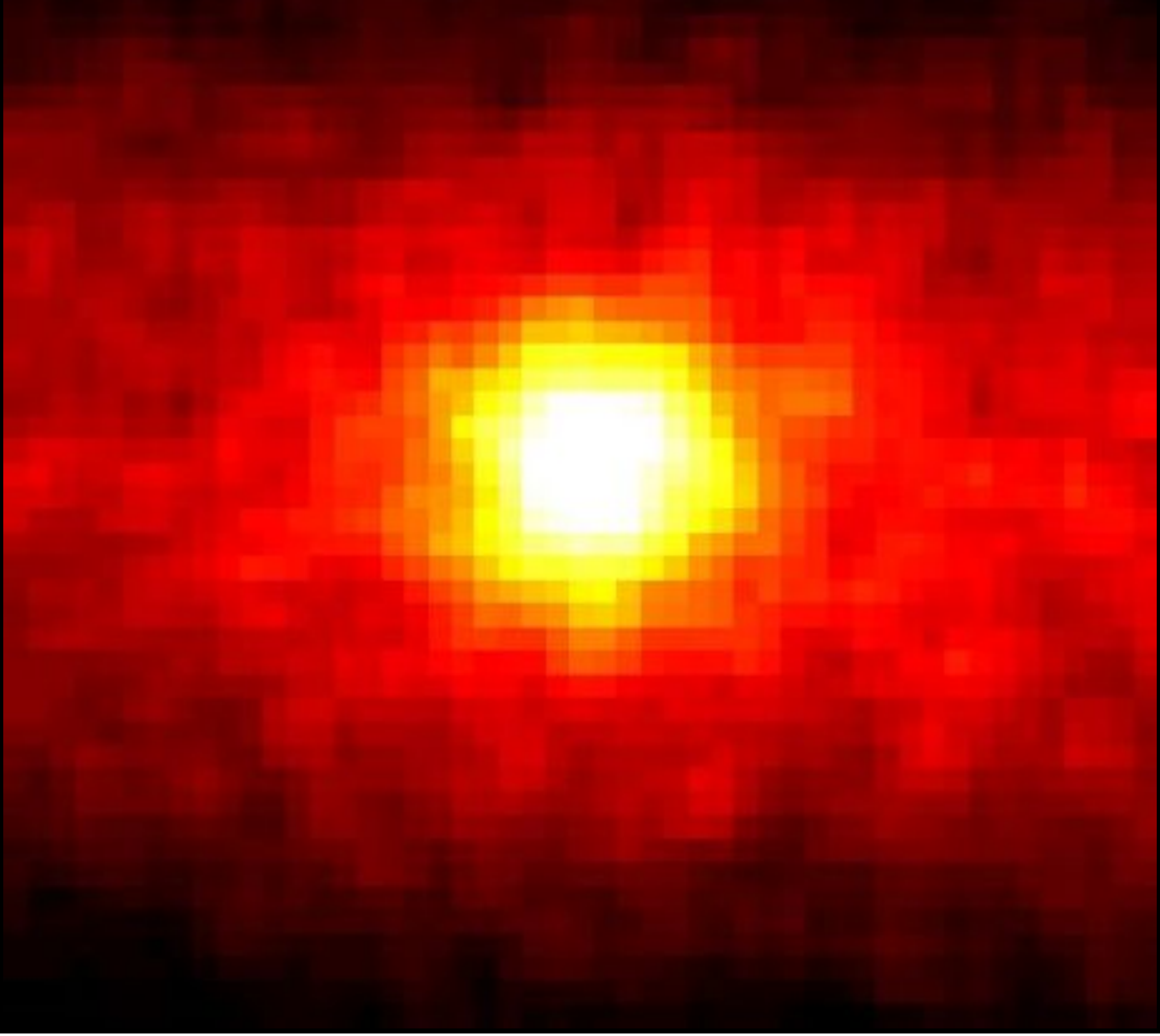
Later: significant improvement from Super-K
(consistent with earlier results)



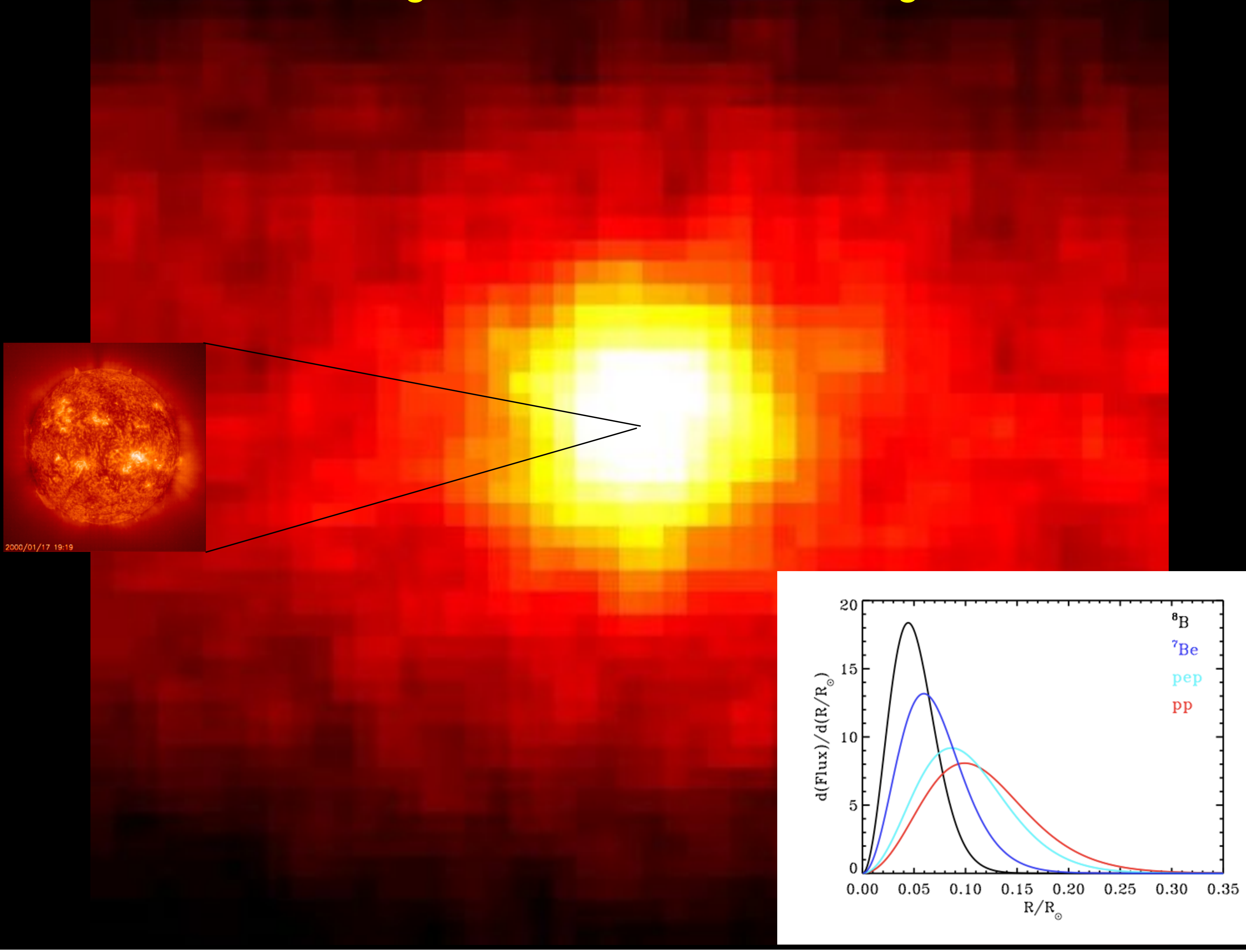


22.5 kton, <~ 5 MeV threshold

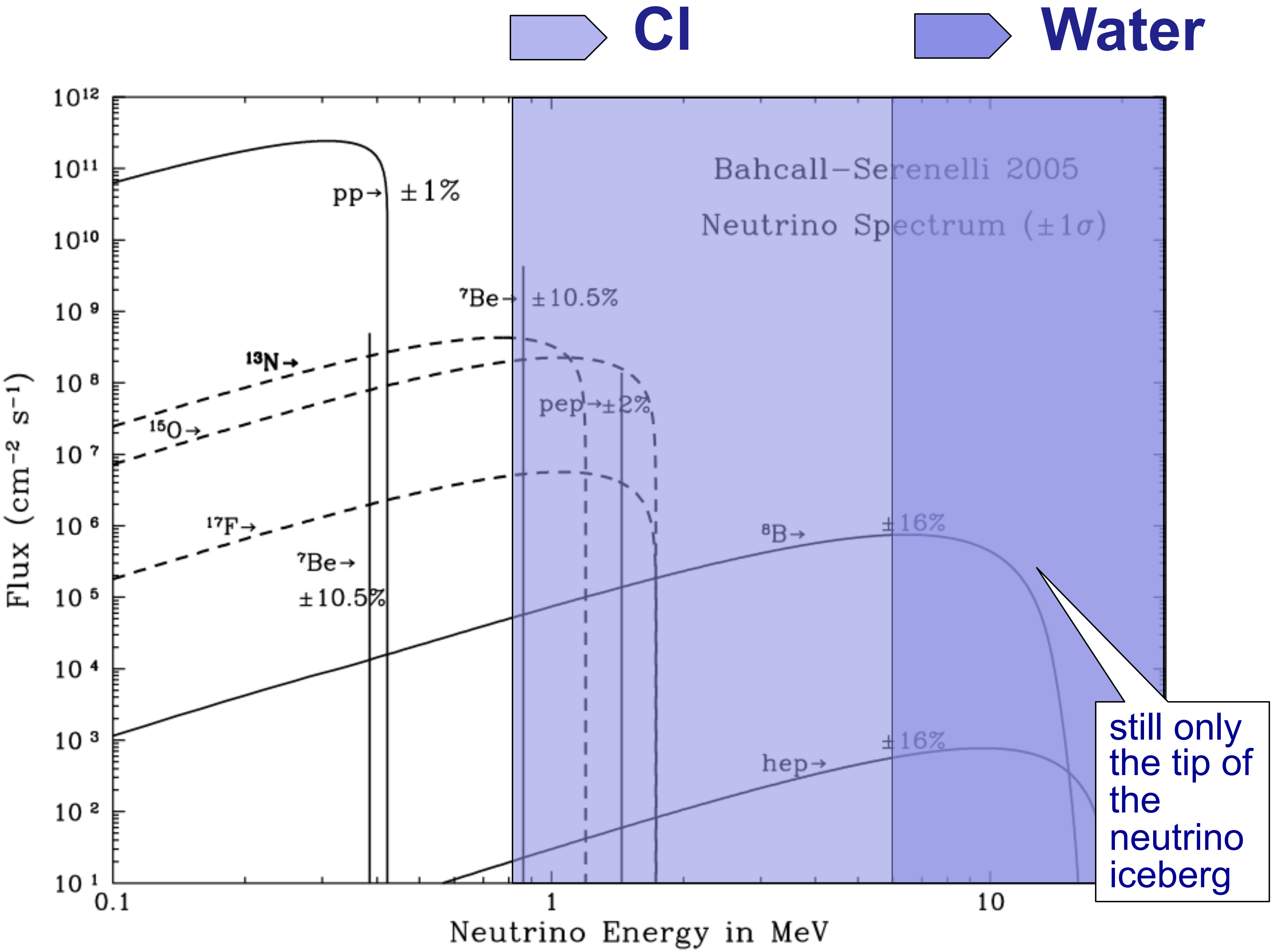
The Sun in neutrinos from Super-K



Disclaimer: the visible Sun occupies < 1 pixel,
and neutrinos emerge from an even smaller region!

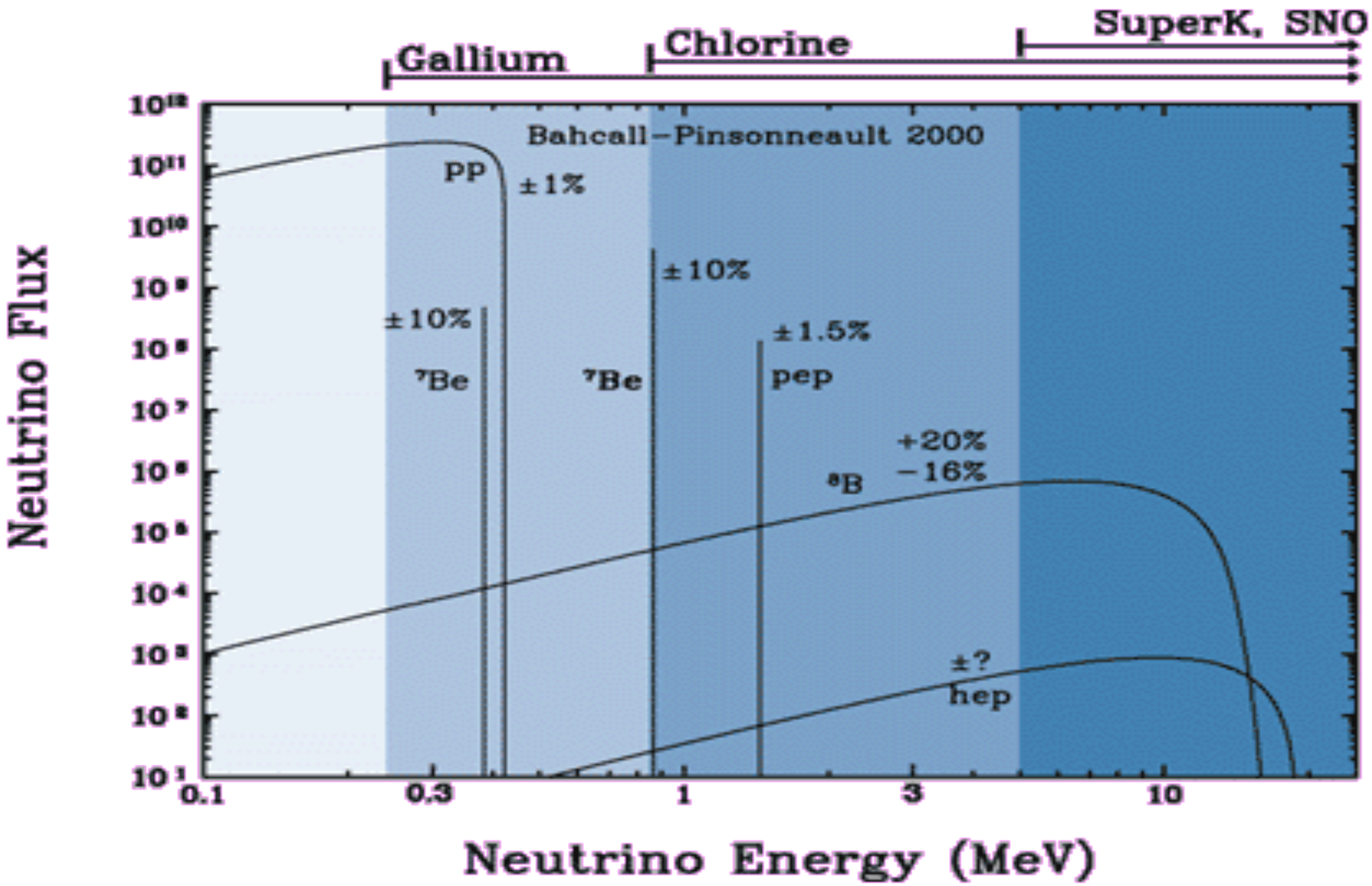


Two measurements at two energy thresholds



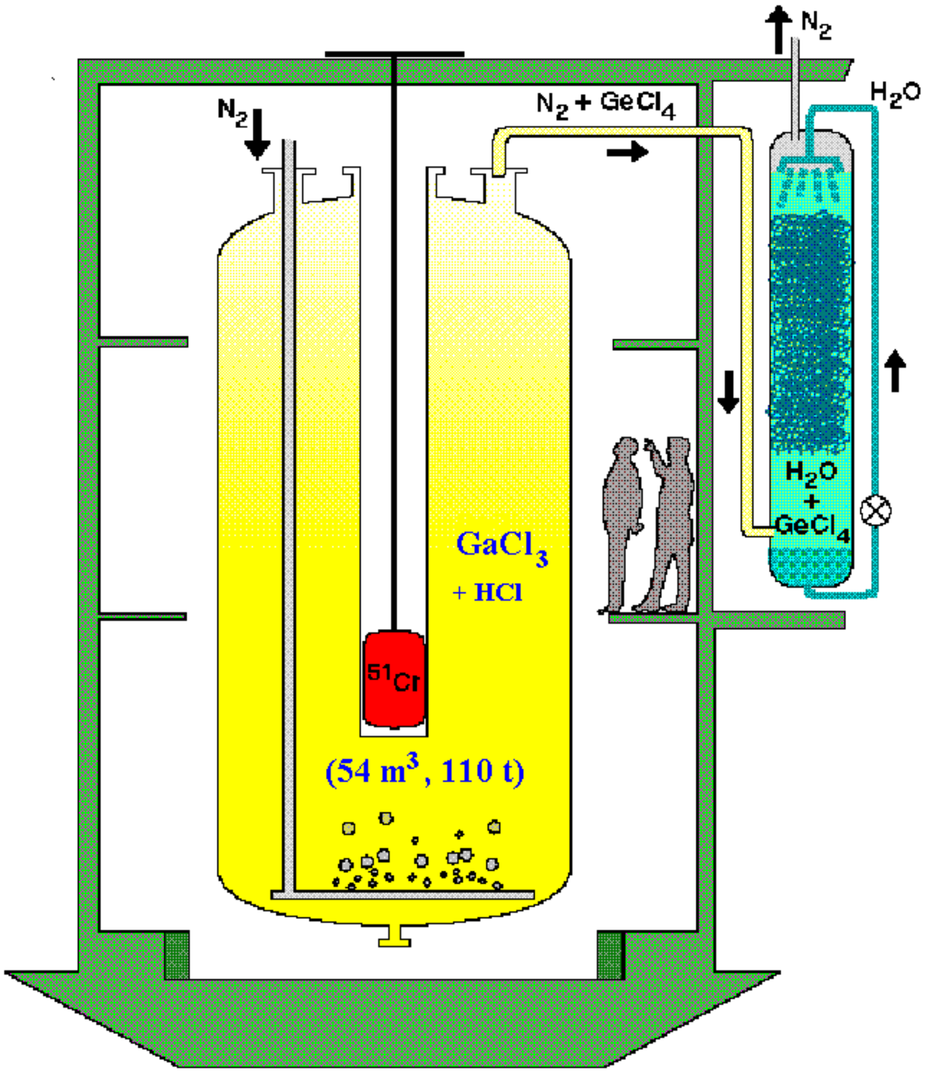
Next: gallium radiochemical experiments

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



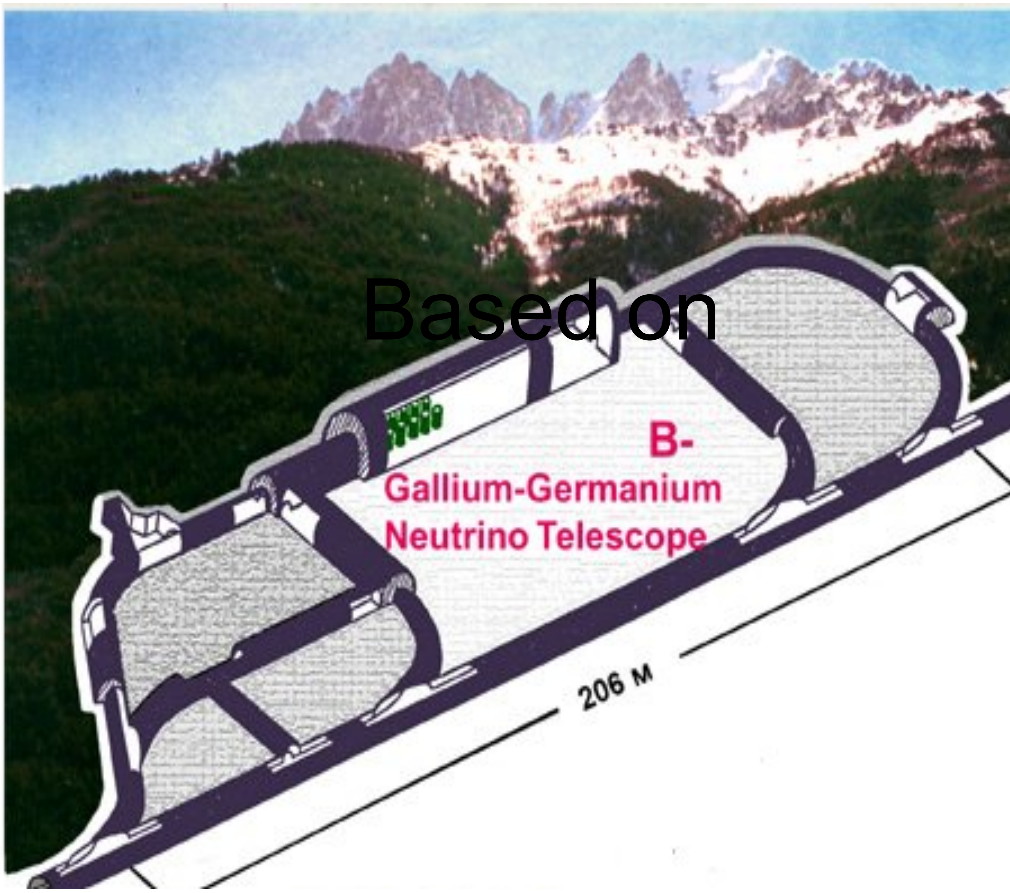
Threshold: 0.23 MeV, 11 day half-life
Sensitive to *pp neutrinos*

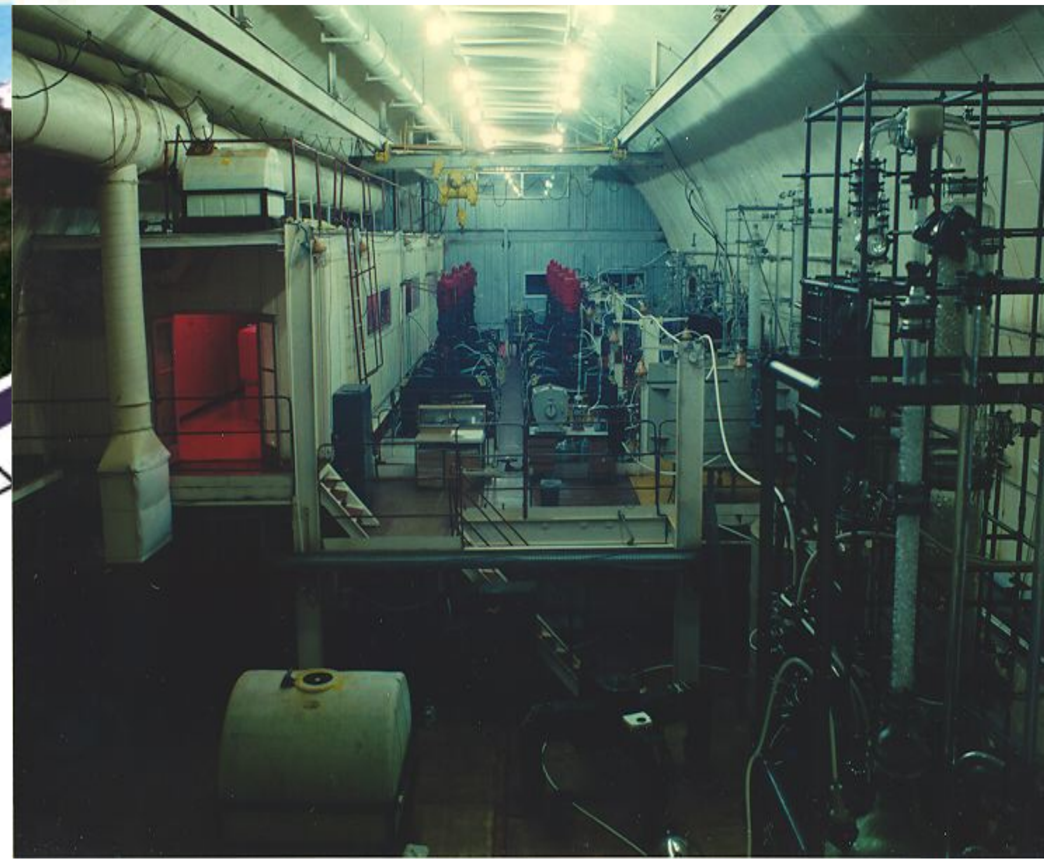
Gallex/GNO (Gallium Neutrino Observatory)
at LNGS, Italy: 1991-2006



Used gallium chloride (30 tons of Ga)

The SAGE Experiment





Caucasus mountains, Russia

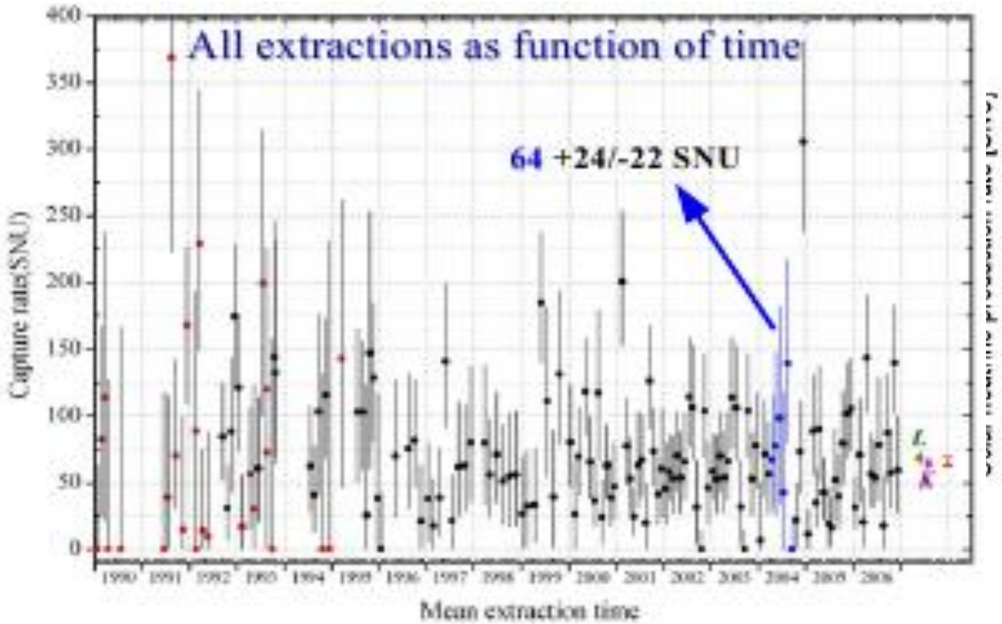
Based on liquid gallium
50 tons

1990-2007

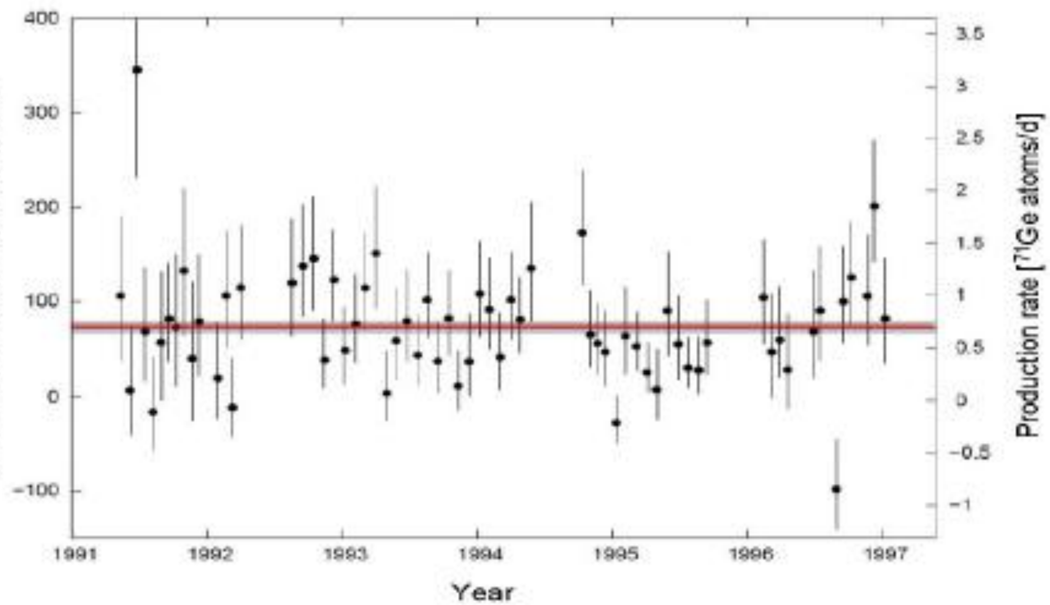
Gallium solar neutrino results

D. Hahn, Nu2008

SAGE

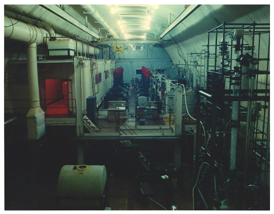


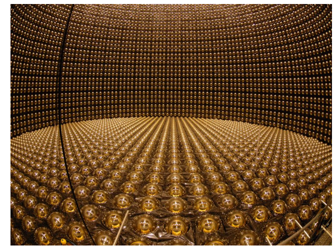
GALLEX

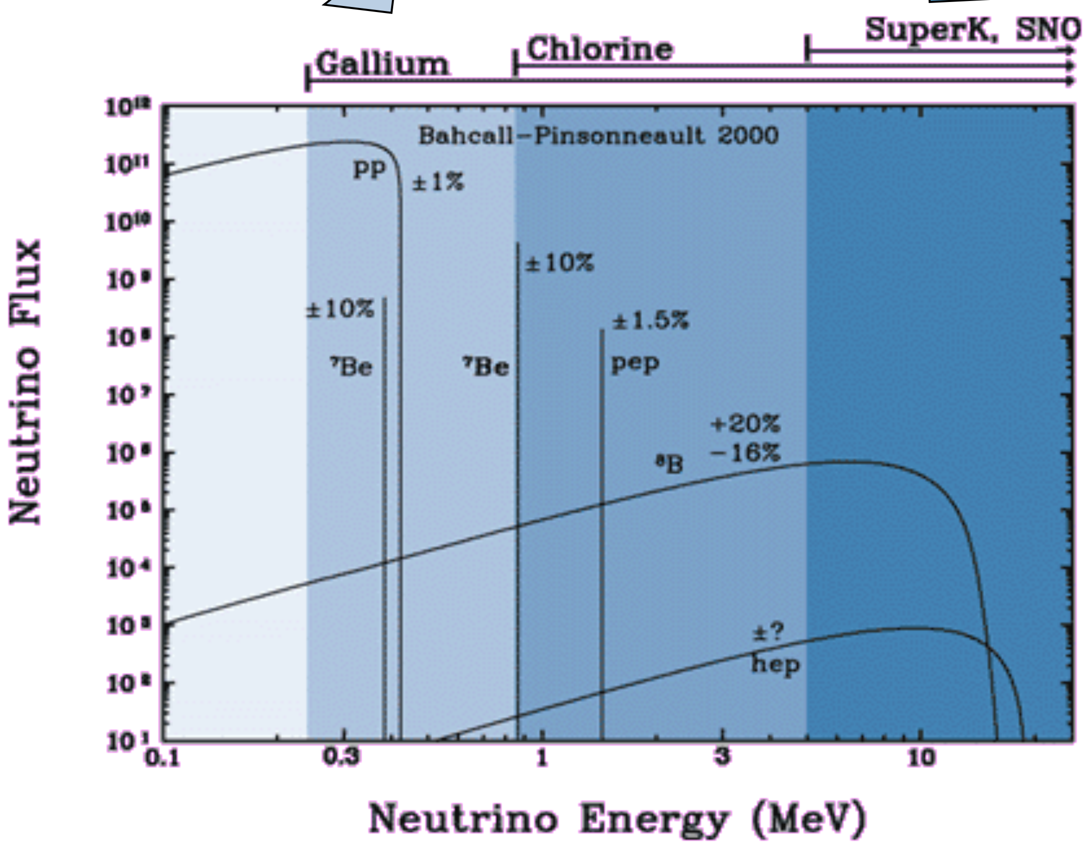


Again clear shortfall: about 60% of standard solar model expectation (pp neutrinos)

The picture in the mid-1990's: the "classic" solar neutrino problem

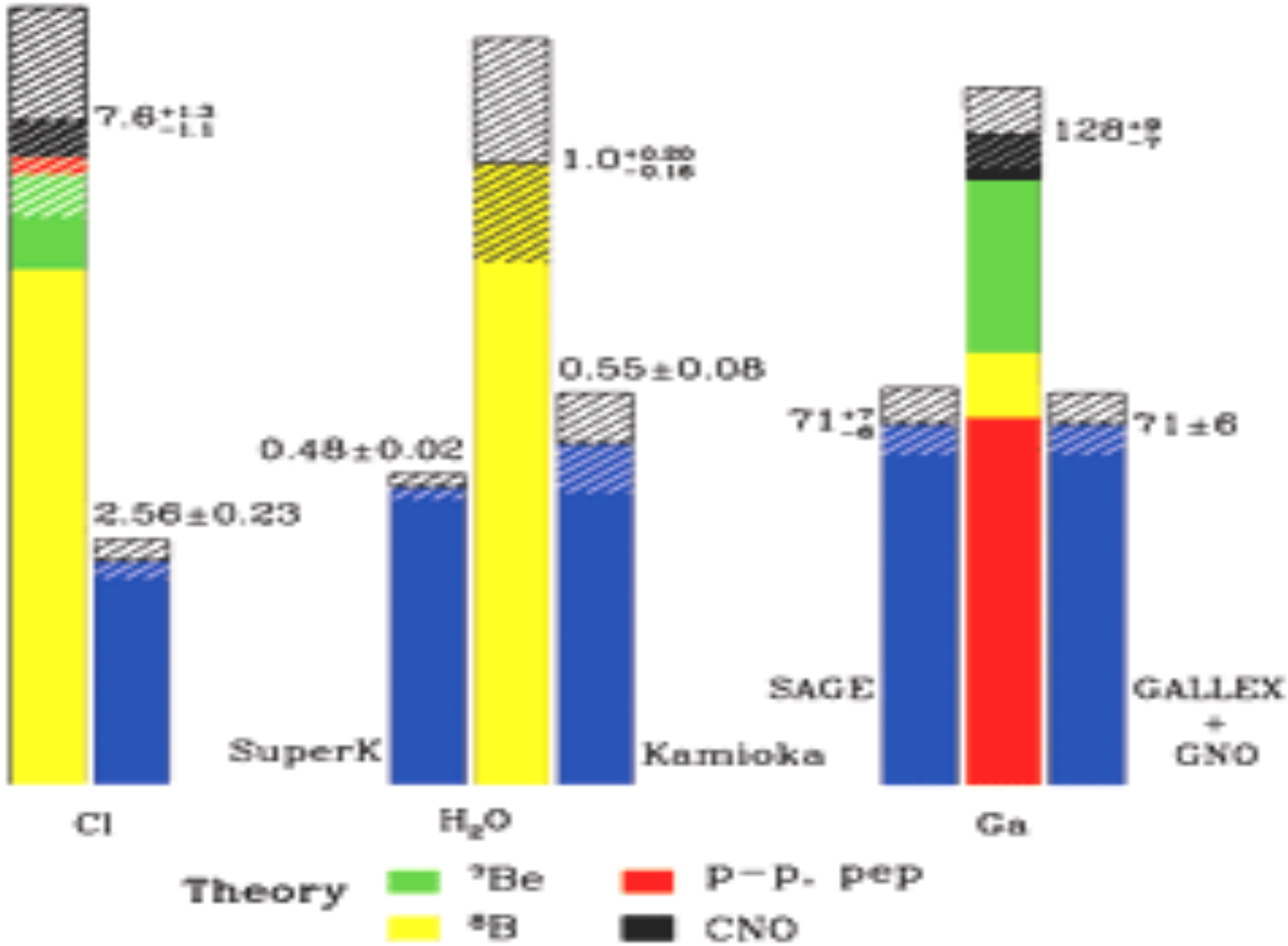






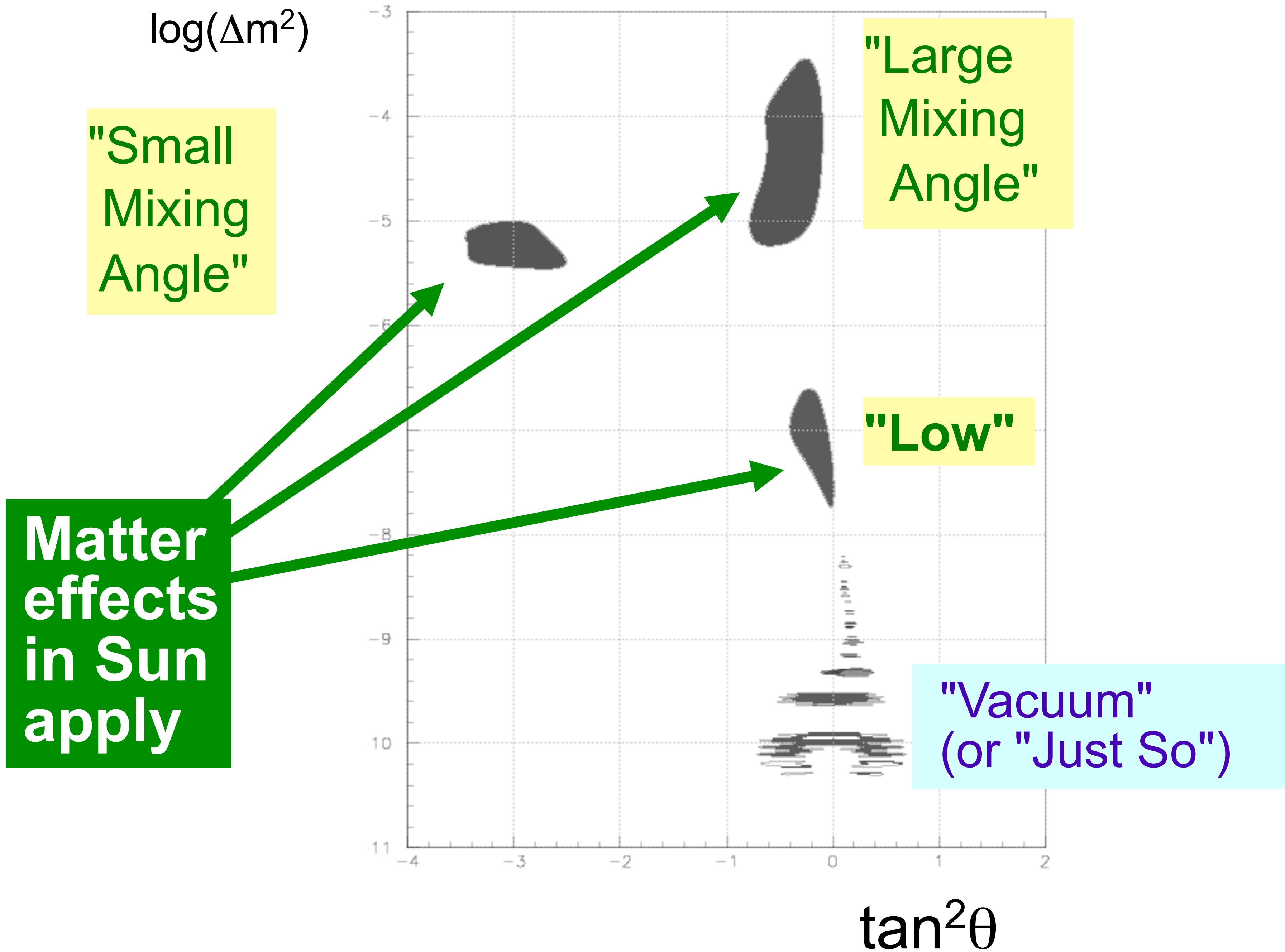
Different detectors are sensitive to different neutrino energy ranges

Energy-dependent suppression observed

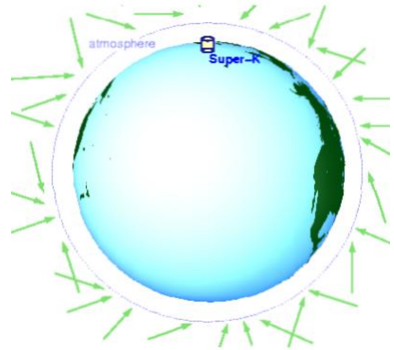


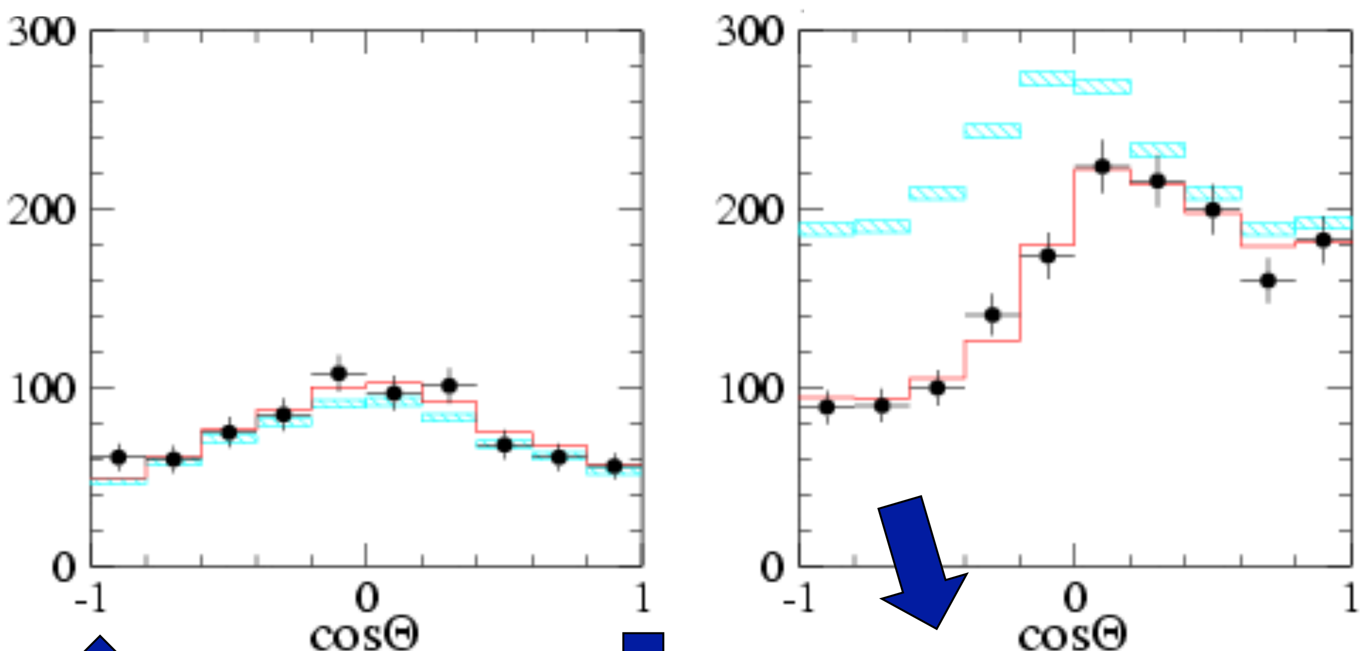
No known solar model could explain...
could it be $\nu_e \longrightarrow \nu_{\mu,\tau}$?

"Classic" allowed parameters for solar neutrino oscillations (Ga+Cl+ water)



In 1998, atmospheric neutrinos results from Super-K show ~ GeV neutrinos are oscillating





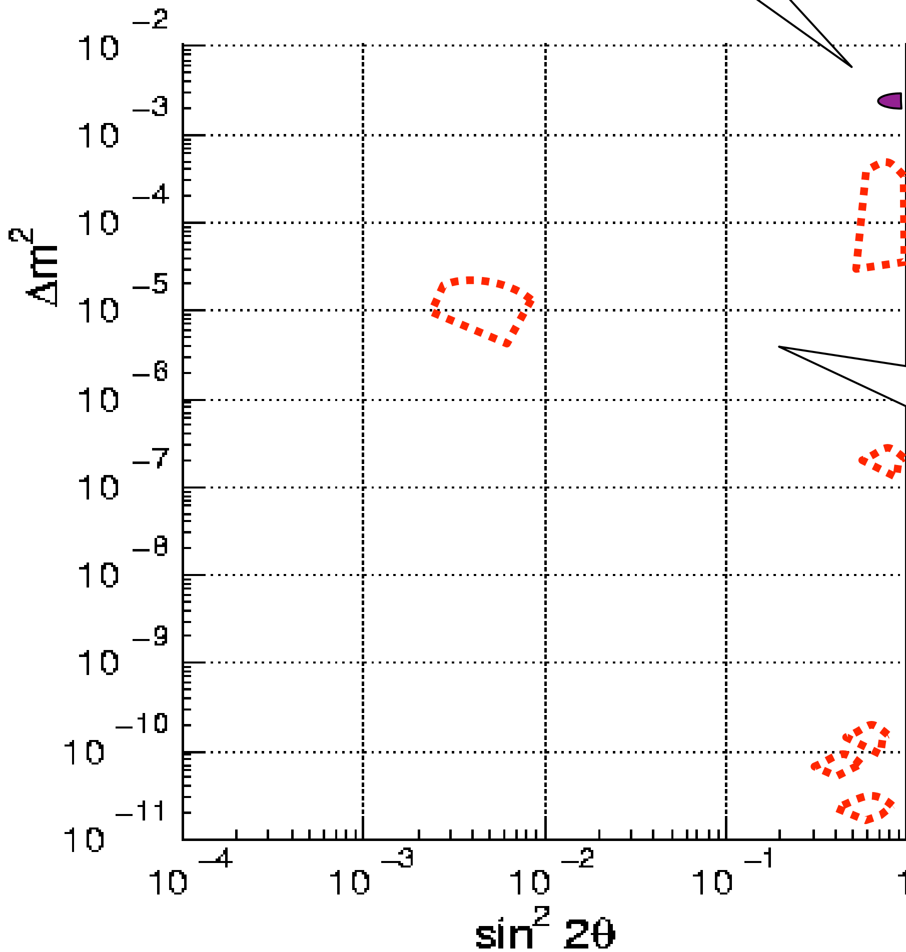
up-going

down-going

Huge deficit of ν_μ from below, consistent with ν_μ to ν_τ oscillation

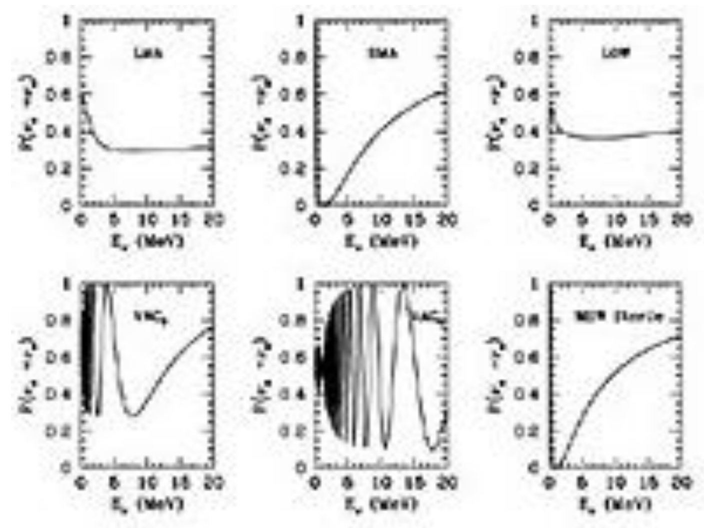
— **ν_μ–ν_τ oscillation (best fit)**

Atmospheric oscillations occupy a different oscillation parameter regime



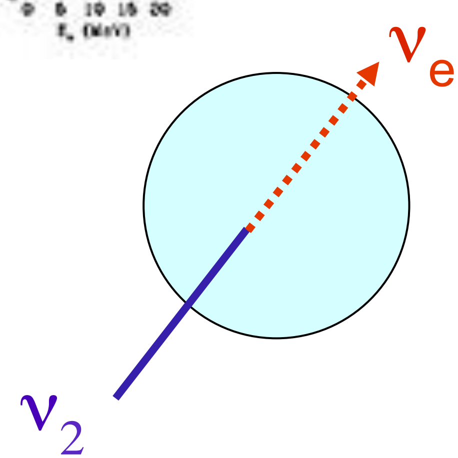
But now solar neutrino oscillations (low energy, longer wavelength) are even more motivated!

Hunting for "Smoking Guns": oscillation signatures

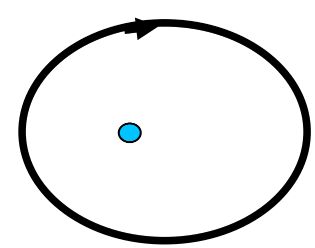


- **Spectral distortion**

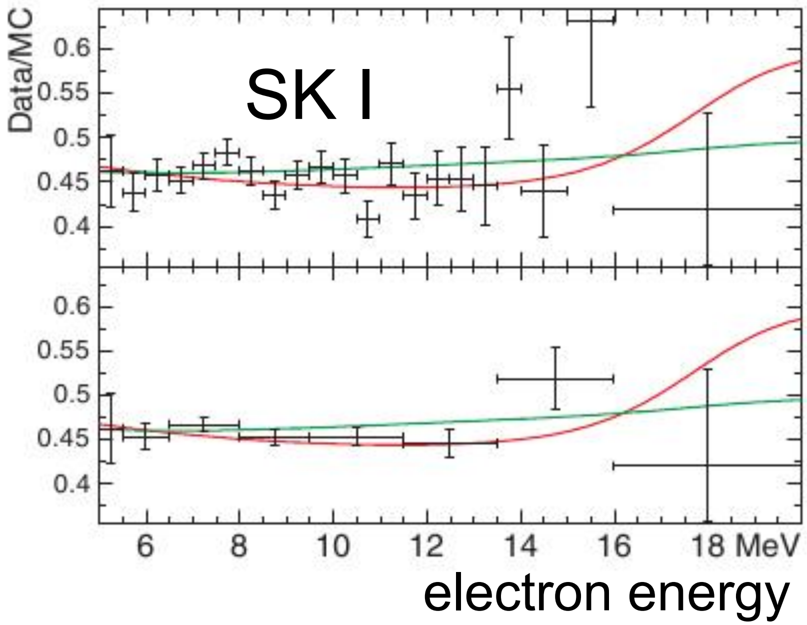
- **Day/night effect:** regeneration of ν_e in Earth due to matter effect enhances ν_e flux at night for some parameters



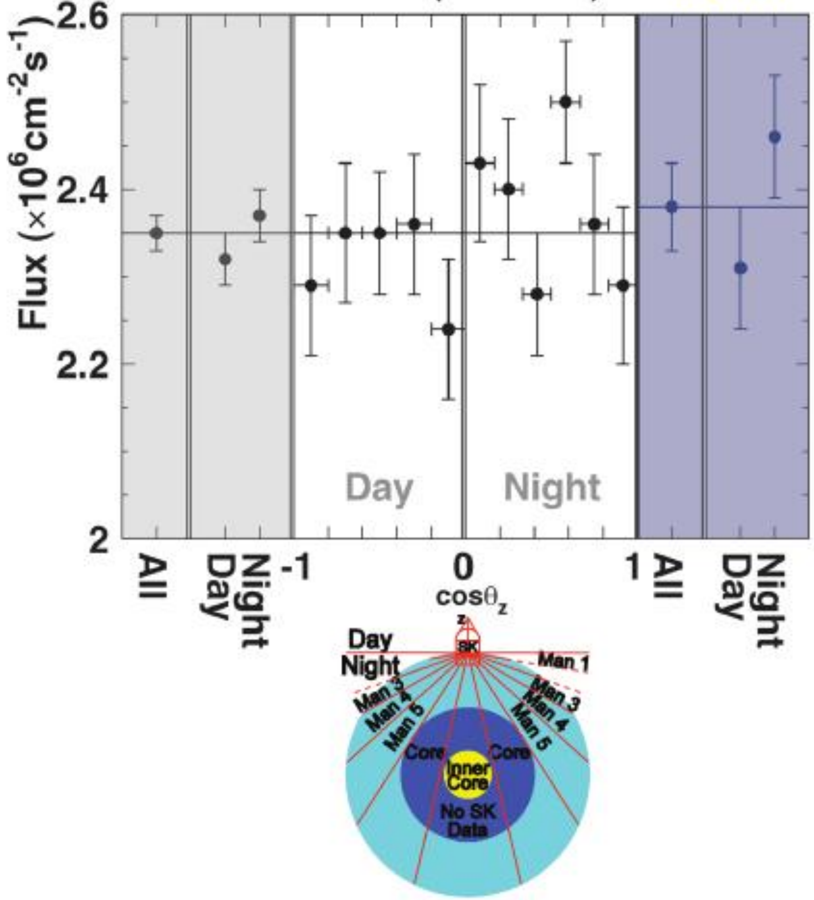
- **Seasonal variation:** variation with L for vacuum oscillation (beyond 7% expected from Earth orbit)



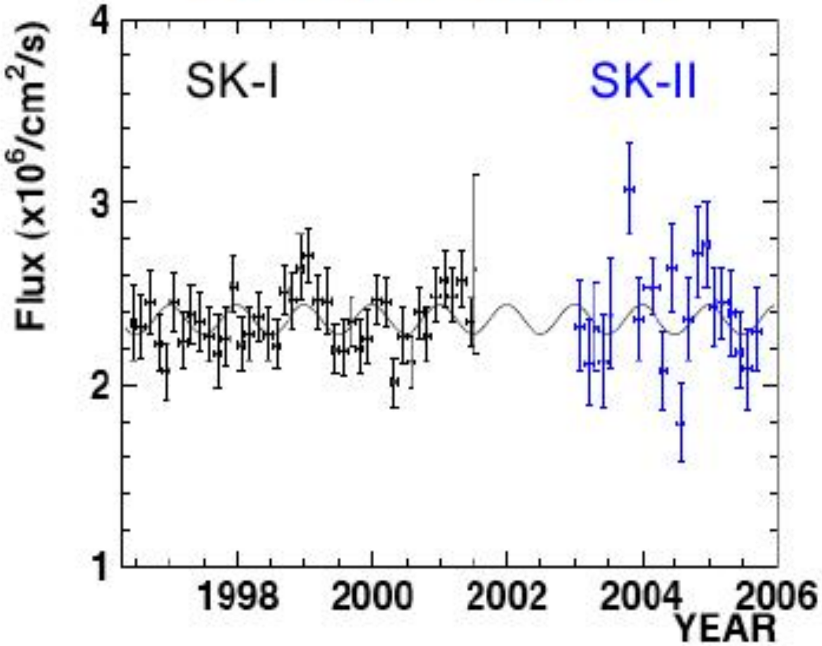
Recoil energy spectrum



Day/night asymmetry



Seasonal variation



No strong effects
(besides suppression)
observed at Super-K
⇒ constrain parameters

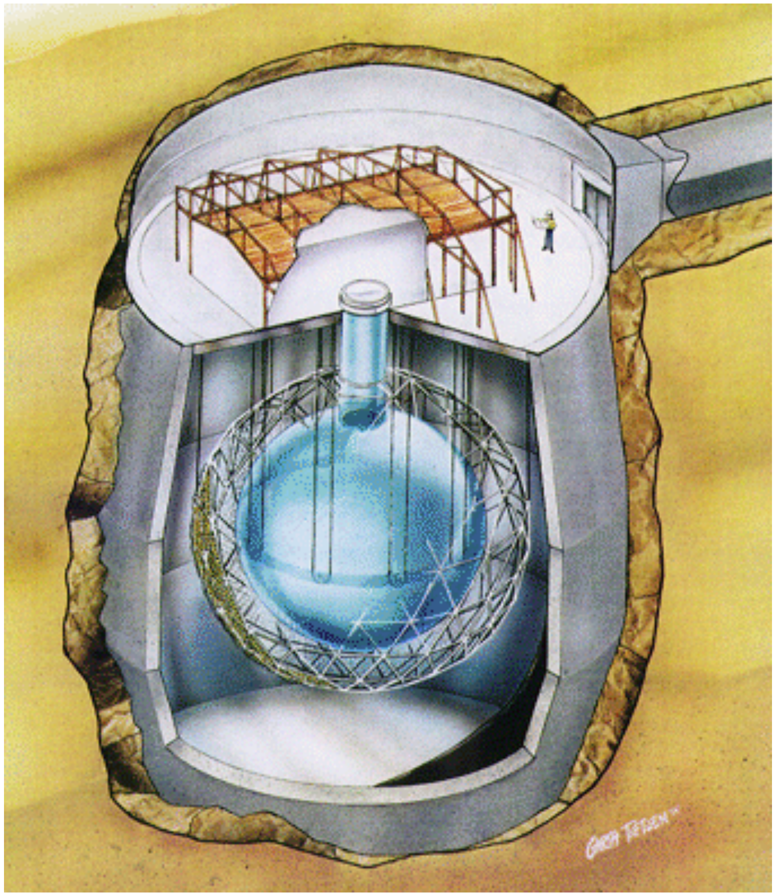
But there's another smoking gun...

- Spectral distortion
- Day/night effect: regeneration of ν_e in Earth due to matter effect enhances ν_e flux at night for some parameters
- Seasonal variation: variation with L (beyond 7% expected from Earth orbit)

No strong effects observed at Super-K (constrain parameters)

Neutral Current Excess: *direct evidence* for flavor transformation

The Sudbury Neutrino Observatory



Sudbury, Canada

1 kton D_2O, 1.7 kton H_2O

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

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

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ Elastic scattering (CC, NC)

Cherenkov light from e^-
Neutron detection

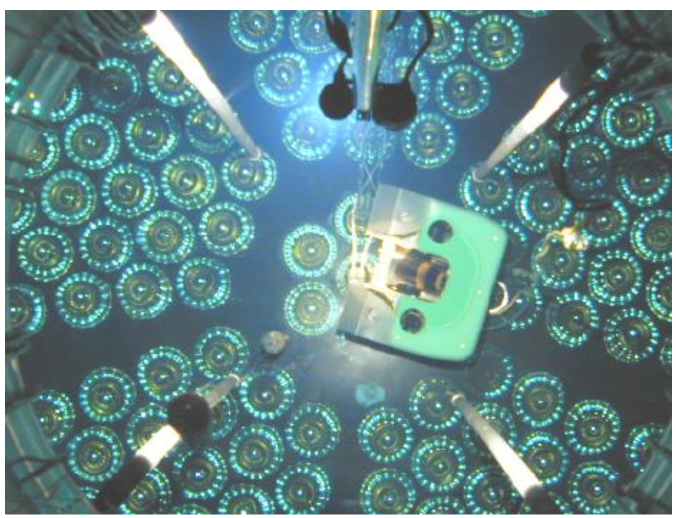
SNO's unique feature: NC detection

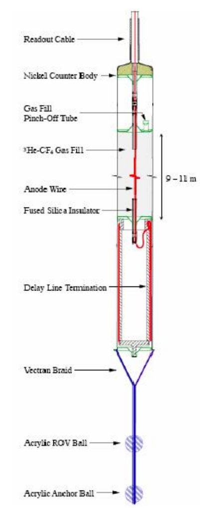
$$\nu_x + d \rightarrow \nu_x + p + n$$

flavor-blind

Tag NC via detection of neutron

- Phase I: capture on d (D_2O) $n + d \rightarrow t + \gamma + 6.25$ MeV
- Phase II: capture on Cl (salt, NaCl) $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV
- Phase III: neutron detectors (NCD) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV





Neutrino flavor information from SNO

$\nu_e + d \rightarrow p + p + e^-$ **CC** specifically tags ν_e ***component***

$\phi_{CC} = \phi(\nu_e)$

$\nu_x + d \rightarrow \nu_x + p + n$ **NC** flavor-blind $\Rightarrow$ measure *total active flux*

$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu,\tau})$ ~ **total flux**

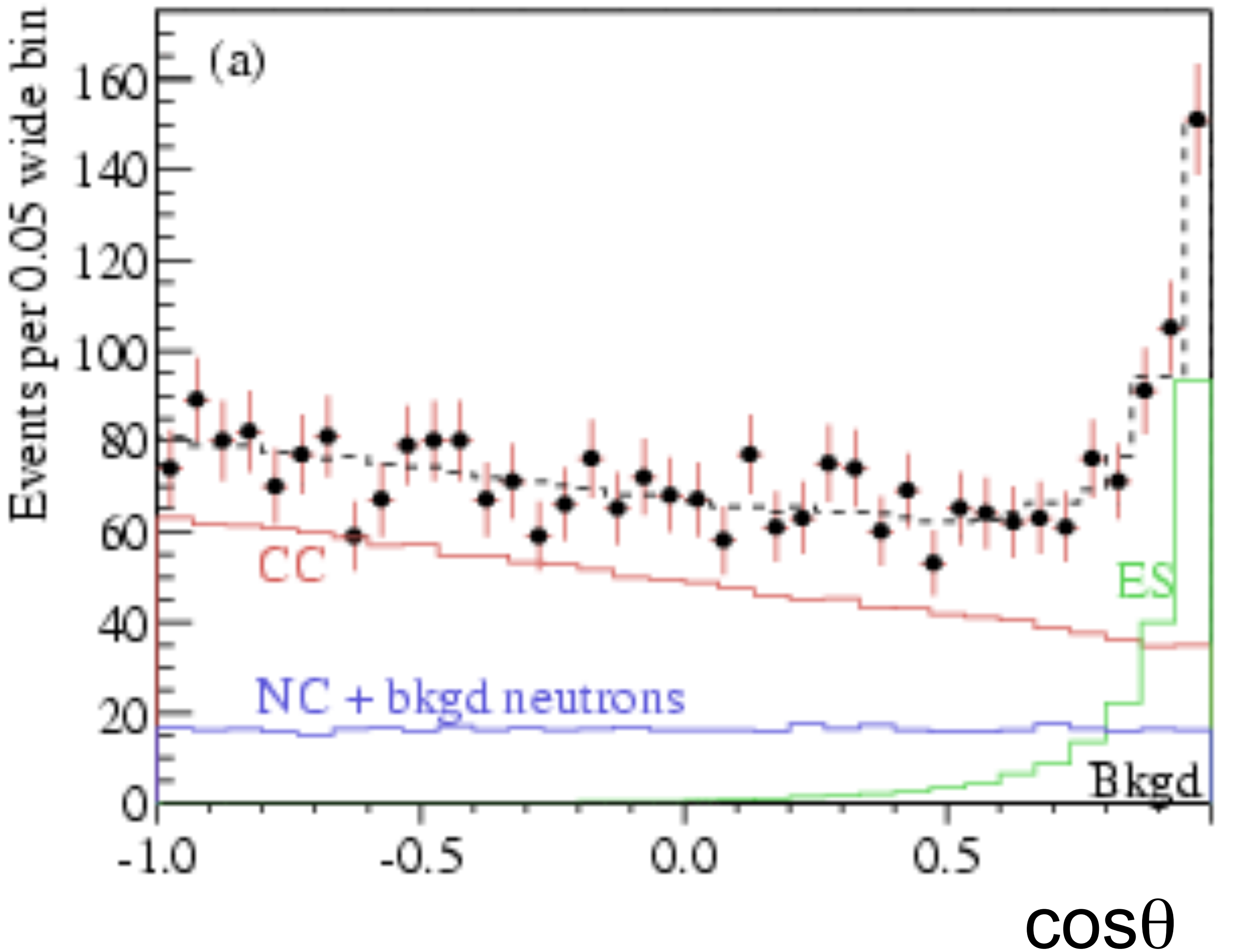
$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ **Elastic scattering (CC, NC)**

mixture of ν_e and all with *known ratio*

$\phi_{ES} = \phi(\nu_e) + 0.15\phi(\nu_{\mu,\tau})$

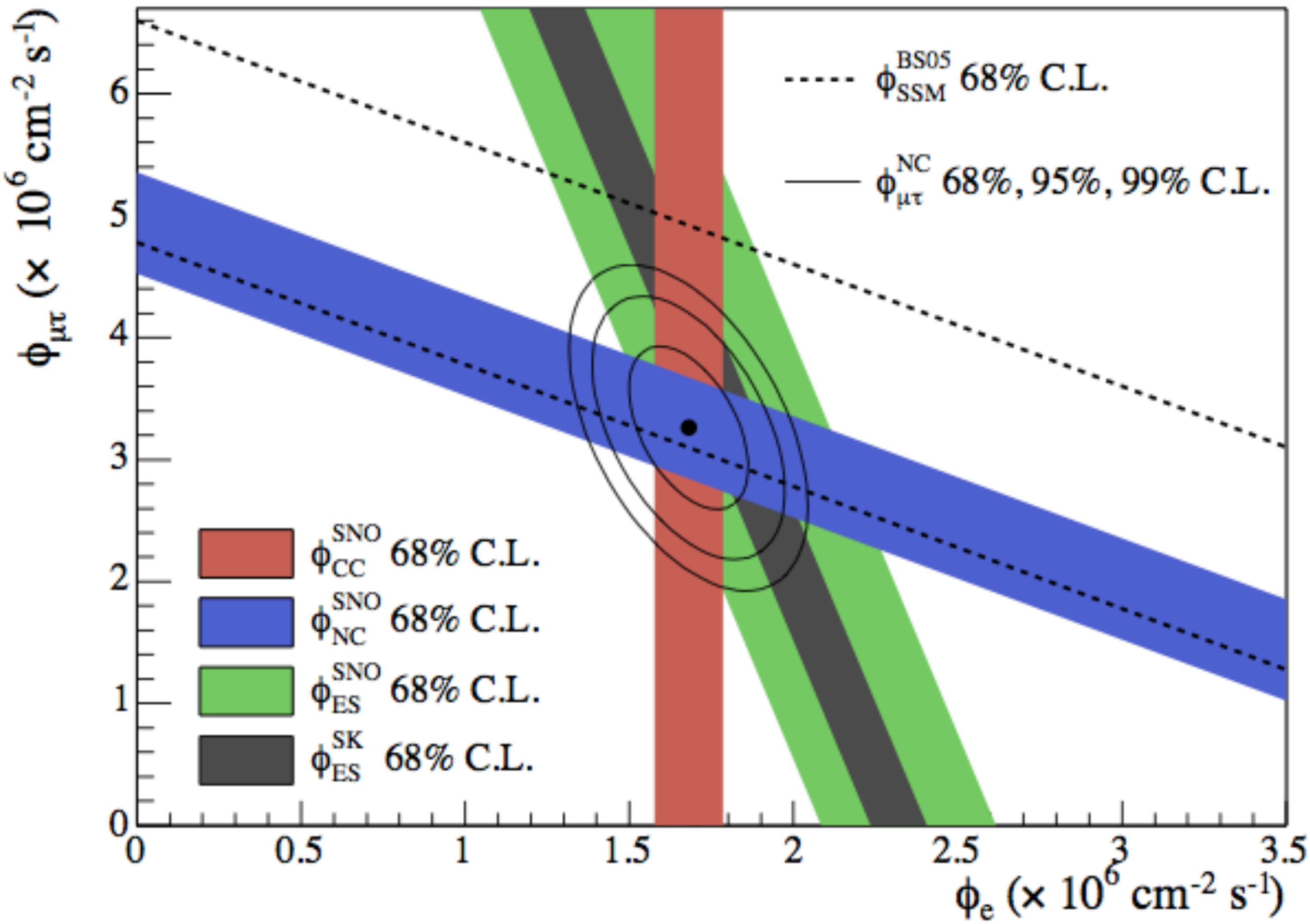
Also look for distortion of CC spectrum, night enhancement

Phase I SNO Results, 2002



Fit data for CC, NC, ES components

Clear evidence from SNO for oscillation to $\nu_{\mu,\tau}$

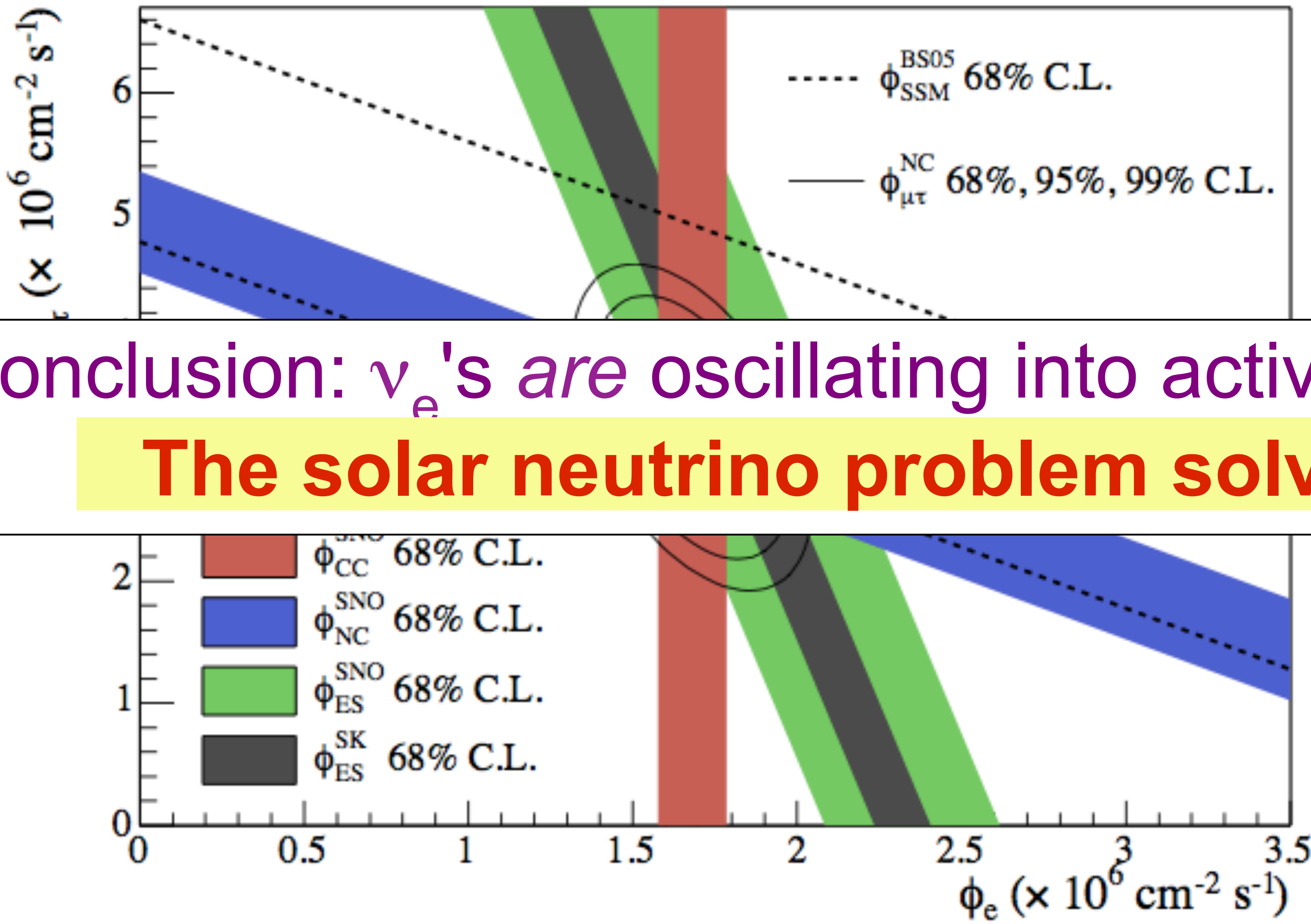


$\phi_{CC}=\phi(\nu_e)$

$\phi_{NC}= \phi(\nu_e) + \phi(\nu_{\mu,\tau})$ ~ total flux

$\phi_{ES}=\phi(\nu_e) + 0.15\phi(\nu_{\mu,\tau})$

Clear evidence from SNO for oscillation to $\nu_{\mu,\tau}$



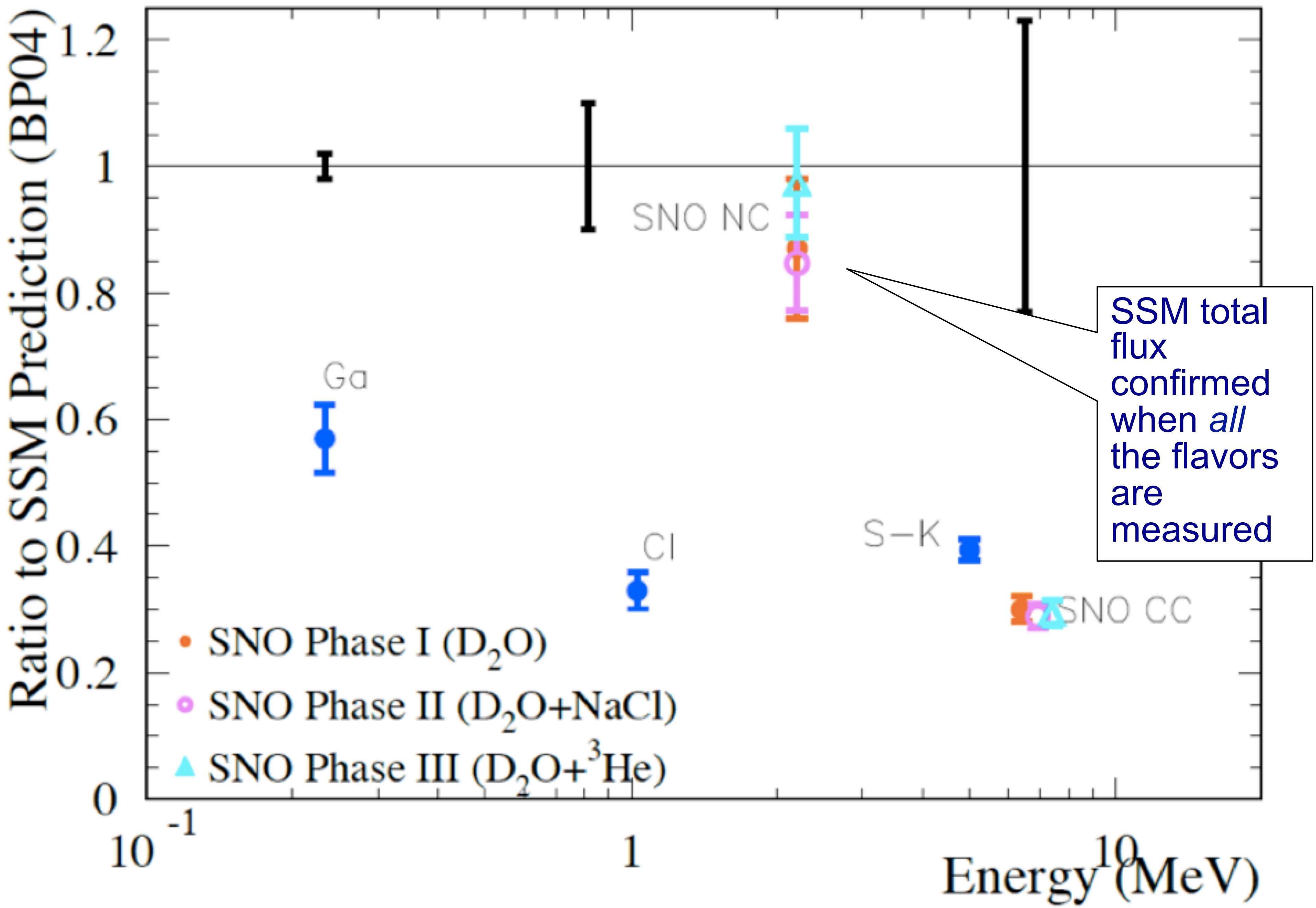
Conclusion: ν_e's *are* oscillating into active ν's!

The solar neutrino problem solved!

$\phi_{CC}=\phi(\nu_e)$

$\phi_{NC}=\phi(\nu_e)+\phi(\nu_{\mu,\tau})$ ~ total flux

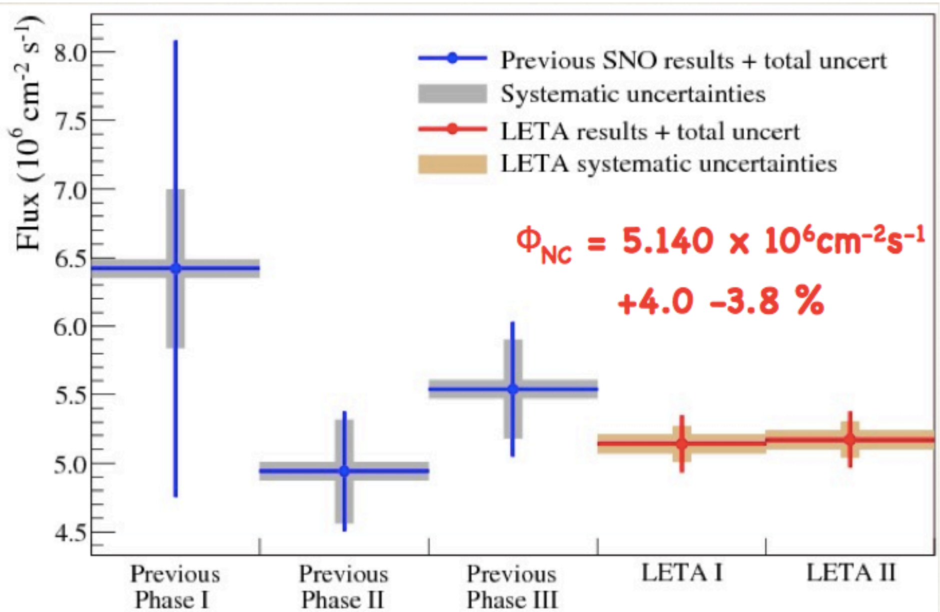
$\phi_{ES}=\phi(\nu_e)+0.15\phi(\nu_{\mu,\tau})$



Ratio to SSM Prediction (BP04)
1.2
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
Energy (MeV)
Ga
Cl
SNO NC
S−K
SNO CC
SNO Phase I (D_2O)
SNO Phase II (D_2O+NaCl)
SNO Phase III ($D_2O+{}^3He$)
SSM total flux confirmed when *all* the flavors are measured

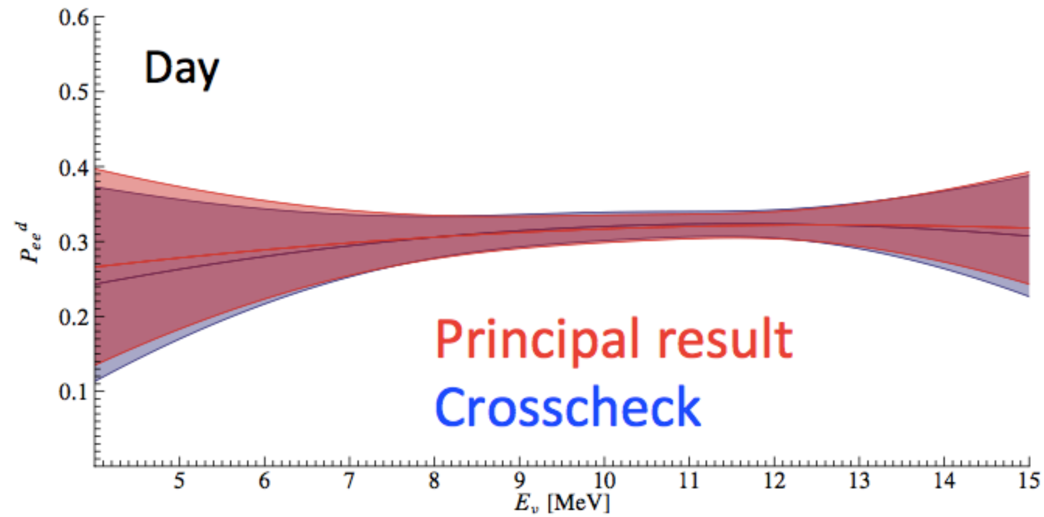
G. Orebi-Gann

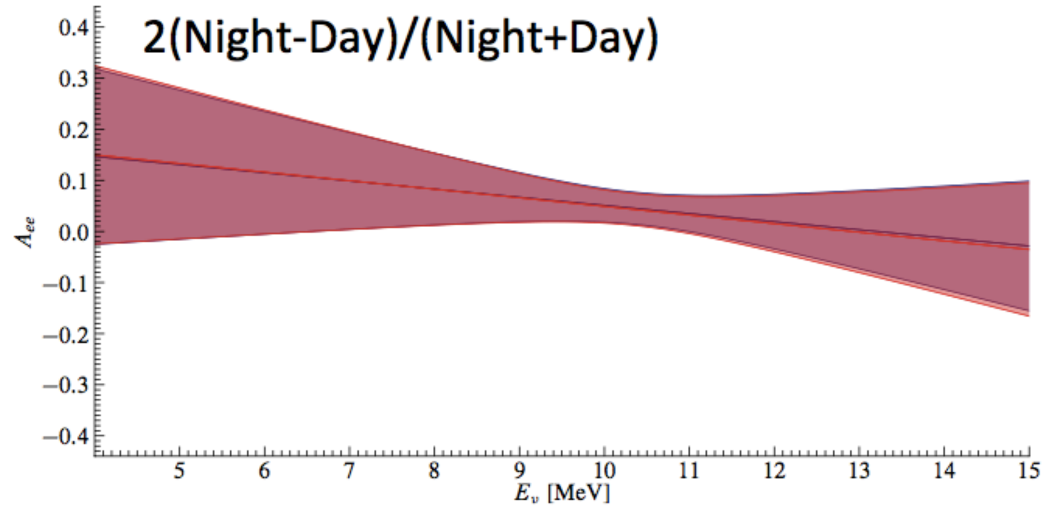
SNO Final Analysis Results



LETA: Low Energy Threshold Analysis

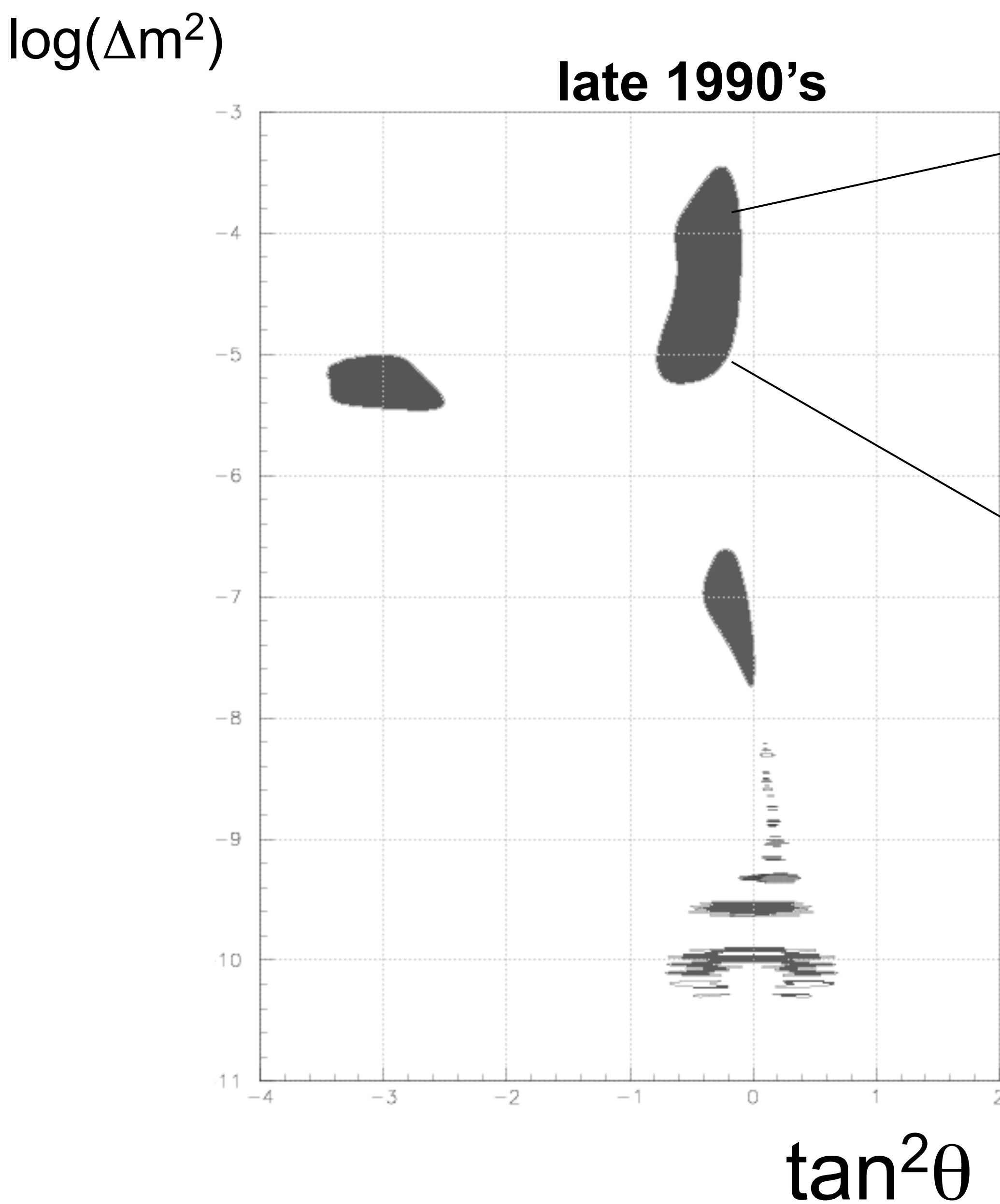
Electron neutrino survival probability vs ν energy

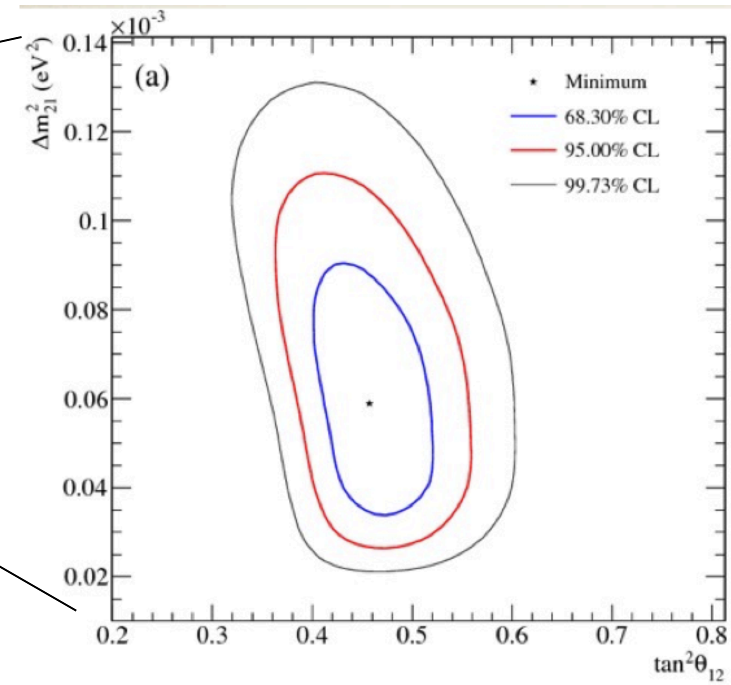




Energy spectrum & day/night effect (matter in Earth) from SNO & SK constrain oscillation parameters

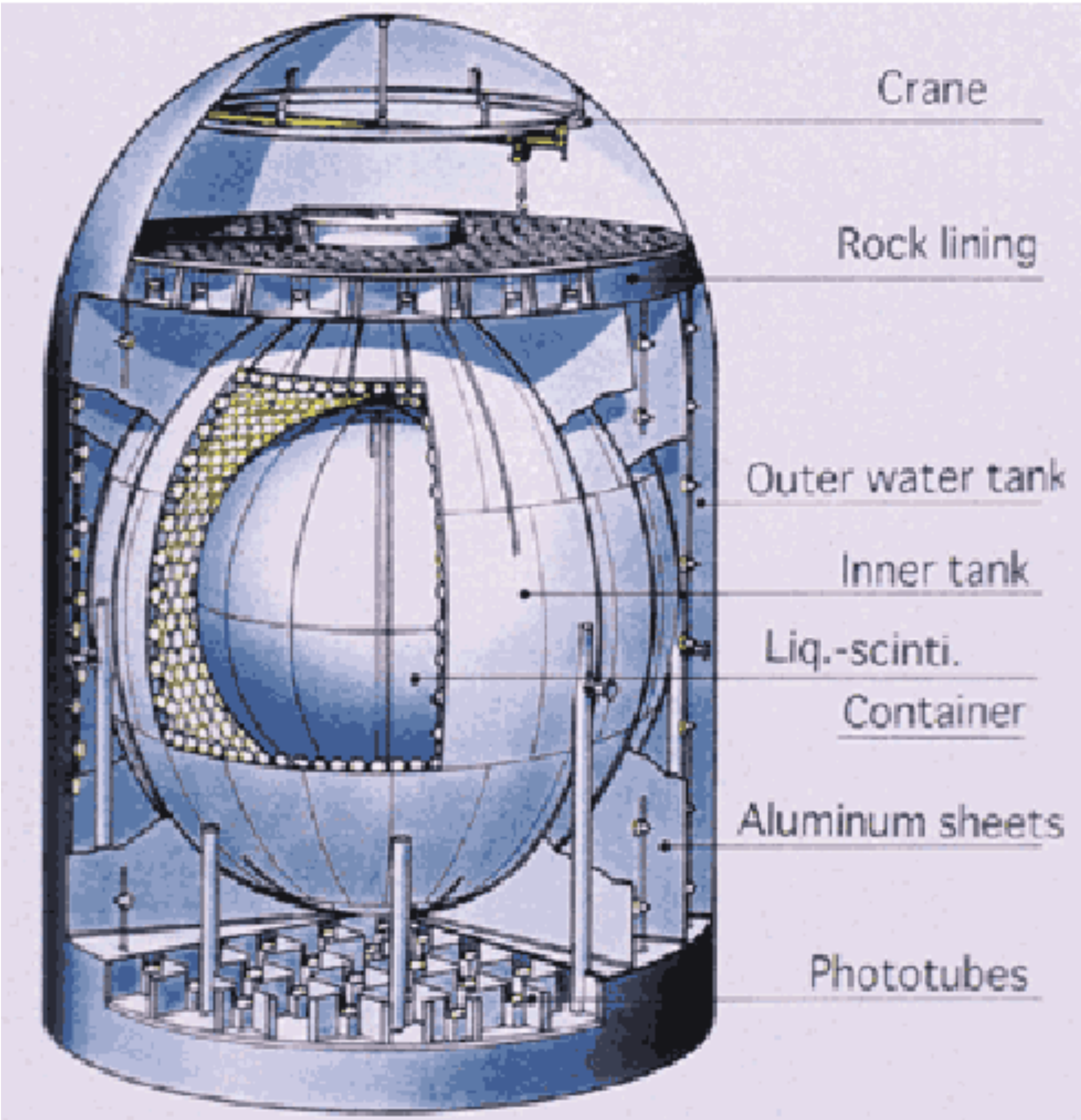
Oscillation parameters measured with “wild” solar neutrinos...





... next, an independent check and more information with “tame” ones...

The KamLAND Experiment

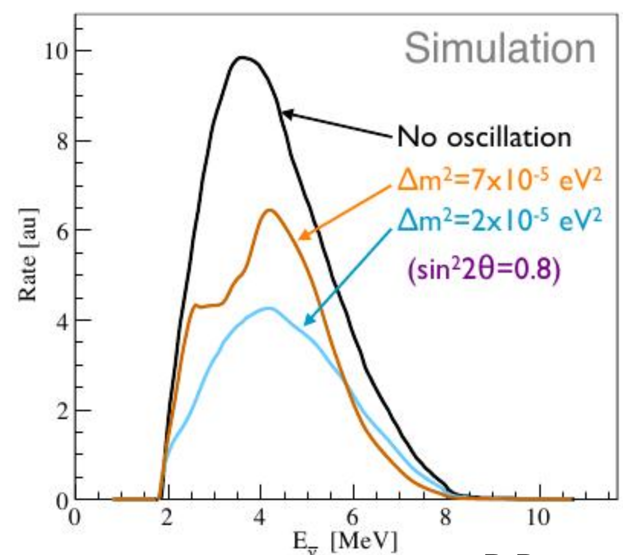


Mozumi, Japan

Look at solar LMA parameter space using *reactor antineutrinos*

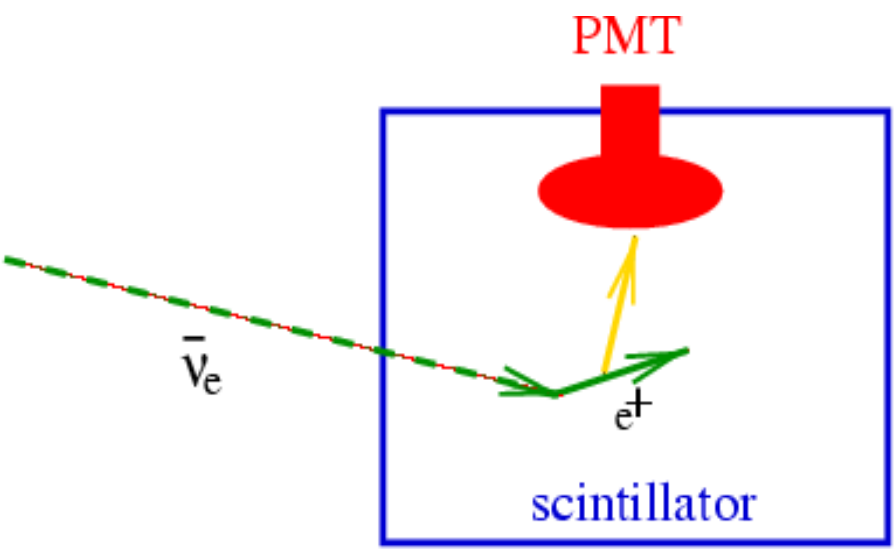
Sum of reactor fluxes from Japan, Korea

E_ν~few MeV, L~180 km (no matter effects)



P. Decowski

Scintillation detectors



Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

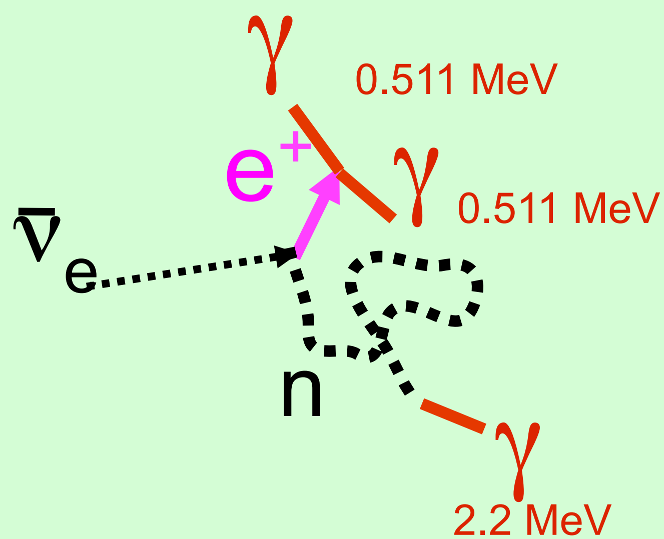
- lots of photons
➔ low threshold, good neutron tagging possible

- little directional capability (light is ~isotropic)

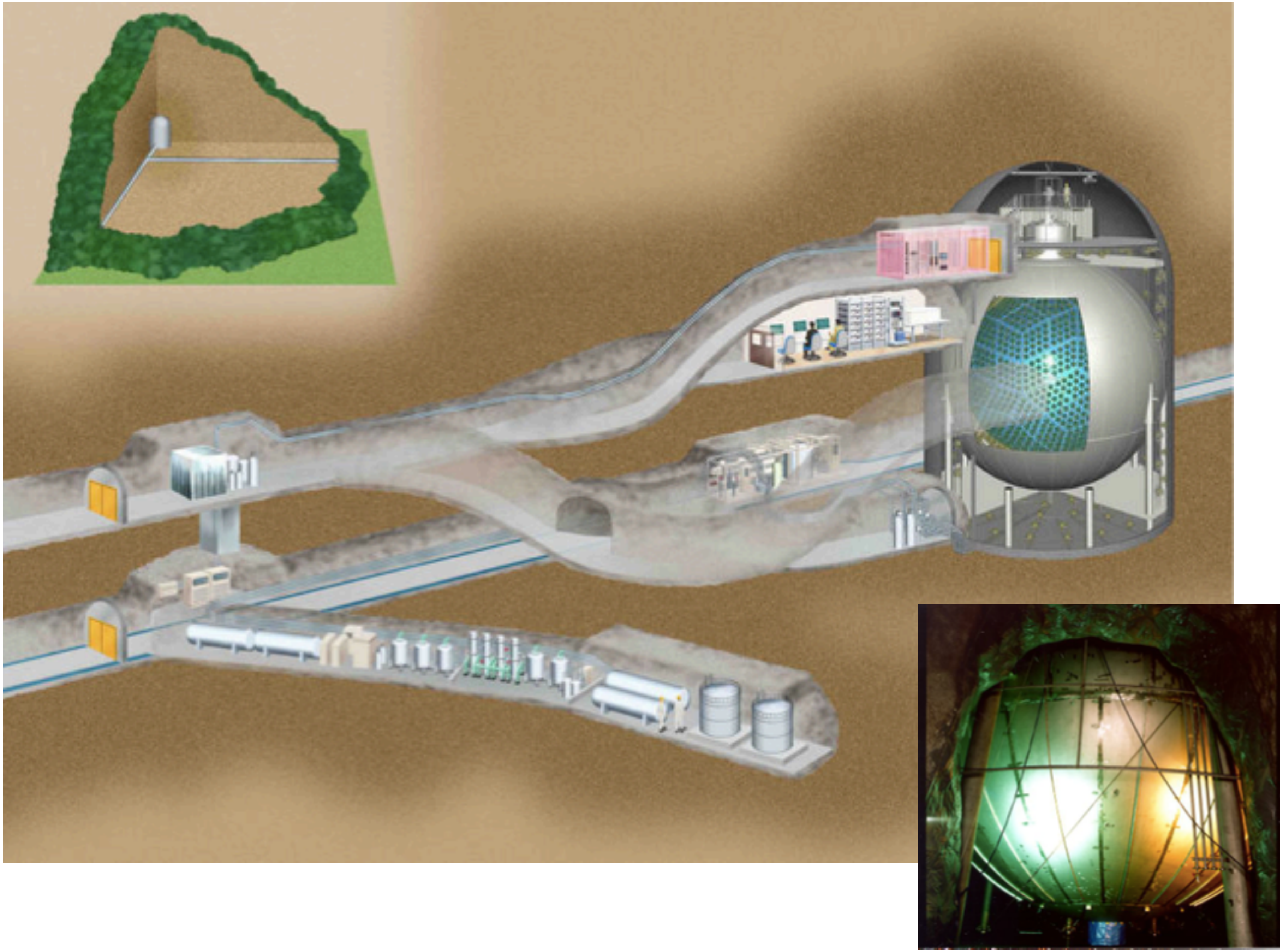
Inverse Beta Decay (CC)

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

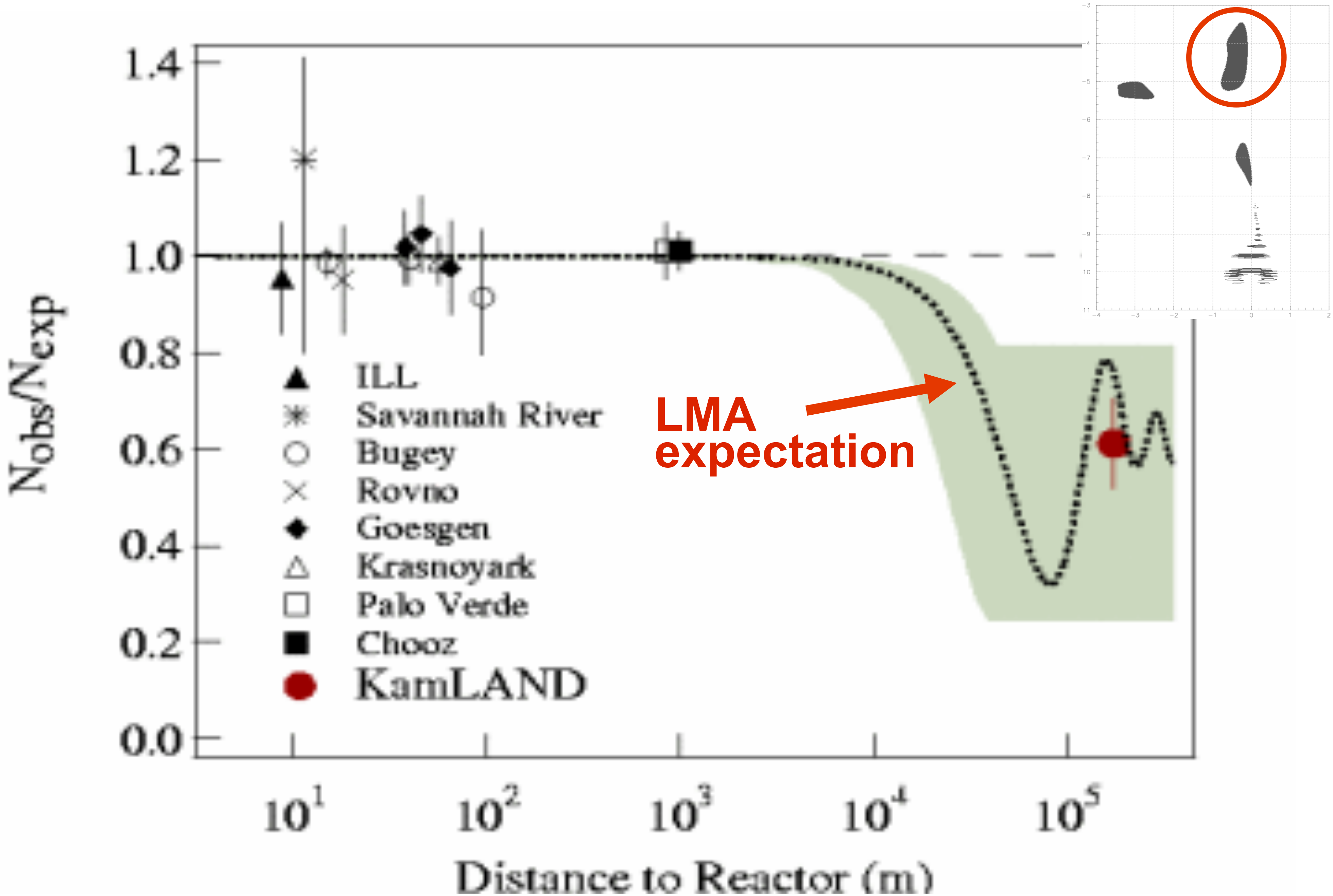
In any detector with lots of free protons (e.g. water, scint) this dominates



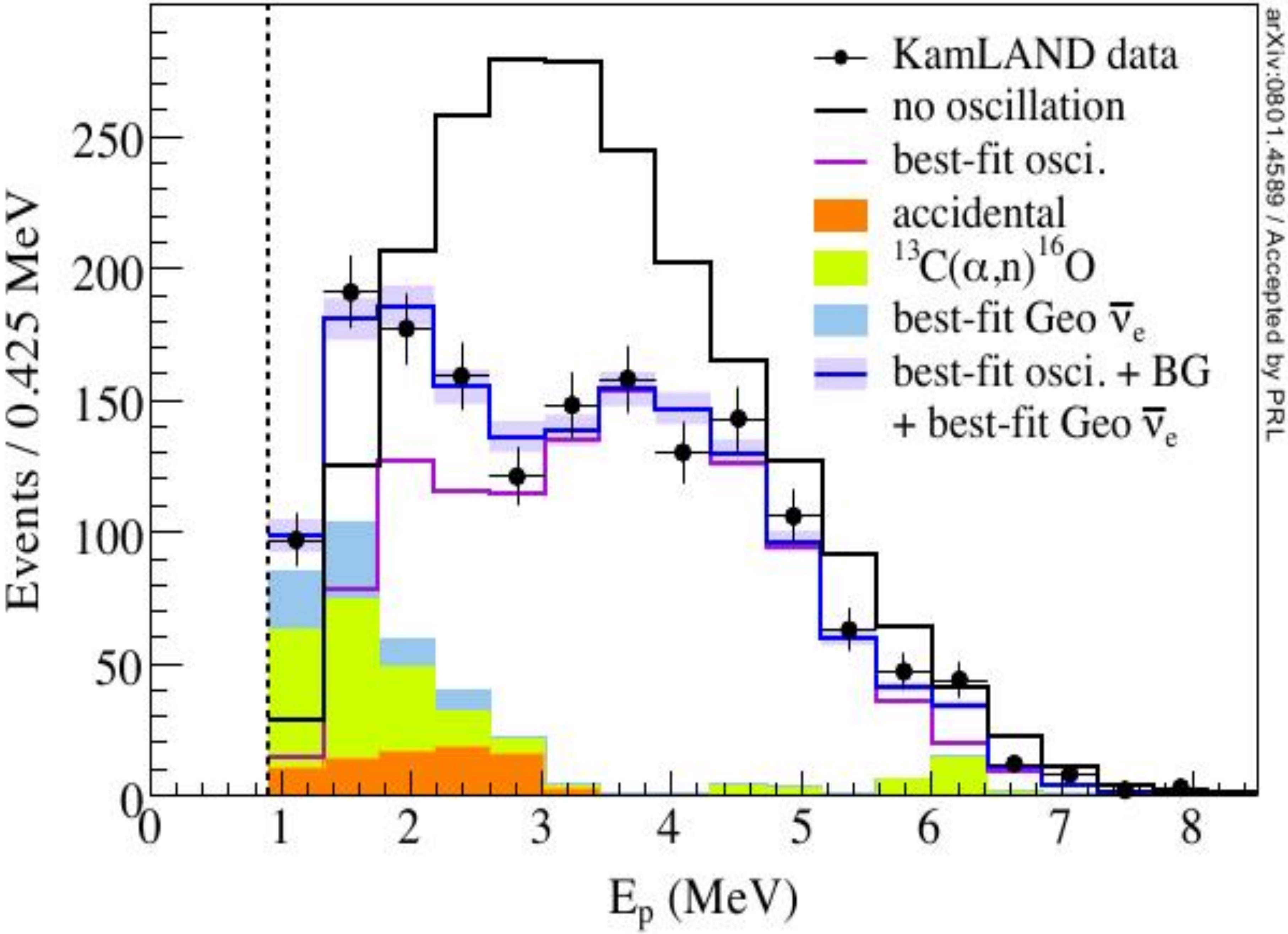
KamLAND: 1 kton scintillator



First KamLAND result (2003): observed suppression of reactor $\overline{\nu}_e$'s selects the LMA region

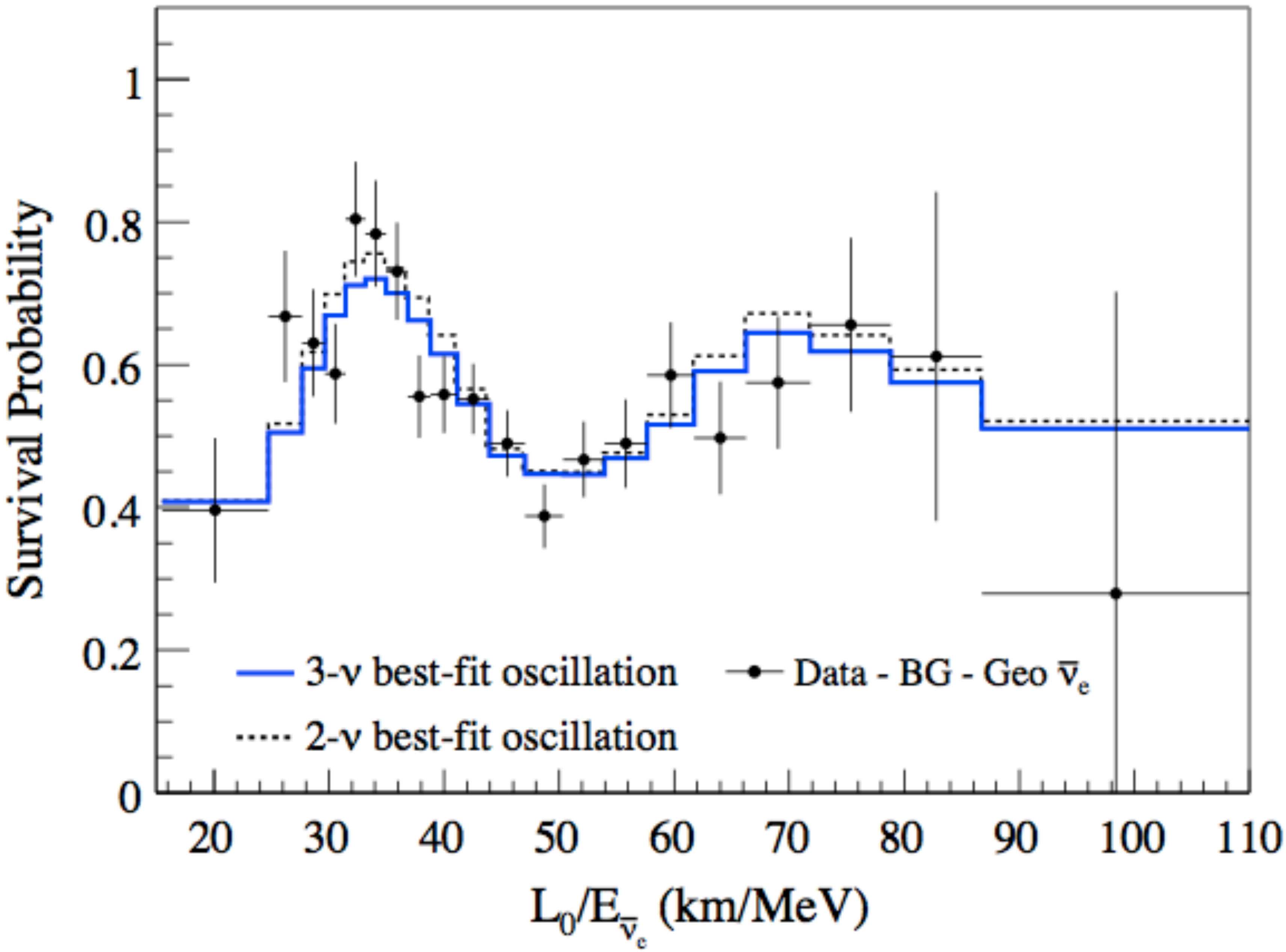


KamLAND observed spectrum



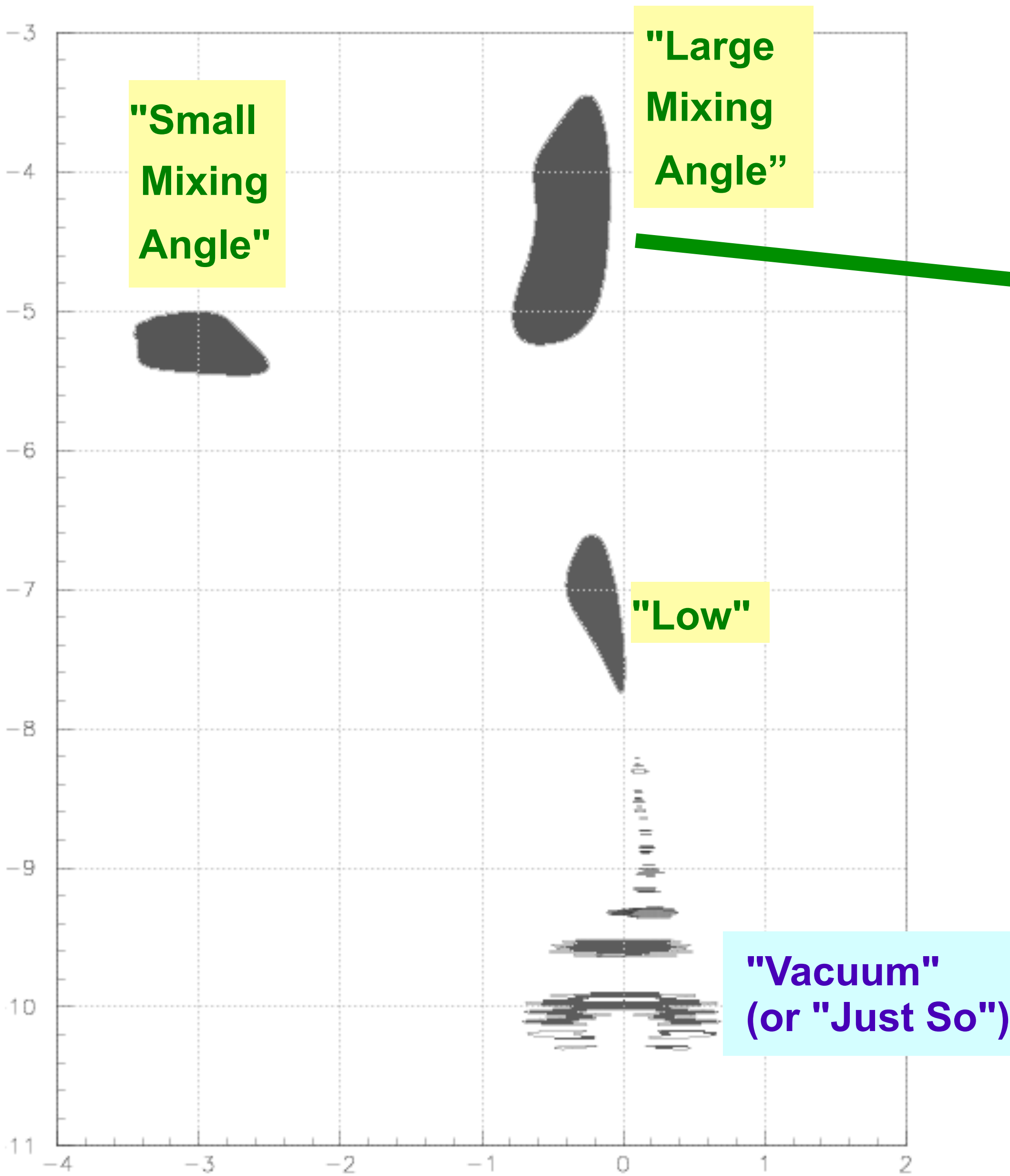
KamLAND oscillation pattern from measured antineutrino spectrum

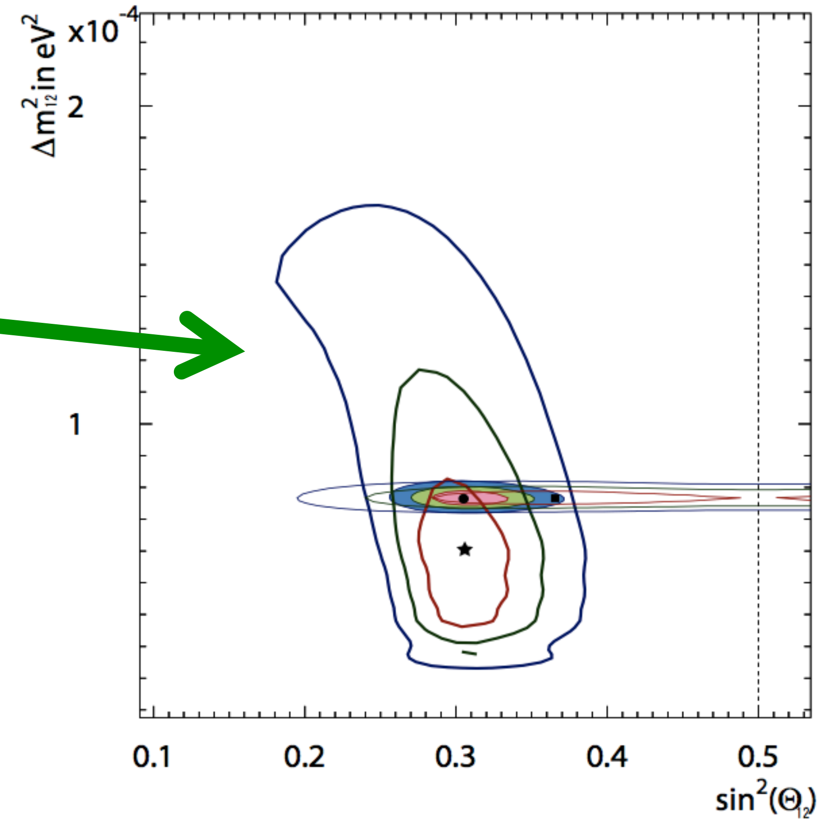
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Average flux-weighted baseline L_0 =180 km

Overall fit to the solar+KamLAND data



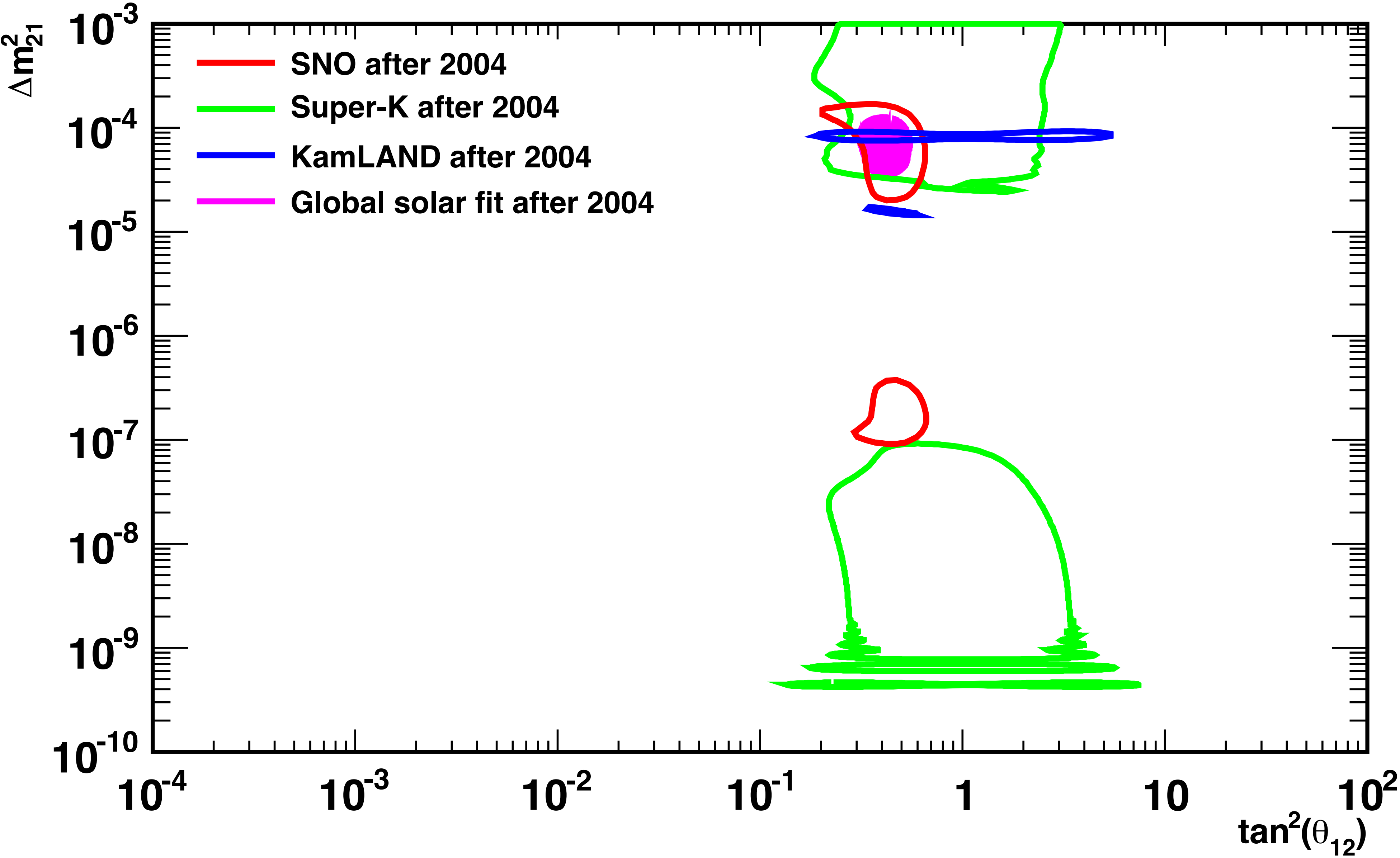


KamLAND narrows the Δm^2 range, in the LMA region

Global fit shows that mixing is *not* maximal

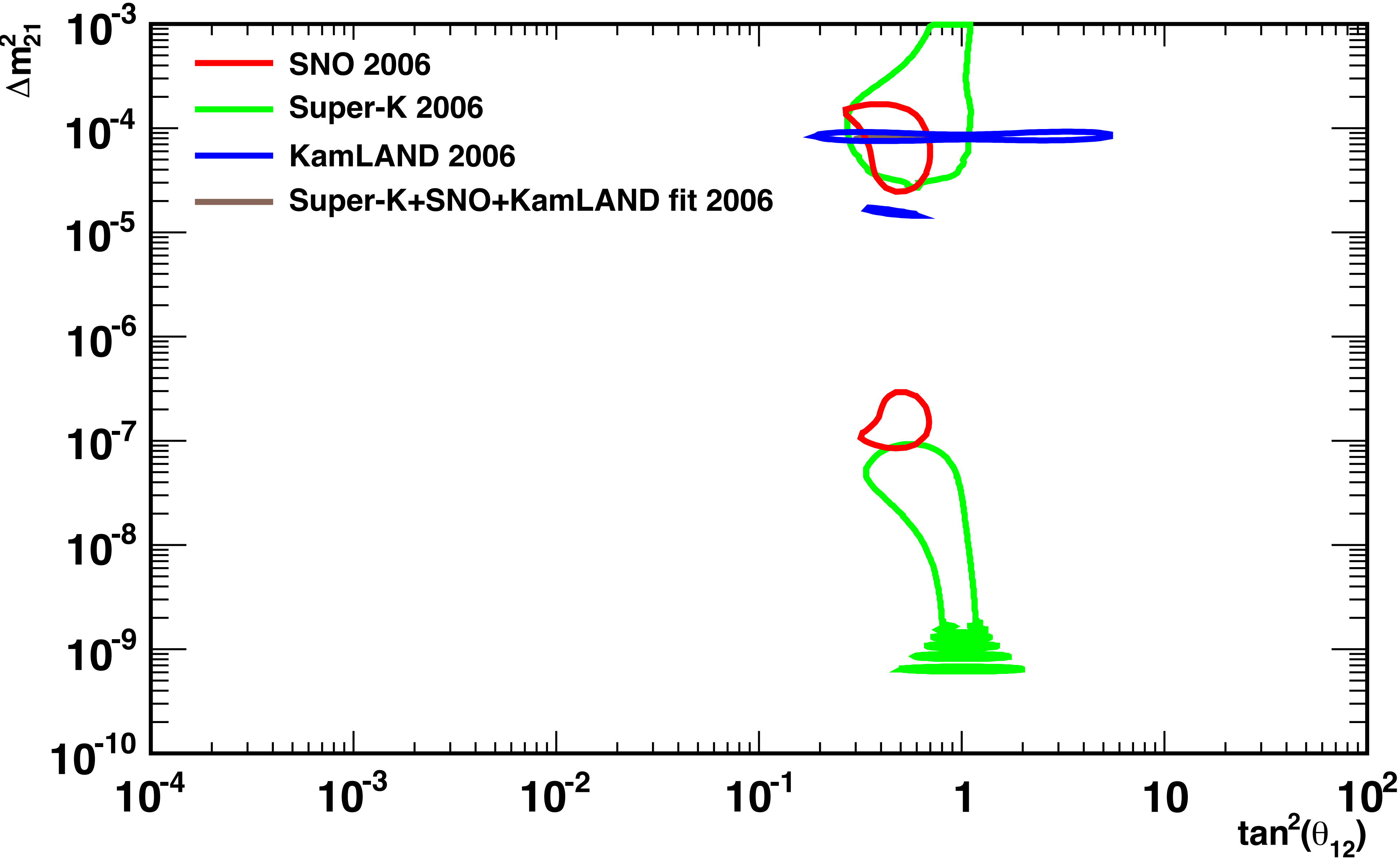
A “movie” over 8 years of solar parameter space

plots made by H. Lim from
H. Murayama’s PDG web page



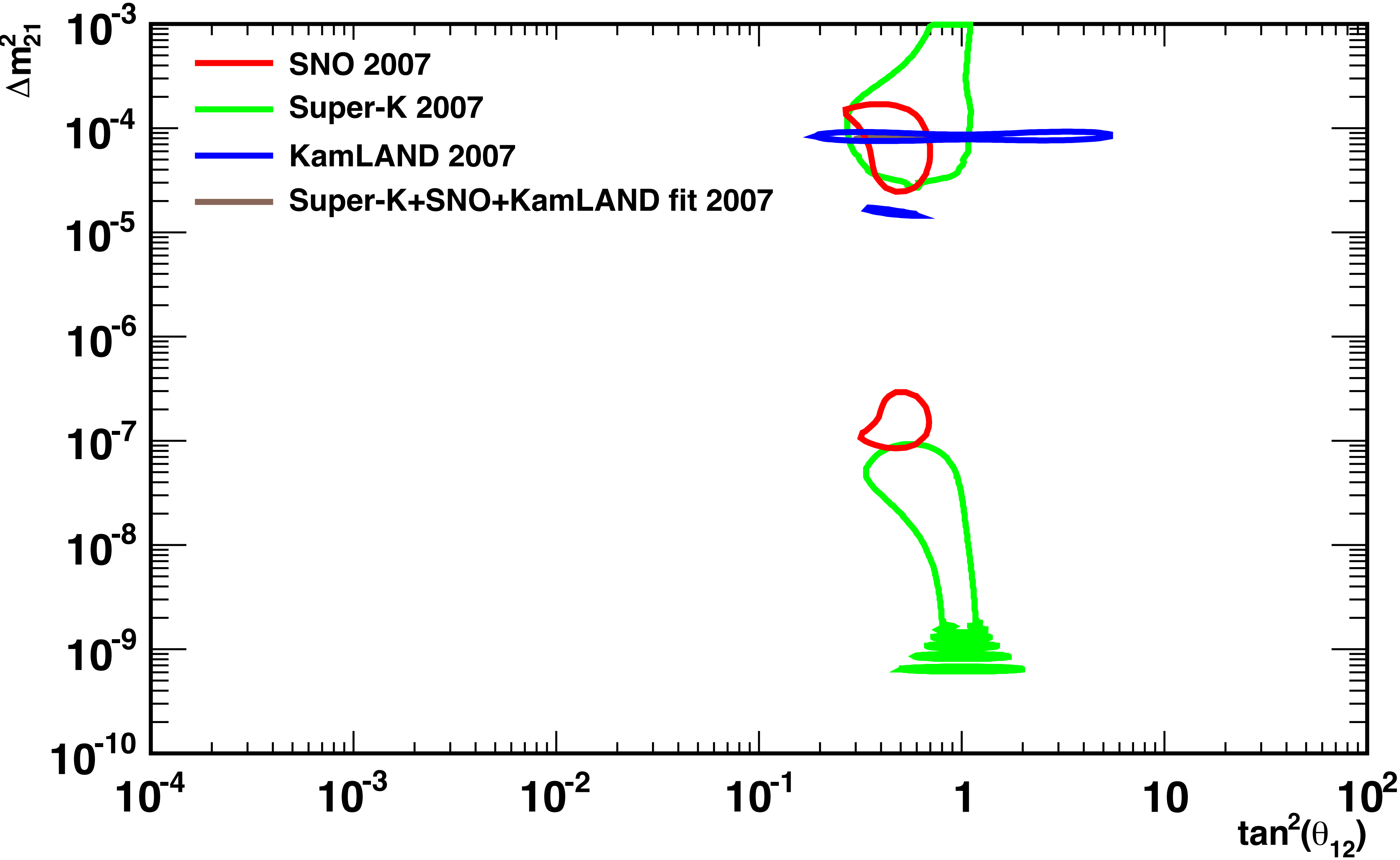
Δm^2_{21}
SNO after 2004
Super-K after 2004
KamLAND after 2004
Global solar fit after 2004
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2004



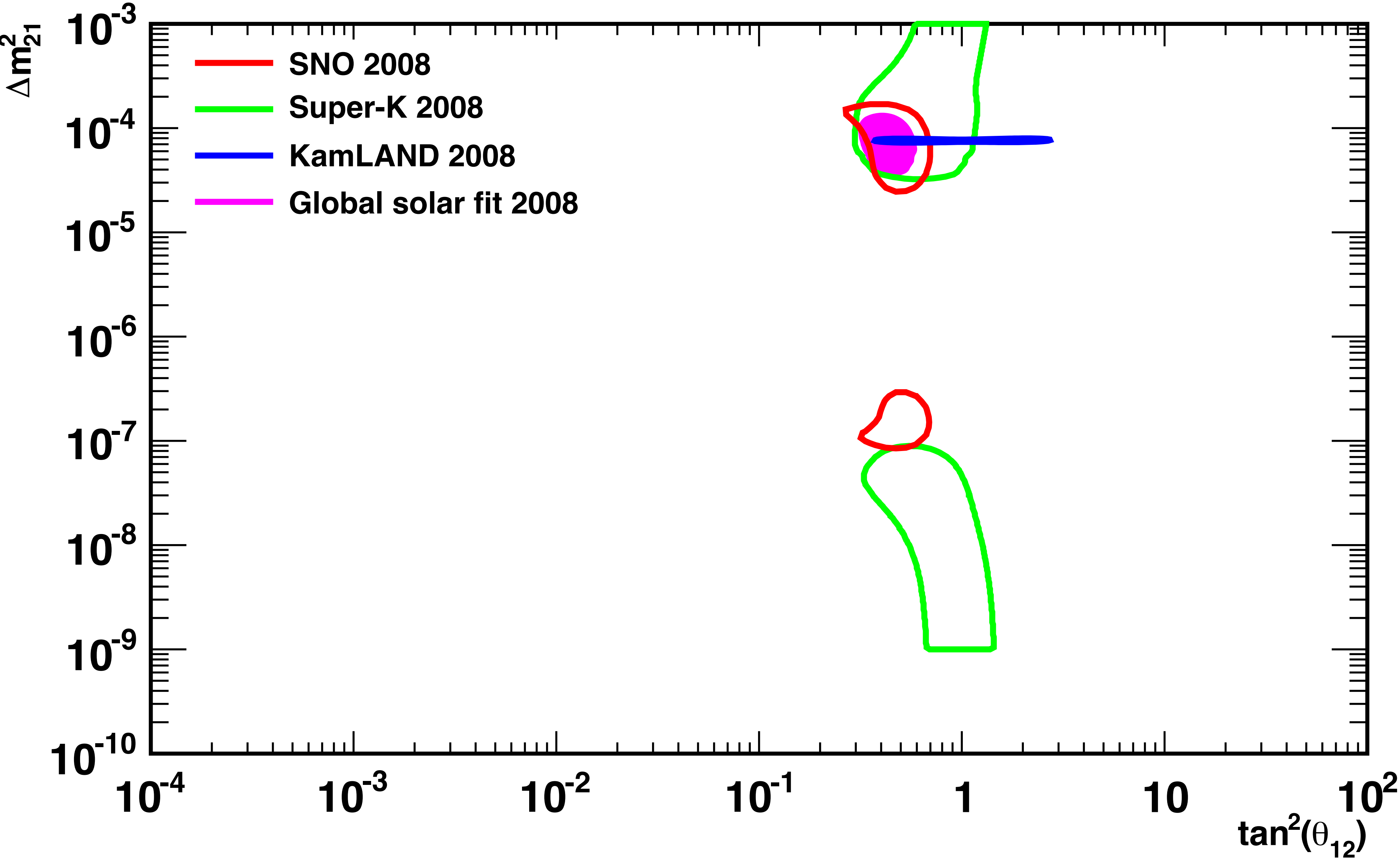
SNO 2006
Super-K 2006
KamLAND 2006
Super-K+SNO+KamLAND fit 2006
Δm^2_{21}
$\tan^2(\theta_{12})$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}

2006



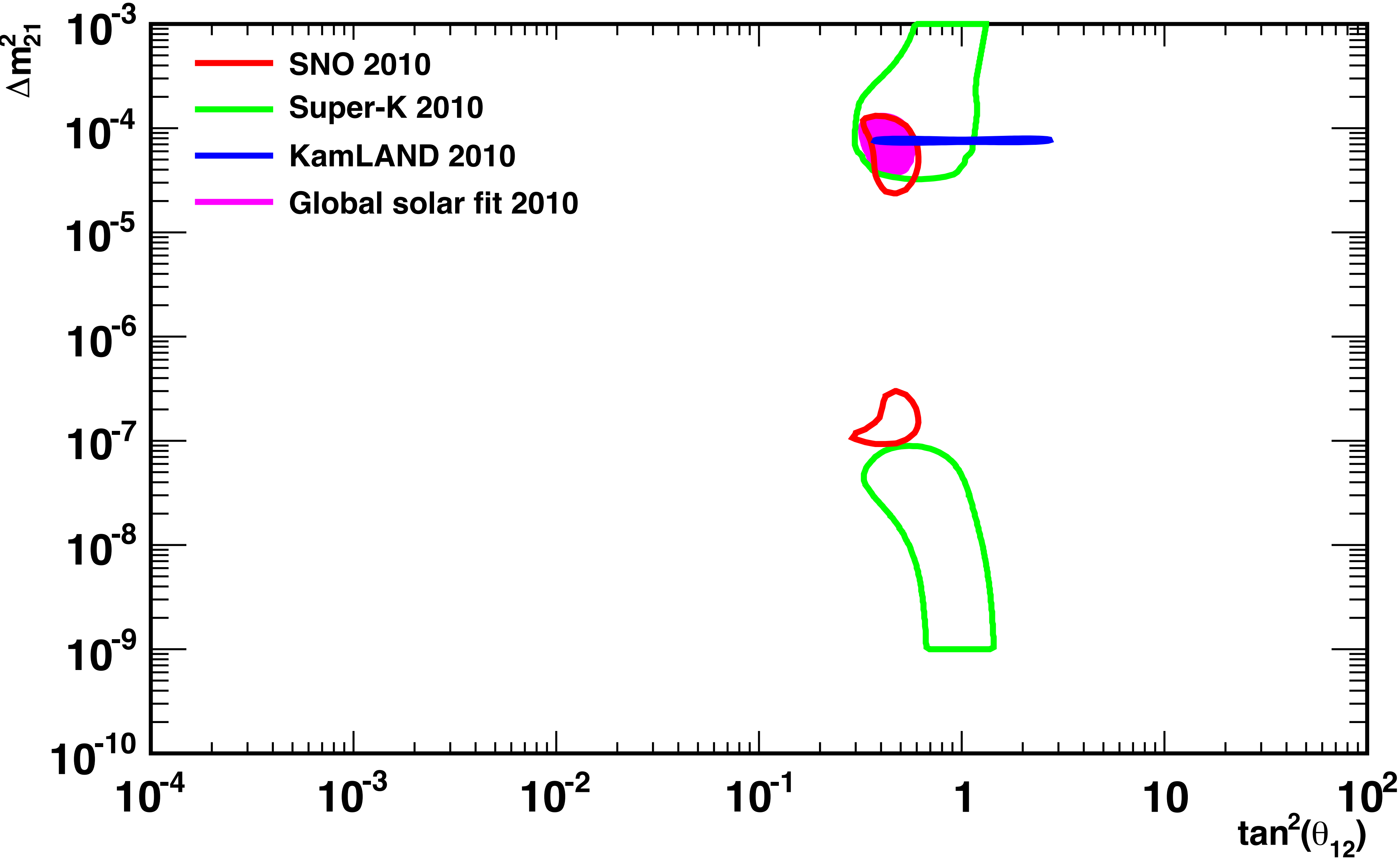
SNO 2007
Super-K 2007
KamLAND 2007
Super-K+SNO+KamLAND fit 2007
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2007

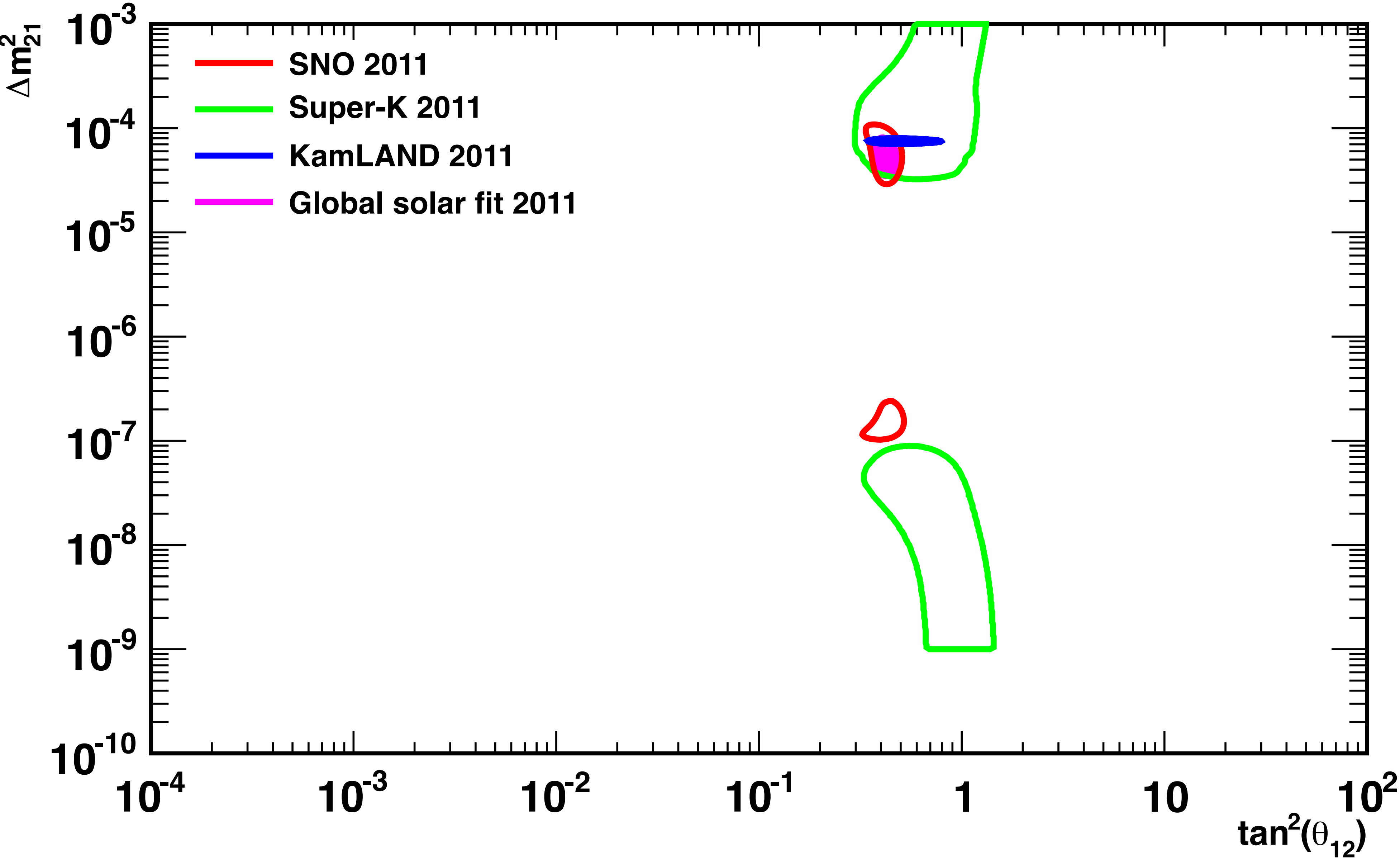


Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2008
Super-K 2008
KamLAND 2008
Global solar fit 2008
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

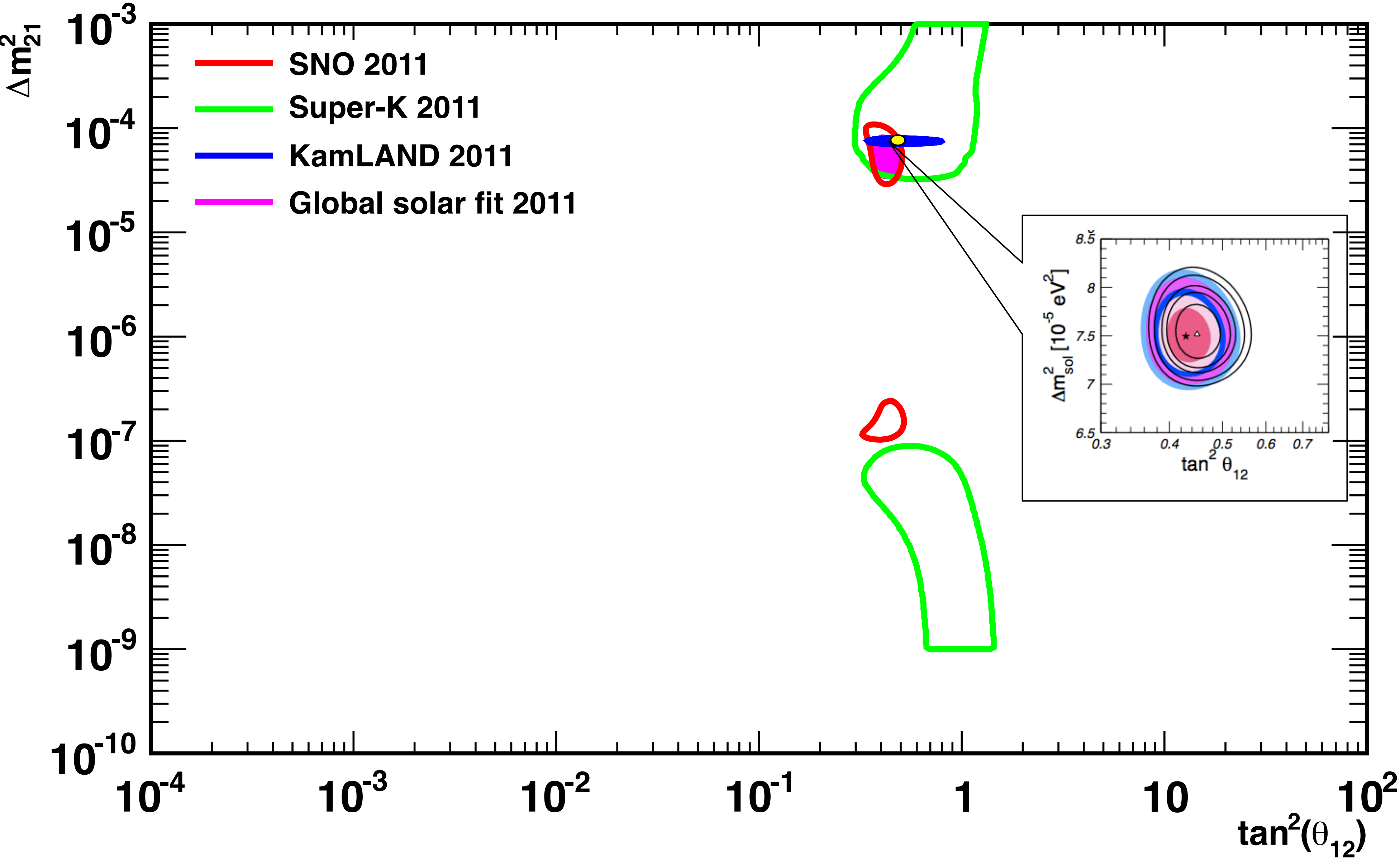
2008


Δm^2_{21}
SNO 2010
Super-K 2010
KamLAND 2010
Global solar fit 2010
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2010


Δm^2_{21}
SNO 2011
Super-K 2011
KamLAND 2011
Global solar fit 2011
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

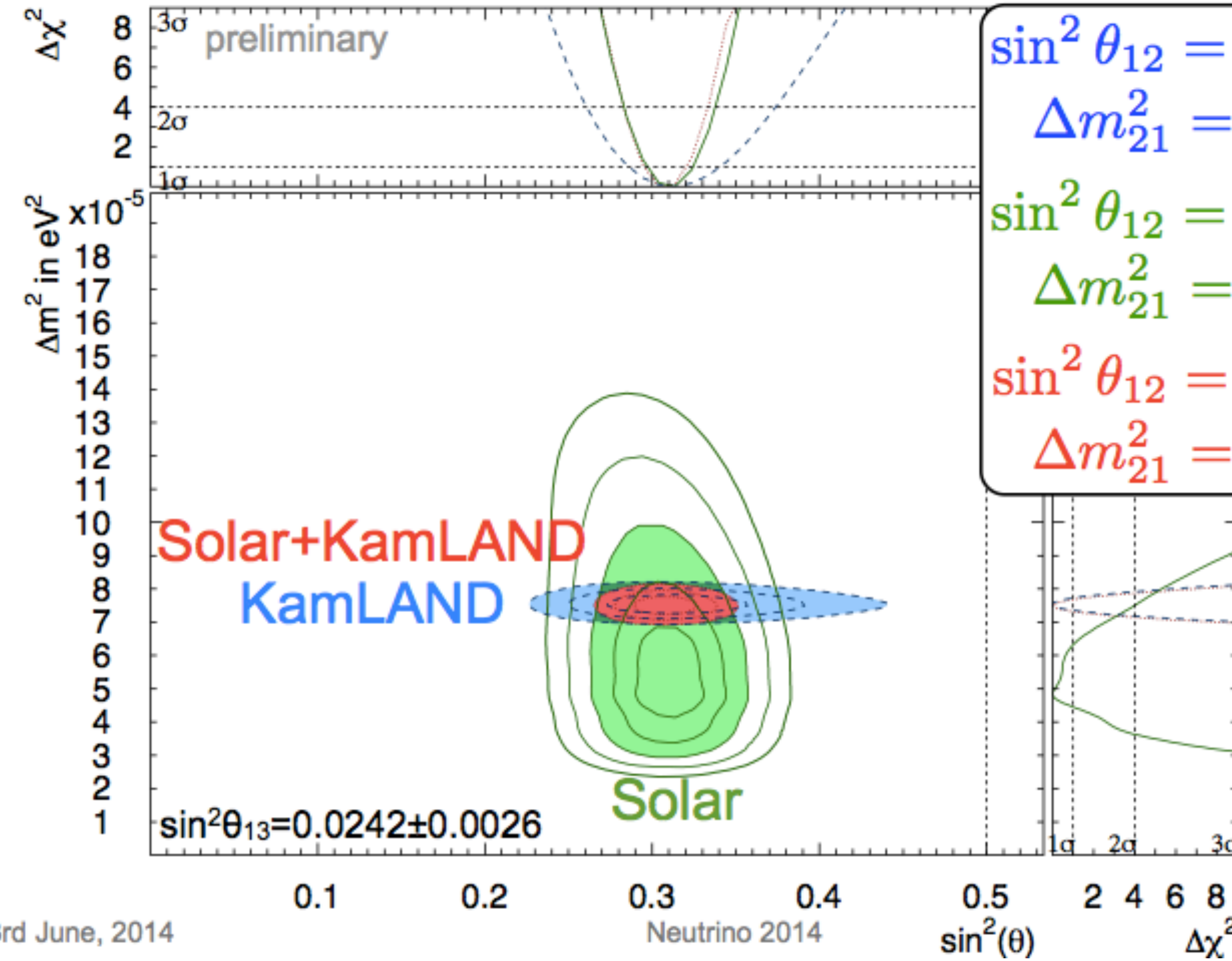
2011



2011

Recent global fit (solar + KL) from C. Gonzalez-Garcia, ICHEP 2012

The very latest global fit



$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$

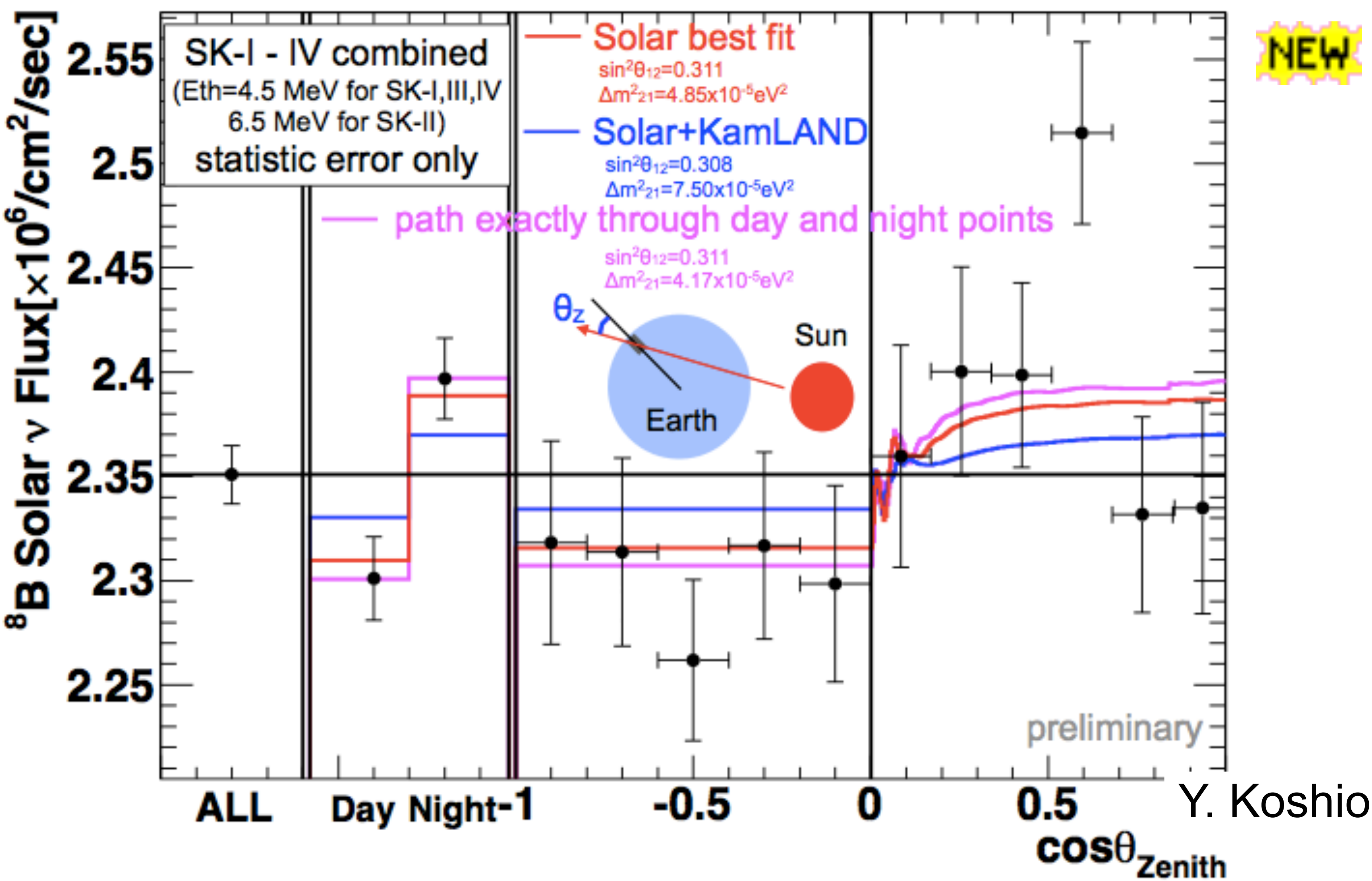
$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$

The unit of Δm^2_{21} is 10^{-5} eV^2

Y. Koshio

And new from SK:

day/night asymmetry observed:
first direct observation of matter effects

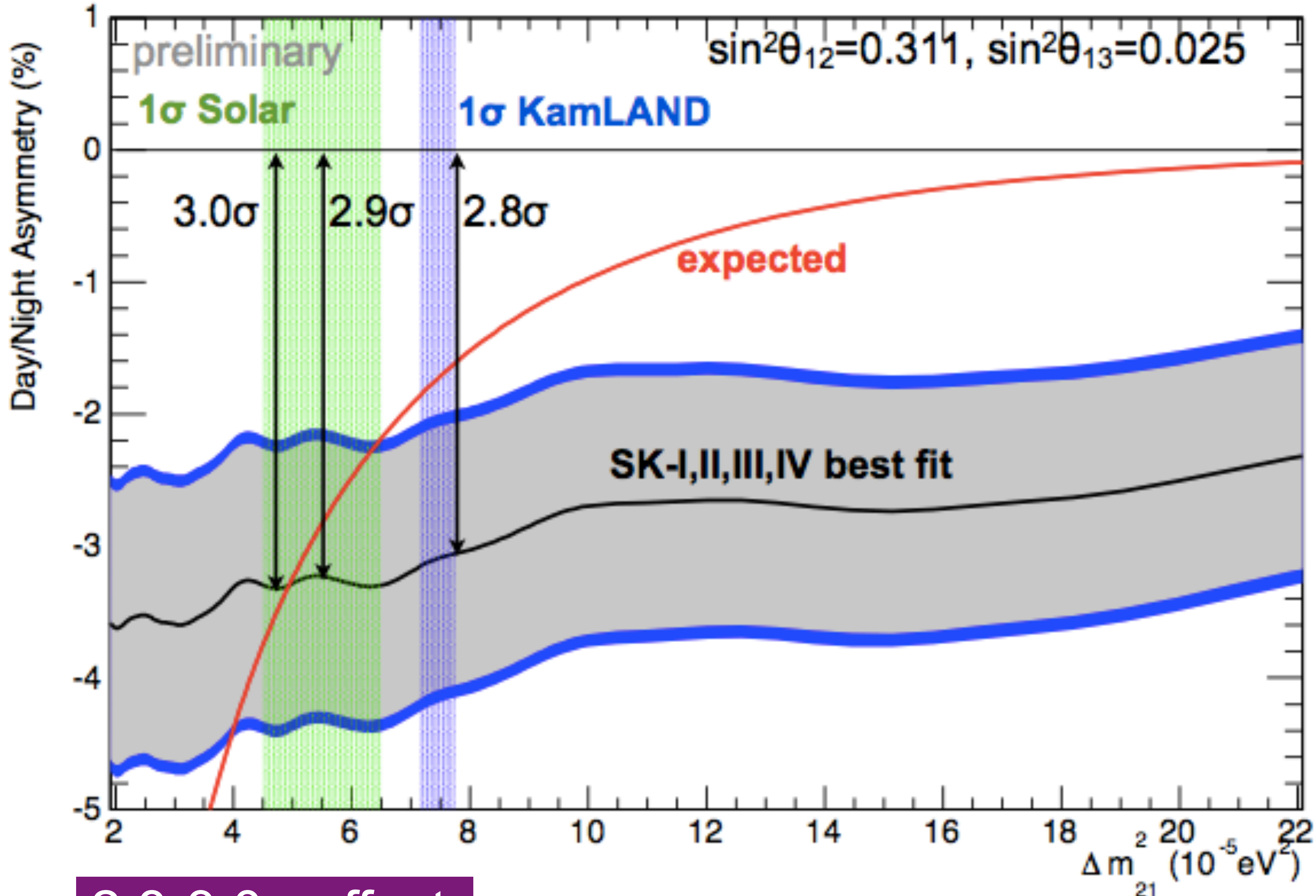


Y. Koshio

rd J

NEW

SK-I/II/III/IV Combine Day/Night Asymmetry

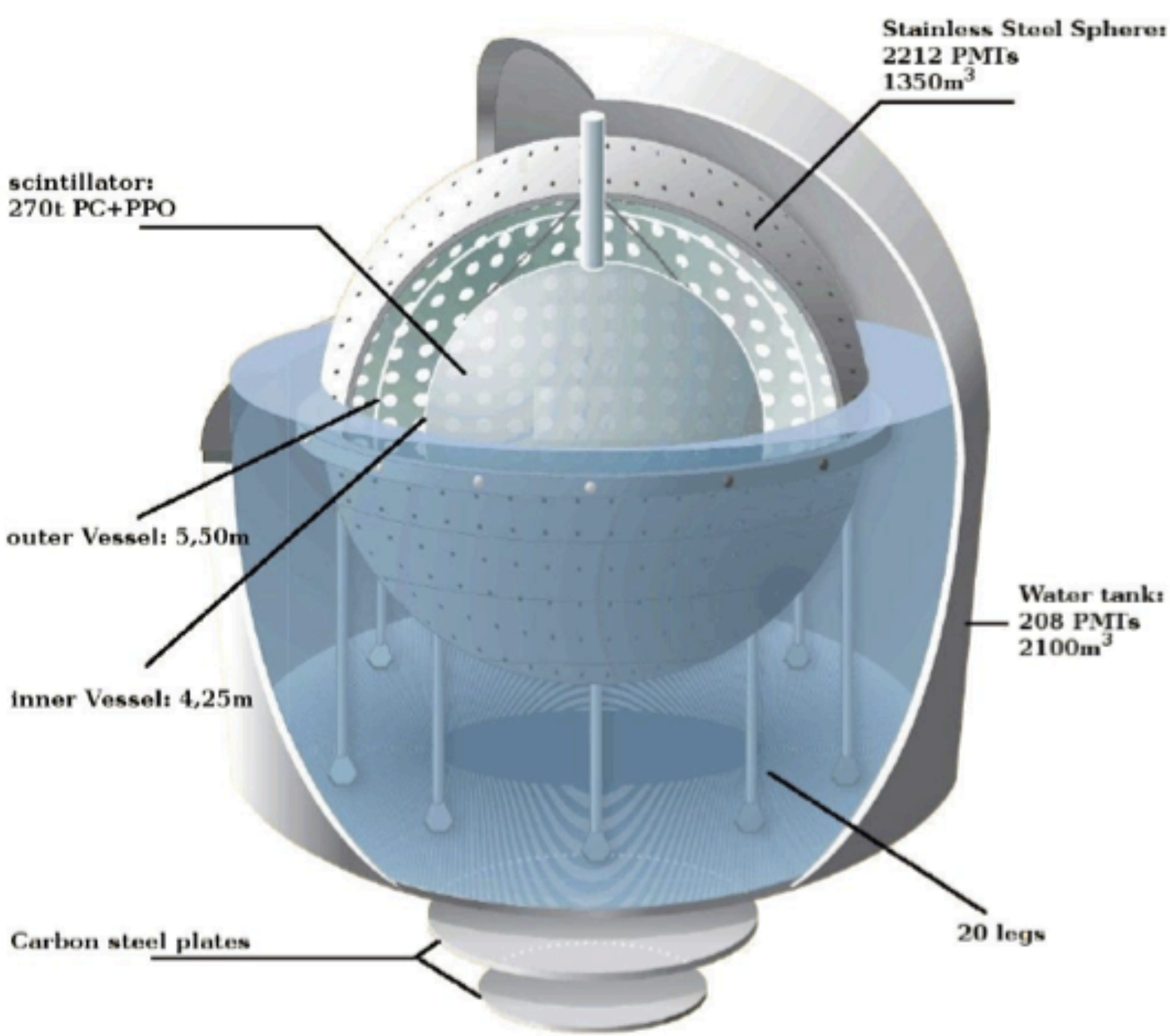


2.8-3.0σ effect

Y. Koshio

But there's more: the Borexino Experiment

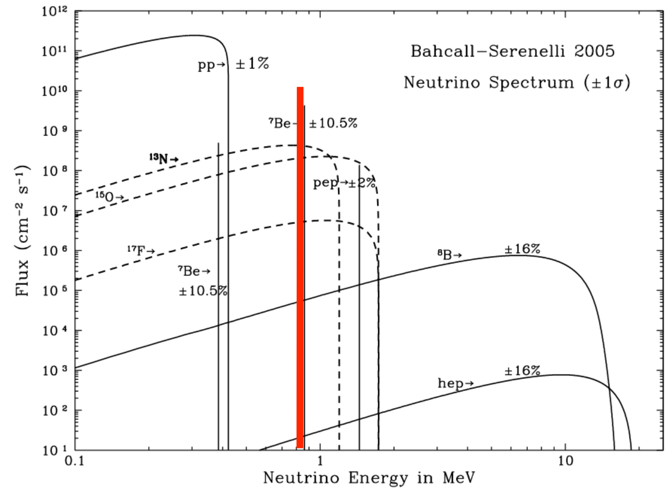
Gran Sasso, Italy

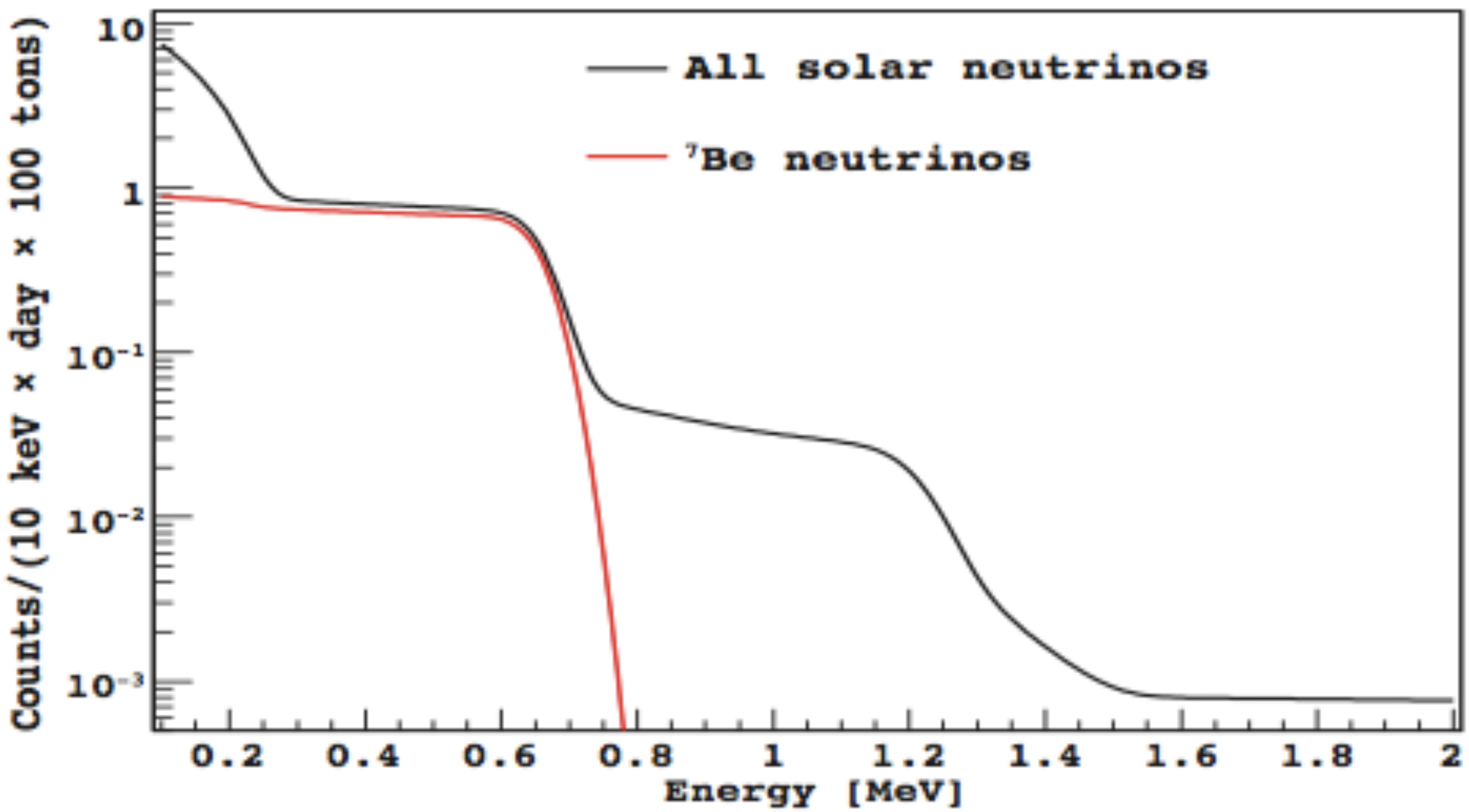


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

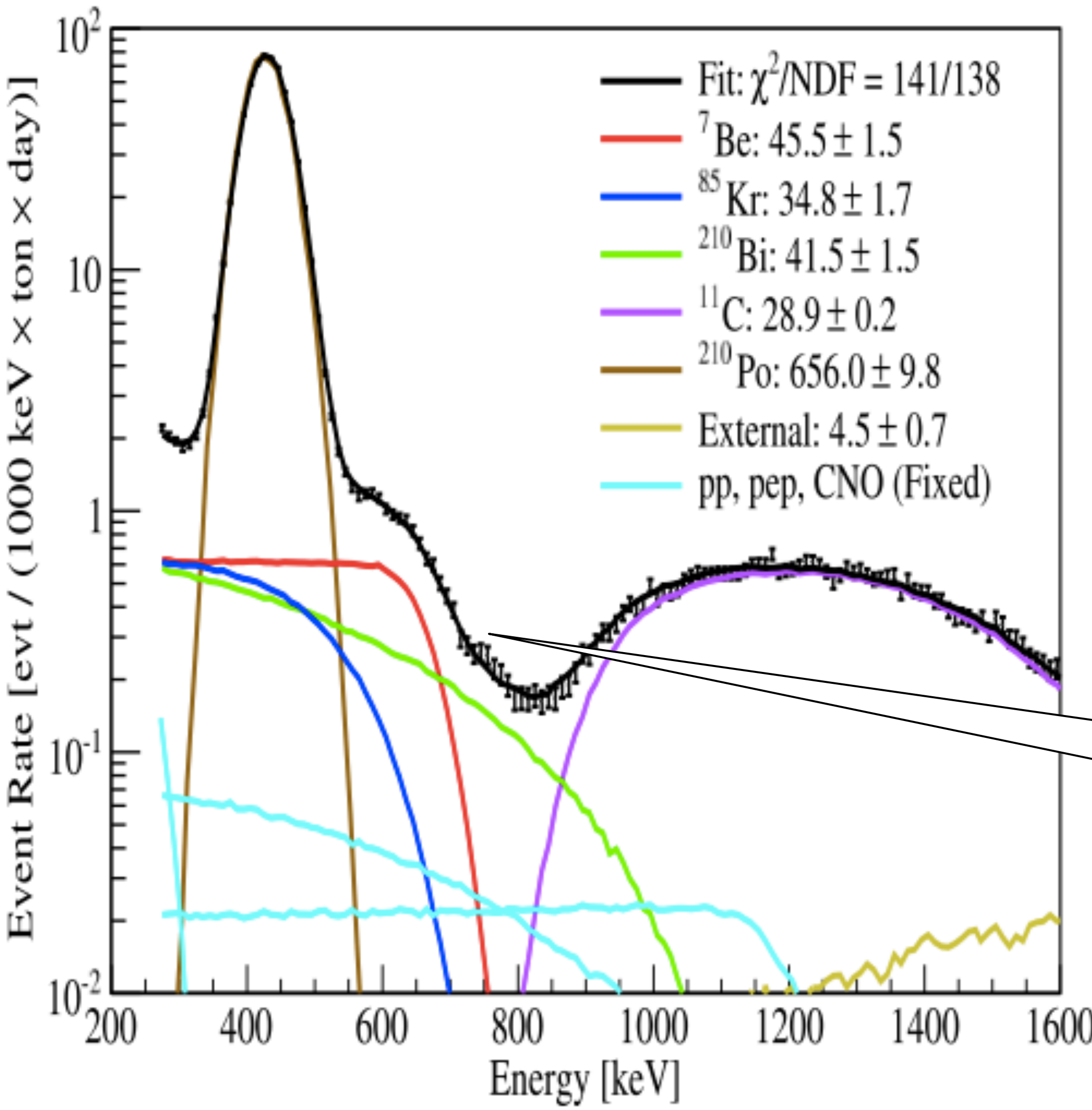
- Scintillator (300 ton)
- Very low threshold (down to ~200 keV)
- Very low radioactivity
- Real time

Go after recoil electrons from the ^{7}Be line



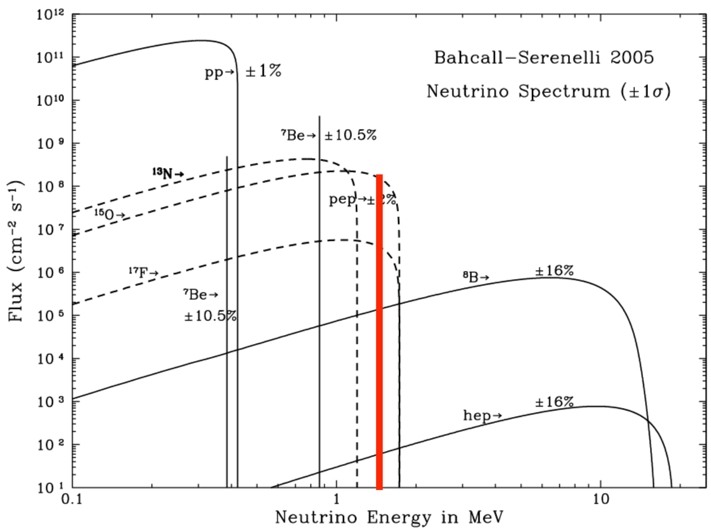


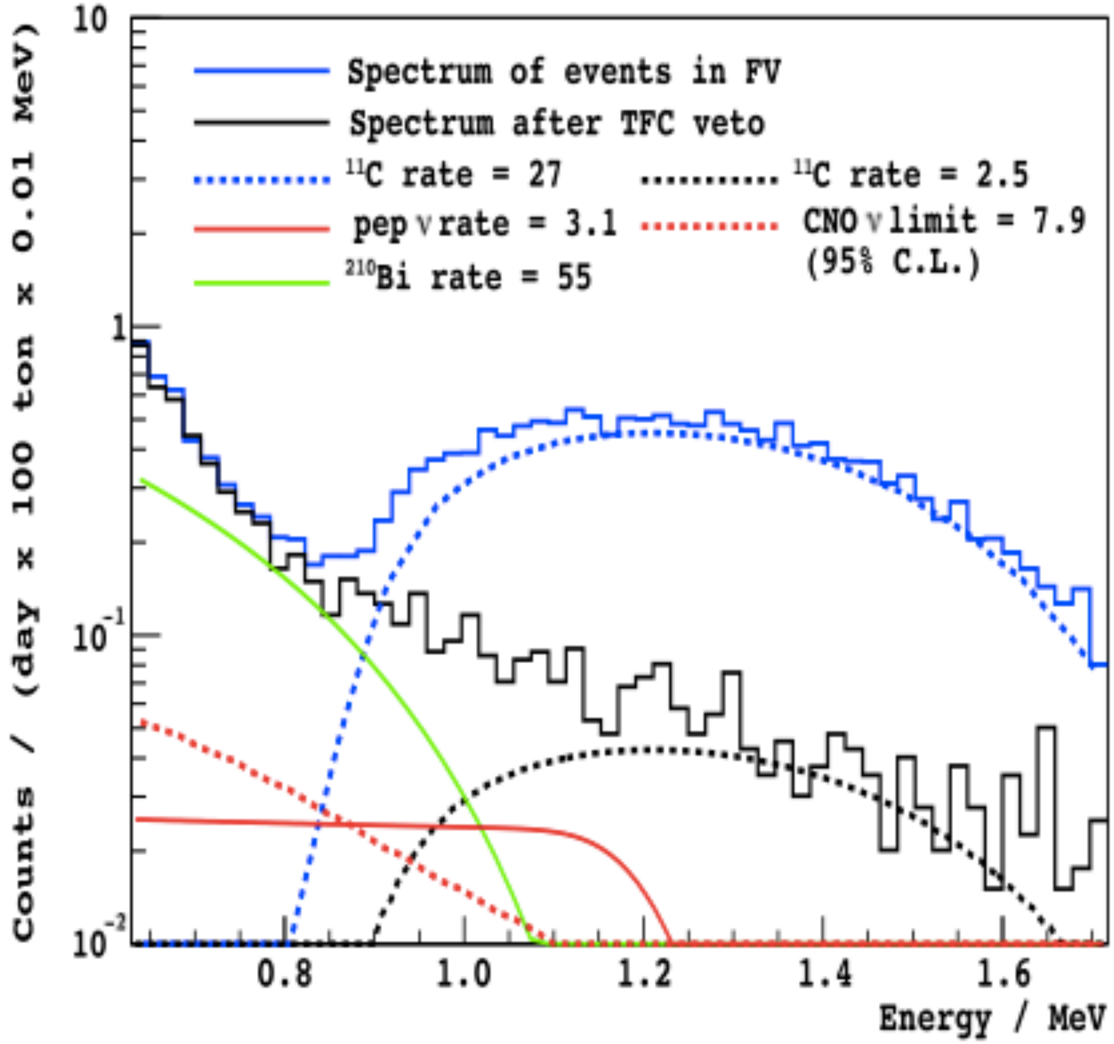
Heroic (and successful) struggle with radioactive (ambient & cosmogenic) backgrounds



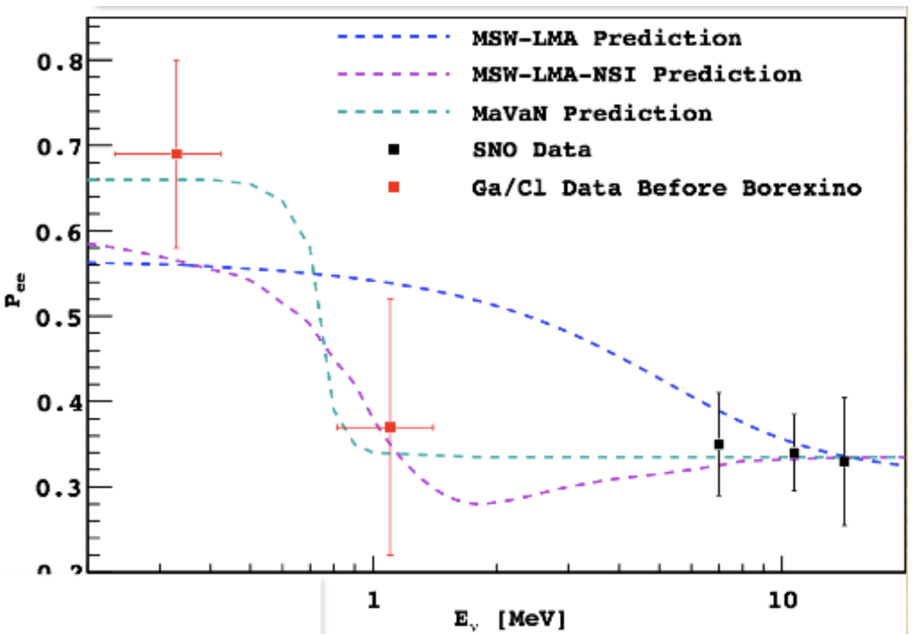
^{7}Be neutrinos identified

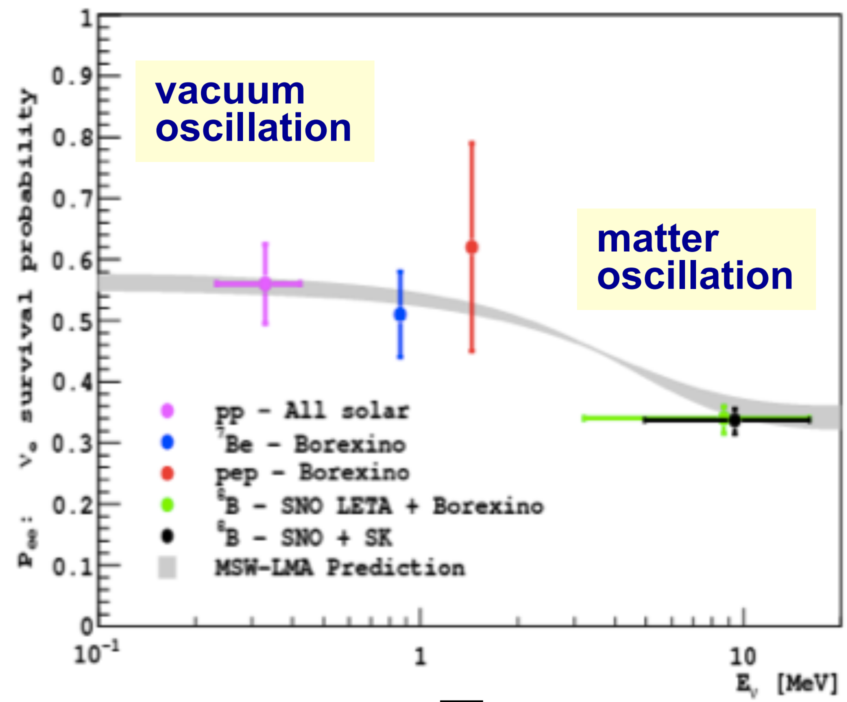
Even more heroic extraction of pep neutrino rates (and limits on CNO neutrinos)





Borexino solar neutrino data at low energy can constrain exotic models





<u>Before:</u> exotic oscillation scenarios allowed

<u>After:</u> consistent with standard solar model and standard matter oscillation scenario

Up-to-date tests of non-standard models

Light sterile neutrino — PRD 83:113011 (2011)

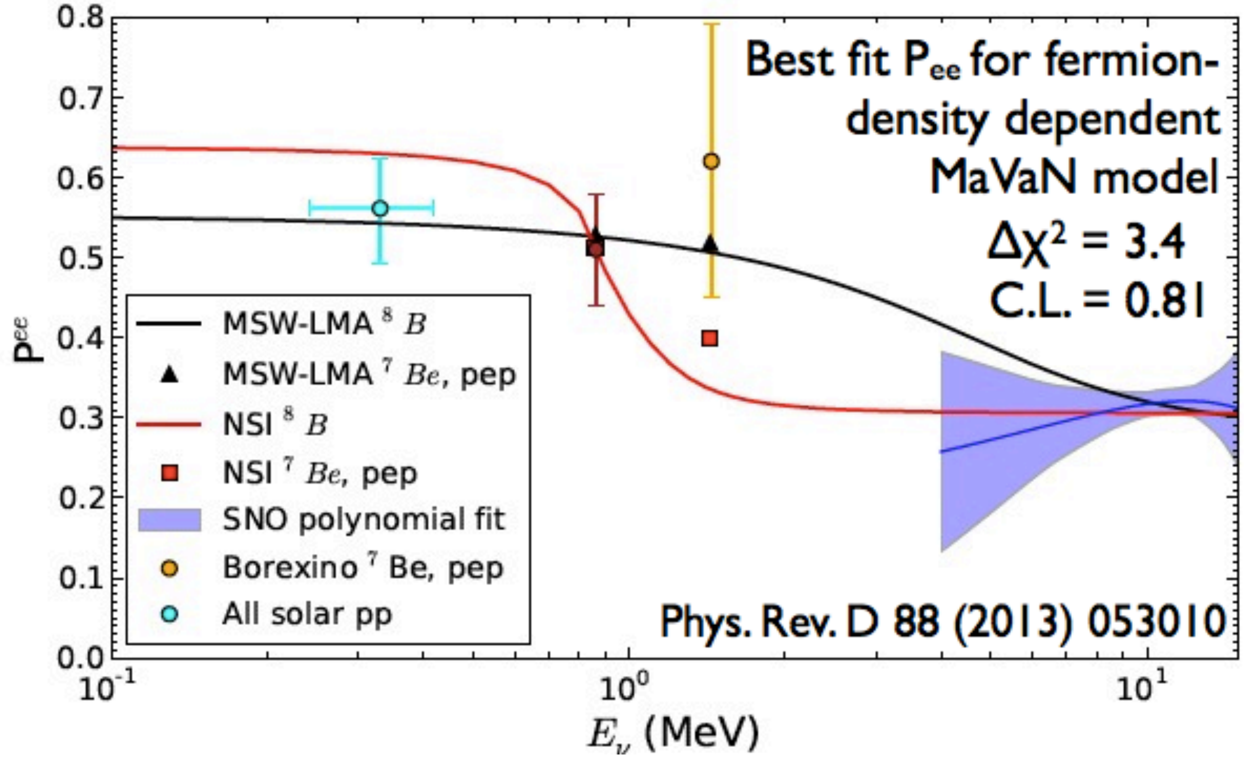
Non-standard MSW Dynamics — PRD 83:101701 (2011)

Non-Standard Models, Solar Neutrinos and Large θ_{13} — PRD 88: 053010 (2013)

- Non-standard forward scattering
- Mass-varying neutrinos
- Long-range leptonic forces
- Non-standard solar model

No significant effects ($< 2\sigma$)

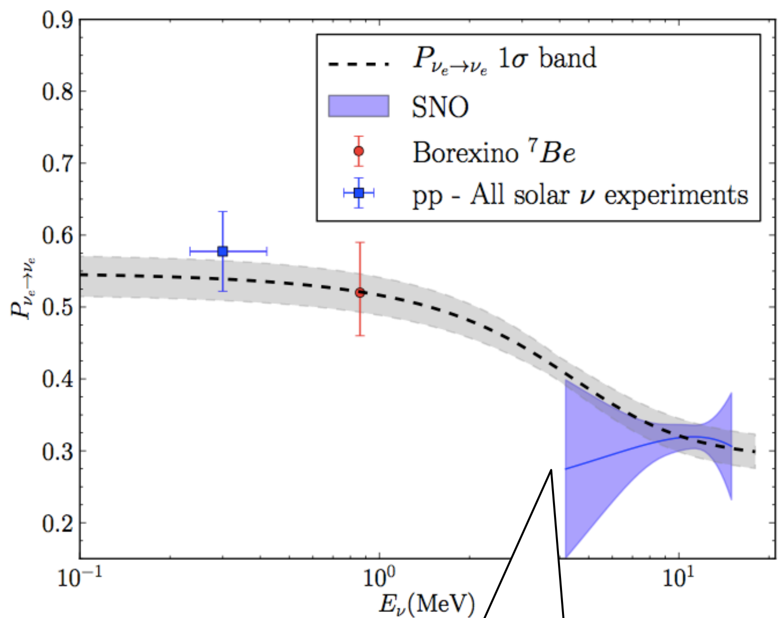
Results limited by experimental precision

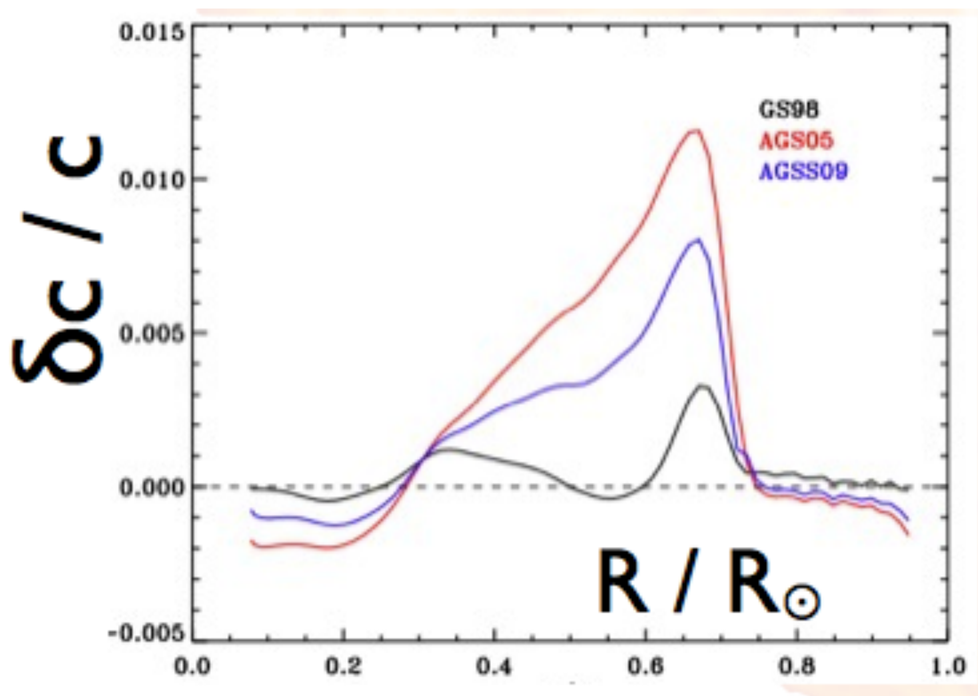


G. Orebi Gann, Neutrino 2014

What's next for solar neutrinos?

We now have the basic picture, but
there are are still gaps & discrepancies...



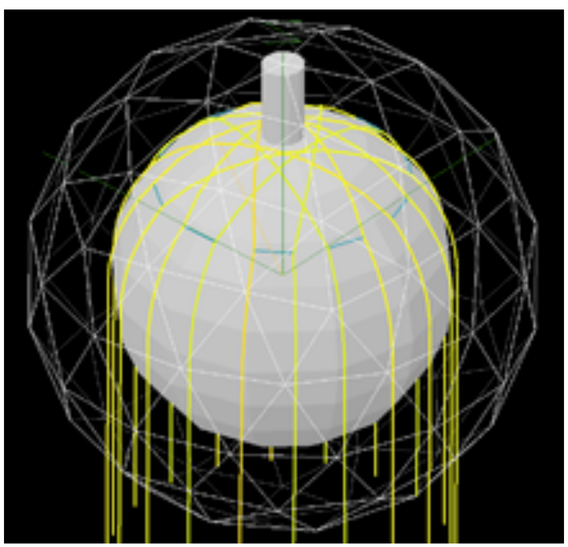


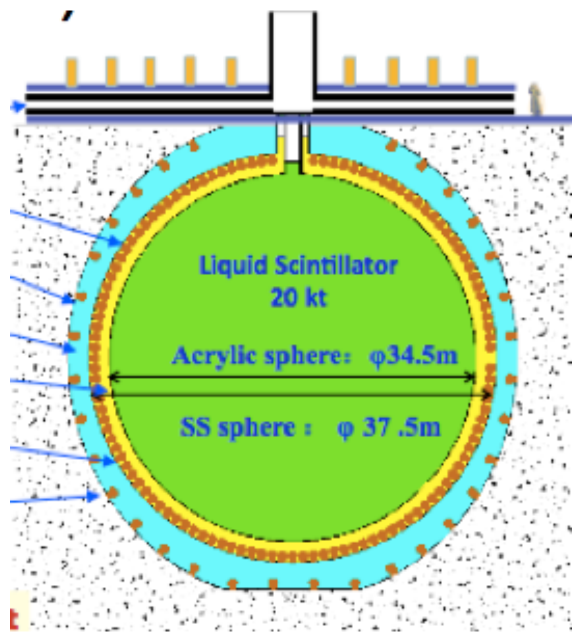
Low energy region
still poorly measured
... still room for
new physics?

Latest solar metallicities
inconsistent with
helioseismology
... neutrino info can help

What experiments are next for solar neutrinos?

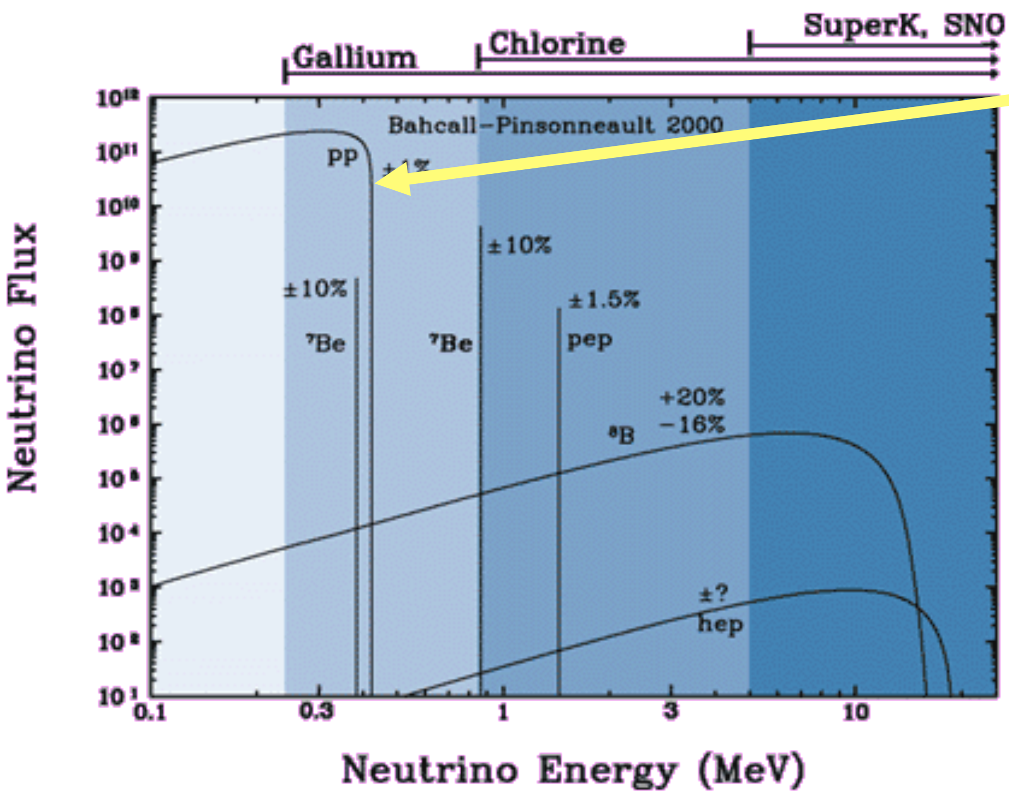
- SK and Borexino still running
- SNO+: SNO acrylic vessel filled
  with scintillator (+Nd for 0nubbk)
- Next: JUNO in CHINA
- Possible farther future: LENA, 50 kt scintillator in Finland
- Water-based scintillator? Load w/ e.g. ^{7}Li?





The Frontier?

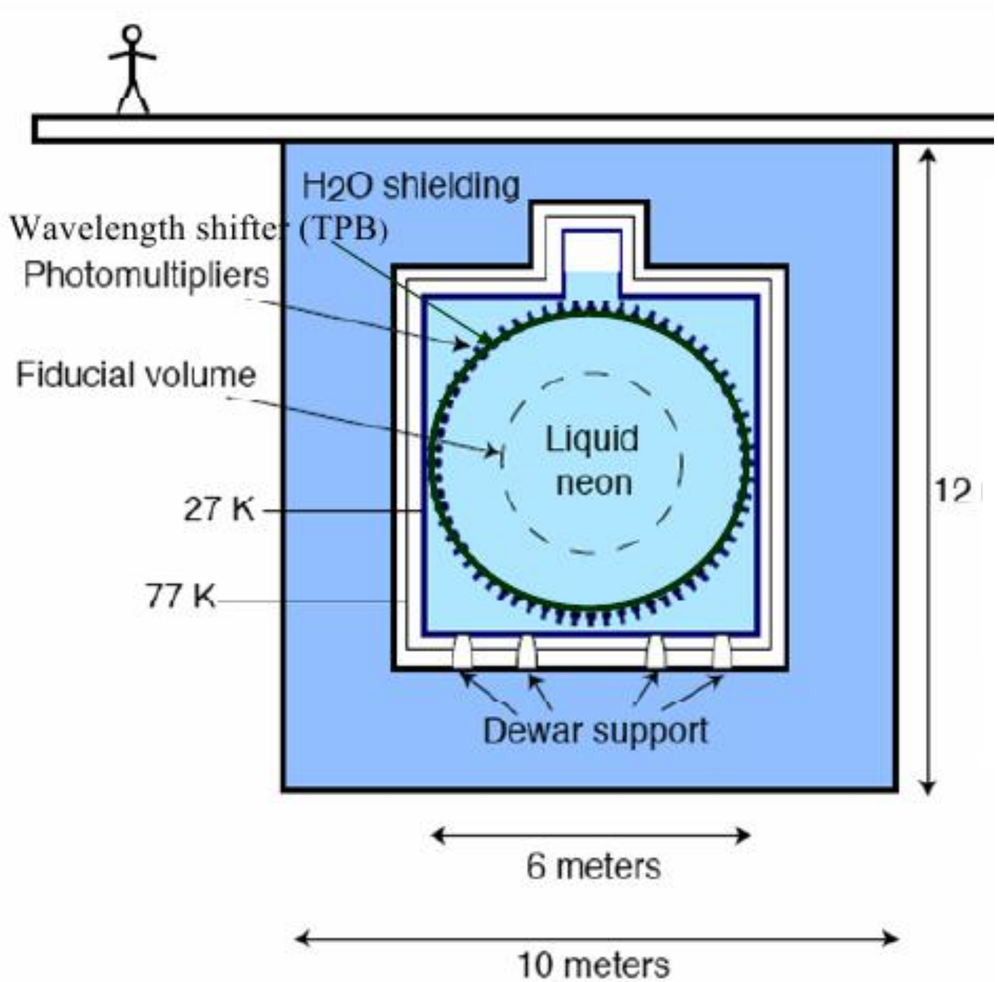
Ultra-low energy (sub MeV) ?
real-time solar pp ν detectors

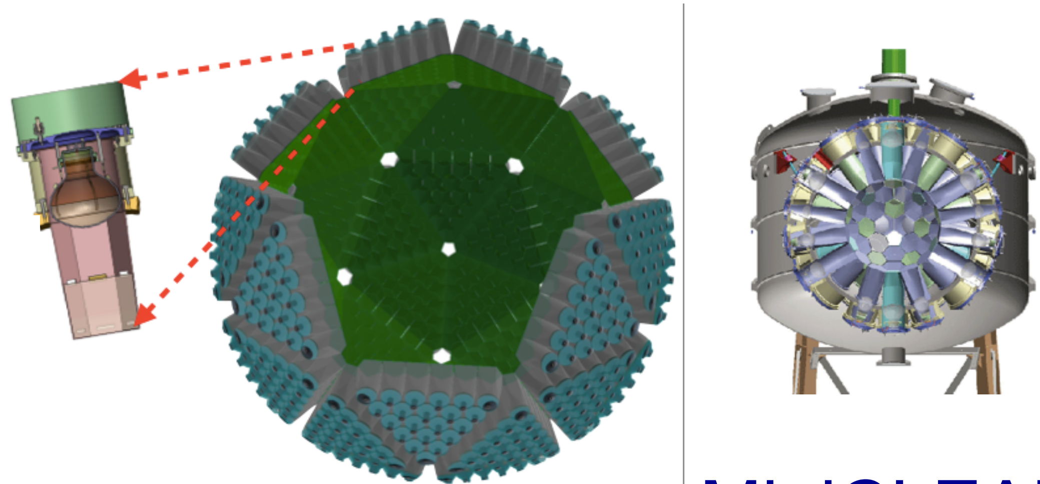


Vast pp neutrino flux
barely touched!

- detectors can be relatively small (~10 tons) thanks to huge pp flux
- want real-time energy resolution
- must be ultra-clean to defeat radioactive background

CLEAN: liquid neon (argon)

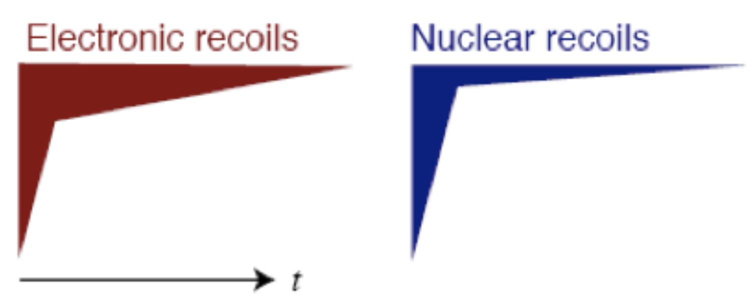




MiniCLEAN

$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$

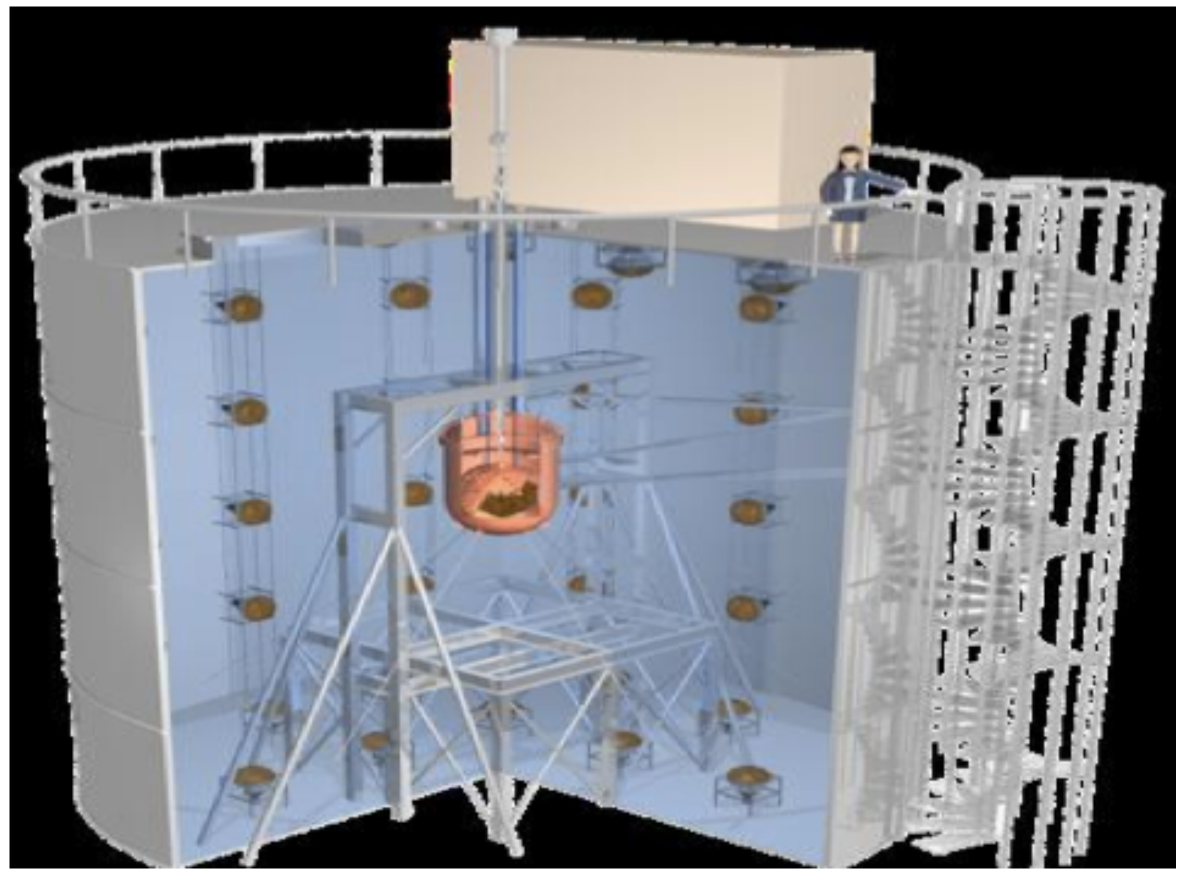
Pulse-shape discrimination



Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

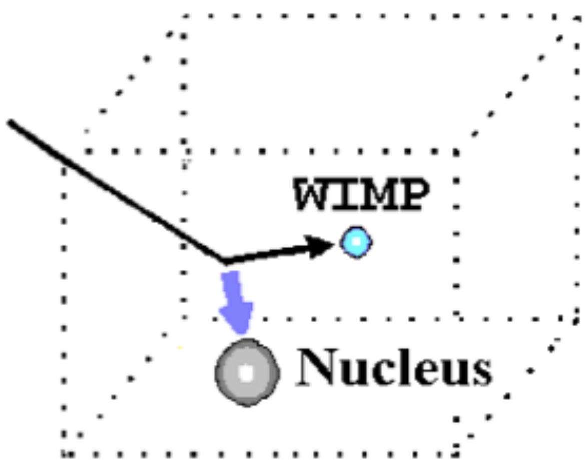
XMASS: liquid xenon

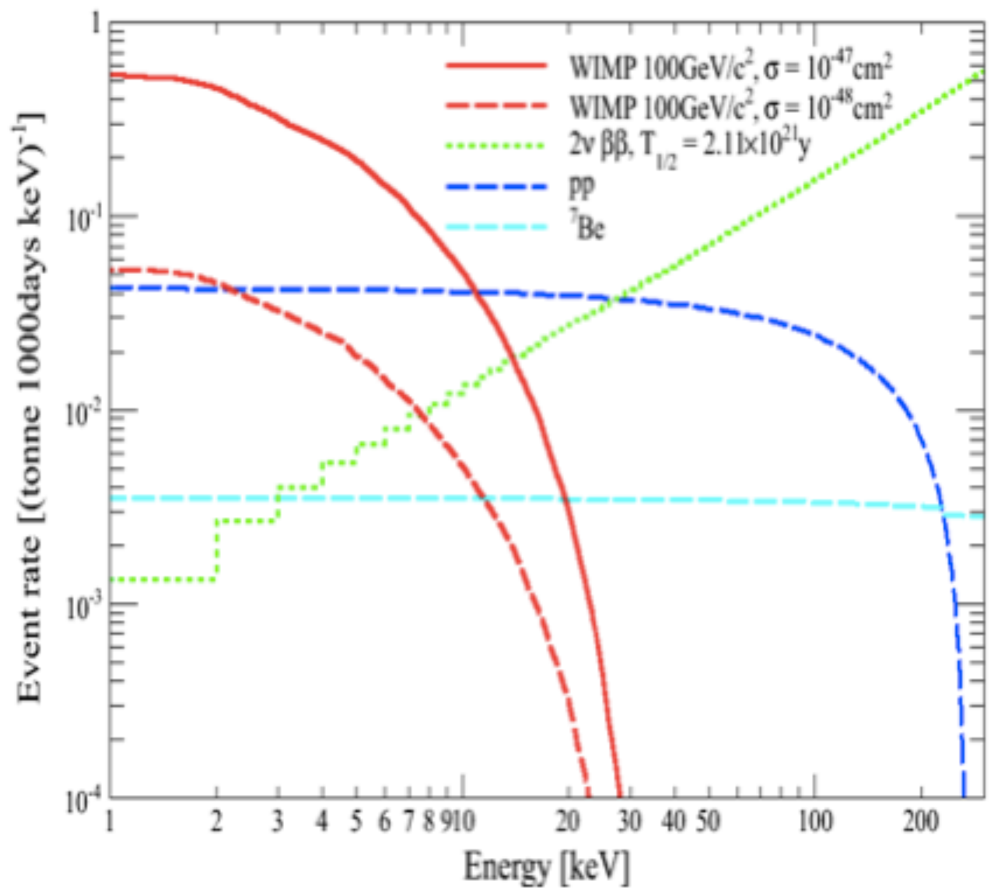
$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$



Note: noble liquid detectors have gotten “distracted” by WIMP searches...

Measured recoil energy spectrum in xenon





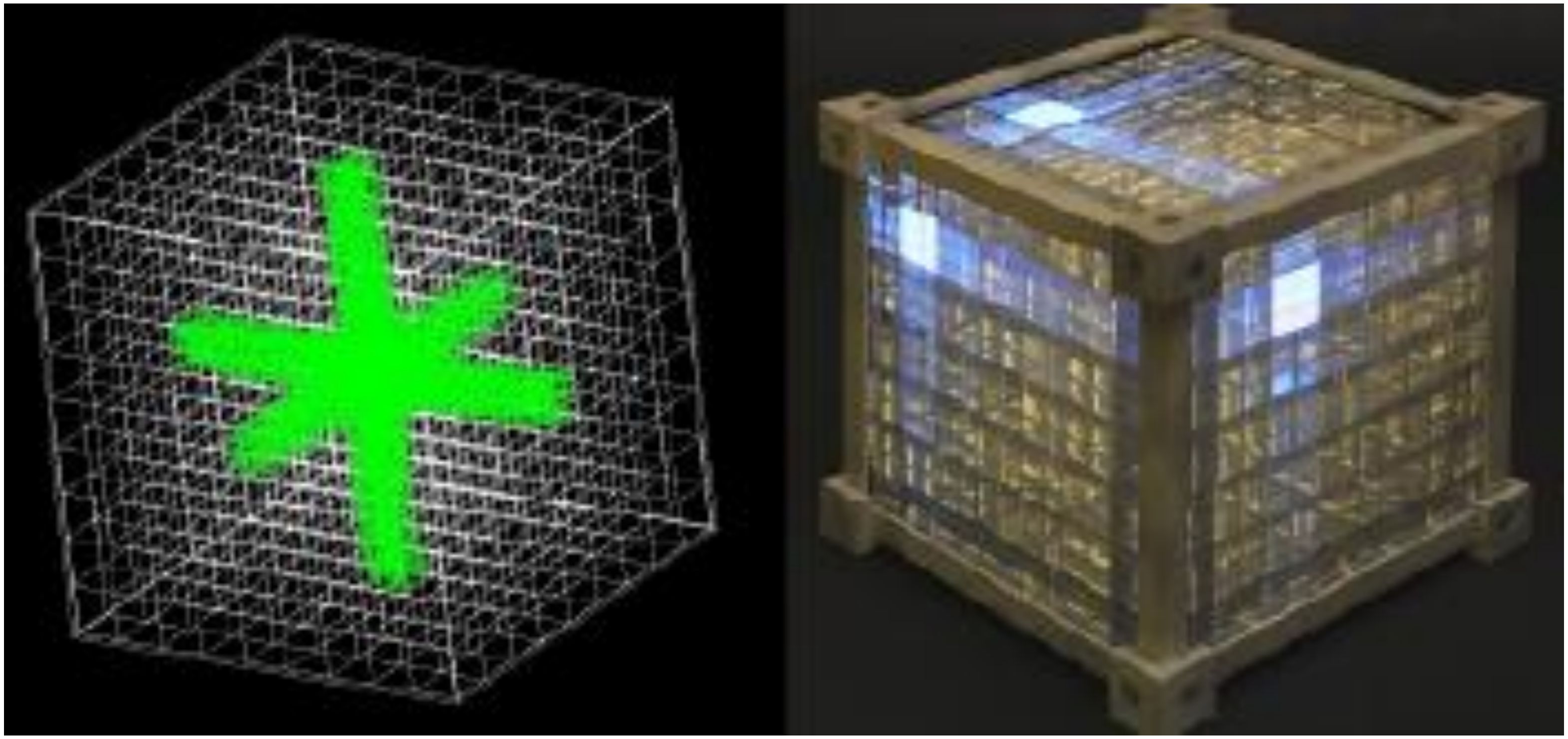
Nuclear recoils induced by DM may be an easier signal!

A dedicated future solar neutrino experiment:

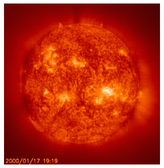
LENS: indium-loaded scintillator

use delayed triple coincidence to reject background

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\mu s) 2\gamma + {}^{115}Sn$$



The Story of Solar Neutrinos

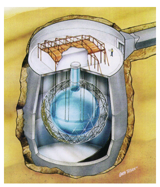


How does the Sun shine?

It's a gigantic nuclear furnace

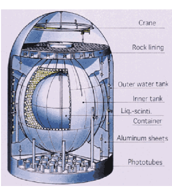
ν-raying the Sun: a classic problem

Electron neutrinos gone missing



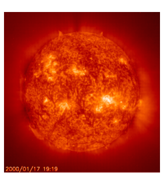
An anomaly resolved … with new physics!

The SSM holds; ν' s are oscillating



"Tame" neutrinos complement the "wild" ones

Reactor neutrinos help squeeze the parameters



How does the Sun shine?
(or maybe yet more new physics...)

Still some discrepancies... more to learn about the Sun and maybe neutrinos!