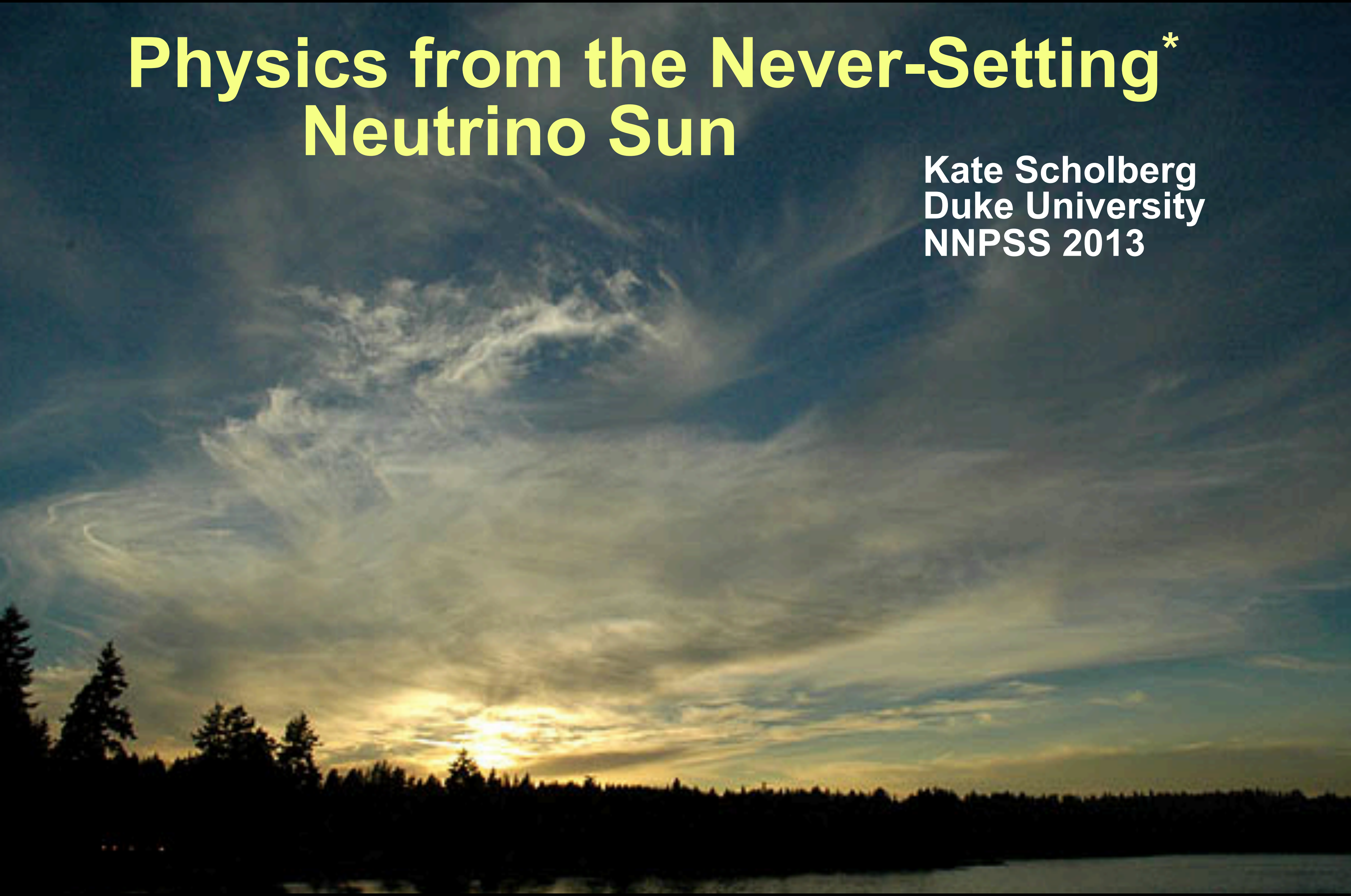


Physics from the Never-Setting* Neutrino Sun

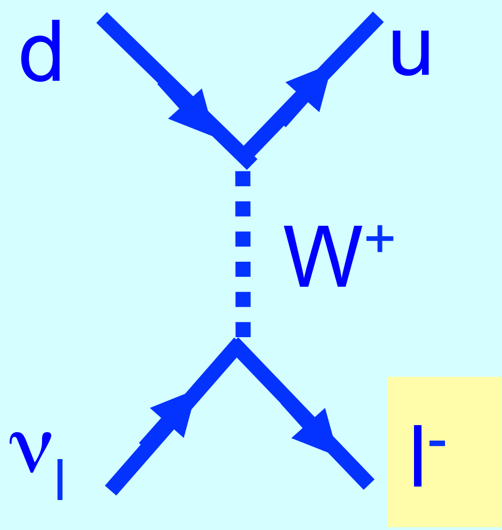
Kate Scholberg
Duke University
NNPSS 2013

* or anti-setting?

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

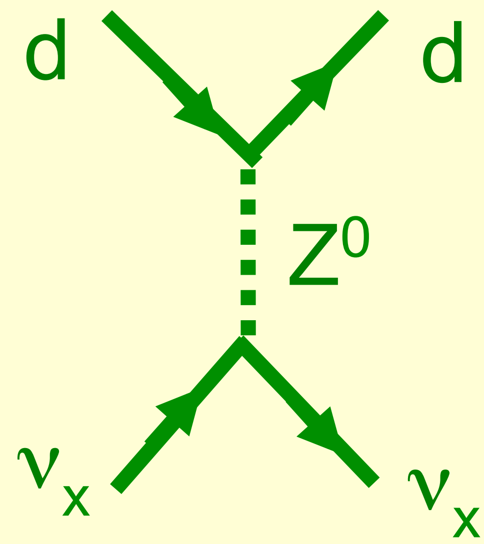


$\nu_l + N \rightarrow l^{\pm} + N'$

Produces lepton with flavor corresponding to neutrino flavor

(must have enough energy to make lepton)

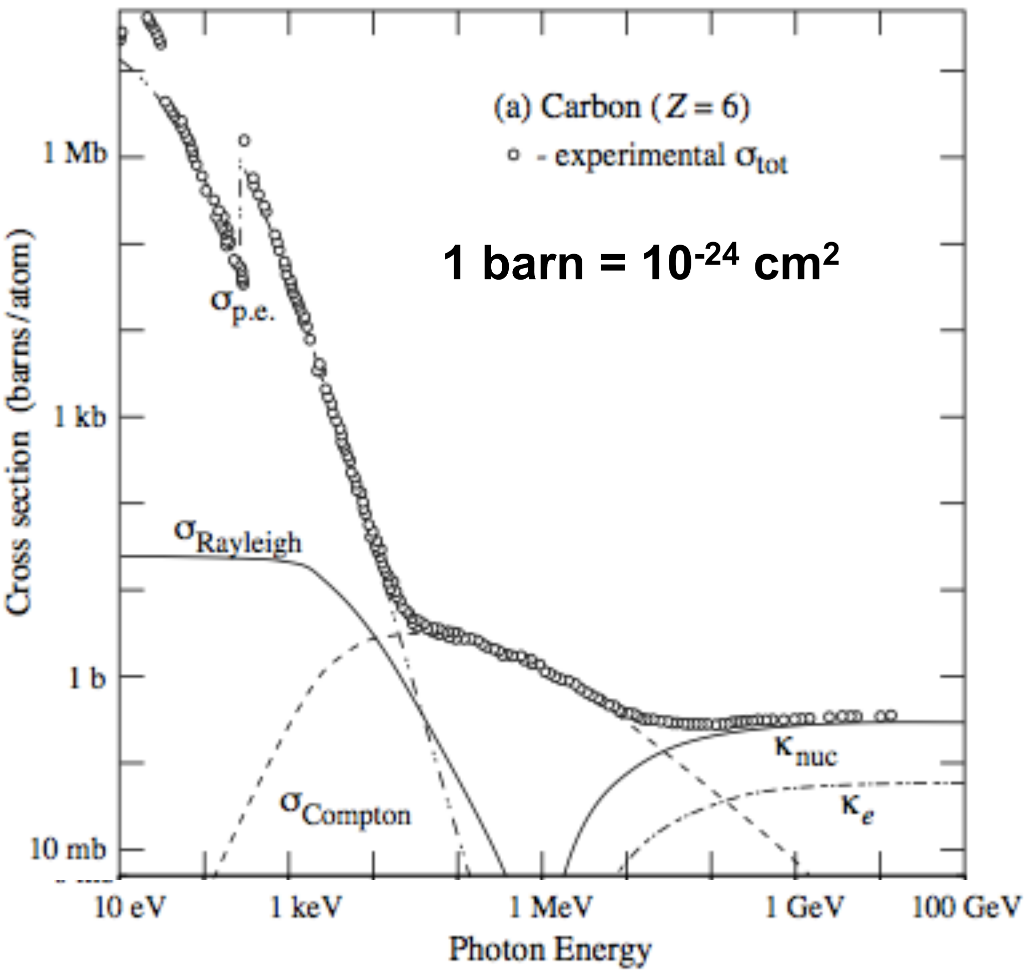
Neutral Current (NC)



Flavor-blind

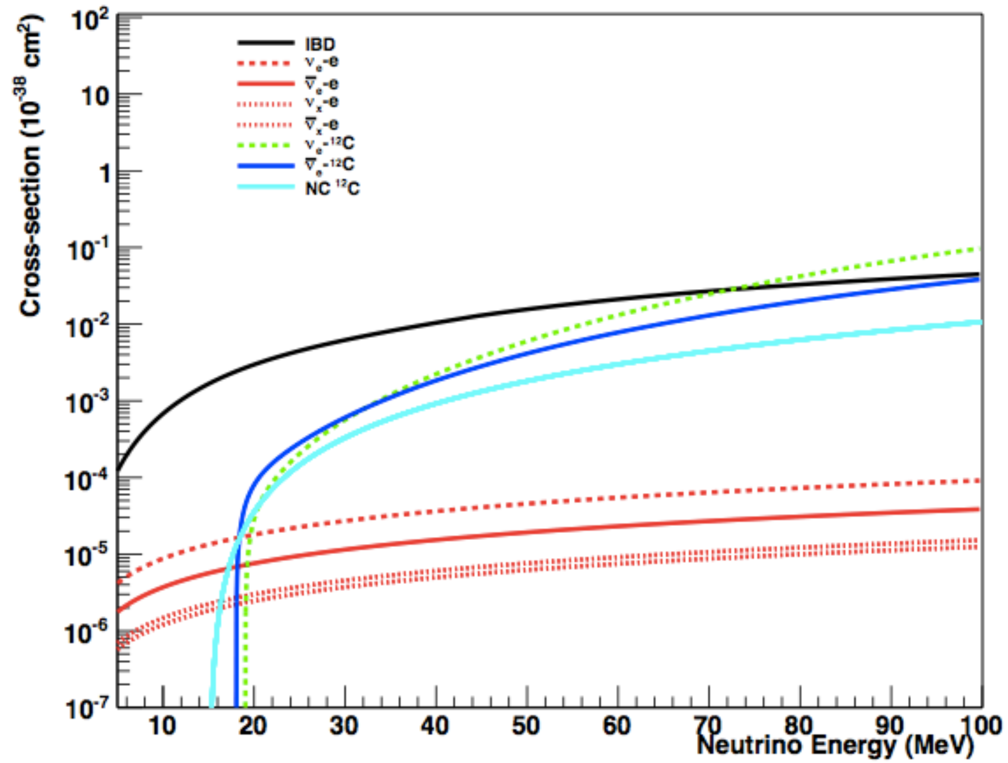
It's called the weak interaction for a reason

Photon-matter cross-sections



~10^{-24} cm^2

Neutrino-matter cross-sections



~10^{-40} cm^2

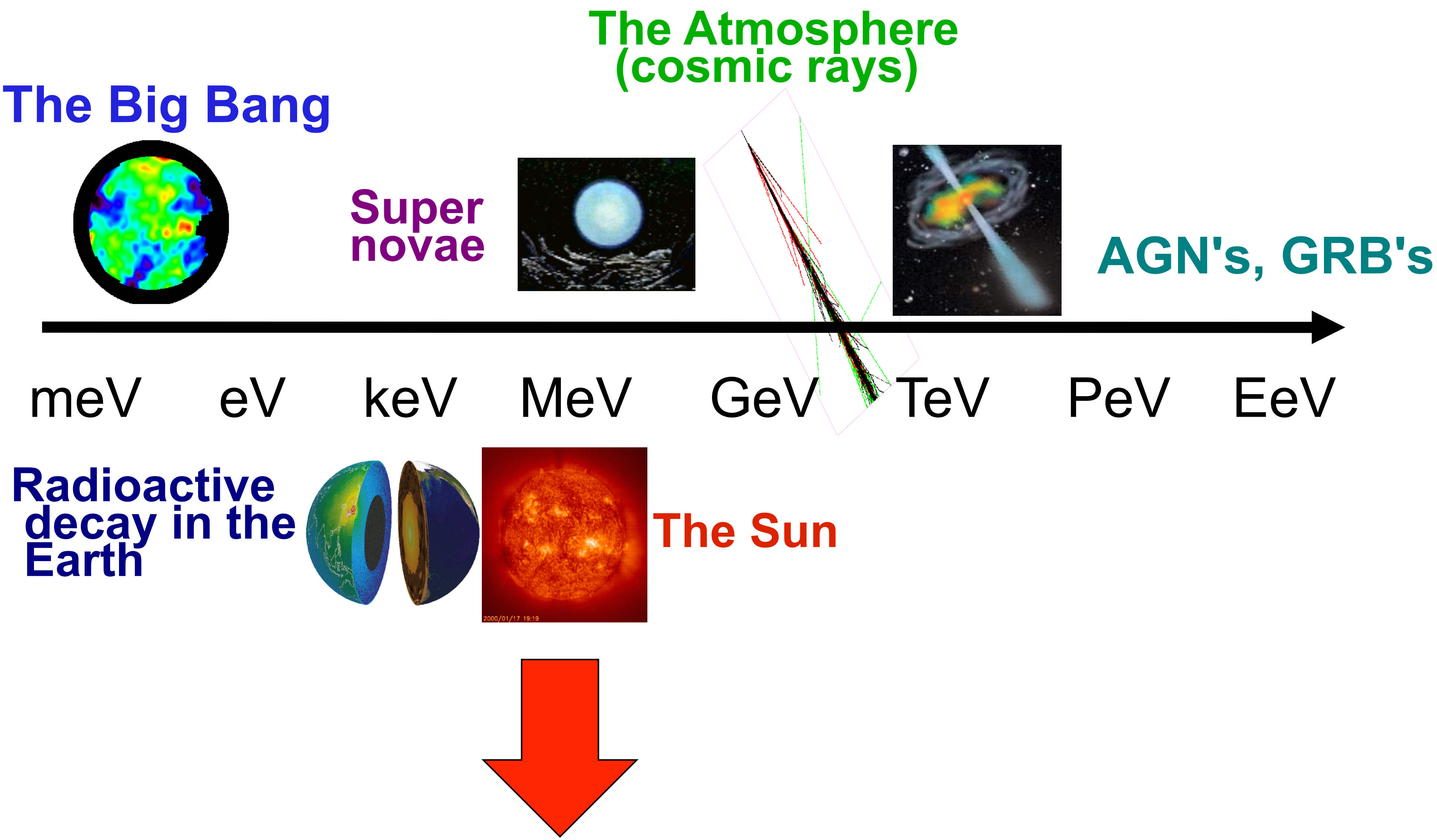
~16-17 orders of magnitude smaller

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

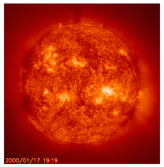
- but they require heroic efforts to detect!

Sources of wild neutrinos



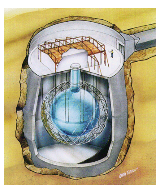
neutrinos leak energy
& bring information from
deep inside the Sun

The Story of Solar Neutrinos

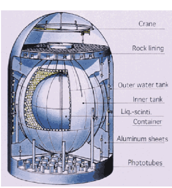


How does the Sun shine?

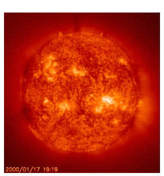
ν-raying the Sun: a classic problem



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?

➔

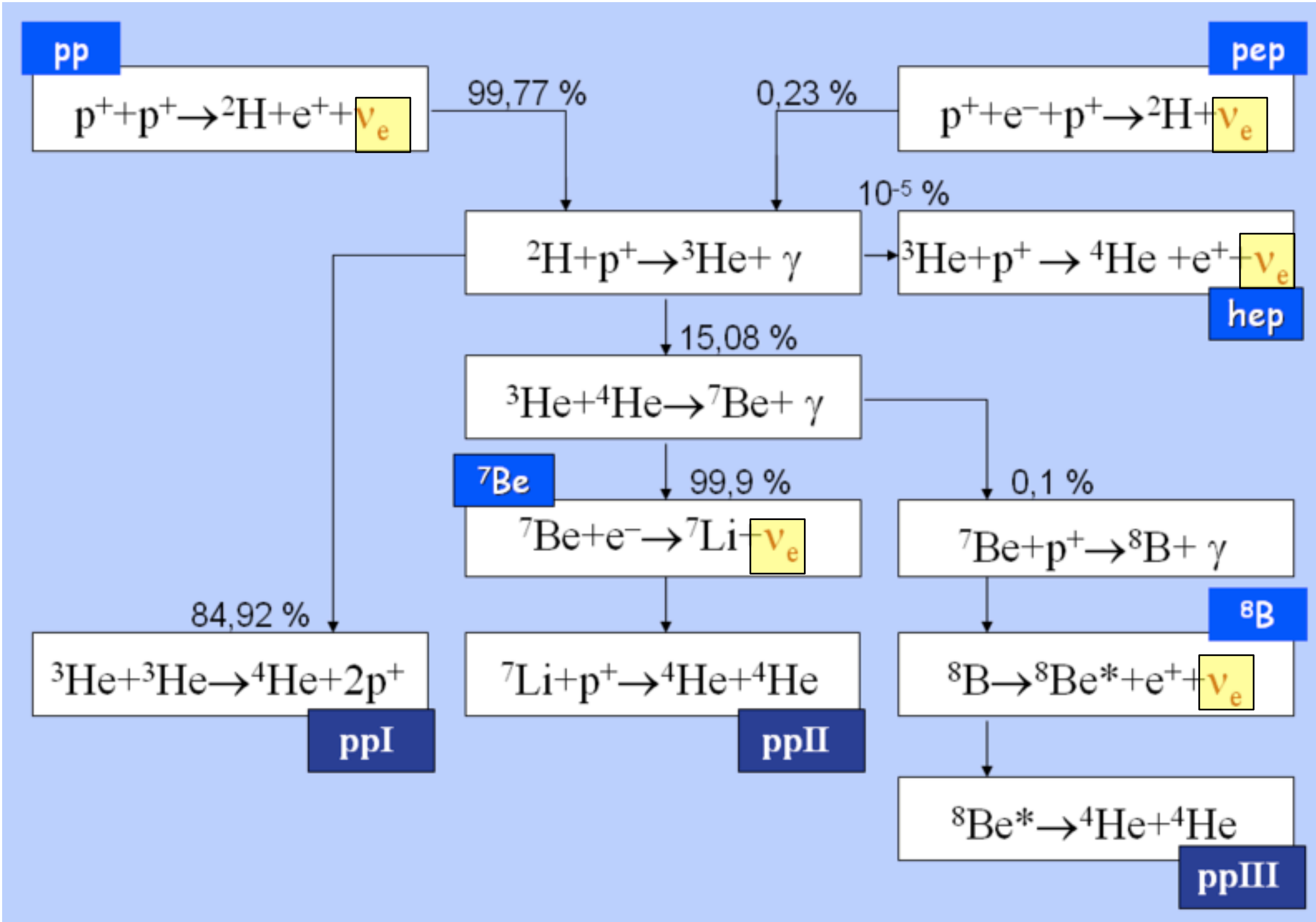
Eddington,
Gamov, Bethe:

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

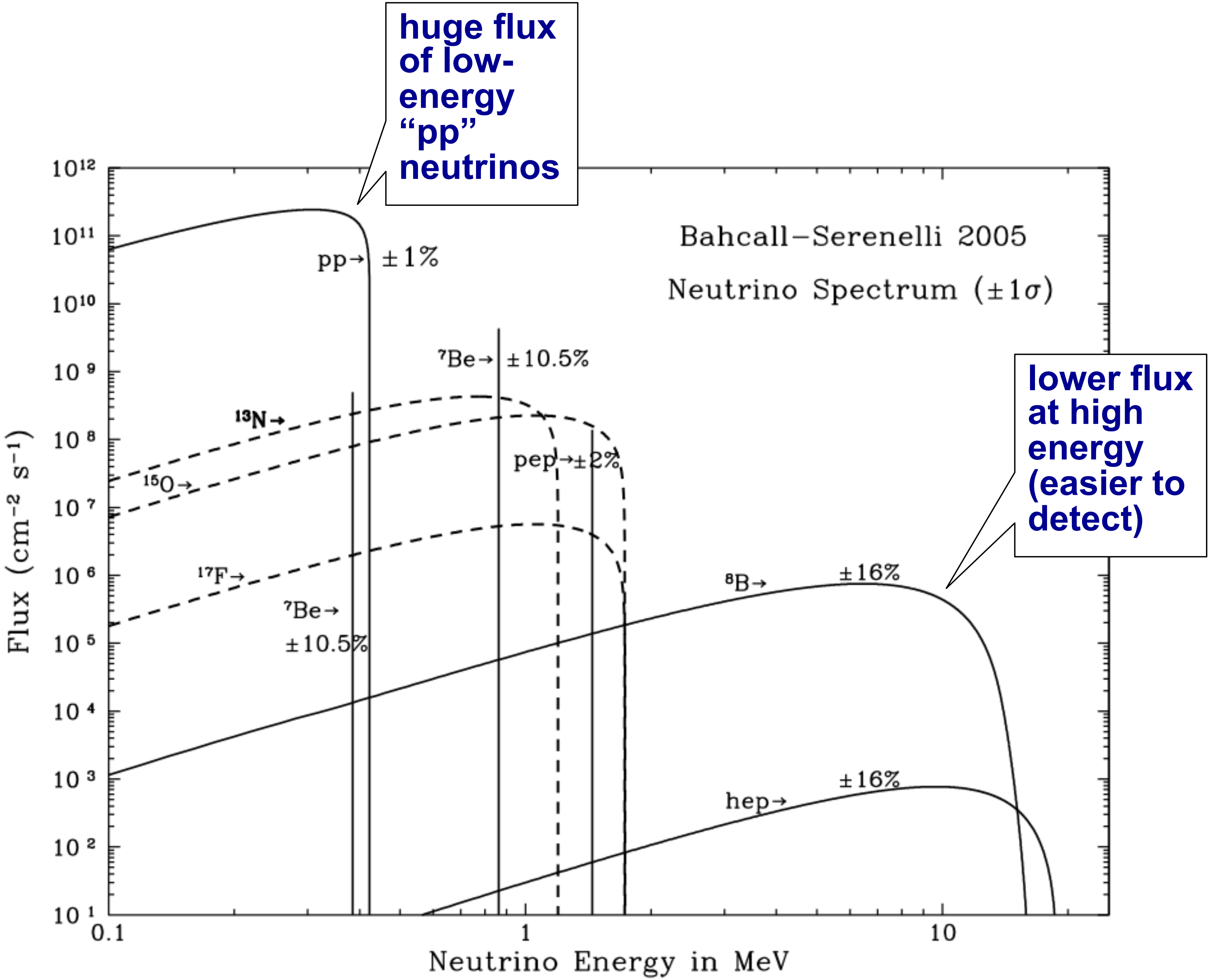
-They Might Be Giants

Solar fusion reactions



ahcall

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



huge flux of low-energy "pp" neutrinos
Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
pep→±2%
¹⁷F→
⁷Be→
±10.5%
⁸B→
±16%
hep→
±16%
lower flux at high energy (easier to detect)
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV

Homestake Chlorine Radiochemical Detector

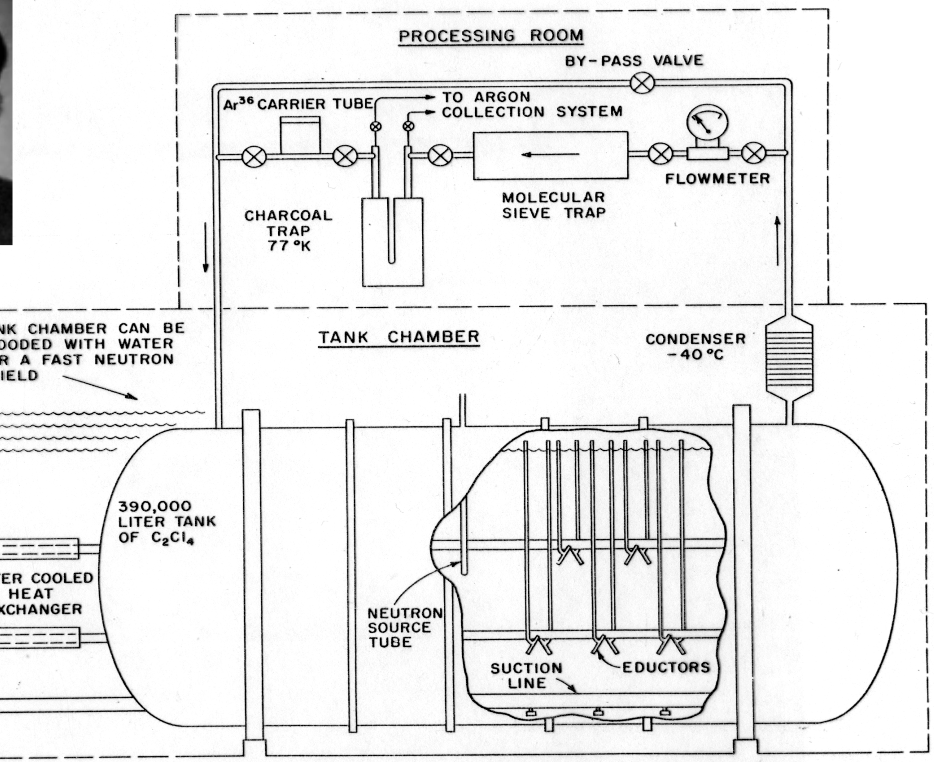


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

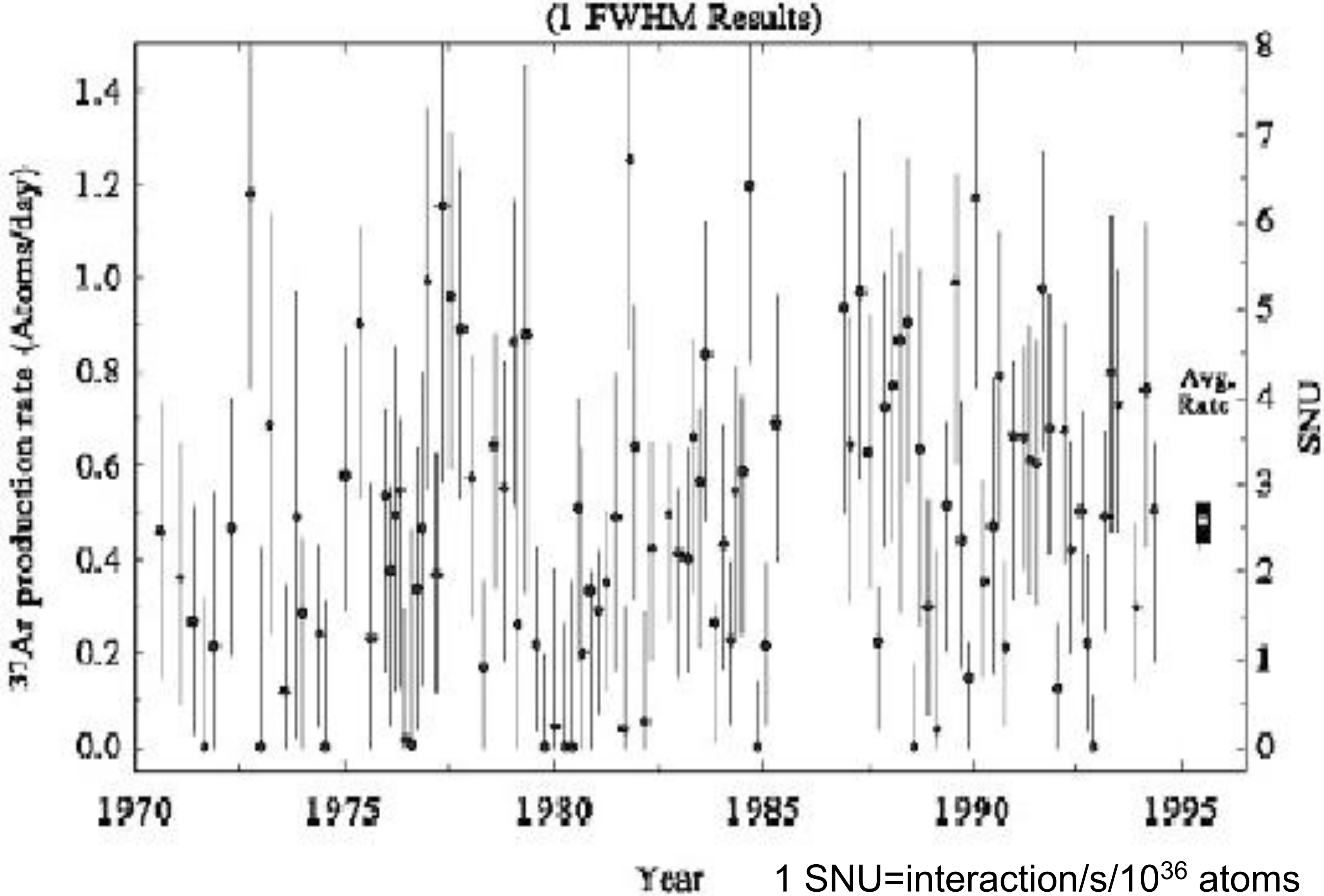
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Threshold: 0.81 MeV

600 tons of cleaning fluid

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

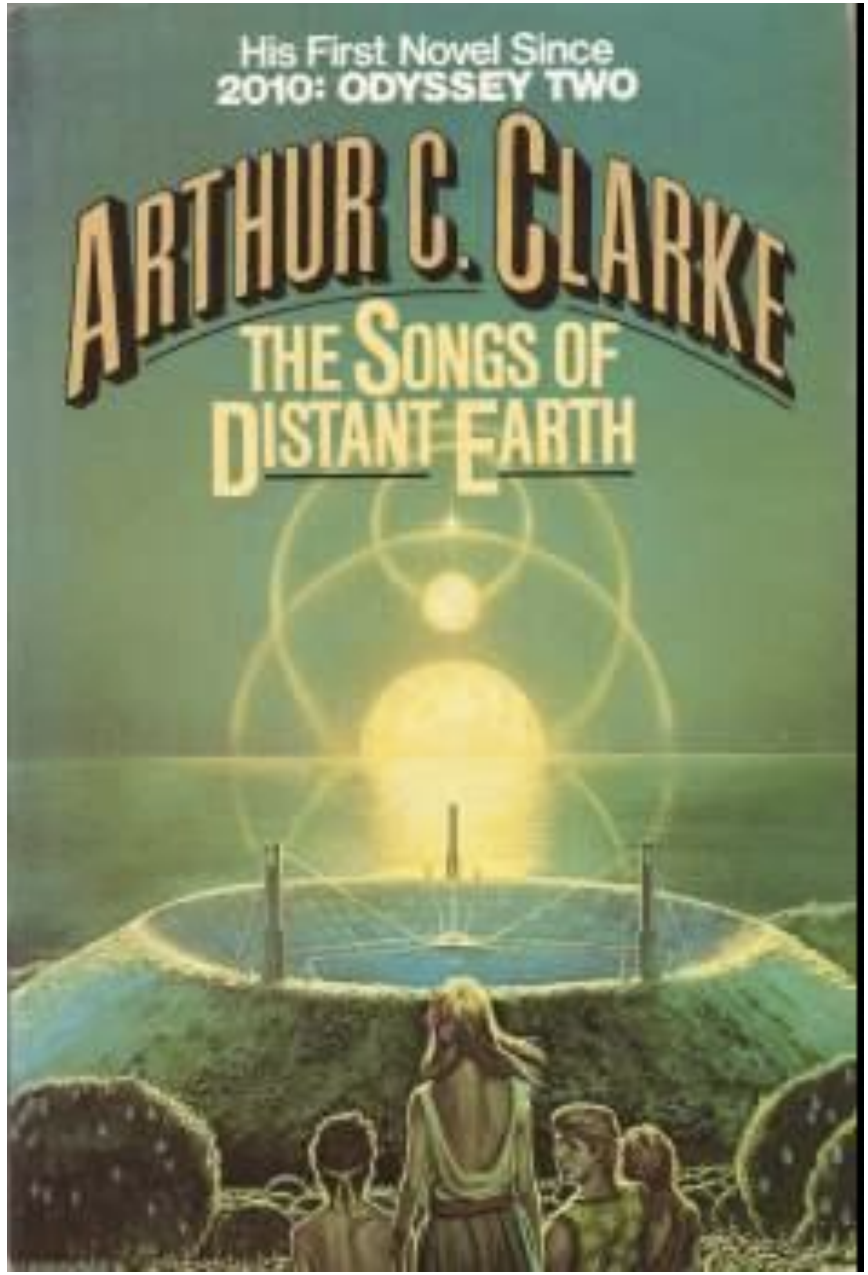
Davis and Bahcall in 1967



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

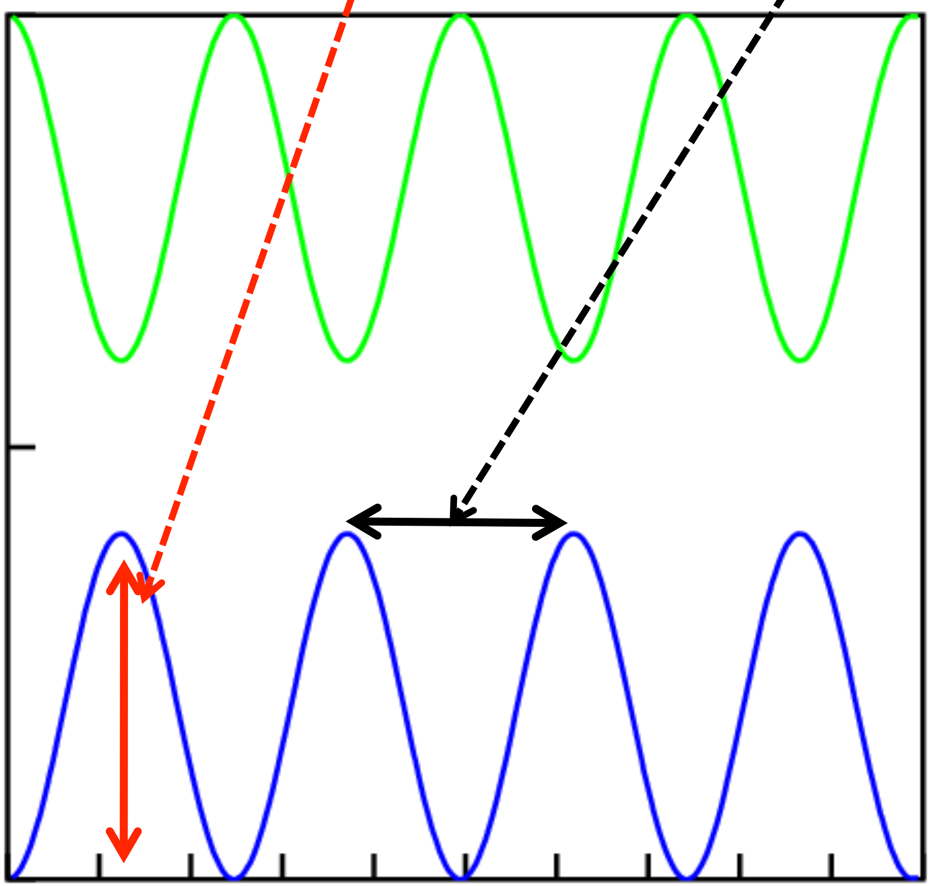
Oscillations, in 2-flavor approximation:

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

amplitude

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

$P(\nu_f \rightarrow \nu_f)$



$P(\nu_f \rightarrow \nu_g)$

Distance traveled

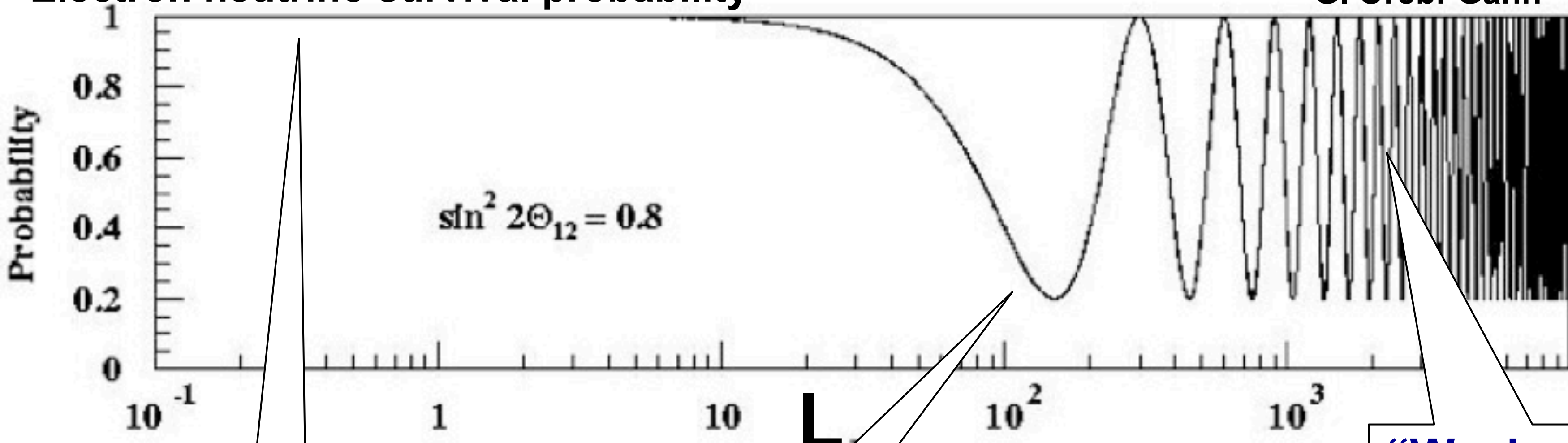
Δm^2, $\sin^2 2\theta$ are the parameters of nature;

L, E depend on the experimental setup

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

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

Example of oscillations in vacuum, for fixed ν energy



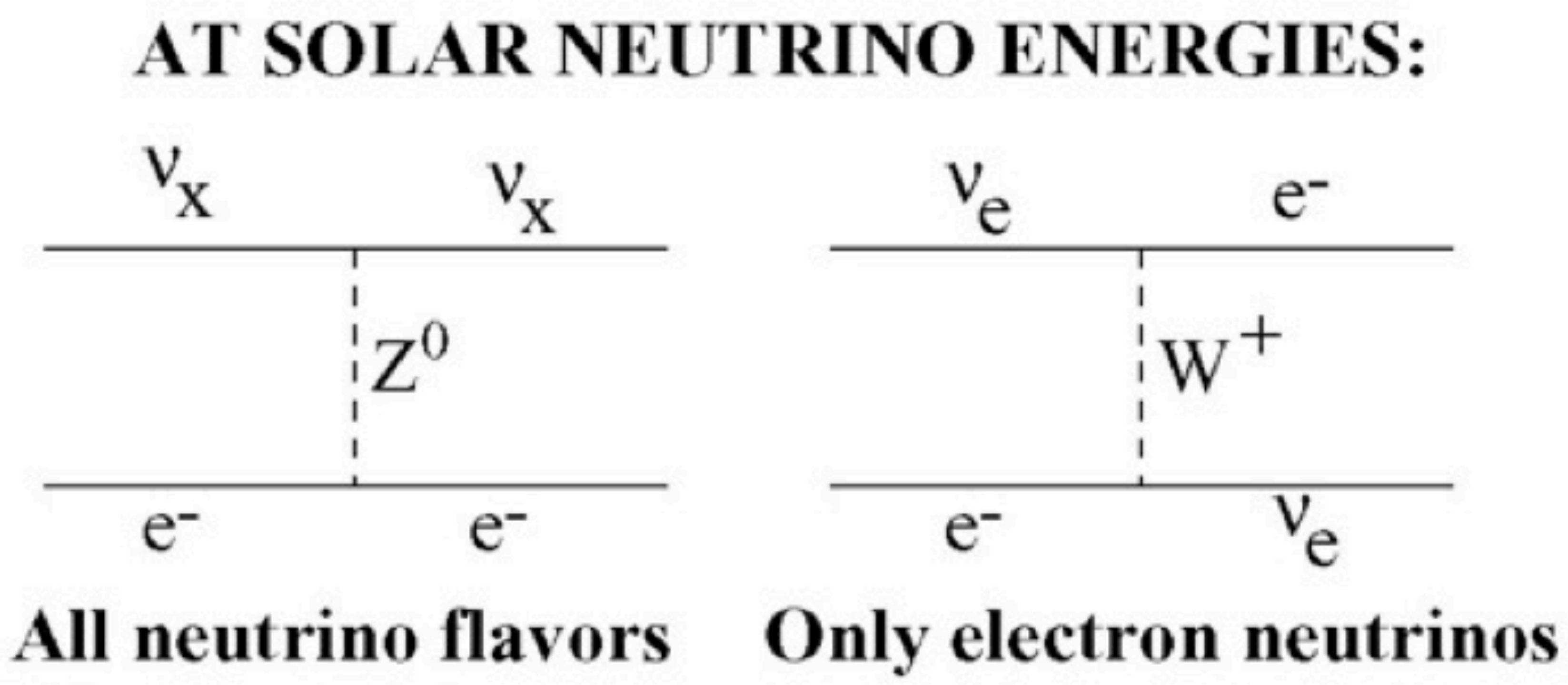
No mixing

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?

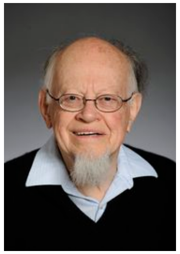
Evolving ideas about oscillations...



The Sun tastes like electrons to solar ν_e

Mikheyev

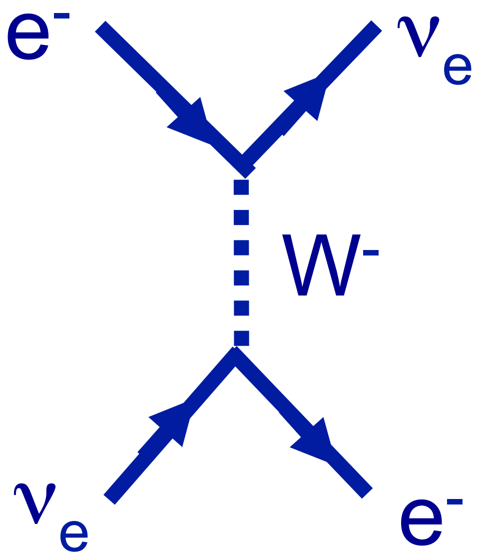
Smirnov



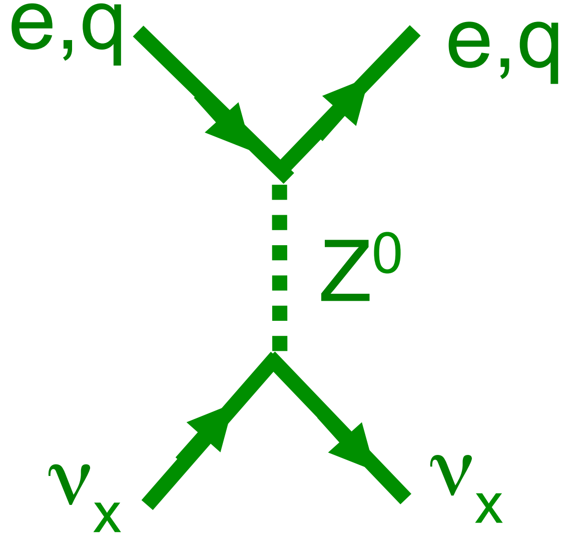
Wolfenstein

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*

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

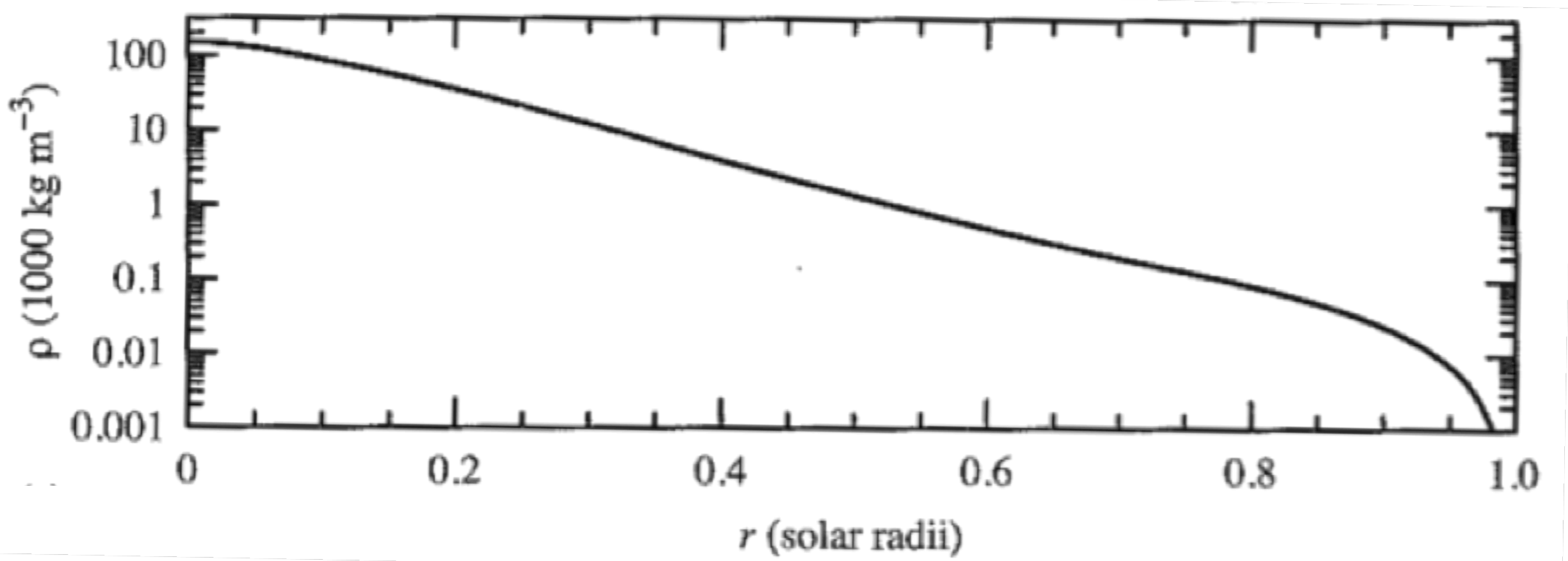
$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

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

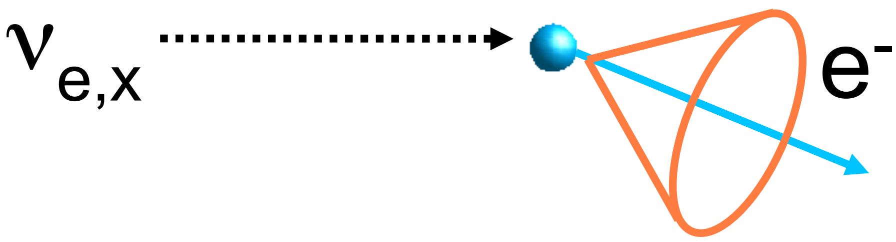
$$\frac{\Delta m^2}{2E}\cos 2\theta = \sqrt{2}G_F N_e$$

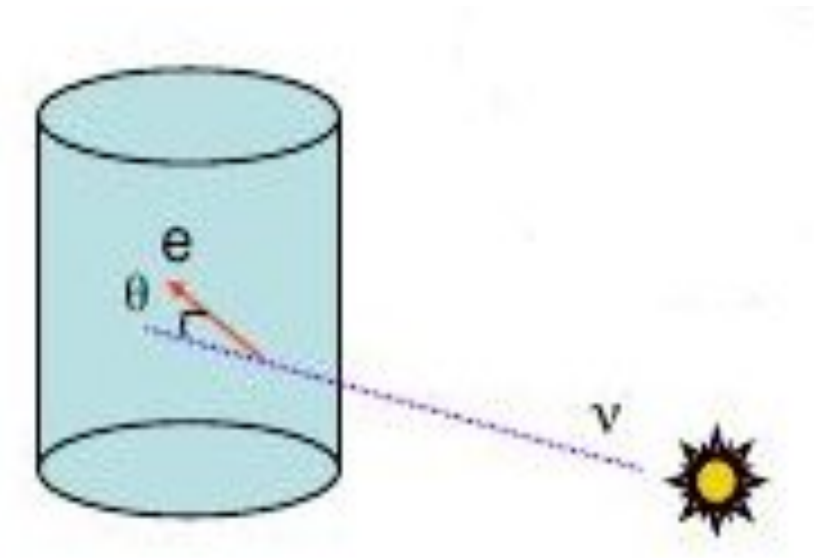
and lead to large flavor transition, even for small intrinsic mixing: MSW resonance

Is this what's happening?

More experimental information coming in...

Water Cherenkov Detectors



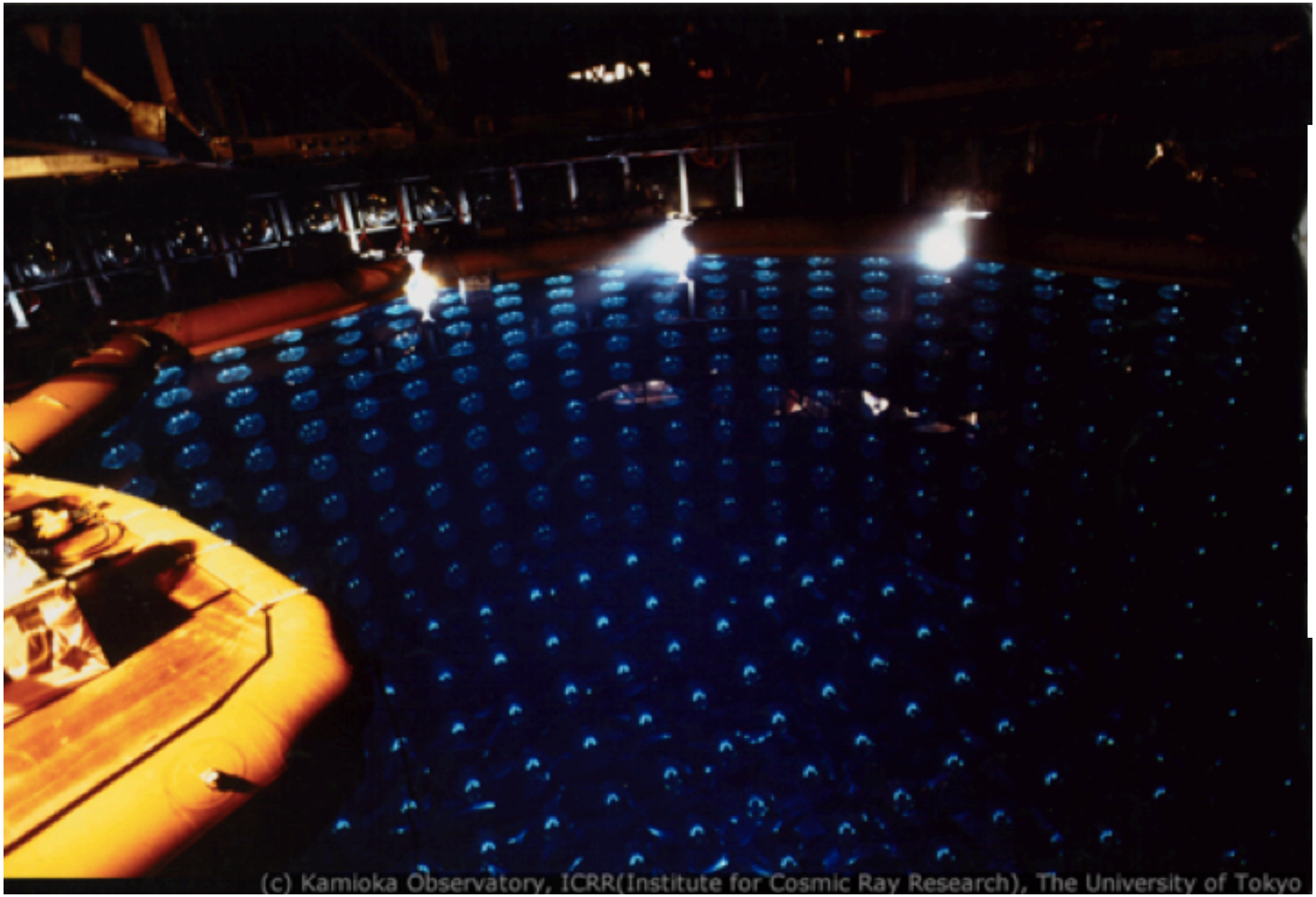


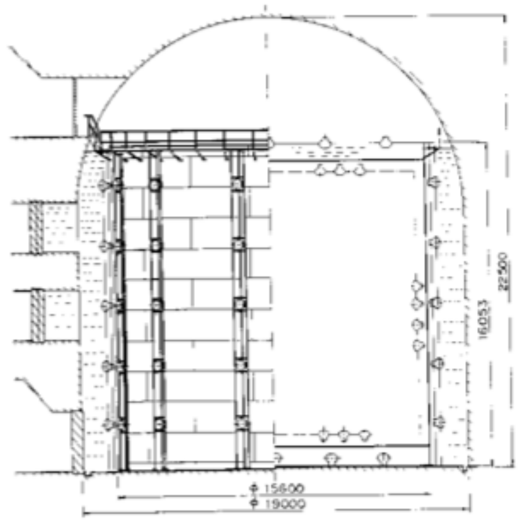
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Elastic scattering of ~MeV solar ν's on electrons

real time detection, with *directionality*

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

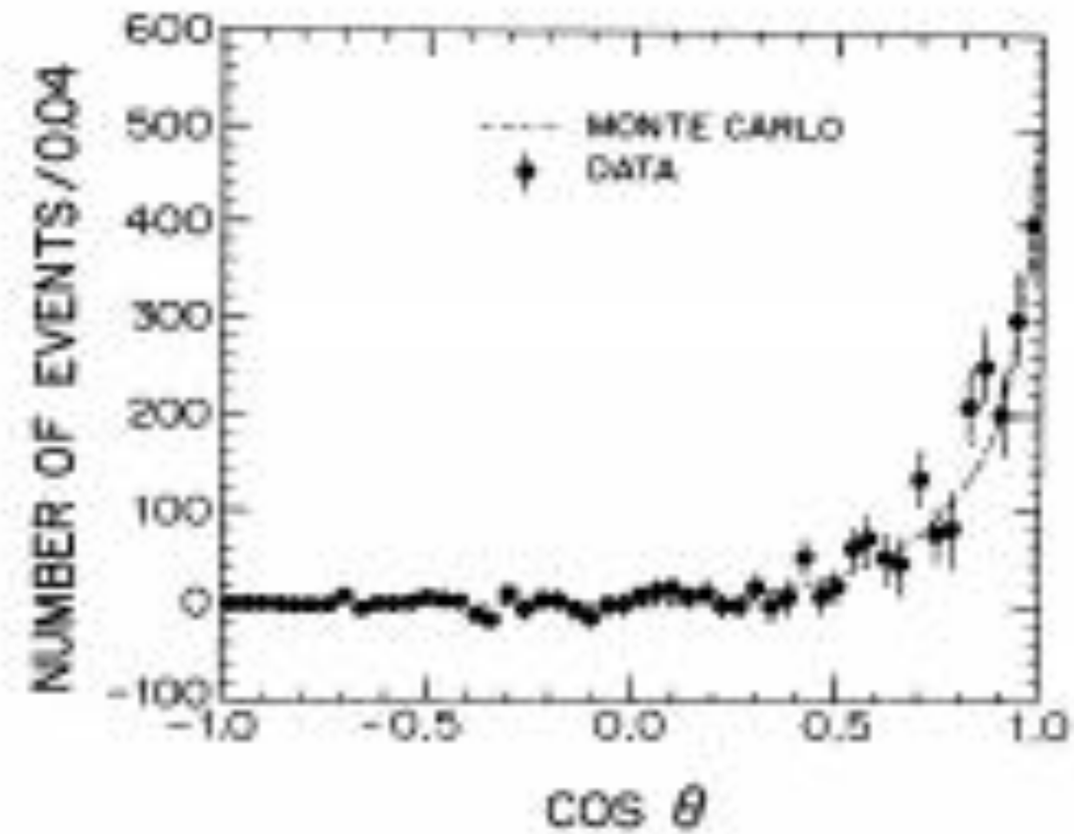




2.1 kton

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

Kamiokande-II, 1991

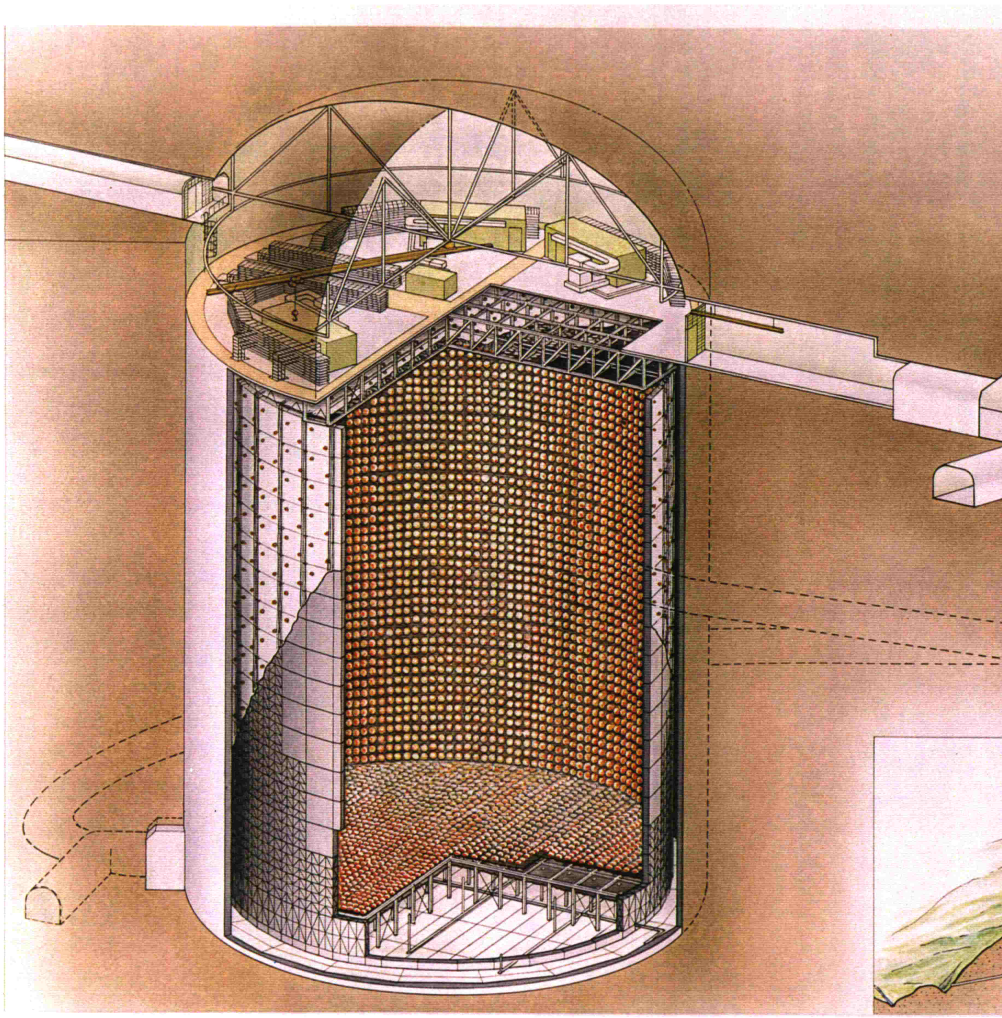


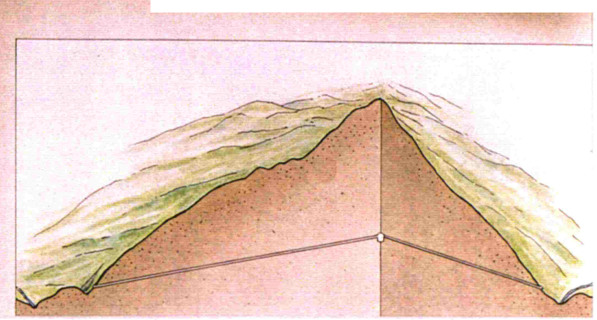
The events point back to the Sun!

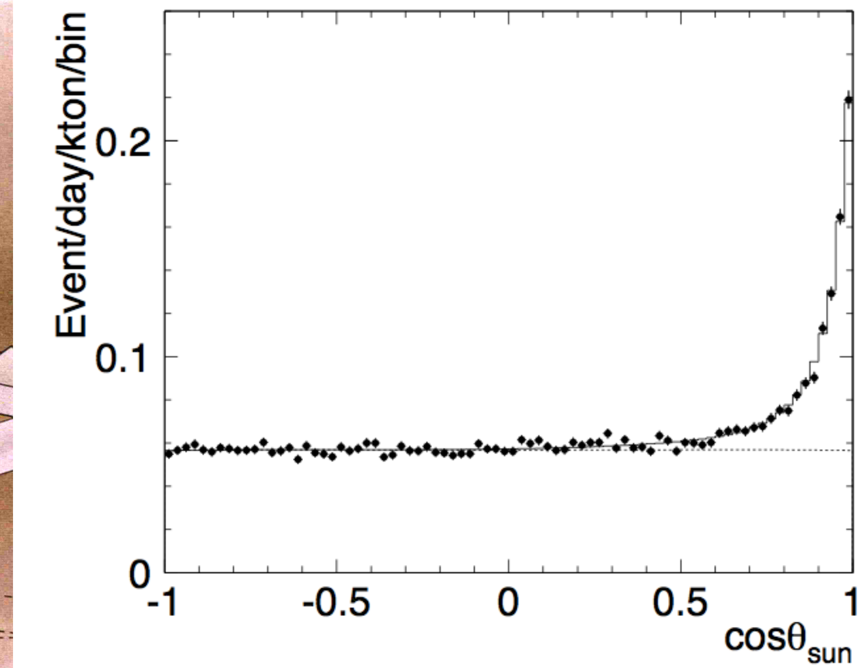
It's really solar neutrinos

~40% of expectation: still a deficit

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





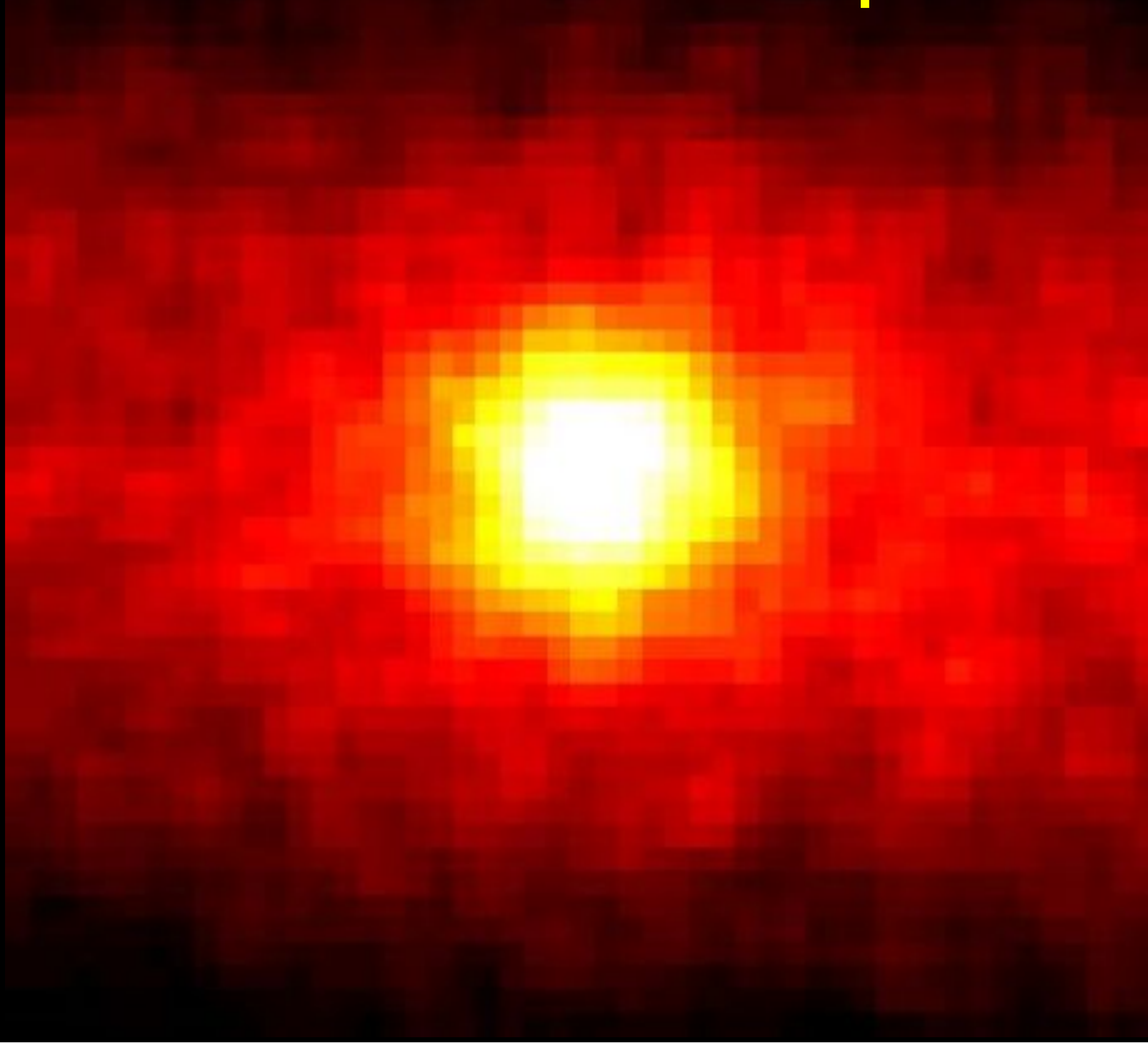


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

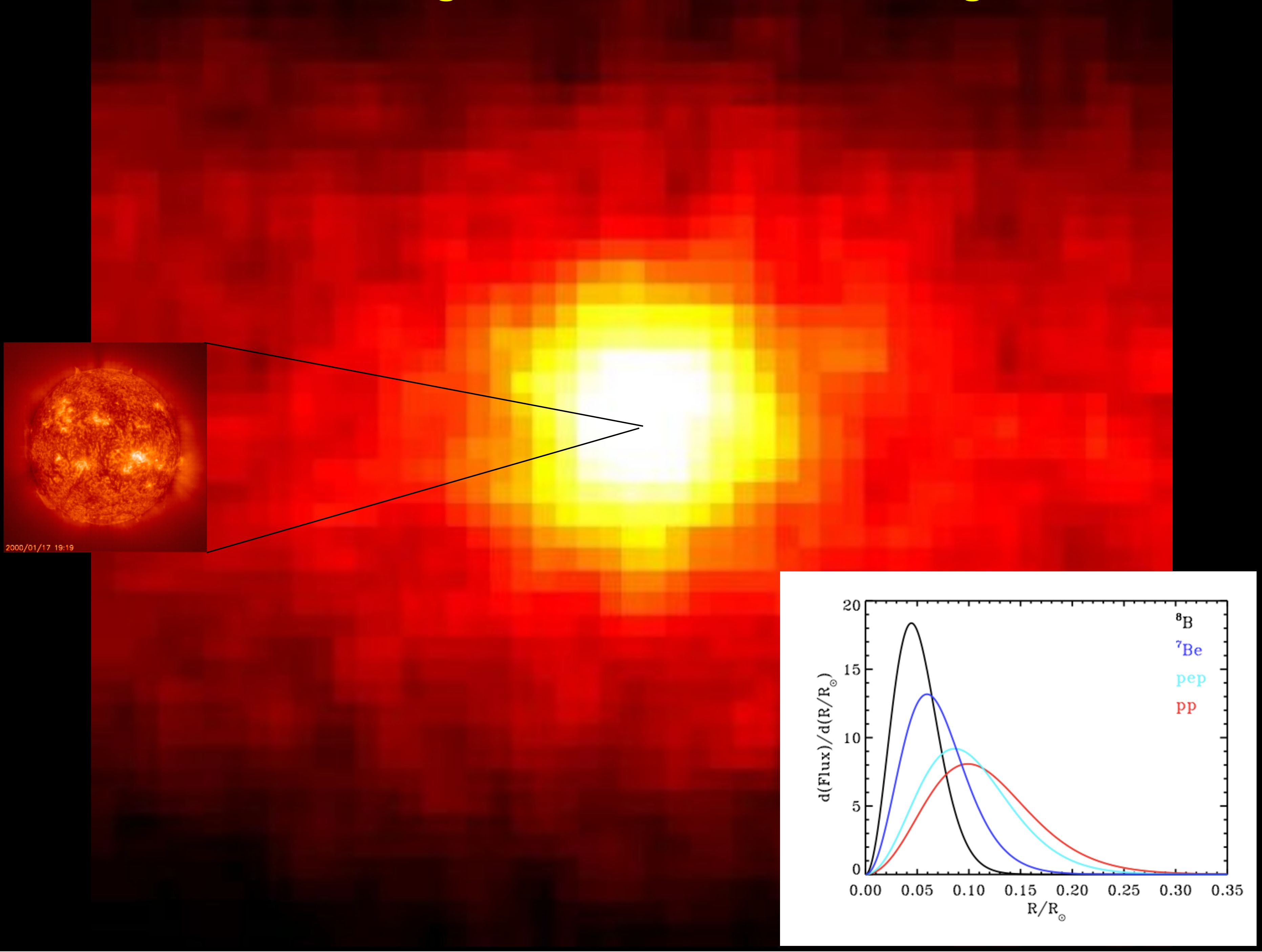
NIKKEN SEKKEI planners | architects | engineers

22.5 kton, <~ 5 MeV threshold

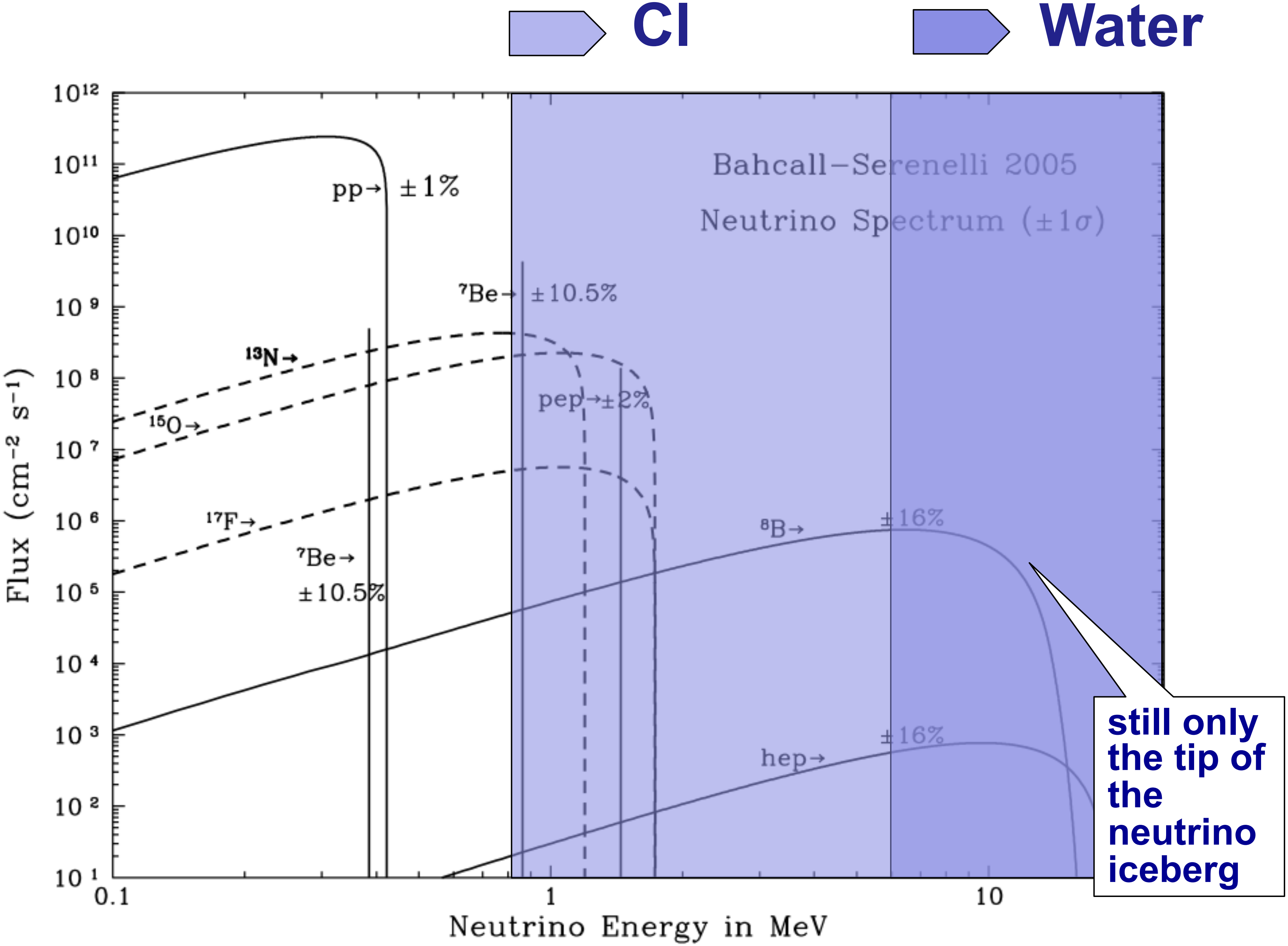
The Sun in neutrinos from Super-K



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

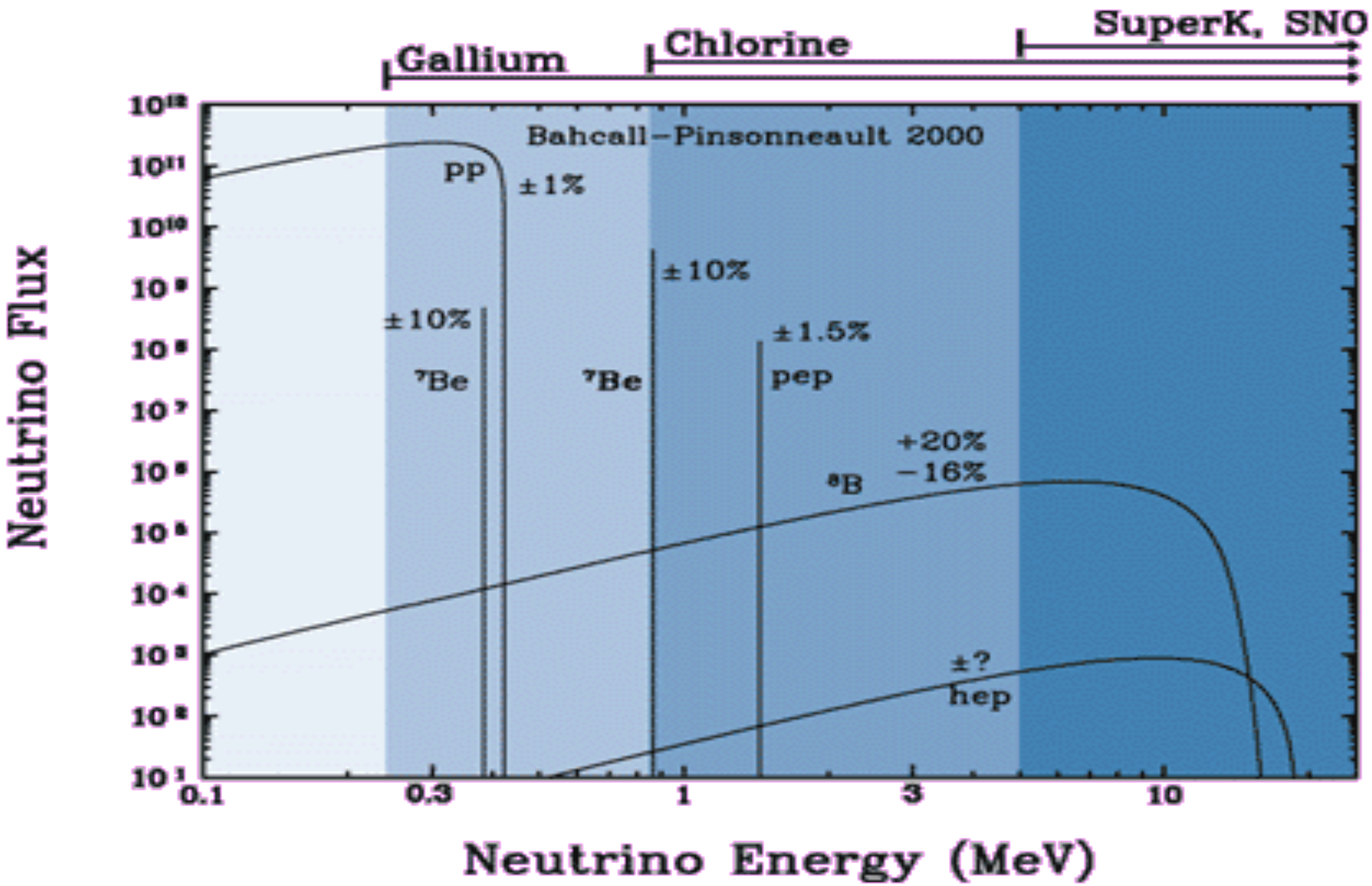


Two measurements at two energy thresholds



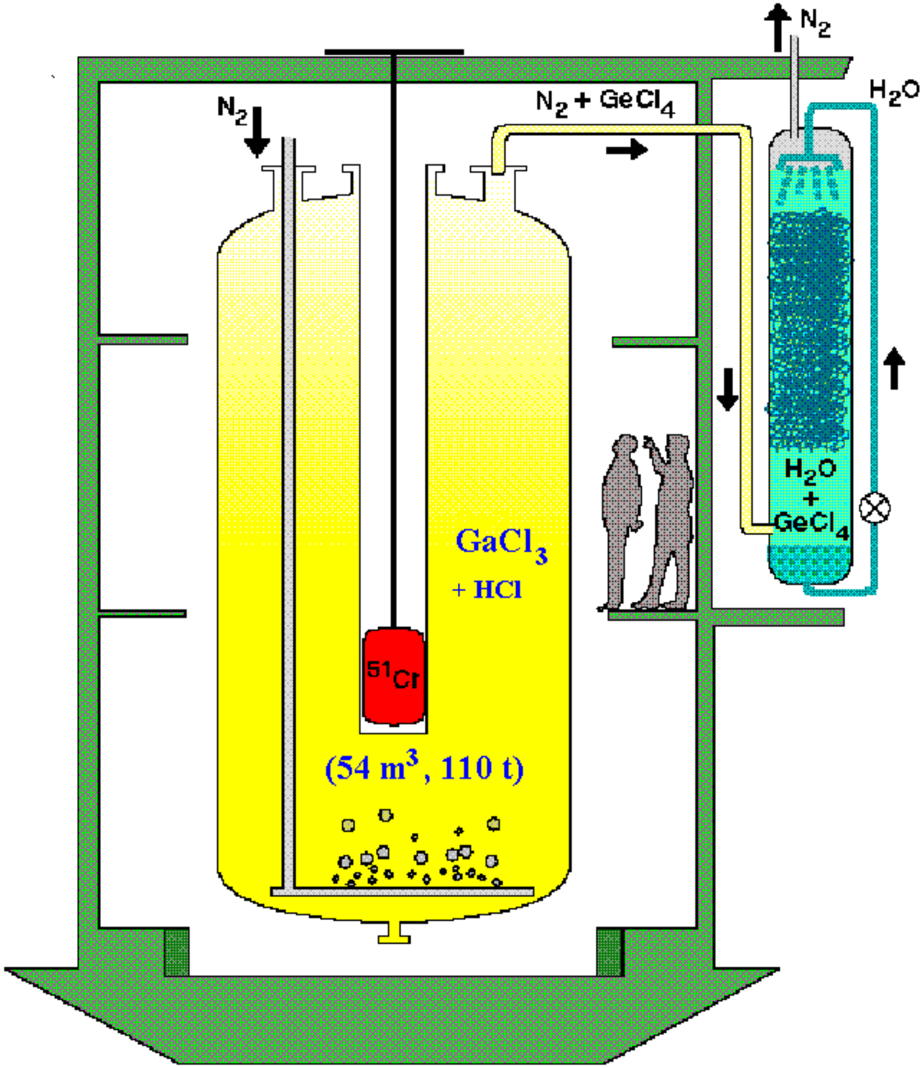
Next: gallium radiochemical experiments

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



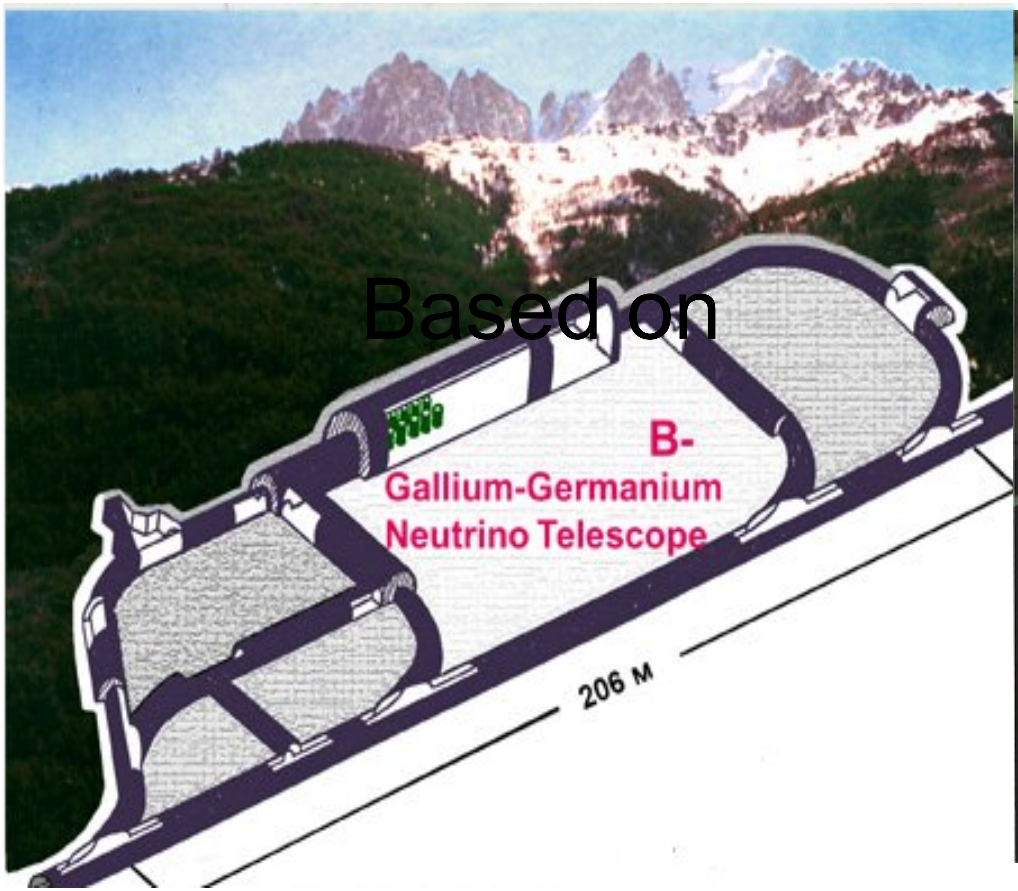
Threshold: 0.23 MeV, 11 day half-life
Sensitive to *pp neutrinos*

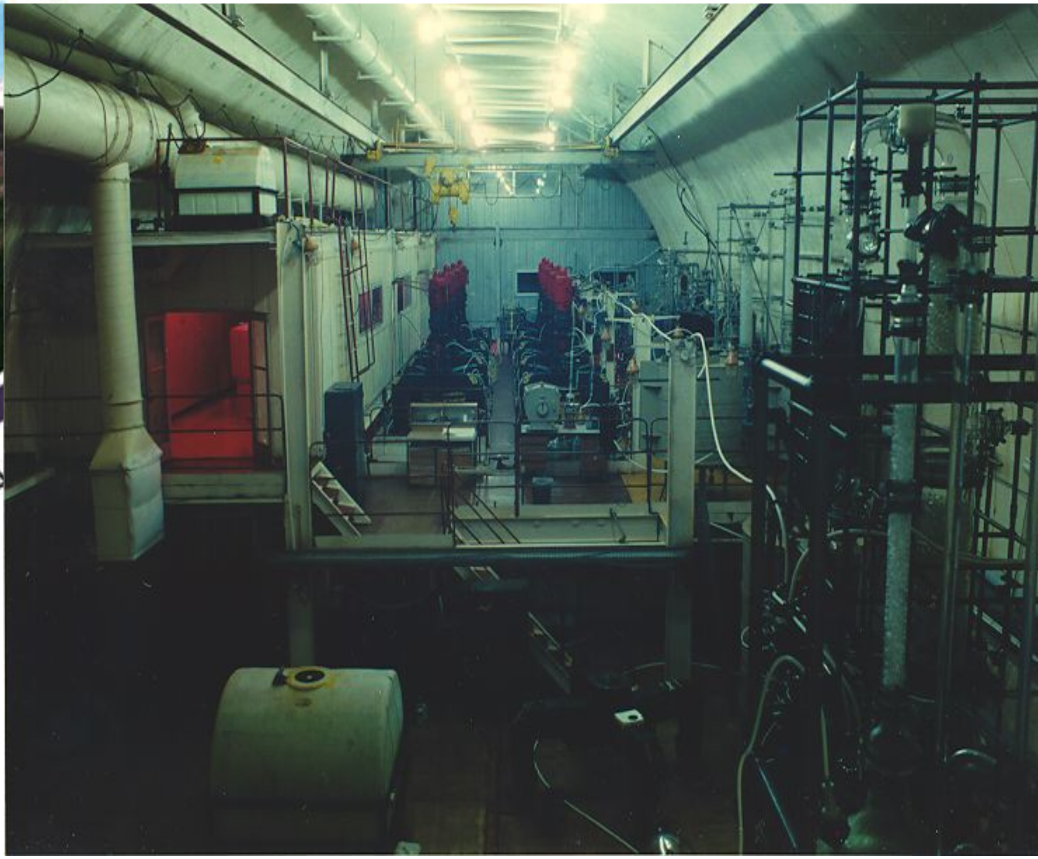
Gallex/GNO (Gallium Neutrino Observatory) at LNGS, Italy: 1991-2006



Used gallium chloride (30 tons of Ga)

The SAGE Experiment





Caucasus mountains, Russia

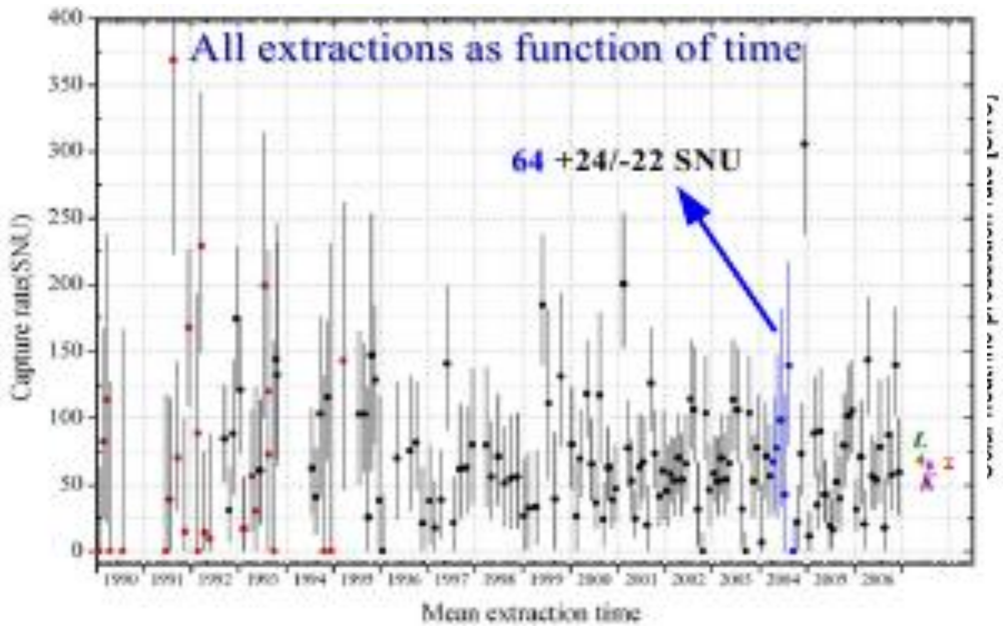
Based on liquid gallium
50 tons

1990-2007

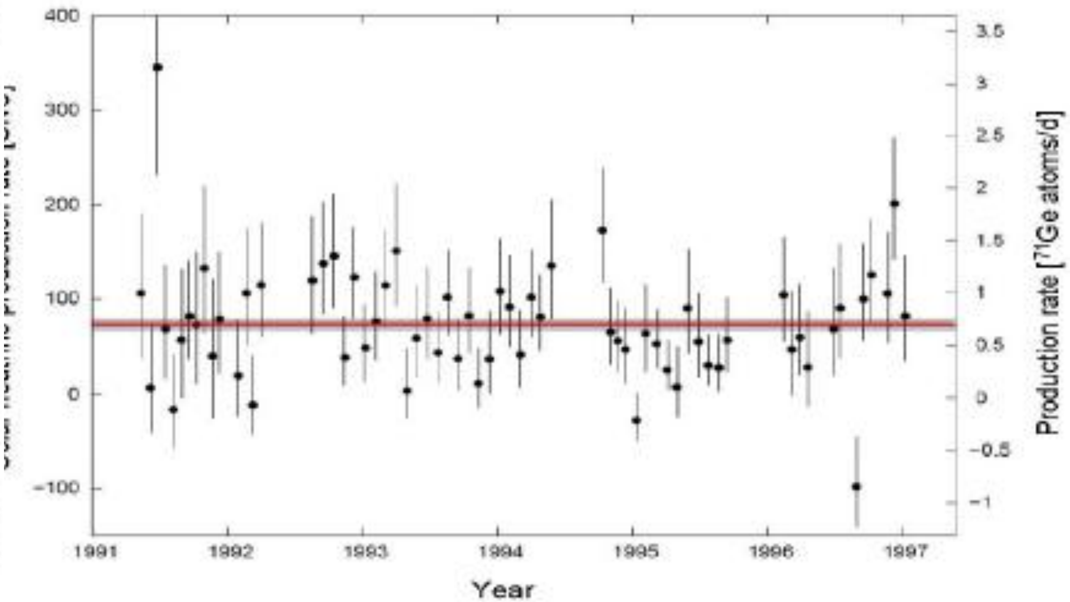
Gallium solar neutrino results

D. Hahn, Nu2008

SAGE

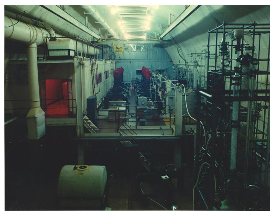


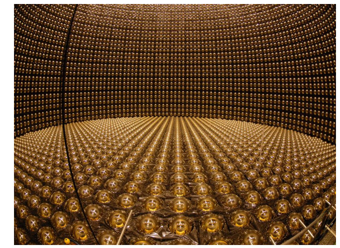
GALLEX

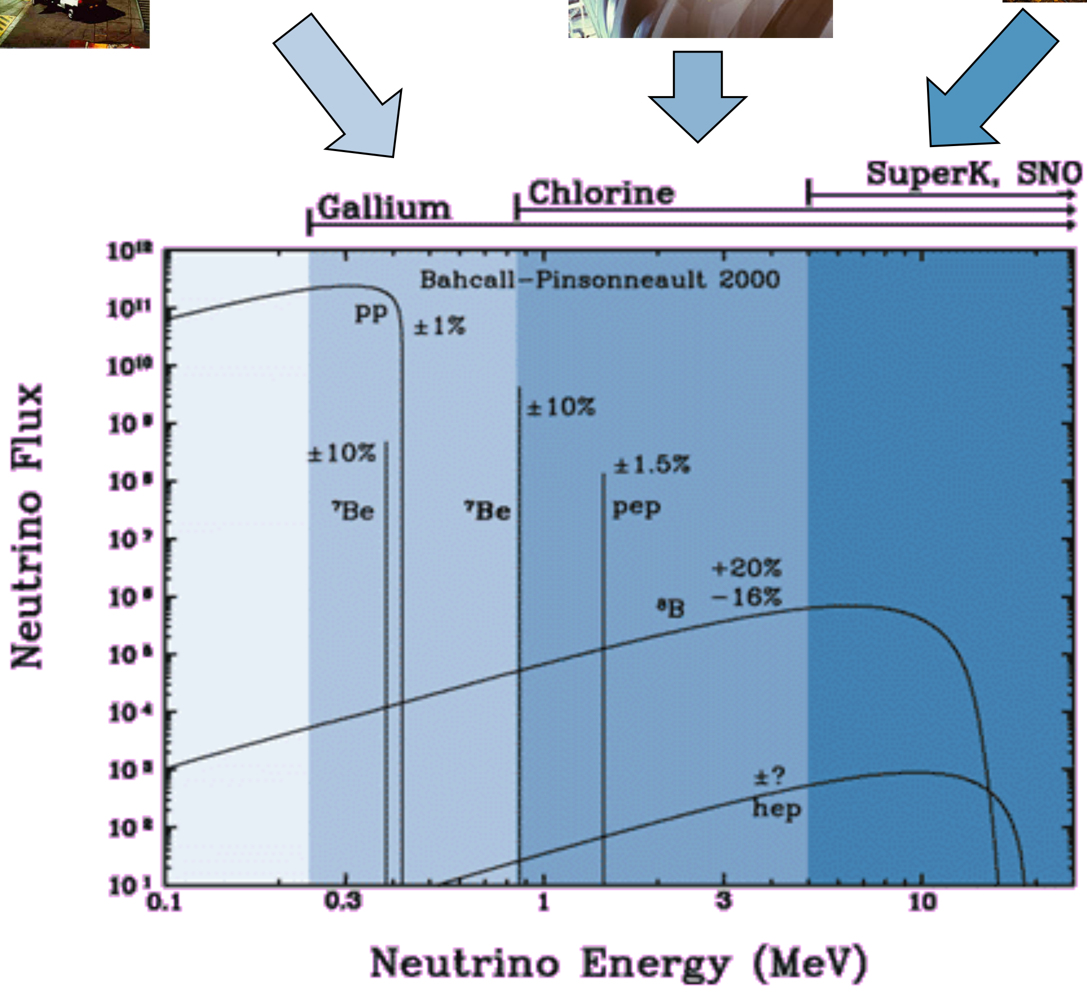


Again clear shortfall: about 60% of standard solar model expectation (pp neutrinos)

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

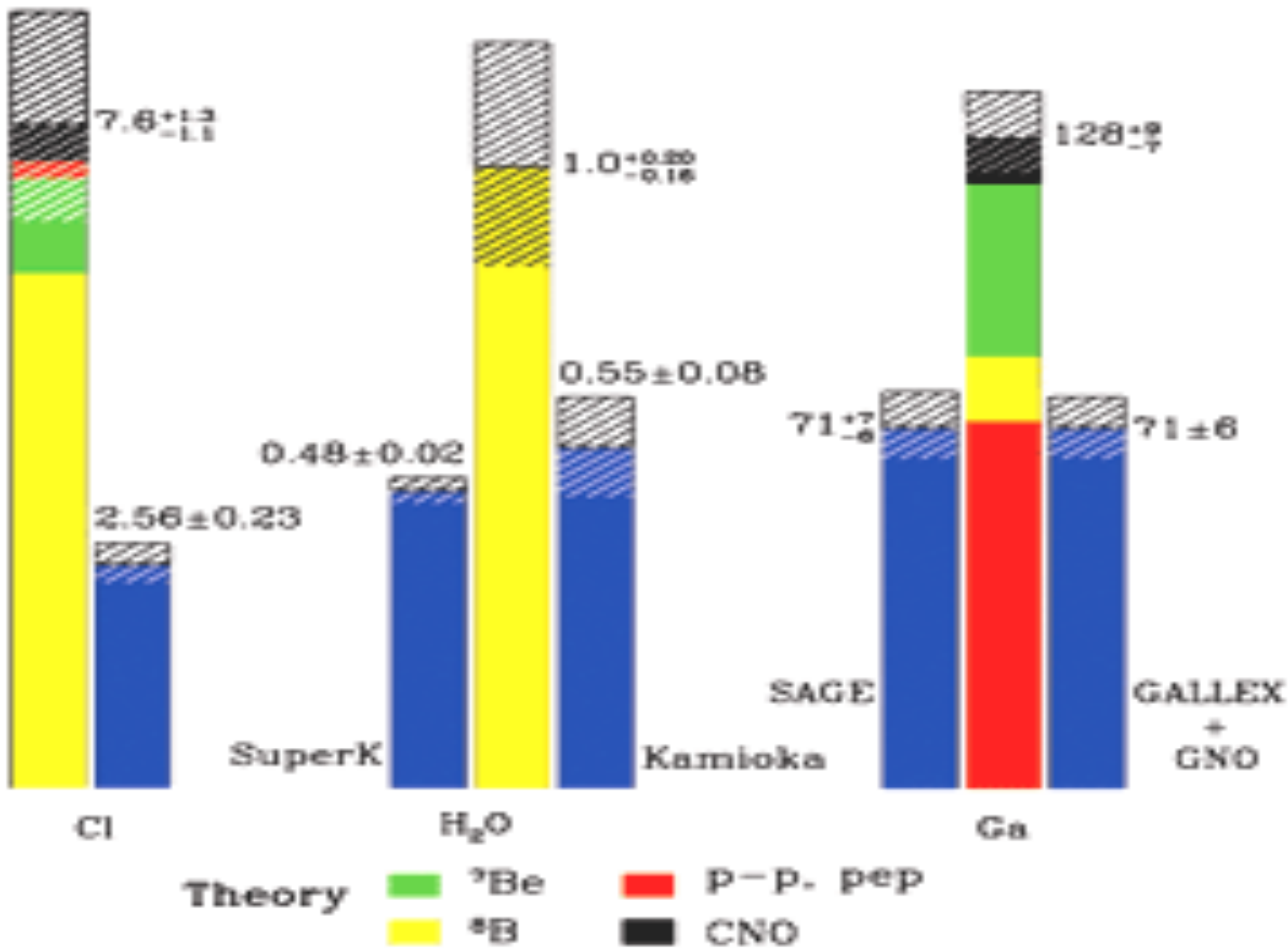






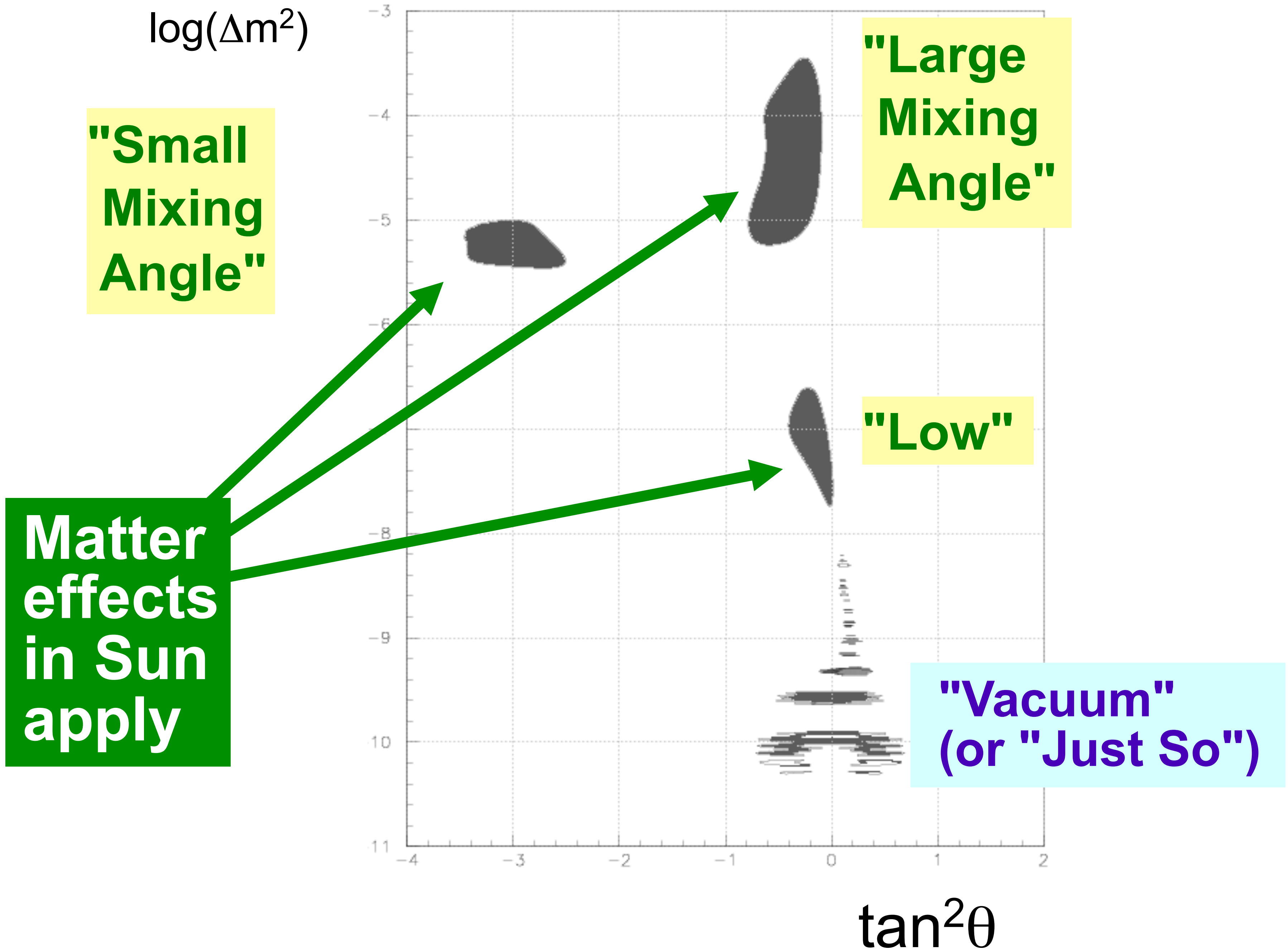
Different detectors are sensitive to different neutrino energy ranges

Energy-dependent suppression observed

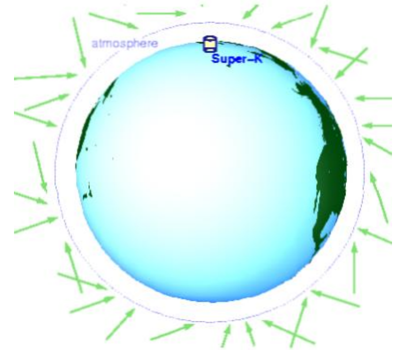


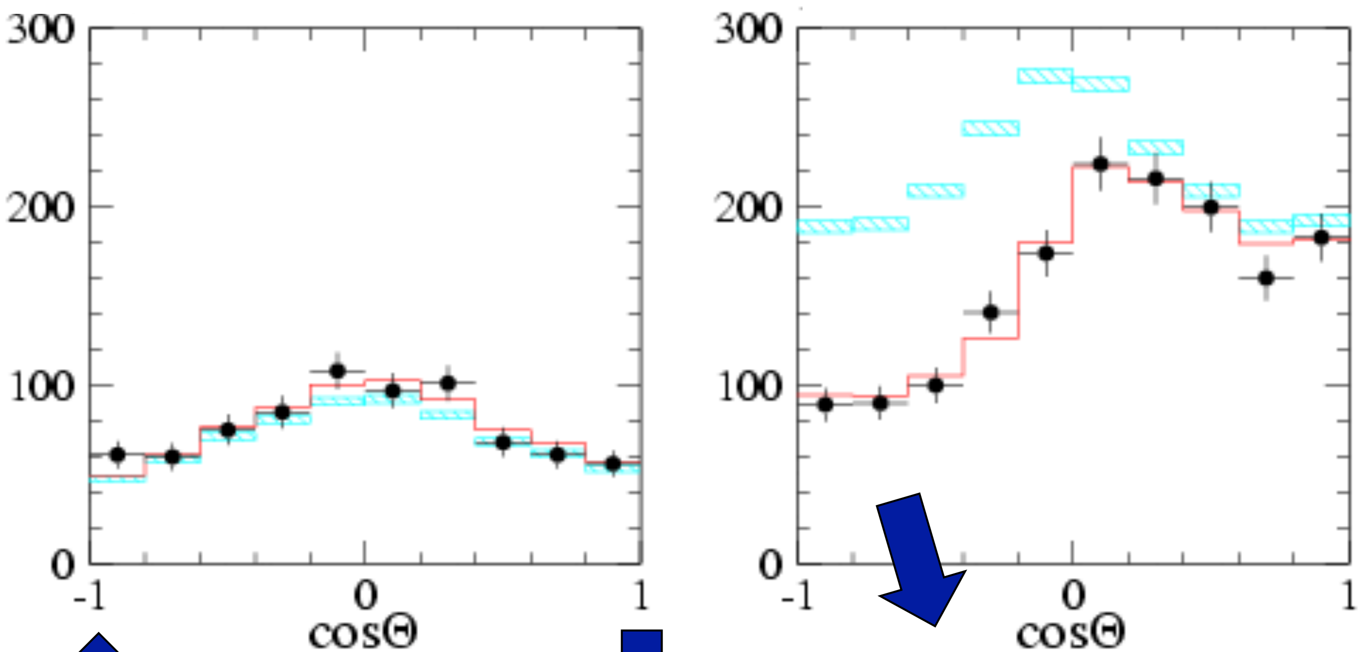
No known solar model could explain...
could it be $\nu_e \rightarrow \nu_{\mu,\tau}$?

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



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



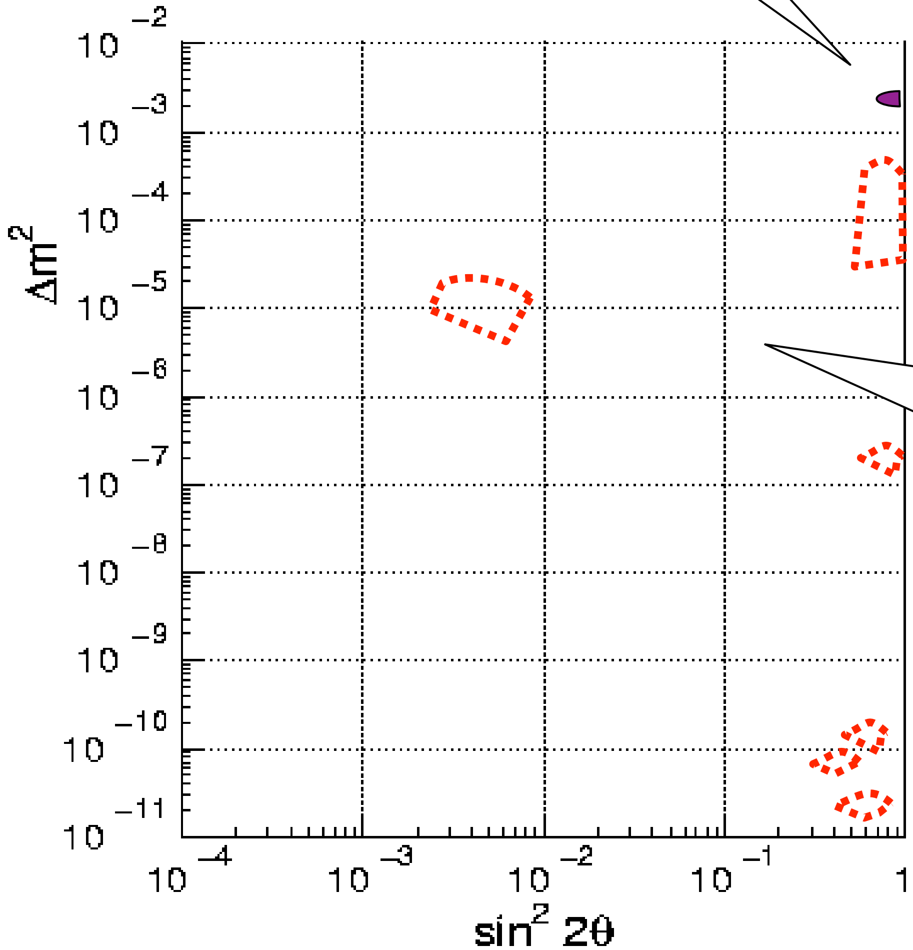


up-going **down-going**

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

— **ν_μ–ν_τ oscillation (best fit)**

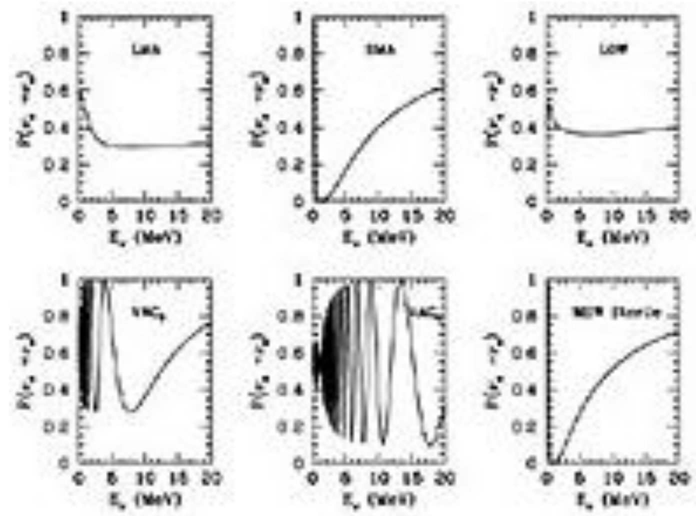
Atmospheric oscillations occupy a different oscillation parameter regime



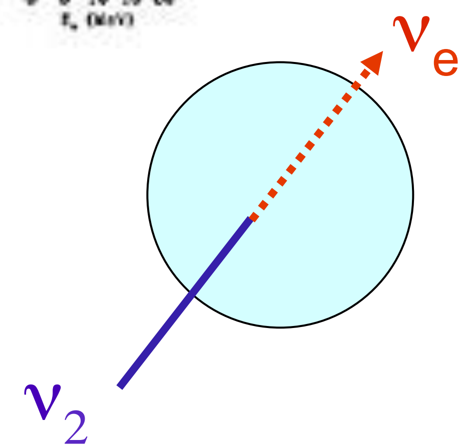
But now solar neutrino oscillations (low energy, longer wavelength) are even more motivated!

Hunting for "Smoking Guns": oscillation signatures

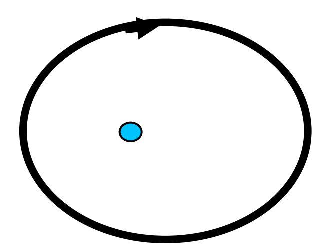
- **Spectral distortion**



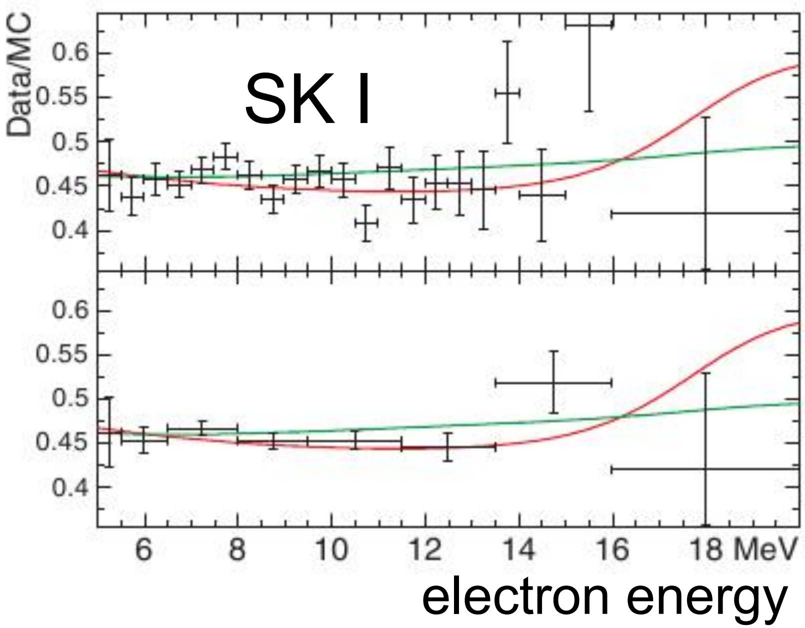
- **Day/night effect:** regeneration of ν_e in Earth due to matter effect enhances ν_e flux at night for some parameters



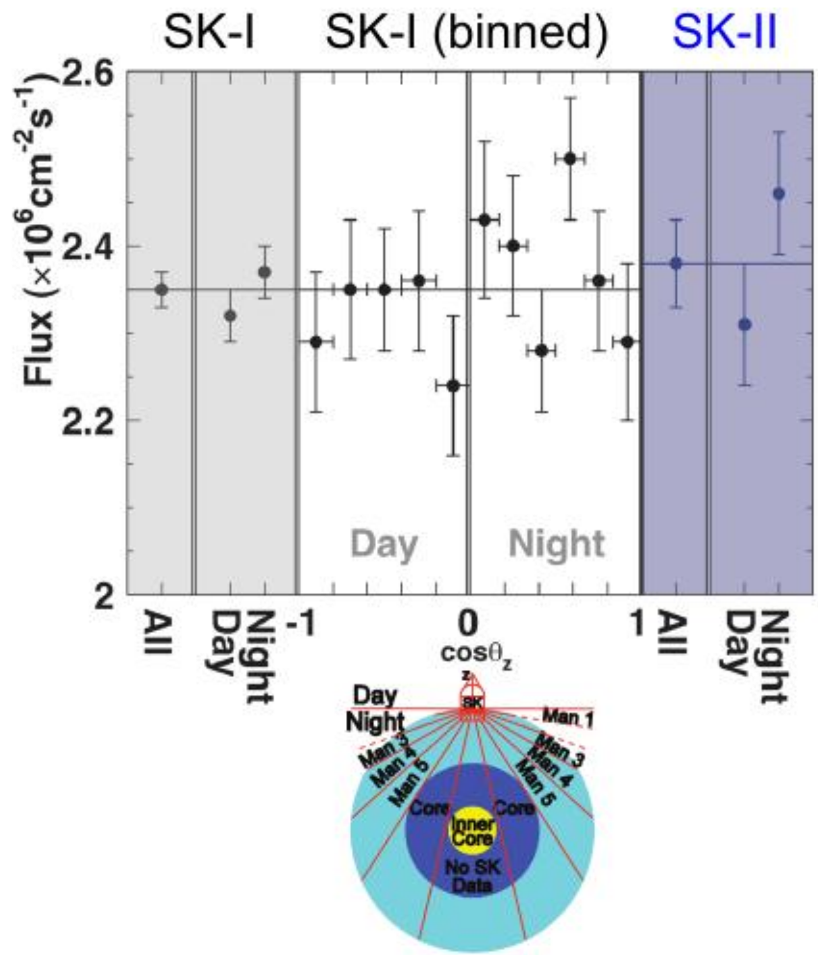
- **Seasonal variation:** variation with L for vacuum oscillation (beyond 7% expected from Earth orbit)



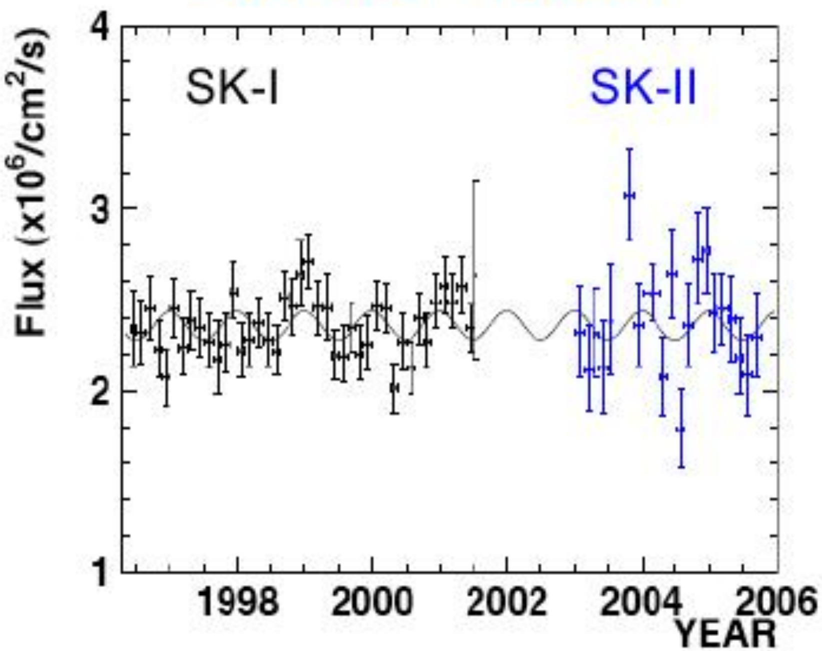
Recoil energy spectrum



Day/night asymmetry



Seasonal variation



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

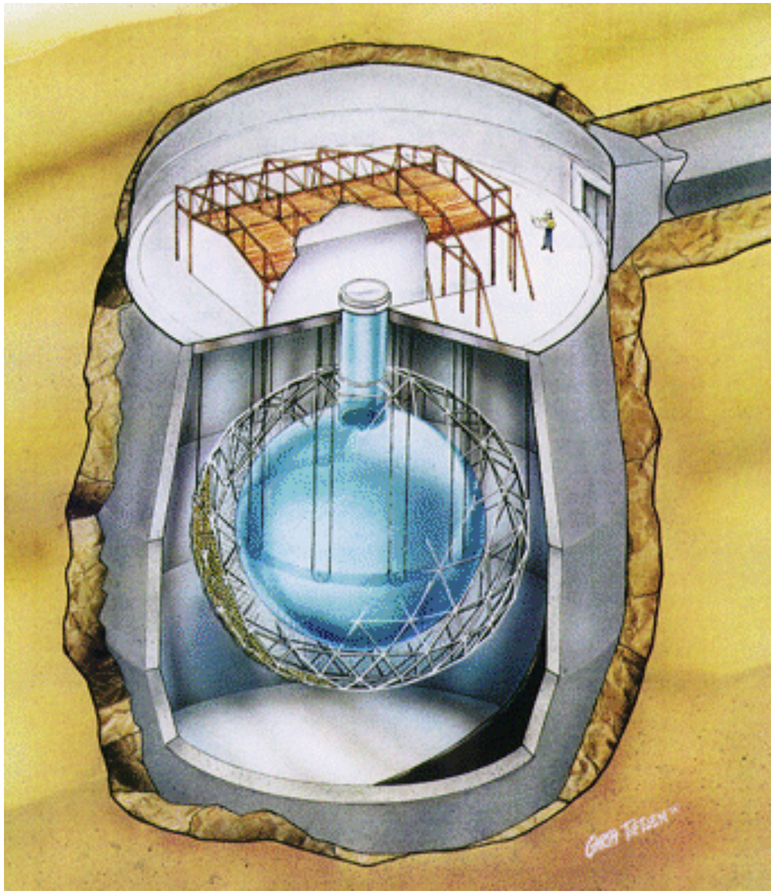
But there's another smoking gun...

- **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^-

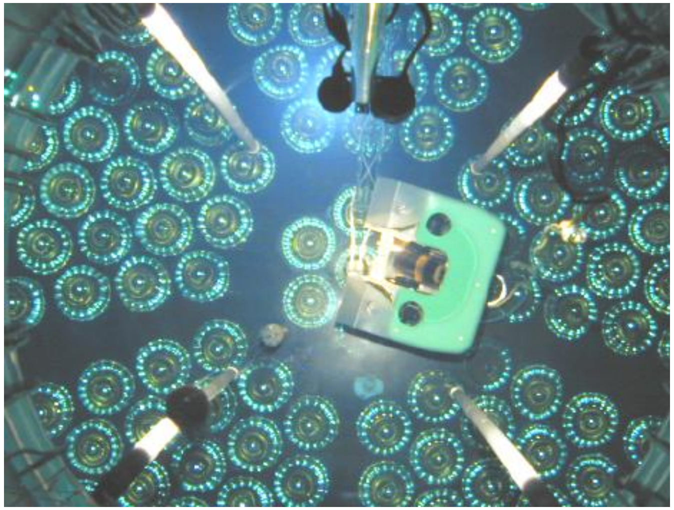
Neutron detection

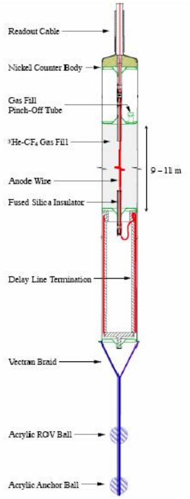
SNO's unique feature: NC detection

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

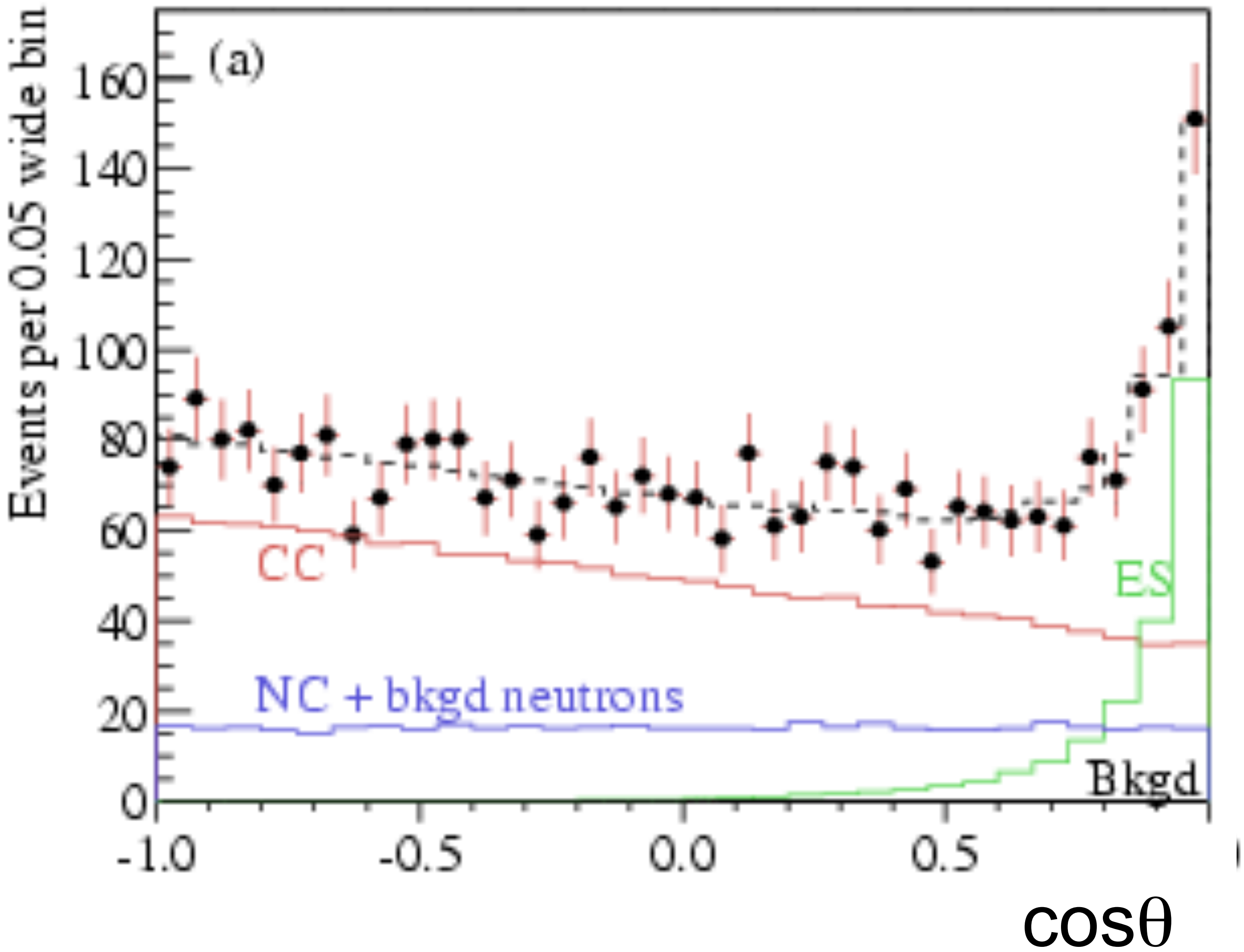
$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu,\tau}) \sim$ total flux

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ **Elastic scattering (CC, NC)** mixture of ν_e and all with *known ratio*

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

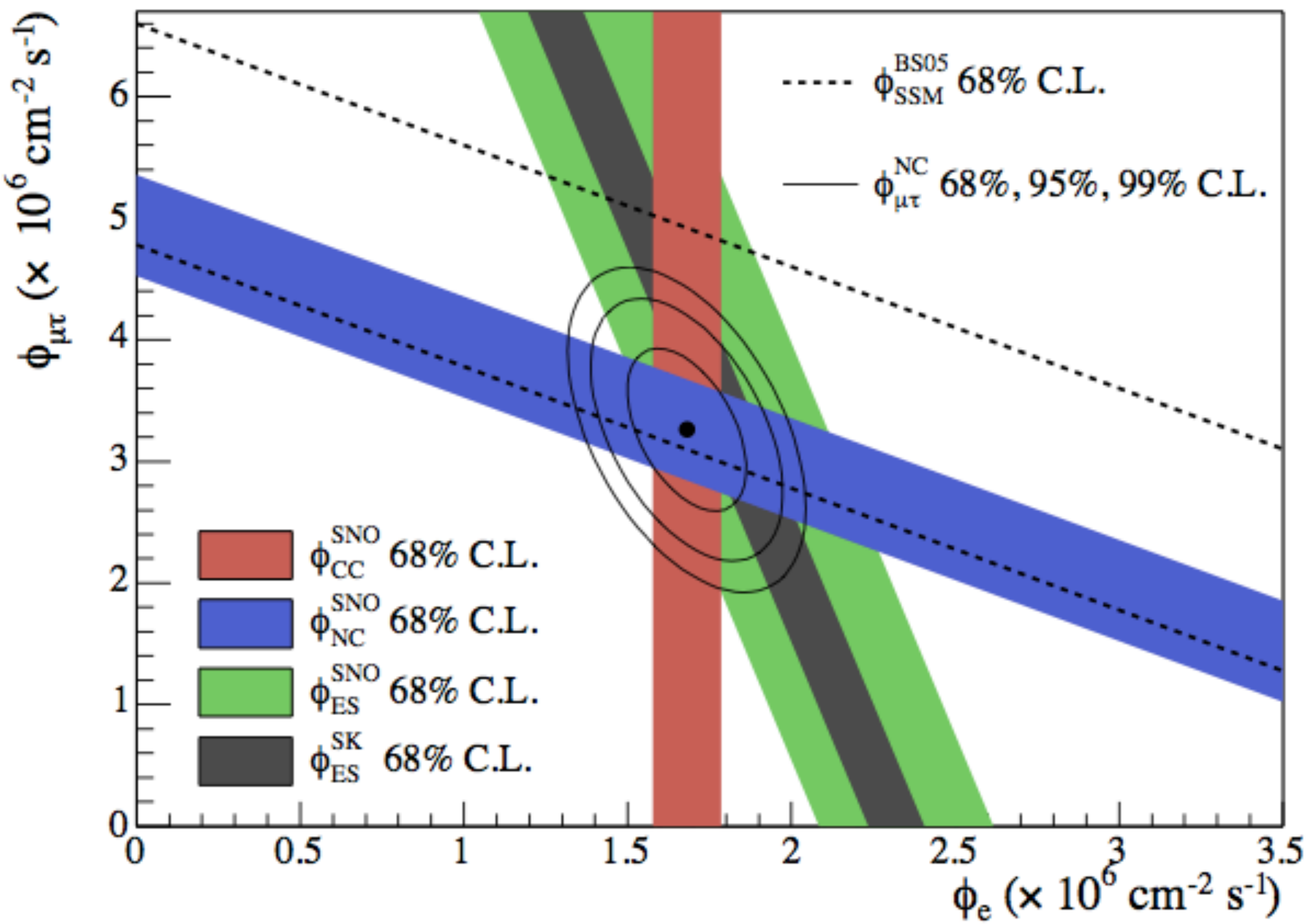
Also look for distortion of CC spectrum, night enhancement

Phase I SNO Results, 2002



Fit data for CC, NC, ES components

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

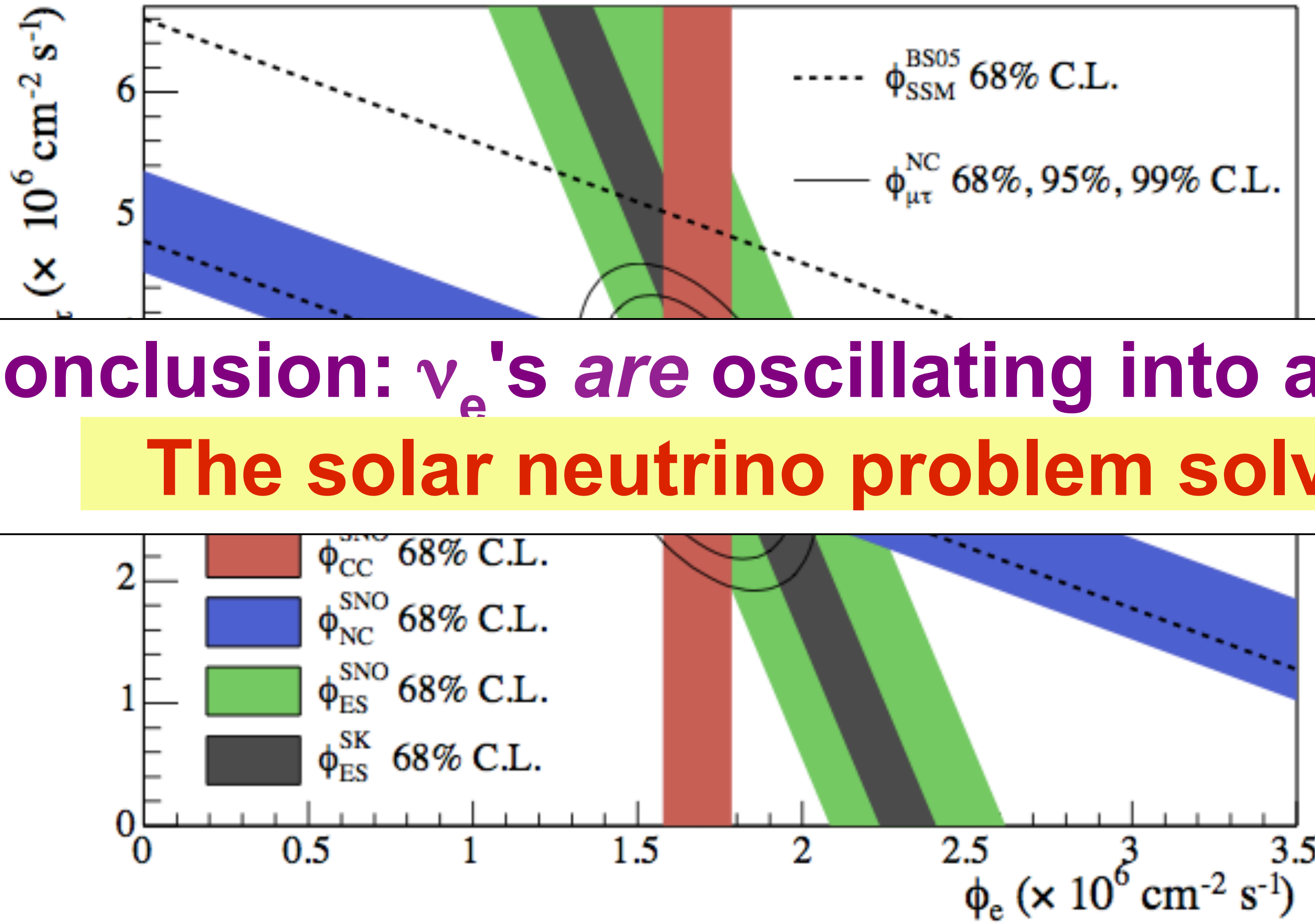


$\phi_{CC}=\phi(\nu_e)$

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

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

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



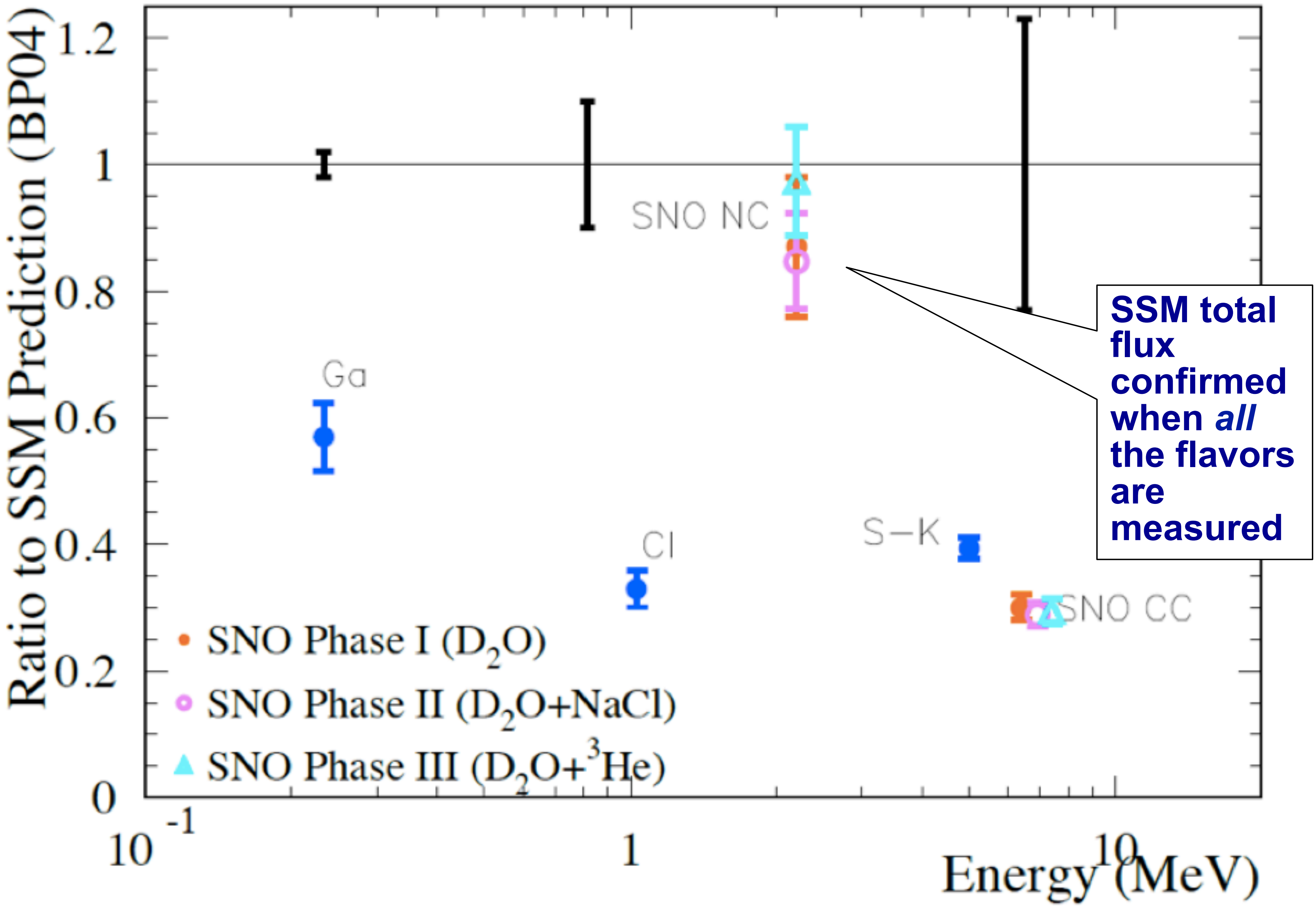
Conclusion: ν_e's *are* oscillating into active ν's!

The solar neutrino problem solved!

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

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

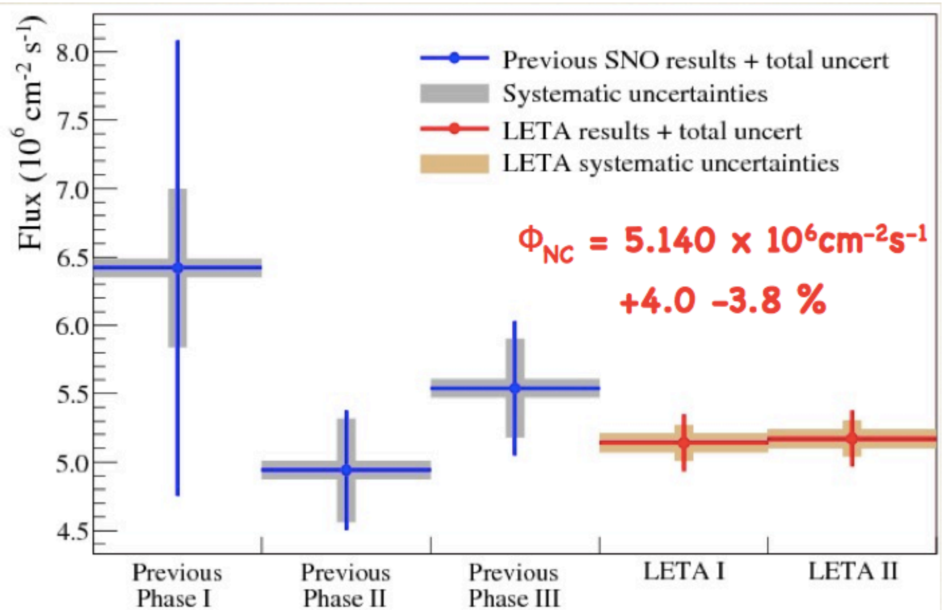
$\phi_{ES}=\phi(\nu_e) + 0.15\phi(\nu_{\mu,\tau})$



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

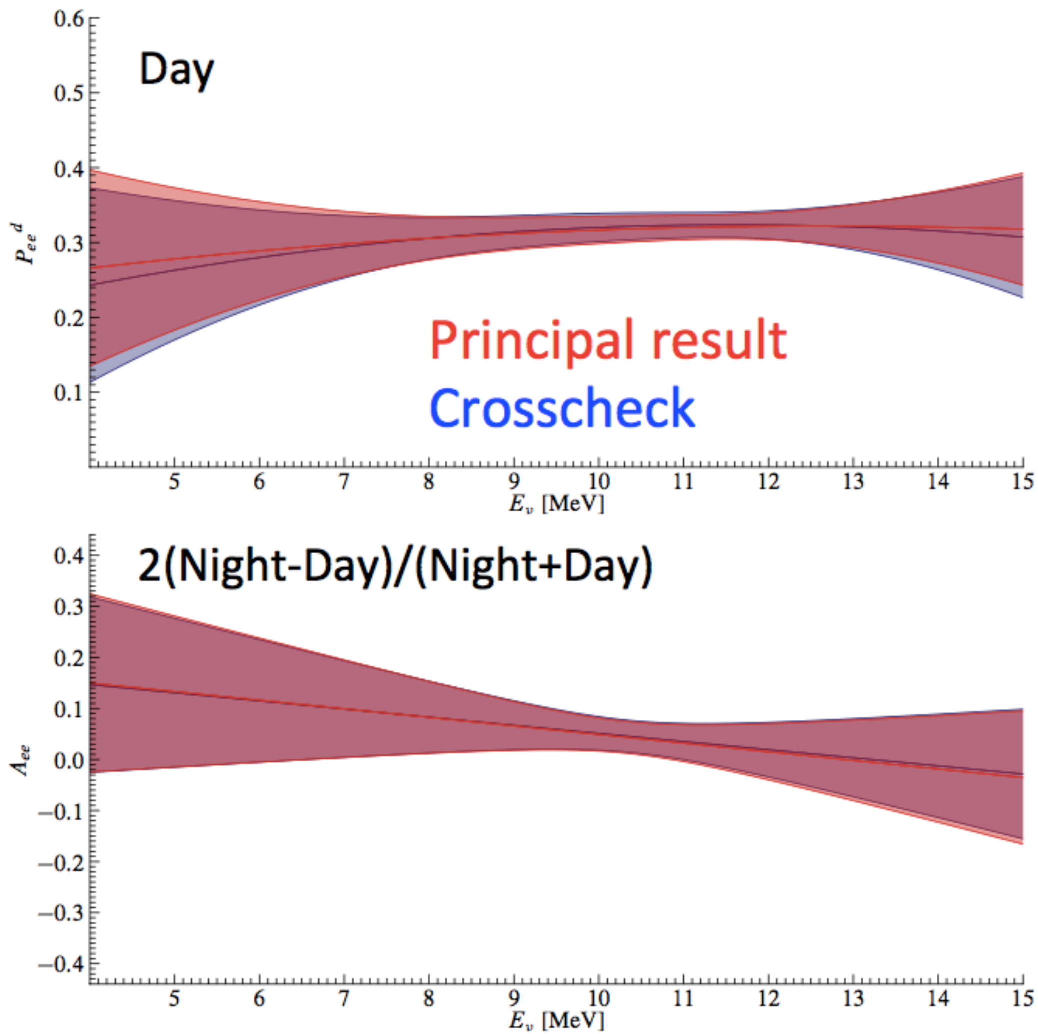
G. Orebi-Gann

SNO Final Analysis Results



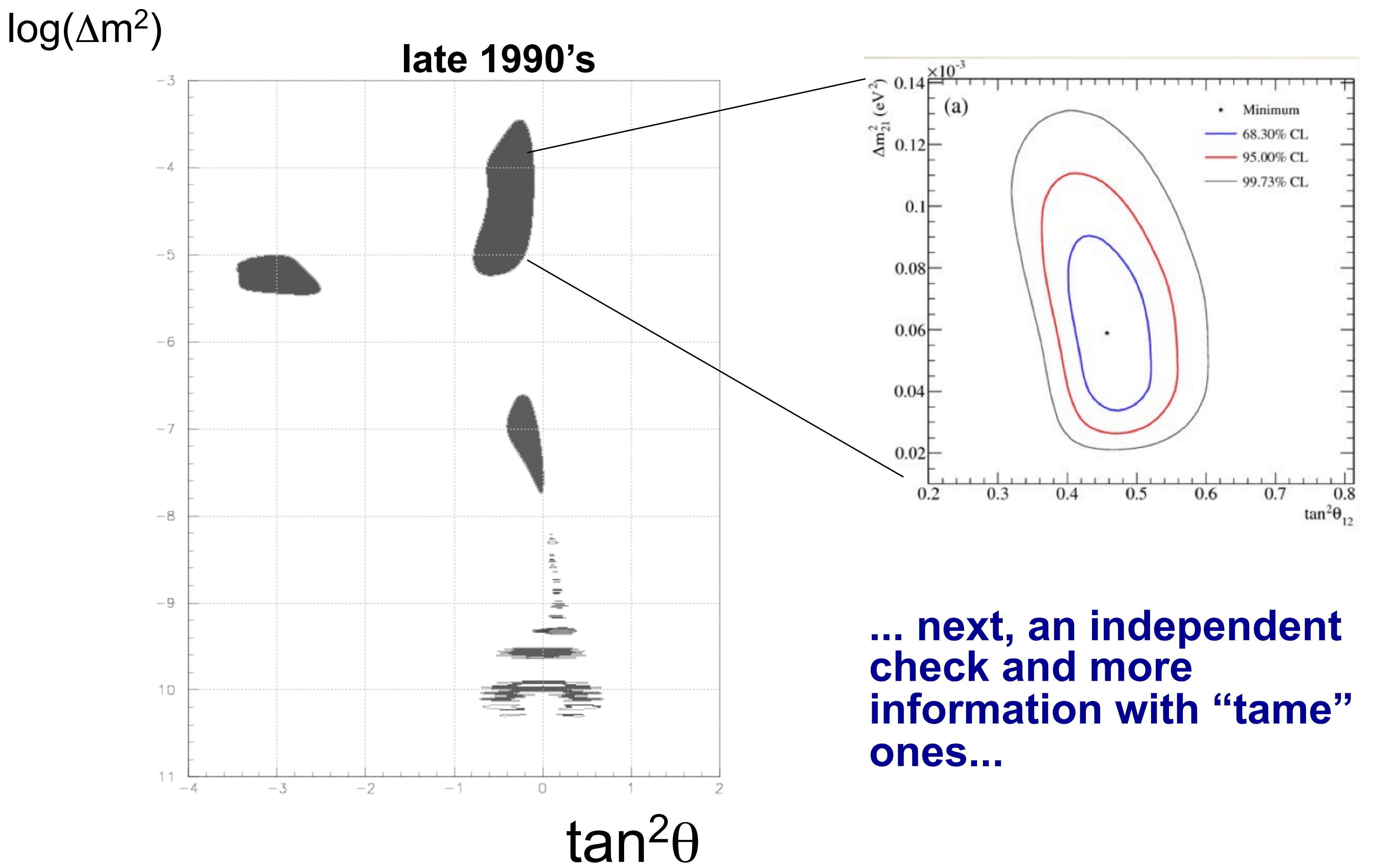
LETA: Low Energy Threshold Analysis

Electron neutrino survival probability vs ν energy



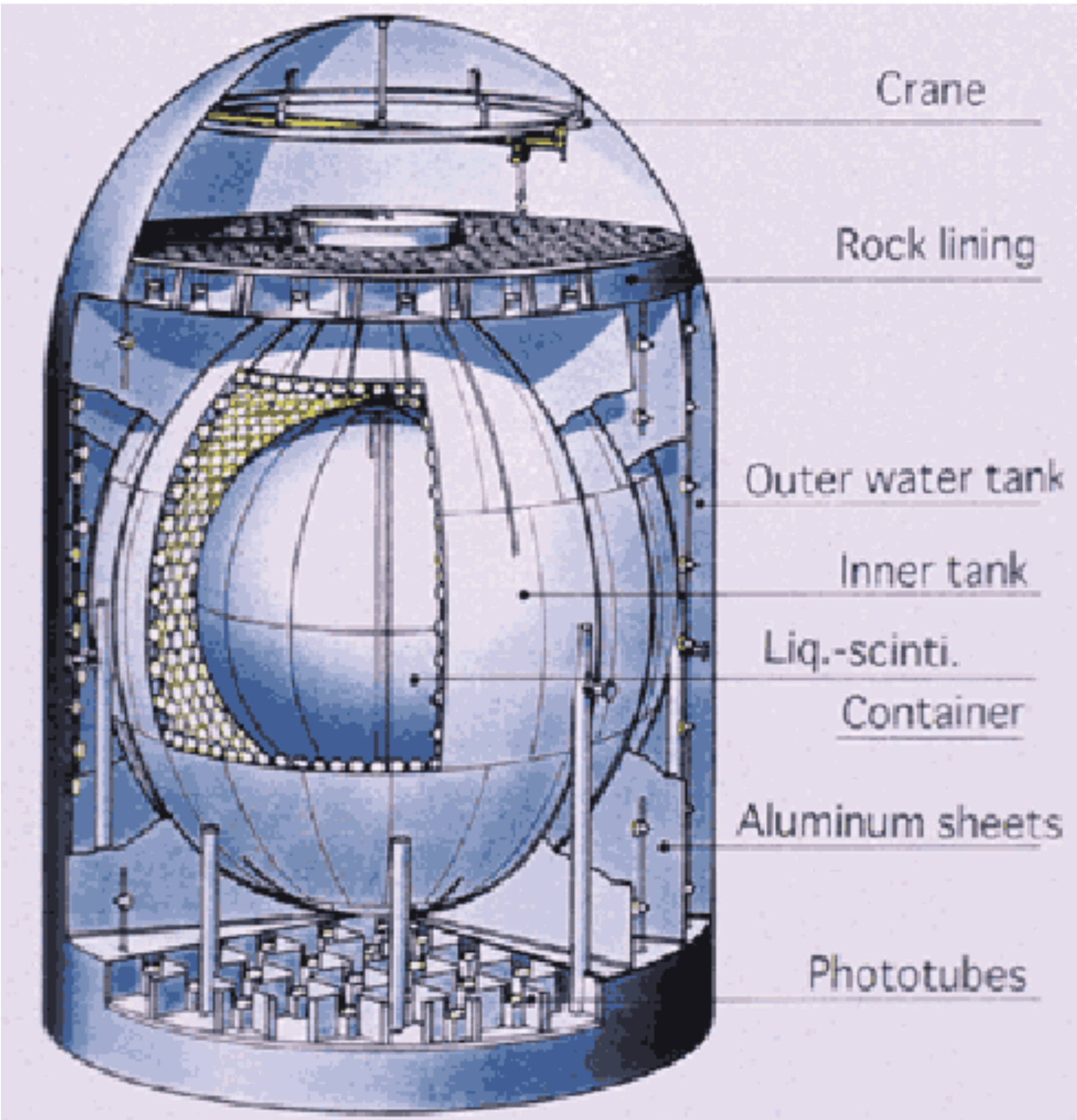
Energy spectrum & day/night effect (matter in Earth) from SNO & SK constrain oscillation parameters

Oscillation parameters measured with "wild" solar neutrinos...



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

The KamLAND Experiment

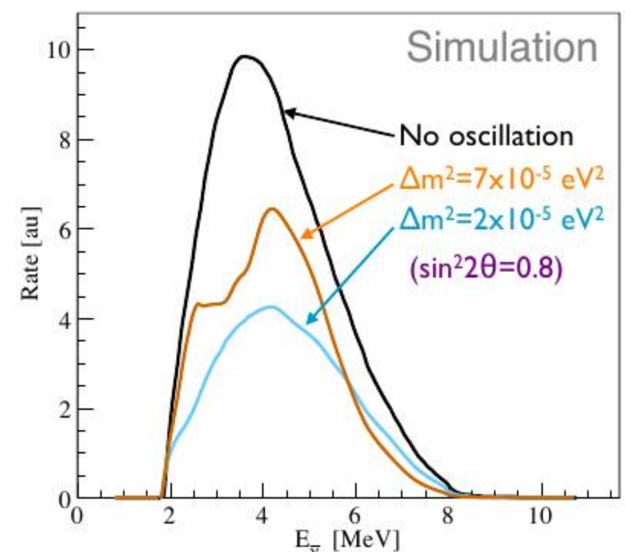


Mozumi, Japan

Look at solar LMA parameter space using *reactor antineutrinos*

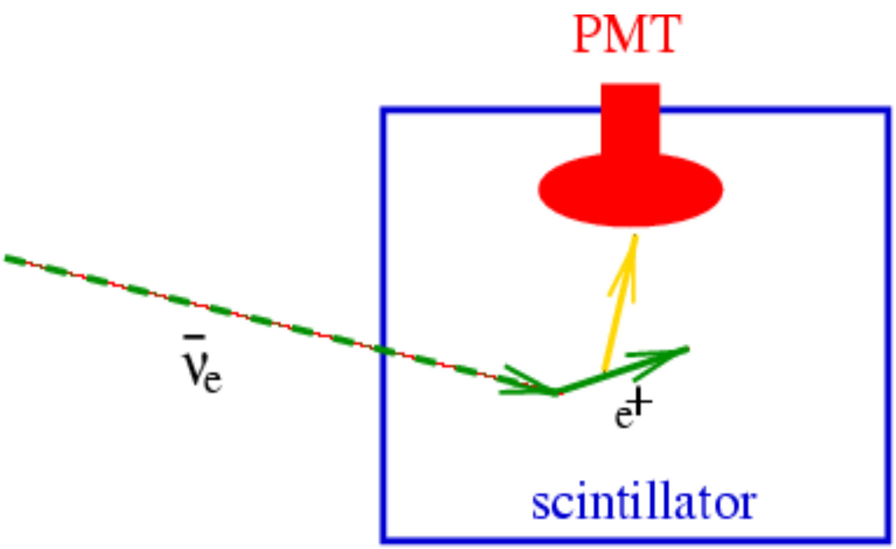
Sum of reactor fluxes from Japan, Korea

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



P. Decowski

Scintillation detectors



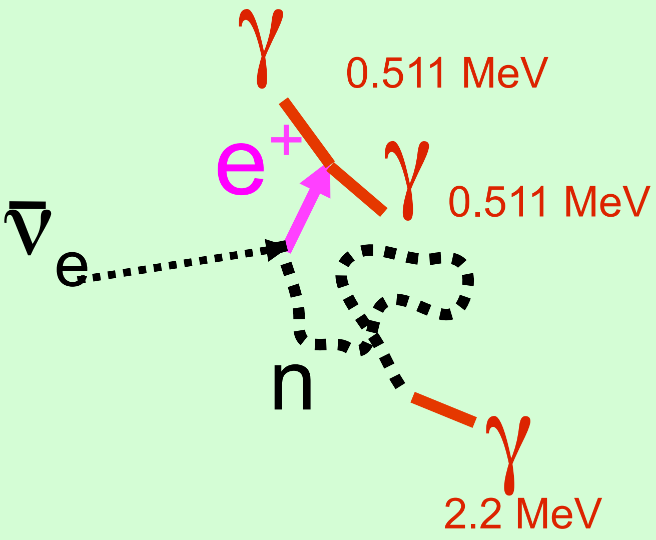
Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

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

- little directional capability (light is ~isotropic)

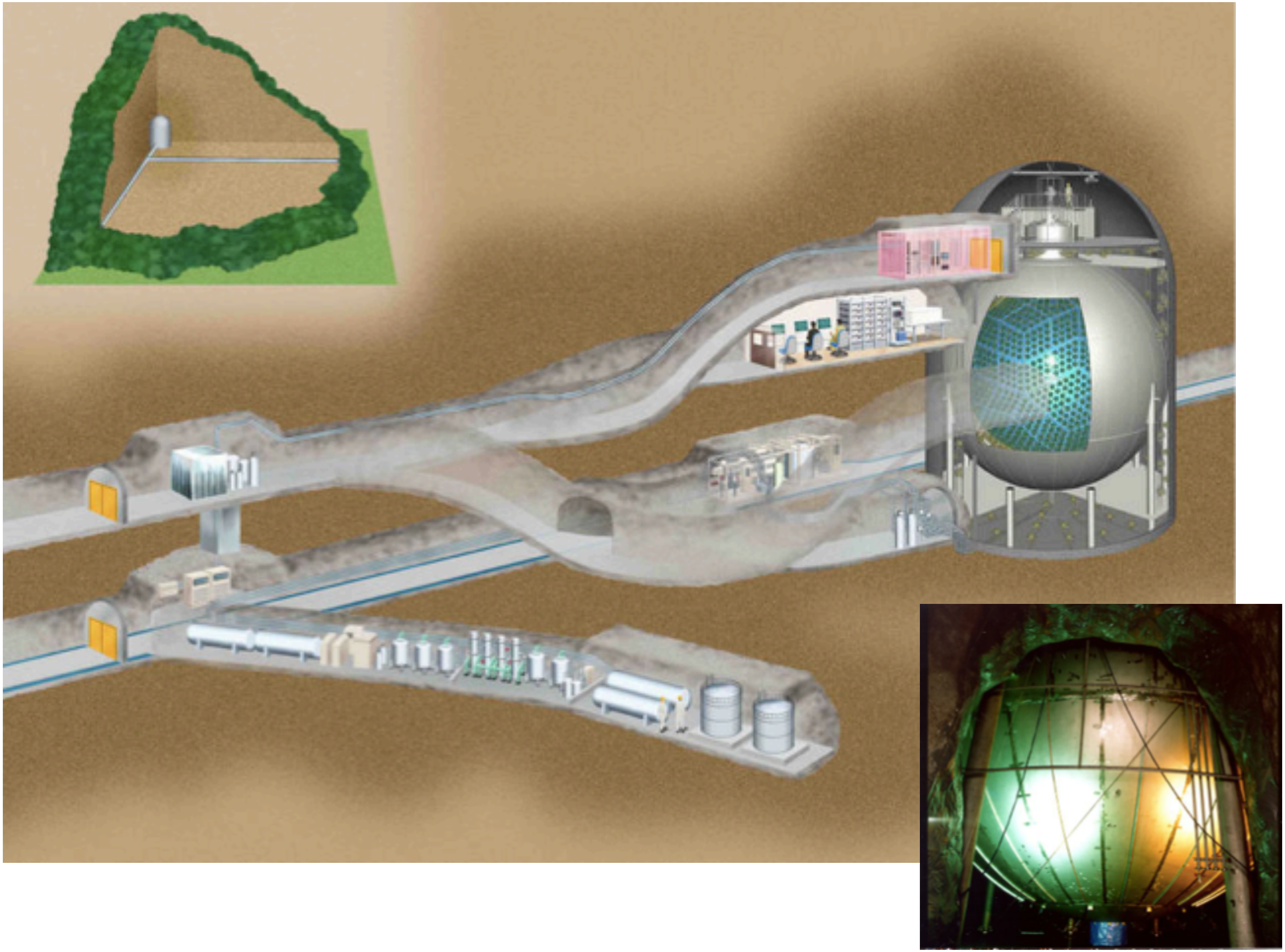
Inverse Beta Decay (CC)

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

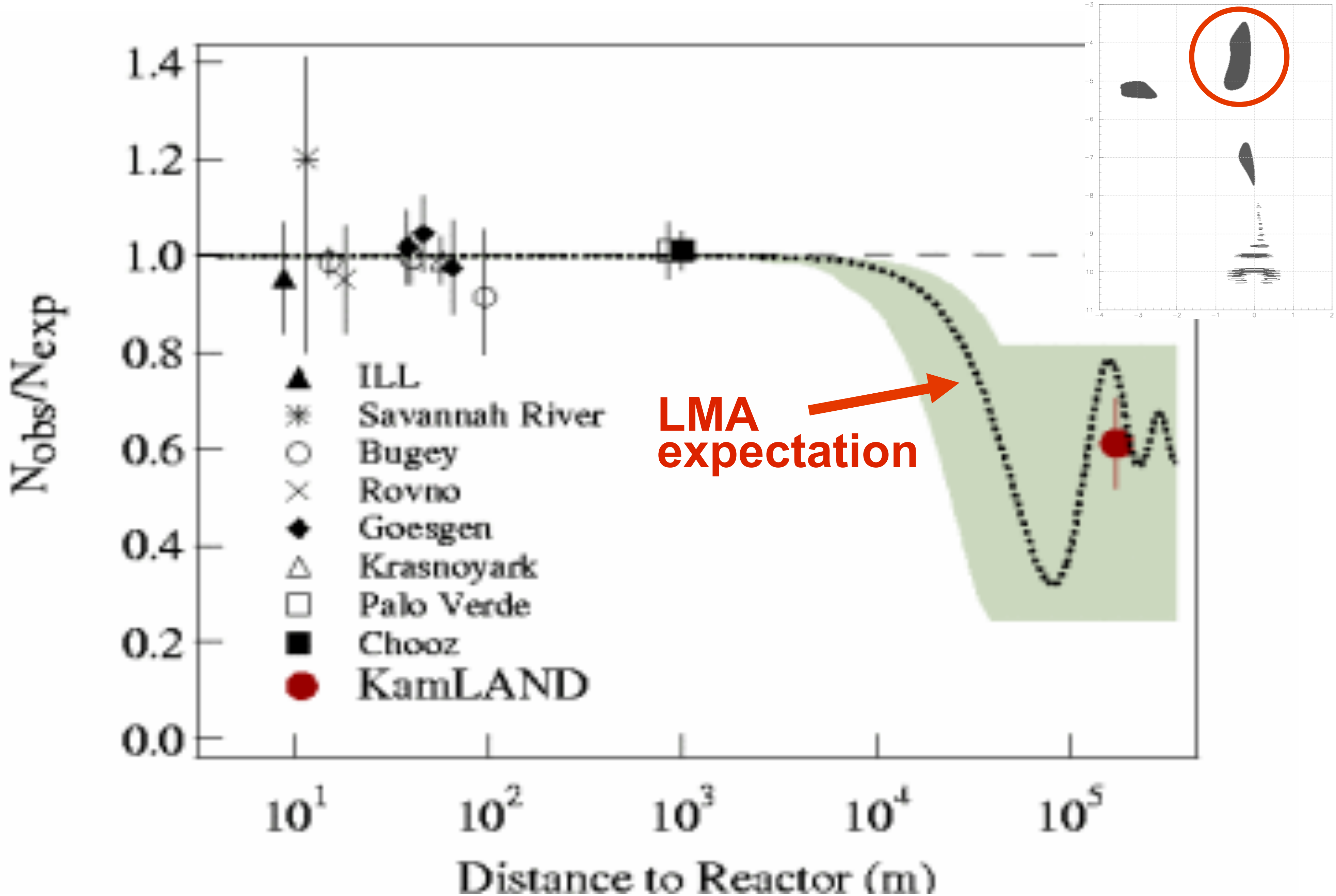


In any detector with lots of free protons (e.g. water, scint) this dominates

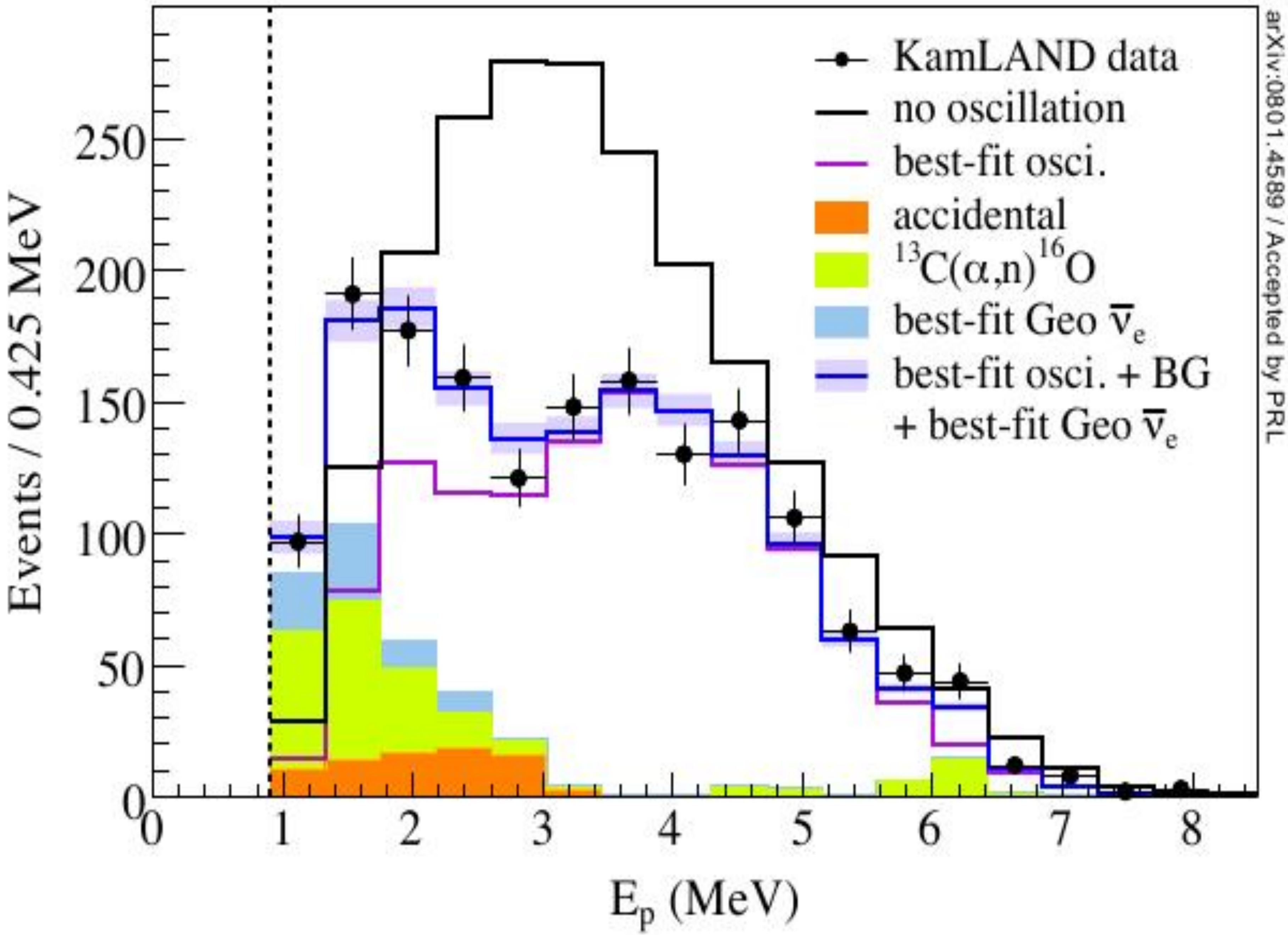
KamLAND: 1 kton scintillator



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

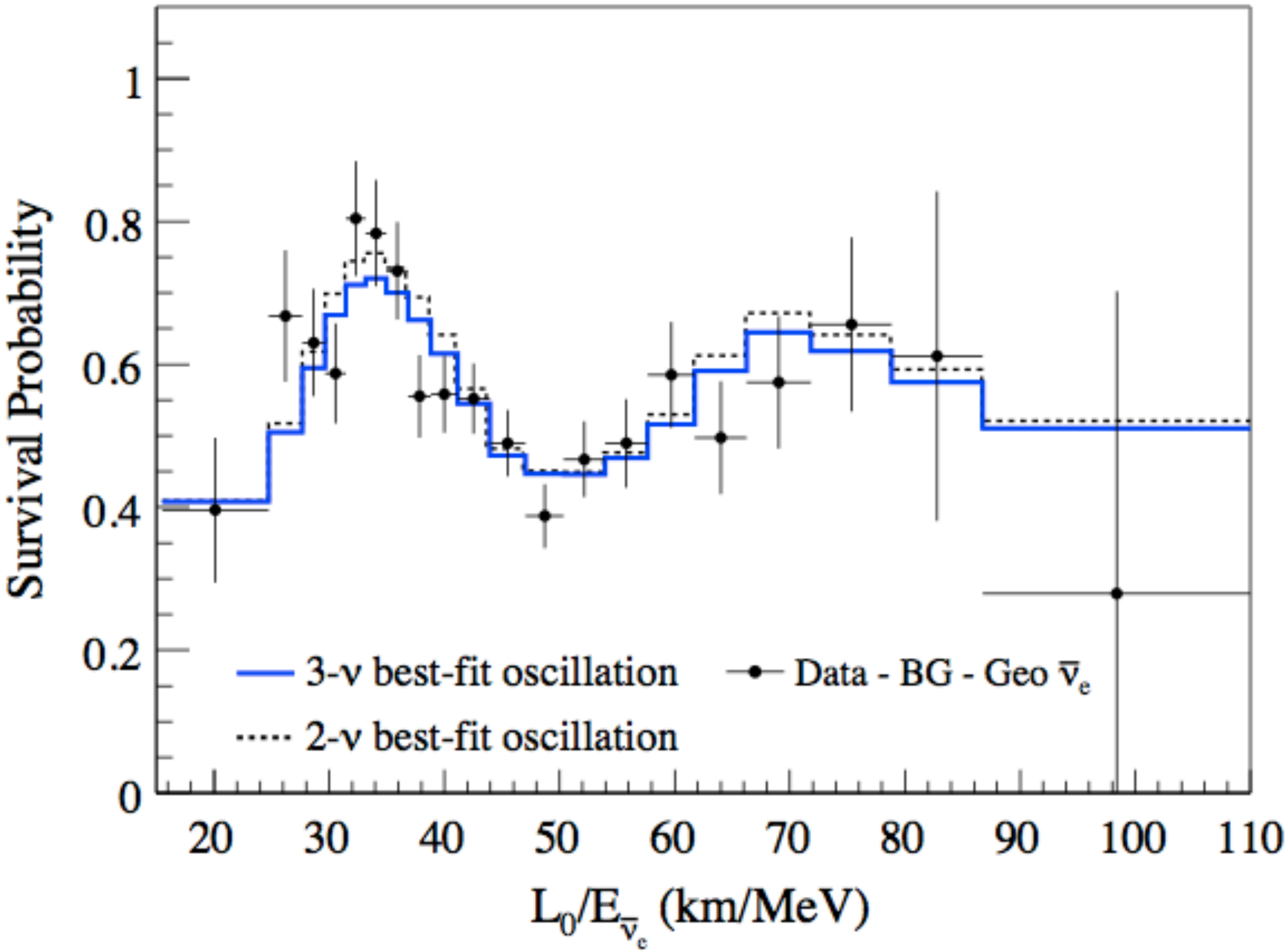


KamLAND observed spectrum



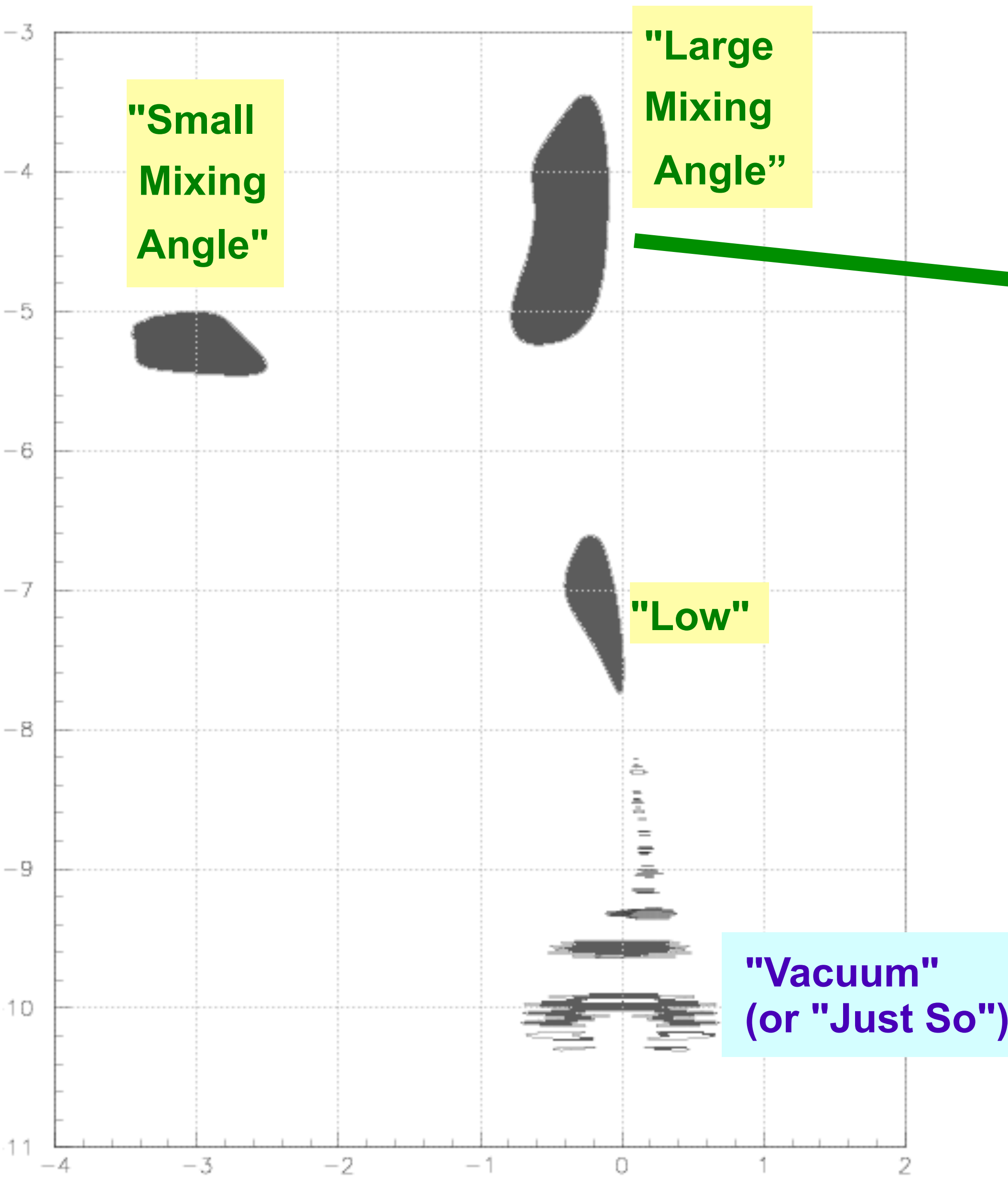
KamLAND oscillation pattern from measured antineutrino spectrum

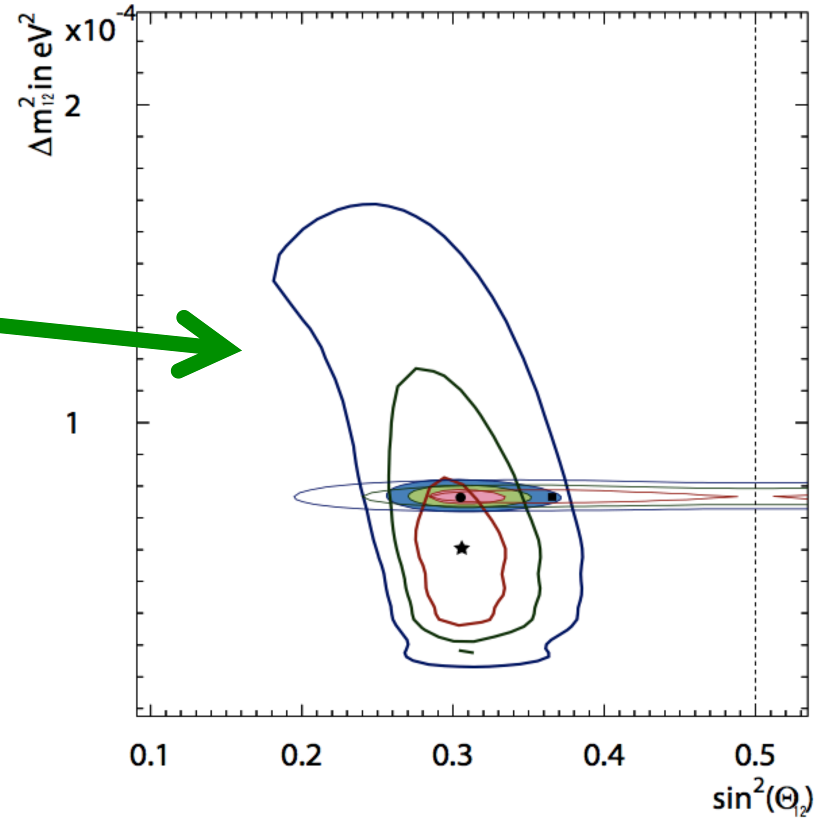
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Average flux-weighted baseline L_0 =180 km

Overall fit to the solar+KamLAND data



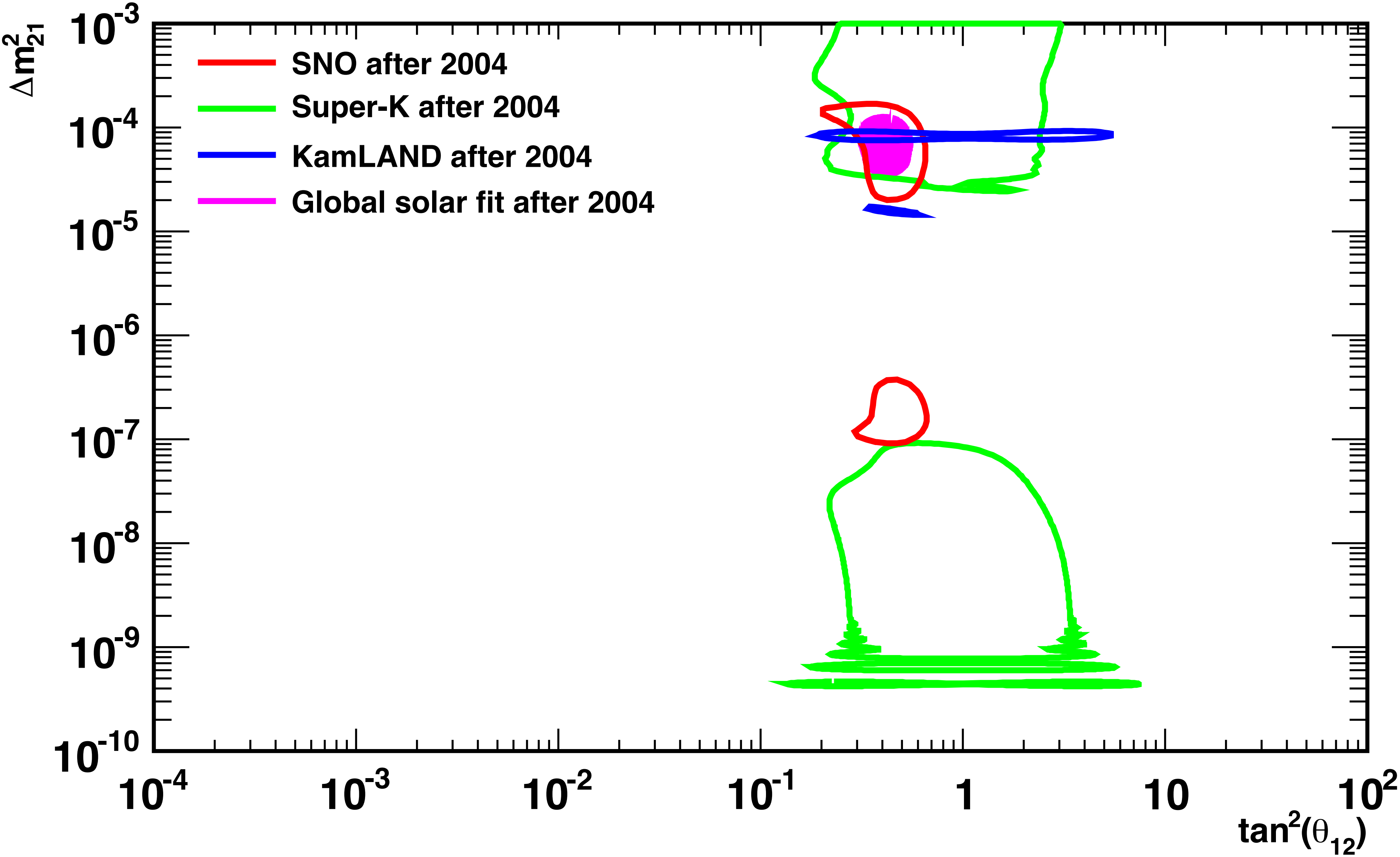


KamLAND narrows the Δm^2 range, in the LMA region

Global fit shows that mixing is *not* maximal

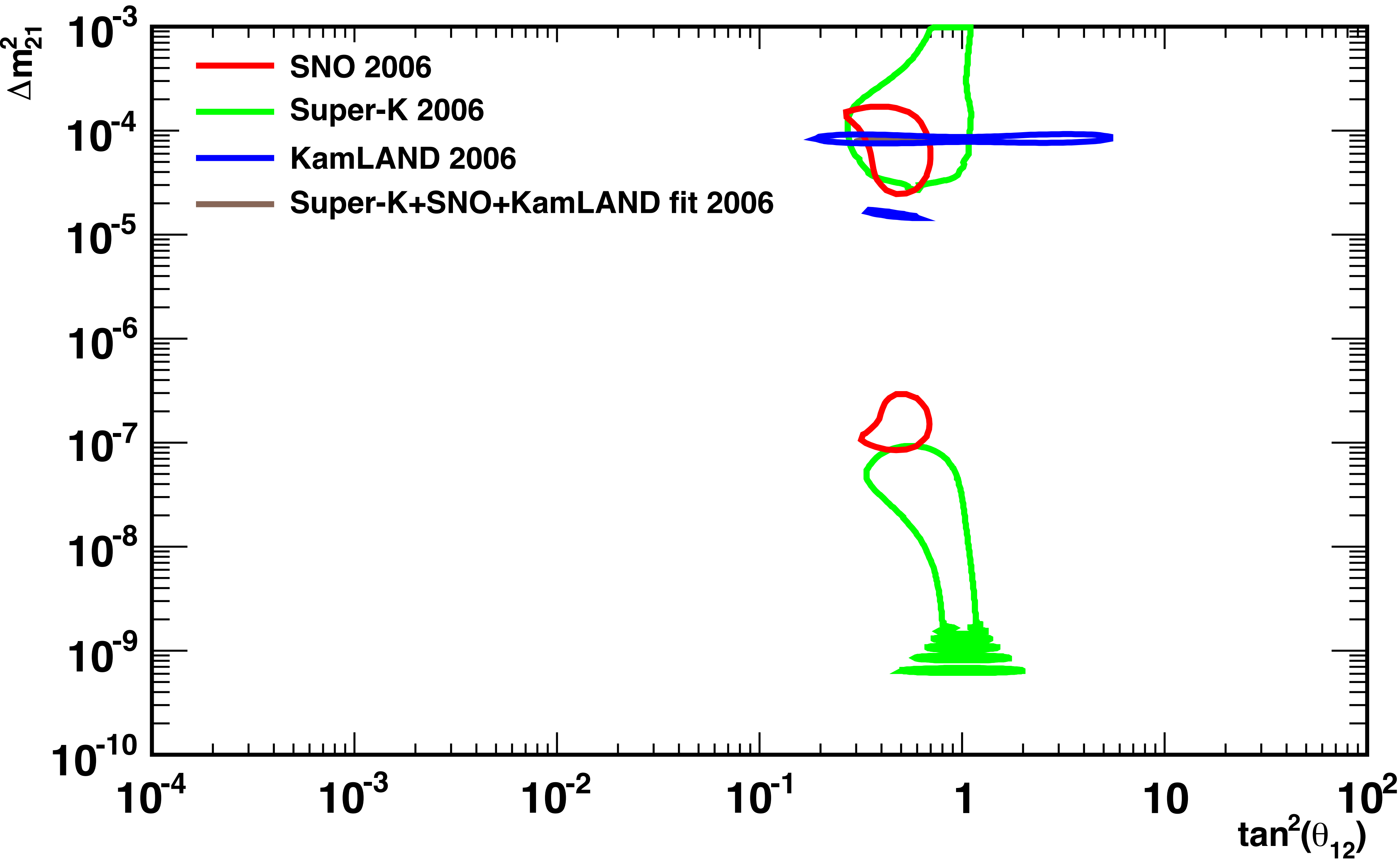
A "movie" of the past 8 years of solar parameter space

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

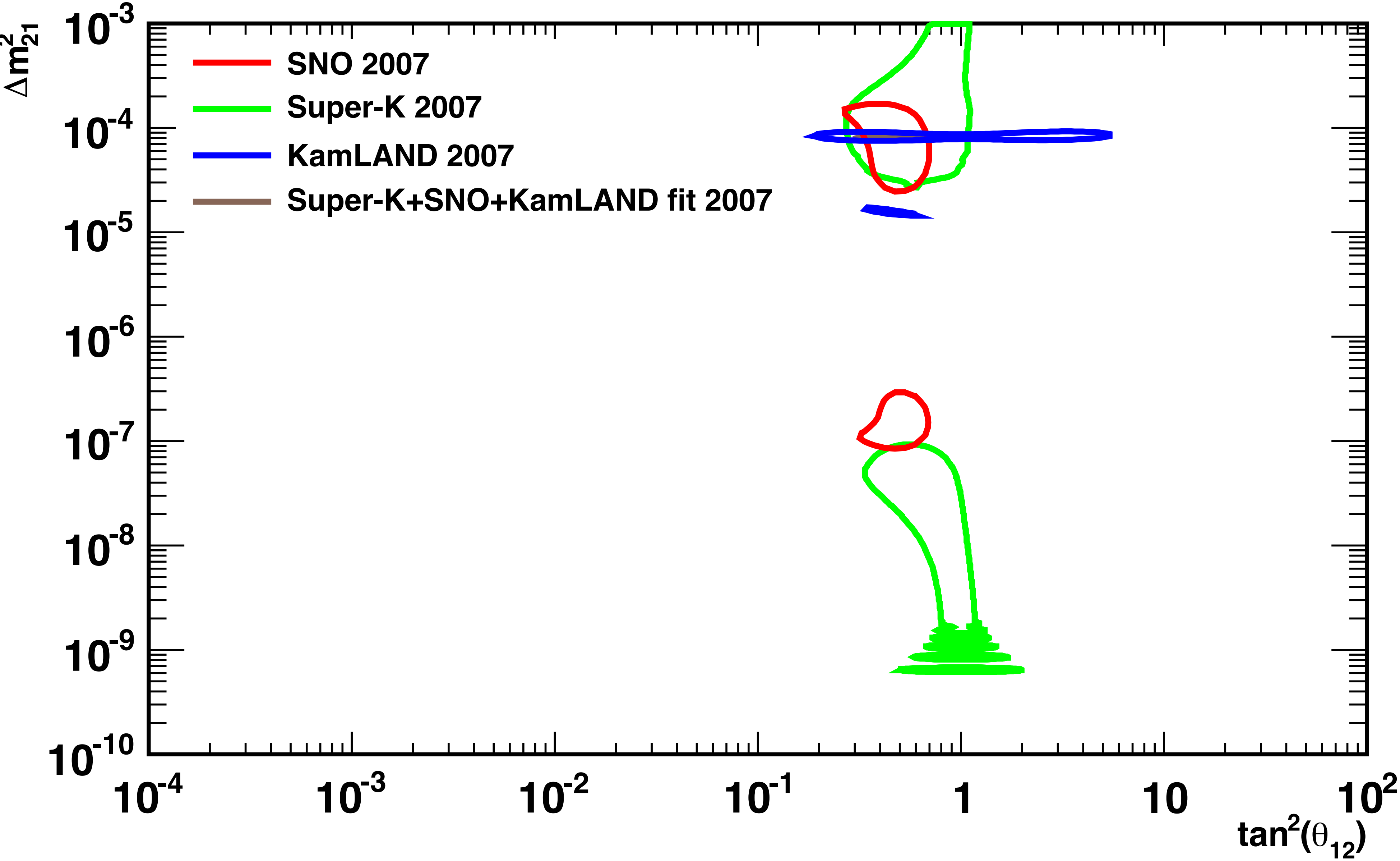


SNO after 2004
Super-K after 2004
KamLAND after 2004
Global solar fit after 2004
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2004

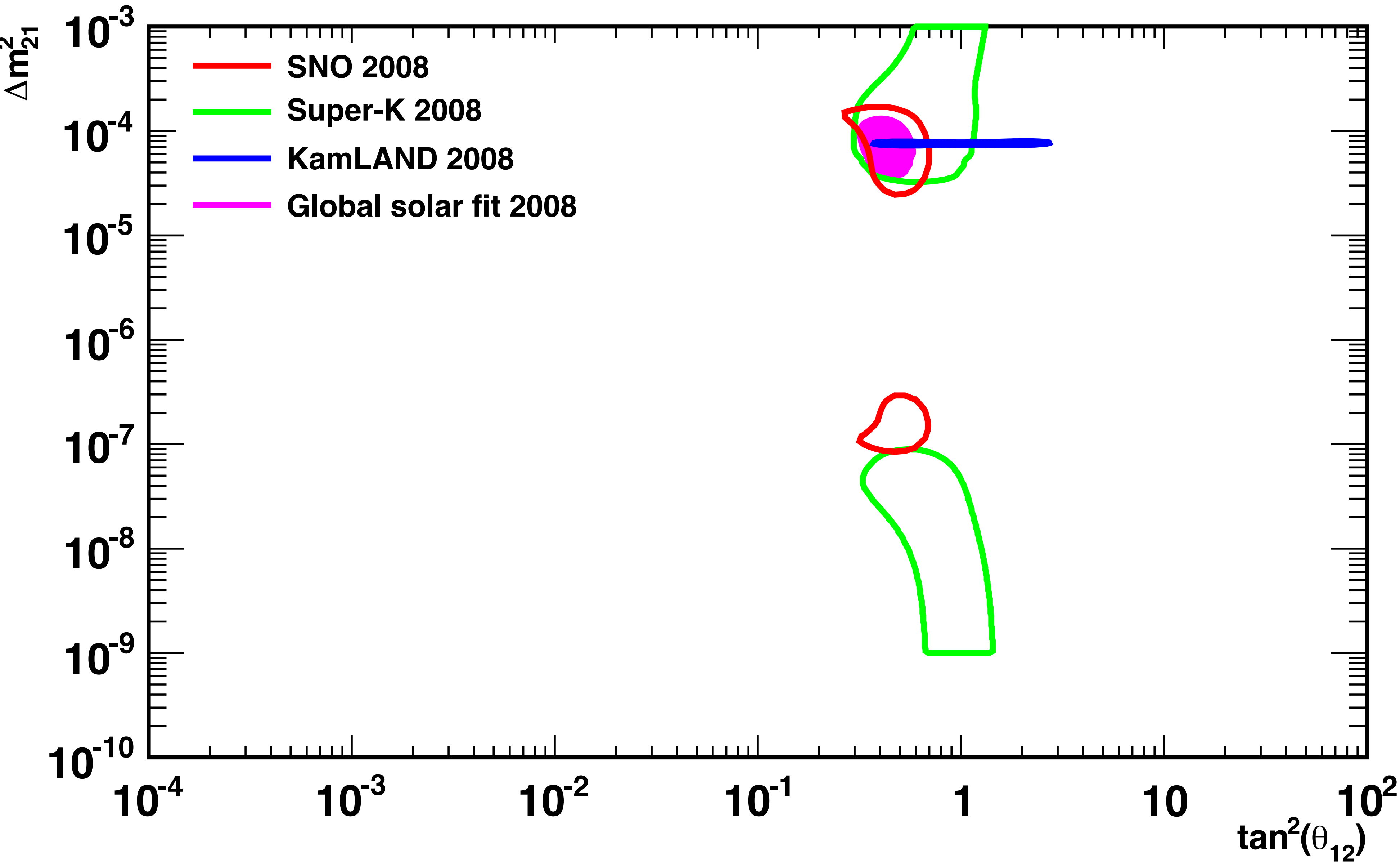

Δm^2_{21}
SNO 2006
Super-K 2006
KamLAND 2006
Super-K+SNO+KamLAND fit 2006
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2006



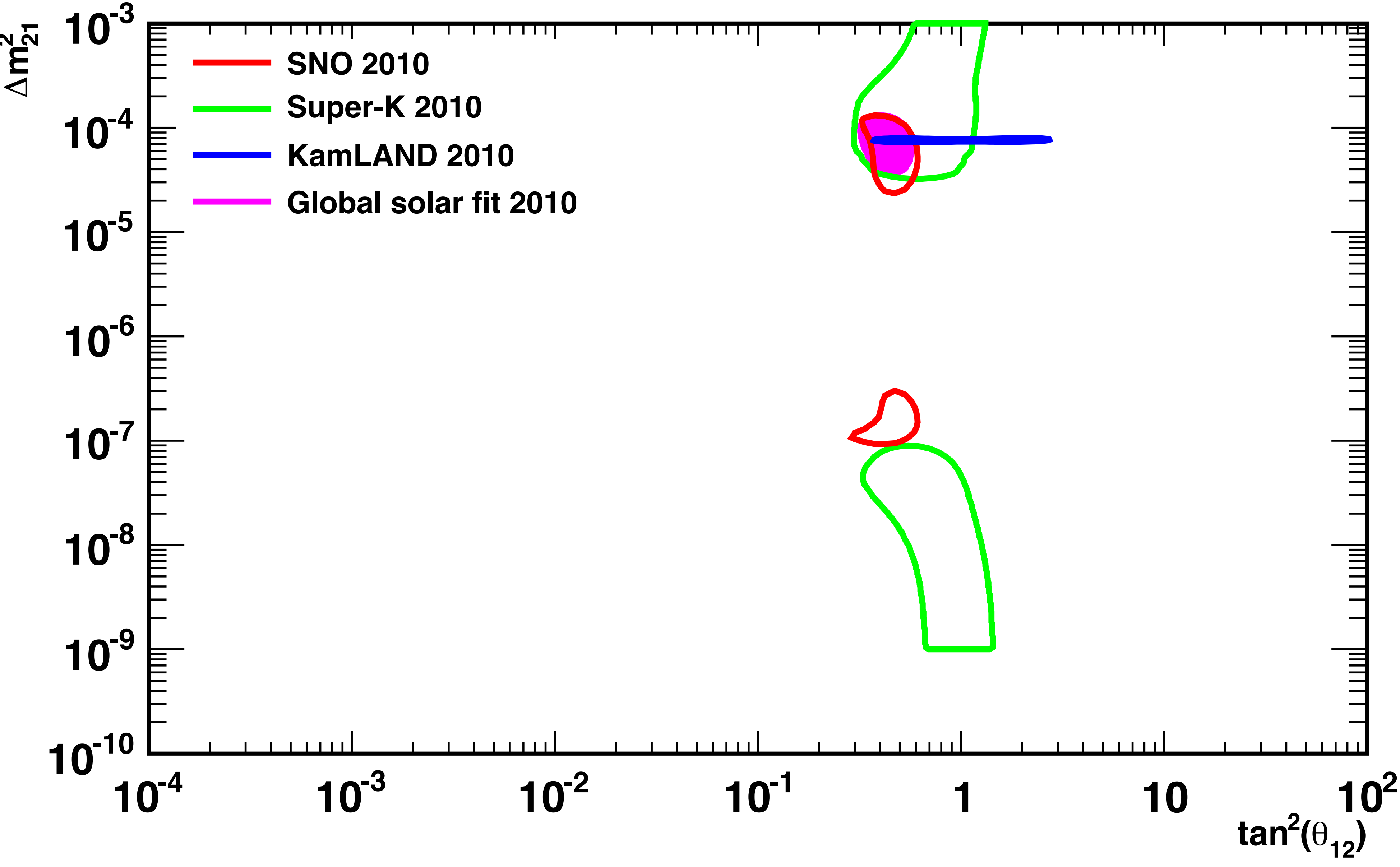
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2007
Super-K 2007
KamLAND 2007
Super-K+SNO+KamLAND fit 2007
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2007



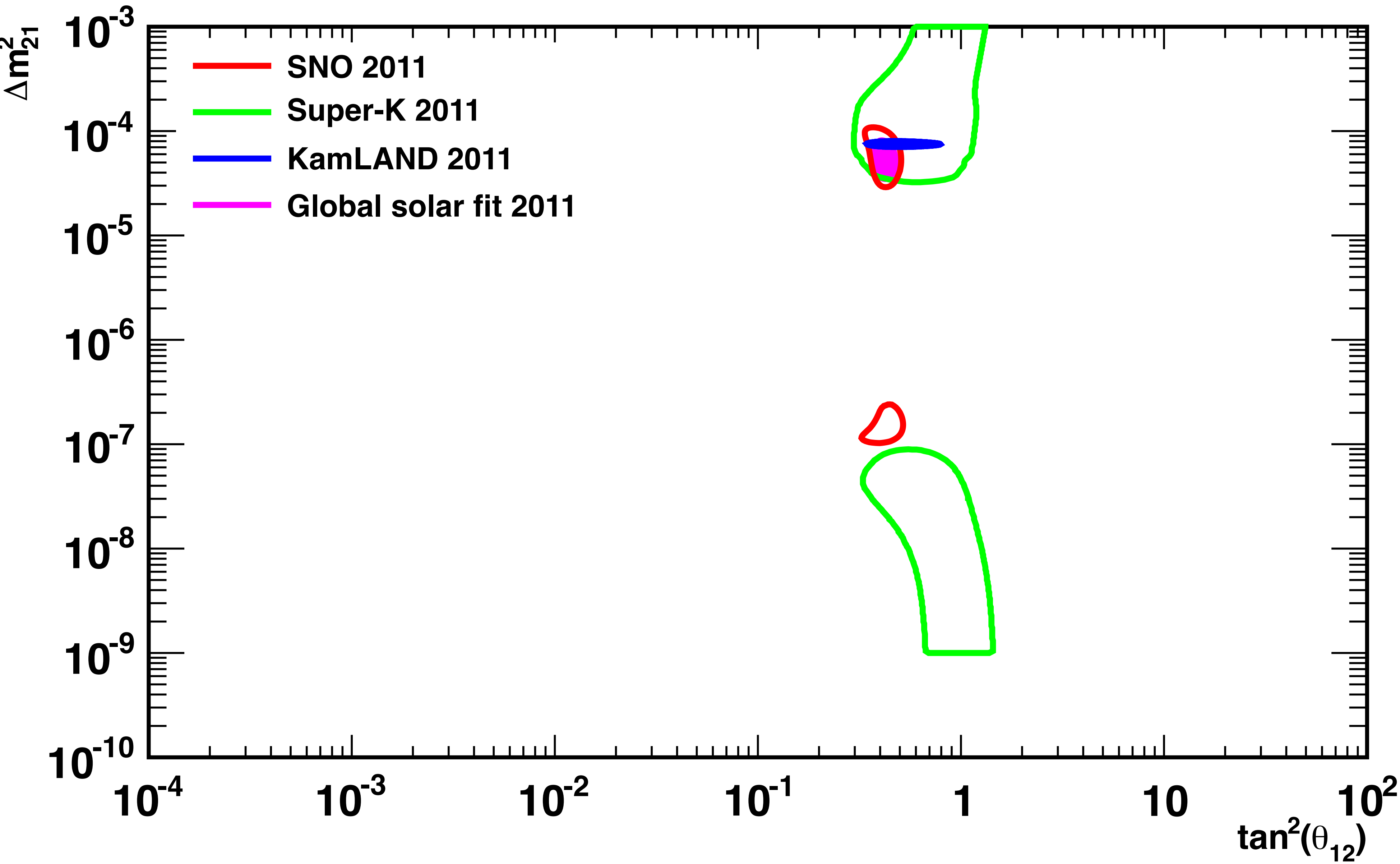
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2008
Super-K 2008
KamLAND 2008
Global solar fit 2008
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2008



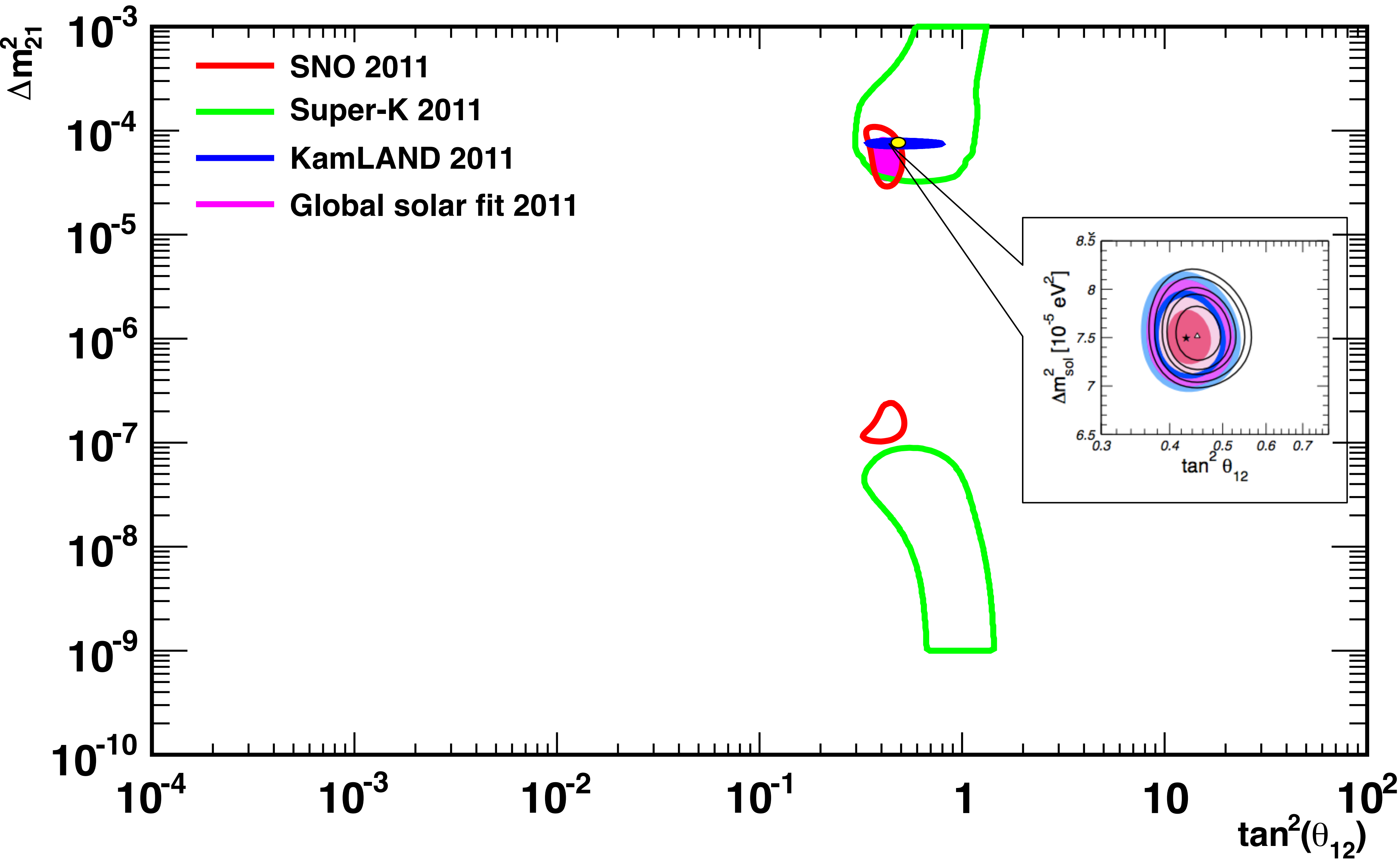
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2010
Super-K 2010
KamLAND 2010
Global solar fit 2010
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2010



SNO 2011
Super-K 2011
KamLAND 2011
Global solar fit 2011
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}
$\tan^2(\theta_{12})$

2011



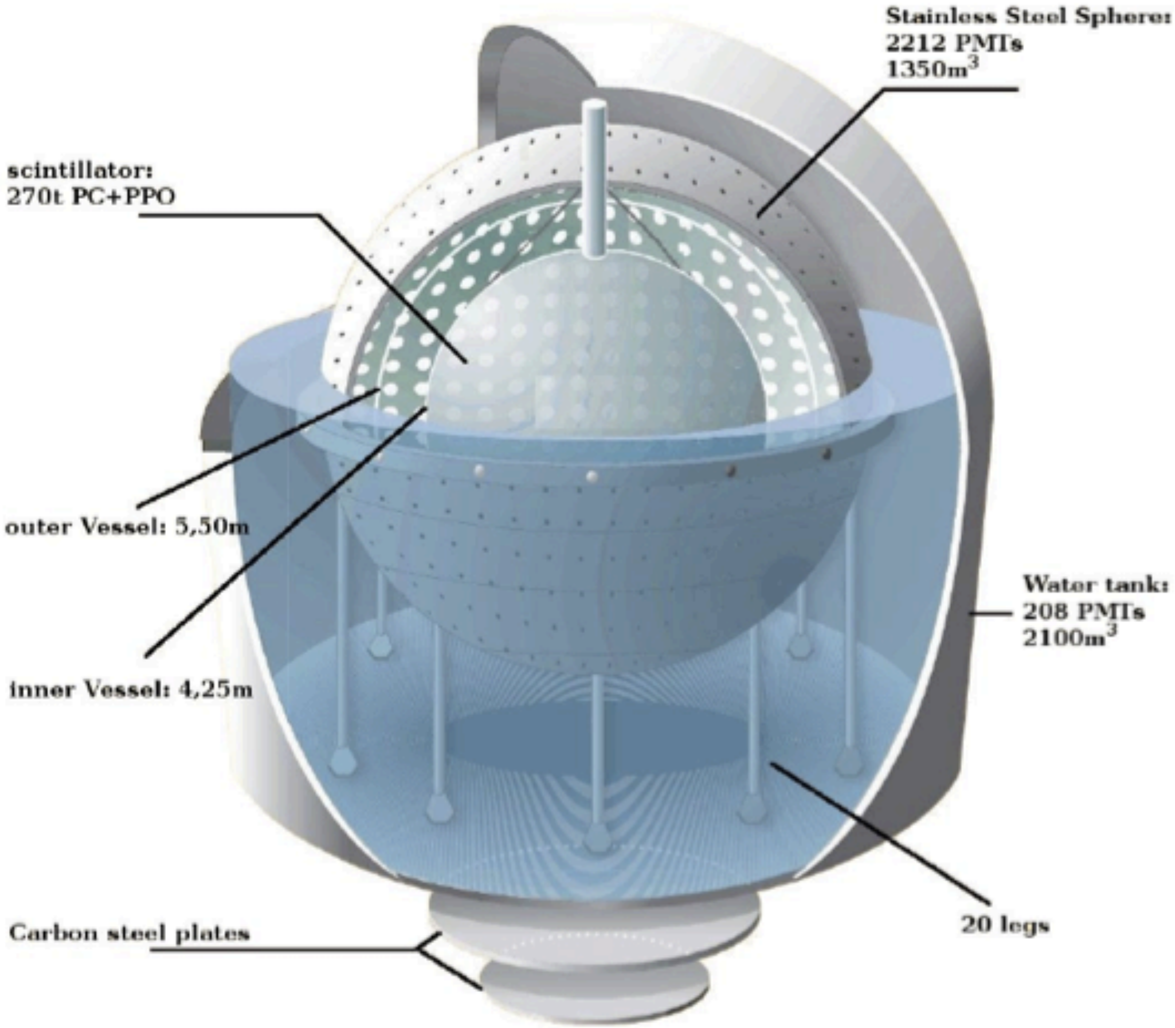
2011

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

But there's more: the Borexino Experiment

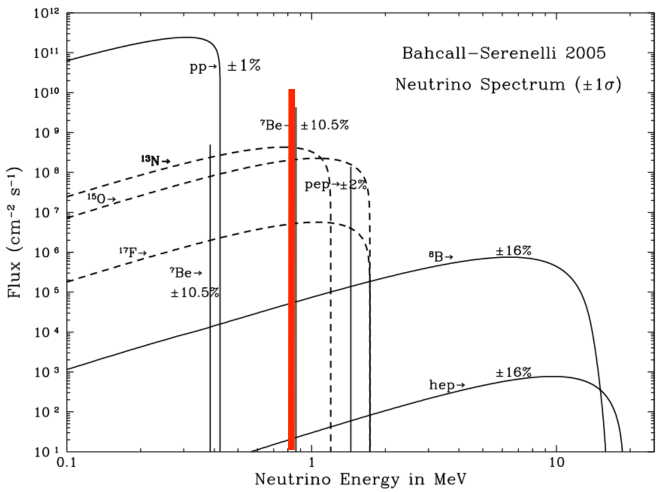
Gran Sasso, Italy

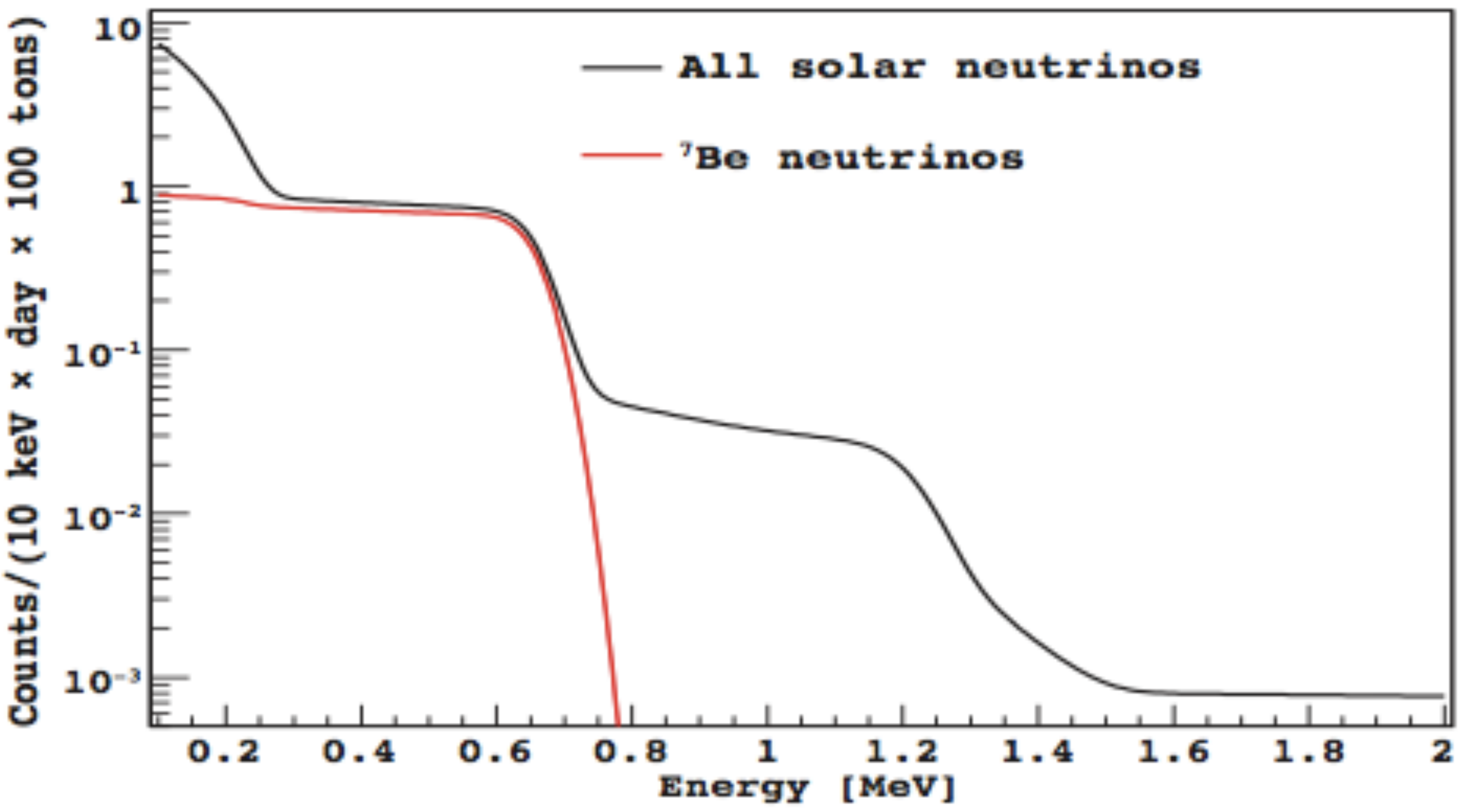
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$



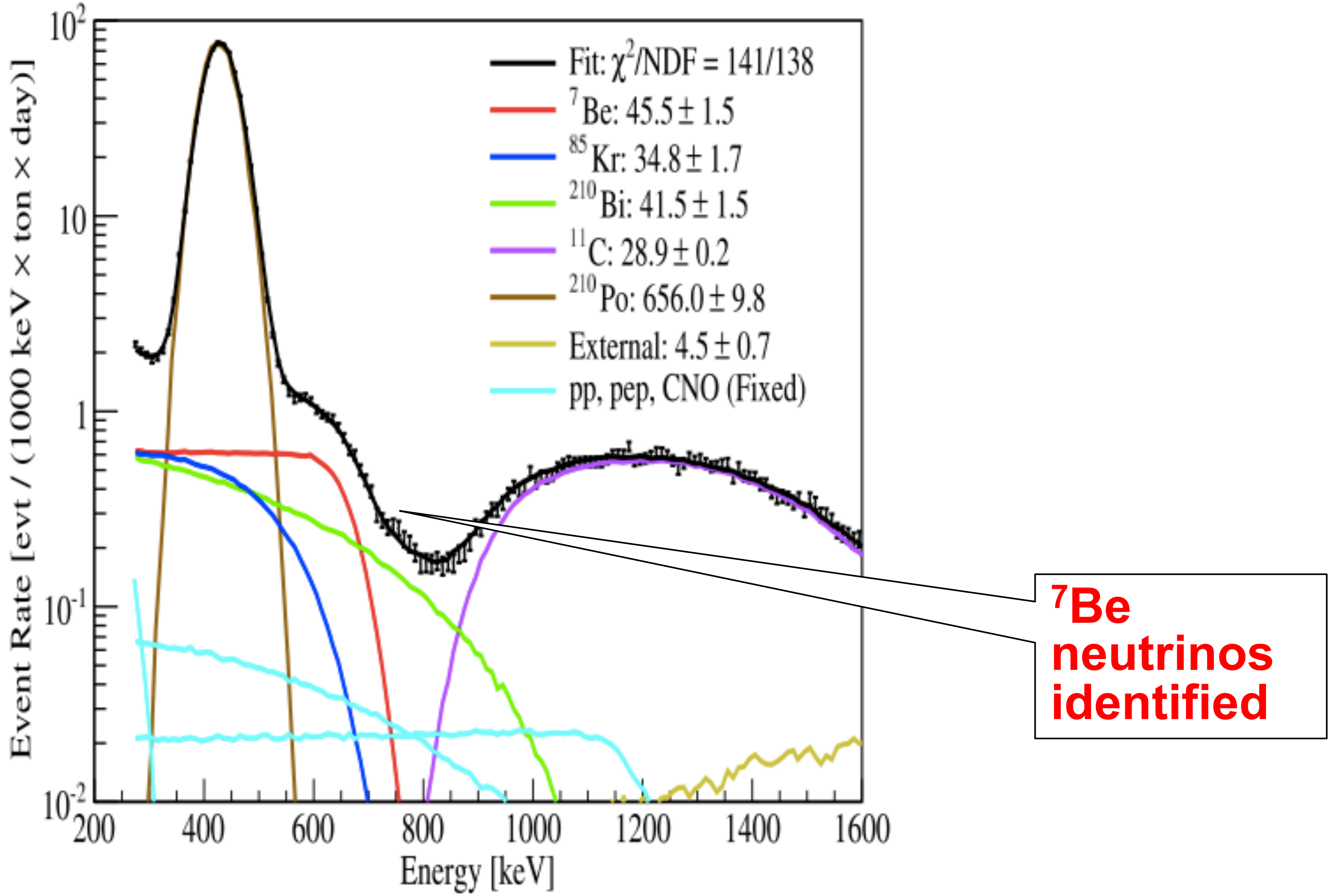
- **Scintillator (300 ton)**
- **Very low threshold (down to ~200 keV)**
- **Very low radioactivity**
- **Real time**

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



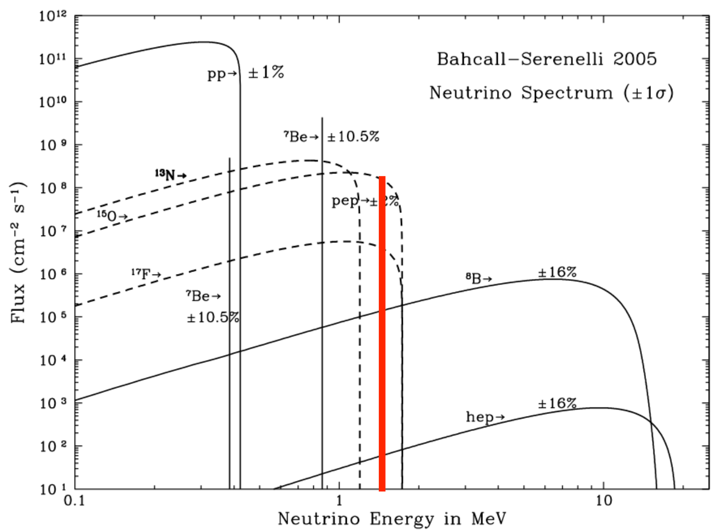


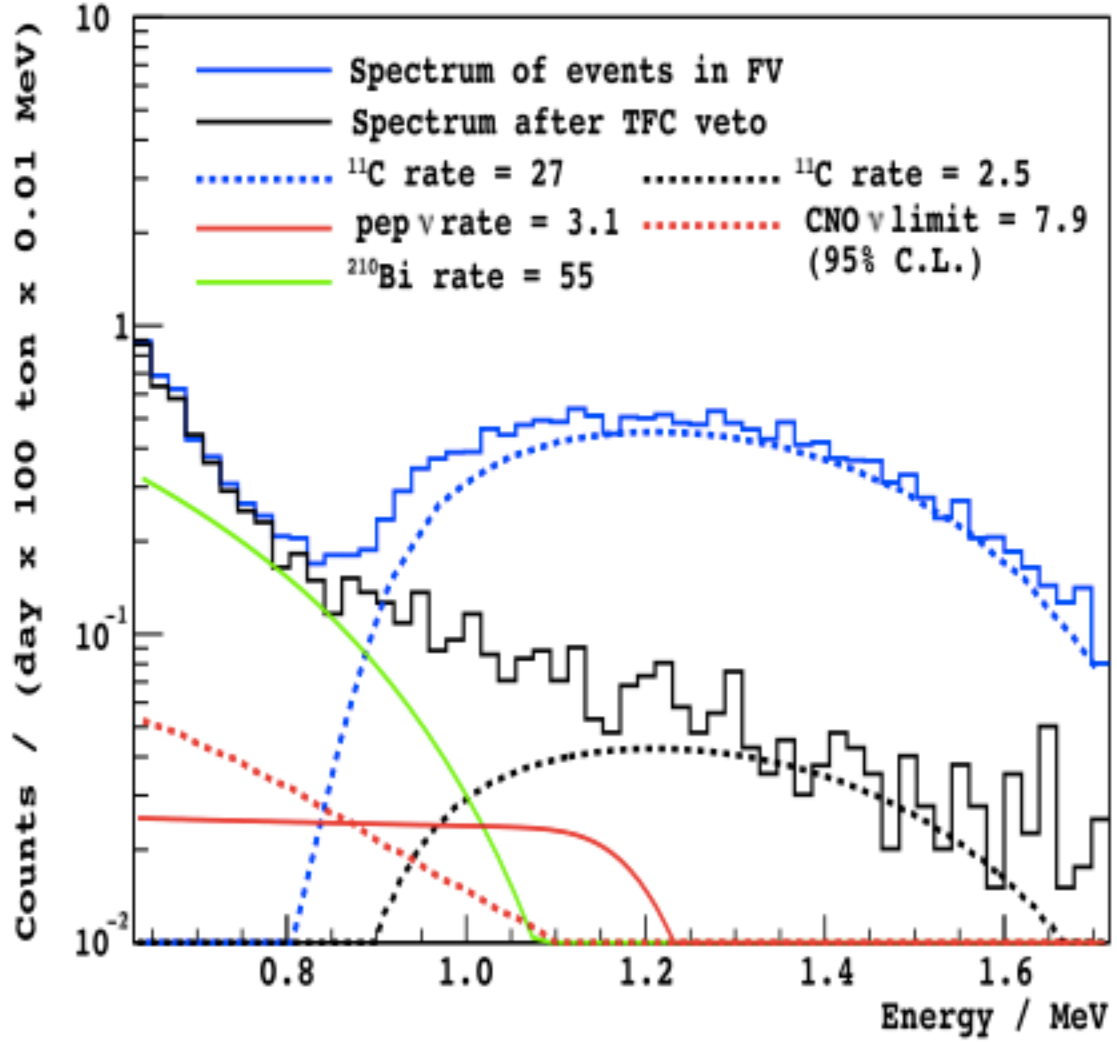
Heroic (and successful) struggle with radioactive (ambient & cosmogenic) backgrounds



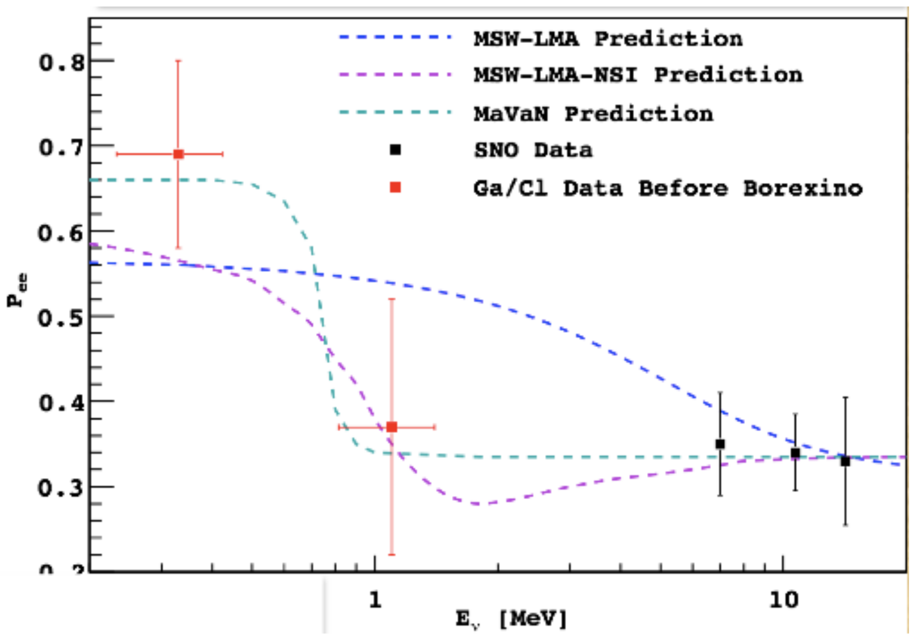
Even more heroic extraction of pep neutrino rates (and limits on CNO neutrinos)

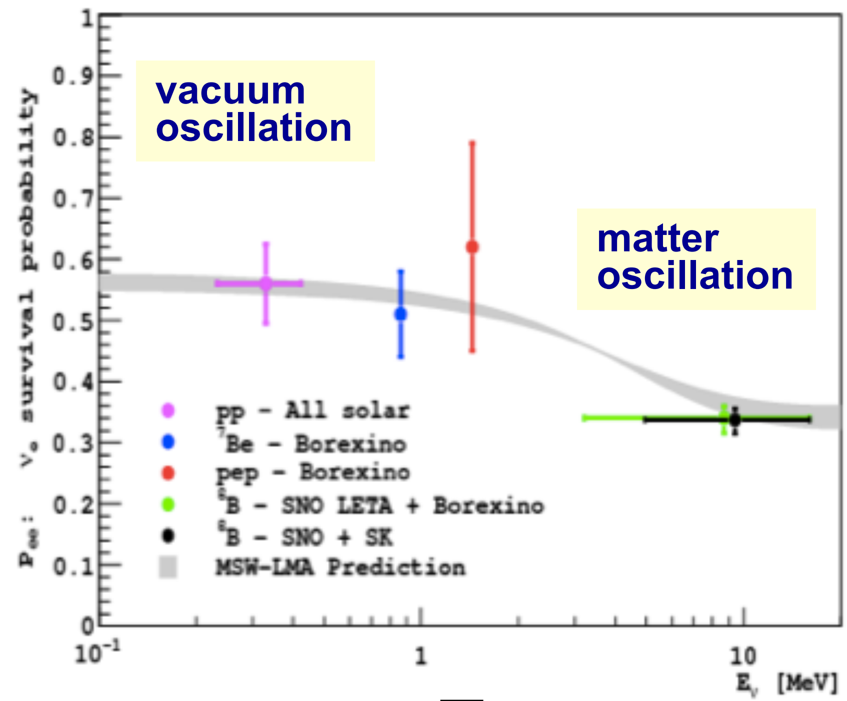
NEW





Borexino solar neutrino data at low energy can constrain exotic models



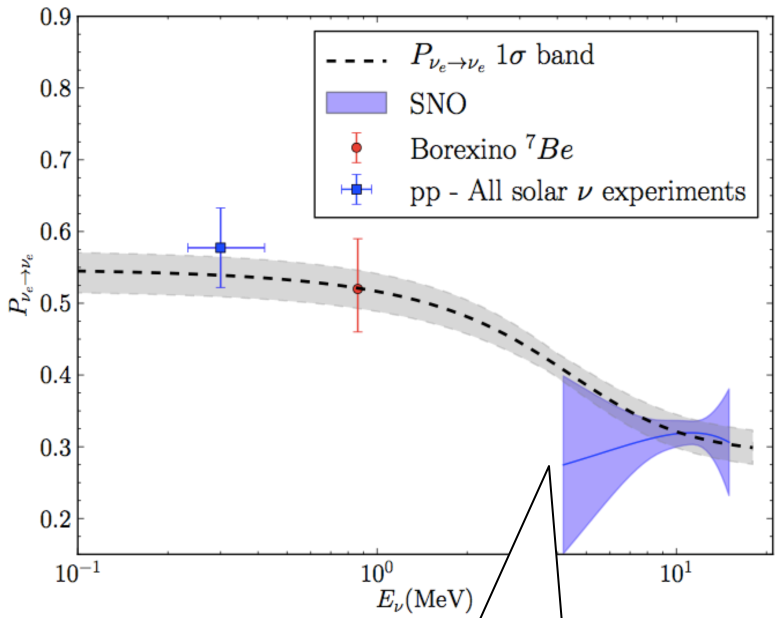


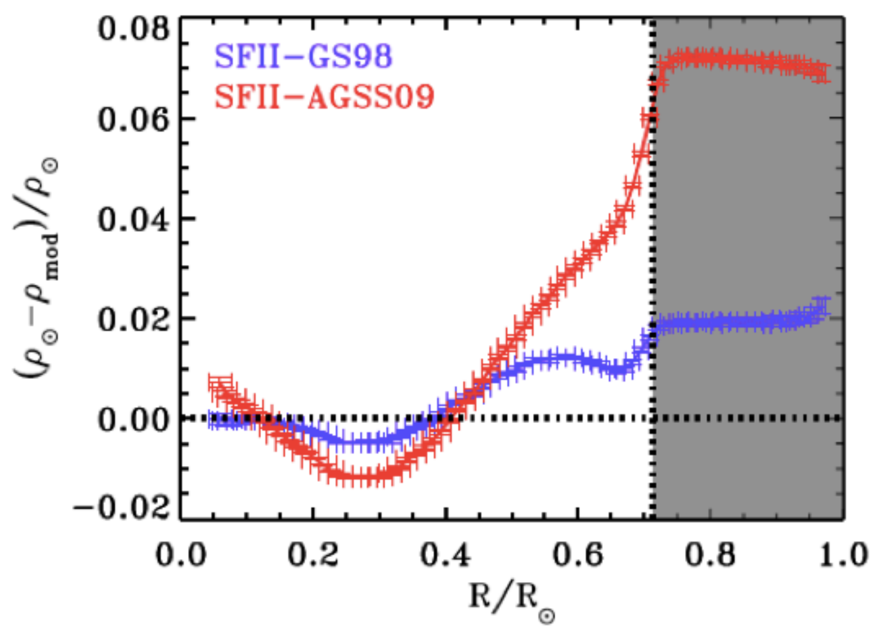
<u>Before:</u> exotic oscillation scenarios allowed

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

What's next for solar neutrinos?

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



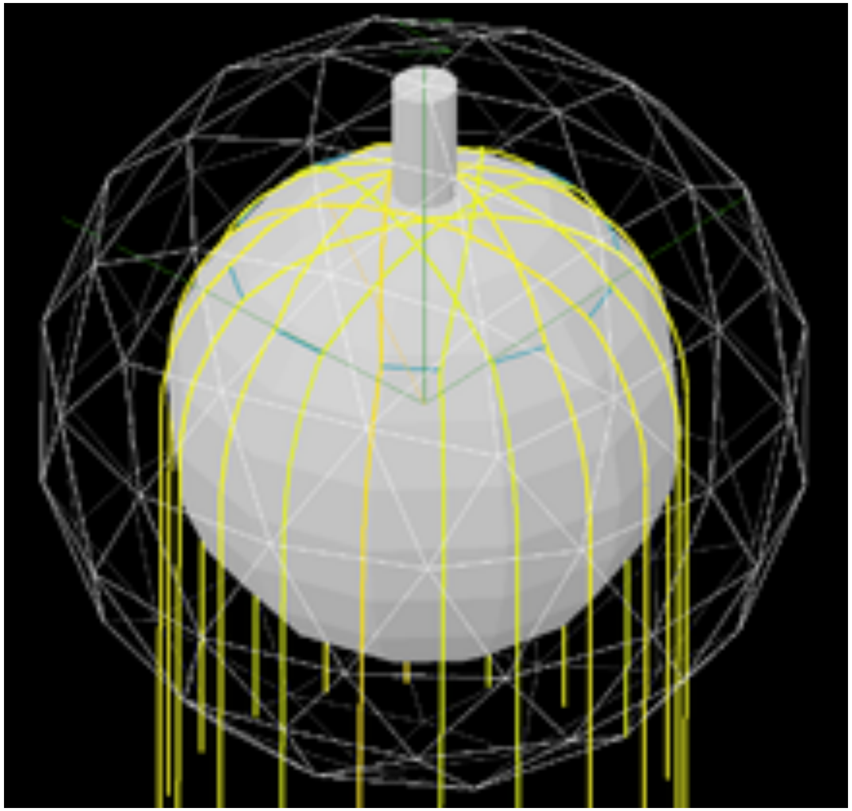


Low energy region still has uncertainties ... still room for new physics?

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

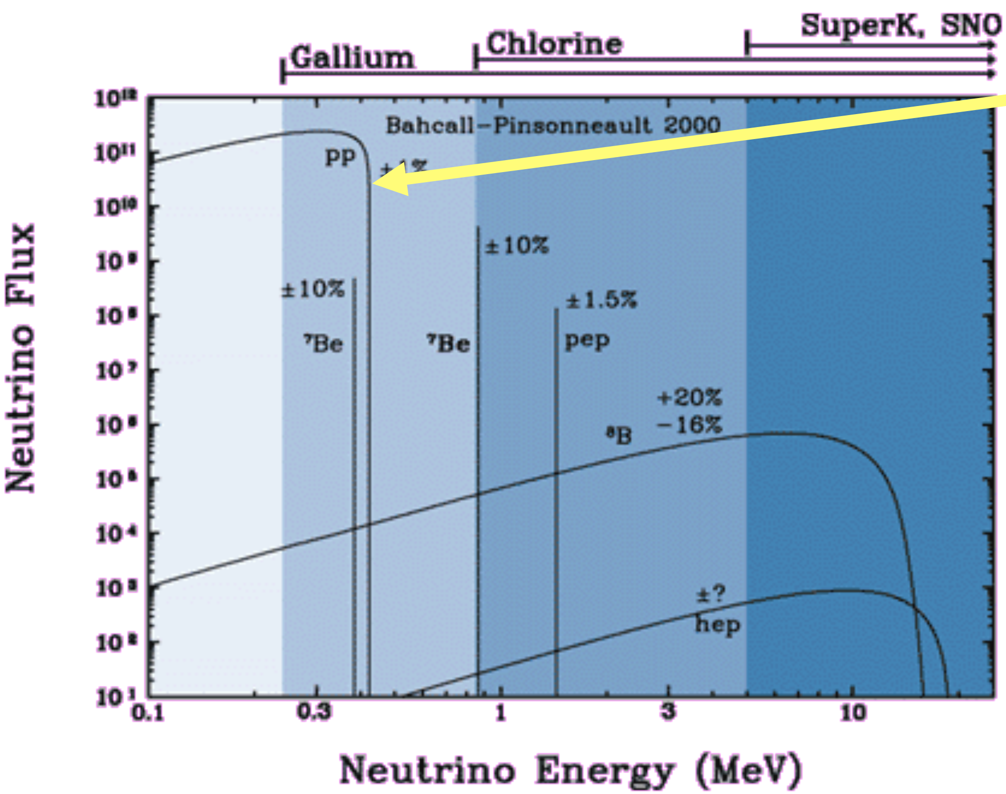
What experiments are next for solar neutrinos?

- SK and Borexino still running
- SNO+: SNO acrylic vessel filled
  with scintillator (+Nd for 0nubbk)
- Farther future: LENA, 50 kt scintillator in Finland



The Frontier

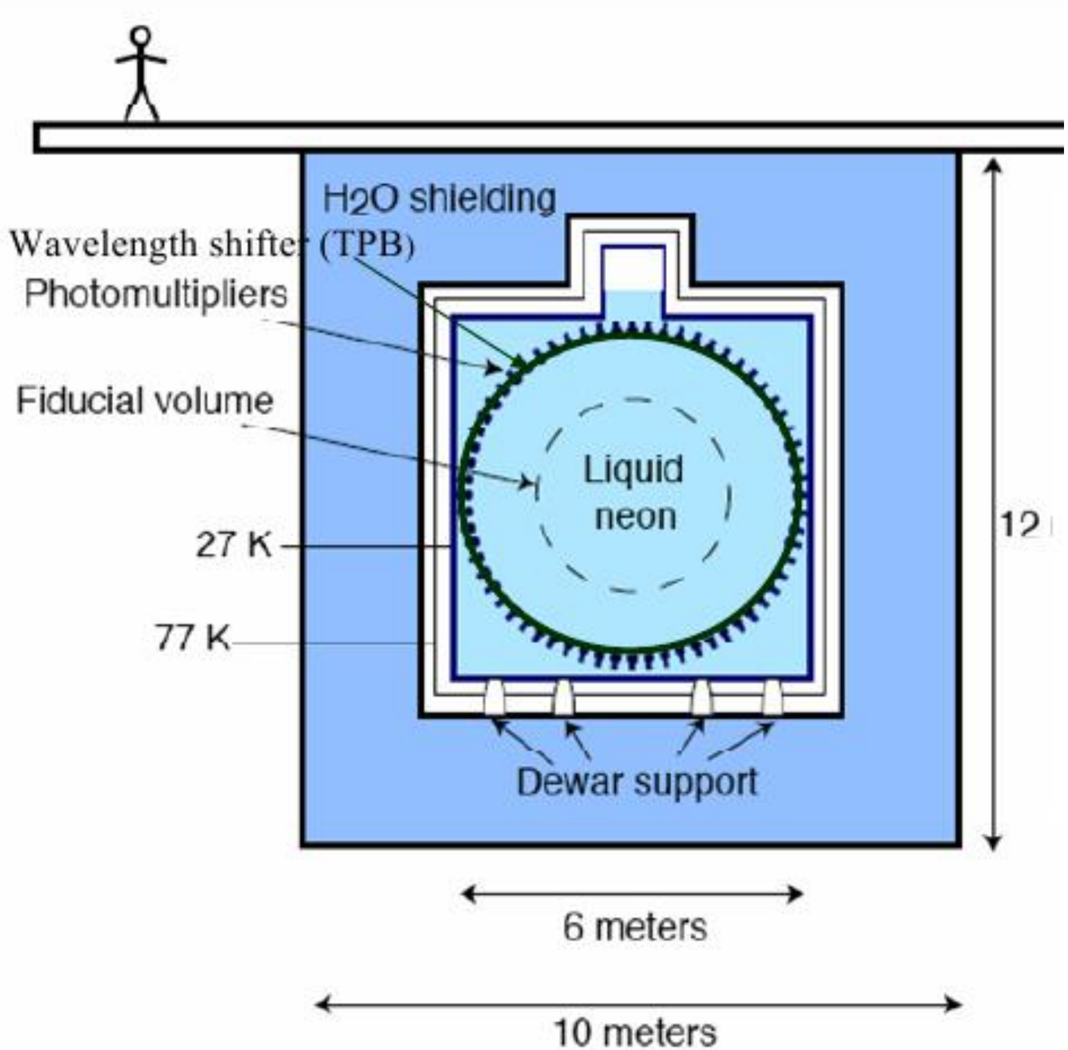
Ultra-low energy (sub MeV) real-time solar pp ν detectors



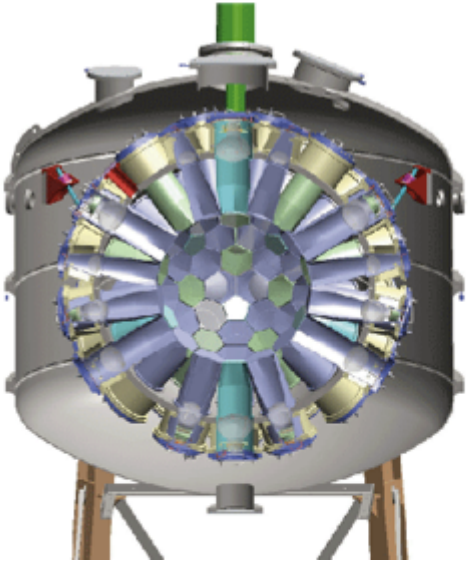
Vast pp neutrino flux barely touched!

- 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)

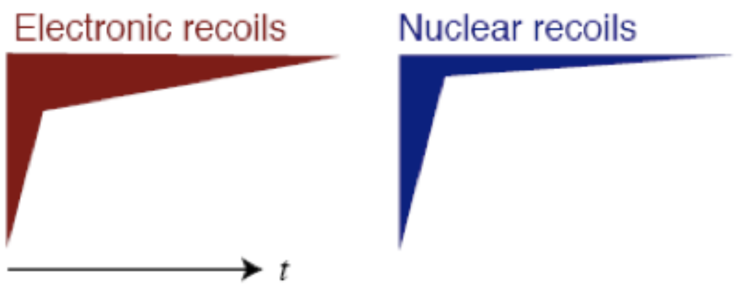


$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$



MiniCLEAN

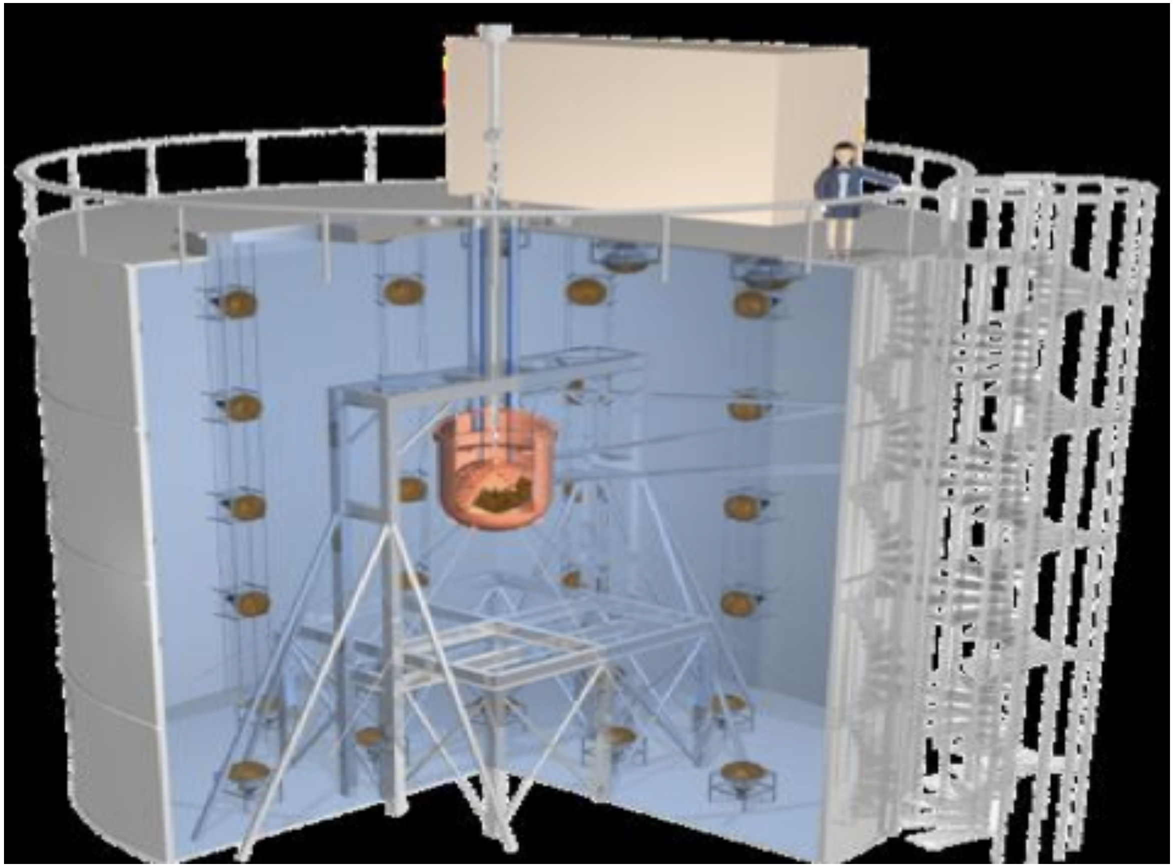
Pulse-shape discrimination



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

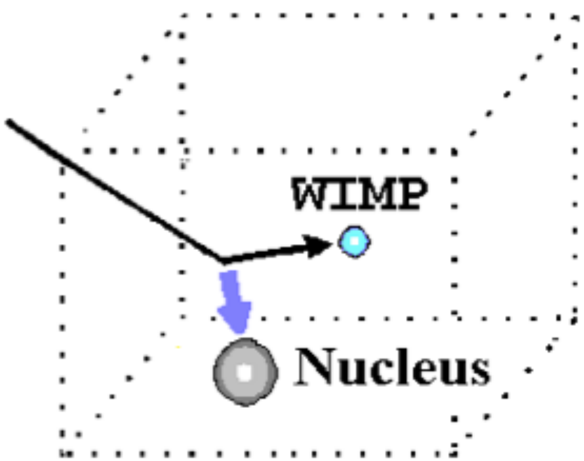
XMASS: liquid xenon

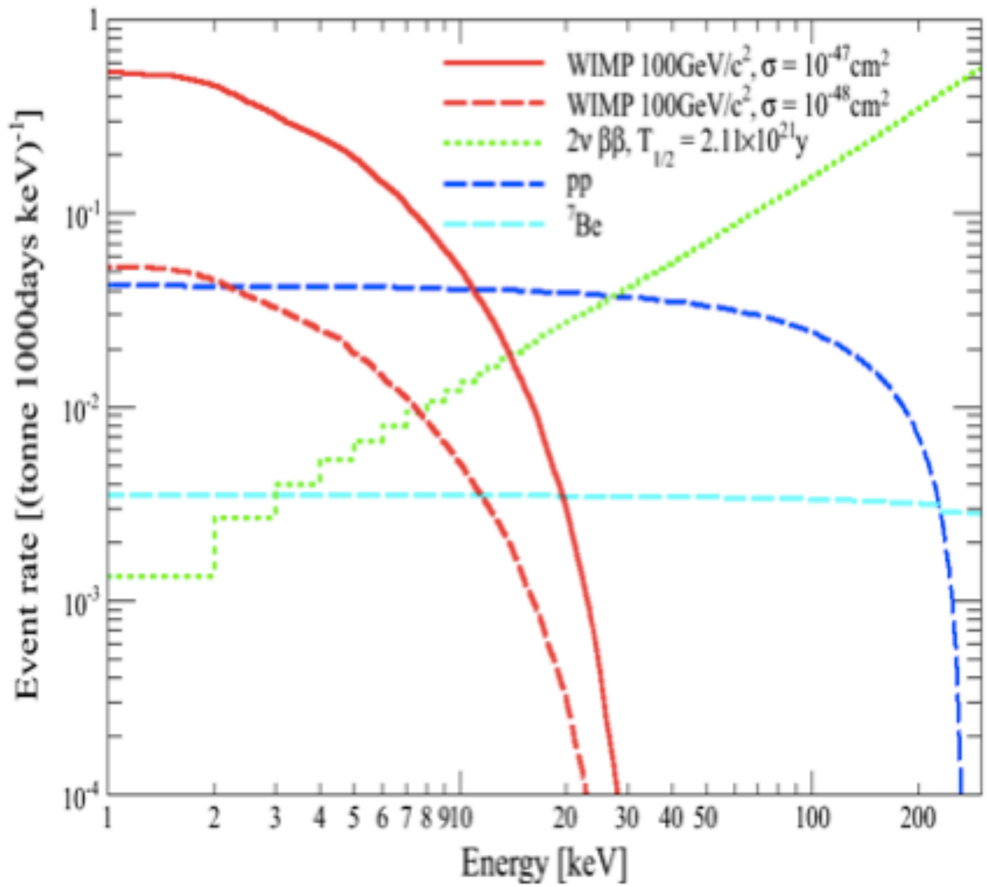
$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$



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

Measured recoil energy spectrum in xenon





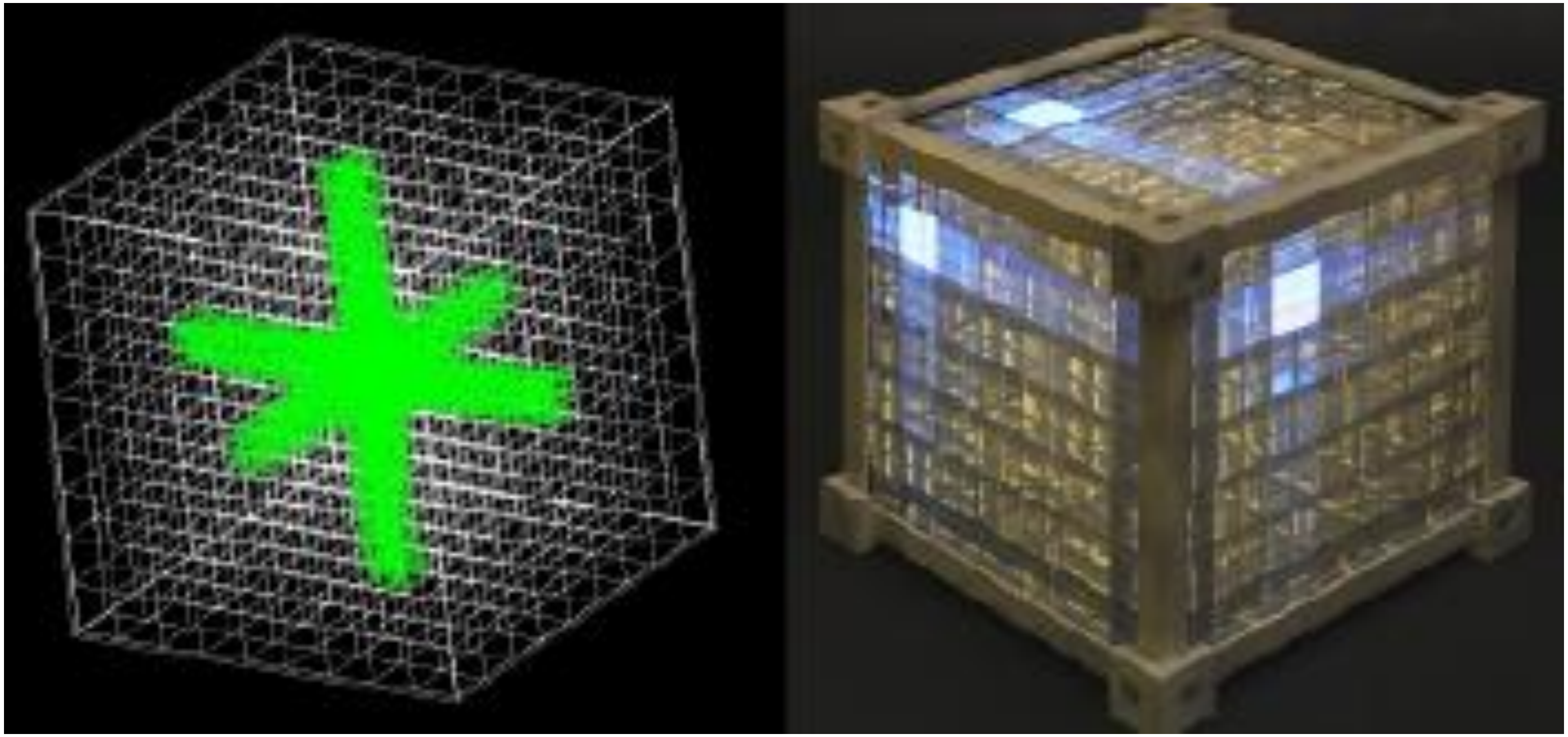
Nuclear recoils induced by DM may be an easier signal!

A dedicated future solar neutrino experiment:

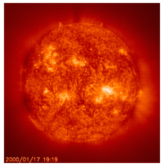
LENS: indium-loaded scintillator

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

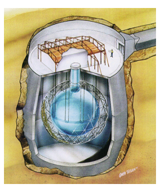


How does the Sun shine?

It's a gigantic nuclear furnace

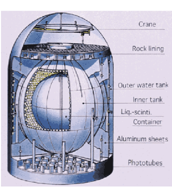
ν-raying the Sun: a classic problem

Electron neutrinos gone missing



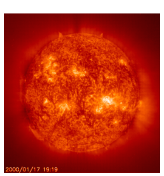
An anomaly resolved … with new physics!

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!