HERE BE DRAGONS

BEYOND THE SOLAR NEUTRINO PROBLEM

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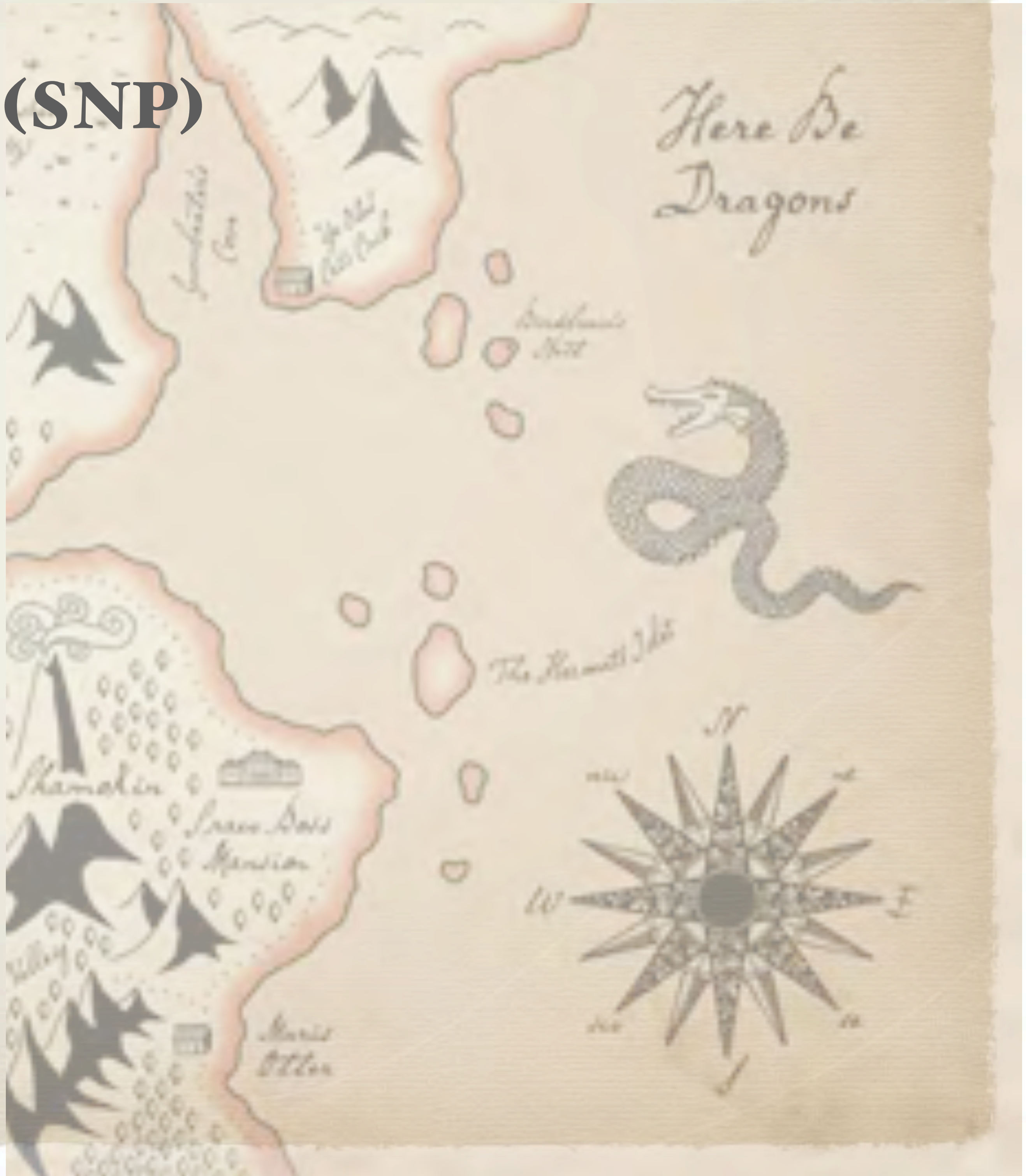
TAUP Summer School

6th Sept 2013

U. C. Berkeley
& LBNL

Solar Neutrinos in 2 Parts

1. **The Solar Neutrino Problem (SNP)**
   * The search for solar νs
   * Testing the SSM
   * The SNO experiment
   * Resolution of the SNP
   * Terrestrial confirmation

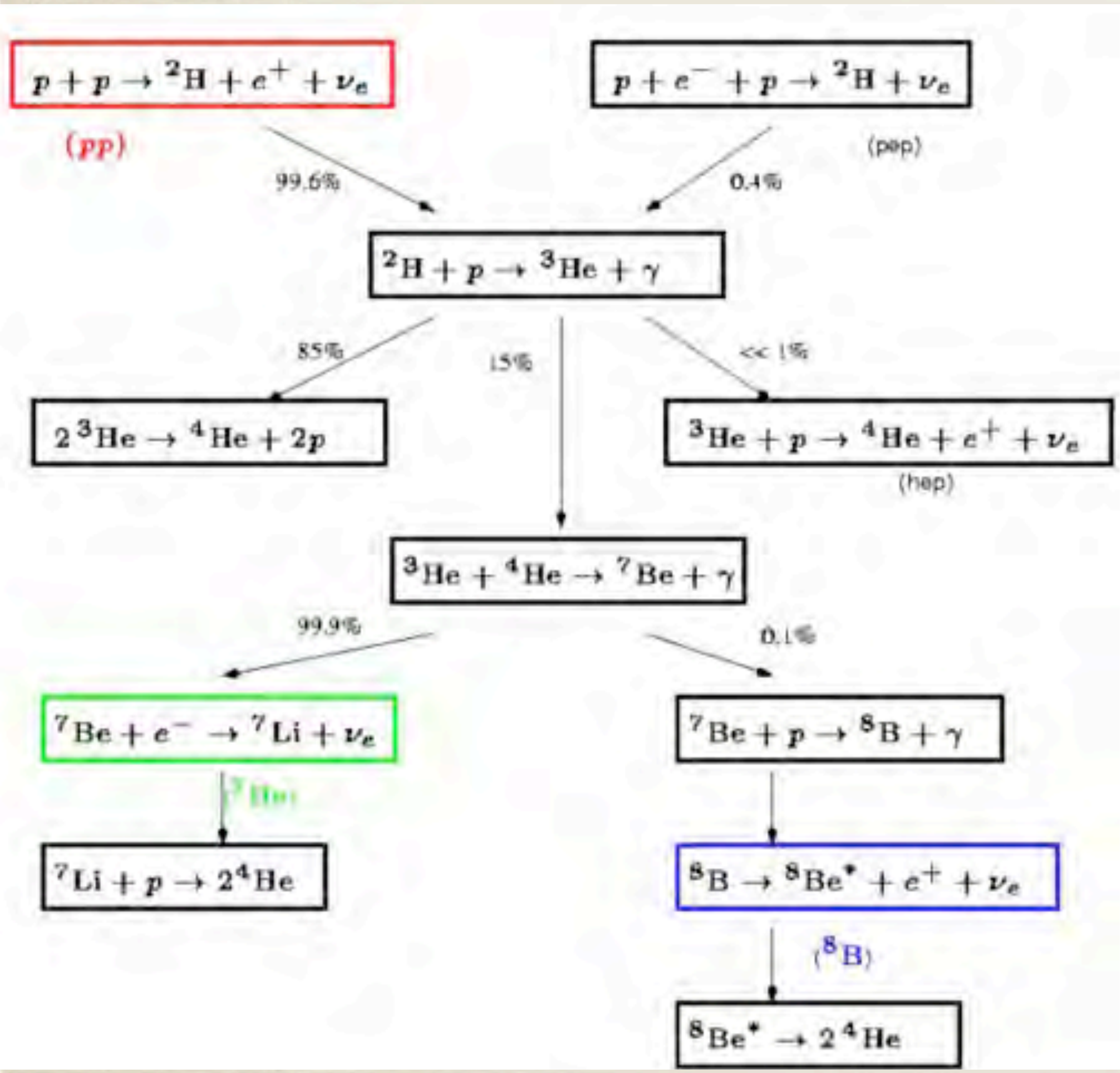


Solar Neutrinos in 2 Parts

2. **The road forward**
   * Open questions
   * Current experiments
   * The next generation

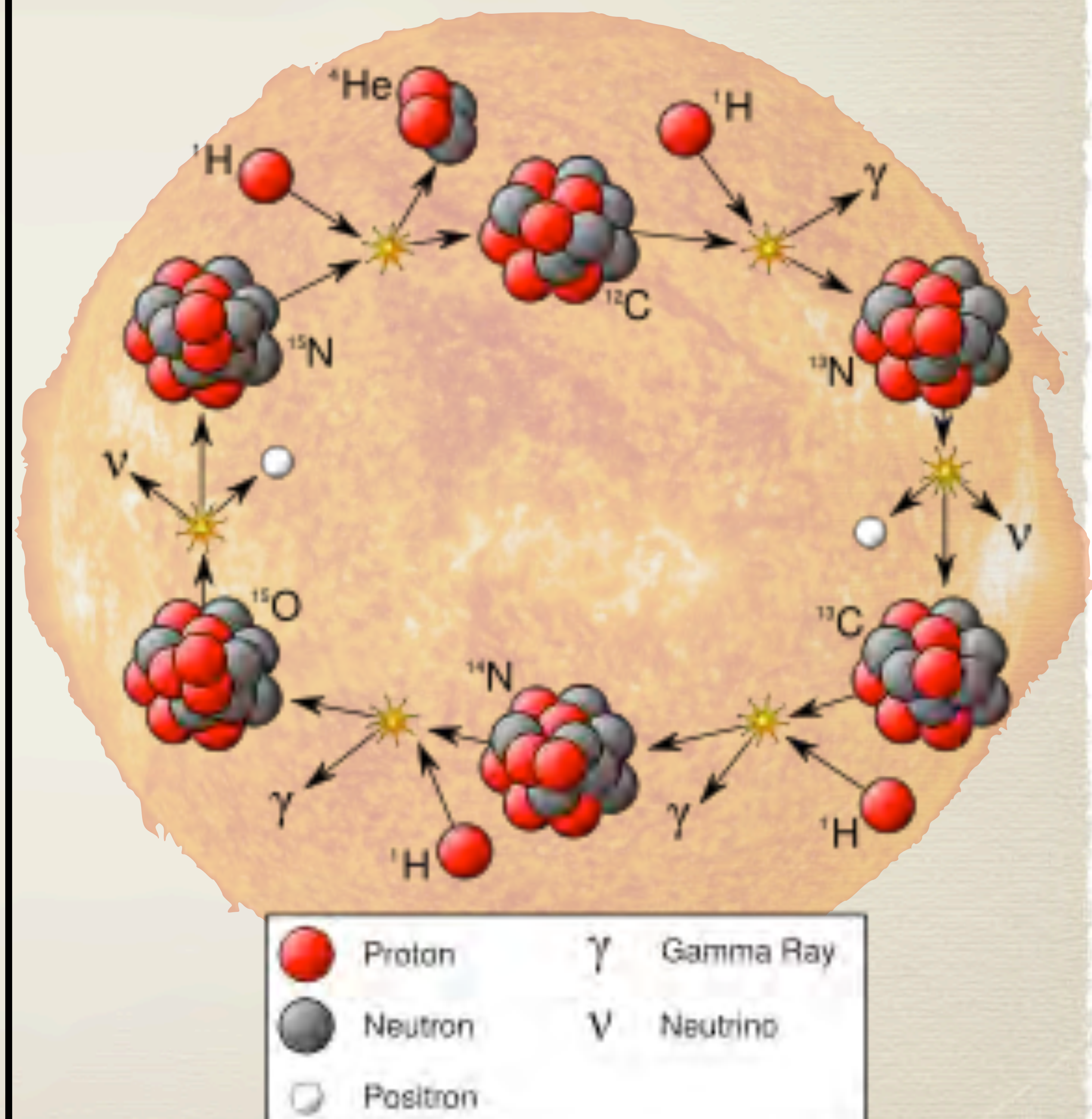
Standard Solar Model (SSM)

pp Chain



CNO Cycle

(contributes ~1% of solar energy)



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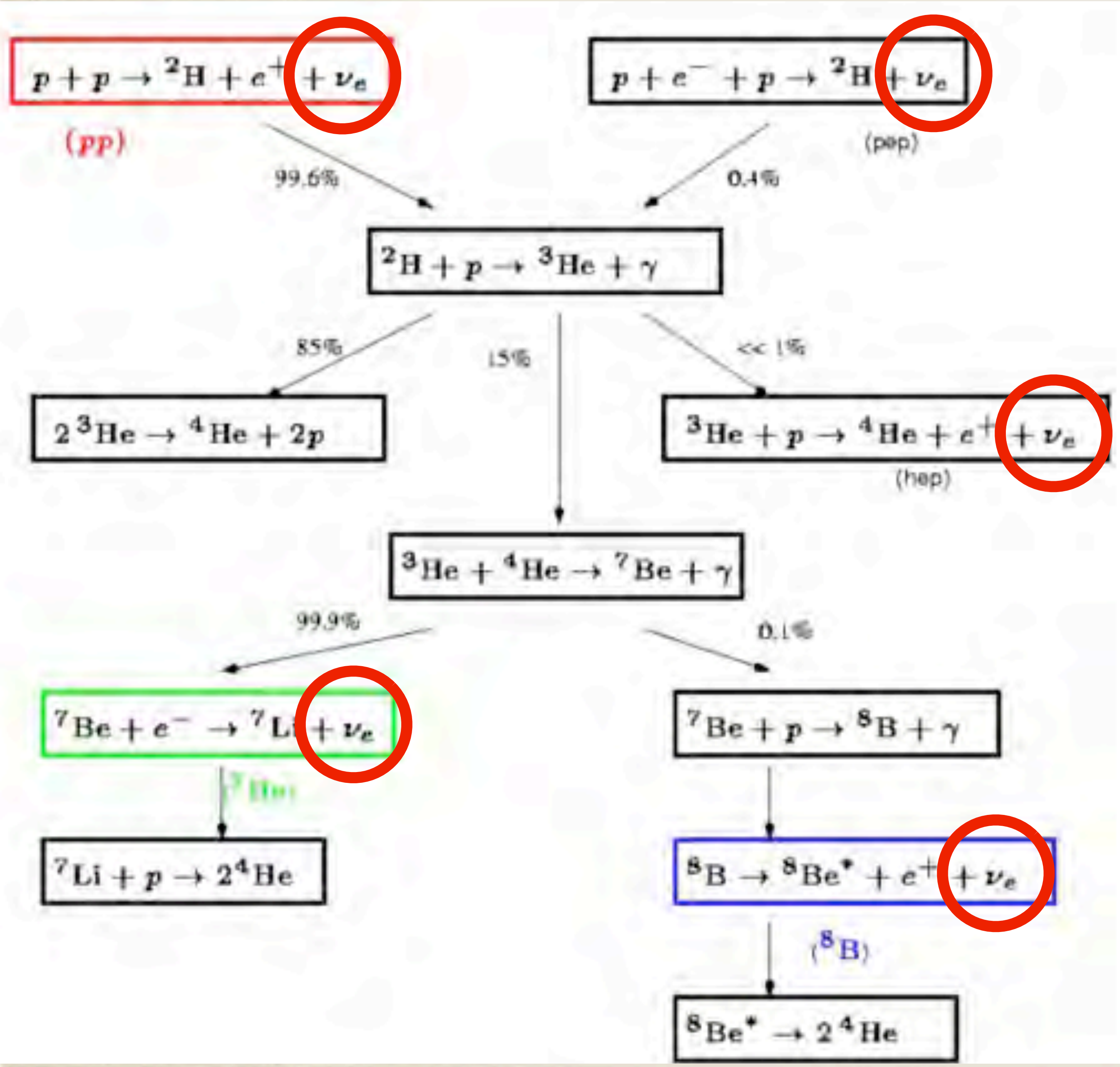

$\to \nu_e$

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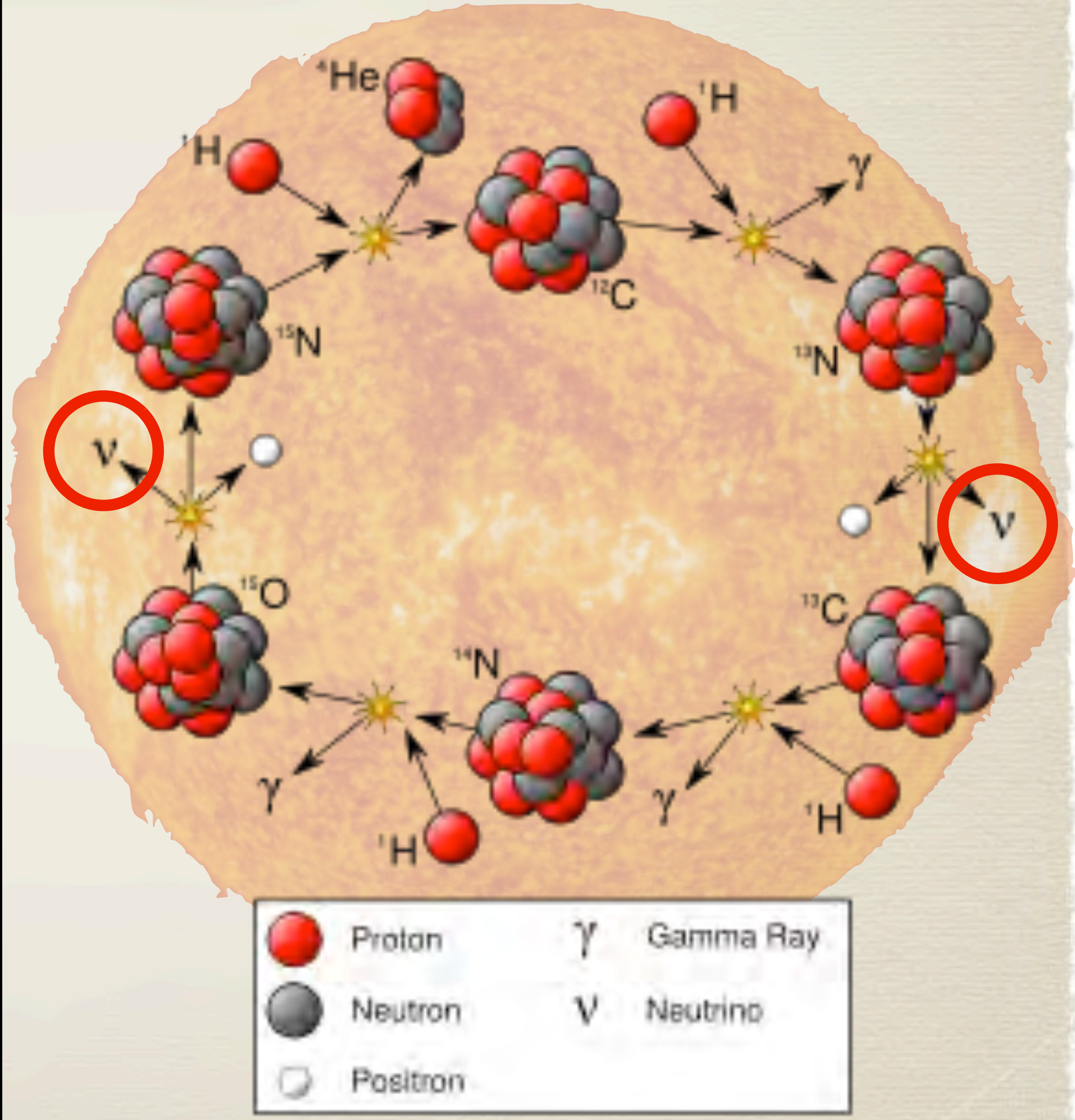
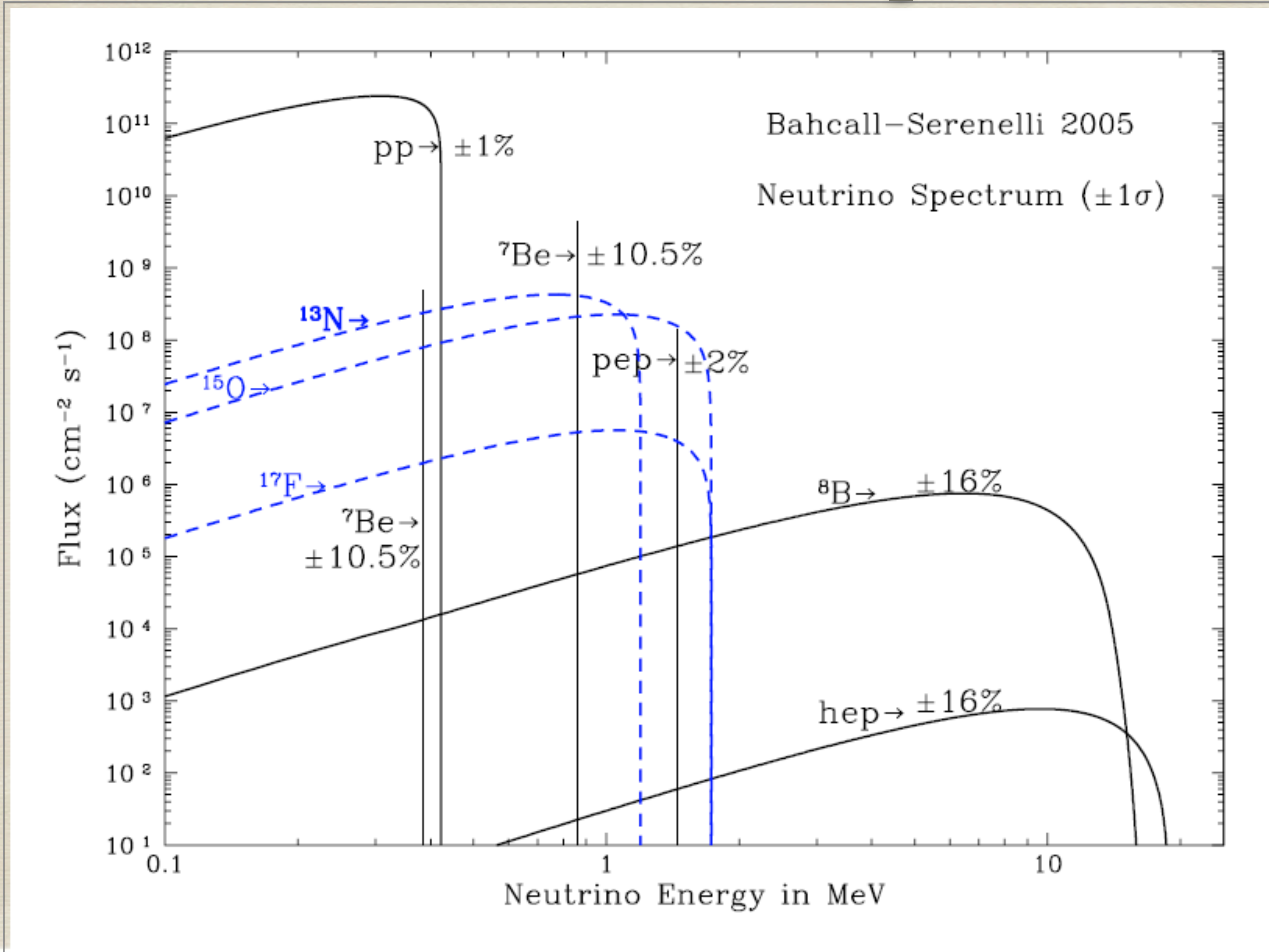


Solar Neutrino Spectra



Continuous Source Experiments

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Inherent Challenges:

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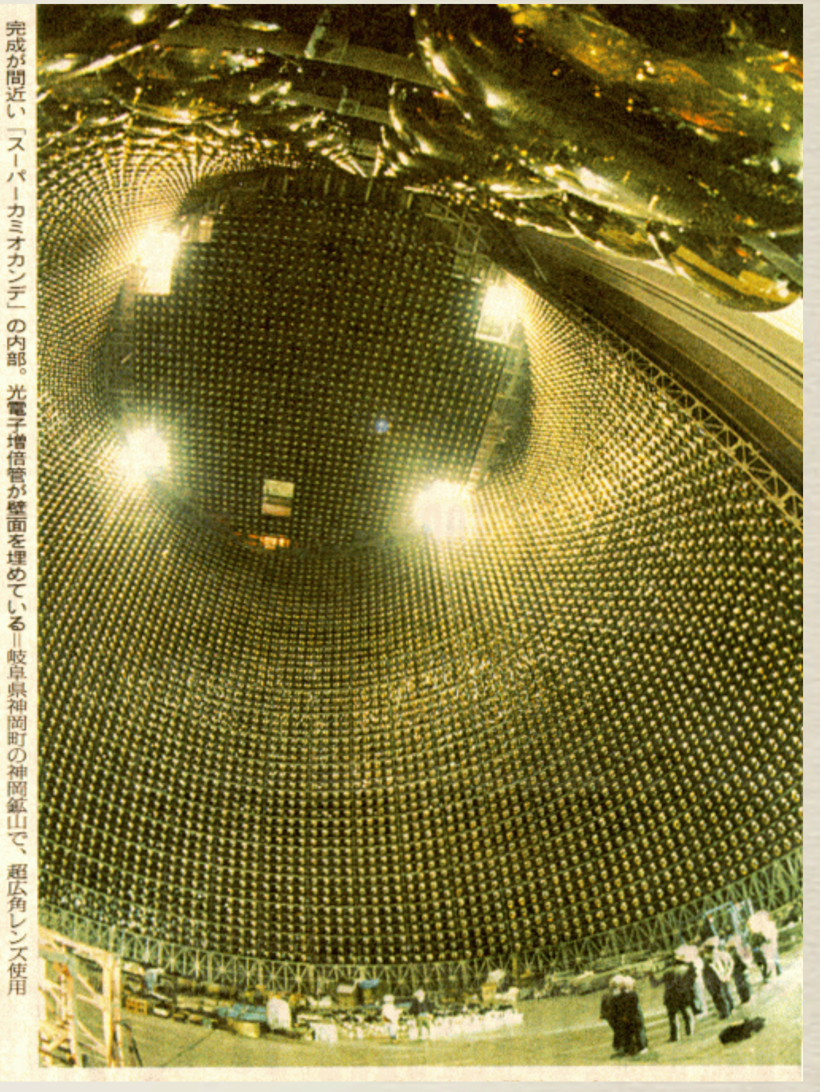
- *Need large, well-understood detectors*



Size is the only handle on low statistics
Is %-level understanding possible at this scale?

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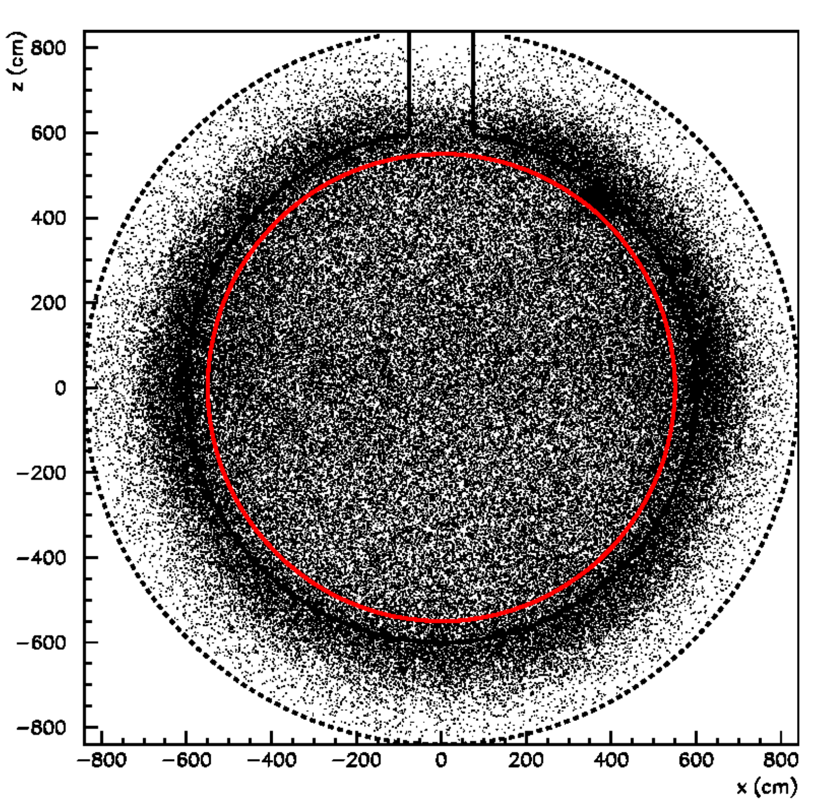
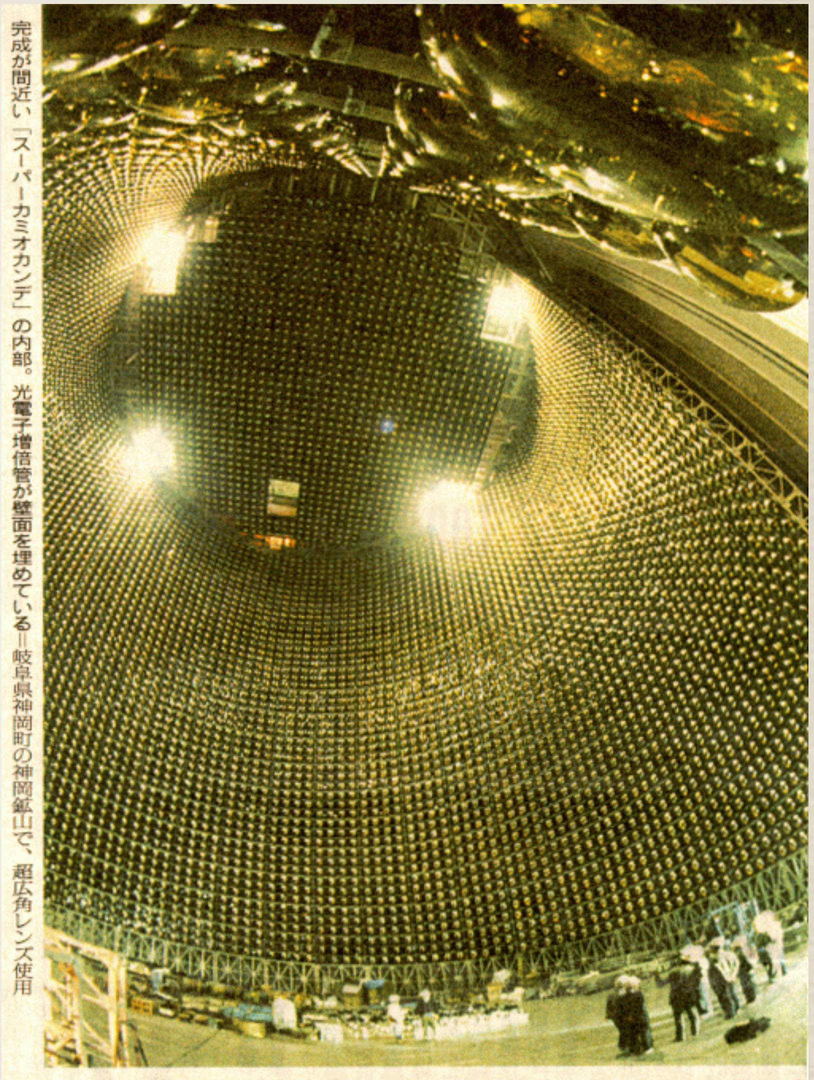


Can’t turn ‘beam’ *or* backgrounds off
Find the 2000 ν events in SNO....



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Continuous Source Experiments

Inherent Challenges:

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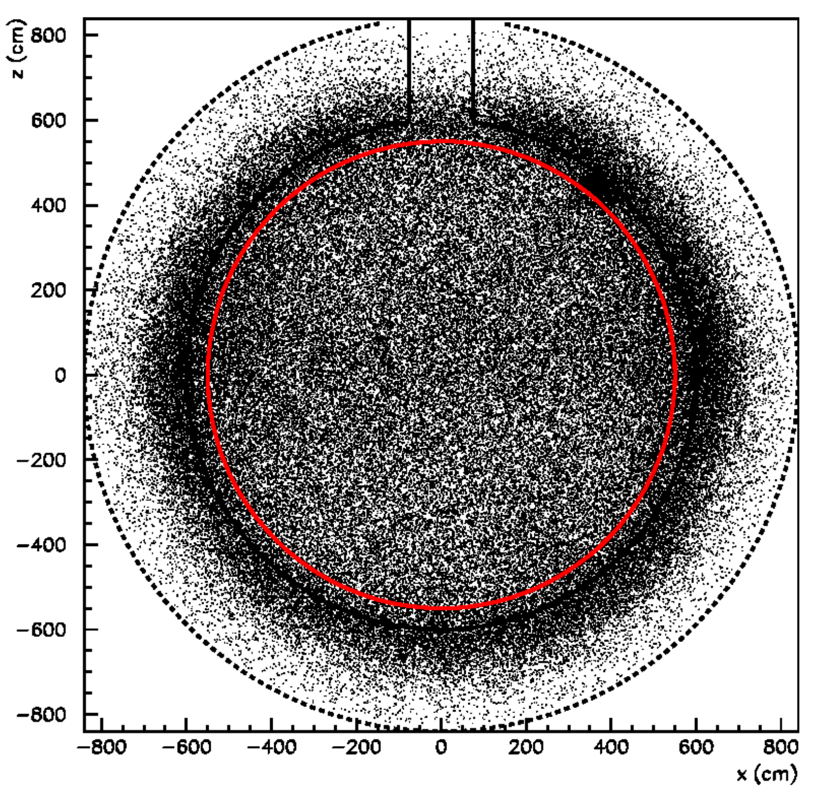
- *Can't rely on knowledge of incident flux*



Solar flux uncertainty ~1-20%

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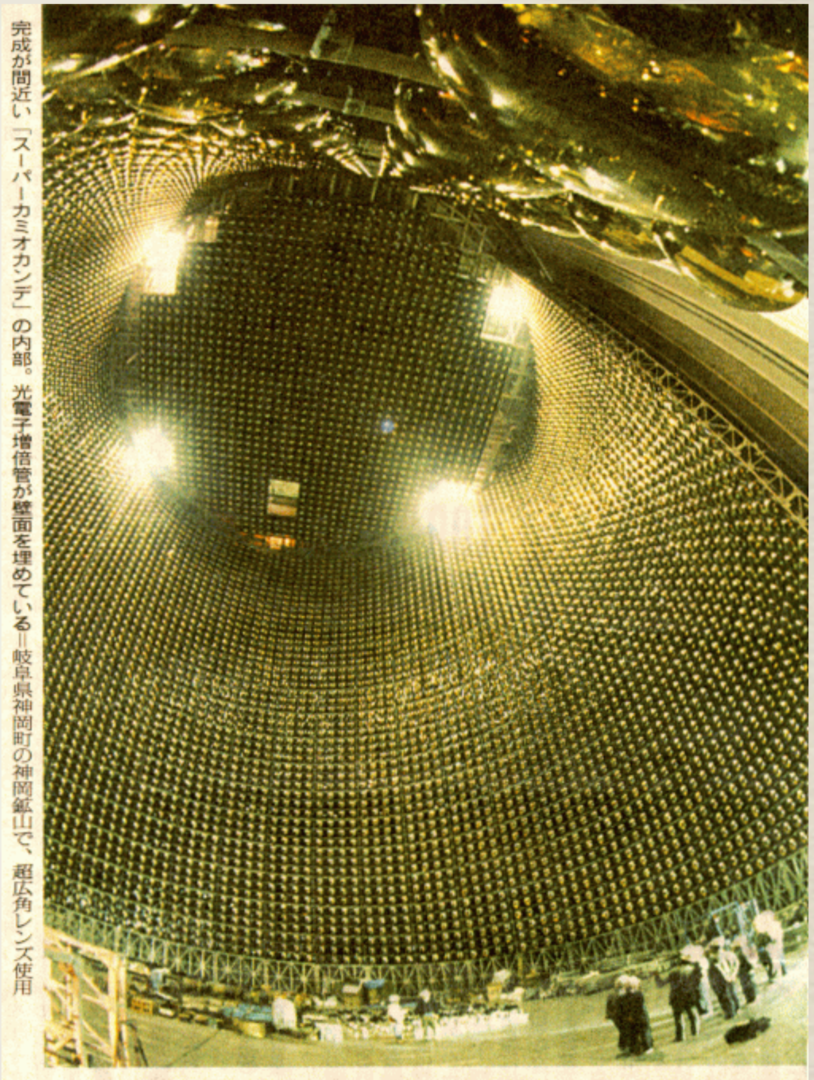

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A Convoluted Process

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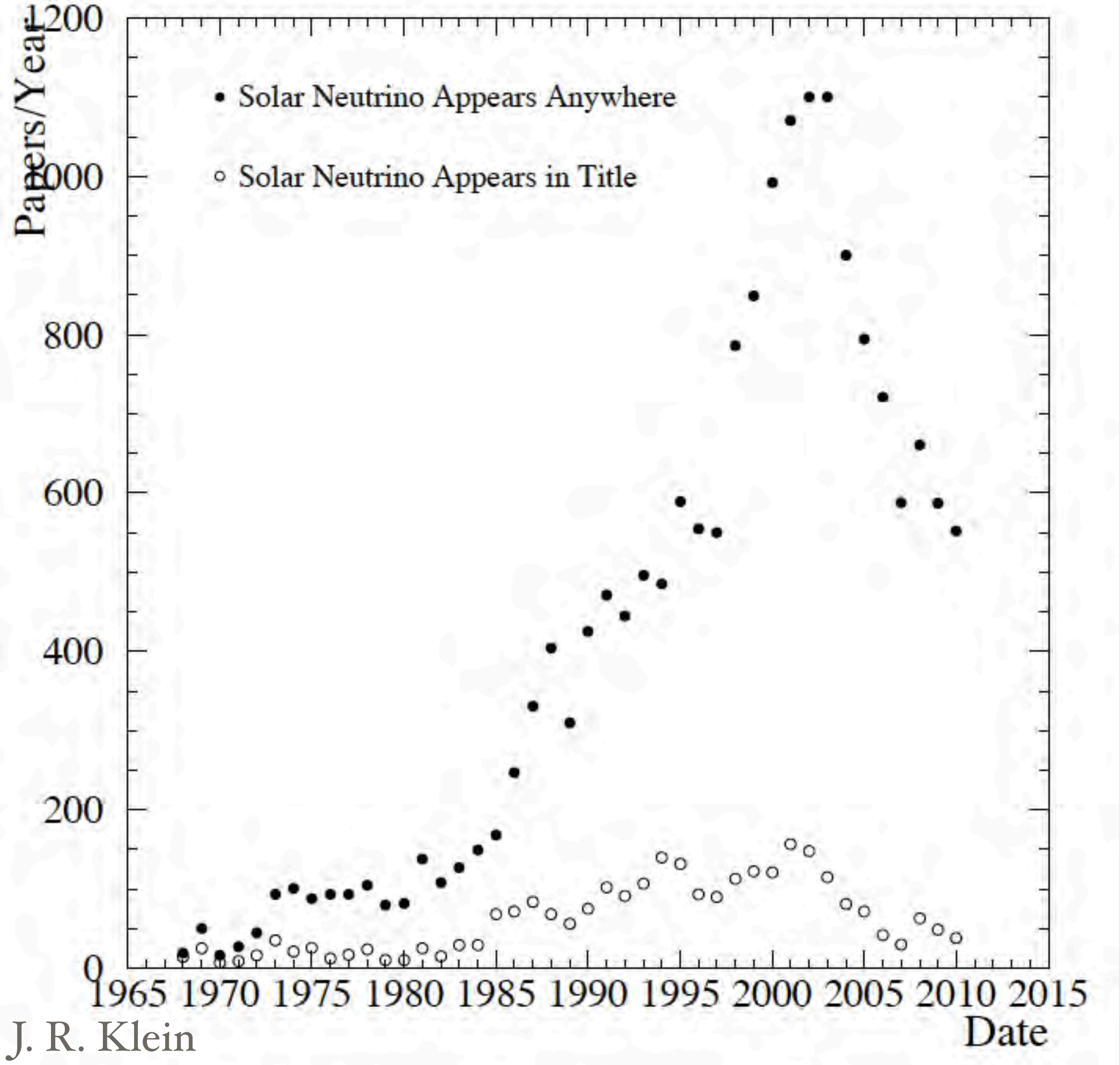

J. R. Klein

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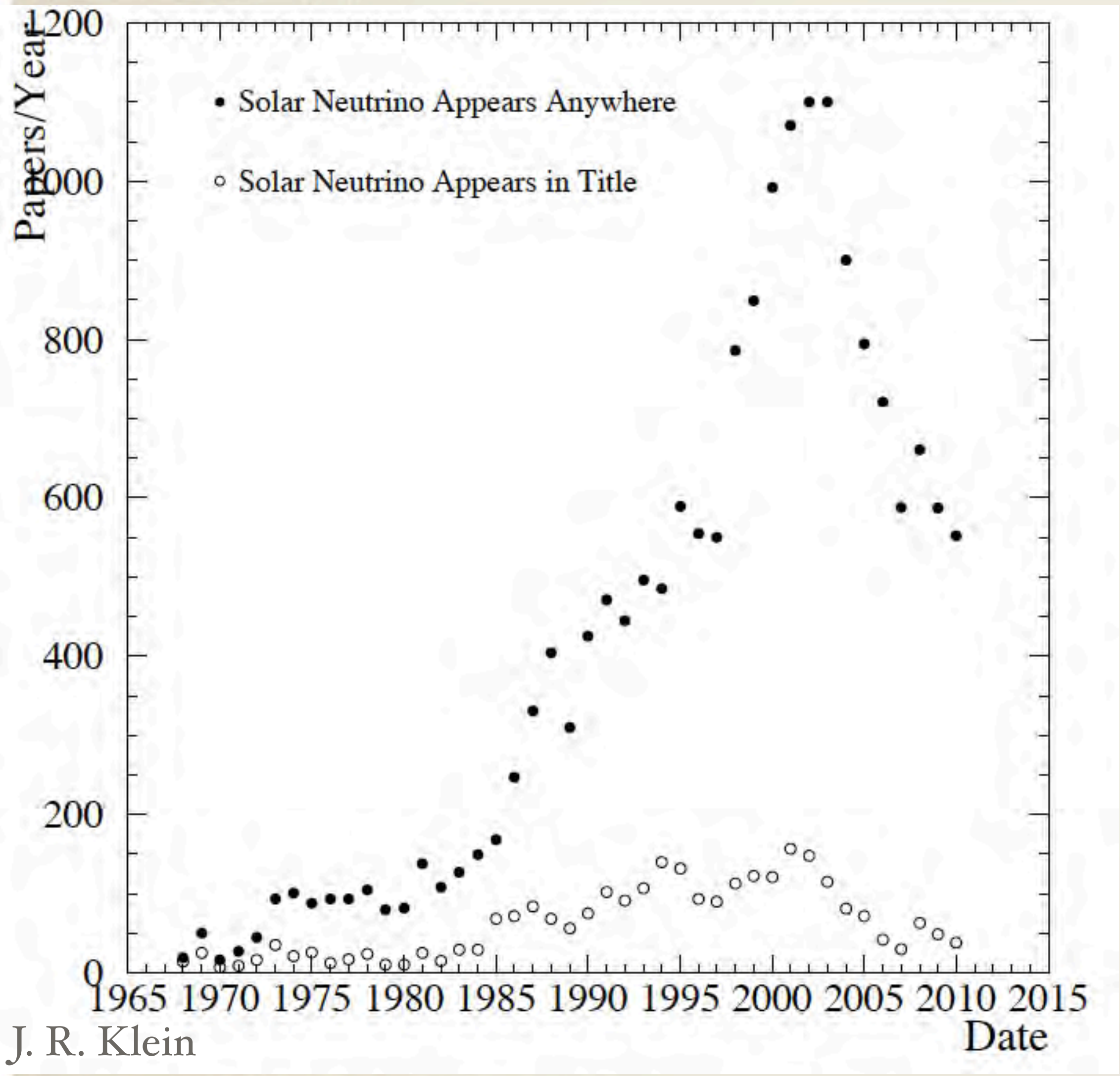

Neutrino oscillations observed:

- Solar: 1960s *(Davis et al.)*
- Atmospheric: 1980s *(K-II, IMB)*

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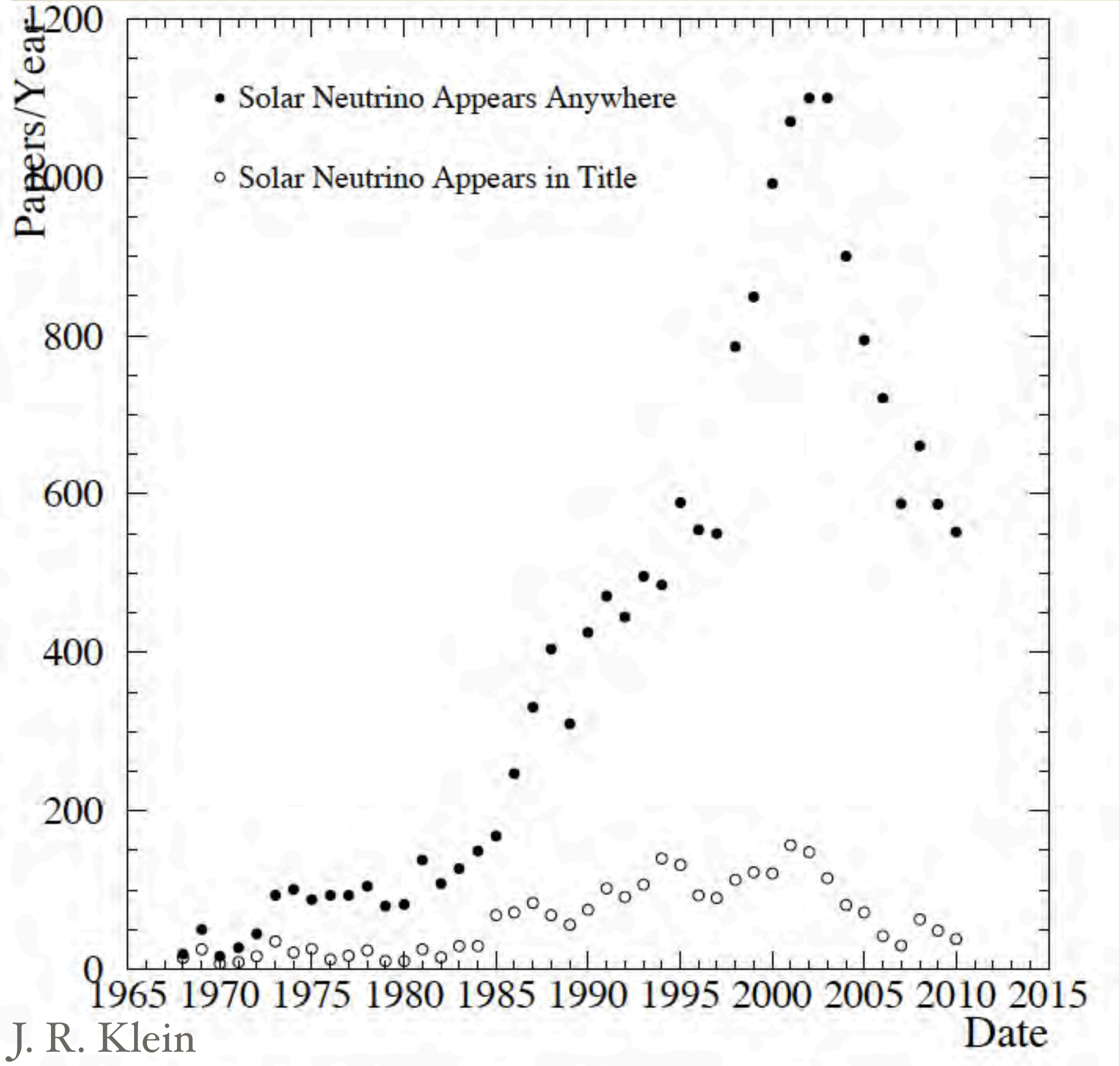

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Neutrino oscillations believed:

- Atmospheric: 1998 *(SK)*
- Solar (+ reactor): 2001 *(SNO, KL)*

The First Solar ν Experiment

$$^{37}Cl + \nu_e \rightarrow ^{37} Ar + e^- (Q = 814 \text{ keV})$$

~600 tons cleaning fluid

4850ft underground

Homestake gold mine, SD

Reduces cosmic backgrounds:

$$\mu + N \rightarrow p + X$$
$$\hookrightarrow p + ^{37} Cl \rightarrow ^{37} Ar + n$$

"Our motivation was to use neutrinos to look into the interior of the sun and thereby test directly the theory of stellar evolution and nuclear energy generation in stars."

Bahcall & Davis, Publ.Astron.Soc.Pac. 112 (2000) 429-433

The First Solar ν Experiment

Ray Davis shows John Bahcall the tank containing 100,000 gallons of perchloroethylene. The picture was taken in the Homestake mine shortly before the experiment began operating.

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“Just plumbing” -- Ray Davis

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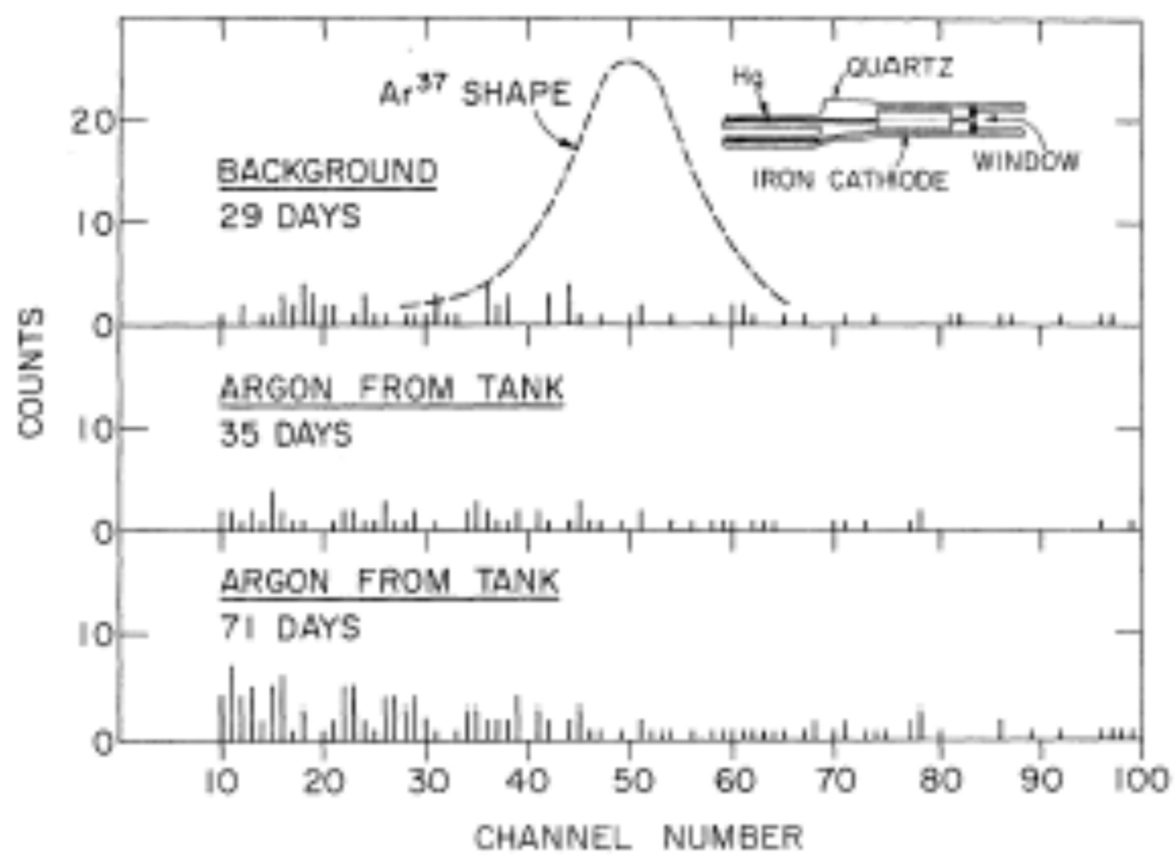

FIG. 2. Pulse-height spectra.

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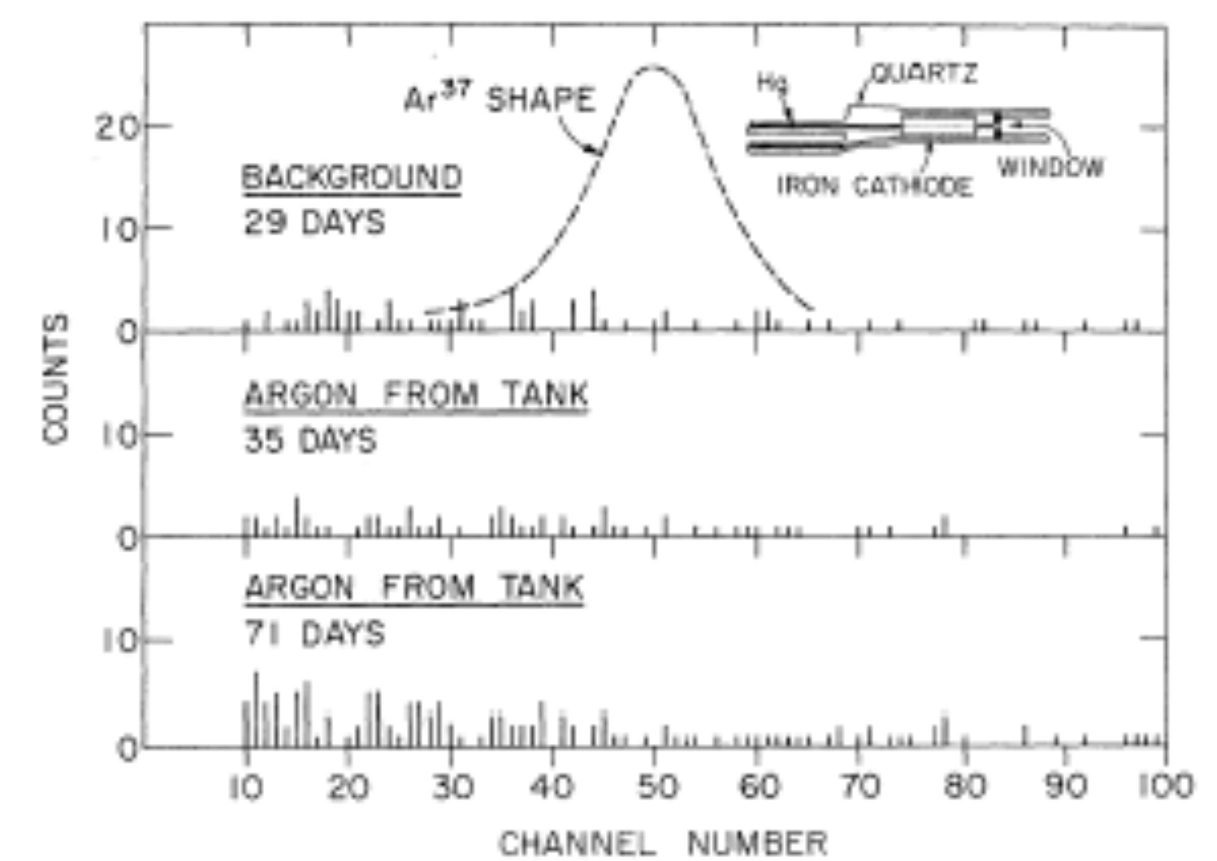

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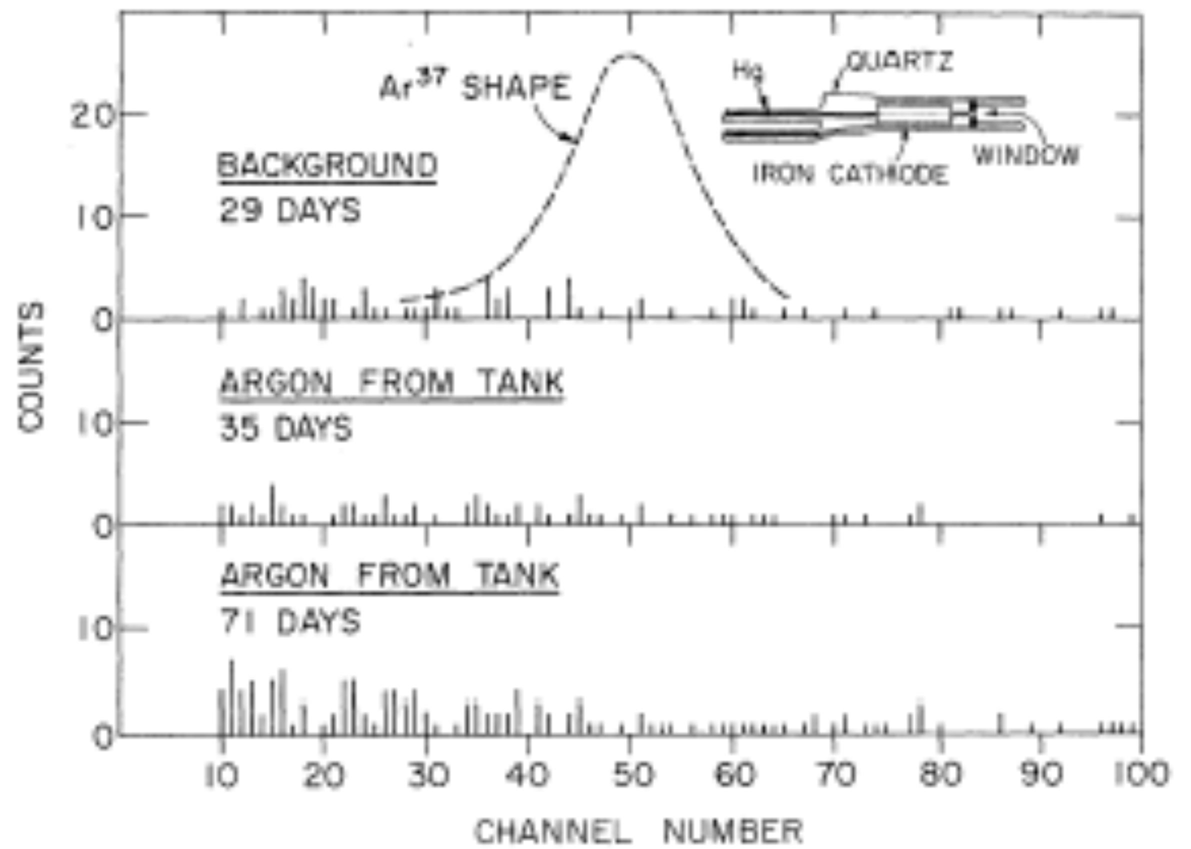

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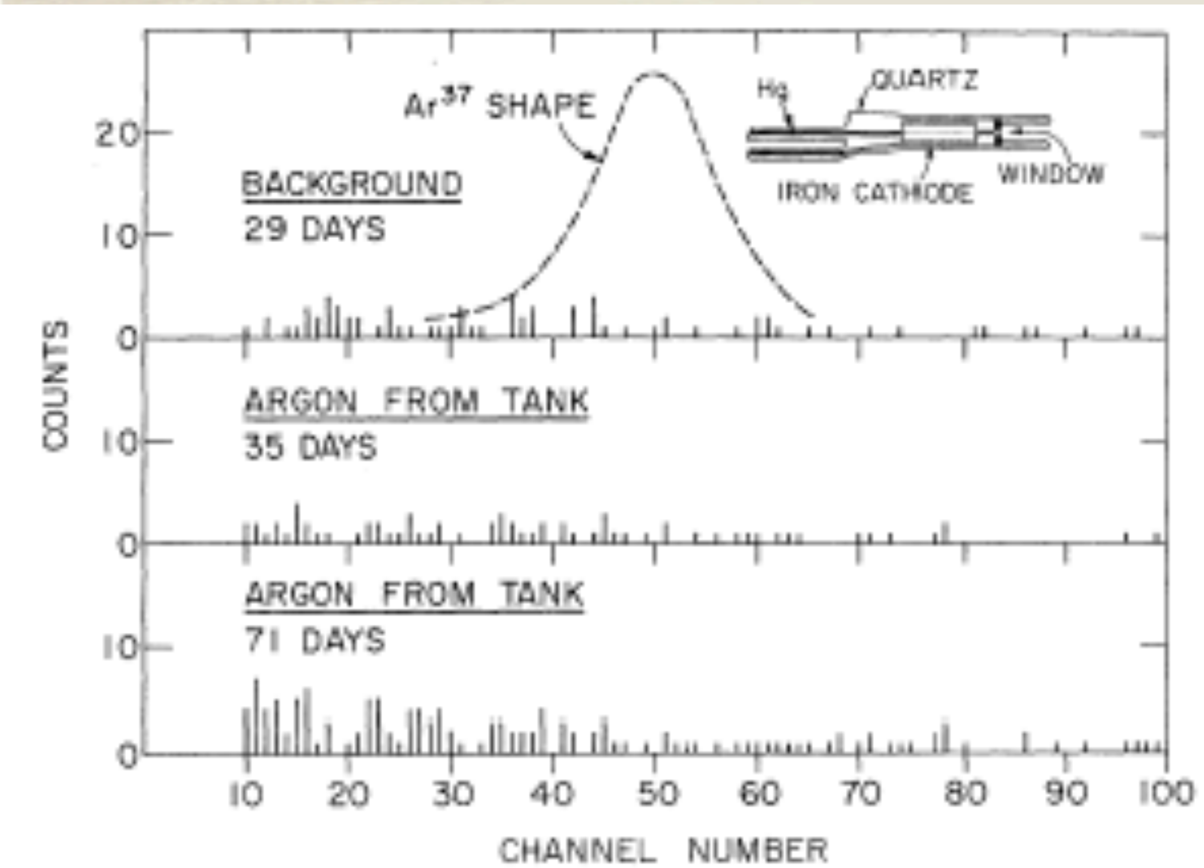

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Bahcall, Bahcall, and Shaviv
best estimate, with large uncertainties:

$$\Phi(^8B) = 4.7 \times 10^6 cm^{-2} s^{-1}$$

When accounting for uncertainties,
"...not in obvious conflict with theory of stellar structure."

First Non-Zero Result

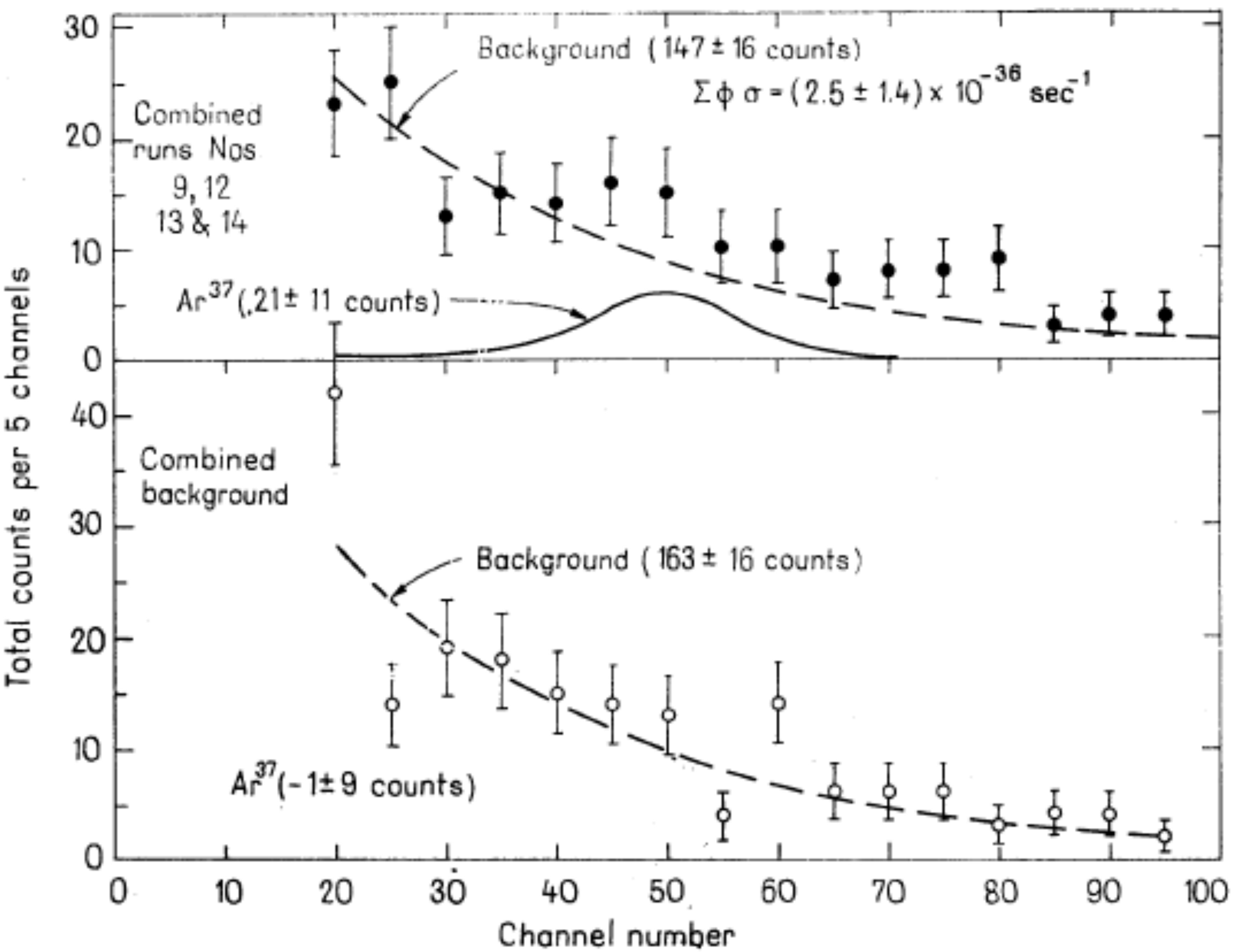

Fig. 2. The sum of counts in each five channels

First Non-Zero Result

MU – 52 *Proc. 11th Int. Conf. on Cosmic Rays, Budapest 1969*

A PROGRESS REPORT
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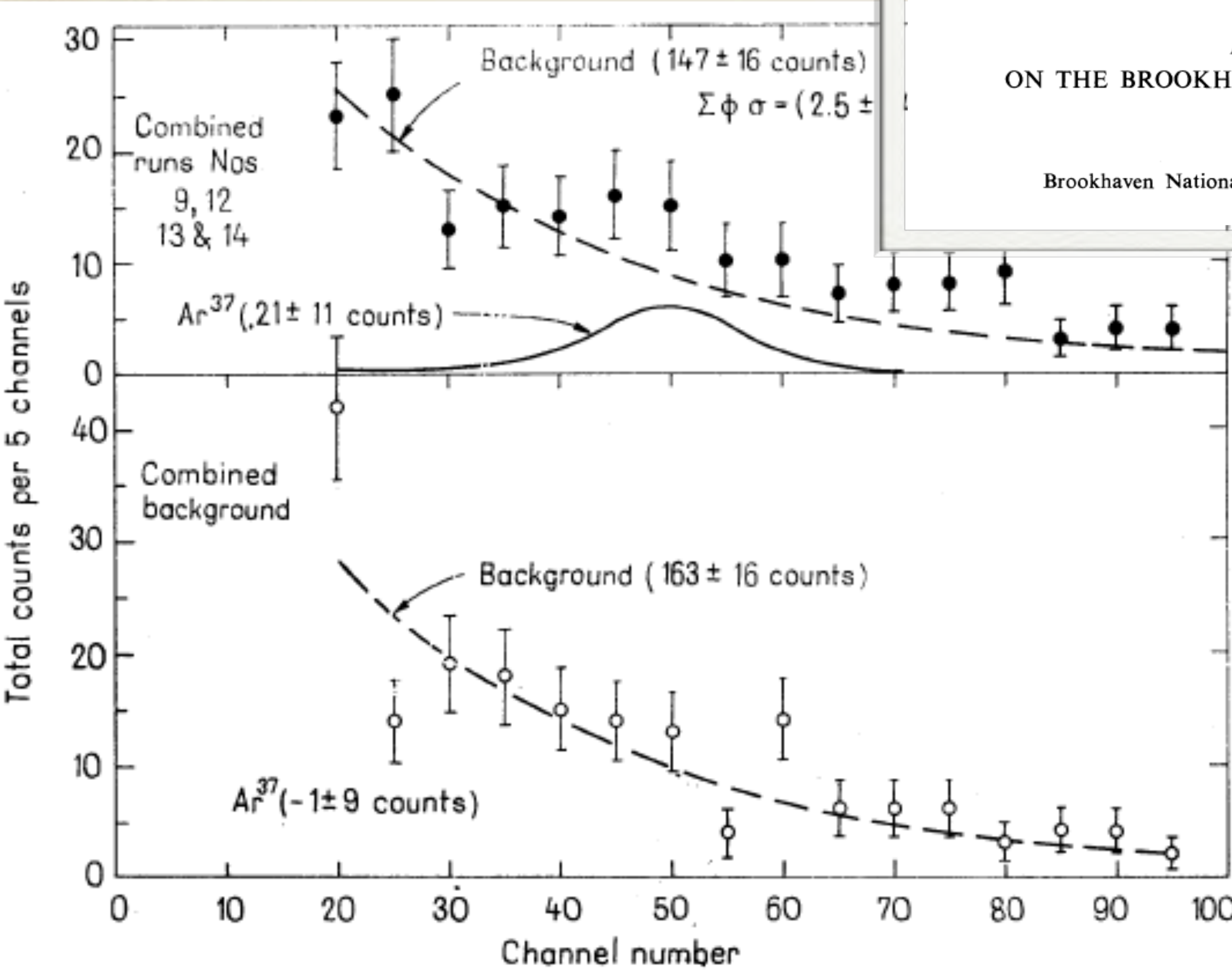
Brookhaven National Laboratory, Upton, New York 11973, U.S.A.



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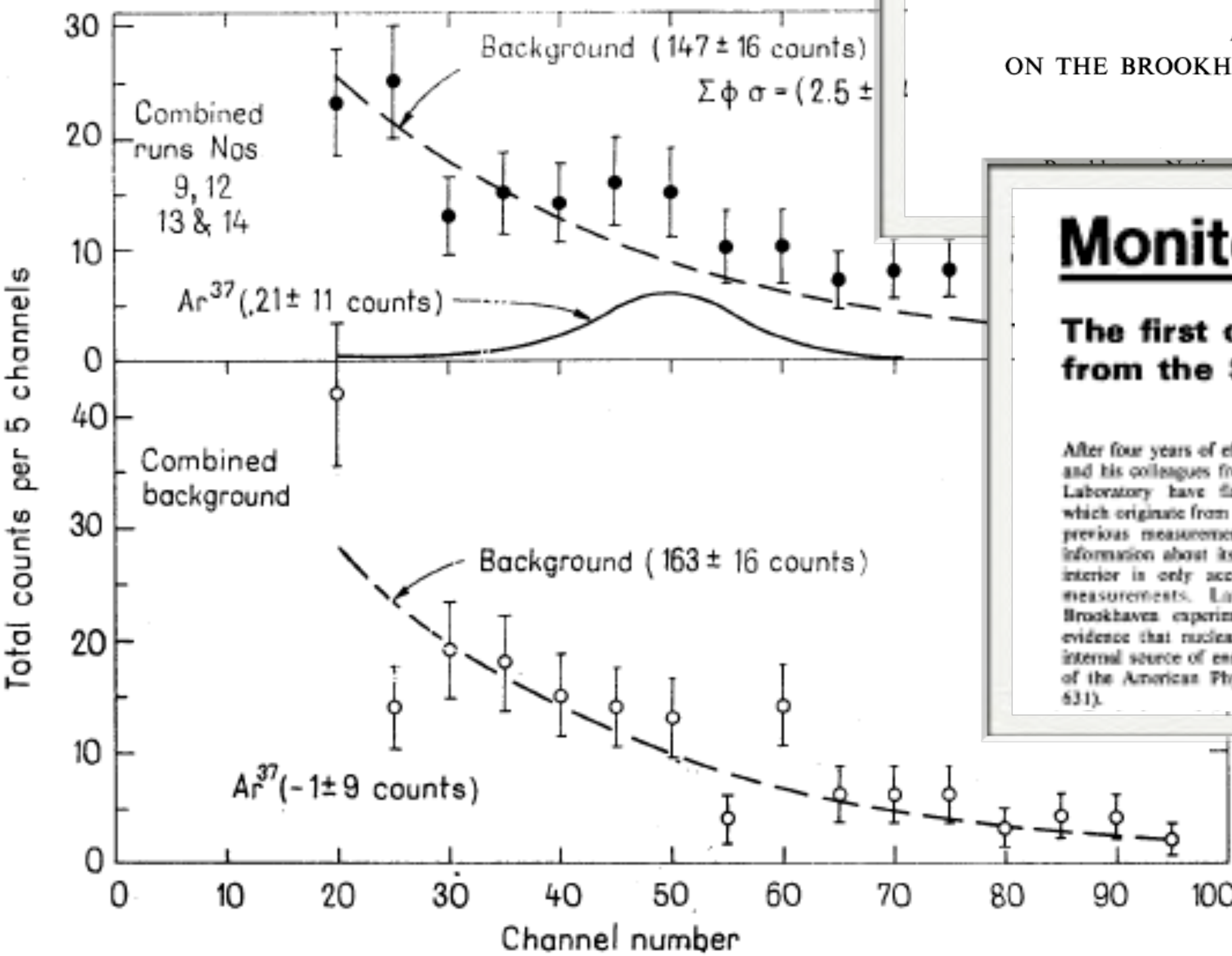

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New Scientist, 1971

Monitor

The first observation of neutrinos from the Sun

After four years of effort, Raymond Davis, Jr., and his colleagues from Brookhaven National Laboratory have finally detected neutrinos which originate from the centre of the Sun. All previous measurements on the Sun give us information about its surface only. The Sun's interior is only accessible through neutrino measurements. Latest results from the Brookhaven experiment are the first direct evidence that nuclear transmutations are the internal source of energy for the Sun (Bulletin of the American Physical Society, vol 16, p 631).

measured all of the accessible reaction rates and can find no easy explanation there for the small discrepancy in the neutrino results. Yet Fowler is confident that nothing is grossly out of order.

One definite conclusion from Davis' results is the dominance of the proton-proton chain over the carbon-nitrogen cycle for solar energy. If the carbon-nitrogen cycle predominated in the Sun, the neutrino flux would have been 30 times the observed value. The neutrino experiment serves to confirm all of the terrestrial nuclear physics experiments and

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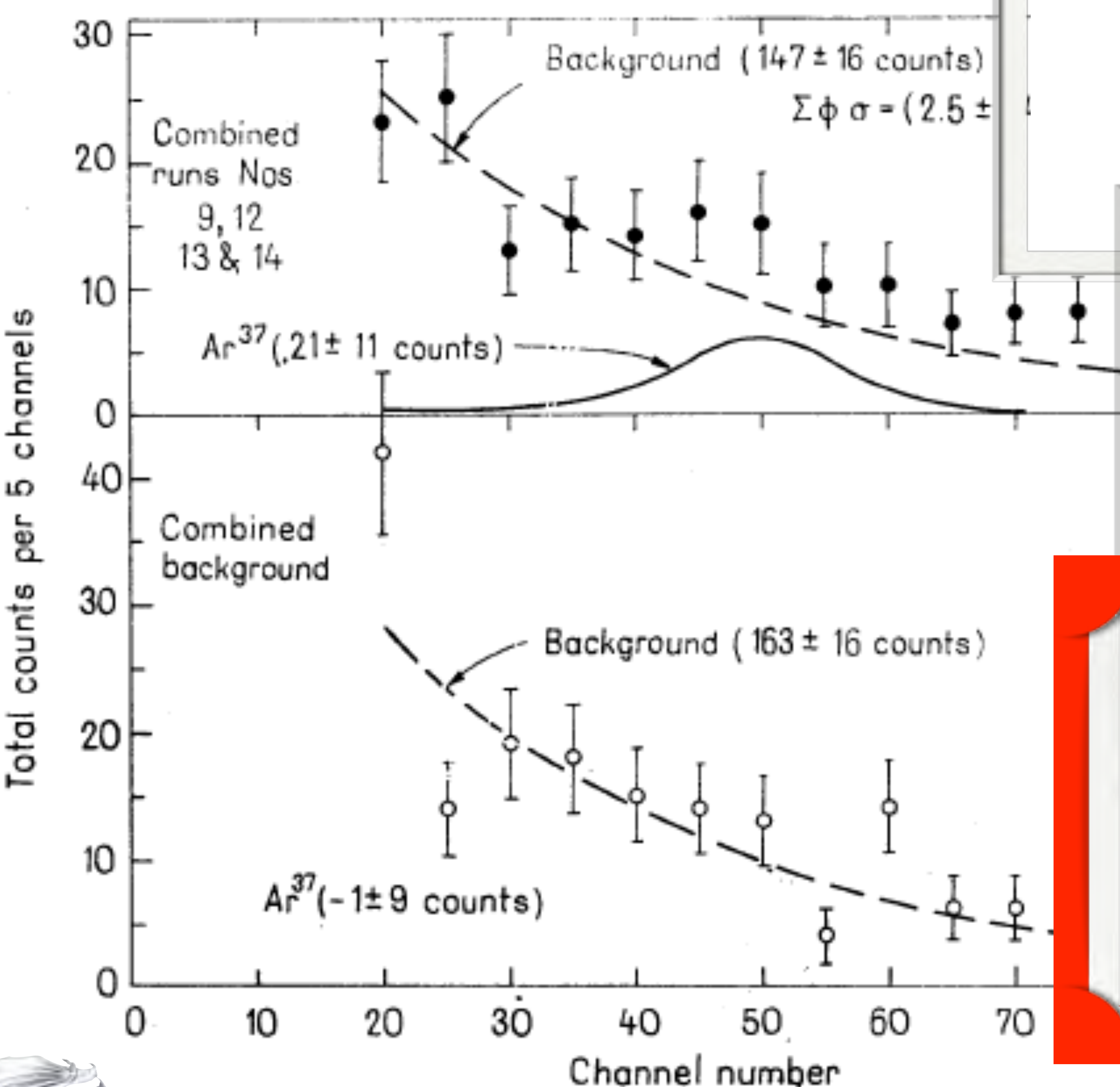

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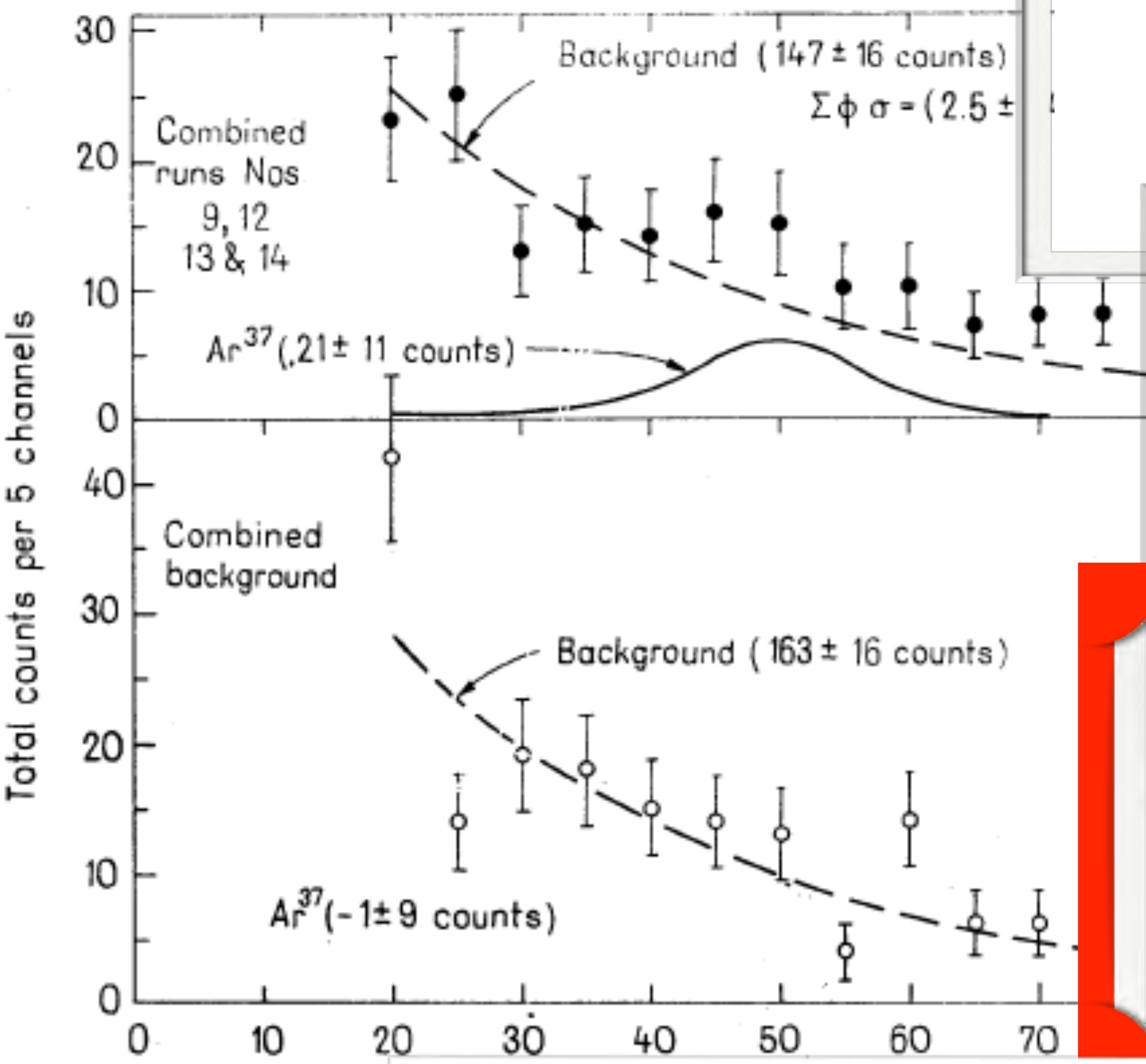

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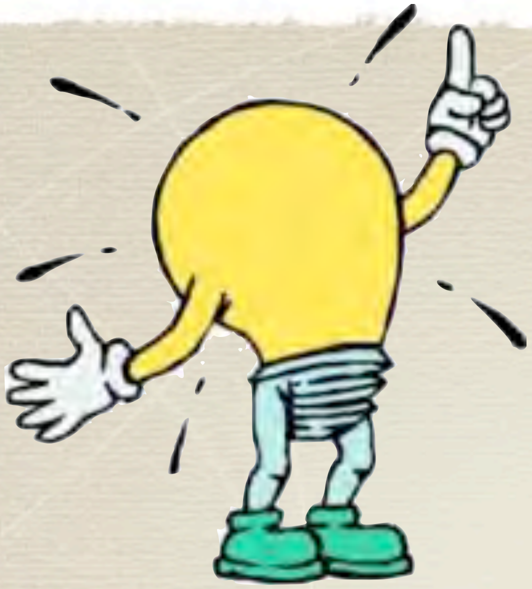
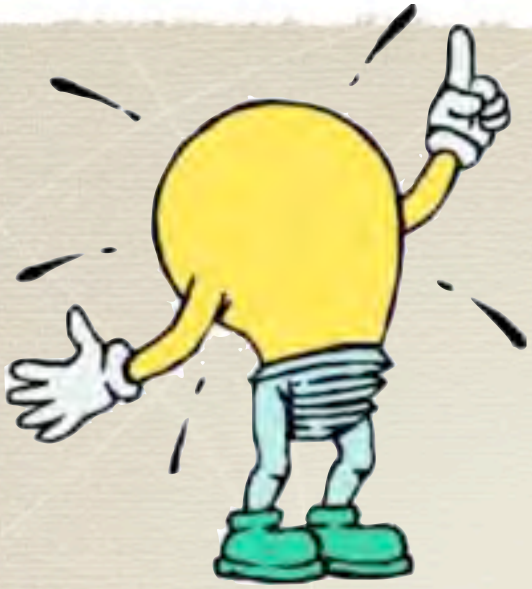
Last solar ν experiment ever done in the US


Here Be Dragons



Neutrino Oscillations in Vacuum?

"It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \leftrightarrow \nu_\mu$ *oscillations, similar to* $K^0 \leftrightarrow \overline{K^0}$ *oscillations."*



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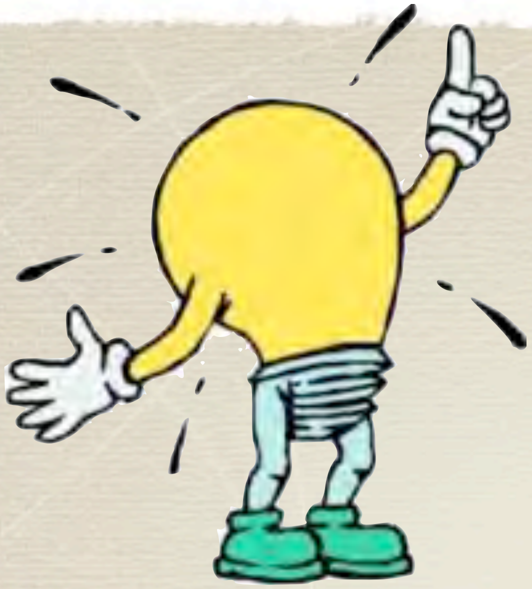

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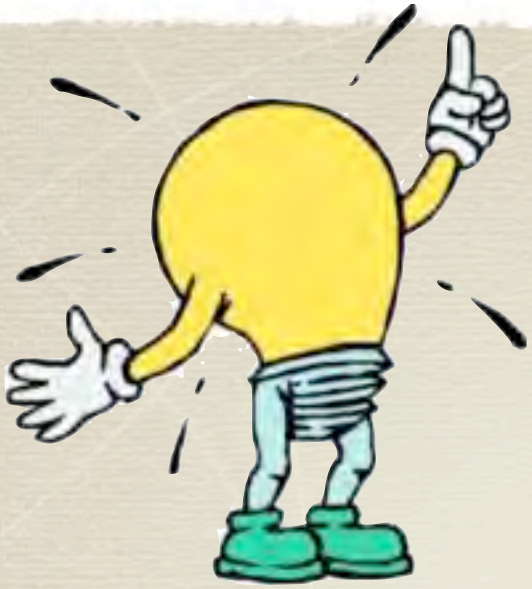

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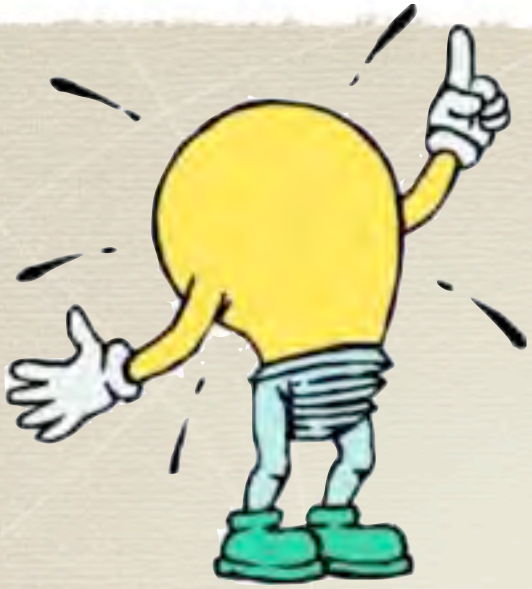

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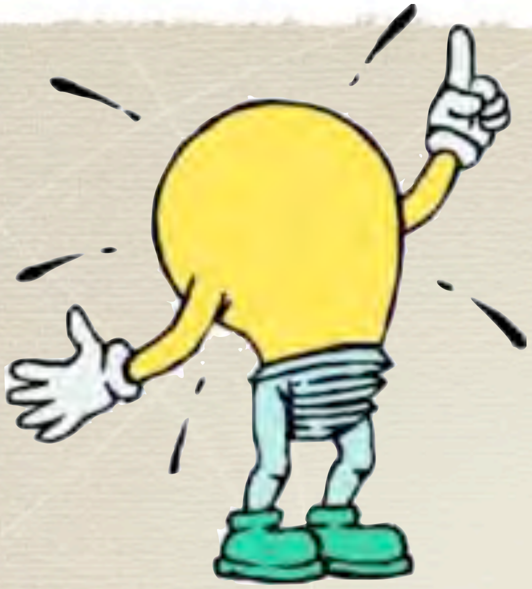

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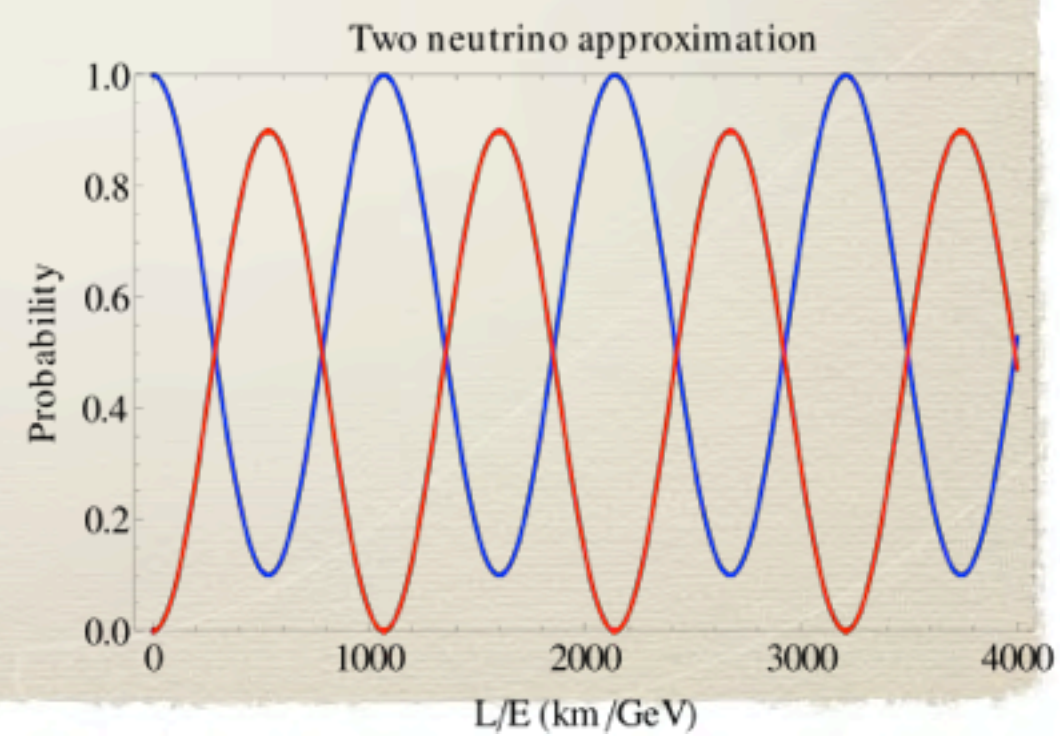

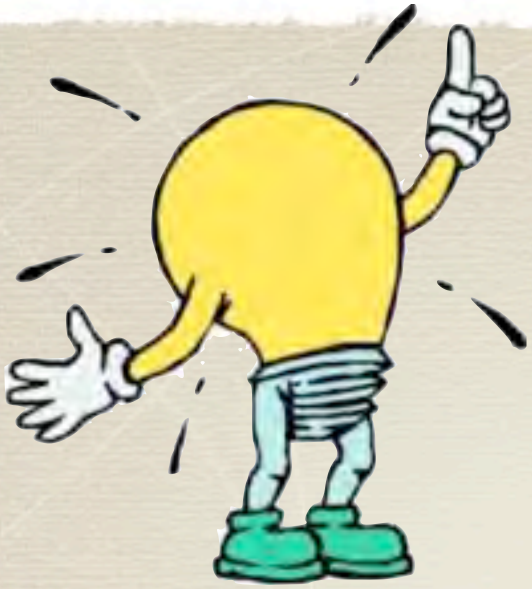

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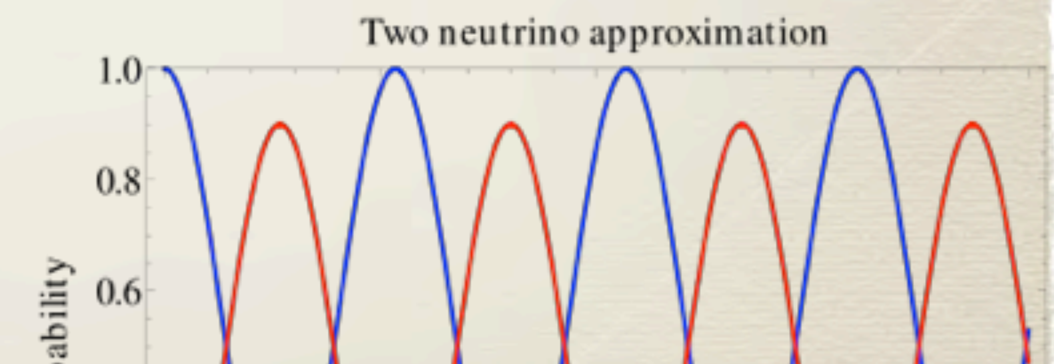
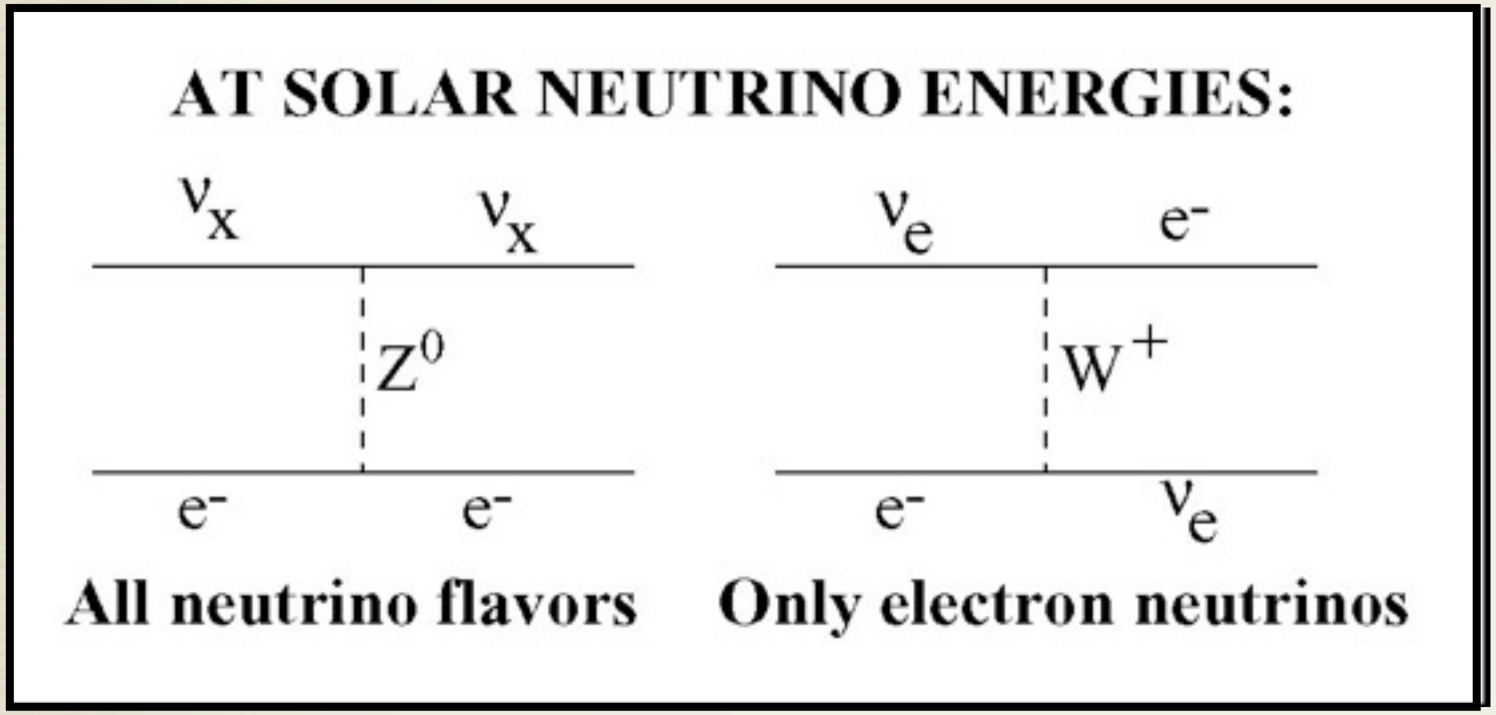


Not enough to produce observed x3 suppression

Further Development

1978: Wolfenstein points out coherent forward scattering of ν_e in the Sun:



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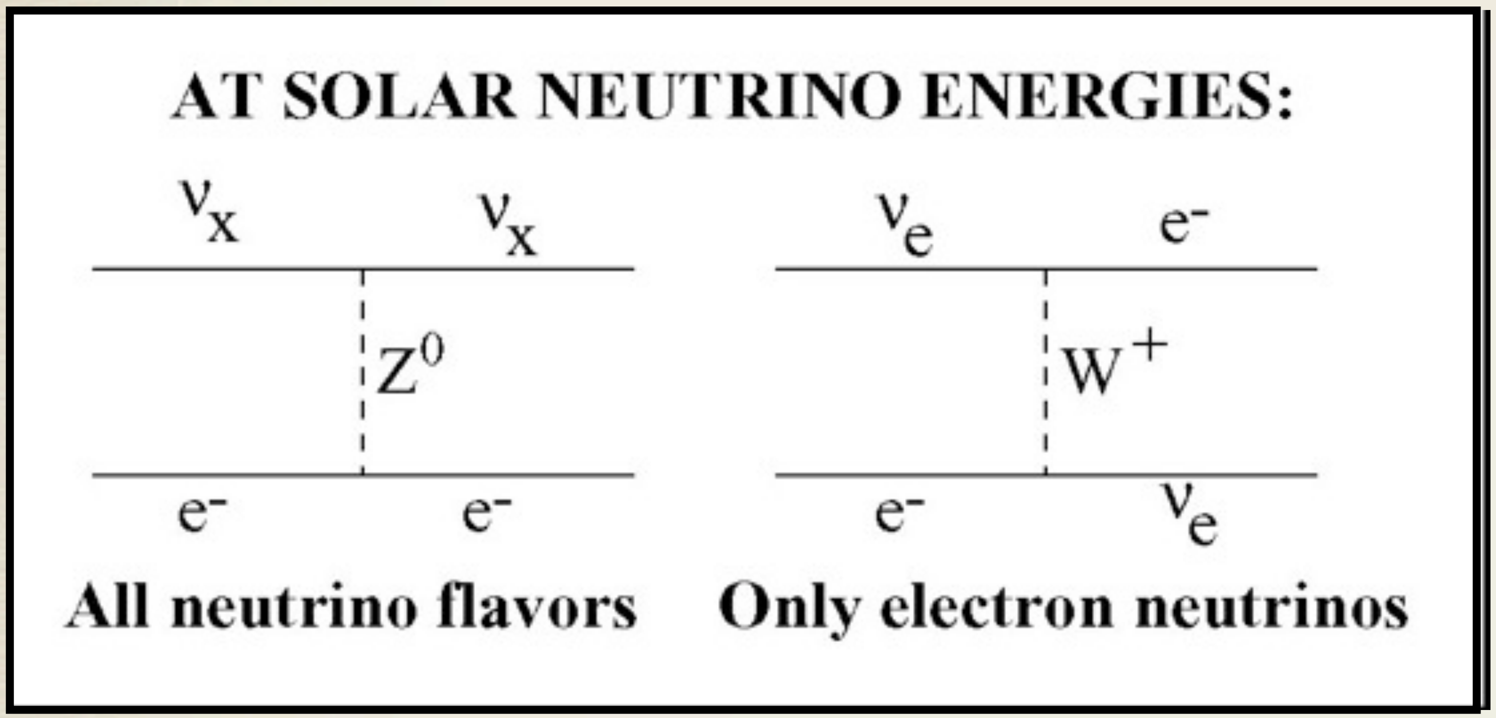

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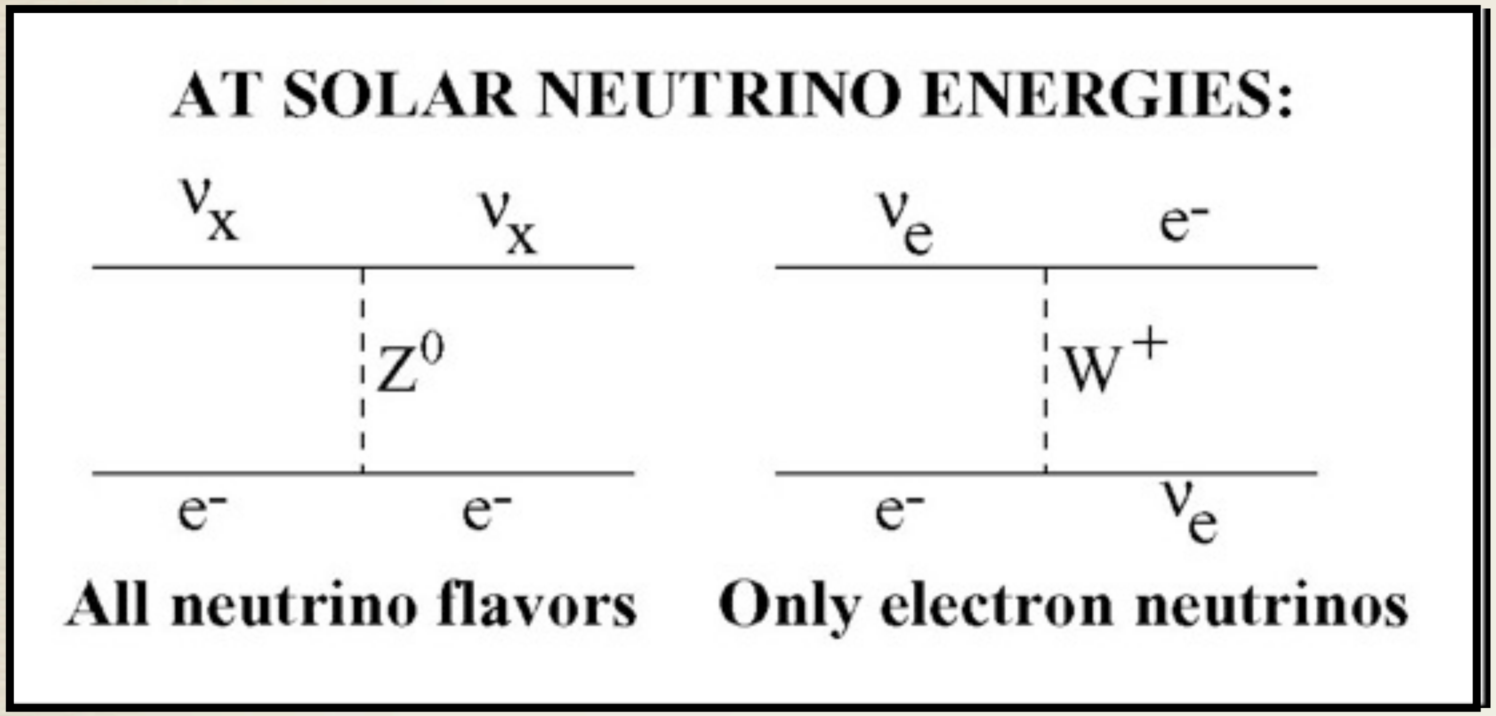

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"...there are no significant oscillations inside the sun or in traversals through the earth"

-- Wolfenstein

The Missing Piece

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⇨ can achieve large suppression from small mixing angles!

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Resonance when ⟶ $$\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e = 0$$

Resonance condition can be met:

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Langacker finds a sign error (carried over from W paper)
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⇨ can achieve large suppression from small mixing angles!

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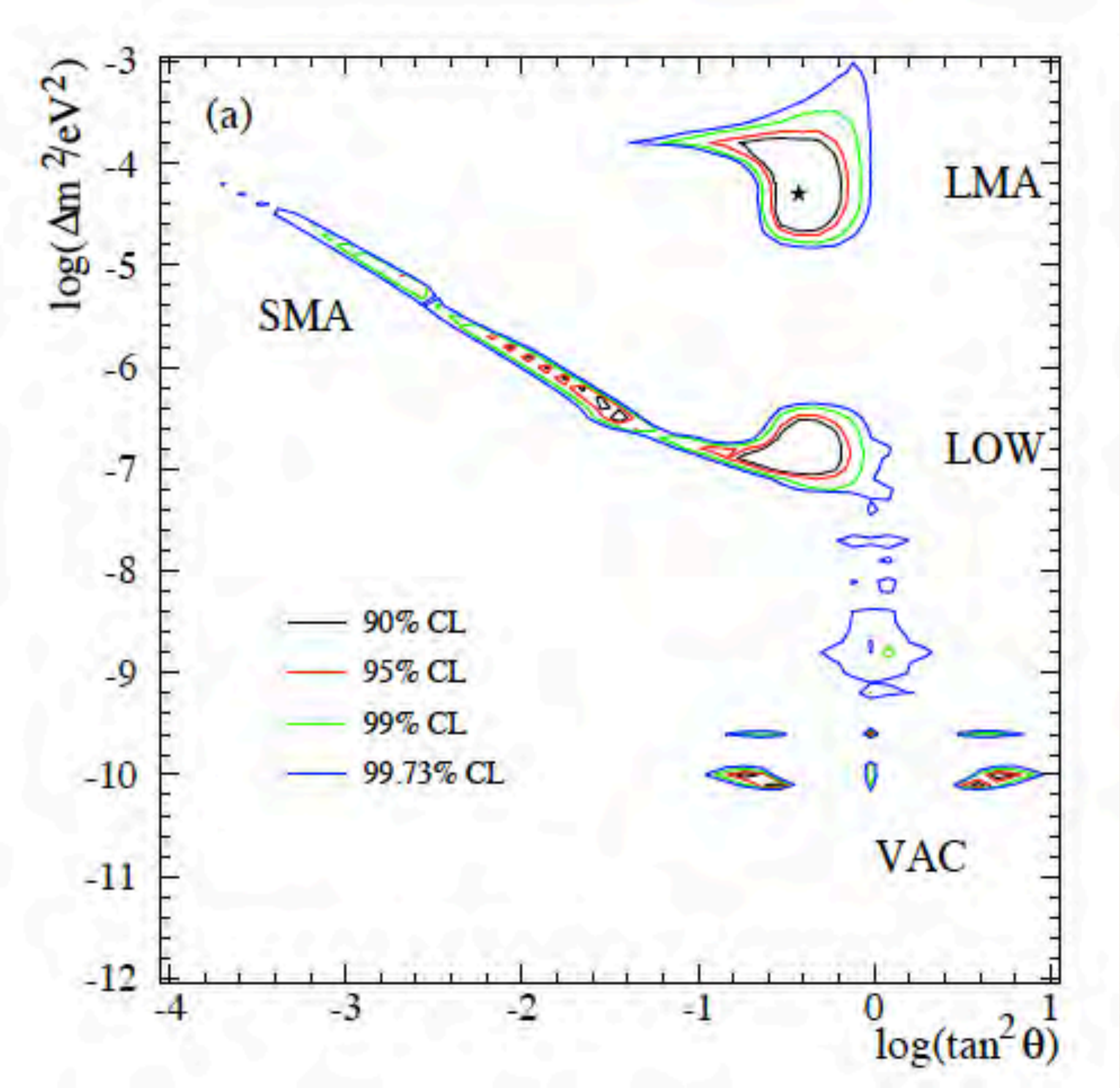

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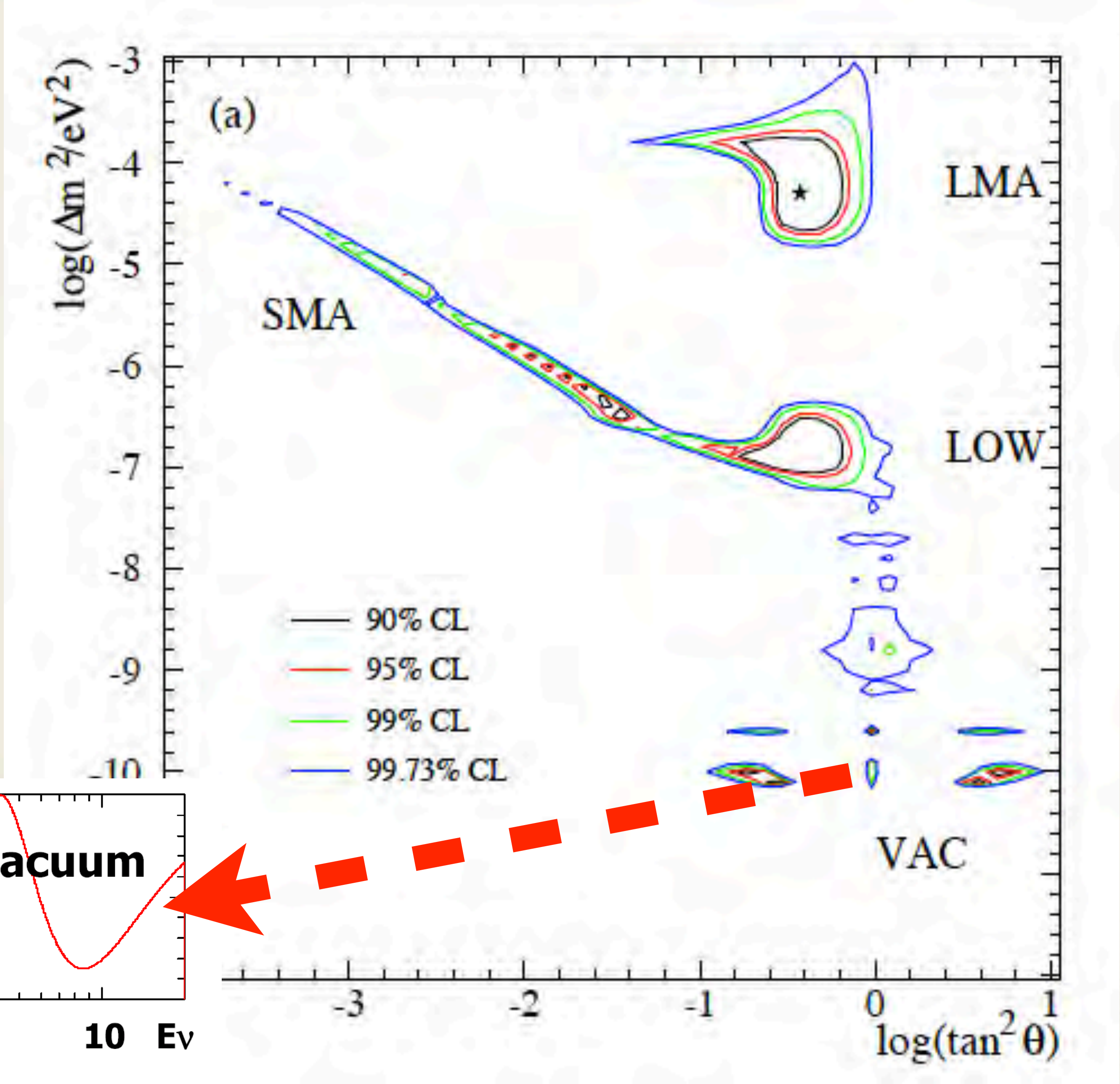

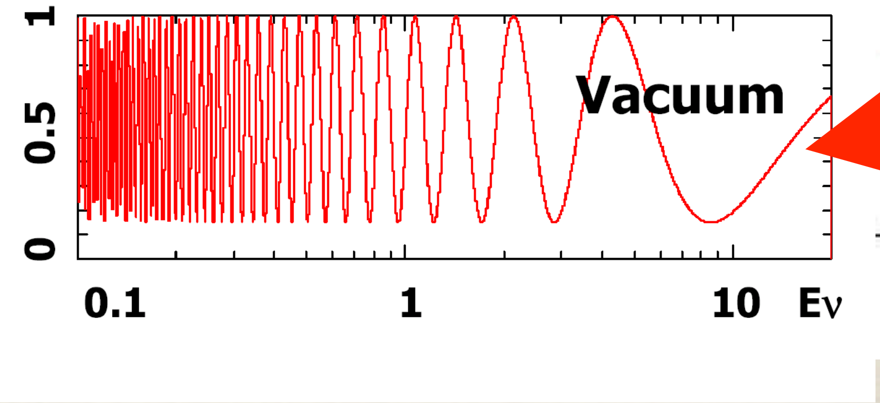

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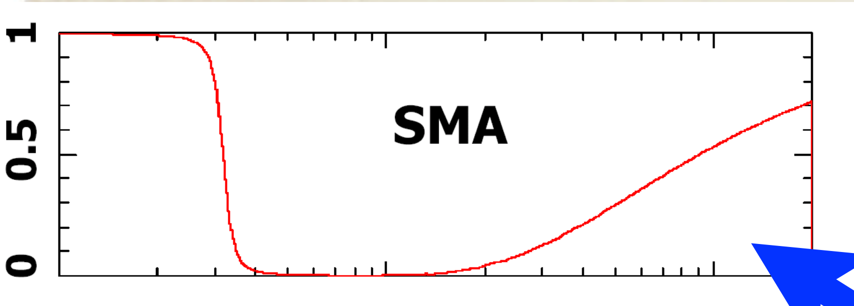

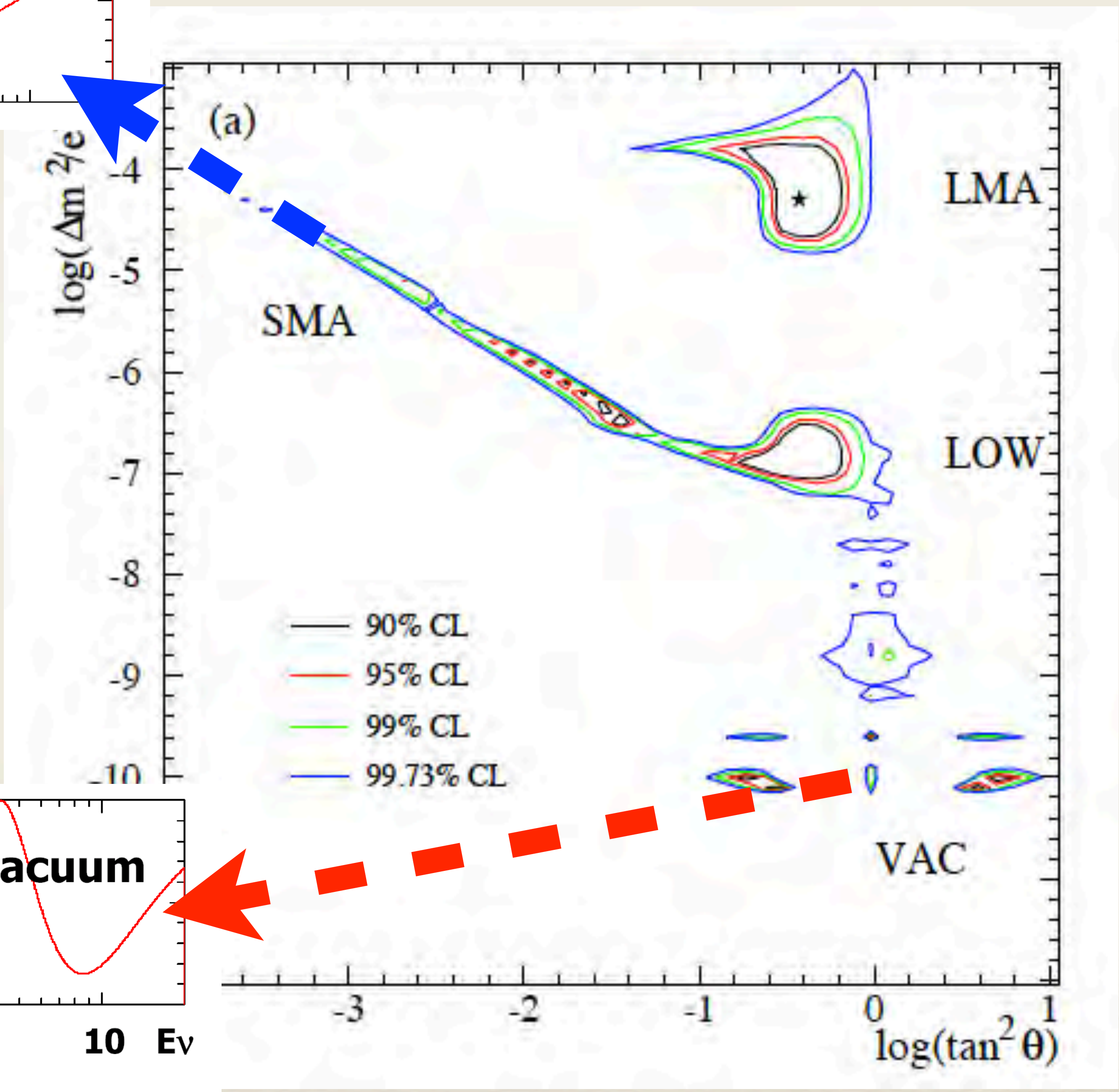

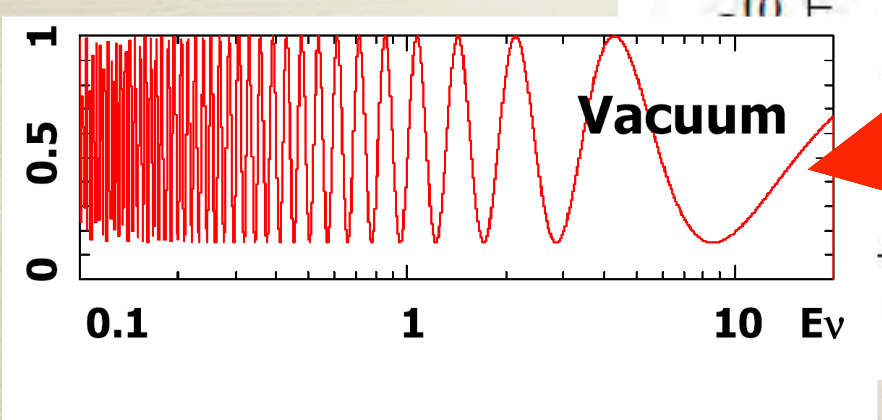

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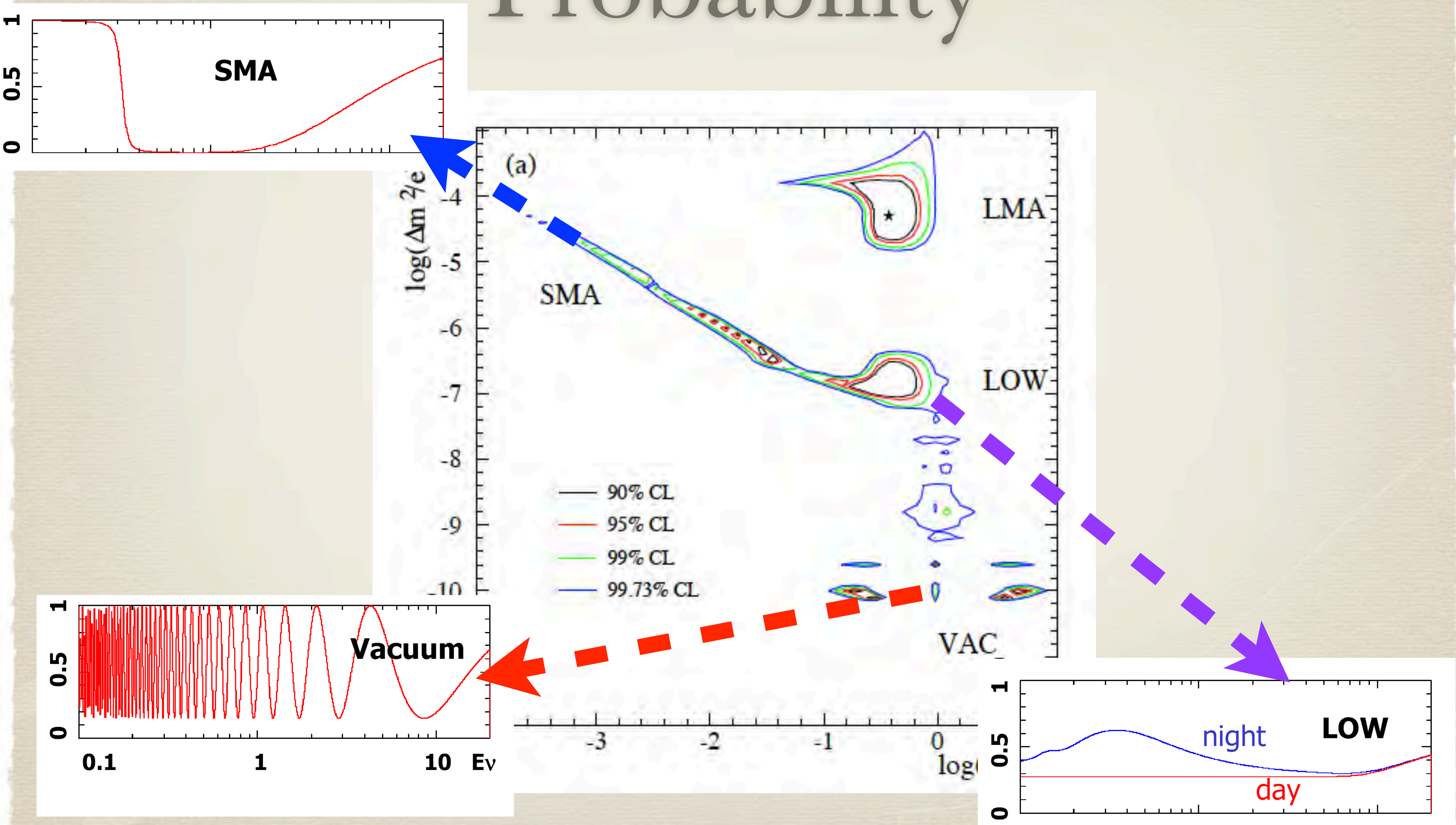

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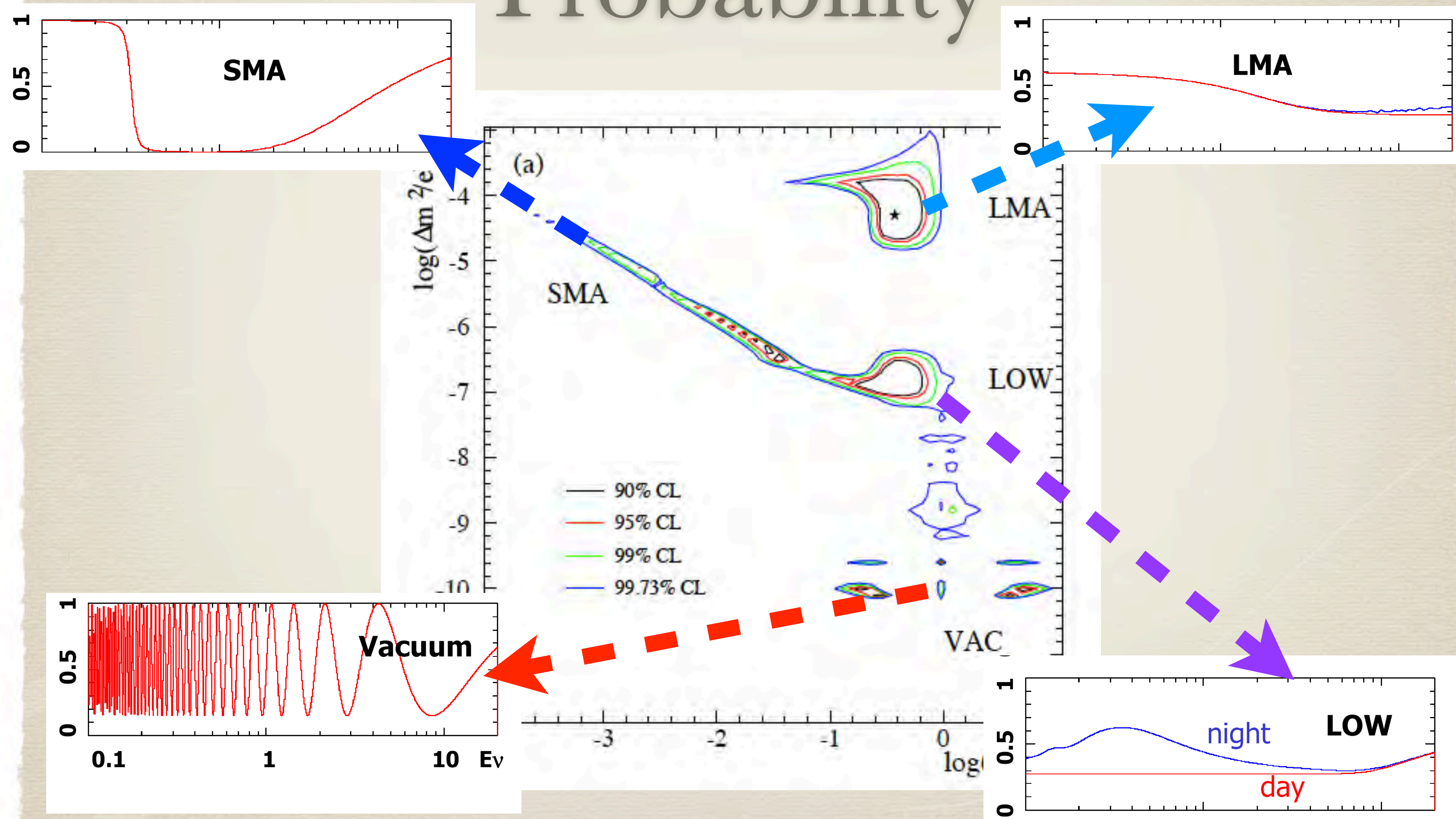
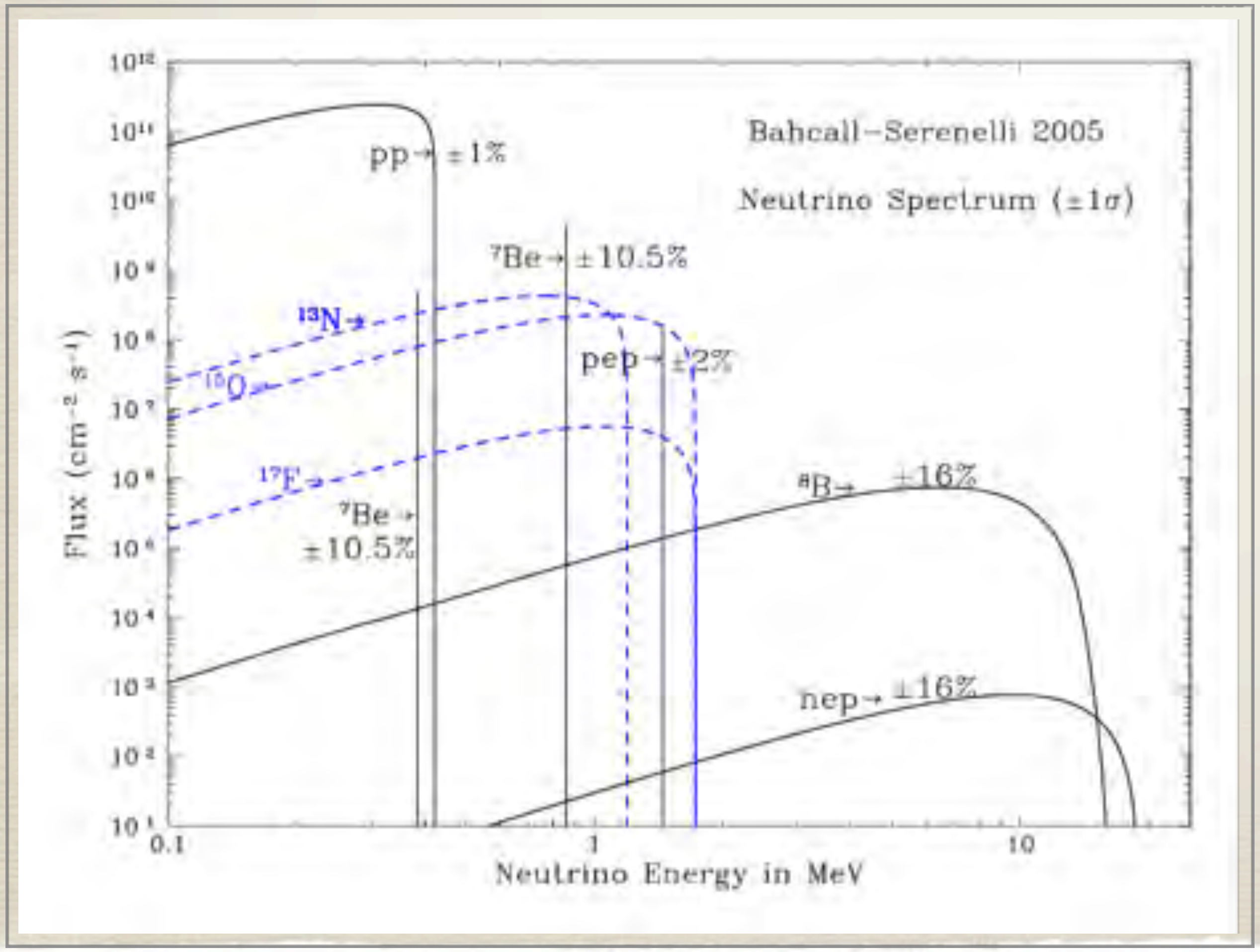
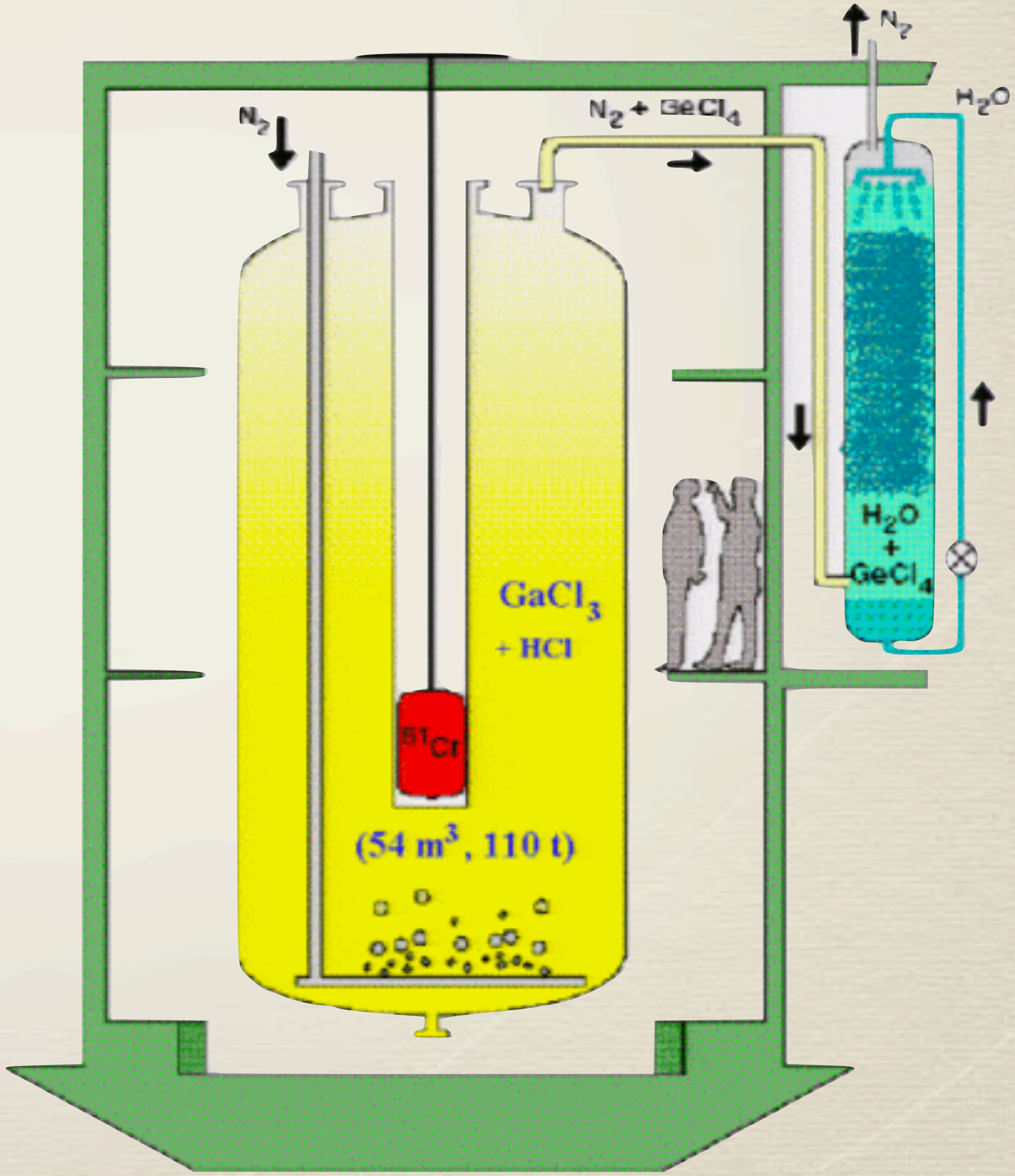


1 SNU = 1 interaction/s in target with 10^36 atoms of ν absorbing isotope

A New Target: Ga

$$^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^{-} (Q = 233 \text{ keV})$$





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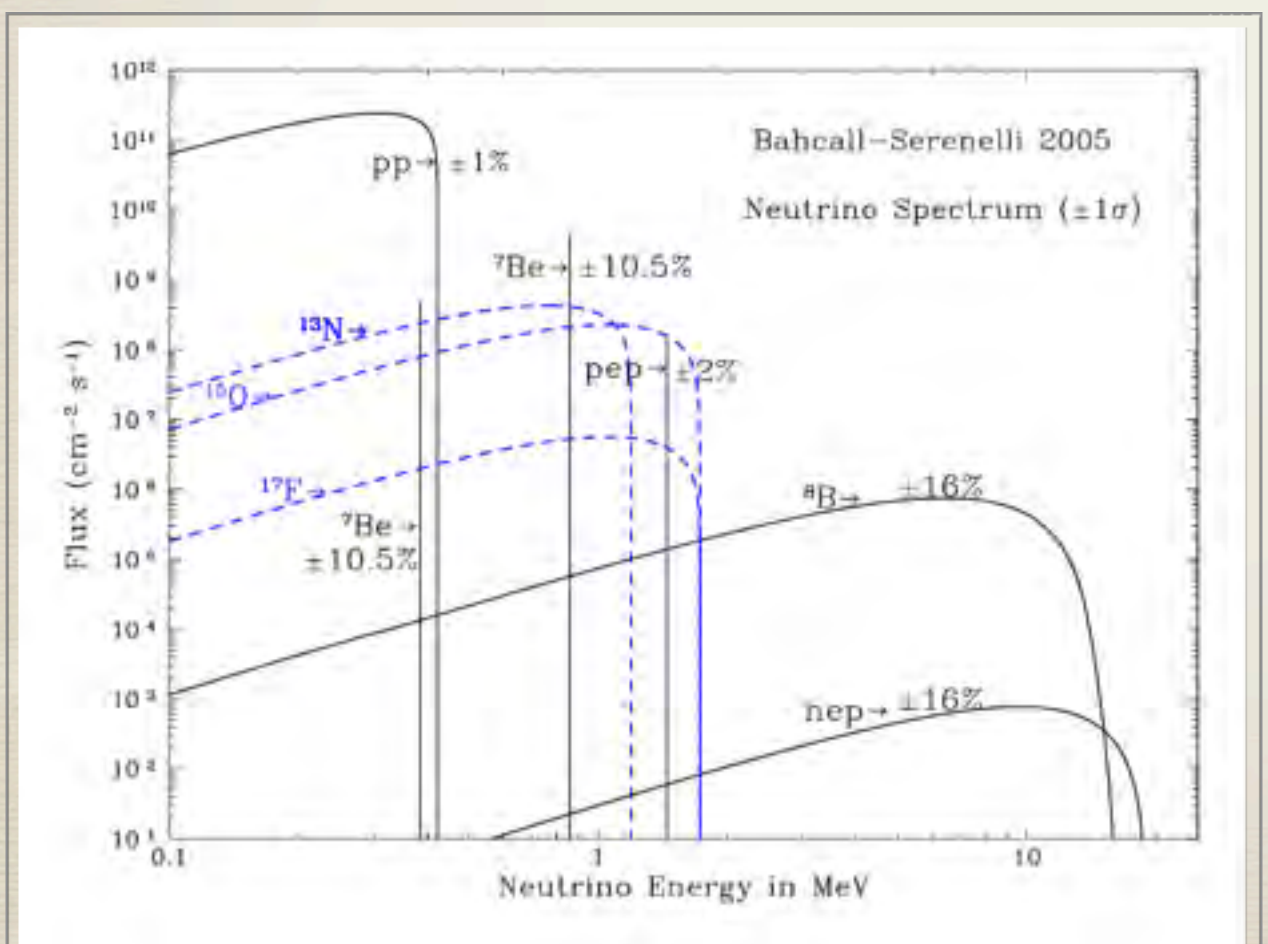

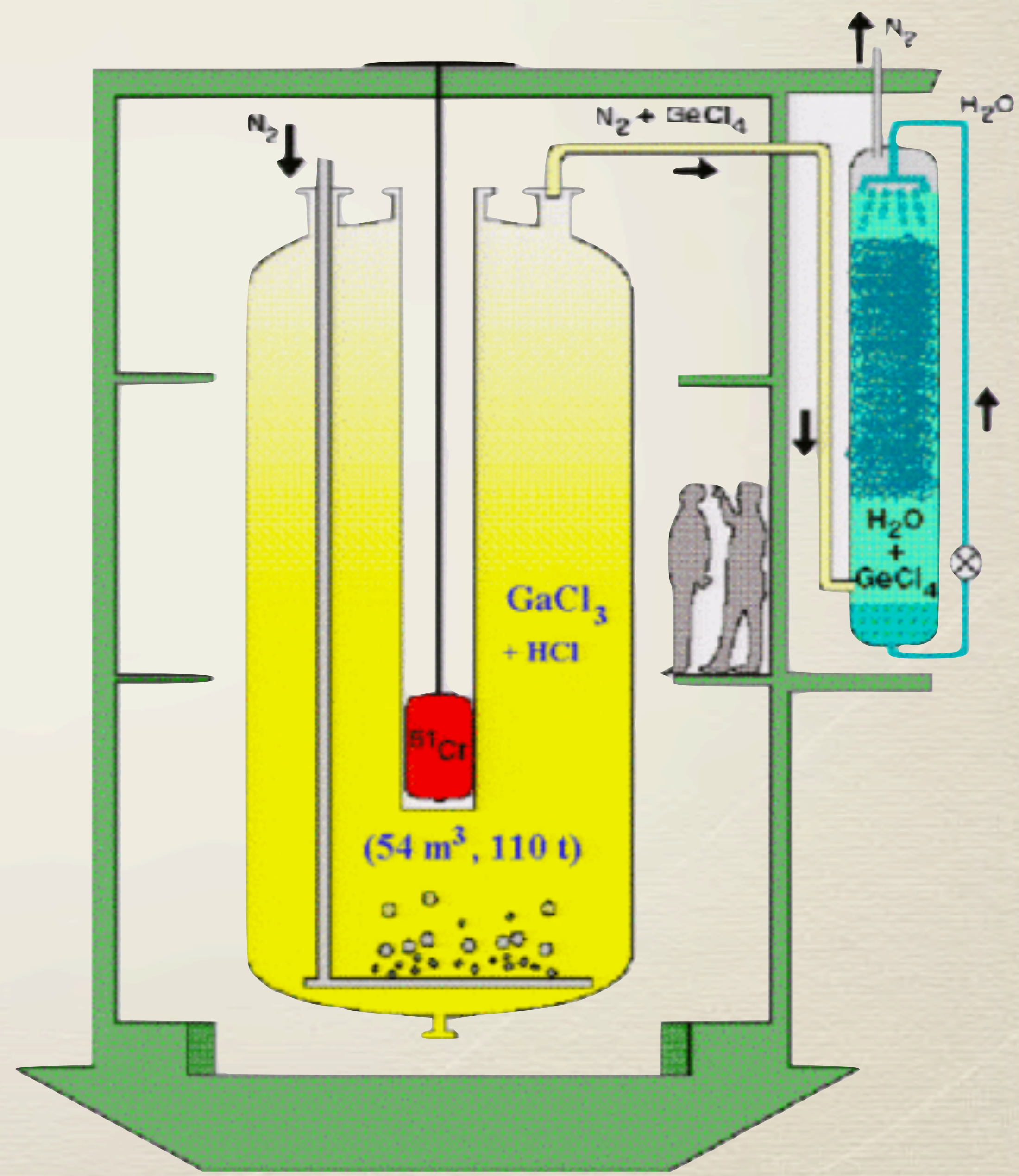

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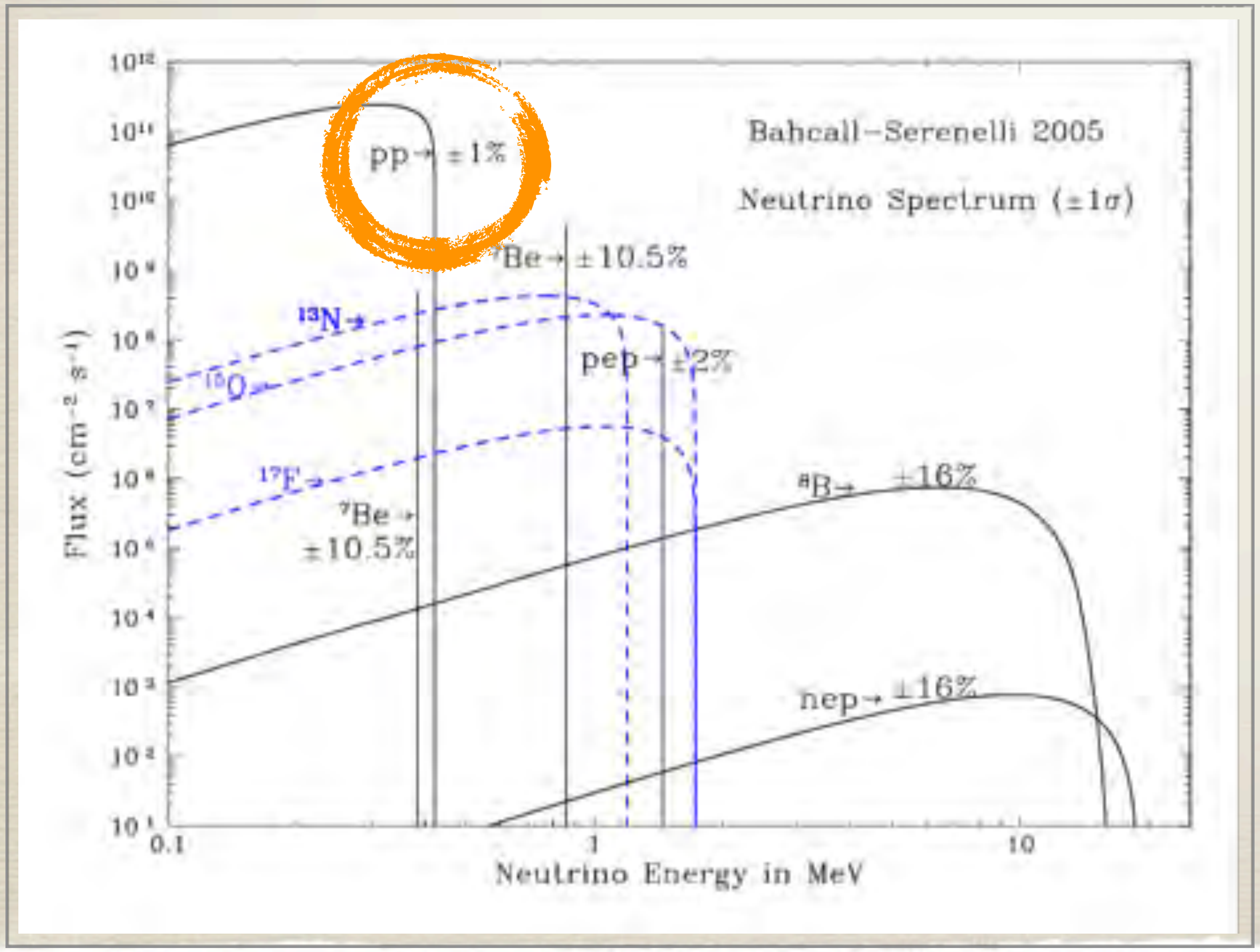

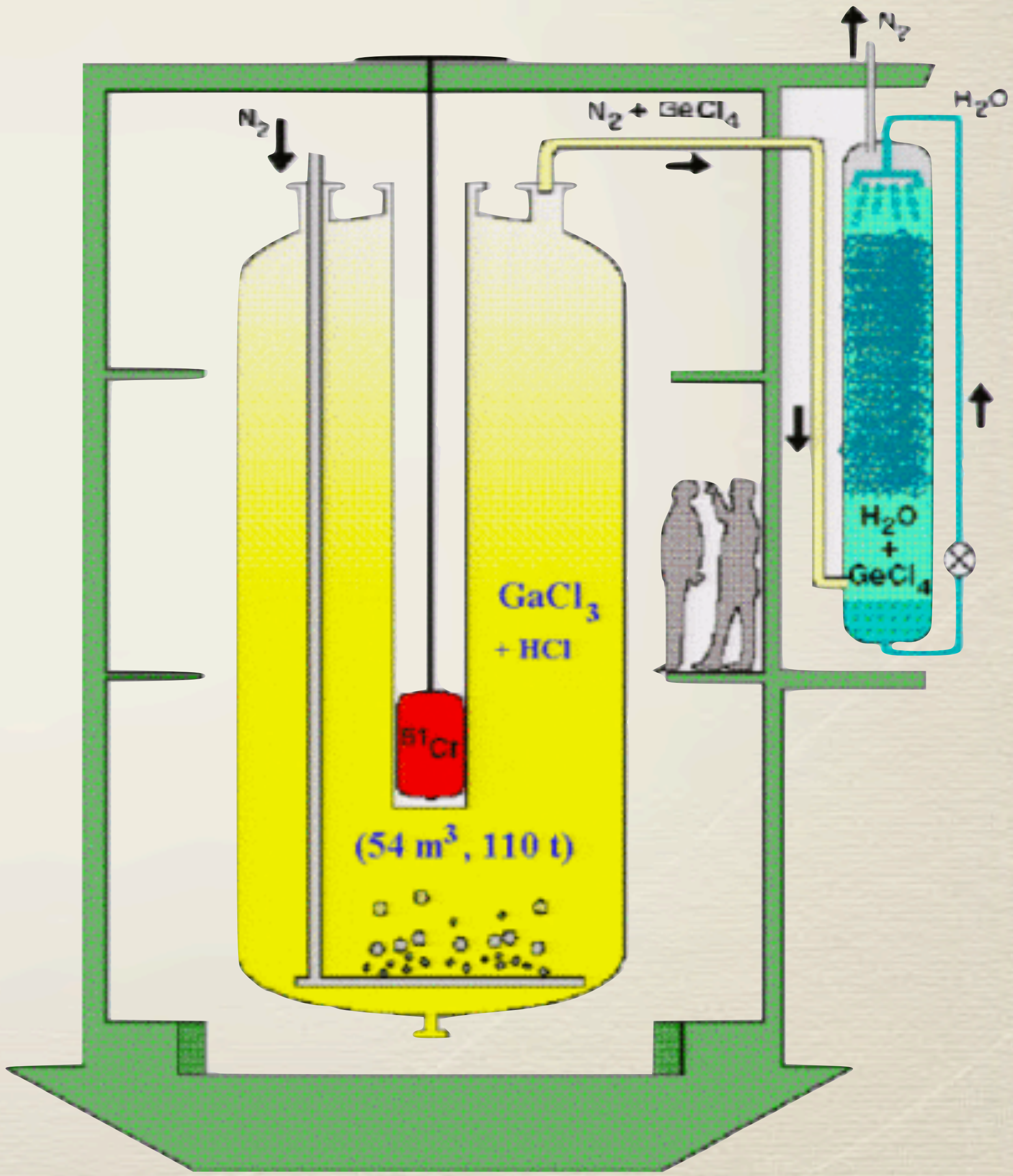

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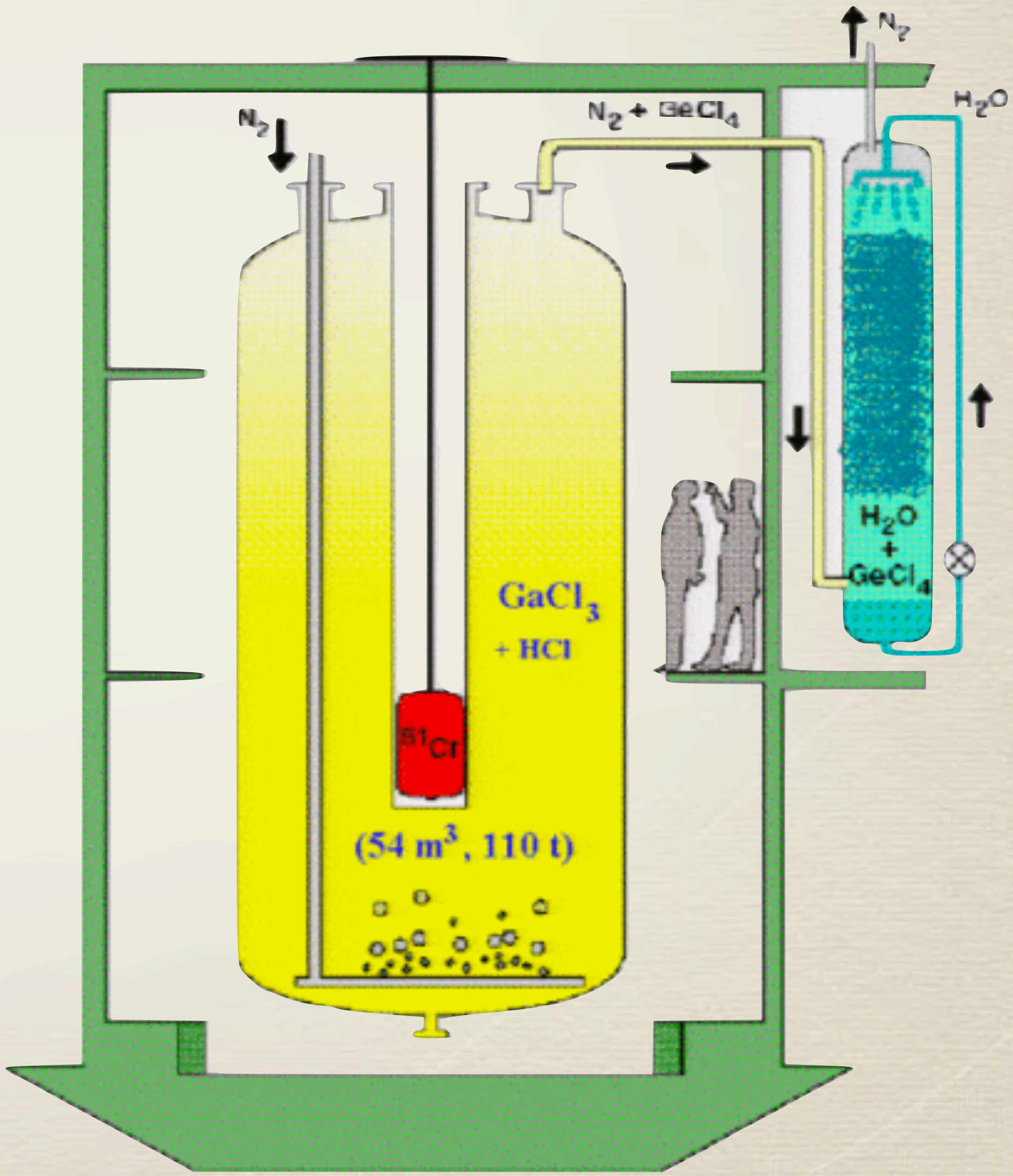

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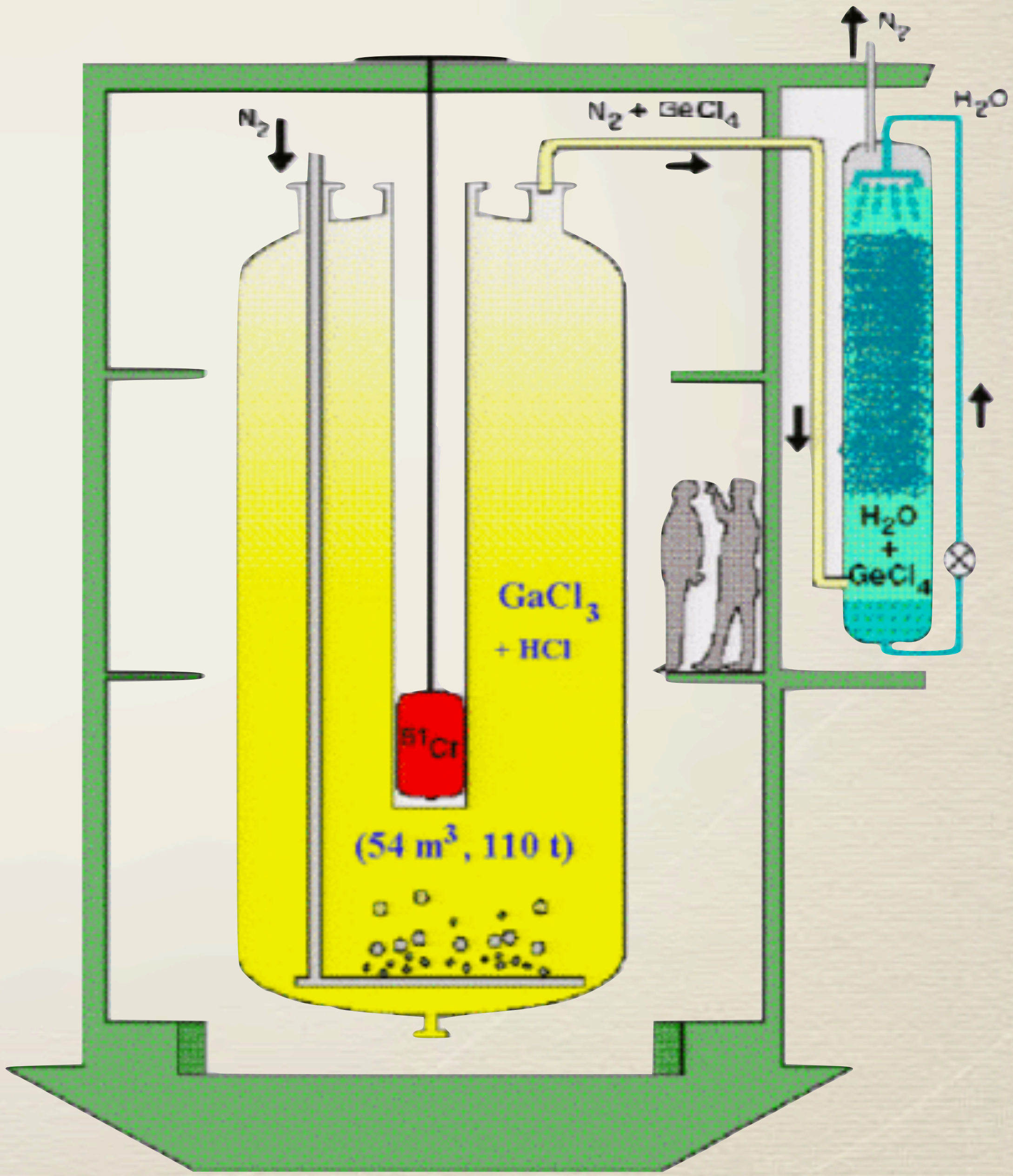
~70 SNU vs 130 SNU SSM prediction



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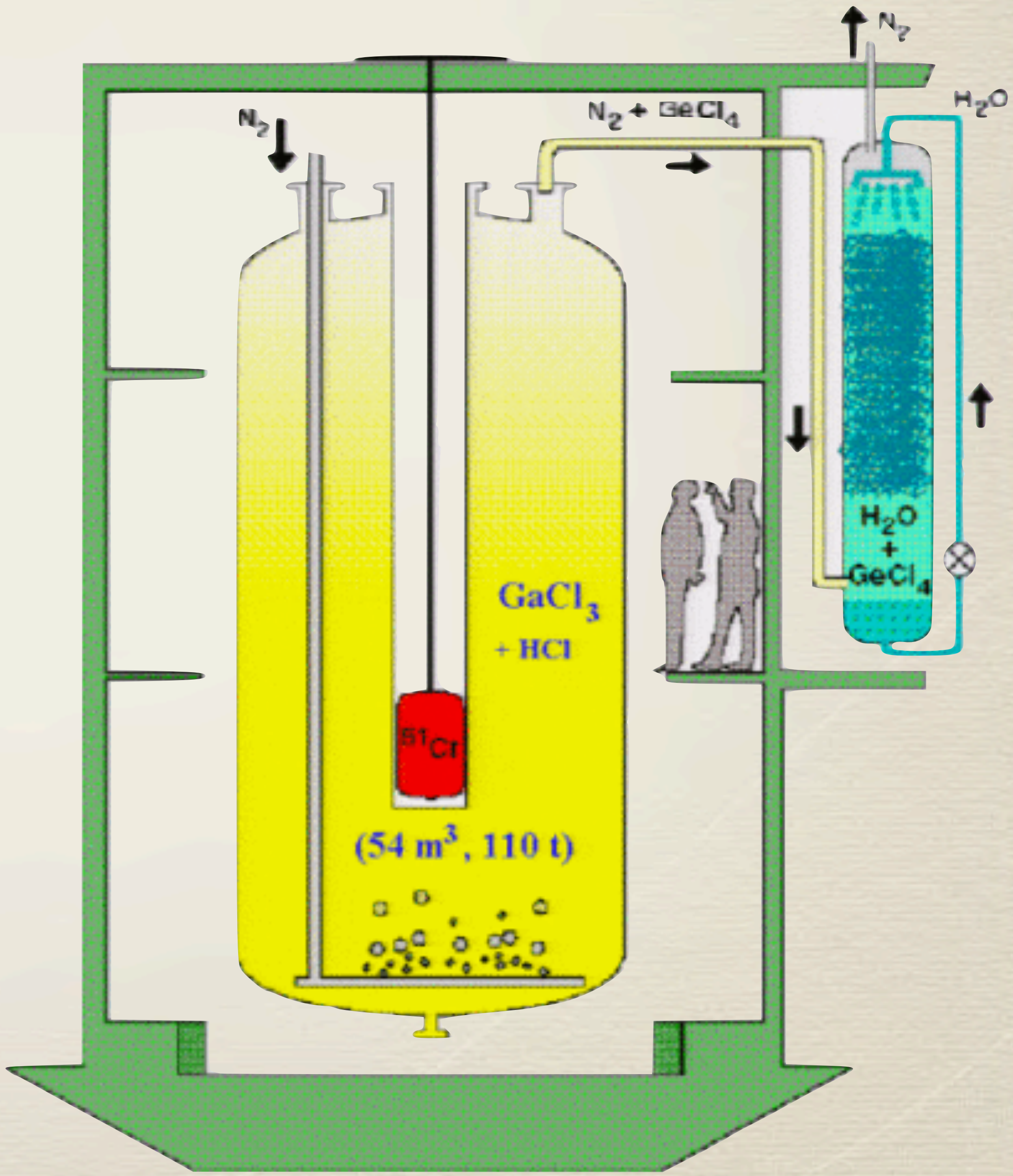

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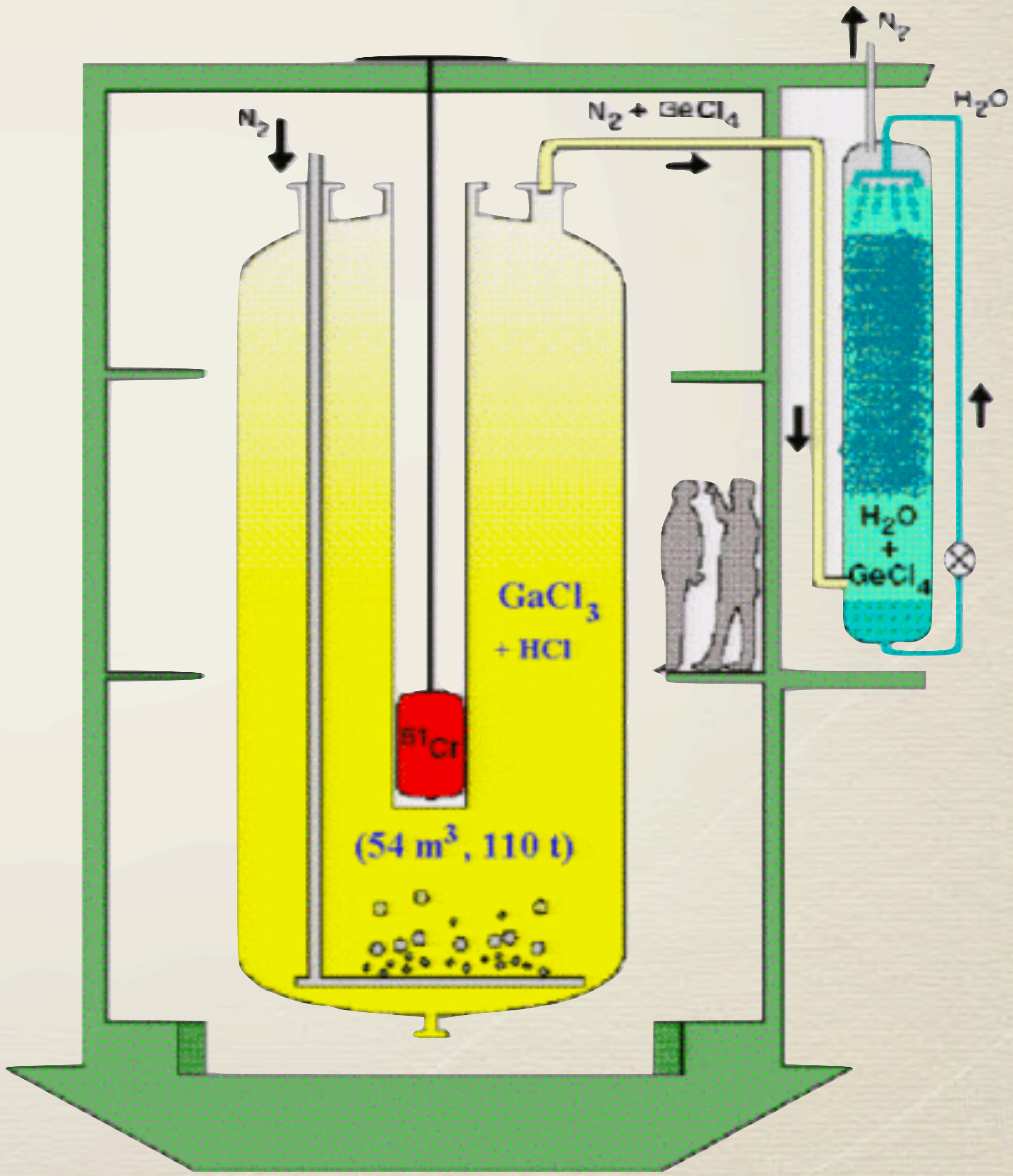
(A) Suppressed rate like Cl (40-60 SNU)
⇒ non-astrophysical solution

(B) Predicted rate ⇒ other expts wrong



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1991-2003

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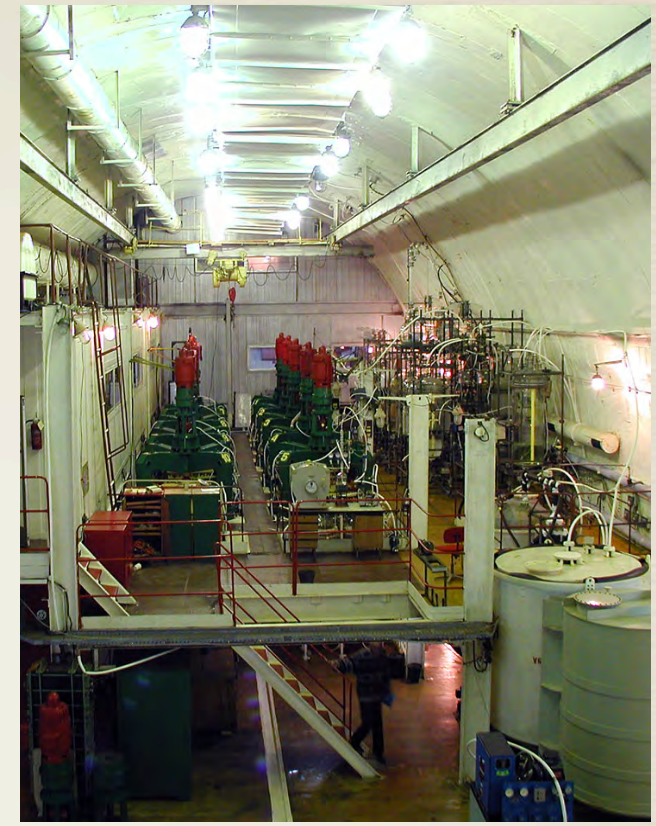

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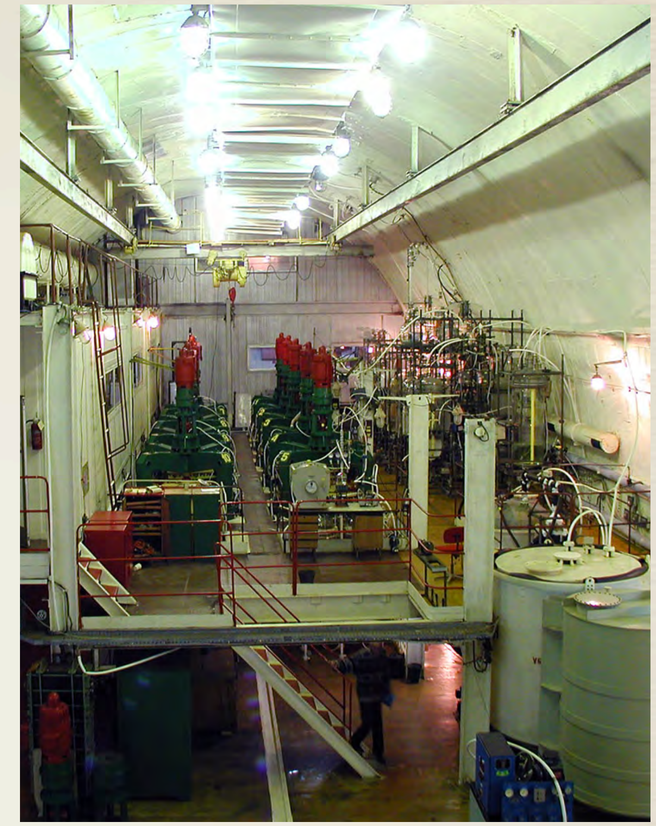

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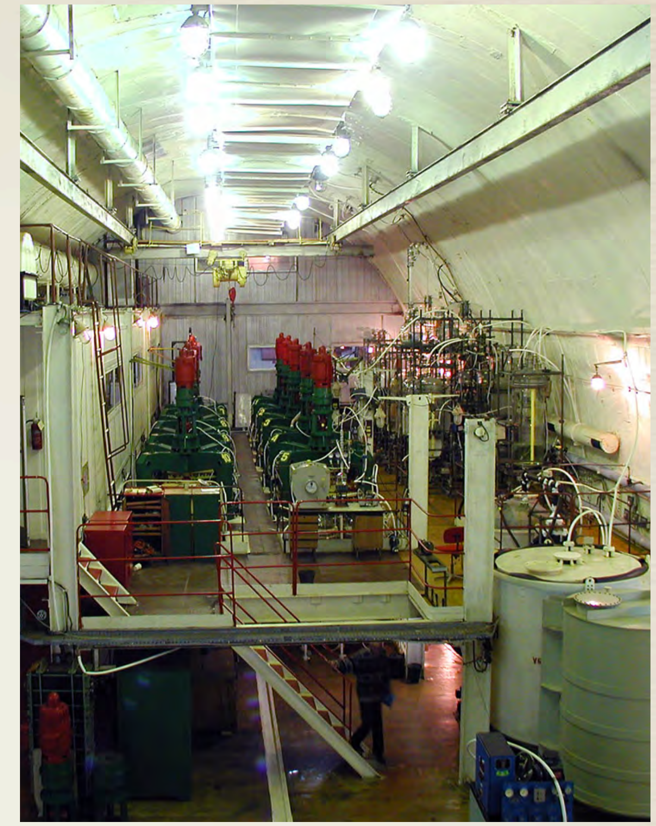

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'99

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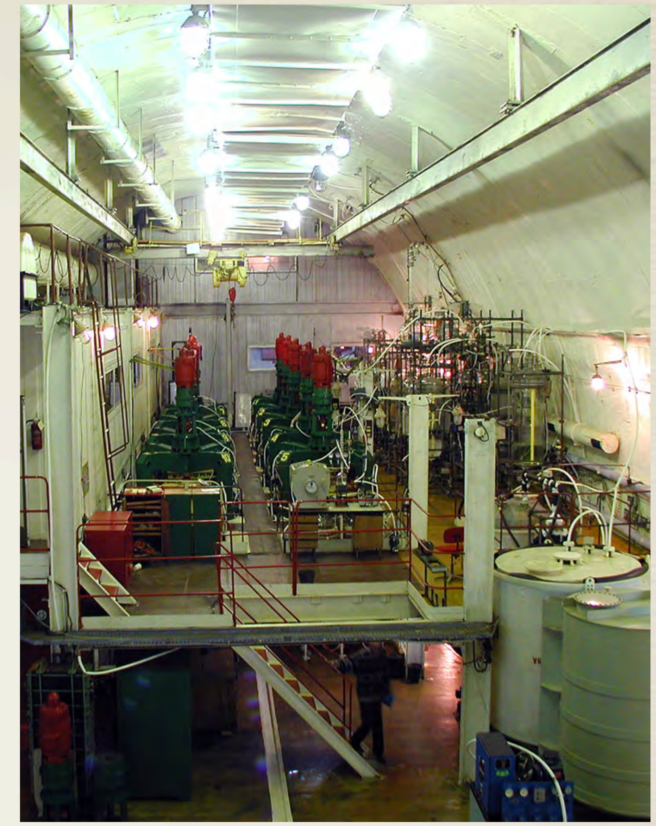

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^{51}Cr Calibration '99

GALLEX, GNO: $77.5 \pm 6.2\,(\text{stat})\,^{+4.3}_{-4.7}\,(\text{syst})$

SAGE: $67.2\,^{+7.2}_{-7.0}\,(\text{stat})\,^{+3.5}_{-3.0}\,(\text{syst})$

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Combined results to-date: 66.1 ± 3.1

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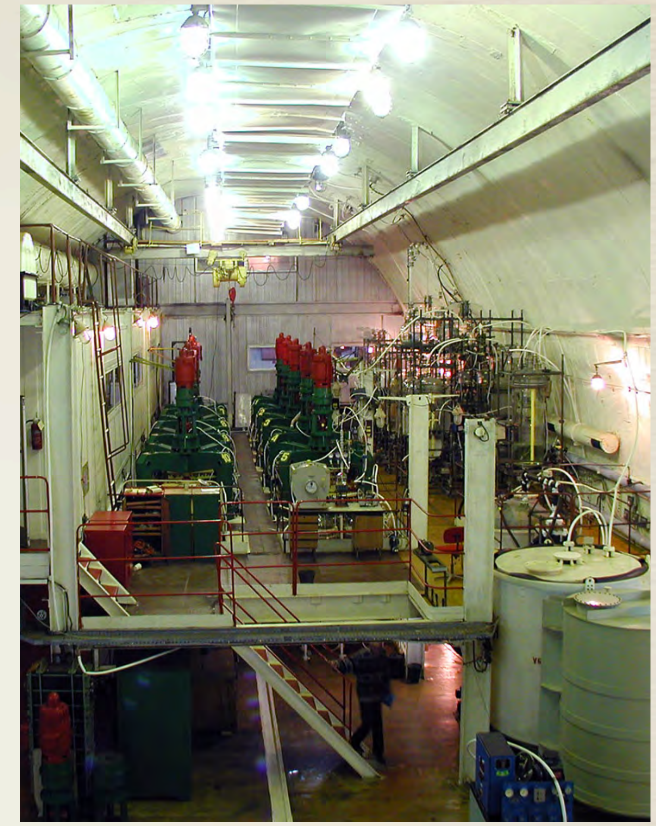


GALLEX, GN

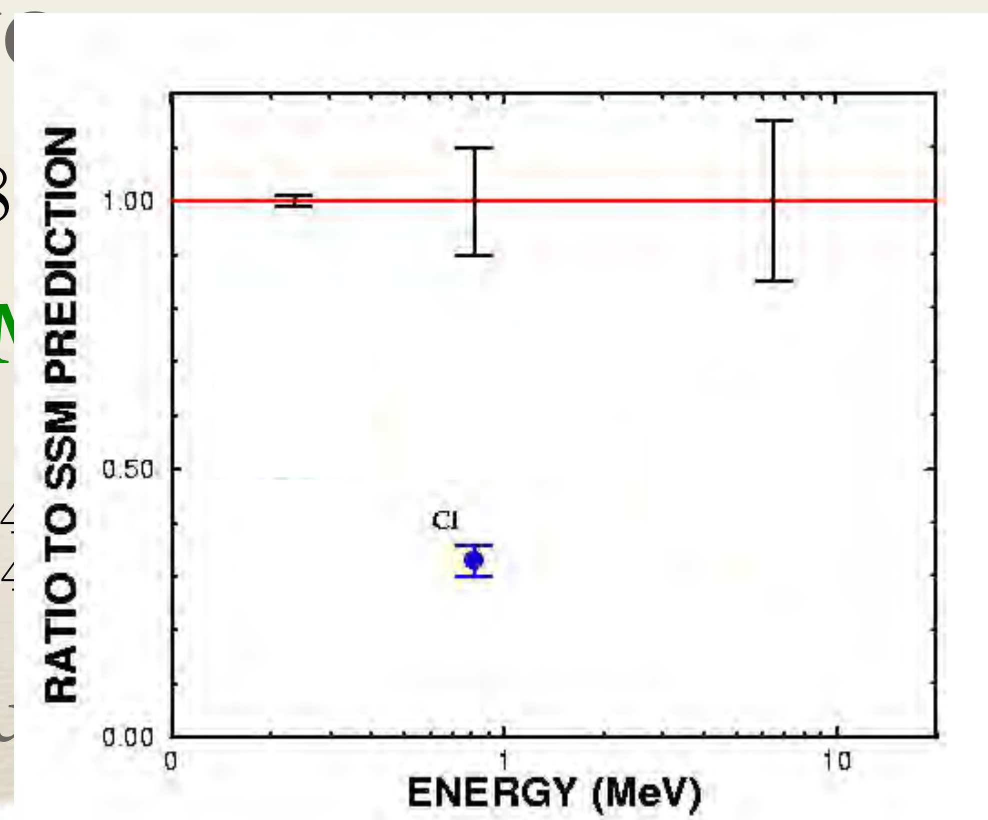
SAGE

83 ± 19 (stat) $\pm$ 8

Consistent with SS

77.5 ± 6.2 (stat)

Combined resu



20^{+15}_{-20} (stat) ± 32 (syst)

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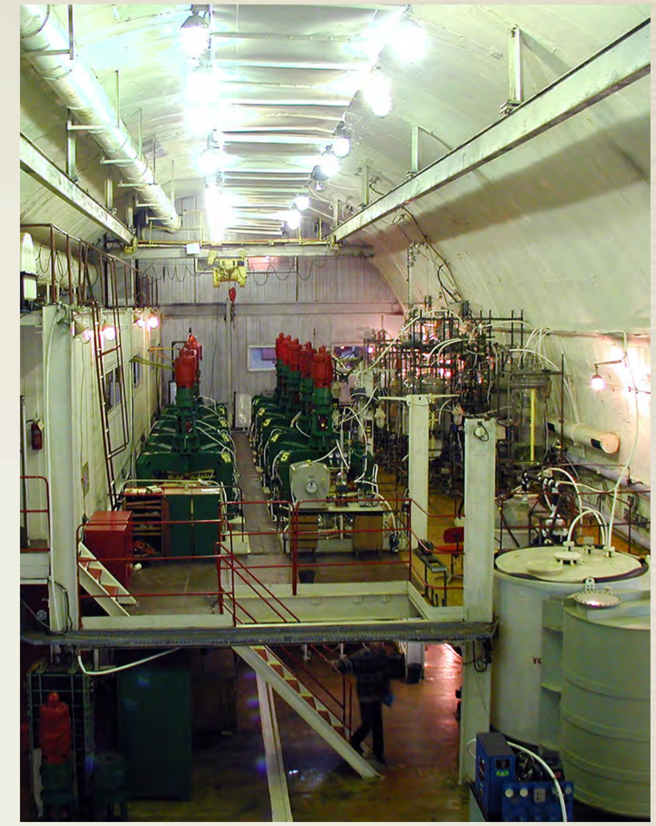

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77.5 ± 6.2 (stat) $^{+4}_{-4}$

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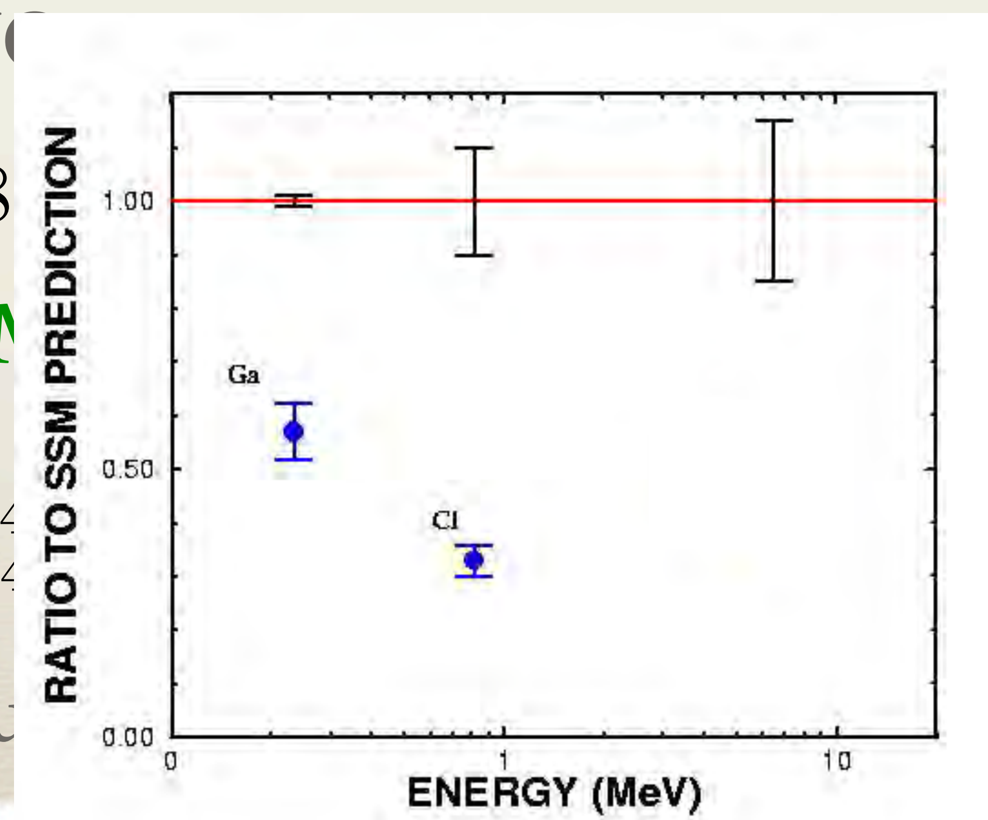

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Approx 0.5 * prediction:
Inconsistent with both Davis & SSM

GALL

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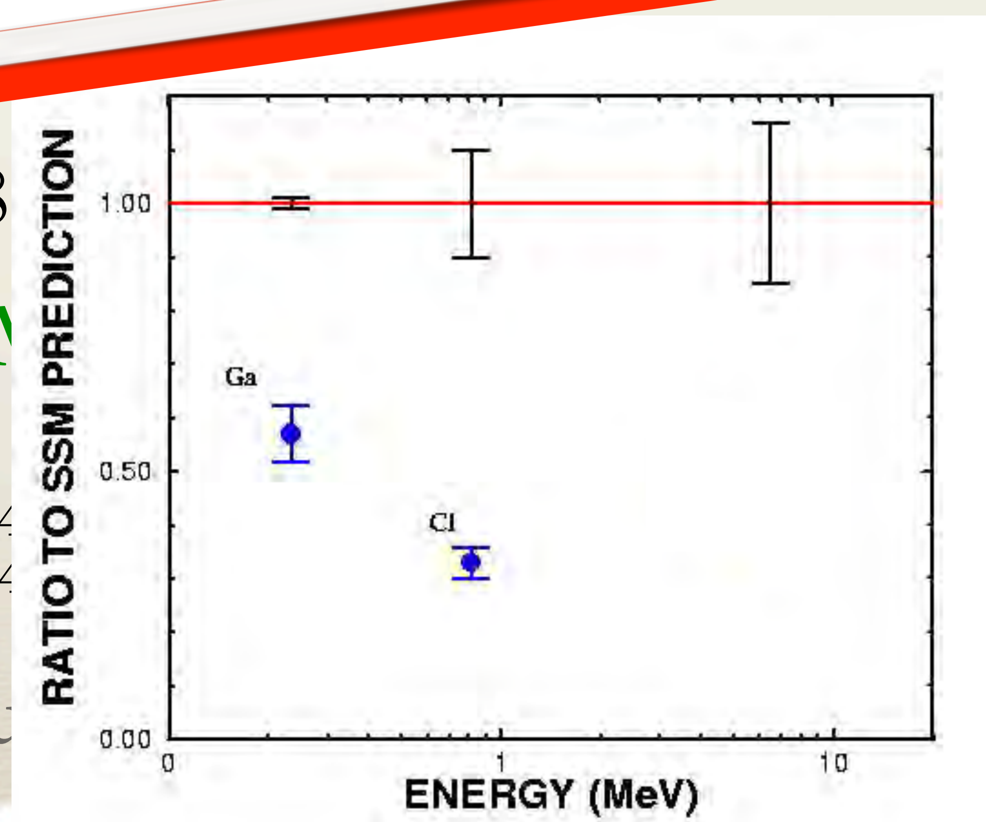

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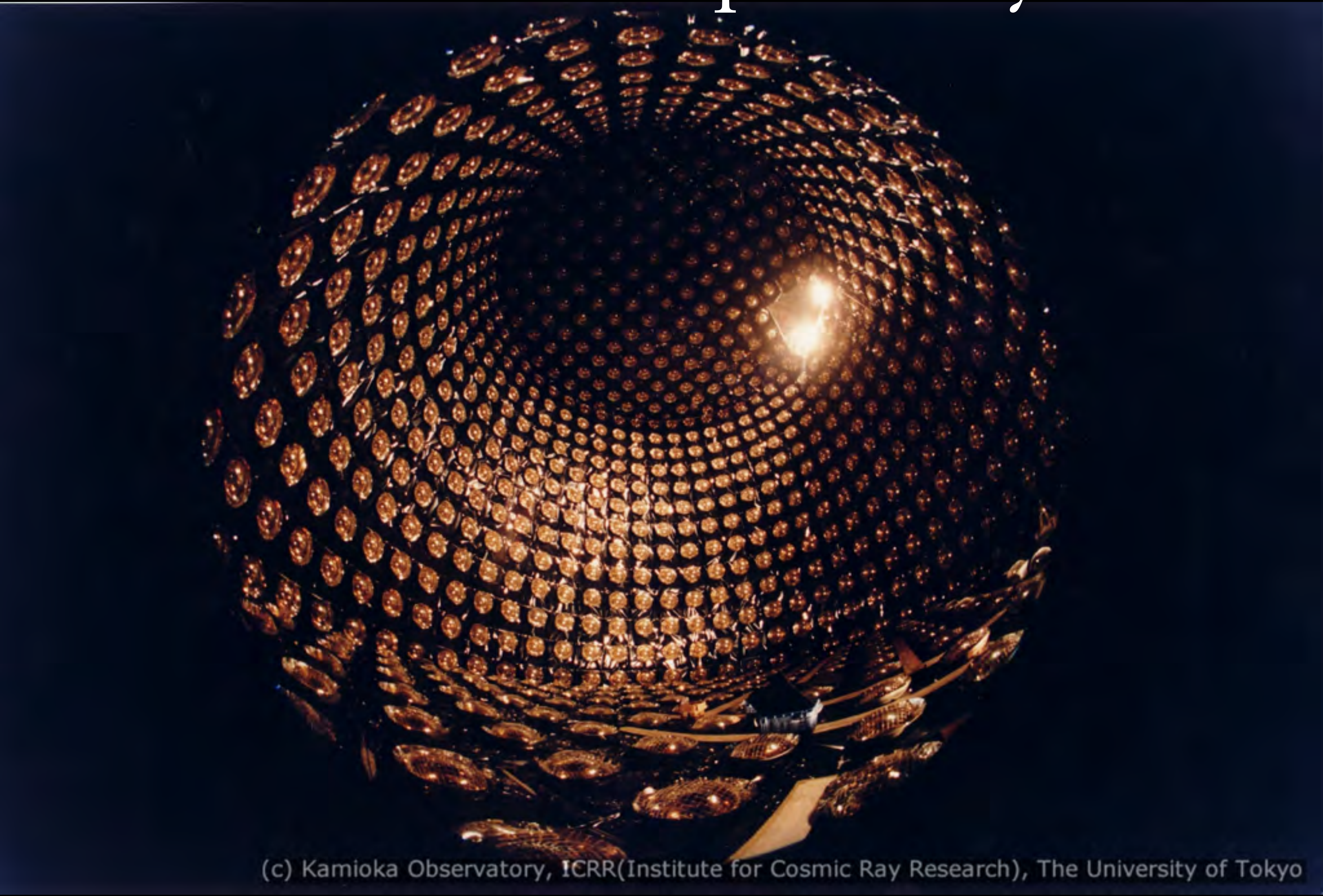
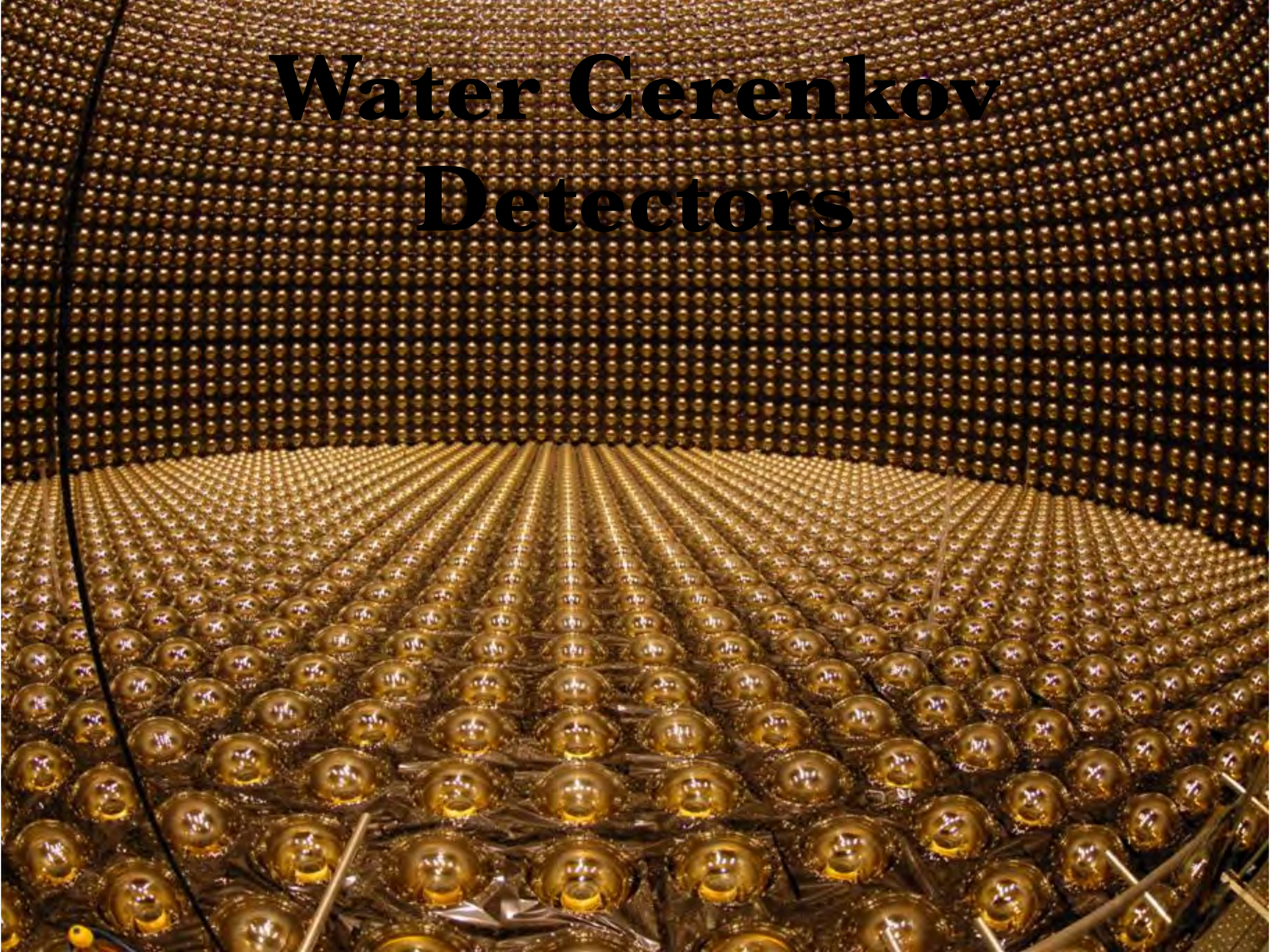
Combined resu

Search for p Decay



Water Cerenkov Detectors



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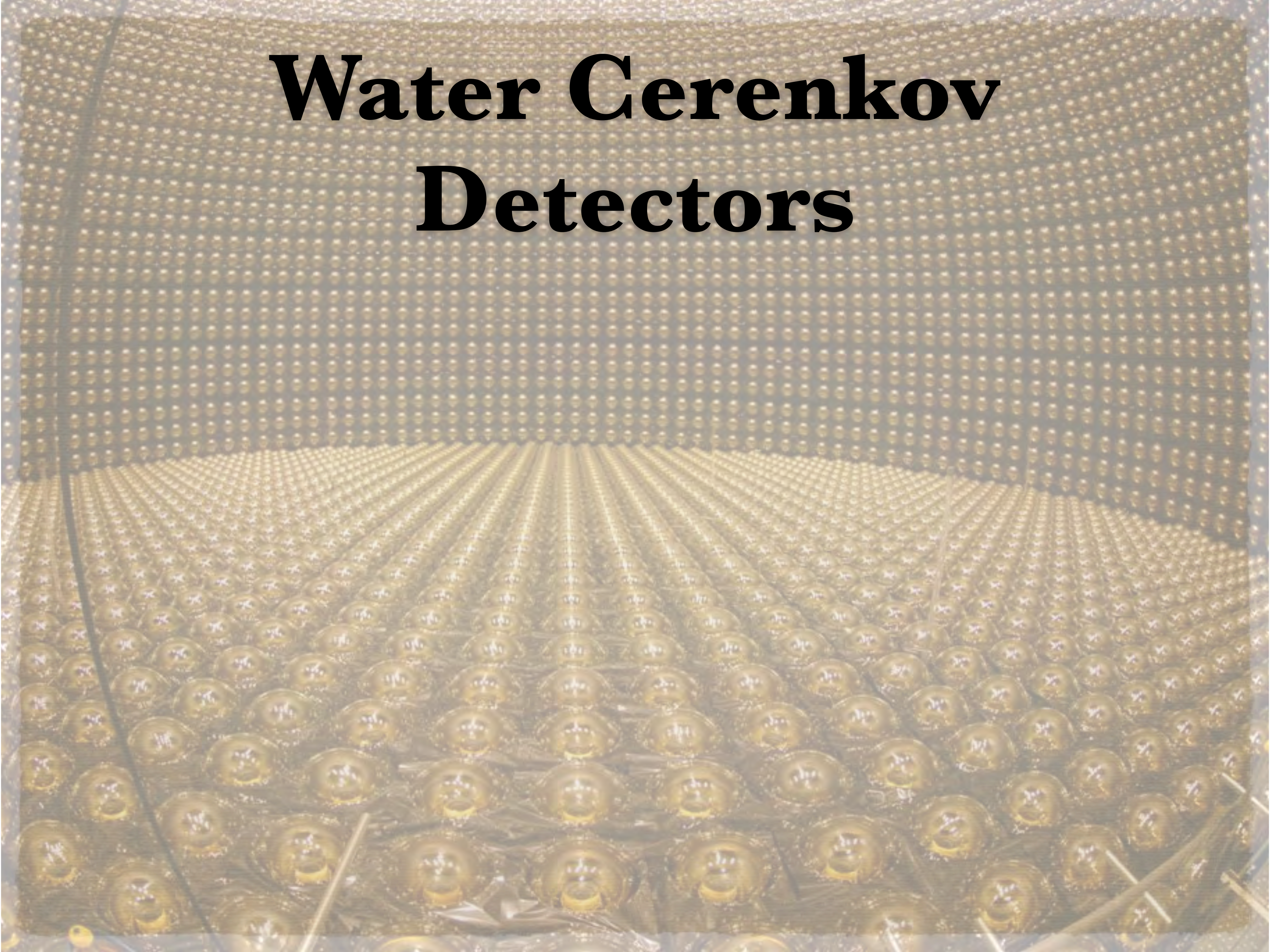

Water Cerenkov Detectors

✴ **Large volume** - - - - - - - - - - ➔ *1000s events/yr (10s/yr for r/c)*

Water Cerenkov Detectors

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- **Real-time detection** - - - - → *Directional information* *Spectral information*

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- **Cerenkov ring** → *Background discrimination*

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- Independent verification - - → *Target, detector, location*

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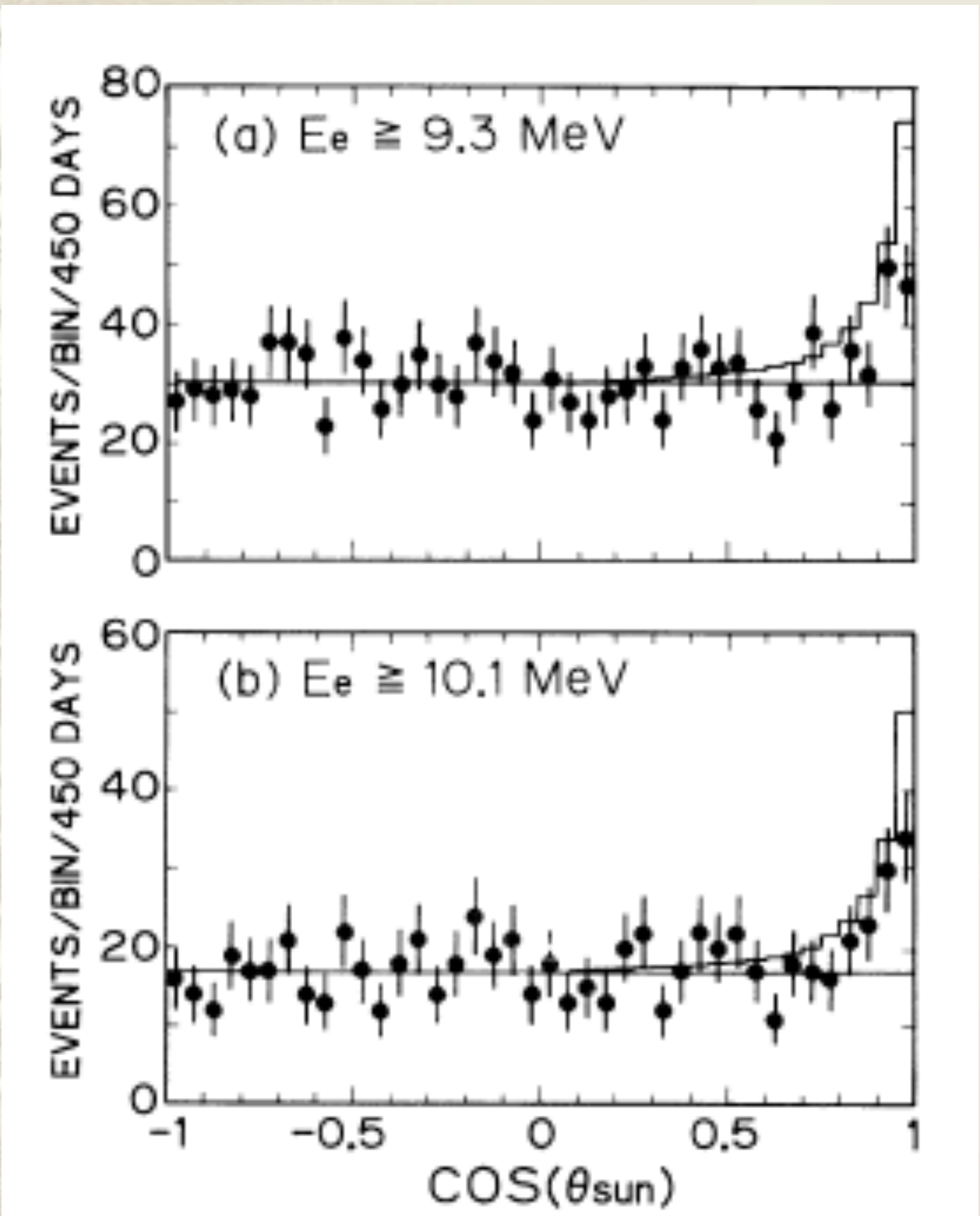
- ✳ **Independent verification** - - → *Target, detector, location*
- ✳ **Cerenkov threshold 0.768MeV** - - - - - - - → *^{8}B & hep νs*

Kamiokande-II: Results



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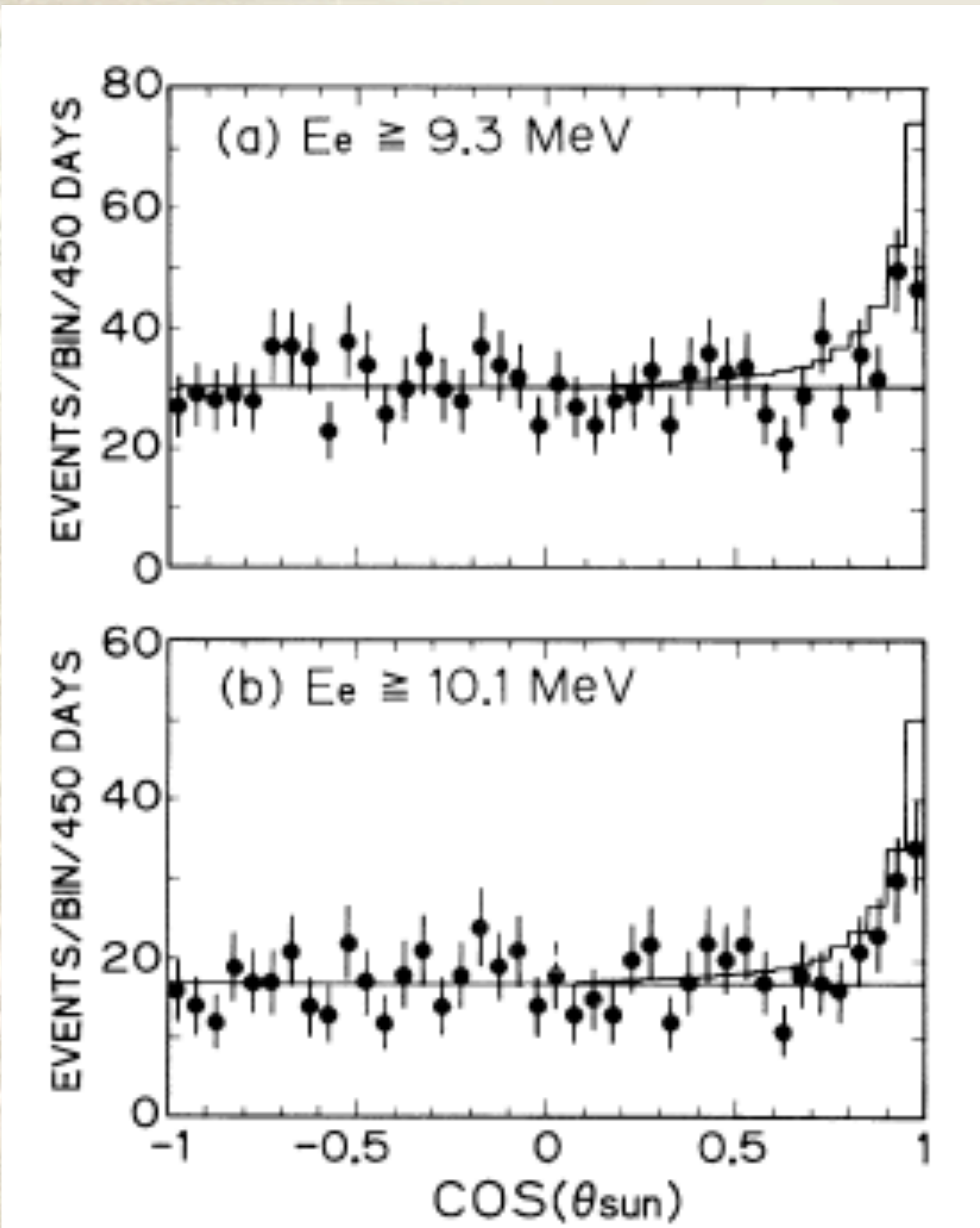

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- Clear enhancement in number of events pointing from the Sun
- First direct demonstration that νs are coming from the Sun

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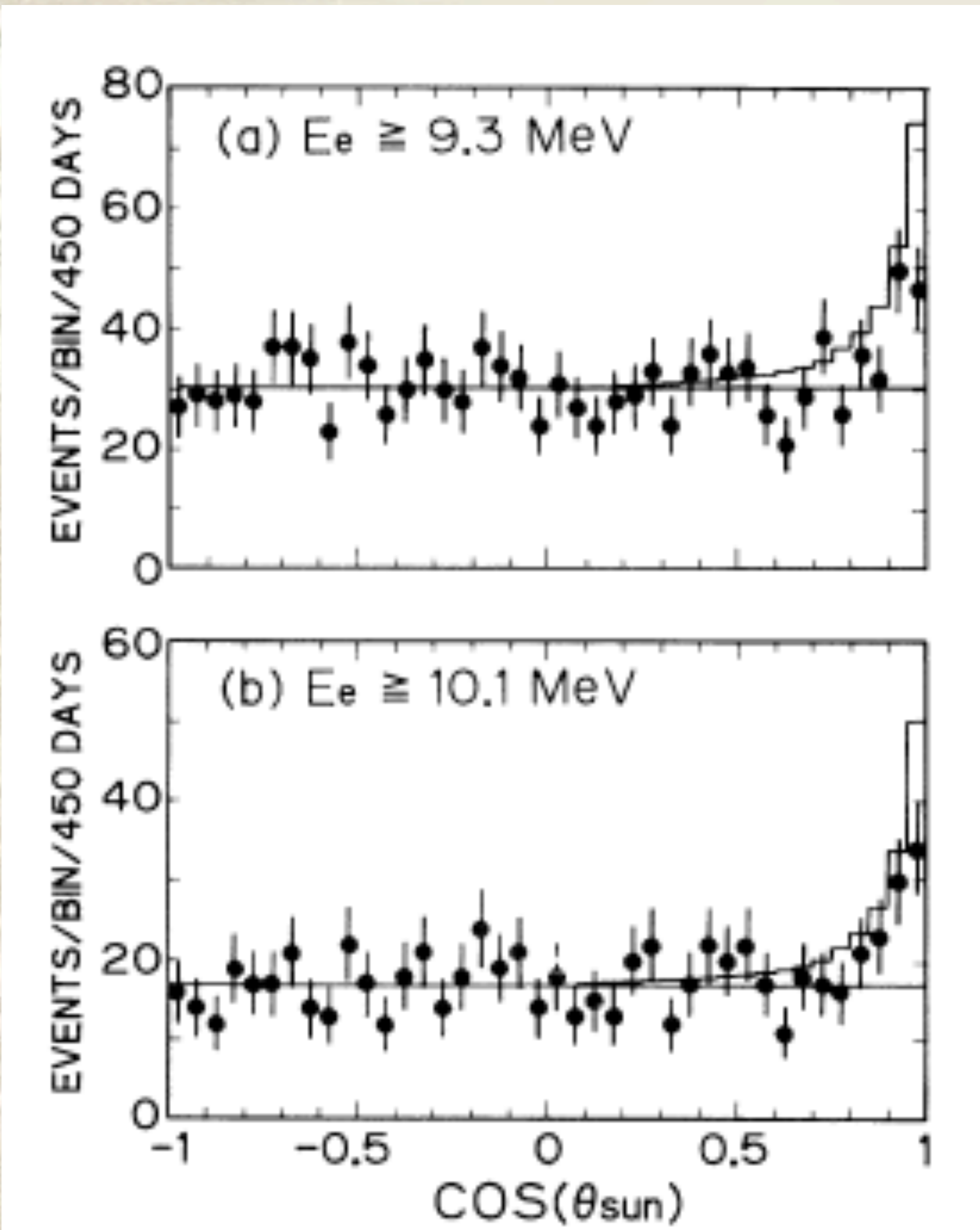

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- First direct demonstration that νs are coming from the Sun

$$\frac{\text{Kam-II data}}{\text{SSM}} = 0.46 \pm 0.13(\text{stat.}) \pm 0.08(\text{syst.}) ,$$

- Tauntingly inconclusive....

SuperKamiokande

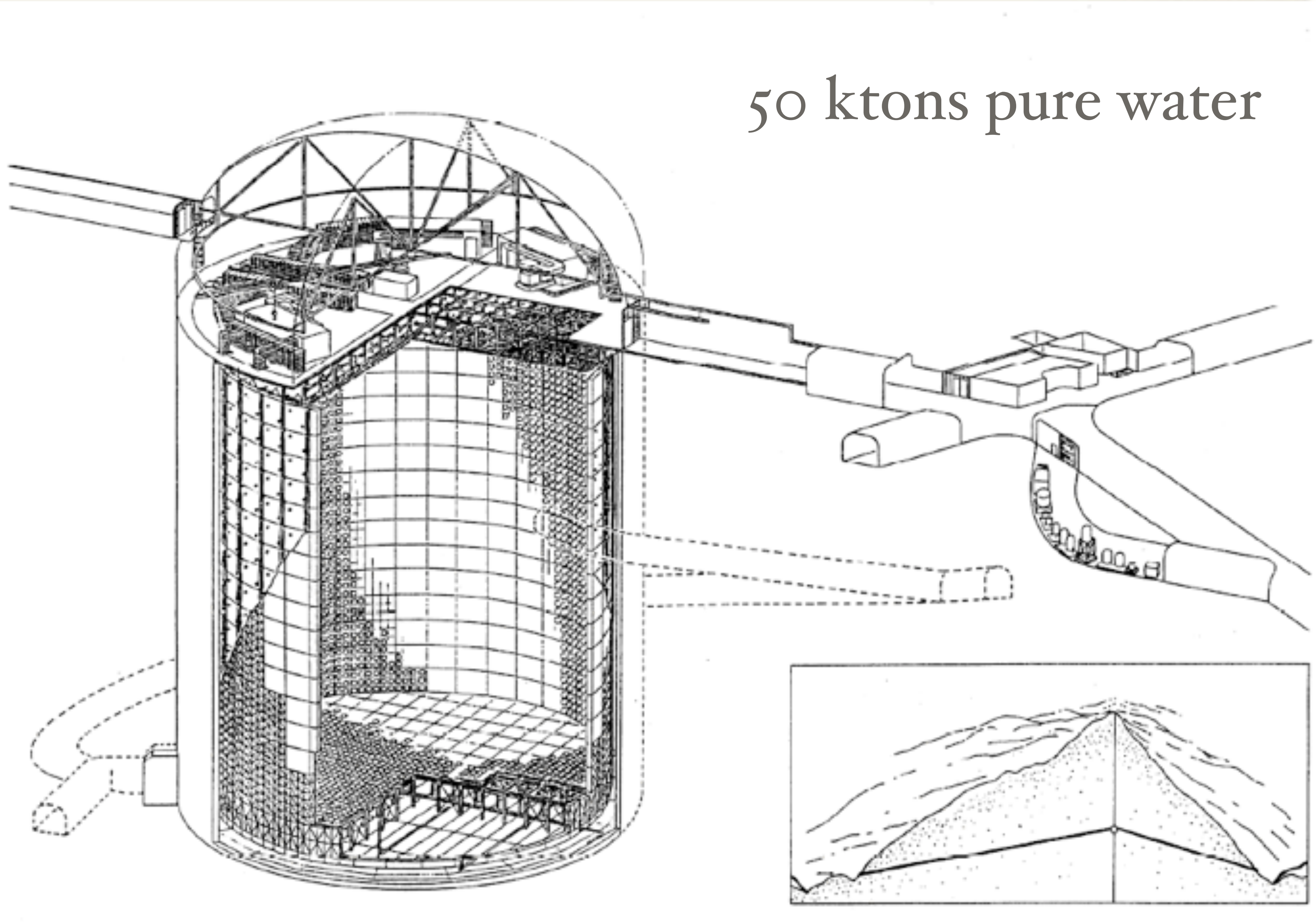
H_2O target for ES interactions:

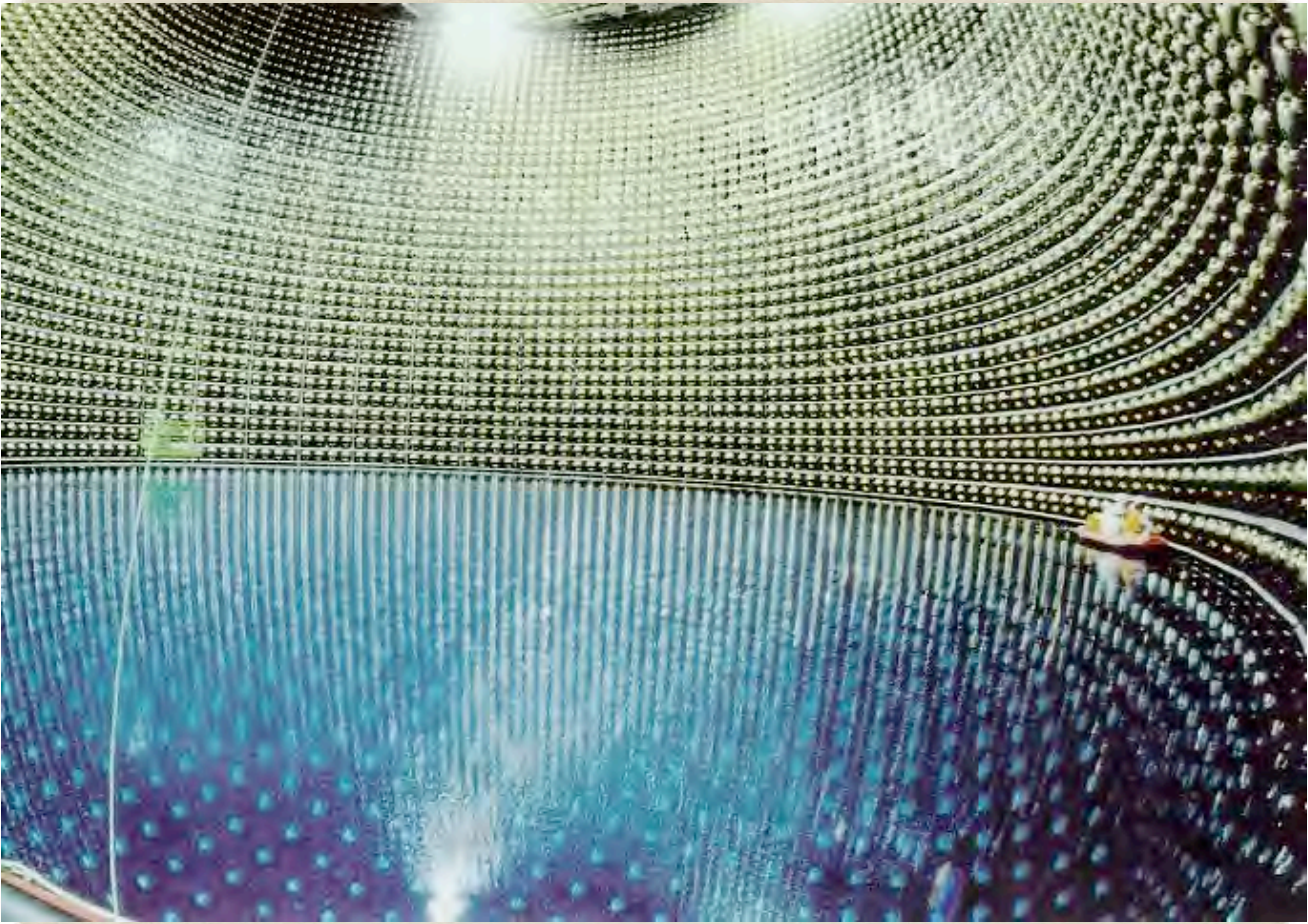
$$e^- + \nu_e \rightarrow e^- + \nu_e$$

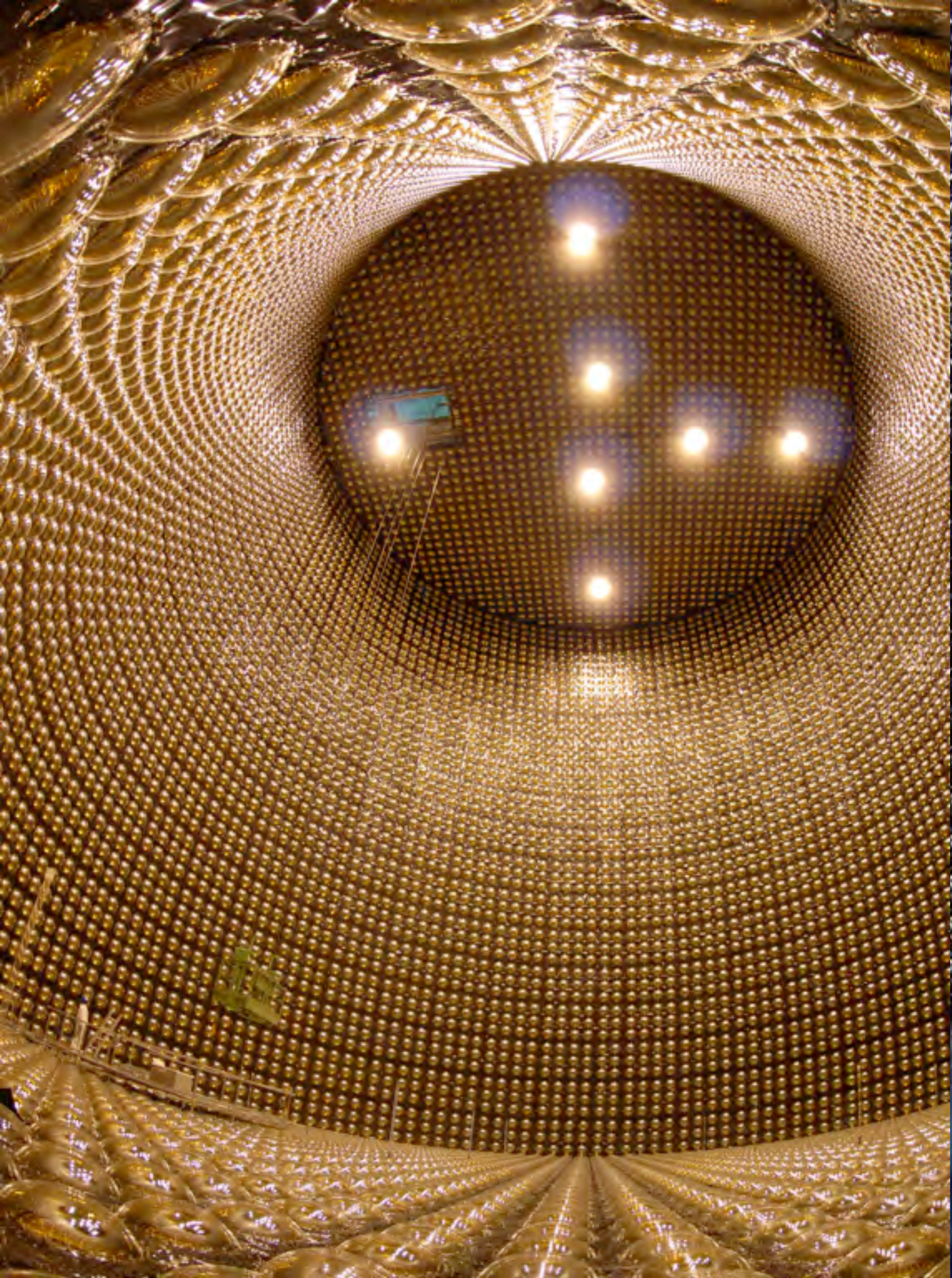
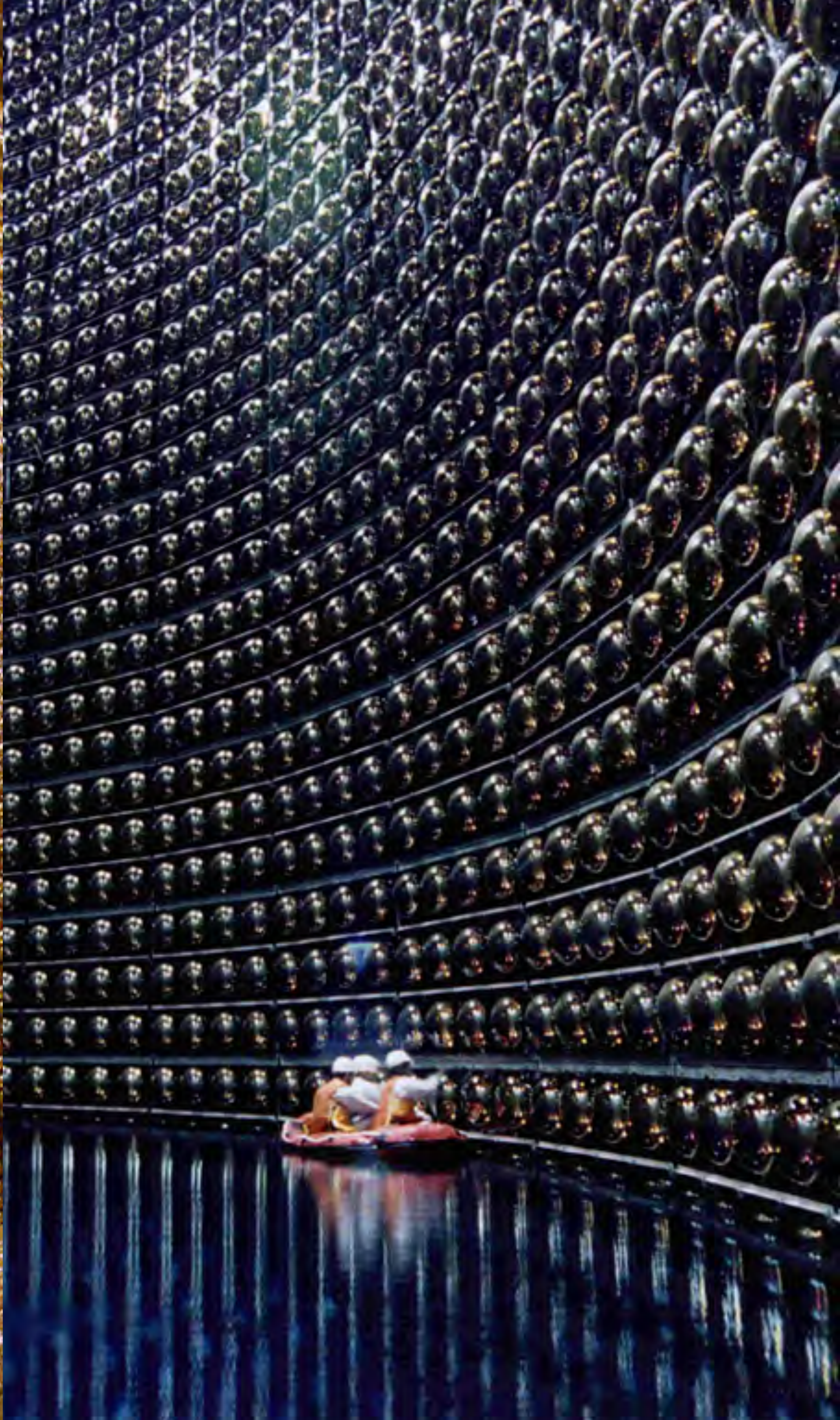
High statistics
~ 15 events / day

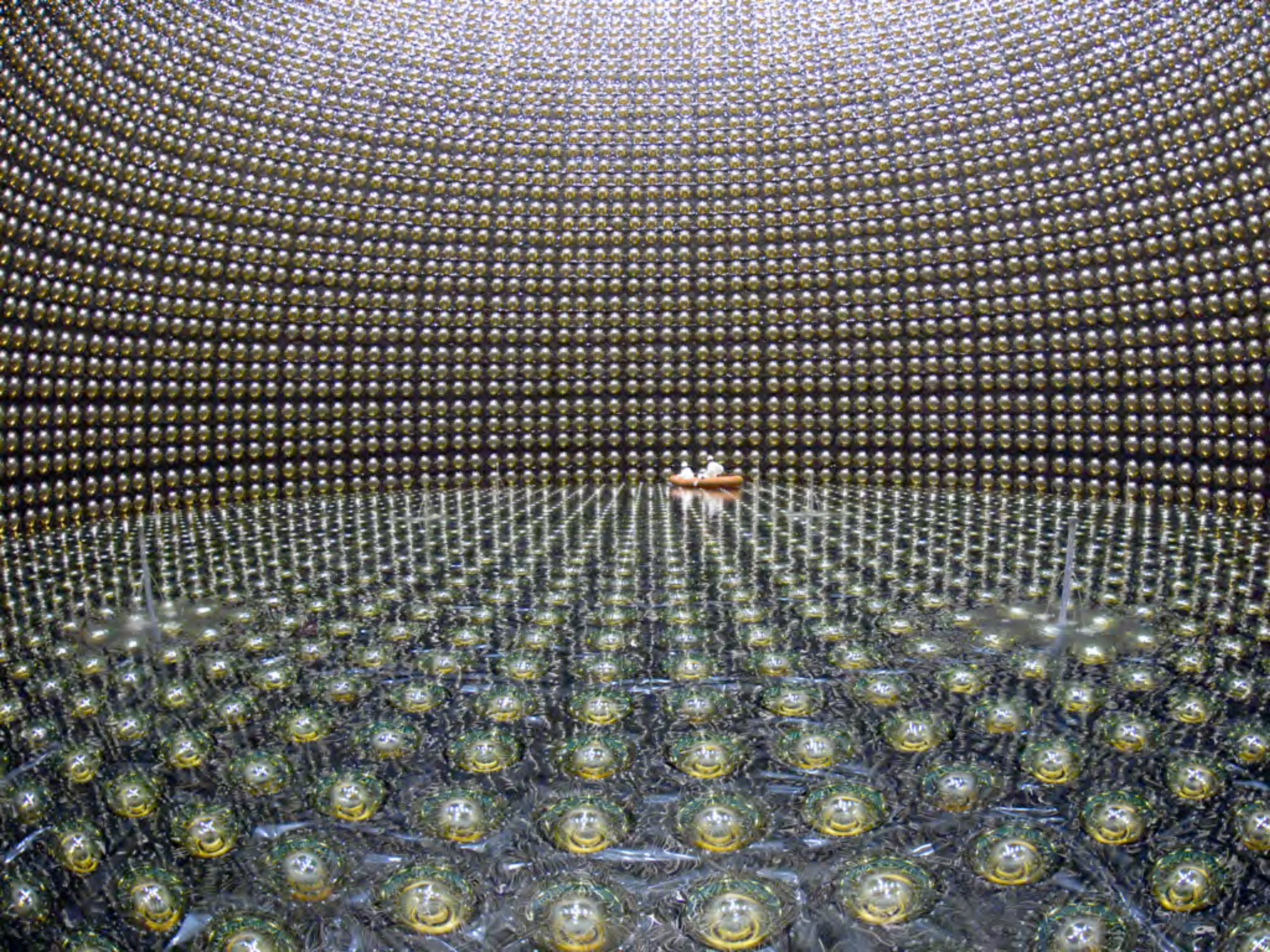
Real-time measure:
⇒ *study time variations*

Extract E spectrum

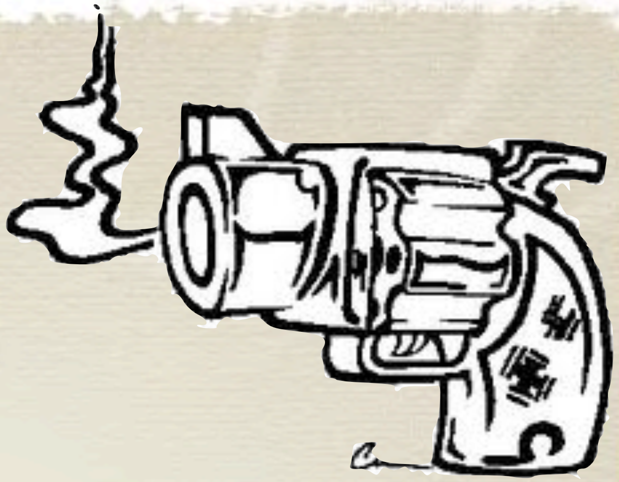


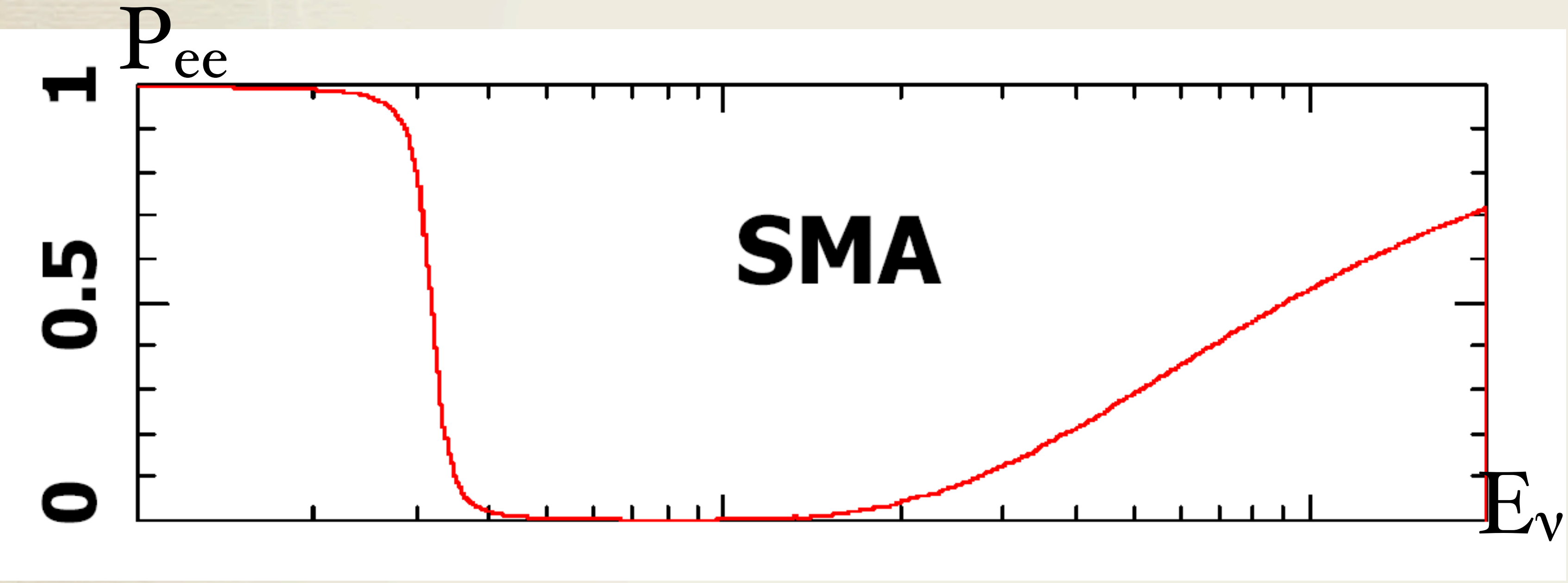




Smoking-Gun Potential





- Small mixing angle scenario predicts huge distortion in E spectrum

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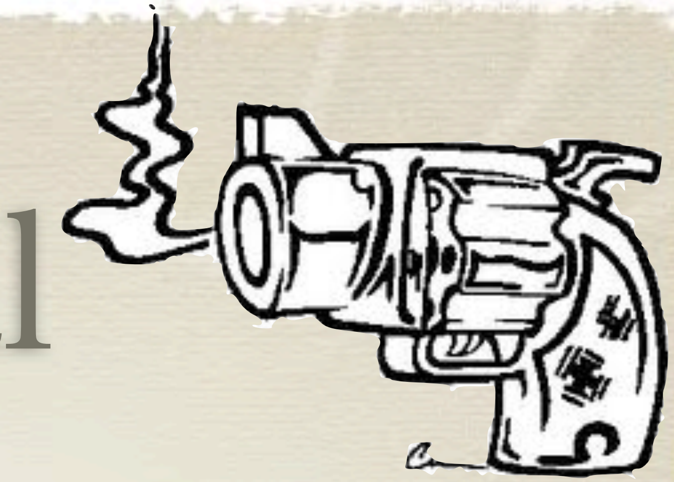
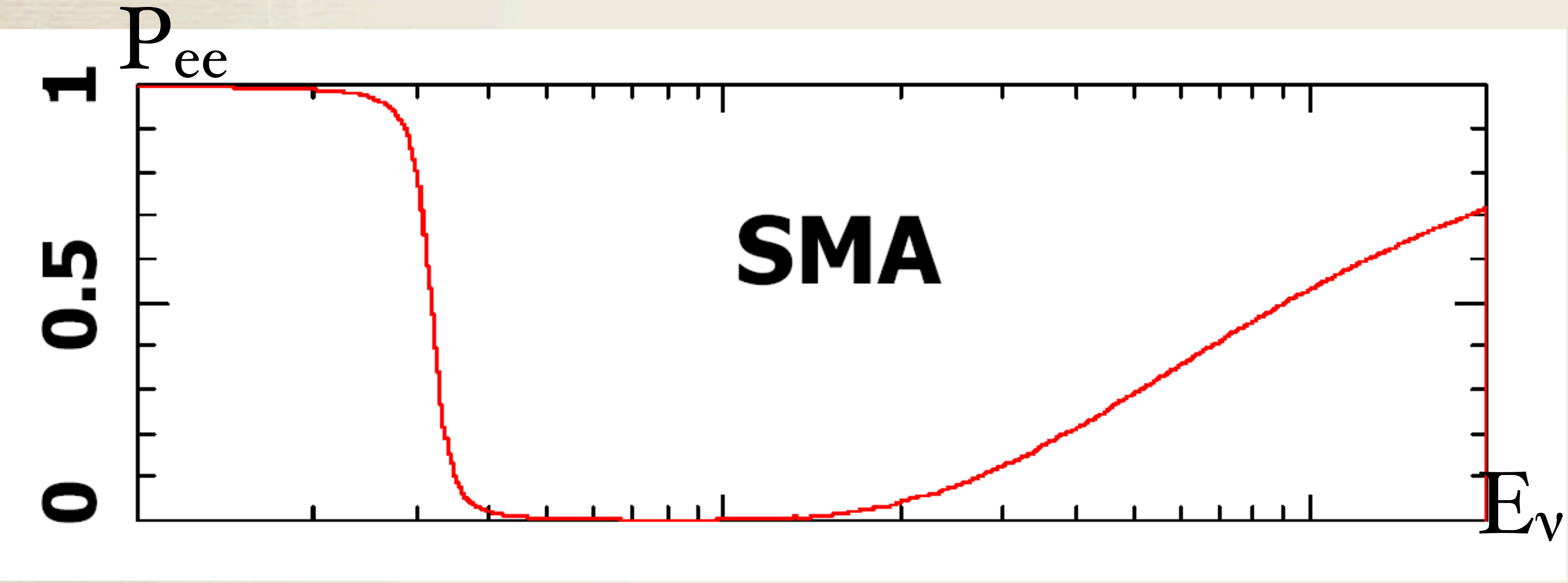
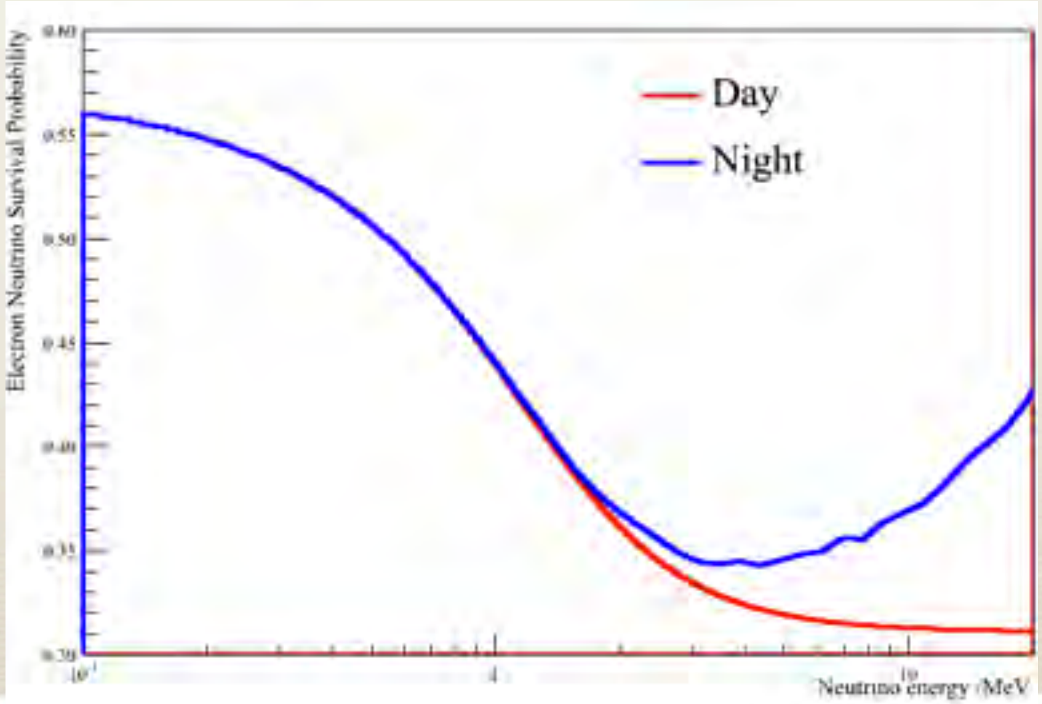


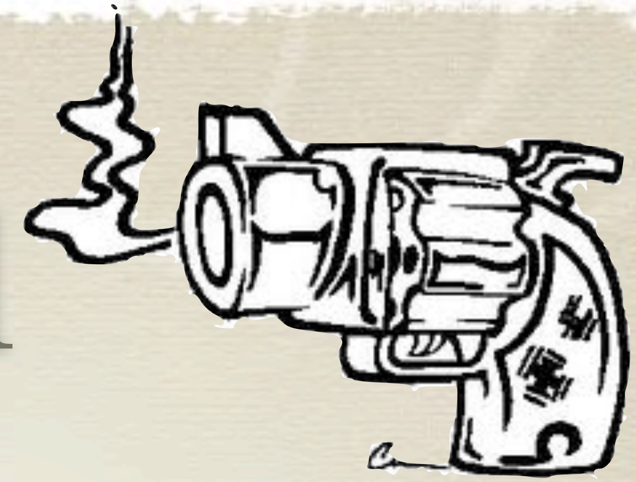


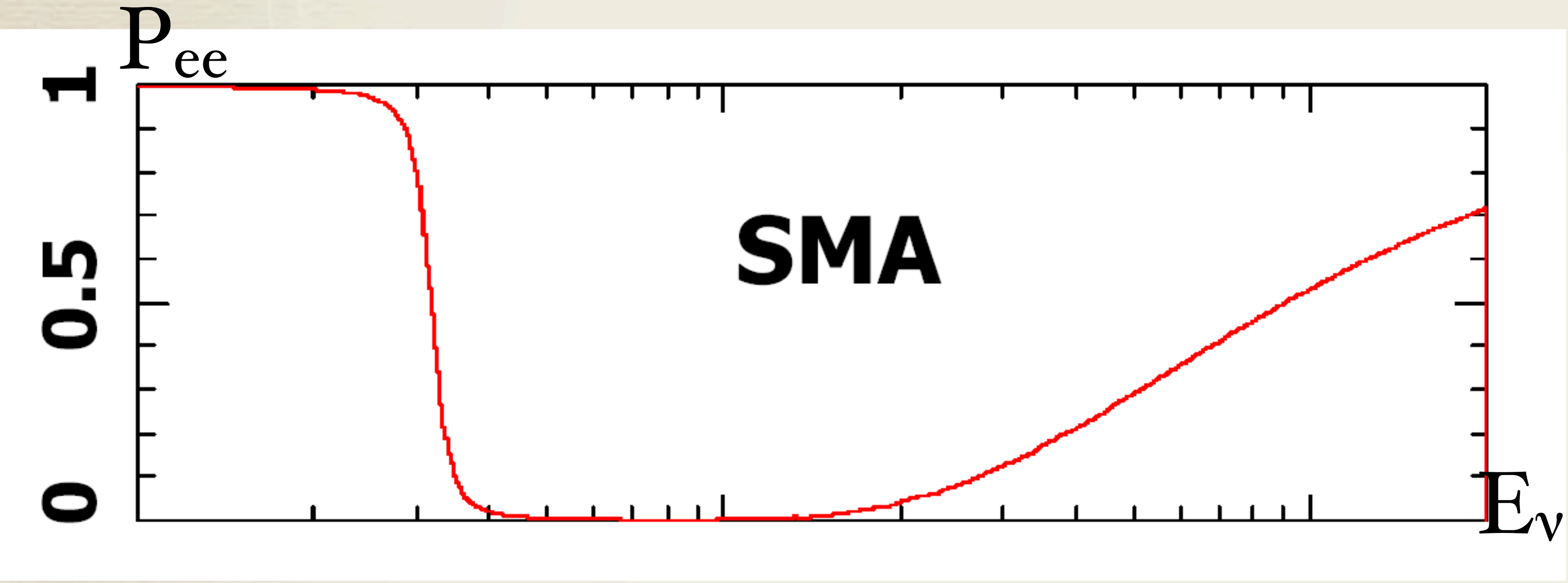
* Small mixing angle scenario predicts huge distortion in E spectrum

* MSW predicts Day / Night asymmetry due to interactions in the Earth



Smoking-Gun Potential





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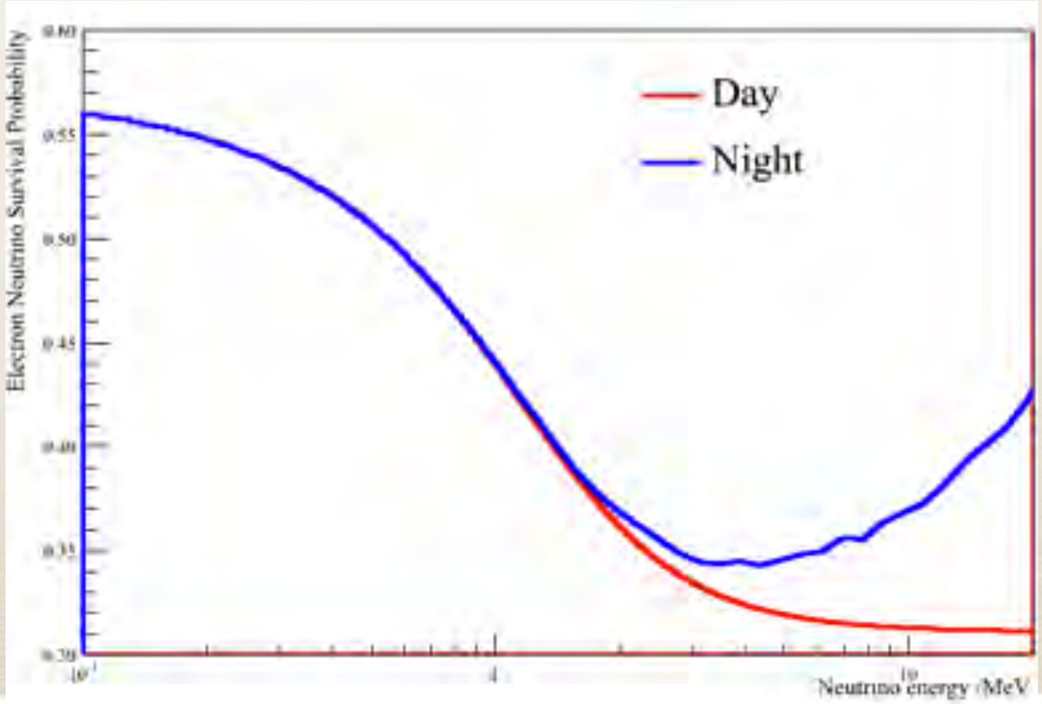
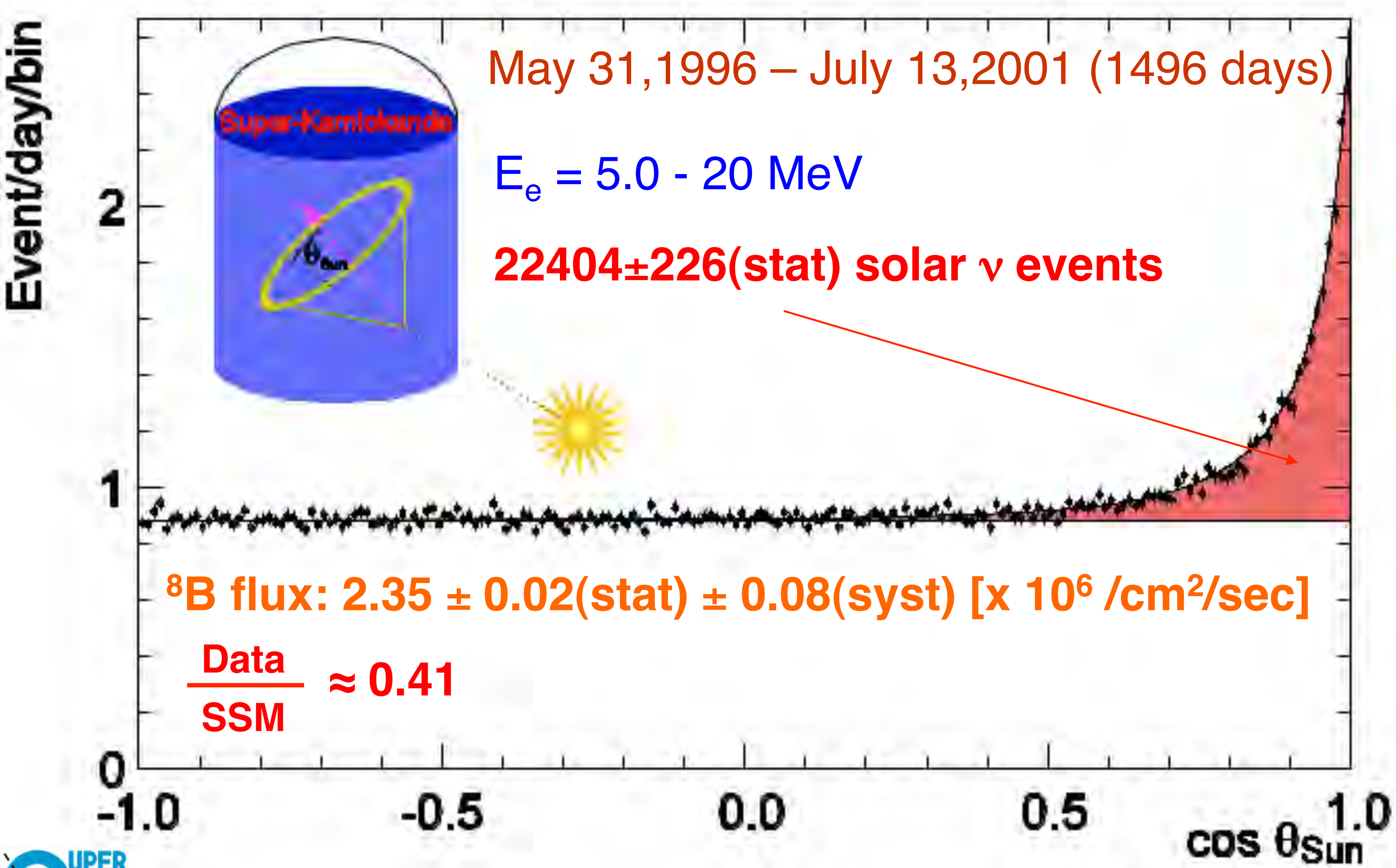


Either ⇒ unambiguous solution to current state of confusion

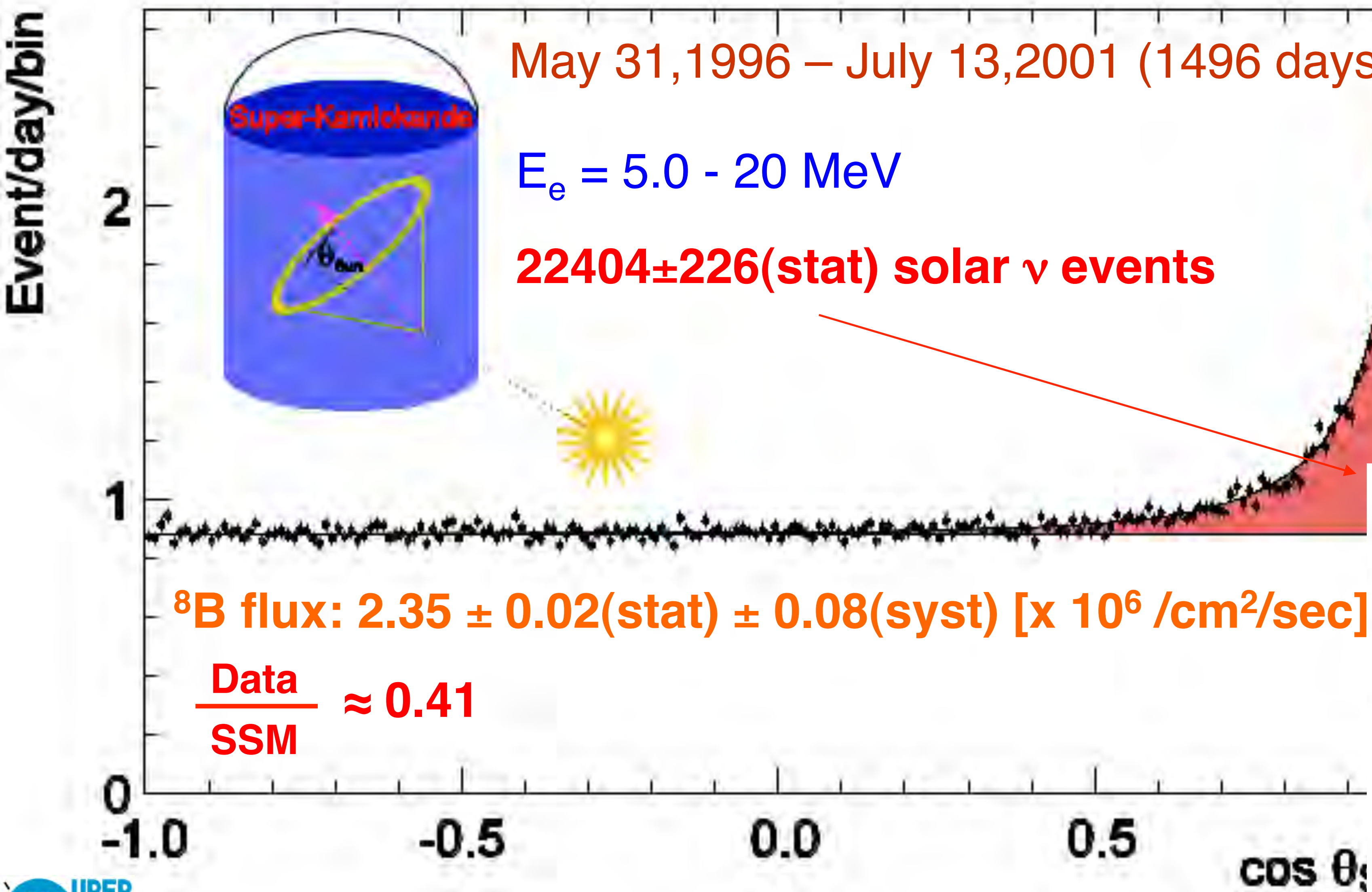
Solar ν Results

Solar ν Results

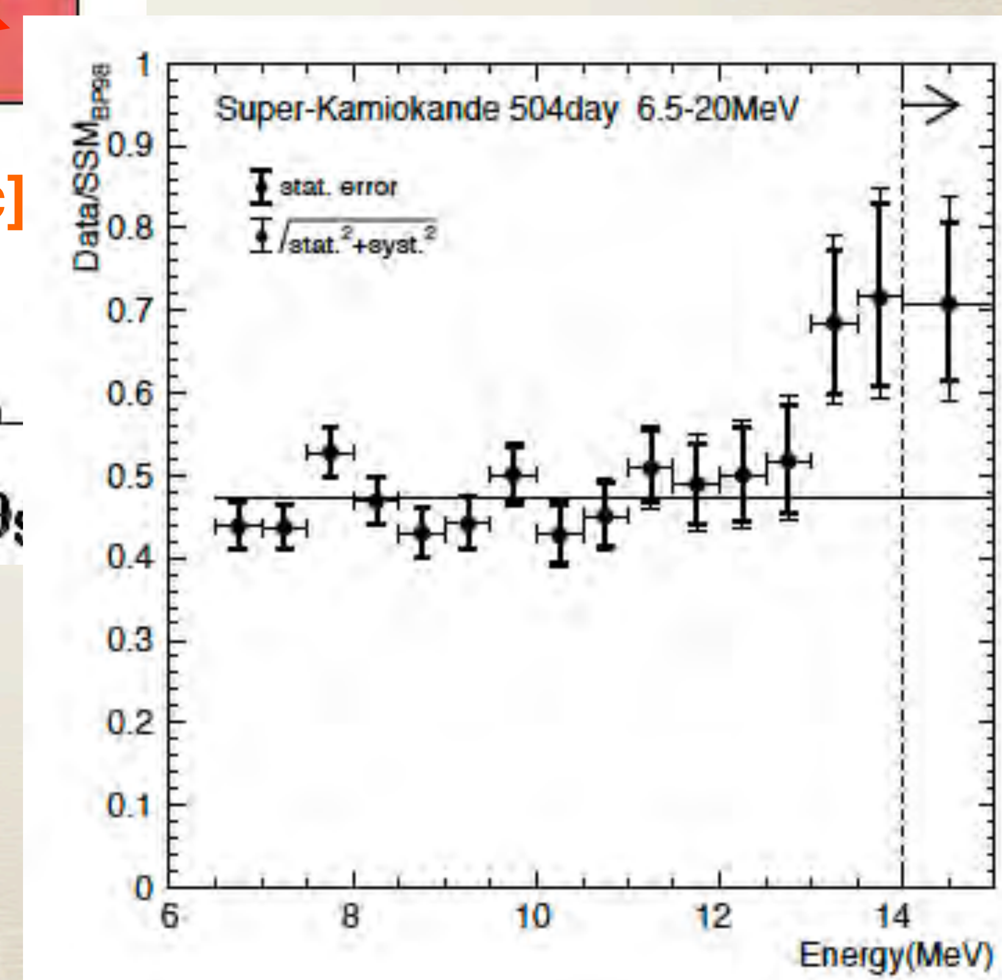


Phys. Rev. D 73, 112001 (2006)

Solar ν Results



Phys. Rev. D 73, 112001 (2006)



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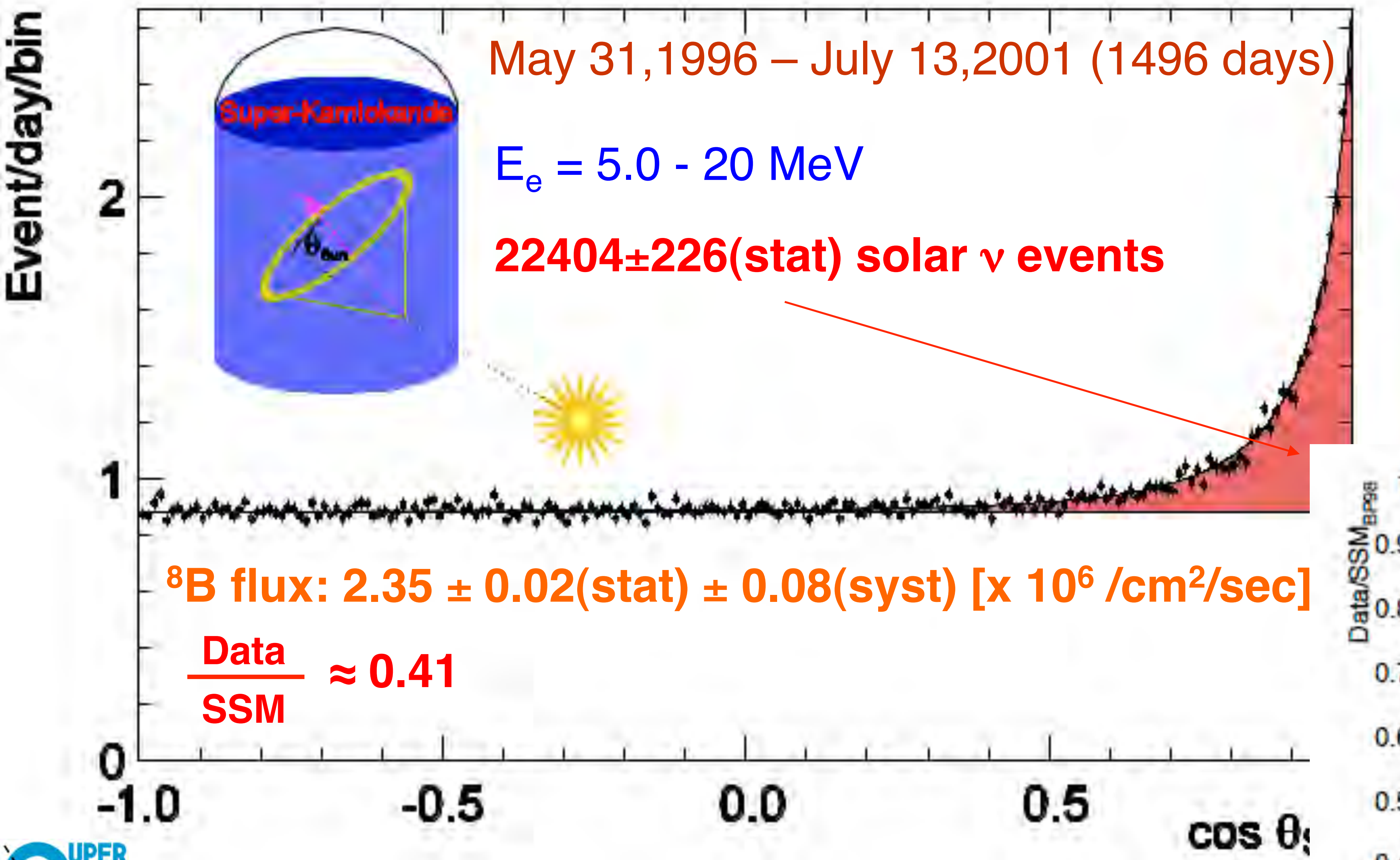

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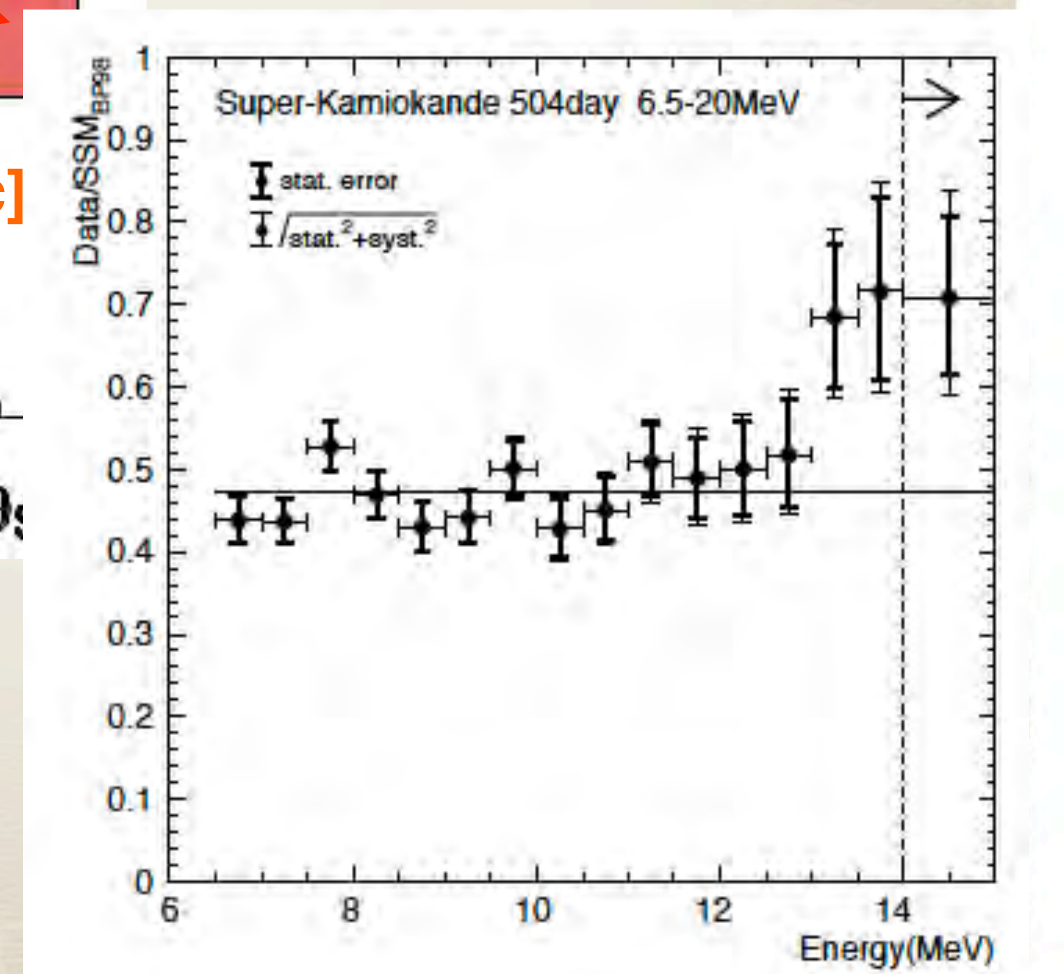
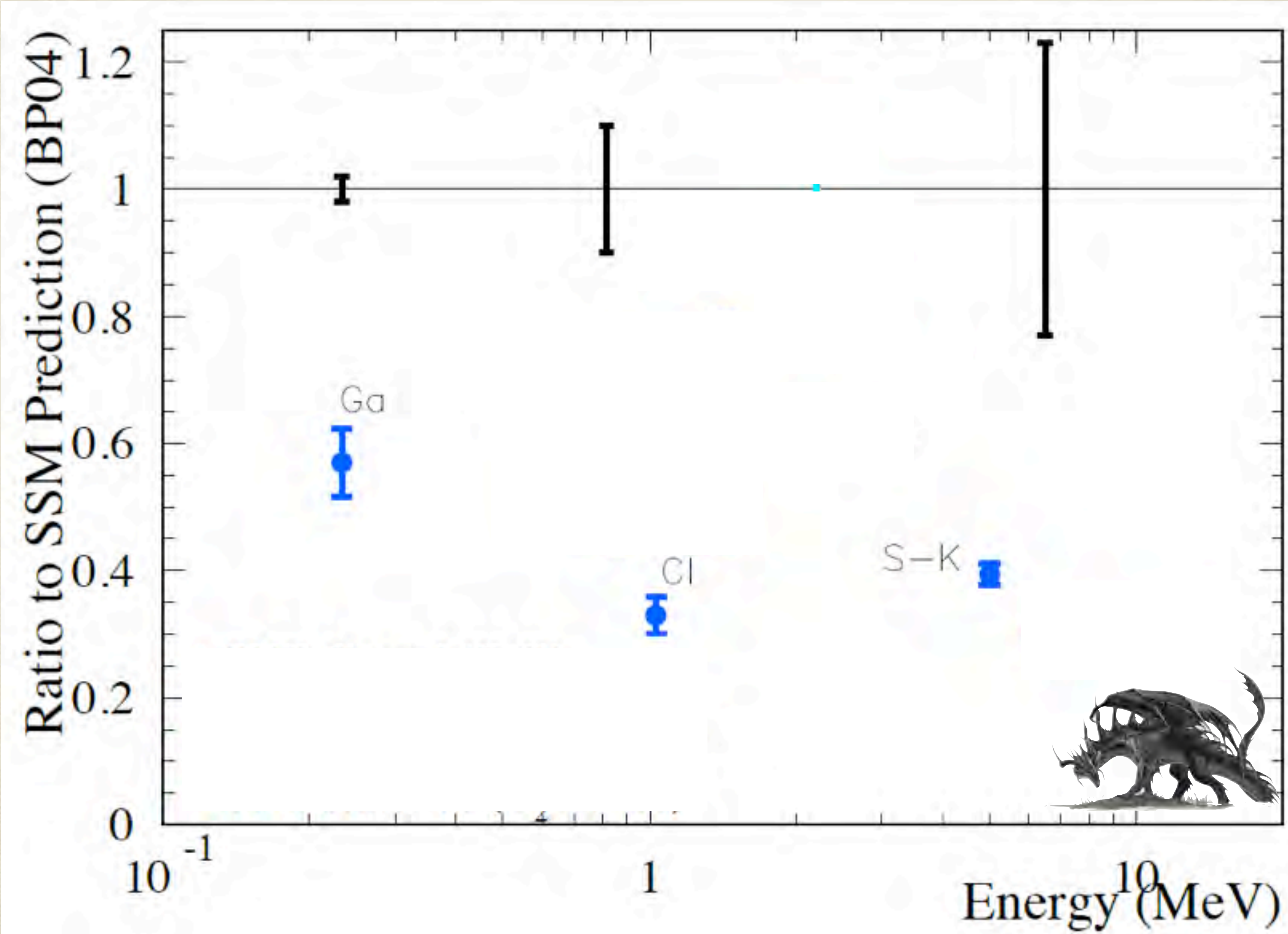


Still not a smoking gun....

Solar Neutrino Problem



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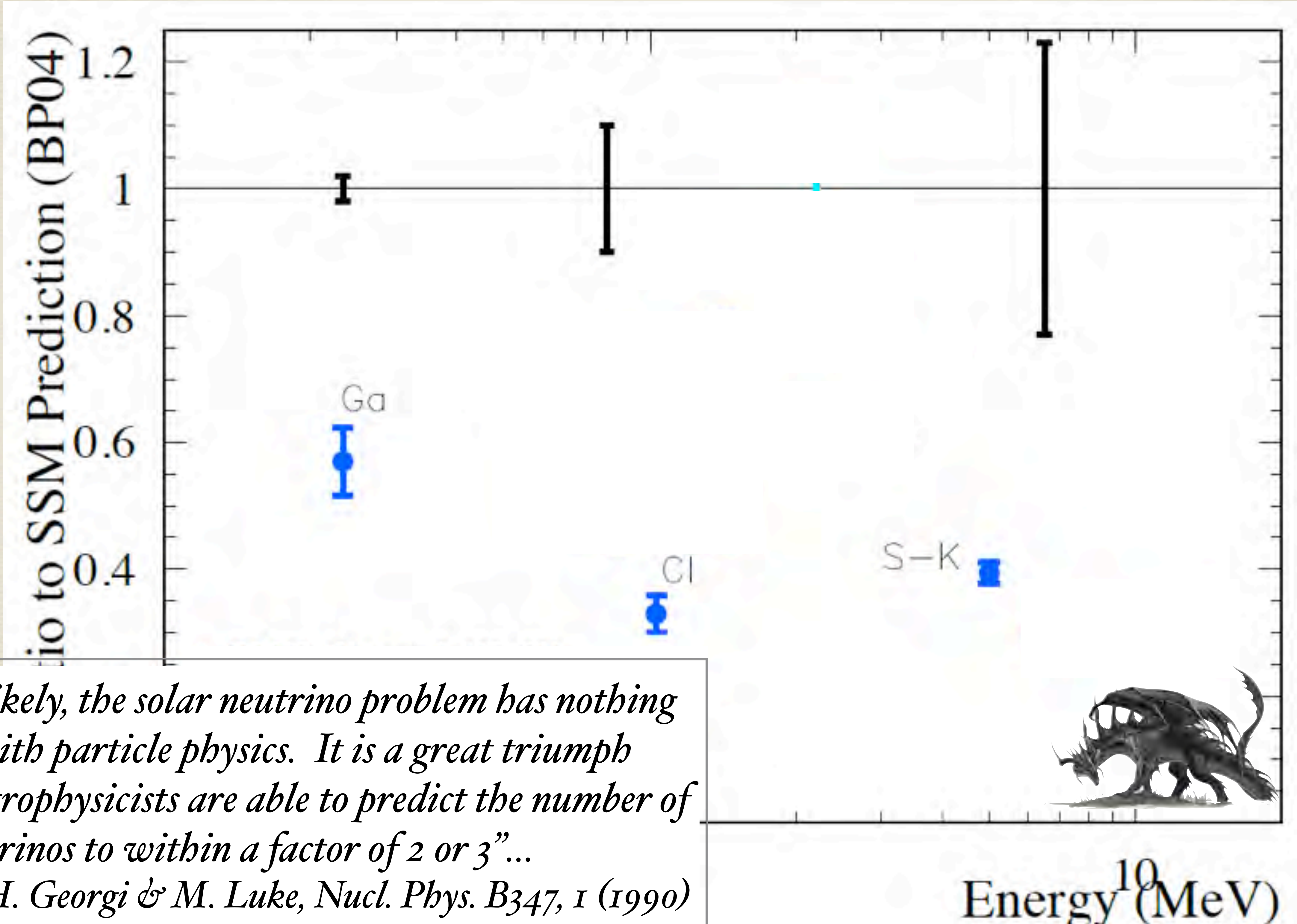
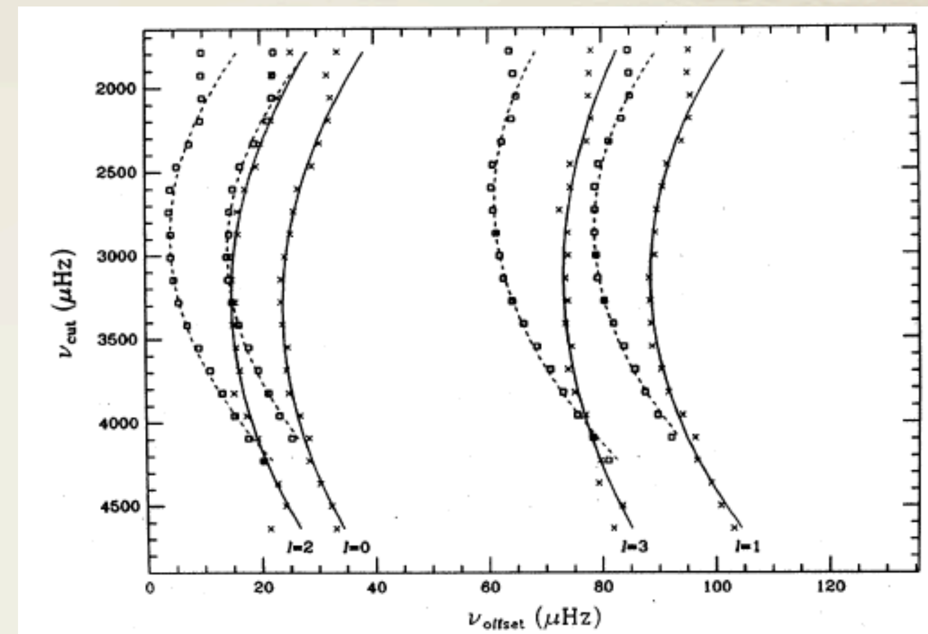


"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3"...

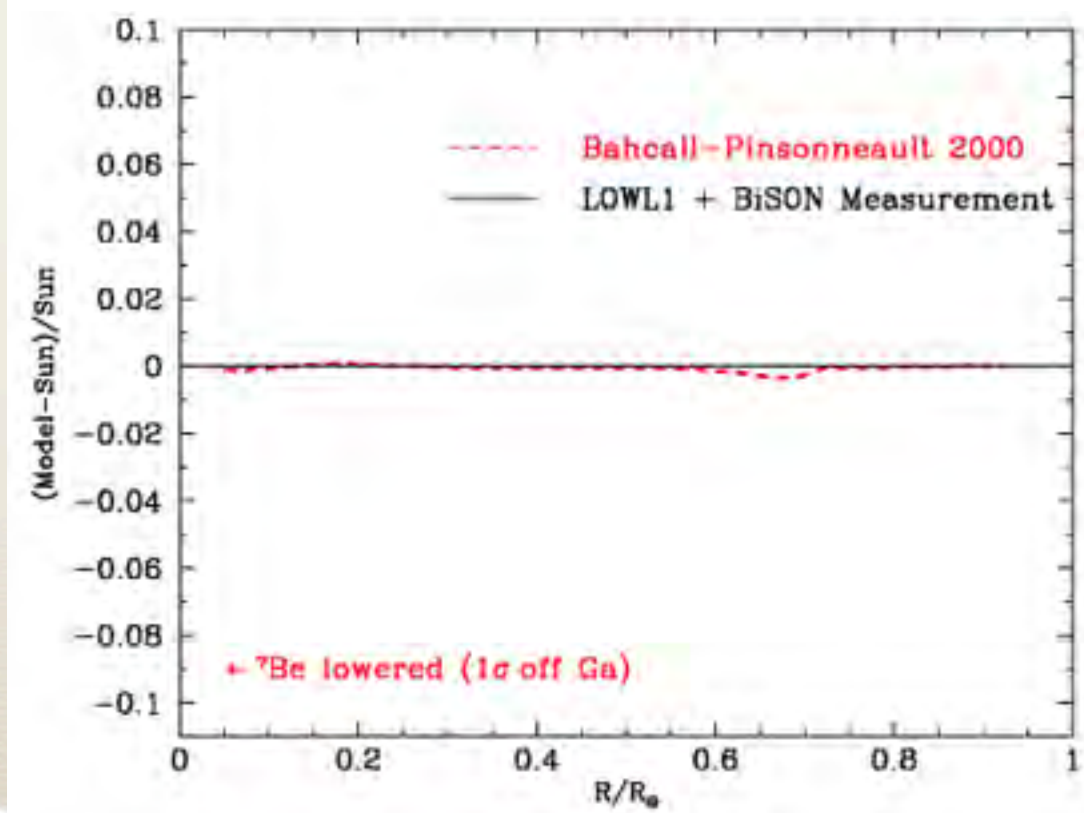
--H. Georgi & M. Luke, Nucl. Phys. B347, 1 (1990)

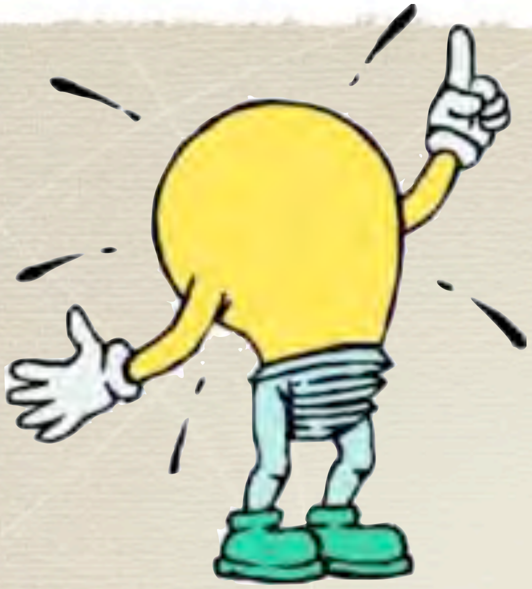
Testable Predictions

- Neutrino fluxes
- Density and temperature profile
  - ➡ speed of sound
- Acoustic modes can be measured very precisely
- Excellent agreement: < 0.5% *(Critical dependence on CNO content)*



Bahcall, Pinsonneault and Basu, Astro. Phys. J 555:990 (2001)





Can We Look For Appearance?

(Inclusive: seeing ν_x)

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

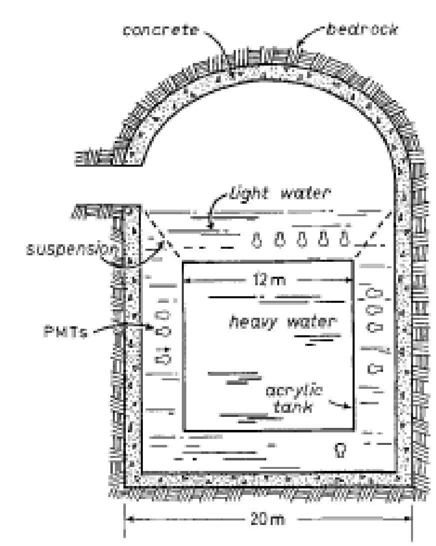
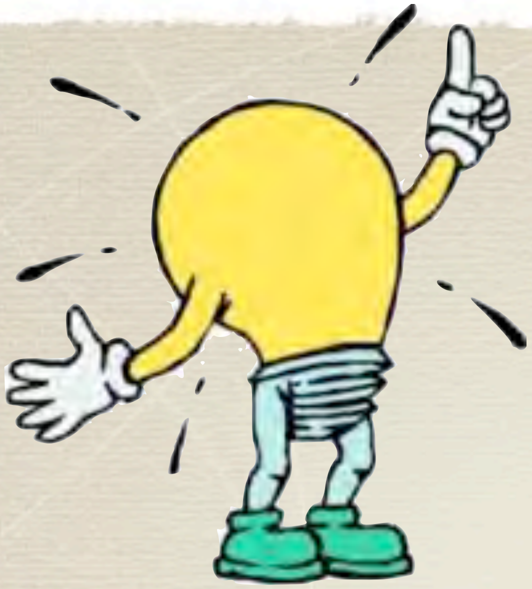


Fig. 5. – Conceptual design of the light/heavy-water detector. The heavy water is contained in an acrylic tank and is shielded from activity in the rock by low activity concrete and light water. The Čerenkov light produced in the water is detected by an array of 2400 50 cm diameter phototubes.



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VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

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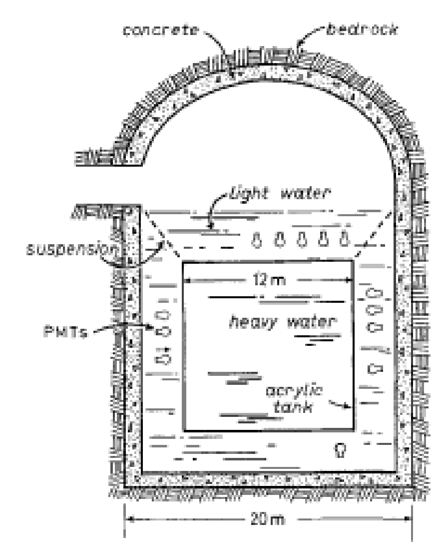
Review committee:



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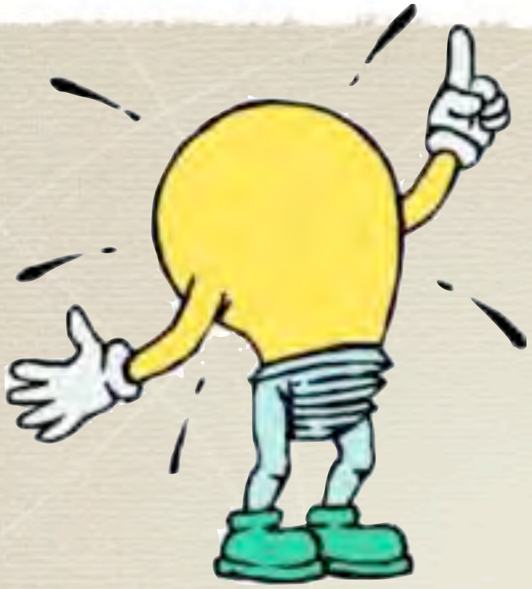

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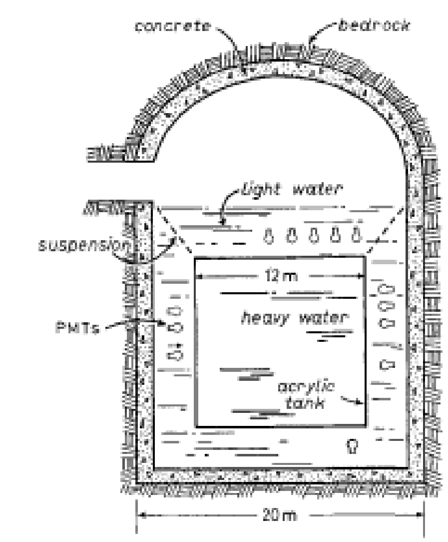

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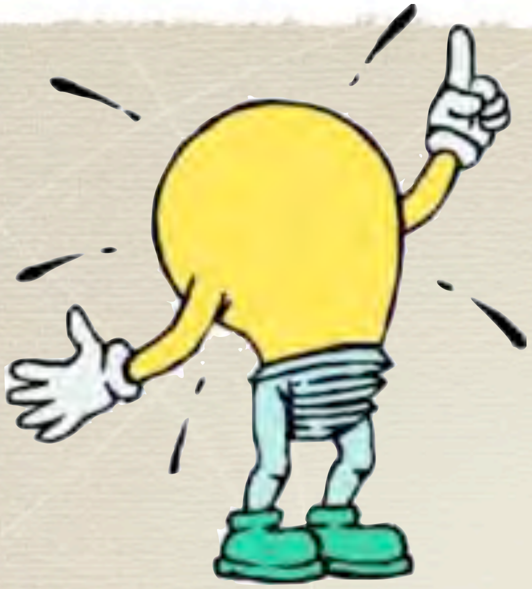
Review committee:

“Physics goals... are of outstanding value”



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(Inclusive: seeing ν_x)

VOLUME 55, NUMBER 14 — PHYSICAL REVIEW LETTERS — 30 SEPTEMBER 1985

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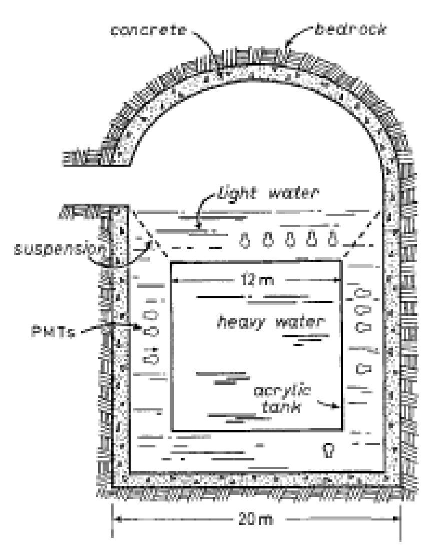

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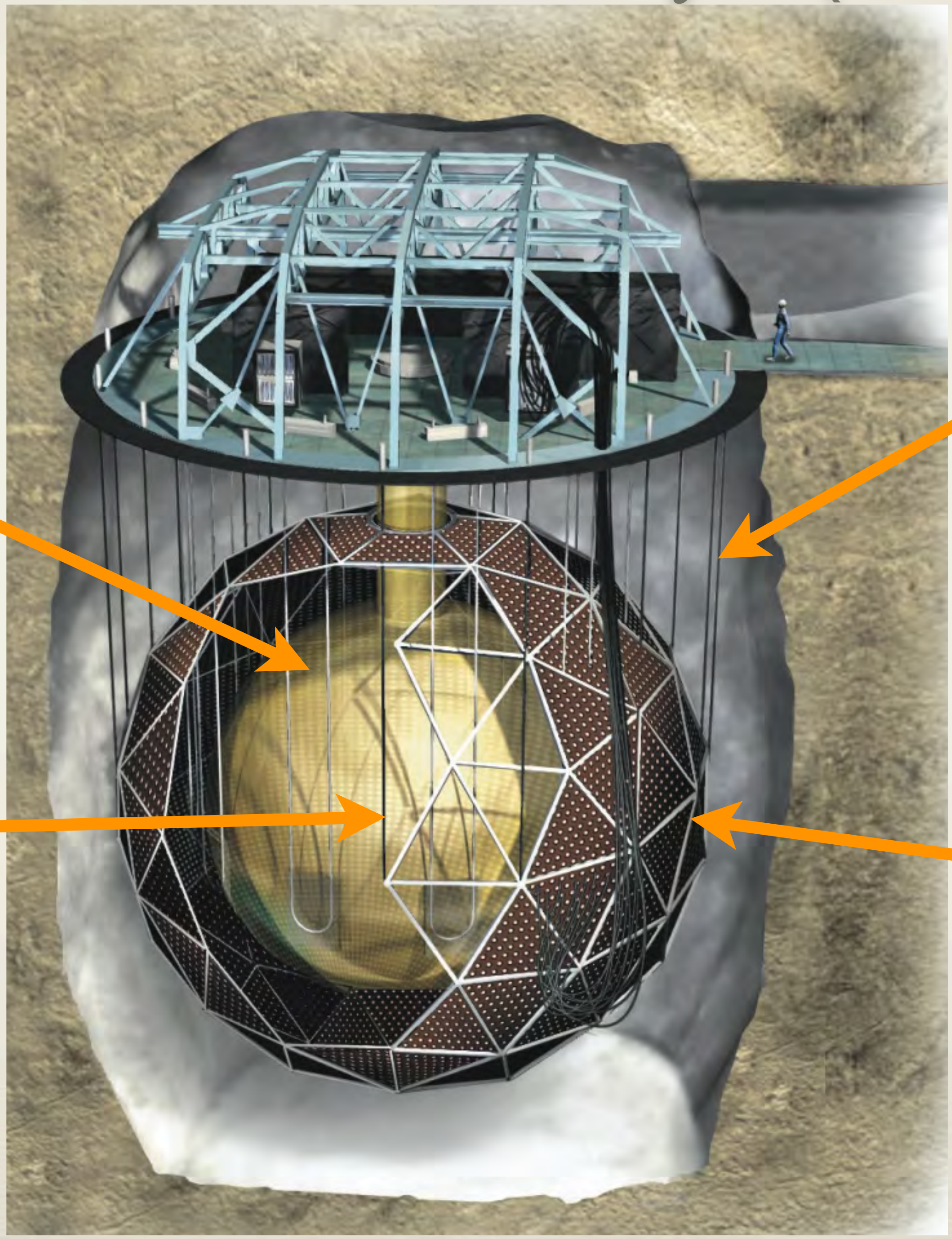
Review committee:

"Physics goals... are of outstanding value"

Funding agency award: $0

Sudbury Neutrino Observatory (SNO)

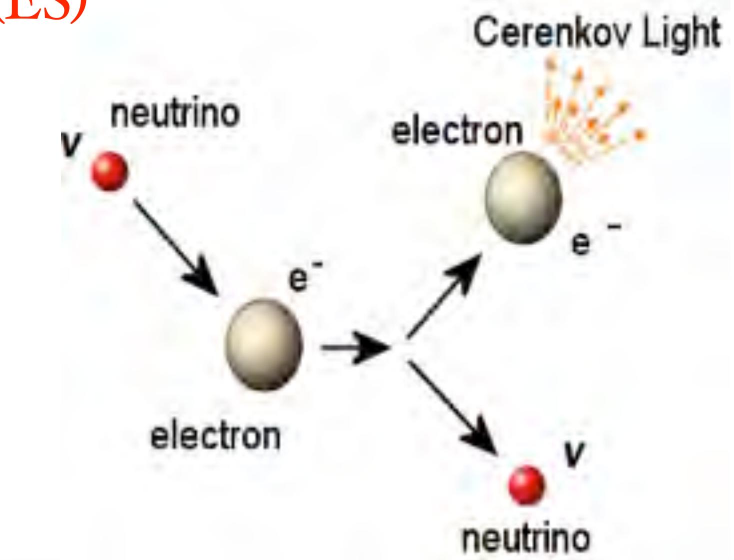
- 12m acrylic vessel
- 1kT D_2O
- 6800ft level
- 5890 m.w.e.



- 1.7kT + 5.3kT H_2O buffer
- 9500 PMTs, 60% coverage

Neutrino Detection

Neutrino-Electron Scattering (ES)

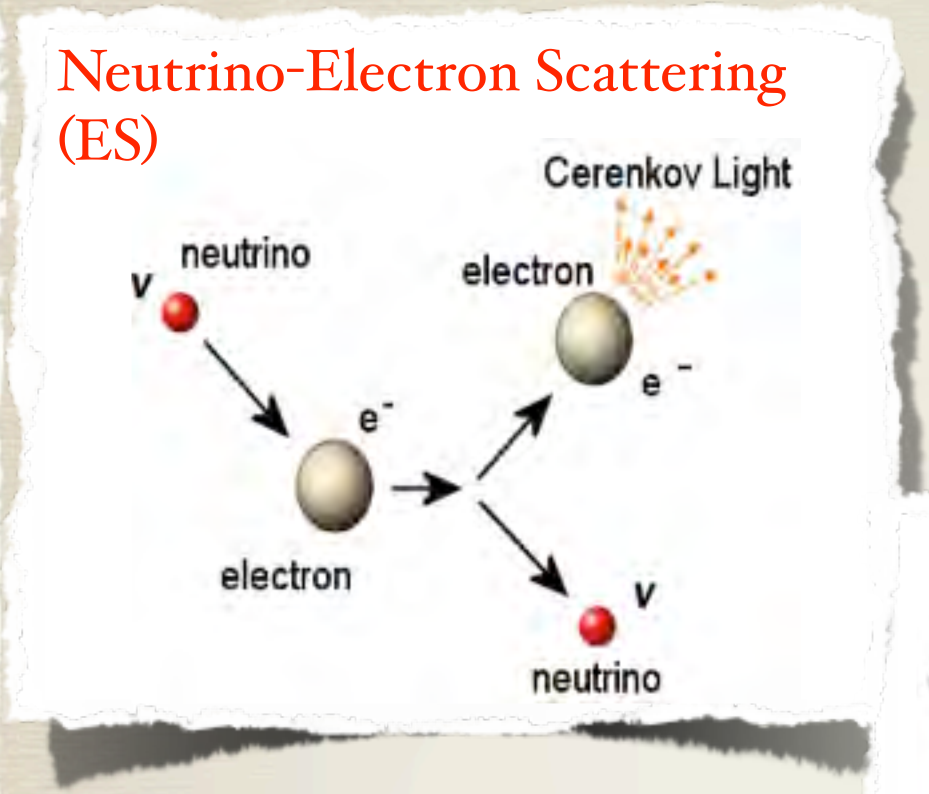


1. Elastic Scattering

Primarily sensitive to ν_e

Measures ν direction

The Answer: Heavy Water



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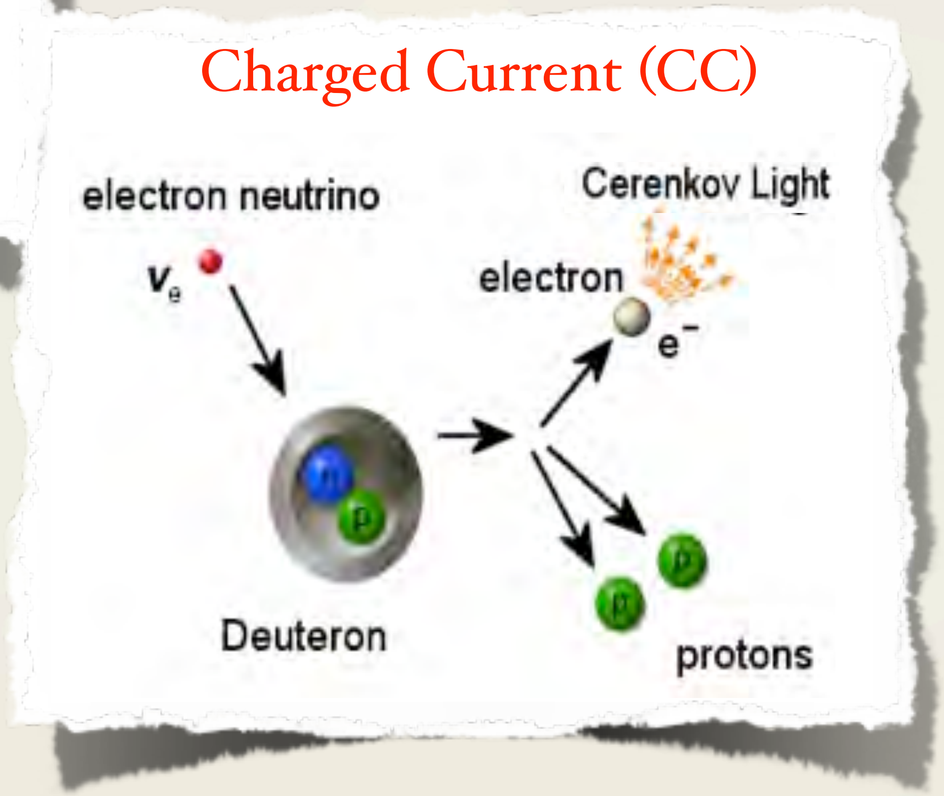
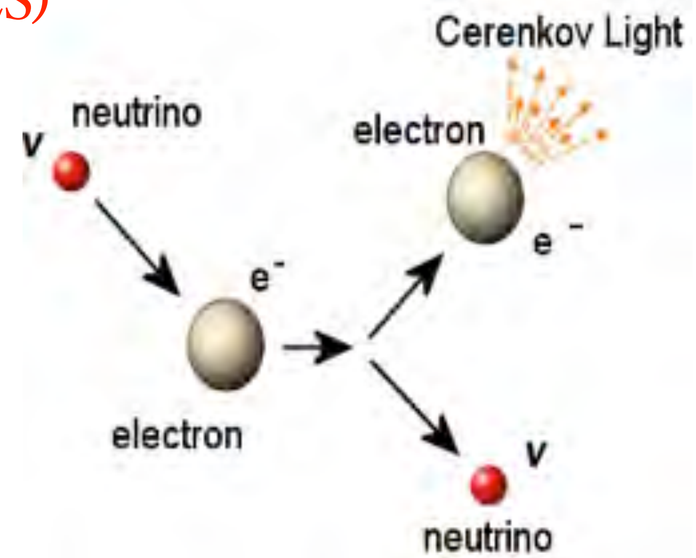
Primarily sensitive to ν_e
Measures ν direction



2. Charged Current
Sensitive only to ν_e
Measures ν energy

The Answer: Heavy Water

Neutrino-Electron Scattering (ES)

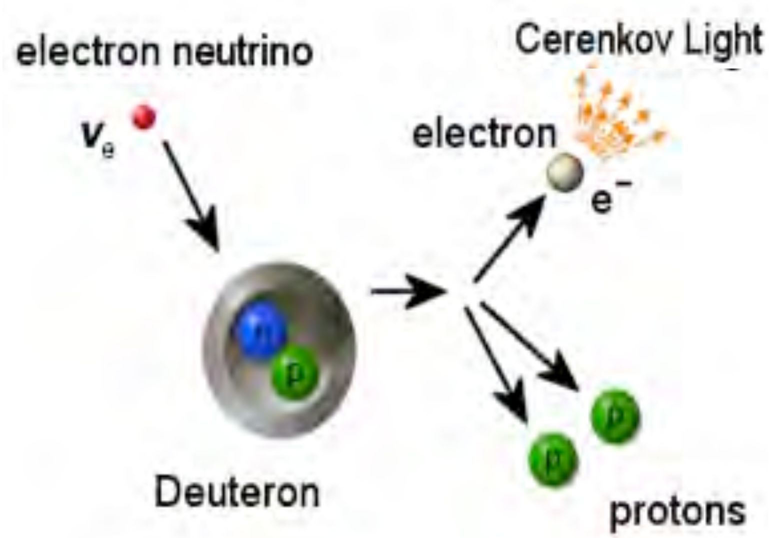


1. Elastic Scattering

Primarily sensitive to ν_e

Measures ν direction

Charged Current (CC)

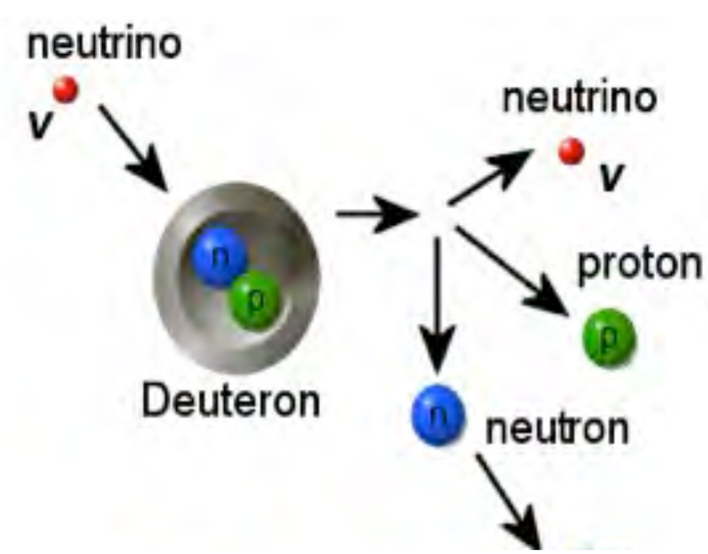


2.Charged Current

Sensitive only to ν_e

Measures ν energy

Neutral Current (NC)



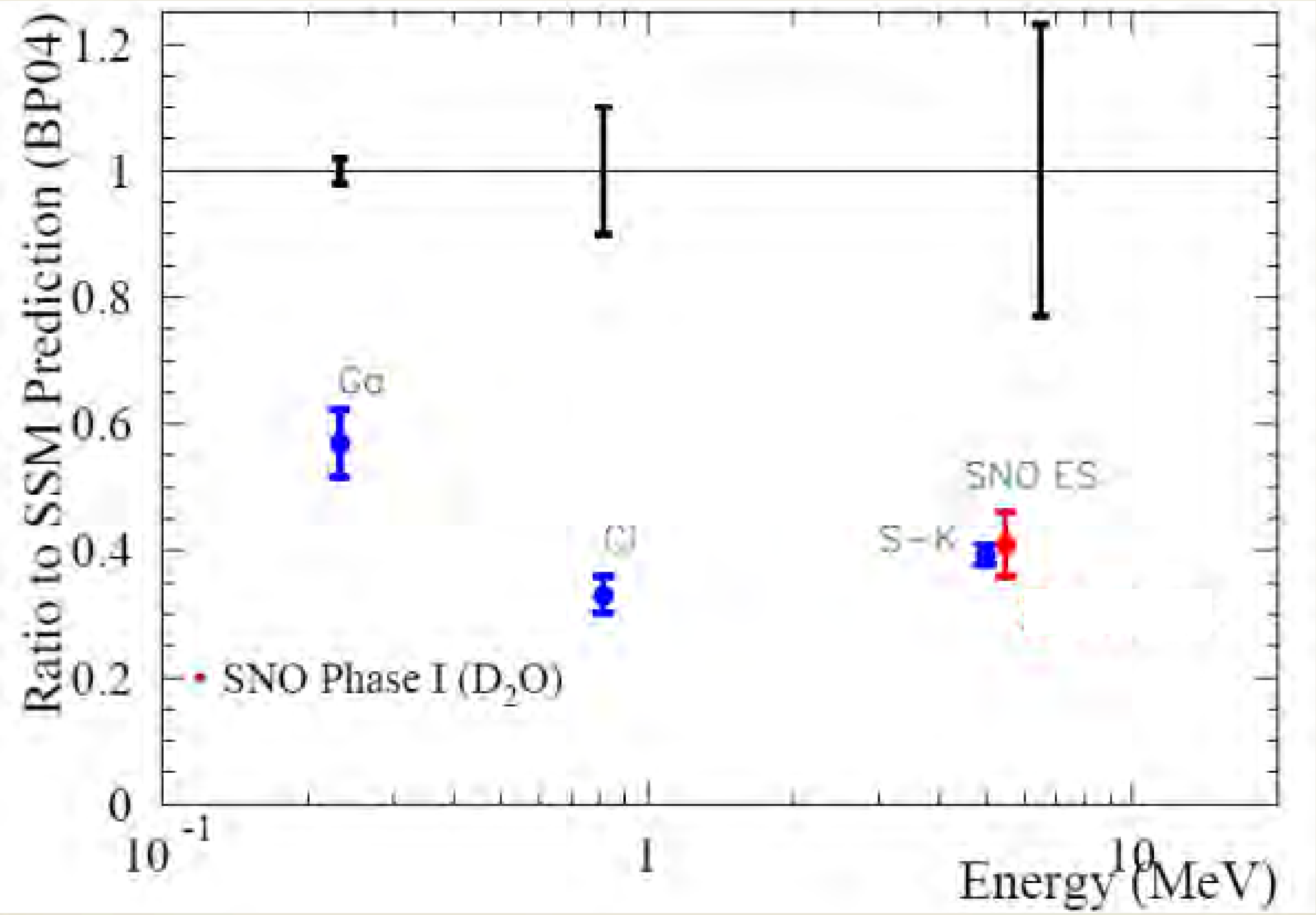
3.Neutral Current

Sensitive to all flavours

Measures total ^8B ν flux

2001: Results

SNO ES in excellent agreement with SK



2001: Results

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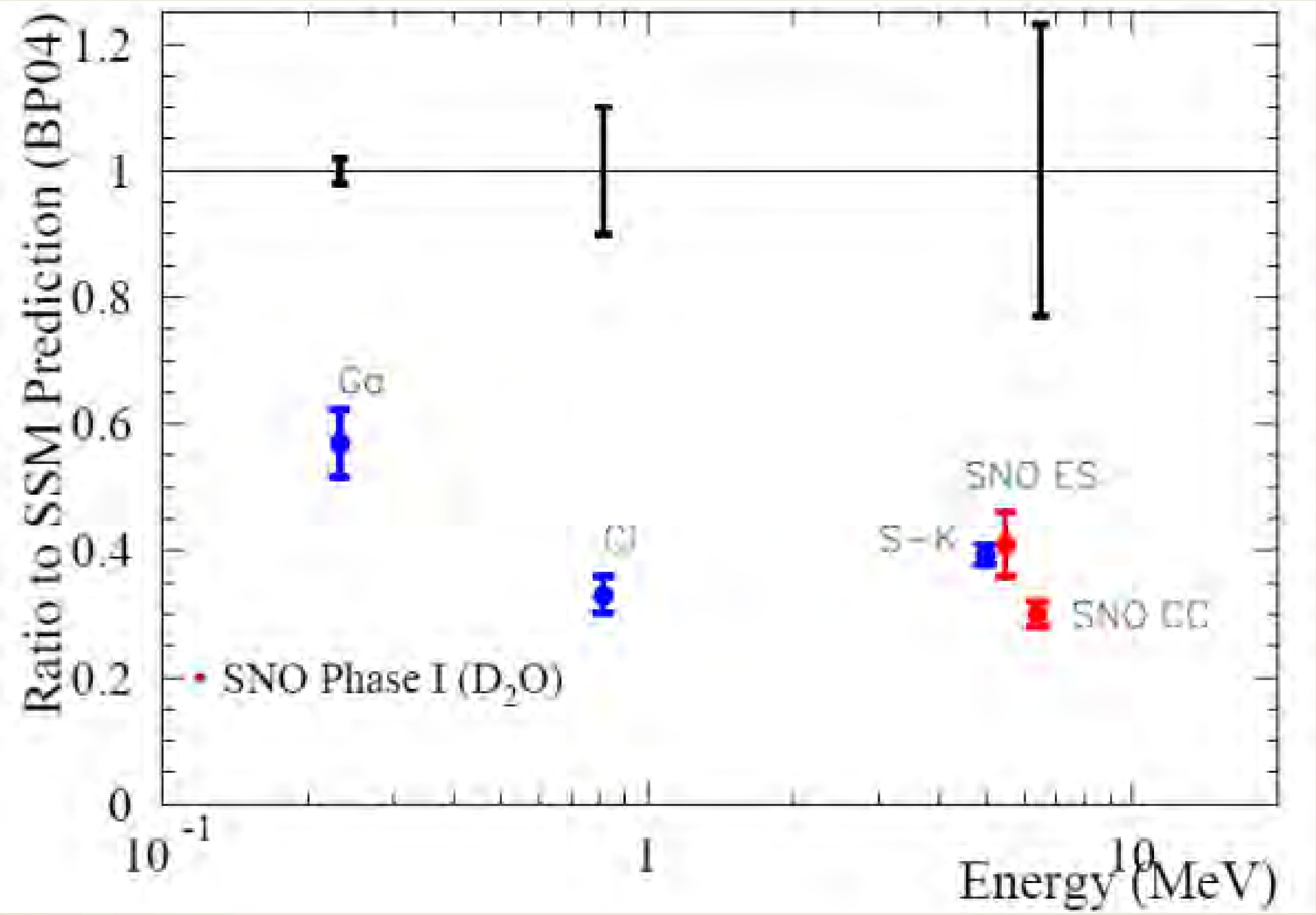


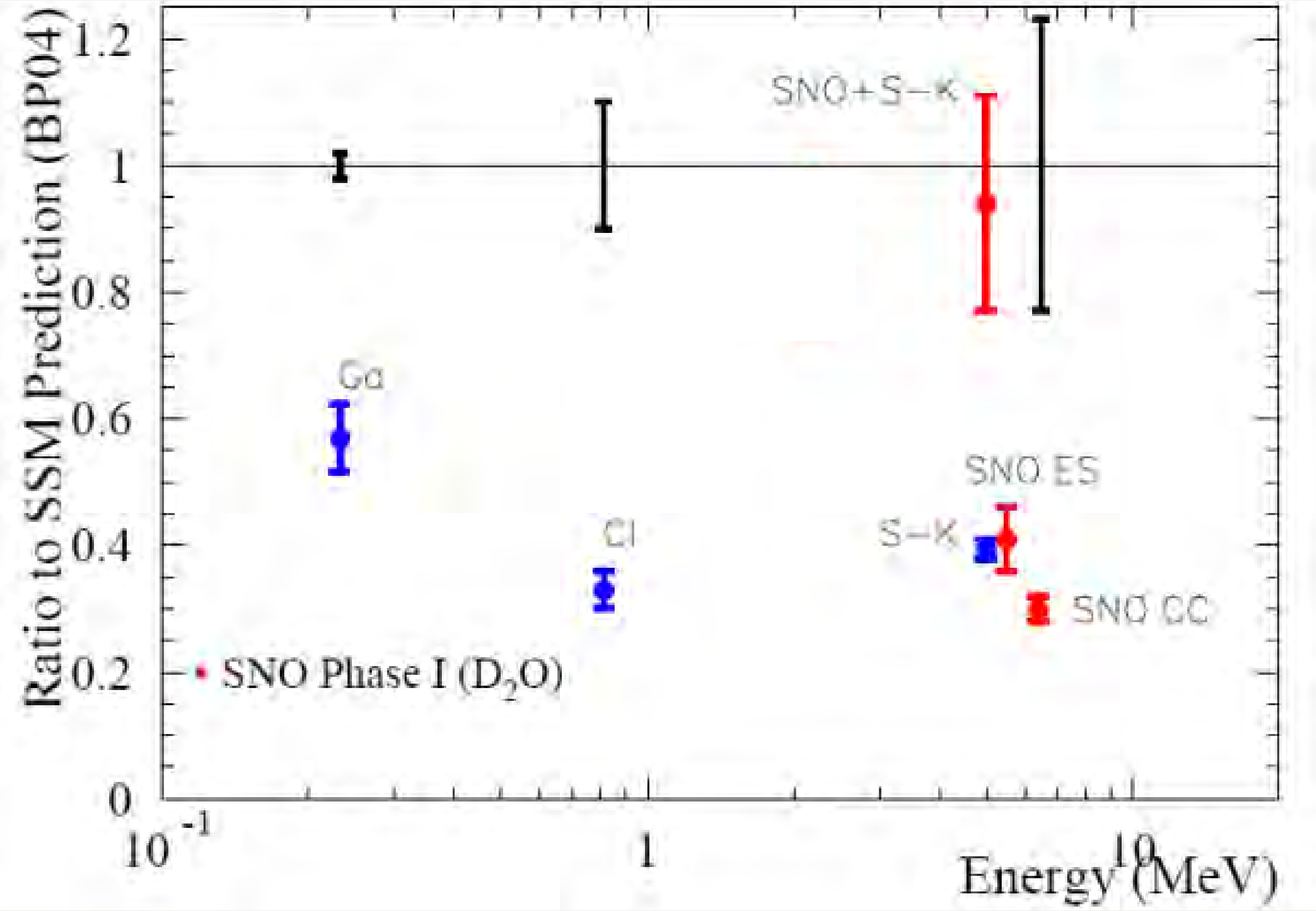
$$\Phi_{ES}^{SK} - \Phi_{CC}^{SNO} = 0.57 \pm 0.17$$

$$\rightarrow 3.3\sigma > 0$$

2001: Results

SNO ES in excellent agreement with SK

SNO + SK in excellent agreement with SSM!!



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A Bayesian World

Phys. Rev. Lett. volume 87, 071301 (2001)

Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^{8}B solar neutrinos at the Sudbury Neutrino Observatory

Q.R. Ahmad[15], R.C. Allen[11], T.C. Andersen[12], J.D. Anglin[7], G. Bühler[11], J.C. Barton[13‡], E.W. Beier[14], M. Bercovitch[7], J. Bigu[4], S. Biller[13], R.A. Black[13], I. Blevis[3], R.J. Boardman[13], J. Boger[2], E. Bonvin[9],

"...the standard model of the Sun appears to be in better shape than the standard model of electroweak interactions"

---Fogli,Lisi,Montanino,Palazzo, Phys. Rev. D64, 2001

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty," Dr. Bahcall said. *"For 33 years, people have called into question my calculations on the Sun."*

---New York Times, 19th June 2001

World News

Mellon Jazz Festival: Penn's Landing party, John Swana, more. Page 4.

The Philadelphia Inquirer

Health & Science

SECTION F MONDAY, JUNE 18, 2001 www.philly.com

The tiny, mysterious particles are everywhere – but elusive. Penn scientists and others are tracking them in a Canadian mine.

On the neutrino's trail

Solving a Cosmic Puzzle

The least understood of the fundamental particles of the universe, **neutrinos** are everywhere, yet nearly impossible to detect. They hardly interact with ordinary matter at all. They simply pass through everything, from animals and people to the entire planet.

The sun generates huge numbers of one of the three types of neutrinos, called **electron neutrinos,** but fewer of these than predicted reach the Earth. One theory of why is that some electron neutrinos are changing into **muon neutrinos** and **tau neutrinos,** which are harder to spot.

Particle physicists are working deep underground to detect neutrinos — and possibly determine whether the three types can switch identities with each other.

How the Detector Works

World News

The Philadelphia Inquirer

Ann Landers 2

THE WASHINGTON POST

NATIONAL NEWS

Neutrino Study Solves One Puzzle and Creates Another

By GUY GUGLIOTTA
Washington Post Staff Writer

Every second of every day, tens of thousands of ghostly subatomic particles called neutrinos—tiny offspring of nuclear fusion in the core of the sun—harmlessly flash through a person's body.

For 30 years physicists have known—or thought they knew—how many neutrinos ought to be reaching Earth, but every measuring device told the same story—there were many fewer arrivals than expected. Either physicists had the wrong idea about solar fusion, or something was happening to the neutrinos en route.

Yesterday, an international team of physicists, working in a lab sunk more than a mile deep in a Canadian nickel mine, presented the first concrete evidence that the "solar neutrino deficit" occurs because while three types of neutrinos reach the Earth, only one—until now—could reliably be counted.

"We have measured the total number of neutrinos coming from the sun, and [the measurement] agrees with predictions made 30 years ago," said research physicist and team member Joshua Klein of the University of Pennsylvania. "It's the oldest, longest-lived puzzle in particle physics."

The findings, reported in the journal Physical Review Letters by 180 authors from the United States, Canada and the United Kingdom, have important implications for both the physics of the very small and the physics of the very large.

By showing that neutrinos toggle back and forth on their journey to Earth among three forms, or "flavors," the experiment provided fresh confirmation that neutrinos have mass. Scientists agree that such "oscillation" can occur only if a substance has mass.

This concept has thrown a sizable monkey wrench into the "Standard Model" of physics, which proposes a massless neutrino as part of its

neutrino.

Solar fusion, the source of the largest share of the Earth's detectable neutrinos, gives off only electron neutrinos, Hahn explained, but far fewer of these particles were showing up than were expected. Many physicists theorized—but could not prove—that the electrons were changing to muons or tau during the trip.

"Think of it as a mix of two basic colors, like red or blue," Hahn said. "You get three shades of purple, but all three are intrinsic to the basic mix." Thus, a single neutrino embodies all three flavors.

Studying neutrinos, which come to Earth in sunshine or cosmic rays, has proved difficult because they are so small. They can pass through anything and are almost impossible to detect, especially when they have to be distinguished from other incoming particles.

Following the experience of other scientific groups, the U.S.-Canada-U.K. team built a neutrino observatory 6,800 feet deep in the underground tunnels of the Creighton Nickel Mine outside Sudbury, Ontario. The massive stone shield blocks the entrance of all but the most persistent neutrinos.

The observatory's detector is a spherical vessel of acrylic plastic 12 meters in diameter filled with 1,000 tons of heavy water—water composed of heavy isotopes of hydrogen or oxygen, or both. Almost 10,000 light sensors detect and photograph tiny flashes of light thrown off when neutrinos are stopped or scattered in the heavy water.

Klein said the heavy water was critical because the hydrogen nucleus in the water molecule has a neutron. When hit with an electron neutrino, the nucleus emits an electron and the neutron changes to a proton.

In this way, the researchers for the first time were able to count electron neutrinos, and determine that they comprised 35 percent of the neutrinos expected to reach the Earth.

BY VINO WONG—THE NIAGARA GAZETTE VIA ASSOCIATED PRESS

At Niagara Falls, New York Gov. George E. Pataki (R), at lectern, discusses plans to protect the Great Lakes by limiting volume of water sent inland.

guidelines approved today.

Five major diversions are in place, the largest of which is the 2.1 billion gallons that is taken each day from Lake Michigan at Chicago. Half the water is for drinking and the rest is used to reverse the flow of the Chicago Sanitary and Ship Canal. The diverted water winds up in the Mississippi River.

"Some might say this is not a serious problem because right now there are no serious [export] proposals in front of us. But if there's ever a serious drought elsewhere in the United States, you can be sure there will be serious proposals," said Michael J. Donahue, president of the Great Lakes Commission, a binational agency that promotes the protection of the Great Lakes.

Donahue said that Great Lakes conservationists have learned from past court cases that "you can't just say

World News

Mellon Jazz Festival: Penn's landing party, John Swana, more. Page 4.

SECTION F

The Philadelphia Inquirer

NATIONAL NEWS

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Neutrino St[udy Solves] Puzzle and [...]

By Guy Gugliotta
Washington Post Staff Writer

THE NEW YORK TIMES, TUESDAY, JUNE 19,

Sun's Missing Neutrinos: Hidden in Plain Si[ght]

By KENNETH CHANG

After three decades of searching, physicists have tracked down subatomic particles that have eluded them for 30 years. The particles, it turns out, were right there all the while but had hidden themselves as if by magic.

"We've solved a 30-year-old puzzle of the missing neutrinos of the Sun," said Dr. Arthur B. McDonald, director of the Sudbury Neutrino Observatory, near Sudbury, Ontario. In doing so, though, the researchers have answered questions about neutrino behavior and the fate of the universe.

Neutrinos are ghostly particles, one of the fundamental building blocks of the universe, like quarks, electrons and photons. Billions of them, produced by fusion reactions within the Sun, fly through every person every second. Minuscule and devoid of electric charge, though, they pass unnoticed. In fact, they are practically undetectable.

In 1968, Dr. John Bahcall, an astrophysicist at the Institute for Advanced Study at Princeton, N.J., calculated that the rate of neutrinos from the Sun passing through one square inch of area should be about 30 million a second.

Experiments beginning in the 1970's counted much lower rates; more than half of the expected neutrinos were never seen. Dr. Bahcall's predictions, refined over the years, remained unchanged.

Yesterday, scientists at the Sudbury Neutrino Observatory announced the first experimental evidence that provides a solution.

During the neutrinos' 93-million-mile journey from the Sun to the Earth, the researchers said, about two-thirds change into other varieties that are more difficult to detect.

The total number of neutrinos from the Sun, they conclude, is about 35 million per square inch per second. "The agreement is pretty good between the predictions and the measurement," said Dr. Joshua R. Klein, a professor of physics at the University of Pennsylvania who coordinated the analysis of the data.

Dr. Bahcall was ecstatic.

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty," Dr. Bahcall said. "For 33 years, people have called into question my calculations on the Sun."

The new finding "shows the calculations were correct," he said. "I feel like dancing," he added.

Less happy is Dr. David O. Caldwell, an emeritus professor of physics at the University of California at Santa Barbara. "My personal reaction is one of great disappointment," Dr. Caldwell said. "I was hoping for a rather different result." The data ran contrary to his hopes of finding a

Lawrence Berkeley National Laboratory

Sudbury Neutrino Observatory

At left, a drawing of the neutrino detector, built 1¼-miles underground and immersed in water within a cavity 110 feet deep. Above, the bottom of the detector.

trino Observatory consists of a 40-foot-wide acrylic sphere containing 1,000 tons of heavy water, in which the two hydrogen atoms of the water molecules have been replaced with deuterium atoms, a heavier version of hydrogen. The sphere is submerged within a 10-story cavity that was carved out of a nickel mine 1¼ miles underground and filled with 40,000 tons of ordinary water.

Occasionally, an electron neutrino will slam into one of the deuterium atoms in the heavy water, splitting it into a proton and a neutron. Detectors around the sphere of heavy water are able to spot the debris. The other two types of neutrinos cannot break up deuterium. The scientists have seen 1,169 such collisions since the experiment began in 1999.

The researchers compared their results with earlier neutrino counts from the Super-Kamiokande neutrino experiment in Japan, which primarily detects collisions between electron neutrinos and electrons. But muon and tau neutrinos can also occasionally bounce off electrons.

If all the neutrinos reaching Earth from the Sun were of the electron variety, then the neutrino rates measured by Super-Kamiokande and Sudbury should match up. But Super-Kamiokande detected more. Since the Sun produces only electron neutrinos — the production of muon and tau neutrinos require higher-energy events, like matter falling into black holes or an exploding star — that means some of them must change

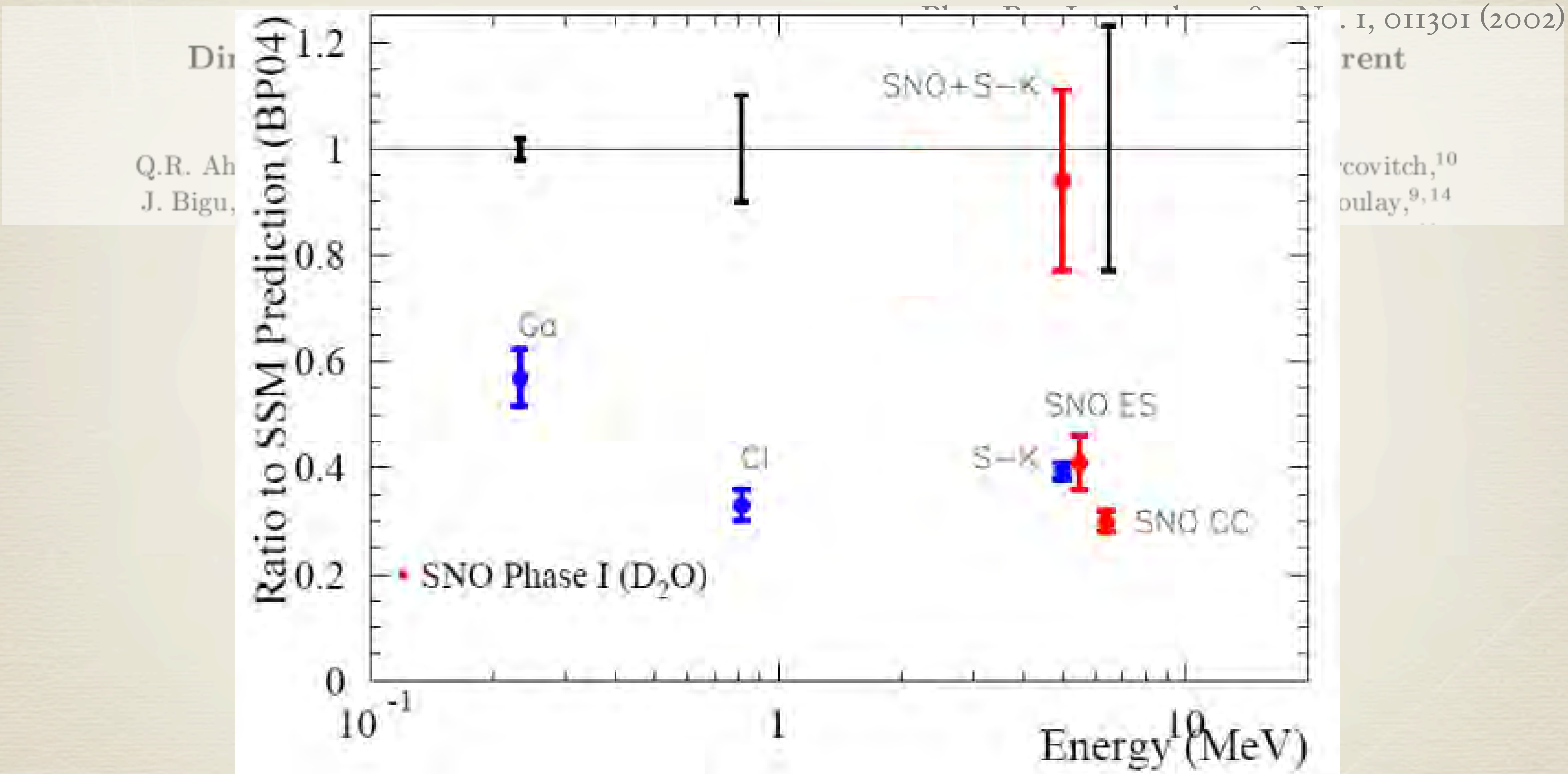
2002: The Clincher

Phys. Rev. Lett. volume 89, No. 1, 011301 (2002)

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

Q.R. Ahmad,[17] R.C. Allen,[4] T.C. Andersen,[6] J.D. Anglin,[10] J.C. Barton,[11,*] E.W. Beier,[12] M. Bercovitch,[10] J. Bigu,[7] S.D. Biller,[11] R.A. Black,[11] I. Blevis,[5] R.J. Boardman,[11] J. Boger,[3] E. Bonvin,[14] M.G. Boulay,[9,14]

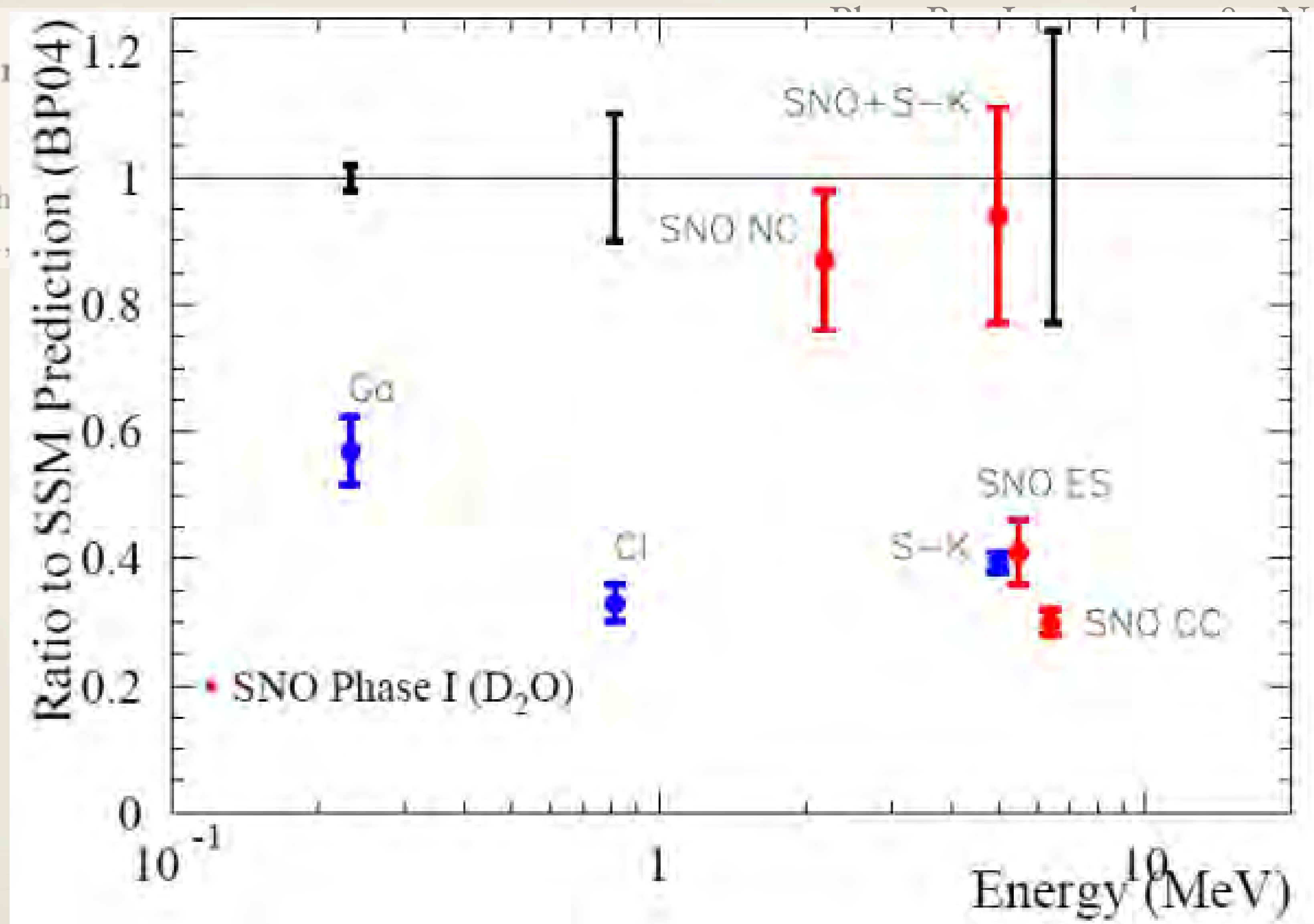
2002: The Clincher



$$\Phi_{\mathrm{ES}}^{\mathrm{SK}} - \Phi_{\mathrm{CC}}^{\mathrm{SNO}} = 0.57 \pm 0.17$$

$$\rightarrow 3.3\sigma > 0$$

2002: The Clincher



$$\Phi_{ES}^{SK} - \Phi_{CC}^{SNO} = 0.57 \pm 0.17$$

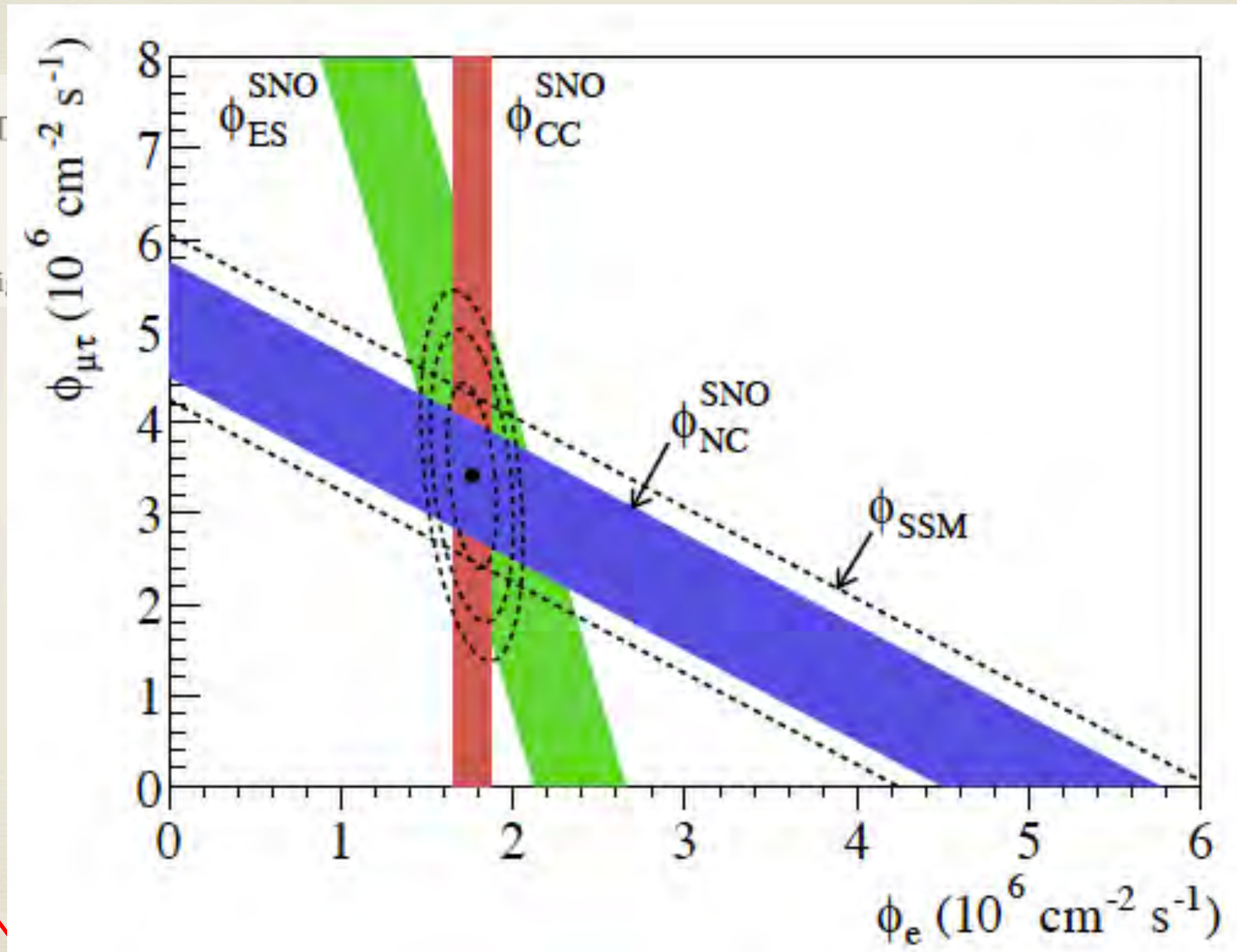
$$\rightarrow 3.3\sigma > 0$$

$$\Phi_{NC}^{SNO} - \Phi_{CC}^{SNO} = \Phi_{\mu\tau}$$

$$\rightarrow 5.3\sigma > 0$$

2002: The Clincher

011301 (2002)



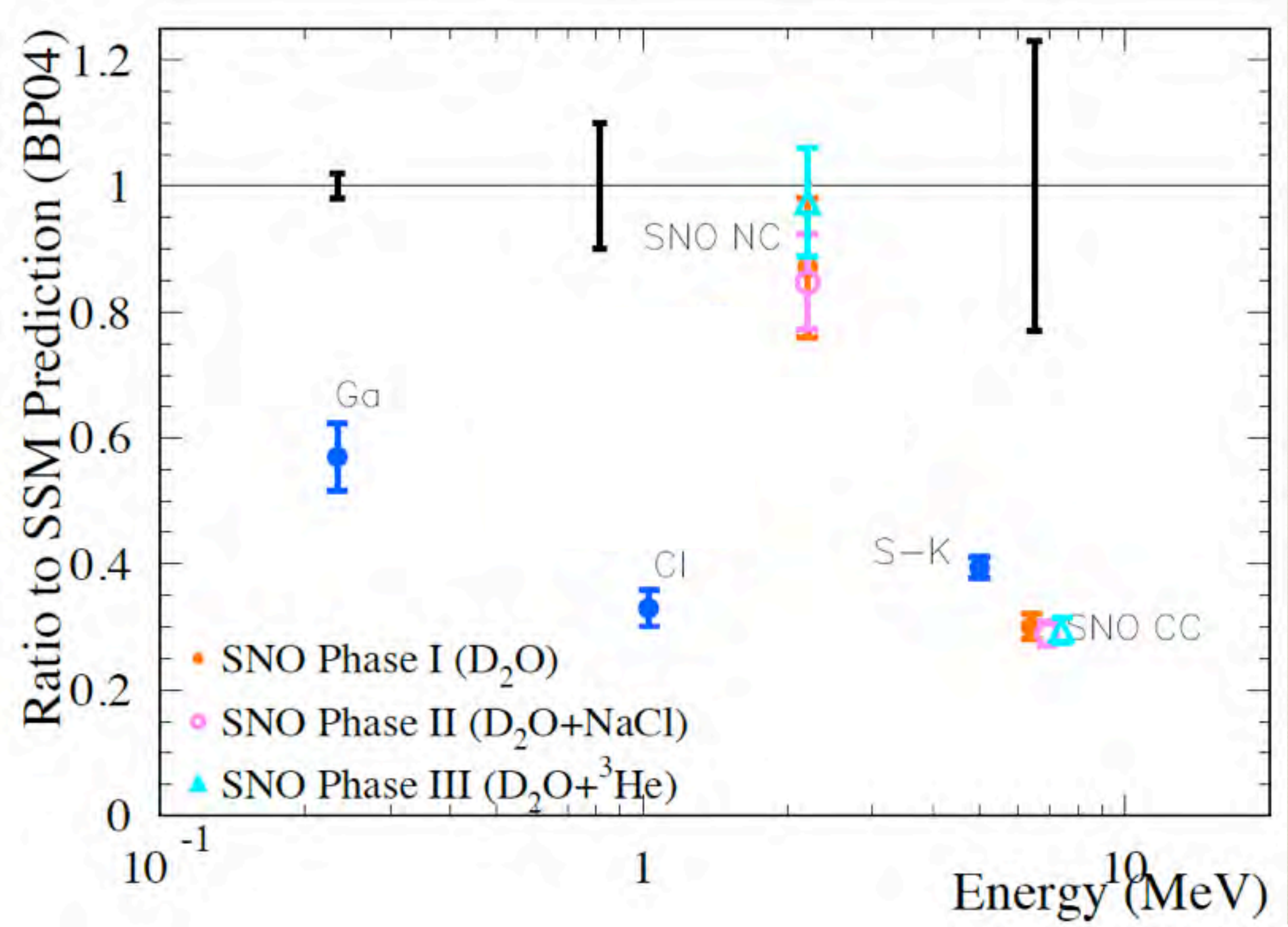
$\Phi^{SK}_{ES} - \Phi^{SN}_{CC}$

$\rightarrow 3.3\sigma > 0$

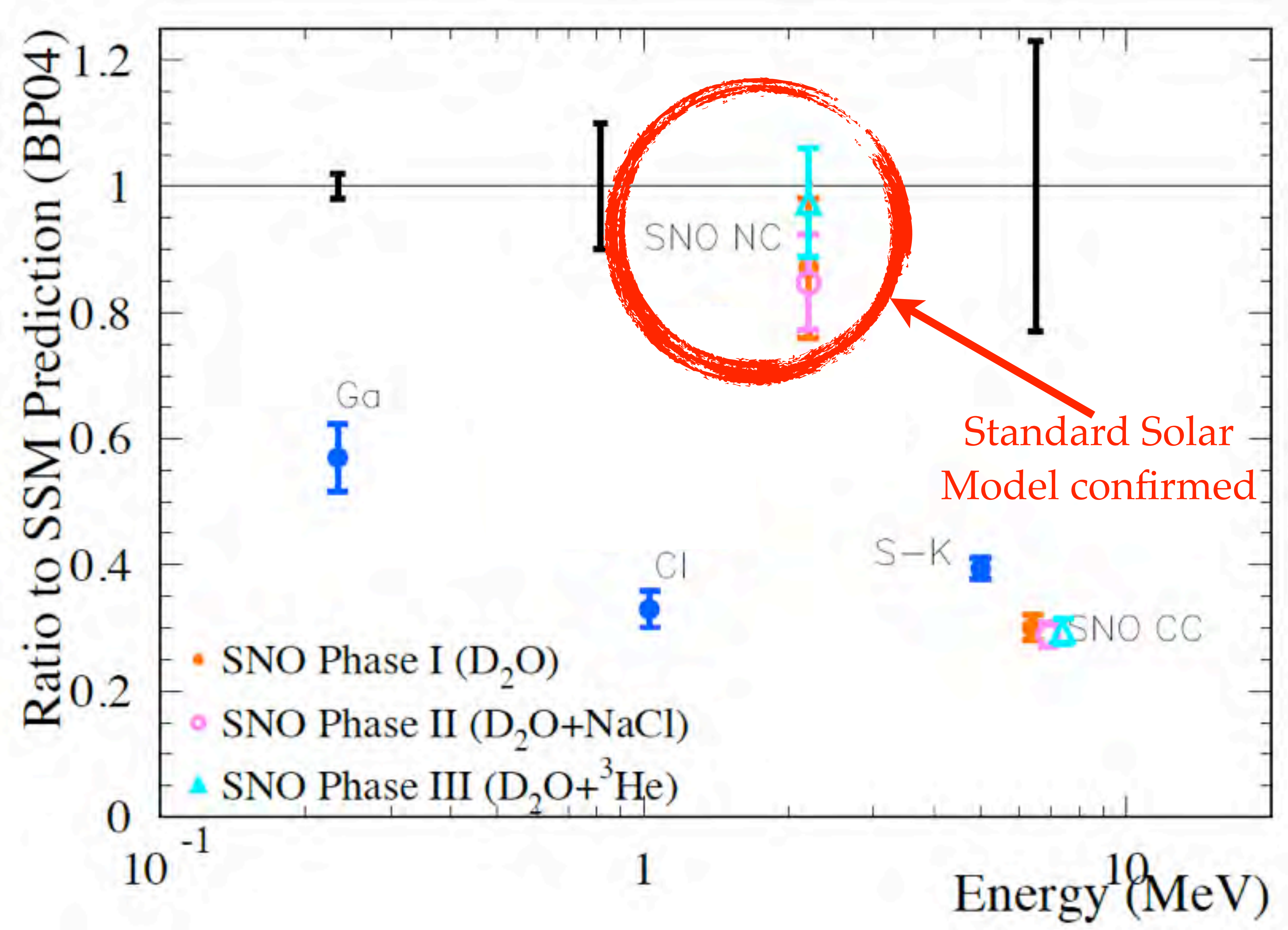
Φ_{NC} Φ_{CC} $\Phi_{\mu\tau}$

$\rightarrow 5.3\sigma > 0$

Improved Results

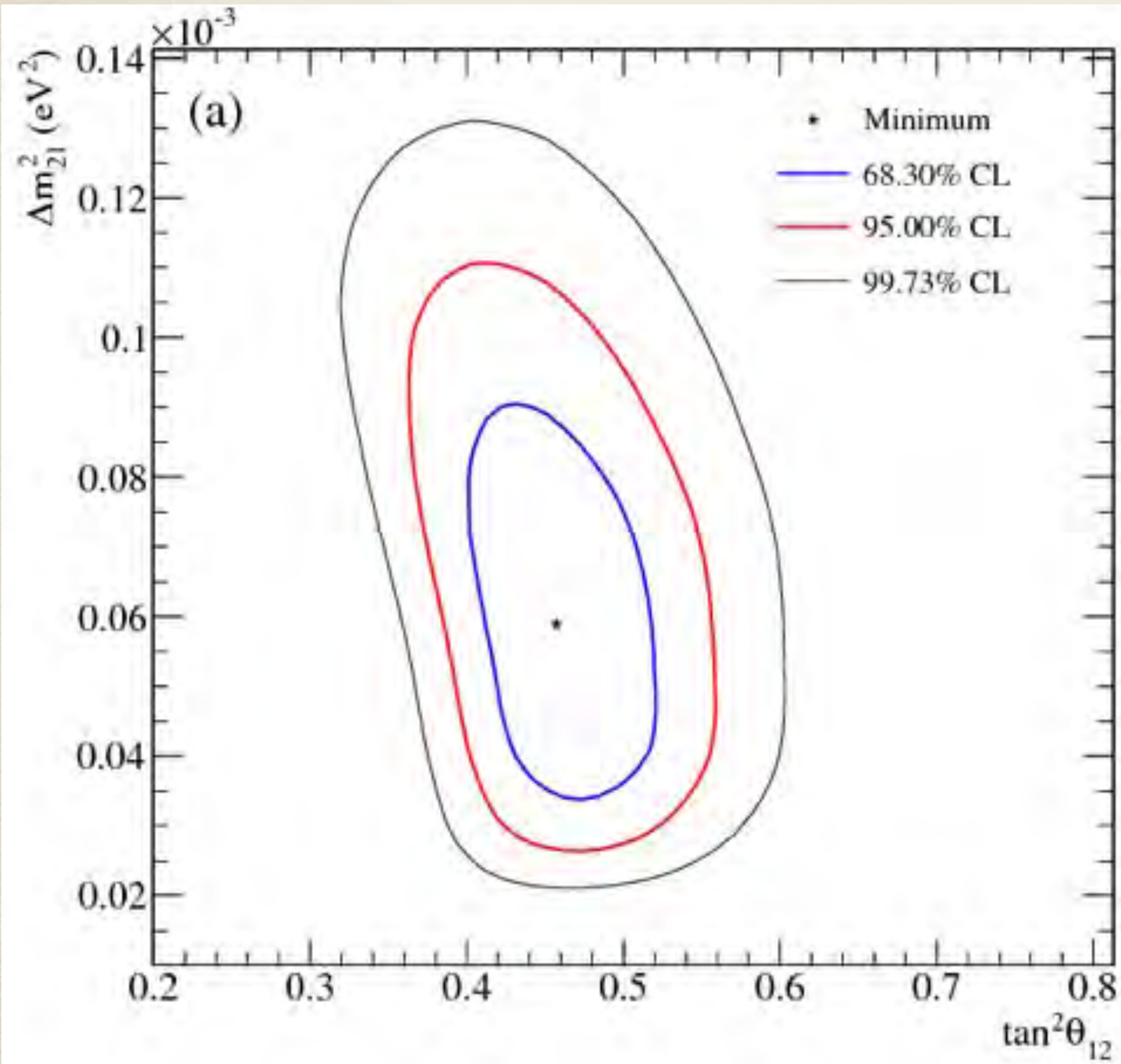


Improved Results



Fortuitous

Solar data:



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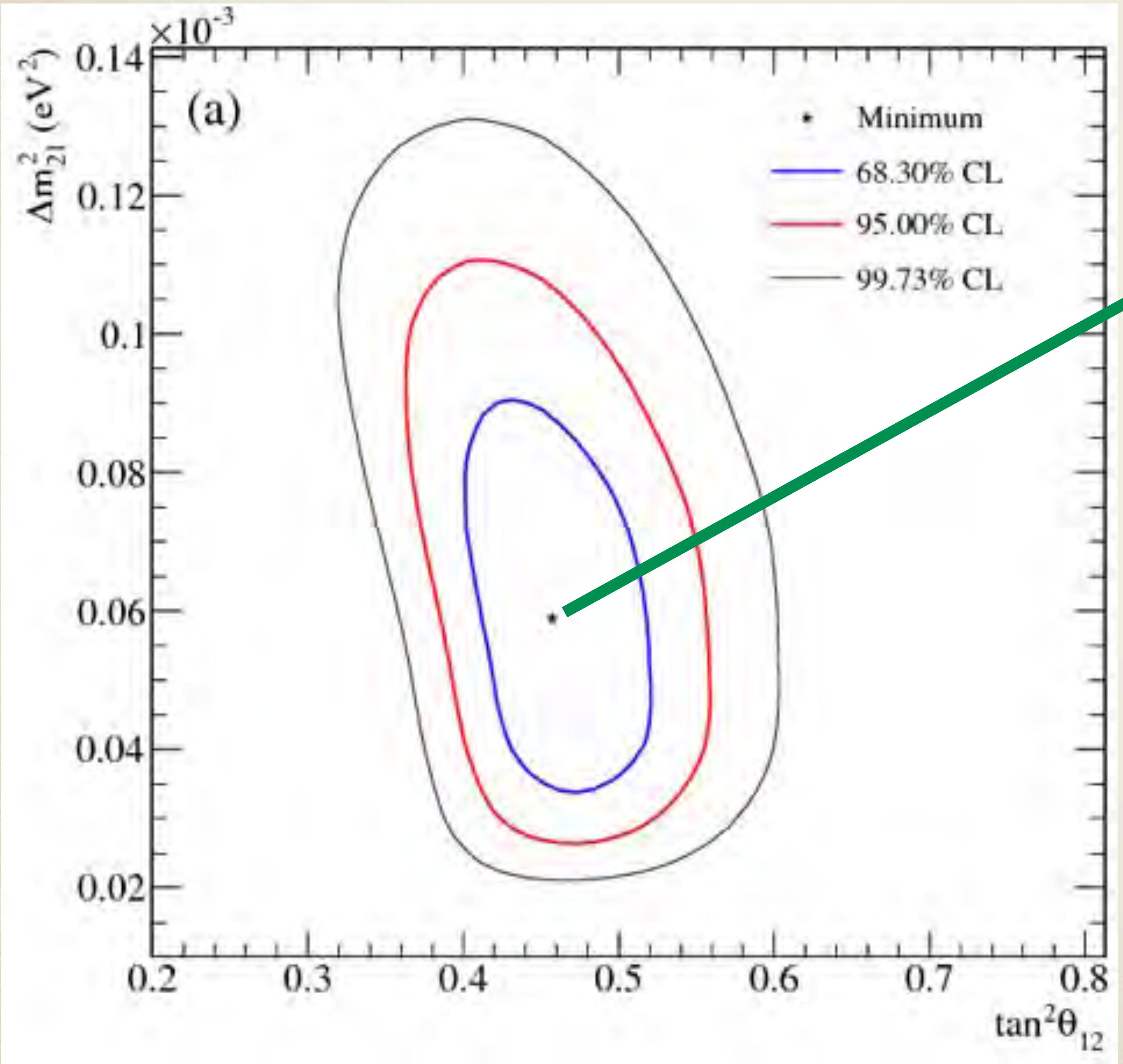

Best-fit point of ***vacuum*** oscillation parameters under the hypothesis of MSW oscillations

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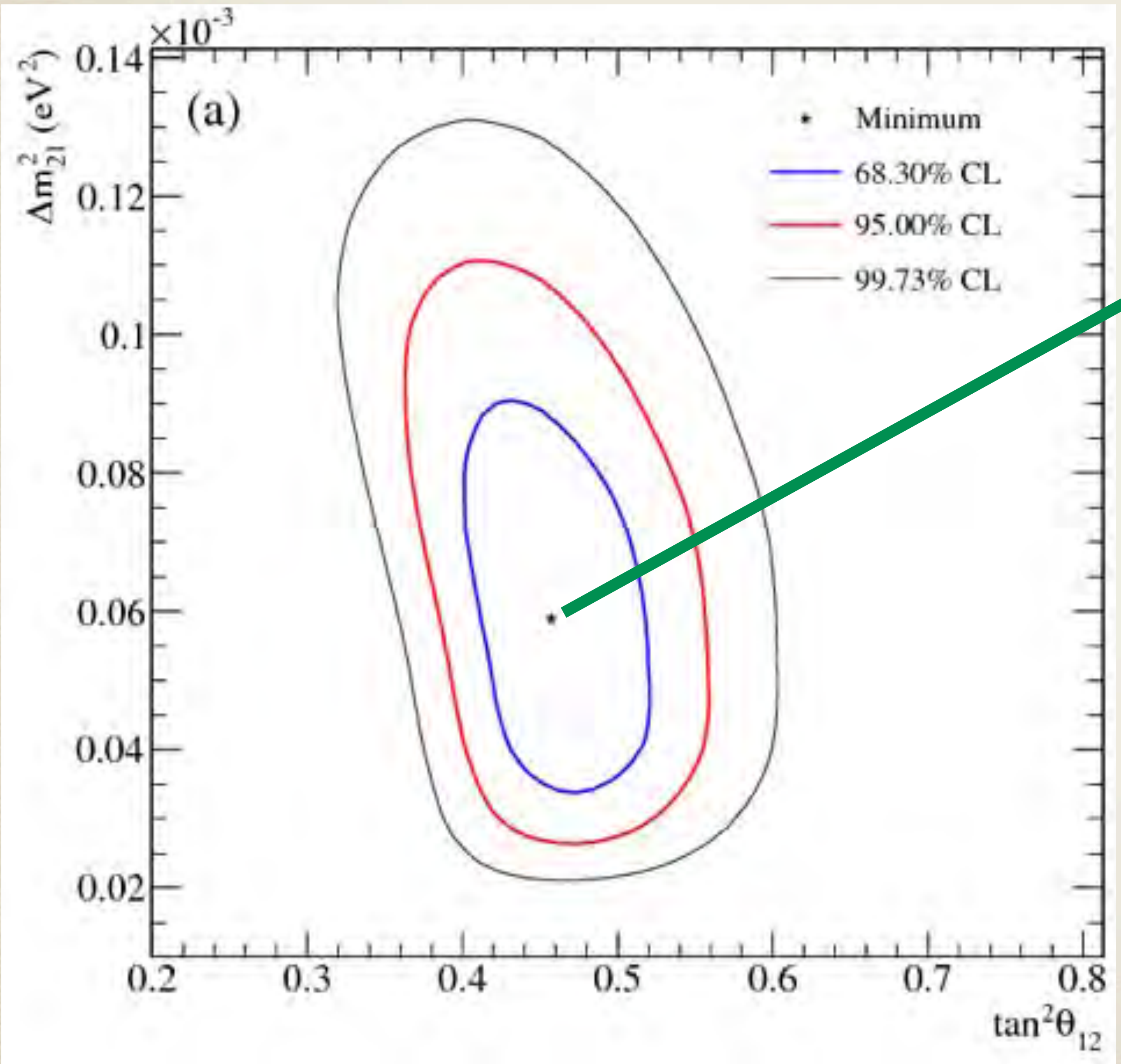
Solar data:



Best-fit point of ***vacuum*** oscillation parameters under the hypothesis of MSW oscillations

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$

L ~ 70 km for E = 4 MeV

Can do this on Earth!

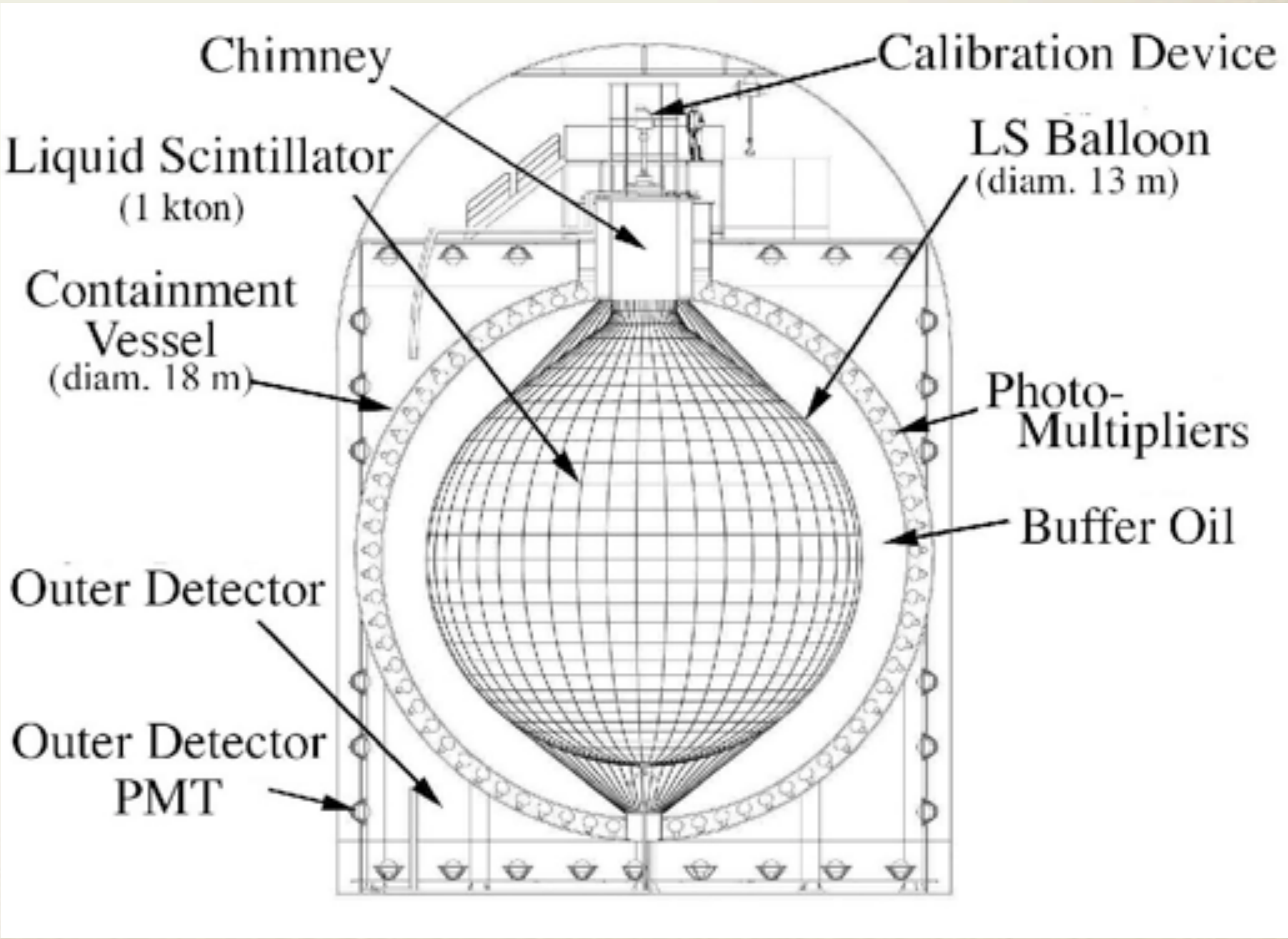
Even More Fortuitous

* KamLAND reactor experiment proposed before SNO data
* Multiple reactors in Japan at L_{ave} = 180 km (flux-weighted average)
* E_ν ~ 2-4 MeV
* 1 kT liquid scintillator
* 34% photocathode coverage
* Inverse beta decay:

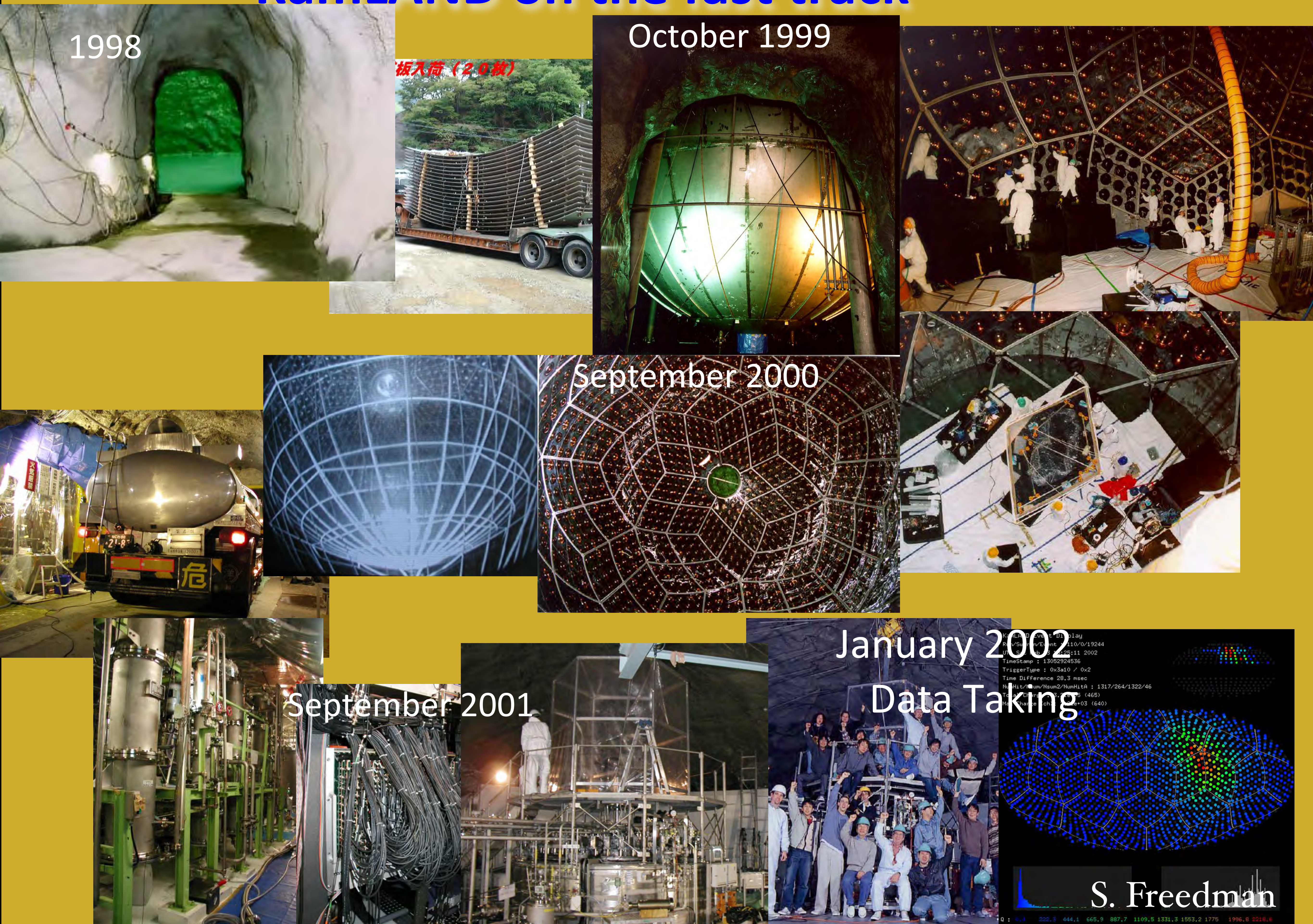
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Same as Reines/Cowan

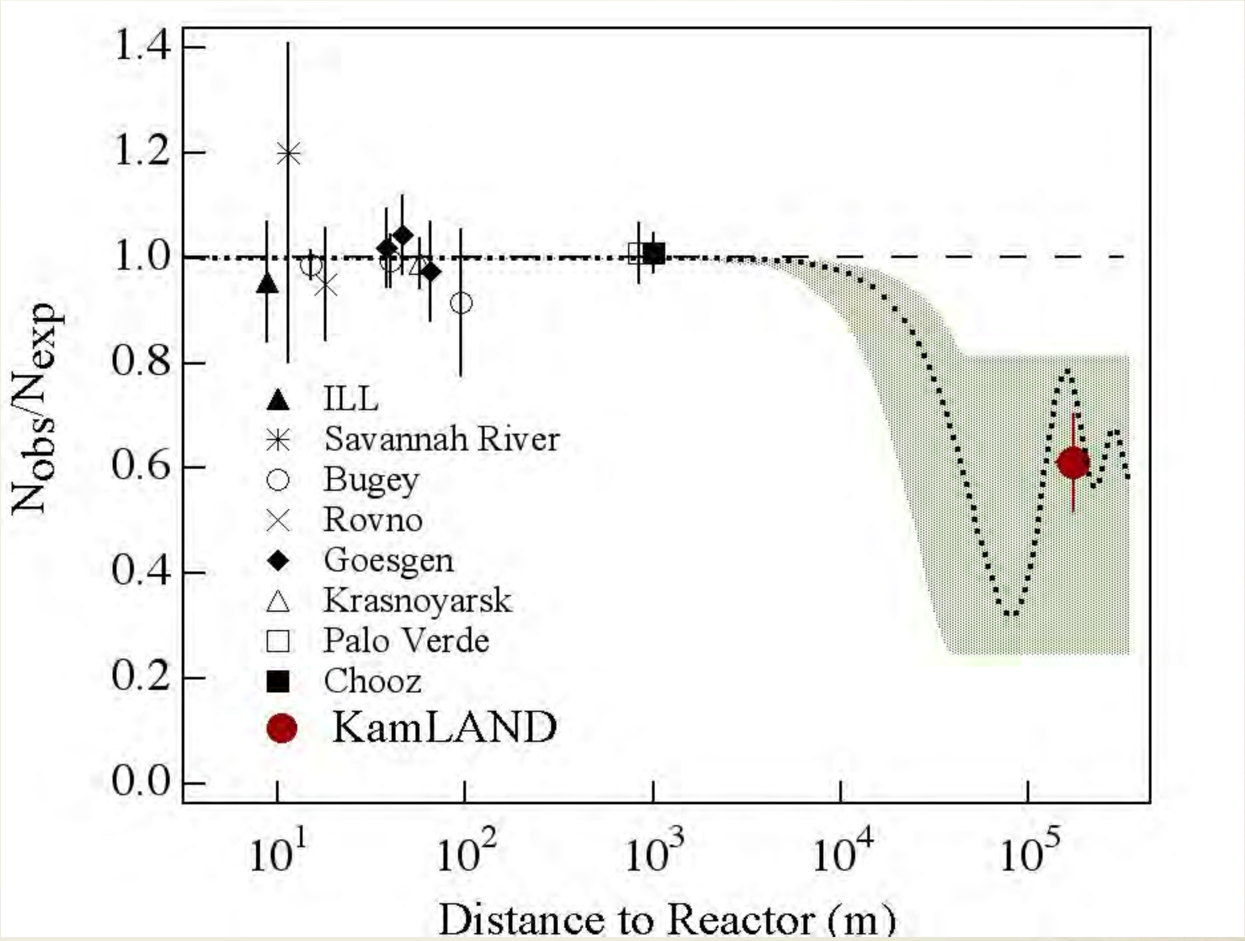
KamLAND



KamLAND on the fast track



Results



PRL, 2003

Most cited physics paper, 2003

Results

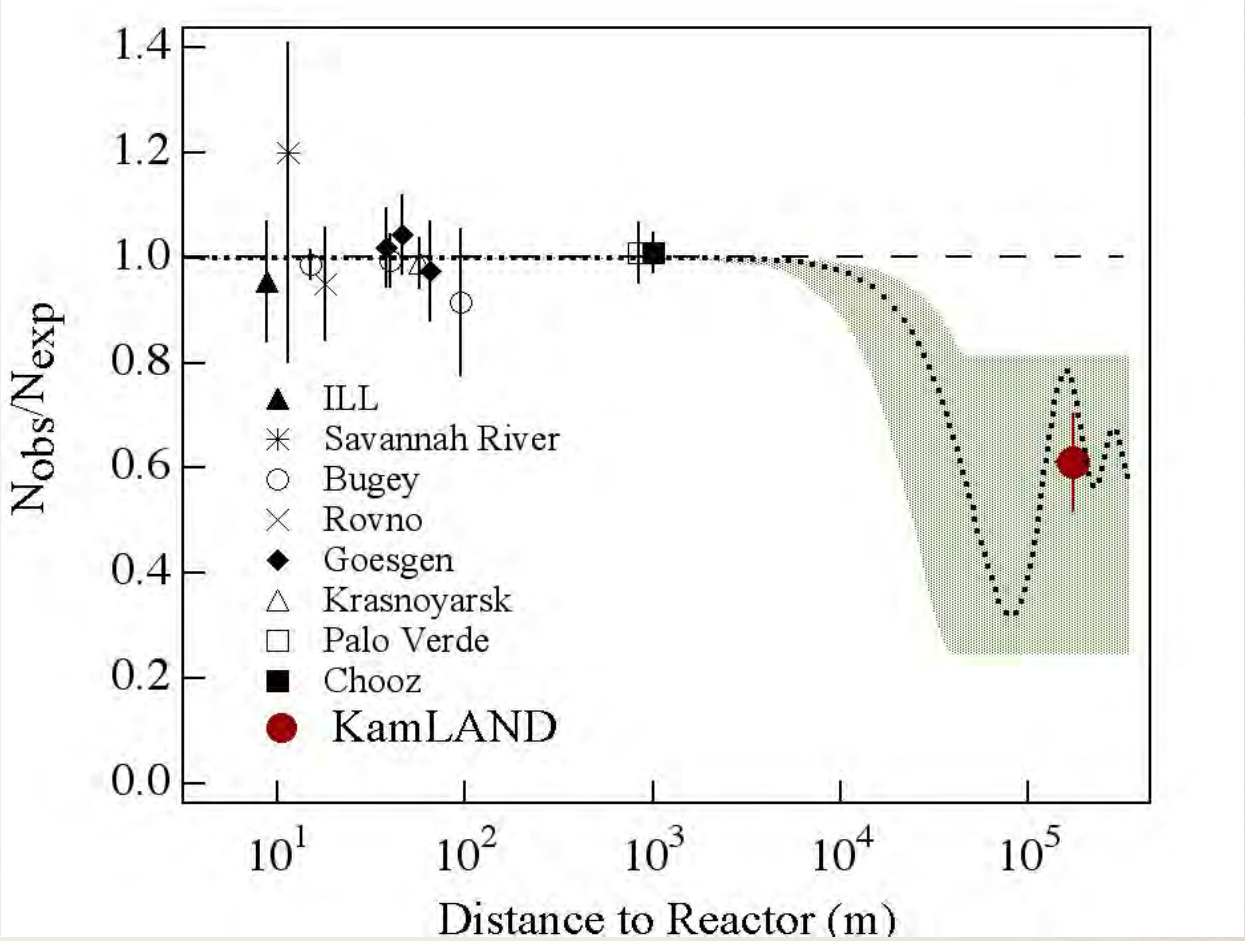
* Flux suppression:

  766 ton-yrs

  expect 365.2 + 17.8 bkg events

  observe 258

* Disappearance at 99.998% significance



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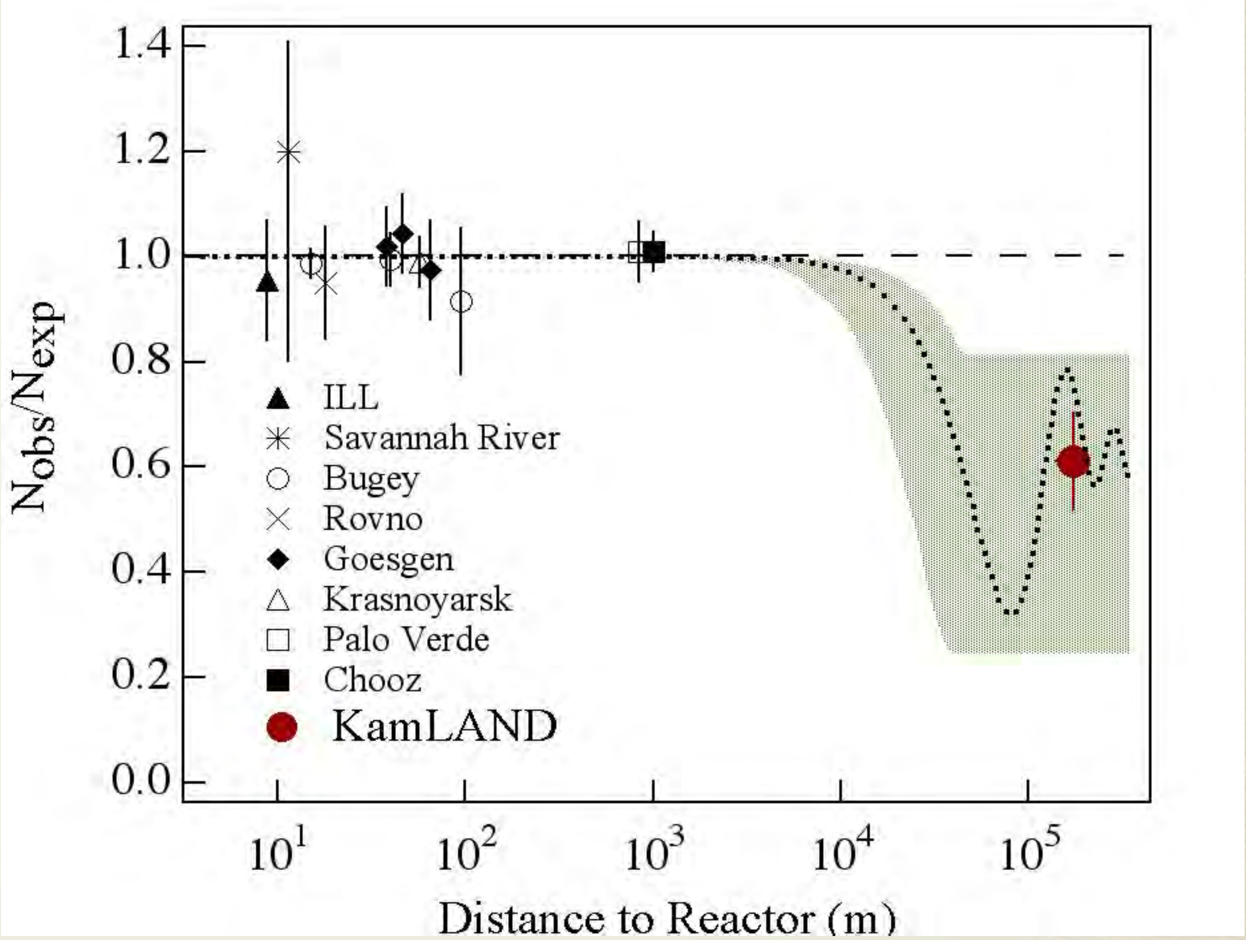

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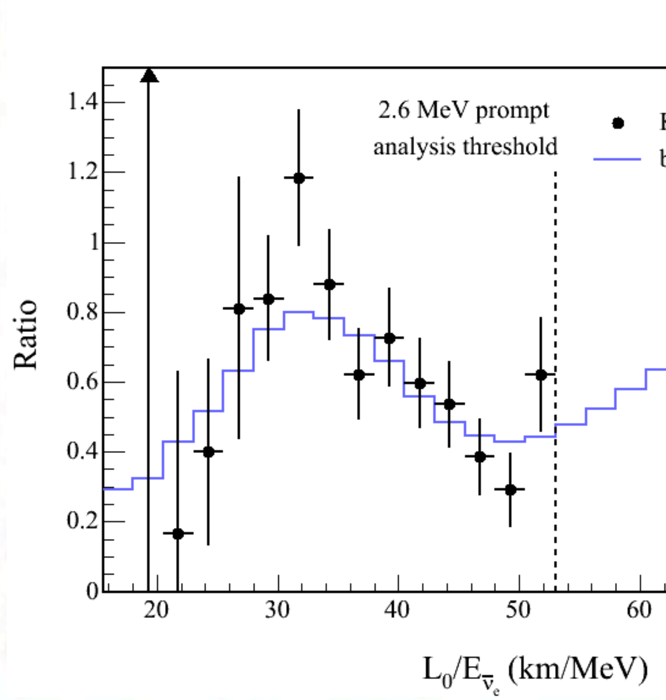
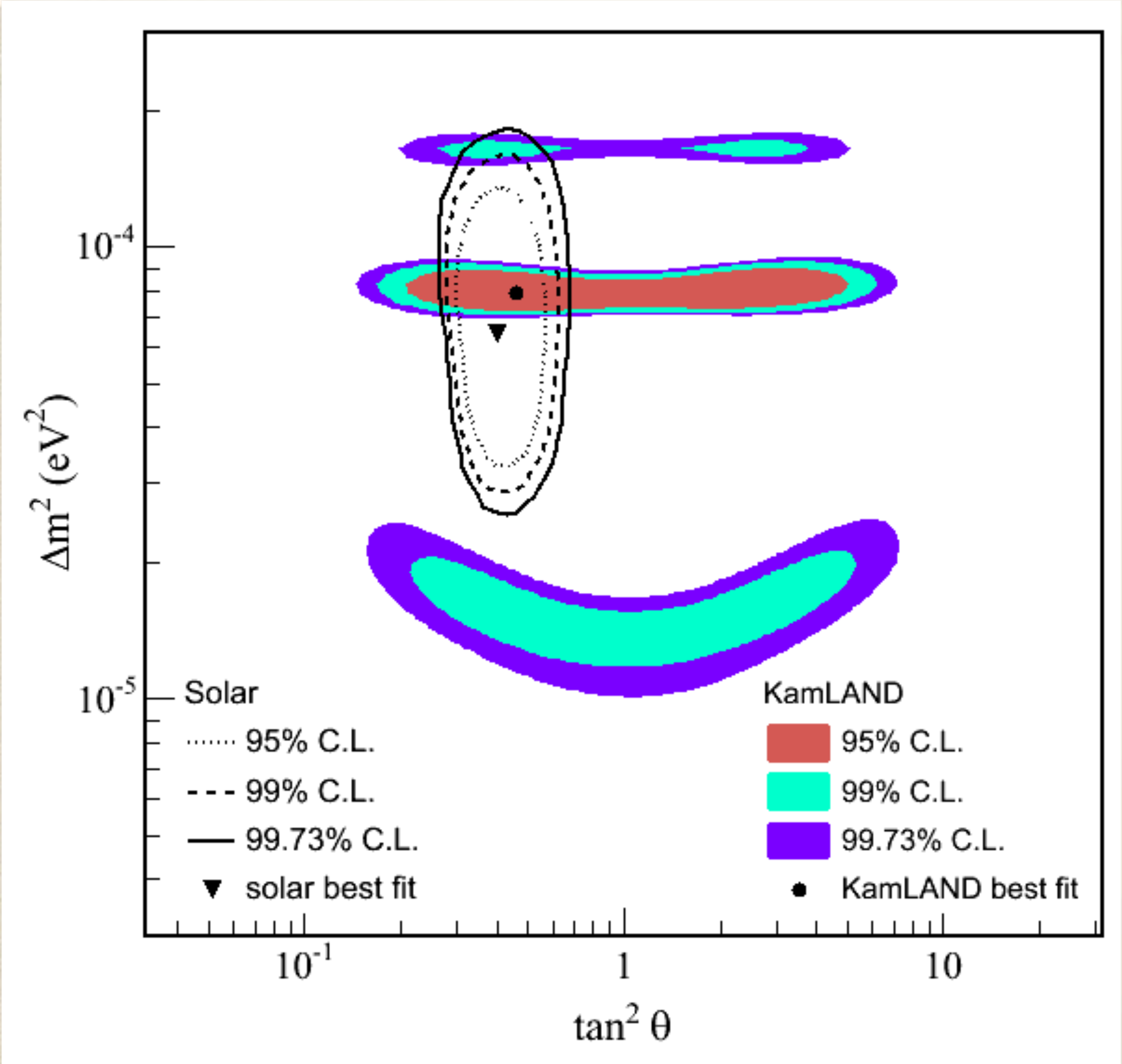


PRL, 2005

+ oscillation pattern clearly observed

Oscillation Parameters



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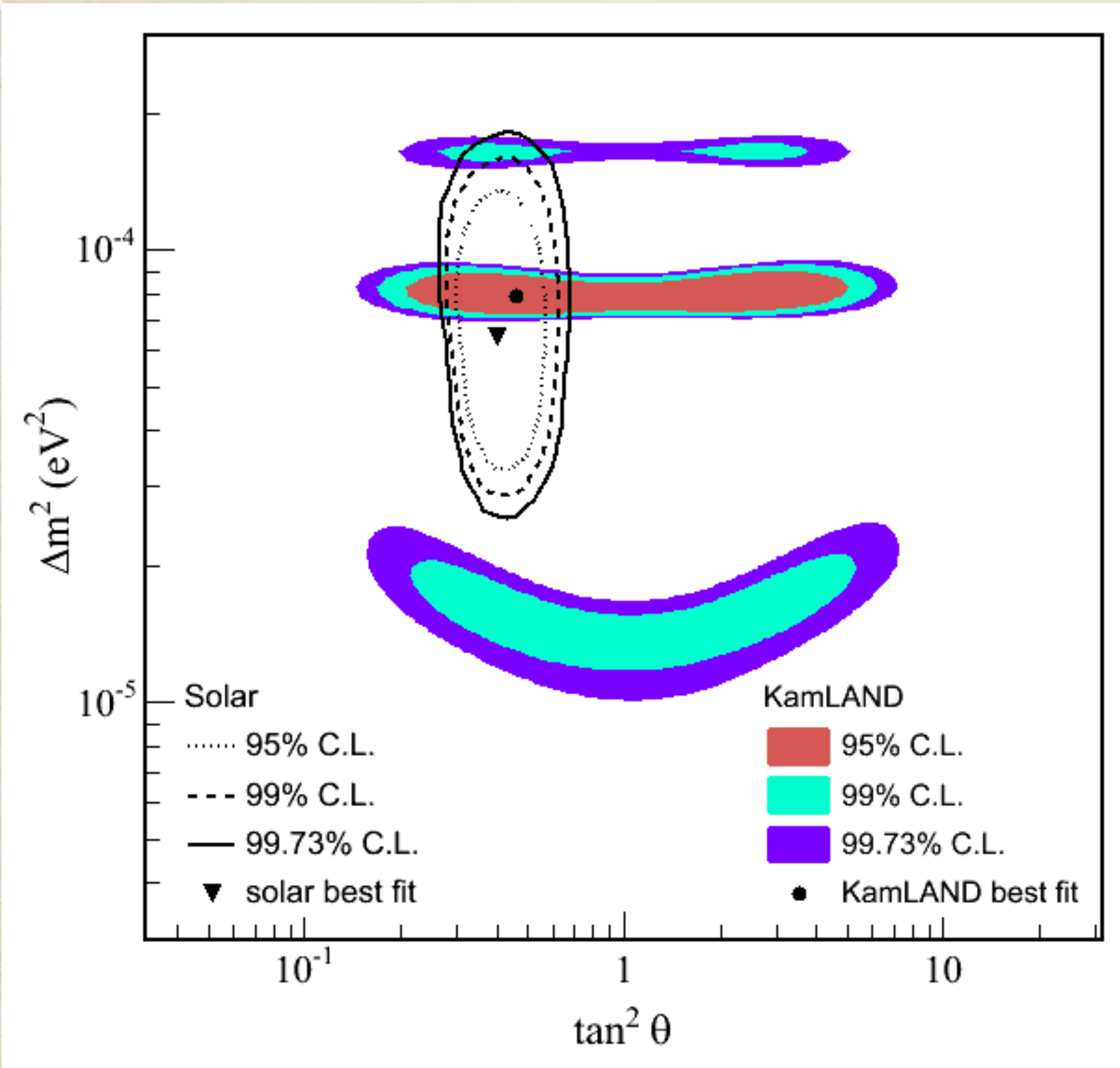
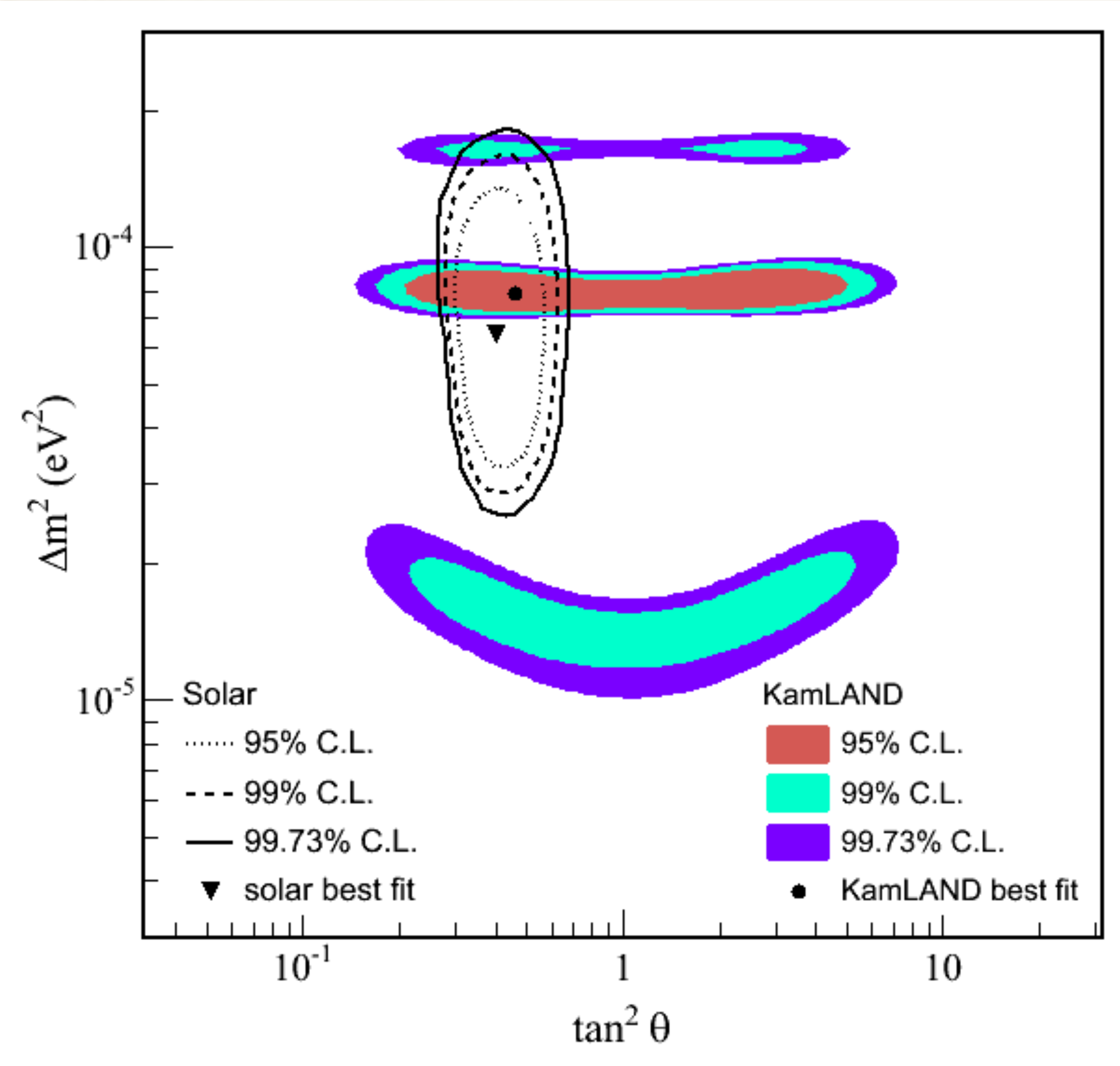


⇒ LMA, Large Mixing Angle

Matter effects dominant at 'high' energies

Oscillation Parameters



- Precision test of SM

	Reactor	Solar
E / MeV	2 - 10	0.1 - 15
L / km	150	1.50E+08
MSW?	No	Yes
Neutrinos	Anti-ν_e	ν_e

⇒ LMA, Large Mixing Angle
Matter effects dominant at 'high' energies

Solar Neutrinos

"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'

Then the SNO results came out.

And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"

--- John Bahcall, 2003

Solar Neutrinos come to Hollywood!

"2012"

"We were warned"

Solar Eruptions Cause Spikes in Neutrino Flux

"The count doubled after the last solar eruptions"

The End of the World...

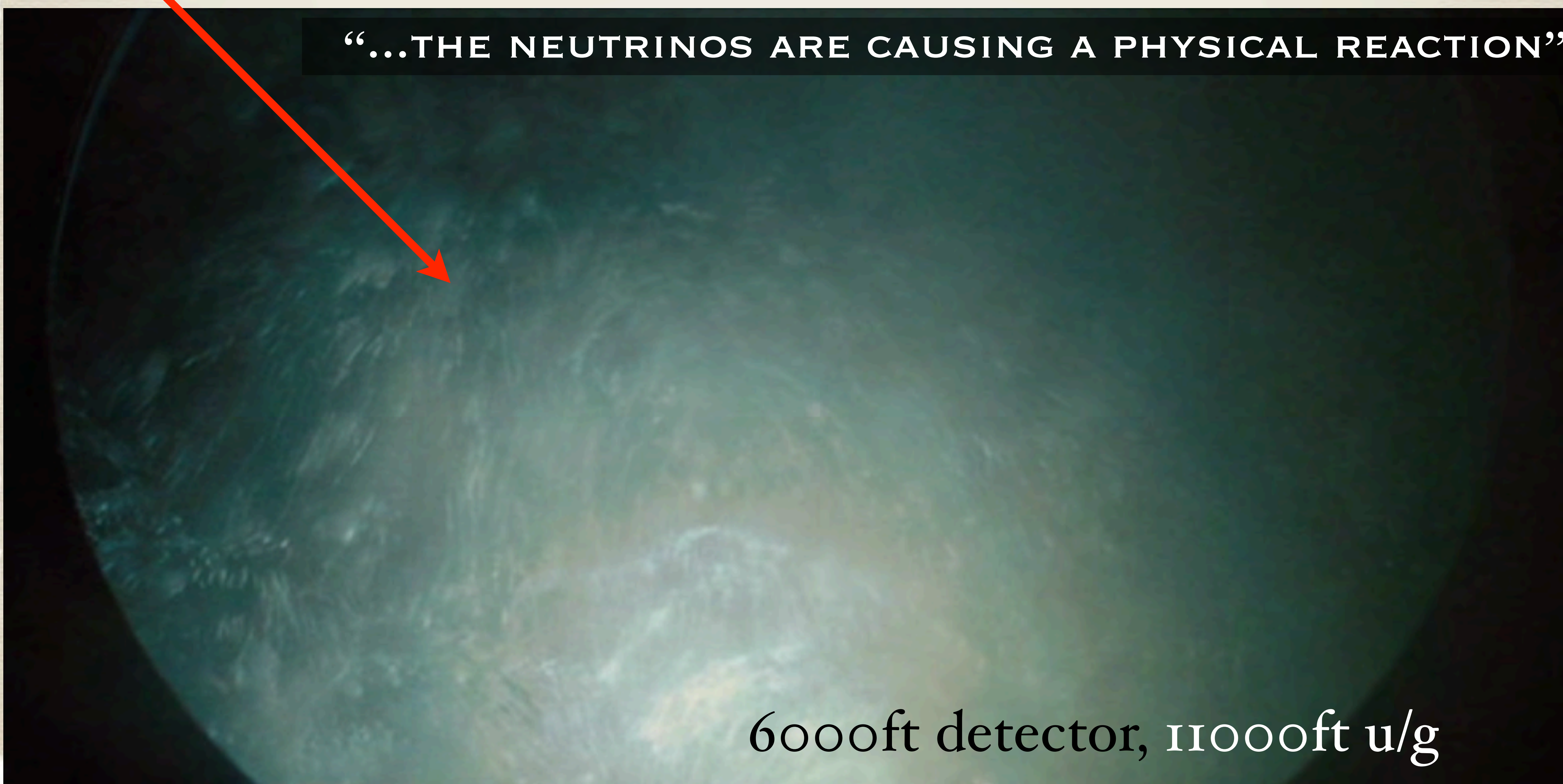
The End of the World...

Incident νs cause water target to boil...

The End of the World...

Incident νs cause water target to boil...

but only underground...



Evidence for MSW?

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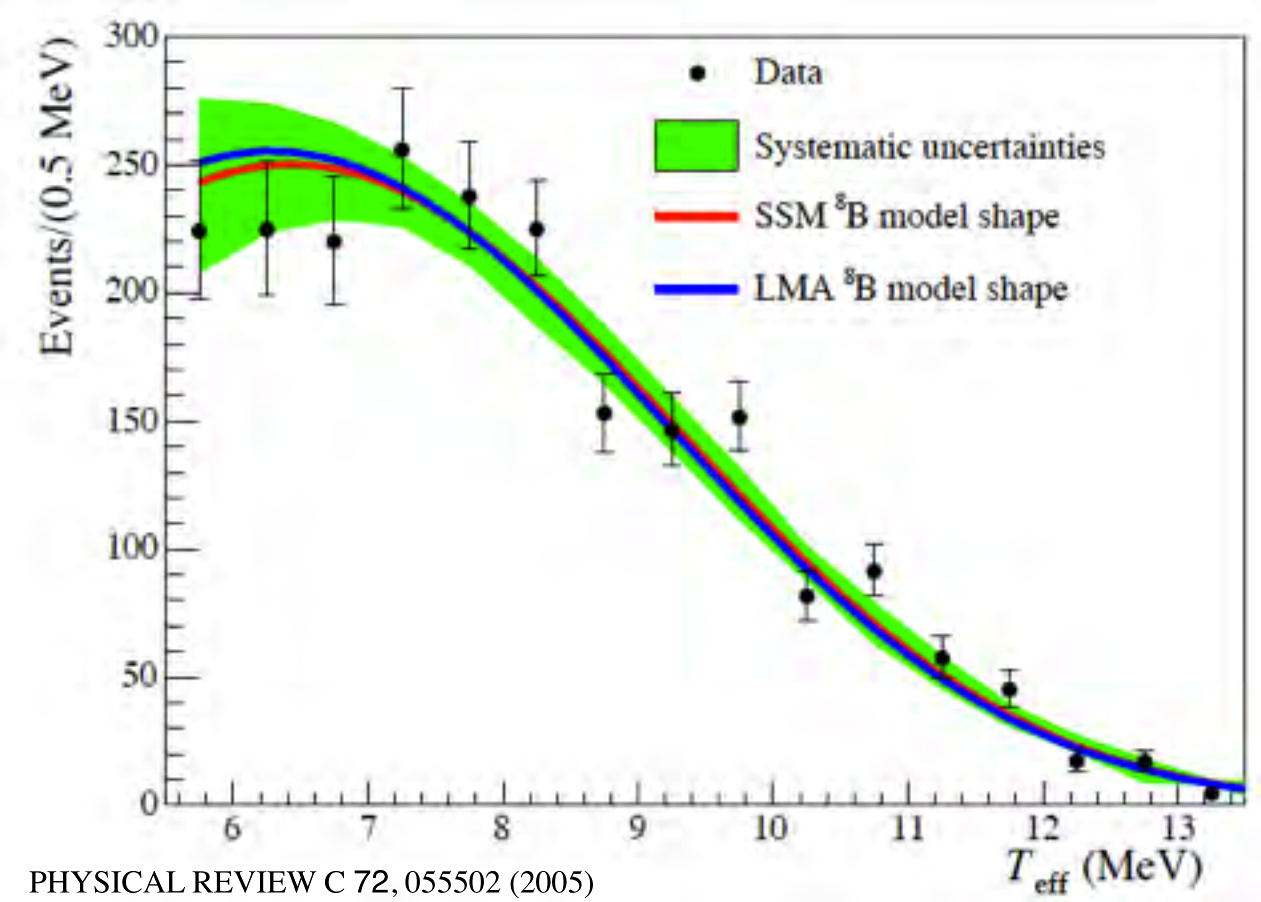
* MSW makes two predictions:

Evidence for MSW?

* MSW makes two predictions:

(1) Spectral distortion



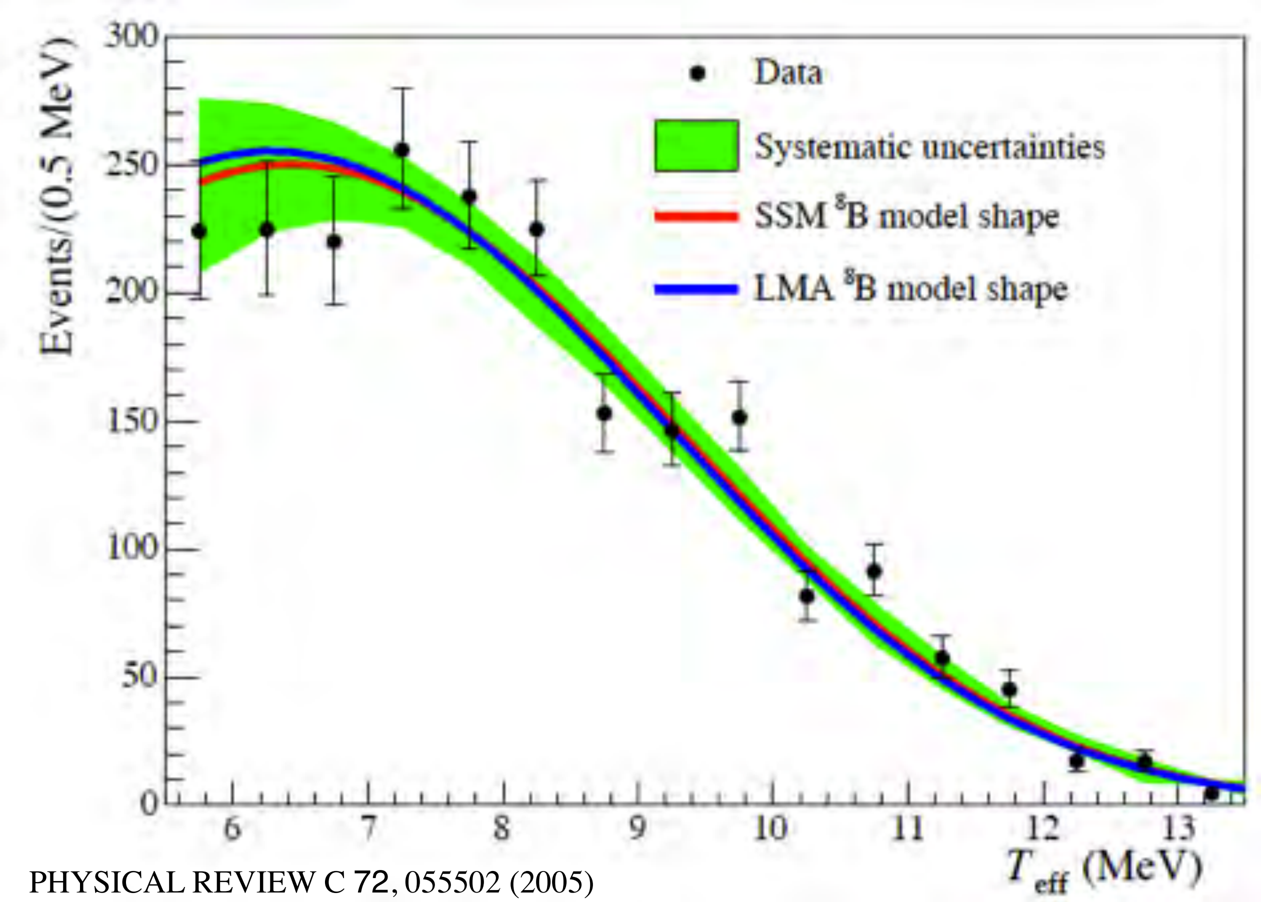
PHYSICAL REVIEW C 72, 055502 (2005)

Evidence for MSW?

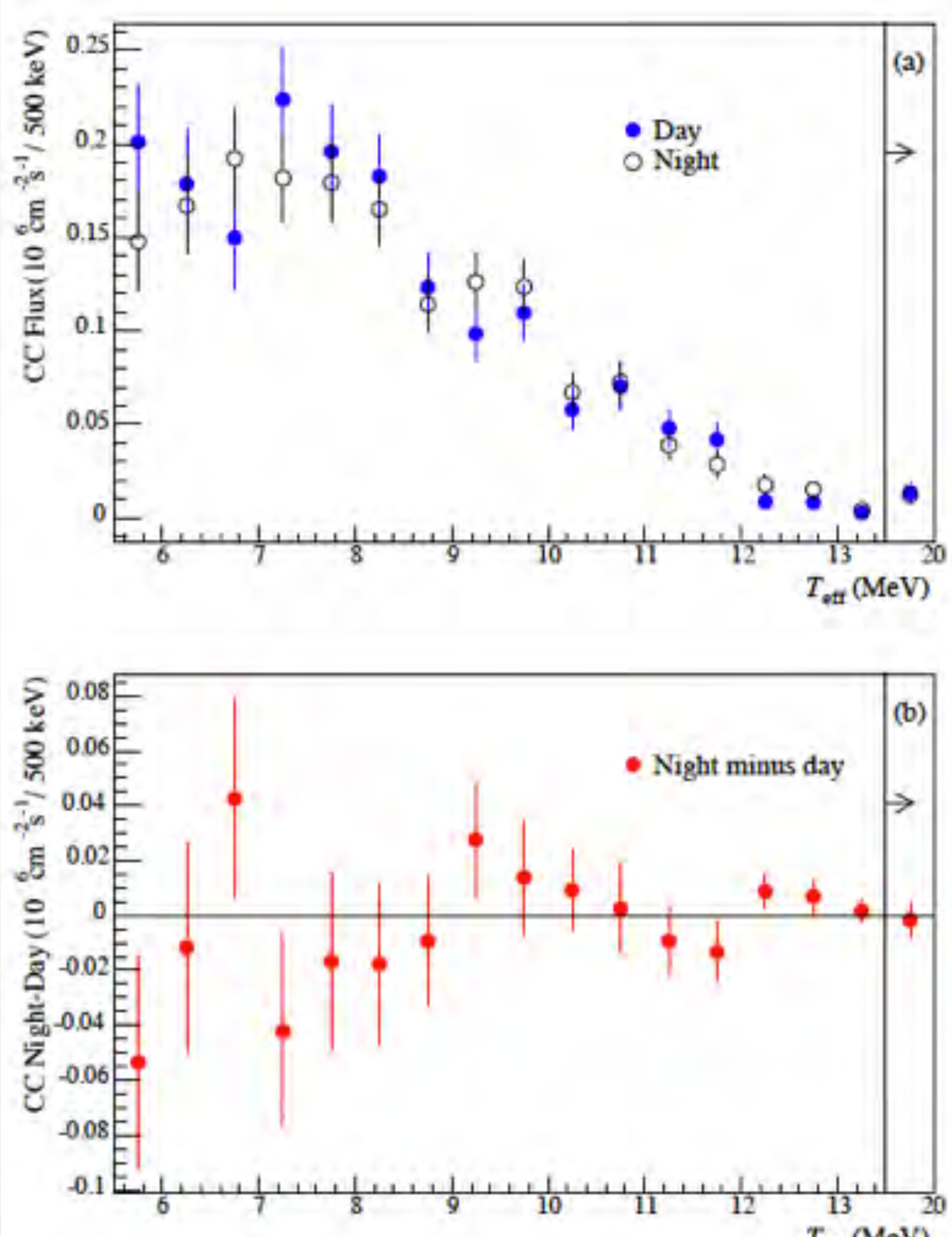
* MSW makes two predictions:

(1) Spectral distortion

(2) Day / night asymmetry



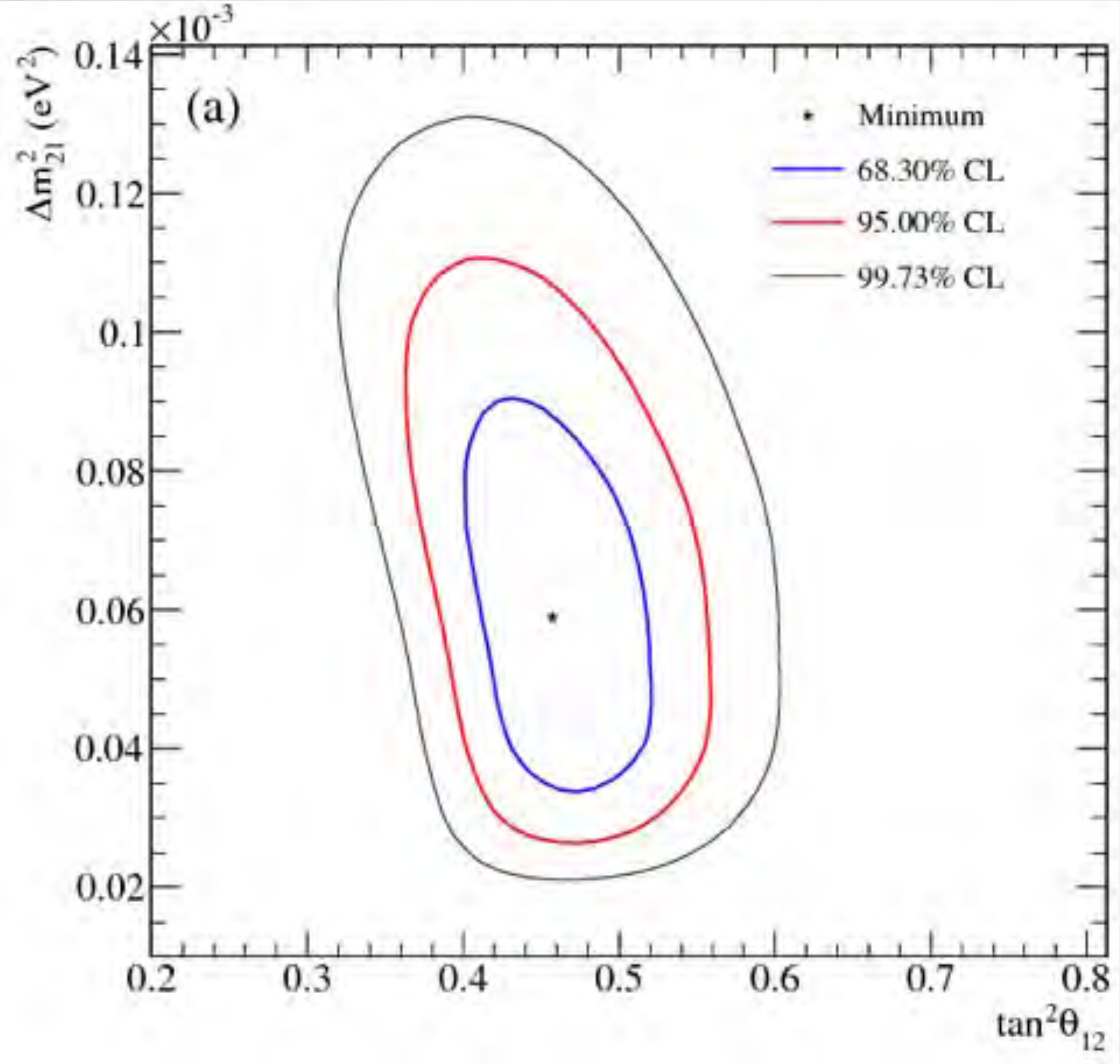
PHYSICAL REVIEW C 72, 055502 (2005)



PHYSICAL REVIEW C 72, 055502 (2005)

Did we just get unlucky?

Solar data:



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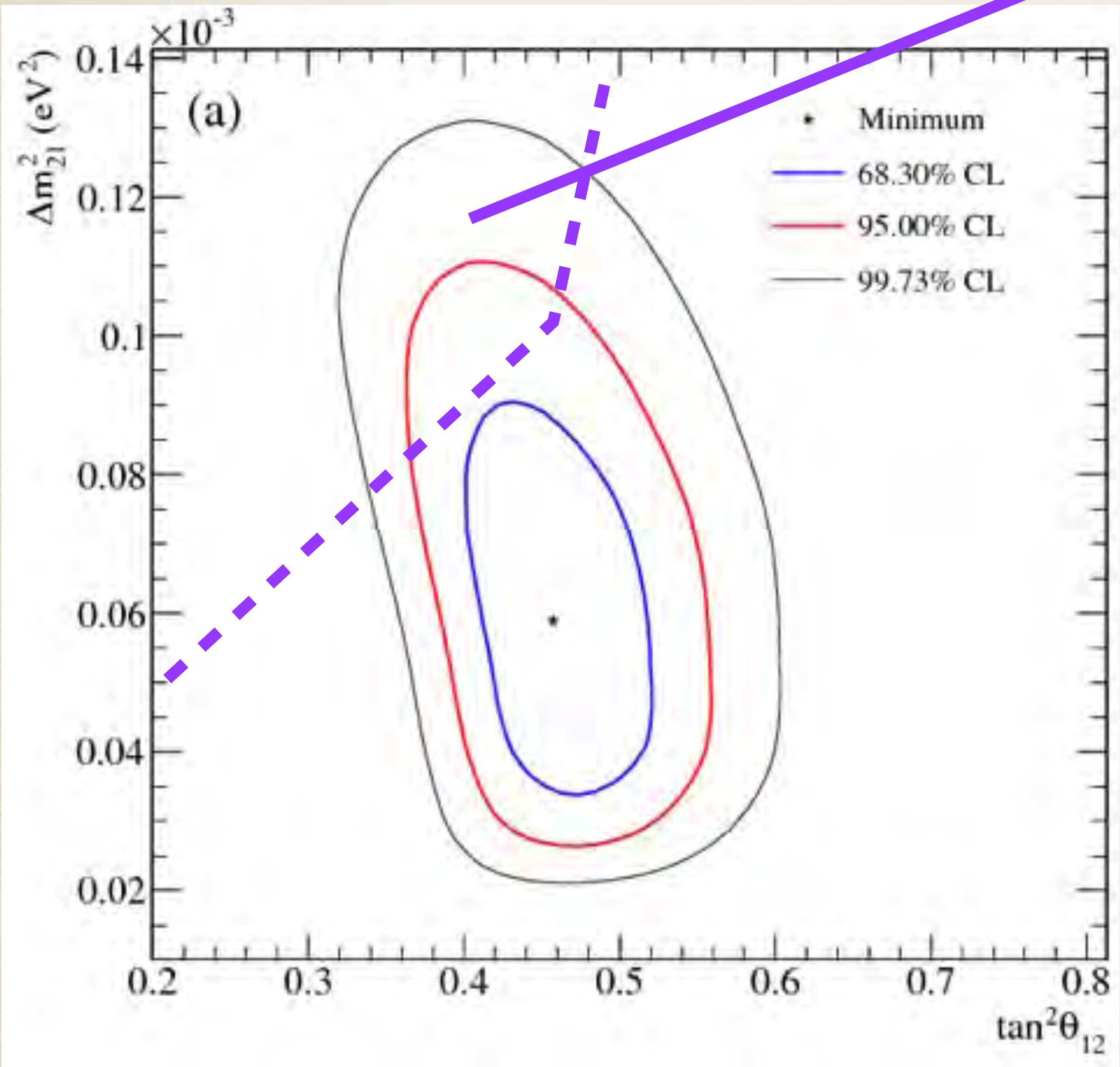
Large spectral distortion



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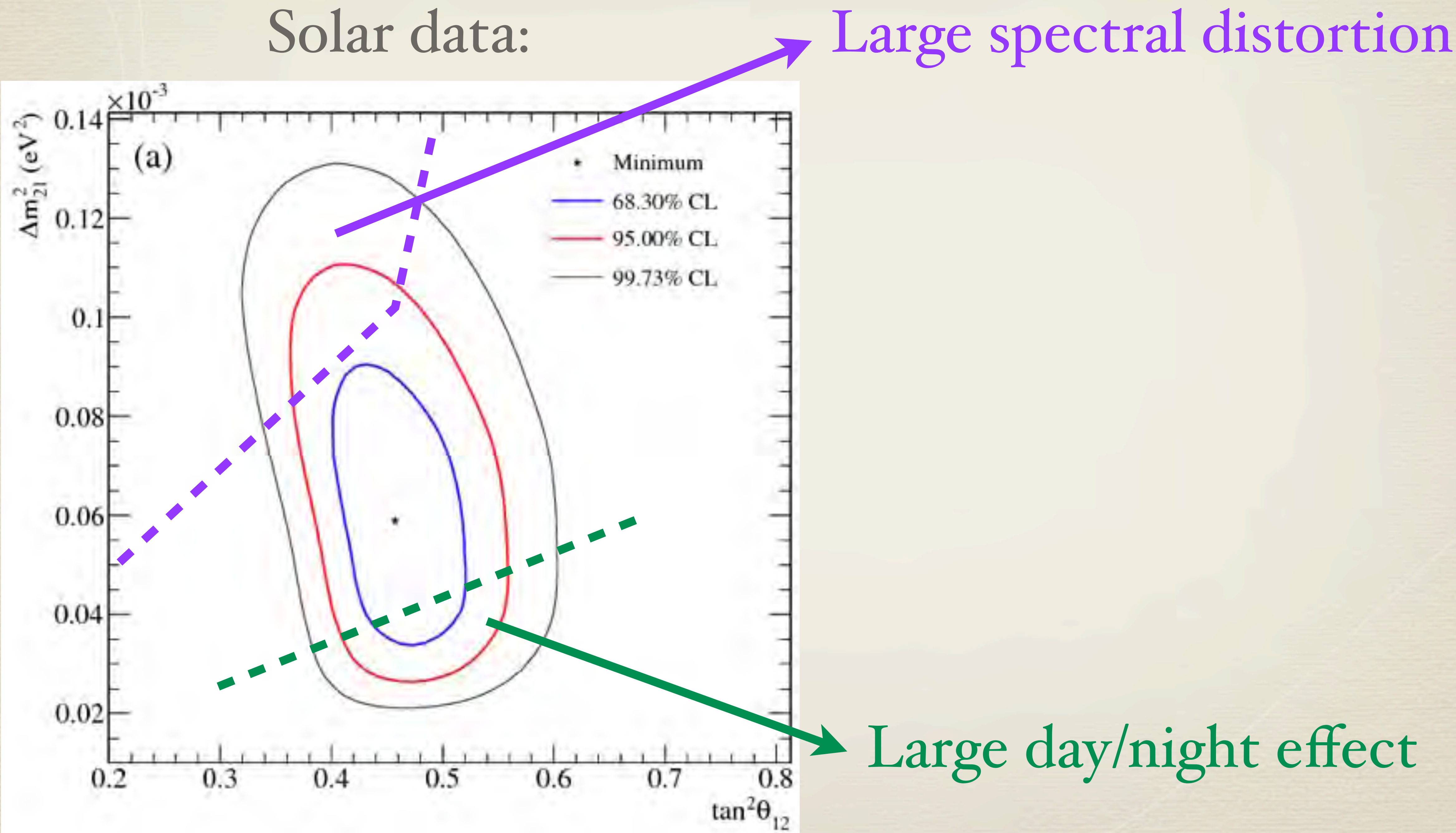

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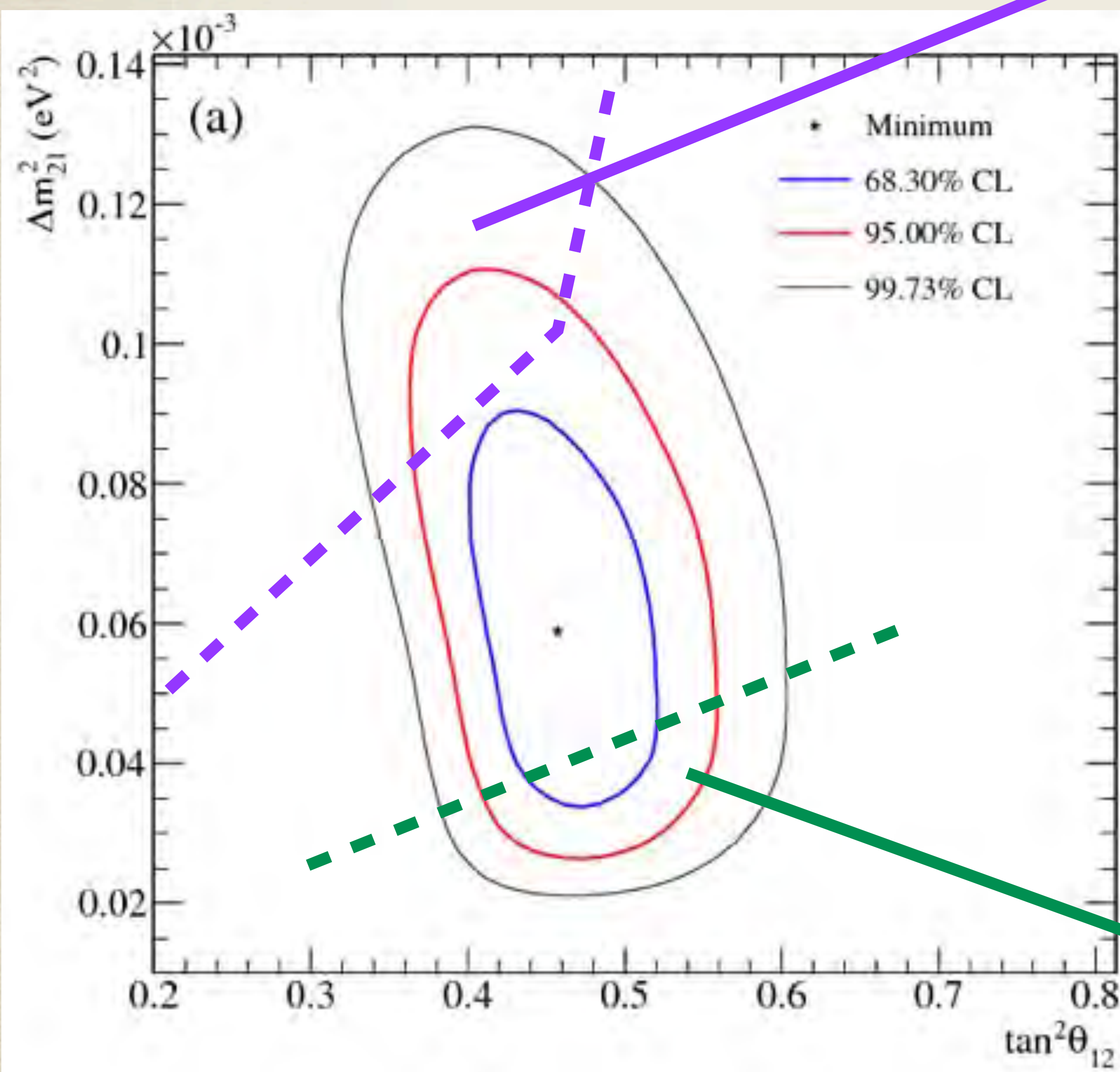


Large spectral distortion

Nature appears to have selected the one region in parameter space with no clear signature...

Large day/night effect

Questions Beyond the SNP

(A) What is the true shape of the ν_e survival probability?

(B) Can we observe the Day / Night effect? (If not, why not??)

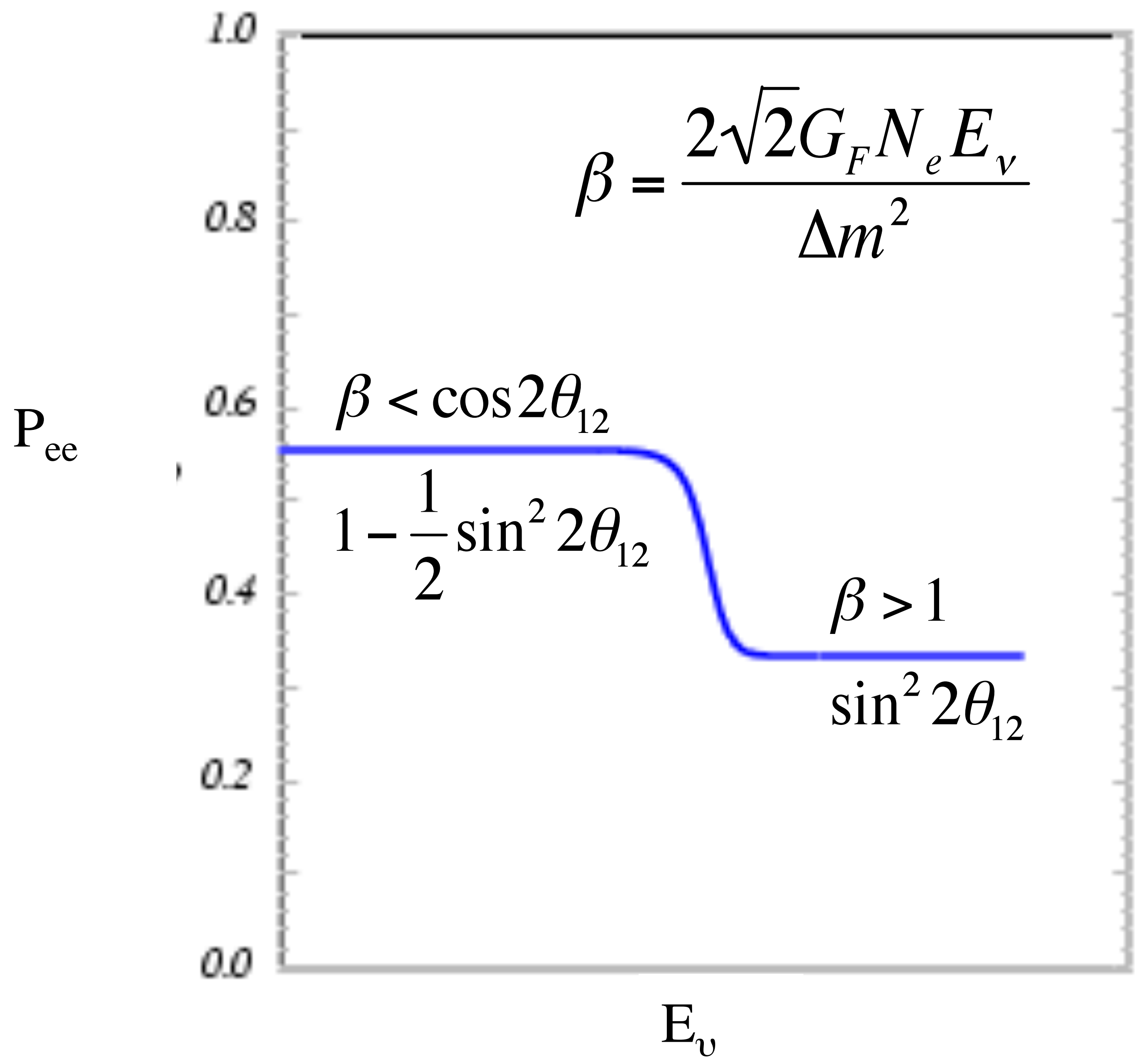
(C) What is the metallicity of the Sun's core?

(D) Can we measure the neutrino luminosity ($\mathcal{L}_\nu$)?

(E) (Are there periodicities / time-dependence to $\mathcal{L}_\nu$?)

(F) (Precision measurements of fluxes & oscillation parameters)

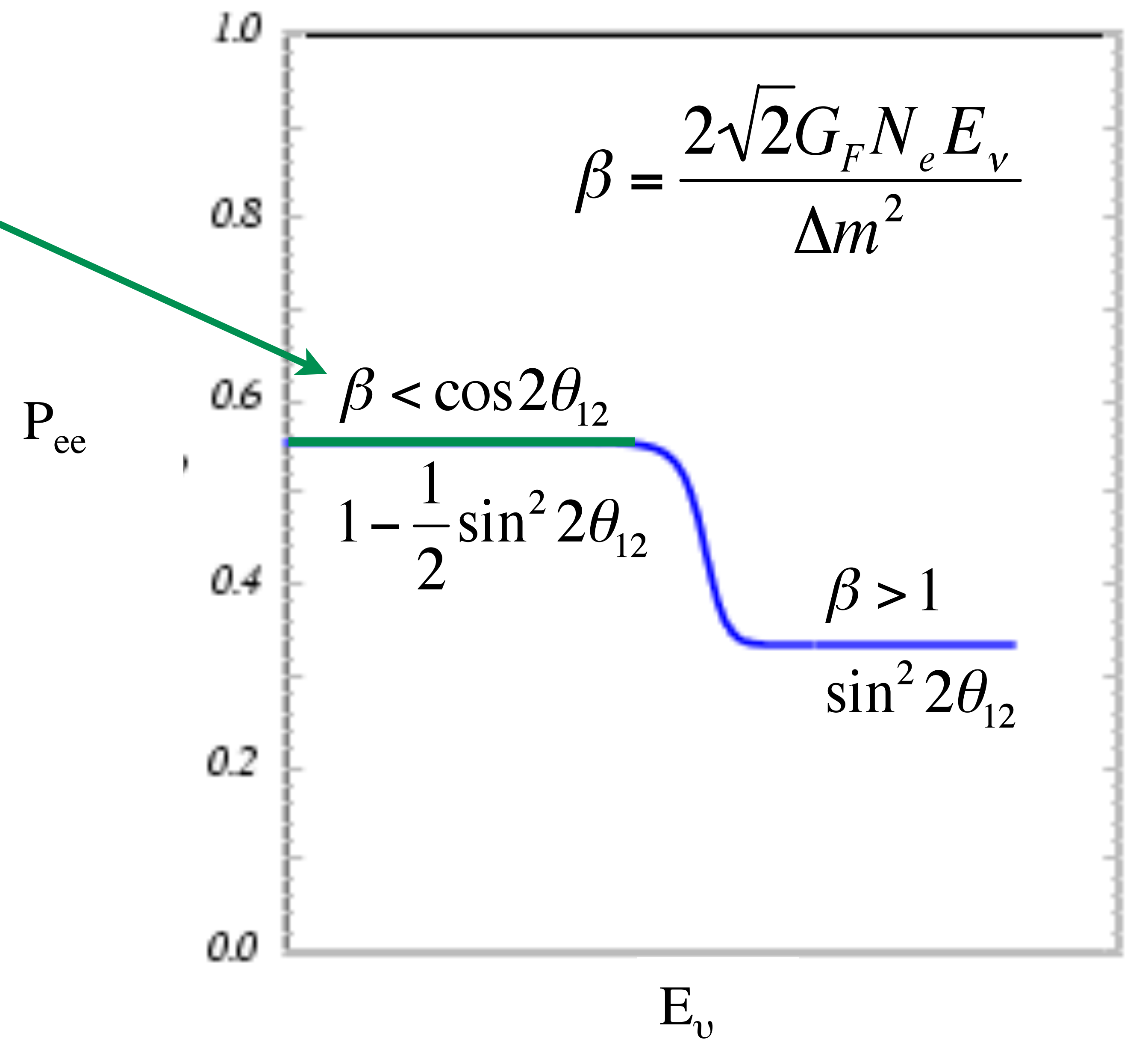
(A) Vacuum-Matter Transition



hep-ph/0305159

(A) Vacuum-Matter Transition

Low energy:
Phase-averaged vacuum oscillations



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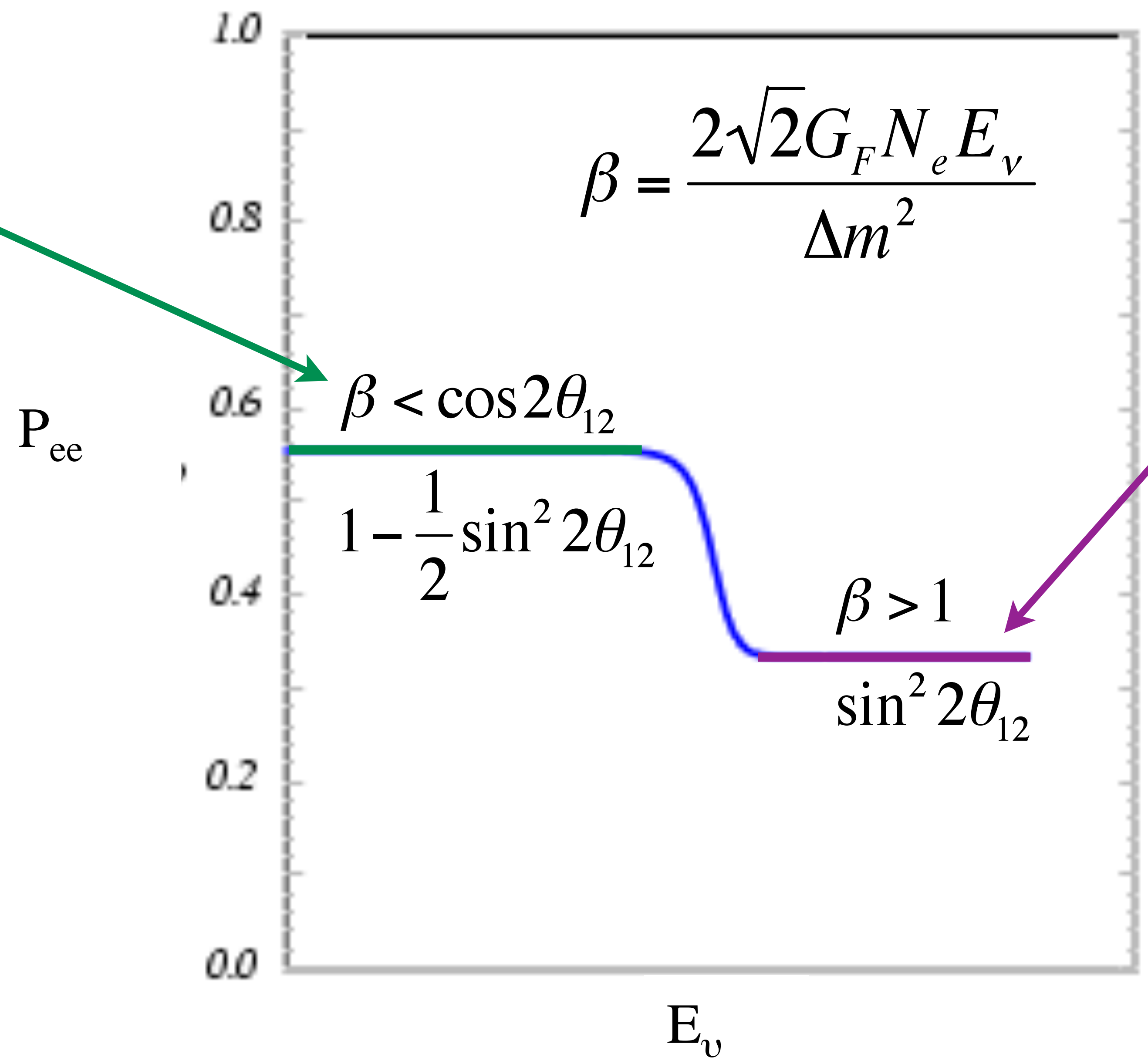

hep-ph/0305159

'High' energy:
Matter-dominated
resonant conversion

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In these regimes, P_{ee} depends only on θ_{12},

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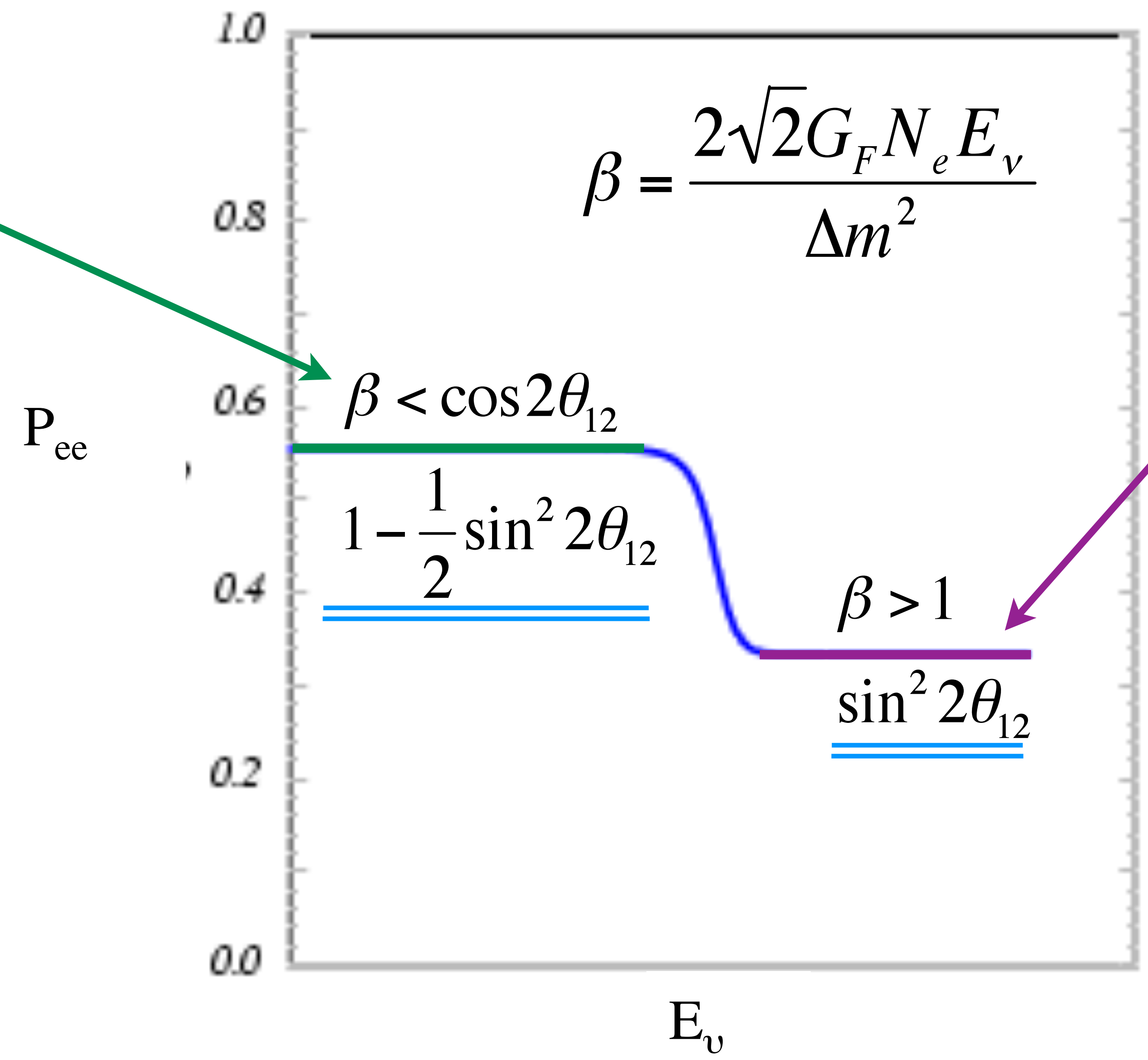

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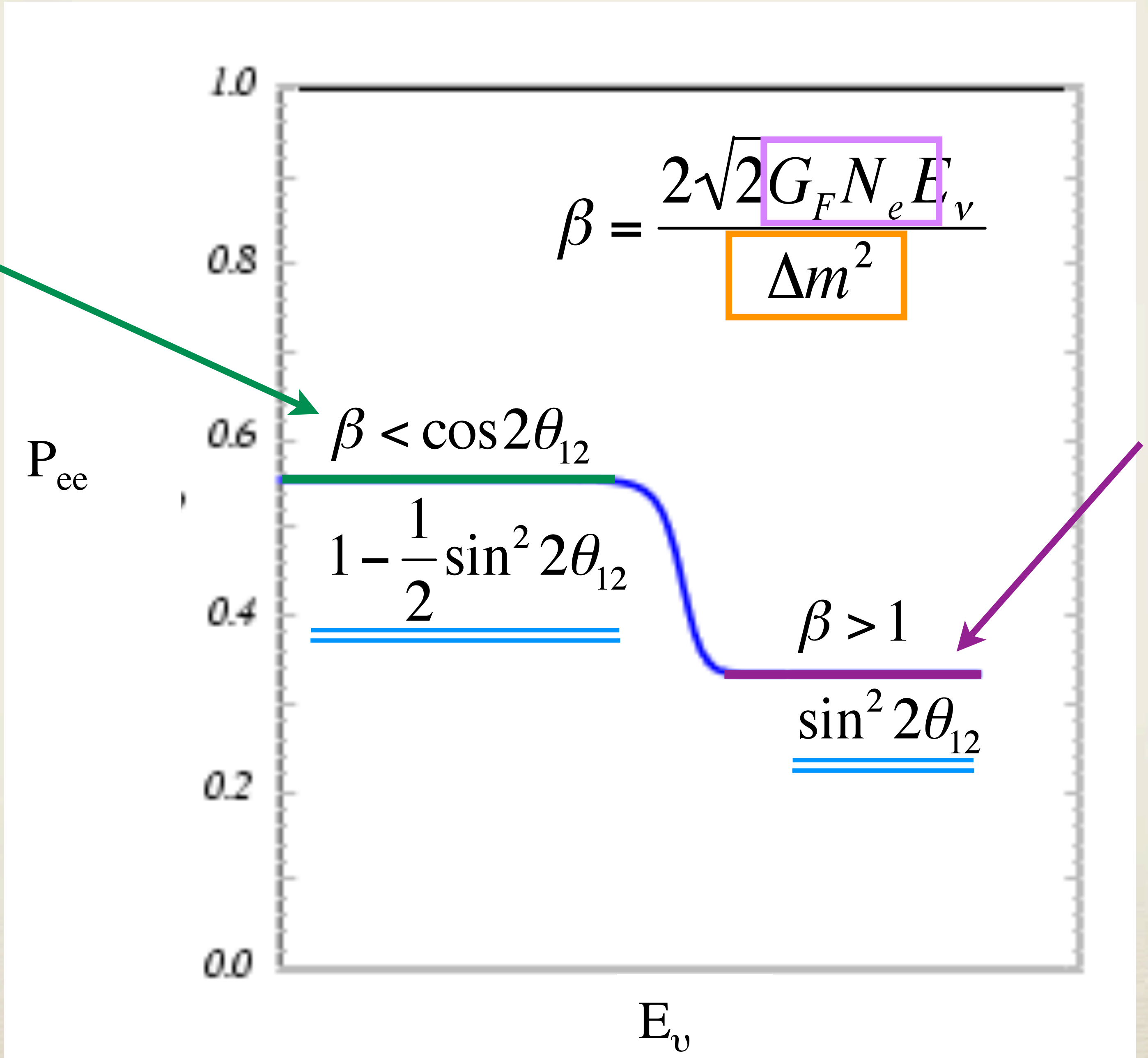

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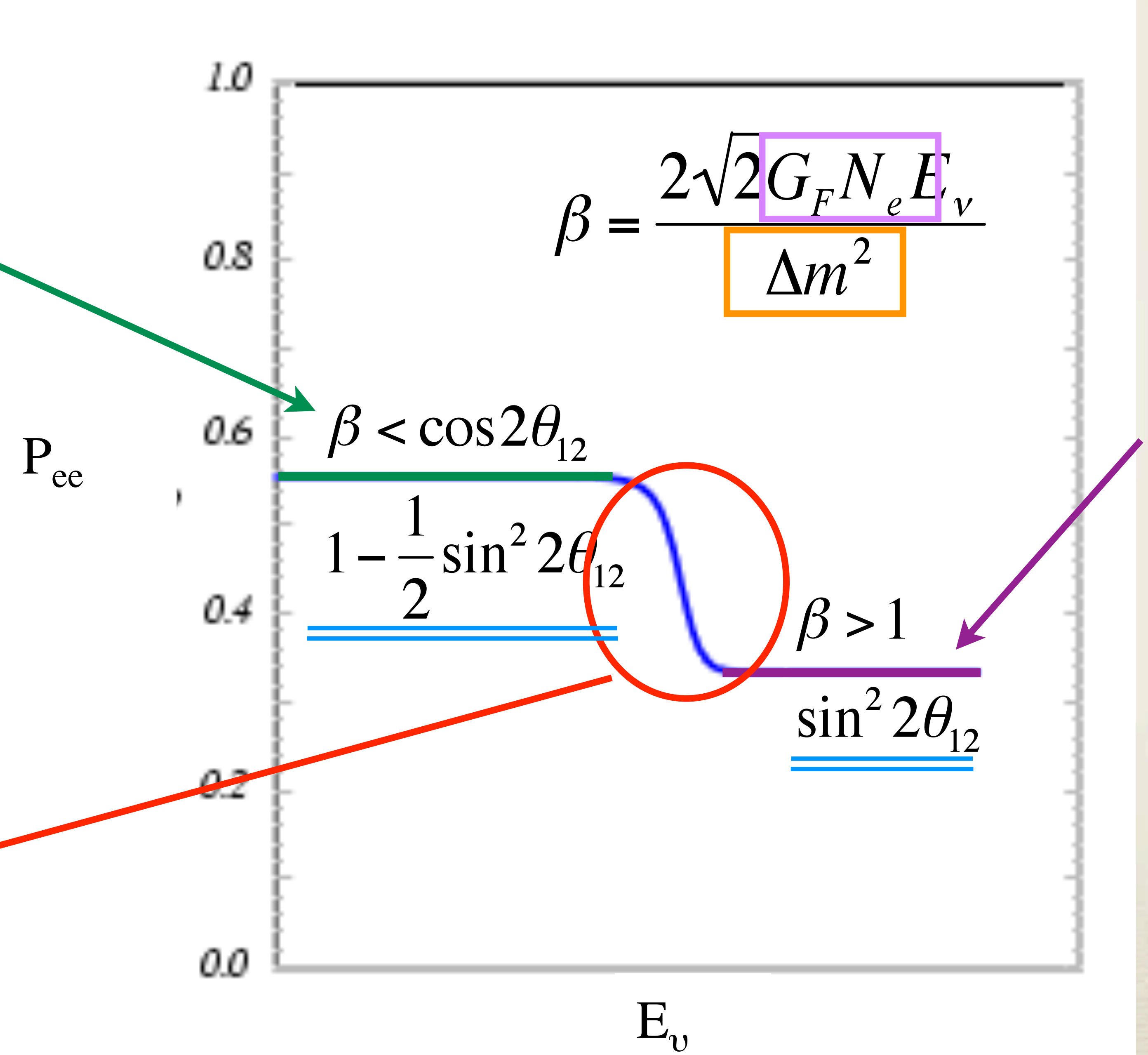


hep-ph/0305159

'High' energy:
Matter-dominated
resonant conversion

Probe transition
region to
confirm MSW

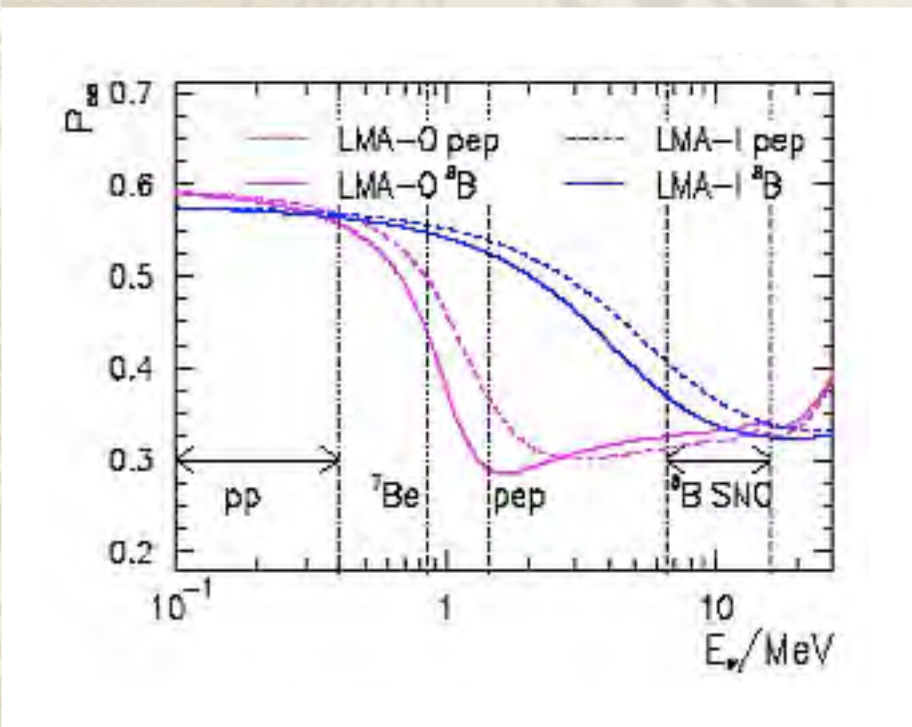
Probing the Unknown

Non-standard physics effects can alter the shape / position of the "MSW rise"

Probing the Unknown

Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions
(flavour changing NC)



Friedland, Lunardini, Peña-Garay,
PLB 594, (2004)

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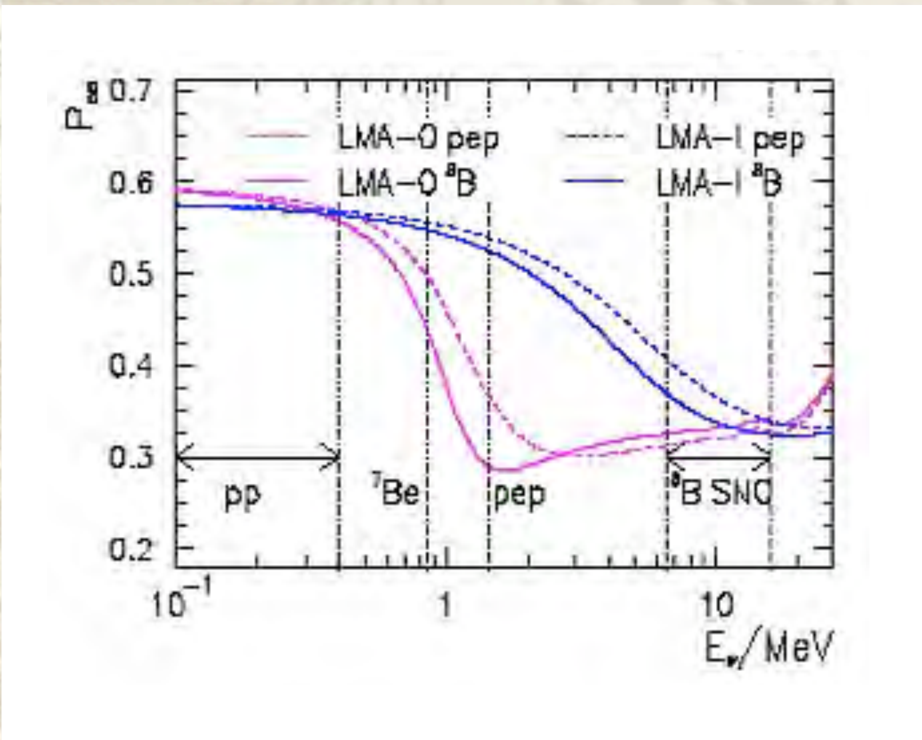
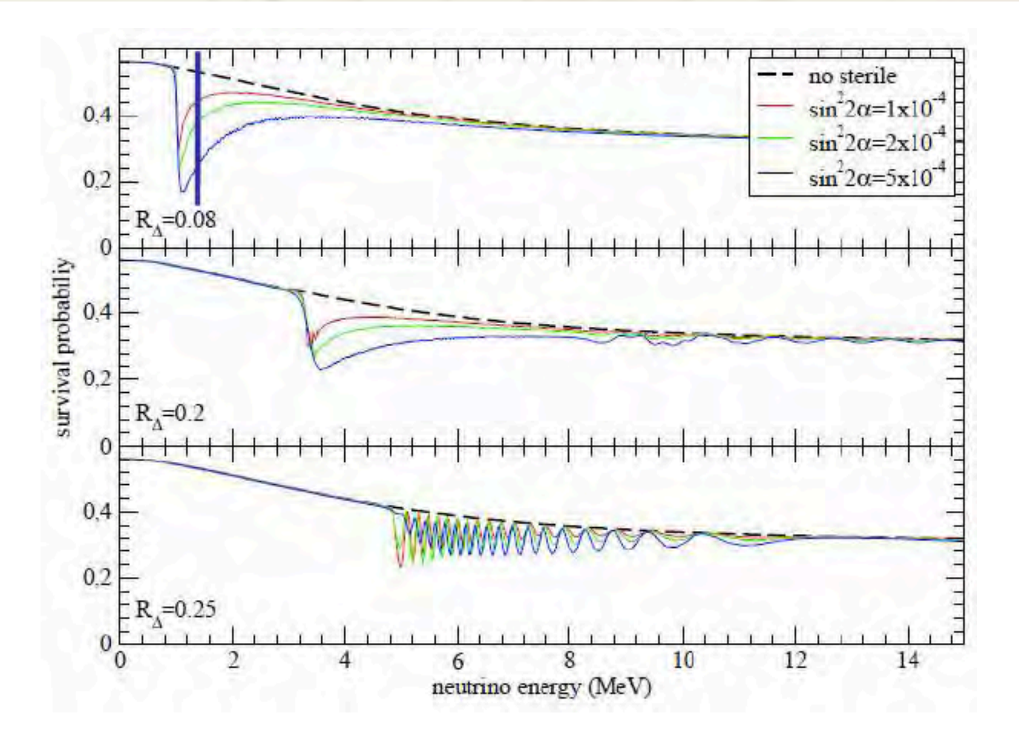


Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov arXiv:1012:5627 (2010)

Here Be Dragons

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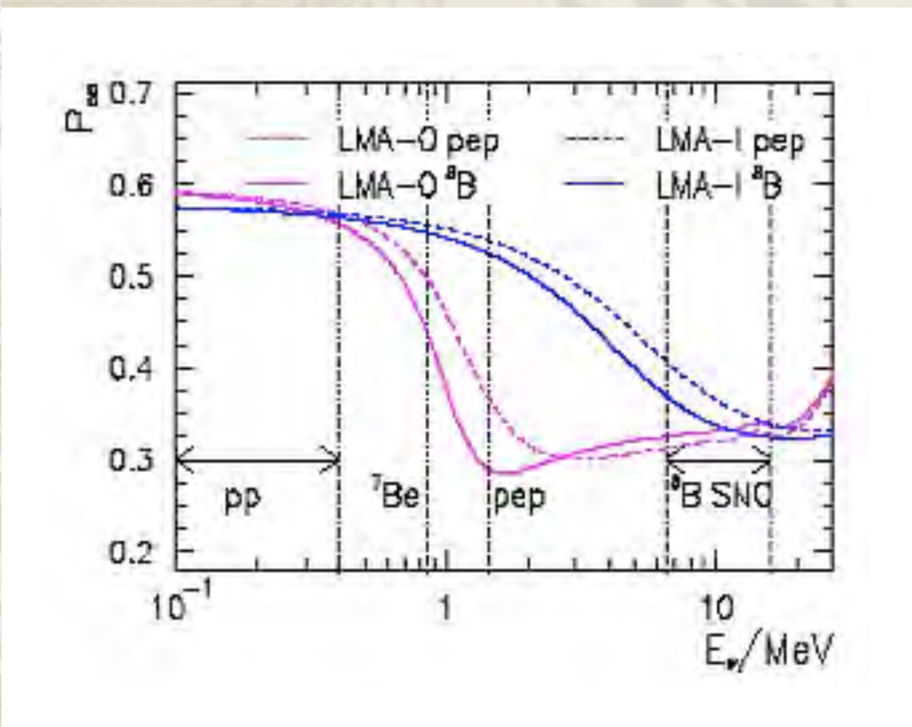

Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

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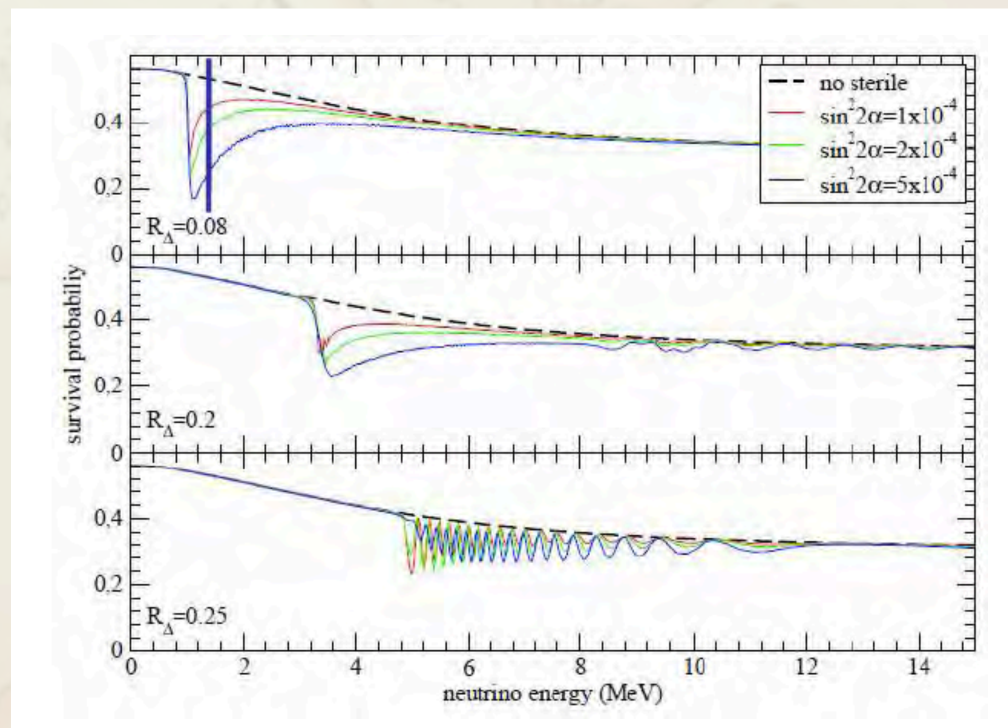
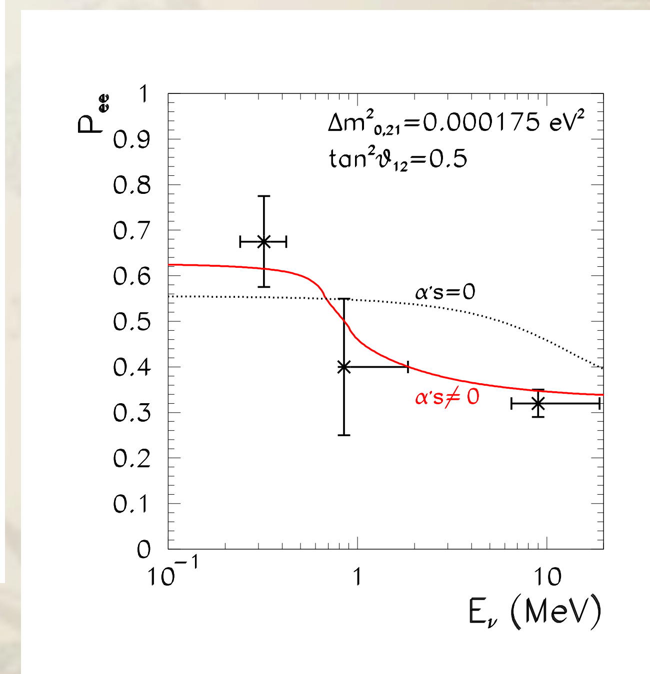


Holanda & Smirnov arXiv:1012:5627 (2010)

Mass varying neutrinos (MaVaNs)

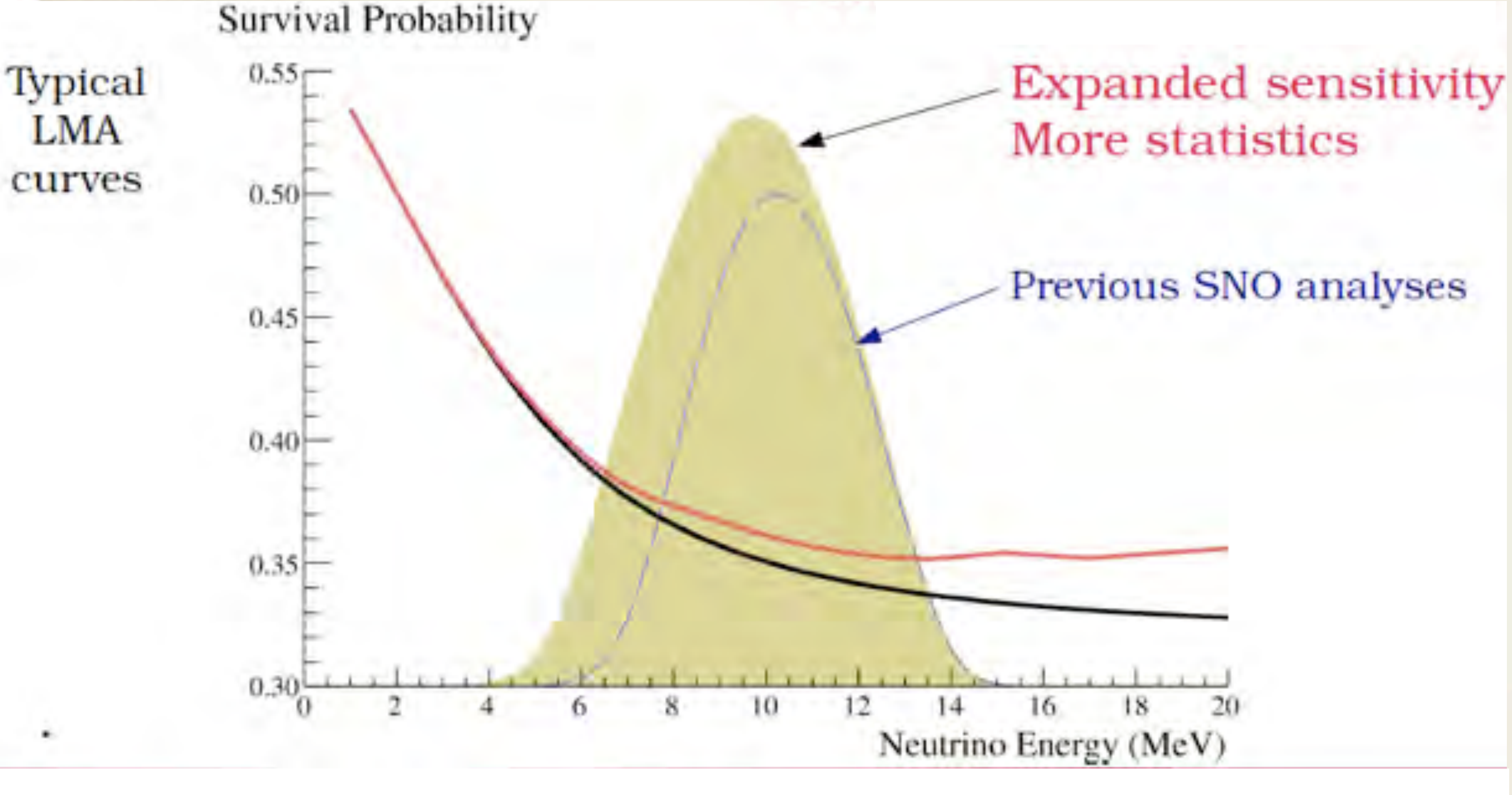


M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

SNO: Precision Era

Low Energy Threshold Analysis

Recoil-electron energy threshold: 5.5 MeV ⇨ 3.5 MeV



Greater sensitivity to low-energy P_{ee}

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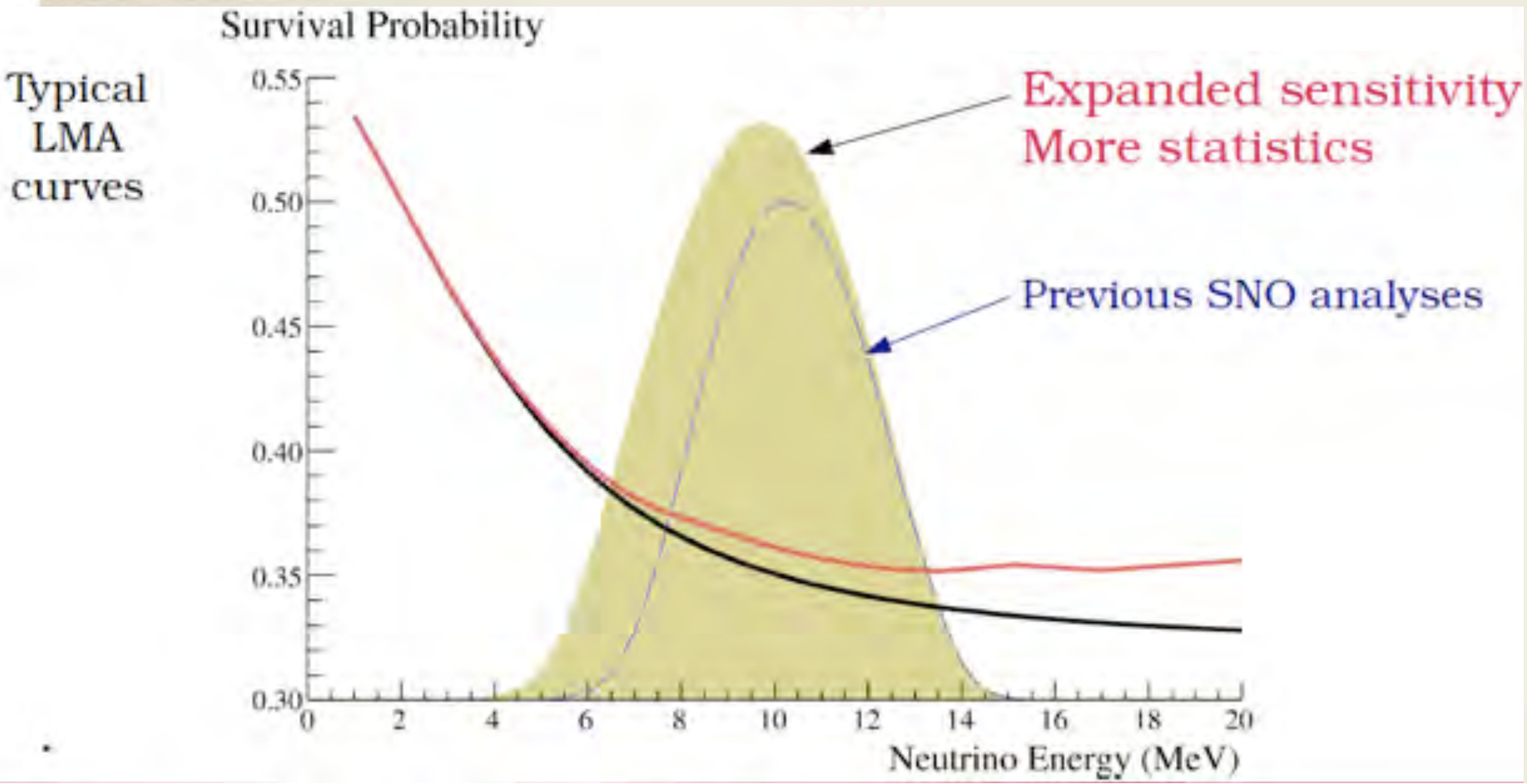
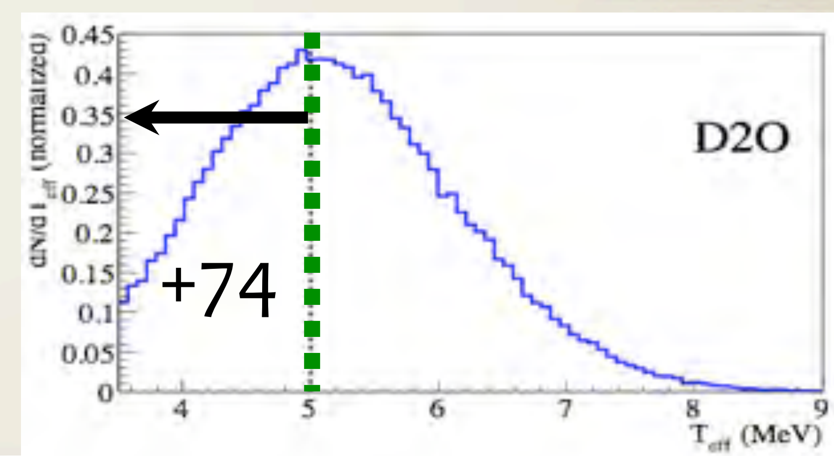


Combine Phases I, II (D_2O, salt)

~2/3 more NC statistics



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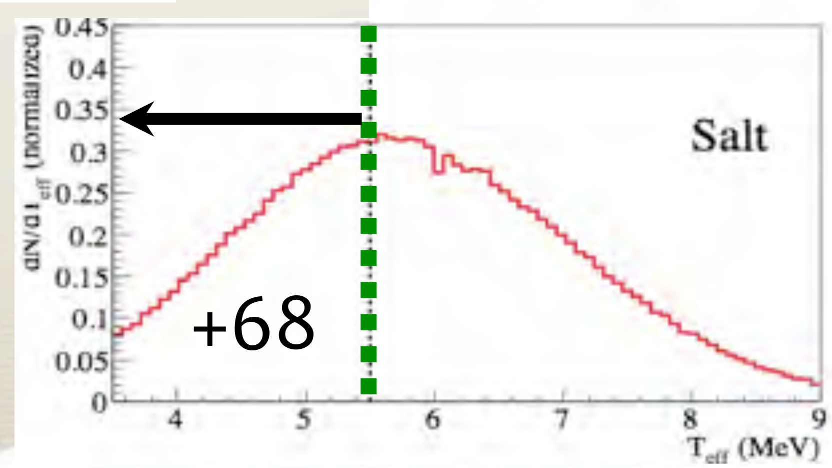
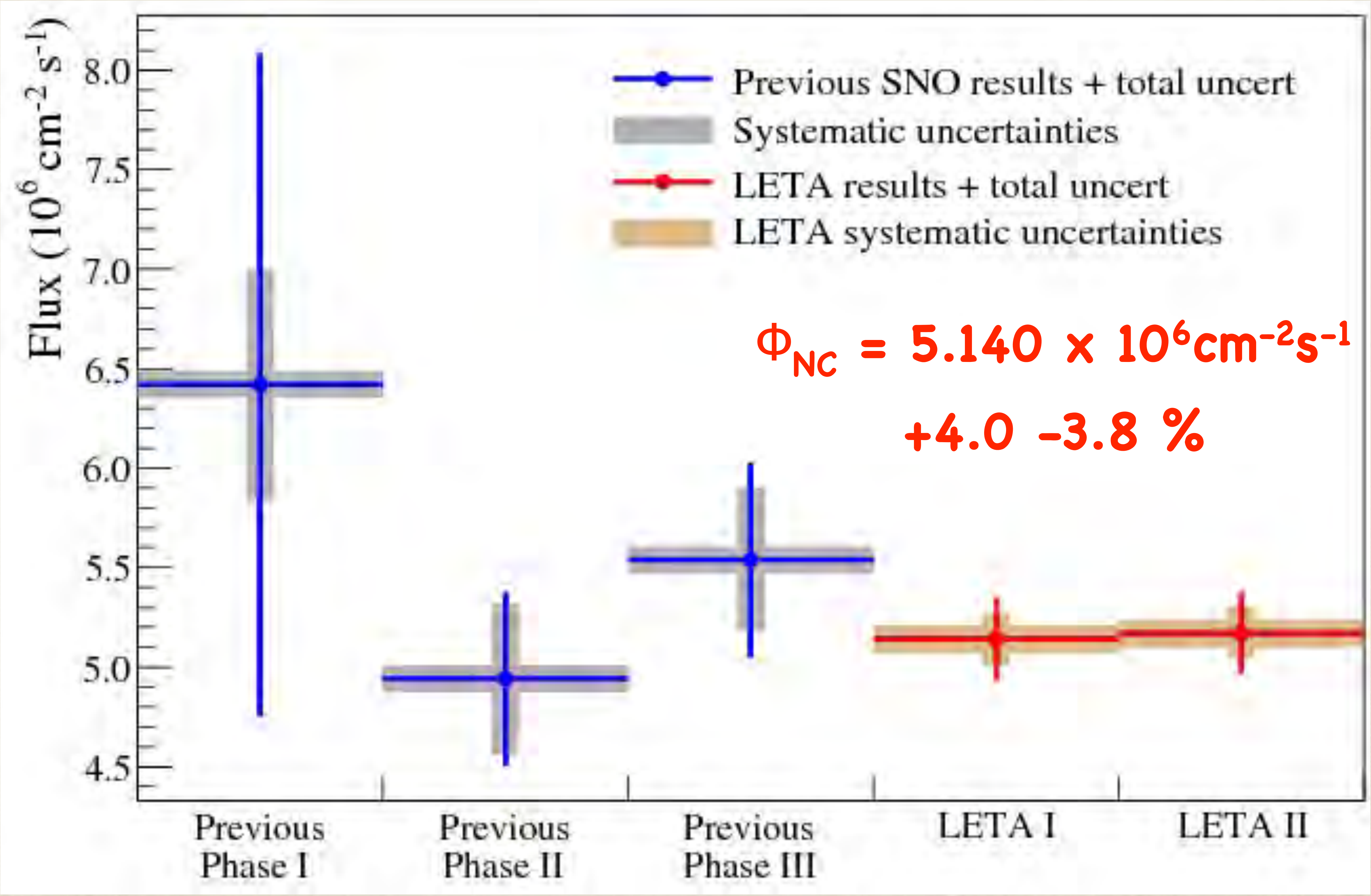


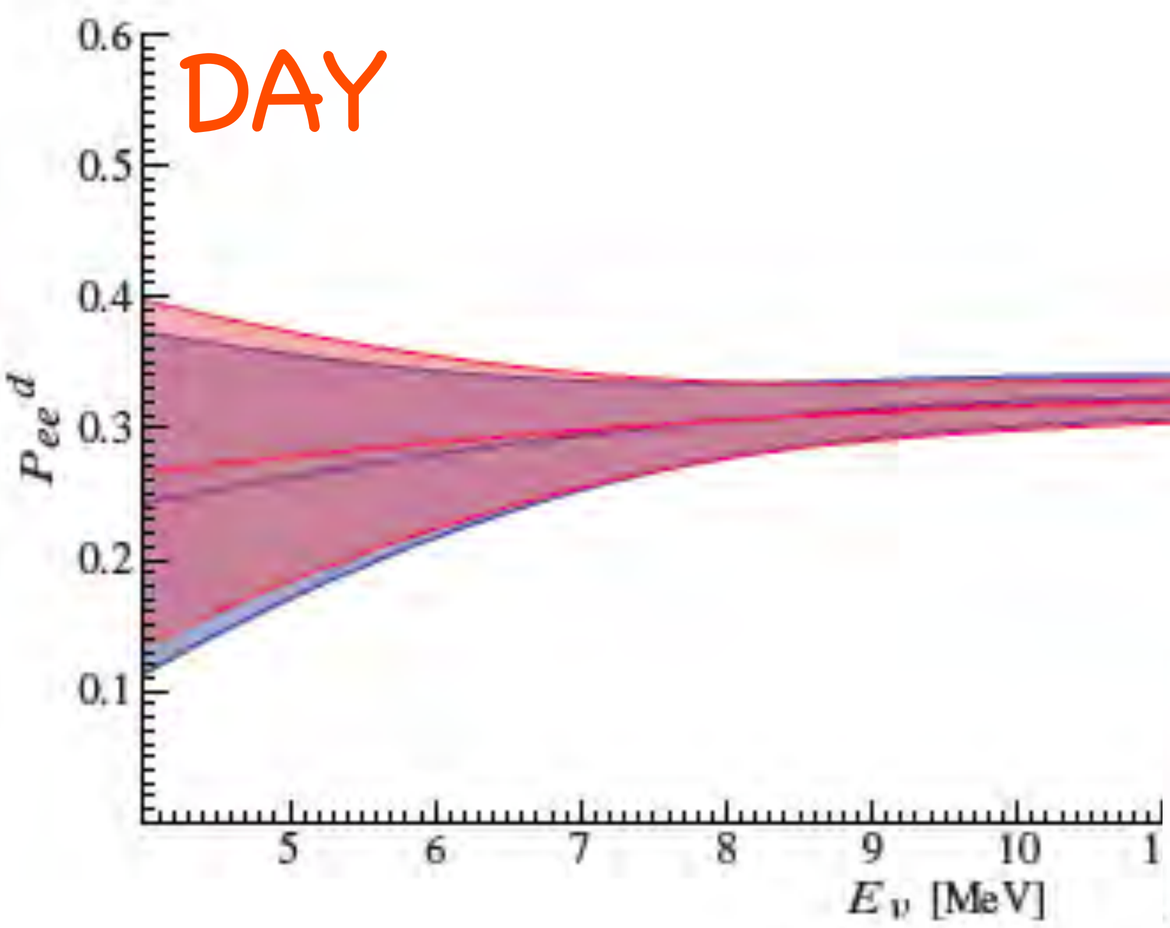
Total ^8B ν_i Flux

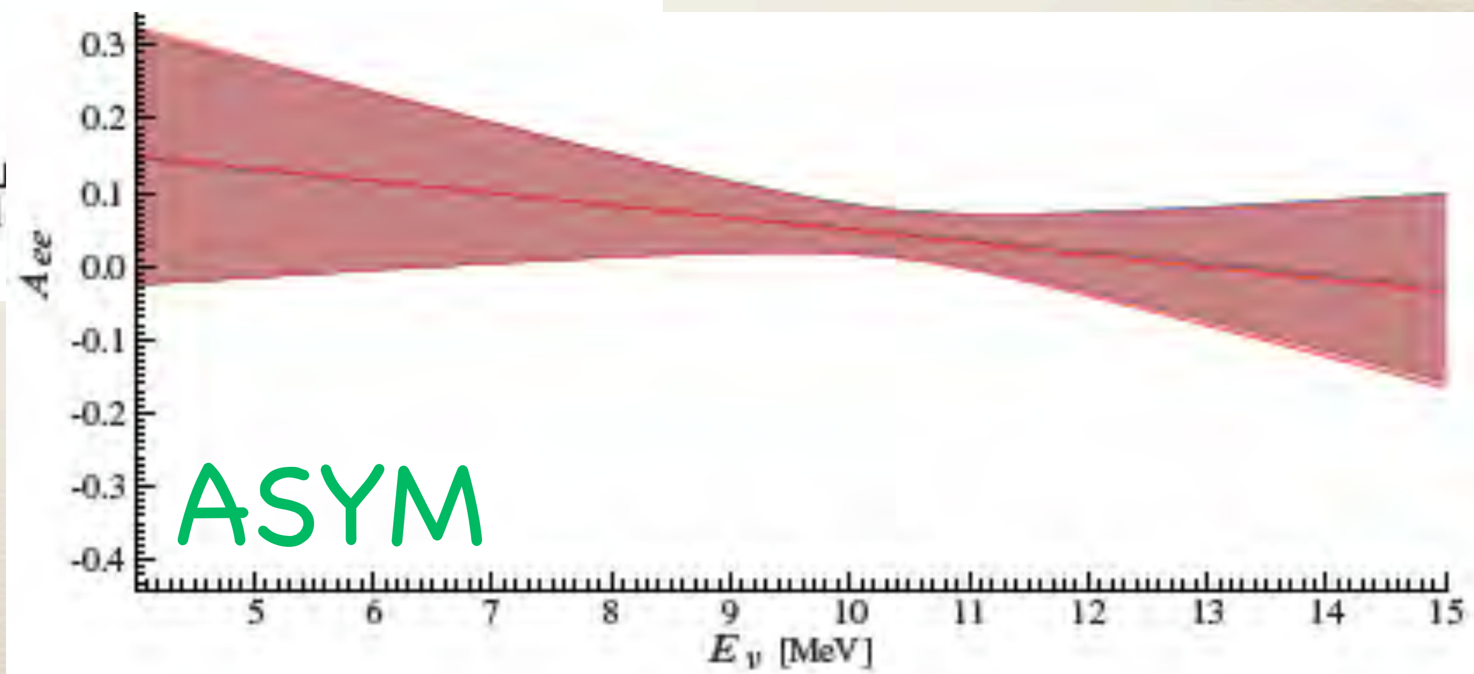


Direct Fit for Energy-Dependent Survival Probability

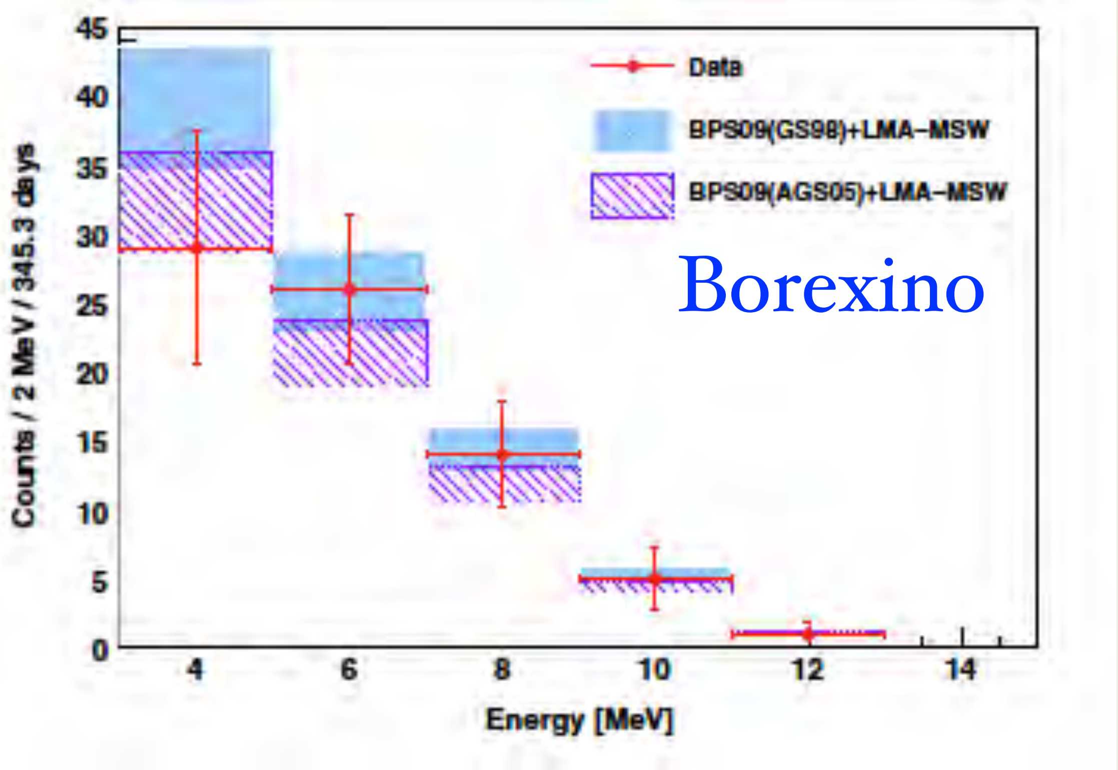
Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory

arXiv:1109.0763v1 [nucl-ex]





Recoil-Electron Spectra



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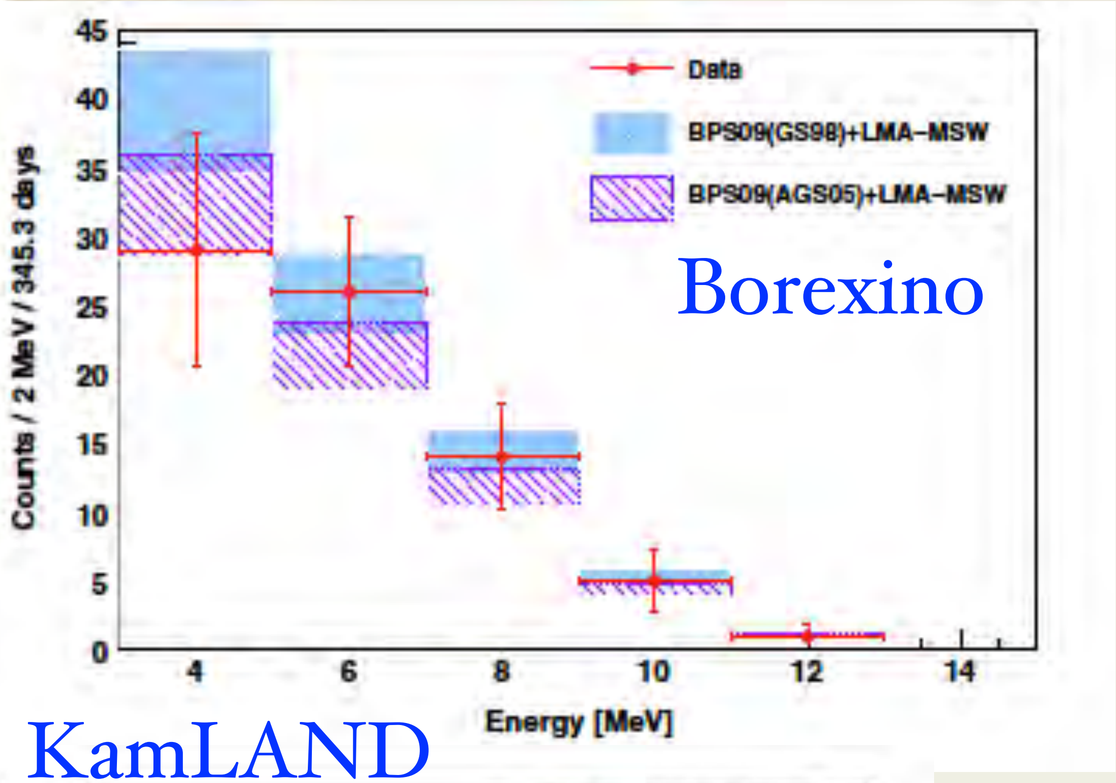
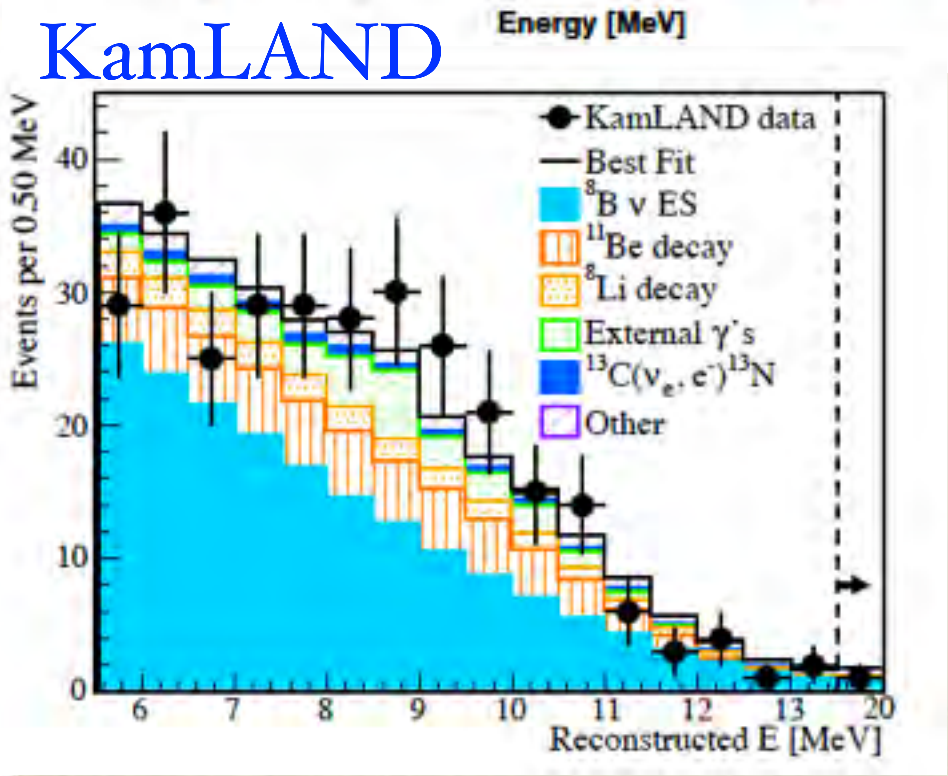
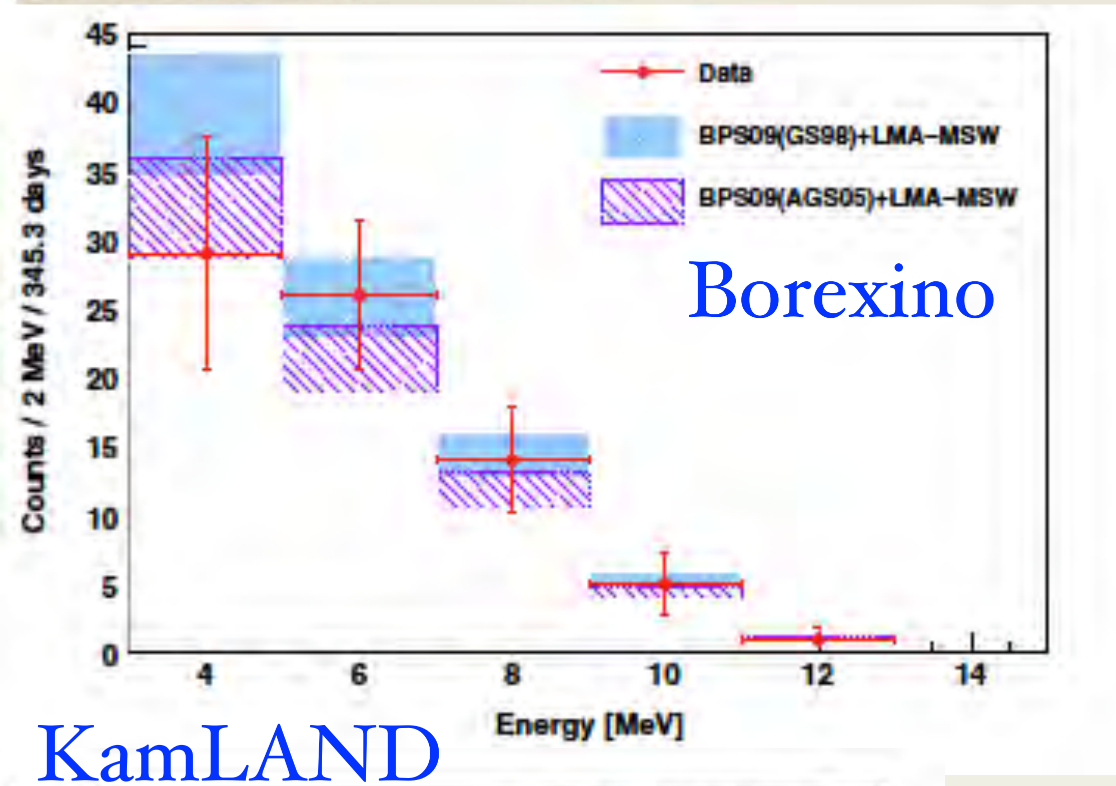
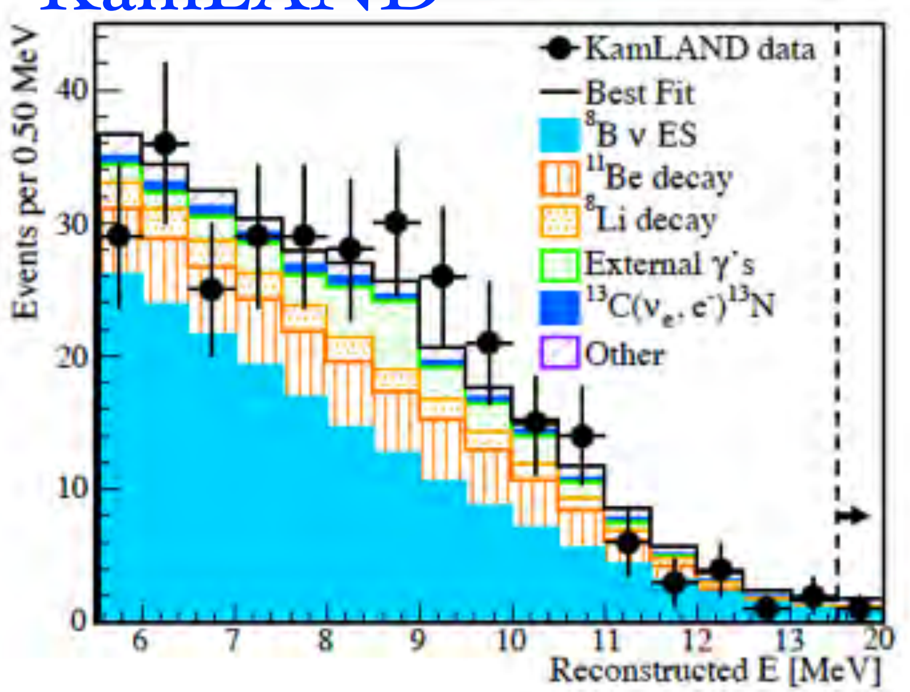


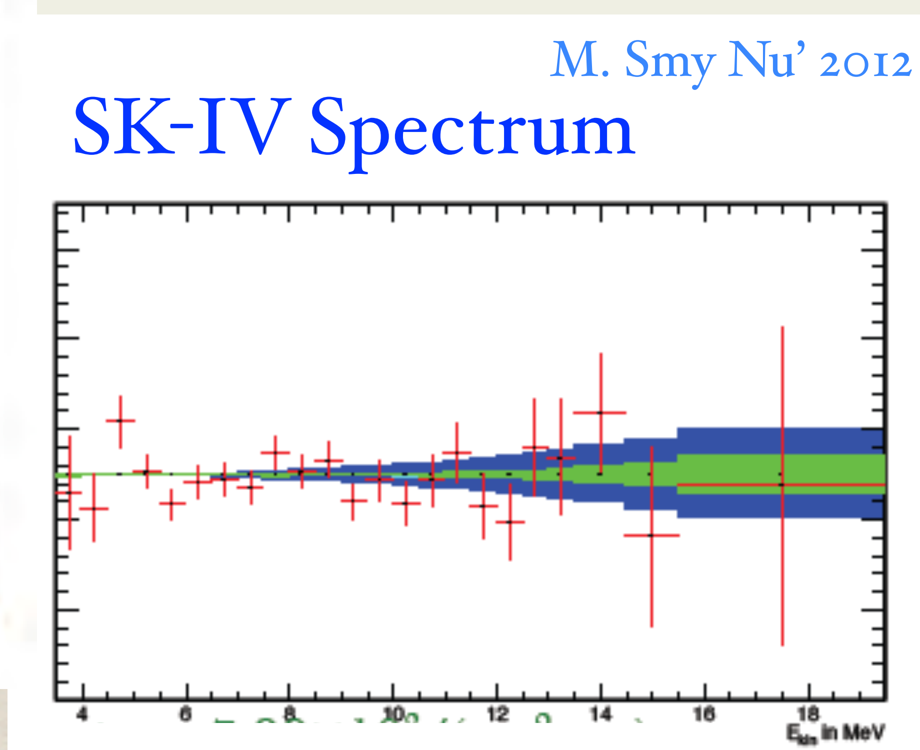


Recoil-Electron Spectra



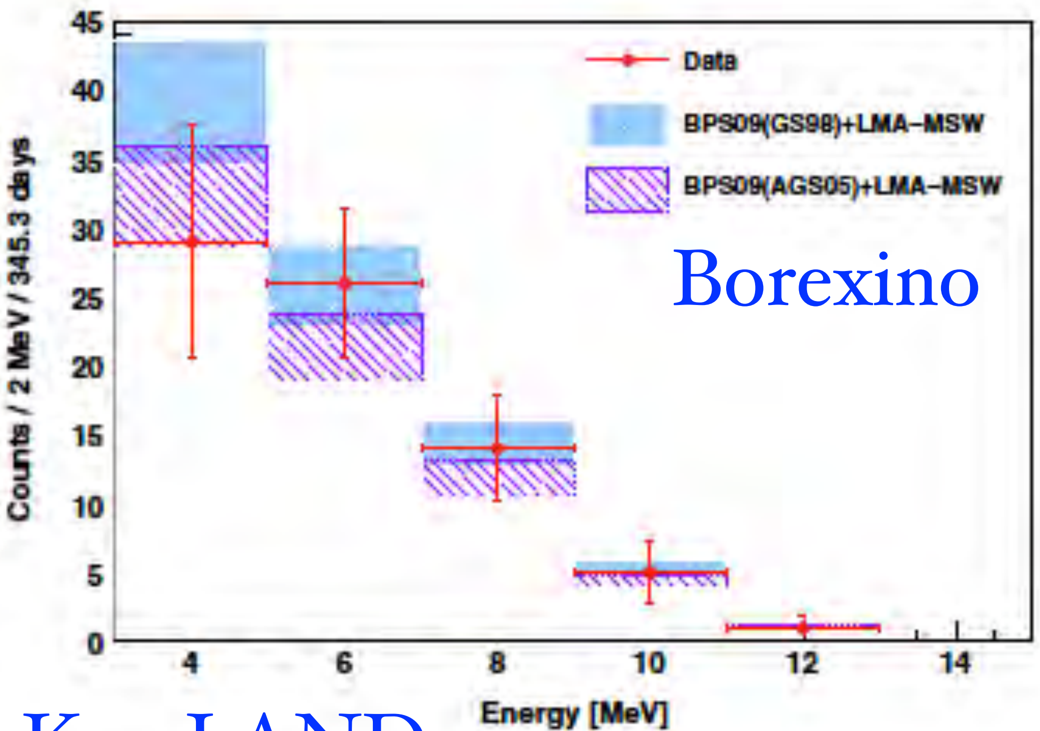
KamLAND



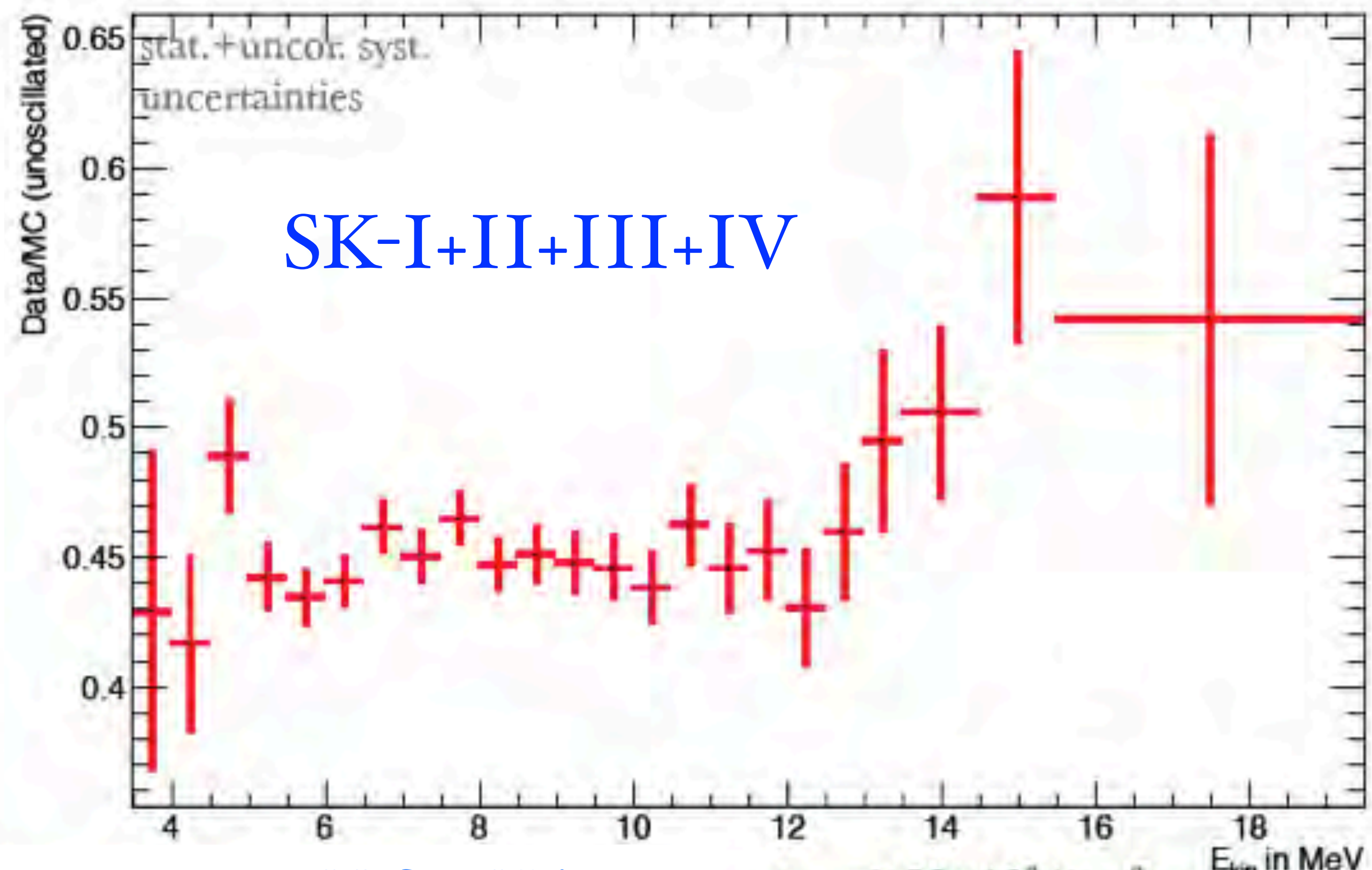


Recoil-Electron Spectra

Borexino

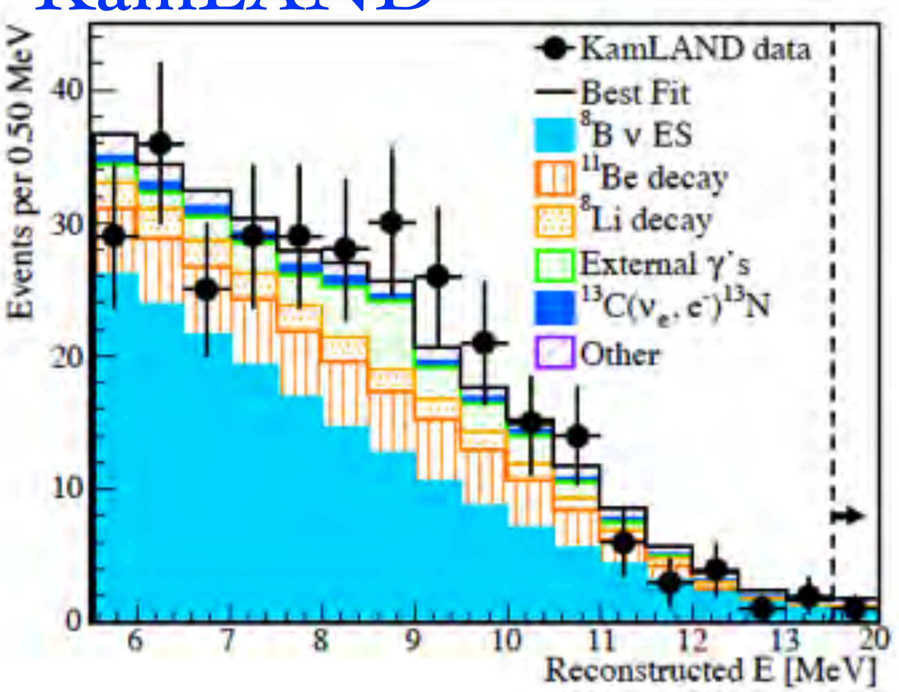


SK-I+II+III+IV

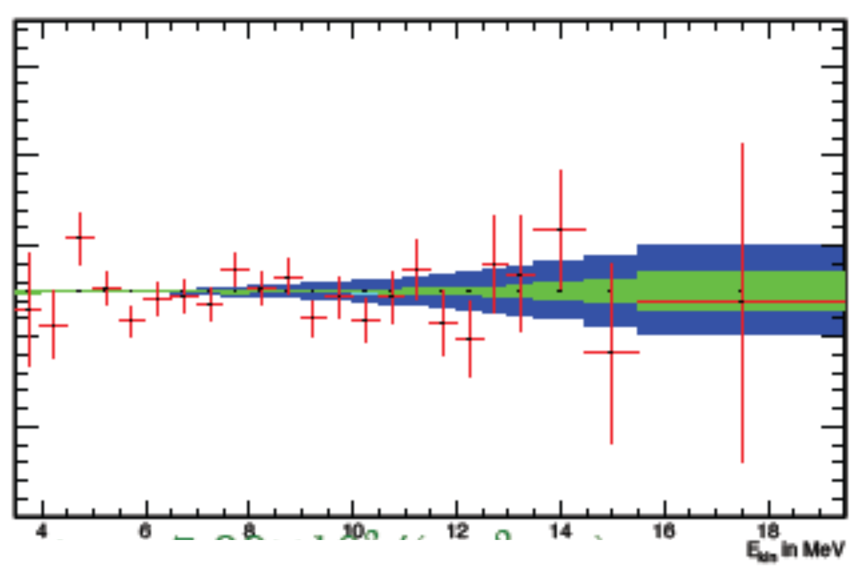


M. Smy Nu' 2012

KamLAND



SK-IV Spectrum



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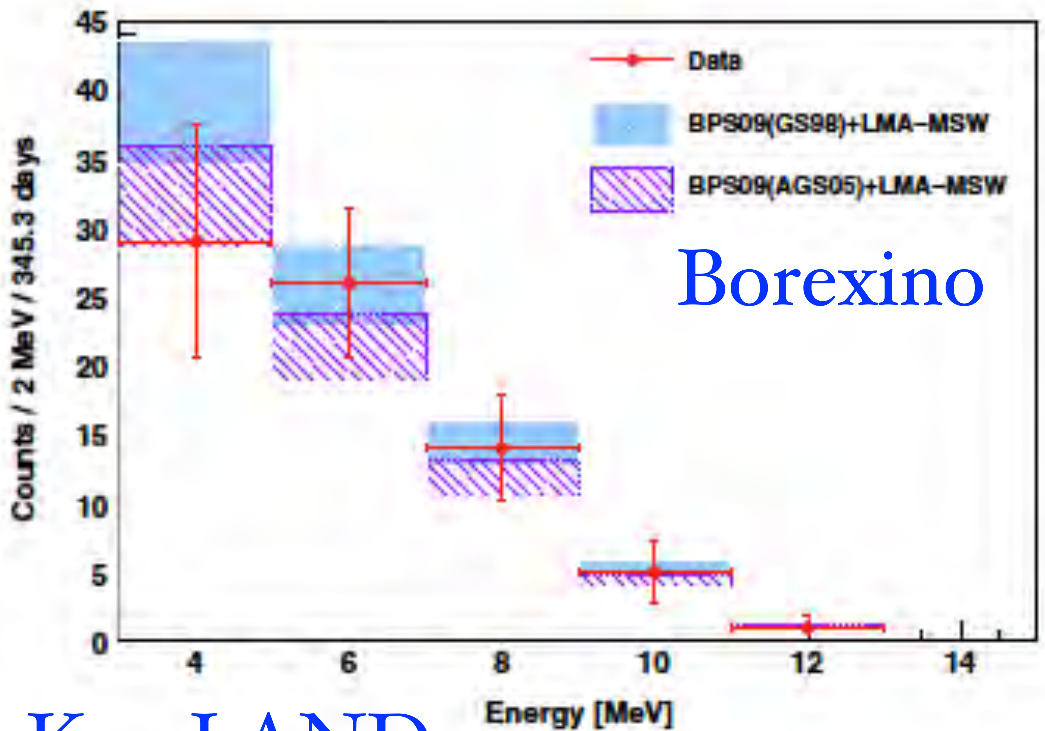

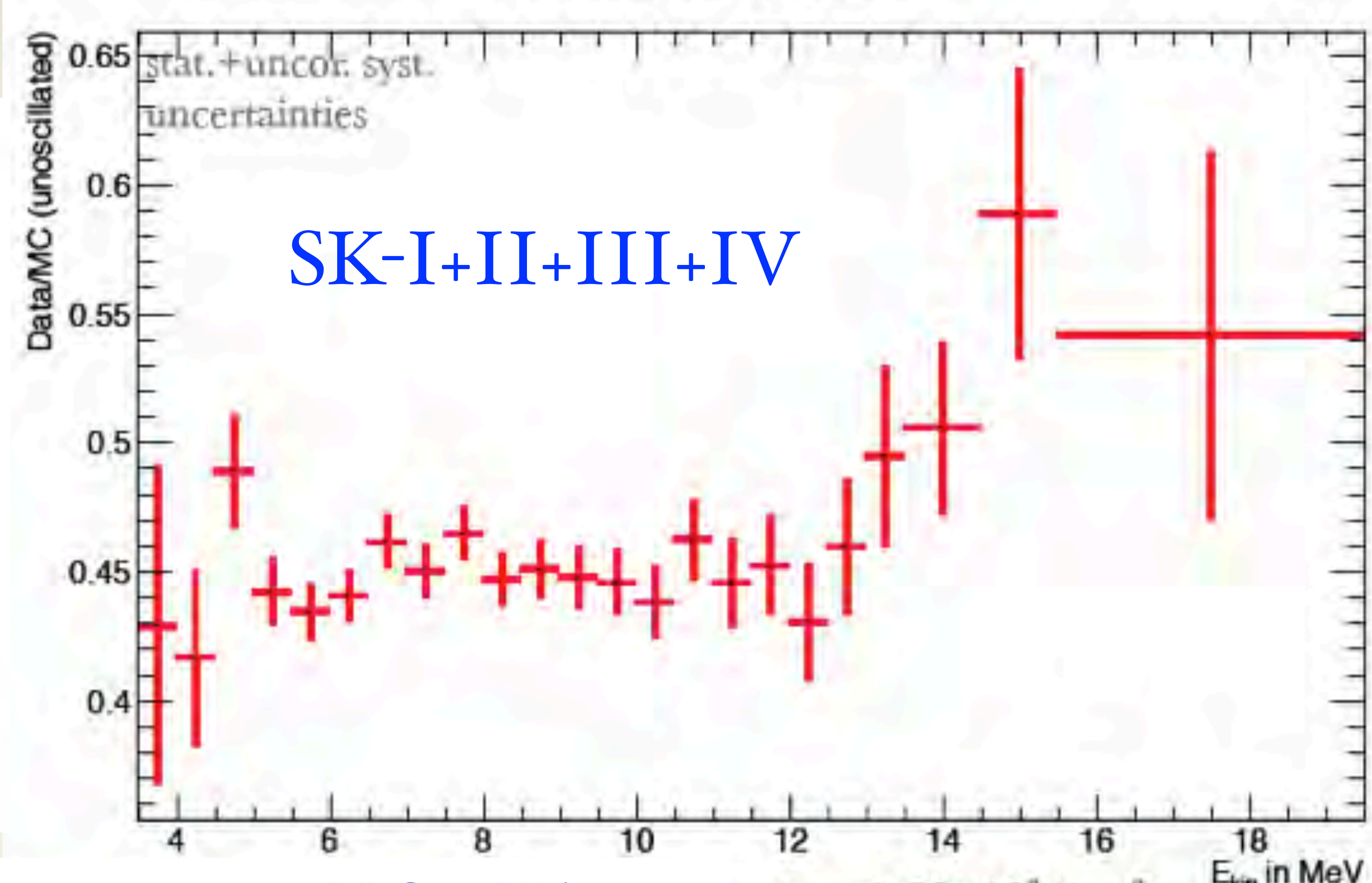

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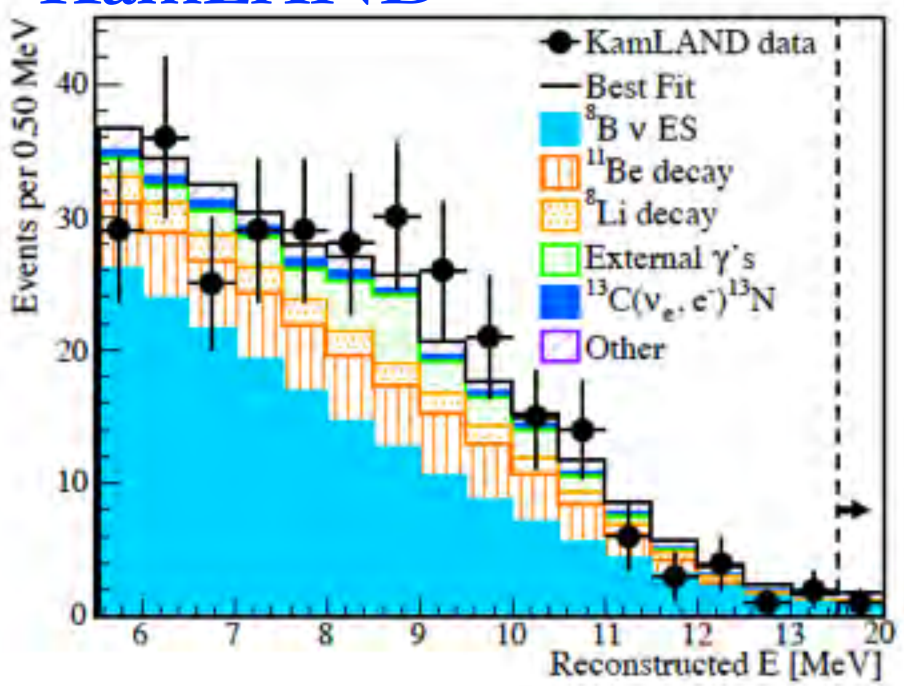

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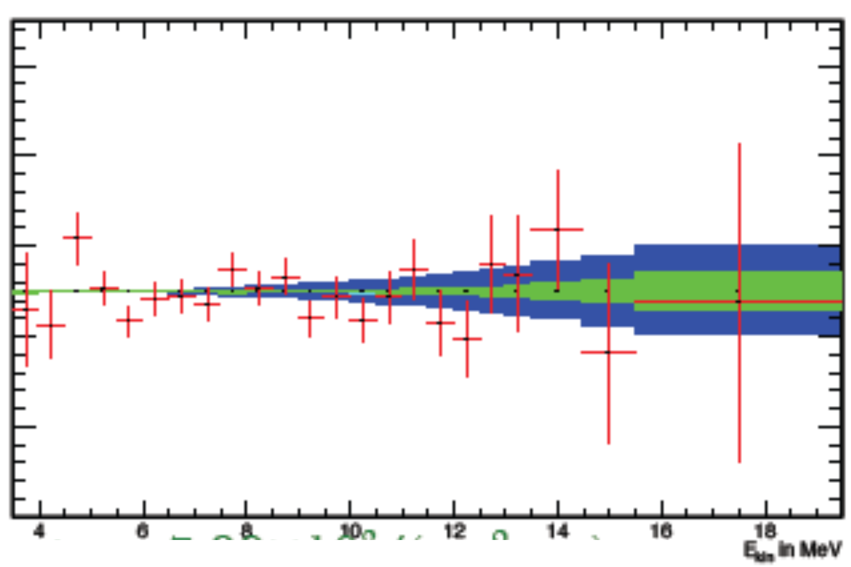
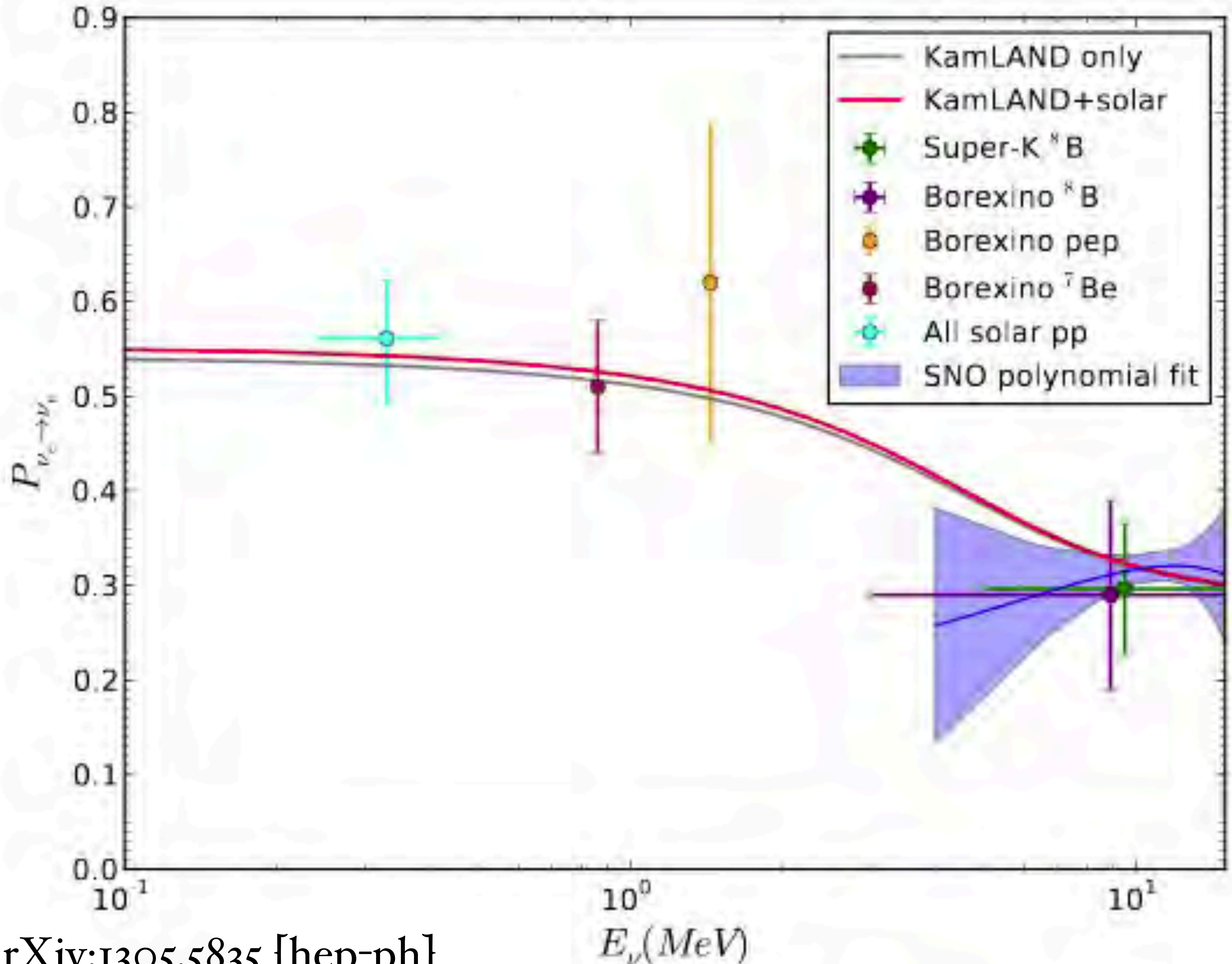


Very
Very
Flat

Survival Probability



arXiv:1305.5835 [hep-ph]

Non-Standard Model Testing

Light sterile neutrino PRD 83:113011 (2011)

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

Non-Standard Models, Solar Neutrinos and Large θ_{13}

arXiv:1305.5835 [hep-ph]

Considers:

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

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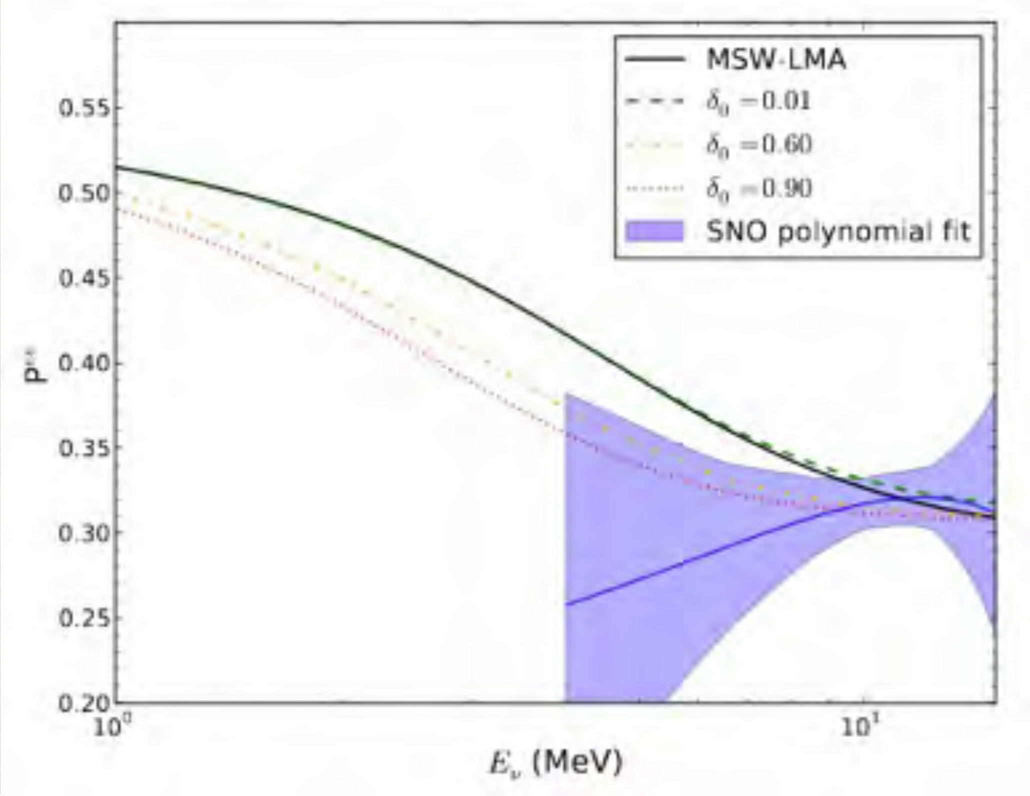

Need 90% change in core density to improve fit

Non-Standard Model Testing

Light sterile neutrino PRD 83:113011 (2011)

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

Non-Standard Models, Solar Neutrinos and Large θ_{13}

arXiv:1305.5835 [hep-ph]

Considers:

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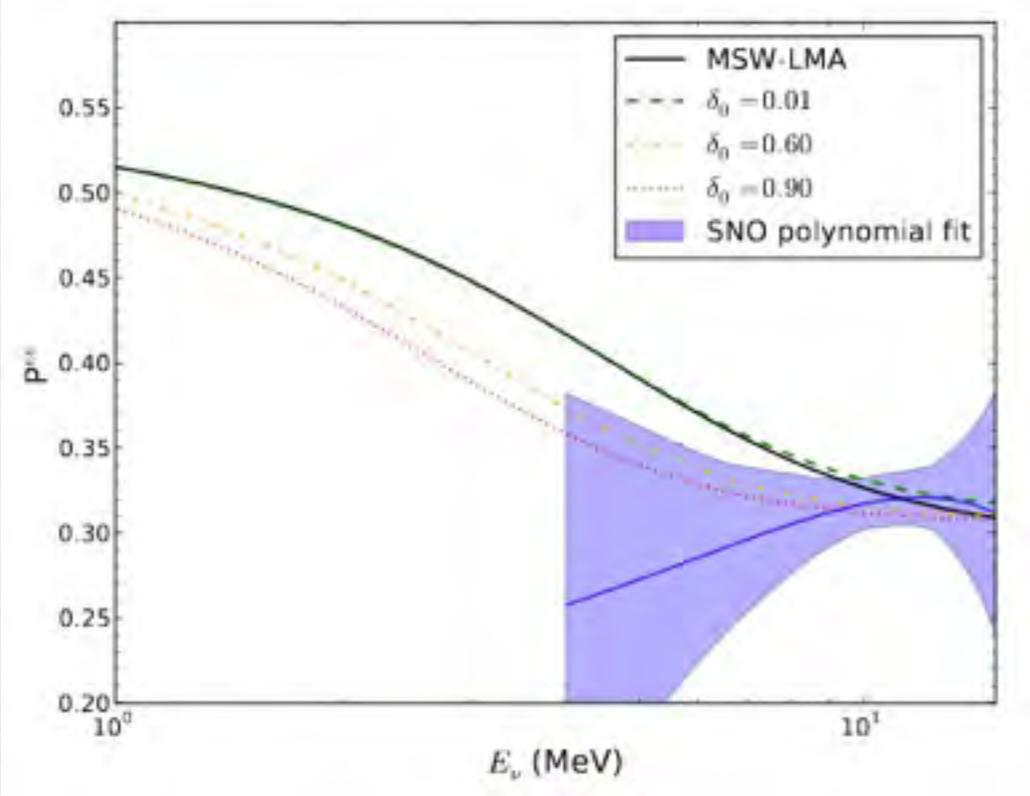
No significant effects



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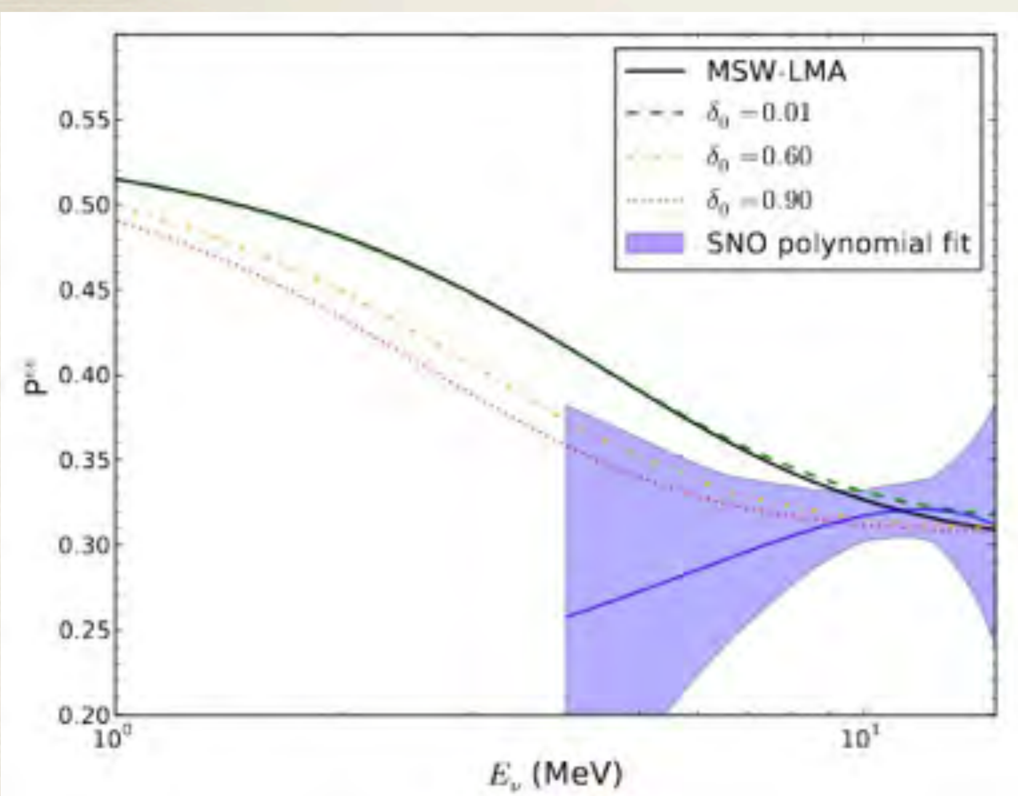

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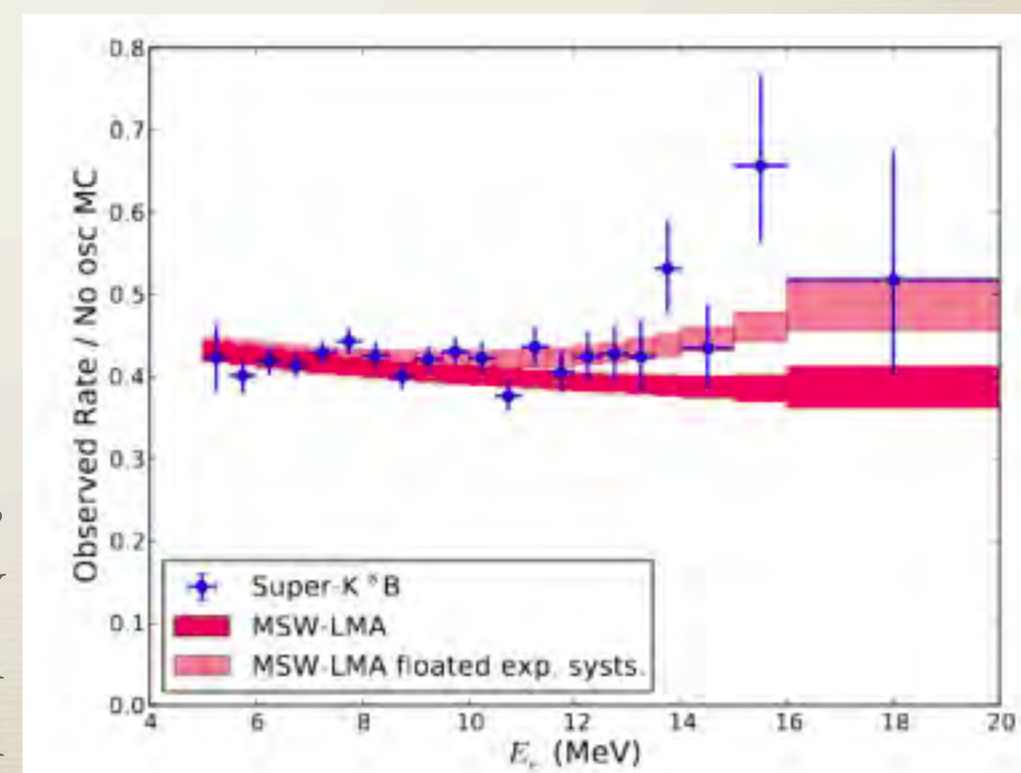
Results limited by experimental precision



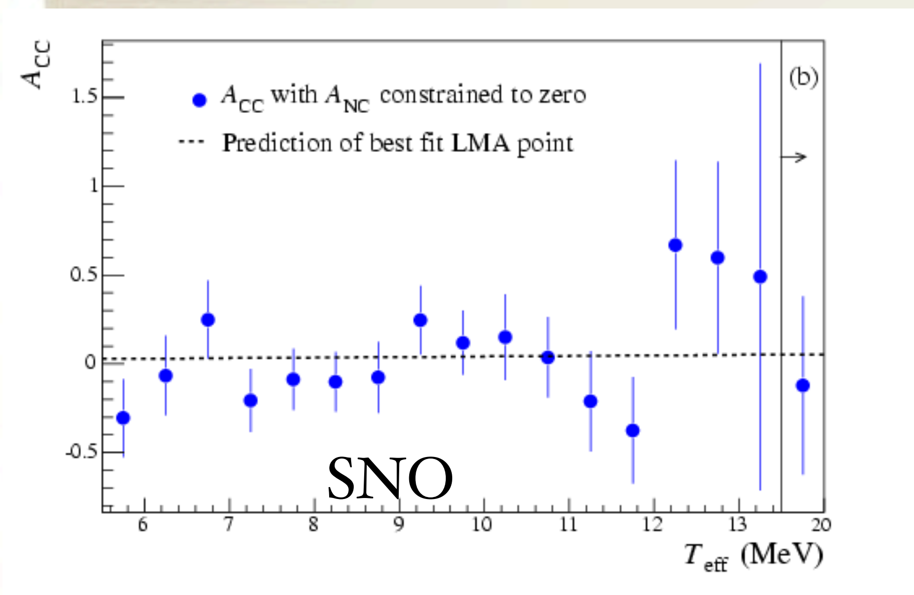
(B) Day / Night Asymmetry

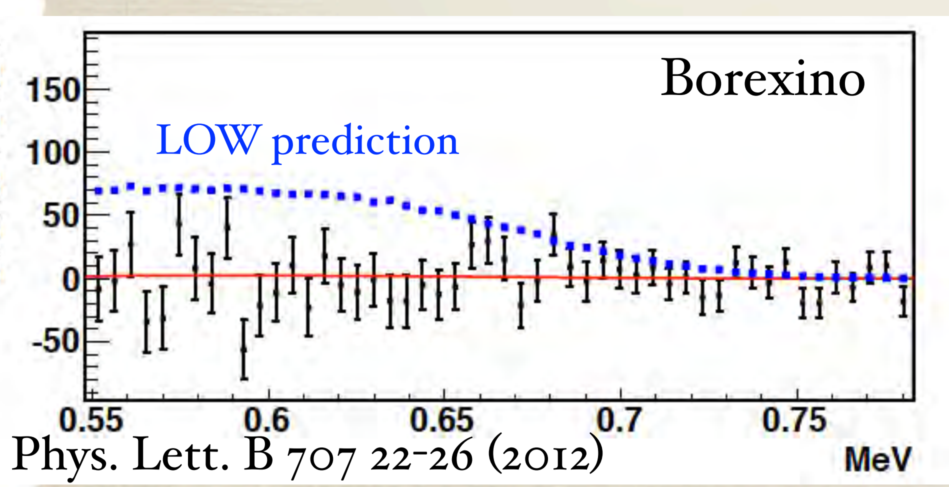
MSW theory predicts regeneration of ν_e state as neutrinos pass through the Earth

Sun Shines Brighter at Night, Scientists Say

(B) Day / Night Asymmetry

SuperK: -0.021 ± 0.020 (stat) ± 0.013 (syst)
SNO: 0.037 ± 0.040 (stat ⊕ syst)
Borexino: 0.001 ± 0.012 (stat) ± 0.007 (syst)





Phys. Lett. B 707 22-26 (2012)

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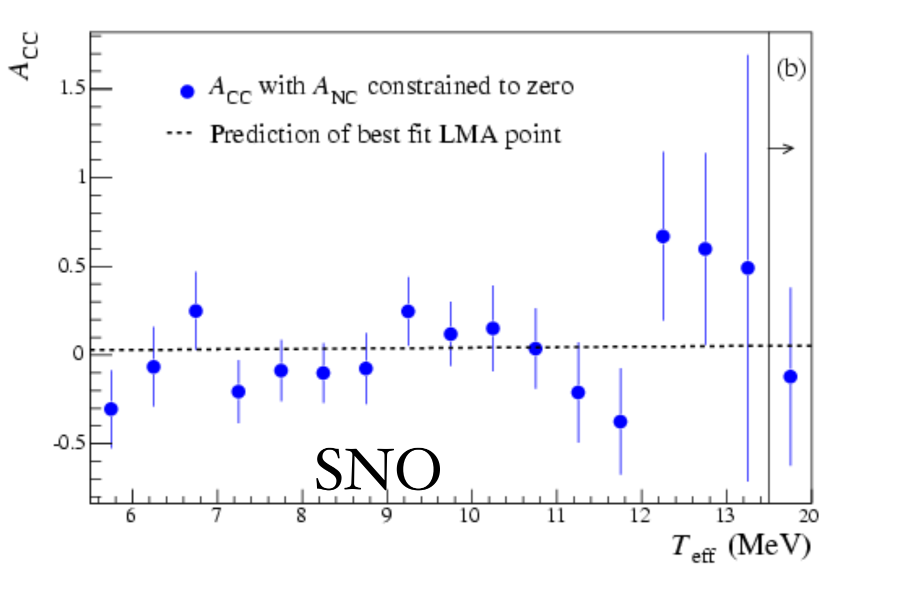
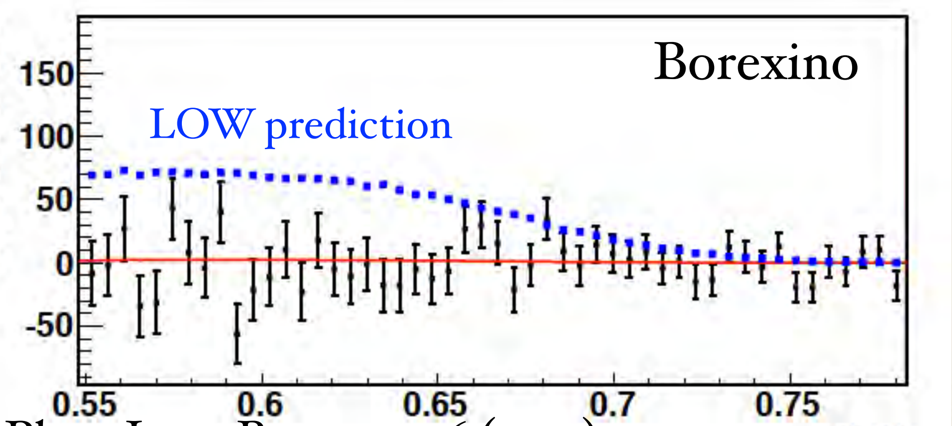
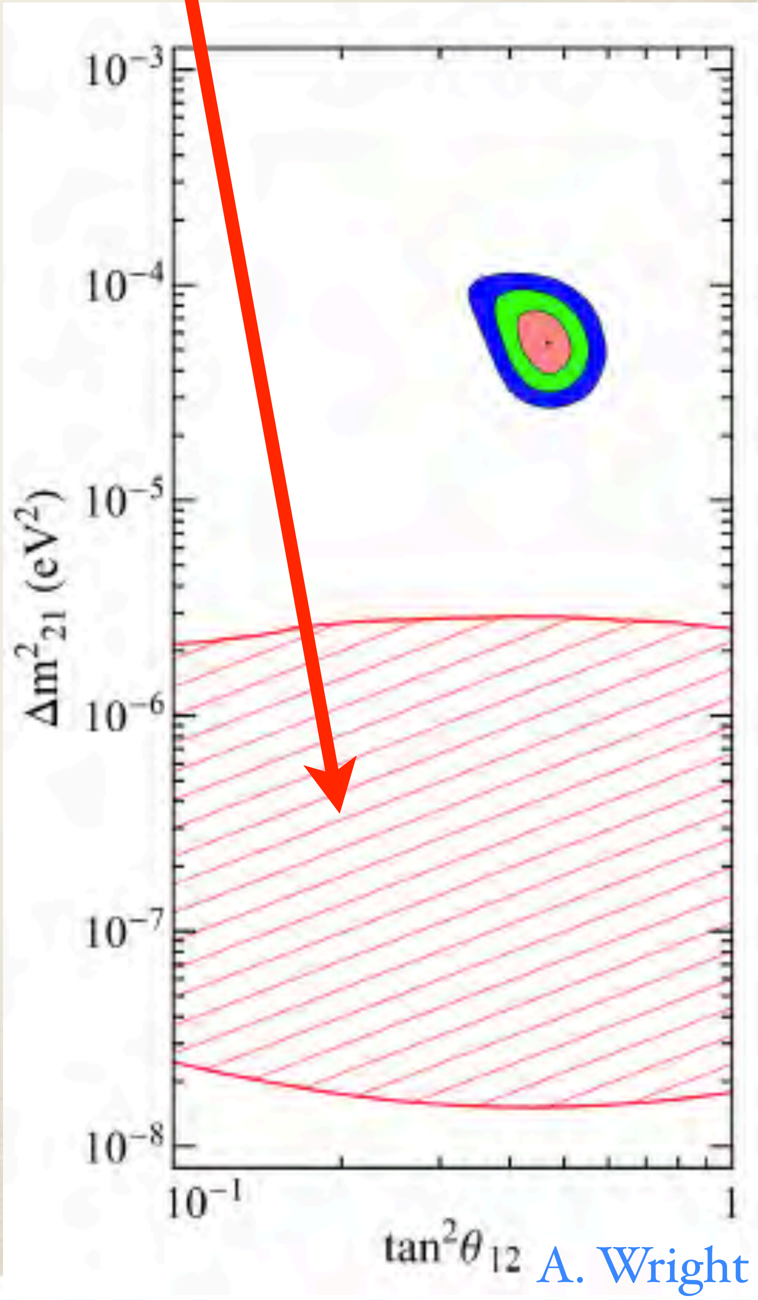




Phys. Lett. B 707 22-26 (2012)

LOW region
ruled out
at > 3σ



A. Wright

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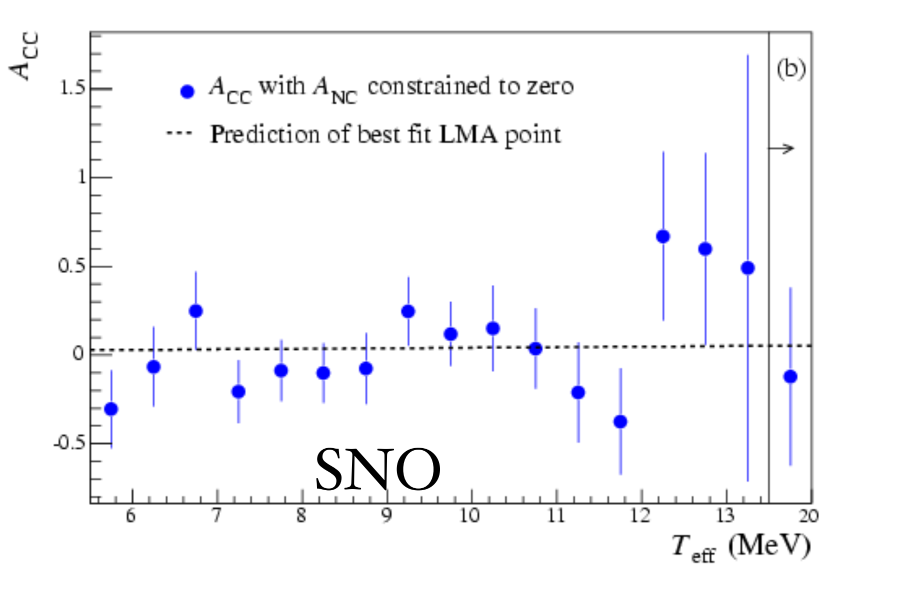
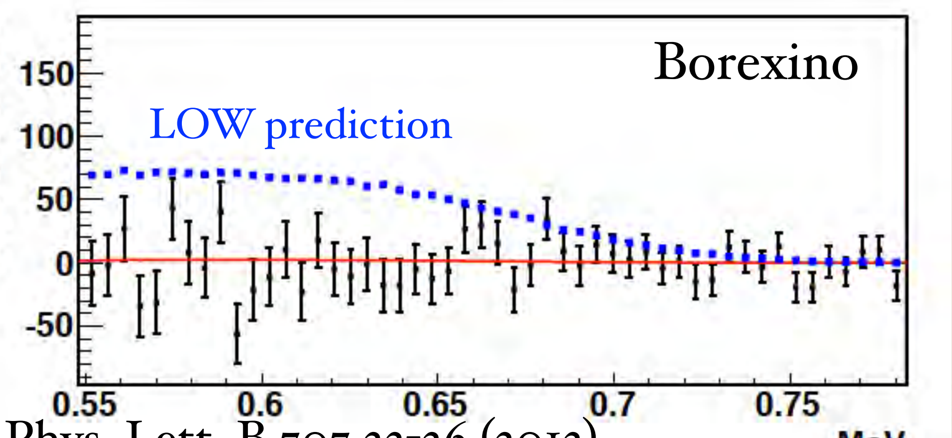
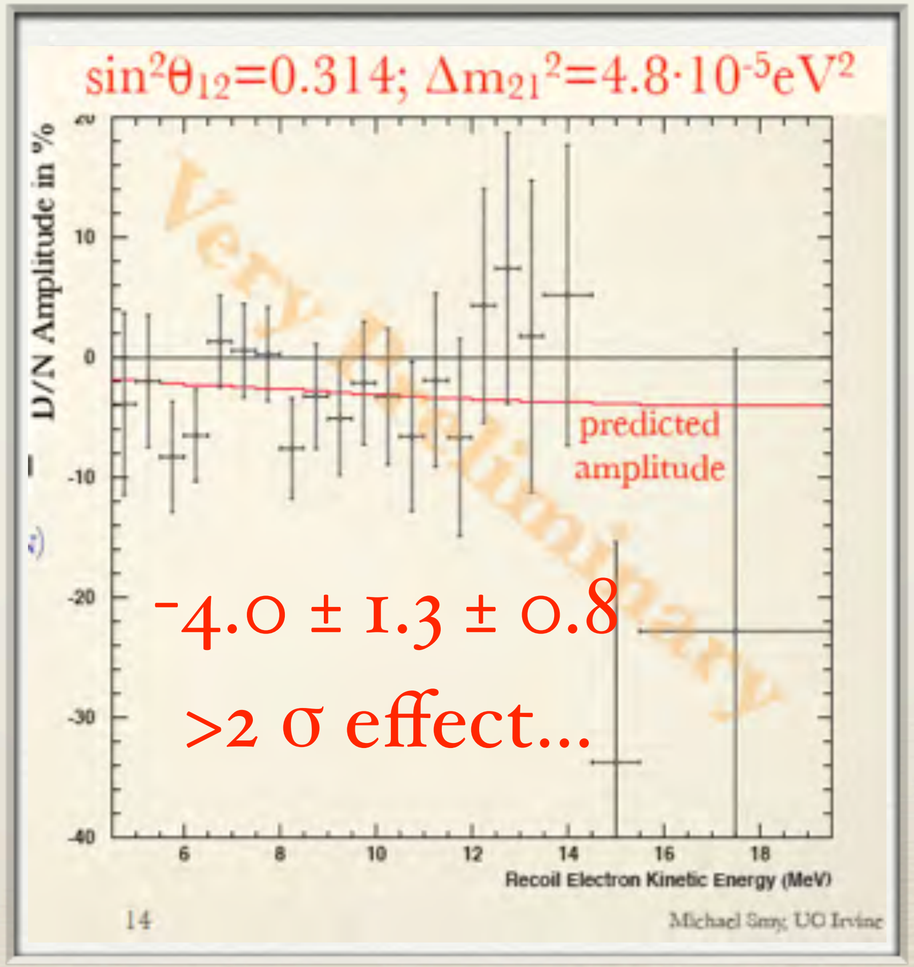


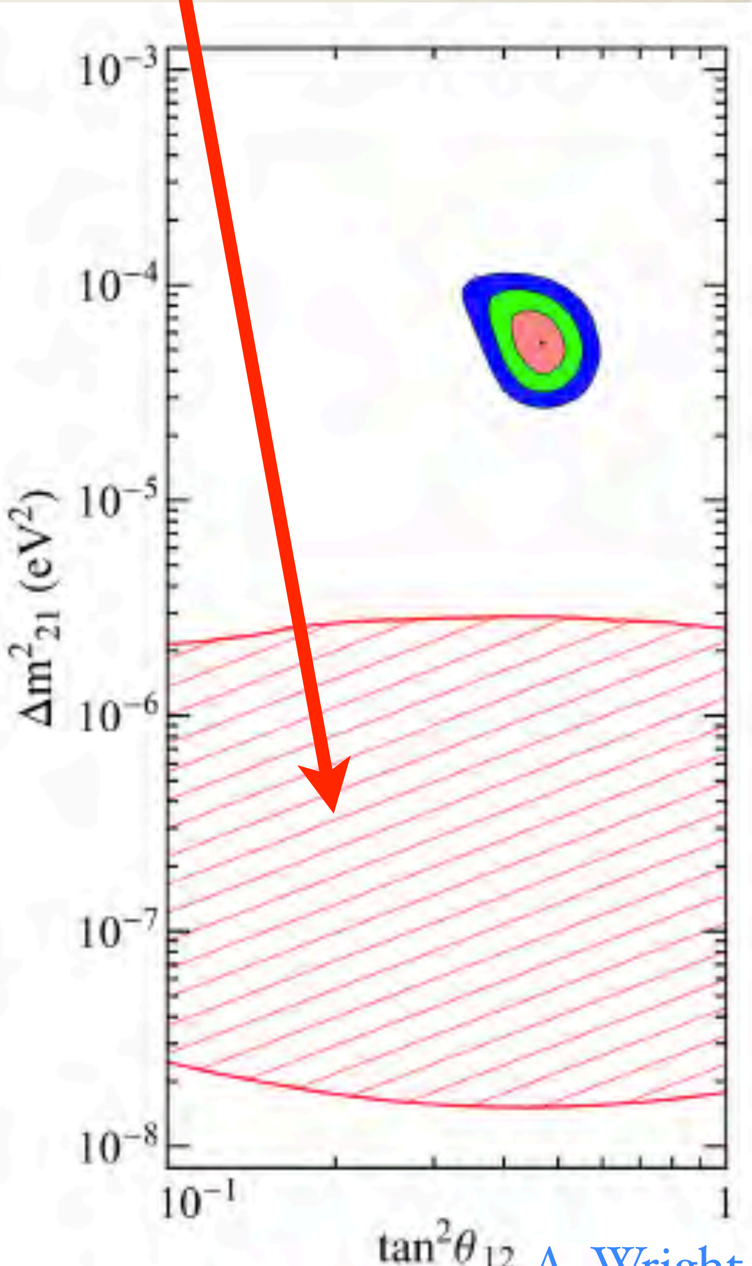


Phys. Lett. B 707 22-26 (2012)

Recent result



-4.0 ± 1.3 ± 0.8
>2 σ effect...



A. Wright

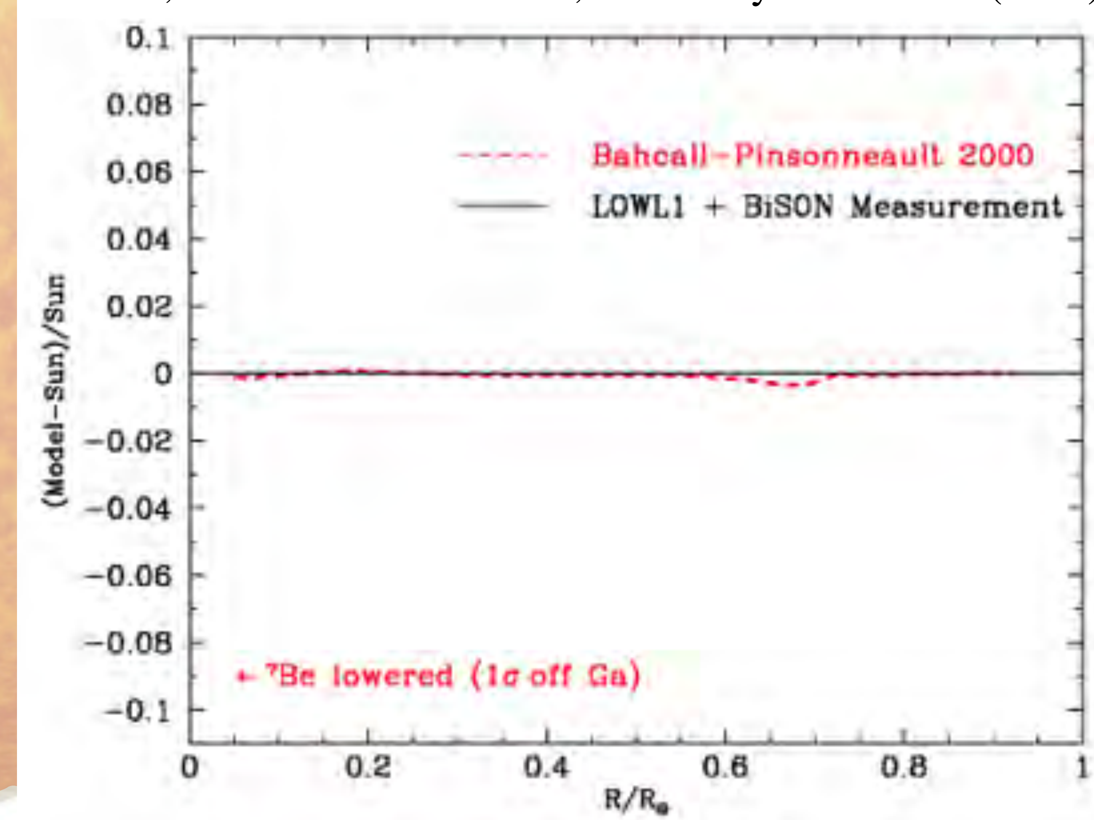
(C) Understanding the Sun

Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

SSM predicts speed of sound through the radial profile of the Sun

Historically, beautiful agreement between SSM and helioseismology ⇛ ⇛ ⇛

Bahcall, Pinsonneault and Basu, Astro. Phys. J 555:990 (2001)



The Problem

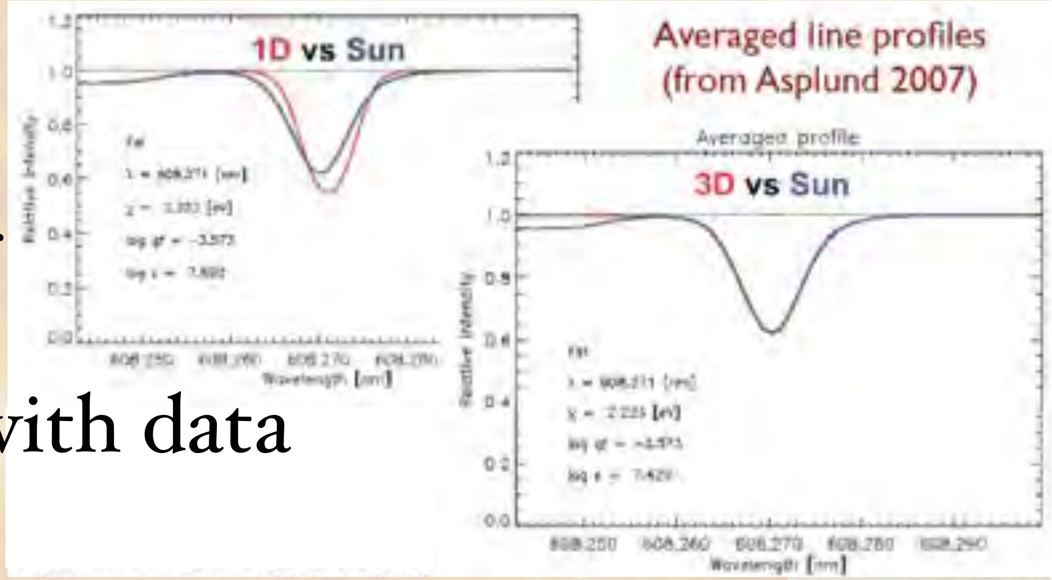
Metals (> H, He) influence solar dynamics & opacity

$\Longrightarrow$ Affect local speed of sound

The Problem

Metals (> H, He) influence solar dynamics & opacity
⟹ Affect local speed of sound

Classic analyses model photosphere in 1D
Ignore stratification, velocities, inhomogeneities



New 3D methods ⟹ better agreement with data

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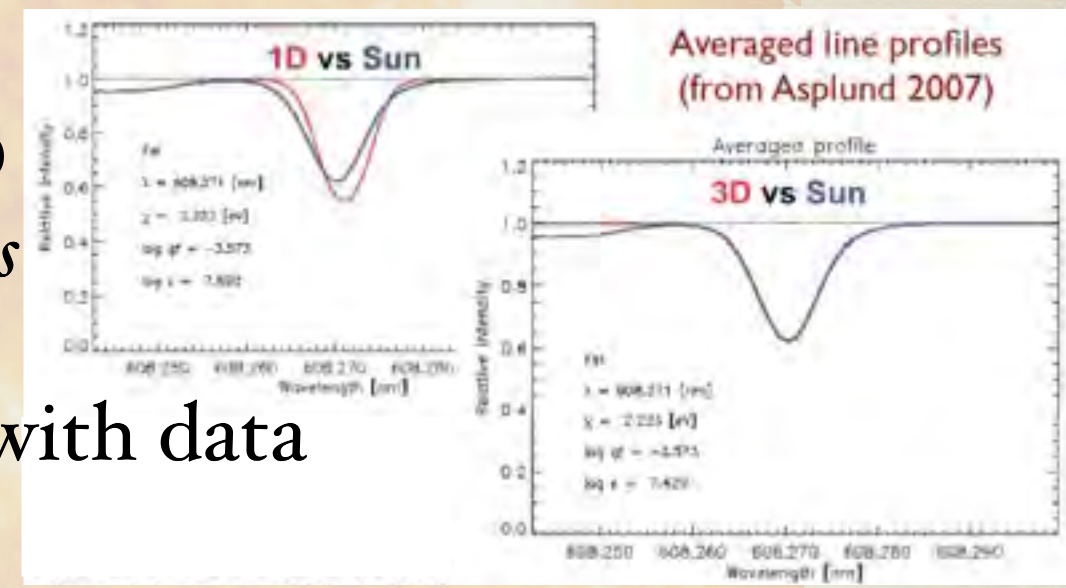

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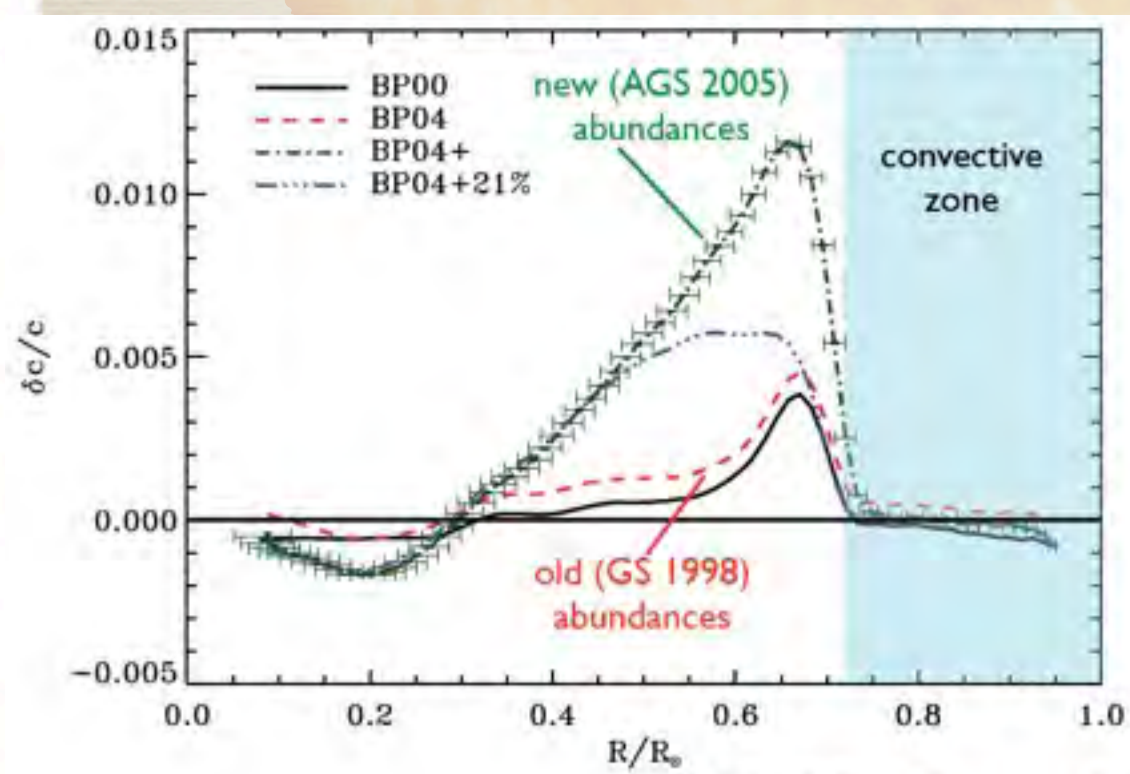


Lower abundance of metals

More consistent with neighbouring stars of similar type

New discrepancy from model

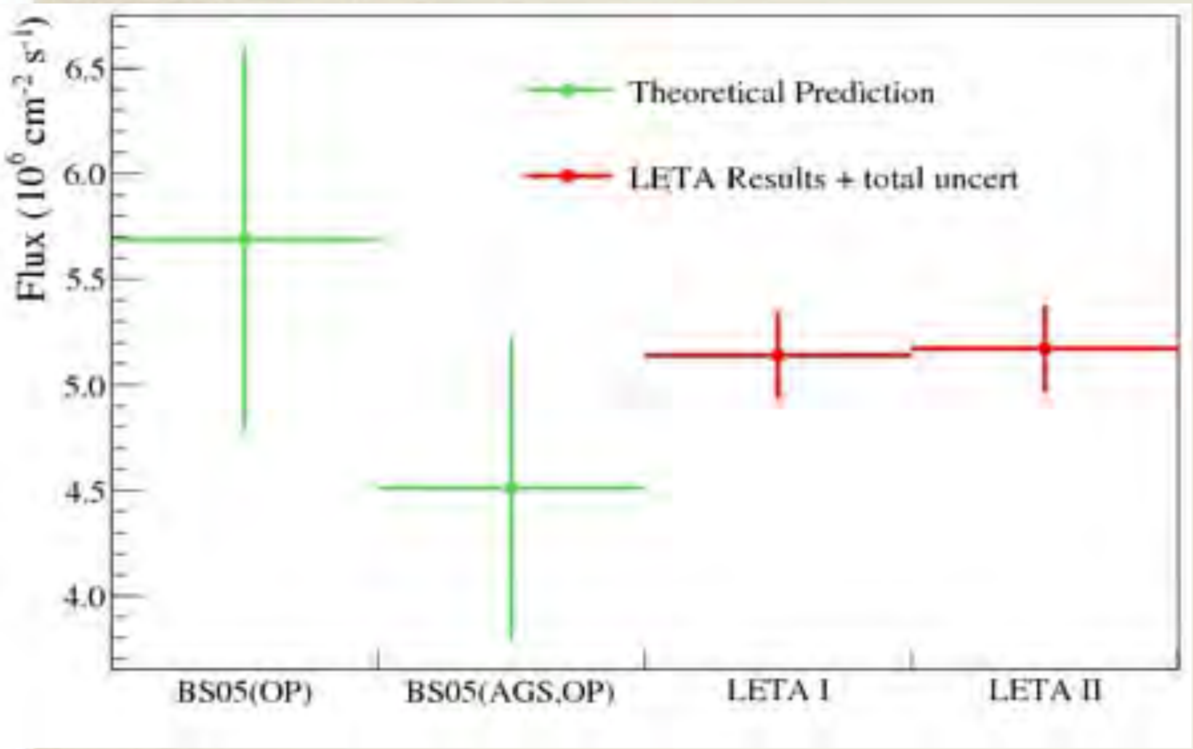
(C) Metallicity Status

Largest effect on pp-chain flux:

~17% reduction of ^{8}B (± 14% theory)

- *Hard to distinguish*
- *Not characteristic*

(C) Metallicity Status



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SNO's ^{8}B obeys the ambiguity principle:

<u>Ambiguity Principle:</u> For any given experimental test of a hypothesis, Nature will always strive to return the most ambiguous answer possible --- J. R. Klein

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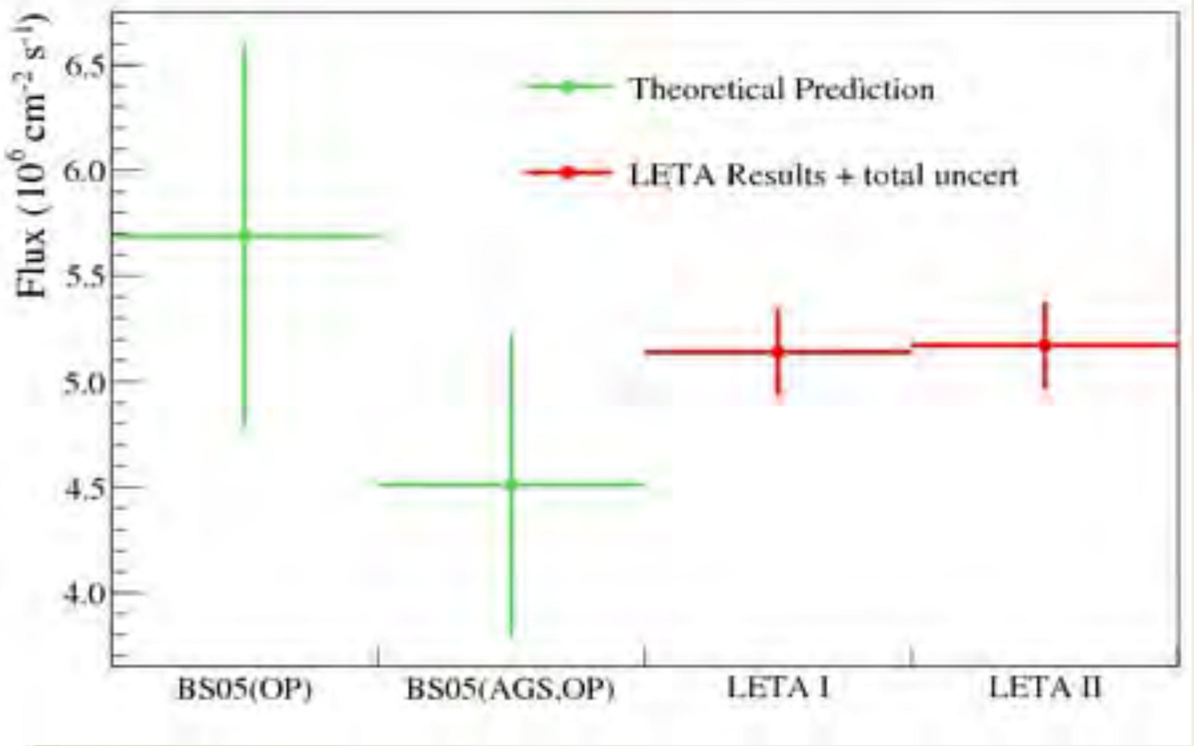

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CNO flux depends linearly on core metallicity

Predictions differ by >30%

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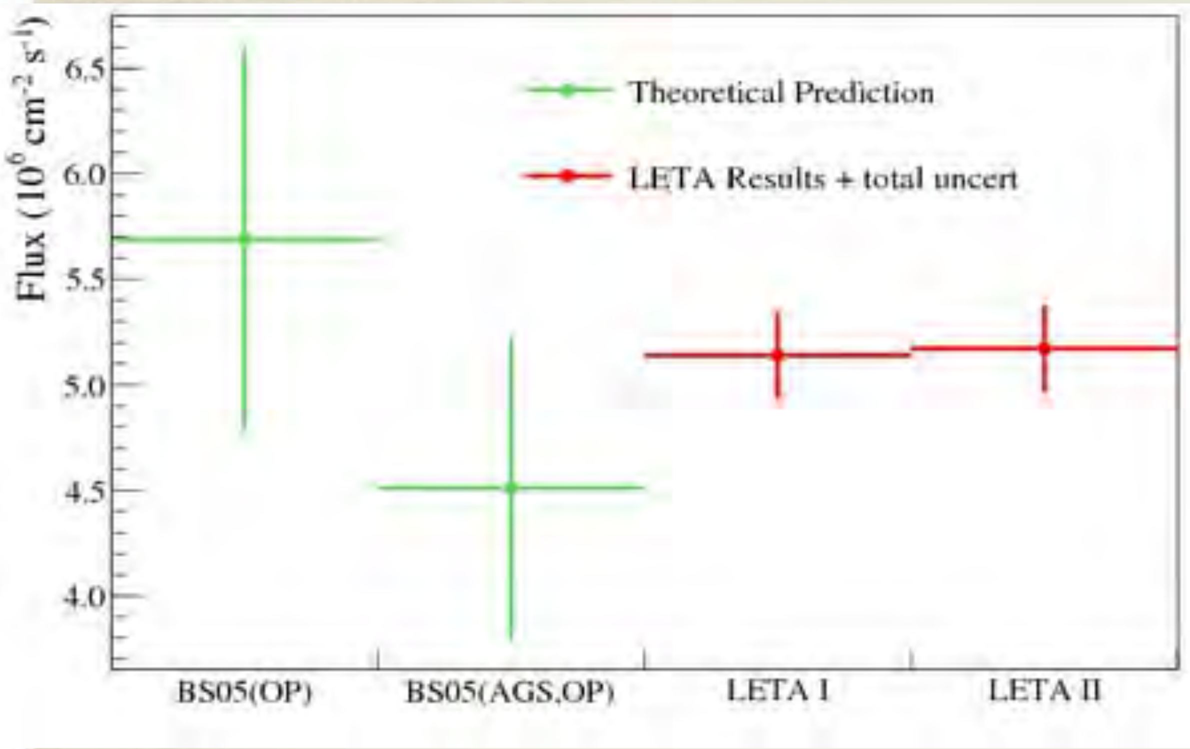

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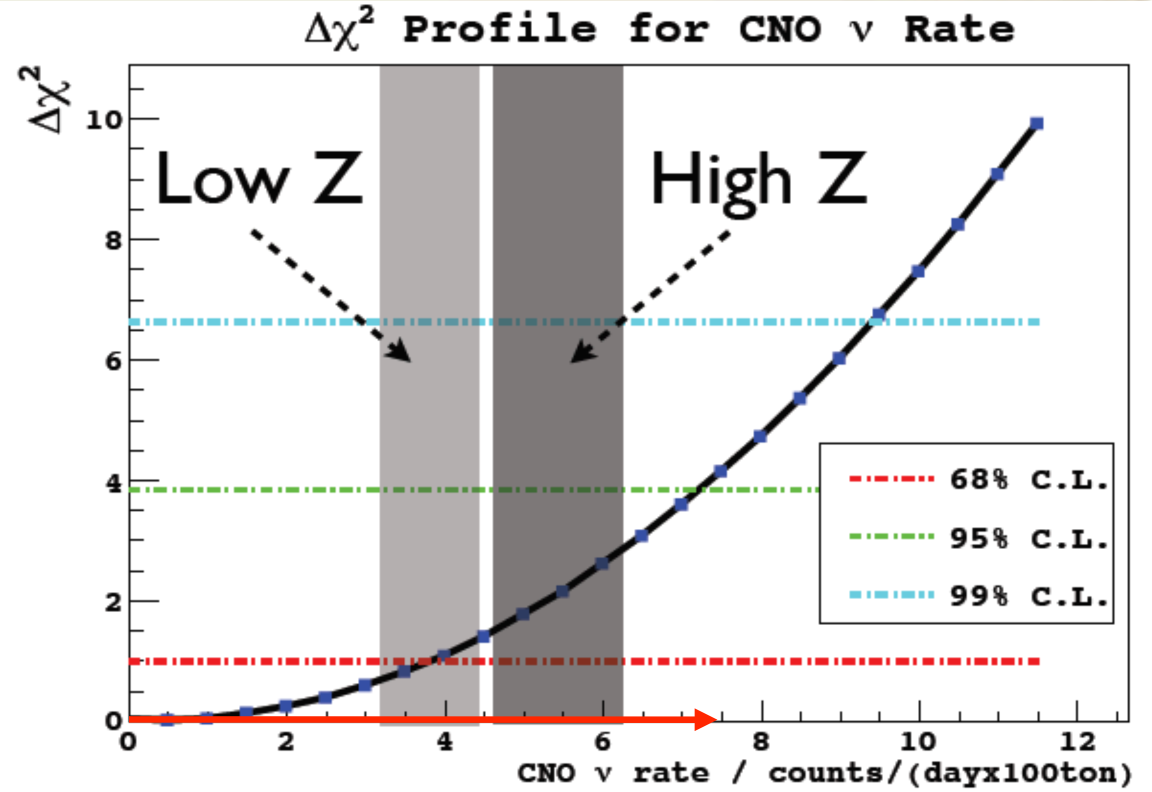
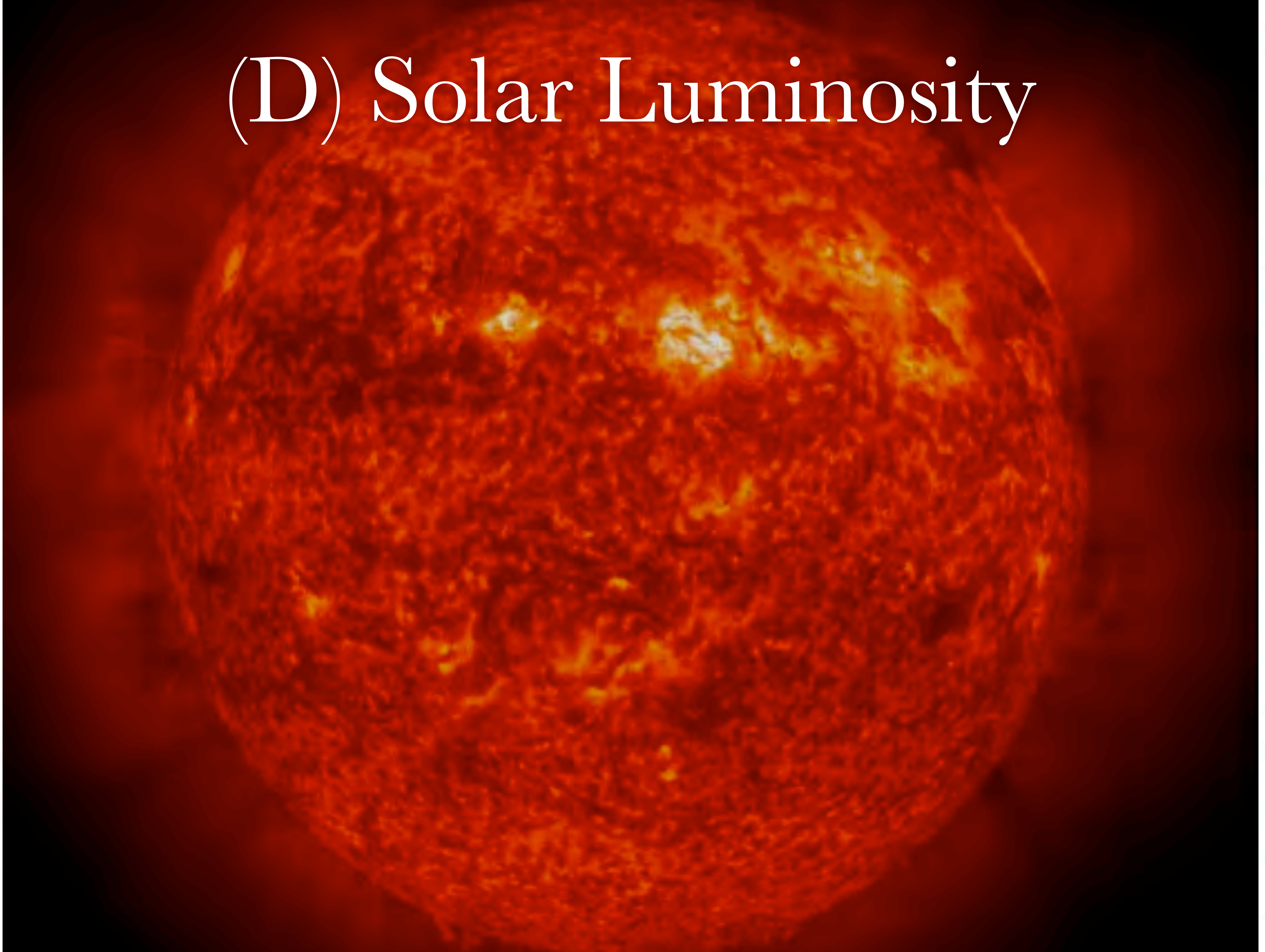
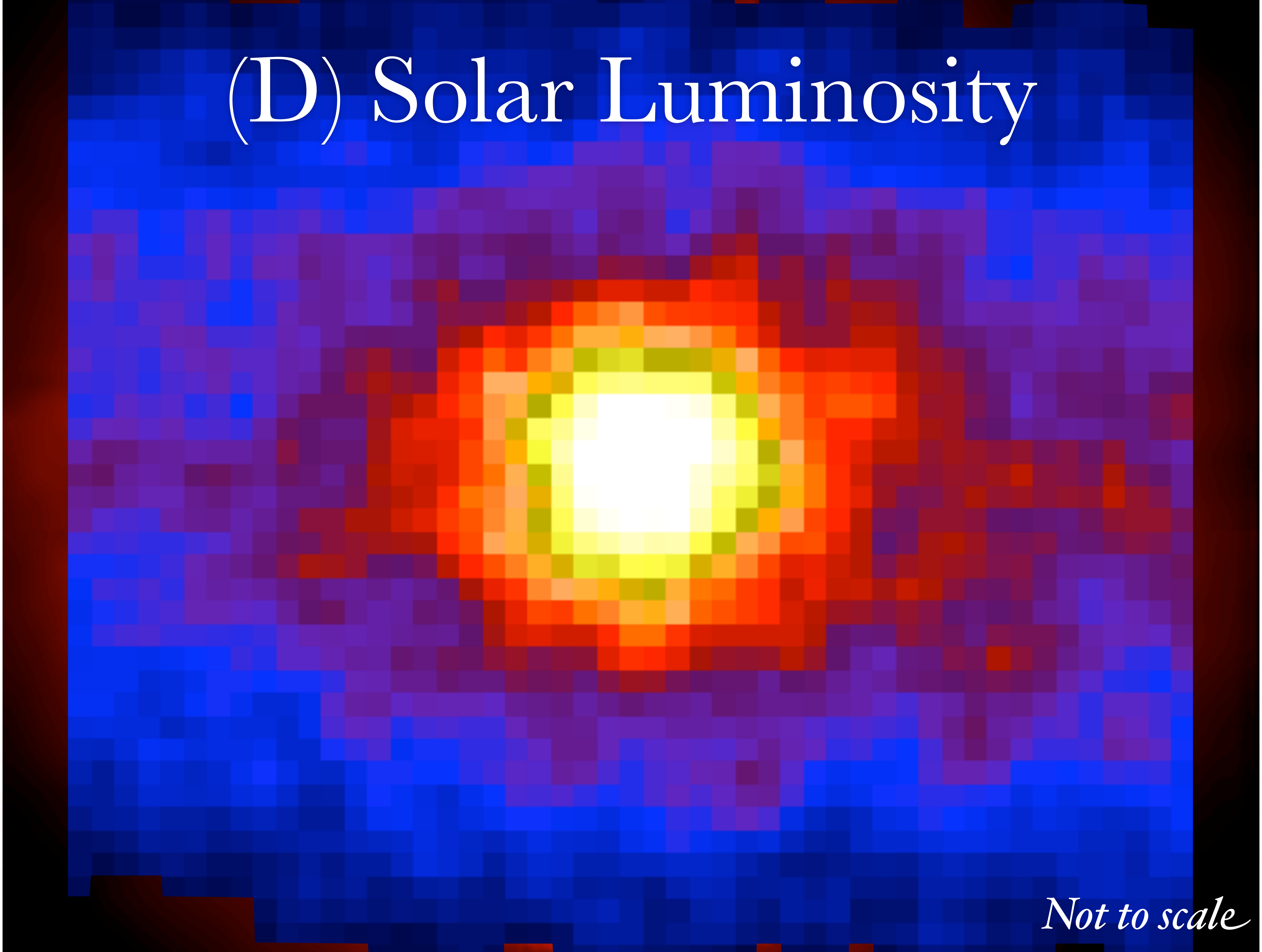


Borexino have the only direct limit:
2-3 * SSM prediction

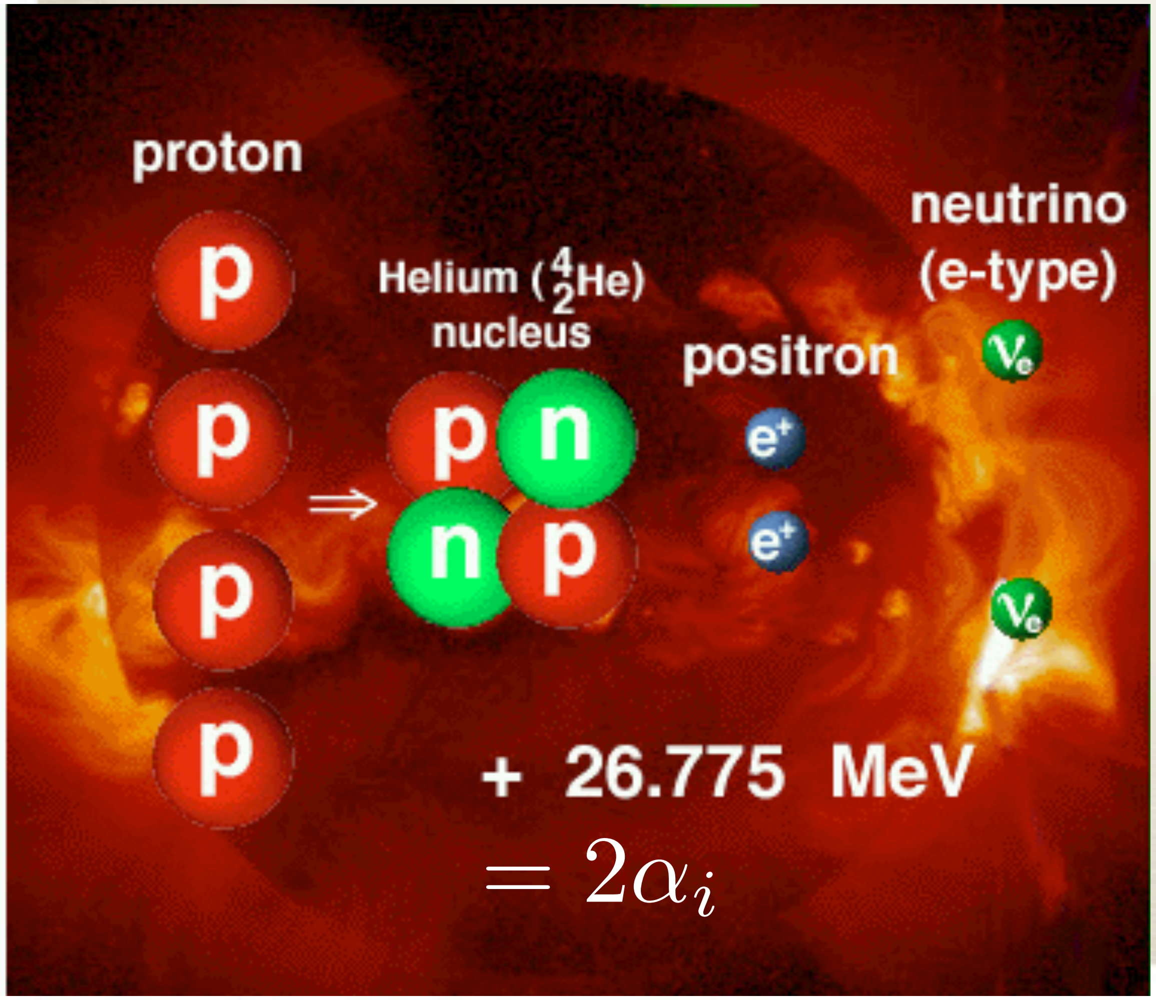
PRL 108, 051302 (2012)


(D) Solar Luminosity


(D) Solar Luminosity
Not to scale

(D) Solar Luminosity

Assume γs & νs produced only in fusion reactions:
⇛ relate γ luminosity to ν luminosity



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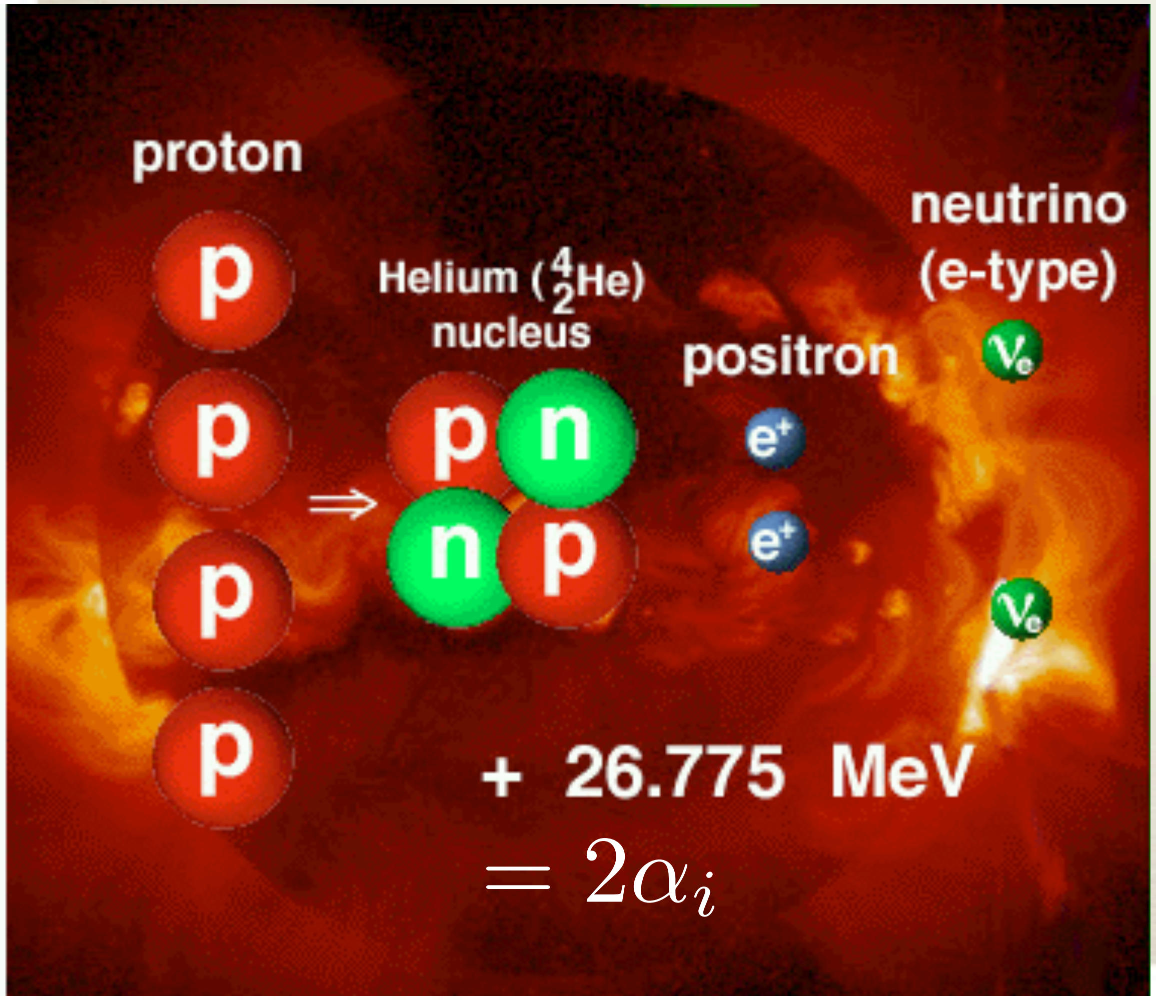
Each ν flux, Φ_i ⇔ specific amount of energy released in the fusion reaction per ν, α_i



$$\frac{\mathcal{L}_\odot}{4\pi\,(A.U)^2} = \sum_i \alpha_i \Phi_i$$

The "Luminosity Constraint"

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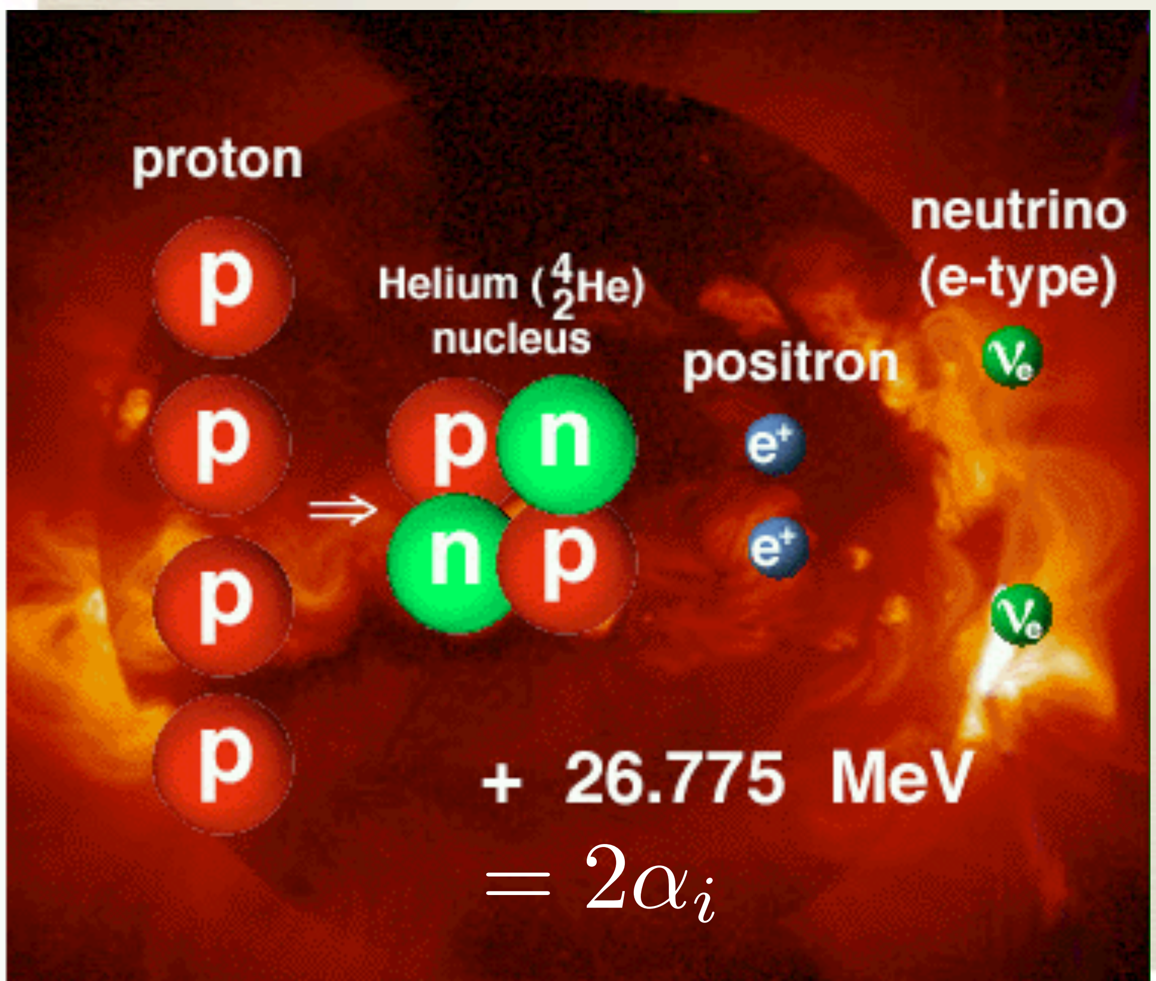

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The "Luminosity Constraint"

Test for:

ν appearance/disappearance

E loss/generation mechanisms

The Road Forward

* What the Sun can tell us about neutrinos

* What neutrinos can tell us about the Sun

The Road Forward

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The Road Forward

* What the Sun can tell us about neutrinos
  - *Precision pep flux*
  - *Low-energy ^8B spectrum*

} Search for new physics in transition region

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Confirm MSW

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Resolve solar metallicity

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Confirm MSW

* What neutrinos can tell us about the Sun
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  - *Direct pp measurement*

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Luminosity constraint

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Confirm MSW

* What neutrinos can tell us about the Sun
  - *CNO flux measurement* — Resolve solar metallicity
  - *Direct pp measurement* — Luminosity constraint

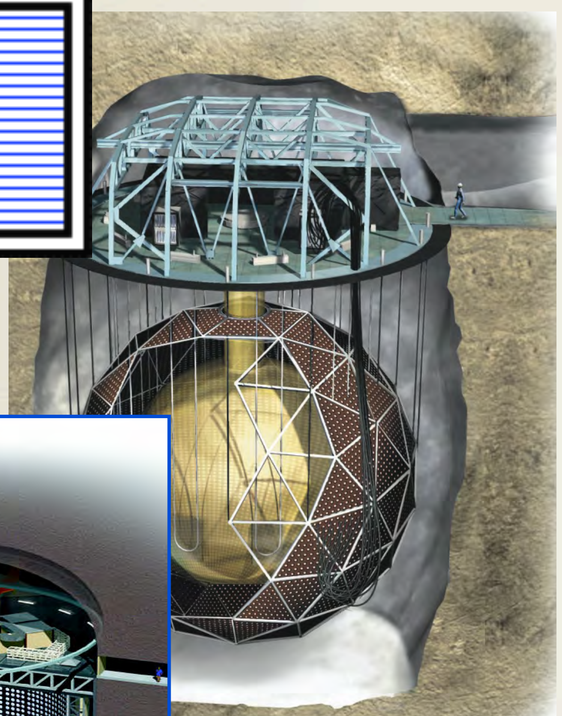
"Gold ring of solar neutrino physics & astronomy"

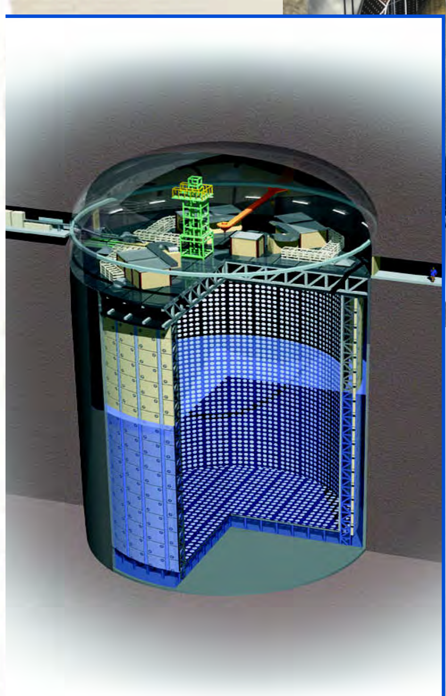
--- John Bahcall

Experiments

Experiments

Water Cerenkov



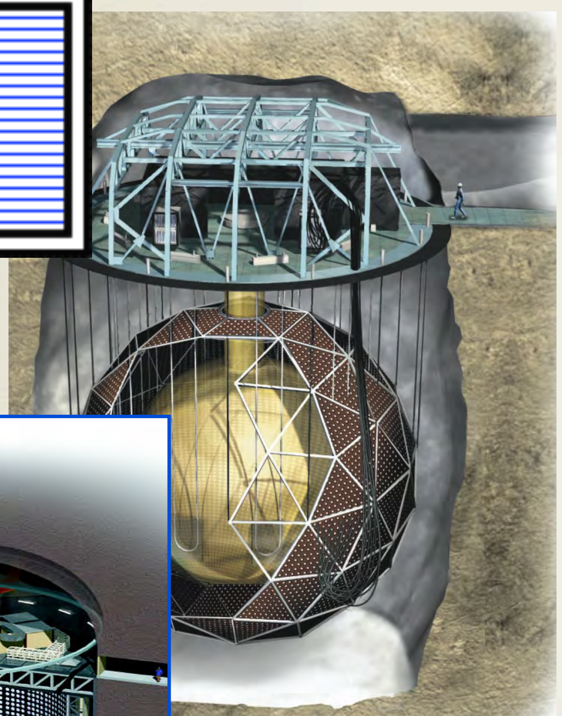


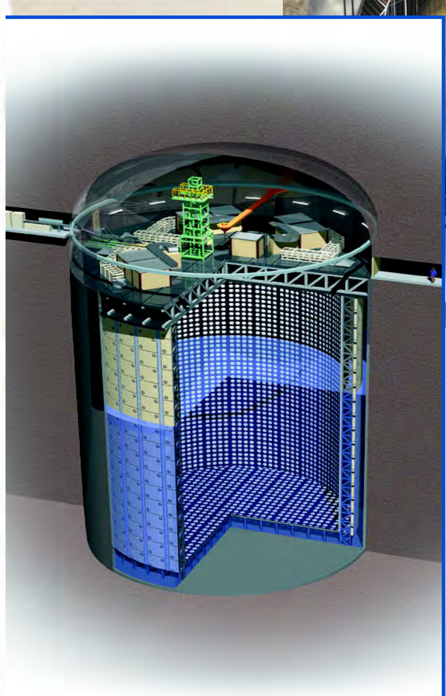
SNO

SuperK

Experiments

Water Cerenkov

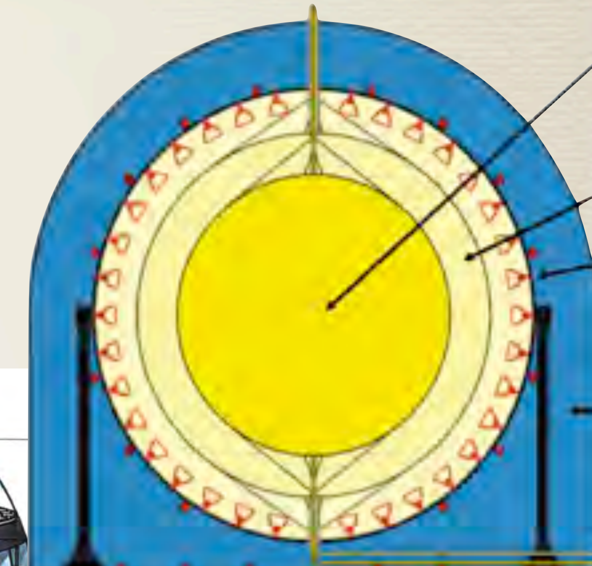


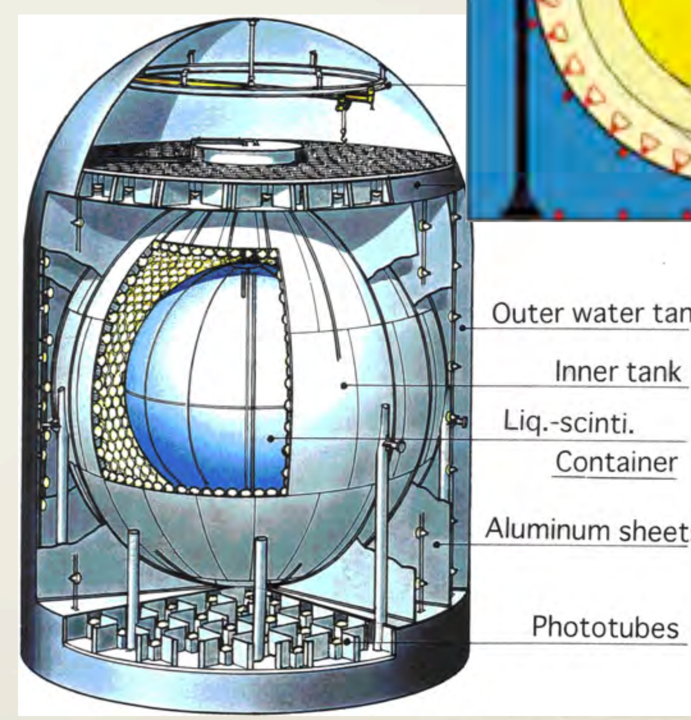


SNO
SuperK

Liquid Scintillator

Borexino
KamLAND





Experiments

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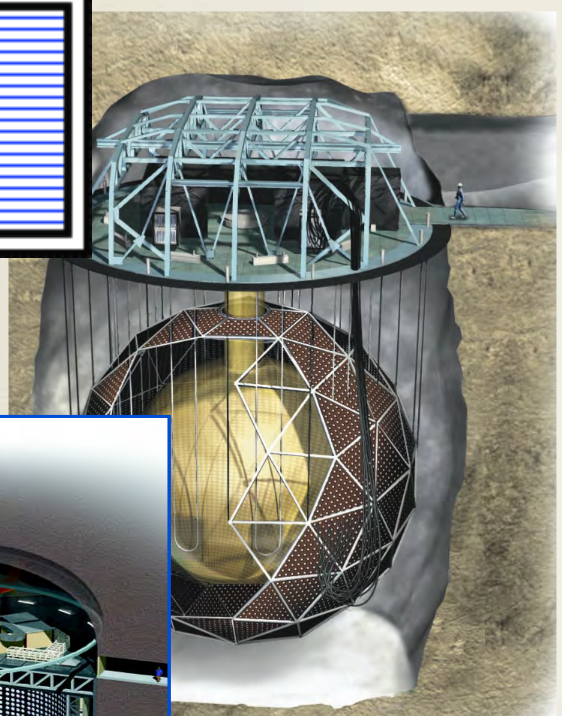
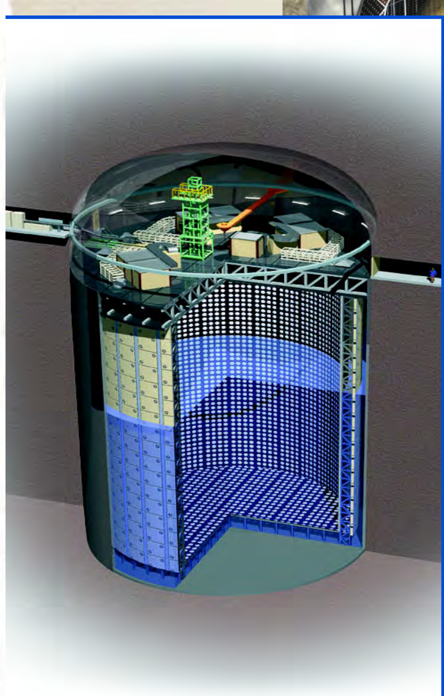




SNO
SuperK

Radiochemical

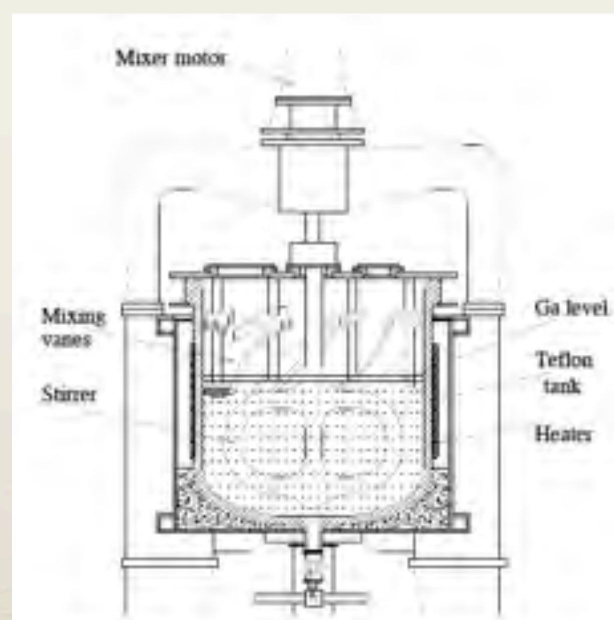


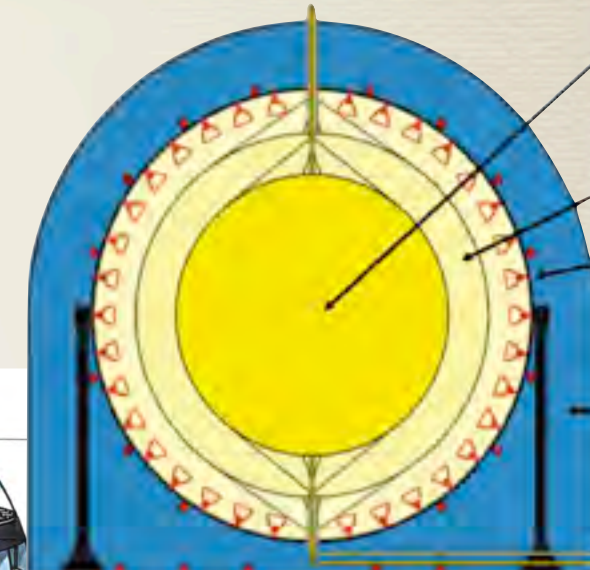
FIG. 1. Chemical reactor for extraction of Ge from Ga.

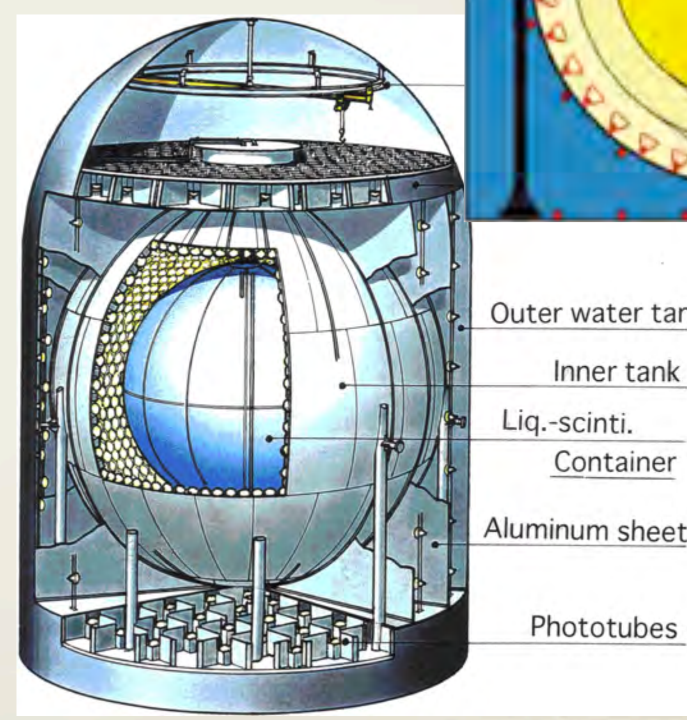
Phys.Rev.C60:055801,1999

SAGE

Liquid Scintillator

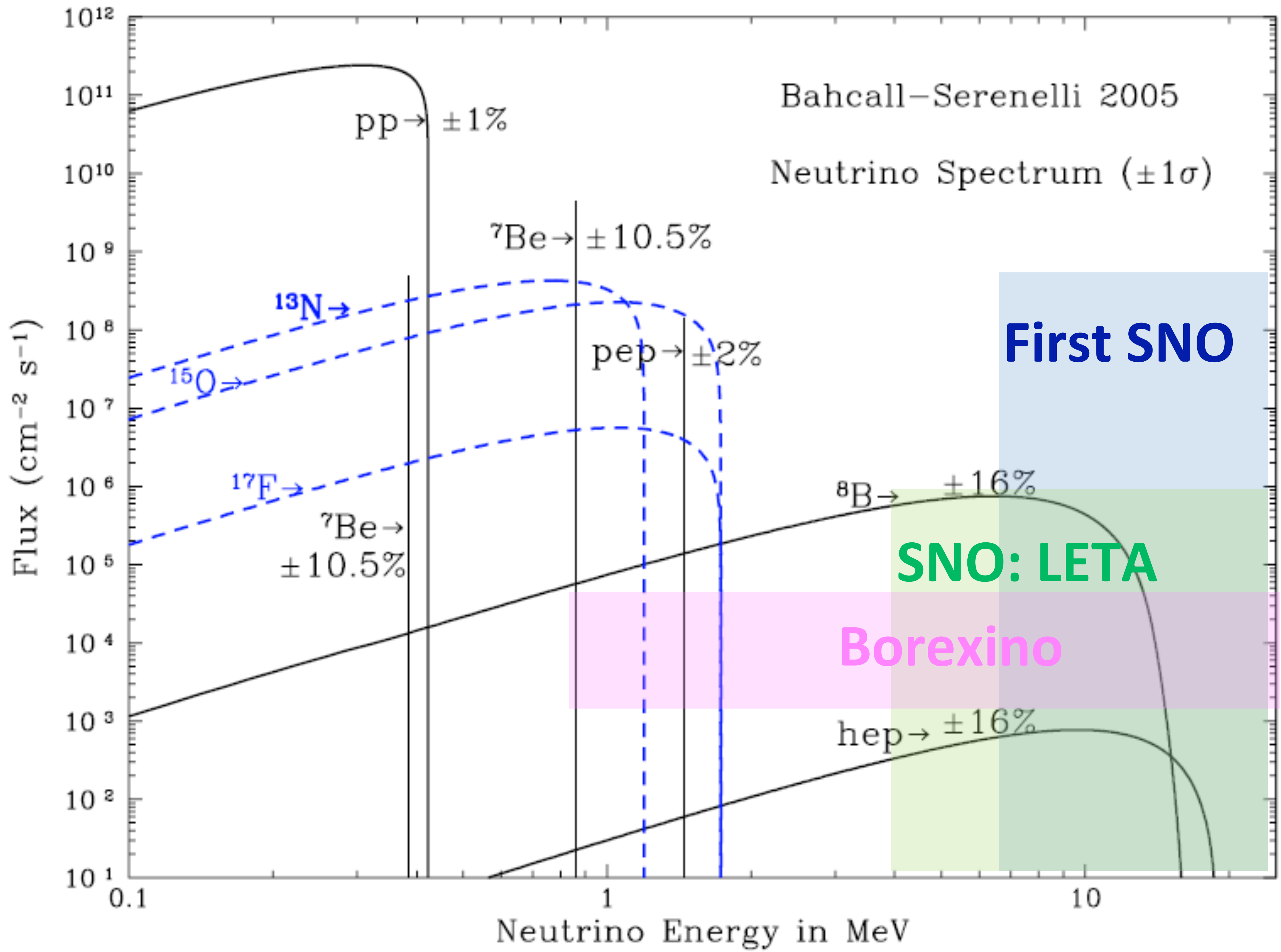
Borexino
KamLAND



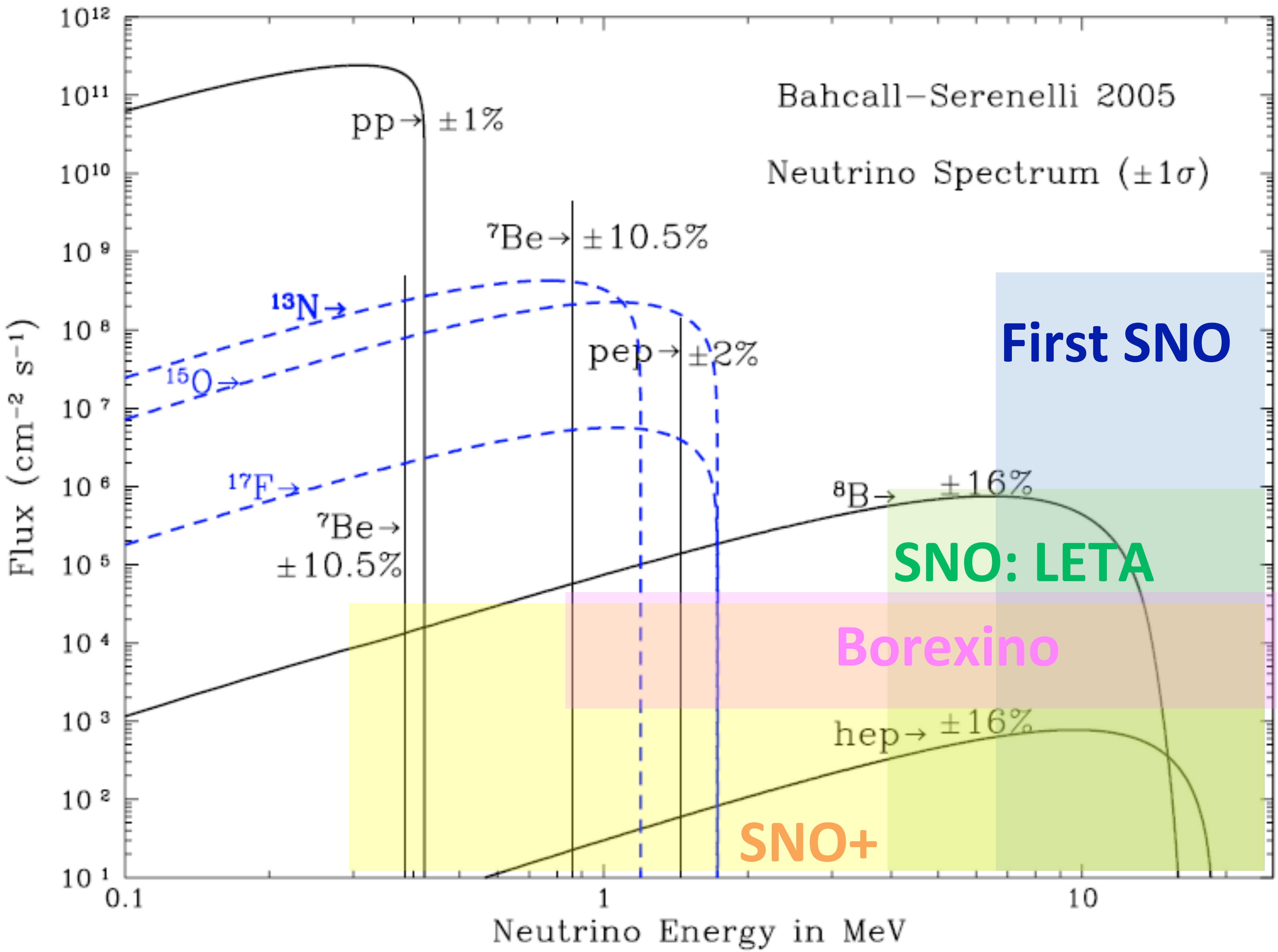



SNO+
The only fully-funded new solar experiment

Solar ν Status



SNO+ Solar ν Prospects



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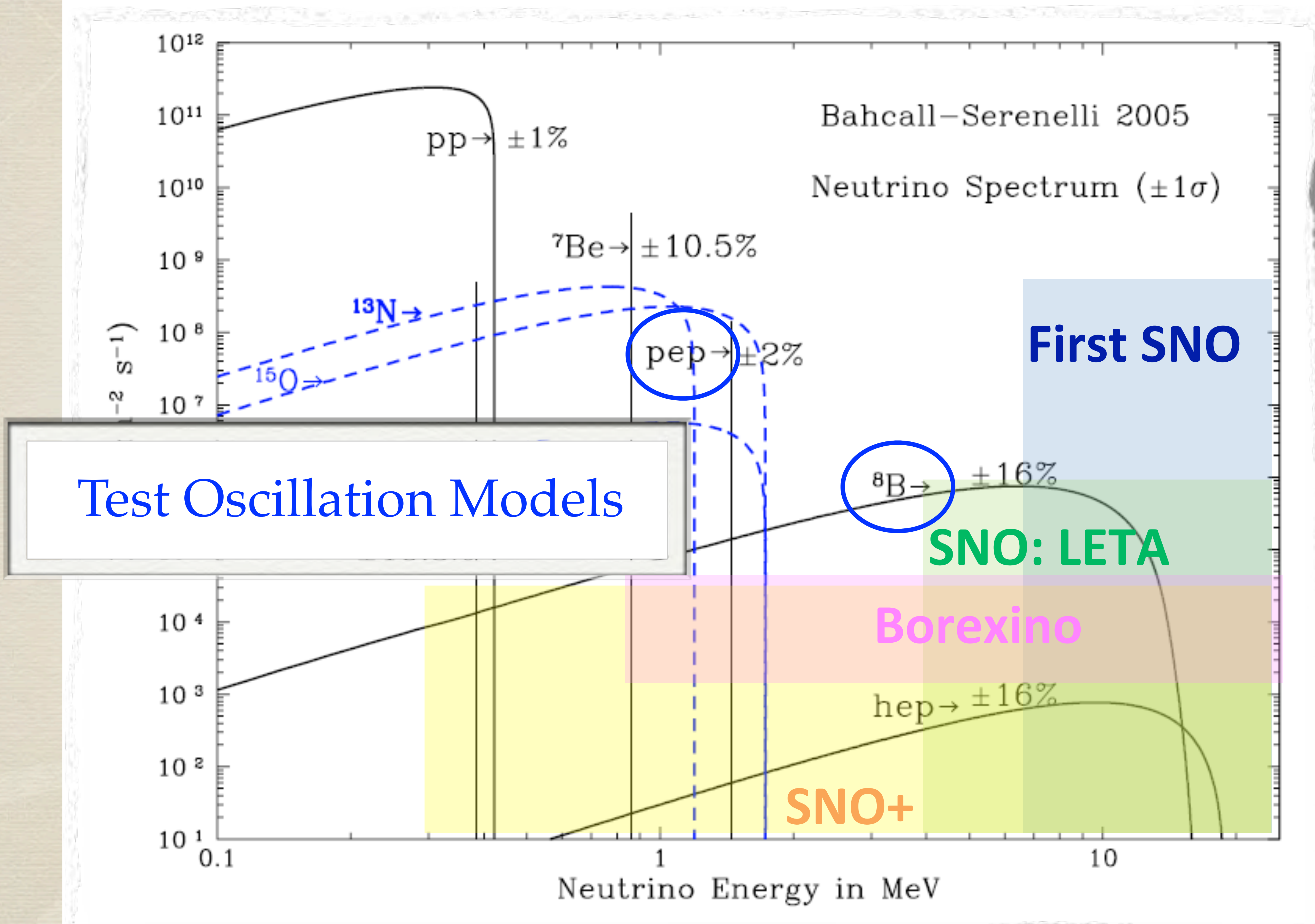

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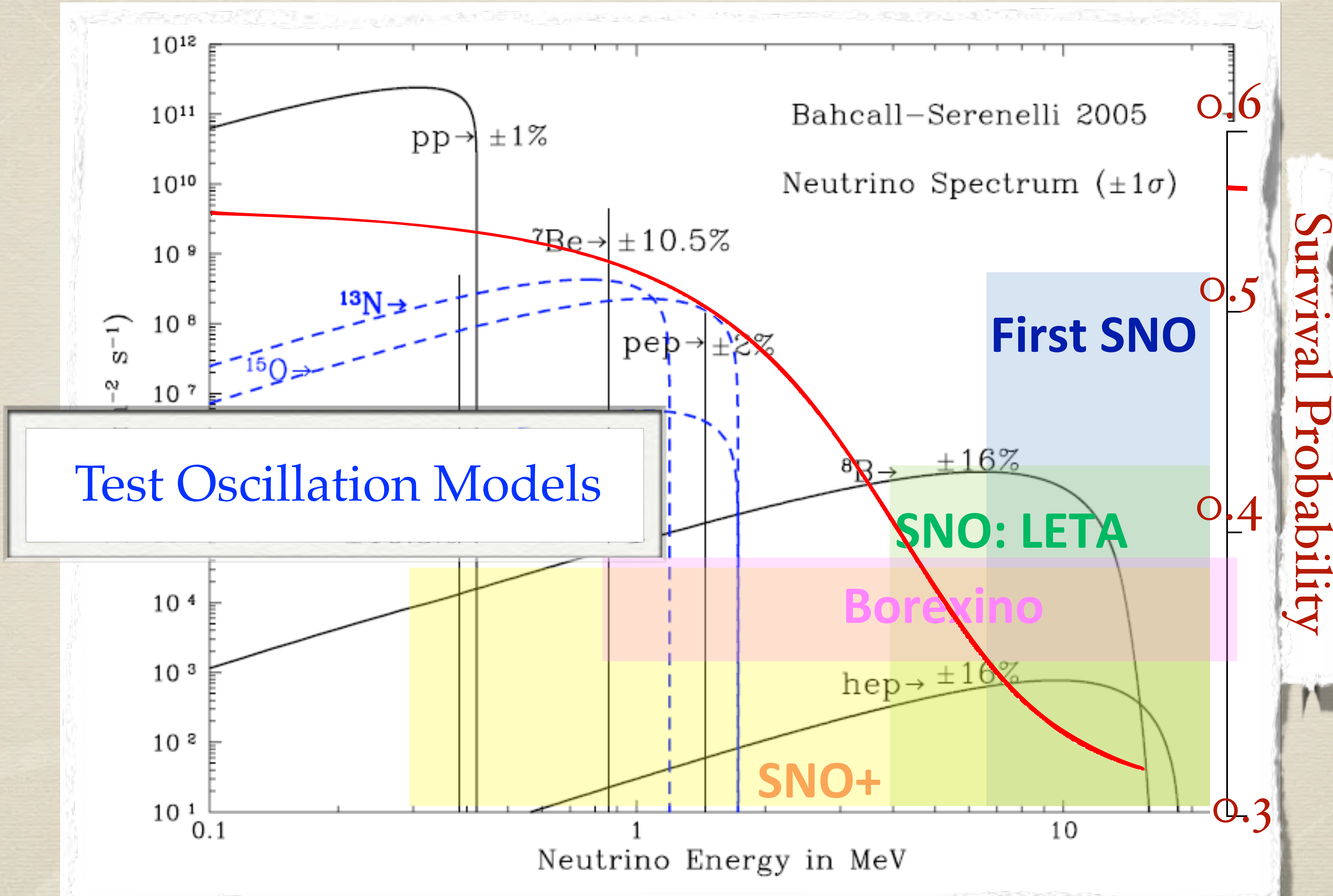

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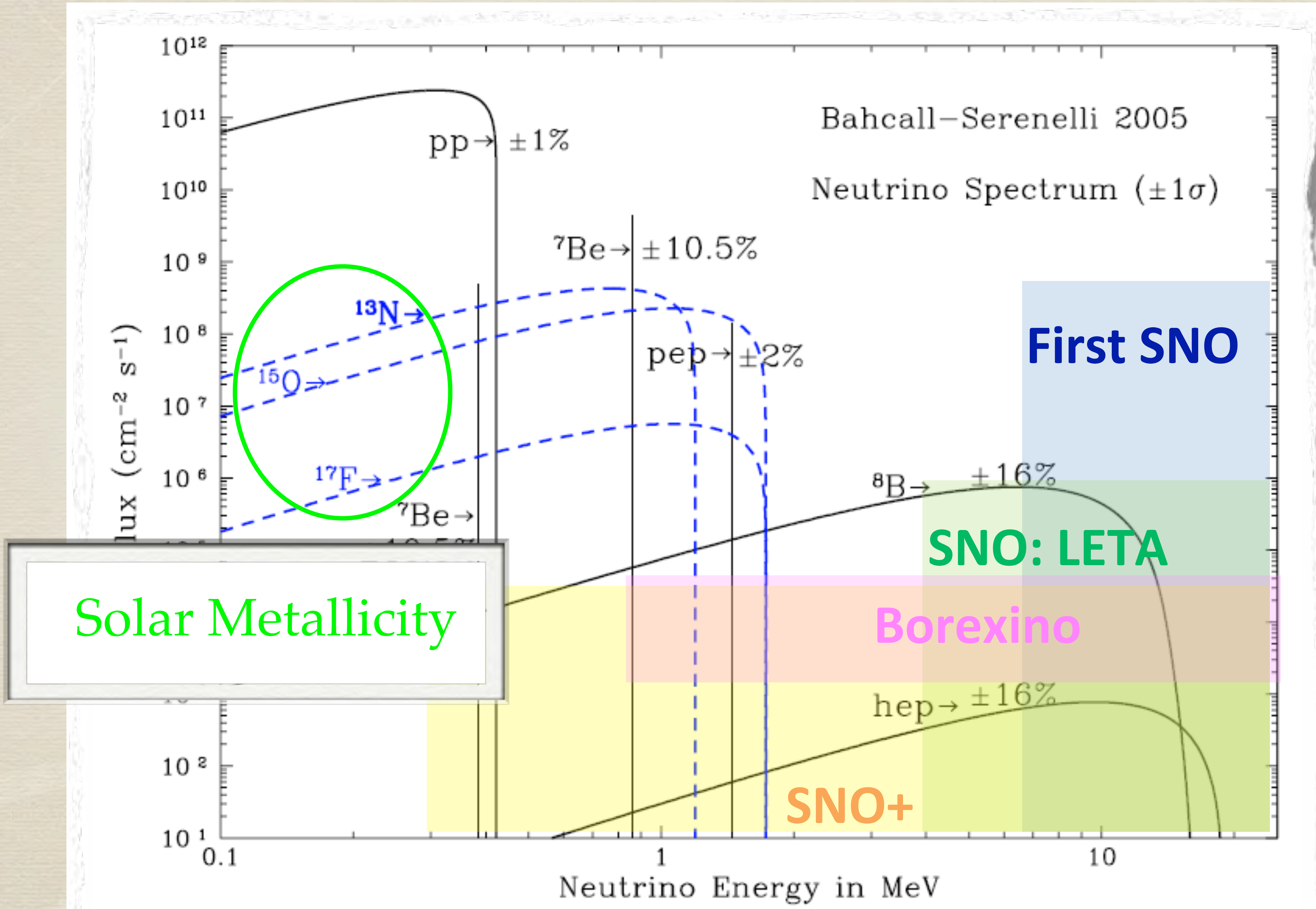

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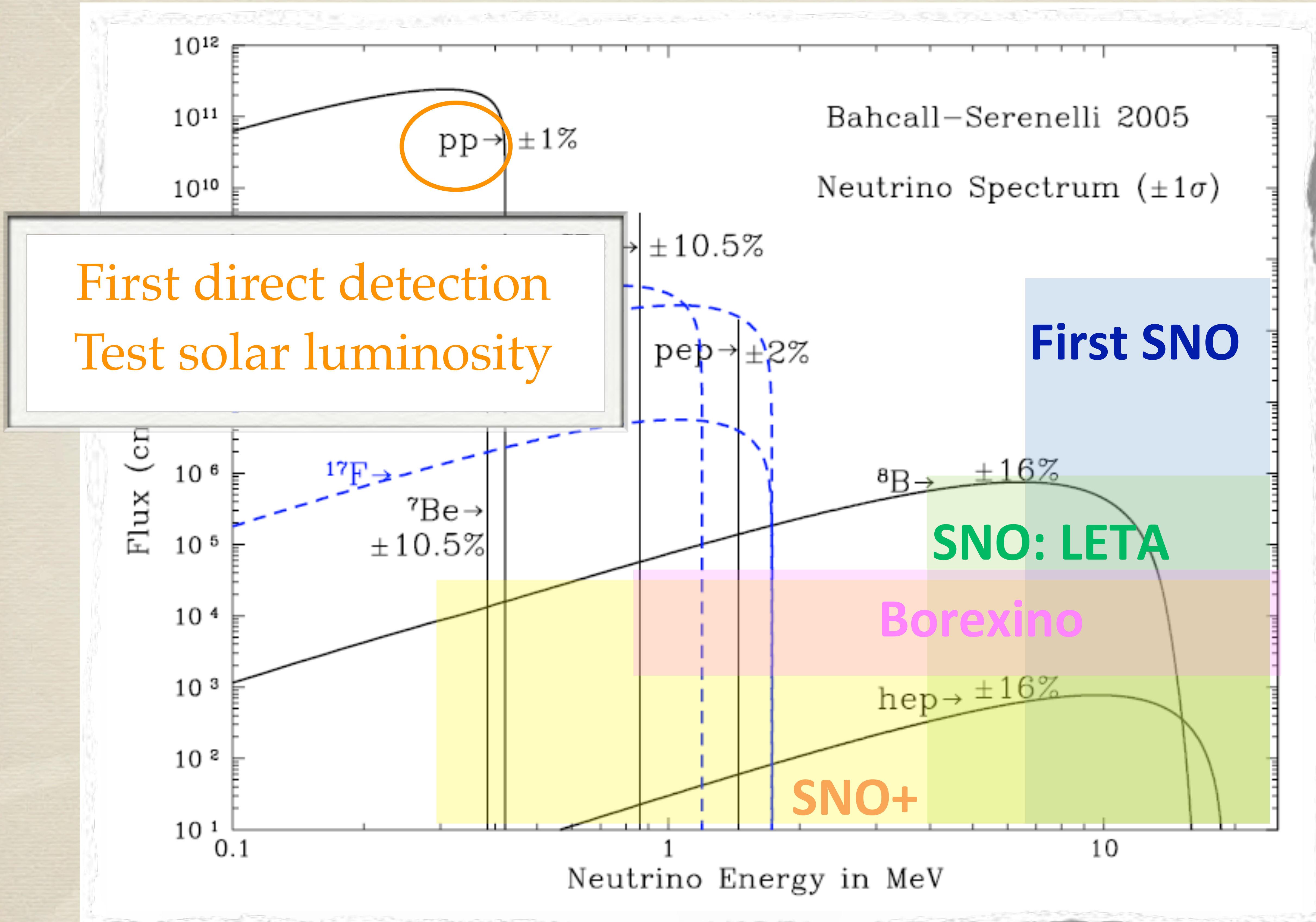
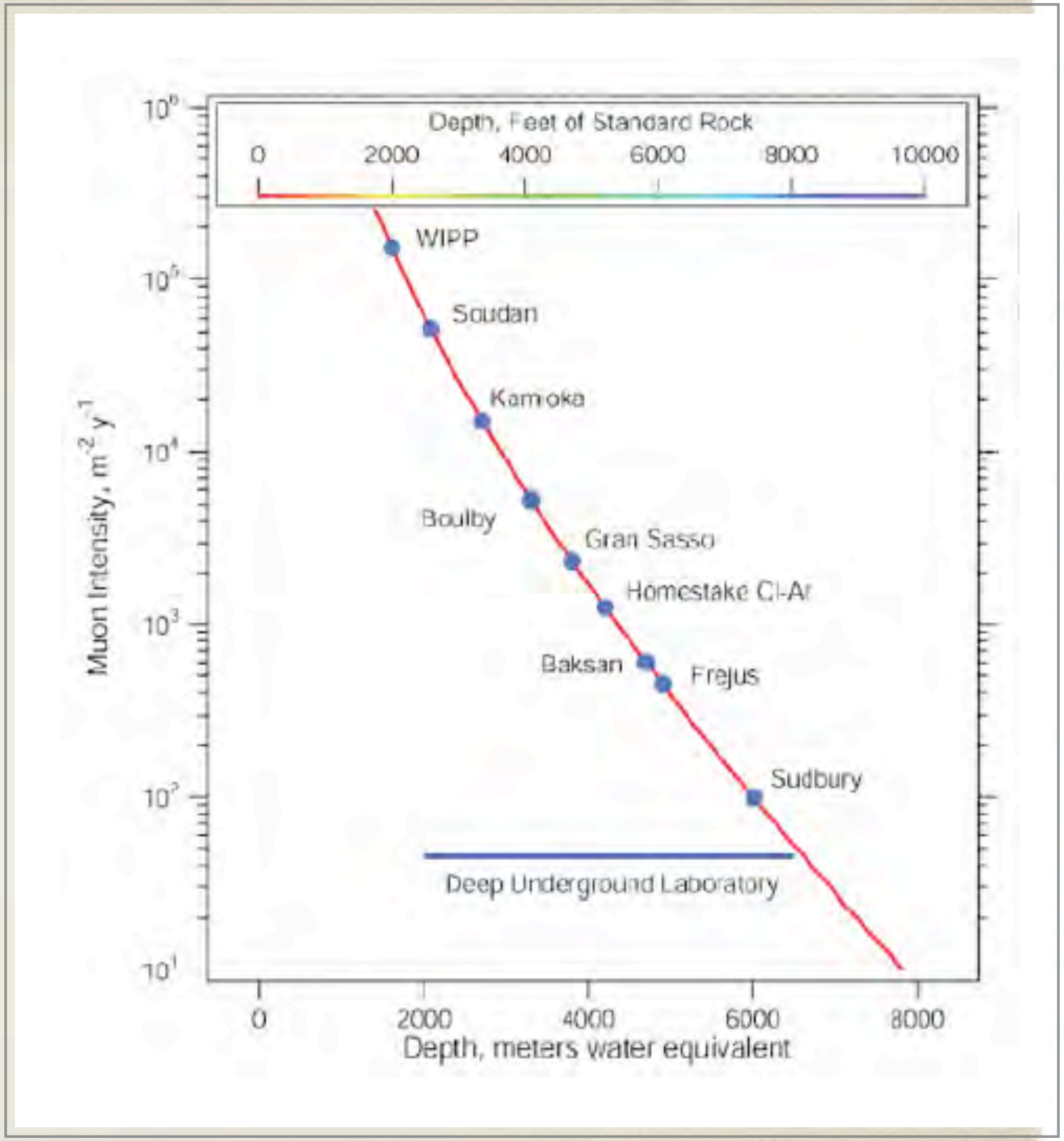


SNO+ Advantages: Depth

^{11}C produced by cosmic μ hitting organic molecules

KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe



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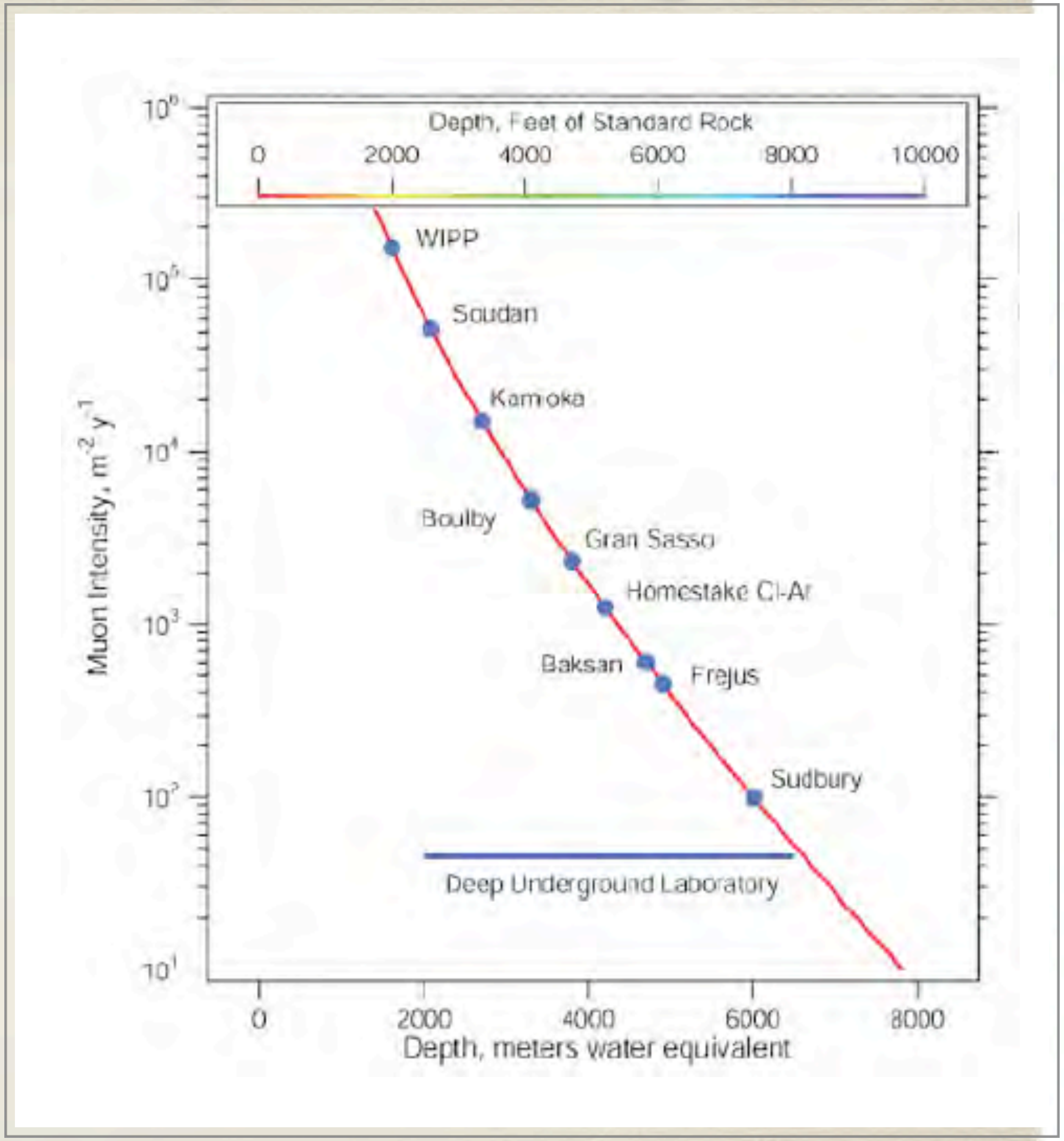

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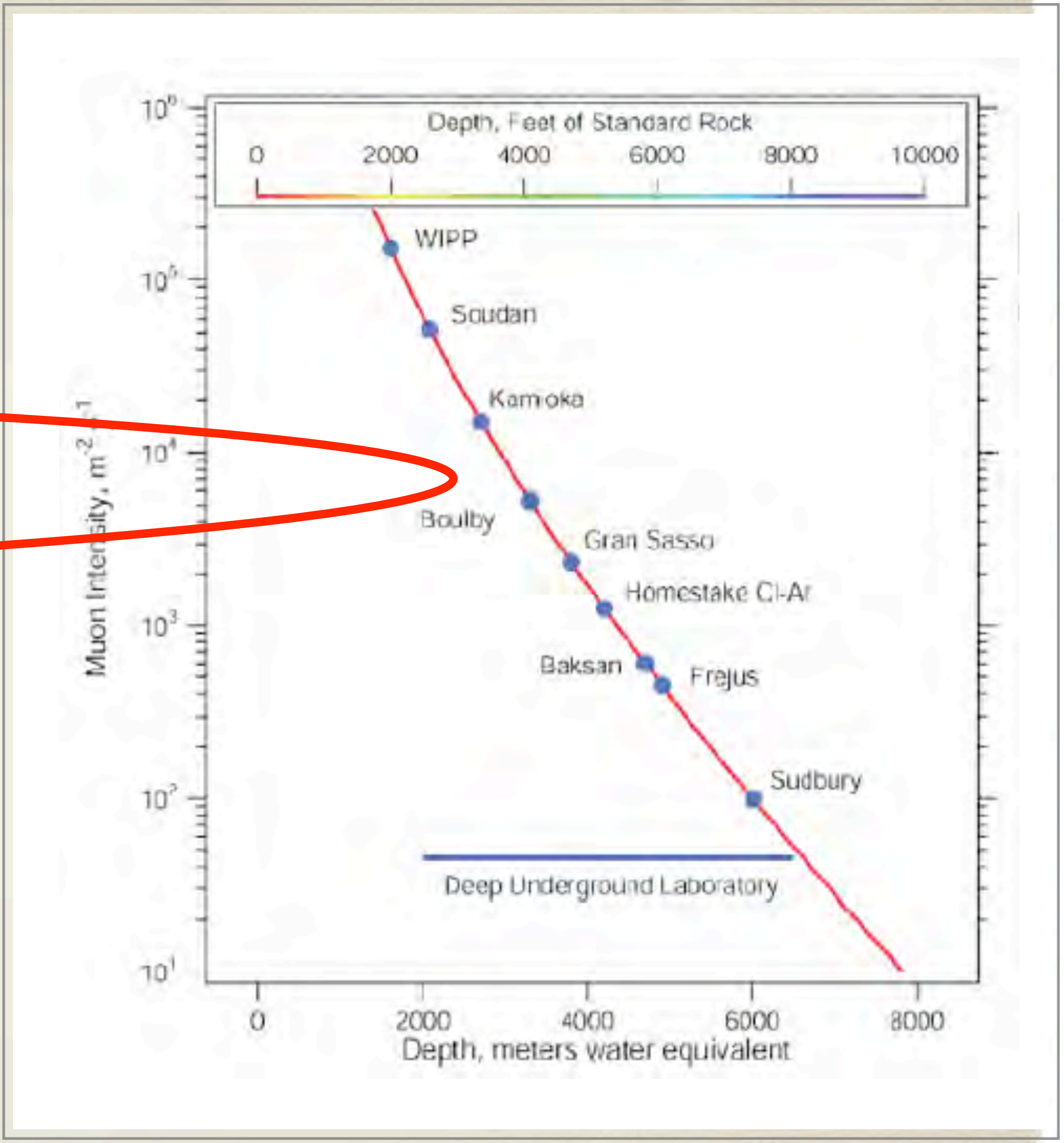
/100

/600



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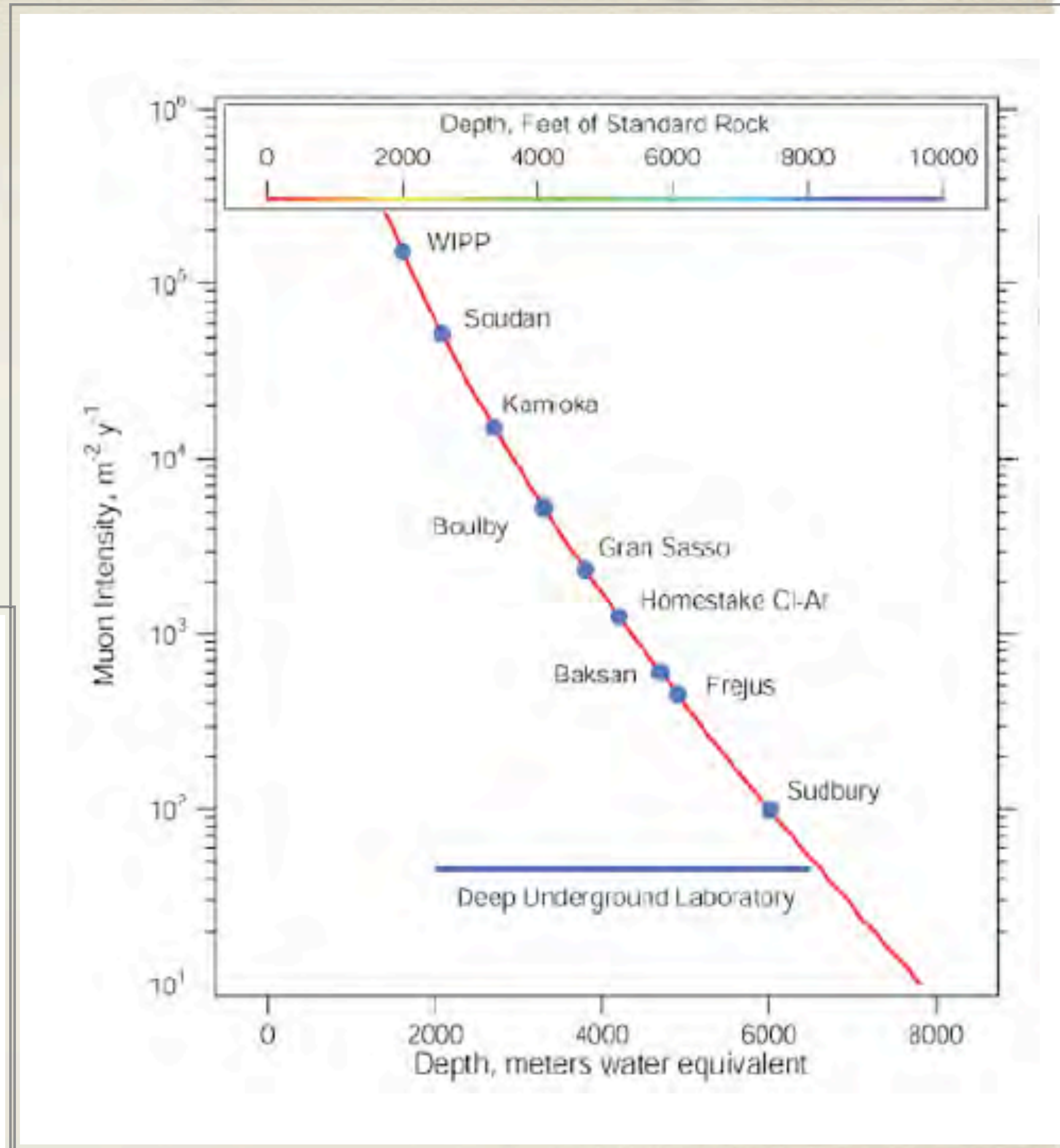

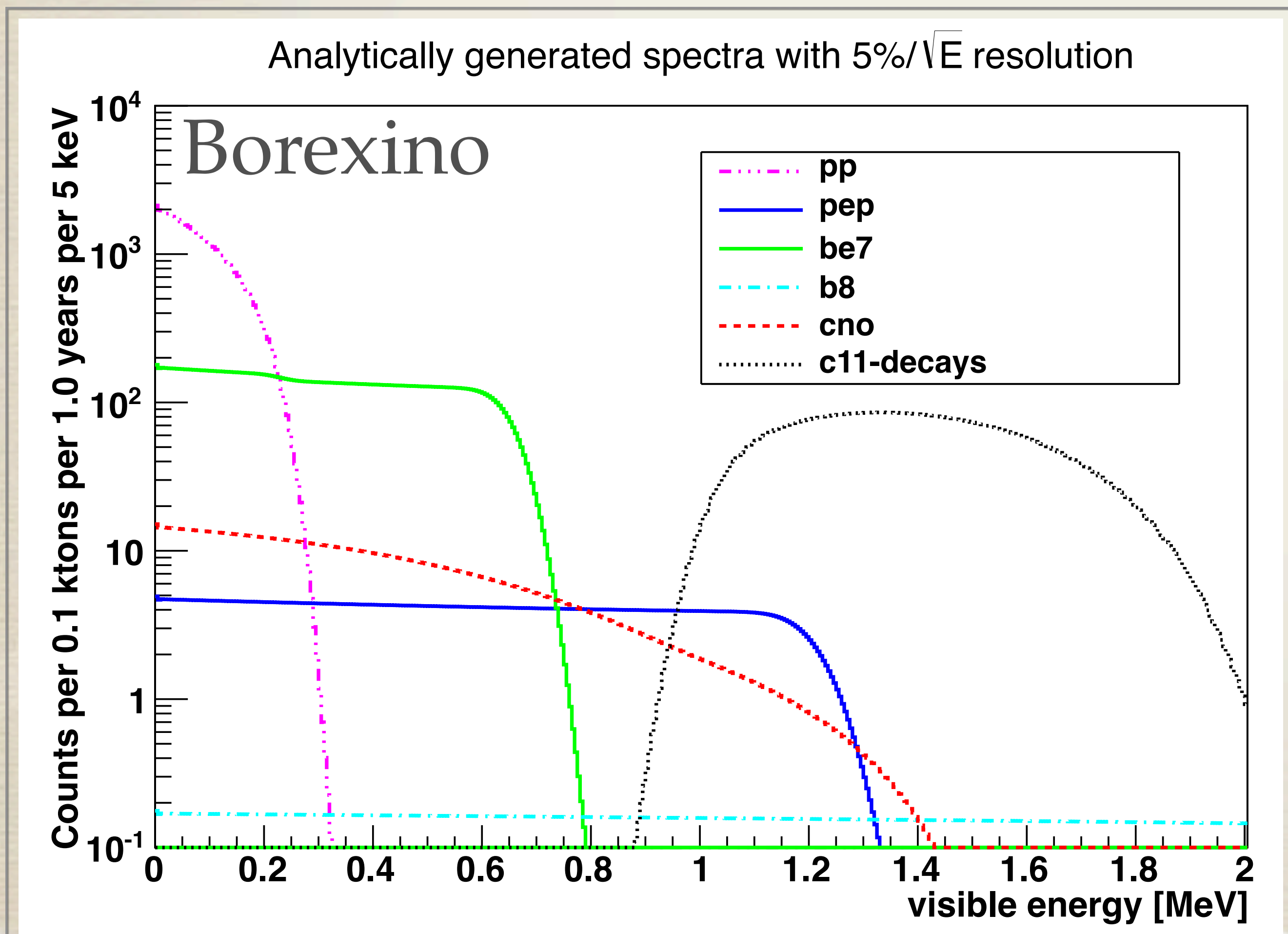

3-fold coincidence cut for 11C rejection
91% rejection, 52% signal loss

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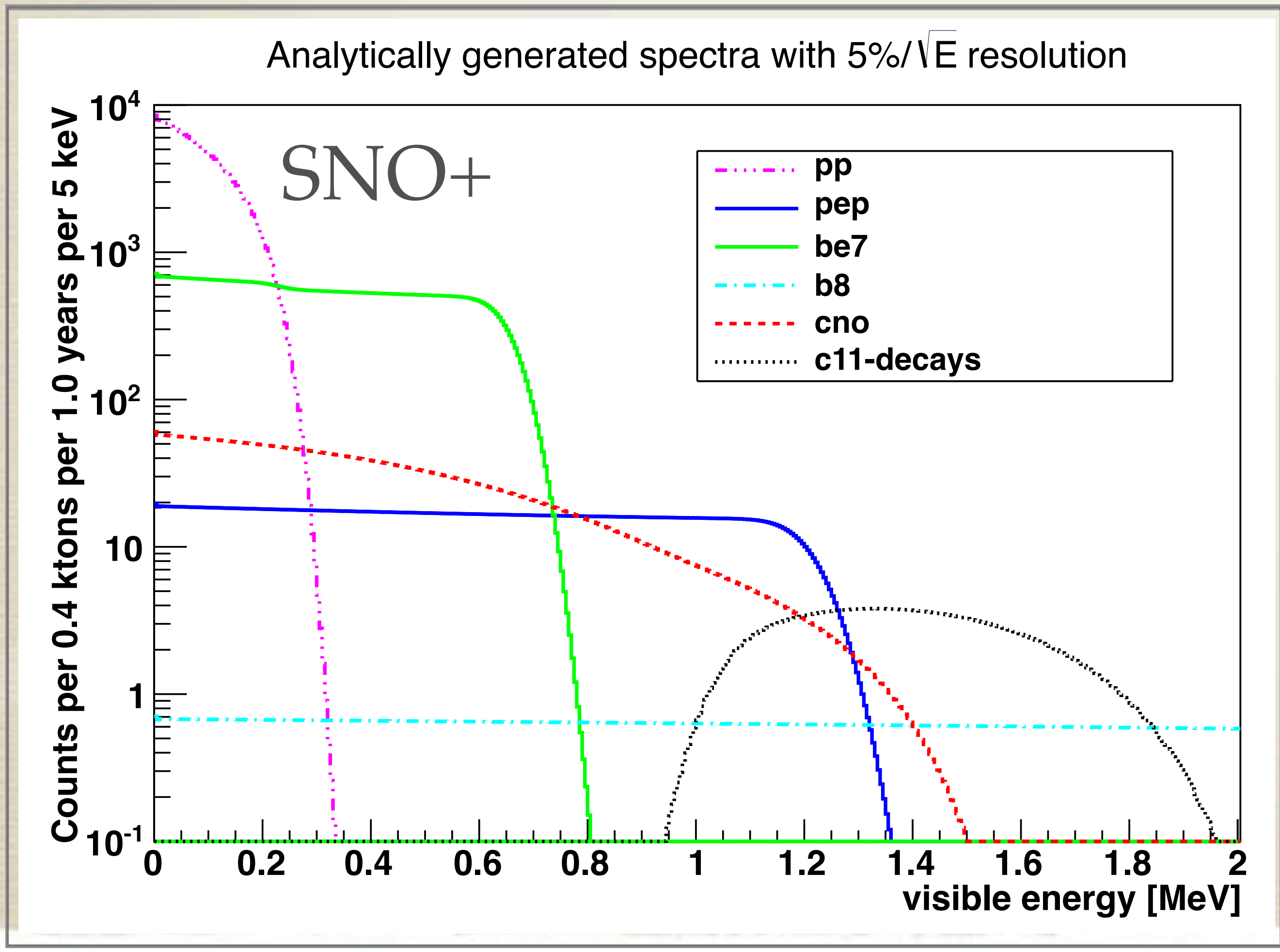
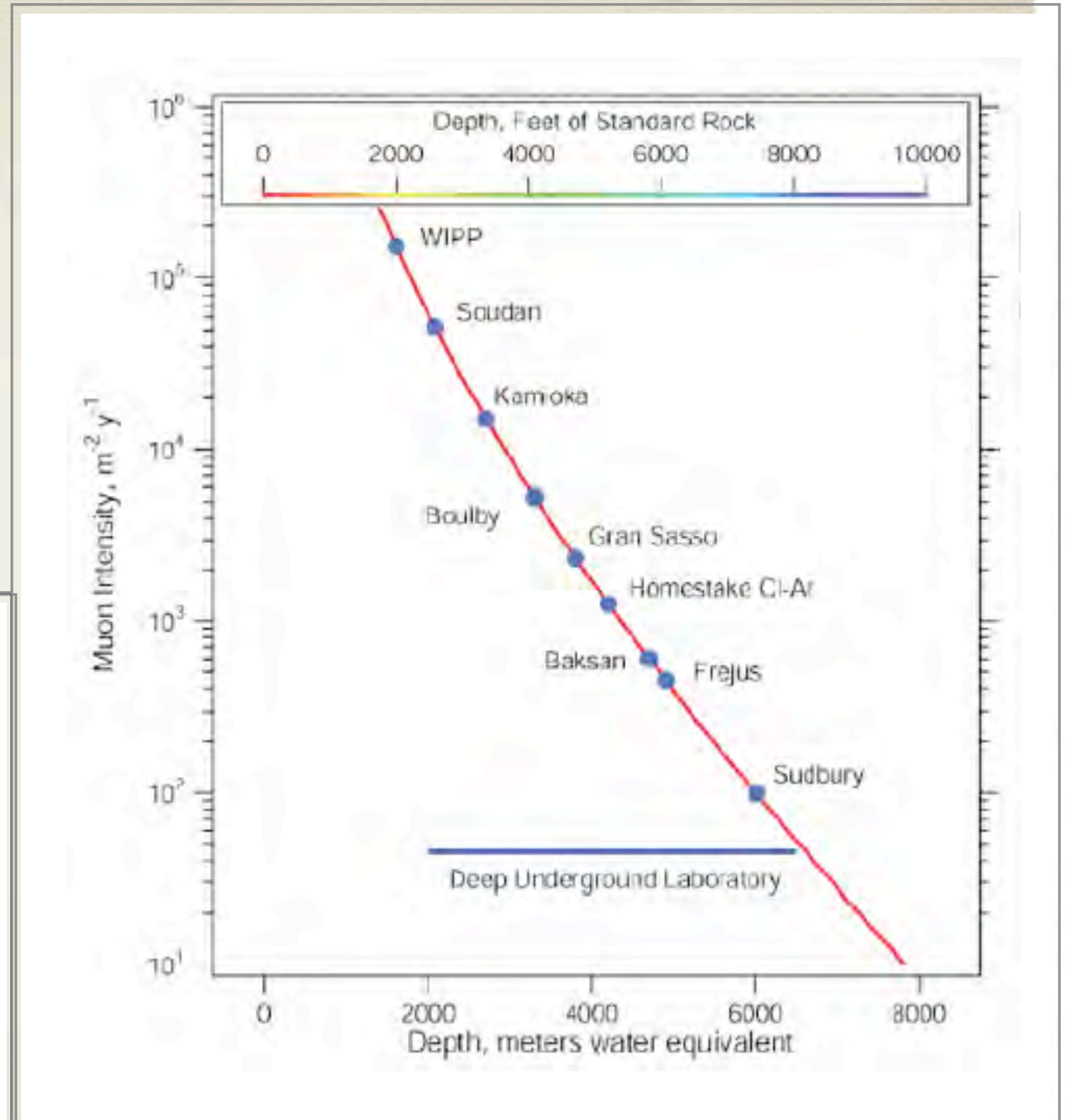
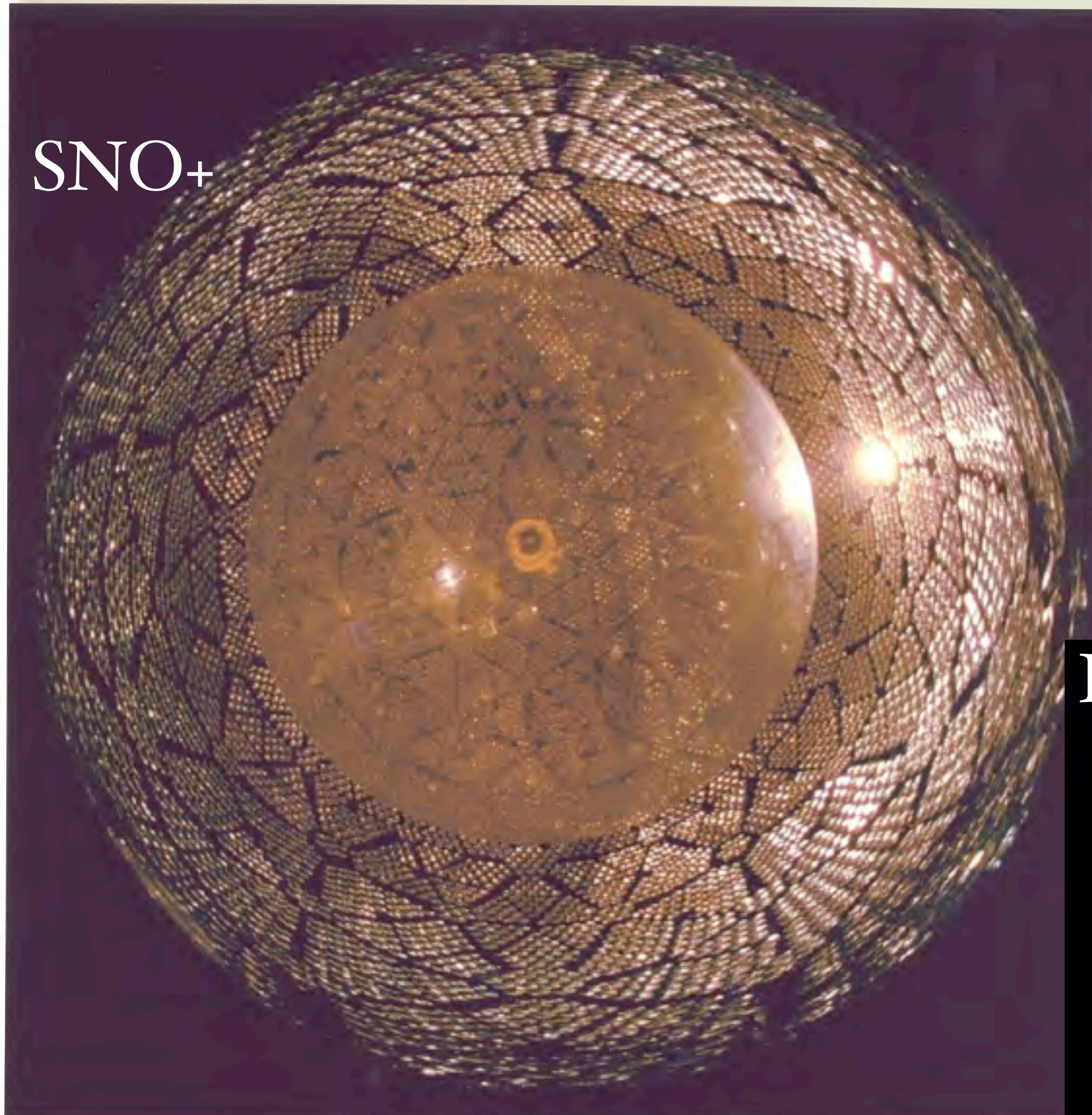




Size Does Matter

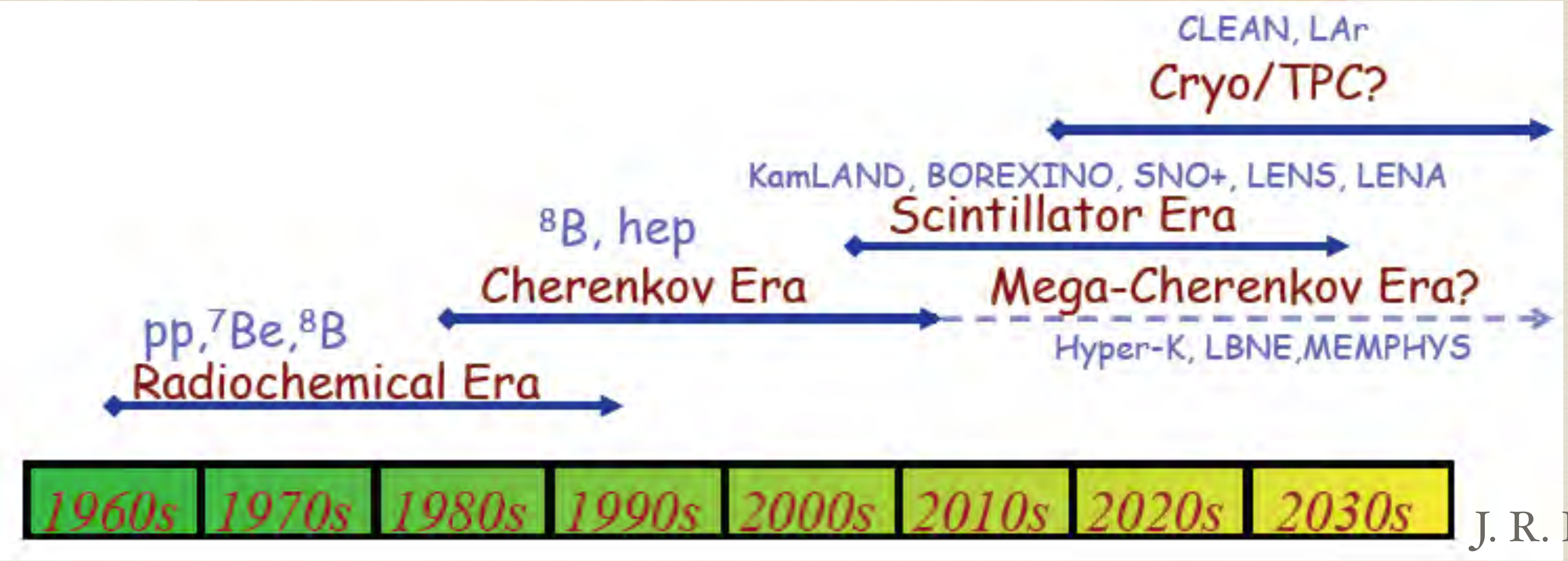


1. Energy resolution:
~2200 vs ~9500 PMTs

2. Size:
278 vs 780ton scintillator
71 vs 400 fiducial

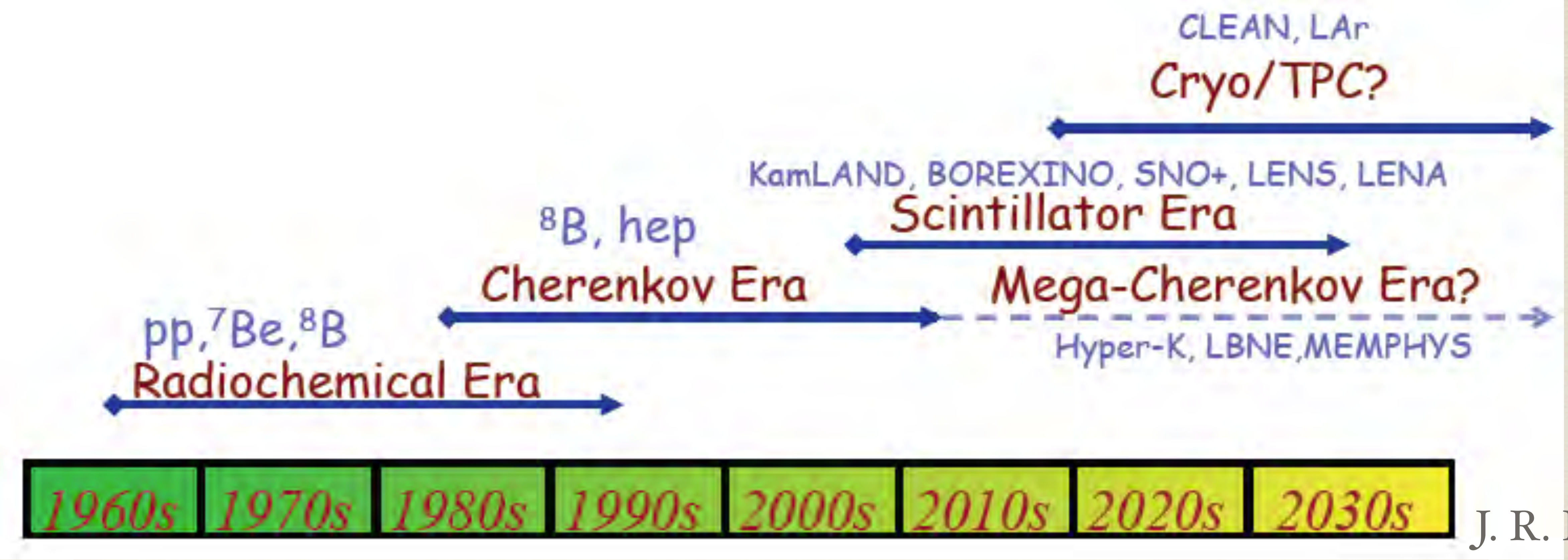
roughly to scale

The Road Ahead



J. R. Klein

The Road Ahead



J. R. Klein

GOALS:

- Precision pep flux
- Low-energy ^{8}B flux
- Day/Night asymmetry
- CNO flux
- Direct pp flux

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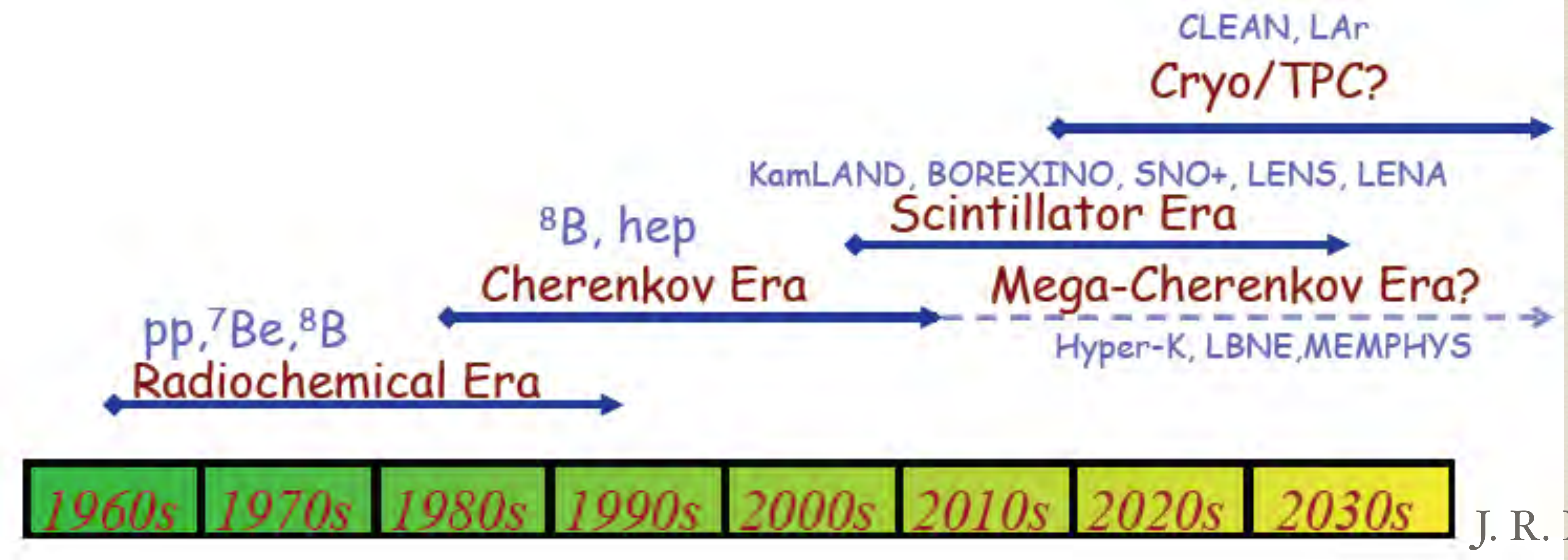


J. R. Klein

GOALS:

- Precision pep flux
- Low-energy ^{8}B flux
- Day/Night asymmetry
- CNO flux
- Direct pp flux

Need:
CC detection (spectrum)
Ultra low bkg
Super-sized detector (stats)

On The Horizon

CC detection: LENS

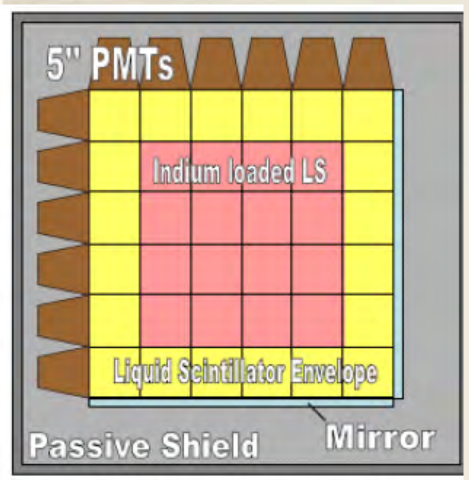
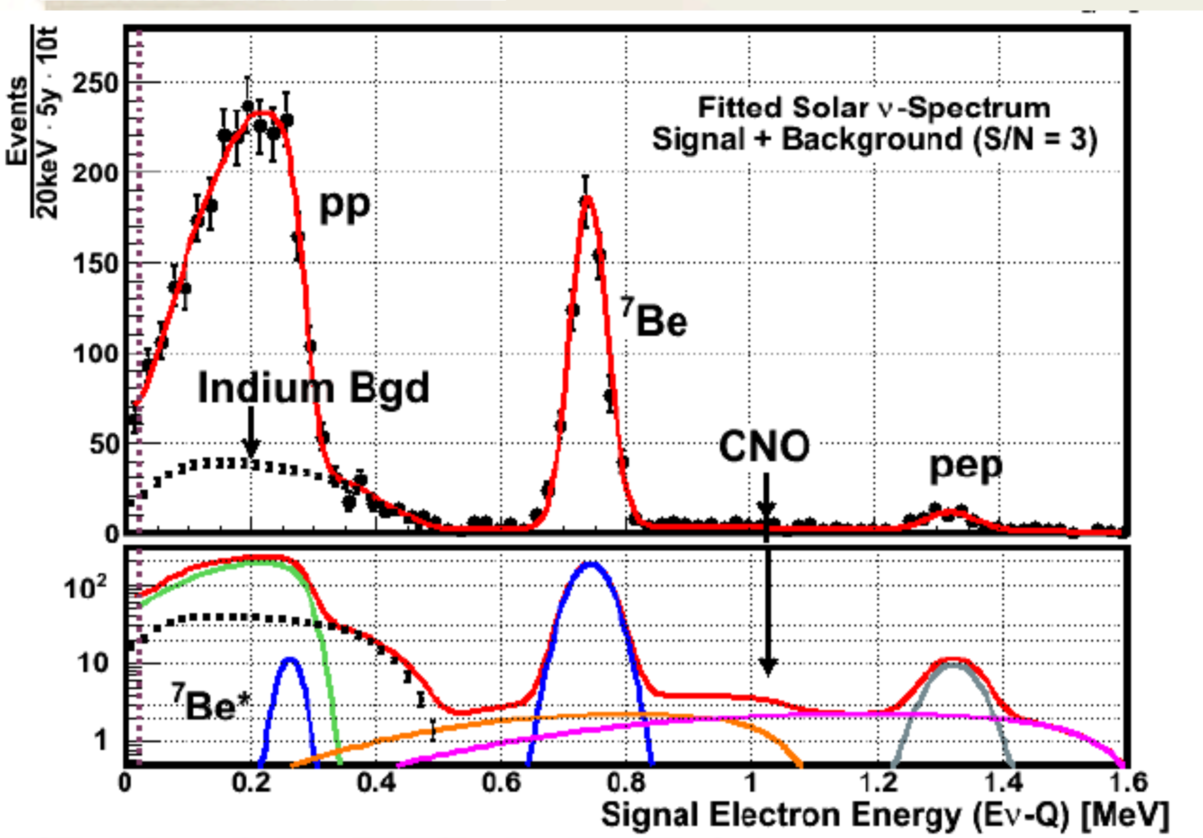


Fig. 12 Schematic design of MINILENS

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



On The Horizon

CC detection: LENS

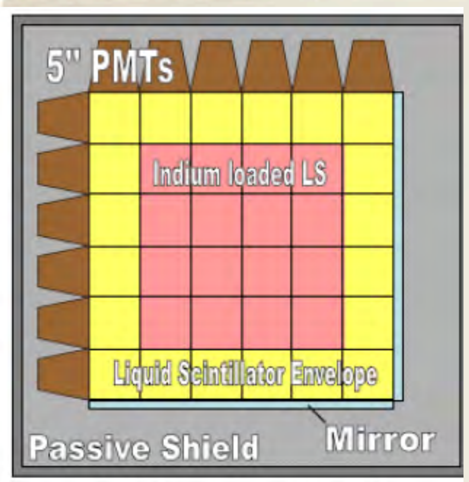
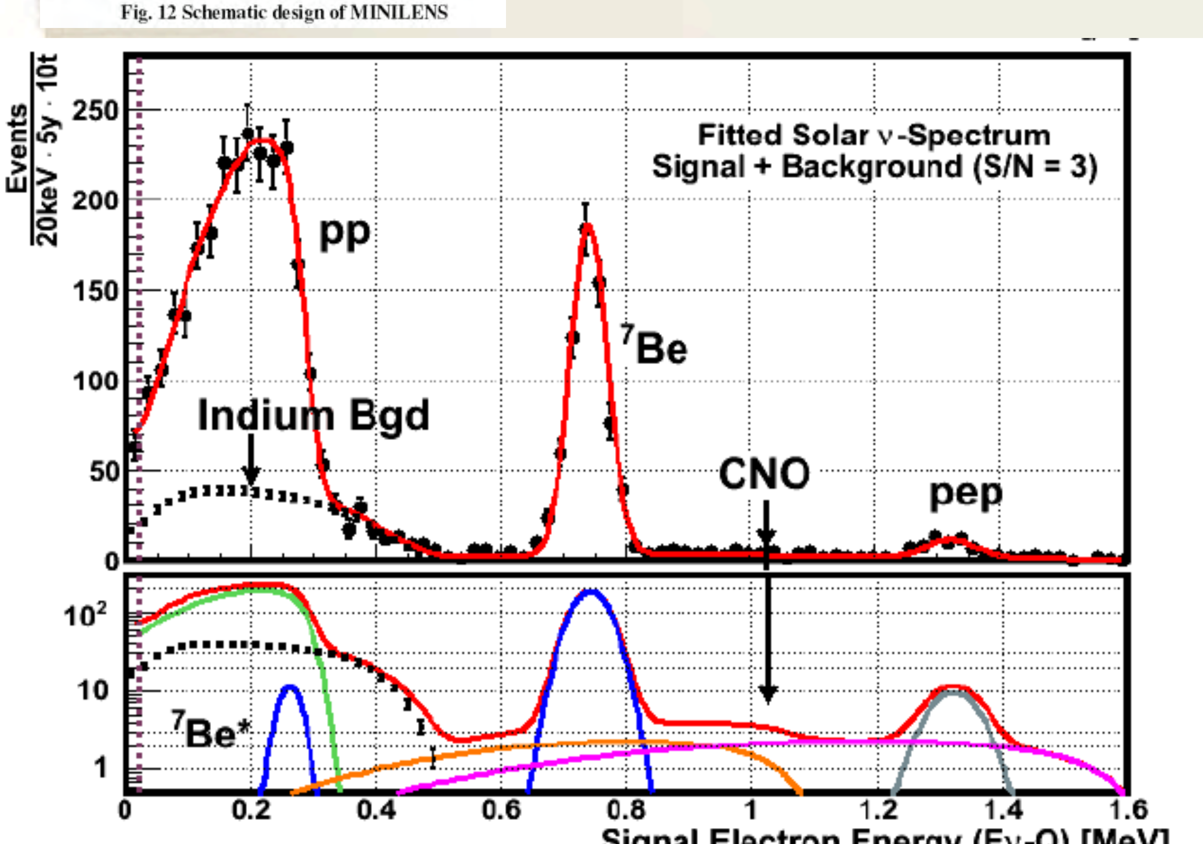


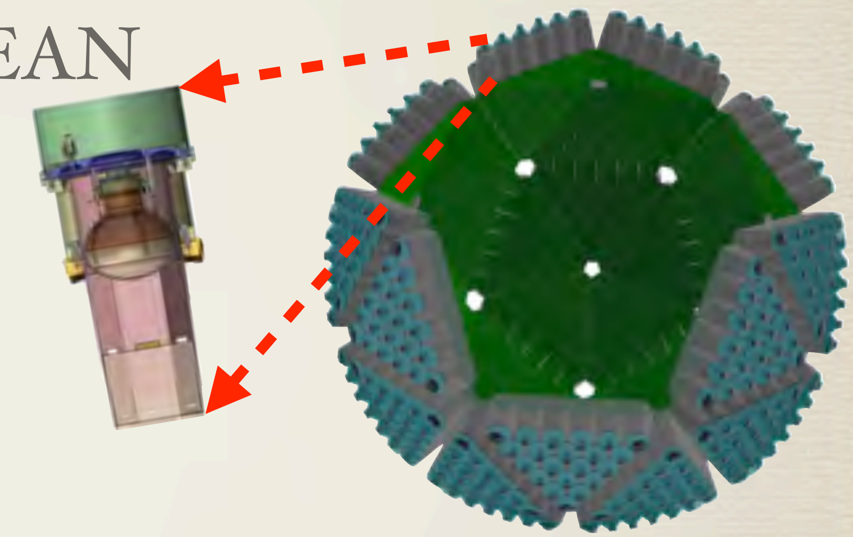
Fig. 12 Schematic design of MINILENS

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

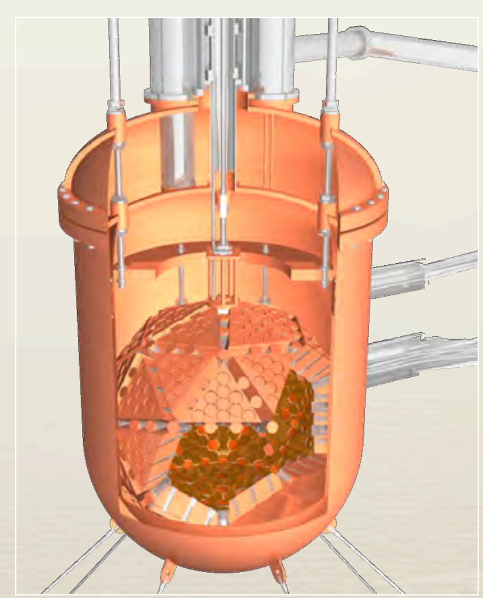


Noble Liquid DM

CLEAN



XMASS



Large-scale LXe, Ne, Ar

Low bkg

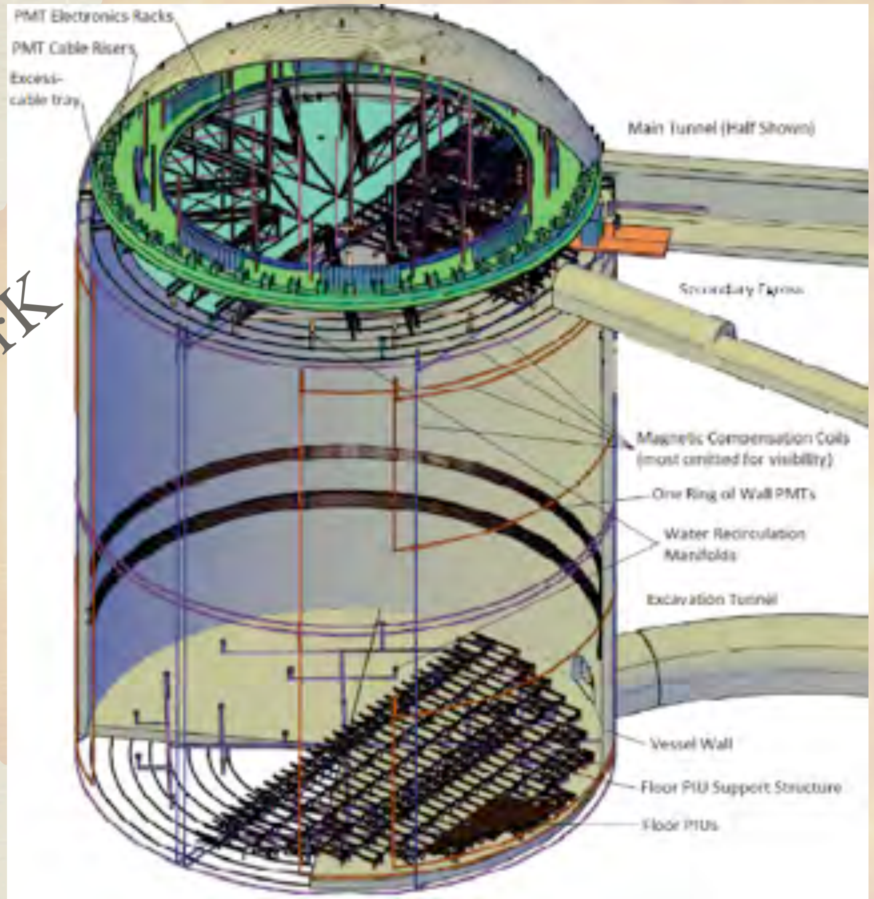
Elastic Scattering

Xe requires depletion of ^{136}Xe ($2\nu\beta\beta$) ~ 100*

Potential for %-level *pp*

Mega-Ton Scale

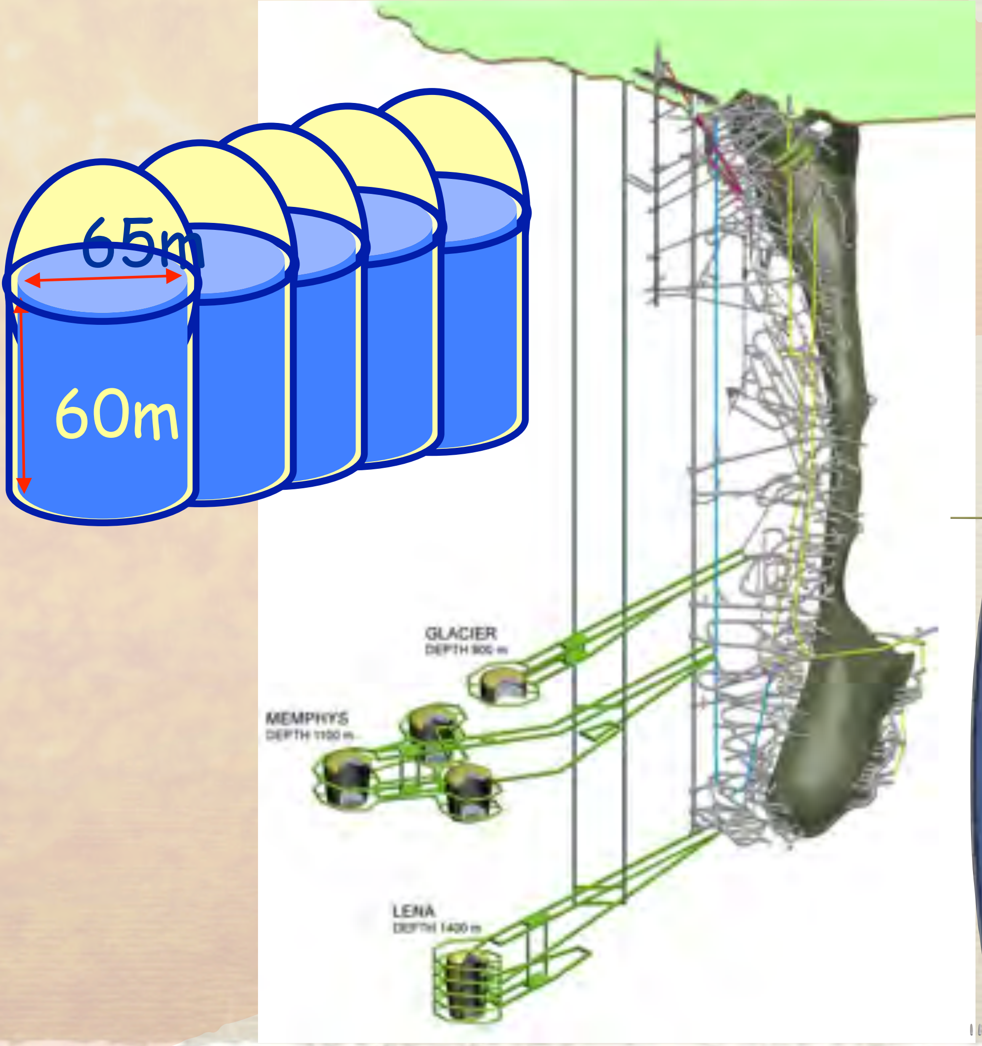
Hyper-Kamiokande

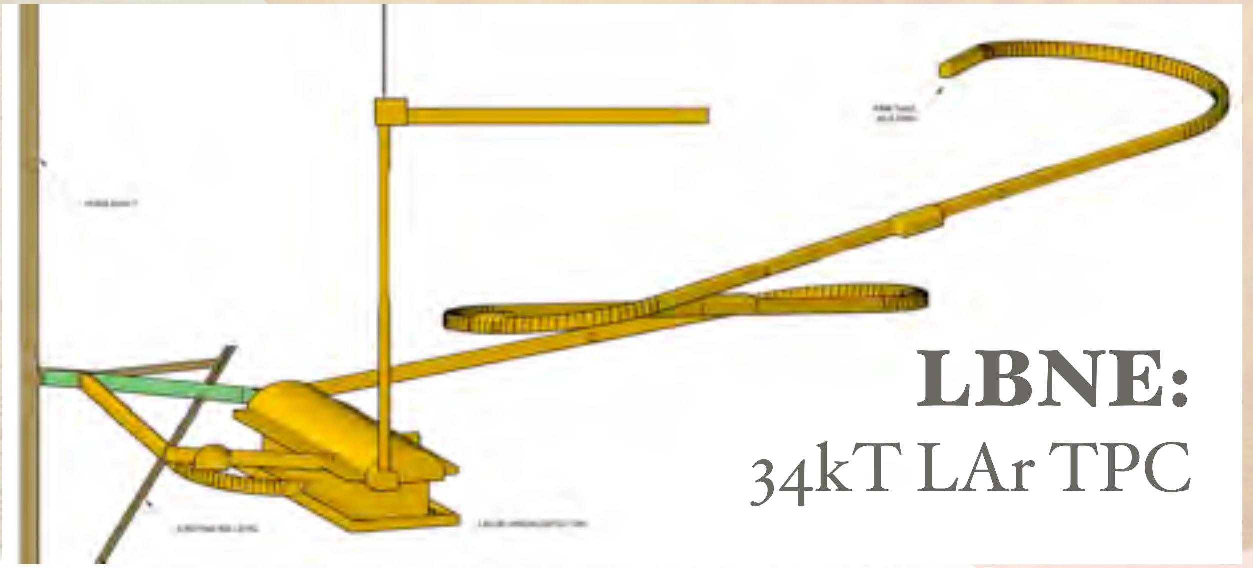


0.99e6 T
20* SuperK

Laguna

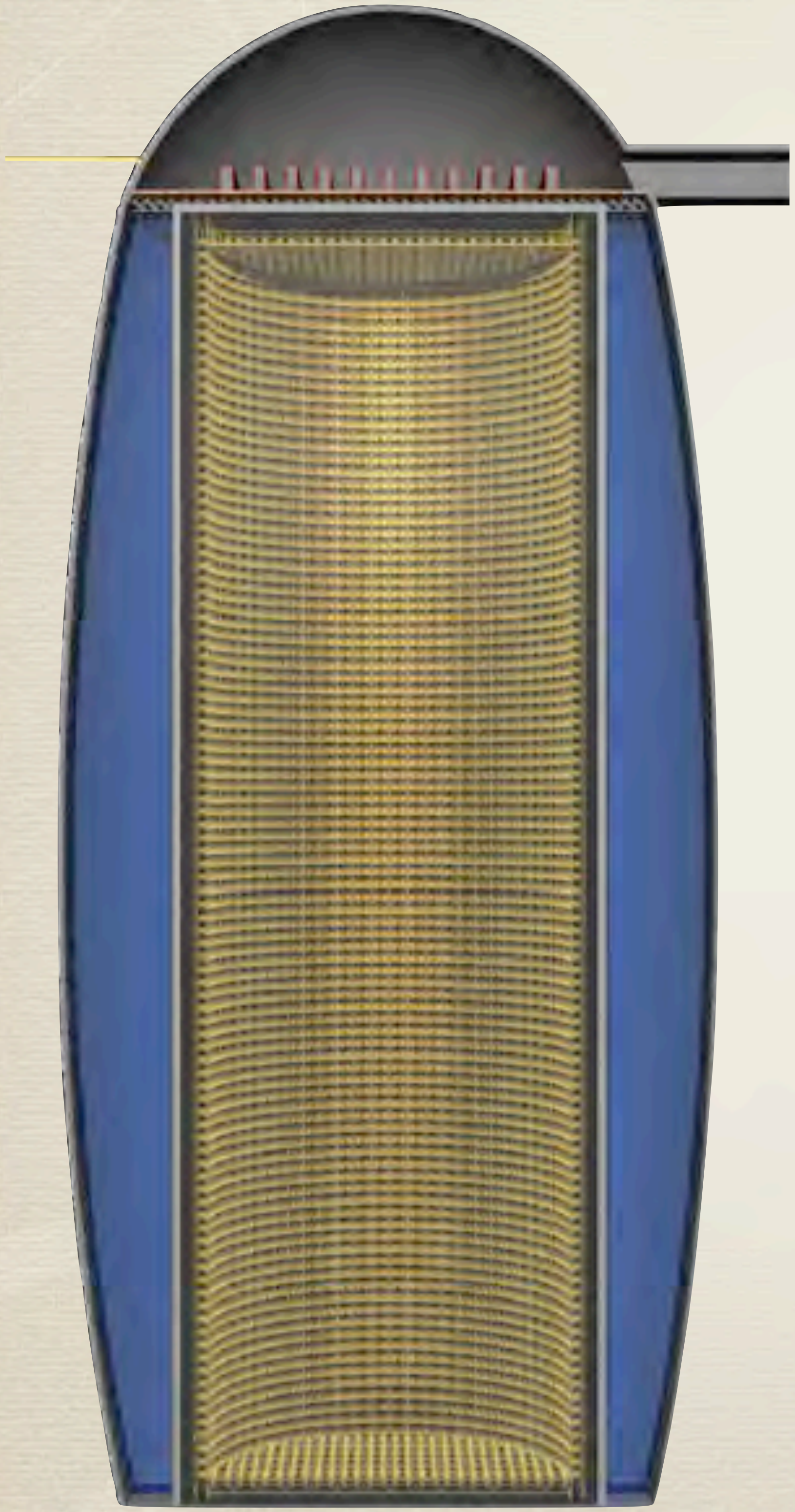
LENA: Liquid scintillator
GLACIER: up to 100kt LAr TPC
MEMPHYS: >400kT Water Cerenkov





LBNE:
34kT LAr TPC

Low Energy Neutrino Astronomy



* 50kT (30kT FV solar),   30% coverage
* Unprecedented statistics
* 3σ discovery potential for 0.5%-amplitude temporal fluctuations in ^{7}Be

Detection Channel	Neutrino Source	BPS08(GS) (cpd) total	BPS08(GS) (cpd) >250 keV	BPS08(AGS) (cpd) total	BPS08(AGS) (cpd) >250 keV
$\nu e \to e\nu$	pp	626±3	41.5±0.3	632±3	42.0±0.2
	pep	785±8	609±6	806±8	626±6
	hep	0.29±0.03	0.27±0.03	0.30±0.05	0.29±0.05
	^{7}Be	14490±864	8307±495	12968±779	7434±447
	^{8}B	141±15	137±15	113±12	108±12
	CNO	2919±468	909±146	1874±279	584±87
$^{13}C(\nu_e, e)^{13}N$	^{8}B	2.9±0.3		2.6±0.2	

* CC on ^{13}C

J. Winter et al, TAUP 2011 Proc.

http://www.e15.ph.tum.de/research_and_projects/lena/

Experimental Techniques
or "How to Scale Up?"

* Increase light collection
    * HQE PMTs + light concentrators
    * LAPPD (Large Area PS Photo Detector)
* Increase light yield
    * Reduce attenuation
    * Additive e.g. quantum dots (*)
* Increase information
    * Directionality from Cherenkov component

(*) "Next Generation Liquid Scintillator Based Detectors: Quantums Dots and Picosecond Timing" L. Windlow

Water-Based LS Target

Dissolution of LS into ultra-pure water

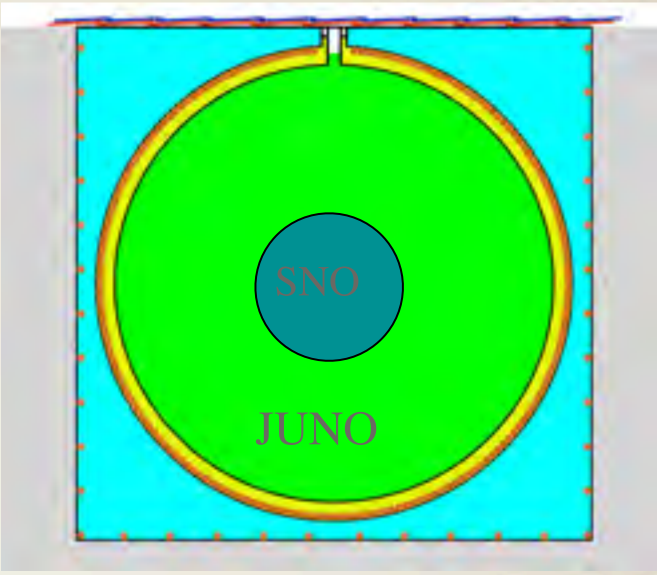
- High light yield of LS
  - ➡ Low energy threshold
  - ➡ Good energy resolution
- Directional info from Cherenkov in H_2O
- Long attenuation of water
- Increased metal loading (hydrophilic ions)

M. Yeh et al., BNL (arXiv 1308.0493)

Dream Detector

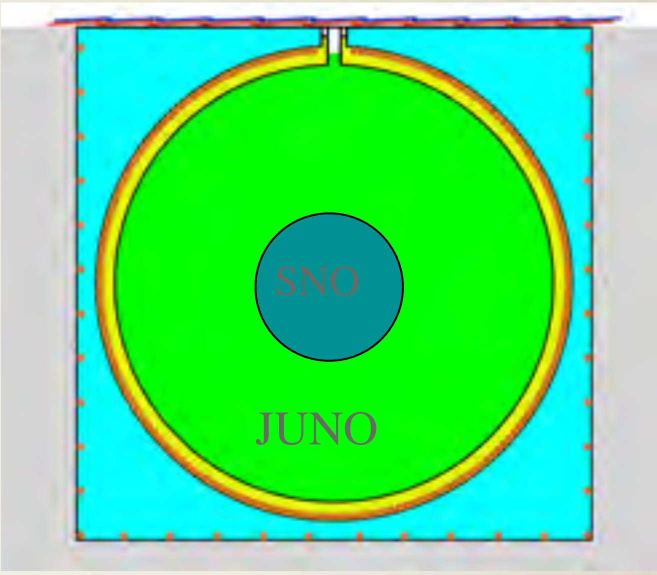
Dream Detector

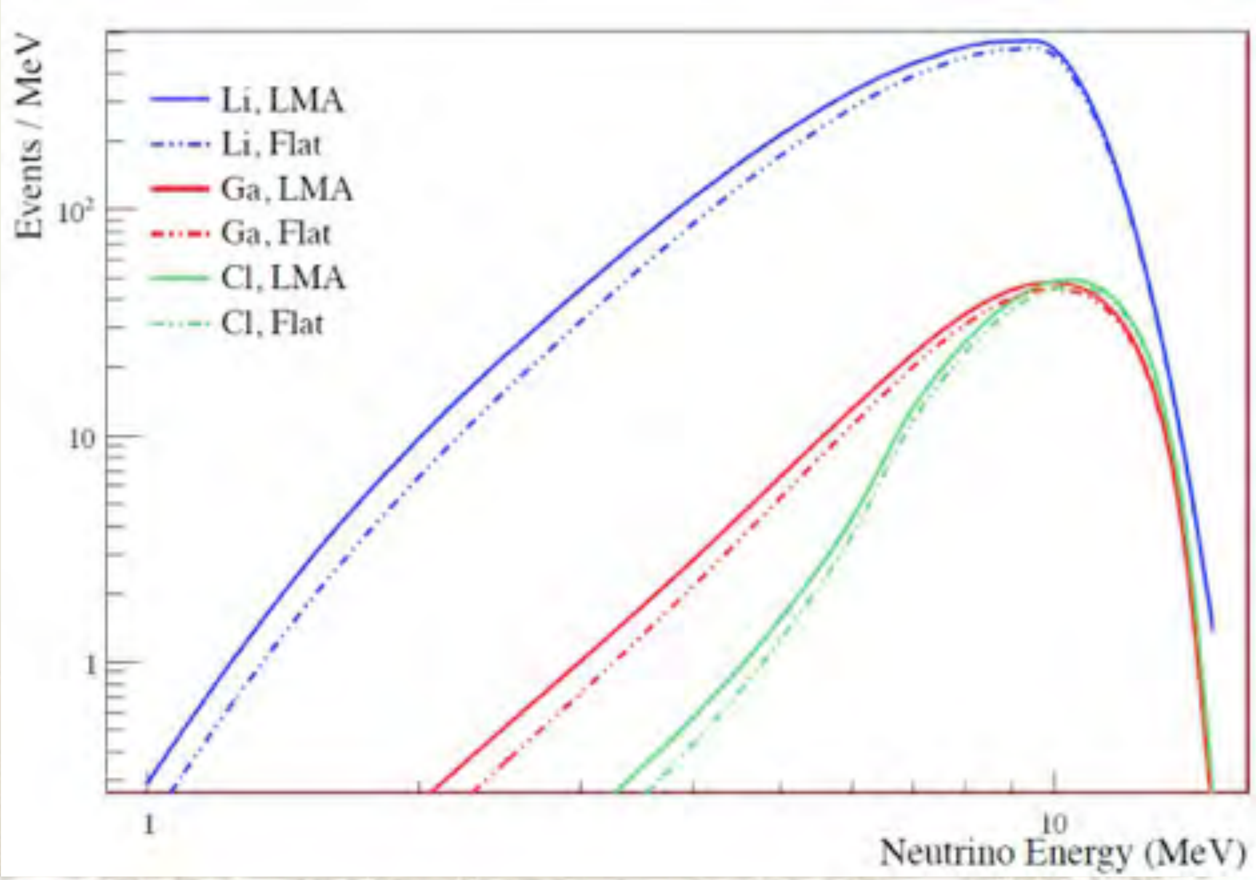
- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution



Dream Detector

- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution
- Load with isotope: CC detection
  - ➡ ^{7}Li, ^{37}Cl, H-WbLS?





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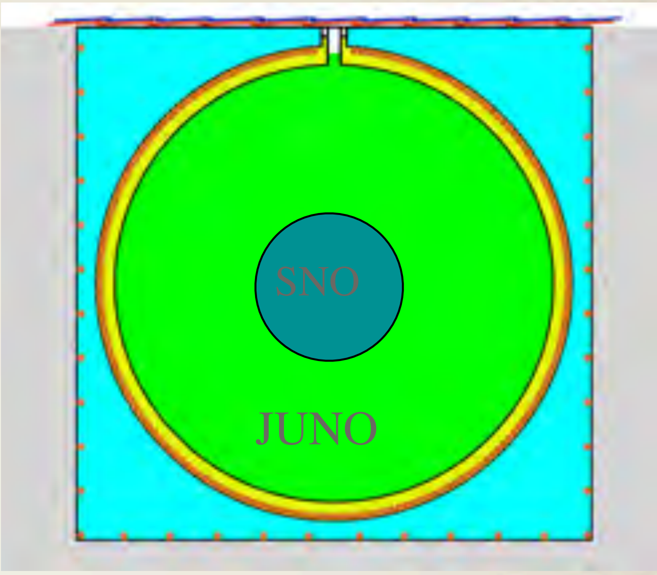
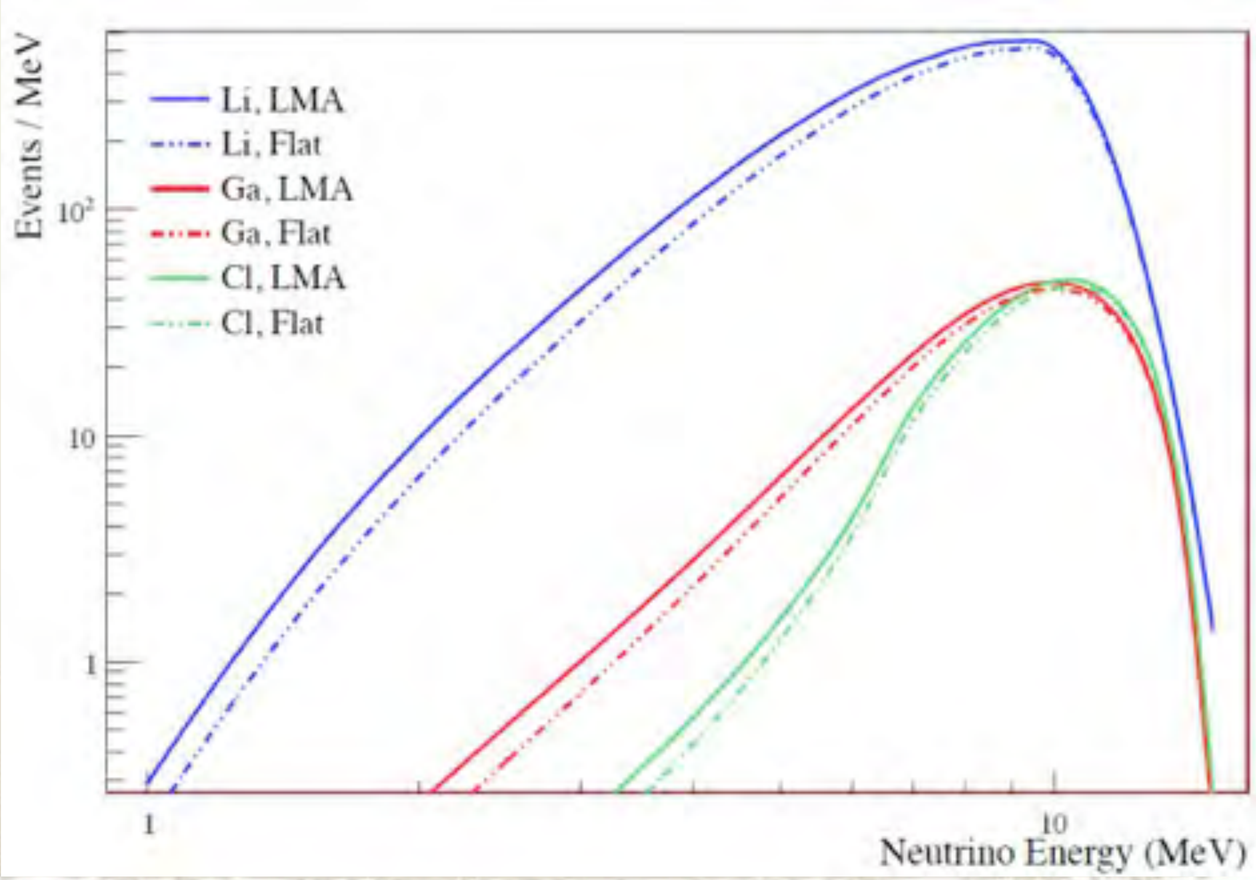


- *Comparable event rates for*
  - *a) 30kT $^{13}C_{nat}$*
  - *b) 5% ^{7}Li in 780T*



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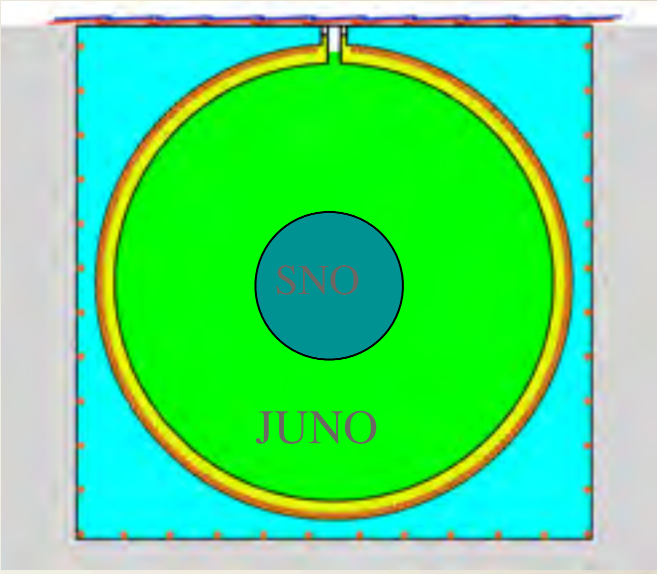
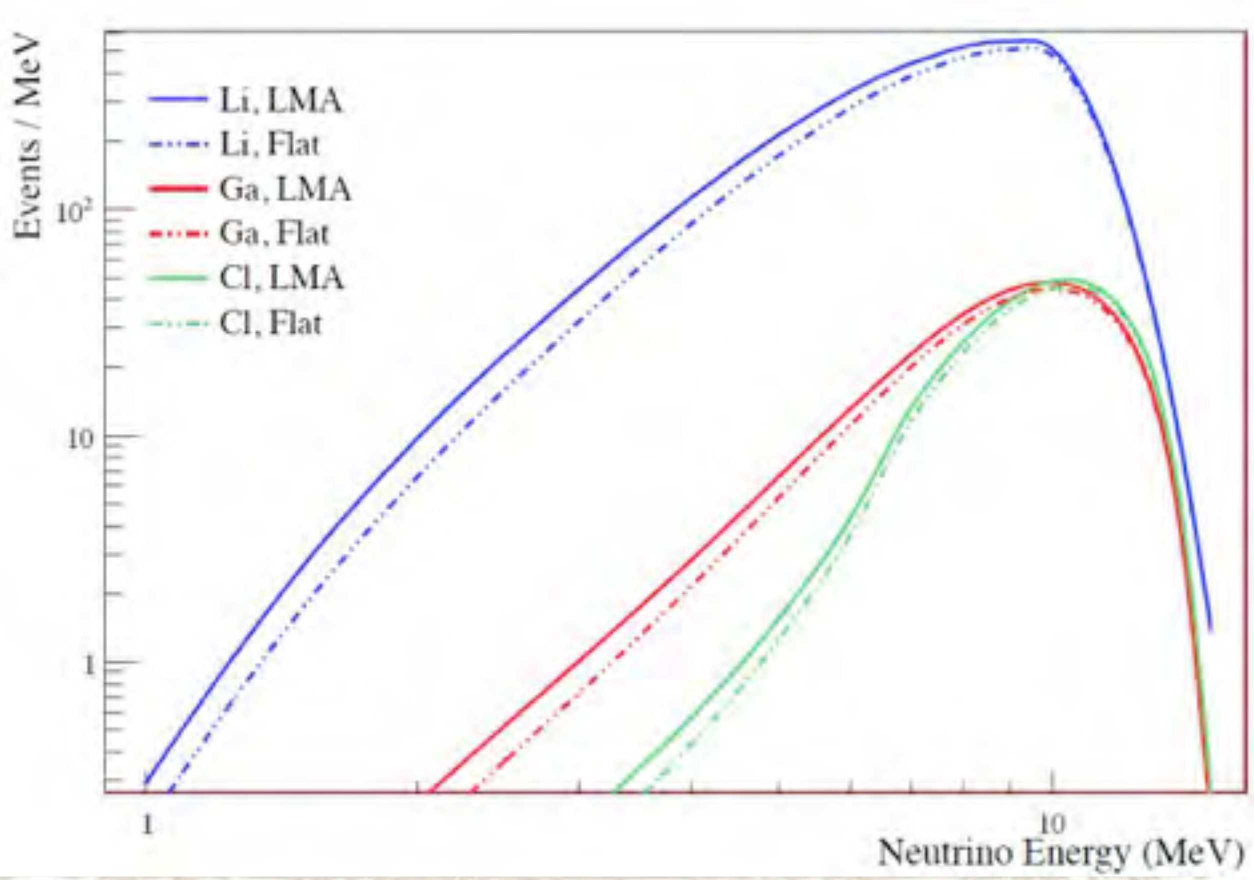
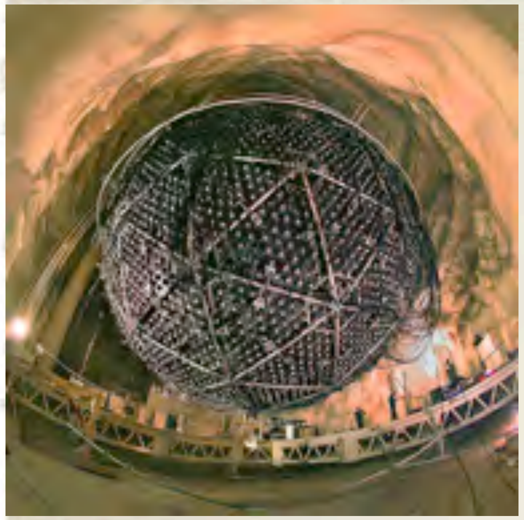


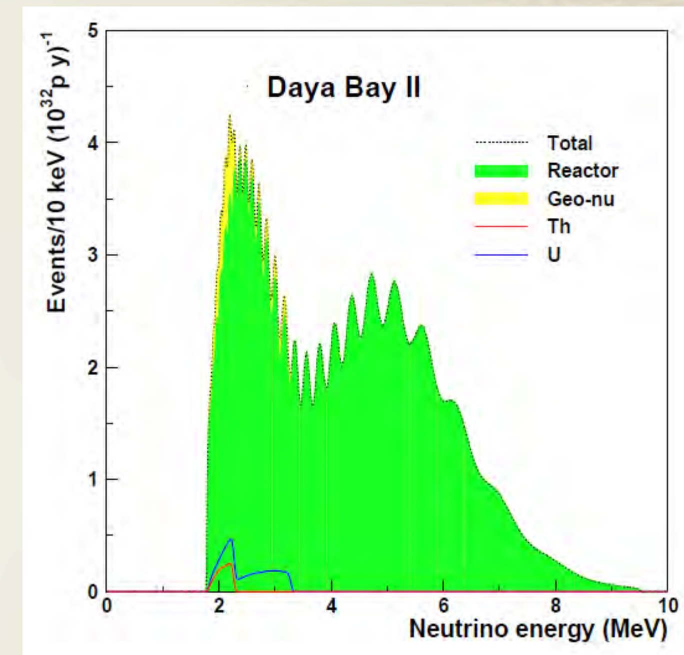
- *Comparable event rates for*
  - *a) 30kT $^{13}C_{nat}$*
  - *b) 5% ^{7}Li in 780T*
  - *6σ in 5 yrs (LMA vs flat)*



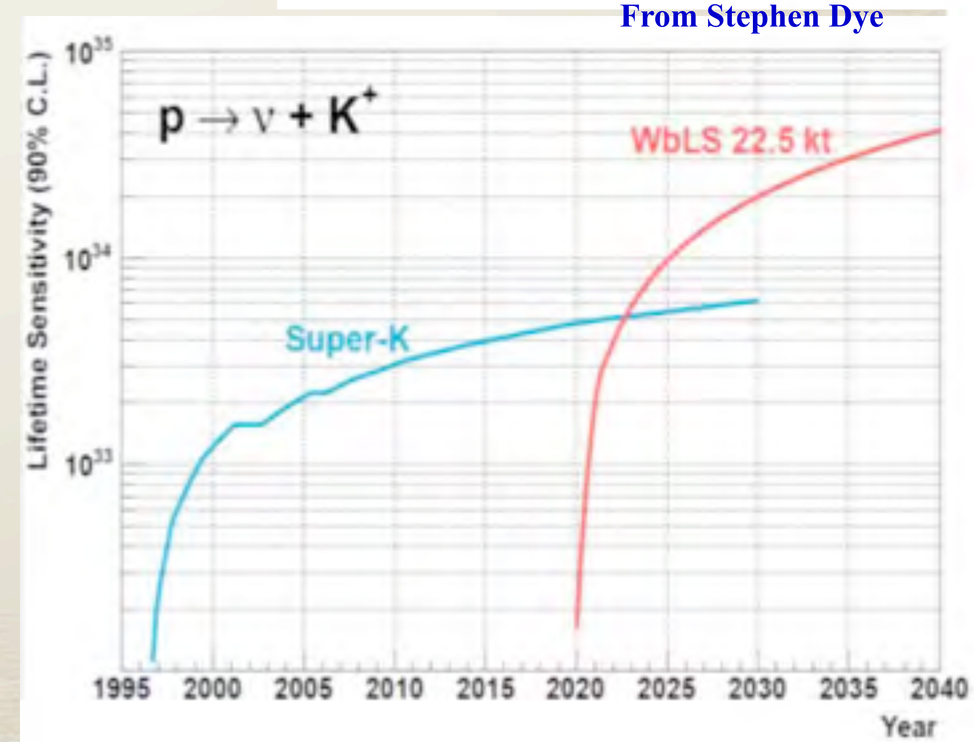
Other Physics (!)



- Neutrinoless DBD
- Neutrino mass hierarchy
- Geoneutrinos
- Supernova neutrinos
- Proton decay



From Stephen Dye



Summary

- Major accomplishments in recent decades
- Many open questions remain
    - *Confirm MSW*
    - *Resolve metalicity*
    - *Determine L constraint*

- Unique opportunity to probe behaviour of neutrinos *and* solar structure
- Need a new, large-scale, high precision experiment!


Thank you
for your
attention